LARGE AREA FLEXIBLE PRINTED CIRCUITS FOR AUTOMOTIVE APPLICATIONS

by

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A Doctoral Thesis

Submitted in partial fulfilment of the requirements

For the award of

Doctor of Philosophy of Loughborough University

31 December 2007

ABSTRACT

To meet the demands for safety and passenger comfort, modern passenger cars offer more and increasingly sophisticated electrical and electronic systems. The wiring harnesses that support such systems become too large, complex and heavy, when designed for a conventional electrical architecture based on 14 volts, posing several challenges to automotive manufacturers. Alternative electrical architectures based on 42 volts and in-vehicle multiplexing promise to reduce the size and weight of the wiring harness, but these architectures are yet to be fully developed and standardized. In the near term, alternative wiring solutions have gained the interest of automotive manufacturers.

Small flexible printed circuits (FPCs) have previously been integrated into automotive instrument clusters. The benefits of reduced weight and space requirements of such FPCs compared to a wire harness has fuelled an interest in much larger FPCs as substitutes for the Instrument Panel and door harnesses in high-volume production cars. This research investigates the materials typically used in FPC manufacture, for applicability within a passenger car.

A methodology for estimating the time required for accelerated ageing of dielectric polymer films intended for use in automobiles has been devised; based on the established rate of hydrolytic degradation of PET film, and the microclimate of a passenger vehicle. Proposals have been presented for a FPC specification that would enable the selection of candidate materials used in the manufacture of large area automotive FPCs.

A secondary problem - that of designing a FPC to replace an existing wiring harness has also been investigated. The two separate design approaches for implementing a large area FPC substitute wiring harness were investigated using a commercial Electronic Design Automation (EDA) suite. Both approaches have yielded an unrealistic and impractical solution, and therefore a recommendation that large area FPCs be designed for new vehicle models has been made. Further, an analysis of the experimental procedure followed in this research has been presented along with recommendations for future work in this area.

ACKNOWLEDGEMENTS

This Thesis would not have been possible without the support and encouragement of a number of people. Firstly, I would like to thank my supervisor, Dr. Andrew West for his extreme patience during my moments of despair, for his guidance and encouragement throughout the past years. I would also like to thank my fellow researchers who have read this thesis, providing useful feedback, especially Dr. Patrick Webb, Mike Cottrill, David Whalley, Paul Palmer and Paul Conway. To Jo Mason, who checked up on me from time to time and ensured my paperwork was in order at all times, I am very grateful.

I am especially indebted to Dr. Graham Farmer of GTS Flexible Materials Ltd, Mark Joyce of Yazaki Europe Ltd and John Astill of In2Connect Ltd (formerly Pressac), for their support and valuable insights into the subject of this thesis. Additional support has been provided by other companies and researchers that are too many to mention, but whose assistance is greatly appreciated.

To my wife, I love you and thank you. For the support and encouragement throughout the years, I thank my friends and family. I dedicate this thesis to my mother who has been supportive of all my endeavours and to my father, who would be proud had he been here today. Finally, I thank God who has been with me at all times.

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1 INTRODUCTION

1.1 Background

Driven by a consumer demand for comfort and safety, new passenger cars offer a greater number of increasingly sophisticated end-user features. Infotainment[1] systems as shown in Figure 1.1 are already available on very-high-end vehicles. Other systems, for example, X-by-wire[2], are under development. Figure 1.2 illustrates a timeline by which it has been forecasted some end-user features would become available as standard options in mid-range and low-cost vehicles [Birch, 1995]. The growth in electrical/electronic content and interconnectivity requirements to support these features has resulted in wire harnesses of greater complexity, size and weight when designed for a conventional 14-volt point-to-point electrical architecture. Already in high-end passenger cars the total length of wire used can exceed 4 km [Leen and Heffernan, 2002], and there may be over 350 connectors and nearly 1500 cut leads (number of circuits) [Miller and Nicastri, 1998].

Figure 1.1 Audi A8 als Multimedia Car [IVM Automotive, 2002]

[1] Acronym for 'Information and Entertainment'

[2] X-by-Wire is a generic term referring to the replacement of mechanical or hydraulic systems, such as braking or steering, by electrical and electronic systems.

Such wire harnesses have presented challenges to automotive OEMs at all stages of the vehicle life cycle, as illustrated in Figure 1.3. Increasing the number of circuits to be included in the harness would naturally add to the difficulties experienced by the harness designer, some of which have been described by Ng, Ritchie and Simmons [2000]. Regardless of size, wire harnesses must minimize voltage drops, provide immunity against Electromagnetic Interference, and yet physically fit within a limited space in the vehicle. Prudent design also requires the use of a de-rating factor for the current-carrying capacity (ampacity) of insulated wires bundled in a harness. To provide adequate protection against ohmic heating in larger wire bundles, wires of increased diameter are therefore required. The attendant increase in harness weight and complexity may also affect assembly into the vehicle, that being a labour intensive and time-consuming process. An increased number of wire joints and connectors would also invariably diminish the reliability of larger, more complex harnesses during its service life.

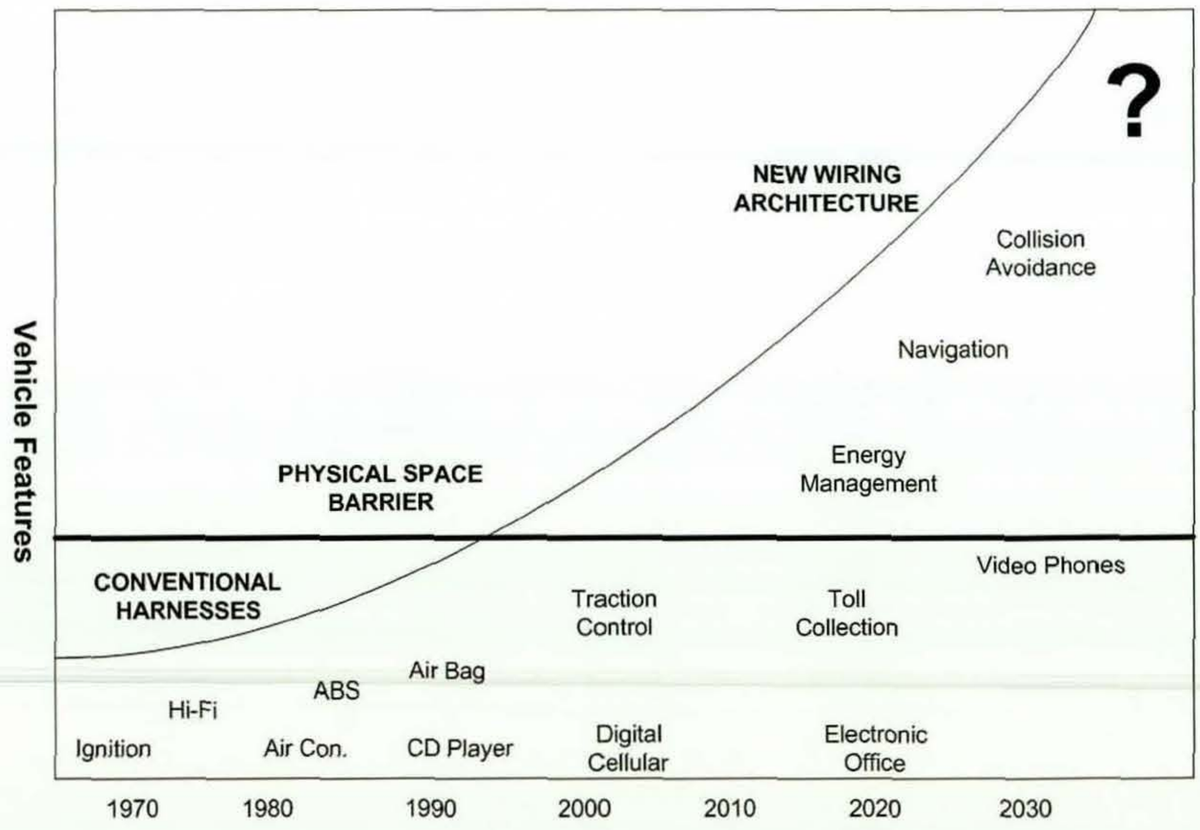

Figure 1.2 Forecasted Growth in Vehicle End User Features [Birch, 1995]

With each additional 50kg load, fuel consumption increases by 0.2 litres per 100 km travelled on a fine-tuned modern passenger car [Leen and Heffernan, 2002]. The additional weight of larger wire harnesses would further contribute to increased vehicle emissions, and this would be a challenge to overcome in any major automotive market where Legislation aiming to reduce emissions has been enacted, such as the European Union [European Union, 2009].

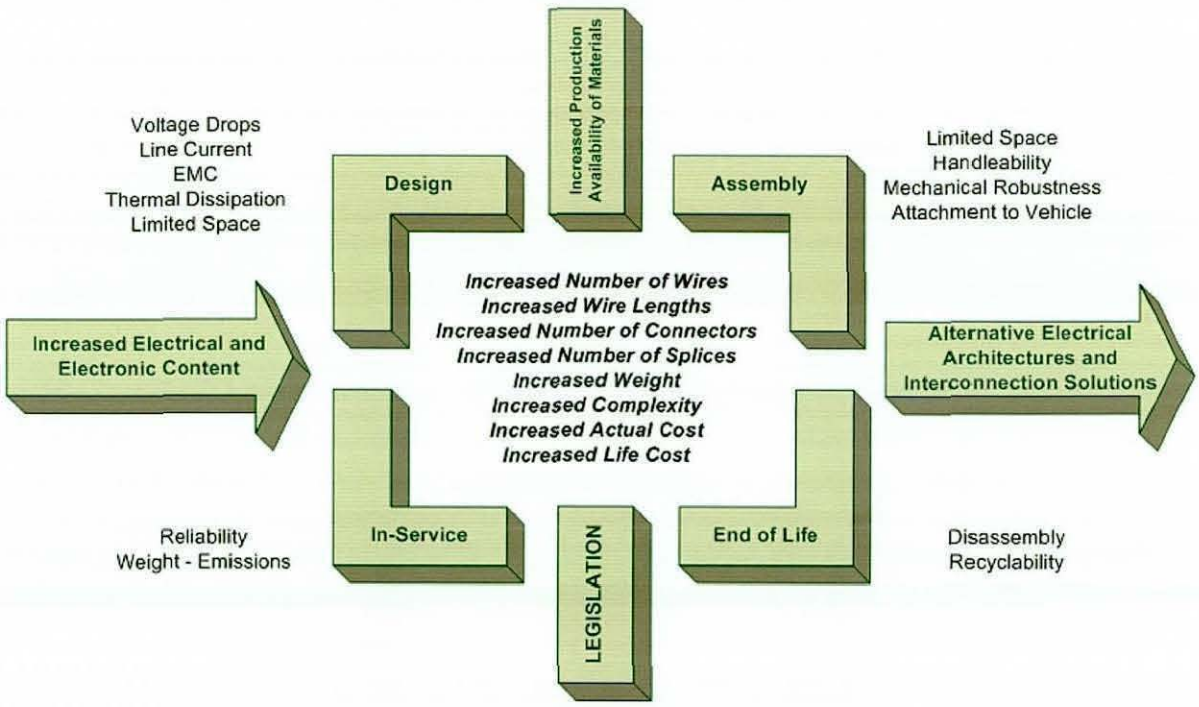

Figure 1.3 Challenges Arising From Increased Electrical and Electronic Content

Another major challenge facing automotive OEMs is the environmental impact of larger wire harnesses in end-of-life vehicles. The disassembly of wire harnesses from end-of-life vehicles, and separating its constituent materials for recycling is costly, labour-intensive and time-consuming, and in Europe, the 'End of Life Vehicles' Directive [European Union, 2000] mandates automotive OEMs to increase by year 2015 the minimum recycled mass of a passenger vehicle to 95%.

Larger wire harnesses could also present challenges along the supply chain. Light vehicle sales in Western Europe between 1999 and 2014 are forecasted to hover near 17 million units annually [J.D. Power and Associates, 1999]. A comparable level of vehicle sales is forecasted for North America. The total worldwide sales in light vehicles are however expected to grow from 55 million units in 1999 to over 71 million units by 2014. At these increased sales levels, coupled with an increase in the copper content used by larger harnesses, the availability of raw materials may become an economic and engineering problem. Further, Aguirre and Raucent [1994] have suggested that there is also an unavailability of automated manufacturing equipment for the production of large complex harnesses. The implication of these factors is a disproportionate increase in the economic cost of large complex wire harnesses.

These challenges aforementioned have contributed to the automotive industry's pursuit in adopting alternative methods of electrical power and signal distribution.

1.2 Alternative Electrical Distribution and Interconnection Systems

The desirability of any electrical distribution system (EDS) intended to replace conventional wiring harnesses designed for a 14-volt point-to-point architecture is dependant not only on a demonstrable reduction in space requirements and weight; improved reliability coupled with a reduced total life-cycle cost are of paramount importance.

Electrical architectures based on 42 volts are inevitable [Kassakian et al, 1996]. Together with CANbus multiplexed networks, these architectures have promised to reduce significantly the size of and number of wires used in harnesses. However, 42-volt systems are not yet fully developed, and multiplexed networks are not prevalent on mid-range and low cost passenger cars. Alternative interconnection systems have gained the interest of automotive OEMs during this transition period.

Moulded interconnection devices (MIDs) have been integrated into seatbelt locking clips and tail-lights [Feldmann and Pohlau, 1998], but applications of such devices are limited to providing internal wiring within sealed components. Flat Flexible Cables (FFCs) consisting of parallel rolled-annealed conductors, insulated within a laminated or extruded dielectric polymer have found increasing applications within passenger cars. FFCs offer very attractive weight and space savings, but face limitations in respect of seamless connectivity to other

FFCs. A further disadvantage of FFCs is the inability to vary conductor width and pitch, disallowing any real discretion in layout [Mortier, 1999].

1.2.1 Flexible Printed Circuits

Flexible Printed Circuits (FPCs), ubiquitous in the electronics industry, offer similar weight and space savings as FFCs. FPCs consist of a conductive pattern, typically insulated within two layers of a dielectric polymer film. FPCs may be constructed using a variety if materials, arranged in any of the sectional configurations illustrated in Figure 1.4. Some typical materials used in the manufacture of FPCs are listed in Table 1.1.

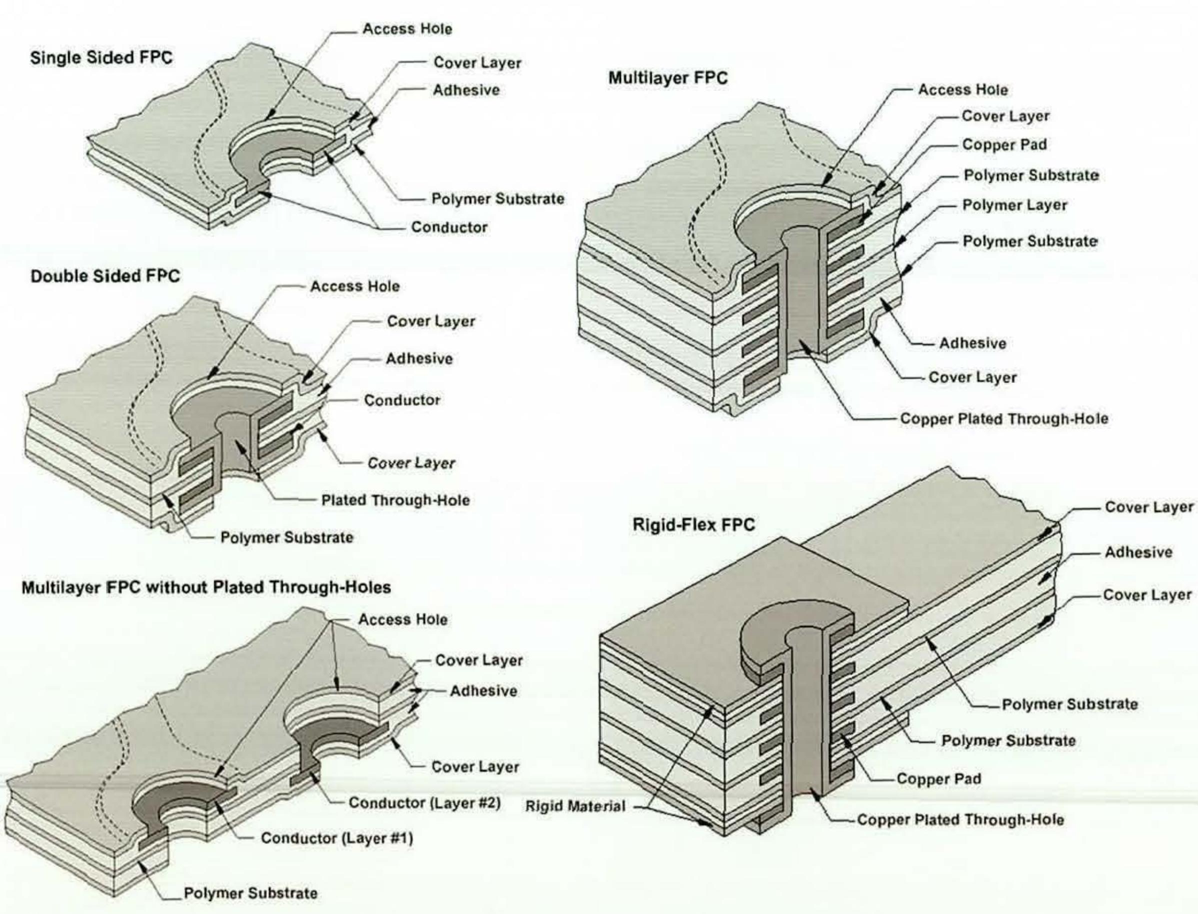

Figure 1.4 Typical FPC Sectional Configurations

Material Function	Material Type	Typical Sizes/Thicknesses (in Inches)
Flexible Insulator	Polyester Terephthalate (PET)	0.0005", 0.001", 0.002", 0.003", 0.005"
	Polyester Naphthalate (PEN)	
	Polyimide (PI)	
	Dielectric Ink (Cover Layer Only)	
Rigid Substrate (Rigid-Flex)	FR-4	Varies between 0.003" and 0.125"
	Polyimide Glass	
Conductor	Copper	0.5oz., 1 oz., 2 oz., 3 oz., 5 oz. (weight per sq. ft Rolled-Annealed or Electrodeposited)
	Beryllium copper	0.003", 0.004"
	Cupro-nickel (70/30 alloy)	0.000625", 0.0009", 0.0013", 0.0019", 0.0023"
	Silver Epoxy, Carbon	0.001"
Metal Finish	Nickel, Gold	0.002", 0.003", 0.005" (Electroless or Electroplated)
Adhesive	acrylic	0.0005", 0.001", 0.002", 0.003", 0.004"
	epoxy	
	Phenolic Butyral	
	Polyester (PET)	
	Pressure-sensitive adhesive (PSA)	0.001", 0.002", 0.005"
	Preimpregnated material (FR-4, Polyimide)	0.002", 0.008"
Stiffener	Copper, Aluminium,, other metals	Varies between 0.003" and 0.125"
	Polyimide	
	FR-4	
	PET	

Table 1.1 Typical Materials used in FPC manufacture

Small FPCs have been previously integrated into automotive instrument clusters, and more recently, have been applied to non-traditional areas of passenger cars, such as roof-liners and steering columns. Some of the benefits and limitations of employing FPCs, compared to the use of conventional round-wire harnesses, and are listed in Table 1.2 [Lindahl, 1995].

Benefits of Flexible Printed Circuits	
Elimination of Splices[3]	Splices are naturally incorporated into FPCs
Weight Savings	Potentially up to 70%
Space Savings	Potentially up to 50%
Electronics Integration	Electronic components can be mounted directly onto FPCs
3D Circuitry	FPCs can conform to most geometric shapes
Mechanical Flexibility	Allowing its use in dynamic flex/bend applications
Heat Dissipation	Larger surface area dissipates heat more efficiently.
Fine Pitch Interconnects	Much smaller conductors compared to minimum size (cross section) of wire used in passenger cars
Ease of handling	Light weight and potentially less bulky
Double-Sided Circuits	Efficient use of space/volume
Improved EMC Performance	FPCs can be specifically designed for EMC
Consistent Product Quality	By virtue of automated manufacture of FPCs
Limitations of Flexible Printed Circuits	
Size Limitations	Manufacturing Equipment unable to process large widths
Current Carrying Capacity	Not properly defined for Engineering purposes
Connector Choices	Limited availability of connectors
Handling[4]	Larger FPCs are not rigid enough to be self-supporting

Table 1.2 Benefits and Limitations of FPCs Compared to Conventional Wire Harnesses

[3] A splice is a node where separate wires are electrically and mechanically joined, typically along the length of a larger power or ground wire.

[4] Not listed by Lindahl [1995], as the author's focus had been small FPCs used in Instrument Clusters.

The established benefits of small FPCs as a means of electrical interconnection within passenger cars has furthered the interest in large area FPCs up to 2m x 10m in dimension as a replacement for entire wiring harness within a vehicle, or for applications within the cockpit, the roof space, and vehicle doors. A number of further potential benefits have been envisaged through the integration of large area FPCs within passenger cars as follows:

Large area FPCs could enable new vehicle design concepts. The use of Electronic Design Automation (EDA) tools for printed circuit layout allows for rapid design change. Whilst nearly all wiring harnesses are manually fabricated, large area FPC fabrication can be fully automated, and readily integrated into the manufacturing processes of the automotive OEM and its 1st and 2nd tier suppliers. By removing a manually intensive assembly process the resultant cost implications can lead to increased competitiveness along the supply chain. Further, the manufacturing trend of increased size of sub-assemblies from Tier 1 suppliers, for example pre-assembled vehicle cockpits, provides an opportunity for integrating large area FPCs earlier in the production sequence.

Large Area FPCs could potentially fill the void of achieving weight and space savings in the near term, particularly in low cost passenger cars that would not normally contain the features of higher end models utilizing multiplexed networks. FPCs that are compliant with the requirements of future automotive electrical architectures may also be used as natural alternatives to round wire harnesses, providing further weight and space benefits in the longer term.

1.3 Scope of Research and Problem Statement

The design and production of small low-cost FPCs on an industrial scale is an established manufacturing practice. Large FPCs of sizes in excess of a metre square can also be produced for specialist applications where cost is not a limiting factor. Vehicle manufacturers have used such high-technology high-cost techniques to create automotive demonstrators, but for realistic and viable automotive applications a number of key business and engineering challenges need to be addressed, including:

i. The impact of implementing such radically new technology on the total product life-cycle cost; consisting of the actual cost per unit, technological added-value, potential savings through new manufacturing processes, subsequent vehicle warranty cost, and end-of-life vehicle recycling cost.

ii. Meeting legislative requirements for safety and recyclability

iii. Manufacturing technology for high volume, low cost production of large area FPCs

iv. Availability of base materials and intrinsic components, particularly connectors

v. Ability of FPCs to handle high current, 14/42 dual system voltages and mixed signal combinations within the automotive environment

vi. Mechanical robustness and reliability over the vehicle lifetime

vii. Size and handleability considerations from design to final assembly and in-service maintenance

The motivation for this research has been the need to assess the capabilities of large area FPCs as a first step in the product development cycle. The investigative work addressing the challenges listed above has been conducted in tandem with other complementary research as part of a collaborative effort involving industrial stakeholders. These included Yazaki Europe Ltd (a wire-harness manufacturer), Pressac Ltd (now In2Connect Ltd - a flexible printed circuit manufacturer), Daewoo Motor Company (an automotive OEM)[5] and GTS Flexible Materials Ltd (GTS - a flexible copper-clad materials supplier).

1.3.1 Approach to Research and Objectives

The approach taken in this research has been to treat the replacement of round-wire harnesses with large area FPCs as a product substitution challenge. There are four basic types of substitution; material, process, design and functional, each being implemented in five steps [Schlabach, 1986]. For large area FPCs, all four types of substitution are applicable.

[5] Daewoo's support was withdrawn in 2001 after declaring bankruptcy.

Once an opportunity for substitution has been defined in terms of cost and performance objectives, the steps in implementation are:

i. Draw on the available research and development stockpile

ii. Begin design and development

iii. Conduct screening tests of viable alternatives

iv. Develop hard design and reliability data, and

v. Evaluate on a pilot scale in the manufacturing environment

One example of substitution in the automotive context was the development of composite wheels, where an opportunity to reduce weight by constructing wheels with lighter composite materials was exploited [Woelfel and Spencer, 1994]. The initial process of substitution included wheel design and reliability testing; which would be followed by proving tests on a road surface. Wheel design was based on existing performance requirements and maintenance equipment. Reliability testing examined the failure mechanisms for composite structures, different to those in metal wheels, yet included traditional test methods for metal wheels, such as exposure to corrosive fluids. A similar approach could potentially be applied to the substitution of round wire harnesses with large area FPCs.

The platform selected for this research has been Class C passenger vehicles, alternatively known as compact cars in the US, and small family cars in the UK. Two examples are the Ford Focus and the Daewoo Nubira, the latter being used for designing the prototype large area FPCs described later in this thesis. This class of vehicle is attractive to the FPC manufacturer because its market size, number of automotive OEMs and vehicle models manufactured. For such passenger cars, the replacement of the Instrument Panel (IP) harness, being the largest and most complicated harness in the vehicle, as well as the door harness have been investigated. Figure 1.5 shows both the instrument panel and door interior of a typical Class C passenger car being assembled.

Two distinct themes within this research have been explored, the first being an investigation of materials used in the manufacture of large area FPCs, and the second being the design of large area FPCs.

Figure 1.5 Interior of Vehicle Showing Cockpit and Door Areas During Assembly

1.3.1.1 Investigating FPC Materials

The selection of appropriate materials and sectional configuration for FPC manufacture is determined by the particular application for which the FPC is required. For large area automotive FPCs, materials selection would be on the basis of lowest cost compatible with an acceptable level of reliability and safety over the lifetime of the vehicle. The requirements for the reliability of large area FPCs used as substitutes for wiring harnesses cannot be overstated. Safety critical systems such as airbags and anti-lock brakes may be connected via the IP harness. Warranty costs should also decrease with increased product reliability. Further, reliable components that are able to withstand operating and environmental conditions lend themselves to encapsulation or over-moulding.

Commercially available base dielectric materials, adhesives and cover layers used in the construction of conventional single-sided and double-sided FPCs have been investigated in this research. Specifically, single and double-sided FPCs constructed from Polyethylene Terephthalate (PET) and Polyethylene Naphthalate (PEN) dielectric films, as illustrated in Figure 1.6, have been preferred because of their cost and manufacturability.

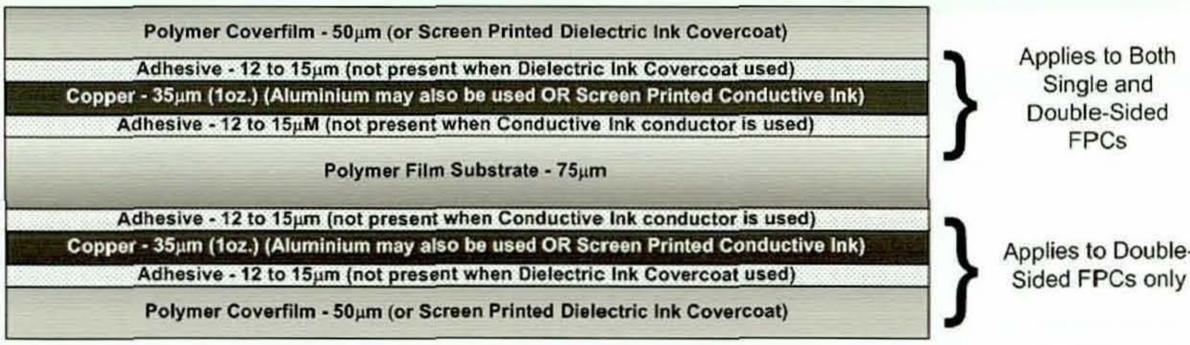

Figure 1.6 Single and Double-Sided FPC Constructions

Although much research on PET and PEN has been published, the ageing properties of these materials, as well as those of composite FPC laminates, have not been established under automotive environmental conditions. The proposed use of PET and PEN copper-clad laminates for large area automotive FPCs should ideally be supported by relevant properties of constituent materials and of the composite laminate; as supplied, and as materials and composite laminate ages throughout the service life of the vehicle.

Several questions arise; the first being the identification of relevant material and composite laminate properties, applicable to automotive wiring. Intuitively, electrical properties, particularly dielectric breakdown strength and mechanical properties, such as tensile strength are the most relevant. Composite laminate properties such as peel strength and flexural endurance may also be relevant. The investigation of these properties would address performance characteristics and long-term reliability within the automotive environment.

Accelerated ageing of materials, followed by the experimental measurement of relevant physical properties has been conducted. An environmental profile for the passenger cabin and door interiors has been proposed. When used in conjunction with established equations for the hydrolytic degradation of PET film, the time required for accelerated ageing has been estimated to be significantly less than that prescribed in automotive standards. Failure modes and mechanisms associated with the metallic conductor, for example copper corrosion, as well as those applicable to multilayer and flex-rigid FPC constructions, side-to-side interconnections such as through-hole vias, and surface mount component attachment have not been investigated, but suggested for future research.

1.3.1.2 Design of FPC Harness

For new electronic products in cars, the automotive industry uses three development stages from prototype to pre-production[6] [Moon, 2000]. The first prototype would be used for confidence testing only. Based on an initial design, it would be hand-assembled and used to demonstrate design intent. Limitations on functionality and appearance would be acceptable. The second prototype stage requires manufacture by the intended assembly process. There would be validation and full functionality testing before going into pre-production.

For this research, a prototype large area FPC has been designed and manufactured in order to demonstrate the concept, and to explore limitations in the design process; such as the ability of large area FPCs to combine power, and transmission lines as well as the capability for rapid product redesign. The current-carrying capabilities of FPCs have been guided by an analysis of complementary experiments. A commercial Electronic Design Automation (EDA) software suite was used to design a large area FPC substitute for an existing wire harness used in a Class C vehicle. The initial design methodology led to unsatisfactory results, evidenced by the manufactured prototype. It has been recommended that circuit design should be performed much earlier in the vehicle design process. Further, it may be impossible to substitute existing wire harnesses with large area FPCs without significant modification to the vehicle design.

1.4 Contributions to Research

This research has made a number of contributions to the development of large area FPCs for use in automotive applications. These include the following:

[6] A large area FPC could be considered as an electronic product. It is also suggested that these development stages do not solely apply to electronic products in cars, but extend to other automotive components.

i. Properties of FPC base substrates and laminates aged under elevated environmental conditions. These ageing properties may be used to determine useful life of FPCs in different localities within passenger vehicles, or other environments.

ii. A methodology for estimating the time required for accelerated ageing of materials at high temperature and humidity.

iii. Proposals for a specification in respect of copper-clad dielectric laminates used in the manufacture of large area flexible circuits. Such a specification would allow for the selection or verification of materials able to withstand conditions of assembly and in-service use.

iv. An evaluation of large area FPC design using a commercial Electronics Design Automation (EDA) suite, highlighting the limitations in transferring a design for wire to a design for FPC.

1.5 Structure of Thesis

This introductory Chapter is followed by a further eight chapters. Chapter Two presents a review of technology in respect of automotive electrical architectures and interconnection. It begins with present and future automotive electrical systems and the likely impact on the requirements of large area FPCs. This is followed by automotive flexible printed circuits and the known properties of materials used in FPC manufacture. A review of a major circuit design challenge, namely the current-carrying capacity of FPC conductors follows an analysis of life prediction models used in the automotive and electronics industries.

Chapter Three details the methods followed in this research, of assessing FPC materials and laminates. Relevant properties of FPCs selected for a designed experiment have been identified from standards and specifications for automotive wire, wire harnesses, and FPCs. Accelerated ageing conditions have also been identified from the standards and specifications. Reducing the size of the experiment has placed limitations on the type of inferences that can be made in respect of the contributions of constituent materials on the FPC base substrate or laminate.

Chapter Four presents the results of materials tests performed throughout the accelerated ageing period. It has been observed that temperature cycling does not significantly affect the performance of both PET and PEN based FPCs. Humidity ageing severely affects the mechanical properties of PET, and to a lesser extent PEN based FPCs. Degradation of the electrical properties of both PET and PEN based FPCs, such as dielectric breakdown strength has not been observed. However, experiment procedures for these latter tests have been criticised given the results of the tests performed being significantly different to those published by GTS.

Chapter Five presents a methodology for estimating the time required for the accelerated ageing of materials at high heat and humidity. Based on the rate of hydrolysis of PET film, it has been estimated that simulating twelve years exposure to natural conditions within a passenger car requires significantly less time than 3000 hour damp heat ageing test prescribed by automotive standards and specifications. It has also been suggested that PET film can potentially be applied to both the Instrument Panel and Door interiors.

Chapter Six presents proposals for a specification and acceptability criteria for flexible copper-clad dielectric materials used in large area automotive flexible printed circuits. The specification is based on standard printed circuit industry tests for flexible copper-clad materials to measure mechanical, electrical and chemical properties relevant to automotive applications. Accelerated ageing of materials under high temperature and high humidity has also been proposed. No recommendation has been made in respect of acceptability criteria for automotive FPCs.

Chapter Seven details the design methodology and analysis for the two prototype large area FPCs. Using Mentor Graphics Board Station (version 8.0), several difficulties were encountered during the design phase. An evaluation has been made of the direct application of the design methodologies and EDA tools used for small rigid printed circuit boards (PCBs), for designing large area FPCs. Further evaluation of the resultant prototypes has led to a recommendation that large area FPCs be used to implement simple electrical architectures or be designed for new vehicle models concurrently with the vehicle structure.

Chapter Eight is a discussion of the limitations of the experiment design followed, validity of test results and further critique of the circuit design process. Quantitative measurements of physical properties before and after accelerated ageing have been recommended as the initial method of material selection. It has been suggested that correlation with in-service data during the first phase of product introduction is necessary. It is asserted that circuit design methods and EDA tools are limited and unable to provide realistic substitute FPC harnesses. FPC design must occur earlier in the vehicle design process, with deliberate designing of the vehicle to accommodate FPCs.

Chapter Nine is the conclusion of this thesis. A summary of the research findings is presented, followed by recommendations for further work on the subject of large area automotive FPCs.

2 TECHNOLOGY REVIEW

2.1 Introduction

This research investigates the potential use of large area FPCs as substitutes for wiring harnesses designed for conventional 14-volt, 14/42 dual voltage, and multiplexed architectures within a passenger car. The service life and characteristics of FPC substitute harnesses are dependant on the properties of its constituent materials and how these degrade over time within the automotive environment. Although the properties of these materials as supplied are to a great extent known, as well as the degradation reactions that occur in different environments, no inference as yet can be made in respect of longevity within a passenger car. Further, the properties of a FPC laminate, as it ages within the automotive environment is unknown. The service life of FPCs may be estimated by using a physics-of-failure approach that addresses failure mechanisms which occur in FPC harnesses exposed to automotive environments. Circuit design is another contributing factor towards the performance of FPC harnesses; in particular the current-carrying and signal transmission capabilities have been reviewed.

2.2 Automotive Electrical Wiring

The conventional 14-volt point-to-point automotive electrical architecture has been in existence since the 1950's [Miller, 1996]. It is commonly referred to as a 12-volt system, having a nominal system voltage of 13.5V but which varies between 6V and 15V depending upon loading, ambient temperature, battery age and state of charge. In high-end, mid-sized cars, up to 10% of circuits would be spliced, the rest being direct point-to-point connections [Engbring and Renner, 2003]. One design constraint for any of the electrical components in the conventional system is survivability of transient events, known as load dumps, which is a result of switching and may vary between 40V and 80V. Although wire harnesses do not perform any other than an electrical function[7], to maintain mechanical integrity, the minimum

[7] M. Joyce, Yazaki Europe Ltd., Hemel Hempstead, UK. Personal Communication, December 1999.

wire size typically used in the conventional 14-volt wire harness is AWG22 ($0.35mm^2$) [Kassakian et al., 1996].

With continued growth in electrical and electronic content within passenger cars, electrical power consumption is expected to increase from the present range of 1.2–1.5 kW to 3-6 kW after year 2010 [Miller and Nicastri, 1998]. To cope with such power demands, a higher voltage system is inevitable. Since 1994, the MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems has conducted research and development of 42-volt systems [Kassakian, Miller and Traub, 2000]. It had been suggested that by year 2010, 50% of all new vehicles shall incorporate 42-volt electrical architectures, with a full transition occurring by year 2020 [Murray, 2002]. Keim [2004] however, asserts that the initial industry expectation may have been over inflated.

Whereas the technical capabilities of 42-volt systems are being refined, the economic cost of crossing over to the new system remains a major hurdle. Further, the propulsion that can be generated at 42V is generally considered too low to make mild-hybrid electric vehicles attractive [Karden et al, 2007]. For electric and hybrid electric vehicles, a voltage significantly higher than 42V is required [Meissner and Richter, 2005][8].

Compatibility with the present 14-volt infrastructure, through the use of a dual voltage system would be necessary during the industry transition. Evans [2000] has cautioned designers of such proposed 14/42 dual voltage systems. The most significant potential failure that could occur in the mixed voltage systems is a short circuit between the 42V and 14V sub-systems. Such faults would cause damage to the battery, electronic devices operating on the 14V side, and due to the indeterminate current flowing in such fault conditions, fuses provided to protect the 42V system under normal conditions may not clear, leading to the risk of thermal incidents. The avoidance of a shared earth point is also necessary, as disconnection of any of the voltage sub-systems could lead to the 14-volt side experiencing the application of -28V, which has serious potential for damage as in the short circuit condition.

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[8] Toyota Prius has a high voltage system operating at over 200V d.c.

The increased use of Electronic Control Units (ECUs) in high-end vehicles, resulting in larger and more complex wiring harnesses has motivated the use of multiplexed networks for data communication [Navet et al., 2005]. Multiplexed networks also provide opportunities for remote load switching, performed by electronic devices. Vehicles may incorporate multiple classes of networks; with data transfer rates ranging from less than 10 kb/s to over 1 MB/s, depending on safety, performance and cost requirements. Controller Area Network (CAN) is the most widely used protocol in vehicle multiplexed networks, particularly in Europe, and although CAN is able to operate up to a speed of 1 MB/s, most manufacturers use it at 500 kb/s to optimize bus speed with maximum allowable bus length [Holland, 2000]. CAN implemented on a twisted pair of copper wires is now a de facto standard in Europe for data transmission in automotive applications, due to its low cost and robustness.

The use of an alternating current system within future vehicles has not been rejected, but remains the choice of individual OEMs [Kassakian et al., 1996]. Whatever the nature of alternative electrical architectures adopted, Kassakian et al [1996] contend that an improvement in the electrical system efficiency, so as to reduce the average electrical load by 100 watts, would produce the same result in respect of fuel economy as removing 50 kg from the vehicle. Although previous authors in the subject area of alternative electrical architectures have assumed the use of round wire or fibre optic media for power and signal distribution, guidelines for the performance requirements of large area FPCs may be inferred.

2.2.1 Performance Requirements of Wire Harnesses

The performance requirements of automotive electrical and electronic components, including wiring harnesses, are specified by individual OEMs. These specifications are complemented by industry standards, for example the Society of Automotive Engineers (SAE) J reports. The two regions of the vehicle of interest in this research are the passenger cabin, more specifically the cockpit[9], and the interior of the vehicle doors. Typical environmental and

[9] The cockpit is the sum of components that include the instrument panel, instrument cluster, HVAC (Heating, Ventilating, Air Conditioning), Audio, AC electronic controls, wiring harness, steering wheel/column, airbags, cross-car beam, and some smaller components such as ducts, glove box, bezels/trim components.

performance requirements for electrical and electronic components within the automotive passenger cabin are listed in Table 2.1 [Johnson et al, 2004], [Inoue et al, 2000], [Lewis, 2000], [Miller et al, 1999], [O'Leary, 1999]. For the 'wet side'[10] of vehicle doors similar conditions apply, in addition to exposure to grease, dirt, and chemicals such as de-icing fluid. The list is not exhaustive, and may vary between different automotive OEMs.

General Withstand Requirements for Electrical & Electronic Components	
Temperature	-40°C to 85°C (average 30°C) with 1800 winter and summer extremes. Operating Temperature under dashboard -30°C to 85°C
Vibration	3-5G_{rms}, 15g @ 100Hz – 2kHz, 3000G (During Assembly – Drop Test)
Fluid Exposure	Benign, but Humidity and Salt Spray are common
Connectors	A pull-off force no less than 18 N
Water Ingress	Splashing water
Dust Ingress	Protection against ingress of solid objects with diameter > I mm
EMC	Whole Vehicle Radiated Susceptibility - 50 V/m (Substitution) Radio Frequency Interference (e.g. ignition noise, electric motors), - 44 dBμV/m at 1m, 30MHz to 1GHz
Transients	Slow - 80V, 200ms decay time; Fast - ±150V, 100ns decay time
Service Life	Average use of 5700 hours (1.6 hours each day for 10 years, with a reduced reliability goal) - 12 years (400 hours/year) - 45,000 on off power cycles (electronic parts)
Reliability	500 parts per million

Table 2.1 General Performance Requirements for Automotive Electrical Components

For hinged locations such as doors, wire harnesses are also required to withstand cyclic bending, and the number of these cycles is listed in Table 2.2 [Inoue et al., 2000].

[10] The 'wet side' of the door is the enclosure into which the window lowers

Required Bending Performance For Wiring Harnesses (cycles)			
Location		At Room Temperature	At Low Temperature[11]
Door	Front	20,000 ~ 80,000	10,000 ~ 30,000
	Rear	20,000 ~ 30,000	10,000 ~ 20,000
	Boot	10,000 ~ 50,000	5,000 ~ 30,000
Sliding Seat		10,000 ~ 30,000	3,000 ~ 10,000

Table 2.2 Required Bending Performance for Wiring Harnesses [Inoue et al., 2000]

Modern passenger cars are designed for a lifespan of ten to twelve years[12]. In addition to handling power and signal distribution, wire harnesses must survive the in-vehicle environment over the entire vehicle lifespan. This includes assembly into the vehicle and in-service usage and maintenance.

2.2.1.1 Vehicle Assembly

Automotive OEMs employ differing assembly methods and philosophies. Some OEMs assemble the IP and door harnesses on the main production line. That practice subjects wire harnesses to forceful handling activities, such as manual picking, dropping, threading and pulling. Other OEMs prefer pre-assembled door and cockpit modules to be presented at final assembly. These modules offer advantages of part reduction and elimination, assembly line optimization, inventory reduction, and sub-system level design and validation [Kovacic, Lanka and Marks, 2002]. Some OEMs, for example Vauxhall[13], assemble door and cockpit modules in-house, off the main production line. Other OEMs outsource completely assembled cockpits, for example Nissan[14] [Harrison, 2004]. However, due to their

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[11] Inoue did not specify the exact temperature.

[12] G. Warry. Daewoo Motor Co. Ltd. (Worthing Technical Centre), Worthing UK. Personal Communication December 1999.

[13] Vauxhall Vectra and Astra Models

[14] For the Nissan Micra

cumbersome size and delicate nature, quality may be compromised during transport to the main assembly plant [Kochan, 2003].

2.2.1.2 Service Life Climatic Conditions

Passenger cars experience a range of climatic and operating conditions during their service life. An expanding global market means that vehicles originally intended for the UK or Europe may have to survive the extreme heat of the Arabian Desert, extreme cold of an Alaskan winter or the combined high heat and humidity of the tropics [O'Leary, 1999]. One method of determining the temperature spectrum within the automotive environment is to use a combination of metrological data, component power dissipation, heat sinks[15], vehicle use time and frequency, and time of day when used [Hu and Salisbury, 1994] [Aldridge, 2004].

Such a method must also take into account the changes that occur during periods of use and non-use. In summer, the temperature within an enclosed passenger cabin is usually higher than the external ambient when the vehicle is not in use [Aldridge, 2004]. This higher temperature is equalized to the external ambient when driving, or is lowered when an air-conditioning system is operating. In winter, when exposed directly to sunlight, or when the vehicle is in use, the temperature inside the passenger cabin is also higher than the external ambient.

There is a void in the literature on the diurnal micro-climate within a passenger car, specifically the hourly temperature and relative humidity experienced in different areas of a vehicle. Some studies have attempted to address this, pursuant to determining a suitable accelerated test for corrosion in automobiles, or for medical research[16].

[15] *This refers to the metallic surfaces in the vehicle.*

[16] Studies related to the determination of time of death where bodies have been retrieved from vehicles. Also, studies to determine temperature inside visiting doctor's bag, to determine temperature stability of formulations. These studies focus on temperature only and not on relative humidity. Despite the authors measuring intra hourly temperature, they report on maximum temperatures only.

The effect of direct exposure to sunlight on the vehicles was reported by Marty, Sygrist and Wyler [2001], who over a five year period in Switzerland measured the internal temperature of three different vehicle models when not in use, and found significantly higher temperatures within the passenger cabin compared to the external ambient. Figure 2.1 to Figure 2.4 graphically represents the elevated temperatures measured by Marty, Sygrist and Wyler. Elevated temperature observations were also reported by Rudland and Jacobs [1994] who measured the temperature inside a doctor's bag placed at different locations inside the passenger cabin and boot. These two studies do not report the relative humidity linked to the higher measured temperatures.

Grundsteen, Meentemeyer and Dowd [2009] conducted temperature measurements within the passenger cabin of one model vehicle, in one location over fifty-eight days, spread over spring, summer and autumn. The authors argue that temperature increases in the car are caused by a greenhouse effect associated with a radiation imbalance and reduced ventilation, a have derived the following model to predict the maximum temperature within the passenger cabin:

$$Cabin\ Temperature = 0.036(solar) + 1.02(ambient) + 8.8$$ **Equation 2.1**

In the equation, "solar" refers to the average daily solar radiation (Wm^{-2}) and "ambient" to maximum ambient air temperatures (°C).

Wang et al [2000, 2001] measured the temperature and relative humidity in vehicle doors, under hood, roofs and under body over a period to two years. Blekkenhorst et al [1988] conducted similar automotive corrosion studies for a period of one and a half years, and although those authors appear to have amassed a significant quantity of data, detailed results for temperature and humidity have not been published. Attridge and Walton [2004] conducted a study on moisture ingression into car door latching systems; conducting experiments on the 'wet side' of automotive doors, but for short periods in a month of February.

The variability in vehicle geometry, local weather conditions and methodology adopted in each study results in a generalized description of the micro-climate only.

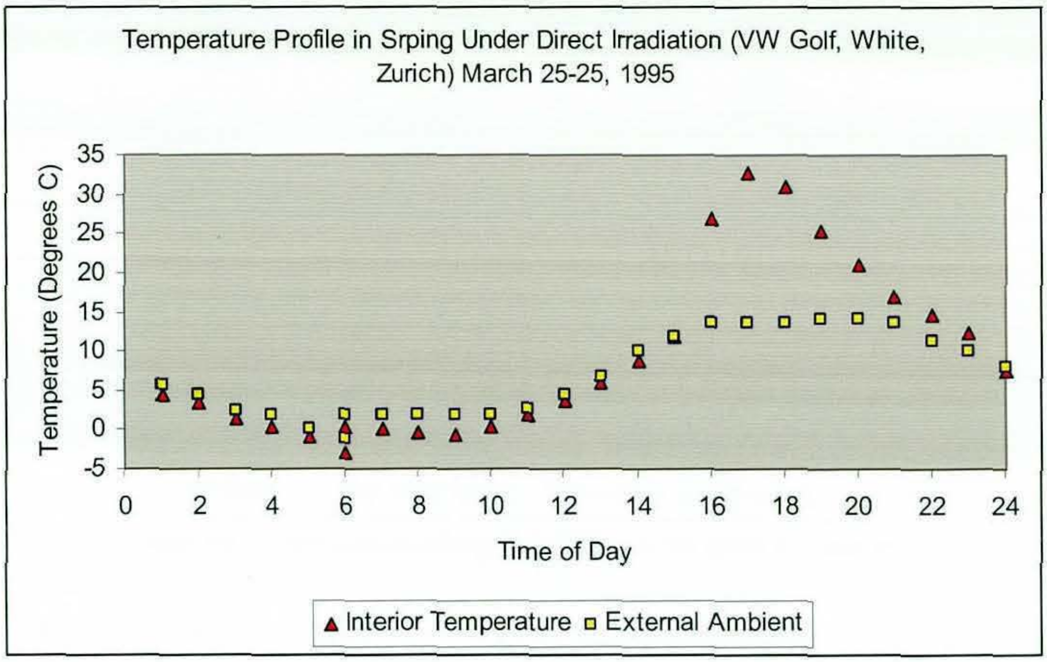

Figure 2.1 Passenger Cabin Temperature in Temperate Climate during spring [Marty, Sygrist and Wyler, 2001]

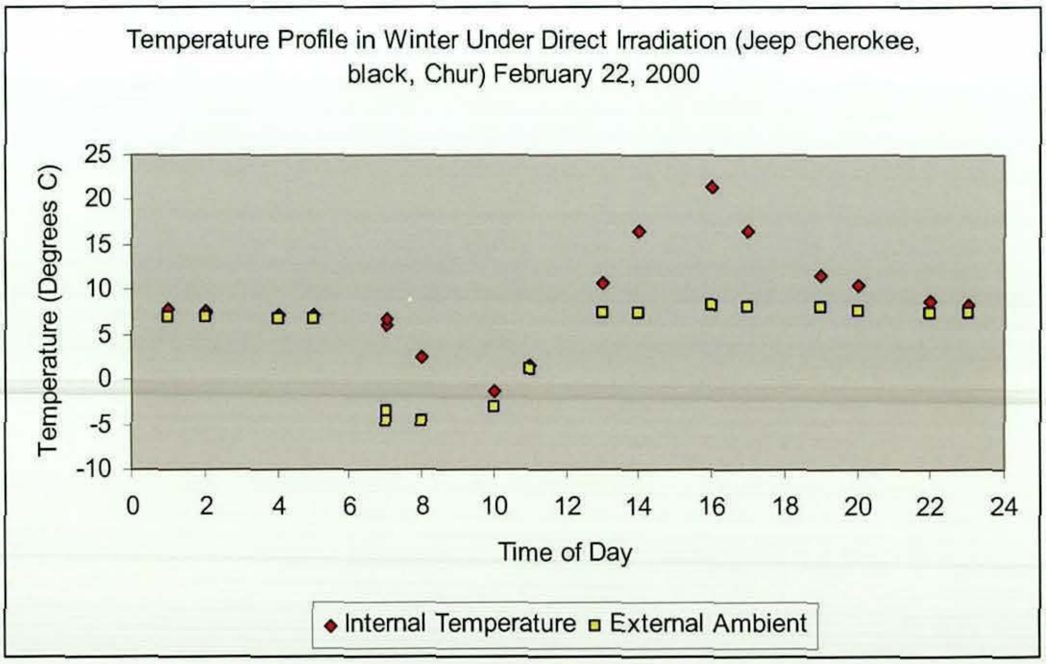

Figure 2.2 Passenger Cabin Temperature in Temperate Climate in late winter [Marty, Sygrist and Wyler, 2001]

Wang et al [2000] conducted their initial study in Detroit, Michigan between January and March and observed for 70% of the time, temperatures inside vehicle doors were within ±3°C compared to the external ambient. The relative humidity inside the door could be less than the external ambient during the first few months of the year but after exposure to rain, or when the external ambient was above 80% RH, the relative humidity inside the door would tend to 100%. This condition persisted for an indeterminate length of time after the improvement of external ambient conditions. Measurements of temperature and relative humidity inside the passenger cabin were limited to the roof area[17], where the relative humidity was observed to be predominantly lower than the external ambient, with the opposite applying to temperature[18]. However the temperature observed in the roof area was not significantly higher than the external ambient.

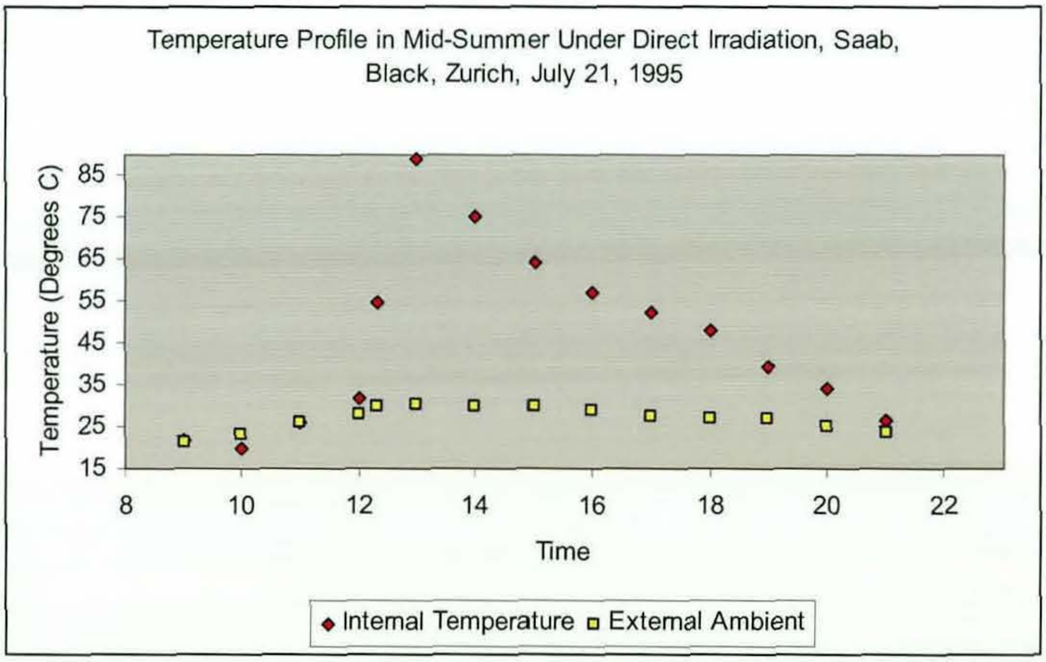

Figure 2.3 Passenger Cabin Temperature in Temperate Climate during mid-Summer [Marty, Sygrist and Wyler, 2001]

[17] Although not a focus area in this research the results are still instructive.

[18] This result would be expected.

The authors conducted further tests in Arizona [Wang et al, 2001] during a month of May and observed for higher external ambient temperatures, lower internal door temperatures. The relative humidity inside the door was also lower than the external ambient, and this was more pronounced when the external relative humidity was in excess of 60%[19]. This general description of relative humidity also applied to the roof area inside the passenger cabin. The authors also observed the internal roof temperature to be less than the external ambient.

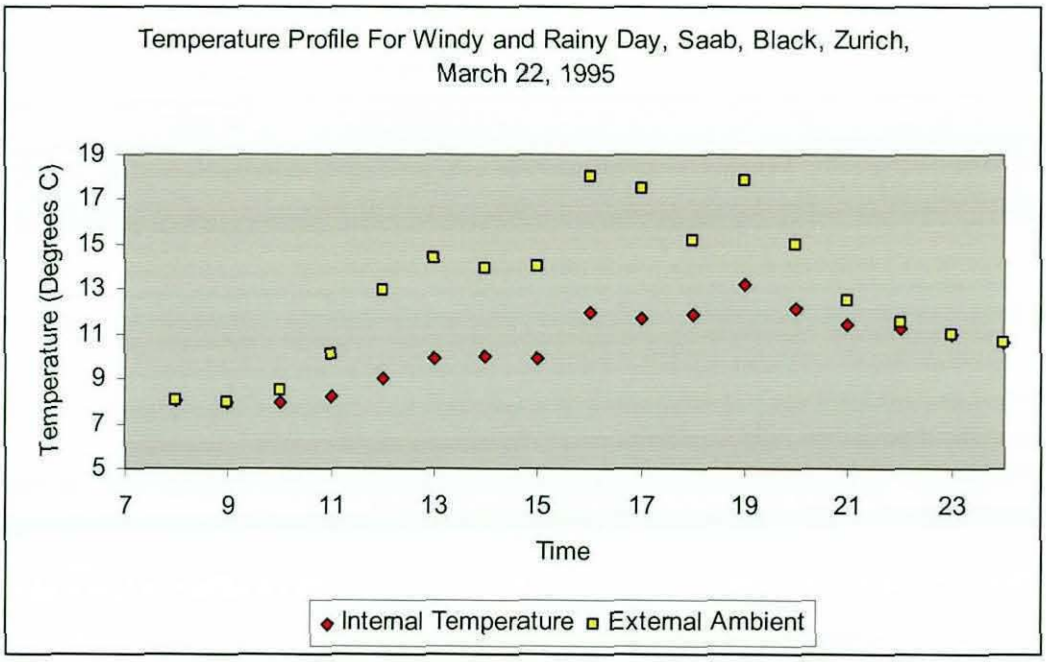

Figure 2.4 Passenger Cabin Temperature in Temperate Climate on a Cloudy Spring day [Marty, Sigrist and Wyler, 2001]

Attridge and Walton [2004] observed an increased temperature inside the door when the heating system inside the passenger cabin was in operation. A common observation in all tests performed in that study was that rapid changes in the relative humidity within the door did not occur unless the temperature within the passenger cabin was increased significantly or heavy rainfall occurred. Natural changes in ambient conditions tended not to have much effect on humidity, implying that the door interior is relatively well sealed[20] from the

[19] This observation is dissimilar to Detroit in the 1st quarter of the year.

[20] or acts as a heat sink

environment. As a result, airflow through the door is minimal and the relative humidity within the door remains high for long periods, even after external ambient conditions have started to improve.

2.3 Large Area Automotive Flexible Printed Circuits

The use of large area FPCs as substitutes for wiring harnesses is not a new concept. Yazaki Corporation and Mazda Motor Corporation [1994] obtained a patent for "An Electrical Harnessing Structure for Vehicle", incorporating FPCs connected to the Instrument Panel. UT Automotive Dearborn Inc [1998] obtained a patent for an "Integrated Interior Trim", to be used on vehicle doors. The patent disclosed the integration of a FPC constructed from copper-clad PET. However, examples of these inventions have not been reported in other literature.

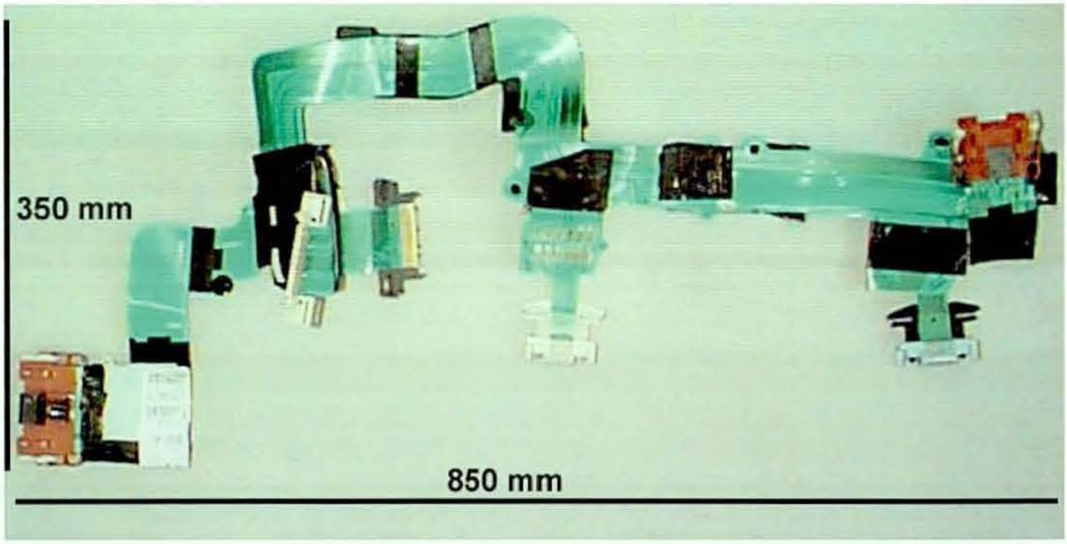

Figure 2.5 FPC-based IP Harness – General Motors Epsilon Platform

General Motors developed a FPC based IP harness for its North American Epsilon vehicle platform circa 1998. Figure 2.5 shows a production model of the harness, which is manufactured from four layers of single-sided copper-clad PET and fits within an area of 850mm x 350mm. Interconnections between layers have been implemented with metallic crimps, and adhesive tape has been used to secure the layers together. Literature on this product is not available in the public domain and it is uncertain whether further development work or introduction into new vehicles has occurred.

Manufacturing processes for large area FPCs up to 1500mm x 750mm in dimension have been explored by Cottrill et al [2002, 2003] and Conway et al [2003]. These studies proposed the production of such FPCs for two mid-range car models over a five-year period would be in the order of one million circuits per year. A production rate of 167 circuits per hour would be required, based on a six-day workweek, operating for 20 hours per day. Reel-to-reel operation of the production lines would be favoured in view of the large volumes involved. However, for 167 circuits of dimensions stated above, a line speed of 250m per hour would be required. This may be reduced through the use of multiple production lines.

Cottrill et al [2002, 2003] further proposed possible process routes not dissimilar to the conventional manufacturing processes for small FPCs. They may be 'Subtractive', in which the conducting paths are chemically etched from a metal-clad dielectric substrate, or 'Additive', in which the conducting paths are applied directly to the substrate, in both cases a polymer film, either by printing conductive ink or by a chemical deposition process. Combined subtractive and additive process may be used for some FPC designs, but time consuming electrolytic processes should be avoided for high-speed reel-to-reel production. The authors identified some processing equipment able to handle the largest sized circuits envisaged, but others would require modification or need to be developed. It has been noted that the use of design techniques such as folding may allow larger circuits to be produced using existing equipment.

2.3.1 Economic Justification

Carrott et al [2002] proposed a business case model for the manufacture of large area FPCs based on the FPC construction options, dimensions and production volumes suggested by Cottrill et al [2002, 2003] and found a considerable spread of possible manufacturing costs. The cost of new plant and equipment was estimated to be approximately £5 Million. This was considered to be small in comparison with the anticipated annual manufacturing cost, estimated to be £30 Million to produce one million circuits. It was recommended that investment should focus on reducing processing costs, especially with the aim of minimising scrap.

The model has shown how a project with apparently healthy margins can still contain financial risks. This observation is supported by Evans et al [2004], having performed a similar investment analysis for the manufacture of rigid automotive PCBs. Product pricing is influenced by the extremely competitive nature of the automotive business, and a small price decrease could make a profitable product unprofitable. Evans et al argue that many automotive suppliers have previously been forced to decrease prices for vehicle components by 5% to 10%, and that focus should instead be on reducing product cost[21].

Both studies, whilst providing an initial business overview, cannot replace a detailed financial and risk analysis. Furthermore, the conclusions arrived upon are applicable to FPC or PCB manufacturers, and do not provide the automotive OEM a cost justification for adopting large area FPCs. A methodology and software tool for economic cost estimation which could be used by automotive OEMs to justify the adoption of a particular electrical architecture has been reported by Afridi [1998]. The 'MAESTrO' tool estimates the cost of proposed electrical designs based on network topology, load types, voltages, power, and load factors. Afridi claimed that 'MAESTrO' allows for comparison and trade-offs, particularly between weight and actual costs. One weakness in 'MAESTrO' is the assumption of using round wire harnesses for electrical interconnection. A further weakness is that 'MAESTrO' does not appear to include the cost of harness assembly into the vehicle.

Although not specifically focussing on automotive wire harnesses, Ong [1993] illustrated how the cost of wire harnesses assembly may be estimated from each activity involved in the assembly process. For FPC harnesses, Weber [2000] suggested shifting assembly tasks to sub-assembly manufacturers so as to achieve the lowest cost of final assembly. The sub-assembly manufacturer would present a harness module to the OEM in the form of a

[21] A reduced product cost should be a natural result of the reduction in processing costs

component carrier incorporating self-aligning connectors. The final assembly would then involve fitting the carrier and attaching the connectors.

2.3.2 Challenges for Suppliers of Large Area FPCs

Whereas large area FPCs may offer several benefits to the automotive OEM, the substitution of conventional wiring harnesses by such new technology may not occur within a short time period. One possible explanation is that "automotive electronics technologies typically follow the mainstream trend with some time delay, due to the requirements of using only proven, mature technologies for mission-critical applications" [Kallenbach and Emig, 2004].

Edwards [2004] argued that the long lead times involved in the substitution process remains a major constraint on change in the automotive industry. The main reasons for this were:

a. Working prototypes, although much reduced in quantity, were still required to demonstrate performance, despite sophisticated computer modelling and simulation techniques.

b. The ability to process the materials needed to be demonstrated, and that was best done physically, under conditions normally experienced in production.

c. Designing, developing, manufacturing and commissioning new tooling and production equipment continued to be a significant drain on time and resources

The business strategy adopted for the composite wheels, suggested by Woelfel and Spencer [1994] may be adapted for other substitute technologies, namely:

(1) Enter the original equipment market with a [*substitute technology that*] would be reliable under the large variety of conditions typically encountered in the automobile service life.

(2) Target and solicit initial business from a low volume, but highly visible customer.

(3) Meet or exceed all the customer requirements and expectations of fitness for use on an automobile, which include: value, performance, durability, reliability, fit, finish, appearance and style.

(4) Utilize initial production to develop and refine the manufacturing process so as to optimize the plant of the future, equipment and processes, while maintaining quality and reliability and minimizing production costs.

