SUSTAINABLE DEVELOPMENT OF REFRIGERATOR SYSTEMS USING REPLACEMENT ENVIRONMENTALLY ACCEPTABLE REFRIGERANTS

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ABSTRACT

Environmental considerations have led to the phase out of chlorofluorocarbon (CFC) refrigerants from the domestic refrigeration industry. One intriguing aspect is that the chlorine in CFCs is a good lubricating agent and any deterioration of system performance may adversely influence other environmental considerations.

Based on the above, the aim of this research is to address the sustainable development of domestic refrigeration systems using the replacement refrigerant HFC-134a. The work focuses on the emissions that may arise if the electrical consumption of the product deteriorates or its durability is curtailed. Tribological characteristics on compressor components influence both of these product attributes and therefore a thorough system analysis was carried out. An in-house built experimental test rig, which monitored slight variations in the electrical power drawn by a reciprocating hermetic compressor, was used under different experimental conditions. Furthermore, a detailed life cycle assessment on a domestic refrigerator was performed to help quantify the ensuing environmental burdens. In this way, a relation between tribological characteristics, power consumption and environmental impact was studied.

Results have shown that the CFC substitute will increase friction and wear characteristics on the aluminium alloy connecting rod and the steel gudgeon pin. These characteristics led to an increase in the electrical energy consumption of the compressor such that the *indirect* global warming implications are set to rise with HFC-134a. If the sustainable development of this product is to be ascertained then a change in refrigerants alone will not suffice. New design considerations, primarily aimed at servicing and extending the life of the hermetic compressor itself, are considered. This work helps stimulate new ideas to address environmental issues influenced by traditional engineering disciplines. For this reason additional future research work, which will help determine these implications further, is outlined.

PUBLICATIONS RESULTING FROM THESIS

Ciantar, C. and Hadfield, M. 1999. Investigating the sustainable development of domestic refrigerating systems working in an HFC-134a environment. In: Tassou, S., (ed.) *Proceedings of the Recent Developments in Refrigeration and Heat Pump Technologies*, London, Professional Engineering Publishing Ltd., ISBN 1 86058 238 9, pp. 47-59.

Ciantar, C. and Hadfield, M. 1999. Life cycle consequences of domestic refrigerating systems working in an HFC-134a environment. In: Lindemann, U., Birkhofer, H., Meerkamm, H. and Vajna, S., (eds.) *Proceedings of the 12th International Conference on Engineering Design, ICED'99,* Vol. 1, Munich, Technische Universität München, ISBN 3-922979-53-X, pp. 269-272.

Ciantar, C., Hadfield, M., Smith, A.M. and Swallow, A. 1999. The influence of lubricant viscosity on the wear of hermetic compressor components in HFC-134a environments. *Wear Journal.* 236, ISSN 0043-1648, pp. 1-8.

Ciantar, C. and Hadfield, M. 2000. An environmental evaluation of mechanical systems using environmentally acceptable refrigerants. *International Journal of Life Cycle Assessment.* 5 (4), ISSN 0948-3349, pp. 209-220.

Ciantar, C. and Hadfield, M. 2000. Factors affecting the sustainable development in domestic refrigerators. *International Appliance Manufacturing. The Annual Review of Domestic Appliance Design and Manufacturing,* 4, Ashokan International, ISSN 1366-5081, pp. 40-44.

Ciantar, C., Hadfield, M., Swallow, A. and Smith, A. 2000. The influence of POE and PVE lubricant blends within hermetic refrigerating compressors operating with HFC-134a refrigerant. *Wear Journal.* 241 (1), ISSN: 0043-1648, pp. 53-64.

Ciantar, C. and Hadfield, M. 2000. Environmental consequences of tribological issues in mechanical systems using replacement refrigerants. In: Hadfield, M. and Ciantar, C., (eds.) *Proceedings of the First International Conference on Tribology in Environmental Design*, Bournemouth, Professional Engineering Publishing, ISBN 1 86058 266 4, pp. 100-110.

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NOMENCLATURE

As	Arsenic
Ba	Barium
Cd	Cadmium
CFC	Chlorofluorocarbon
CFC-11	Trichloromonofluoromethane
CFC-11 equivalent	See impact equivalent; unit of contribution for ozone depletion
CFC-12	Dichlorodifluoromethane
CO_2	Carbon dioxide
CO_2 equivalent	See impact equivalent; unit of contribution for global warming
COD	Chemical oxygen demand
COP	Coefficient of performance; used to measure the performance of a refrigeration or a heat pump system
Cr	Chromium
Cr equivalent	See impact equivalent; unit of contribution for ecotoxicity
Direct emissions	The chemical action a compound has as a greenhouse gas
Dust equivalent	See impact equivalent; unit of contribution for winter smog
EDX	Energy dispersive x-ray microanalysis
EP	Extreme pressure
Ethene equivalent	See impact equivalent; unit of contribution for summer smog
eV	Electron volts used in XPS analysis
FU	Functional unit; a reference product in an LCA study
GWP	Global warming potential
HC	Hydrocarbon
HCl	Hydrochloric acid
HF	Hydrogen fluoride
HFC	Hydrofluorocarbon
HFC-134a	Tetrafluoroethane
HV	Vickers Hardness number
Impact equivalent	Unit of potential contribution (including the contribution of emissions known to contribute to the impact category)
Indirect emissions	Emissions resulting from the burning of fuels needed to energise equipment which synthesises, uses and recovers a compound
IPCC	Intergovernmental Panel on Climate Change
Item	Functional unit parts (like compressor) combined for simplicity of presentation throughout the LCA study
ITH	Integrated time horizon; used in GWP calculations to account for the different atmospheric lifetimes of gases
kg/kg equivalent	See impact equivalent; unit of contribution for human toxicity
LCA	Life cycle assessment

LCWI	Life cycle warming impact
LED	Light emitting diode
Load face	The surfaces between the pin and rod and the rod and driveshaft experiencing the greater pressure during piston compression
Mass balance	For each process in the LCA study, *mass in* equals *mass out*
Mt	Million tonnes
N	Nitrogen
N_2O	Nitrogen dioxide
NH_3	Ammonia
NH_3 equivalent	See impact equivalent; unit of contribution for odours
Ni	Nickel
NO_X	Nitrogen oxides
NO_X equivalent	See impact equivalent; unit of contribution for summer smog
ODP	Ozone depletion potential
Oil equivalent	See impact equivalent; unit of contribution for abiotic depletion
PAG	Polyalkalyene glycol oil; a synthetic lubricant for HFC-134a
PAH	Polycyclic aromatic hydrocarbon
PAH equivalent	See impact equivalent; unit of contribution for carcinogens
Pb	Lead
Pb equivalent	See impact equivalent; unit of contribution for heavy metals
PEMS	Pira Environmental Management System; an LCA software tool
PET spirit	Petroleum ether solvent
PO_4	Phosphate
PO_4 equivalent	See impact equivalent; unit of contribution for nutrification
POE	Polyol ester oil; a synthetic lubricant for HFC-134a
PUR	Polyurethane used as a foam blowing agent in refrigerator insulation
PVC	Polyvinyl chloride
PVE	Polyvinylether oil; a synthetic lubricant for HFC-134a
SAE	Society of Automotive Engineers
SEM	Scanning electron microscope
SETAC	Society of Environmental Toxicology and Chemistry
SO_2	Sulphur dioxide
SO_2 equivalent	See impact equivalent; unit of contribution for acidification
SO_X	Sulphur oxides
TEWI	Total equivalent warming impact
TSP	Total suspended particulates
Unit	Assembly of a group of *items* considered to pertain to the same function within the functional unit
V	Vanadium
VG	Viscosity grade of lubricants
VOC	Volatile organic carbon
XPS	X-ray photoelectron spectroscopy

1 INTRODUCTION

The result of substituting a chlorinated refrigerant with an environmentally acceptable compound should be that of an environmental benefit. However, it is inevitable that this change in refrigerant has unforeseen consequences with a possibility of adverse environmental effects. These conspicuous considerations need to be understood to address the sustainable development of refrigeration systems. This is achieved by adopting a multi-disciplinary approach as will be highlighted throughout this chapter. Furthermore, this chapter defines sustainable development, its implications as well as presents life cycle assessment as an appropriate tool to support this concept. After highlighting the state of the art knowledge relevant to this investigation, this chapter will define the research problem and present an overview of the research work as put forward throughout this thesis.