2.4 Materials for Large Area FPCs for Automotive Applications

A previous attempt at addressing the selection of candidate materials for automotive FPCs was performed by Belopolsky and Killian [1991]. The authors outline a methodology requiring candidate FPC materials to be exposed to thermal ageing, thermal cycling, 85°C/85%RH and automotive fluids, followed by tests to determine peel strength or solder joint resistance. This work was purportedly conducted over a three-year period, with the accumulation of a large volume of experimental results; however the authors have briefly reported their experimental results, which are applicable to polyimide FPCs only. Such FPCs may be employed in applications requiring resistance to high temperatures, for example in the engine compartment. However, Polyimide based FPCs cost three to four times more than Polyester based FPCs [Dean, 1996], and are therefore unattractive for use in more moderate environments such as vehicle doors and cockpits.

Cottrill et al [2002, 2003] proposed that for such areas of the vehicle, circuits would be based on PET or PEN substrates, the latter being suggested for high humidity applications, such as in the wet side of vehicle doors. The metallic conductor would most probably be copper because of its high electrical conductivity, relative ease of processing and good solderability. The cover layer applied to provide protection for the circuit would be of identical material to the base substrate. A printed cover layer or covercoat, it was argued, could only be used if it demonstrated satisfactory resistance to mechanical damage during assembly and in service.

It was suggested that additive processes were unlikely to be used for manufacturing the main circuit panel, but could be employed for the production of small 'patch' circuits that would later be attached to the former. Alternative methods of implementing through-hole vias were proposed, for example through the use of silvered inks or crimps. No proposals were made in respect of adhesives, but one expectation is that any adhesive used in the FPC laminate would possess required properties, such as temperature stability and humidity resistance.

2.4.1 Polyester Terephthalate (PET) Film

Biaxially drawn polyester film based on PET was developed by ICI in Europe and DuPont in the USA in the 1950's with DuPont introducing the first commercial film line in the late 1950's [MacDonald, Mace and Polack., 2002]. PET films used in FPC manufacture for example Mylar and Melinex, are supplied in various thicknesses, containing a volume of PET in the range of 55-100% [DuPont Teijin Films, 2007b, 2007c]. Fillers and additives may be blended in to change the appearance, surface texture, crystallinity, diffusivity characteristics and susceptibility to hydrolysis. The properties of un-aged Mylar are well established [DuPont Teijin Films, 2007a], [Amborski and Flierl, 1953].

The principal failure mechanism for polyester film in aging studies and actual field failures is embrittlement induced by hydrolysis due to the intentional or inadvertent introduction of water [Walker, 1997]. Hydrolytic degradation of the polymer causes random chain scissions to occur, normally at the ester linkages, which causes a reduction in molecular weight and in turn a reduction in mechanical integrity. This degradation process is particularly prevalent under elevated temperature and humidity conditions [Ferrito, 1996]. Thermal degradation and oxidation are other mechanisms which lead to failure in PET film. PET absorbs light with a wavelength in the range of 290 to 350nm and as it does, degrades photolytically [Wypych, 1995, p. 361]. PET film is resistant to chemicals, as demonstrated by retention of tensile strength when exposed to such solvents as ethyl acetate, acetone, xylene, dioxane, trichloroethylene, and glacial acetic acid. Its resistance to acid is better than its resistance to bases [Ambroski and Flierl, 1953].

Numerous studies have been performed on PET. The most relevant to this research is the work reported by McMahon et al [1959]. In that study, the authors established equations for the rate of hydrolytic degradation of 12.5 micron and 250 micron Mylar A films. The experimental method involved exposing strips of film at 60, 71, 82, 90 and 99°C and 20, 50, 75 and 95% relative humidity, followed by quantifying the number of carboxyl groups formed. The activation energy for hydrolytic degradation of Mylar film was found to be in the range of 107.6 – 124.4 kJ/mol, with higher activation energy values obtained in thicker films. This was postulated as being due to differences in the moisture diffusivity characteristics for thin and thicker films[22]. McMahon observed that hydrolyzed PET film does not lose its dielectric strength until it is brittle and physically weak and suggested a safe operating limit for PET is before it loses one-third of its tensile strength.

Golike and Lasoski [1960] argued that diffusivity and moisture content were factors that affected the rate of hydrolytic degradation in PET films. The authors affirmed the approach by McMahon et al in determining the rate equations, but went further to propose modified equations that took into account film diffusivity and moisture content. Those equations, along with the inferences made by Golike and Lasoski were rejected by Davies et al [1962], for the incorrect application of mathematical formulae and invalid assumptions made by the former. Davies et al cited research conducted by Ravens and Ward [1961], having similar experimental findings as Golike and Lasoski. Ravens and Ward inferred the nature of the chemical reaction; i.e. autocatalysis attributable to carboxyl groups was responsible for the differences in the rate of film degradation. Further, Mishra, Goje and Zope [2003] noted that the rate of hydrolytic diffusion in PET was "orders of magnitude greater than the reaction rate".

The activation energy for thermal degradation of PET was determined by Marshall and Todd [1953] as being 133.9 kJ/mol. McMahon et al [1959] determined the rate of hydrolysis of Mylar A to be 10,000 times greater than that of purely thermal degradation, and 5,000 times greater than the rate of oxidation, and that other degradation mechanisms are inconsequential when compared to hydrolysis.

Several authors have reported on the changes in material properties when PET films have been aged under various temperature and humidity conditions, [Ferrito, 1996] [McCoy and Brinkman, 1985] [Lemm, 1992] [Minnick, 1999]. These provide comparative data, although less detailed than the earlier reported studies.

[22] Shown to be an incorrect hypothesis by later authors

McCoy and Brinkman [1985] investigated the effects of ageing PET film in power transformers. The samples (25μm in thickness) were aged in Sulphur Hexafluoride (SF_6) at 70, 110, 135 and 160°C for 32,700 hours. There were no indications that ageing affected dielectric breakdown voltage. An important observation was that when bonded to aluminium, the differences in thermal expansion of both materials caused deformation in the PET film. The authors suggested that repetitive thermal cycling could result in metal-clad PET film failing.

Lemm [1992] conducted ageing tests on PET film from which "Arrhenius life plots" were obtained. Lemm based the Arrhenius plots on the time required for test samples to lose 50% reduction in tensile strength. PET film samples were observed to experience a 10% reduction in tensile strength when thermally cycled over 2,400 hours.

Minnick [1999] performed heat ageing experiments on Mylar film of 190μm thickness. The samples were aged in air at 140C for up to 75 days, with measurement in Tensile Strength performed at 37 days and 75 days. It was observed that the samples retained 76% of its original Tensile Strength after 37 days, measured in the Transverse Direction, and 73% when measured in the Machine Direction. After 75 days, 78% retention in Tensile Strength was observed in the Transverse Direction, with a significant drop to 16% retention in the Machine Direction. Minnick suggested the rate of embrittlement in PET films may be affected by contact fluids, as in that study, the author observed the "plasticising effect" of certain lubricants contributed to a greater retention of Tensile Strength.

Other studies on PET film have been performed by some authors, the results of which confirm the manufacturer data, for example Yilmaz and Kalenderli [1995] confirmed PET dielectric breakdown strength decreases with increasing temperature and Ford, Doreswamy and Bassapa [1994] confirmed a similar trend for volume and surface resistivity. Research published by Amborski and Flierl [1953], based at DuPont, have been reproduced in the Mylar data sheets [DuPont, 2007a].

2.4.2 Polyethylene Naphthalate (PEN) Film

Although the superior properties of PEN [Massey, 2004, Chapter 18, pp. 65-69] [DuPont Teijin Films, 2007d], compared to PET, have been known for many years, the development of commercial markets has been delayed by the unavailability of the naphthalate monomer until 1995 [Callander, 2003]. This may possibly explain the greater volume of literature in respect of PET vis-à-vis PEN film. Hu, Ottenbrite and Siddiqui [2003] support this contention, noting the number of papers and patents published on PEN during this early commercialization period has been almost twice that of the previous thirty five years.

The enhanced properties of PEN are due to presence of a double aromatic ring, illustrated in Figure 2.6. As with PET films, PEN films, such as Kaladex and Teonex, have been employed in a variety of applications and are supplied in different thicknesses. The use of additives and fillers are however significantly lower in PEN films than in PET, with Teonex containing 99.5% PEN by volume [DuPont Teijin Films, 2007e]. PEN films are also more amorphous and tend not to crystallize as easily as PET films.

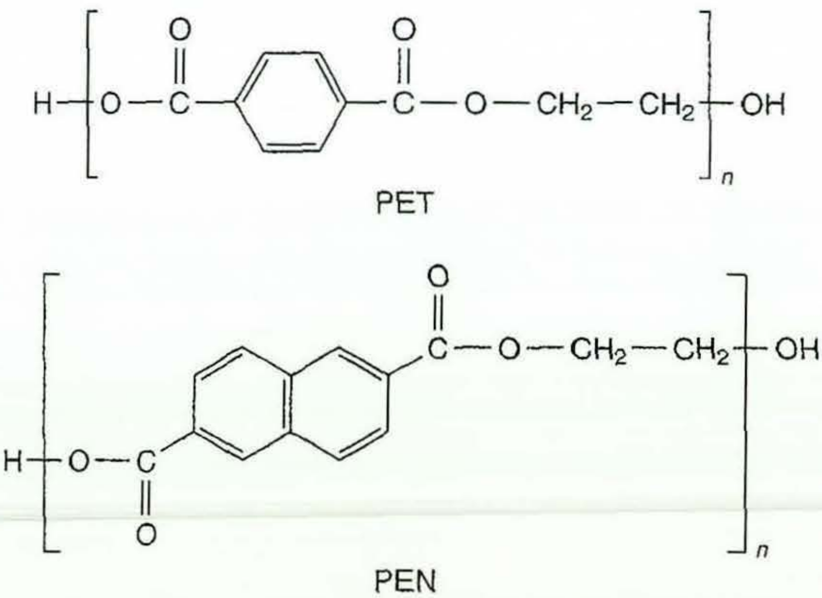

Figure 2.6 Chemical Structure of PET and PEN

The main degradation mechanisms in PEN are similar to those in PET i.e. hydrolytic, thermal, oxidative and photolytic. Zhang and Ward [1995] compared the rates of hydrolytic degradation of cast PET film and uniaxially drawn PEN films. The rates of reaction were determined, as in the case of studies on PET, by measurement of the concentration of carboxyl groups in aqueous solution. The activation energy for hydrolysis of cast PET film was lower than that reported for biaxially stretched film. The activation energy for hydrolysis of uniaxially drawn PEN film was determined as 109 ± 6 kJ/mol, but the rate of reaction was two to five times lower than in PET[23]. This lower rate of reaction for PEN has been suggested as the result of that film's lower moisture diffusion coefficient compared to PET.

Bellomo et al [1995] investigated the dielectric properties of PET and PEN films (25μm thickness) after thermal ageing at 120, 150, 180 and 210°C. Samples were tested after 100, 300, 700 and 1000 hours, without any observed trend in breakdown voltage. Cygan et al [1993] exposed PEN film to temperatures in excess of its glass transition point and observed an increase in dielectric breakdown strength in samples exposed to temperatures above 258°C; attributed to the increase in the crystallinity, the crystallite size and orientation of the film.

Investigation of the dielectric properties of PEN film aged under humid conditions appears to focus on permittivity and dissipation measurements. However given the resistance to hydrolysis, it may be inferred that PEN would retain its dielectric strength until brittle, as with PET, but confirmation of this is needed. Similarly, mechanical properties of PEN film aged under humid conditions have not been reported in detail. It is known that PEN retains 90% of its tensile strength after immersion in water at 90C for 70 days [MacDonald, Mace and Polack, 2002] [Hu, Ottenbrite and Siddiqui, 2003]. Further work in this area is needed.

2.4.3 Copper Foils

Avery [1988] presented a comparison of copper foils used in FPC manufacture. There are different classes of foil, depending on the method of manufacture, having different tensile and ductility characteristics. Whereas electrodeposited copper foils have the lowest

[23] In reaction kinetics, activation energy is a component of the rate of reaction equation

economic cost, they are unsuitable for dynamic flex applications. However, they may be used in applications where flexing is mainly required during assembly and maintenance. Avery suggested that stress relieved electrodeposited copper foil is suitable for automotive applications, but further notes that they are difficult to handle, and unsuitable for roll-to-roll lamination processes. Rolled-annealed copper, despite having the highest economic cost, may be necessary for large area FPC manufacture.

A potential failure mechanism in FPCs is copper ion migration, identified in the adhesive layer of polyimide based FPCs by Kawashima, Sugimoto and Ogawa [1999]. In this study the adhesive was a nitrile rubber (NBR)/epoxy resin.

2.4.4 Adhesives

The function of adhesives in FPC laminates is to bond the cover layers and/or the copper foils to the dielectric base material, and in multilayer and rigid flex FPCs, the adhesive is used to bond the inner layers together. The performance of a FPC laminate is determined by the combined properties of the adhesive and supporting dielectric film. Adhesives are the known weak link in FPC laminates, so their properties are of greater importance compared to the dielectric film for the following reasons [Harper, 2000, pp5.17-5.23]:

1) The adhesive is the dielectric that surrounds the etched copper conductors. It is therefore the primary insulation in FPCs, and determines electrical properties such as volume and surface resistivity, dielectric constant, and dissipation factor.
2) Flammability is adhesive driven. Most adhesives support combustion unless they are formulated to include suppressors.
3) Adhesives control thermal ratings.
4) Bond [Peel] strength is an adhesive property.
5) Chemical resistance is also an adhesive function.
6) Adhesive type and thickness affect the flexural endurance of FPC laminates.

The precise chemical composition and process used in the commercial manufacture of adhesives for flexible copper-clad laminates are proprietary to individual suppliers, and are normally not published or patented[24]. There are four basic categories of laminating adhesive commonly used. These are waterborne, solvent based, reactive 100% solid (solventless liquid), and hot melt. Each category has a number of applicable base polymers and a wide variety of formulation possibilities. The specific formulations will heavily depend on the nature of the laminating process employed, the nature of the film substrate, and the final physical properties desired [Petrie, 2005]. Acrylic, epoxy and modified epoxy, polyester and modified polyester, phenolic and butryal phenolic, and polyurethane adhesives are commonly employed in FPC laminates.

The mechanisms of adhesion have been investigated for years and several theories have been proposed in an attempt to provide an explanation for adhesion phenomena. Theories include adsorption, chemisorption, mechanical interlocking, diffusion and electrostatic interaction. The bonding of an adhesive to an object or a surface may involve a number of mechanical, physical, and chemical forces that overlap and influence one another [SpecialChem, 2007]

There are different modes of mechanical failure in adhesive joints. These are typically adhesive, cohesive or a combination of both. Adhesive failure occurs at the interfacial boundary between the adhesive layer and the adherend, whilst cohesive failure occurs within the adhesive layer itself. Adhesive degradation is known to be dependant on temperature and humidity, and may be catalyzed by the presence of metals [Murray, Hillman and Pecht, 2003]. Herr, Nikolic and Schultz [2001] have noted in respect of the epoxy adhesive used in their study that the mode of failure can change from cohesive to adhesive with prolonged soak time in a humid environment. Fatigue of electronic adhesives also results from differential thermal expansion of adherends.

The variability in adhesive formulation, bonding and bond degradation mechanisms means that any inferences drawn in previous studies on FPC adhesives are likely to be limited to the

[24] G. Farmer, GTS Flexible Materials Ltd, Ebbw Vale, UK. Personal Communication, August 2006.

particular formulation itself and may not be applicable to other adhesives of the same type name.

2.5 FPC Reliability

Previous studies on the reliability of electronic products have focussed on the failure of rigid substrates, or component attachment to rigid substrates using soldered joints or conductive adhesives. There is a void in the literature on the reliability of electronic products containing FPCs. Studies by Illyefalvi-Vitez et al [2007] and Detert et al [2006] have partially identified this problem, and focus on the failure of surface mount soldered joints on FPC base laminates. The authors of both studies present initial results of their experimental work. The contribution of constituent materials and construction to the reliability of FPCs requires further investigative work.

2.6 Estimating FPC Service Life

One approach to selecting appropriate materials is to compare the service life of FPCs manufactured from different combinations of materials when exposed to the operating conditions experienced within a passenger car. There are essentially three approaches to estimating service life. These are real or simulated service trials (durability testing), experience, and accelerated life testing [Brown and Greenwood, 2002, p.6]. The first and second approaches cannot be applied at this stage of product evaluation for time and cost reasons; therefore accelerated life testing would be used for materials selection in this research.

2.6.1 Accelerated Life Tests

Accelerated life testing[25], when properly applied, yields the same type of failures as would be identified during normal durability testing. Accelerated life tests expose products to environments that are above the design limits, without extending into product destruct limits [Capitano, Anderson and Sverzhinsky, 2000]. Criticism and caution in respect of this

[25] This term is interchangeably used with Accelerated Ageing.

approach to life estimation has been noted by various authors [Meeker and Escobar, 1998] [Caruso and Dasgupta, 1998] [Brown and Greenwood, 2002, pp.49-50]. Such criticism and caution cite the misapplication of accelerated life tests; particularly test conditions and inferences from derived failure data.

A commonsense approach to reliability test design is to incorporate any known or anticipated environmental and operational factors that affect the product during its lifetime into a test whose duration is determined by the expected product lifetime and reliability goal [Lewis, 2000] [Aldridge, 1993]. This is known as tailoring and the goal of such is to ensure that all failure mechanisms are excited, without generating any irrelevant failure mechanisms, and that any damage caused is equivalent to that which the product will experience under the typical field use environment [Agarwal, 1996]. For automotive FPCs, temperature, humidity, ingress of contaminants or chemicals, voltage/current, and vibration are possible environmental factors.

Products failing accelerated tests may still be adequate if the test conditions are too severe [Hu, 1995]. By contrast however, Krasich [2003] proposed that reliability could be expressed as a relationship between mean strength and mean load. Therefore, if a product is successfully tested to an accumulated stress higher than the stress expected to be accumulated during the product life period, it will demonstrate its strength. Conversely, given the variance in the severity of customer use, a reliability test target that demonstrates 95% of severity could significantly reduce the test times required [Lu and Rudy, 2000].

For timely availability of accelerated life test data, acceleration factors must be built into the test profiles to compress the test time to a reasonable period. The acceleration factor (AF) for an accelerated test is defined as the ratio of time to failure at service conditions and the time to failure at test conditions, keeping the failure modes and mechanisms the same [Murray, Hillman and Pecht, 2003] Accelerated life tests require a deep understanding of the failure modes and mechanisms of the materials, parts and assemblies. Where there are many sub-assemblies, containing multiple failure mechanisms, the weakest failure mechanism determines the overall product reliability [Agarwal, 1996].

2.6.2 *Accelerated Life Models*

Various models for the life estimation of electronic products have been published over the years [Caruso and Dasgupta, 1998] [Pecht et al, 1997]. The models are based on a physics-of-failure approach, addressing one or more failure mechanisms. The Arrhenius Model, stated in Equation 2.2, is the most common life model. In the equation AF is the acceleration factor, t_{use} is the desired service life, t_{test} is the accelerated test period, E_A is the activation energy for the failure mechanism being excited, k is the Boltzmann constant, T_{use} is the normal service temperature and T_{test} is the test temperature.

$$AF = \frac{t_{use}}{t_{test}} = \exp\left[\frac{E_A}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)\right]$$

Equation 2.2

The Arrhenius model is applicable to failure mechanisms that are activated by temperature overstress only. In many, if not most applications, this does not apply. Meeker, Escobar and Lu [1998] recommend where there are parallel one-step failure mechanisms contributing to failure, whose acceleration rates are dissimilar, it is in general necessary to model each degradation process individually. Consideration must also be given as to the linearity of degradation mechanisms.

Where the synergistic effects of multiple stresses are to be considered, the Eyring model may be applied. One modified form of this model has been proposed by Peck [1986] to account for the effect of humidity and temperature in epoxy packages encapsulating a silicon die. Peck's model is stated in Equation 2.3. In the equation, the Arrhenius exponent is the same as before, M_{use} is the moisture level in service, M_{test} is the moisture level during the accelerated test and n is a material constant between -2.5 and -5 [Bojta, Németh and Harsányi, 2002], but needs to be determined for other materials.

$$AF = \left(\frac{M_{use}}{M_{test}}\right)^{-n} \exp\left[\frac{E_A}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)\right]$$

Equation 2.3

An important assumption of this model is that the effects of temperature and the other applied loads are independent (not synergistic). However, in real life, the moisture term may also be temperature dependant. This would introduce new coefficients and change the resulting estimate. Furthermore, the effect of moisture content within a system may be more detrimental than environmental moisture [Pecht el al, 1997]; there may be higher humidity levels within the component itself compared to external environment, as observed by Lam, Maul and McBride [2004] in respect of automotive connectors, and Attridge and Walton [2004] in respect of automotive doors.

Murray, Hillman and Pecht [2003] studied the ageing of a siloxane-polyimide-epoxy adhesive on copper metalized substrates and developed a model for ageing as a function of temperature and humidity. A physics-of-failure approach was used in this study. The activation energy for hydrolysis of the adhesive or for breaking the adhesive bond is an unknown, thus the Arrhenius and Peck models could not be applied directly[26]. To determine acceleration factors, different test temperatures and humidity were used, followed by regression analysis of peel strength values. In that study, cohesive failure was observed as the main failure mode of the adhesive.

The authors proposed, correctly, that where a process followed a first-order kinetic reaction, the acceleration factor is the ratio of the rate of reaction at accelerated test conditions to the rate of reaction during service conditions. By implication therefore, using the equations for the rate of hydrolytic degradation of Mylar established by McMahon et al [1959], the service life of that material can be estimated by a mathematical process. This approach to life estimation of polymer materials has been favored by Verdu et al [2007], and forms the basis for the life estimation of polymer films later in this thesis.

Eriksson, Carlsson and Wallinder [2001] designed accelerated corrosion tests for exposed copper in automotive environments. The model derived is stated in Equation 2.4, where M_{1test}, M_{1use} and x are constants at a given corrosivity, and t_{use} and t_{test} are the service life and

[26] The authors assumed the rate of adhesive degradation, measured by Peel Strength, would nevertheless follow a first order reaction.

test duration respectively. In that study, the values were obtained for M_{1test}, M_{1use} and x were determined from automotive field experiments in Scandinavian countries.

$$AF = \frac{t_{use}}{t_{test}} \left(\frac{M_{1_{test}}}{M_{1_{use}}} \right)^{\frac{1}{x}}$$ **Equation 2.4**

For metal fatigue due to cyclical stress, the Coffin-Manson model is widely applied [Caruso and Dasgupta, 1998]. For thermal cycling, the model is as stated in Equation 2.5, where N_{use} and N_{test} are the number of cycles, and ΔT_{test} and ΔT_{use} are the temperature differences experienced during service life and accelerated test respectively. For vibration stress, ΔT is replaced by G, the rms response of the product in service and during test.

$$AF = \frac{N_{use}}{N_{test}} = \left[\frac{\Delta T_{test}}{\Delta T_{use}} \right]^{\beta}$$ **Equation 2.5**

The exponent β represents a fatigue characteristic of the material under test, derived from the slope of the material's S-N curve (log-log plot). Caruso and Dasgupta [1998] noted that the value of β for the same material may be different for temperature cycling and vibration, and may change as a function of mean temperature for the same material.

Englemaier and Wagner [1988] found an unsatisfactory correlation between predicted and actual fatigue life using the Coffin-Manson model applied to copper traces on polyimide laminates. The underlying cause was suggested to be the effect of the adhesive layer in the FPC construction. Additionally, the Coffin-Manson model does not take into consideration the temperature profile used in thermal cycling. Motivated by this, Zhai, Sidarth and Blish [2003] modelled the effect of ramp rate and dwell time on solder fatigue, and proposed that dwell time has more of an impact on solder fatigue life than ramp rate due to longer exposure to peak inelastic strain.

2.6.3 Test Methods, Specifications and Standards

Accelerated ageing of FPCs would necessarily be followed by tests for relevant material properties. According to Brown [2002], "the property value obtained may vary according to the test method used. Many of our test methods use quite arbitrary conditions and procedures. The data obtained from this routine type of test, whilst admirable for quality control and perhaps as an indication of service performance if interpreted carefully, will rarely give the designer the values upon which to base his calculations. The closer a test approaches the real conditions of service the more relevant or significant it is likely to be in terms of predicting service performance. The more fundamental a result is in terms of it being independent of test piece shape or conditions the more relevant it will be for design purposes".

Brown [2002] states further, "Standards are the documents which define requirements for products and how they are to be tested. Hence, they are crucially important to a test laboratory. To avoid misunderstanding over terminology it is as well to note that the British Standards Institution (BSI) call all their documents standards and the word specification is reserved for those standards which specify minimum requirements for materials or products. Other types of standard are Methods of Test, Glossaries of Terms and Codes of Practice. It follows that test methods are the building blocks of specifications and a specification may refer to several methods of test". It is not uncommon for a standard or specification to refer the user to other standards and specifications, creating a complex web or chain of documents.

Generally, the sources of standards can be placed into three groups: International organisations, National organisations, and Individual companies [Brown, 2002]. Brown notes that "the situation is rapidly being reached where ISO, CEN and British Standards are effectively the same thing[27] and are dual or triple numbered, e.g., BS EN ISO xxxx, BS EN xxxx or BS ISO xxxx. There must be literally millions of company standards in existence. Although they have relatively little significance in a national or international sense, they are the basis of many commercial contracts. It would save a great deal of pain and confusion if those writing commercial specifications would wherever possible use published standard test

[27] Here, Brown is referring to Harmonized standards.

methods, preferably those of ISO".

Jia and Kagan [2000] noted that the American automotive industry has adopted or is in the process of adopting ISO standards, when the majority of testing in North America is conducted using ASTM standards. Those authors performed tensile strength tests on PET samples using both ASTM and ISO standards for comparison and found that the methods defined in those standards produces closely matched results.

Brown [2002] contends, "Different styles or types of published standard test methods can be recognised. In the simplest case a particular apparatus is specified, one set of mandatory test conditions given and no choice allowed as to the parameters to be reported; this is the form in which the specification writer needs a test method. Many national and international test methods have become rather more complex. This is partially a result of compromise but more importantly because the measurements being described are not intrinsically simple and the method will be required for a number of different purposes and probably for many different end products. The specification user must therefore select the particular conditions which best suit his individual purposes".

2.7 FPC Design

The secondary problem within this research is the design of large area FPCs. Sheehan and Rider [1999] *proposed preliminary design requirements for and capabilities of* FPCs *intended* as substitutes for wiring harnesses, as listed in Table 2.3.

Electrical Requirements	Mechanical Requirements	Manufacturing	Installation	Connectors
High Current	Mechanical Strength	Process-Technology	Location	Availability
Signal Current	Fixing Methods	Assembly	Fit	
Electromagnetic Compatibility - (EMC)	Environmental Sealing	Test	Handling	
Insulation		Packaging		

Table 2.3 Design Considerations for Replacing Round-Wire Harnesses with FPCs

Printed circuit design practices and guidelines established by the electronics industry may be found the IPC-2221 [IPC, 1998a] and IPC-2223 [IPC, 1998b] standards, and the Minco Flex Circuits Design Guide [Minco, 2007]. Design guidelines for cost effective manufacture of FPCs have also been presented by Kober [1992]. Present day design practice and guidelines however, do not fully address the current-carrying capacity (ampacity) and signal transmission properties of etched conductors.

2.7.1 Thermal Management and Ampacity

One weakness in FPCs is the irreparability of damaged conductor traces. In addition to cracking or breakage due to mechanical stress, conductor traces and the surrounding substrate material could melt under high temperature, resulting from a flow of excessive current. Thermal management is a critical function that must be designed into the FPC. Different methods may be employed, such as the direct attachment of heat sinks, or forced convection cooling. The most attractive method not requiring external mechanisms is trace sizing, i.e. selecting a trace cross-sectional area for the required current flow and temperature rise. Trace sizing also impacts on the overall size of the FPC. With surface area at a premium, it is important to fit as many traces into the smallest possible area.

A trace width equivalent to round wire cross-section area (or wire gauge) can be found in the IPC-D-330 Design Guide [IPC, 1992]. This may provide a first estimate for trace sizing. However, for further reductions in trace size, the IPC-2221 standard [IPC, 1998a] includes nomographs for sizing of external and internal conductors on phenolic boards. The nomographs allow PCB designers to select the minimum trace width required for a given current flow and temperature rise, or to determine the ampacity of a given trace width.

McHardy and Gandhi [1997] argue that the low current data on the nomographs are difficult to read, leading the authors to develop a mathematical model to fit the curves. This model is stated in Equation 2.6. In the equation, 'I' represents current in Amperes, 'A' is the cross-sectional area in square mils[28], 'ΔT' is the temperature rise in °C, and 'α' and 'β' are

[28] US measure of length. 1 mil = 0.001 inches

constants. As the nomographs have been developed for rigid PCBs, they may not be accurate for FPC trace sizing.

$$I = k\Delta T^{\alpha} A^{\beta}$$ **Equation 2.6**

Brooks [1998b] revised the model taking into account the uneven contribution in heat dissipation between trace width (W) and thickness (Th) in Equation 2.7. Datasets from IPC and Design-News (DN) [cited in Brooks, 1998b] have been used to derive the values for k, α, β, β1 and β2, listed in Table 2.4.

$$I = k\Delta T^{\alpha} W^{\beta 1} Th^{\beta 2}$$ **Equation 2.7**

	McHardy and Gandhi (IPC)	Brooks (IPC external trace)	Brooks (IPC internal trace)	Brooks (DN external trace)	Brooks (DN 1oz & 5oz copper)	Brooks (DN 2oz copper)
	Equation 2.6	Equation 2.6	Equation 2.6	Equation 2.6	Equation 2.7	Equation 2.7
k (external trace)	0.048	0.065		0.040	0.028	0.034
k (internal trace)	0.024		0.15			
α	0.44	0.43	0.55	0.45	0.46	0.46
β	0.725	0.68	0.74	0.69		
β1					0.76	0.76
β2					0.54	0.54

Table 2.4 Derived Values for Curve Fitting Equations

In addition to the cross-sectional area of conductor traces, a number of other factors have been noted to contribute to ampacity, namely:

i. Substrate material

ii. Number of traces carrying current at any instant

iii. Trace location on board

iv. Trace separation

v. Presence or absence of copper planes and proximity to traces

vi. Extrinsic cooling mechanisms and PCB mounting arrangement

Jouppi and Mason [2000] investigated the ampacity of rigid PCBs in a vacuum, simulating conditions in space and heat dissipation through radiation. That study focussed on internal conductors, as in a multilayer configuration, with and without an additional copper plane. It was shown that a large disparity exists between the IPC nomographs and the authors' experimental results. A 60% increase in ampacity where there was no internal plane, and 198% when incorporating an additional internal copper plane was observed. A further 18% increase in ampacity was observed during testing in air. Jouppi and Mason argued that the IPC charts were too conservative.

Ling [2002] used simplified mathematical models to determine the AC and DC ampacity of rigid PCBs and proposed that under natural convection, internal traces were no hotter than external traces and recommended the use of external trace chart only. Previous studies considered DC ampacity, but for AC ampacity, it was only necessary to use the mean square value of the AC current. Traces at the centre of the printed circuit were shown to be hotter than those at edges. Where parallel traces are powered, the IPC-2221 [IPC, 1998a] recommendation of summation of currents and cross-sectional area is argued as being valid. By contrast to Jouppi and Mason's argument, Ling produced conductor-sizing charts for FR4 boards that were slightly more conservative than the IPC external trace chart.

Pan, Poulson and Blair [1993] considered the effect of closely spaced and powered, parallel conductors on a rigid substrate in miniaturized applications such as Multi-Chip Modules (MCMs). Using a finite element model to generate ampacity charts for traces spaced 0.2 mm apart, it was shown that when parallel traces were powered, ampacity was significantly reduced compared to the IPC nomograph. The model incorporated the effect of natural convection, radiation and conduction in heat dissipation, however only low currents and narrow trace widths have been considered.

Using FLOTHERM simulation, Adam [2004] obtained temperature/current correlations for different PCB scenarios. The simulation model was checked against the IPC-2221 nomograph and the model developed by Brooks above, and found to have a very close match. Circuits containing a greater volume of copper were shown to have a higher ampacity, suggesting that the etching process remove no more copper than is necessary to isolate individual traces. The results for a single trace on polyimide film showed a much lower ampacity compared to FR4 and ceramic materials[29]. For a trace thickness of 70μm (2 oz Copper), ampacity is increased by a factor of $\sqrt{2}$.

For fine-line conductors, Rainal [1981] devised equations for the temperature rise. It was established that as a critical current I_c was approached, the conductor temperature continued to rise infinitely until melting occurred, known as 'thermal runaway'. This could be calculated using Equation 2.8, where R_1 is the resistance of the conductor (ohms) at ambient temperature, α is the ambient temperature coefficient for copper, and R_T is the thermal resistance of the conductor for the particular circuit board form (°C/Watt). The temperature rise for transient currents (ΔT) can be approximated using Equation 2.9, where I is the current in Amperes, R_1 is the same as above, t is the time duration and C is the thermal capacity of the substrate material (Joules/°C). It should be noted that the flexural performance of fine line conductors is less than that of wider traces, and this should be considered when designing the FPC.

$$I_C = \frac{1}{\sqrt{\alpha R_1 R_T}}$$ **Equation 2.8**

$$\Delta T = \frac{I^2 R_1 t}{C}$$ **Equation 2.9**

Traces could be designed with constrictions where necessary to facilitate layout, or contain notches if damaged. Localized heating can occur at these points and this could result in a printed circuit being rejected where notches are large. Rainal [1976], in an earlier study

[29] Contrary to the view of FPCs having a higher ampacity compared to rigid PCBs.

proposed linear differential equations to determine temperature rise at constrictions that could be used as a guide for specifying the maximum allowable size of constriction or notch. Constrictions that were 80% the width of the surrounding conductors had a temperature rise no greater than 1.152 times that of the surrounding. Some experimental results showed a lesser temperature rise when compared to the theoretical model.

Thermal runaway could be used to design traces that act as protective fuses. Brooks [1998a] proposed the model stated in Equation 2.10 to calculate a trace cross-sectional area that would allow known current (I) to flow for a predetermined time (t) before fusing occurred. In the equation A is the cross-sectional area of the trace in square mils.

$$I = 0.188\,At^{5}$$ **Equation 2.10**

Engbring and Renner [2003] suggested a simple model based on ohmic heating for FFC design [which may also be valid for FPCs]. The model is stated in Equation 2.11, where ΔT is the rise in temperature for a flat conductor of width b and thickness d, ρ being the specific resistance for the conductor and α being a surface heat transfer parameter composed of three parts, representing heat transfer by conduction, radiation and convection. The authors claimed a high degree of correlation between calculated and measured results. The method used to derive the model, as well as the test conditions and results have not been published.

$$\Delta T = \frac{I^2 \rho}{\alpha b^2 d}$$ **Equation 2.11**

The ampacity of FPCs has not been satisfactorily modelled in the previous research, and remains an area for further investigation. A new IPC standard – IPC 2152 [IPC, 2009], on the current carrying capacity of printed circuit traces has been published. The standard aims to address the historical inadequacies in printed circuit trace sizing. According to Jouppi[30], much of what is contained in the standard is reported in the 8th edition of the Printed Circuits Handbook [Coombs, 2008, pp16.1-16.21]. Despite the stated intention of the new standard, no mathematical models for ampacity have been presented. New guidelines for trace sizing have been forwarded, but the designer must use experience to ascertain the most suitable trace size.

2.7.2 Signal Traces and EMC

The application of multiplexing to automotive electrical and electronic circuits requires the establishment of circuit configurations and track design features that are not sensitive to electromagnetic and radio frequency interference. Kibler et al [2004] argued that FPCs and FFCs were only suitable for power lines and low clock-rate data transmission links, and to accommodate high-bandwidth circuits, optical cables would be required. Such cables could be incorporated within FFCs either by lamination or extrusion.

Webb et al [2004] investigated the electromagnetic compatibility (EMC) or RF interference noise rejection function of FPC harness, as compared to wire harness. The authors assert that a wiring harness would act as an aerial to couple RF energy into or out of devices interconnected by the FPC, and the amount of RF noise coupled into a circuit would depend more strongly on geometry; i.e. lengths and layout of current paths, than on the type of interconnection media.

Radio Frequency (RF) interference in a wire harness may be avoided by using a twisted wire pair for, or by shielding the specific circuits requiring protection. Saltzberg and Neller [1996] demonstrated the application of Polymer Thick Films for electromagnetic shielding on rigid PCBs in automotive applications. Webb et al [2004] investigated whether similar levels of protection could be achieved with suitable trace layout on a FPC harness.

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[30] M. Jouppi, Denver Colorado, Personal Communication, November 2009.

The approach taken was comparative, i.e. the degree of coupling between radiated electromagnetic fields and twisted-pair wires or FPC trace configurations were measured and compared in a high-speed CANbus application. To simulate a twisted-pair on FPC, a plated through-hole crossover pattern was used, or alternatively a zigzag pattern as illustrated in Figure 2.7. It was observed that the plated through-hole crossover pattern performed as well as automotive twisted pair conductors.

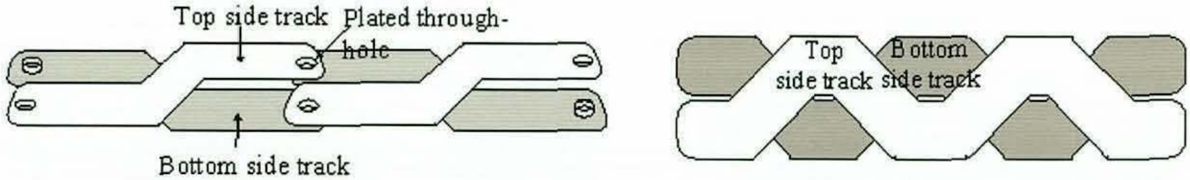

Figure 2.7 Twisted Pair Configurations For FPC [Webb et al., 2004]

2.7.3 Connectors

Several authors have cited the unavailability of automotive FPC connectors as a limitation in such circuits [Sheehan and Rider, 1999] [Cottrill et al, 2002] [Terenuma, Ide and Kusugi 2002]. Terenuma, Ide and Kusugi [2002] noted that available FPC connectors were limited to low current applications. The status of standardization, in addition to the availability of suitable automotive FPC connectors is at present unclear. Two automotive FPC connector manufacturers – JST and FCI[31], have published specifications for their products [FCI, 2009] [JST UK Ltd, 2009] on the internet[32].

JST manufactures three connectors, each accommodating between 8 and 30 pins. The available pin pitches for these connectors are 1mm, 1.25mm and 2.0mm, and their current-carrying capacity range between 0.6A to 1.5A. FCI manufactures nineteen similar connectors accommodating either 10 or 22 pins only. The available pin pitches for these connectors are 2.54mm and 5.08mm; however no information regarding current-carrying capacity have been published by FCI. The connectors offered by both manufacturers attach to one single or double-sided FPC only.

[31] Acronym meaning unknown for both companies.

[32] Based on an internet search using Google

2.7.4 Design for Manufacture

Circuit design should provide for a greater ease of manufacture as well as lower cost of manufacture. Cottrill et al [2002] noted that the process of choosing a preferred design and construction option, or options, includes identification of all the design requirements; available manufacturing technology and its capability; quantity requirements; material utilisation, process and assembly costs; capital investment requirements; space requirements and manning levels. The assessment must take into account the requirements of stakeholders, namely vehicle manufacturers, equipment and circuit manufacturers together with garage and maintenance operations and vehicle owners, as listed in Table 2.5.

Requirements Of Vehicle Manufacturers	Requirements Of Equipment / Circuit Manufacturers	Requirements Of Garages And Vehicle Owners
Handleability	Ease of manufacture	Reliability in service
Assembleability	Handling	Ease of maintenance
Ease of redesign / modification	Design requirements	Low maintenance costs
Reliability - to withstand assembly and in service conditions	Testability	
Integration of functions	Material utilisation	
Simple interconnection		
Weight saving		
Cost effectiveness		

Table 2.5 Requirements of Stakeholders for Large Area FPCs

Cottrill et al [2002] further noted that a major factor in the decision process is the availability of equipment having the necessary capability for all of the process stages involved to deliver circuits to the required specification, level of accuracy and quality and in the projected volumes. Designing the FPC to maximize the use of material can be accomplished by using appropriate folding features and detachable arms. This method may allow the use of using standard material widths, enabling the use of industry standard equipment over bespoke machinery.

3 METHOD OF INVESTIGATING FPC MATERIALS

3.1 Introduction

Large area FPCs, whether deployed as drop-in substitutes for existing wiring harnesses or as purpose designed wiring, must survive the vehicle assembly process and also the in-service conditions experienced throughout the vehicle's lifespan. To demonstrate such survivability during the initial product development phase, in the absence of established reliability data; an assessment of relevant FPC properties should be performed before, during and after exposure to accelerated ageing conditions. A supplementary objective of the assessment is an analysis of the effect of different constituent FPC materials on the properties under investigation. To satisfy these objectives, the assessment would take the form of a designed experiment as illustrated in Figure 3.1. An analysis of the results of the experiment may assist designers in the selection of appropriate materials for manufacturing large area automotive FPCs.

Identifying FPC properties that are relevant to automotive applications however, is hindered by ambiguities in respect of the method of assembly of proposed large area FPCs into the vehicle, in-service environmental conditions expected over the vehicle lifespan and the mode of application [for example, as an electrical interconnect without electronic components attached, or as a hybrid electrical and electronic interconnect with integrated electronic components]. To assist in identifying relevant FPC properties and accelerated ageing conditions, are the established standards and specifications for both automotive round wire harnesses and for FPCs. Large area FPCs designed as drop-in substitutes would implement all the electrical circuits of an existing wiring harness and be assembled within the same locality of the vehicle. Therefore, the relevant FPC material properties and in-service environmental conditions should be those equivalents to the required properties of insulated round wire and wiring harnesses; as stated in the standards and specifications. These and any additional relevant FPC properties can then be determined through the use of test methods defined in standards and specifications for FPCs.

This chapter presents the methodology followed in this research; of assessing the properties of FPCs deemed relevant to automotive applications. A review of automotive and FPC standards and specifications is followed by a presentation of the materials and the experiment design adopted.

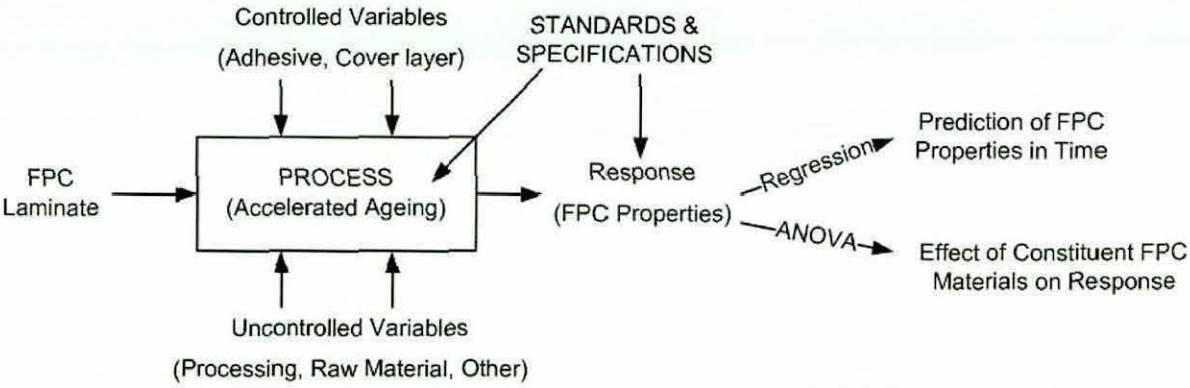

Figure 3.1 Experiment Design for Assessing FPC properties

3.2 Standards and Specifications for Automotive Round Wire

Although numerous standards and specifications for automotive insulated wire have been published by various issuing bodies such as the ISO, SAE, and automotive OEMs[33], there is commonality between them. For example, specifications used by Daewoo Motor Company [1991] and Ford Motor Company [1999] for their automobiles require insulated wire specimens to undergo a subset of the physical tests prescribed by SAE J1128 [Society of Automotive Engineers, 2005], SAE J1678 [Society of Automotive Engineers, 2004] and ISO 6722[34] [ISO, 2006a] standards. The working group of German automotive manufacturers[35] have adopted their own standard – LV 112 [AK Group, 2005]; which includes a number of ISO 6722 tests as defined.

The underlying emphasis in the SAE and ISO standards is the importance of the integrity of the wire insulation, specifically its dielectric breakdown or voltage withstand strength and

[33] See Labco [2007] for a non-exhaustive list of standards and specifications issued by international and national standards organizations, and automotive OEMs.

[34] The test schedule prescribed by the ISO 6722 standard is reproduced in Appendix A. Identical test procedures are cited in ISO 14752 (multi-core cables), SAE J1128, SAE J1678 and OEM standards/specifications.

[35] AK Group: AUDI, BMW, DaimlerChrysler, Porsche and Volkswagen

resistance to cracking, the latter being a potential cause leading to short circuit failure. This is supported by the majority of test procedures listed in the SAE and ISO standards requiring a dielectric breakdown/voltage withstand test to be performed after exposing the insulated wire to mechanical, chemical, abrasion or climatic stress[36]. The standards and specifications for automotive insulated wire do not otherwise disclose mandatory performance requirements.

3.3 Standards, Specifications and Test Methods for FPCs

Standards and specifications for single and double-sided FPCs without through-hole connections, automotive FPCs, dielectric and copper-clad dielectric films published by various standards organizations and automotive OEMs are listed below[37].

SAE

J771	[Society of Automotive Engineers, 1986]
AMS3613C[38]	[Society of Automotive Engineers, 1998]
AMS3612B	[Society of Automotive Engineers, 1993]

Automotive OEM

Ford: WSFM22P5-A	[Ford Motor Company, 1996]
General Motors: GME 4221	[General Motors, 2004]

[36] The level, duration and method of application of these stress types appear to be without scientific foundation, and are more likely to be based on industry experience.

[37] *This is a non-exhaustive list, which is to be read in conjunction with the Standards and Specification cited* within, but not listed here.

[38] AMS3613C is an aerospace standard for polyester FPCs, and requires polyester films used in such FPCs to conform to the requirements of AMS3612B

British Standards[39]

BS EN 61249-3-3:1999	[British Standards Institution, 1999]
BS EN 123400:1992	[British Standards Institution, 1992a]
BS EN 123400-800:1992	[British Standards Institution, 1992b]
BS 123400-003:2001[40]	[British Standards Institution, 2001]

ASTM

D2861-87[41]	[ASTM, 2004b]
D2305-02	[ASTM, 2002]

Underwriters Laboratories

UL796F	[Underwriters Laboratories, 2000]
UL746F	[Underwriters Laboratories, 2006]

IPC[42]

FC-231C	[IPC, 1992a]
FC-232C	[IPC, 1992b]
FC-241C	[IPC, 1992c]
TM-650	[IPC, 2007]

[39] Although several British Standards have been published for FPCs such as the BS, BS EN and BS CECC 12300 series, BS 6221 series and BS EN 61249 series, there is no significant divergence between any of the series.

[40] Test methods listed are to be found in BS 6221-2:1991, and requirements for copper-clad polyester in BS 60249-2-8:1994

[41] D2861-87 requires dielectric films used in FPCs to conform to the requirements of D2305-02

[42] FC-231C, FC-232C and FC-241C have been superseded by IPC-4202, IPC-4203 and IPC-4204 respectively

The prescribed test methods for assessing FPC properties, as detailed in the listed standards and specifications, are to an extent included in the IPC standards.

3.4 Relevant FPC Properties

The following quantifiable FPC properties have been selected for assessment, using the test methods as stated or modified[43]:

Tensile Strength and Elongation - IPC 2.4.19

This test would determine the susceptibility of the film or FPC laminate [especially in areas of the FPC where the metallic conductor may be absent] to break if subjected to strain at any time throughout the vehicle lifetime, and is of particular importance to PET, which exhibits a decrease in tensile strength on exposure to elevated temperature and humidity. Retention of tensile strength shall be indicative of the film, adhesive and FPC laminate resistance to degradation resulting from exposure to an automotive environment.

Peel Strength (Foil Bond Strength and Coverlay Adhesion) - IPC 2.4. [Method A or B]

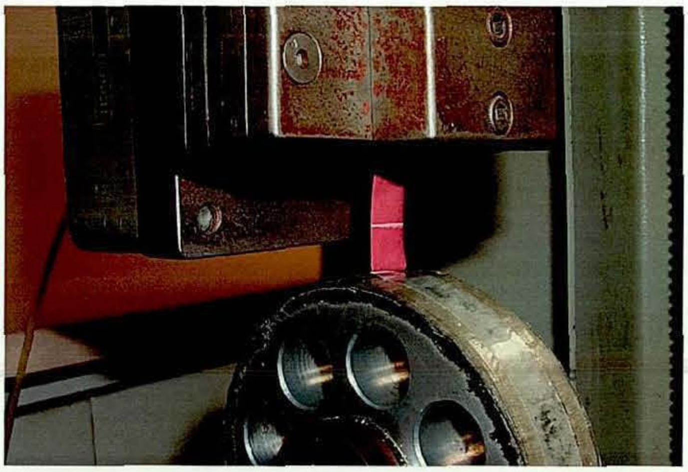

Figure 3.2 Peel Strength Test using a German Wheel

[43] Test coupons would not be stabilised by environmental conditioning prior to testing where such conditioning requires additional resources that were not available during this research.

Adhesives in an FPC may be susceptible to hydrolytic degradation when exposed to humid environments or may be unstable at high temperature, resulting in cohesive and/or adhesive failure. Delamination of the copper traces, coverlays or bond ply [if present] may result. Peel strength tests provide an indication of the adhesive bond strength over the vehicle lifespan, and retention of this material property is desirable. Figure 3.2 shows a peel strength test being performed with a 'German Wheel', with the translucent base dielectric film attached to the circumference of the wheel, while the copper conductor is peeled away from the film at a 90 degree angle.

Initiation Tear Strength - IPC 2.4.16

This test shall determine the force required to produce tearing in a small area of stress concentration. Figure 3.3 shows the test coupon used for the initiation tear test and its V-shaped outline held between the grips of a universal testing machine. It is relevant to assembly into the vehicle and reliability throughout the vehicle lifetime, because areas of the FPC that are poorly designed and have no reinforcement may be susceptible to tearing as the FPC ages in an automotive environment.

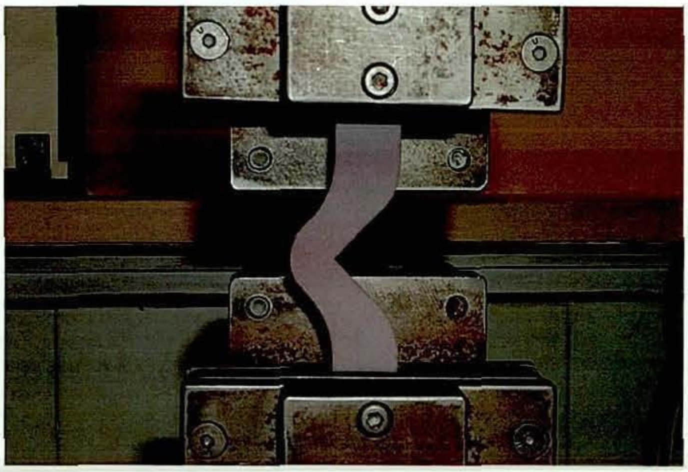

Figure 3.3 Initiation Tear Test

Propagation Tear Strength - IPC 2.4.17.1

Areas of the FPC that have been designed to accommodate folding[44] may be susceptible to tearing, as are areas of the FPC where the angular direction of the outline shape changes rapidly[45]. The continuous application of force after a tear has been initiated in the FPC may cause the tear to propagate, leading to the possible detachment of sections of the FPC, or the exposure of the metallic conductor. Figure 3.4 shows a test coupon undergoing a propagation tear strength test.

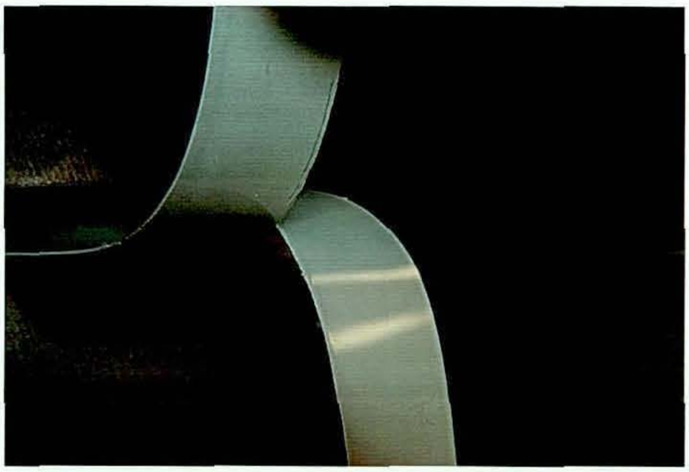

Figure 3.4 Base Dielectric Film Undergoing a Propagation Tear Strength Test

Flexural Testing - IPC 2.4.3.1

Flexural tests are applicable to hinged areas of the vehicle such as doors, where the FPC would be expected to bend. The test method allows for the determination of the flexural fatigue life of the FPC [indicated by an electrical discontinuity, caused by crack formation in the metallic conductor] for a given bend radius, and which may be affected by the type and thickness of the materials used in the construction of the FPC. Although the test method is normally used to determine the flexural fatigue of a FPC for any bend radius [via multiple tests using different bend radii]; its inclusion in this research, using a single bend radius may

[44] See Figure 7.10 for an example of design for folding and for which propagation tear strength is relevant.

[45] Good design practice is to use a circular outline at the point where the FPC outline changes direction. The minimum recommended circular radius is 1.6mm [IPC, 1998b].

provide additional comparative data for the different FPC materials. Figure 3.5 shows a FPC undergoing a flex test.

Figure 3.5 FPC Undergoing Flexural Fatigue Life Test Using a Universal Flex Tester

Insulation and Moisture Resistance, Flexible Base Dielectric - IPC 2.6.3.2b [Modified Test]

This test would determine the insulation properties of the adhesive surrounding conductive traces [and to a lesser extent the base dielectric film]. The test method requires the concurrent application of elevated electrical and environmental stress; which although valid, requires additional resources not available during this research. A modified test has been devised. This requires test coupons to be exposed to accelerated ageing, followed by the application of a ramp voltage until dielectric breakdown occurs.

Dielectric Breakdown Strength - ASTM D149-97a [ASTM, 2004a]

Dielectric breakdown of insulating films and adhesives is a potential mechanism by which short circuit failures may occur as the film and adhesive ages and degrades. This test would determine the dielectric breakdown strength in an orthogonal direction to the surface of the FPC. Two sets of stainless steel electrodes would be used for applying an alternating voltage at commercial frequency (50Hz) ramped at 500V per second in each test, the first being opposing cylinders of 25 mm diameter, and the second being opposing rods of 6.4 mm in diameter. Test coupons would be placed between the electrodes, and kept in an insulated enclosure as illustrated in Figure 3.6. The electrodes would be cleaned prior to each test. Test coupons would not be cleaned so as to prevent the removal of the adhesive layer that remained after chemical etching. The rationale for not cleaning the test coupons is to investigate the effect of by-products formed in the film or FPC structure during accelerated ageing.

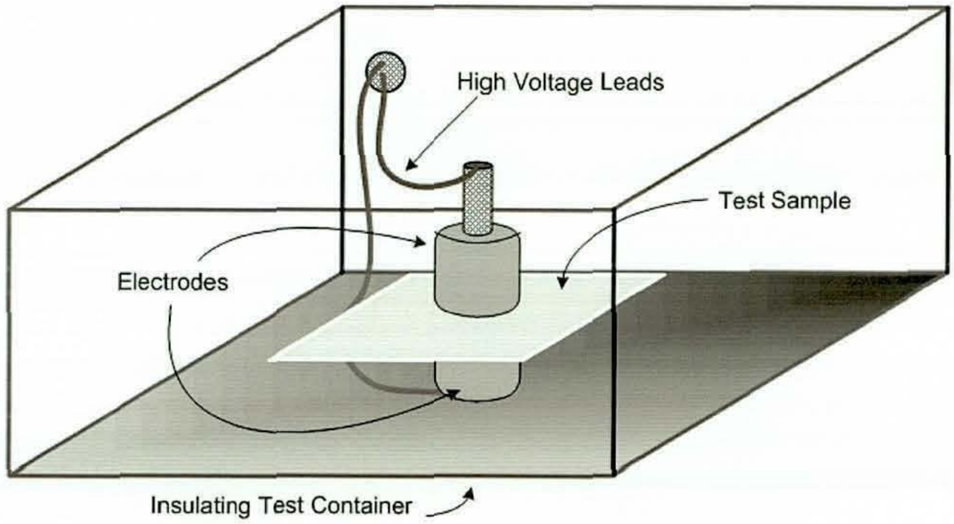

Figure 3.6 Illustration of Dielectric Breakdown Test

Volume Resistivity & Surface Resistance - IPC 2.5.17 [Modified Test]

This test[46] is based on the ASTM D257 [ASTM, 2007] test method and would determine the volume and surface resistivity of base dielectric film, coverlay film and the adhesive in copper-clad test coupons. The test method specifies environmental conditioning of test coupons at elevated relative humidity levels; which requires additional environmental conditioning resources not available during this research. A modified test has been devised. This requires test coupons to undergo the electric test aspect of ASTM D257 at steady state ambient room conditions. The electrode system would be flat metal plates (concentric circular brass electrodes). Electrodes would be cleaned prior to each test, but test coupons would not be cleaned.

[46] IPC 2.5.17 is a complementary test to IPC 2.6.3.2f

Flammability of Interior Materials – FMVSS 302

The requirements of other standards or specifications, although not pertaining directly to insulated round wire or FPCs, must be met where legislation mandates it. Of specific relevance is FMVSS 302 [UNITED STATES, 1991], adopted by Daewoo [1990], which sets the burn rate of materials located within the occupant compartment to be no more than 4 inches per minute. The test method specifies environmental conditioning of test coupons prior to the application of the flame, and performance of the test to be within a specially designed Burn Test Cabinet; additional equipment resources not available during this research. A modified test has been devised, requiring the test to be performed in a standard fume cabinet at steady state ambient room temperature and relative humidity. Further, to investigate the effect of copper content on flammability, experiments would be performed on test coupons that are fully etched (0% copper), not etched (100% copper) and etched with parallel conductors as illustrated in Figure 3.7.

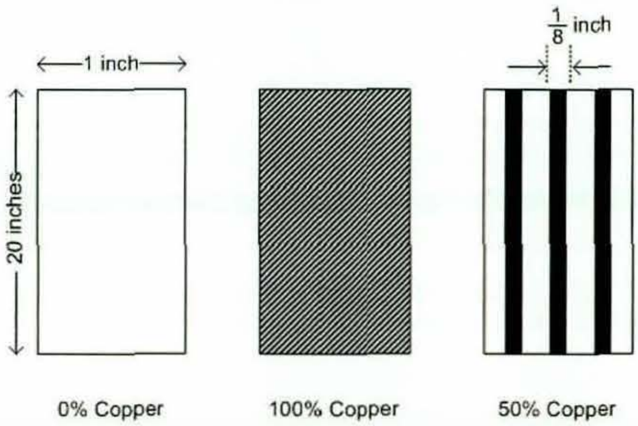

Figure 3.7 Test Coupons for Flammability Tests

3.5 Environmental Conditions for Accelerated Ageing

To simulate changes in the selected FPC properties over the lifespan of a vehicle, accelerated ageing of the test coupons becomes a necessary component of the experiment design. The preferred accelerated ageing conditions are the elevated levels of such in-service environmental conditions that normally lead to FPC degradation. Although the standards and specifications for automotive round wire and for FPCs do not employ the term "accelerated ageing", a number of prescribed tests and test methods require the exposure of test coupons to elevated electrical, mechanical, chemical, or other environmental stress conditions prior to testing. Additional pre-test environmental stress conditions relevant to electrical and electronic equipment mounted within a passenger vehicle are prescribed in the following standards:

i. SAE J1211: Recommended Environmental Practices for Electronic Equipment Design [Society of Automotive Engineers, 1978]

ii. ISO 16750: Road vehicles - Environmental conditions and testing for electrical and electronic equipment [Parts 1 to 5] [ISO, 2006b, 2006c, 2006d, 2003a, 2003b]

The environmental conditions prescribed in the standards and specifications vary in duration and severity; and may either be too severe, not severe enough to properly simulate FPC degradation over the vehicle's lifespan, or not relevant to the degradation mechanisms applicable to FPCs. However, the following relevant accelerated ageing conditions have been selected from the standards and specifications:

High Temperature and High Humidity Exposure (Damp Heat Ageing)

Standard/Specification	Damp Heat Ageing Conditions
ISO 16750:4	504 hours at either 30 or 40°C and either 85 or 93%RH (4 combinations)
SAE J1678	3000hrs at 85°C uncontrolled humidity (Class A wire) (different temperatures are prescribed for other wire classes)
ISO 6722	same as SAE J1678
LV 112	3000hrs at 85°C/85%RH [specification applies to both round wire and FPCs][47]
GTS Meeting Notes [Flexelec, 2000]	3000hrs at 85°C/95%RH [based on a draft DaimlerChrysler Specification[48]]

Table 3.1 Specified conditions for accelerated ageing at high temperature and humidity

[47] M. Joyce, Yazaki Europe Ltd., Hemel Hempstead, UK. Personal Communication, November 2009.

[48] G. Farmer, GTS Flexible Materials Ltd, Ebbw Vale, UK. Personal Communication, November 2009.

Exposure to high temperature and humidity would induce hydrolytic degradation of the FPC. The temperature and relative humidity used for damp heat ageing, as specified in the automotive standards and specifications, are listed in Table 3.1. Control of both temperature and relative humidity is preferable as it allows for repeatability and replication of the experiment, and damp heat ageing of FPCs in this research would be performed at 85°C/95%RH for 3000 hours; the most severe accelerated ageing conditions specified[49].

Temperature Cycling

Standard/Specification	Temperature Cycling Conditions
ISO 16750:4	User choice between several upper and lower temperature limits, dwell time, changeover time, duration and controlled humidity
SAE J1678	-40°C to 85°C for 320 hrs (40 cycles) (Class A wire) (different temperatures are prescribed for other wire classes); controlled humidity between 80% to 100% RH (no set level specified)
ISO 6722	same as SAE J1678
GME4221	20 cycles (≤200 hours in total), user choice of upper and lower temperature limits; humidity kept below 50% RH (at 35°C)

Table 3.2 Temperature Cycling Conditions as defined in Standards and Specifications

Temperature cycling would be used to simulate thermal induced stress in FPCs due to differences in the coefficient of thermal expansion (CTE) between the different layers. During the high temperature cycle, the presence of moisture can also induce hydrolysis in the FPC[50]. Standards and Specifications for Temperature Cycling of automotive wire, FPCs and electrical/electronic equipment prescribe widely varying conditions, as highlighted in Table 3.2. For the experiment design, temperature cycling between -40°C and 85°C and

[49] This was also selected to evaluate whether the DaimlerChyrsler specification was realistic – given the increasing interest of automotive OEMs in FPCs.

[50] This may provide comparative data to illustrate the effect of high relative humidity exposure.

uncontrolled humidity would be performed for 3000 hours[51]. Each cycle would be eight hours duration with dwell times at maximum and minimum temperatures of three hours and temperature rise/fall time of one hour.

3.6 Candidate Materials

The candidate materials investigated in this research are those which are commercially available and used in the manufacture of FPCs. Table 3.3 describes[52] the materials that have been provided, with Data Sheets[53] included in the Appendix. The film utilized in the base substrates and coverlays are of 75 and 50 microns thickness respectively. No information has been provided on the specific characteristics of the PET and PEN films, for example, the particular variant of PET or PEN film (e.g. Mylar A, Mylar C, Melinex™, Teonex™). The copper layer is 35 microns (1 oz) and comprises either rolled-annealed or electrodeposited copper.

3.7 Experiment Matrix

The primary objective of the experiment design in this research is to investigate the effect of accelerated ageing on the relevant FPC properties over time[54]. The supplemental objective of the experiment design is to investigate the effect of each element of the FPC on the FPC properties over time[55]. The controlled elements (factors) and their variants (levels) that have been incorporated into the experiment design are shown in Figure 3.8. These form the basis of a factorial experiment, which can then be reduced in size[56].

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[51] This was due to equipment capabilities. Controlled humidity would be preferred.

[52] Commercial sensitivity precludes a detailed description of the base and coverlay films and the chemical composition of the adhesives; as cited by GTS.

[53] Data Sheets for L950139 and 924-00-01 were updated according to the damp heat ageing tests in this research

[54] Regression analysis could be used to develop a mathematical model for FPC property degradation with time.

[55] This could be determined by using analysis of variance (ANOVA) techniques. The analysis may further reveal which of the factors has the dominant effect on the Responses and whether factors interact.

[56] Methods for the statistical design and analysis of experiments have been published by notable authors including Fisher [Montgomery, 2001, p.17-19], Plackett and Burman [1946], and Taguchi [Roy, 1990, p.7].