1.1 A multi-disciplinary approach towards sustainability

An increase in the environmental consciousness of governments (Muys, et al. 1997), companies (Turner and Little 1999) and individuals (Keoleian and Menerey 1994) has shaped the discussion on the environmental impact of products (Alting, et al. 1997). This impact is a multi-dimensional issue since it is affected by different scientific disciplines (DeSimone and Popoff 1997; Kurakawa and Kiriyama 1999). As a consequence, any trade-offs required (Navinchandra 1994; Thurston 1994;

Kurakawa, et al. 1997) to limit the possibility of a potential environmental benefit from producing an increase in environmental pollution may lead to a complication of understanding (van der Horst and Zweers 1994). Addressing the life cycle of a product (Alting 1995; Tomiyama, et al. 1997) may not only minimise the aggregate environmental impact (Keoleian 1993) by exploring alternative routes but also maintains other life cycle values (Ishii 1995).

This life cycle concept supports sustainability (Dahlman 1998; Legarth, et al. 2000) but requires knowledge of all life cycle activities (Allenby 1999a; Tomiyama 1999). This knowledge makes this life cycle approach to be complex, given the many stakeholders that influence it, its dynamic nature as well as its geographic scope (Keoleian and Menerey 1994). The problem lies with integrating science, technology and the environment which involve complex systems and interactions that, in many cases, are not well understood or characterised (Allenby 1999b). Tomiyama (1997) argues that engineering developed compartments, such as tribology or refrigeration, which have been maintained and developed independently of other compartments. Unfortunately, the deeper the compartments develop the more difficult the applicable domain becomes making it harder to establish universal solutions to global issues. One solution highlighted by Allenby (1999b) is that this *reductionist science* needs to be augmented to a more systems-based comprehensive approach. This employs wider perspectives to examine the performance of a projected solution as part of a system (Solem and Brattebo 1999).

The ensuing argument highlights that novel research that addresses sustainability must adopt a multi-disciplinary approach (EPSRC 2000). Knowledge of areas where a small change has large consequences, termed as *hot spots* (Heijungs 1996), must be identified and accurately known before any conclusions are made. This is achieved by addressing the long and short term as well as the direct and indirect effects (Eekels 1994; DETR 1998). This is unlikely to be an easy feat because the concept of sustainability is still relatively unknown. Often it is used with different meanings determined by the different value criteria of various interest groups. These groups consider their situation unique and tend to accept tailor proposed measurements to fit specific needs (Alting, et al. 1998).

1.2 Sustainable development

At this stage it is appropriate to mention that the terms sustainability and sustainable development are often used in a vague interchangeable way, which prevents a proper understanding of their implications (FF 2000). Throughout this thesis, sustainability is defined as the ability to maintain and where possible increase an environmental awareness into the long-term future. Alternatively, sustainable development is referred to as a process that manages economic growth with protection of the environment and social equity as detailed in the following sections.

1.2.1 Definition

The term sustainable development was first introduced in a report commissioned by the UN in 1983. Its task was to study the relationship between the environment and the development in the world today and on this background to propose a global programme for changes. This report, produced by the Brundtland Commission, named after its chairperson Gro Harlem Brundtland, was called *Our Common Future* (WCED 1987) and identified sustainable development as the only possible and acceptable development if human civilisation is not to collapse in the near future. Sustainable development was defined as '... *development that meets the needs of the present without compromising the ability of future generations to meet their own needs*'. Henceforth, the concept of sustainable development was introduced and became the centre of much international political discussion and government action to minimise the influence that the human impact has on the environment (Rowledge, et al. 1999).

1.2.2 Framework

The concept of sustainable development has developed to incorporate a social, an economic and an environmental dimension (FF 2000). The social dimension addresses political, cultural and ethical policies. The economic dimension addresses market and sales proliferation through added value and cost reduction. The environmental dimension is linked to the effective protection of the environment and the efficient use of resources. Both the economic and environmental dimensions depend on objective technological research whilst the social aspect remains heavily normative (Allenby 1999b). This makes the social perspective complex since it needs to be defined in terms of developed or developing and market-oriented or centrally planned countries. Other issues, such as the redistribution of wealth, population control, equal status and equal rights are additional factors that need to be considered in the light of religious and cultural beliefs (Allenby 1999b).