Label	Part No.	Type	Main Use	Description
1	550130EDTC	PET	Base Substrate	Polyester film laminated to rolled-annealed copper on one side, incorporating a polyester adhesive
2x	556130ED	PET	Base Substrate	Same as above, but with a higher temperature and improved solvent resistant adhesive that is stable at high temperature (but not high humidity)
2y	556131ED	PET	Base Substrate	Double-sided version of 556130ED (above)
3	L950139	PET	Base Substrate	Polyester film laminated to electrodeposited copper on one side, incorporating an aqueous epoxy adhesive that is stable at high temperature and humidity.
4	924-00-01	PET	Base Substrate	Polyester film laminated to electrodeposited copper on one side, incorporating a modified Polyurethane adhesive
5	567130	PEN	Base Substrate	PEN film laminated to rolled-annealed copper on one side, incorporating a modified flame retardant (bromide) epoxy adhesive system
a	302120	PET	Coverlay	Polyester film coated on one side with a modified polyester adhesive incorporating a blocked IsoCyanide catalyst (activated at 120°C; thermosetting)
b	348110	PET	Coverlay	Polyester film coated on one side with a modified flame retardant epoxy adhesive (thermosetting), having high temperature and humidity resistance
c	348120	PET	Coverlay	Similar to 348110: variation in adhesive (epoxy)
d	364110	PEN	Coverlay	PEN film coated on one side with a modified flame retardant epoxy adhesive (thermosetting), having high temperature and humidity resistance (same adhesive as 348110)
e	Not applicable	INK	Covercoat	Dielectric Ink used by Pressac

Table 3.3 Candidate Materials for Large Area Automotive FPCs

Controllable factors such as manufacturing process parameters; and batch variables such as raw materials have not been included in the design. For the experiment, it was assumed that both electrodeposited and rolled-annealed copper would have the same effect on FPC properties, and could be removed as a factor. This creates an experiment having two factors of six levels each (6 base substrates, and 6 cover layers). To further reduce the experiment, PEN films would not be combined with PET films. The resulting factorial experiment is shown in Table 3.4. The experiment runs can be randomised and replicated, but blocking has not been incorporated.

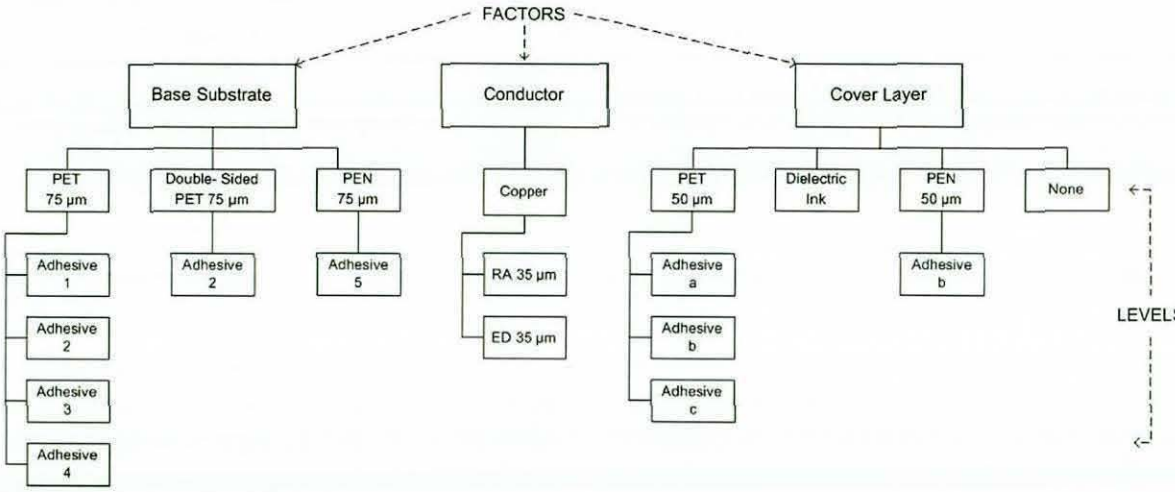

Figure 3.8 Controlled Factors and Levels for Experiment Design

Without further reduction, this experiment is impractical[57]. However, whereas established statistical techniques for reducing full factorial experiment designs are particularly suited to 2^f and 3^f experiments (i.e. multi-factor experiments where each factor have no more than 2 or 3 levels); they are not suited to multi-level 2-factor experiments[58][59]. To partially reduce the

[57] The total number of experiment runs would be the product of (28 x number of FPC properties x number of replications x number of measurements over 3000 hrs x number of accelerated ageing conditions). Potentially, experiment runs = (28 x 9 x 5 x 10 x 2) = 25,200.

[58] For example, an experiment with 2 factors at 5 levels each could use the L25 Taguchi Orthogonal Array (used for up to 6 factors at 5 levels). The number of runs required by this array is 25; thus there is no reduction from the full factorial design.

[59] Plackett and Burman [1946] developed methods to avoid complete factorial experiments. According to the authors, "Practically all useful solutions of this [method] have been found when each factor appears at two

experiment, only those commercially realistic laminate combinations would be included. These laminate combinations, as advised by GTS, are listed in Table 3.5. Using this approach, the primary objective of the experiment may be achievable, but the supplementary objective requires additional comparative tests, which would be performed on the six base substrates.

Run	Test Coupon ID	Base + Adhesive	Cover + Adhesive
1	1a	PET + 1	PET + a
2	1b	PET + 1	PET + b
3	1c	PET + 1	PET + c
4	1e	PET + 1	Ink
5	1	PET + 1	none
6	2xa	PET + 2	PET + a
7	2xb	PET + 2	PET + b
8	2xc	PET + 2	PET + c
9	2xe	PET + 2	Ink
10	2x	PET + 2	none
11	3a	PET + 3	PET + a
12	3b	PET + 3	PET + b
13	3c	PET + 3	PET + c
14	3e	PET + 3	Ink
15	3	PET + 3	none
16	4a	PET + 4	PET + a
17	4b	PET + 4	PET + b
18	4c	PET + 4	PET + c
19	4e	PET + 4	Ink
20	4	PET + 4	none
21	2ya	PET + 2 + 2	(PET + a) x 2
22	2yb	PET + 2 + 2	(PET + b) x 2
23	2yc	PET + 2 + 2	(PET + c) x 2
24	2ye	PET + 2 + 2	Ink x 2
25	2y	PET + 2 + 2	none
26	5d	PEN + 5	PEN + b
27	5e	PEN + 5	Ink
28	5	PEN + 5	none

Table 3.4 Factorial Experiment for Candidate FPC Materials

levels, but the solutions for more than two levels are fairly limited". Tables of designs for 2, 3, 5 and 7 level factors have been provided.

Run	Test Coupon ID	Base + Adhesive	Cover + Adhesive
1	1a	PET + 1	PET + a
2	2xb	PET + 2	PET + b
3	2xc	PET + 2	PET + c
4	2xe	PET + 2	Ink
5	3b	PET + 3	PET + b
6	3c	PET + 3	PET + c
7	3e	PET + 3	Ink
8	4b	PET + 4	PET + b
9	5d	PEN + 5	PEN + b

Table 3.5 Laminate Combinations for reduced experiment design

Further, each test method may introduce additional requirements for test coupons. For example, peel strength tests are applicable to copper-clad substrates. For the orthogonal electrical tests, i.e. dielectric breakdown strength and volume and surface resistivity, adhesive coated base films and coverlays would be tested, because failure of either of these individual layers may lead to short-circuit faults in the FPC. Laminates would not be included in the tests for peel strength, dielectric breakdown strength and volume and surface resistivity.

Temperature Cycling was performed at Loughborough University and damp heat ageing performed at GTS Flexible Materials Ltd (GTS). The experiments were also split between Loughborough University and GTS, with test coupons being shipped between locations.

The experiment matrix followed in this research is presented in Table 3.6

Table 3.6 Experiment Matrix

TEST	PROPERTIES	TEST METHOD	TEST COUPONS	Base Substrates	Coverlays	Laminates	TEST LOCATION	Etching Requirements
1	Tensile Strength	IPC 2.4.19	5 MD, 5 TD	✓		✓	GTS	Etch Completely
2	Peel Strength	IPC 2.4.9	2 MD, 2 TD	✓			GTS	No Etch
3	Initiation Tear Strength	IPC 2.4.16	5 MD, 5 TD	✓		✓	GTS	Etch Completely
4	Propagation Tear Strength	IPC 2.4.17.1	5 MD, 5 TD	✓		✓	GTS	Etch Completely
5	Flexural Testing	IPC 2.4.3.1	3	✓		✓	GTS	Etch According to Test Method
6	Insulation Resistance	IPC 2.5.11	3	✓		✓	Loughborough	Etch According to Test Method
7	Dielectric Strength	ASTM D149-97a	3	✓	✓		Loughborough	Etch Completely
8	Volume & Surface Resistivity	IPC 2.5.17	3	✓	✓		Loughborough	Etch According to Test Method
9	Flame Resistance	MVSS302	3	✓		✓	Loughborough	No Etch, 50% Etch, 100% Etch

(Yellow) Temperature Cycling: -40°C to 85°C for 3000 Hours: Test every 24 Hours for first 240 hours, then less frequently (but no longer than 184 hours between tests)
Damp Heat Ageing: 85°C / 95%RH for 3000 Hours: Test every 24 Hours for first 240 hours, then less frequently (but no longer than 184 hours between tests)

(Orange) Damp Heat Ageing and Temperature Cycling as above: Test at 0, 1500 and 3000 Hours

MD = Machine Direction

TD = Transverse Direction

Base Substrates = 1, 2x, 2y, 3, 4, 5

Coverlays = a, b, c, d

Laminates = 1a, 2xb, 2xc, 2xe, 3b, 3c, 3e, 4b, 5d

4 PROPERTIES OF FPCS AFTER ACCELERATED AGEING

4.1 Introduction

The properties of selected FPC laminate combinations as they age are presented in this chapter. Such ageing properties have not been previously established. Temperature cycling between -40 and 85°C did not lead to discernable material degradation trends. Terminal degradation and discernable degradation trends have been observed with accelerated ageing at 85°C/95%RH; however, limitations and outliners in the experimental results have precluded a forecast of the degradation in some material properties using simple regression analysis. A robust regression analysis using a commercial software tool has allowed the determination of linear degradation trends in material properties. In addition to the new knowledge of the degradation of FPC laminates and candidate materials, analysis of the experimental results have also allowed for proposals to be made in respect of a draft automotive FPC specification later in this thesis.

The tensile strength of FPC laminates may be dominated by the base dielectric layer in single-sided FPCs. Conventional adhesives used in FPC deployed in mainstream electronic products exhibit poor retention in peel strength, however the other adhesives that have been tested may be more suitable for automotive applications. The electrical properties of the test coupons including insulation and moisture resistance, dielectric breakdown strength, and volume and surface resistivity could not be precisely measured after temperature cycling and accelerated ageing at 85°C/95%RH. Flammability tests have been inconclusive, with the initial combustion of test coupons being sensitive to the location of the Bunsen burner flame relative to the test coupon.

4.2 Test Coupons and Environmental Chambers

The manufacture of test coupons followed the route illustrated in Figure 4.1. A conventional "wet" reel-to-reel process was used for preparing the copper clad base substrate. Where required, dielectric ink was screen printed onto the reel before panelization. Panelization of the coverlay film incorporated the profiling of "windows"[60]. Manual lamination of the panels was followed by laser profiling of the individual test coupons. Panels were designed to include one or more of each test coupon pattern, oriented in both machine and transverse direction.

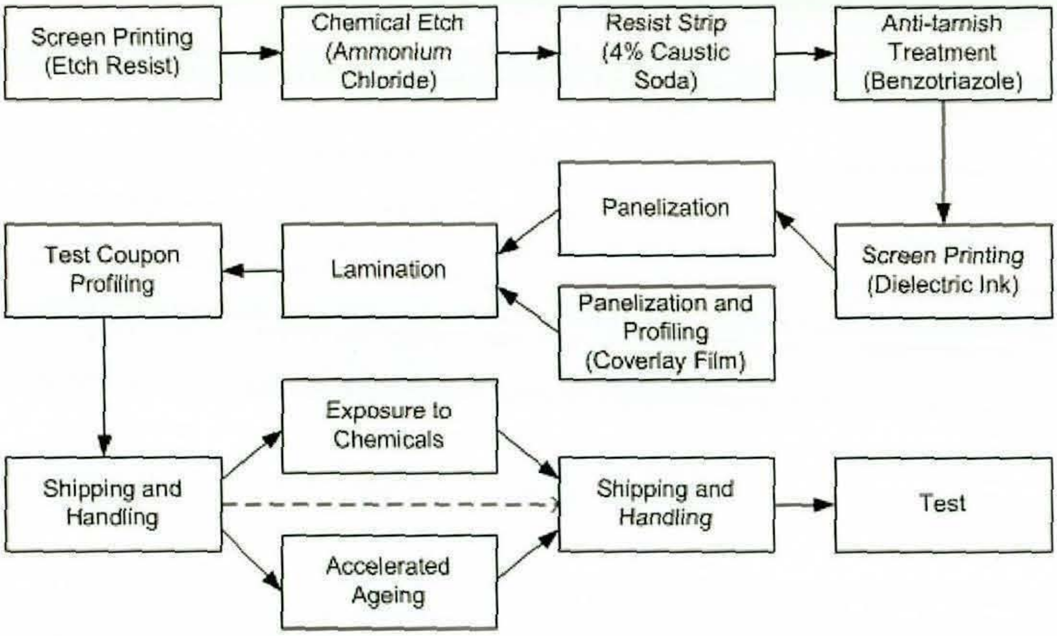

Figure 4.1 Manufacturing Route for Test Coupons

Temperature cycling was performed in a large environmental chamber, with panels containing the test coupons suspended from a wooden test rig shown in Figure 4.2. Thermocouples were placed in free flowing air next to the test rig, and at the centre of the suspended panels. It can be seen in Figure 4.3 that the temperature of the air flowing between the panels followed that of the free flowing air without significant divergence. Although programmed to deliver a dwell time of three hours at each extreme temperature, the cooling capacity of the chamber limited the dwell time at -40°C to only two hours. This however is the minimum dwell time specified in the SAE J1211 standard [Society of Automotive Engineers, 1978]. The relative humidity within the temperature cycling chamber was uncontrolled at all times, and a classical linked temperature/relative humidity profile was

[60] For test coupons requiring no coverlay, or for coupons with a printed ink coverlay

observed[61]. A total of 375 temperature cycles were completed, with test coupons exposed to 85°C for no less than 1500 hours. For accelerated ageing at 85°C/95%RH, test panels were loaded individually into trays within the environmental chamber.

Figure 4.2 Test coupon panel in Temperature Cycling Chamber

4.3 Limitations in the experimental results

The experiment results released by GTS for use in this thesis are for a subset of the experiments performed. This is due to the commercial sensitivity of the results, particularly for the adhesives that were being developed during this research. Further, an inadequate number of test coupons of the required cross sections were manufactured for the experiments, due to limited quantities of materials. This resulted in some tests being conducted less frequently than desired, particularly for test coupons exposed to damp heat ageing. Further, test coupons for damp heat ageing were completely depleted by 1687 hours, with some test coupons being depleted after only 216 hours. Temperature cycling was performed for 3000 hours. Additionally, PEN based laminates were manufactured incorrectly; having a PET coverlay instead of PEN. The limitations in the experiment results stymie the inferences that

[61] At temperatures below 10°C, the relative humidity of the air inside the chamber would tend to saturation. During the heating cycle, the relative humidity at 85°C would tend to 45%. Continuous measurements of the relative humidity within the chamber were not recorded.

can be made. The results are therefore a "first look" at the properties of FPCs as they age and inform the inferences that have been made. Table 4.1 lists the labels for the substrates and laminates reported in this Chapter, together with a brief description of the material.

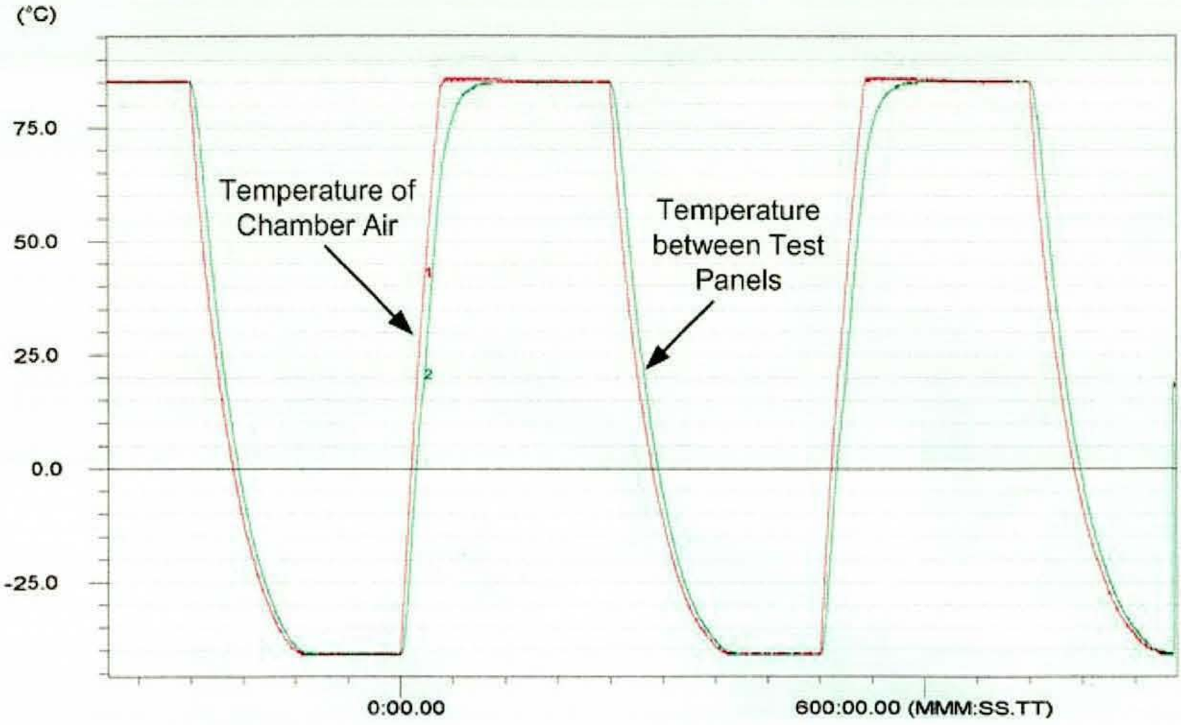

Figure 4.3 Temperature within Temperature Cycling Chamber during Accelerated Ageing

Test Coupon ID	Base	Coverlay	Base + Adhesive	Cover + Adhesive
1a	1	a	PET + 1	PET + a
2xb	2x	b	PET + 2	PET + b
2xc	2x	c	PET + 2	PET + c
2xe	2x	e	PET + 2	Ink
2y	2y	none	PET + 2 + 2 (double-sided)	none
3b	3	b	PET + 3	PET + b
3c	3	c	PET + 3	PET + c
3e	3	e	PET + 3	Ink
4b	4	c	PET + 4	PET + b
5b	5	b	PEN + 5	PET + b

Table 4.1 Test Coupon Labelling

4.4 Tensile Strength

The tensile strength of the test coupons after damp heat ageing is presented in Table 4.2, and shown in Figure 4.4. The results show the different general trends in tensile strength degradation for PET and PEN based laminates. Whereas a linear degradation was observed by Mahon et al [1959] in respect of the tensile strength of Mylar A film after damp heat ageing, similar observations have not been made in respect of the adhesive coated PET and PEN films and laminates tested.

Hours	Tensile Strength (MPa) – High Temperature and Humidity Ageing									
Ageing	1a	2xb	2xc	2xe	2y	3b	3c	3e	4b	5b
0	158.705		169.460		194.870				165.590	
24	133.630	145.145		141.540		152.695				
48	142.455		147.195		194.290		84.940			
120	145.450	107.700		155.045						196.595
144	136.810							130.525		
168	171.750	126.905		131.115						
216	127.280						164.900			
336						140.280				
384									96.850	
408						119.410				
456										189.330
480							109.500			
504								102.92		
528										181.865
639								111.57		
660									97.070	
684										166.860
756							90.785			
804								93.245		
828									84.360	
852										222.440
924							109.490			
967								108.74		
1015								98.51		187.200
1135										
1183										184.950
1303								39.29		
1327									53.030	
1423							69.160			153.630
1519										170.930
1687										163.770

Table 4.2 Tensile Strength of Candidate Materials after 85°C/95%RH Ageing

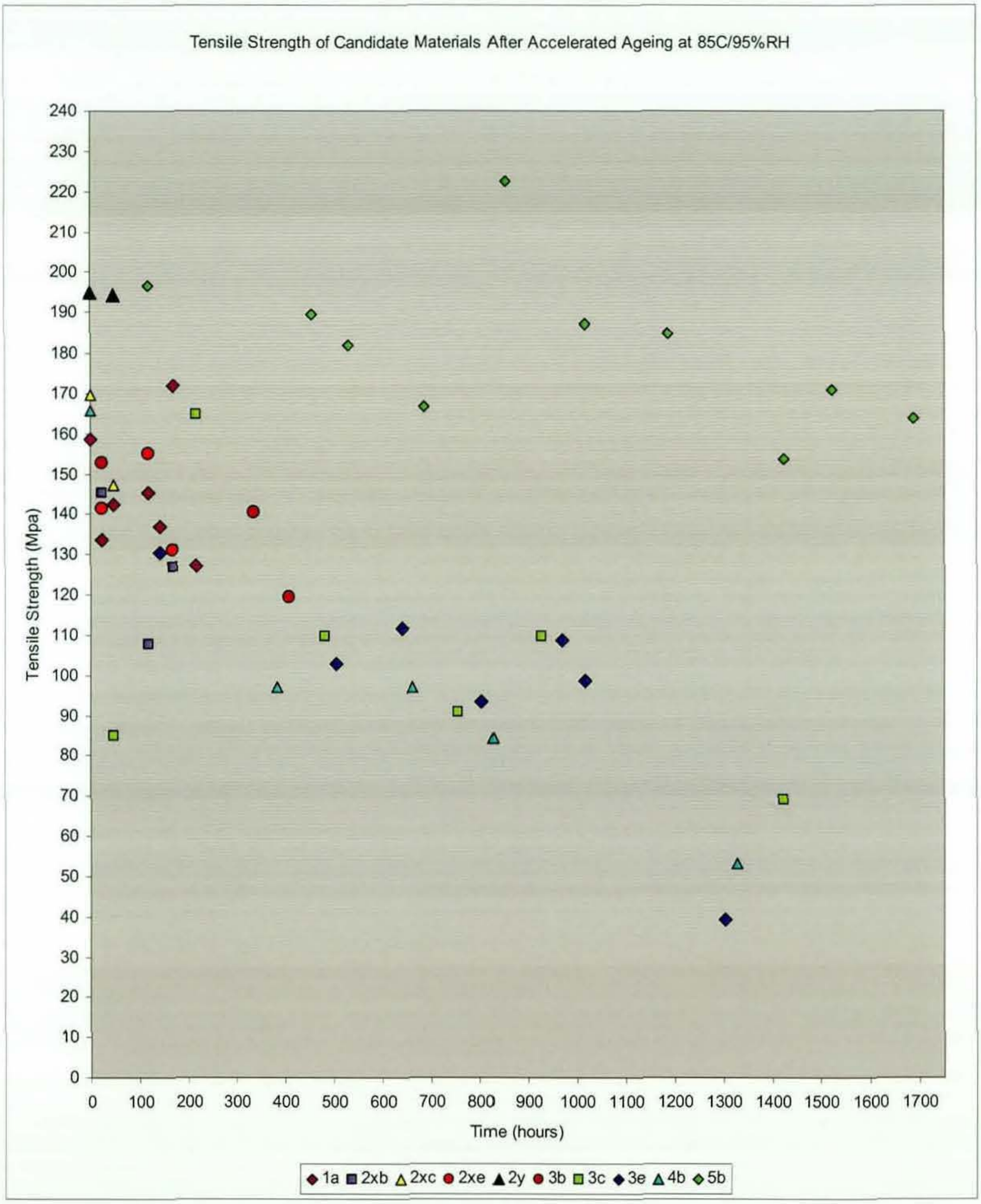

Figure 4.4 Comparison of Tensile Strength of Laminate Combinations after 85°C/95%RH Ageing

Li and Jiao [2000] asserted the core layer is the primary load-bearing structure in a flexible substrate. The results for laminates 3c (film coverlay) and 3e (ink covercoat) provide some support for that assertion. However, the adhesive layer appears to contribute to tensile strength, as evidenced by the difference in initial values for the PET substrates, particularly for the double-sided substrate 2y. Insufficiency in the number of data points precludes further inferences regarding the contribution of the different layers. Determining whether interactions between the materials exist, or the contributory effect of the constituent layers and film variant on tensile strength, would require further experiments.

To determine the best fit curves, robust regression analysis has been performed using a commercial software tool, namely Sagata 'Regression Professional 2004'. Figure 4.5 compares the linear trend line for tensile strength degradation in laminate 1a after accelerated ageing at 85°C/95%RH, obtained using Least Squares, Least Absolute Deviation (LAD) and M-fair models. The least squares trend line does not exhibit robustness towards the data at 24 and 168 hours, unlike the LAD and M-fair degradation trend lines. From the M-fair and LAD degradation trend lines, laminate 1a appears to retain at least 80% of its original tensile strength after 200 hours accelerated ageing at 85°C/95%RH.

Degradation trends for laminate 2xb are shown in Figure 4.6. Whereas the regression models suggest this laminate would retain greater than 70% of its original tensile strength after 200 hours accelerated ageing at 85°C/95%RH, the outliner in the original data at 120 hours together with the absence of further data points do not provide confidence in this trend line. This scenario also applies to laminate 2xe, shown in Figure 4.7. Note that regression data points are obscuring the original data point in Figure 4.7. Further, no inferences can be made in respect of laminates 2xc and 2y for insufficiency in the data.

Degradation trends for laminate 3b and 3c are shown in Figure 4.8 and Figure 4.9 respectively. The regression models suggest both laminates would retain greater than 70% of its original tensile strength after 200 hours accelerated ageing at 85°C/95%RH; however, more data points would be required for greater confidence in the regression analysis for laminate 3b. Degradation trends for laminate 3e and 4b and 5b are shown in Figure 4.10, Figure 4.11 and Figure 4.12 respectively. The regression models suggest these laminates would retain greater than 70% of its original tensile strength after 200 hours accelerated ageing at 85°C/95%RH.

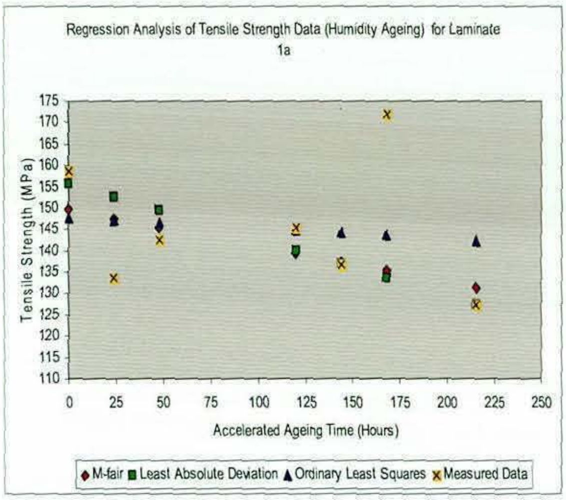

Figure 4.5 Tensile Strength of Laminate 1a

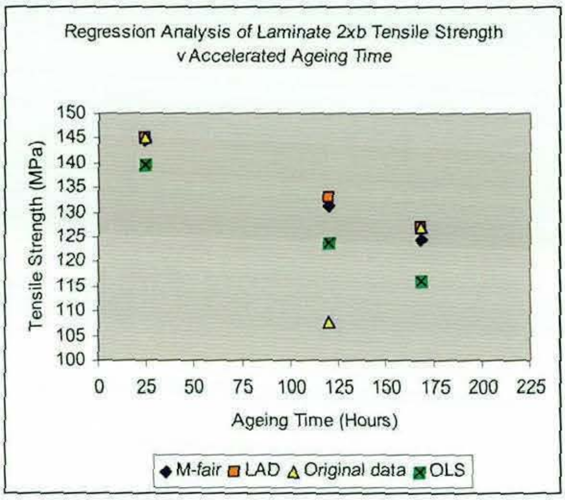

Figure 4.6 Tensile Strength of Laminate 2xb

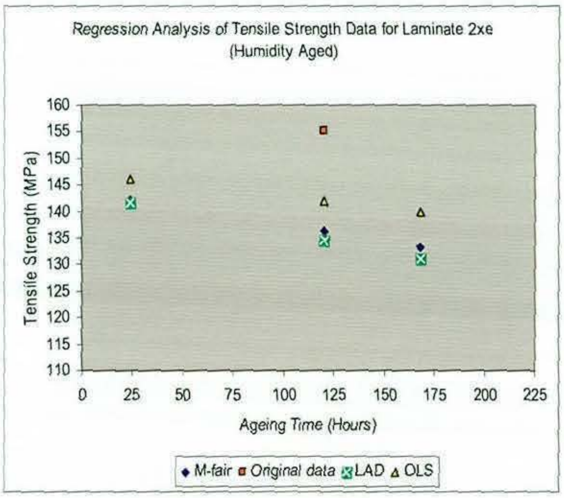

Figure 4.7 Tensile Strength of Laminate 2xe

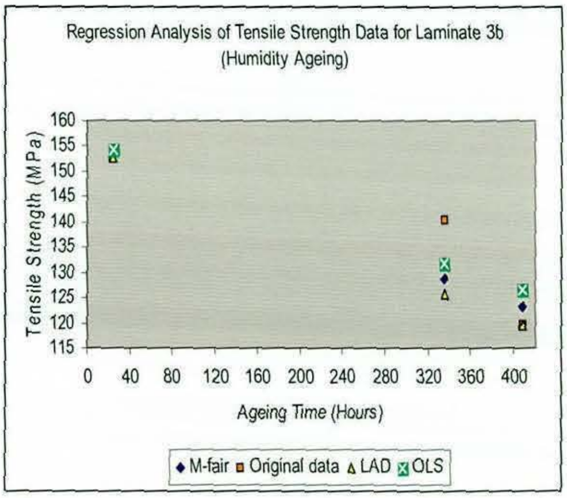

Figure 4.8 Tensile Strength of Laminate 3b

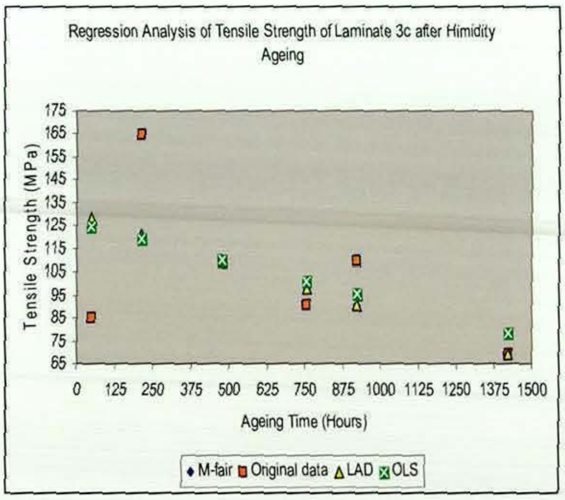

Figure 4.9 Tensile Strength of Laminate 3c

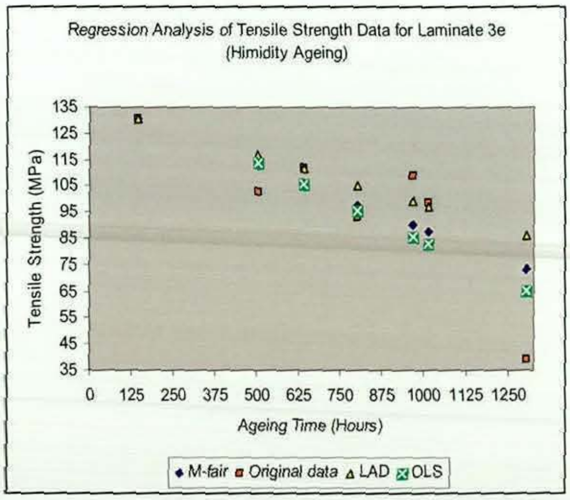

Figure 4.10 Tensile Strength of Laminate 3e

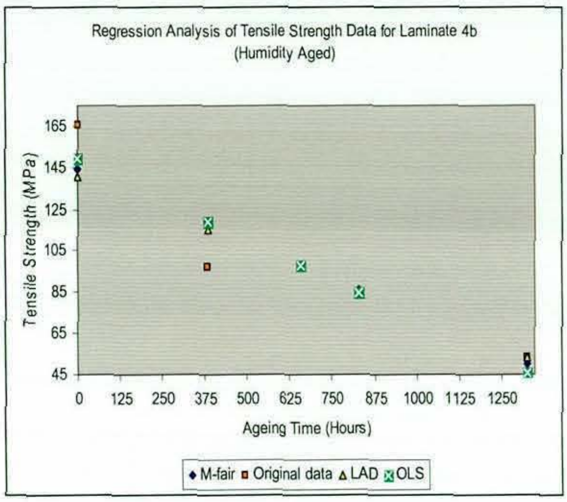

Figure 4.11 Tensile Strength of Laminate 4b

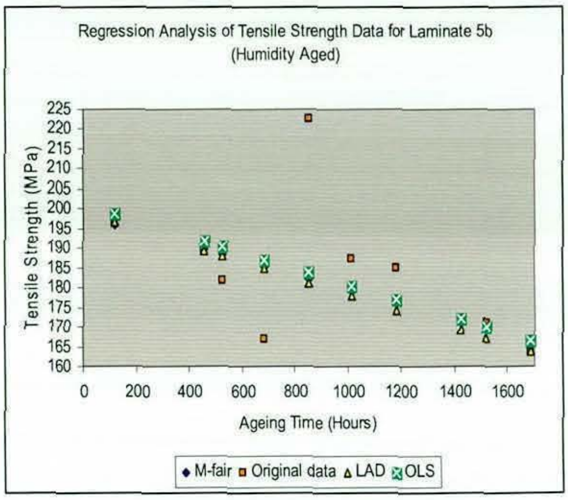

Figure 4.12 Tensile Strength of Laminate 5b

4.5 Peel Strength

Hours Ageing	Peel Strength (N / mm)– Temperature Cycling				
	1	2x	3	4	5
0	1.43	1.24	0.65	1.09	1.06
192		1.1		0.82	1.24
872	1.36				
1040	1.35	1.43	0.84	0.39	1.47
1880	1.08	1.77	0.9	0.38	1.52
2552	1.25	1.43	0.78	0.71	1.33
3050	1.35	1.08	0.7	0.61	1.37

Table 4.3 Peel Strength of Base Laminates after Temperature Cycling

The peel strength of base substrates, when aged by temperature cycling is presented in Table 4.3 and shown in Figure 4.13. Initially, there is improvement for base materials 2x, 3 and 5, possibly as a result of additional adhesive curing during the high temperature cycles[62]. This contention requires further experiments to be confirmed. Although there is continuous degradation in peel strength of materials 2x and 3 after 2000 hours, there is no similar trend for the other adhesives. The results suggest the uncontrolled humidity during temperature

[62] G. Farmer, GTS Flexible Materials Ltd, Ebbw Vale, UK. Personal Communication, August 2006.

cycling, as well as any differences in CTE between the base film, adhesive and copper conductor have a negligible effect on peel strength. Thermal degradation of the adhesive is therefore an unlikely failure mechanism in FPCs.

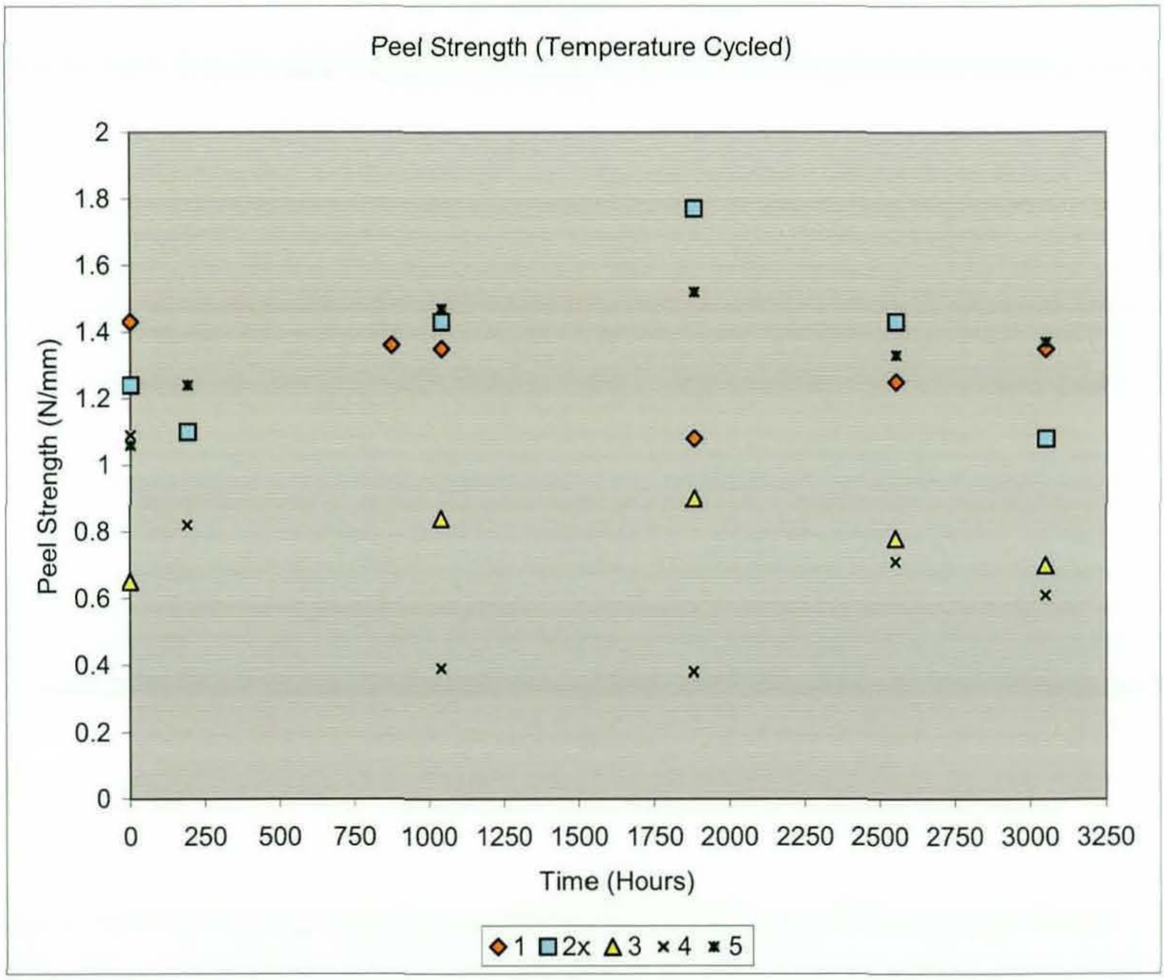

Figure 4.13 Peel Strength of Base Laminates after Temperature Cycling

Peel strength after damp heat ageing is presented in Table 4.4 and Figure 4.14. For base substrate 1, there was an initial improvement in peel strength, but insufficient results preclude any inferences being drawn for this adhesive. An identical adhesive is used in base substrates 2x and 2y, which failed before 100 hours. The adhesive used in base substrate 3 showed very scattered results. However, although it appeared that this adhesive may survive over 500 hours, further experimental data is required for confirmation and confidence. The base adhesives that exhibit long-term survivability are those used in base substrates 4 and 5.

Hours Ageing	Peel Strength (N / mm) – High Temperature and Humidity Ageing					
	1	2x	2y	3	4	5
0	1.1569	1.1742	1.1746		1.504	
24	1.1852	1.171		0.6373		
48	1.386	0.3446	0.223	0.5245		
120						1.2187
144				0.7867		
168					1.4183	
192				0.4691		
384					1.4291	
456						1.1386
504				0.6948		
528						1.0645
660					0.7298	
684						1.0339
828					0.6277	
852						0.6373
991					0.1544	
1015						0.7275
1423						0.5373

Table 4.4 Peel Strength of Base Laminates after 85°C/95%RH Ageing

The adhesive in base substrate 4 exhibited a non-linear degradation, possibly due to two separate rates of degradation occurring before and after 500 hours. A second possibility may be a change from cohesive to adhesive failure, or the reverse. The adhesive in base substrate 5 exhibits a linear degradation in peel strength throughout humidity ageing. As the chemical formulation of adhesives used by different manufacturers vary, this method of test appears appropriate for screening adhesives used in automotive FPCs.

However care must be exercised in the interpretation of peel strength tests. Kinloch [1997] emphasizes "that the peel test does not measure the intrinsic adhesion of the joint or laminate, even if true interfacial failure between the adhesive and substrate does occur. Nor does it directly assess the toughness of the adhesive. The reasons for these shortcomings of the peel test derive from the very complex deformation behaviour which occurs in this apparently simplest of common test methods". Kinloch [1997] states further "a large amount of experimental work … has shown that the measured peel load per unit width depends not only upon the degree of intrinsic adhesion acting and the adhesive employed but also upon the peel angle and the thickness and mechanical properties of the peel arm. Further, since polymeric adhesives are viscoelastic materials, the measured peel load, like other mechanical properties of the adhesive, will be dependent upon the test rate and temperature".

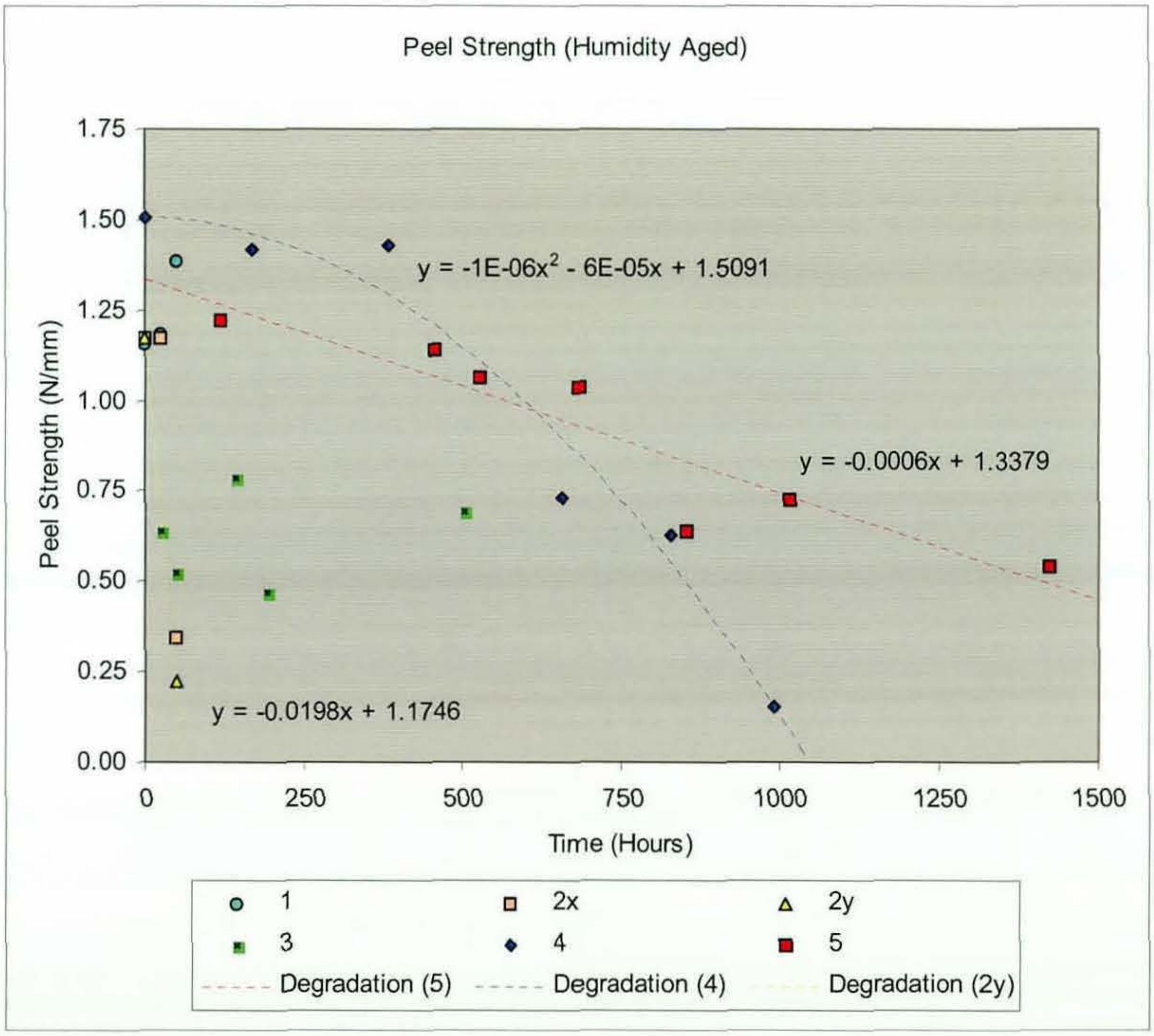

Figure 4.14 Peel Strength of Laminates after 85°C/95%RH Ageing

4.6 Initiation Tear Strength

The initiation tear strength of the five base substrates after temperature cycling is presented in Table 4.5 and shown in Figure 4.15. As with the results for peel strength, substrates 2, 3 and 5 exhibit increasing tear strength until 1000 hours ageing, after which degradation begins.

Further experiments are required to confirm this trend, and to establish the cause. Possible reasons for the improvement in tear strength include the additional curing of the adhesive, and heat conditioning of the base film.

Hours Ageing	Initiation Tear Strength (N) – Temperature Cycling				
	1	2x	3	4	5
0	60.4	41.9	28.4	45.62	23.95
192	57.2	42.5	31.1	42.5	36.5
1040	58	42.1	32.8	41.1	38.4
1880	56.18	36.4	30.2	45.25	30.68
2552	48.8	34	28.6	38.1	28
3050	53.93	36.5	32.6	41.7	27.8

Table 4.5 Initiation Tear Strength of Base Laminates after Temperature Cycling

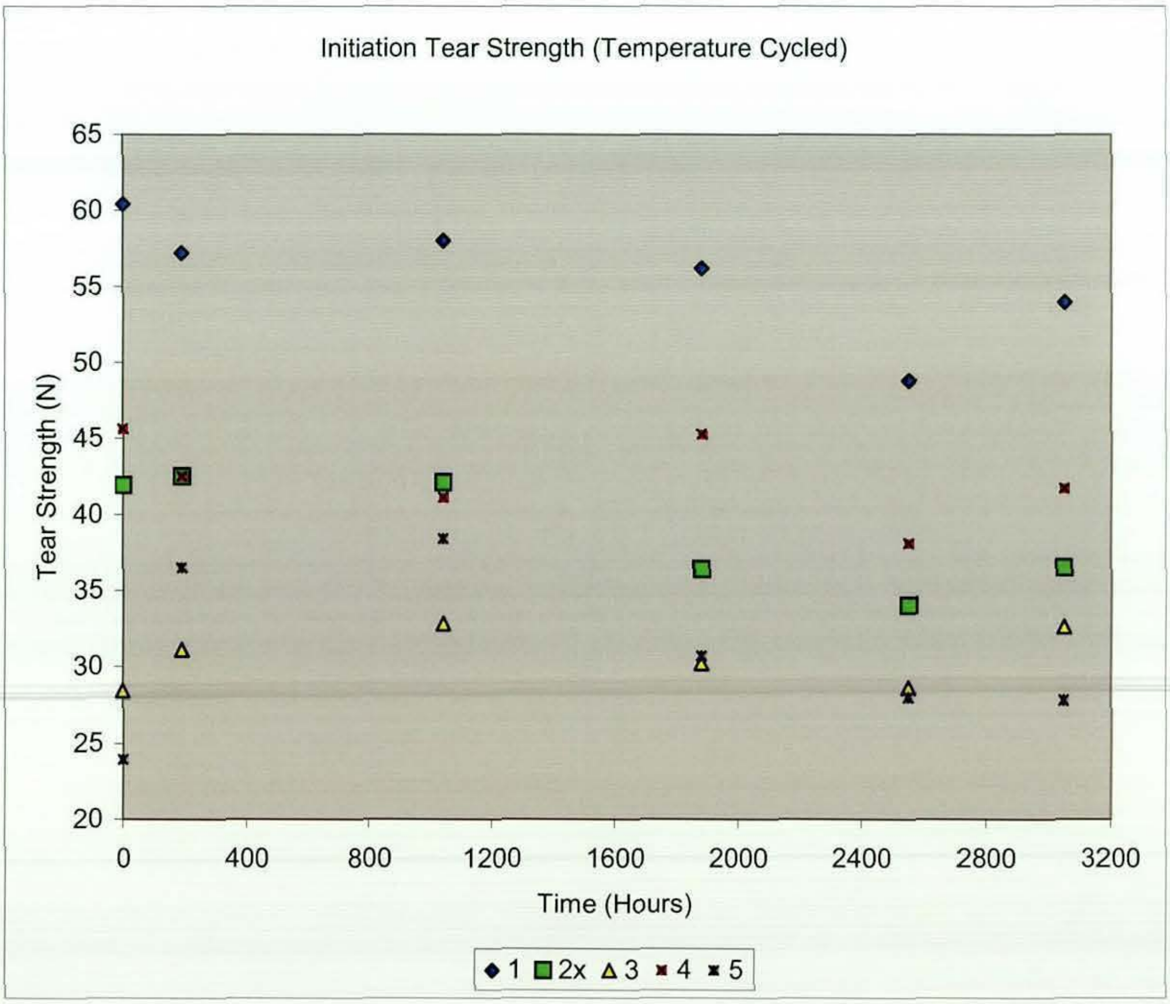

Figure 4.15 Initiation Tear Strength of Base Laminates after Temperature Cycling

Test results at 2552 hours show a reduction in tear strength when compared to adjacent data points. This may be caused by the test set up for that batch of test coupons. The results show that, as in the case of peel strength the base materials are not affected by thermal degradation, or by differential expansion of the constituent layers due to CTE mismatch.

Hours Ageing	Initiation Tear Strength (N) – High Temperature and Humidity Ageing					
	1a	2xe	2y	3e	4b	5b
0	60.4	41.9	32.8		45.62	
24	51.53	31.35		28.4		
48	50.71		31.47	29.86		
120	51.18	29				23.95
144	50	31.37	33.17	26.21		
168	47.98	26.75			32.69	
192	49	28.42	26.67	26.65		
216	46.8	28.75		26.89		
336				24.16		
360						21.67
384					33.55	
408				20.77		
432				21.21		
456						24.05
480				19.7		
504				19.58		
528						20.71
639				20.17		
660					23.98	
684						19.64
756				8.5		
804				17.03		
828					14.07	
852						18.15
924				10.7		
967					9.84	
1015						17.67
1135				3.82		
1183						14.32
1270				2.3		
1303				1.72		
1423				1.08		20.43
1519						17

Table 4.6 Initiation Tear Strength of Materials after 85°C/95%RH Ageing

Initiation tear strength of the different FPC laminates after damp heat ageing is presented in Table 4.6 and shown in Figure 4.16. Laminates 3e and 4b retain 50% initiation tear strength after 600 hours and for laminate 5b, a higher retention of this property was observed throughout the ageing period. It can be seen that PEN based laminates tear more easily than PET base laminates, until the degradation of the latter by hydrolysis after 700 hours. Regression analysis of the initiation tear strength data suggest all base laminates would retain greater than 70% of their initial value after 200 hours accelerated ageing at 85°C/95%RH. Compared to the results for tensile strength, initiation tear strength exhibits less variability and provides complementary results to the tensile strength tests.

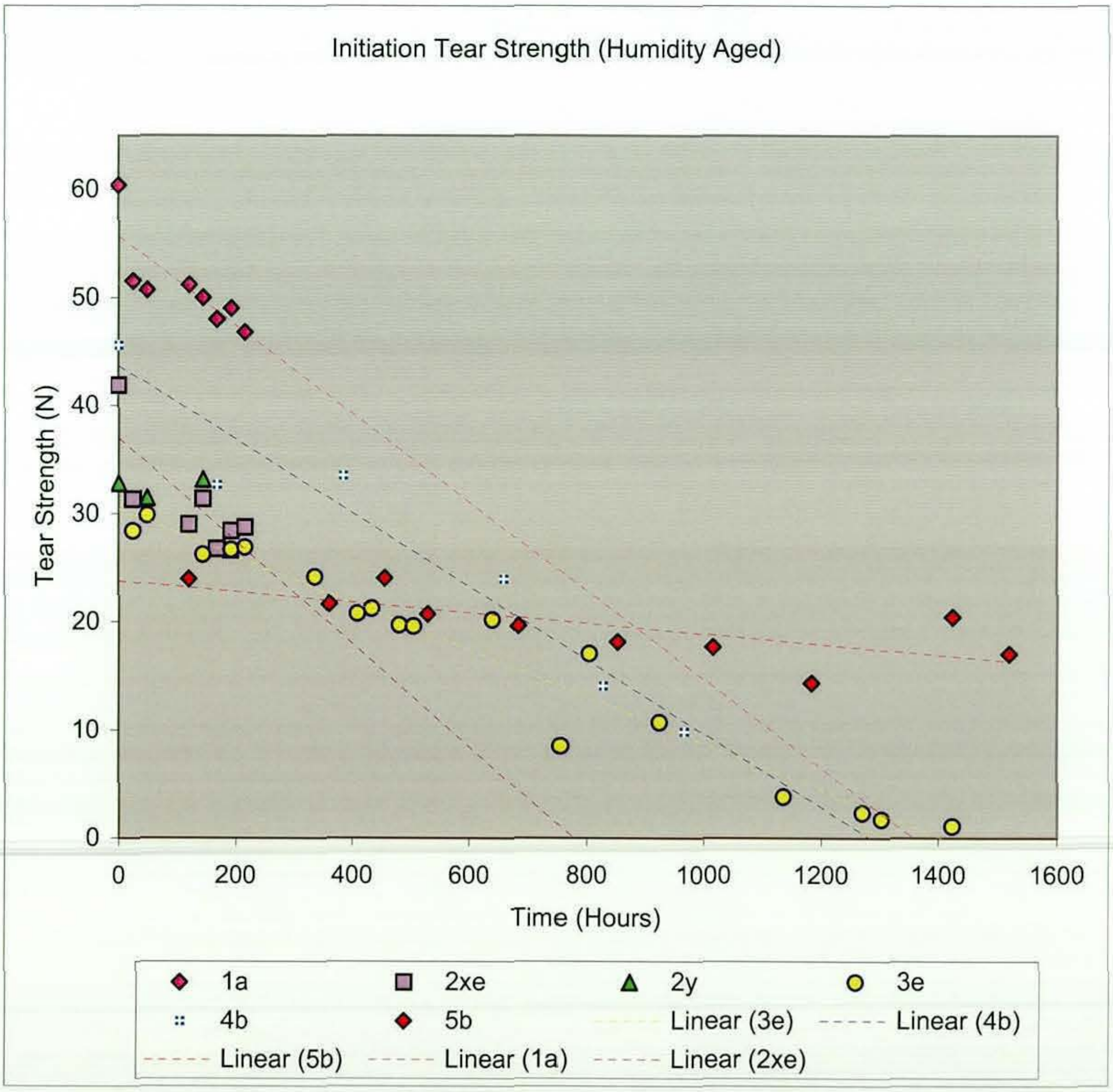

Figure 4.16 Initiation Tear Strength of Base Laminates after 85°C/95%RH Ageing

4.7 Propagation Tear Strength

The propagation tear strength results for the five base substrates after temperature cycling is presented in Table 4.7 shown in Figure 4.17. The results are similar to those of the initiation tear strength tests after temperature cycling. Further experiments are required to statistically treat with variability in the results due to batch processes, including test set up. The temperature cycling tests indicate no degradation trend otherwise, supporting the inference that thermal degradation and differential expansion due to CTE mismatch are insignificant for both PET and PEN based substrates. As with initiation tear strength, it is observed that the PEN substrate tears more easily than the PET substrates.

Hours Ageing	Propagation Tear Strength (N) – Temperature Cycling				
	1	2x	3	4	5
0	1.94	0.77	0.95	1.23	0.57
192	1.48	0.67	0.91	1.15	0.6
1040	1.7	0.75	0.77	1.48	0.47
1880	1.82	0.89	0.94	1.29	0.52
2552	1.39	0.65	0.86	1.41	0.37
3050	1.55	0.975	0.92	1.3	0.48

Table 4.7 Propagation Tear Strength of Base Laminates after Temperature Cycling

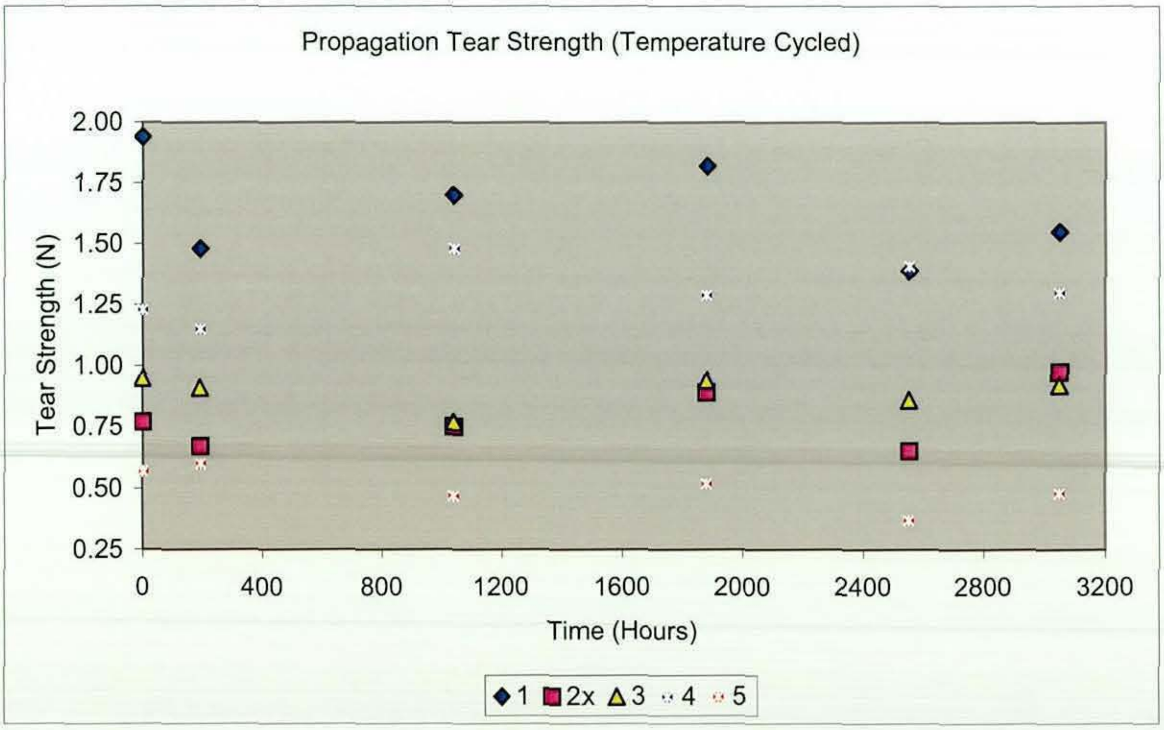

Figure 4.17 Propagation Tear Strength of Base Laminates after Temperature Cycling

Hours Ageing	Propagation Tear Strength (N) – High Temperature and Humidity Ageing					
	1a	2xe	2y	3e	4b	5b
0	1.94	0.77	0.92		1.23	
24	2.34	0.71		0.95		
48	1.99	0.75	1	0.98		
120	1.13	0.73				0.57
144	0.86	0.19	0.54	0.11		
168	1.19	0.66			1.43	
216	1.18			0.34		
336				0.31		
360						0.68
384					1.47	
408				0.78		
456						0.53
480				0.6		
504				0.78		
528						0.58
639				0.37		
660					1.32	
756				0.46		
804				0.53		
828					1.32	
852						0.625
924				0.4		
967				0.37		
1015						0.61
1135				0.875		
1183						0.905
1279				0.47		
1303				0.25		
1423				0.33		0.578
1495					0.37	
1510						0.45

Table 4.8 Propagation Tear Strength of Materials after 85°C/95%RH Ageing

Propagation tear strength results after damp heat ageing is presented in Table 4.8 and shown in Figure 4.18. Laminate 1a exhibits a rapid initial decrease in propagation tear strength, to less than 70% of its original value at 150 hours. Laminates 3e and 5b exhibit a linear trend in degradation. Regression analysis of the results for laminate 2xe suggest it may retain greater than 70% of its original propagation tear strength after 200 hours, but further data points are required for confirmation and confidence. Regression analysis of laminates 3e, 4b and 5b suggest these laminates would retain greater than 70% of their original propagation tear strength after 200 hours. Laminate 4b increases in propagation tear strength until 400 hours ageing, after which it degrades. This trend is similar to the results for peel strength of this laminate, suggesting the adhesive may have an influence in the test results; further suggesting that propagation tear strength potentially could be used as a complementary test to peel strength tests. Further experiments are required to establish this.

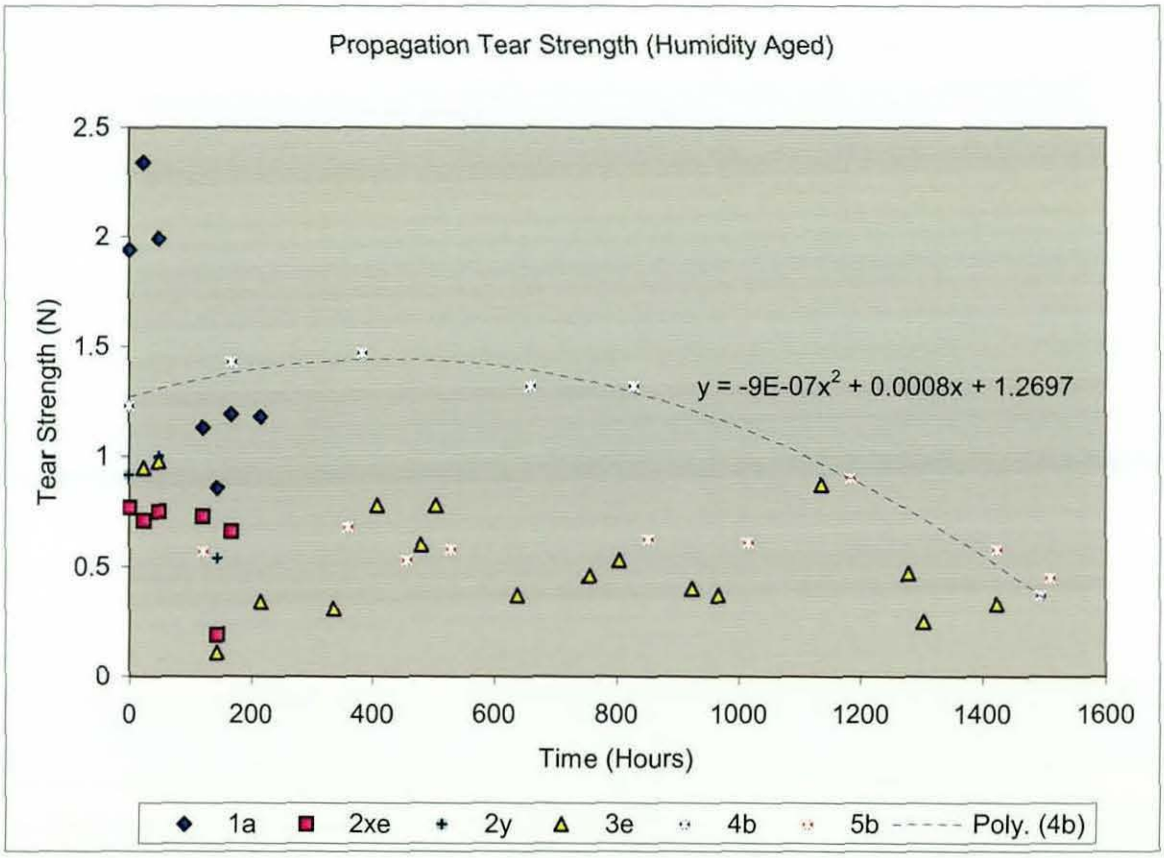

Figure 4.18 Propagation Tear Strength of Base Laminates after 85°C/95%RH Ageing

4.8 Flexural Endurance

The number of flexural cycles before failure for damp heat aged laminates is presented in Table 4.9 and shown in Figure 4.19. Laminate 3c has the highest flex life. Substrate 2y and laminates 2xb and 3c exhibit an initial increase in flexural endurance before degradation is observed. Some tests continued for 10,000 flex cycles. However, such results were observed in laminates with film coverlays, which may have allowed broken conductors to remain in contact with each other. Examination of the individual test coupon would be required to confirm actual conductor breakage. Further experiments are required before degradation trends can be established, particularly for laminates 2xc and 3e.

Hours Ageing	Flex Cycles to Failure – High Temperature and Humidity Ageing									
	1a	2xb	2xc	2xe	2y	3b	3c	3e	4b	5b
0	1632.5		746		70.5				952	
24	9797	775		340.5		846.5				
48	10000		5484.5		164.5		2673.5			
120		951		256						710.5
144			10000		215			108		
168	901	893		166.5					901	
192	1220				152	806.5				
216	602.5	758					2906			
360										605
384									1297	
408						378				
432							2306.5			
456										520
480							3390			
528										490

Table 4.9 Number of Flex Cycles to Failure after 85°C/95%RH Ageing

It is recommended that the effect of different size mandrels be investigated to obtain acceleration factors to predict flexural performance in service. Although it may be argued that with increasing humidity age the number of flexural cycles required to pass the test are less, there is an absence of accumulated stress and strain from prior flexing, as would normally occur throughout the vehicle life. Laminates could therefore be subjected to flexing whist exposed to environmental ageing conditions.