However, from a technological perspective, the concept of sustainable development ensures that environmental costs are no longer seen as a burden but as an opportunity for cost reduction, product innovation and increased product value (Hawken, et al. 1999). This requires that economic growth be uncoupled from the *free use* of resource and energy consumption, so shifting from an era of quantitative sufficiency to qualitative satisfaction (Tomiyama and Umeda 1997). To incorporate these sustainable development considerations a framework, adapted from (Allenby 1999b), is explained (Figure 1.1).

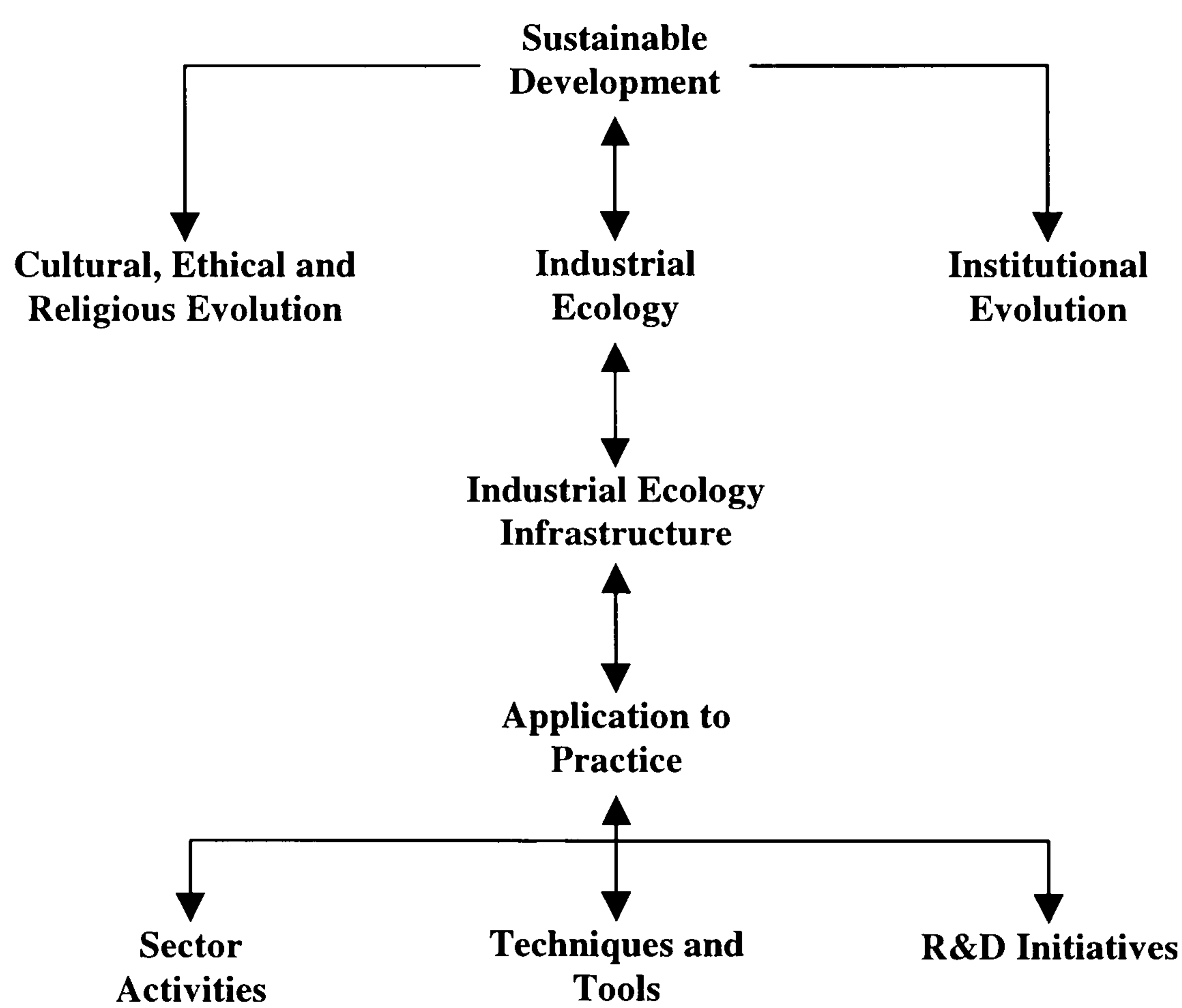


Figure 1.1. A structure for understanding the components of sustainable development (Allenby 1999b)

It has been argued (Section 1.1) that an environmental opportunity must be addressed by developing knowledge to support an understanding of environmental preference and towards which distinct disciplines must contribute. The level within the framework (Figure 1.1) which understands these components of sustainable development is termed *Industrial Ecology* (Figure 1.1). Industrial ecology is defined as a broad activity applied to both products and processes which aids initially in the evaluation and subsequently in the minimisation of environmental impacts (Ishii 1998). Undoubtedly, it would be impractical to include all the environmental impacts surrounding a particular system but a sensitivity towards ensuring a high probability of environmental preference must be sought whilst maintaining technological and economical feasibility. The next step in the process (Figure 1.1) requires that the acquired knowledge be captured within an appropriate infrastructure. Translating and codifying the environmental consequences of alternatives into a form that will assist individuals to make decisions with the least life cycle environmental impacts is seen as an *Industrial Ecology Infrastructure* project. A methodology to develop computational means based on the *reality* of design is thoroughly addressed by Tomiyama, et al. (1995) and Duffy and O'Donnell (1998). This knowledge may then be implemented in the final level of the framework, *Application to Practice* (Figure 1.1), which may be split into three distinct categories. The first category relies on short-term improvements within similar organisations given the current state of knowledge. Such incremental changes are already under way with some leading companies challenging old assumptions and feeling their way through *uncharted territory* creating a trail that others may follow (Rowledge, et al. 1999). The second category requires a set of rules, guidelines or procedures that are more universal in their applicability, as compared to the first category, and which may be productively used by firms regardless of sector. The third category is that which, although initiated immediately, will not result in any direct environmentally preferable practices. Rather, this contributes to the development of the knowledge base necessary to support the development of longer-term applications. This sustainable development framework (Figure 1.1) will be adapted for this research work (Chapter 6) in the same way that it may be constructed for a variety of other sectors.

From the preceding explanation, it is clearly difficult to realise or define what a sustainable system will look like or how it may perform. However, until present sustainable development policies are further understood and translated, any system that attempts to address conspicuous environmental issues is seen as one that has achieved sustainability (Tipnis 1993). It may not necessarily imply that the system is in itself sustainable but rather that it accepts two fundamental issues of sustainable development, that is, the prudent use of resources and the health of the environment in which our own and future generations must live (Hawken, et al. 1999).

1.3 Implications of sustainable development

For reasons disclosed in Section 1.2, the implications of sustainable development vary depending on opinion. Those relevant to this research work addressed the technological approach (Section 1.2.2) and centred upon the product use phase and the *useful lifetime* (OECD 1982) of the product. The consequent environmental impacts resulting from these two product attributes were vital and the key to the overall findings of the thesis.

1.3.1 Product use phase and life extension

The effective use of natural resources and the consequent reduction in waste and emissions (Section 1.2.2) are influenced by the consumption of energy throughout the use phase of *active* products (Hanssen 1995; Alting and Legarth 1995; Dannheim, et al. 1997) as well as by the extension of their useful life (Keoleian and Menerey 1994; Legarth and Alting 1995). Tribological characteristics play a significant role in both of these product attributes as a consequence of friction and wear, which curtail product durability and hence product efficiency, performance as well as life extension.

The interrelation between surfaces in relative motion and product durability was highlighted in a UK Government study, commissioned in 1964, to investigate the position of lubrication education and research and to highlight the needs industry had in this respect. This report is commonly referred to as the Jost Report (Jost 1966) after Professor H. Peter Jost, chairman of the working group subsequently formed. It identifies several weaknesses in the way lubrication (or tribology) was being dealt with in industry. One of the key conclusions is that industrial designers overlooked tribological issues and were unable to foresee their economic implications as a result of energy consumption, product efficiency and product life extension. Similar conclusions are reached by a subsequent study commissioned by the then Energy Research and Development Administration of the US (ASME 1977).

Savings due to tribological characteristics result from the energy consumption during product use or, in the case of failure, from a reduction in the re-manufacture of parts or complete products and in the production of materials for replacement parts or products (Jost 1981). Additionally, savings resulting from the capital equipment for the manufacture, transportation and disposal of these parts or products will also be recognised (Jost 1981). Any potential cost savings resulting from the above considerations will also imply savings on environmental impact. If tribological constraints are appropriately addressed in an attempt to reduce costs by improving the use phase of products, then both product efficiency and product durability will reduce the overall impact on the environment.