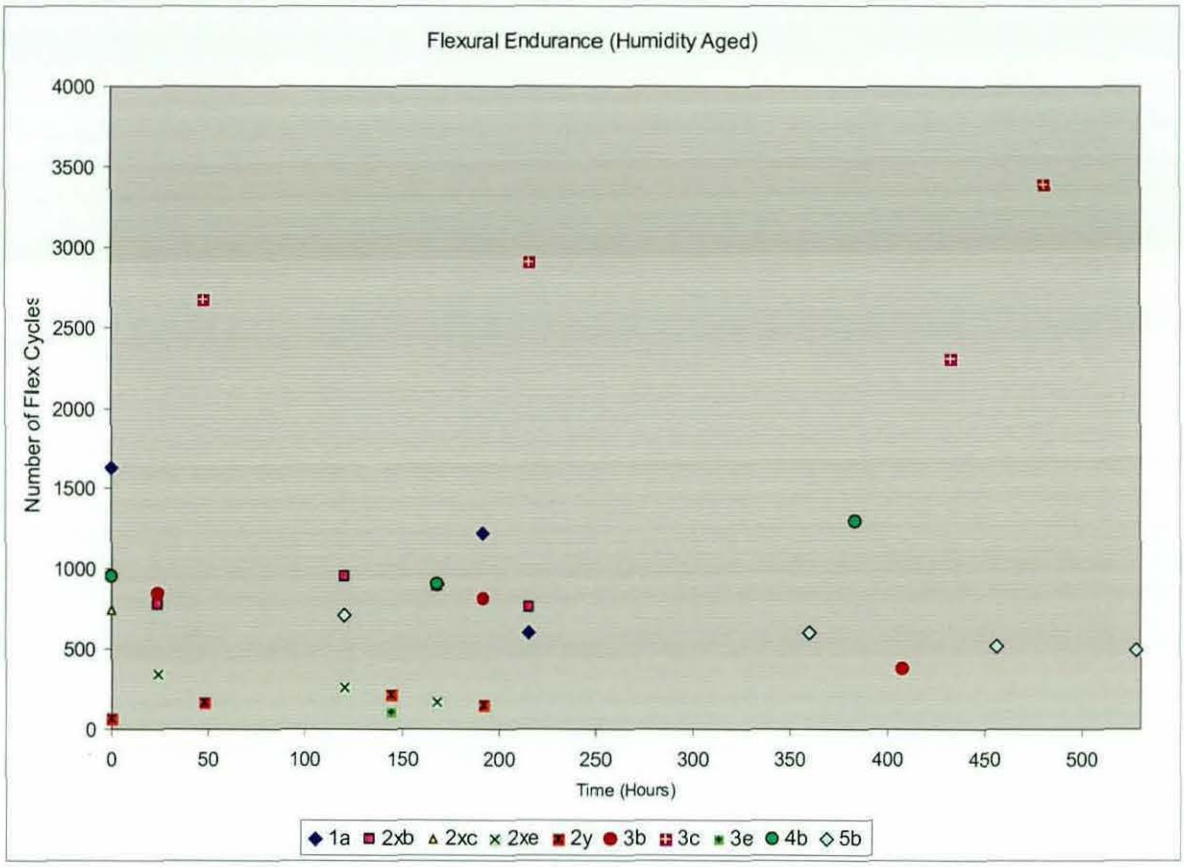

Figure 4.19 Flexural Endurance of Laminates after 85°C/95%RH Ageing

4.9 Insulation and Moisture Resistance [Modified Test]

For the modified Insulation and Moisture Resistance test, a ramp voltage was applied across interweaving comb-pattern circuits manufactured from base substrates 1, 2x, 3, 4, and 5. The width of and space between conductors in the test coupon was 1 mm. When the applied voltage difference between the conductors was ramped at 100 volts (ac) per second, flashover between opposing conductors occurred just before the application of 3 kV, as shown in Figure 4.20. This result was observed for all test coupons aged by temperature cycling to 3000 hours and similarly for those aged at 85°C/95%RH to 1500 hours. One possibility for this is the dielectric breakdown of air between the conductors. To confirm this, the experiment would need to be performed in a dielectric oil bath.

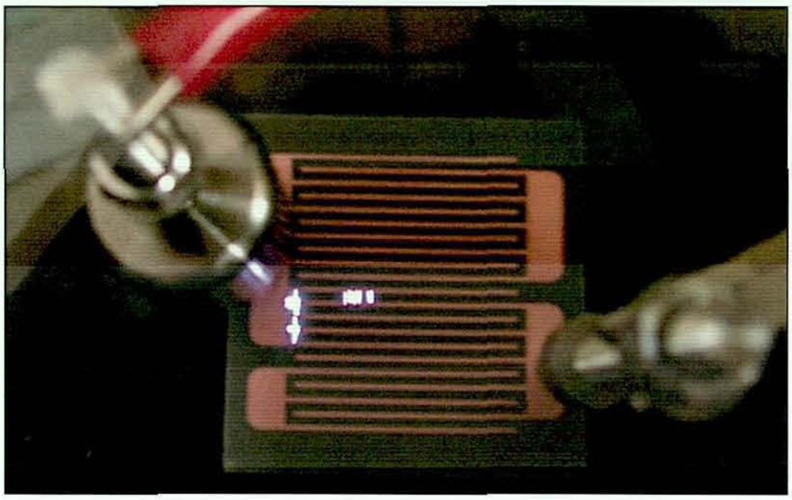

Figure 4.20 Flashover during the Insulation and Moisture Resistance Test

4.10 Dielectric Breakdown Strength

For each test coupon aged under temperature cycling or 85°C/95% RH, dielectric breakdown through the thickness of the material was not observed. A ramp voltage was applied, and above 24 kV (ac), flashover occurred. When repeated at a lower voltage ramp rate, in stepped voltage increments, or with the different pairs of electrodes, similar results were observed. This trend continued throughout the materials ageing period. This unexpected result is significantly different to that published in the Data Sheets for the base substrates.

Figure 4.21 Flashover across the Base Substrate

According to the Data Sheets, dielectric breakdown of both PET and PEN base substrates should occur above 12 kV. Possible causes include insufficient contact pressure between the electrodes and the test coupon, test equipment or other experimental errors.

To investigate surface dielectric breakdown, both large electrodes were placed on the same side of the test coupon with a fixed separation distance of 9.65 mm between the cylinder walls as shown in Figure 4.21. Coupons were tested on both the 'adhesive side' and 'film side' by a ramp increase in voltage as before. Surface flashover occurred above 22 kV (ac) in each test throughout the temperature cycling and humidity ageing period. It is recommended that the dielectric breakdown test be repeated in a dielectric oil bath, ensuring the electrodes are securely fixed to the test coupon.

4.11 Volume and Surface Resistivity

Volume and surface resistance tests were conducted on the six base substrates in accordance with IPC 2.5.17. The megohmeter used in these tests was a model RM 175-LZ manufactured by British Physical Laboratories, using concentric brass electrodes mounted on a Perspex fixture. For each test, coupons were mounted and hand tightened and placed in an enclosed cabinet before commencing the test.

All coupons consisted of a 'film side' and an 'adhesive' side, with the exception of base substrate 2y, having two 'adhesive' sides. Although IPC 2.5.17 requires single-sided coupons to be coated with silvered ink on the 'film' side, this requirement is not included in ASTM D257-93. The latter test method provides for the use of the concentric metal electrodes tightened so that the sample under test becomes compressed. Coupons were not cleaned prior to testing in order to investigate the effect of any by-product formed on the surface of the test coupons during the ageing process. For some humidity-aged coupons, air pockets developed between the copper conductor and the film where failure of the adhesive occurred. Such test coupons were not used.

For both temperature-cycled and humidity-aged coupons, a precise measurement of volume resistance and surface resistance could not be made. The megohmeter was observed to be highly sensitive to movement by persons in the vicinity of the test cabinet, airflow within the room and the switching of lights. However, the values observed were in the order of 10^{28} ohm for both volume and surface resistance. At this resistance, the calculated volume resistivity and surface resistivity using IPC 2.5.17 would be in the order of 10^{28} ohm.m and 10^{30} ohm (per square) respectively. As for the dielectric breakdown strength tests, these observations were much higher than the stated values in the Data Sheets. Possible causes for this include insufficient pressure applied between the electrodes and the test coupons, test equipment or other experimental errors.

4.12 Flammability

Whereas the FMVSS 302 standard requires the use of a small enclosed steel cabinet for conducting flammability tests, in this research, flammability tests were performed using a larger laboratory fume cabinet. It is contended that the results of the flammability tests would not be different using the fume cabinet, given the purpose of the smaller steel enclosure to prevent air from being blown directly onto the sample during test. In the fume cabinet, test coupons were clamped at one end and allowed to stand freely in a horizontal plane. Test coupons with film coverlays were inherently rigid and needed no extra supporting mechanism. Test coupons with a dielectric ink coverlay and test coupons without any coverlay were supported by a tripod stand.

The results of the flammability tests apply to test coupons aged by temperature cycling and to test coupons aged at 85°C/95%RH. It was observed that the outcome of the flammability test was dependant on the position of the test coupon relative to the Bunsen burner flame. Initial trials with the Bunsen burner flame at the distance specified by FMVSS 302 led to the test coupons igniting, with the resultant flame becoming extinguished upon withdrawal of the Bunsen burner. However, moving the Bunsen burner flame so that it further impinged upon the test coupon by less than 5mm, as illustrated in Figure 4.22, resulted in a sustained combustion of the test coupon.

When sustained combustion was achieved, all test coupons containing 0% copper failed to meet the burn rate requirements set by FMVSS 302, burning at a rate greater than 1 cm/sec.

This result also occurred in test coupons containing a flame retardant adhesive, and test coupons containing 50% copper traces. For unetched test coupons (100% copper), the result of the flammability test was dependant on the surface of the test coupon closest to the flame. When the copper side of the test coupon was positioned facing downward to the Bunsen burner flame, the occurrence of sustained combustion was random. However, when sustained combustion was achieved, test coupons failed the FMVSS 302 requirements for burn rate. Sustained combustion of the test coupon occurred more frequently when the test coupon was oriented so that the film side was closest to the Bunsen burner flame.

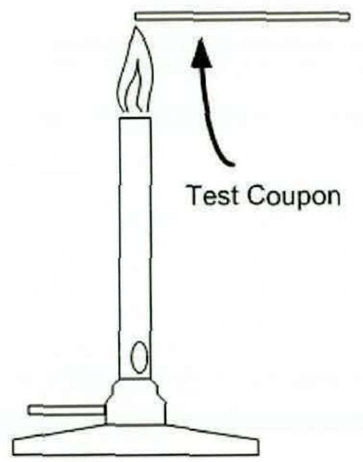

Figure 4.22 Positioning of Bunsen burner for Flammability tests

The sensitivity of the flammability test to the position of the Bunsen burner flame and the randomness of the test results may lead to invalid inferences being made in respect of the burn rate. The MVSS302 test may not be realistic for evaluating the suitability of FPCs, and alternative qualification tests should be investigated.

4.13 Additional Observations and Recommendations

Although a reduction in tensile strength has been observed for all the base substrates and laminates, there is insufficient data to support inferences in respect of the contribution of film, adhesive and coverlay towards tensile strength of substrates and laminates. The assertion that the base film in the substrate or laminate is the dominant contributor towards tensile strength requires experimental verification. Providing the validity of that assertion, tensile strength tests could be performed on the base film of the FPC only.

Tensile strength tests for FPC laminates exhibited more variability in the data compared to the initiation tear tests, and further experiments are required to validate this. With variability in the tensile strength data, initiation tear strength tests may be used to complement the tensile strength test in cases of marginal acceptability. For adhesive evaluation, peel strength tests provide a direct indication of suitability, but it should be complemented by propagation tear strength and flexural endurance test in cases of marginal acceptability. A recommendation is made for conducting a scratch/abrasion resistance or hardness test on the dielectric ink covercoat.

There is a need to re-assess the experiment procedure followed for the electrical property tests; i.e. moisture and insulation resistance, dielectric breakdown strength and volume and surface resistivity. Whereas the importance of this FPC property is underscored, under normal automotive operating conditions, high voltages as those causing dielectric breakdown may not occur. Therefore demonstrating the base substrate, coverlay and laminate ability to withstand a selected threshold voltage could be an alternative approach to testing FPC materials.

Flammability tests results suggest the FPC materials and laminate combinations would fail the requirements of the FMVSS 302 standard. However, it is recommended that flammability tests are repeated using the prescribed flame cabinet within the FMVSS 302 standard. Failure to meet the FMVSS 302 standard does not necessarily preclude the use of a particular FPC material in automobiles; it would be necessary to assemble such FPCs beyond the boundary of the occupant compartment as specified in the legislation.

Random sampling from the test coupon panels may not have occurred consistently. Such batch processes, including experiment set up, must be designed into the experiment. This would increase the size of the experiment, but allow for a statistical treatment of the results, leading to more sustainable inferences being made.

5 ESTIMATING EXPOSURE TIME REQUIRED FOR DAMP HEAT AGEING

5.1 Introduction

During the initial damp heat ageing of test coupons, samples of conventional PET and PEN substrates (substrates 1 and 5 respectively) were aged for 96 hours at 100% RH, 105°C and elevated pressure in an autoclave. This allowed for rapid observation of anticipated laminate failure, as well as indicating any unanticipated failure mechanisms. The resulting damage to the conventional PET substrate is shown in Figure 5.1. There was an observable change of colour accompanying a failure of the adhesive which allowed some of the etched copper conductors to be dislodged in situ. The PET film tore easily by hand, but was not brittle as it was able to fold onto itself. The PEN substrate did not appear affected by the autoclave ageing and test coupons of this material remained slightly opaque.

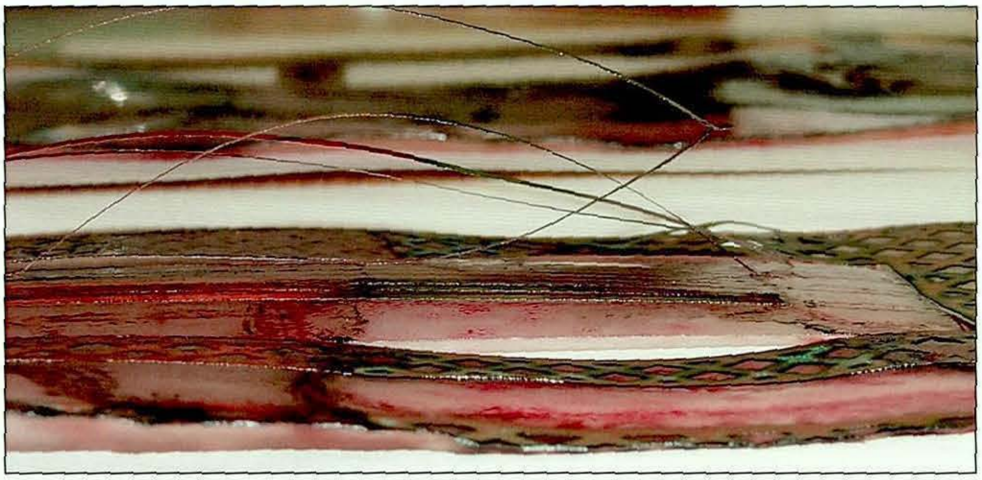

Figure 5.1 FPC Damage after 96 Hours in Pressure Cooker

Without a correlation between the accelerated ageing conditions, specifically temperature, humidity and exposure time to an equivalent in-service life, drawing direct inferences from the experimental results obtained in this research with respect to the suitability of materials for automotive applications would be difficult. It is proposed that the time required for accelerated ageing of materials at 85°C/95%RH so as to simulate 12 years in-service, may be estimated from the accelerated ageing time required for a benchmark; Mylar-A film of 75 micron thickness, typically used as the base substrate in automotive FPCs.

This chapter presents the physics-of-failure methodology used to estimate the time required for damp heat ageing of candidate materials. An Eyring model for the hydrolytic degradation of Mylar A film at any temperature and relative humidity is developed from empirical equations established by McMahon et al [1959]. To apply the developed model, an assumptive model for the microclimate of a cockpit and door interior is devised. It has been estimated that the time required for accelerated ageing of dielectric films and other materials used in automotive FPCs is 206 hours at 85°C/95%RH; significantly less than the 3000 hours prescribed by the ISO 6722 and LV112 standards[63]. The established properties of Mylar A film after ageing for the estimated time suggests 75 micron PET film may be used in vehicle doors and cockpits.

5.2 Acceleration Factor

Hydrolytic degradation of PET film is a first order chemical reaction, the reactants being PET and water. The rate of hydrolysis of Mylar-A film, a biaxially stretched film containing 100% PET, at any given temperature can be calculated by using Equation 5.1 to Equation 5.10 established by McMahon et al [1959]. In the equations, T is the absolute temperature in Kelvin, and $k_{x\%RH}$ is the rate of hydrolysis at x%RH. Equation 5.1 to Equation 5.5 is applicable to films of 12.5 micron thickness, and a relative humidity of 100%, 95%, 75%, 50% and 20% respectively. Equation 5.6 to Equation 5.10 is applicable to films of 250 micron thickness. The error component in the equations has been omitted for simplicity[64].

$$\log k_{100\%RH} = -3.998936 + (-5583.93)\left[\frac{1}{T} - 0.0027752\right]$$ **Equation 5.1**

$$\log k_{95\%RH} = -4.5932075 + (-5583.93)\left[\frac{1}{T} - 0.0028704\right]$$ **Equation 5.2**

[63] The standards relate to round wire, but are applied to FPCs by some automotive OEMs.

[64] The equations have a confidence limit of 0.95, allowing time estimates to be made within reasonable limits.

$$\log k_{75\% RH} = -4.7252725 + (-5583.93)\left[\frac{1}{T} - 0.0028704\right]$$ **Equation 5.3**

$$\log k_{50\% RH} = -4.619297 + (-5583.93)\left[\frac{1}{T} - 0.0028262\right]$$ **Equation 5.4**

$$\log k_{20\% RH} = -4.89569 + (-5563.93)\left[\frac{1}{T} - 0.0027917\right]$$ **Equation 5.5**

$$\log k_{100\% RH} = -4.34742 + (-6456.11)\left[\frac{1}{T} - 0.00277521\right]$$ **Equation 5.6**

$$\log k_{95\% RH} = -4.97059 + (-6456.11)\left[\frac{1}{T} - 0.00287042\right]$$ **Equation 5.7**

$$\log k_{75\% RH} = -4.92443 + (-6456.11)\left[\frac{1}{T} - 0.00282889\right]$$ **Equation 5.8**

$$\log k_{50\% RH} = -4.97023 + (-6456.11)\left[\frac{1}{T} - 0.00279172\right]$$ **Equation 5.9**

$$\log k_{20\% RH} = -5.33451 + (-6456.11)\left[\frac{1}{T} - 0.0027533\right]$$ **Equation 5.10**

In a first order kinetic reaction, the rate of reaction determines the time required for a fixed quantity of reactants to be consumed. For accelerated ageing, the goal is to consume the same quantity of reactants, albeit in a reduced time at a higher rate of reaction. The relationship between the two rates of reaction can be expressed simply as:

$$k_{test} t_{test} = k_{use} t_{use}$$ **Equation 5.11**

Where k_{test} is the rate of reaction during accelerated ageing, k_{use} is the rate of reaction during normal use, t_{test} is the reaction time for the accelerated ageing, and t_{use} is the time of normal use. The acceleration factor, AF, is the ratio of the rate of hydrolysis during accelerated ageing, k_{test}, and the rate of hydrolysis during service life, k_{use}, as stated in Equation 5.12. This equation may be used to determine appropriate accelerated ageing conditions given a fixed ageing time, or conversely, to determine the required time given the accelerated ageing conditions.

$$AF = \frac{k_{test}}{k_{use}} = \frac{t_{use}}{t_{test}}$$ **Equation 5.12**

The acceleration factor for Mylar film aged at 85°C/95%RH for different service conditions is shown in Figure 5.3. The graph reveals the high degree of sensitivity of the acceleration factor to changes in temperature and relative humidity. It is therefore necessary to include diurnal variations in temperature and relative humidity over the product lifetime in order to determine the acceleration factor applicable to vehicle cockpits and door interiors. A further refinement of Equation 5.12 is necessary.

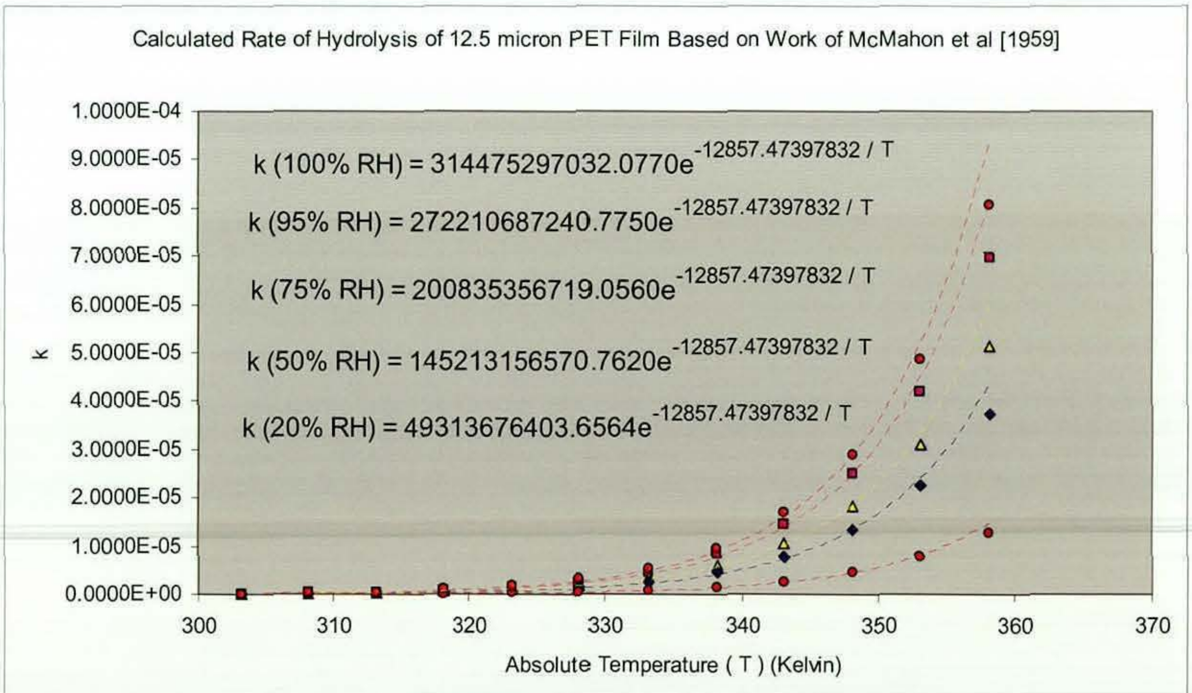

Figure 5.2 Rate of Hydrolysis of 12.5 micron PET Film Based on Equations by McMahon et al [1959]

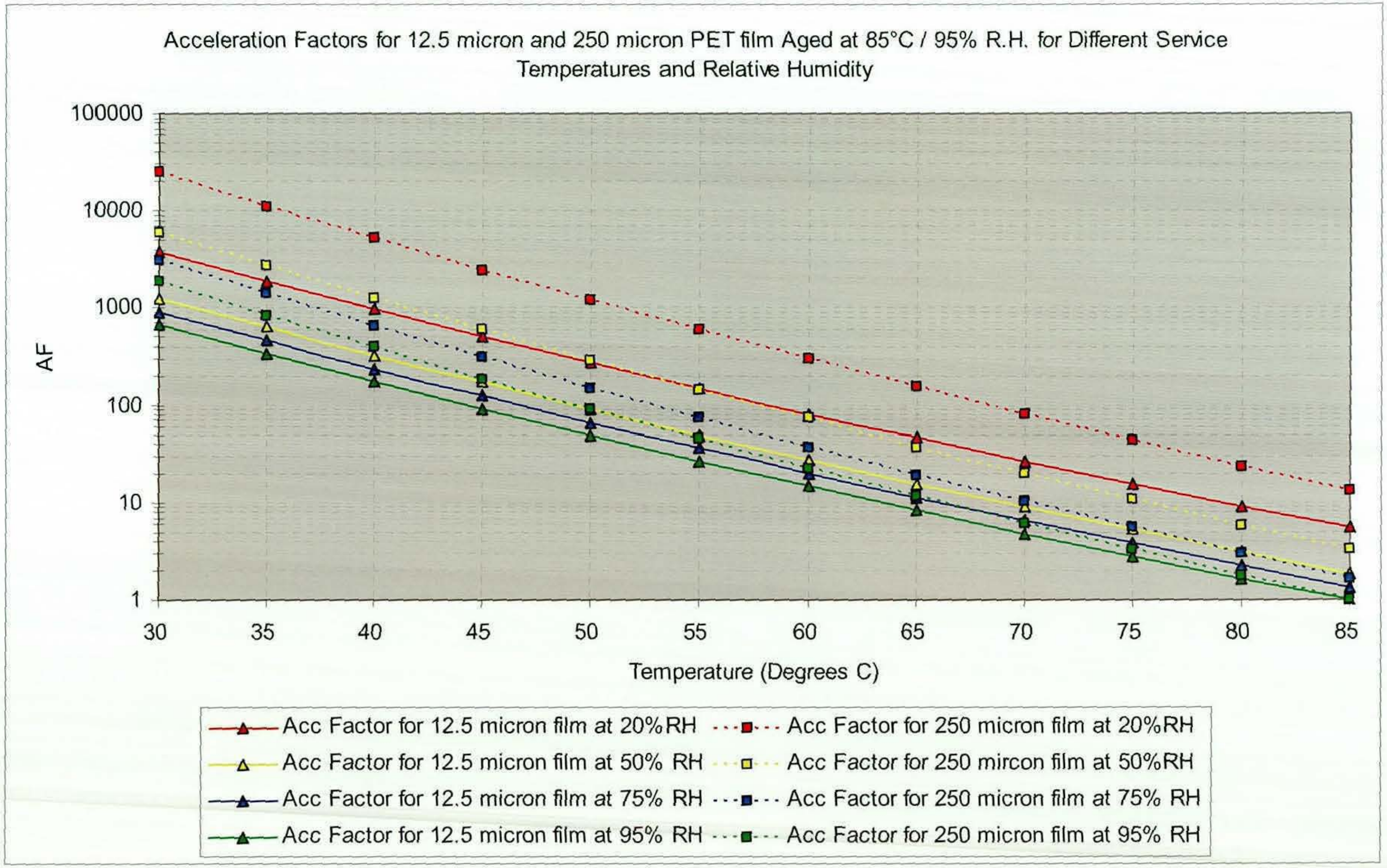

Figure 5.3 Acceleration Factors for Humidity Ageing of PET Films at 85°C/95%RH

The rate of hydrolysis of Mylar film at different temperatures and relative humidity is shown in Figure 5.2. Trend lines have been plotted, and the equations are included on the graph. The trend lines in Figure 5.2 reveal a rate of hydrolysis, k, which can be expressed in the form:

$$k = \lambda e^{-\frac{\beta}{T}}$$ **Equation 5.13**

Where λ is a variable term, β is a constant and T is the absolute temperature in Kelvin. The relationship between λ and relative humidity is shown in Figure 5.4. The trend line drawn reveals a power relationship, indicated in the graph. Substituting for λ in the above equation gives:

$$k_{(T,M)} = \alpha (M)^{\eta} e^{-\frac{\beta}{T}}$$ **Equation 5.14**

Where:

$k_{(T,M)}$ is the rate of hydrolysis at any temperature and relative humidity

T is the absolute temperature in Kelvin and M is the percentage relative humidity

$\eta = 1.10966$

$\alpha = 1792057675.67019$ and

$\beta = 12857.47398$

Following the same procedure for 250 micron films, the following values are obtained:

$\eta = 1.64954$

$\alpha = 18595753791.9819$ and

$\beta = 14865.74264$

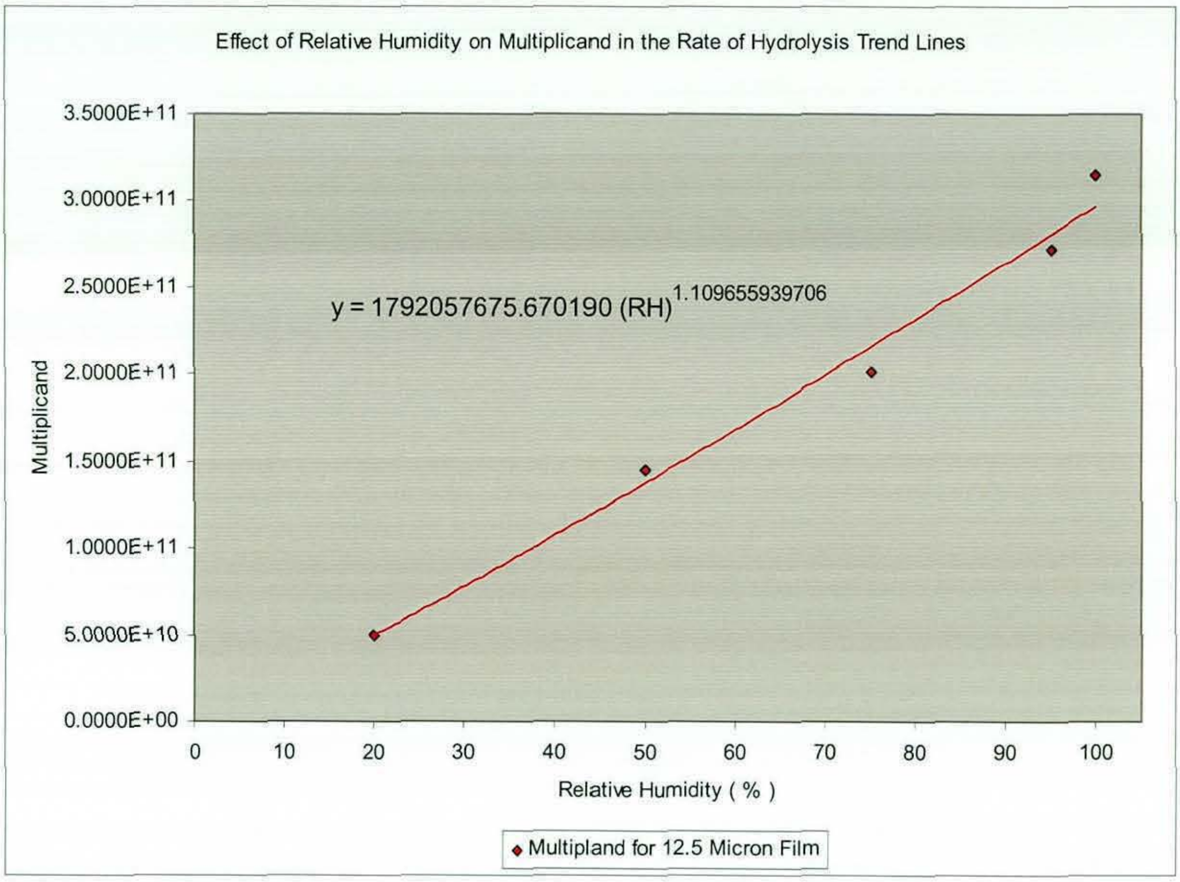

Figure 5.4 Proposed Multiplicand for Hydrolysis of Automotive FPCs

The acceleration factor for any temperature and relative humidity can now be expressed as follows:

$$AF = \frac{k_{test}}{k_{use}} = \left(\frac{M_{use}}{M_{test}}\right)^{-\eta} e^{\beta\left[\frac{1}{T_{use}} - \frac{1}{T_{test}}\right]} \qquad \textbf{Equation 5.15}$$

Where:

M_{use} and M_{test} are Relative Humidity in service and at accelerated ageing respectively

T_{use} and T_{test} are the Absolute Temperature in Kelvin, during service and at accelerated ageing respectively.

For 12.5 micron film, the value of β is comparable to the value of $E_A/k = 12951$[65], where $E_A = 107.61\ kJmol^{-1}$ is the activation energy for hydrolysis of 12.5 micron Mylar film and k is the Boltzmann constant. Similarly, for 250 micron film, the value of β can be compared to the value of $E_A/k = 14971$, where $E_A = 124.39\ kJmol^{-1}$ is the activation energy for hydrolysis of 250 micron Mylar film and k is the Boltzmann constant. Equation 5.15 can therefore be rewritten as:

$$AF = \frac{k_{test}}{k_{use}} = \left(\frac{M_{use}}{M_{test}}\right)^{-\eta} e^{\frac{E_A}{k}\left[\frac{1}{T_{use}} - \frac{1}{T_{test}}\right]}$$ **Equation 5.16**

This Eyring type model is similar to Peck's model. However, the model in Equation 5.15 is based on a chemical process and therefore includes the synergistic effects of temperature and moisture[66].

5.3 Diurnal Automotive Climatic Conditions

As stated in Section 2.2.1.2, there is a void in the literature on the diurnal linked temperature and relative humidity experienced in automobiles. It is necessary to model these variables for both the cockpit and door interiors based on valid assumptions, published climatic data and the generalizations of the micro-climate within the door and passenger cabins. One inherent difficulty in modelling the temperature and relative humidity profile for the cockpit and door lies in the wide spectrum of climatic conditions experienced in different geographic regions, and variability in customer usage.

One approach is to use Military specifications [UNITED STATES, 1997] [GREAT BRITAIN, 2006] [UNITED STATES, 2000], as these provide diurnal temperature and

[65] Difference due to selected trend line in Figure 5.4

[66] It must be noted that the value of η needs to be adjusted to match the trend line in Figure 5.4 if β is to be substituted by the value of E_A/k.

relative humidity for different geographic regions. For example, the 'Basic' geographic region "includes the most densely populated and heavily industrialized parts of the world as well as the humid tropics. The entire range of basic design conditions does not necessarily occur in any one place. Each single condition (high temperature, low temperature, high humidity) occurs in a wide area. When taken together, the design values should be valid for materiel used throughout the area", [UNITED STATES, 2000, at Part 1, C-3]. Figure 5.5 is a graph of the induced diurnal temperature and relative humidity values for this region [UNITED STATES, 2000].

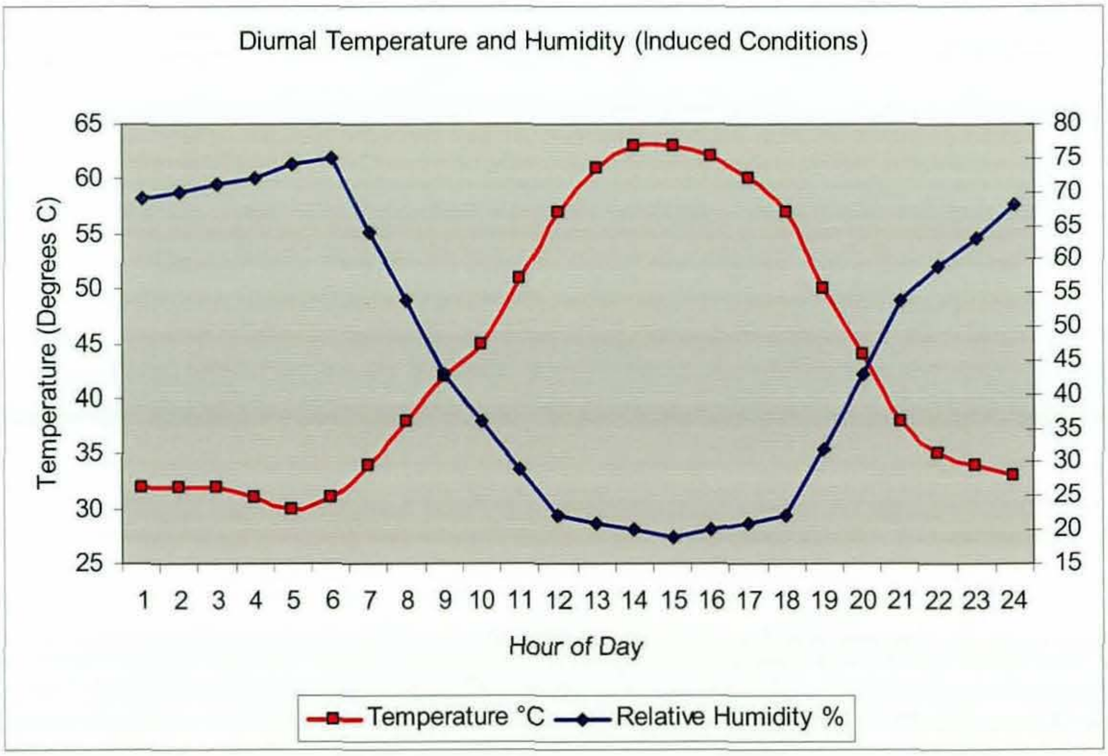

Figure 5.5 Temperature and Relative Humidity for the 'Basic' Region [UNITED STATES, 2000]

There are however, notable weaknesses in the Military specifications. The temperature and humidity values are representative of the most extreme conditions, only exceeded for 1% of the time. The specifications also claim to be harmonized, but the classification of geographic regions differs. Further, induced conditions in US military specifications, occurring at times of direct sunlight exposure is cited as normal conditions in British military specifications. Where the data in the specifications appear similar, the differences in how they are applied within the specifications lead to uncertainty. Despite these inconsistencies, the diurnal temperature and relative humidity values may be used to estimate the accelerated ageing time for automotive FPCs deployed worldwide.

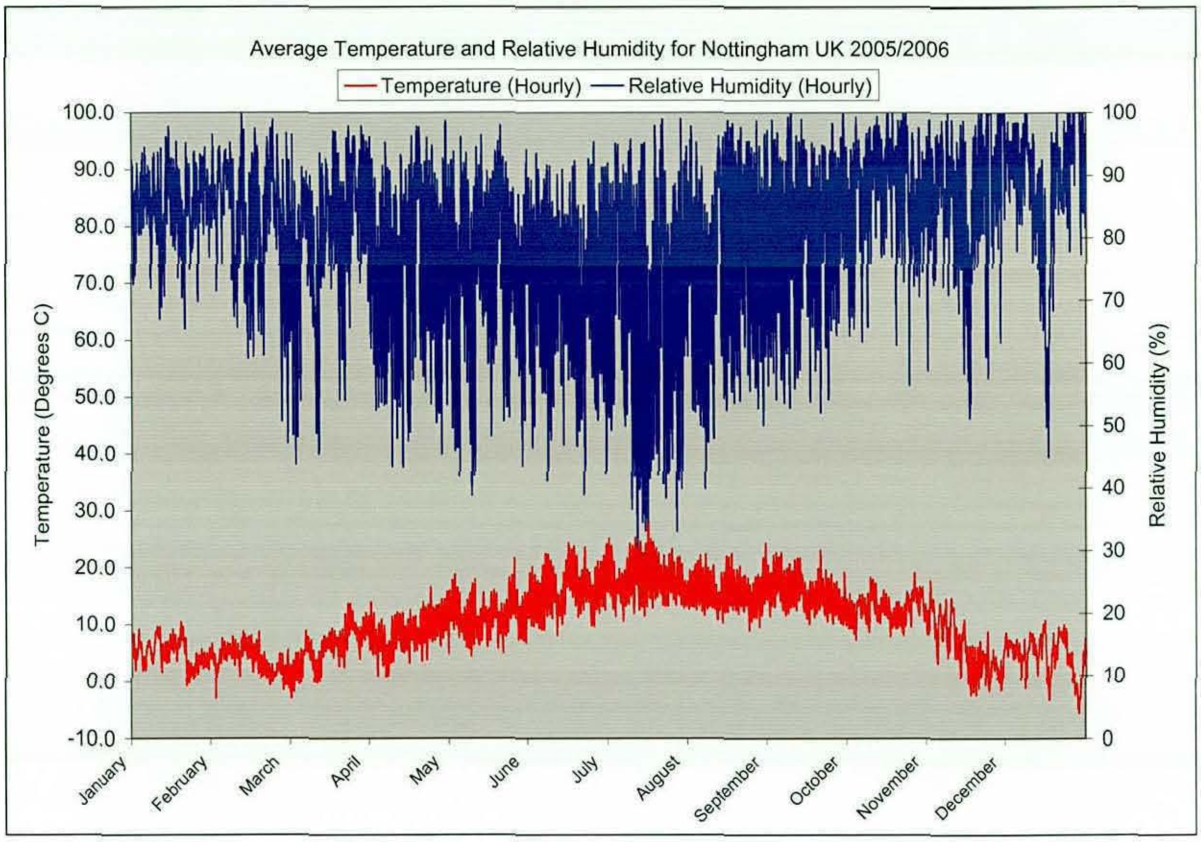

Figure 5.6 Average Hourly Temperature and Relative Humidity for Nottingham UK (2005/2006)

Whilst an automotive component designed for worldwide deployment may be attractive to the OEM, the cost of such components may be economically unattractive. A more realistic approach would be to design components for climatic conditions experienced by the n^{th} percentile end-user[67], which could be determined from automotive sales forecasts and trends. One assumption is that the n^{th} percentile end-user would be located in a sub-tropical or temperate climate. The diurnal temperature and relative humidity for England, specifically Nottingham, has been selected as a starting point for estimating accelerated ageing times, on

[67] For example, Lu and Rudy [2000] proposed the 95^{th} percentile end user.

the basis of availability of data. Figure 5.6 shows the average hourly temperature and relative humidity for Nottingham, in 2005 and 2006, as provided by the UK Meteorological Office[68].

5.4 Proposed Temperature and Relative Humidity Profile

A temperature and relative humidity model is now proposed, based on the average monthly maximum and minimum temperatures in England between 1971 and 2000, as published by the UK Meteorological Office [Met Office, 2007]. Figure 5.7 presents the actual measured averages and proposed averages. Due to the periodic nature of the annual and diurnal weather cycles, a simple sinusoidal model provides a good fit for the average temperatures[69].

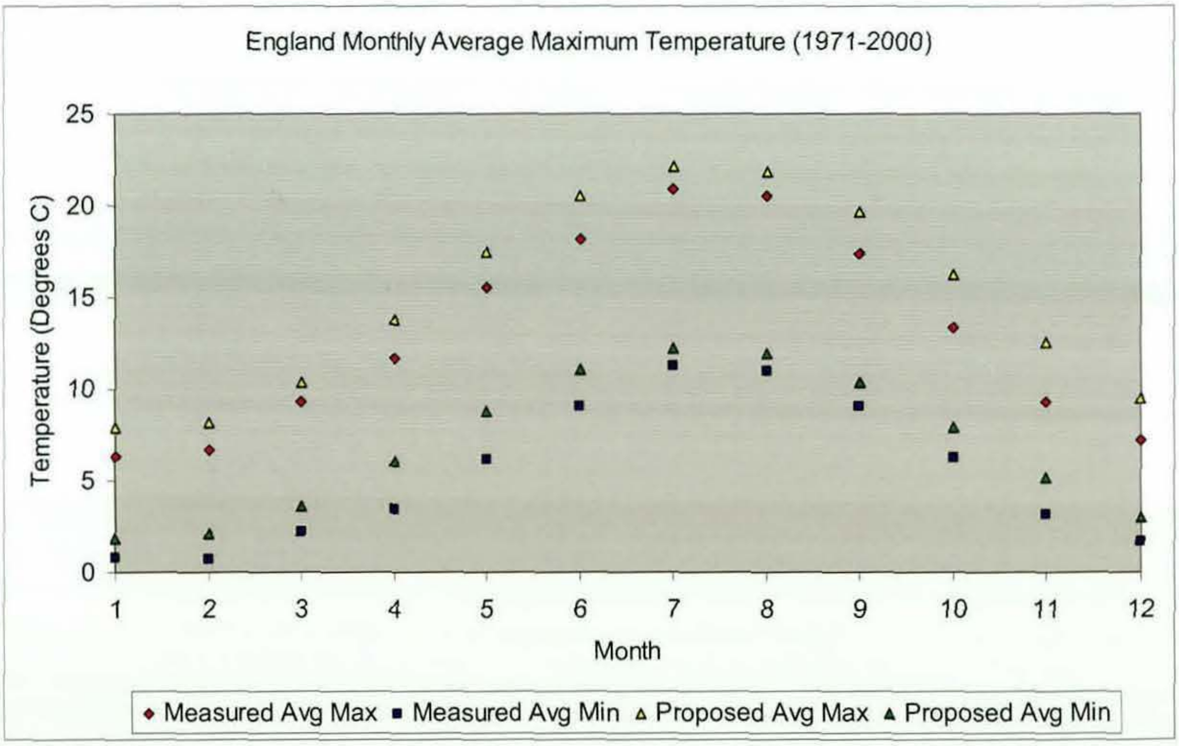

Figure 5.7 Proposed Monthly Average Maximum and Minimum Temperature for England

[68] This data is commercially available from the UK Met Office

[69] A Time Series analysis of the Meteorological data could provide a more precise model.

From the graph, the proposed daily average maximum and minimum temperature can be, $T_{max,daily}$ and $T_{min,daily}$ respectively can be represented as:

$$T_{max,daily} = 7.25\sin\psi + 15$$ **Equation 5.17**

$$T_{min,daily} = 5.25\sin\psi + 7$$ **Equation 5.18**

Where ψ is the daily angle in degrees = $\left(\frac{360}{365}\times \text{Day of Year}\right) - 100^{\circ}$ **Equation 5.19**

The temperature at hour 'i', $T_{hourly,i}$ can now be represented as:

$$T_{hourly,\ i} = \left[\frac{T_{max,\ daily} - T_{min,\ daily}}{2}\sin\phi_i\right] + \left[\frac{T_{max,\ daily} + T_{min,\ daily}}{2}\right]$$ **Equation 5.20**

Where ϕ_i is the hourly angle in degrees = $-90^{\circ} + \left(\frac{360}{24}\times i\right)$ **Equation 5.21**

A similar approach has been used to model the Relative Humidity. The model has been has been designed to fit the maximum and minimum humidity trend lines in the Nottingham data. The humidity model shown in Figure 5.8 is 180° out of phase with the temperature

$$M_{max,daily} = 5\sin(\psi + 180) + 95$$ **Equation 5.22**

$$M_{min,daily} = 5\sin(\psi + 180) + 90$$ **Equation 5.23**

Where ψ is as before

The relative humidity at hour 'i', $M_{hourly,i}$ is represented as:

$$M_{hourly,\, i} = \left[\frac{M_{max,\, daily} - M_{min,\, daily}}{2}\sin\left(\phi_i + 180\right)\right] + \left[\frac{M_{max,\, daily} + M_{min,\, daily}}{2}\right] \qquad \textbf{Equation 5.24}$$

Where Φ_i is as before

Equation 5.17 to Equation 5.24 defines the base temperature and relative humidity profiles for external ambient conditions in England. These profiles must however be modified to take into account the effect of sunlight exposure.

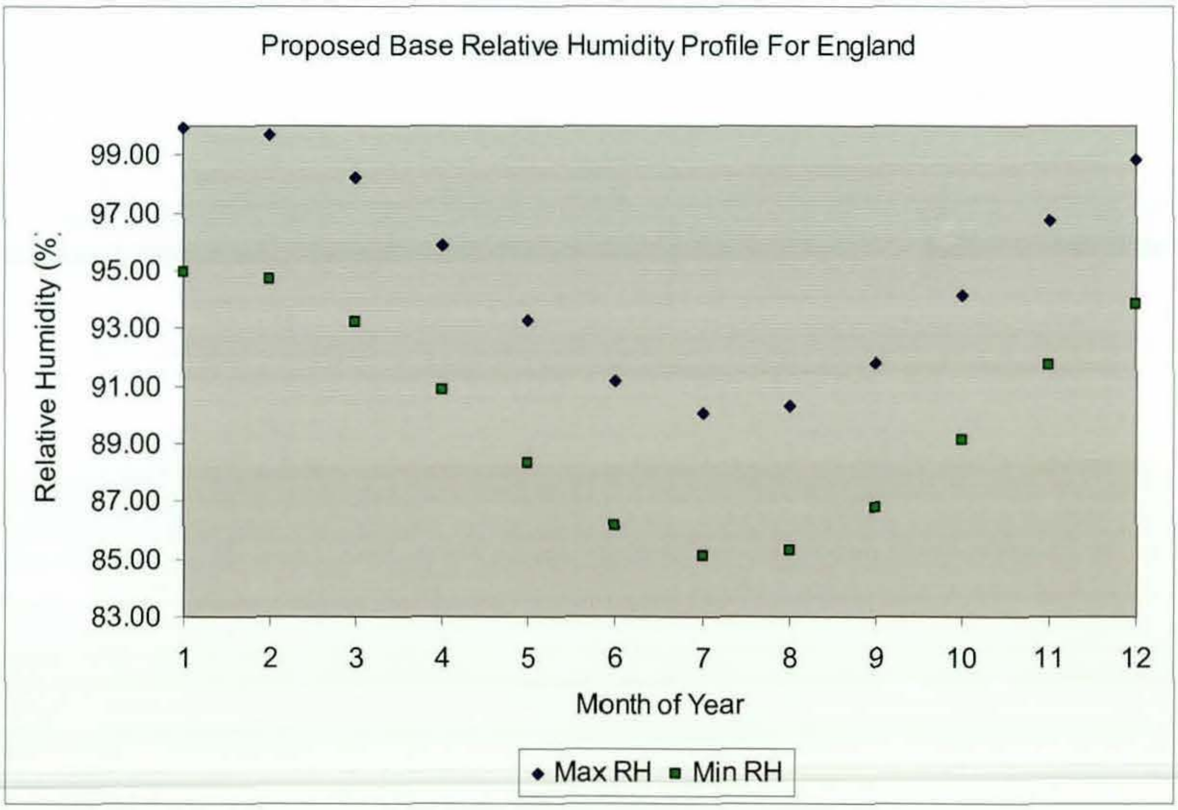

Figure 5.8 Base Relative Humidity Profile for England

5.4.1 Effect of Direct Exposure to Sunlight

There are three types of solar effects that affect the temperature within the passenger cabin of a vehicle [ASHRAE, 2005b]. These are:

1. Vertical: Maximum intensity occurs at or near noon. Solar heat gain through all glass surface area normal to the incident light is a substantial fraction of the cooling load[70].
2. Horizontal and reflected radiation: Intensity is significantly less, but the glass area is large enough to merit consideration.
3. Surface heating: Surface temperature is a function of the solar energy absorbed, the interior and ambient temperatures, and the automobile's velocity.

Enclosed vehicles that are exposed to sunlight experience an increase in temperature inside the passenger cabin and to a lesser extent the doors. Based on the temperature measurements of Marty, Sigrist and Wyler [2001], the temperature inside the passenger cabin can be four times the external ambient when exposed to sunlight during the summer months. Inside the vehicle doors can experience temperatures up to ten degrees higher than the external ambient [Wang et al, 2001].

The measured average number of hours per month of sunlight in England is shown in Figure 5.9 [Met Office, 2007]. This average varies between 20 % in winter months to 50% in the summer months, of the maximum possible number of hours of sunshine [Met Office, 1973].

[70] In respect of the automobile air-conditioning system.

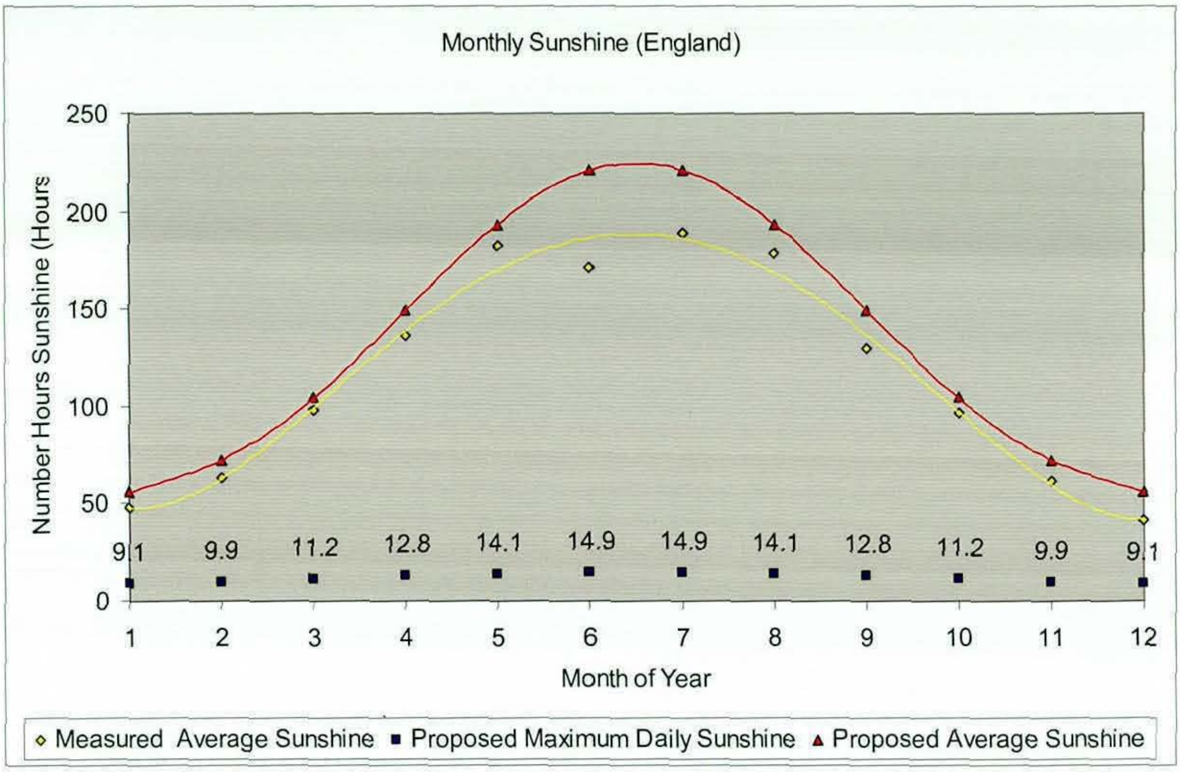

Figure 5.9 Measured and Proposed Average Sunshine for England

The proposed sunshine profile, shown in Figure 5.9 is represented by:

$$S_{daily,\max} = 3\sin(\psi + 25) + 12$$ **Equation 5.25**

$$S_{\%\ total\ possible} = 15\sin(\psi + 25) + 35$$ **Equation 5.26**

$$S_{daily} = (15\sin(\psi + 25) + 35) \times (3\sin(\psi + 25) + 12)$$ **Equation 5.27**

Where:

$S_{daily,max}$ is the maximum possible number of hours of sunshine per day

$S_{\%\ total\ possible}$ is the percentage of total possible sunshine per month

S_{daily} is the daily number of hours of sunshine and ψ is as before.

To model the effect of sunlight exposure on the temperature profile inside the passenger cabin and doors, further assumptions are made, namely:

1. The highest external and internal vehicle temperature occurs coincidently at midday.[71]
2. The lowest external and internal vehicle temperature occurs coincidently at midnight.
3. The sun is highest in the sky at midday; therefore the number of hours of sunshine is equally distributed before and after midday.
4. The rise in temperature inside the passenger cabin and door is proportional to the external ambient temperature[72].
5. The temperature and relative humidity inside the passenger cabin and door follow the external ambient at all other times

When exposed to sunlight, the temperature inside the passenger cabin increases to four times the external ambient, and the temperature inside the doors increase to 1.5 times the external ambient. A section of the sunlight induced temperature profile for the passenger cabin is shown in Figure 5.10.

[71] Although assumptions 1 and 2 are literally incorrect, there is an inherent compensation in the model such that the duration of exposure to the higher remains the same.

[72] This assumption has also been proposed by Hu [1995] for automotive electronic products.

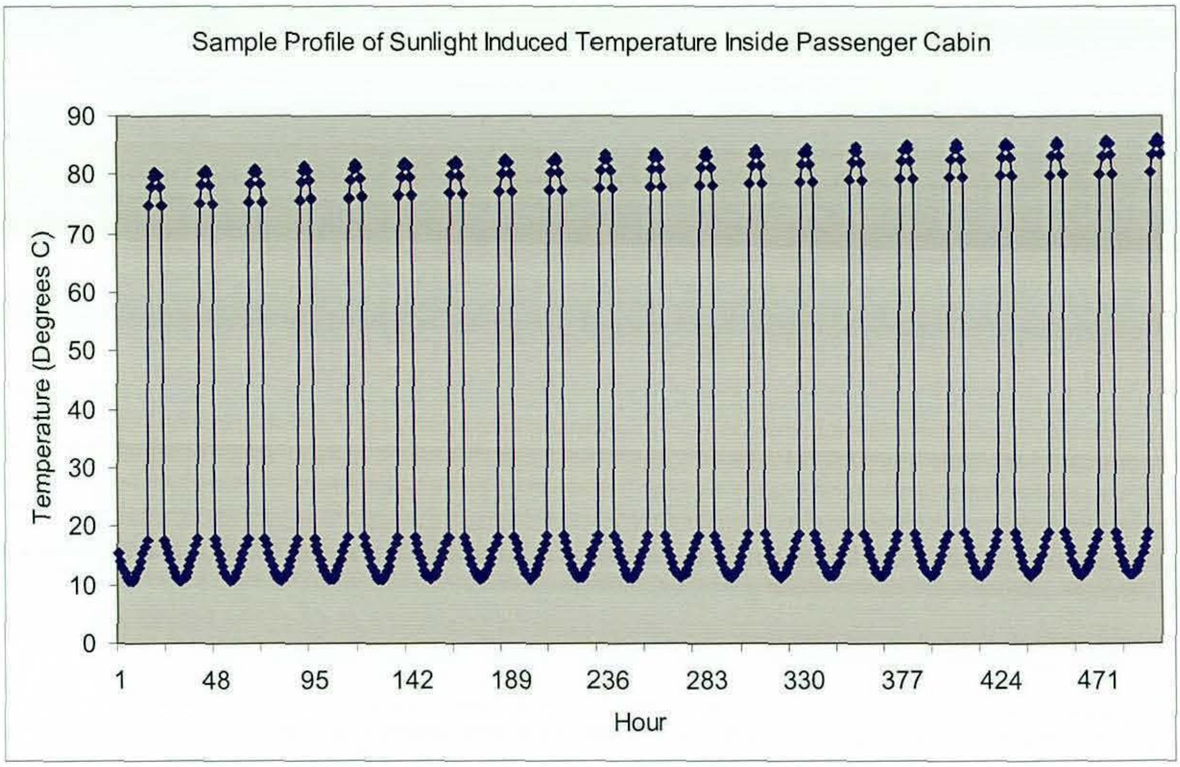

Figure 5.10 Section of Sunlight Induced Temperature Profile for Passenger Cabin

5.4.1.1 Relative Humidity in Passenger Cabin and Wet Side of Door

It is a natural phenomenon that as the temperature of an enclosed space increases, the relative humidity of the air within that space decreases, provided there is no introduction of additional moisture from an external source. The base relative humidity profile must therefore be modified to reflect this. Relative humidity is defined as the ratio of the mole fraction of water vapour x_w in a given moist air sample to the mole fraction x_{ws} in an air sample saturated at the same temperature and pressure [ASHRAE, 2005a]. Relative humidity can also be expressed as the ratio of the partial pressure of water vapour p_w to the saturation pressure of water vapour in the absence of air at the given temperature p_{ws}, as in Equation 5.28.

$$RH = \frac{p_w}{p_{ws}} \times 100\%$$ **Equation 5.28**

The saturation pressure of water vapour, p_{ws} can be calculated from equations derived by Hyland and Wexler [see ASHRAE, 2005a citing Hyland and Wexler, 1983]. For the temperature range of 0 to 200°C, the saturation pressure over liquid water is calculated as follows:

$$\ln p_{ws} = \frac{C_0}{T} + C_1 + C_2T + C_3T^2 + C_4T^3 + \left(C_5 \times \ln T\right)$$ **Equation 5.29**

Where:

p_{ws} = saturation pressure in Pascals

T = absolute temperature in Kelvin

$C_0 = -5.8002206 \times 10^3$

$C_1 = 1.3914993$

$C_2 = -48640239 \times 10^{-2}$

$C_3 = 4.1764768 \times 10^{-5}$

$C_4 = -1.4452093 \times 10^{-8}$

$C_5 = 6.5459673$

Given the value of RH is known from the model in Equation 5.24; the value of p_w can be calculated. It follows therefore that given the relative humidity at temperature T_1, it is possible to calculate the relative humidity when the temperature is increased to T_2. This assertion holds true based on the assumption that there is no additional introduction of water within the enclosed spaces. The corresponding section of sunlight induced relative humidity profile for the passenger cabin, linked to the temperature profile in Figure 5.10 is shown in Figure 5.11.

For the wet side of vehicle doors, a constant relative humidity of 100% has been selected. Although unrealistic, it is used to demonstrate the suitability of PET film for such areas of the vehicle, as discussed below.

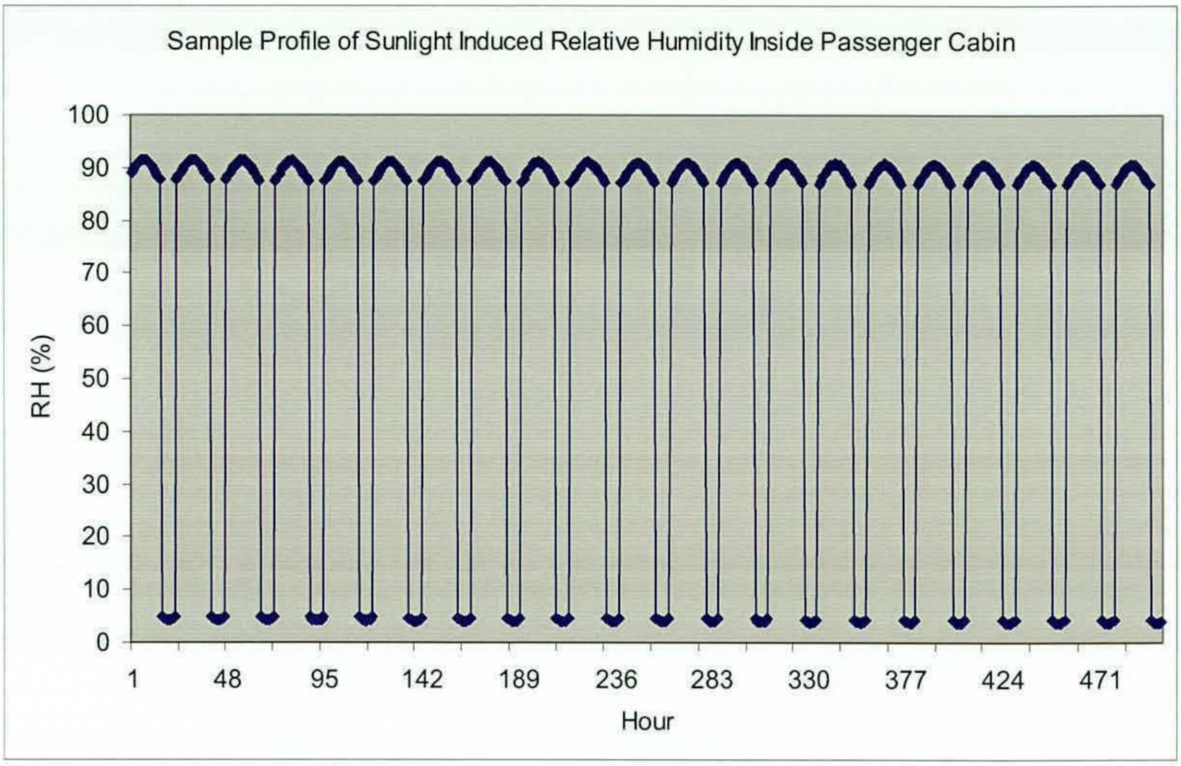

Figure 5.11 Section of Sunlight Induced Relative Humidity Profile for Passenger Cabin

5.4.2 Estimated Time Required for Accelerated Ageing at 85°C/95%RH

With the proposed diurnal temperature and relative humidity profiles, the time required to simulate twelve years vehicle life by ageing PET film at 85°C/95%RH is as follows:

$$\frac{\sum_{i=1}^{i=8760} k_{use,i}}{k_{test}} \times 12 = t_{test}$$ **Equation 5.30**

Where:

$k_{use,i}$ is the rate of hydrolysis during the i^{th} hour of the year

k_{test} is the rate of hydrolysis at 85°C/95%RH

t_{test} is the time required for accelerated ageing

Temperature & RH Profile	No Of Hours To Simulate 12 Years (12.5 μm Film)		
	External	Cockpit	Door
Actual Measured (Nottingham)	9.035		
Proposed (England)	**11.946**	**262.986**	**29.551**
Military (Basic Region -Induced Conditions)		595.891	
	No Of Hours To Simulate 12 Years (250 μm Film)		
	External	Cockpit	Door
Actual Measured (Nottingham)	2.015		
Proposed (England)	**2.979**	**46.063**	**9.668**
Military (Basic Region -Induced Conditions)		176.922	
	No Of Hours To Simulate 12 Years (75 μm Film)		
	External	Cockpit	Door
Actual Measured (Nottingham)	7.815		
Proposed (England)	**9.583**	**205.895**	**24.321**
Military (Basic Region -Induced Conditions)		485.635	

Table 5.1 Estimated Time for Accelerated Ageing at 85°C/95%RH

Table 5.1 lists the estimated time required for the accelerated ageing of Mylar films. It can be seen for 12.5 micron and 250 micron films, that the proposed base temperature and relative humidity profile requires more time to simulate 12 years service life as compared to the actual measured temperature and relative humidity profile for Nottingham. This suggests the proposed profile is more detrimental to Mylar film than real conditions. A further consequence of the proposed profile is that the wet side of vehicle doors is less harsh to PET film than the cockpit. Included for comparison is the estimate of accelerated ageing time applicable to FPCs integrated in the cockpit. For this estimate, the Military Handbook diurnal temperature and relative humidity data has been used.

5.4.2.1 Estimating Time required for 75 micron Film

The typical base film thickness proposed for automotive FPCs is 75 microns. Further, the total thickness of a single-sided circuit is in the order of 185 microns. The time required for accelerated ageing for 75 micron films cannot be accurately determined, because the reason for the difference in the rates of hydrolysis for 12.5 and 250 micron films is inconclusive. Further, for the composite laminate, only one side of the film is exposed to the conditions within the vehicle. The diffusivity of the adhesive layer may prevent moisture ingress, or conversely moisture could be trapped within that layer. However, trapped moisture within the adhesive layer may be more likely to cause hydrolytic degradation of the adhesive itself, and the interfacial bonds. At worst case therefore, the time required for degradation of 75 micron film is no more than that required for the 12.5 micron film.

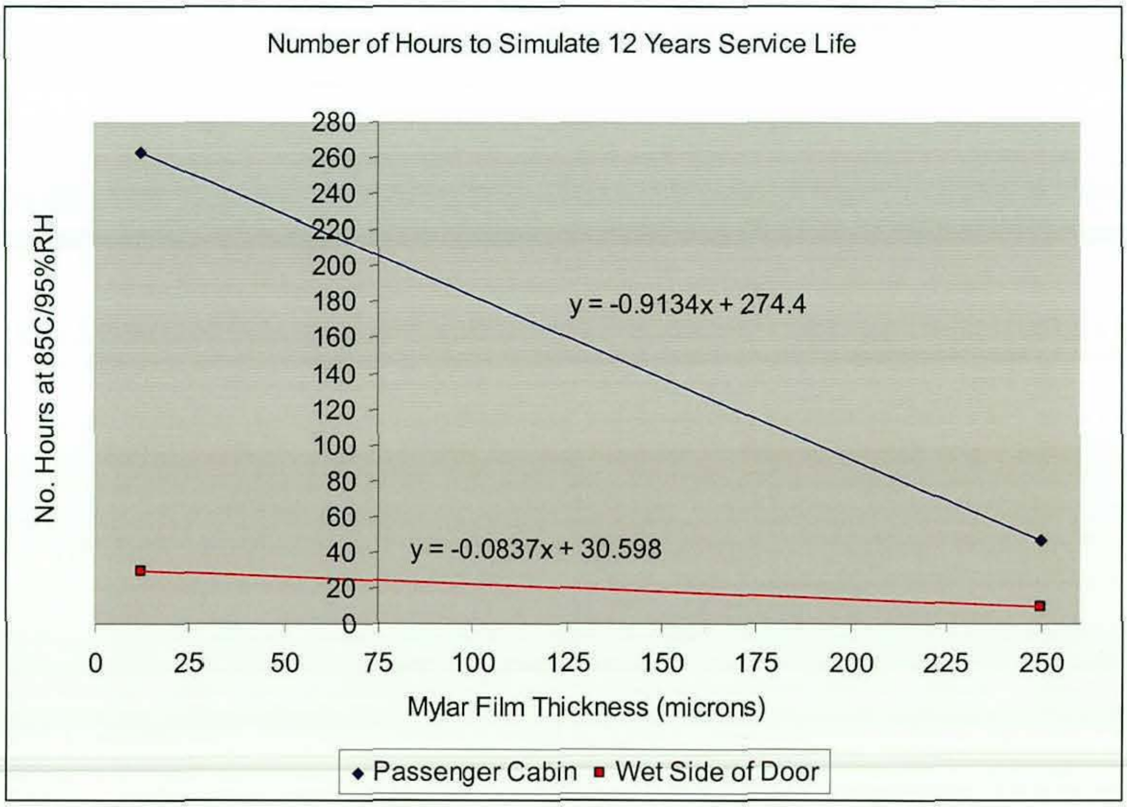

Figure 5.12 Estimated Time Required for Ageing 75 micron Mylar film

The significant difference in the accelerated ageing time required by 12.5 and 250 micron films however, cannot be ignored. A final assumption is that at worst, a linear relationship exists between the time required for accelerated ageing and film thickness, as shown in

Figure 5.12. For a linear relationship between the required accelerated ageing time and film thickness, it is estimated that 75 micron films to be used in vehicle cockpits require 205.895 hours exposure at 85°C/95%RH. For vehicle door applications, 75 micron films require 24.321 hours exposure at 85°C/95%RH.

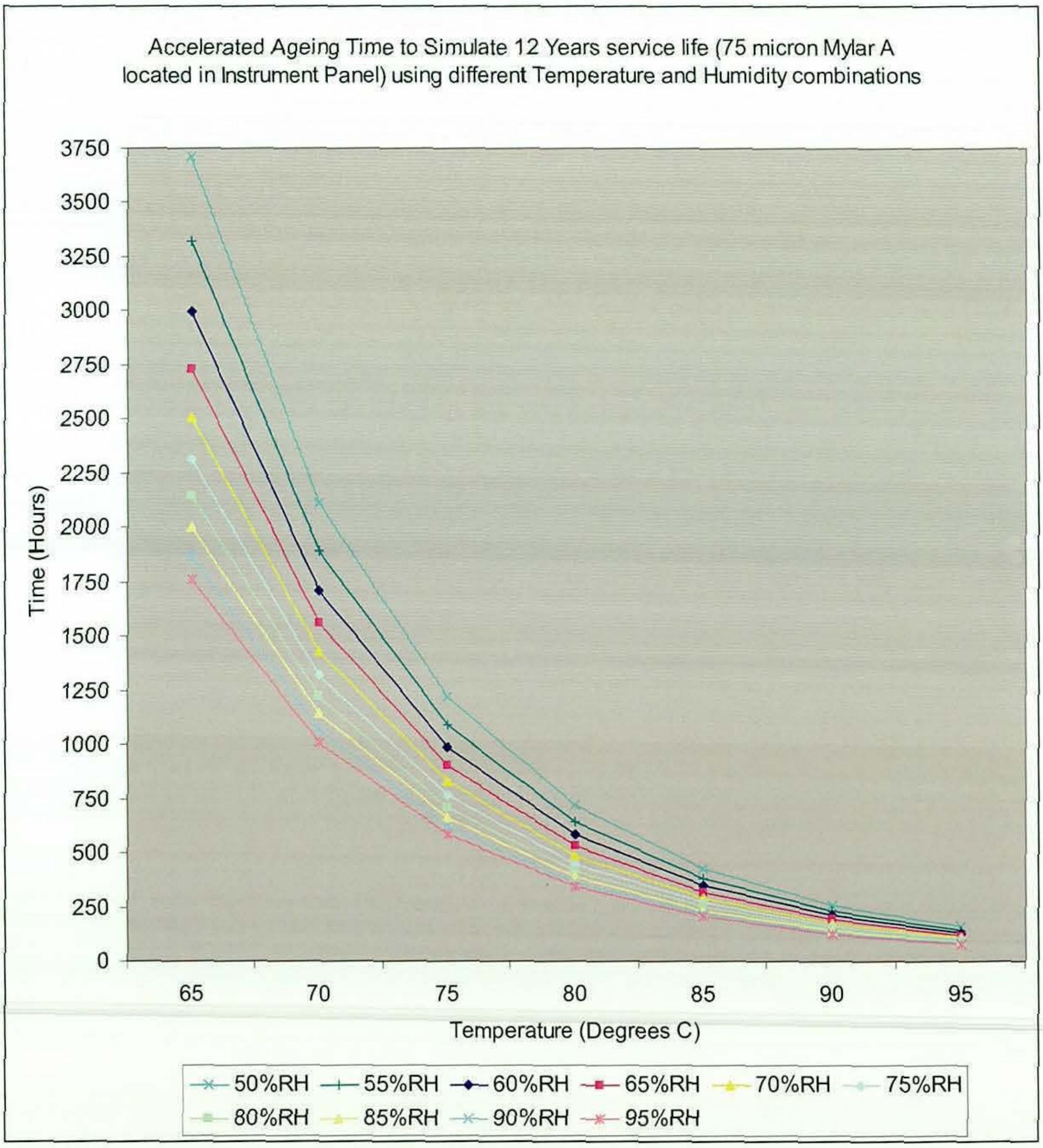

Figure 5.13 Time Required for Accelerated ageing under different conditions for 75 micron Mylar A to simulate 12 years service life in a vehicle cockpit

Using this rationale, the time required for accelerated ageing of 75 micron Mylar A film at different temperatures and humidity, to simulate twelve years in a vehicle deployed in England, is shown in Figure 5.13 and Figure 5.14 for the Instrument Panel and wet side of the door respectively.

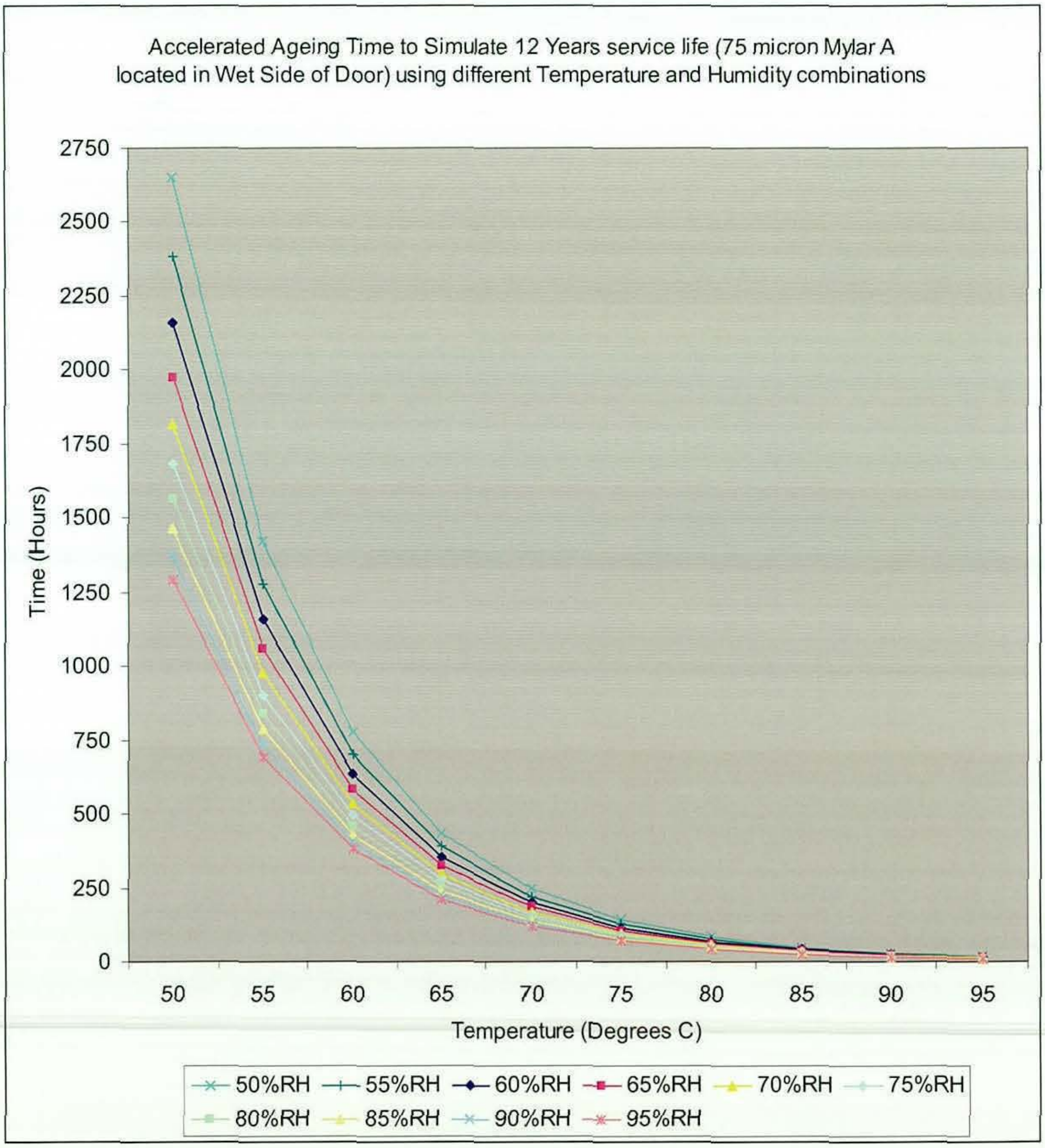

Figure 5.14 Time Required for Accelerated ageing under different conditions for 75 micron Mylar A to simulate 12 years service life in the wet side of vehicle doors

As illustrated in the graphs, it is high temperature rather than high humidity that significantly controls the accelerated ageing time. There are practical implications to this, for example, the cost of environmental chambers capable of maintaining high humidity conditions.

To determine the time required for accelerated ageing of 75 micron Mylar A to simulate any number of years in service within the vehicle, Equation 5.30 may be rewritten as:

$$\frac{\sum_{i=1}^{i=8760} k_{use,i}}{k_{test}} \times N = t_{test}$$ **Equation 5.31**

Where N is the number of years in service within the vehicle

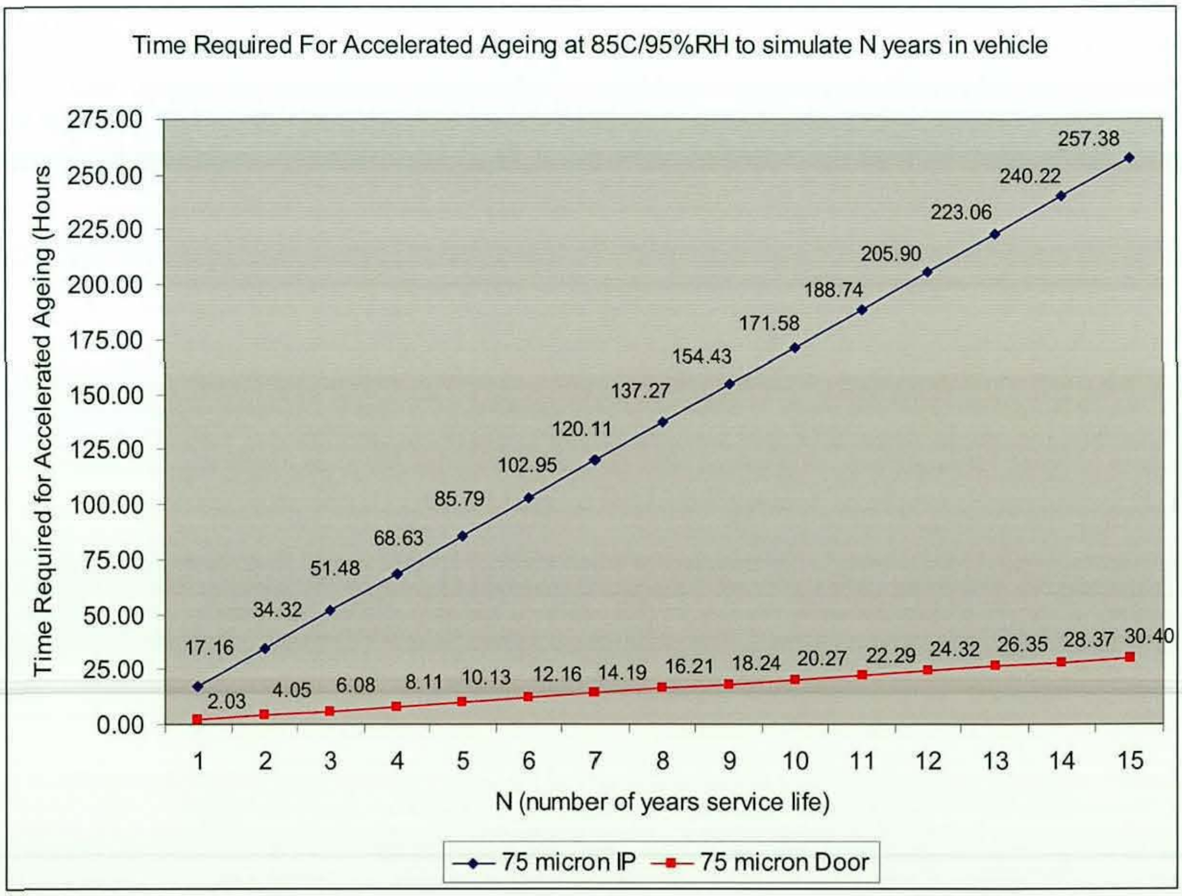

Figure 5.15 Time Required for Accelerated Ageing of 75 micron Mylar A to simulate N years in a vehicle

Figure 5.15 shows the time required for accelerated ageing at 85°C/95%RH of 75 micron Mylar A, to simulate N number of years in service within a passenger car deployed in England.

5.4.2.2 Time Required for Other Materials

A further point must be noted for other materials used in FPC constructions. Hypothetically, if the predominant mechanism of degradation in the material is hydrolysis, then a direct comparison to the time required for accelerated ageing of PET film can be made. Assuming the rate of hydrolysis of the given material, for example the adhesive, at service temperature and humidity is α times that for PET film, where α is a positive variable number greater than one; and β times that of PET at test conditions, where β is also a positive real number greater than α, then:

$$k_{test\_adh} t_{test} = k_{use\_adh} t_{use}$$ **Equation 5.32**

Where: k_{test_adh} and k_{use_adh} are the rates of hydrolysis of the adhesive at test and service conditions respectively.

Substituting for k_{test_adh} and k_{use_adh} in the above equation gives:

$$\beta k_{test\_PET} t_{test} = \alpha k_{use\_PET} t_{use}$$ **Equation 5.33**

Where: k_{test_PET} and k_{use_PET} are the rates of hydrolysis of Mylar Film at test and service conditions respectively.

The time required for accelerated ageing can therefore be determined from Equation 5.34

$$\frac{\sum_{i=1}^{i=8760} \alpha_i \mathrm{k}_{\mathrm{use},i,PET}}{\beta \mathrm{k}_{\mathrm{test}\_PET}} \times 12 = \mathrm{t}_{\mathrm{test}\_adh}$$ **Equation 5.34**

Where: $k_{use,i,PET}$ is the rate of hydrolysis of Mylar at hour i, t_{test_adh} is the time required for accelerated ageing of the adhesive and α_i is the hourly value of α.

If it is further assumed that β is a multiple of α at all times, the above equation can be rewritten as follows:

$$\frac{\sum_{i=1}^{i=8760} \frac{\beta}{\gamma_i} \mathrm{k}_{\mathrm{use},i,PET}}{\beta \mathrm{k}_{\mathrm{test}\_PET}} \times 12 = \mathrm{t}_{\mathrm{test}\_adh}$$ **Equation 5.35**

Where: γ_i is a positive variable number.

From Equation 5.35, the time required for accelerated ageing of the adhesive to simulate 12 years service life will be less than or equal to that required for Mylar film. The situation is identical in the case where hydrolysis occurs at a slower rate compared to PET film. Assuming the rate of hydrolysis of the given material, for example PEN film, at service temperature and humidity is $1/\alpha$ times that for PET film, where α is a positive variable number greater than one; and $1/\beta$ times that of PET at test conditions, where β is also a positive real number, but less than α, then Equation 5.33 may be rewritten as:

$$\frac{1}{\beta}\mathrm{k}_{\mathrm{test}\_PET}\mathrm{t}_{\mathrm{test}} = \frac{1}{\alpha}\mathrm{k}_{\mathrm{use}\_PET}\mathrm{t}_{\mathrm{use}}$$ **Equation 5.36**

And Equation 5.34 may be rewritten as:

$$\frac{\sum_{i=1}^{i=8760} \frac{1}{\alpha_i} k_{use,i,PET}}{\frac{1}{\beta} k_{test\_PET}} \times 12 = t_{test\_PEN}$$ **Equation 5.37**

If it is assumed that α is a multiple of β at all times, the above equation can be rewritten as follows:

$$\frac{\sum_{i=1}^{i=8760} \frac{1}{\beta\gamma_i} k_{use,i,PET}}{\frac{1}{\beta} k_{test\_PET}} \times 12 = t_{test\_adh}$$ **Equation 5.38**

This effectively is the same result derived in Equation 5.35, and is contradictory given difference in the estimated time required for accelerated ageing of 12.5 micron and 250 micron PET films. The previous calculations suggested that where a higher rate of hydrolysis applied, the time required to simulate 12 years service life would be greater. Therefore, a direct comparison of the time required to simulate the ageing of other materials cannot be made using the method outlined above, unless the variables are resolved. One method of so doing would be to determine the actual rates of hydrolysis of the materials through experiment.

A likely generalisation for the time required for accelerated ageing of different materials and FPC laminates is that for lower rates of hydrolysis compared to PET film, less time is required compared to PET film. The converse applies for materials and FPC laminates having a higher rate of hydrolysis compared to PET film. Such materials and FPC would require a longer accelerated ageing time compared to PET film, however, no estimate can be made as to the additional length of time required without a knowledge of the rate of hydrolysis all materials.

Nevertheless, the precise time required by other materials to simulate 12 years service life in a passenger vehicle is not required. Materials having the same or lower hydrolytic degradation rate should exhibit matching or superior retention in material properties compared to Mylar A film. Therefore, the time required to simulate the accelerated ageing of 75 micron Mylar A film (25 and 206 hours for door and cockpit applications respectively at 85°C/95%RH) may be used as a benchmark for candidate materials known to have similar or lower rates of hydrolytic degradation, with material selection based on the retention of the properties of interest.

5.5 Suitability of PET films

Walker [1997] noted that the electric motor industry and PET film manufacturers use a variety of criteria to define when failure of insulating film occurs, such as:

i. The point at which 50% of original elongation remains

ii. The point at which 50% of the original strength remains[73]

iii. When the elongation reaches an absolute value of 10% or less

iv. When the intrinsic viscosity reaches a critical value

v. When the film cannot be folded upon itself without fracture

vi. When a critical density is reached.

McMahon et al [1959] observed that 12.5 micron film exposed to 82°C/95%RH for 336 hours retains no less than 90% of its original tensile strength, and 250 micron film exposed to the same conditions retains no less than 97% of its original tensile strength. Also, 12.5 and 250 micron films would not experience degradation in Dielectric Breakdown Strength under such exposure conditions. Based on the above failure criteria, it is suggested that Mylar film may be suitable for both vehicle doors and cockpit applications. Further, where thin films exhibit unsatisfactory retention of physical properties, the use of thicker films is suggested as

[73] There was no clarification as to whether this meant dielectric strength or tensile strength, but it is suggested that the author was referring to tensile strength.

such films would not have degraded hydrolytically to the same extent as thinner films. These suggestions apply to PET film only and not necessarily to the composite FPC laminate.

5.6 Review of Experiment Results

McMahon et al [1959] suggested that Mylar film retains its dielectric properties until it becomes brittle and weak; recommending the retention in tensile strength to be no less than 66%. The results of the experiments are reviewed here, using 70% retention of initial FPC property value as the benchmark for acceptability for use in automotive applications. For convenience, the graphs of the results for tensile strength, peel strength, initiation tear, propagation tear and flexural endurance are repeated in the relevant subsections below.

5.6.1 Tensile Strength

From the M-fair and LAD degradation trend lines in Figure 5.16, it is suggested that laminate 1a (conventional PET laminate) would retain greater than 80% of its original tensile strength after 206 hours accelerated ageing at 85°C/95%RH, and indicates the suitability of this material combination for application in vehicle cockpits and doors.

In Figure 5.17, the regression models suggest laminate 2xb would retain greater than 70% of its original tensile strength after 206 hours accelerated ageing at 85°C/95%RH, however the insufficiency in the data precludes recommending this FPC laminate for automotive applications. This scenario also applies to laminate 2xe, shown in Figure 5.18. Further, no recommendation is made in respect of laminates 2xc and 2y for insufficiency in the data.

The regression models for laminate 3b and 3c, as shown in Figure 5.19 and Figure 5.20 respectively, suggest both laminates would retain greater than 70% of its original tensile strength after 206 hours accelerated ageing at 85°C/95%RH; however, more data points would be required for greater confidence in recommending laminate 3b. The regression model for laminate 3e and 4b and 5b, shown in Figure 5.21, Figure 5.22 and Figure 5.23 respectively, suggest these laminates would retain greater than 70% of its original tensile strength after 206 hours accelerated ageing at 85°C/95%RH.

Regression analysis of the tensile strength data for the FPC laminates support the use of all laminates tested for applications within vehicle doors. For the cockpit, laminates 1a, 3c, 3e, 4b and 5b appear to be suitable. Laminates 2xb, 2xe and 3b may potentially be used in vehicle cockpits, but further data is required for confidence. No recommendation could be made for laminates 2xc and 2y as a consequence of insufficient data.

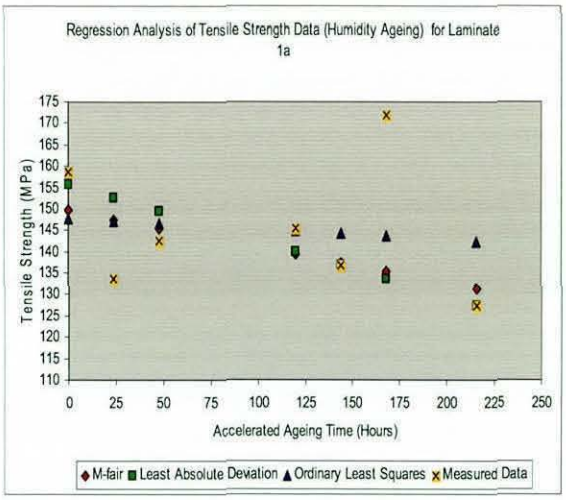

Figure 5.16 Tensile Strength of Laminate 1a

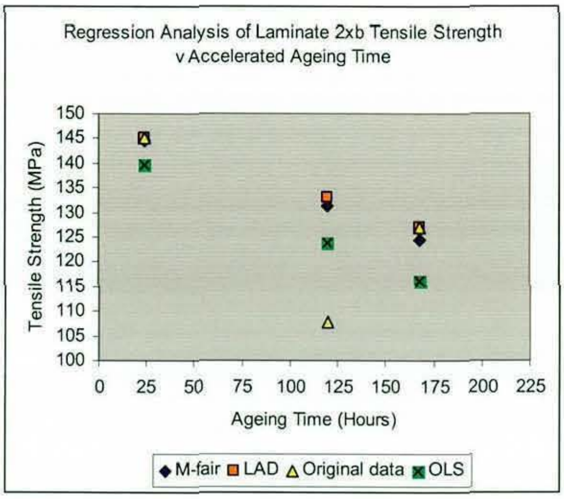

Figure 5.17 Tensile Strength of Laminate 2xb

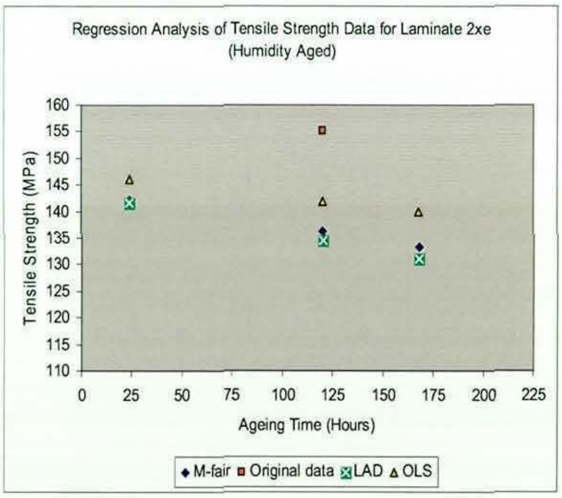

Figure 5.18 Tensile Strength of Laminate 2xe

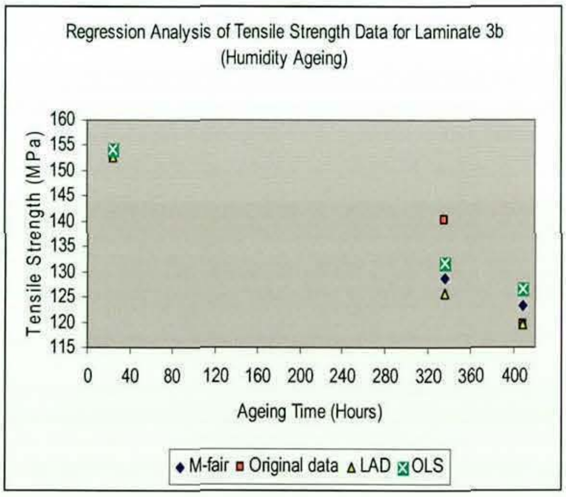

Figure 5.19 Tensile Strength of Laminate 3b

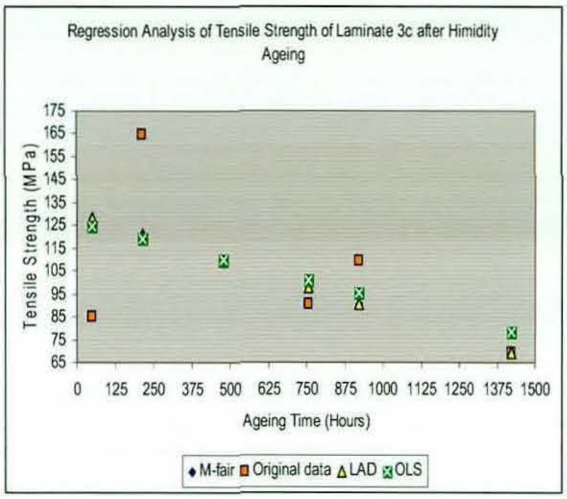

Figure 5.20 Tensile Strength of Laminate 3c

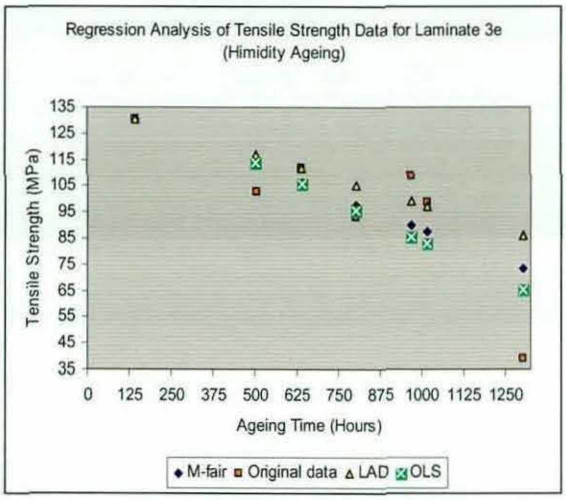

Figure 5.21 Tensile Strength of Laminate 3e

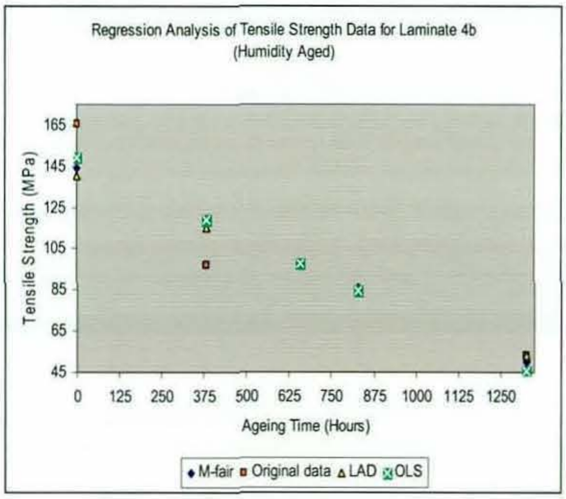

Figure 5.22 Tensile Strength of Laminate 4b

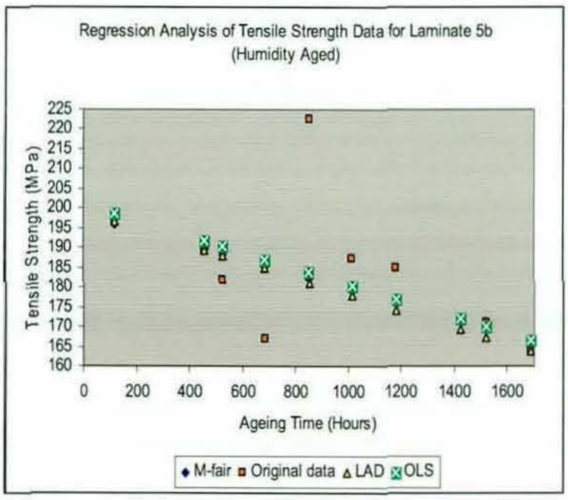

Figure 5.23 Tensile Strength of Laminate 5b

5.6.2 Peel Strength

In Figure 5.24, insufficient data points for substrate 1 (conventional PET) preclude any inferences being drawn for this adhesive. The adhesive in substrates 2x and 2y degrades within 50 hours accelerated ageing at 85°C/95%RH and is unsuitable for both door and cockpit applications. The adhesive is substrate 3 appears to survive over 206 hours, and may potentially be suitable for both cockpit and door applications, however further data is required for confidence. The adhesives in substrates 4 and 5 are suitable for both vehicle cockpits and doors; retaining at least 70% of their initial peel strength after 206 hours.

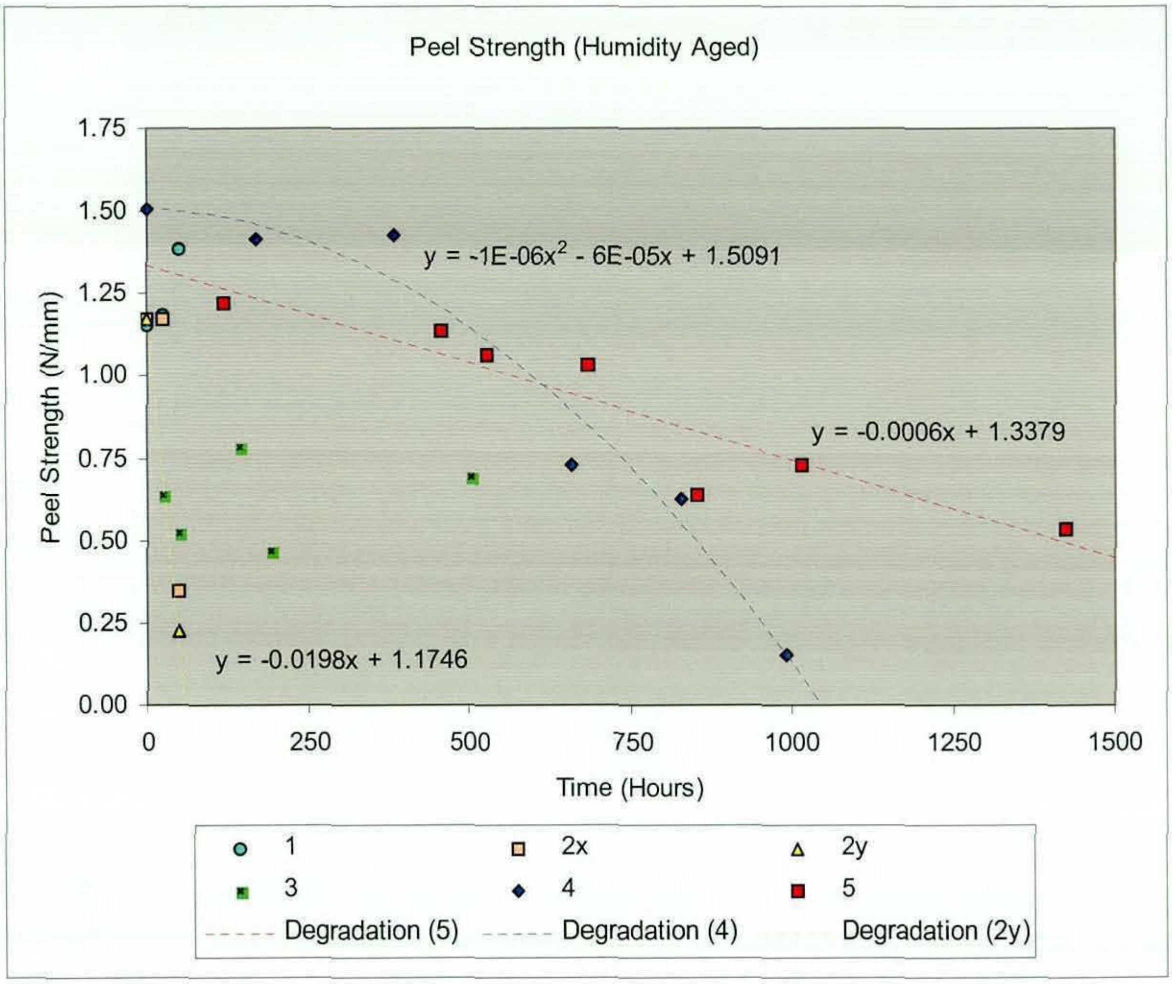

Figure 5.24 Peel Strength of Laminates after 85°C/95%RH Ageing

5.6.3 Initiation Tear Strength

Regression analysis of the initiation tear strength data suggest all laminates tested would retain greater than 70% of their initial value after 206 hours accelerated ageing at 85°C/95%RH. Viewed in isolation, initiation tear strength may not be suitable as an indicator of material suitability for automotive applications, given the results of the tensile strength test and propagation tear strength tests below.

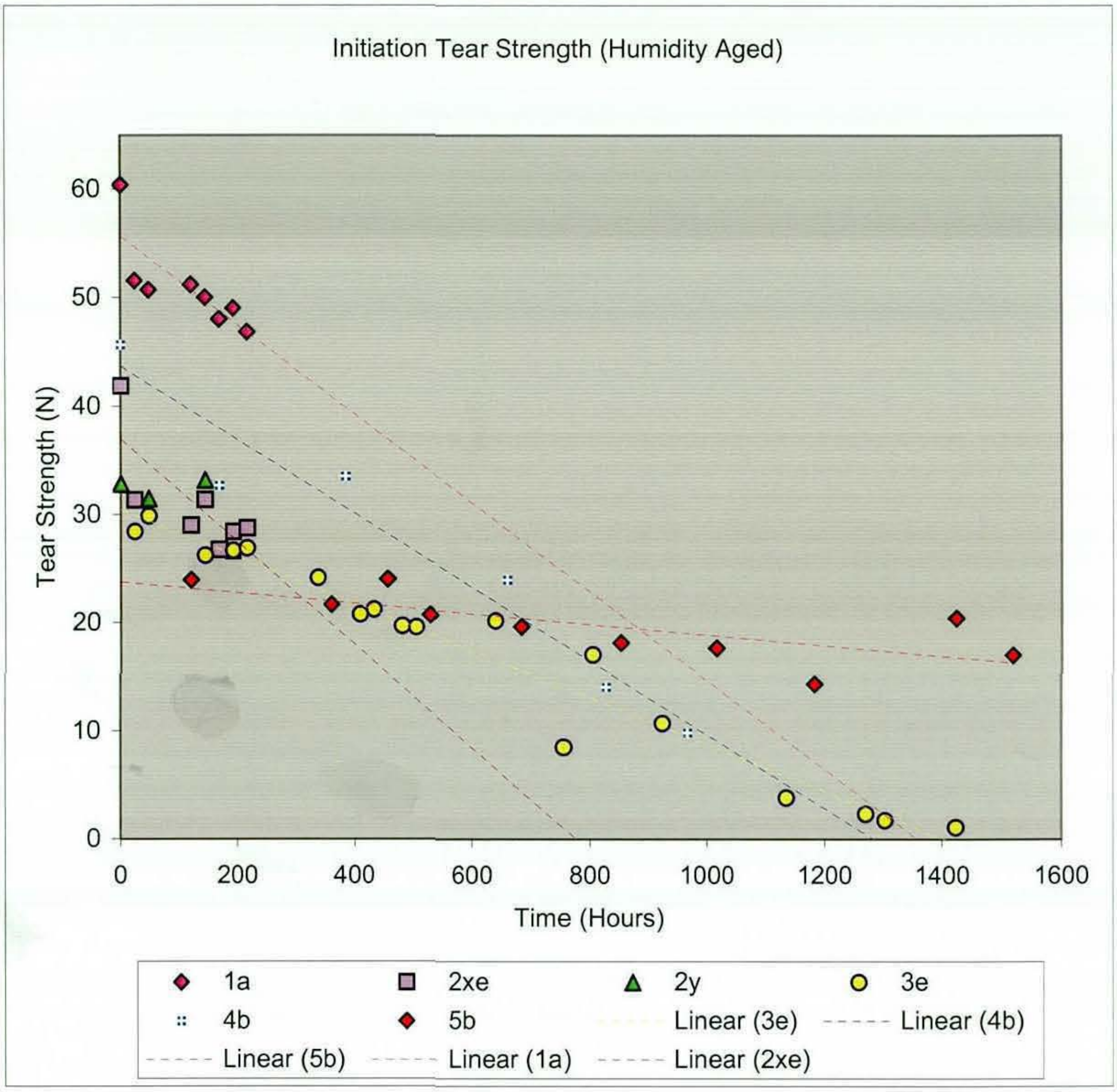

Figure 5.25 Initiation Tear Strength of Base Laminates after 85°C/95%RH Ageing

5.6.4 Propagation Tear Strength

In Figure 5.26, laminate 1a exhibits a rapid initial decrease in propagation tear strength to less than 70% its original value by 150 hours; indicating suitability for vehicle doors only. Regression analysis of the results for laminate 2xe suggests it may retain greater than 70% of its original propagation tear strength after 206 hours, but further data points are required for confirmation and confidence. Substrate 2y retains at least 70% of its initial propagation strength at 25 hours, but less than 50% by 206 hours; indicating suitability for doors only – unless used with a cover layer that improves retention of propagation tear strength. Laminates 3e, 4b and 5b appear to retain 70% of their initial propagation tear strength at 206 hours. However, the scattered results for laminates 3b and 5b preclude firm inferences being made in respect of suitability for automotive applications.

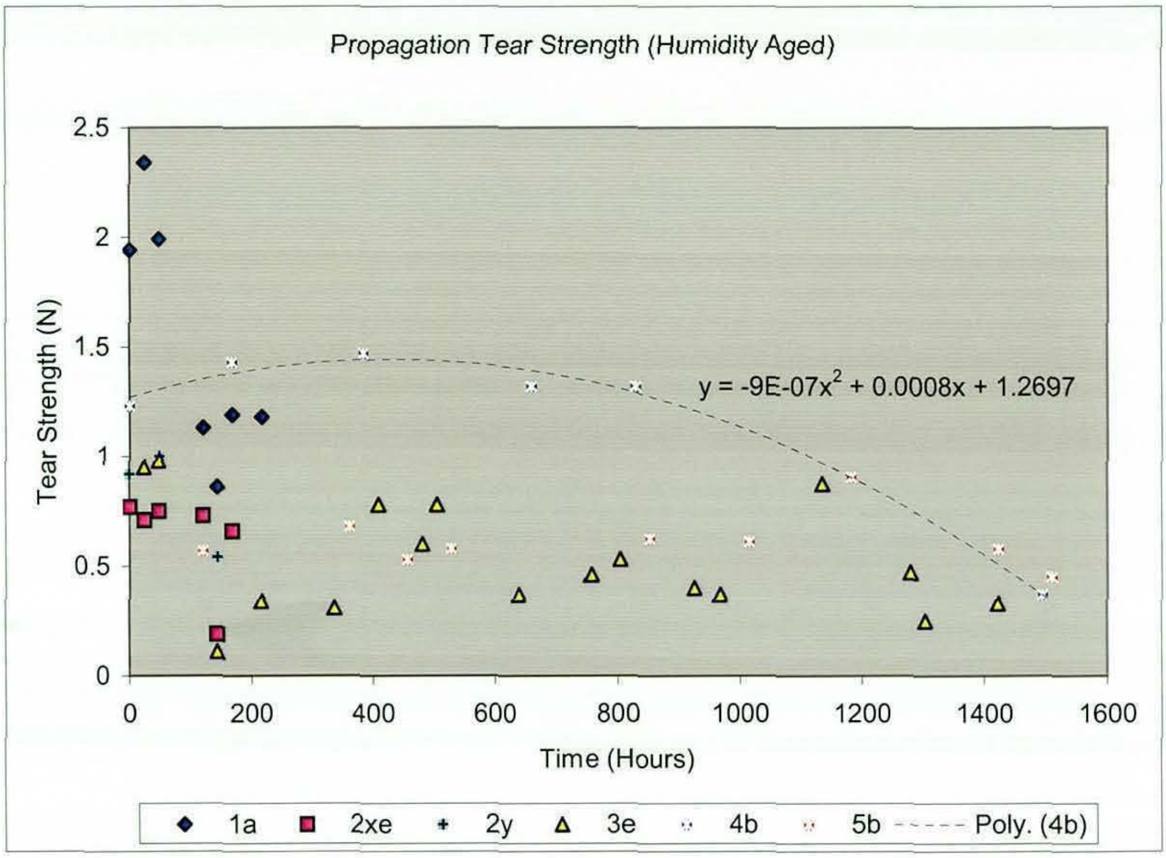

Figure 5.26 Propagation Tear Strength of Base Laminates after 85°C/95%RH Ageing

5.6.5 Flexural Endurance

From Figure 5.27, laminate 1a retains 70% of its flexural endurance at 200 hours, but the sharp decline at 216 hours precludes recommending this laminate for cockpit applications, without further data. Substrate 2y and laminates 2xb, 3b, 3c, 4b and 5b retains 70% of their initial flexural endurance at 206 hours. Insufficient data for laminate 2xc and 3e precludes any inferences being made regarding the suitability of these laminates for doors or cockpits. Laminate 2xe retains 70% of its tensile strength at 25 hours, but not at 206 hours, suggesting it is suitable for doors only.

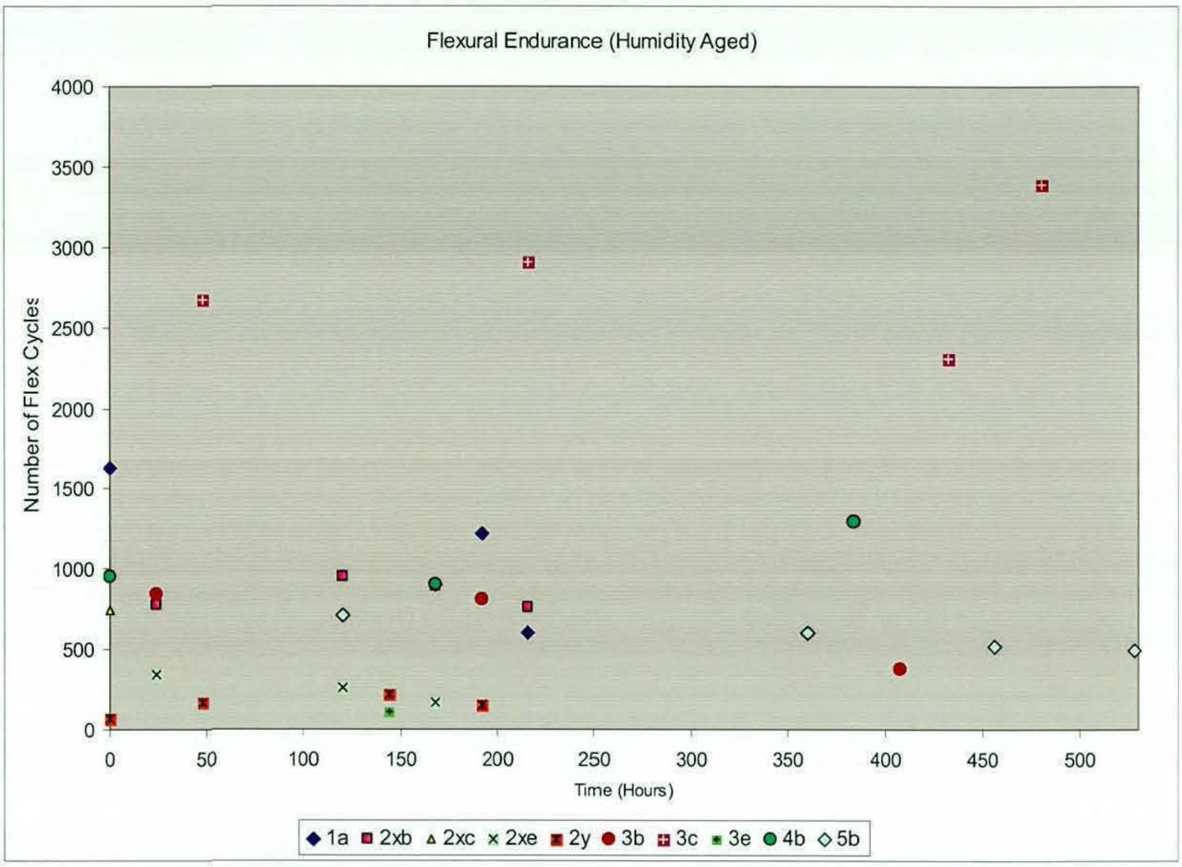

Figure 5.27 Flexural Endurance of Laminates after 85°C/95%RH Ageing

5.6.6 Recommendations for Materials Selection

FPC Property	Doors	Cockpits	Insufficient Data
Tensile Strength	1a, 3c, 3e, 4b, 5b	1a, 3c, 3e, 4b, 5b	2xb, 2xc, 2xe, 2y, 3b (doors, cockpits)
Peel Strength	4, 5	4, 5	2x, 2y (doors); 3 (cockpits)
Initiation Tear	1a, 2xe, 2y, 3e, 4b, 5b	1a, 2xe, 2y, 3e, 4b, 5b	
Propagation Tear	1a, 2y, 4b	4b	2xe (cockpits); 3e, 5b (cockpits)
Flexural Endurance	1a, 2xe, 2y, 2xb, 3b, 3c, 4b, 5b	2y, 2xb, 3b, 3c, 4b, 5b	2xc, 3e (doors, cockpits)

Table 5.2 Summary of Material Recommendations

The experimental results support the use of 75 micron PET base dielectric and 50 micron PET coverlay films for automotive FPCs, provided such FPCs are manufactured using suitable adhesives. Both PET and PEN based FPCs may be used in vehicle doors. Table 5.2 presents the recommended substrates and laminates for vehicle doors and cockpits, and materials for which further data is required before any recommendation can be made. Base substrate 4 (GTS part no. 924-00-01 – PET base film with Polyurethane adhesive) and 5 (GTS part no. 567130 – PEN base film with flame retardant epoxy adhesive) demonstrate suitability for both cockpit and door applications in all material tests performed after damp heat ageing.

6 PROPOSALS FOR A DRAFT AUTOMOTIVE FPC SPECIFICATION

6.1 Introduction

Identifying relevant FPC properties for evaluation has revealed a notable absence of standards and specifications pertaining to automotive FPCs. Whereas the standards and specifications for round wire prescribe damp heat ageing tests, the automotive FPC standards and specifications that have been published do not address the most probable failure mechanism i.e. hydrolysis of the dielectric film and adhesive. As such, they may be more appropriate for quality conformance purposes, and inappropriate for material selection. Further, recommended acceptance criteria for material properties listed in automotive FPC standards and specifications have been adopted unchanged from standards and specifications for FPCs deployed in mainstream consumer electronic products, and may be incompatible with the requirements of automotive applications.

An opportunity therefore exists to propose a more appropriate standard/specification for automotive FPCs. This chapter presents proposals for such a draft specification[74], intended for use by automotive OEMs and their suppliers to select appropriate base dielectric films, cover layers and adhesive materials used in the manufacture of large area automotive FPCs that are to be integrated in vehicle doors and the instrument panel. The draft specification has been limited to single and double-sided FPCs without plated through-hole vias, and do not address the metallic conductor, metallic finishes, connectors, multilayer or flex-rigid constructions, and surface mount or through-hole component attachment. Accelerated ageing conditions and the experimental tests to determine material properties that have been matched to the intended functions of the FPC and location within the vehicle have also been included in the draft FPC specification.

[74] Used in the same context as a 'Draft for Development', defined in *section 6.2*

6.2 Key Terms

In this thesis, the following terms have the same definition used by the British Standards Institution (BSI) [2005a] [2005b] namely:

1. Standard: A "document established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context". Further, "Standards should be based on the consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits".
2. Specification: A "standard that sets out detailed requirements, to be satisfied by a product, material, process, service or system, and the procedures for checking conformity to these requirements".
3. Draft for Development: A "provisional document, developed under broadly the same processes as a formal standard and published when standardization of a particular subject is urgently required, but further research or development is required before it can be published as a British Standard".

6.3 Approach to Developing the Draft Specification

For each application of large area FPCs within the vehicle, for example, within the instrument panel, vehicle door or roof liner; and for each material property requiring assessment, the draft specification should define the method of test [preferably industrially recognized test methods], including stress type and stress level, test duration/number of cycles, sample size, and the number of failures allowed or other acceptability criteria. The most relevant test methods and accelerated ageing conditions have been identified earlier in Chapter 3. Additional test methods and environmental conditions are identified in the standards and specifications shown in Figure 6.1. Together with the experiment results reported in Chapter 4, and the proposals for accelerated ageing in Chapter 5, these form the basis of the draft specification.

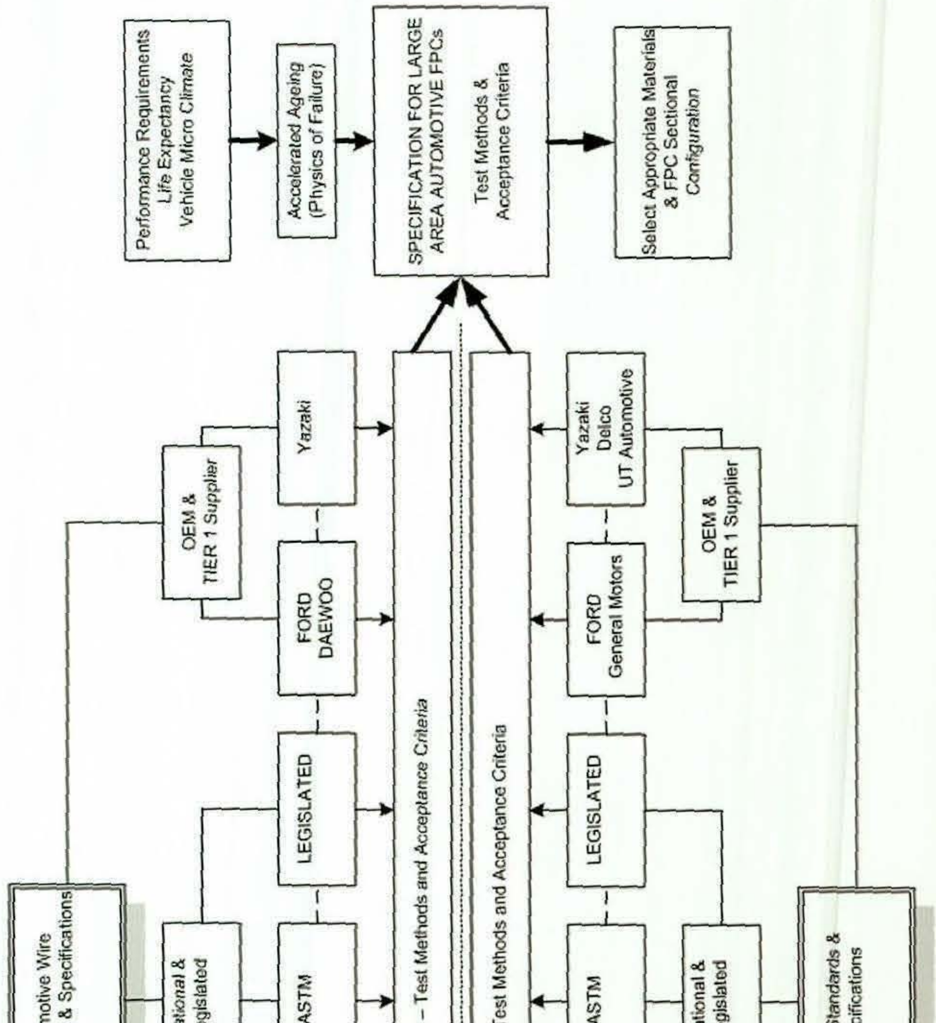

Figure 6.1 Sources Used and Flows of Information for Designing the Draft Automotive FPC Specification

6.4 Test Coupons

Using the outline shape of test coupons detailed in each test method, tests would be conducted on coupons constructed in accordance to one or more of the cross sections illustrated in Figure 6.2. Tests for physical properties would be performed on coupons before and during exposure to accelerated ageing conditions.

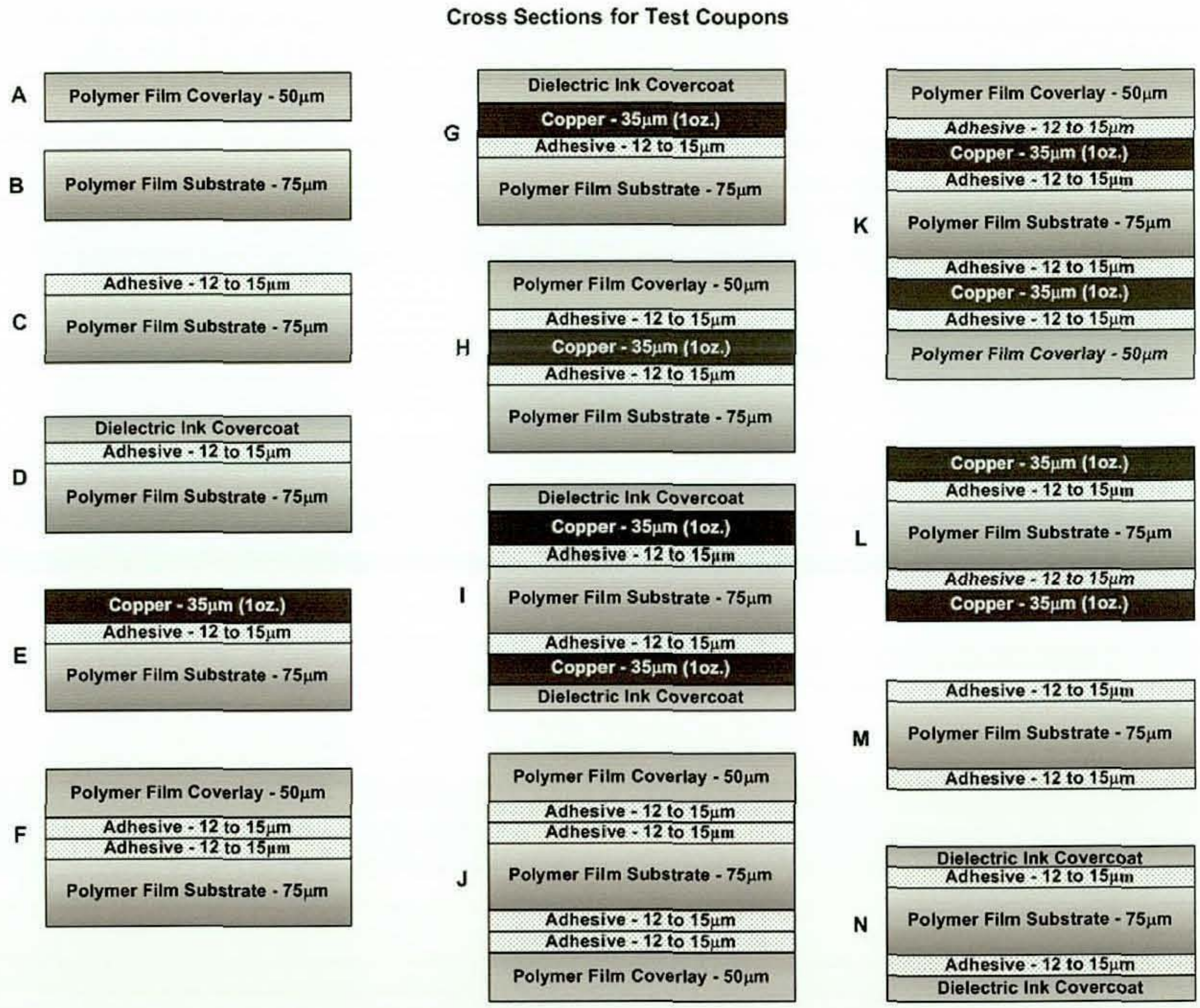

Figure 6.2 FPC Cross Sections for Test Coupons

The following is a description of the cross sections:

A. Coverlay film only - as supplied (typically 50 micron in thickness)

B. Base film only, without adhesive - as supplied (typically 75 micron in thickness)

C. Copper-clad base substrate with copper completely etched away[75]

D. Copper-clad base substrate with copper completely etched away, and having a printed dielectric ink covercoat

E. Copper-clad base substrate as supplied or etched per test method requirements

F. Single-sided FPC laminate comprising a copper-clad base substrate with copper completely etched away, and having a film coverlay laminated with an adhesive

G. Single-sided FPC laminate comprising a copper-clad base substrate as supplied or etched per test method requirements, and having a printed dielectric ink covercoat

H. Single-sided FPC laminate comprising a copper-clad base substrate as supplied or etched per test method requirements, and having a film coverlay laminated with an adhesive

I. Double-sided version of cross section G

J. Double-sided version of cross section F

K. Double-sided version of cross section H

L. Double-sided version of cross section E

M. Double-sided version of cross section C

N. Double-sided version of cross section D

6.5 FPC Properties and Test Methods

The following FPC properties and test methods are recommended for inclusion in the draft specification:

<u>Tensile Strength and Elongation - IPC 2.4.19</u>

Test coupons would have the same dimensions as defined in the IPC 2.4.19 test method. This test is applicable to cross sections A, B, C, D, F, J, M and N of Figure 6.2.

[75] The adhesive layer is not removed by the etching process

Peel Strength (Foil Bond Strength and Coverlay Adhesion) - IPC 2.4.9

Peel strength tests are applicable to copper-clad test coupons manufactured according to the requirements of the IPC 2.4.9 test method [Type B specimens and Test Method B]. For coverlay adhesion, peel strength test may be performed on laminates consisting of a copper-clad base dielectric film and adhesive coated coverlay film, or an adhesive coated base dielectric film and adhesive coated coverlay film [See cross sections E, F, H, J K and L of Figure 6.2 which are applicable to this test].

Initiation Tear Strength - IPC 2.4.16 - Optional

Initiation tear strength test may be performed on materials likely to be exposed to the tearing risk, where tensile strength tests are inconclusive. This test is applicable to base dielectric film, coverlay film, and laminates comprising of an adhesive coated base dielectric film and an adhesive coated coverlay or printed ink covercoat [See cross sections A, B, C, D, F, J, M and N of Figure 6.2].

Propagation Tear Strength - IPC 2.4.17.1 - Optional

Propagation tear strength tests may be performed on materials where peel strength tests are inconclusive. This test is applicable to laminates comprising of an adhesive coated base dielectric film and an adhesive coated coverlay or printed ink covercoat [See cross sections C, D, F, J, M and N of Figure 6.2].

Flexural Testing - IPC 2.4.3.1 - Optional

This test may be used for the comparison of candidate adhesives required for flexing applications, and is applicable to single and double-sided copper-clad base substrates with and without a film coverlay or printed ink covercoat [See cross sections E, G, H, I, K and L of Figure 6.2]

Folding - IPC 2.4.5 – Optional

For areas of the FPC designed to accommodate folding of the circuit over itself, this folding test would determine the resistance of the FPC, and particularly the metallic conductor to crack formation [which may lead to an increase in resistance or electrical discontinuity] after exposure to 180 degree bending. This optional test may be performed at less frequent intervals[76] during the accelerated ageing period on single and double-sided copper-clad base substrates with and without a film coverlay or printed ink covercoat [See cross sections E, G, H, I, K and L of Figure 6.2]. After folding, visual inspection or electrical resistance tests would be performed on the test coupons.

Low Temperature Flexibility - IPC 2.6.18a - Optional

Areas of a FPC simultaneously exposed to extreme cold and bending [for example at grommets in a vehicle door which is being opened in winter conditions], may be susceptible to crack formation during bending. For verification purposes, this optional qualitative test may be performed at less frequent intervals during the accelerated ageing period on single and double-sided copper-clad base substrates with and without a film coverlay or printed ink covercoat [See cross sections E, G, H, I, K and L of Figure 6.2].

Abrasion/Scratch resistance - IPC 2.4.27.1 - Optional

Areas of the FPC in contact with metal or rough plastic surfaces may be susceptible to abrasive wear. Speculatively, abrasion of the base dielectric film, coverlay film or dielectric ink covercoat may be induced by vibration, occurring when the vehicle is in motion, and may eventually lead to the conductive traces being exposed, creating a risk of short-circuit faults. After test coupons have been abraded, visual inspection and dielectric breakdown strength tests would be performed. Base dielectric films, coverlay films and laminates constructed of a base dielectric film and dielectric ink covercoat would be tested [See cross sections A, B and D of Figure 6.2] at less frequent intervals during the accelerated ageing period. An alternative test method is prescribed in GME4221 [General Motors, 2004; section 4.2.7, which is based on section 9.3 of the ISO6722 standard]

[76] Compared to tests conducted 'periodically'.

Dimensional stability - IPC 2.2.4 - Optional

Dielectric films used in the construction of FPCs are known to shrink during the chemical etching process [Harper, 2000, p 5.3]. The application of this test would determine the extent of, if occurring, accelerated ageing induced dimensional change. Tests would be performed on base dielectric films and coverlay films [See cross sections A, B, C and M of Figure 6.2], at less frequent intervals during the accelerated ageing period [Disregarding Test Method A, B and C of IPC 2.2.4].