1.3.2 Impacts on the environment

It has been established that, pursuant to sustainable development, the product use phase and product life extension, influenced by issues of friction and wear in active products, contribute to an overall environmental impact due to the use of resources and consequent emissions. The effects of these environmental impacts are normally classified depending on the extent their influence has on the environment. The three classifications are:

- *global*: these effects are characterised by their long lifetime within the atmosphere and atmospheric mobility and due to the large quantities emitted leading to their widespread dispersal,
- *regional*: these, compared to global effects, are characterised by their shorter atmospheric lifetimes and are likely to effect the area nearer to the source,
- *local*: these occur in the vicinity of the source and are most likely to affect the working environment or a local community.

It is not the intention of this thesis to elaborate further either on the individual impact categories relevant to this work (Chapter 5), which influence the three classifications mentioned in this section, or on their environmental consequences. However, the impact categories relevant to this research work have been defined in Appendix A. For a more scientific background on the issues raised in this section the reader is referred to (Wigley and Raper 1992; Wellburn 1994; IPCC 1996; Jackson and Jackson 1996; Wade, et al. 1999).

To be able to characterise the impact on the environment resulting from a product and its system, a product environmental assessment is required. In (Wenzel, et al. 1997) this assessment '... *defines and quantifies the service provided by the product, to identify and to quantify the environmental exchanges caused by the way in which the service is provided and to ascribe these exchanges and their potential impacts to the service'*. In Section 1.4, a tool to carry out such an environmental assessment will be elaborated upon.

1.4 Life cycle assessment as a tool for sustainable development

To assess the product environmentally (Section 1.3.2), life cycle assessment is seen as an appropriate tool (Bor 1994a; Züst and Caduff 1995; Stevels, et al. 1999) and firmly rooted in the concept of sustainable development (DTI 2000), explained in Section 1.2. The volume of information required for such studies seems to make this technique too complex and time consuming (Ishii 1995) and consequently the results may only be interpreted by a small number of scientists and engineers (Hunt, et al. 1992; Boustead 1999). As a consequence of these implications (Bretz 1998), considerable research efforts are underway to simplify this environmental evaluation of products and formulate eco-indicators (Mueller, et al. 1998; Bey, et al. 1999; Jakobsen and Støren 1999; Klöcker and Müller 1999). However, this simplification may lead to further confusion and disillusionment, which may arise when an attempt is made to satisfy too many different needs in a single simple analysis (Boustead 1999). Environmental impact is influenced by numerous factors (Section 1.1) which only life cycle assessment may diagnose separately (Alting and Legarth 1995). Unlike eco-indicators, LCA helps in learning more about the product, about its system and beyond its boundaries (Tillman 2000). This helps to identify the absolute environmental contribution or opportunity of each design parameter, eradicate preconceptions (Teulon 1997) and help to understand the exact measure of the environmental problem as well as which trade-offs may lead to the desired objectives (Coulon, et al. 1997). This contributes to large environmental improvements and functionally better products (Weidma 1994; Alting, et al. 1998) giving life cycle assessment a prominent role in promoting competitive and sustainable products.

1.4.1 Background to life cycle assessment

Considerable documentation exists (Hunt, et al. 1992; Jensen, et al. 1997; Wenzel, et al. 1997) regarding the historical context of life cycle assessment. Boustead (1999) highlights how the first cradle-to-grave studies were initiated in the late 1960s when the need to know more, not just on the energy required to manufacture the different types of products but, on the different production, use and disposal systems, was felt. These studies, motivated by the fact that decisions were then based on economics, initially focused on the physical flows of materials and energy and extended from the extraction of raw materials from the earth through to their final disposal back into the earth. However, throughout the 1980s, the technique was extended to air emissions, emissions to water, solid wastes, etc. to address environmental considerations in decision-making processes. This led to a variety of problems particularly when interpreting the results. Problems had to be aggregated into global, regional and local issues (Section 1.3.2) but even this led to difficulties of interpretation since the seriousness of the different environmental impacts relative to one another varied. Faced with such problems, the early 1990s saw the establishment of a number of conferences with the international scientific society of environmental chemists, SETAC (*Society of Environmental Toxicology and Chemistry*), becoming the international forum for discussion and introducing the term Life Cycle Assessment (LCA).