Insulation and Moisture Resistance, Flexible Base Dielectric - IPC 2.6.3.2b

This test may be performed periodically during the accelerated ageing period on copper-clad dielectric films with or without a coverlay or covercoat [See cross section E, G, H, I, K, L of Figure 6.2]

Dielectric Breakdown Strength - ASTM D149-97a [ASTM, 2004a]

This test may be performed periodically throughout the accelerated ageing period, and is applicable to base dielectric films, coverlay films, and laminates comprising of an adhesive coated base dielectric film and an adhesive coated coverlay or printed ink covercoat [See cross sections A, B, C, D, F, J, M and N of Figure 6.2].

Volume Resistivity & Surface Resistance - IPC 2.5.17 - Optional

This optional test may be performed periodically during the accelerated ageing period on single and double-sided copper-clad dielectric films without a coverlay or covercoat [See cross section E and L of Figure 6.2]

Flammability of Interior Materials – If Required by Legislation:

All FPC substrates and laminates tested in this research supported combustion. Alternative test methods include IPC 2.3.8.1 (Flammability of Flexible Printed Wiring) and IPC 2.3.29 (Flammability, Flexible Flat Cable). IPC 2.3.8.1 is a simple evaluative test to determine whether materials support combustion, whereas IPC 2.3.29 evaluates burn rates at 45° degree angles. IPC 2.3.29 is therefore preferred and may be used for comparative purposes.

Another flammability test, prescribed in UL796F [Underwriters Laboratory, 2000], is UL 94 [Underwriters Laboratory, 1996]. This standard details both vertical and horizontal burn tests, used to classify materials according to burn rate.

6.6 Environmental Ageing Conditions

Exposing test coupons to elevated environmental stress should be performed as follows:

High Temperature and High Humidity Exposure (Damp Heat ageing)

Damp heat ageing induces the hydrolytic degradation of FPC constituent materials. The time required for exposing test coupons at any given temperature and humidity should be equal to the minimum time required for simulating 12 years ageing of Mylar A film in a vehicle.

Temperature Cycling

From the experiment results, it was observed that temperature cycling under uncontrolled humidity did not lead to discernable degradation of the FPC properties under test. Temperature cycling under high humidity may provide more realistic multi-stress accelerated aging conditions. This approach could be applied as an alternative to Damp Heat ageing, with the accelerated ageing exposure time estimated from the positive temperature cycles. Where control of humidity is not possible, temperature cycling should be limited to its traditional areas of investigation, such as soldered joint and plated through-hole vias.

Exposure to chemicals

Within the passenger cabin, cleaners (interior and glass), and beverages containing caffeine and sugar may be found. In addition to these chemical substances, within the interior of the door, windscreen washing liquid, salt water, lubricants and grease may also be found. Test coupons could be immersed in glass cleaner, coffee, a carbonated cola beverage, windscreen washing liquid and salt water for up to 96 hours. Tests for tensile strength, peel strength, insulation resistance and dielectric breakdown strength would then be performed at 24, 48 and 96 hours.

Other Environmental Stress Conditions

Other stress conditions include vibration, temperature shock and electrical overstress. By themselves, these stresses are unlikely to induce material degradation in simple single and double-sided FPCs. They may however be considered for multi-stress accelerated ageing, where applicable.

6.7 Draft Specification Test Matrix

The proposed test matrix for the draft FPC specification is detailed in Table 6.1. There is no requirement for tests to be performed on all applicable cross-sections, and experiments can be reduced using statistical methods. Folding and Low Temperature Flexibility tests are optional, but are suggested for specialized vehicles deployed in extremely cold geographic regions. Additionally, dimensional stability tests are optional; as it is unlikely the low-shrink materials typically supplied for FPC manufacture would shrink to such an extent that induces failure. Dimensional stability may be more relevant to the FPC manufacturing process. Volume and surface resistivity is an alternative to the insulation and moisture resistance test, and is therefore optional.

Exposure to chemicals should be performed as proposed. However, the soak time requires correlation to service life. The chemical exposure tests may indicate susceptibilities of a material to degrade upon contact with selected fluids, but this may not provide sufficient justification for material acceptability or rejection. A similar argument is made for abrasion testing. The question of 'how much is enough?' in respect of test level and duration applies.

TEST	PROPERTIES	TEST METHOD	Applicable Cross Section	Damp Heat	Chemical
1	Tensile Strength	IPC 2.4.19	A, B, C, D, F, J, M, N	✓	✓
2	Peel Strength	IPC 2.4.9	E, F, H, J,K, L	✓	✓
3	Initiation Tear Strength	IPC 2.4.16	A, B, C, D, F, J, M, N	**Optional**	-
4	Propagation Tear Strength	IPC 2.4.17.1	C, D, F, J, M, N	**Optional**	-
5	Flexural Testing	IPC 2.4.3.1	E, G, H, I, K, L	**Optional**	-
6	Folding	IPC 2.4.5	E, G, H, I, K, L	**Optional**	-
7	Low Temperature Flexibility	IPC 2.6.18a	E, G, H, I, K, L	**Optional**	-
8	Abrasion/Scratch Resistance	IPC 2.4.27.1	A, B, D	**Optional**	-
9	Dimensional Stability	IPC 2.2.4	A, B, C, M	**Optional**	-
10	Insulation and Moisture Resistance	IPC 2.6.3.2b	E, G, H, I, K, L	✓	✓
11	Dielectric Breakdown Strength	ASTM D149-97a	A, B, C, D, F, J, M, N	✓	✓
12	Volume & Surface Resistivity	IPC 2.5.17	E, L	**Optional**	-
14	Flammability	IPC 2.3.29	**ALL**	✓	-

COLOUR LEGEND

(yellow)	Test at 0 hours, then at such frequent intervals depending on accelerated ageing conditions
(orange)	Test 0 hours if required – no accelerated ageing to be performed
(green)	Test at 0 hours, at middle and end of accelerated ageing time
(blue)	Exposure to Chemicals – Test at 0, 24, 48 and 96 hours

Table 6.1 Draft Specification Test Matrix for Selection of Candidate Materials

TEST	PROPERTIES	TEST METHOD	RECOMMENDED VALUES
1	Tensile Strength and Elongation	IPC 2.4.19	117 MPa [SAE J-771]
			138 MPa [IPC]
2	Peel Strength	IPC 2.4.9	Minimum of 71.5 g/mm (107.3 g/mm average) n/a to Temperature cycling [SAE J-771]
			89.4 g/mm (71.5 g/mm after temperature cycling) [IPC]
3	Initiation Tear Strength	IPC 2.4.16	Min 226 N.m [SAE J-771]
			800 g [IPC]
4	Propagation Tear Strength	IPC 2.4.17.1	20 g (material thickness <100 microns) and 50 g (material thickness >100 microns) [IPC]
5	Flexural Testing	IPC 2.4.3.1	TBA with end user
6	Folding	IPC 2.4.5	Minimum of 2mm bulge, without conductor cracking [Ford Motor Company]
7	Low Temperature Flexibility	IPC 2.6.18a	No conductor cracking
8	Abrasion/Scratch resistance	IPC 2.4.27.1	Minimum equivalent to 300 mm sand paper [SAE J-1128]
9	Dimensional stability	IPC 2.2.4	0.5% TD ; 1.0% MD [Ford Motor Company]
			0.4% (class II) / 0.5% (class III) [IPC]
10	Insulation Resistance within layers	IPC 2.6.3.2b	Pass Dielectric Strength Test
11	Dielectric Strength	ASTM D149-97a	500 V/mil (19.7kV/mm) [SAE J-771]
			2,500 V/mil (class III) [IPC]
12	Volume Resistivity & Surface Resistivity	IPC 2.5.17	Volume Resistivity: 10^6 megohm-cm [IPC]
			Surface Resistivity: 10^3 to 10^5 megohm [IPC]
13	Fluid Resistance	IPC 2.3.2f	Pass Dielectric Strength Test
14	Flame Resistance	IPC 2.3.29	Not specified
		UL 94	Rated according to burn time / burn distance

Table 6.2 Recommended Acceptance Criteria in Published FPC Specifications

6.8 Acceptance Criteria

A large area FPC would be considered to have failed when it can no longer carry the intended electrical signal, or do so safely. Hence a short circuit due to degradation in physical properties such as dielectric breakdown and insulation resistance, or an open circuit created by increased resistance in copper due to environmental exposure, are potential failure modes. Open and short circuits may also be the result of cracks in the copper traces, or other mechanical failures such as tearing and de-lamination. Electrical and mechanical failures may occur after FPC exposure to corrosive chemicals commonly found around the automotive environment, such as grease, lubricant, and occupant introduced fluids such as coffee and carbonated beverages. Table 6.2 lists acceptance criteria for copper-clad laminates[77], extracted from the specifications published by the SAE, IPC, automotive OEMs and legislation for comparative purposes only. The retention of a minimum of 70% of original property value after accelerated ageing could be used as a selection criterion for materials; provided such ageing simulates at least 12 years in-service life in a vehicle.

[77] Acceptance criteria for modified tests have been adopted from the published specifications.

7 DESIGN AND MANUFACTURE OF PROTOTYPES

7.1 Introduction

Before a FPC is manufactured its outline shape, components and special features must be drawn, circuit traces routed and all artwork for the production process created. Whereas this practice has long been established in the commercial production of small rigid and flexible printed circuits, the design and trace routing of large area FPCs for automotive applications is novel. To explore the secondary theme in this research, i.e. circuit design, a commercial EDA suite was used to design two prototype large area FPCs based on different manufacturing strategies, intended as substitutes for an in-production IP wire harness. The prototype design was based on automotive OEM wire harness schematic drawings and wire harness electrical load test characteristics. The unavailability of standardized automotive FPC connectors and side-to-side[78] interconnects necessitated an assumption of shape, current and connectivity characteristics of conceptual connectors[79] and side-to-side interconnects.

Design problems that have been identified in the literature and those evident in the design process have not been fully resolved, for example, although trace width and space have been selected according to the results of complementary research, the thermal management and current-carrying capacity (ampacity) of circuit traces have not been experimentally verified for the prototypes. Automatic trace routing exhibited a high degree of sensitivity to minor changes in the FPC outline shape, orientation and placement of components, resulting in some circuits being unroutable. The automated design of large area FPCs intended for deployment in a three dimensional space was further limited by the inherent bias of the EDA suite, in particular the auto-routing tool, towards designing two dimensional circuits. The evaluation of the manufactured prototypes supports the limited application of large area FPCs to simple circuit layouts or entirely new vehicle designs. This chapter presents the design of

[78] A side-to-side interconnect is used to describe a physical object that provides electrical connectivity between the layers of the FPC, for example a plated through-hole via or crimp.

[79] A connector in this thesis is a combination of metal pins and its associated housing. In other publications, a connector may refer to a metal pin alone.

the large area FPC prototypes, the processes and strategies employed and an analysis of the results.

7.2 Prototype Large Area FPC Design and Manufacture Objectives

One objective of designing and manufacturing the prototypes in this research was to implement variant models of a large area FPC intended as a perfect or near[80] substitute for a large and complex IP harness belonging to a modern full-feature Class C passenger car, namely a Daewoo Nubira. This would allow possible design routes and manufacturing strategies to be explored and demonstrate weight and space savings, and the potential for integrating intelligent components into the FPC substitute. A second objective was that a commercial EDA suite, namely Mentor Graphics 'BoardStation' (version 8.0) would be used for circuit design. It is proposed that employing such software applications would be preferred for designing future automotive large area FPCs.

7.2.1 Design Philosophy and Concepts

Total cost minimization was the most important requirement in designing the prototypes. However there are tradeoffs to be made between cost, manufacturability, assembly, and reliability, and these are dependant on the automotive OEM priorities. A number of FPC design variables which impact on the total cost of a solution are shown in Figure 7.1. To achieve a minimized cost, the following design options and manufacturing strategies have been proposed[81], as illustrated in Figure 7.3.

[80] A perfect substitute would implement all the circuits within the original wire harness, maintaining the point-to point connections and connector pin assignments, and would be assembled without changes to the vehicle design. A near substitute would require minor changes to the vehicle design, or would not implement the circuits within the wiring harness, or both.

[81] The design options described are not exhaustive, and there may be difficulties in implementation as discussed in Section 7.3.4.

Single Large Area FPC

This is a large area FPC that could be single or double-sided, having side-to-side interconnections, traces of different widths and surface mount devices attached. This option requires the lowest number of connectors and attachments, and therefore offers the highest reliability. However, material usage could be high as effective panelization may be difficult to achieve. Additionally, the outline may be of such a dimension as requiring bespoke manufacturing equipment, increasing the total cost.

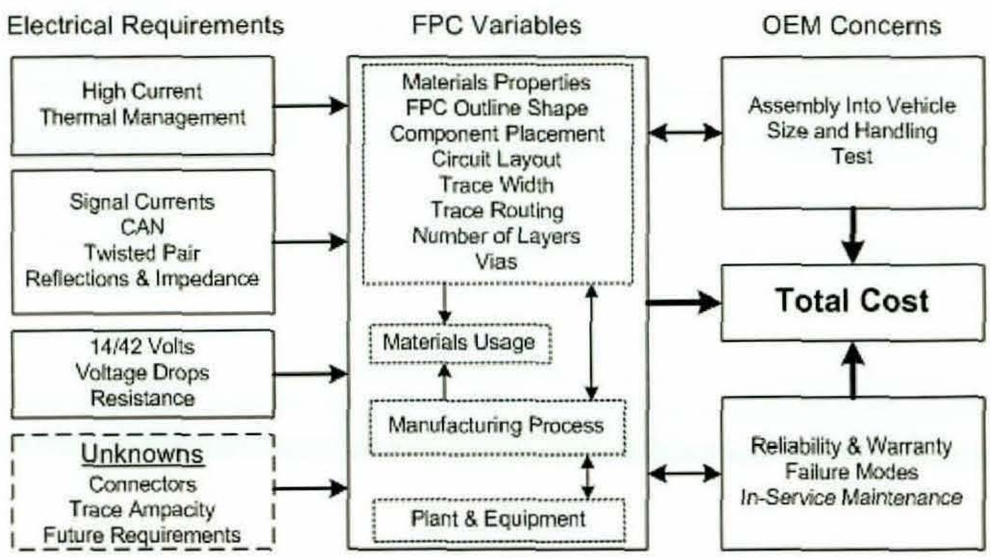

Figure 7.1 FPC Design Considerations

Large Area FPC with Detachable Arms

This option is in all respects similar to the single large area FPC, with the exception of having detachable 'arms'. A more efficient use of materials would be achieved in panelization. However, this option creates twice the number of electrical connection points and requires additional mechanisms to secure the attached arms, making this a more unreliable solution.

Patch Circuit

A 'patch' circuit is a small single/double-sided or multilayer FPC, or rigid/flex-rigid printed circuit board having plated through-holes/side-to-side interconnects and attached electronic devices. The patch may be attached to a large area FPC using a joining process such as soldering or lap welding. Patch circuits allow for ease of manufacture by removing electronic device assembly from the large area FPC. An example of a patch circuit is Sheldahl's Density Patch [Sheldahl, 2007], shown in Figure 7.2.

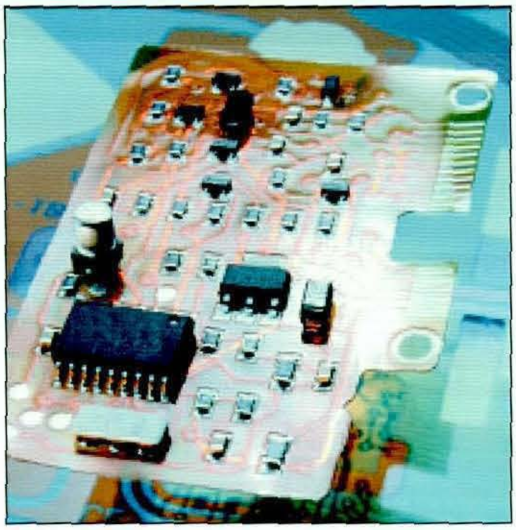

Figure 7.2 Sheldahl's Density Patch [Sheldahl, 2007]

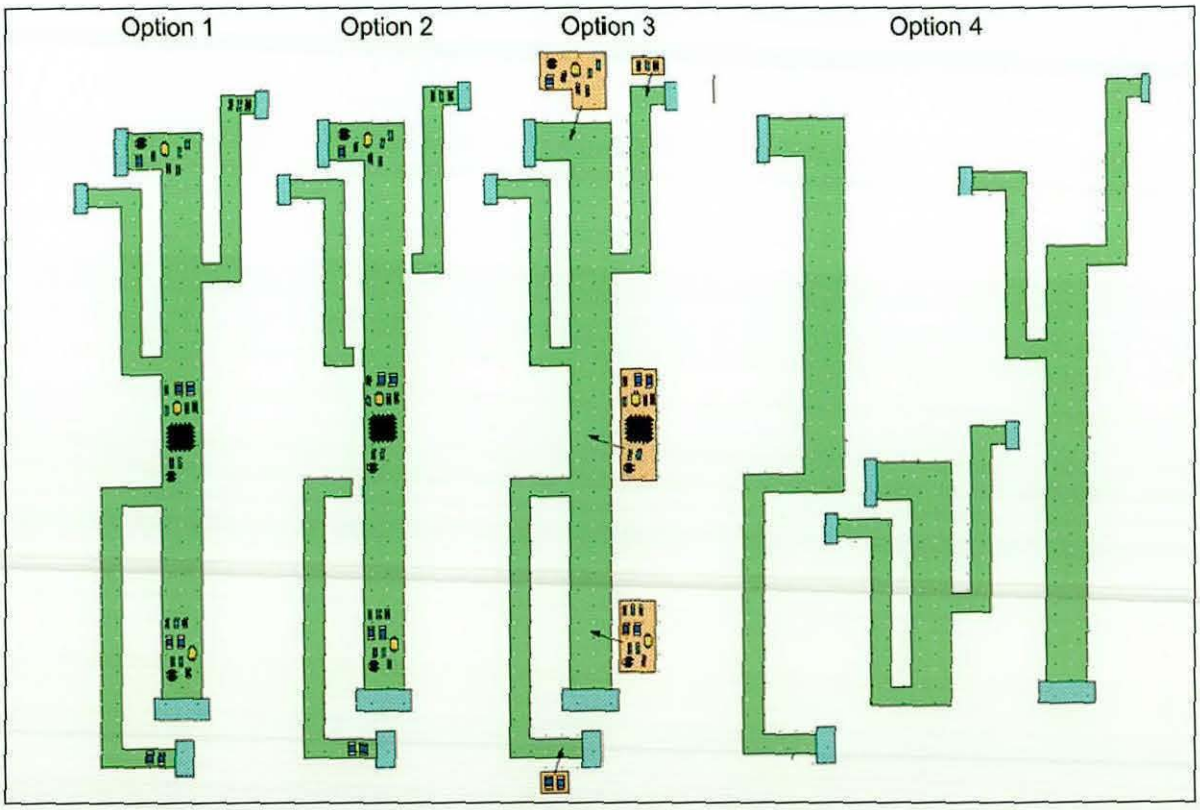

Figure 7.3 FPC Design Options

Multilayer Circuit

This option uses multiple layers of smaller single or double-sided FPCs. Continuation of traces over different layers would be implemented at connectors and other layer attachment points such as crimps, where used to secure the different layers. Decreased reliability would be due to additional connection and attachment points, and handling of several small circuits could present additional problems. However, the multilayer option may be the most inexpensive to manufacture, as smaller individual FPCs could be produced with conventional processes.

7.2.2 Selected Design Options

The first prototype would be designed as a large single FPC, and the second as a multilayer FPC as a cost analysis by Conway et al [2003] suggested these formats would have the lowest manufacturing cost for high volume production. Both prototypes were to be manufactured using copper-clad PET laminates of 1oz thickness, and had to be designed for minimum overall size and side-to-side interconnections. A detachable 'patch' FPC that performed a simple electronic function, demonstrating the potential intelligence capability of FPCs over round wire was to be integrated into both prototypes. Additionally, the prototypes had to be assembled into the vehicle cockpit to demonstrate readiness for use on a vehicle assembly line.

7.2.3 Daewoo J-100 Platform

The platform around which the prototypes were designed was the J-100 IP harness, belonging to the Daewoo Nubira. A model 96237581kk IP harness - a left-hand drive, North American variant of the J-100 shown in Figure 7.4, together with the harness schematic, assembly drawings and electrical test report were supplied by Daewoo Motors for the prototype design research. Analysis of the J-100 schematic drawings provided interconnectivity and layout data, and the electrical test report provided circuit currents. Point-to-point (P2P) connectivity was extracted from the tables within schematic drawings listing wire numbers, wire specification inclusive of cross-sectional area, and a circuit address identifying the start and end points by connector or splice name for all 88 variants of the J-100. There were 208 wires, 39 connectors, 6 splices, 6 splice packs, 3 ring terminals and 1 coaxial cable listed for the 96237581kk[82].

Figure 7.4 Daewoo 96237581kk IP Harness.

The listed wire cross sectional area provides a weak indication of circuit current, due in part to the step changes in wire gauge diameter and the use of a de-rating factor for bundled wires. Preference has been given to actual currents measured in each wire under load so as to determine precise trace widths. The load currents have been extracted from the J-100 electrical report[83].

The J-100 layout schematic detailed the individual wire lengths between connectors and the relative positions of connectors in respect of each other on a two-dimensional plane. The layout schematic also detailed the absolute position of I/O pins within each connector. There was a close match between the flat physical layout of the harness and the two-dimensional

[82] Inspection of the supplied harness revealed some inconsistencies in the form of incorrect or missing connectors were observed when compared to the drawings. This may have been the result of revision changes to the harness, or a different variant J-100 supplied. It was decided to use the OEM drawings only.

[83] Referred to by Daewoo as a 'Power and Signal Distribution System (PASDS) analysis'.

schematic, that is to say the harness could be arranged on a flat surface to reflect the shape drawn in the schematic. A Daewoo Nubira cockpit was reconstructed as shown in Figure 7.5, to verify measurements of length, physical routing and connector locations within the three dimensional space.

Figure 7.5 Nubira Cockpit Showing Assembled IP Harness.

7.3 Large Area FPC Design in Mentor Graphics

Mentor Graphic Board Station (version 8) employs a modular approach to design, and the modules listed below were used for the following design functions:

- ***Design Architect*** - Schematic capture.
- ***Librarian*** - Drawing of outline shapes for the prototype physical layers, part footprints, and definitions of parts electrical characteristics created.
- ***Package*** - Allocation of I/O pins to absolute positions within connectors.
- ***Layout*** - Connector placement and trace routing.
- ***Fablink*** – Output the production artwork for the prototypes.

Figure 7.6 illustrates the use of the Board Station modules for designing the prototypes, and the issues and considerations that were evident in the design process.

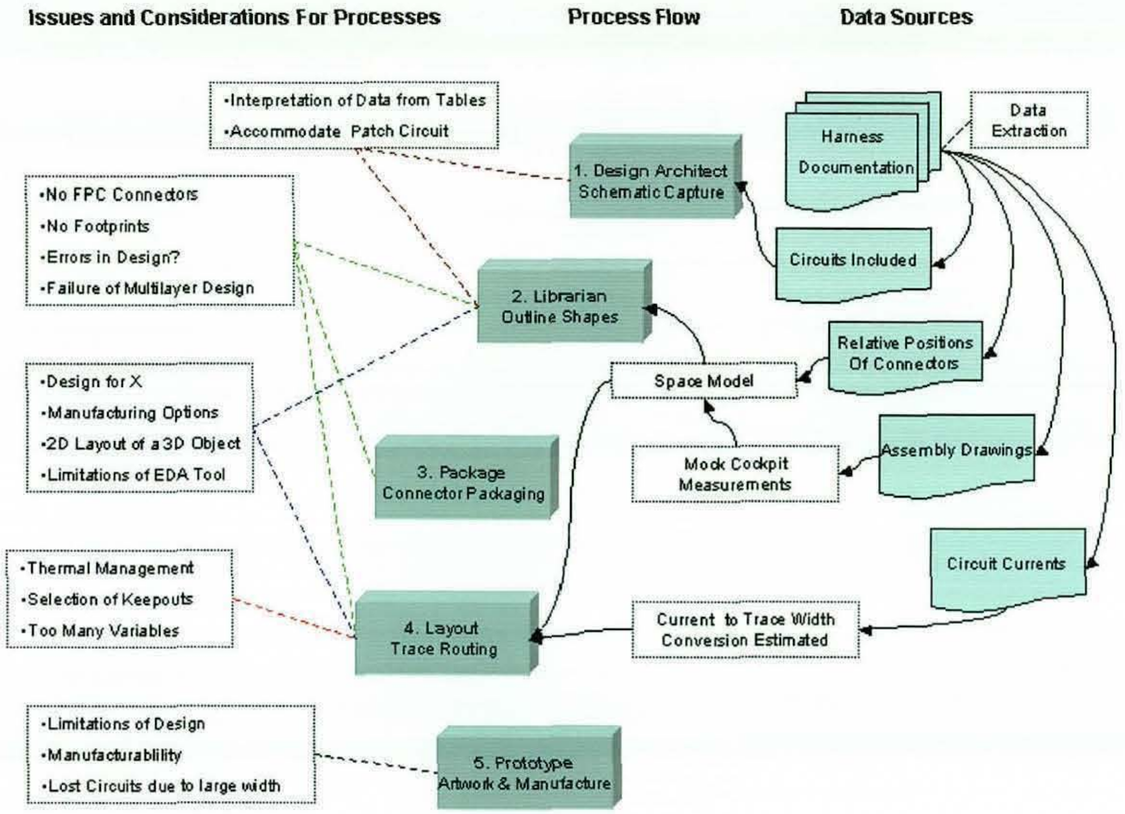

Figure 7.6 FPC Prototype Design Process Using Mentor Graphics Board Station

7.3.1 Schematic Capture

Simulating the wire harness required the selection of appropriate components in the Board Station parts library. A *connector* symbol within Design Architect simulated a single physical I/O pin. Multiple connector symbols having the same assigned reference name were used to simulate the physical connector of that name. For analog or digital circuit simulation, these connector symbols could be unidirectional (input or output only) or bi-directional. The latter was selected to overcome design rule constraints applicable to unidirectional connectors. Conductive paths were drawn between named bi-directional connector symbol pairs as listed in the harness drawing, simulating the physical wire connections within the harness. The conductive paths called *nets* were assigned the same wire number for the point-to-point connection implemented to assist in identification. User-created net types called *High*, *Medium*, and *Low* were assigned to nets, depending on the load current carried by the wire. *Low* nets were assigned for circuits carrying up to 1 Amp, *Medium* nets were assigned to circuits carrying up to 2.5 Amps and *High* nets were assigned to circuits carrying more than 2.5 Amps. Net types were assigned trace widths in *Layout*.

Although connector-to-connector circuits (as distinct to point-to-point connections) could be captured as above, splices and splice-packs were implemented indirectly. Splices are electrical nodes where two or more wires are joined, usually for the purpose of distributing power or connecting to ground. Splice-packs are connectors, shunted between distinct groups of pins to create multiple splices. Splices not accommodated within splice-packs were connected to power or ground via wires to *Fusebox* connector pins added to the schematic diagram[84]. The FPC prototypes would therefore not be perfect substitutes for the wire harness.

Three wires were terminated with rings, used for making secure ground connections to the vehicle chassis. These were treated as a splices and simulated using connectors, this being the mechanism for terminating FPCs. The single coaxial cable in the wire harness and its associated connectors were not included in the design because of potential trace routing problems later in the design process.

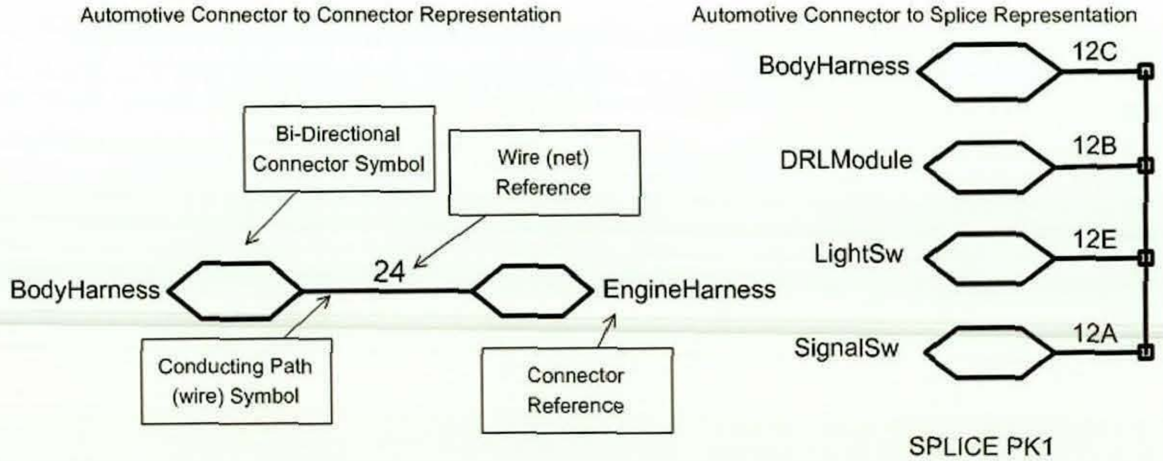

Figure 7.7 Section of Harness Schematic in Design Architect.

[84] This may have introduced errors into the design.

The patch FPC required for the prototypes would be used to implement a dimmer control for a courtesy lamp. This was treated as a physical connector. This required additional I/O pins to be allocated on the *Body*, *Engine* and *Fusebox* connectors for wiring power, ground and control signals to the patch[85]. Figure 7.7 illustrates a section of schematic diagram for the IP harness drawn in Design Architect.

7.3.2 Prototype Parts Definitions

Creating the parts list for the prototypes in Librarian was performed concurrently with schematic capture. The following parts were defined:

1. Board Outline
2. Connectors and Patch
3. Through-hole Vias
4. Crimps

7.3.2.1 Board Outline

The need to make changes to simulated boundaries, in addition to component placement and orientation was facilitated by the use of a rectangular outline. The dimension of 1000mm x 750mm was selected for the first prototype to reflect the operating limits of available FPC manufacturing equipment. Movable area and trace keep-outs were used to define the boundaries within the rectangular board outline where copper traces were allowed, therefore simulating a physical FPC outline. For the second prototype, a rectangular board outline of 2000mm x 1400mm was used to demonstrate the allocation of traces to different layers in a multilayer arrangement.

[85] This may have also introduced errors into the design.

7.3.2.2 Connectors and Side-to-Side Interconnects

The commercial unavailability of medium and high-current FPC connectors provided an opportunity to design conceptual model connectors for the prototypes. The model connectors were designed as single in-line packages, and the footprints used are illustrated in Figure 7.8.

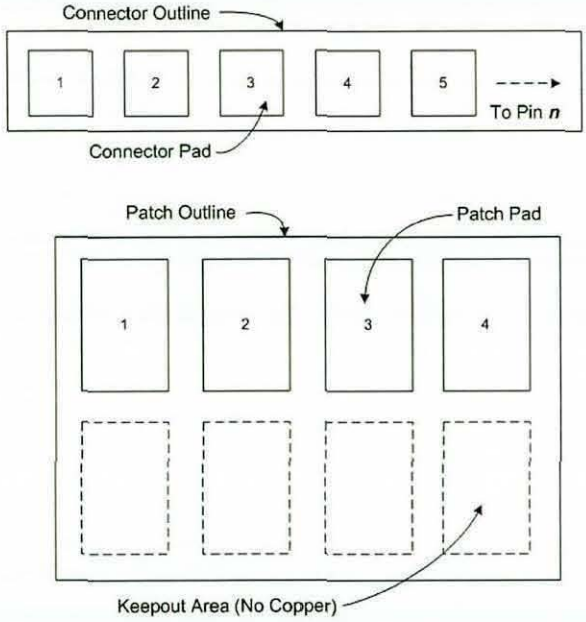

Figure 7.8 Conceptual FPC and Patch Connector Footprints

Table 7.1 lists the connectors created and their attributes. Connector pads were assigned attributes to simulate side-to-side (through-hole) interconnectivity (for application in double-sided and multilayer FPCs). The connector pad dimensions were selected to accommodate the trace widths assigned to *Low*, *Medium* and *High* nets, but the pitch and space were based on existing FPC connectors[86]. Three current ranges were considered so as to minimize overall use of space on the FPC, with the example of a 50-way low-current connector requiring less surface area than a 10-way high-current connector carrying the same load current.

[86] This approach ignores the thermal effects of closely spaced conductors.

For the prototypes, crimps were preferred for implementing side-to-side interconnections as these were in use on Pressac's production line. Crimps were simulated with two pads having the same dimension and spacing of pads used in the Patch connector.

Current Rating	Pad Dimensions (mm)	Pitch [Space] (mm)	No. of I/Os
Low (<= 1A)	1.25 x 2.5	2.5 [1.25]	5, 10, 15, 20, 30, 40, 50
Medium (<= 2.5A)	2.5 x 5.0	5.0 [2.5]	5, 10, 15, 25
High (> 2.5A)	5.0 x 5.0	7.5 [2.5]	2, 5, 10
Patch	6.0 x 5.0	8.0 [3.0]	4

Table 7.1 FPC Concept Connectors

7.3.3 Connector Pin Allocation

The assignment of bi-directional connector symbols to distinct locations within individual physical connectors was performed in the Package module. Table 7.2 shows that most connectors on the 96237581kk handled multiple ranges of circuit current. A number of model connectors for different current ranges were required to implement a single automotive connector in these instances. Unused I/O pins or spares within individual connectors allowed for pin swapping[87].

Pin swapping was complimented with connector swapping. This is where pins were swapped between two or more connectors having the same reference name. Where a small number of circuits were allocated to a single connector, they could be later reassigned to a larger adjacent connector containing spare I/O pins. Connector swapping may be used to further minimize the number of connectors required for the prototypes.

[87] Pin swapping is used to facilitate trace routing by reassigning I/O pins to different positions within the connector. Connectors allow for unrestricted pin swapping as each I/O pin is a stand-alone input/output terminal without any relationship between adjacent pins. Where pin swapping was performed, there would also be a requirement to reassign pins on the external connectors, and this invalidates the FPC harness as a direct replacement for the existing wire harness.

CONNECTOR	Normal (1Amp) /1mm	Low (2~5 Amps) /5mm	Medium (6~10 Amps) /10mm	High (> 10 Amps) /20mm	Total Pins
ABS	7	2	2		11
Anti-theft ECU	9	3	3		15
Ashtray Lamp	2				2
Audio	5	4	5		14
Blinker Relay		2			2
Blower Motor				2	2
Blower Motor Relay	3			1	4
Blower Resistor	3	1			4
Body Harness	29	9	13	9	60
Brake Sw		1			1
Chime Bell	6	1	1		8
Cigar Lighter			2		2
Clock Spring	1				1
Clutch Sw		1	1		2
Cruise Cont Sw	1				1
Dimmer & HDLP Sw	1				1
Dimmer Sw	1				1
DRL Module	3	2	1		6
Earth Ring Term		3	3	1	7
Engine Harness	17	5	1		23
Flasher Unit		1			1
Fuse Box	5	8	3	2	18
Glove Box Lamp	2				2
Glove Box Light Sw	1				1
Glove Box Sw	1				1
Hazard Sw	2	3	1	2	8
HDLP LVL	1				1
HVAC Sw	11				11
Ignition Sw		1	1	4	6
Int Wiper Relay	3	1	1	1	6
Int Wiper Sw	1	1			2
Key Remind Sw	2				2
Light Sw	3				3
Meter Set 1	15	1			16
Meter Set 2	12	1	1		14
ODB/DIAG	5	2			7
Signal Sw	5	3	1		9
SIR Harness	3	1	1		5
Wiper Sw	2	1	1	4	8

Table 7.2 Current Ranges for Individual Connectors

7.3.4 Circuit Layout

Circuit layout is concerned with the placement of components and the routing of circuit traces within the board outline, both of which may be performed manually, automatically or semi-automatically. Placement of components was performed manually, and trace routing performed automatically using the Specctra auto-router; a shape-based router noted by Grigoriev and Panchak [2006] as "the most perfect router for printed circuit boards and is widely used for development of complex devices". For this stage of the design process, the following guidelines and strategies have been adopted:

7.3.4.1 Design for Panelization

The ability of FPCs to bend and be folded allows for efficient panelization. Figure 7.9 illustrates the principle. Folding may also be used to minimize the number of crossover traces implemented with side-to-side interconnections and potentially remove the need for additional copper layers, as illustrated by Figure 7.10.

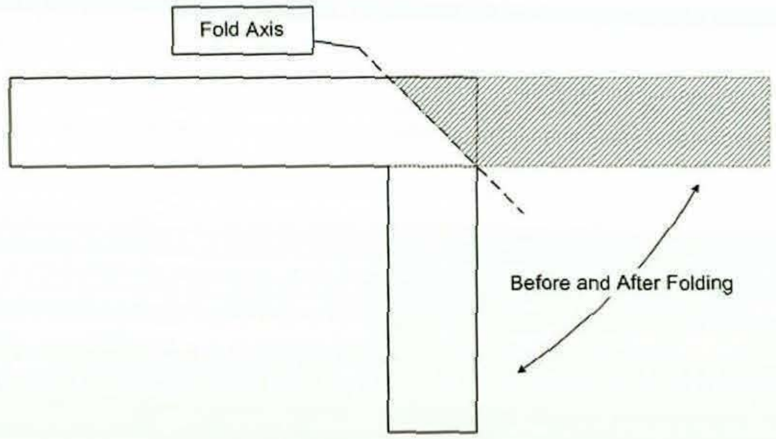

Figure 7.9 Folding Principle

Although folding is a recognized practice, the number of different folding arrangements for a large area FPC having multiple arms of different lengths and widths means there could be an infinite number of potential outline shapes. However there is a natural limitation on the number of possible outline shapes, as minor changes in position of FPC arms may cause some traces to become unroutable. One disadvantage of folding is the requirement of an additional mechanism to maintain the fold, for example clips. These add cost and weight and may require manual assembly onto the FPC. As would be demonstrated below, the single large prototype was panellized by incorporating folding to allow for manufacture with available processing equipment.

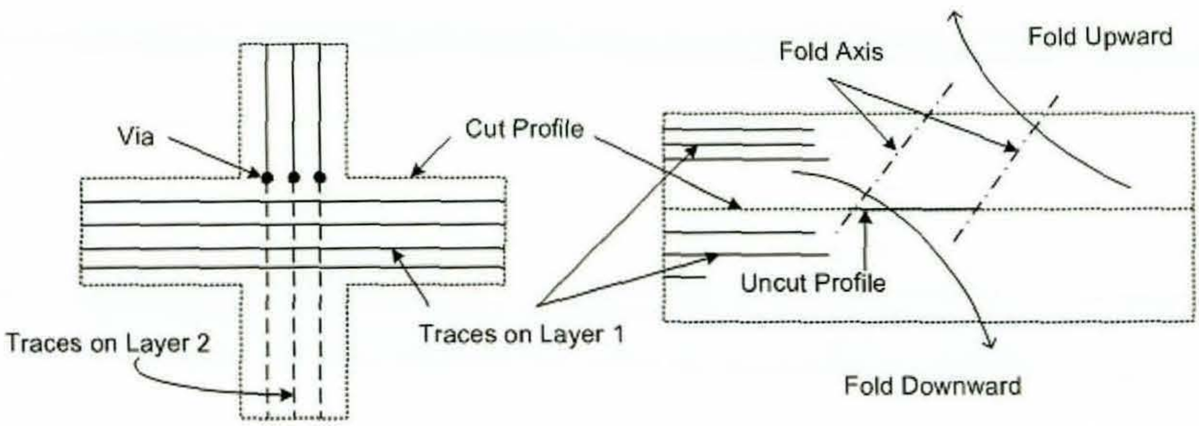

Figure 7.10 Folding For Removing Trace Crossovers and Vias

7.3.4.2 Twisted Pair Emulation

FPC twisted pair emulators have been described by Webb et al [2004] for automotive CAN applications, and illustrated in Figure 2.7. These have not been employed in the prototype design as they effectively act as a barrier to orthogonal traces requiring crossovers, thereby restricting trace routing. This may be remedied by locating the twisted pair emulator along the outline of the large single circuit, or by routing these traces initially, adding an outline profile around it before routing the other normal traces. For the multilayer circuit, twisted pair emulators may be routed on a separate double-sided FPC which could then be included as a separate layer.

7.3.4.3 FPC Trace Width and Thermal Management

FPC thermal management and the heating effect of circuit traces are of particular importance in the design process. Heat ageing at the DuPont recommended service temperature of 150°C has shown to reduce significantly the tensile properties of PET after 3000 hours [DuPont Teijin Films, 2007a]. Both prototypes would be designed for a maximum allowable temperature of 105°C. According to Sheehan and Rider [1999], this temperature is calculated by a 20% de-rating of the maximum recommended continuous use temperature for polyester of 130°C. The maximum ambient temperature within the passenger cabin of 85°C allows for an increase of 20°C on the FPC itself.

Thermal management is affected by multiple factors, including trace width, current flow, trace location on the FPC and in relation to other traces, location within the vehicle and surrounding materials. The use of heat sinks and forced convection cooling was not considered as these add reliability and cost burdens to the large area FPC solution and could be impractical to achieve in the passenger cabin, door and roof spaces. Another method of achieving thermal management is the use of a copper backplane; practically implemented with a double-sided laminate and unetched on one side. The additional materials cost could be offset by an overall reduction in FPC size, but such strategies require economic justification.

From the literature, printed circuit temperature rise is predominantly dependant on the width of copper traces. Using the nomograph for a rigid PCB in the IPC-2221 standard, a 20°C rise in temperature would result from the flow of 1 Amp in a 1oz. copper trace of 0.23mm width. For a flow of 5 Amps, the trace width is 2mm. The Minco Application guide [Minco, 2007] suggests the use of wider traces. For a 1oz. Copper trace carrying 1 Amp, the Minco Application guide recommends a width of 0.63mm.

7.3.4.3.1 *Yazaki FPC Ampacity Experiments*

Trace ampacity for flexible copper-clad materials have not previously been established in the literature. In complementary research, Yazaki (Europe Ltd.) conducted experiments to determine temperature rise in parallel FPC traces intending to establish a minimum width and pitch for FPC traces that would permit a desired load current without exceeding a specified temperature limit. The experimental data has been provided for analysis in this research and is reported here with permission from Yazaki.

For the experiments, test coupons were manufactured using a single-sided 1oz copper-clad PET base laminate, having 13 parallel traces of 1.2mm in width and pitch, and 500mm in length. The coupon was laminated using a PET coverlay film, having windows of approximate dimension 3mm x 5mm pierced to allow attachment of thermocouples at the mid length of the exposed copper traces. Two identical test coupons were then attached to each other using a double-sided adhesive tape as shown in Figure 7.11.

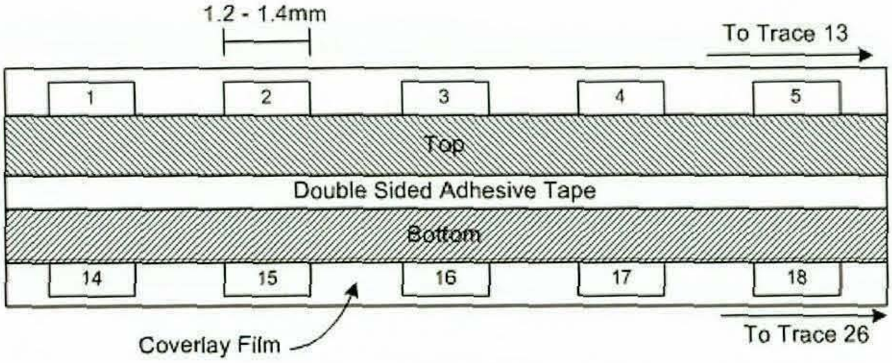

Figure 7.11 Yazaki Test FPC

Thermocouples were attached to odd-numbered traces on the topside and even-numbered traces on the underside layer, and the coupon was then suspended horizontally in air at room temperature. Experiments were also performed for similar test coupons having traces of 1.3mm and 1.4mm width and pitch. The experiments were repeated for test coupons manufactured using a 2oz copper-clad base laminate.

When a load current was applied to a single trace on a test coupon, the resulting temperature of the trace is shown in Figure 7.12. A greater ampacity was observed in the experimental results compared to the simulation results reported by Adam [2004] for polyimide FPCs having similar trace sizes. When a load current is simultaneously applied to all traces on test coupon, the resulting temperature of the traces is shown in Figure 7.13 and Figure 7.14.

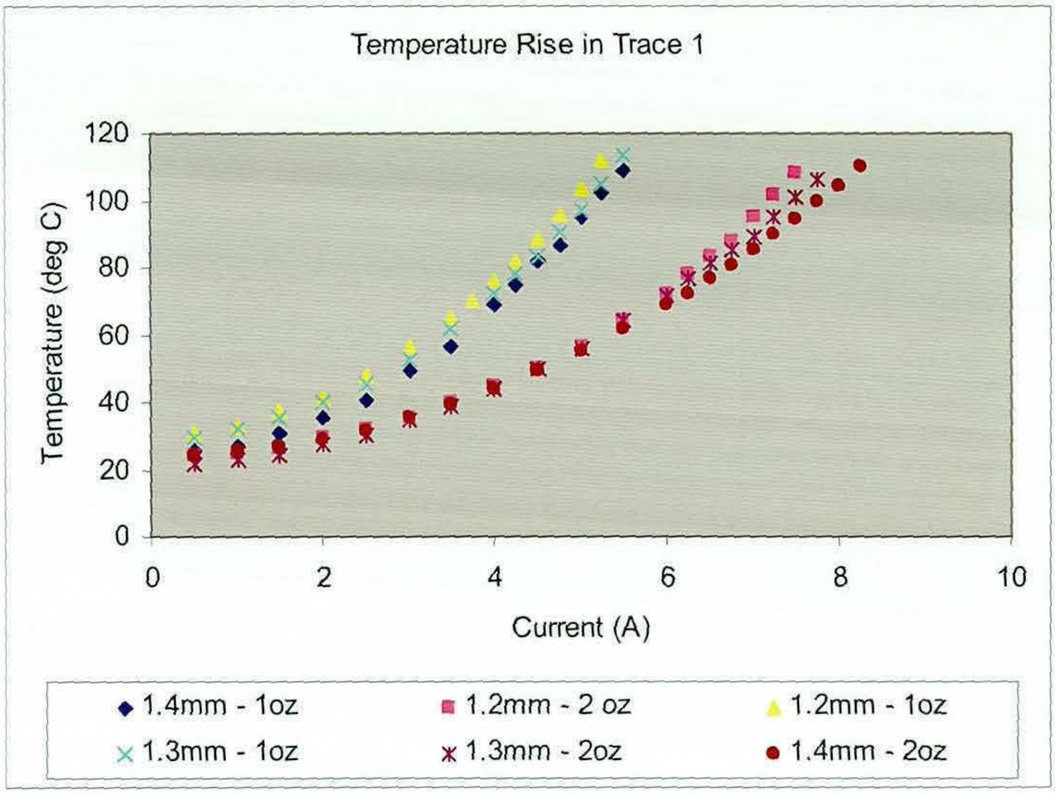

Figure 7.12 Temperature Rise in a Single FPC Trace

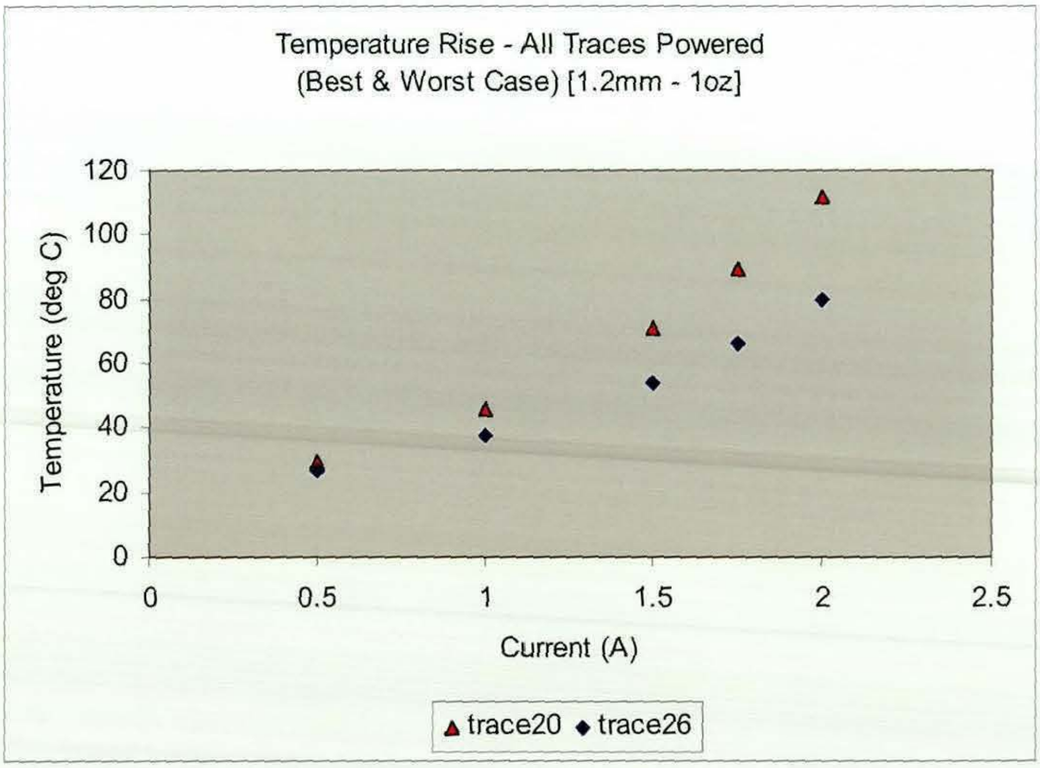

Figure 7.13 Temperature Rise in All Traces Carrying Same Current

For a group of adjacent traces under load, the largest temperature rise would occur in traces towards the centre of the group, and the least temperature rise would occur in traces at the extremities of the group. Figure 7.13 compares the temperature rise in traces of 1.2mm width on a 1oz base laminate, located near the edge of the test coupon (trace 26) and traces in the centre of the test coupon (trace 20). Traces of 1.3mm and 1.4mm width showed only a slightly lower temperature rise. The temperature spectrum across the powered parallel traces is shown in Figure 7.14. In the diagram, each axis represents an individual trace and is labelled according to the trace number. When a load current of 2 Amps is carried by each trace, the highest temperature attained (trace 7 and trace 20) is greater than 100°C, and the lowest temperature attained (trace 1 and trace 14) is above 80°C.

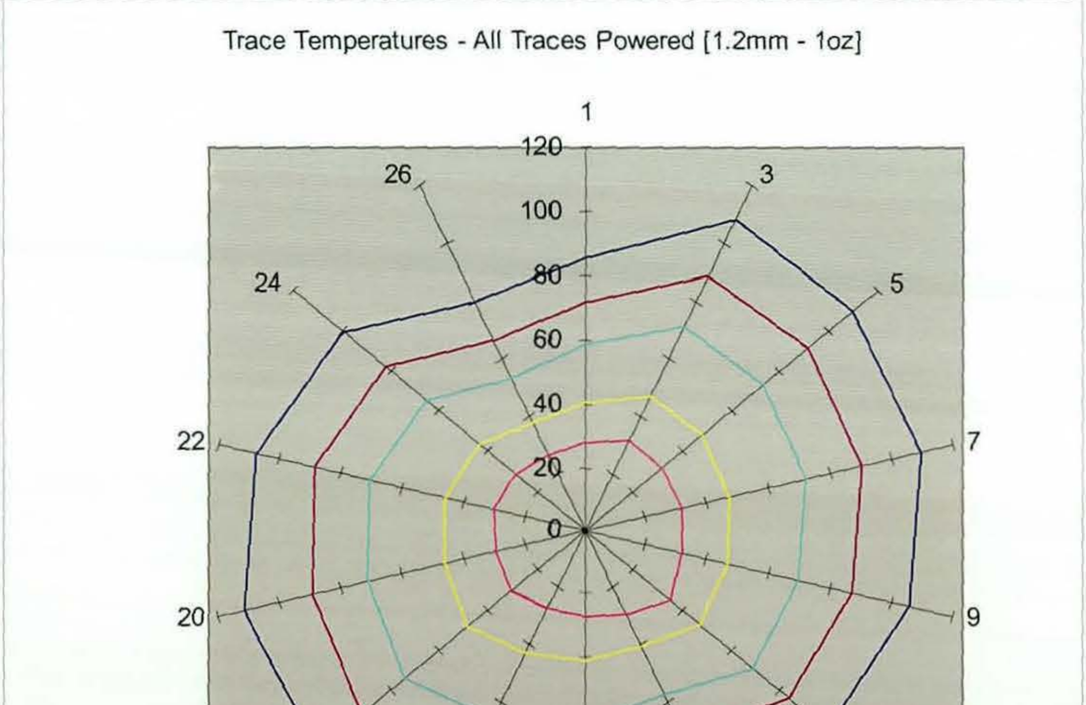

Figure 7.14 Temperature Spectrum across Powered Parallel Traces

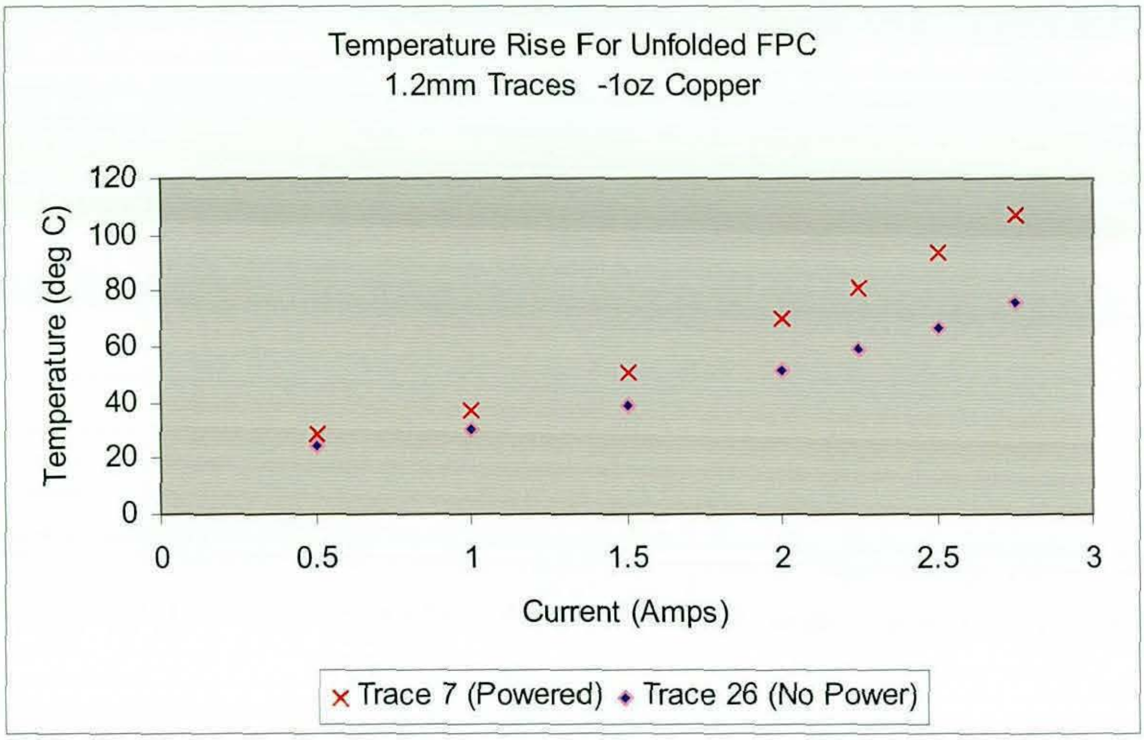

Figure 7.15 Temperature Rise for Unfolded FPCs

When traces on the topside only are powered, this can simulate unfolded single-sided FPCs. The trace temperature shown in Figure 7.15 is lower compared to traces carrying a load current on both the topside and underside layers. The experiment demonstrates that in multilayer FPCs and areas containing folds, a higher temperature would be experienced compared to a single-sided FPC[88].

7.3.4.3.2 FPC Trace Width for 1oz Copper-clad laminates

The experiments do not completely solve the problem of ampacity, as traces would not be parallel throughout its entire length, or carry similar current. Also, where higher ambient temperatures were found such as in the vehicle roof space, smaller load currents would be sufficient to raise the trace temperature above 105°C. A conservative trace width of 1mm per Amp was chosen, with the minimum trace being 1mm (*Low* nets). For currents between 1 and 2.5Amps (*Medium* nets), a 2.5mm trace was used, and between 2.5 and 5 Amps (*High*

[88] Potentially, where the FPC is integrated into a larger part using over-moulding, ampacity may be affected by the thermal conductivity of the encapsulating material.

nets), a 5mm trace was used. Circuits carrying currents greater than 5 Amps were not implemented with a wide trace width, as these would increase the overall size of the prototype beyond the limits of the processing equipment, as well as being unroutable. It is suggested that high-current circuits would require the use of a relay switch, operating with a signal current less than 1 Amp, and could therefore be implemented using a 1mm trace[89].

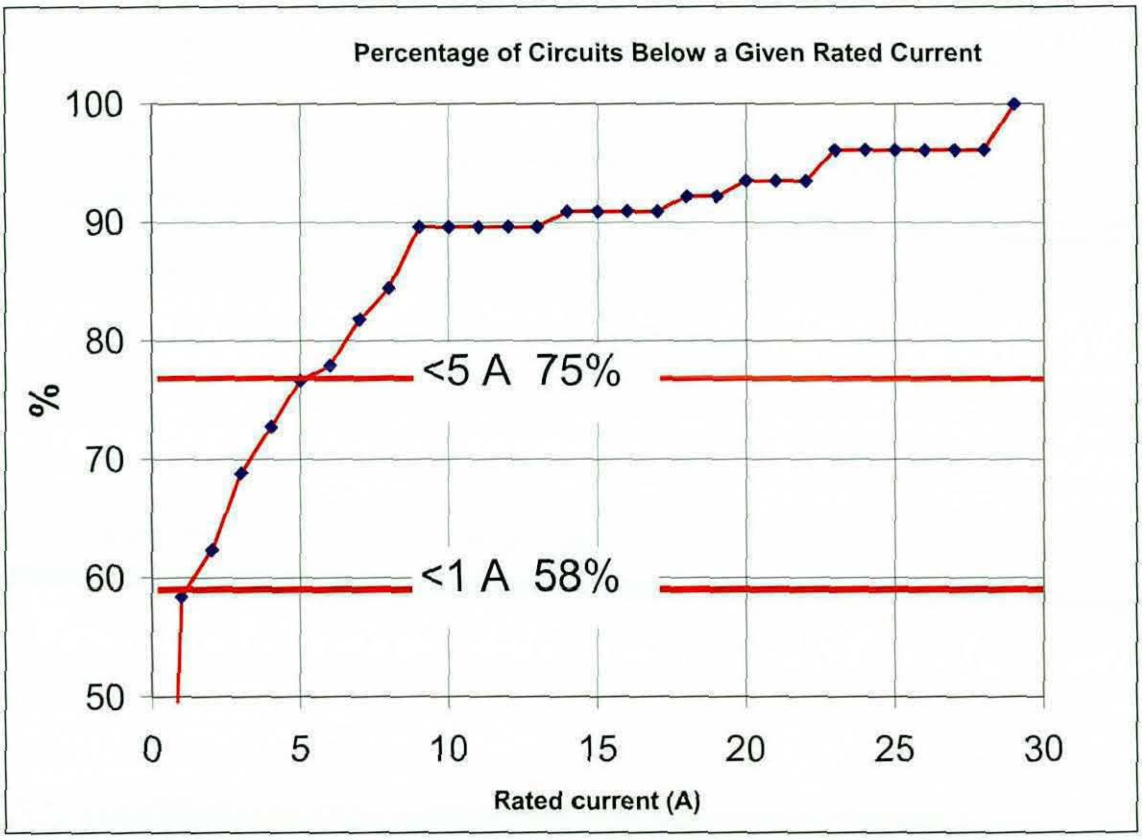

Figure 7.16 Number of Wires below a Particular Current on the J-100

Figure 7.16 shows the percentage of wires within the 96237581kk harness carrying less than a given load current. Approximately 25% of circuits on the harness carry more than 5 Amps, which would need to be implemented with 1mm traces and relay switches. Implementing the high-current traces in this manner further invalidates the large area FPC as a drop-in substitute harness, and arguably a near substitute as well.

[89] Alternatively, several smaller traces may be used to implement a single high current trace.

7.3.4.4 Component Placement and Trace Routing

To approximate the final outline shape used for the single large prototype, a paper 'space model' illustrated in Figure 7.17, was created and assembled into the cockpit to verity length and the positioning of connectors. The space model assumed a double-sided FPC solution, having 1mm conductor traces, and where only connector-to-connector circuits would be included[90]. Although it would be narrower than the final outline, the model was nonetheless useful as a guide for the placement of components, area and trace keep-outs.

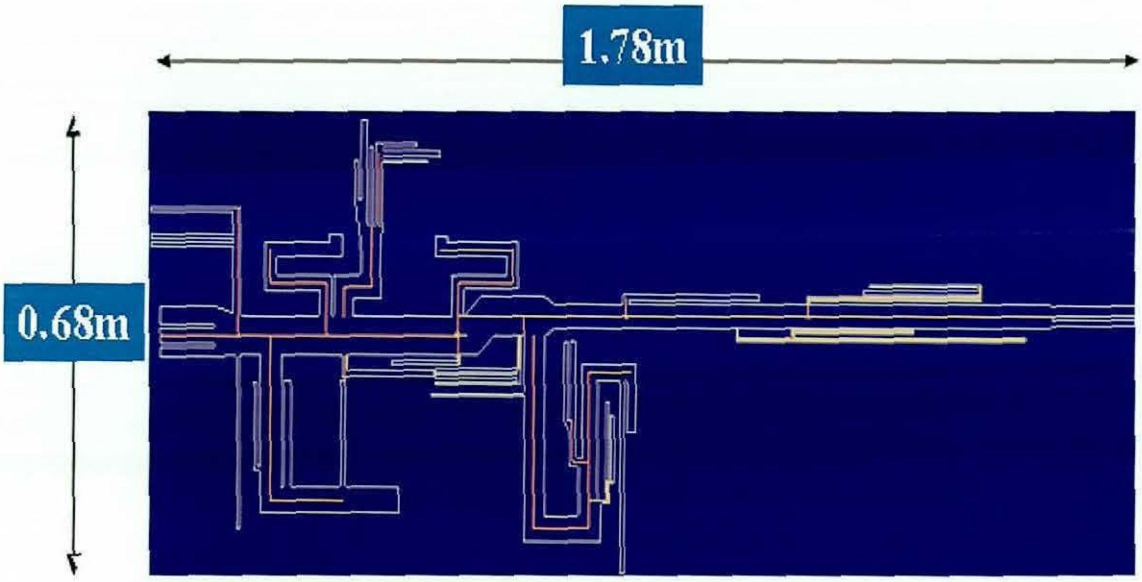

Figure 7.17 Model FPC Outline

Component placement was followed by a 'rats nest' minimization in order to reduce trace lengths, achieved by using pin and connector swapping. Auto-routing was the preferred method of routing traces, given the complexity of the rats nest. A routing grid was set to 0.1mm spacing and grid-snapping disabled. T-junctions and other intra-layer nodes were permitted, as these allow for routing of splices. Additionally, 'any-direction' routing was allowed so that traces may be routed at any angle to each other.

[90] Splice packs were associated with a large number of wires in the harness, and this approach would have been erroneous, resulting in a smaller space model.

In the auto-router, one layer was used for routing traces, simulating the use of a single-sided copper-clad laminate. To establish trace routability, unrestricted auto-routing was performed using a trace width of 1mm only, and without the use of keep-outs. This first pass revealed a large number of traces were unroutable, and a solution having two or more layers was required. Further, the use of simulated crimps contributed significantly to traces being unroutable. Through-hole vias having a circular footprint of 1mm, but without a specified hole diameter were used as an alternative in both prototype designs.

Figure 7.18 illustrates the result of unrestricted routing using two layers, simulating the use of a double-sided copper-clad laminate. There was an apparent bias in the auto-router towards orthogonal traces, and this was observed for all further auto-routing attempts. All circuits were routed and the completed design contained 98 through-hole vias. The solution was unrealistic and unmanufacturable, having no outline profile to distinguish individual arms.

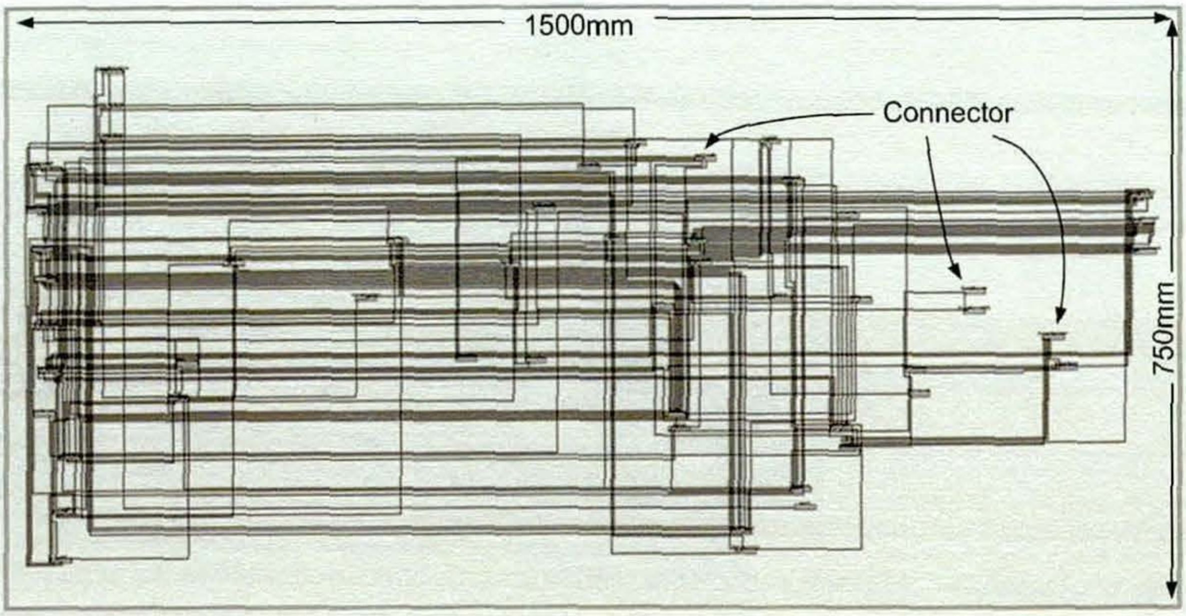

Figure 7.18 Double Sided Routing After First Pass

Using area and trace keep-outs, a board outline approximating that of the space model was simulated. No attempt was made to incorporate folding for material use optimization. Auto-routing resulted in a large number of unrouted traces, indicating a different board outline was necessary in order to achieve a solution. Several iterations of resizing and repositioning keep-out areas so as to simulate different board outlines were performed. The result of using a less restrictive keep-out area is illustrated in Figure 7.19. In this solution, most traces have been routed, incorporating 114 through-hole vias. Unrouted traces are drawn as non-orthogonal lines. As with previous auto-routed attempts, there were no means of profiling individual circuit arms.

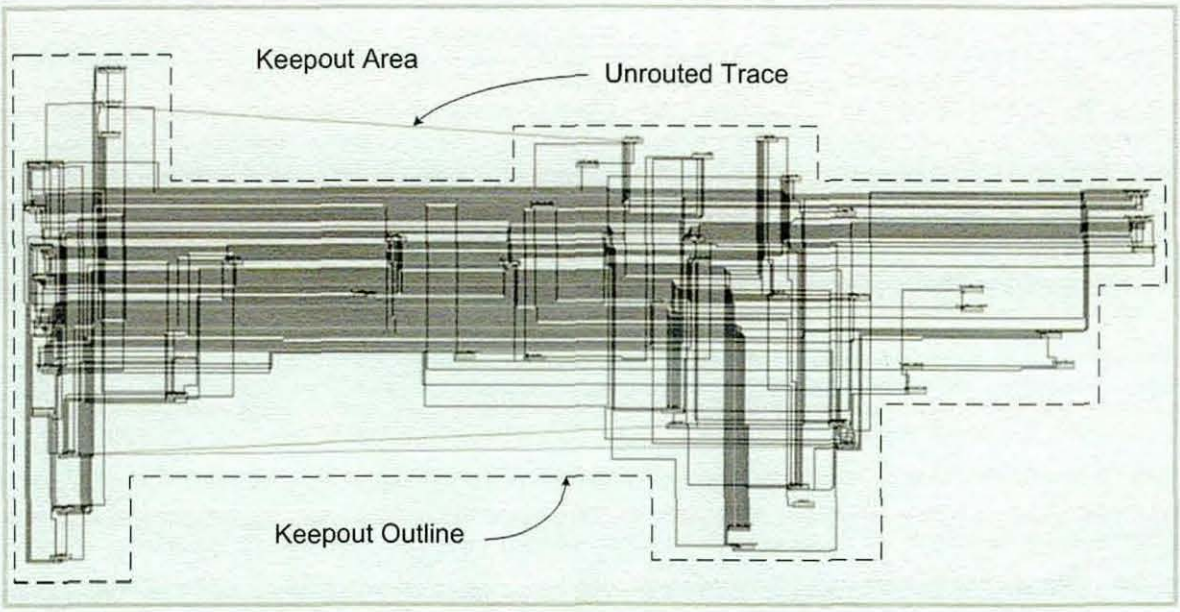

Figure 7.19 Routing With Restrictions on Trace Area

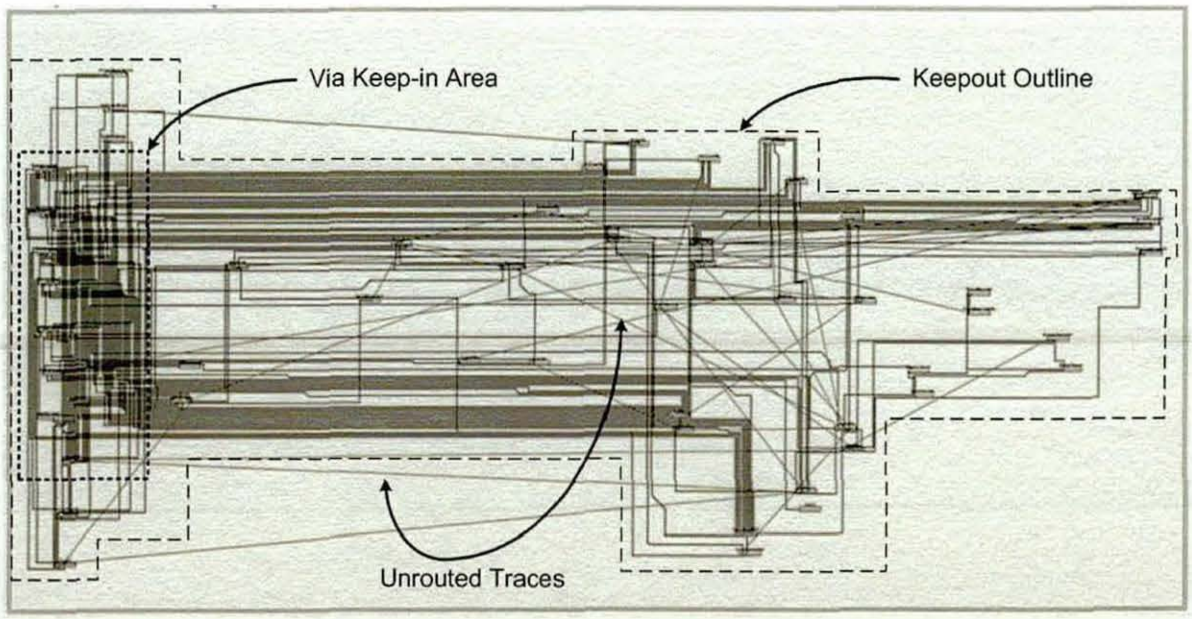

Figure 7.20 C-Shape FPC with Vias Restricted To Left

Another approach was to restrict the location of through-hole vias within specific areas of the board outline by using via 'keep-in' areas, and decreasing the keep-out area restrictions for traces. Figure 7.20 illustrates the resultant C-shaped solution having a via keep-in to the left side of the board outline. For this solution, an increase in the number of unrouted traces and through-hole vias was observed. Using a second via keep-in area to the centre cluster of connectors resulted in better shape and routing as illustrated in Figure 7.21.

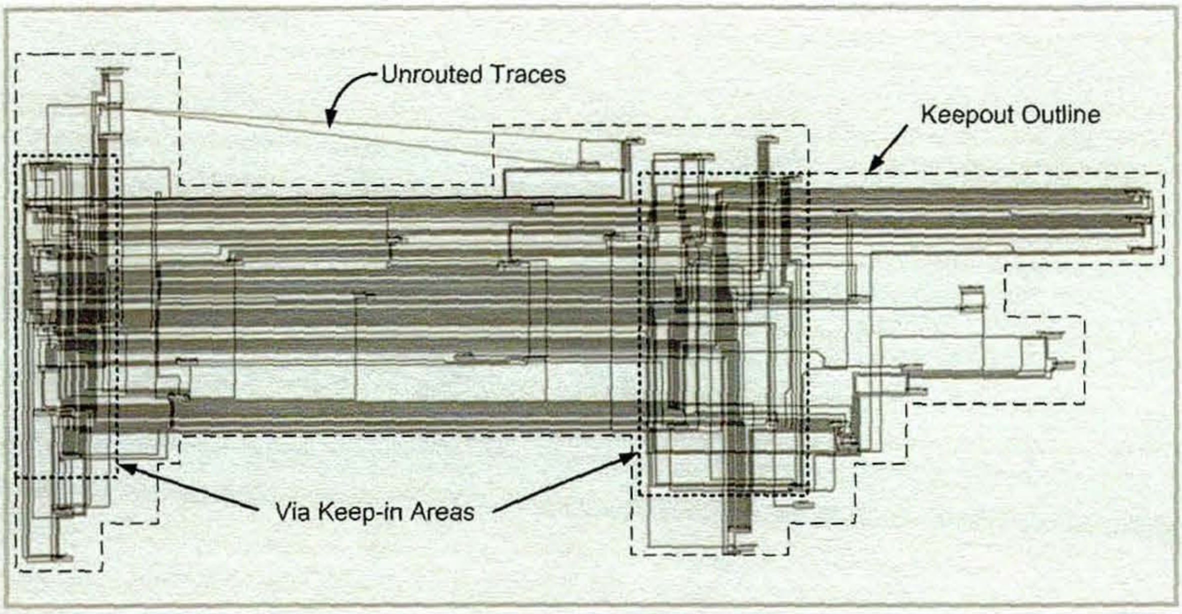

Figure 7.21 Routing Using Two Via Keep-in Areas and Trace Keep-outs

For all iterations of board outline change, there was a consistent problem of traces being unroutable and no identifiable path which could be used as the FPC profile. This problem was only solved by placing connectors along a small rectangular perimeter within the board outline as shown in Figure 7.22, with the patch placed within the inner boundary of the connectors. The perimeter was approximately 420mm x 300mm, determined by connector dimensions. Further reductions in the rectangular area resulted in a number of traces being unrouted.

Auto-routing this configuration resulted in all traces being routed, but the corresponding increase in via count to 222 was a departure from the objective to minimize side-to-side interconnections. Once routed, connectors were moved to their final location in a postprocessing step by extending the board outline and manually routing traces. Having all trace crossovers and vias within the central core circuit enabled the FPC arms to contain parallel traces. This solution lends itself to the second design option – a large area FPC with detachable arms.

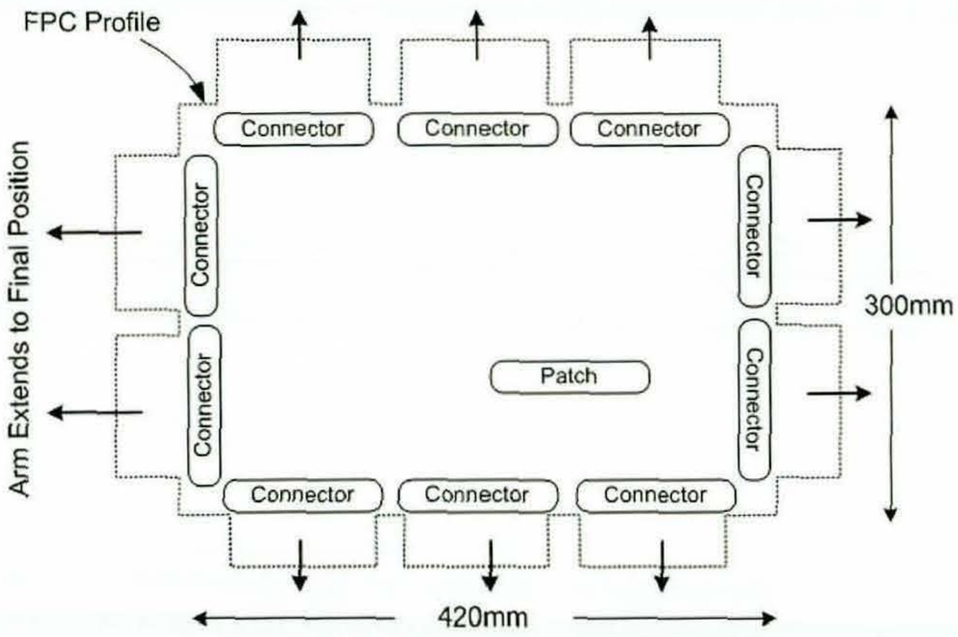

Figure 7.22 Connector Placement for Full Trace Routing and Shape Control

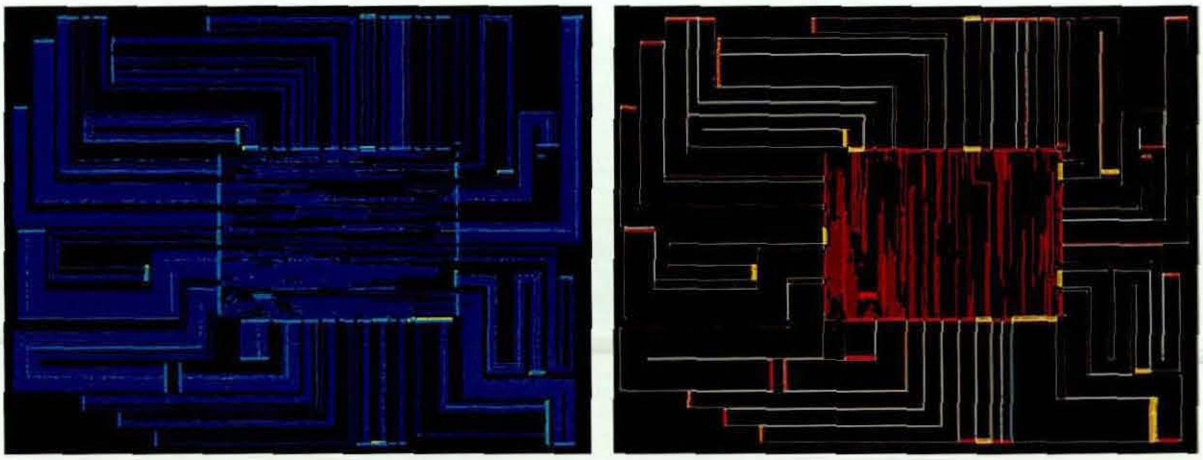

Figure 7.23 Topside and Bottom-side artwork for Single Large Area FPC prototype.

The artworks for the topside and bottom-side layers of the first prototype are shown in Figure 7.23. It was observed that the auto-router routed traces in only one direction on any given layer. Despite the simplicity of routing parallel traces in the FPC arms on the topside layer, the auto-router was unable to perform this task, and this had to be performed manually. On the bottom-side layer, traces were confined within the central core. This solution would result in the highly inefficient use of copper-clad base materials. An alternative would be the use of a double-sided core circuit and detachable single-sided arms. To attain the necessary arm lengths and to use a manufacturing panel of dimensions of 750mm x 1000mm, the connectors were positioned and the arms profiled as shown. On completion of routing, the artwork files were generated and the prototype manufactured.

7.4 Single Large Area FPC Prototype

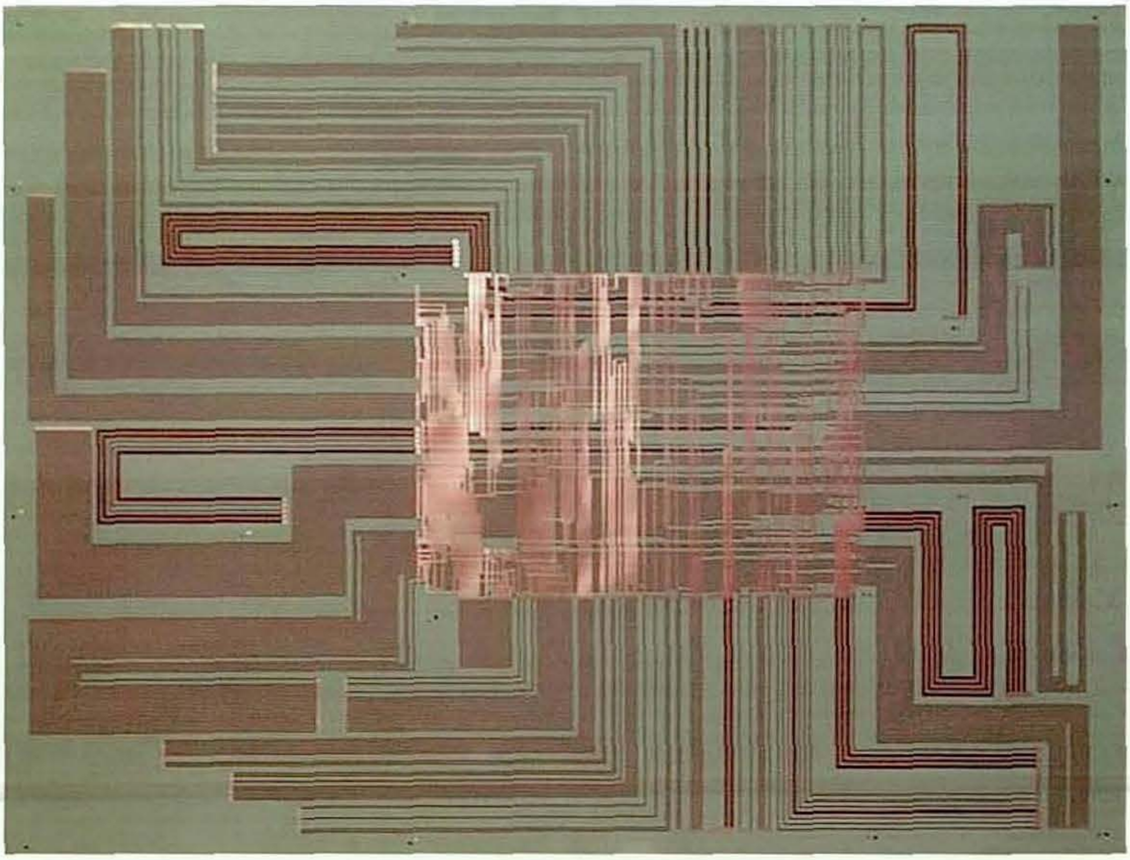

Figure 7.24 Manufactured Single Large Area FPC

The manufactured single large area FPC is shown in Figure 7.24. This prototype was manufactured using a double-sided copper-clad PET substrate of 75μm thickness, within an area of 1000mm x 750mm. Through-hole vias numbered 222 and were confined to the central core circuit. These were filled with silvered ink. When assembled into the centre of the Daewoo Nubira cockpit shown in Figure 7.5, most connectors were able to reach their intended location. However due to the difficulty in assembling the FPC arms throughout the cockpit, the single large FPC may not be a feasible solution for use in conventional cockpits.

The FPC implemented 75% of the current-carrying capacity of the 96237581kk, with the highest currents requiring an additional relay switching and implemented with 1mm traces. As anticipated there was a significant reduction in weight. The mass of the single large area FPC was 0.4kg, compared to 2.3kg for the 96237581kk harness. Added value was derived from the inclusion of the patch circuit, which was soldered by hand onto the FPC. The estimated cost of such a single large FPC solution was £23, based on a production volume of 1 million units per annum [Cottrill et al., 2003]. However the cost estimate is not inclusive of the patch circuit and connectors. This estimated cost can be compared to that of £50 -£69 for the equivalent wiring harness inclusive of connectors, produced at a rate of 700,000 units per annum.

7.5 Multilayer FPC Prototype

The objective of designing the multilayer FPC was to eliminate, as far as possible, the total number of side-to-side interconnections required for electrical connectivity and mechanical attachment. A number of strategies were devised for this process. The multilayer FPC would be constrained to 12 physical layers, representing 6 double-sided laminates. Each double-sided laminate would be attached at common zones by the use of crimps as illustrated in Figure 7.25.

In addition to these crimps, connector pins would be used for side-to-side interconnections. Connectors were assumed to accept multiple circuit layers, and for realistic handling, connectors would terminate 2 double-sided arms, or 4 circuit layers. The connectors created previously were used for the multilayer design and they were placed in the final locations as in the first pass iteration for the single large FPC. Unlike the previous prototype, traces on the multilayer FPC would be manually routed, with a final pass being performed using the auto-router for problematic traces.

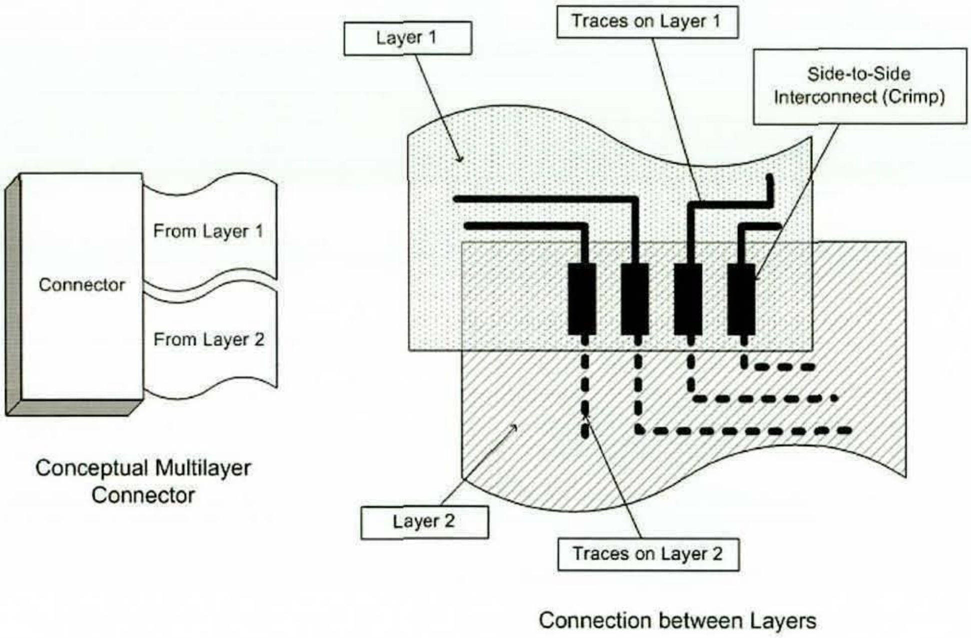

Figure 7.25 Multilayer FPC Implementation Concept

7.5.1 Trace-Layer Allocation

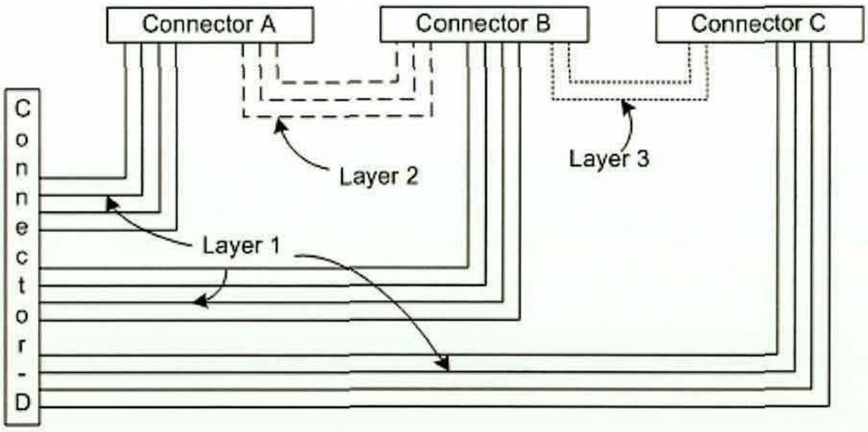

Figure 7.26 Method of Allocating Circuits to Layers.

Separation of traces into different layers was necessary in order to maximize material usage. The allocation of traces to different layers was done by identifying connector pairs sharing the largest number of circuits. These would be placed and routed on the same layer. Connector pairs sharing a lesser number of circuits would be placed and routed on sequential layers with the remaining traces routed on a single 'mop-up' layer. The method is illustrated in Figure 7.26, but does not take into consideration different trace widths. Complementing this approach, splices and splice packs could be eliminated by converting such nodes into individual connector-to-connector traces. The total number of connector pins required in the conversion can be calculated using Equation 7.1.

$$Number\_Pins = \sum_{x}\left(\sum_{n}(n-1)\right)$$ **Equation 7.1**

In the equation x is the number of splices inclusive of those contained within splice packs, and n is the number of connectors joined at each splice. If the splices and splice packs were to be converted into direct connector-to-connector traces, then using this approach would result in a total of 645 I/O pins. Although it is hypothetically possible to reduce the number of side-to-side interconnects to zero, trace routing may not be possible as previously demonstrated. Keeping the splices in the 96237581kk harness results in a total of 90 I/O pins, but side-to-side interconnects increase to 112. The final number of side-to-side interconnects would be determined by the actual routing of the circuits.

7.5.2 Impractical Design Results

The trace-layer allocation method was time consuming and produced an impractical solution, shown in Figure 7.27. Traces on the different layers are identified by colour; with layers translated in the x and y directions for highlighting purposes only[91], hence the common area shown in the illustration would be smaller in the actual multilayer FPC. The underlying assumption within the trace-layer allocation method is the availability of sufficient connector-to-connector pairs to form wide FPC arms. For the 96237581kk wire harness, this did not materialise, as most connector-to-connector pairs were limited to a single trace. Figure 7.28 shows the layer with most connector-to-connector traces. The problem of handling such a large layer with inherently narrow arms makes this unattractive. This would be exaggerated for each additional layer.

[91] It is for this purpose that the board outline was set at 2000mm x 1400mm

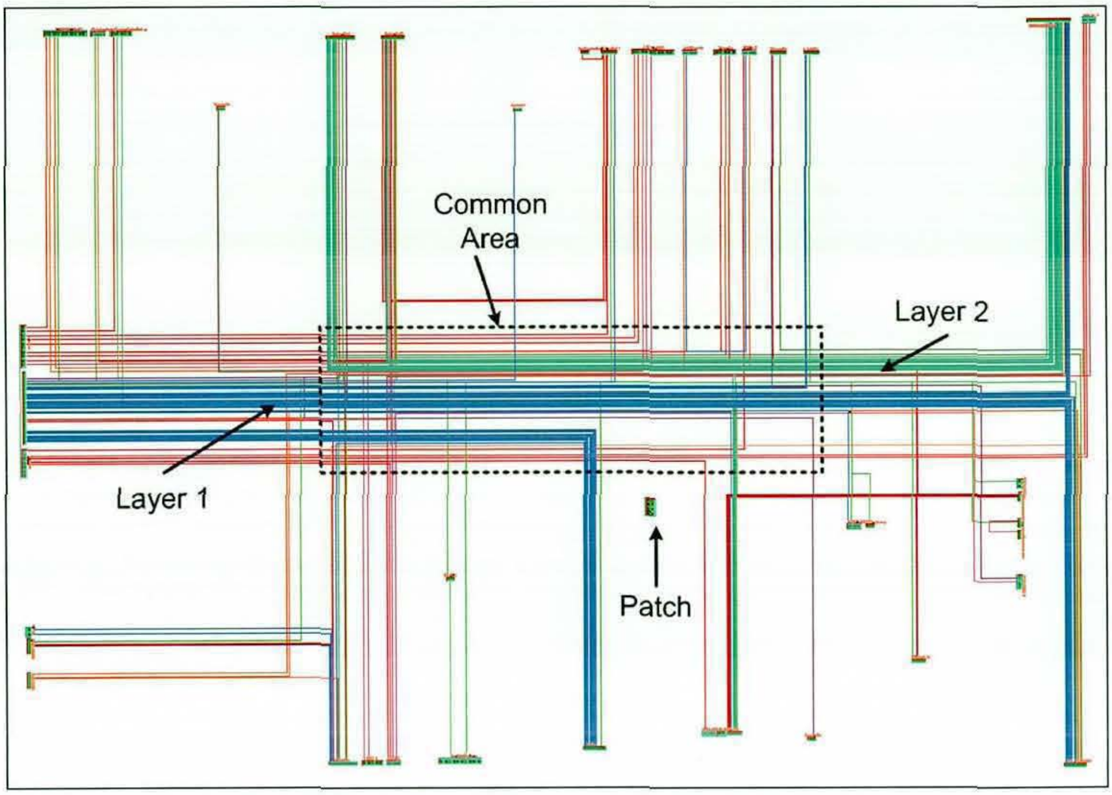

Figure 7.27 Multilayer FPC Designed Using the Trace-Layer Allocation Method

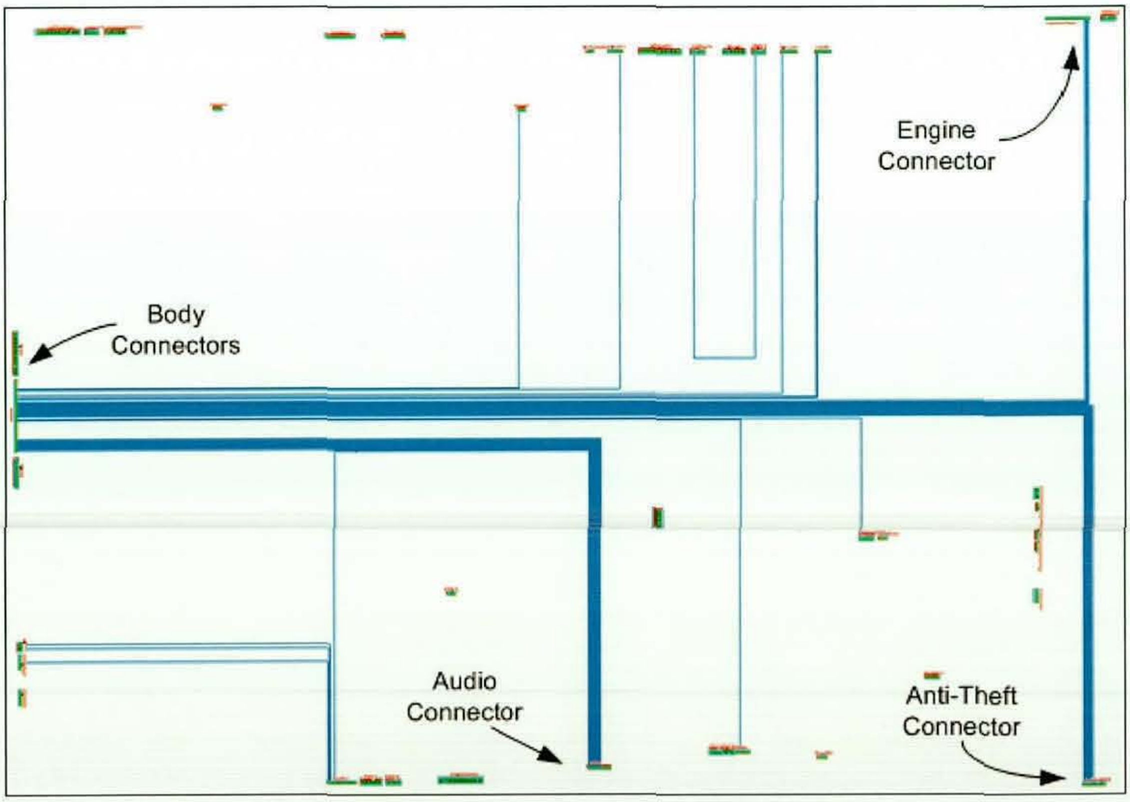

Figure 7.28 Single Largest Layer in Multilayer FPC

Another layer of interest was the ground circuit, routed on its own layer as shown in Figure 7.29. The routing of the ground circuit demonstrates the effect of including splices in the multilayer design. For the ground circuit, manufacturability and handling would be problematic. A single layer backplane may be used to overcome this problem, but it introduces additional routing and layer interconnection challenges.

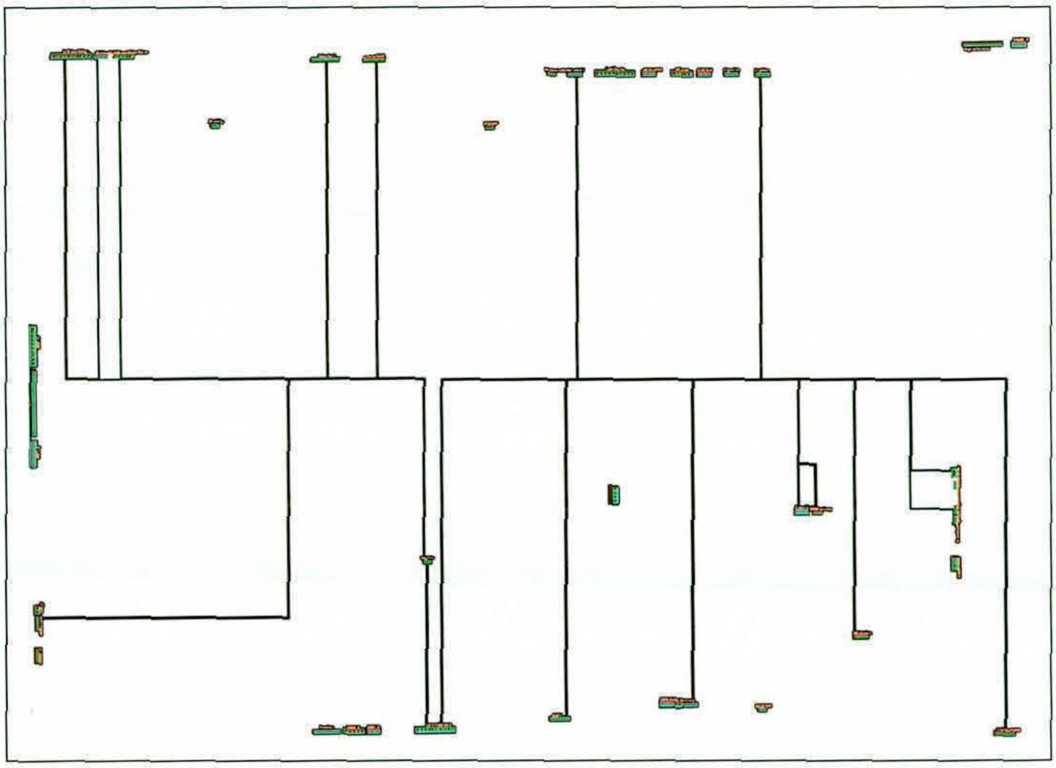

Figure 7.29 Pervasive Ground Trace

For the majority of connectors, there were more than three layers routed to I/O pins as illustrated in Figure 7.30, with the worst case having eight layers. Further, some connectors would have high current traces. If a majority of traces entering the connector were high current, it does not present any problem. However, if a single high current trace were to be routed to a connector, the disadvantage would be that the connector itself would need to be high current. The problem would be solved by using a single type of connector for all circuits. This may require wider arms, but the question of connector ampacity and physical construction remains central to routing both the single large and multilayer FPCs.

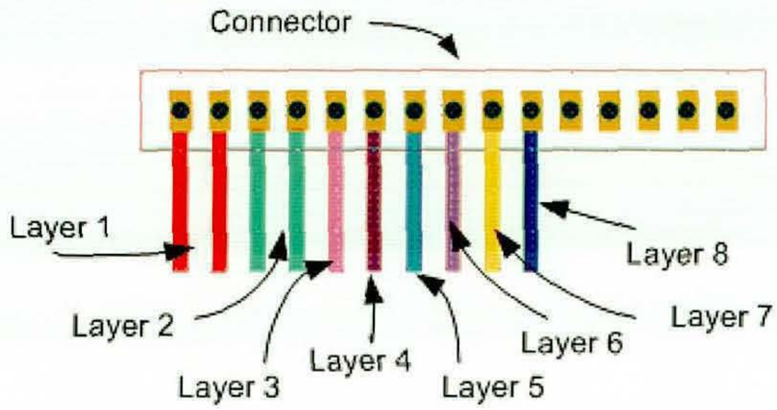

Figure 7.30 Too Many Layers Routed To a Single Connector

7.6 Design Observations and Recommendations

One advantage of using the EDA tools was that it allowed for rapid design changes, and the investigation of different design options, circuit outline and trace routing. In most cases, only the changes made to the circuit in the *Layout* module were required to effect a different design option. Minor changes in the preceding modules were only necessary to activate a particular feature when required, such as a change from plated through-hole vias to crimps in *Librarian*. However, the Mentor Graphics output files were not universally portable to other CAD/CAM suites.

Initial assumptions of non-problematic trace routing, which formed a partial foundation for the conceived design options were incorrect given the performance of the Specctra auto-router. The trace-layer allocation method used to design the multilayer FPC produced an impractical and unmanufacturable solution. Both design exercises highlight the challenges in obtaining a suitable replacement FPC for the 96237581kk harness. Although it may be impossible to eliminate side-to-side connections completely, they could be limited to a small area, as demonstrated by the single large prototype. Further, even when a complete routing of traces is achieved, the solution may be unacceptable. The process of interpreting the Daewoo schematic drawings and the method of implementing the harness in Mentor Graphics may have contributed to the unsatisfactory design results. For example, using multiple FPC connectors for the different current ranges may have contributed to trace unroutability.

The trace sizing experiments performed by Yazaki have provided a preliminary indication of the ampacity of traces on 1 oz. and 2 oz. copper-clad PET film. A single powered trace of 1.2 mm on a 1 oz. base substrate can carry 4.5 Amps (dc) with a temperature rise of 85°C. This ampacity is decreased to 2.25 Amps (dc) when parallel traces are powered, and is further decreased to 1.6 Amps (dc) when additional traces on the underside of the FPC are powered. Larger trace widths and/or the use of a 2 oz. copper-clad base would lead to an increased ampacity, but presents a trade-off in cost, manufacturability, and weight of the FPC.

The ability of FPCs to be folded introduces variability in the possible placement and orientation of components, and the FPC outline. Whereas this is advantageous in respect for materials usage, the time consuming process of defining a board outline, placing components and trace routing for each possible folding configuration presents a disadvantage.

Designing large area FPCs as drop-in replacements for existing wire harnesses may not be possible, because of the trace size requirements for high current circuits. Implementing such circuits on FPC would require the use of switches; adding cost, weight and complexity to the FPC solution. Therefore, designing an FPC solution for an existing harness is not recommended, unless the harness is simple and contains very few or no high current circuits.

Although large area FPCs may not be suited as drop-in substitute harnesses, they could potentially be used to implement bus architectures such as CANBus, and such solutions should be investigated more fully.

In contrast with conventional wiring harnesses which are usually designed during the last stage of the vehicle design process, large area FPCs should be designed much earlier. Further, more realistic FPC solutions may be achieved if the EDA design tool is allowed to capture and process the entire vehicle electrical schematic instead of one harness schematic at a time. Better opportunities for applying large area FPCs are more likely to emerge in new vehicle models; where the entire vehicle electrical system can be designed early and where the vehicle can be purposely designed around large area FPCs.

8 DISCUSSION

This chapter presents an evaluation of this research addressing some of the engineering challenges at the first stage of the product development cycle.

8.1 Experiment Design

The methodology devised for the selection of candidate materials used in the manufacture of FPCs as proposed in this research may be applied to other vehicle classes or products containing such circuits. By establishing the degradation or retention of important material properties as supplied and as they change over the service life of the product, through the application of accelerated life tests, appropriate materials may be selected.

The method of application of FPCs should be known, including the mechanical, electrical, chemical and other stresses experienced throughout the service life of the circuit. Further, appropriate test methods should be adopted for experimental validation of the material properties. A physics-of-failure approach to selecting accelerated ageing variables such as temperature, humidity and vibration should also be followed. For product substitution, the use of published standards for acceptability of materials may assist in the identification of relevant material properties; however such properties should be identified according to the individual application.

FPCs lend themselves to simple comparative experiments. However, statistically designed experiments are large, given the number of factors and levels involved. Reducing the number of test coupons required is possible through tailoring the accelerated ageing parameters so as to reduce the time required for accelerated ageing. Knowledge of the properties of the constituent FPC materials and how they change when exposed to different environments can assist in limiting the number of factors and levels requiring investigation.

The experiment design in this research assumed rolled-annealed and electrodeposited copper would have the same effect on material properties, and could be ignored as a factor. Other controllable factors that could have affected material properties but not included in the experiment design include:

1. Base film and coverlay variants, such as fillers (e.g. Melinex™ PET film)
2. Base film and coverlay thickness
3. Copper thickness [and the use of other conductors, such as conductive ink]
4. Construction features such as multiple layers and through-hole vias

The experiment design did not incorporate blocking, to treat random factors or batch processes. These include manufacturing processes, manufacturing defects, and raw materials. These factors could have influenced the experiment results and there is a need to either include them in a revised experiment design, or to control them.

Limiting FPCs to one type of film used in any construction, i.e. PET or PEN allows for an investigation of the adhesive only, provided there are no negative interactions between the film and adhesive. Such an investigation could be in the form of a peel strength test.

8.2 Materials Testing and Results

The materials testing phase of this research has been stymied by an insufficient number of test coupons. This has been indirectly a result of materials supply and poor design of test panels. Economisation of test coupons was necessary, but in some cases, test coupons were depleted before degradation trends could be established. The results still indicate the degradation of candidate materials, and can inform the inferences that can be made. For greater confidence, additional data points should be obtained, and this would necessarily involve further experiments. This would allow for the statistical treatment of the results, and more sustainable inferences to be made.

It is suggested that tensile strength, peel strength and dielectric breakdown strength are the most relevant material properties for material selection. Whilst the other quantifiable material properties investigated provide a comparative basis for material selection, they do not without further investigation indicate life expectancy within the automotive environment. Temperature cycling does not induce failure in the FPC materials or simple constructions. This argument may not be applicable however to solder joint and side-to-side interconnection reliability. Similarly, it is uncertain, although unlikely that the rapid temperature change experienced in thermal shock accelerated ageing would induce failure in the FPC materials or simple constructions. For materials selection, temperature cycling may therefore be omitted.

The limitation in the experiment results have been further exacerbated by the stochastic nature of the results for some tests. This reinforces the need to test sufficient numbers of test coupons, based on a statistically designed experiment. The results that have been presented offer a first look at the ageing properties of the FPC materials investigated.

Peel strength should be applied to FPCs designed with exposed metallic conductors, such as at edge connectors involved in frequent plug-unplug operations. Where a protective coverlay or covercoat is employed, and where the FPC is terminated with a fixed connector, peel strength may become less important. Further, reliability tests for attached components on FPCs should note the effect of hydrolytic degradation of adhesives and adhesive bonds at high temperature and humidity.

As a consequence of the large variation in possible adhesive formulation and the mechanism of adhesion, peel strength test results obtained in the experiments would be applicable only to the adhesive under test, and may not represent the behaviour of adhesives within the same class (for example epoxy or acrylic). Therefore each candidate adhesive would be required to undergo peel strength tests. An alternative approach to the selection of candidate adhesives is based on the reaction kinetics of hydrolysis of the adhesive.

A change in the test method used to assess flexural endurance is recommended. The IPC 2.4.3.1 test method, used to determine the flexural endurance around a specific mandrel diameter should be replaced by the IPC 2.4.3 test method. The latter test method provides for a simpler comparison of the performance of different adhesives for dynamic flex applications. A further refinement of the flex test, to be performed during accelerated ageing at high temperature and humidity, is the inclusion of the concept of accumulated flex cycles. As a vehicle ages, the number of flex cycles would accumulate. Therefore, test coupons should be exposed to cycles of accelerated ageing and flexing.

The electrical property tests need to be re-visited to ascertain whether experimental procedures contributed to the results observed. This is particularly applicable to the dielectric breakdown and volume and surface resistivity tests. Further, dielectric breakdown tests could be omitted provided the voltage levels experienced in the vehicle's electrical system are much lower than the material's dielectric breakdown strength. It is recommended that resistance measurements be performed for the Insulation and Moisture Resistance test, and not a test for dielectric breakdown strength. Conducting a resistance measurement test allows the volume and surface resistivity test to be an optional test.

Flame resistance testing should be performed using the specified apparatus in the MVSS302 standard, and should only be performed on materials as supplied as the legislation does not require further tests on aged materials. It is likely that the FPC test coupons may fail the flammability tests, and justified use of such materials would be required if such use is within the legislated boundaries of the occupant compartment of a passenger vehicle.

8.3 Estimation of Time for Accelerated Ageing

Inferences in respect of the suitability of candidate materials after accelerated ageing may be erroneous without correlating the time exposed to accelerated ageing conditions to an equivalent accrued service life within a vehicle. Such a correlation has been devised using a physics-of-failure approach based on the established rates of hydrolytic degradation of Mylar A films. Using accelerated ageing conditions of 85°C/95%RH, a significantly reduced accelerated ageing time of 206 hours (compared to the damp heat ageing time of 3000 hours prescribed in the automotive standards) has been recommended.

The time required for accelerated ageing of PET in automotive environments may also be used as the benchmark for comparing different candidate materials, specifically the retention of material properties. This however, only applies to such materials known to have the same or lower rate of hydrolytic degradation compared to 75 micron Mylar A film.

The estimated time for accelerated ageing of 206 hours is based on a devised model for the average diurnal temperature and relative humidity of England. Variations in different regions of the United Kingdom and Europe may lead to a greater or lesser time required for accelerated ageing. Longer accelerated ageing times would be required for warmer geographic regions and potentially those areas having a longer annual exposure to sunlight. The method of estimating the time for accelerated ageing can be applied to vehicles deployed in different geographic regions with knowledge of the diurnal climate and allows for the selection of the lowest cost materials appropriate for use in the geographic region of interest.

The accuracy of the estimate devised depends on the correctness of the assumptions made in respect of climatic conditions experienced throughout the service life of the vehicle. During winter conditions and non-use periods, the temperature inside vehicle may be higher than the external temperature, and in summer conditions and in-use periods, the temperature inside the vehicle may be lower than the external temperature. Further, the relative humidity inside the vehicle during periods of use would be affected by the use of the HVAC system. An assumption has been made that the periods of use would be of negligible duration over the vehicle life, for example, a passenger vehicle may be in use for less than two hours per day.

Verifying the accuracy of the accelerated ageing time requires further lab-field correlation. Lab-field correlation would involve the evaluation of properties of FPCs already in use within vehicles and comparing them with those exposed to accelerated ageing in the laboratory.

8.4 Recommend Materials

Viewed in isolation, the experiment results do not provide a basis for recommendations to me made regarding the suitability of candidate materials for automotive applications. Applying to the experiment results the estimated time of 206 hours for damp heat ageing, together with an acceptability criterion of 70% retention in initial property value, allows some recommendations to be made. Base substrates 924-00-01 (PET film with polyurethane adhesive), and 567130 (PEN film with flame retarding epoxy adhesive) are suited to both door and cockpit applications. Insufficient data precludes further recommendations being made.

In warmer geographic regions, PEN based laminates may be more suitable for cockpit applications, but such a contention may be invalidated by applying the diurnal climate data of such regions to the model developed for accelerated ageing time. Further, the use of thicker PET film provides an alternative solution to the use of PEN film in the cockpit, as thicker films degrade hydrolytically at a lower rate compared to thinner films. This recommendation is a departure from previous suggestions that PET film would be suitable for cockpit areas only, and PEN film for use in vehicle doors. Other films such as PET/PEN blends and Poly (ether-ether ketone) (PEEK) having a higher glass transition temperature and better resistance to hydrolytic degradation should be investigated, provided they offer a more attractive economic cost. See Friedman and Walsh [2002] for other examples of polymer films which may be potentially used in FPCs.

Inferences in respect of the suitability of candidate adhesives are unlikely to be properly arrived at without further investigation of the reaction kinetics of hydrolysis of each adhesive. However, adhesives exhibiting resistance to humidity ageing, as evidenced by retention in peel strength, may be suitable for automotive applications. Both film and dielectric ink coverlays require further investigation, specifically, the effect of abrasion on insulating properties.

8.5 Draft Specification

One objective of using a specification for the selection of candidate materials is the identification of changes to a material when subjected to accelerated ageing and physical testing. Such changes may indicate a greater or lesser likelihood of the material to fail during its service life. The extent of the changes to the material properties may be used as an acceptability criterion. However, such an approach requires a cautious determination of the acceptable levels of the material properties of interest. Brown and Greenwood [2002, p.13], summarizes the problem succinctly;

"*Failure occurs when the component ceases to perform its required function. In the case of catastrophic failure, such as the rupture of a pipe or electrical breakdown of an insulator, this is obvious, but in many cases there is no such clear end of life. For example, is the end point when a small amount of environmental stress cracking has occurred, or when cracks have reached 5 mm in length? Broadly, the definition of end point is that a property has reached a level at which safety, performance or market acceptance dictates that the component or product can no longer be used*".

For new products, experience may determine appropriate acceptability criteria.

Failure criteria required for completeness of a specification have not been proposed due to ambiguities in the method of application of large area FPCs; however, it suggested where applicable, that the initial and a minimum retained[92] quantity (actual value or percentage) of a material property may be used as acceptance criteria.

8.5.1 Failure Modes and Mechanisms not included in the Draft Specification

Potential failure modes and mechanisms associated with the following elements of large area FPCs have not been included in the draft specification:

(a) The conductive layer, including various forms of copper and aluminium. Failures may include changes to the resistivity of the metal through oxidation and corrosion. Catalysis of the hydrolytic degradation of the FPC adhesive layers in the presence of the oxidized or corroded metal is a speculative failure mechanism. Temperature rises in corroded or oxidised traces may also lead to FPC failure.

(b) Side-to-side interconnections, including through-hole vias, crimps, rivets and eyelets. Failures include detachment caused by differences in the materials CTEs.

(c) Solder joints. Failures such as crack formation may occur as a result of differences in the materials CTEs.

[92] After accelerated ageing

(d) Failures induced by vibration. In PET, the effect of vibration may lead to failures before that materials become brittle. Multi-stress ageing at elevated temperature, humidity and vibration should be investigated.

(e) Failures induced by multiple stresses of temperature, humidity and applied voltage.

8.6 Circuit Design

The preliminary exploration of large area FPC design revealed limitations in present day commercial EDA tools for designing drop-in substitutes for modern large complex wiring harnesses, such as the IP harness. Whereas a complex wiring harness containing splices may be captured into an electrical schematic, the physical implementation of the schematic requires several variables to be known. Primary variables include the physical characteristics of connectors and side-to-side interconnects having suitable ampacity, appropriate trace size, and preferred FPC outline. Secondary variables include the manufacturing process and materials to be used, location within the vehicle and method of assembly. Without detailed knowledge of the primary and secondary variables, the design can only explore a 'what if' scenario.

Further investigation into the use of a patch to implement side-to-side interconnections is needed. The use of a patch for implementing side-to-side interconnections would allow high production rates, as electroplating would be removed from the main reel-to-reel process.

Thermal management and the ampacity of FPC traces and plated through-hole vias require further investigation. Provided a satisfactory resolution of the ampacity problem in respect of moulded components, the integration of large area FPCs within such components as the dashboard at the Tier 1 stage would eliminate problems associated with handling and assembly by the OEM.

Other important issues were not considered and must be included in future designs. These include the incorporation of digital signals, high current traces, resistance and voltage drops. A 3D routing algorithm or the use of a 3D board outline would improve on results, provided the exact location of connectors and guides for routing FPC arms are known. The FPC prototypes have been designed with a tool that assumes all circuit boards are flat, leading to a 2-dimensional solution for a 3-dimensional problem. The large area FPC design should be repeated using EDA software having 3D layout capabilities, which may speculatively result in a more realistic solution. Provided an acceptable solution for large area FPCs has been designed, realistic testing of prototypes would be the next stage in product development.

8.7 Final points

A total life-cycle cost for large area automotive FPCs is required. A further investigation of assembly into the vehicle, maintenance and end-of-life recovery is also required. Whereas large area FPCs can potentially be used as substitutes for conventional automotive wiring harnesses, the design of such circuits presents the greatest challenge. The application of large area FPCs requires the electrical system design to coincide with the initial stages of vehicular design. This presents a shift in the current design practice, where wire harnesses are designed as an afterthought, and is the last stage of vehicle design. The inability of realistic FPC drop-in substitutes to be designed limits the use of large area FPCs to new vehicle models.

9 CONCLUSION

The increasing electrical and electronic content of modern passenger vehicles, reflective of consumer demand for safety and comfort, has resulted in round wire harnesses of increased size, complexity and weight when designed for a conventional 14-volt point-to-point automotive electrical architecture. The inherent penalties at each stage of the automotive life cycle resulting from the application of such large wire harnesses has stimulated the interest of automotive industry stakeholders in alternative electrical and signal distribution technologies. Although limited by developmental and cost challenges at present, higher voltage and multiplexed network architectures are potential solutions in the longer term. A near term solution, motivated by the benefits derived from the application of small FPCs, is that of large area FPCs of such dimensions capable of replacing an entire wiring loom.

This research has investigated in respect of a large area FPC solution, engineering and design challenges at the first phase of the product development cycle. Emphasis within this research has been placed on the substitution of an existing instrument panel and door harness with large area FPCs designed for conventional 14-volts, 14/42 dual voltage and multiplexed electrical architectures and manufactured via established industrial practices, utilizing commercially available materials. Two distinct themes have been explored, the first being an investigation of preferred materials for automotive FPC manufacture and the second being FPC design.

To investigate FPC materials, a factorial experiment is preferred. However, for manageability, a reduced experiment was performed, focussing on commercially realistic substrate and laminate combinations. Limitations in the experiment results, due to commercial sensitivities and inadequate test coupons have precluded a detailed assessment of the candidate materials. From the limited results however, some degradation trends have been observed. Temperature cycling under uncontrolled humidity did not induce material degradation. Degradation of materials occurred under damp heat ageing. PET based substrates and laminates do not retain their initial material properties and degrade rapidly during damp heat ageing. PEN based substrates and laminates show better resistance to damp heat ageing and retain their initial material properties for a longer period during damp heat ageing. Recommendations have been made for further experiments to be performed and the experiment procedures to be reviewed for electrical property tests.

A departure from the industrial practice of damp heat ageing candidate materials for 3000 hours is proposed. The required time for damp heat ageing, so as to simulate 12 years in a vehicle, has been estimated through the use of an Eyring model based on the rate of hydrolysis of Mylar A film, and an assumptive model for the micro-climate within the vehicle passenger cabin and door interiors. The time required for damp heat ageing in this research has been estimated to be 206 hours. When reviewed using this time estimate, the experiment results support the applicability of both PET and PEN based FPCs in both cockpit and door areas.

Proposals for a draft specification for automotive FPCs have been presented, guided by existing standards and specifications for automotive round wire and for conventional FPCs. The specification defines the physical tests to be performed on candidate materials before and/or after accelerated ageing by means of exposure to elevated environmental conditions, used to stimulate degradation mechanisms occurring in a vehicle.

A prototype large area FPC was designed using the Mentor Graphics Board Station (version 8.0) EDA suite to implement a substitute for an in-production IP harness. Design challenges such as rules for circuit trace sizing and unavailability of automotive FPC connectors led to an impractical solution for a wire harness substitute. An alternative approach to circuit design by way of a multilayer FPC solution also resulted in an inelegant and impractical solution. Further design philosophies require investigation, including an economic justification for any resulting solution. The investigation of the FPC design process highlighted the inability of large area FPCs to be designed as drop-in substitutes for existing complex wire harnesses. However, large area FPCs may be better suited to alternative electrical architectures such as CANBus. Further, for new vehicle models, the design of the electrical wiring system should occur much earlier in the vehicle design process.

9.1 Recommendations for Further Work

The following recommendations have been made in respect of further investigations of large area FPCs for automotive applications:

i. Further experiments on FPC materials to establish the contribution of different materials and layers of the FPC on relevant properties.

ii. An investigation of the reaction kinetics of the hydrolysis of 75 micron Mylar A film is recommended. Specifically, equations for the rate of hydrolysis of 75 micron Mylar A film at different temperatures and humidity should be established, to enable a more precise estimation of time required for accelerated ageing. The method of investigation employed by McMahon et al [1959] should be followed.

iii. A similar investigation of alternative films, for example, PET/PEN blends, Poly(ether-ether ketone) (PEEK), and films having a higher melting point/glass transition should be conducted as such films may offer improved resistance to hydrolytic degradation and potentially allow large area FPCs to be assembled at the Body-in-White stage of vehicle assembly.

iv. The rate of hydrolysis of candidate adhesives at different temperatures and humidity should be established.

v. An investigation of the diurnal temperature and relative humidity within the vehicle doors and cockpit deployed in different geographic regions should be conducted.

vi. The effect of vibration on the reliability of large area automotive FPCs should be investigated.

vii. An investigation of the FPC under the application of multiple stresses [temperature, humidity and voltage] should be performed for both 14-volt and 14/42-volt automotive applications.

viii. The reliability of side-to-side interconnections, for example, plated through-hole vias and crimps, should be investigated for automotive operating conditions.

ix. The ampacity of electrodeposited and conductive ink vias and crimps, including thermal behaviour during normal operation within the automobile should be established.

x. Component attachment, in particular the reliability of lead-free solder joints under automotive operating conditions should be investigated. Although the European Union directives on waste electrical and electronic equipment (WEEE) [European Community, 2003b] and reduction of hazardous substances in electrical and electronic equipment (RoHS) [European Community, 2003a] do not at present apply to automotive electrical and electronic products, it is anticipated that such products would nonetheless be manufactured using lead free solder in the future.

xi. A further survey of available automotive FPC connectors and an investigation of their potential failures modes and mechanisms should be performed.

xii. The development of a comprehensive specification for automotive FPCs, to include the requirements for constituent materials (aged and un-aged) and performance requirements for intra-circuit connections and component attachment is required.

xiii. Strategies for handling and assembly into the vehicle, repair and maintenance, and end-of life recycling processes should be investigated.

xiv. Further investigation of FPC design methodologies, including the use of 3-dimensional CAD tools should be conducted.

xv. The economic justification for substituting wire harnesses with large area FPCs should be established. Contributing factors to the total automobile life cycle cost, for example, cost per FPC, technological added-value, savings accrued through new manufacturing processes, vehicle warranty costs, and end-of-life vehicle recycling cost, should be investigated.

xvi. A lab-field correlation of material properties to verify the accuracy of the derived time for accelerated ageing should be performed.

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GLOSSARY

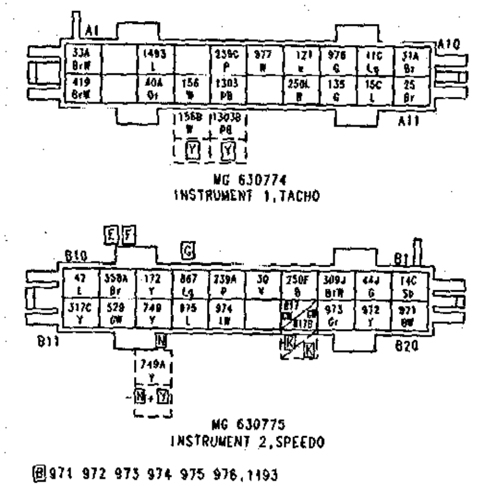
Splice	A node where separate wires are electrically and mechanically joined, typically along the length of a larger power or ground wire.
Standard	A "document established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context". Further, "Standards should be based on the consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits".
Specification	A "standard that sets out detailed requirements, to be satisfied by a product, material, process, service or system, and the procedures for checking conformity to these requirements".
Draft for Development	A "provisional document, developed under broadly the same processes as a formal standard and published when standardization of a particular subject is urgently required, but further research or development is required before it can be published as a British Standard".