1.4.2 Types of LCA

There are a variety of LCAs, mainly based on the level of detail and the extent to which these may be used in decision-making (Jensen, et al. 1997). A clear-cut distinction between the different types of LCAs is difficult to achieve, in particular, since all studies must include the full life cycle of the product and examine all its inputs (consumption) and outputs (emissions).

The conceptual LCA (Jensen, et al. 1997) is considered to be the simplest form of study and is based on a limited and usually a qualitative inventory. Its limitations both in inventory and the number of examined parameters do limit its possibilities but may help identify a competitive advantage in products in terms of reduced environmental impacts.

The simplified LCA (Jensen, et al. 1997) increases the level of detail of the conceptual LCA by primarily identifying those parts of the system life cycle that are either unimportant, have data gaps or those parts which can be left out. This process is known as *screening*. The next step in a simplified LCA is the *simplification* step. Throughout this step work is focused on those important parts identified in the screening phase. After simplification, an assessment on the reliability of the results takes place to ensure that these are not influenced by the simplification of the study.

Although detailed LCA studies have been going on for a number of years, it is only recently that a set of tools and guidelines have been published by the International Organisation of Standardisation (ISO) (BS 1997; BS 1998; ISO 1997; ISO 1999). The latter two publications are still in draft format at the time this thesis is written. The idea was to reach an international consensus and make LCA results more comparable and comprehensive and less variable (Tipnis 1995). As a consequence of this series of publications the following framework has been accepted in detailed LCA studies:

- goal and scope definition,
- inventory analysis,
- impact assessment,
- interpretation.

In brief it may be said that the definition of the purpose of the LCA study is described in the *goal* definition. The *scope* definition describes which phases of the life cycle of the product are to be included in the LCA. A decision is also made here on the criteria on which the product is to be assessed and, if appropriate, the timeframe for which the LCA applies. In the *inventory analysis*, information is gathered on the exchanges that the product has with its surroundings via the various processes in the product system. These exchanges include both inputs and outputs of substances to and from the global, regional and local environment (Section 1.3.2). In the *impact assessment*, information from the inventory is interpreted to identify what is the magnitude of the contribution towards the individual impact categories (global warming, ozone depletion, acidification, nutrification, etc., see Appendix A). Finally, the *interpretation* seeks to identify which environmental issues are the most significant.

Each of these four phases described is further subdivided into sections to improve both the manageability and transparency of the data handled. Although more detail on the LCA study carried out on the product relevant to this work is presented in Chapter 3 and Chapter 5, it is not the scope of this thesis to explain this framework further. For a more comprehensive explanation the reader is referred to the following works (Vigon, et al. 1994; Lindfors, et al. 1995; Jensen, et al. 1997; Wenzel, et al. 1997).