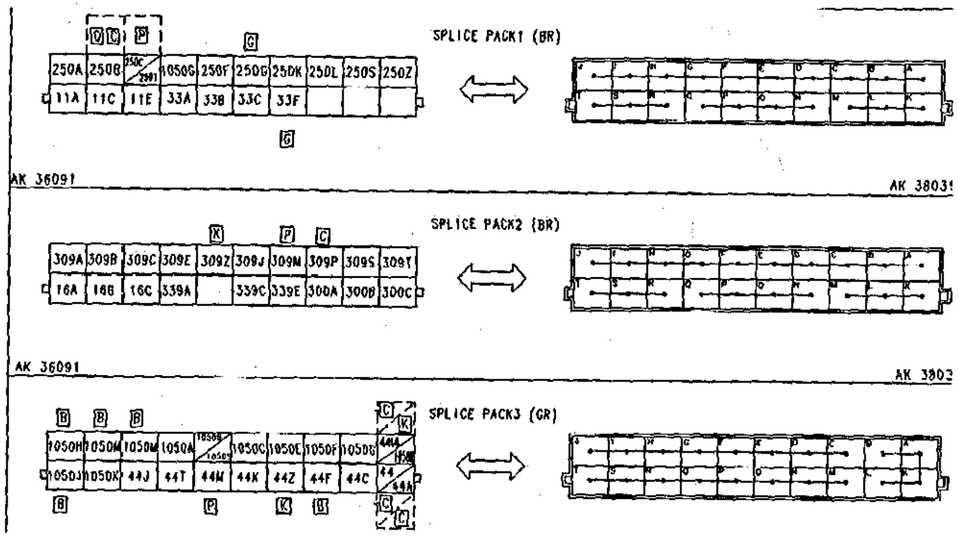
APPENDIX

ISO 6722 TEST MATRIX

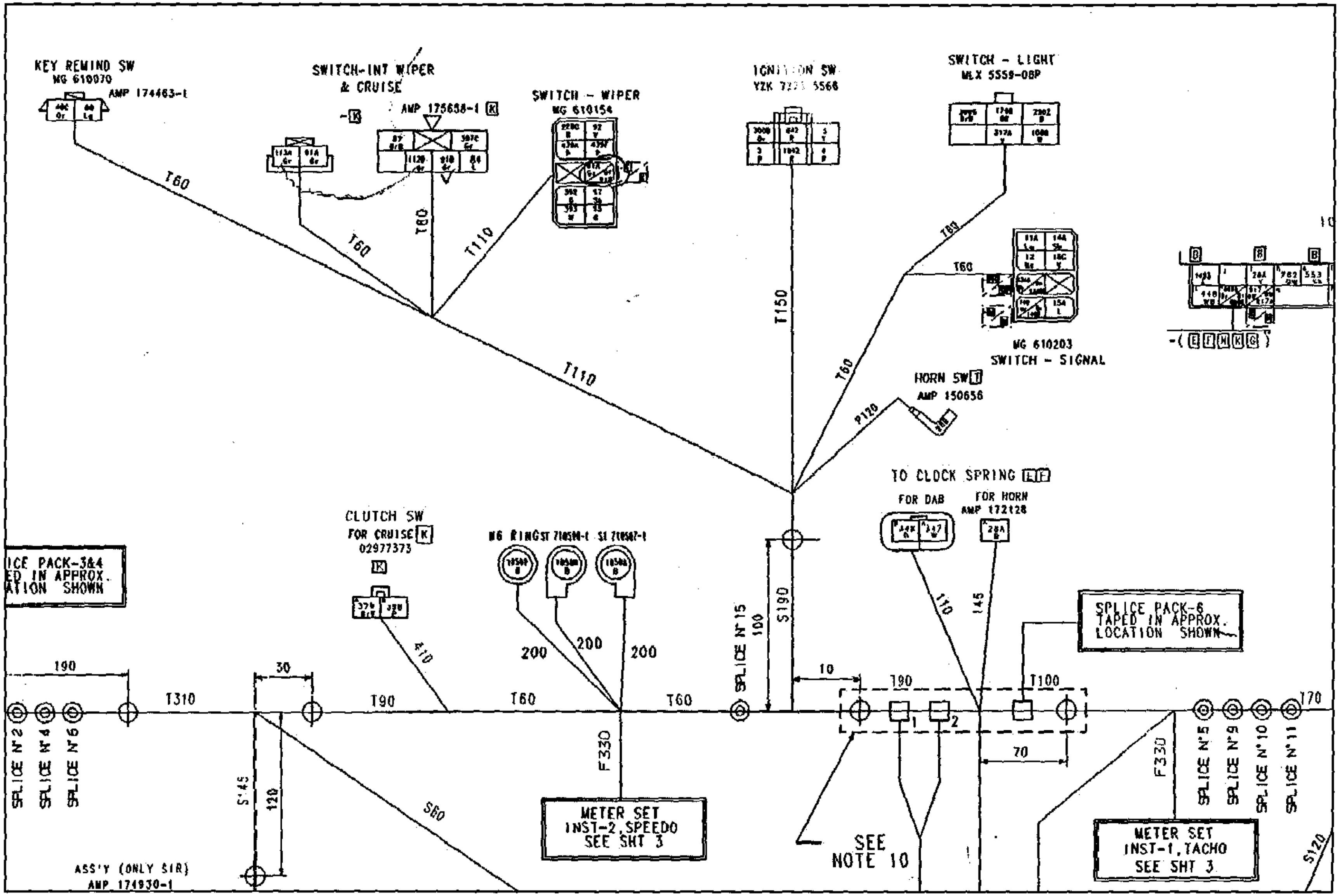
Test Description	Tests During Manufacture	Test For Certification		Test If Required	
		Initial	Periodic	Initial	Periodic
Dimensions					
Outside cable diameter		✓	✓		
Insulation thickness		✓	✓		
Conductor diameter				✓	✓
Electrical characteristics					
Conductor resistance		✓	✓		
Withstand voltage		✓	✓		
Insulation faults	✓				
Insulation volume resistivity				✓	✓
Mechanical characteristics					
Pressure (Pinch Test) at high temperature		✓	✓		
Strip force				✓	✓
Low-temperature characteristics					
Winding		✓	✓		
Impact (Drop Test)				✓	✓
Resistance to abrasion					
Sandpaper abrasion OR		✓	✓		
Scrape abrasion					
Heat ageing					
Long-term ageing, 3000hrs		✓			
Short-term ageing, 240hrs		✓	✓		
Thermal overload				✓	✓
Shrinkage by heat		✓	✓		
Resistance to chemicals					
Fluid compatibility		✓		✓	
Durability of cable marking				✓	✓
Resistance to ozone				✓	
Resistance to hot water				✓	
Temperature & humidity cycling				✓	
Resistance to flame propagation		✓	✓		
✓	To be applied				

J-100 SPLICE PACK DRAWING

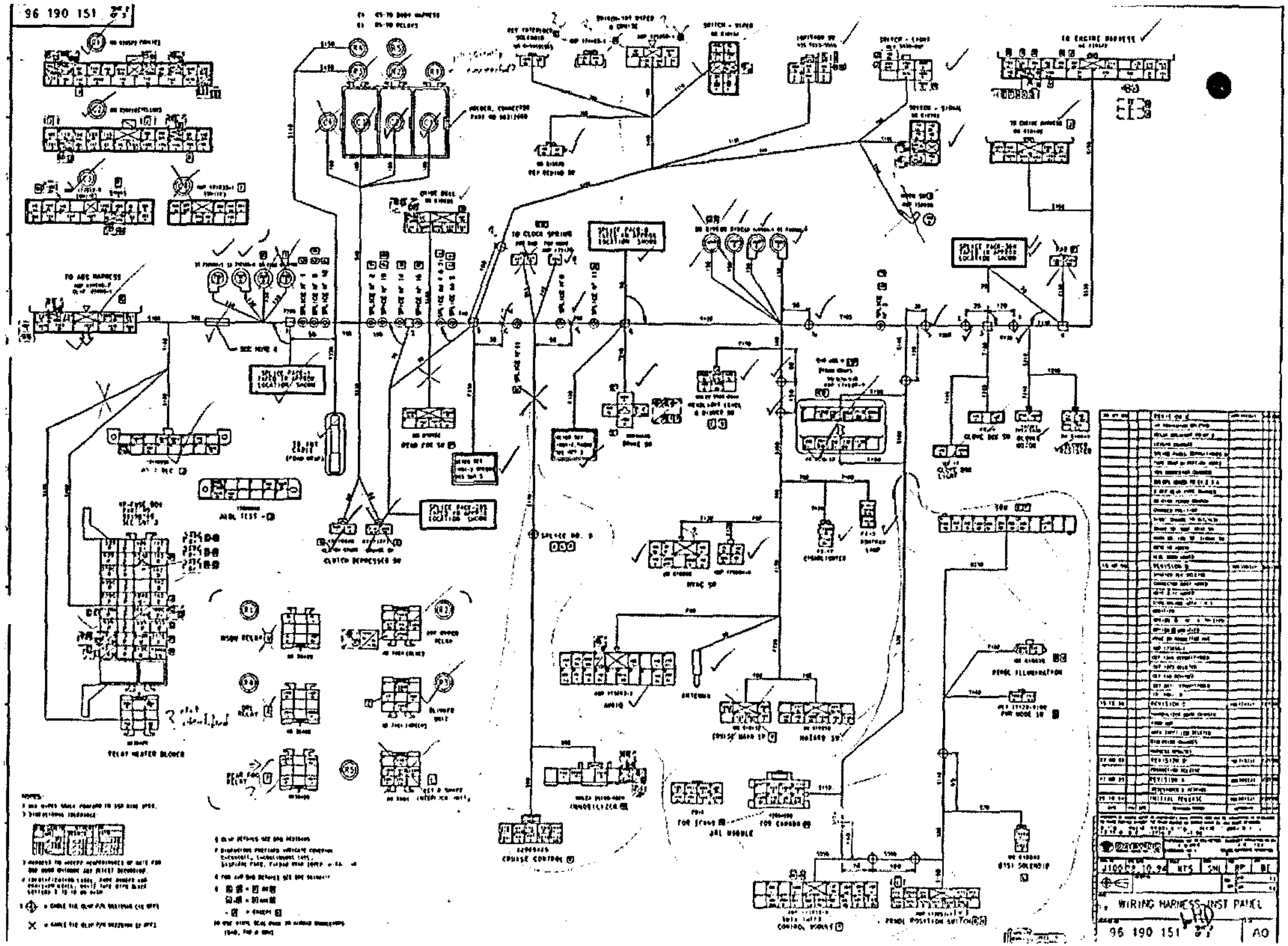




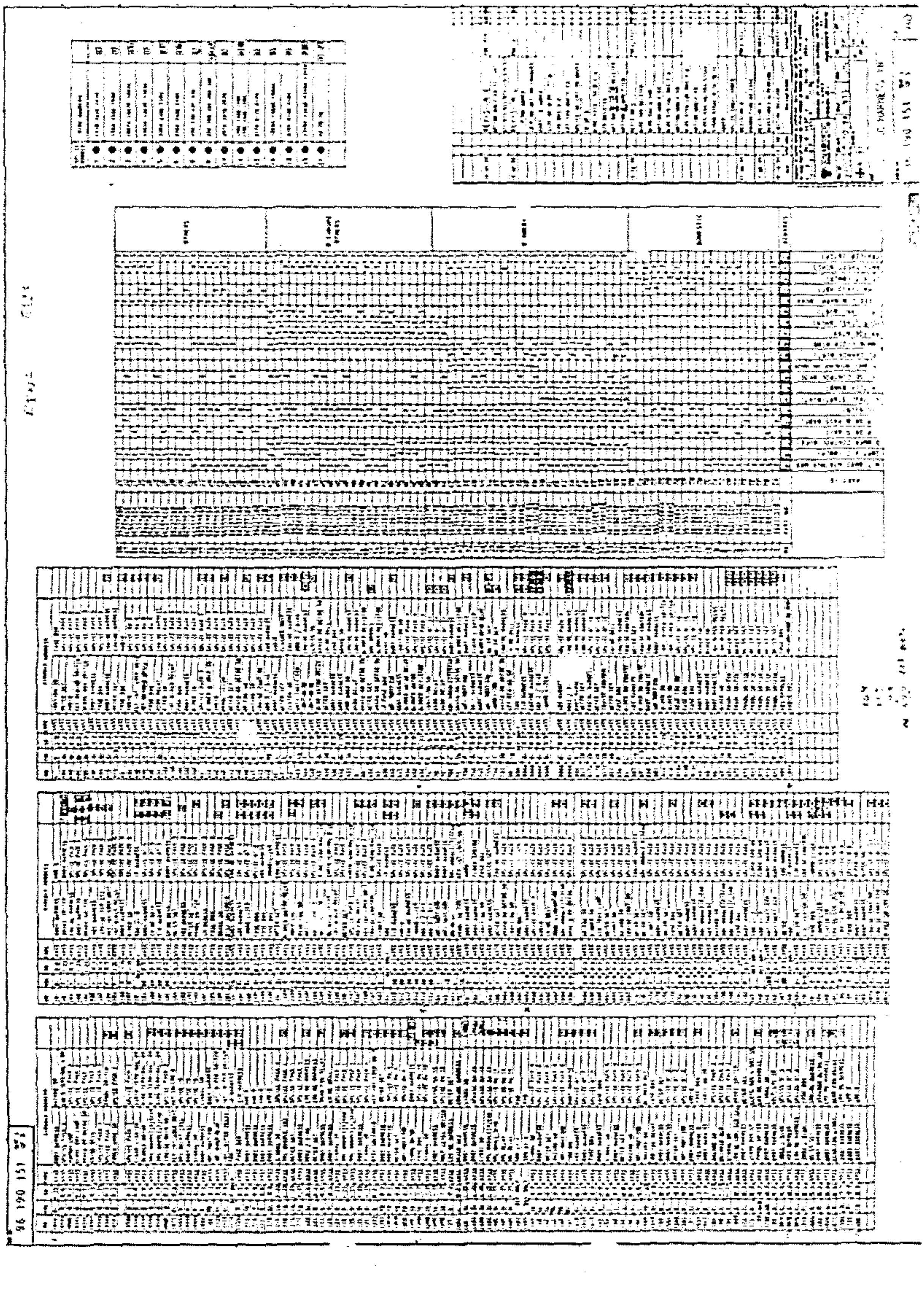
SECTION OF J-100 SCHEMATIC LAYOUT DIAGRAM



J-100 LAYOUT SCHEMATIC [REDUCED VIEW]



J-100 CONNECTIVITY TABLE [REDUCED VIEW]



J-100 CIRCUITS

Circuit No.	Start	End	Wire CSA (mmsq.)	Load Current (mean) (Amps)
1040	Body Harness	Hazard Sw	1.25	3.81
1050A	Splice Pk3	Earth Term-A RH	0.80	2.06
1050B	Ashtray Lamp	Splice Pk 3	0.30	0.09
1050C	Glove Box Lamp	Splice Pk 3	0.30	0.76
1050E	HVAC & RR Defog SW	Splice Pk 3	0.30	0.03035
1050F	Chime Bell	Splice Pk 3	0.30	0.04
1050G	Splice Pk1	Splice Pk 3	1.25	2.02
1050N	Cigar Lighter	Earth Term RH	0.80	8.5
1050P	Blower Motor	Ring Term RH	2.00	28.42
1050Q	DRL Module (E) CAN	Ring Term RH	0.80	6.88
1080	Body Harness	Signal Sw	0.30	0.17
109	Anti-theft ECU	Body Harness	0.30	0.25
112A	Int. Wiper Relay	Int. Wiper Sw	0.50	0.01332
1139A	Fuse Box	SIR Harness	0.50	3.54
115	Body Harness	Audio	0.80	0.21
116	Body Harness	Audio	0.80	7.4
117	Body Harness	Audio	0.80	8.5
118	Body Harness	Audio	0.80	0.05
11A	Signal Sw	Splice Pk 1	1.25	0.09
11B	DRL Module (B)	Splice Pk 1	1.25	1.86
11C	Meter Set	Splice Pk 1	1.25	0.09
11E	Body Harness	Splice Pk 1	1.25	19.55
120	OBD2/DIAG	Engine Harness	0.50	3.54
121	Meter Set	Engine Harness	0.30	0.76
126	Body Harness	Chime Bell	0.30	6.88
12A	Signal Sw	Splice Pk 1	1.25	2.06
12B	DRL Module (C) CAN	Splice Pk 1	1.25	3.81
12C	Body Harness	Splice Pk 1	1.25	22.5
12E	Signal Sw	Splice Pk 1	1.25	3.81
1303A	Body Harness	Splice No 4	0.30	0.75
1303B	Meter Set	Splice No 4	0.30	0.75
1303C	Anti-theft ECU	Splice No 4	0.30	0.12
1346	Signal Sw	Body Harness	1.25	2.02
135	Engine Harness	Meter Set	0.30	0.12
141B	ABS Harness	Splice No 1	0.30	4.66
141C	Body Harness	Splice No 1	0.30	0.18
141E	Fuse Box	Splice No 1	0.30	0.04
142	Body Harness	Fuse Box	2.00	8.91
14A	Signal Sw	Splice Pk 6	0.80	0.21
14B	Body Harness	Splice Pk 6	0.80	3.54
14C	Meter Set	Splice Pk 6	0.50	0.05

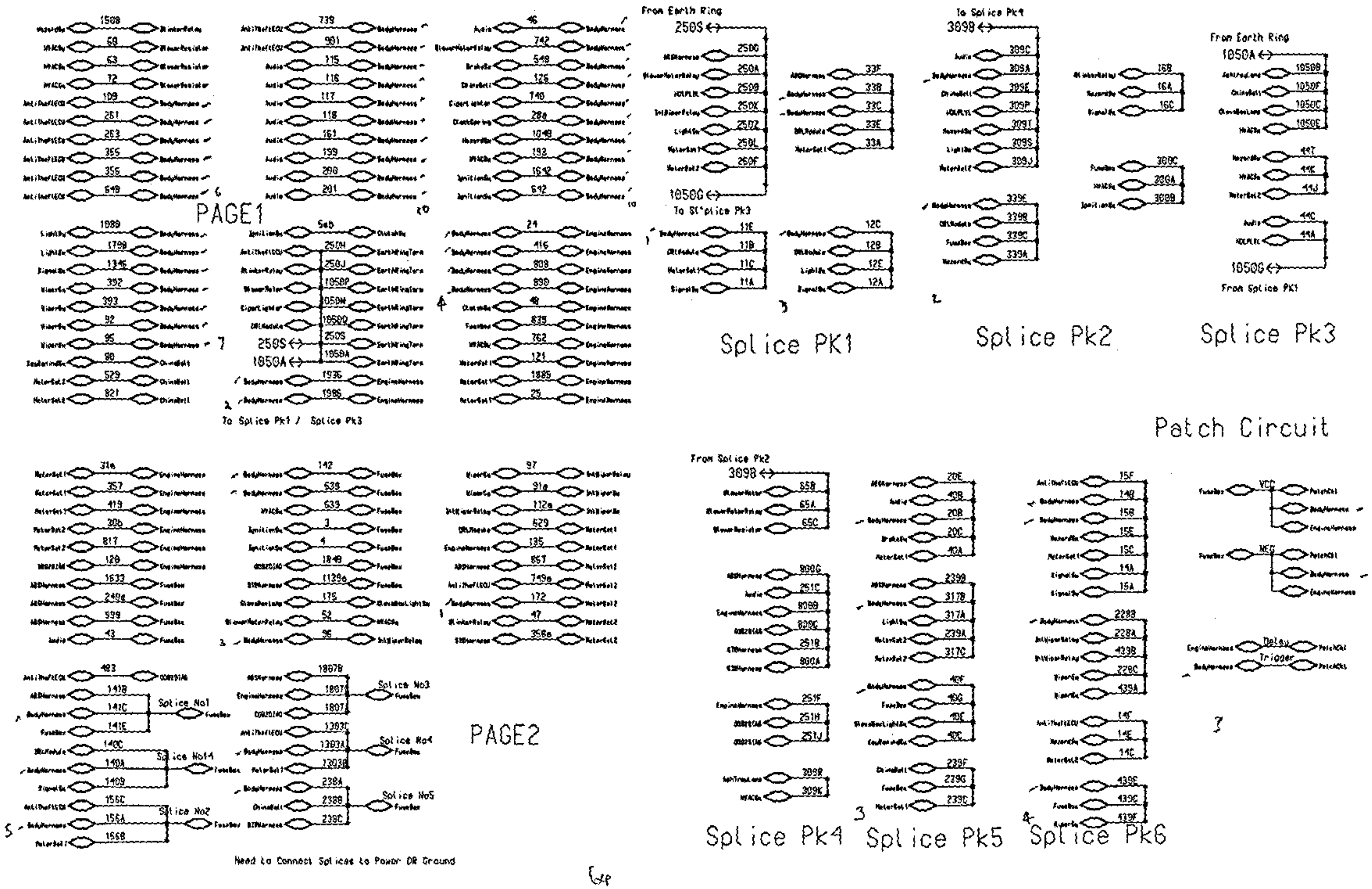
Circuit No.	Start	End	Wire CSA (mmsq.)	Load Current (mean) (Amps)
14E	Hazard Sw	Splice Pk 6	0.80	2.06
14F	Anti-theft ECU	Splice Pk 6	0.80	0.05
1508	Hazard Sw	Splice Pk 6	1.25	2.06
156A	Body Harness	Splice No 2	0.30	0.89
156B	Meter Set	Splice No 2	0.30	0.21
156C	Anti-theft ECU	Splice No 2	0.30	4.26
15A	Signal Sw	Splice Pk 6	0.80	0.05
15B	Body Harness	Splice Pk 6	0.80	8.5
15C	Meter Set	Splice Pk 6	0.80	0.05
15E	Hazard Sw	Splice Pk 6	0.80	6.88
15F	Anti-theft ECU	Splice Pk 6	0.80	6.88
161	Body Harness	Audio	0.30	0.25
1633	ABS Harness	Fuse Box	2.00	7.4
1642	Body Harness	Ignition Sw	2.00	13.08
16A	Hazard Sw	Splice Pk 2	1.25	17.07
16B	Blinker Rly	Splice Pk 2	1.25	2.06
16C	Signal Sw	Splice Pk 2	1.25	5.43
172	Body Harness	Meter Set	0.30	0.17
175	Glove Box Lamp	Glove Box Light Sw	0.30	0.76
1798	Body Harness	Signal Sw	0.30	0.17
1807A	OBD2/DIAG	Splice No 3	0.30	0.09
1807B	ABS Harness	Splice No 3	0.30	0.45
1807C	Engine Harness	Splice No 3	0.30	0.04
1840	OBD2/DIAG	Fuse Box	0.30	0.21
1885	Meter Set	Engine Harness	0.30	0.25
193	Body Harness	HVAC & RR Defog Sw	0.30	0.16
1936	Body Harness	Engine Harness	0.30	0.0029
1986	Body Harness	Engine Harness	0.50	0.0001
199	Body Harness	Audio	0.80	8.5
200	Body Harness	Audio	0.80	7.4
201	Body Harness	Audio	0.80	8.5
20B	Body Harness	Splice Pk 5	1.25	1.86
20C	Brake Sw	Splice Pk 5	1.25	1.86
20E	ABS Harness	Splice Pk 5	0.50	0.12
228A	Int Wiper Relay	Splice Pk 6	1.25	2.06
228B	Body Harness	Splice Pk 6	1.25	17.07
228C	Wiper Sw	Splice Pk 6	1.25	0.09
238A	Body Harness	Splice No 5	0.30	0.00073
238B	Chime Bell	Splice No 5	0.30	0.89
238C	SIR Harness	Splice No 5	0.30	0.04
239A	Meter Set	Splice Pk 5	0.30	0.45
239B	ABS Harness	Splice Pk 5	0.30	0.00073
239C	Meter Set	Splice Pk 5	0.30	0.21

Circuit No.	Start	End	Wire CSA (mmsq.)	Load Current (mean) (Amps)
239F	Chime Bell	Splice Pk 5	0.30	0.02
239G	Fuse Box	Splice Pk 5	0.30	2.13
24	Body Harness	Engine Harness	0.80	2.06
240E	Fuse Box	ABS Harness	0.30	1.02
25	Meter Set	Engine Harness	0.30	0.17
250A	Blower Motor Relay	Splice Pk 1	0.30	0.18
250B	HDLP LVL	Splice PK 1	0.30	0.12
250F	Meter Set	Splice Pk 1	0.30	0.09
250G	ABS Harness	Splice Pk 1	0.30	0.00073
250H	Anti-theft ECU	Ring Term LH	0.50	4.1
250J	Blinker Rly	Earth Term -B LH	0.80	2.06
250K	Int Wiper Relay	Splice Pk 1	0.50	0.02579
250L	Meter Set	Splice Pk 1	0.80	0.21
250S	Splice Pk 1	Earth Term -A LH	0.80	6.88
250W	Key Lock Int Unit	Splice Pk 1	0.30	0.00006
250Z	Light Sw	Splice Pk 1	0.30	0.76
251B	SIR Harness	Splice Pk 4	0.30	0.75
251C	Audio	Splice Pk 4	0.30	4.66
251F	Engine Harness	Splice Pk4	0.30	0.01375
251H	OBD2/DIAG	Splice Pk 4	0.30	0.3
251J	OBD2/DIAG	Splice Pk4	0.30	0.2
261	Anti-theft ECU	Body Harness	0.30	6.88
263	Anti-theft ECU	Body Harness	0.30	0.17
28A	Body Harness	Clock Spring	0.50	0.0001
3	Ignition Sw	Fuse Box	2.00	22.5
300A	HVAC & RR Defog Sw	Splice Pk2	2.00	0.03035
300B	Ignition Sw	Splice Pk2	2.00	22.5
300C	Fuse Box	Splice Pk2	2.00	0.79
309A	Body Harness	Splice Pk2	0.30	0.12
309B	Splice Pk 4	Splice Pk2	0.30	0.45
309C	Audio	Splice Pk2	0.30	0.25
309E	Chime Bell	Splice Pk2	0.30	4.26
309J	Meter Set	Splice Pk 2	0.30	0.89
309K	HVAC & RR Defog Sw	Splice Pk 4	0.30	0.3
309P	Dimmer Sw	Splice Pk 2	0.30	0.09
309R	Ash Tray Lamp	Splice Pk 4	0.30	0.09
309S	Light Sw	Splice Pk 2	0.30	0.00006
309T	Hazard Sw	Splice Pk 2	0.30	0.3
309Z	Cruise Cont Sw	Splice Pk 2	0.30	0.0029
30B	Meter Set	Engine Harness	0.30	0.75
317A	Light Sw	Splice Pk 5	0.30	0.09
317B	Body Harness	Splice Pk 5	0.30	0.16
317C	Meter Set	Splice Pk 5	0.30	0.03035

Circuit No.	Start	End	Wire CSA (mmsq.)	Load Current (mean) (Amps)
31A	Meter Set	Engine Harness	0.30	0.00655
339A	Hazard Sw	Splice Pk 2	1.25	22.5
339B	DRL Module (F) CAN	Splice Pk 2	0.50	0.01332
339C	Fuse Box	Splice Pk 2	1.25	2.02
339E	Body Harness	Splice Pk 2	0.50	0.12
33A	Meter Set	Splice Pk 1	0.30	1.02
33B	Body Harness	Splice Pk 1	0.30	0.00073
33C	Body Harness	Splice Pk 1	0.30	0.3
33E	DRL Module (D) CAN	Splice Pk 1	0.30	0.16
33F	ABS Harness	Splice Pk 1	0.30	0.01375
355	Anti-theft ECU	Body Harness	0.30	0.04
356	Anti-theft ECU	Body Harness	0.30	0.18
357	Meter Set	Engine Harness	0.50	0.02579
358A	Meter Set	SIR Harness	0.50	6.77
392	Body Harness	Wiper Sw	1.25	3.81
393	Body Harness	Wiper Sw	1.25	5.43
39A	Immobilizer	Splice No 9	0.30	0.0029
4	Ignition Sw	Fuse Box	2.00	1.02
40A	Meter Set	Splice Pk 5	0.30	0.09
40B	Audio	Splice Pk 5	0.30	4.26
40C	Key Remind Sw	Splice Pk 5	0.30	0.2
40E	Glove Box Sw	Splice Pk 5	0.30	0.25
40F	Body Harness	Splice Pk 5	0.30	0.00655
40G	Fuse Box	Splice Pk 5	0.30	0
416	Body Harness	Engine Harness	0.30	0.00006
419	Meter Set	Engine Harness	0.30	0.16
43	Fuse Box	Audio	0.30	1.02
439A	Wiper Sw	Splice Pk 6	1.25	17.07
439B	Int Wiper Relay	Splice Pk 6	1.25	5.43
439C	Fuse Box	Splice Pk 6	1.25	22.5
439E	Body Harness	Splice Pk 6	1.25	0.09
439F	Wiper Sw	Splice Pk 6	1.25	19.55
44A	Dimmer & HDLP Sw	Splice Pk 3	0.30	0.16
44C	Audio	Splice Pk 3	0.30	0.25
44J	Meter Set	Splice Pk 3	0.30	0.89
44K	HVAC & RR Defog Sw	Splice Pk 3	0.30	0.3
44T	Hazard Sw	Splice Pk 3	0.30	0.89
46	Body Harness	Audio	0.80	3.54
47	Meter Set	Flasher Unit	0.50	2.22
48	Clutch Sw	Engine Harness	2.00	1.02
483	Anti-theft ECU	OBD2/DIAG	0.30	2.13
52	Blwr Motor Relay	HVAC & RR Defog Sw	1.00	0.19
529	Meter Set	Chime Bell	0.30	0.09

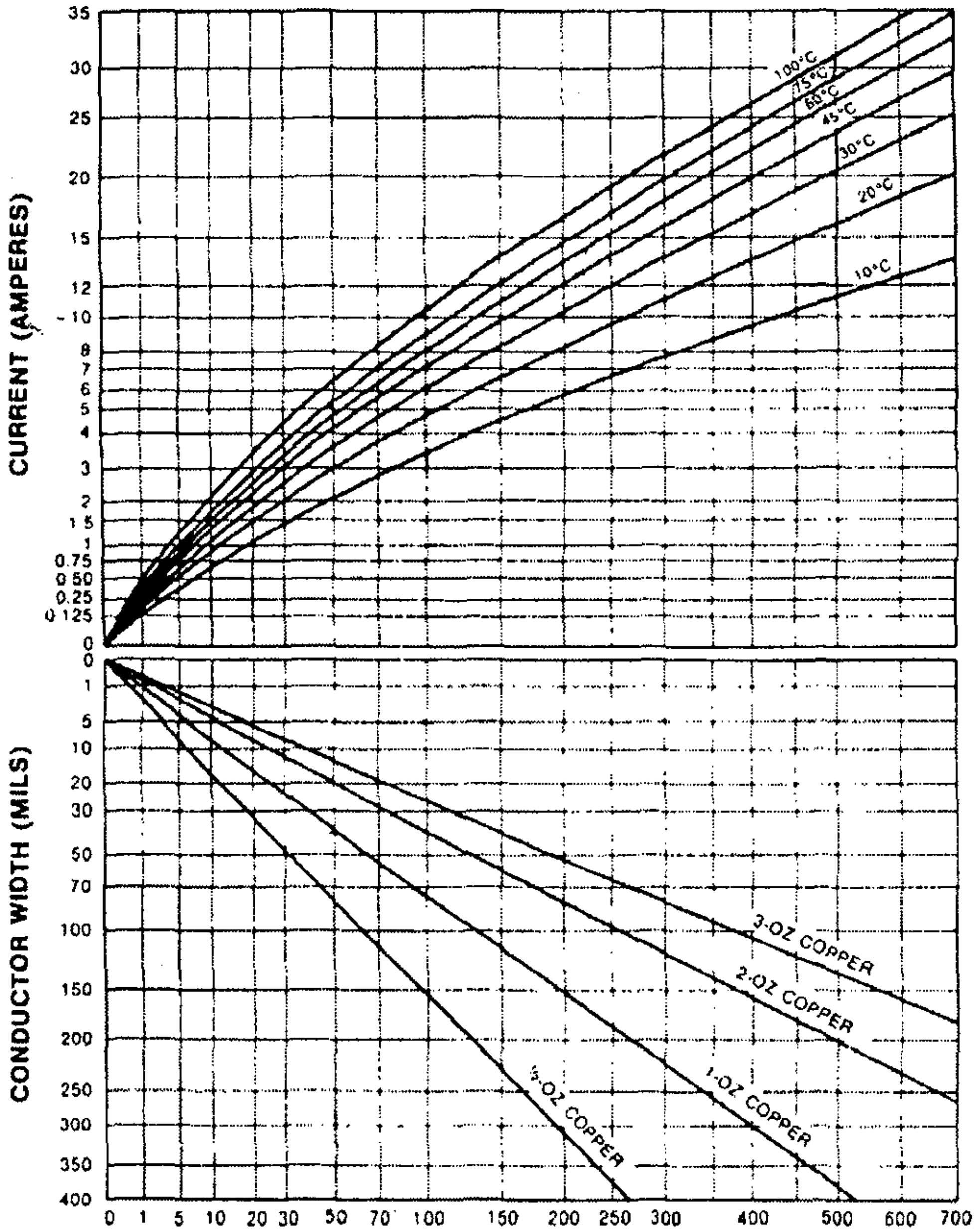
Circuit No.	Start	End	Wire CSA (mmsq.)	Load Current (mean) (Amps)
539	Body Harness	Fuse Box	0.50	2.22
540	Body Harness	Brake Sw	1.25	5.43
5AB	Ignition Sw	Clutch Sw	2.00	7.4
6	NSBU Relay	Engine Harness	2.00	8.84
60	HVAC & RR Defog Sw	Blower Resistor	1.00	0.19
629	Meter Set	DRL Module	0.30	0
63	HVAC & RR Defog Sw	Blower Resistor	1.00	0.19
639	Fuse Box	HVAC Sw	0.30	0.16
640	Anti-theft ECU	Body Harness	0.50	6.77
642	Body Harness	Ignition Sw	2.00	22.5
65A	Blwr Motor Relay	Splice Pk 4	2.00	0.03035
65B	Blower Motor	Splice Pk 4	2.00	28.42
65C	Blower Resistor	Splice Pk 4	1.25	1.86
72	HVAC & RR Defog Sw	Blower Resistor	1.00	0.19
739	Anti-theft ECU	Body Harness	0.30	0.2
740	Body Harness	Cigar Lighter	0.80	8.5
742	Body Harness	Blower Motor Relay	2.00	22.5
749A	Anti-theft ECU	Meter Set	0.30	0.89
762	HVAC & RR Defog Sw	Engine Harness	1.00	0.19
80	Key Remind Sw	Chime Bell	0.30	0.04
800A	SIR Harness	Splice Pk 4	0.30	0.02
800B	Engine Harness	Splice Pk 4	0.30	0.76
800C	OBD2/DIAG	Splice Pk 4	0.30	0.12
800G	ABS Harness	Splice Pk 4	0.30	0.76
808	Body Harness	Engine Harness	0.30	0.75
817	Meter Set	Engine Harness	0.30	0.00073
821	Meter Set	Chime Bell	0.30	0.02
839	Fuse Box	Engine Harness	0.80	3.54
867	ABS Harness	Meter Set	0.30	0.12
890	Body Harness	Engine Harness	0.30	4.66
901	Anti-theft ECU	Body Harness	0.30	0.00073
91A	Wiper Sw	Int Wiper Sw	1.25	2.02
92	Body Harness	Wiper Sw	1.25	19.55
95	Body Harness	Wiper Sw	1.25	17.07
96	Body Harness	Int Wiper Relay	1.25	19.55
97	Wiper Sw	Int Wiper Relay	0.50	0.05
999	ABS Harness	Fuse Box	0.80	7.4

J-100 SCHEMATIC CAPTURE IN MENTOR GRAPHICS



CONDUCTOR THICKNESS AND WIDTH

(For use in determining current carrying capacity and sizes of etched copper conductors for various temperature rises above ambient)



GTS 3480 - HIGH TEMPERATURE ADHESIVE POLYESTER TAPES

GTS 3480 tapes are constructed from Polyethylene Terephthalate (PET) film coated on one or both sides with a fire retardant epoxy based adhesive system.

The adhesive coating is flexible, non-tacky and of low friction which allows easy positioning. The adhesive system is thermosetting, making it resistant to heat and also fire-retardant, making the tapes self-extinguishing.

GTS 3480 is 94 V-O UL recognised with a UL No. E 172854.

Processing - GTS 3480 tapes may be processed by roll-to-roll lamination. Typical parameters are speed 1.5 m/minute, temperature 160°C, pressure 8-10 kg/cm² (110-150 psi) or by press at 150°C 30 minutes, pressure 7-10 kg/cm² (100-150 psi).

Applications - GTS 3480 tapes are designed for rigid or flexible circuitry insulation and are particularly suitable for insulating circuitry which is to be exposed to high temperature, also suitable for manufacture of jumpers, flat cables and general bonding.

Availability - film thickness 25, 50, 75, 100 and 125 microns (1, 2, 3, 4 and 5 mils). Adhesive thickness 12 to 50 microns (½ to 2 mils).

Rolls - standard width 610 mm (24 inches).

14.07.99

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GTS 3480 TECHNICAL DATA

PROPERTIES	TEST SPECIFICATION	TYPICAL VALUE	UNITS
PHYSICAL			
Peel strength	IPC-TM-650 2.4.9	0.8	N/mm
Elongation *	ASTM D-882-88	120	%
Tensile strength *	ASTM D-882-88	170	Mpa
Youngs Modulus *	ASTM D-882-88	3800	Mpa
THERMAL			
Shrinkage - MD - TD	IPC-TM-650 2.2.4	1.5 1.0	% %
Melting Point *	-	262	°C
Tg *	-	82	°C
ELECTRICAL			
Breakdown Voltage *	ASTM D-149-81	12	KV

* Film data refers to 75 micron film

GTS 3640 -HIGH TEMPERATURE POLYESTER (PEN) TAPES

GTS 3640 tapes are constructed from Polyethylene Naphthalate (PEN) film coated on one or both sides with a fire retardant epoxy based adhesive system.

The adhesive coating is flexible, non-tacky and of low friction which allows easy positioning. The adhesive system is thermosetting, making it resistant to heat and also fire-retardant, making the tapes self-extinguishing.

Processing - GTS 3640 tapes may be processed by roll-to-roll lamination. Typical parameters are speed 1.5 m/minute, temperature 160°C, pressure 8-10 kg/cm² (110-150 psi) or by press at 150°C 30 *minutes*, pressure 7-10 kg/cm² (100-150 psi).

Applications - GTS 3640 tapes are designed for rigid or flexible circuitry insulation and are particularly suitable for insulating circuitry which is to be exposed to soldering temperature, also suitable for manufacture of jumpers, flat cables and general bonding.

Availability - film thickness 25, 50, 75, 100 and 125 microns (1, 2, 3, 4 and 5 mils). Adhesive thickness 12 to 50 microns (½ to 2 mils).

Rolls - standard width 610 mm (24 inches).

27.09.96

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GTS 3640 TECHNICAL DATA

PROPERTIES	TEST SPECIFICATION	TYPICAL VALUE	UNITS
PHYSICAL			
Peel strength	IPC-TM-650 2.4.9	0.8	N/mm
Elongation *	ASTM D-882-88	60	%
Tensile strength *	ASTM D-882-88	220	Mpa
Youngs Modulus *	ASTM D-882-88	6000	Mpa
THERMAL			
Shrinkage - MD - TD	IPC-TM-650 2.2.4	0.5 0.2	% %
Melting Point	-	262	°C
Tg	-	120	°C
ELECTRICAL			
Breakdown Voltage *	ASTM D-149-81	12	KV

* Film data refers to 75 micron film

GTS300 - POLYESTER BASED ADHESIVE TAPES

GTS300 tapes are constructed from polyester film coated on one or both sides with polyester based thermoplastic adhesives.

The adhesive coating is flexible, non-tacky and of low friction, which allows easy positioning. Its composition matches the electrical and dimensional properties of the film and bonds to a large variety of surfaces.

Processing - press materials between 0.17 - 0.69N/mm² (25-100psi) at a temperature of 150 - 170°C (300 - 338°F) for a period of 5 - 10 minutes. Please see separate data sheet on sealing procedures.

GTS Polyester tapes are available with the addition of a blocked catalyst as the GTS302 series or with the addition of fire retardant additives as the GTS340 series.

Visible evidence of seal - the adhesive changes from a cloudy to a clear appearance.

Availability - polyester in thicknessess of 12, 23, 50, 75, 100, 125 to 350 microns (½, 1, 2, 3, 4, 5 to 15 mil). Adhesive thicknesses from 6 to 50 microns (1/4 to 2 mil) on one or both sides.

Rolls - standard width 610mm (24 inch).

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GTS 300 TECHNICAL DATA

(Typical values for 23 micron Polyester & 25 micron Adhesive unless otherwise noted)

PHYSICAL	TEST SPECIFICATION	TYPICAL VALUE	UNITS
Ultimate tensile strength (MD 23°C)	ASTM-D882-64T	172 25,000	MPa psi
#Ultimate elongation (MD at 23°C)	ASTM D-882-64T	120	%
#Tensile modulus (MD at 23°C)	ASTM D-882-64T ASTM D-882-64T	5.1 550,000	GPa psi
Initial tear strength (Graves at 23°C)	ASTM D-1004-61	2.5 10,000	N g/mm
Propogating tear strength (Elmendorf at 23°C)	ASTM D-1922-61T	780 80	mN g
Folding endurance (MIT at 23°C)	ASTM D-2176-63T	50,000	cycles
Moisture absorption	-	0.8	%
Water vapour permeability (24hrs at 37.8°C)	ASTM E-96-63T	7	g/m^2
Hydrogen permeability (24hrs at 23°C)	ASTM D-1434-60	200	ml/m^2
Fungus resistance	IPC-TM-650 2.6.1	Inert	-
Shelf life	Observation	>5	years
Peel strength (adhesive to adhesive)	BS 4584/15/77 IPC-TM-650 2.4.9	0.7 4.0	N/mm lb/in
@Density	ASTM D-1505-68	1.00	g/cm^2
DIMENSIONAL			
Thickness tolerance	ASTM D-374	±10%	%
Coefficient of linear expansion	ASTM D-696-70	2.1×10^{-5}	°C
Coefficient of hydroscopic expansion	-	0.7×10^{-5}	%rh
THERMAL			
Melting temperature range of adhesive	-	135-175	°C
Service temperature intermittant	-	125	-
Service temperature continuous	-	80	°C
Thermal shrinkage MD (30mins at 150°C)TD	IPC-TM-650 2.2.4A	1.1 0.6	% %
ELECTRICAL			
*Dielectric strength (23°C 50Hz)	ASTM-D-149	280-320	KV/mm
Permittivity (23°C 1MHz)	ASTM D-150-64 IPC-TM-650 2.5.5.3	3.3	-
Dissipation factor (23°C 1MHz)	ASTM D-150-64 IPC-TM-650 2.5.5.3	0.02	-
Volume resistivity	ASTM-D-257 IPC-TM-650 2.5.17	1×10^{17}	ohm-cm
Surface resistivity	ASTM D-257 IPC-TM-650 2.5.17	3×10^{9}	ohm-sq

Exclusive of adhesive
@ Varies with adhesive thickness
* For 25µ film

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GTS 5670 - COPPER POLYESTER (PEN) LAMINATES

GTS 5670 laminates are constructed from Polyethylene Naphthalate (PEN) film bonded on one or both sides to high purity electrodeposited or rolled annealed copper foil.

The adhesive is a high temperature fire retardant epoxy system that matches the PEN film giving a high bond strength with excellent flexibility.

GTS 5670 is designed for flexible circuitry applications that require improved stability and solderability with the added advantage of economy.

PEN film has a higher Tg than that of PET film which reduces warpage and shrinkage during high temperature operations such as wave soldering.

GTS 5670 is available in rolls, offering the capability of continuous roll to roll processing.

GTS 5670 is available in copper thickness of 18, 35, 70 and 105 microns (½, 1, 2 and 3 oz/sq ft) with PEN thickness of 25, 50, 75, 100 and 125 microns (1, 2, 3, 4 and 5 mils).

Rolls - standard width of 610 mm (24 inches).

27.09.96

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GTS 5670 TECHNICAL DATA

PROPERTIES	TEST SPECIFICATION	TYPICAL VALUE	UNITS
PHYSICAL			
Peel Strength	IPC-TM-650 2.4.9	1.0	N/mm
Elongation *	ASTM D-882-88	60	%
Tensile Strength *	ASTM D-882-88	220	Mpa
Youngs Modulus *	ASTM D-882-88	6000	Mpa
THERMAL			
Shrinkage - Thermal MD TD - Etch MD TD	IPC TM 650 2.2.4	0.5 0.2 0.06 0.04	% % % %
Melting point	-	262	°C
Tg	-	120	°C
ELECTRICAL			
Breakdown Voltage *	ASTM D-149-81	12	KV
Surface Resistivity	ASTM D-257-83	10^{15}	ohm/sq
Volume Resistivity	ASTM D-257-83	10^{16}	ohm-m

* Film data refers to 75 micron film

GTS 5500 - COPPER POLYESTER LAMINATES

GTS 5500 laminates are constructed from polyester film, bonded on one or both sides to high purity electrodeposited or rolled annealed copper foil.

The adhesive system matches the polyester film, giving a high bond strength with excellent flexibility.

GTS 5500 is available in rolls, offering the capability of continuous roll to roll processing.

The copper polyester laminates are available with fire retardant additions as the GTS 5570 series and also with a higher temperature, improved solvent resistance adhesive system as the GTS 5560 series.

The adhesive system can be offered in colours.

GTS 5500 is available in copper thickness of 18, 35, 70 and 105 microns ((½,1, 2 and 3oz/sq ft) with polyester thickness of 12, 25, 50, 75, 100 and 125 microns (½, 1, 2, 3, 4 and 5 mils).

Rolls - widths up to 1200 mm (48 inches).

24.04.97

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GTS 5500 TECHNICAL DATA

PROPERTIES	TEST SPECIFICATION	TYPICAL VALUE	UNITS
PHYSICAL			
Peel Strength	IPC-TM-650 2.4.9	0.7	N/mm
Elongation	ASTM D-882-75	125	%
Tensile Strength	ASTM D-882-75	19.6	Mpa
THERMAL			
Shrinkage - Thermal MD TD - Etch MD TD	IPC-TM 650 2.2.4	 1.0 0.5 0.3 0.15	 % % % %
ELECTRICAL			
Breakdown Voltage *	ASTM D-149-81	12	KV
Surface Resistivity	ASTM D-257-83	10^{13}	ohm/sq
Volume Resistivity	ASTM D-257-83	10^{15}	ohm-m

* Film data refers to 75 micron film

GTS, one of Europe's leading manufacturers of flexible electrical laminares, specialise in the manufacture and design of flexible laminates and adhesive tapes to meet specific requirements. Combinations of materials, fabrics, scrims, metal foils, plastic films, can generate very strong and very lightweight composites.

GTS, ein in Europa führender Hersteller von flexiblen Elektrolaminaten, spezialisiert in der Entwicklung und Produktion flexibler Laminate und Klebebänder, die Spezifikationen und Kundenwünsche erfüllen.
Materialkombinationen, wie z. B. Gewebe, Leinen oder Metallfolien, verklebt mit Kunststoffolien, ergeben leichte, sehr stabile Verbundwerkstoffe.

GTS, un des premiers fabricants Européens de laminés électriques souples est spécialisé dans l'étude et la fabrication de laminés souples et de bandes adhésives répondant à vos besoins spécifiques. La combinaison de matières, tissus, grilles, feuillards métalliques, films plastiques, peut conduire à des composites très résistants et très légers.

Official distributor of APICAL® polyimide films in Europe

GTS 5560 - COPPER POLYESTER LAMINATES

GTS 5560 laminates are constructed from polyester film, bonded on one or both sides to high purity electrodeposited or rolled annealed copper foil.

The adhesive is a purple, high temperature polyurethane system giving good chemical and temperature resistance and a high bond strength with excellent flexibility.

The main uses for GTS 5560 are flexible circuitry applications that require a higher continuous service temperature and chemical resistance eg. nickel-gold plating.

GTS 5560 is available in rolls, offering the capability of continuous roll to roll processing.

GTS 5560 is available in copper thickness of 18, 35, 70 and 105 microns (½,1, 2 and 3oz/sq ft) with polyester thickness of 12, 23, 36, 50, 75, 100 and 125 microns (½, 1, 1½, 2, 3, 4 and 5 mils).

Rolls - widths up to 1200 mm (48 inches).

5.02.04

GTS 5560 TECHNICAL DATA

PROPERTIES	TEST SPECIFICATION	TYPICAL VALUE	UNITS
PHYSICAL			
Peel Strength	IPC-TM-650 2.4.9	1.0	N/mm
Elongation *	ASTM D-882-88	120	%
Tensile Strength *	ASTM D-882-88	200	Mpa
Youngs Modulus *	ASTM D-882-88	3550	Mpa
THERMAL			
Shrinkage - Thermal MD TD - Etch MD TD	IPC-TM 650 2.2.4	 1.0 0.5 0.3 0.15	 % % % %
Operating Temperature	IPC TM 650 2.6.21	120	°C
ELECTRICAL			
Breakdown Voltage *	ASTM D-149-81	12	KV
Surface Resistivity	ASTM D-257-83	10^{13}	ohm/sq
Volume Resistivity	ASTM D-257-83	10^{15}	ohm-m

* Film data refers to 75 micron film

PRODUCT INFORMATION

PRELIMINARY DATA SHEET

PRODUCT:	L950139
CONSTRUCTIONS:	35 Microns (1oz) Electrodeposited Copper Foil laminated to 75 Microns (3 mil) Polyethylene Terephthalate (PET) film using an aqueous epoxy adhesive system.
APPLICATIONS:	Flexible Circuitry, particularly those applications requiring good resistance to humidity ageing.

TECHNICAL DATA.

Thickness	125 Microns	
Bond Strength	0.8 N/MM	IPC TM 650 2.4.9.
Chemical Resistance	Excellent	IPC TM 650 2.3.2.
Shrinkage, Thermal MD	0.5%	IPC TM 650 2.2.4.
Thermal TD	0.5%	IPC TM 650 2.2.4.
Etch MD	0.1%	IPC TM 650 2.2.4.
Etch TD	0.1%	IPC TM 650 2.2.4.

HUMIDITY AGEING.

Test conditions of 85°C, 95% RH for over 1000 hours show bond reduction of 10 to 20% with the adhesive remaining flexible and tack free.

Under these conditions Copper foil shows oxidation and requires protection.

AVAILABILITY.

L950139 is available in rolls at customers required widths.

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PRELIMINARY PRODUCT INFORMATION SHEET.

PRODUCT: 924-00-01.

DESCRIPTION: 35 Micron (1oz) Electrodeposited Copper Foil bonded to 75 Micron Polyester film using a modified Polyurethane adhesive system.

APPLICATION: Car wiring with increased humidity resistance of the bonding adhesive.

PROCESSING: All standard FPC processes can be used.

TECHNICAL DATA:

THICKNESS:	130 Microns (nominal).	
PEEL STRENGTH:	> 0.7 N/MM	IPC TM 650 2.4.9.
SHRINKAGE: THERMAL:	MD 0.7% TD 0.3%	IPC TM 650 2.2.4.
CHEMICAL RESISTANCE:	Pass	IPC TM 650 2.3.2.
HUMIDITY RESISTANCE:	1000 hours	(95% RH, 85°C)

SUPPLY: Rolls slit to customers required width on 3 or 6 inch cores.

28/06/06

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Foresight Vehicle: Specification and Acceptability Criteria for Copper-Clad Dielectric Materials Used in Large Automotive Flexible Printed Circuits

W. A. Jaggernauth, D. P. Webb, M. C. W. Cottrill, P. J. Palmer, P. P. Conway and A. A. West
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Reprinted From: Foresight Vehicle Technology: Design, ITS, Safety, Electronics, and Materials (SP–1695)

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Foresight Vehicle: Specification and Acceptability Criteria for Copper-clad Dielectric Materials used in Large Automotive Flexible Printed Circuits

W.A.Jaggernauth, D.P.Webb, M.C.W.Cottrill, P.J.Palmer, P.P.Conway and A.A.West
Loughborough University, UK

ABSTRACT

Flexible Printed Circuits (FPCs) have been used extensively in instrument clusters and more recently in headliners of some vehicles. Interest in large area FPCs as a replacement for traditional wiring harnesses has been propelled by the potential benefits, which include weight and space savings, ease of assembly into the vehicle, intelligence through direct mounting of electronic components, and creative design opportunities. This paper describes the development of a specification for flexible copper-clad dielectric materials to be used in the construction of a large FPC intended to replace an instrument panel wiring harness.

INTRODUCTION

Changes in legislation, such as the US Clean Air Act and the EU End of Life Vehicle directive, consumer demand, automotive electrical architecture [1] and manufacturing practices have generated a greater interest in FPCs as an alternative to traditional round-wire harnesses for the purpose of electrical wiring. The inherent properties of FPC provide greater weight and space savings, and offers increased functionality through the mounting of intelligent components. Small area FPCs have been used extensively in instrument clusters and more recently, the headliners of some vehicles. Large area FPCs, will potentially be used in the first instance in the occupant compartment of passenger cars as a replacement for round-wire door and instrument panel harnesses. However, the selection of materials to be used in the construction of automotive FPC wiring harnesses of the lowest cost, compatible with an acceptable level of reliability and safety over the lifetime of the vehicle, is hampered by the absence of specifications and acceptability standards pertaining to material properties. The automotive FPC standards that do exist have been adopted largely unchanged from those of the electronics industry and are not tailored to the specific environmental conditions experienced in a vehicle. Automotive standards for round wire, while relevant to the vehicle environment, are inappropriate for FPC harnesses because of the differing material constructions of both. This paper describes a testing program, leading to the development of a specification for laminate materials for large FPCs in the occupant compartment of a passenger vehicle.

DEVELOPMENT OF AN AUTOMOTIVE FPC SPECIFICATION

Flexible copper-clad materials used in FPC manufacture, are fabricated by laminating rolled-annealed copper to one or both sides of a plastic insulating dielectric film. Figure 1 shows a cross-section of a single sided laminate, including typical dimensions. The most common plastics used for the base dielectric, in increasing cost per unit area are Polyethylene Terephthalate (PET), Polyethylene Naphthalate (PEN) and Polyimide. The adhesive used depends on the required properties, such as temperature stability and humidity resistance. Circuit traces that will conduct electric signals are formed through chemical etching of the copper layer, and to protect the copper traces, a cover layer or coverlay of plastic dielectric film is laminated, or dielectric ink is screen printed over the FPC.

Coverlay: 50µ
Copper: 35µ (1oz.)
Adhesive: 12 ~ 15µ
Base Dielectric: 75µ

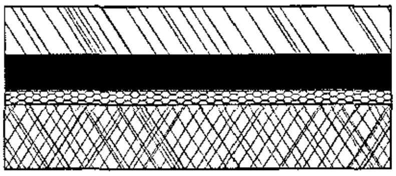

Figure 1. Typical Construction of a FPC laminate

In developing a material specification, the intended functions of the FPC, physical location and vehicle assembly process are used to determine relevant test methods and acceptability criteria. For an instrument panel harness, the following features were considered:

- FPC Manufacturing method is variable.
- Located within the cockpit or in front of the firewall

- Assembly method unknown
- A 14/42 Dual Voltage architecture
- Multiplexing (CAN)
- High Current traces
- Mixed signal traces
- Cost of FPC harness
- Cost saving associated with weight and space saving
- Environment within the passenger compartment
- Vehicle life span of 10 to 12 years
- Relevant Automotive Standards, including test and acceptability criteria

Existing standards for both round wire and FPCs were examined, as well as available data from accelerated life tests performed on similar materials [2]. Low voltage primary cable standards were used as a reference point.

STANDARDS FOR ROUND WIRE – Table 1 lists the round wire standards:

Issuing Body	Standard Number	Title
ISO/DIS	6722	Road Vehicles – 60V and 600V single core cables – Dimensions, test methods and requirements
SAE	J1128	Low – Tension Primary Cable
SAE	J1678	Low – Voltage Ultrathin Wall Primary Cable
SAE	J1292	Automobile, Truck-Tractor, Trailer and Motor Coach Wiring
SAE	J1211	Recommended Environmental Practices For Electronic Equipment Design

Table 1. Round Wire Standards

Most standards by different issuing bodies are similar in scope, prescribed tests and acceptance criteria. Round wire test methods applicable to FPC are listed below:

Dimensions - Cable Diameter, Insulation thickness, Conductor diameter.

Electrical Characteristics - Conductor resistance, withstand voltage, insulation faults, insulation volume resistivity.

Mechanical Characteristics - Pressure test at high temperature, strip force.

Low temperature characteristics - Winding at low temperature, impact.

Resistance to abrasion - Sand paper abrasion, scrape abrasion.

Heat ageing - Short term ageing 240h, long term ageing 3000h, thermal overload, shrinkage by heat

Chemical resistance - Fluid compatibility, durability of cable marking, resistance to ozone, resistance to hot water, environmental cycling.

STANDARDS FOR FPC – Table 2 lists the existing FPC standards. SAE J771 and ARP1612A are automotive FPC standards, adapted from the ANSI/IPC and ASTM standards. As with the round-wire standards, both ANSI/IPC and ASTM specifications are similar.

Issuing Body	Standard Number	Title
SAE	J771	Automotive Printed Circuits
SAE	ARP1612A	Fabrication of Polyimide Printed Circuit Boards
ANSI/IPC	FC-231	Flexible Base Dielectrics for Use in Flexible Printed Wiring
ANSI/IPC	FC-232	Adhesive Coated Dielectric Films for Use as Cover Sheets for Flexible Printed Wiring and Flexible Bonding Films
ANSI/IPC	FC-241	Flexible Metal-Clad Dielectrics for Use in Fabrication of Flexible Printed Wiring
ASTM	D2381	Standard Test Methods for Flexible Composite Materials used for Electrical Insulation
ASTM	D2681	Standard Test Methods For Flexible Composites of Copper Foil with Dielectric Film or Treated Fabrics

Table 2. FPC Standards

TEST METHODS FOR FPC – Test methods with similar scope to the round wire standards are listed below. These tests would be performed throughout an accelerated ageing process, to verify the reliability and life models of the candidate materials.

Tensile Strength and Elongation - IPC 2.4.19. This test is used to determine the tensile strength and elongation of materials exposed to mechanical loads. Initial values are relevant to assembly into the vehicle, while values obtained during accelerated ageing would determine the susceptibility of the material to break if subjected to strain at any time throughout the vehicle lifetime, for example that caused by poor design. This is particularly relevant in the case of PET, recognized to lose tensile strength through moisture absorption, which changes the chemical structure of the material.

Peel Strength (Foil Bond Strength and Coverlay Adhesion) - IPC 2.4.9. Adhesives between the base dielectric and copper layers in an FPC may be susceptible to attack by moisture or be unstable at high temperature, which lowers the bond strength. Detachment of the circuit traces may result.

Initiation Tear Strength - IPC 2.4.16. This determines the force required to initiate a tear in flexible insulating materials and is based on ASTM D1004-66. It is relevant to assembly and mechanical performance *during the vehicle lifetime. Poor design of the FPC* harness may introduce areas prone to tearing as the materials age.

Propagation Tear Strength - IPC 2.4.17.1. Once a tear in the material occurs, this test will determine the force required to propagate the tear, which could eventually lead to sections of the FPC detaching. This is based on ASTM D1938-67.

Flexural Testing - IPC 2.4.3.1. This is applicable to hinged areas such as doors. The test determines the flexural fatigue life for any given bend radius.

Folding - IPC 2.4.5. This is relevant to processing, handing, storage and assembly. It is a qualitative test to determine the resistance to cracking of the copper layer to 180 degree bending.

Low Temperature Flexibility - IPC 2.6.18a. Applicable to areas that are simultaneously exposed to both extreme cold and bending, as a door hinge in winter conditions.

Abrasion/Scratch resistance - IPC 2.4.27.1. In many instances there may be areas of the FPC harness in contact with metal or rough plastic surfaces. With vibration through normal driving, abrasion may lead to copper traces being exposed, and potentially shorting. This test is related to the sandpaper abrasion test for round-wire.

Dimensional stability - IPC 2.2.4. This test determines the temperature induced dimensional change, and that associated with the removal of copper in the chemical etching process.

Insulation and Moisture Resistance within layers - IPC 2.5.11. The insulation resistance of the base dielectric may be lowered by the absorption of moisture. Closely spaced circuit traces may develop short circuits as a result.

Dielectric Strength - ASTM D149-97a. This test determines the dielectric strength, or dielectric breakdown voltage of solid insulating materials at commercial frequencies. The test can be performed under D.C. conditions, however the voltage required to cause dielectric breakdown is 3 to 4 times greater than the A.C. breakdown voltage. Dielectric breakdown is of importance as it is a mechanism by which short circuit failures can occur.

Volume Resistivity & Surface Resistance - IPC 2.5.17. Determines the cross-sectional and surface electrical resistance of the dielectric material under humid conditions. It is based on ASTM D 257

Fluid Resistance - IPC 2.3.2f. Windscreen washing liquid, wax, salt water, lubricants, grease, de-icing fluid, coffee and coca-cola are chemicals that can be found within the passenger compartment of a vehicle, and exposure to these may change the chemical structure of the dielectric materials or the adhesive, causing a decrease in the dielectric strength or bond strength. Materials should be exposed in these chemicals and then tested for peel strength and dielectric strength.

Table 3 lists the recommended acceptance criteria for non-aged flexible dielectric materials, based on the industry standards outlined above. These recommendations are adopted with little change from the IPC standards, and may be an over specification for the intended application. However, they are accepted as the starting values for the indicated tests. None of the standards referenced, for both round-wire and FPC, contain acceptance criteria for tests performed during accelerated ageing, but most round-wire specifications contain a pass/fail test performed after long-term ageing.

PROPERTIES	TEST METHOD	RECOMMENDED VALUES (IPC/SAE/OEM)
Tensile Strength and Elongation	IPC 2.4.19	17,000 –20,000 Psi [>=80% original value, after ageing]
Peel Strength, Foil Bond Strength and Coverlay Adhesion	IPC 2.4.9	4 – 6 lb/inch
Initiation Tear Strength	IPC 2.4.16	226 N.m. (Some standards state 800g)
Propagation Tear Strength	IPC 2.4.17.1	20 gms / 50 gms (<100 microns />100 microns material thickness)
Flexural Testing	IPC 2.4.3.1	Not specified
Folding	IPC 2.4.5	Min of 2mm bulge, without conductor cracking
Low Temperature Flexibility	IPC 2.6.18a	Qualitative. Not Specified
Abrasion/Scratch resistance	IPC 2.4.27.1	Min equivalent to 300 mm sand paper
Dimensional stability	IPC 2.2.4	0.5% Transverse Direction ; 1.0% Machine Direction
Insulation Resistance within layers	IPC 2.5.11	Max 10% change between cycles
Dielectric Strength	ASTM D149-97a	500 V/mil (19.7kV/mm) to 2,500V/mil depending on application
Volume Resistivity & Surface Resistance	IPC 2.5.17	Not specified
Fluid Resistance	*IPC 2.3.2f*	*IPC 2.4.9 / ASTM D149-97a*
Flame Resistance	MVSS302	Max Burn/Flame Transmission rate across surface 102mm/min

Table 3. Existing FPC Acceptance Criteria

Test methods for FPC not relevant to wire harnesses are listed in Table 4.

LEGISLATED STANDARDS – In addition to industry standards, legislation enacted for passenger safety defines specific test procedures and acceptability criteria for materials and component performance.

Flammability of Interior Materials – The US Federal Motor Vehicle Standard (49 CFR Part 571), 'MVSS302', specifies burn resistance requirements for materials used in the occupant compartments of motor vehicles. *The material will be considered pass for a burn rate of* no more than 120mm per minute.

PROGRAM FOR MATERIALS TESTING

ACCELERATED AGEING –Accelerated ageing subjects materials, parts and assemblies to environments exceeding the design limits, and replicates failure modes normally seen during operation [3]. The life expectancy of passenger cars varies between automotive manufacturers, but is on average 12 years. The accelerated ageing parameters used, are based on standard industry practice adopted with little change. .Due to insufficient life data for PET and PEN as well as for round wire, a multivariable accelerated test schedule, was devised to identify the most common failure modes. A large area FPC would be considered to have failed when it can no longer carry the intended electrical signal. Hence a short circuit due to degradation in dielectric properties such as dielectric breakdown and insulation resistance, or an open circuit created by increased resistance in copper due to environmental exposure, are potential failure modes. Open and short circuits can also be caused by cracks in the copper traces, or other mechanical failures such as tearing and de-lamination. Electrical and mechanical failures may result after FPC exposure to corrosive chemicals commonly found around the automotive environment, such as grease, lubricant, and user introduced fluids such as coffee and carbonated beverages.

REJECTED TESTS	Title	Comment
IPC2.1.13	Inspection for inclusions and voids in flexible printed wiring materials	This is a manufacturing issue. No documentation suggesting a degradation in material properties.
IPC2.3.8	Flammability, Flexible Insulating Materials.	Does not give the burn rate of the material, as required by legislation.
IPC2.3.8.1	Flammability of flexible printed wiring.	MVSS 302 is the method is similar, and legally recognized. It can be adapted to be closer to this test, by changing the angle the material is held.
IPC2.3.29	Flammability, Flexible Flat Cable	Relates to FFC, but can be modified to suit FPC using MVSS320 guidelines
IPC2.4.3	Flexural Endurance, Flexible printed wiring materials	Similar to 2.4.3.1, but does not flex around a bend.
IPC2.4.3.2	Flexural Fatigue and Ductility, Flexible Metal Clad Dielectrics	Ductility was not deemed to be a critical parameter due to the nature of the application.
IPC2.4.9.1	Peel Strength of Flexible Circuits.	Specific to Anisotropic Conductive Adhesives. Not in the scope of the project.
IPC2.4.11	Shear Strength, Flexible Dielectric Materials	Deals with manufacturing, and the force required to punch holes in the material.
IPC2.4.13	Solder Float Resistance, Flexible Printed Wiring Materials	Polyester will not survive this test. Alternative 'Heat Treatment' test should be explored, as it is applicable to component soldering.
IPC2.4.20	Terminal Bond Strength, Flexible Printed Wiring	Interesting qualitative test, dealing with the effects of repeated soldering on the bond strength.
IPC2.4.29	Adhesion, Solder Mask, Flexible Circuit	IPC 2.4.5 Test for Folding can be used for this. Applicable to printed ink coverlay.
IPC2.5.5.3	Permittivity (Dielectric Constant) and Loss Tangent (Dissipation Factor) of Materials	Complex test equipment. Other methods used for Dielectric Strength. Permittivity and Loss Tangent are not critical factors to consider at this time.
IPC2.5.8	Dissipation Factor of Flexible Printed Wiring Materials	As above
IPC2.5.13	Resistance of Copper Foil	Actual values for Resistance Vs Conductor Width is needed. A separate test program will determine this.
IPC2.5.15	Guidelines and Test Methods for RFI-EMI Shielding of Flat Cables	A separate Test Program for EMC will be carried out.
IPC2.5.28	Q Resonance, Flexible Wiring Materials	Relates to resonant frequencies and the damping factor 'Q'. Not a critical factor to be explored at this time.
IPC2.6.2	Moisture Absorption, Flexible Printed Wiring	This just determines the amount of water absorbed when material is dipped in water. The procedure can be added to other tests.
IPC2.6.3e	Moisture and Insulation Resistance, Printed Boards	Qualitative test for rigid boards. There is an equivalent test for Flex.
IPC2.6.3.2	Moisture and Insulation Resistance	Superseded by IPC 2.5.11 which is being performed during Accelerated Ageing.
IPC2.6.7	Thermal Shock and Continuity, Printed Board	Reference for Temperature Cycling.
IPC2.6.17	Hydrolytic Stability, Flexible Printed Wiring Material	This is a qualitative test that is not suitable for measuring moisture induced degradation.
IPC2.6.21	Service Temperature of Flexible Printed Wiring	There is no defined service temperature of the product. This test will also be superseded by the ageing tests.

Table 4. FPC Non applicable FPC tests

Materials Test Schedule – Tests were performed on the following materials:

1. Six different copper-clad dielectric films, fabricated from 1oz. Copper, PET or PEN base dielectrics and different adhesives.
2. Five different coverlays, fabricated from PET, PEN and Dielectric Ink.
3. Nine variations of FPC harness laminate fabricated with the above base copper-clad and coverlays.

Samples were aged by temperature cycling only, temperature/humidity cycle only, or exposure to chemicals only. The ageing parameters for the accelerated life testing are:

- Temperature Cycling between –40 and +85°C for 3000 hours. Dwell time at –40 and +85°C set to 2 hours, with ramp up and ramp down times set to 2 hours.

- Temperature/Humidity exposure of 85°C/95%RH for 3000 hours, without variation.
- Immersion in different automotive fluids for up to 72 hours

Table 5 shows the materials tested for each property test. Tests performed on both base dielectric and FPC harness laminate are for comparison of the mechanical protection offered by the coverlay.

Property Test	Base Dielectric	Coverlay	FPC Harness
Tensile Strength	X		
Peel Strength	X		
Initiation Tear	X		X
Propagation Tear	X		X
Flexural Testing	X		X
Folding	X		
Low Temp Flexibility	X		X
Abrasion resistance		X	
Dimensional stability	X		
Insulation Resistance	X		
Dielectric Breakdown	X	X	X
Volume/Surface Resistivity	X		
Fluid Resistance	X		X
Flame Resistance	X	X	X

Table 5. Materials Test Schedule

PRELIMINARY RESULTS

Temperature/Humidity Aging – after 1000 hours

1. Tensile strength of PET reduced by 70%
2. Tensile strength of PEN reduced by 10%
3. Dielectric breakdown shows no significant decrease in both PET and PEN for automotive applications
4. Insulation Resistance shows no significant decrease in both PET and PEN for automotive applications

Temperature Cycling – after 1000 hours

1. No significant decrease in tensile strength in both PET and PEN. This trend should continue, based on previous studies [2]
2. Dielectric Breakdown shows no significant decrease in both PET and PEN for automotive applications
3. Insulation Resistance shows no significant decrease in both PET and PEN for automotive applications

The initial results suggest that PEN is more suitable for the construction of a large area FPC instrument panel harness. Although 3000 hours of accelerated ageing has been an accepted industry practice, further work is needed to adjust the parameters most suited for automotive FPC. Simulating 10-12 years would involve the correlation of field results with those obtained through experiment. As Large FPCs have not been introduced in commercial production, field experiments would not be possible at this time. However, lab-field correlation can be done on round wire, aged under the same conditions [4].

CONCLUSION

This paper presented the development of a specification and acceptability criteria for flexible copper-clad dielectric materials used in large area automotive flexible printed circuits. The specification is based on standard printed circuit industry test for flexible copper-clad materials to measure mechanical, electrical and chemical properties relevant to automotive applications. A test program has been instituted to identify acceptability criteria, including accelerated ageing test parameters. An initial assessment of candidate materials has been discussed. It is expected that the criteria identified by the test program can be modified further by comparison between lab and field data.

ACKNOWLEDGMENTS

The author acknowledges the support of the Flexelec project, funded by the UK Engineering and Physical Sciences Research Council (EPSRC), Grant ref: GR/M75075. This is a collaborative project between Pressac Interconnect Limited (UK), GTS Flexible Materials (UK), Yazaki Europe, and Loughborough University.

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