1.5 State of the art from literature survey

1.5.1 Direct and indirect impacts on the environment pertaining to refrigerants

As a result of a landmark treaty, the Montreal Protocol (EPA 1995), the ozone depletion potential (ODP) is presently used to measure the potency a chemical has to destroy the stratospheric ozone (Vesilind, et al. 1990; Wellburn 1994) and hence to regulate the production and release of compounds containing bromine and chlorine. This constraint led industry - in particular the refrigeration industry - to embark on a search for adequate replacements, investing substantial resources to overcome the problems identified with chlorofluorocarbons (CFCs), a compound containing chlorine, and yet meet its outstanding performance. Ten years later, the Framework Convention on Climate Change held a treaty, known as the Kyoto Protocol (UN 1997), to reduce future global warming from the release of greenhouse gases. As a result of this treaty, the focus is presently centred upon the potential a gas has to absorb the infrared energy radiated by the earth which offsets incoming solar energy and results in atmospheric warming (Wellburn 1994) with the ensuing environmental consequences (IPCC 1996; Wade, et al. 1999). The indicator used is the global warming potential (GWP), a relative measure usually referenced to the primary greenhouse gas carbon dioxide (CO_2) (IPCC 1996). Unfortunately, like the ODP (note that both indicators are linked in many ways (Calm and Didion 1997)), this indicator is influenced by the atmospheric concentration and lifetime as well as by the amount of infrared energy the chemical absorbs once it is released into the environment. Therefore, scientific assessments on climate change generally assume that production is equivalent to emissions (Wuebbles and Calm 1997) and do not gauge the impact on global warming of other influential life cycle phases, which would result anyway if no direct emissions (through venting, leaks, etc.) occur. This is somewhat misleading since both the *direct* as well as the *indirect* effects of a compound influence emissions. In the former case, this accounts for the chemical action a compound has as a greenhouse gas and hence is a property of the gas. In the latter case, this accounts for the energy related effect (Sand, et al. 1997), that is, the effect resulting from the combustion of fossil fuels needed to energise equipment which synthesises, uses and recovers a compound. To account for the two effects the *total equivalent warming impact* (TEWI) or the *life cycle warming impact* (LCWI) is usually calculated. For the TEWI, the indirect effect accounts for the total amount of CO_2 equivalent contributions released as a result of the energy used throughout the use phase of a product (Kusik, et al. 1991). The LCWI incorporates the CO_2 equivalent contributions associated with the manufacture, use, disposal and transportation of the chemical compound in question (Papasavva 1997). Both indices are relative numbers as they depend on the choice of the *integrated time horizon* (ITH). This is an assumed time frame which ranges from 20 to 500 years and is used in direct GWP calculations to account for the different atmospheric lifetimes of gases (Calm 1993; Papasavva 1997). Because this work will focus on the indirect effects, rather than the direct effects, the ITH and hence the warming impacts just mentioned would not be dealt with further here.

It is also important to keep in mind that throughout the remainder of this thesis the term indirect effects differs from that used by atmospheric scientists or by the *Intergovernmental Panel on Climate Change* (IPCC) (IPCC 1996). Rather than the energy related contributions, both parties refer to the indirect effects as the impact of breakdown products, themselves greenhouse gases, produced in the atmosphere as a result of chemical reactions when an emission occurs (Calm 1993).

Subsequent to the Montreal Protocol, the total production of hydrofluorocarbons (HFCs) in the UK is set to increase from 25 tonnes in 1990 to 19,000 tonnes in 2010 (DETR 1999). However, in compliance with the Kyoto Protocol, the UK Government now proposes to replace HFCs in the future due to their direct GWP, which makes them an unsustainable technology in the long term (DETR 2000). This is in itself oxymoronic due to the high initial investment required for the development of this compound, which makes it impossible to be ignored (Papasavva and Moomaw 1997) without serious opposition and a consequent detriment to the environment. *Grace periods* sought by developing countries to be able to comply with new regulations, with the subsequent black market economies, will be inevitable as is still the case with the phase out of CFCs (Papasavva and Moomaw 1997; Anon 1998).

1.5.2 Extended producer responsibility

This concept of *extended producer responsibility* is a new and powerful instrument (Solem and Brattebo 1999) requiring the obligation of producers to extend far beyond the warranty period of their products (Tipnis 1993). Recycling is presently taken care of by waste management services within society with little obligation from industry (Thurston 1994). Given its competitive market potential (Solem and Brattebo 1999), yet restrained by an appropriate logistical infrastructure (Legarth and Alting 1995), industry must seek alternative routes to address this responsibility which is already a requirement for some products within the EU (Solem and Brattebo 1999).

One possibility is for industry to shift from an economy of goods and purchases to one of *service* (Hawken, et al. 1999). Allowing a product to be physically or functionally upgraded to overcome technological or psychological obsolescence (OECD 1982) will generate additional value through a longer life and a higher reliability (Nonomura, et al. 1999). This compensates for a decrease in the consequent production volume (Tomiyama 1997). A *growth-sustaining* product (Tomiyama 1997) is one whose function is maintained indefinitely (Gu, et al. 1997) by *clumping* (Marks, et al. 1993; Ishii, et al. 1994) the product into modules (Pahl and Beitz 1995) and performing successive maintenance on these modules. The replaced module may then be recycled or reused after appropriate maintenance has taken place. Furthermore, this concept aides in shifting from mass production (uncoupling economic growth from resource consumption - Section 1.2.2) to mass customisation (Pine II, et al. 1993) by building products exactly as the customer wants. It may even render private possession an illusion since individuals may lease products and in turn pay for the service provided.

Simulation studies (Johansen, et al. 1997; Tomiyama and Umeda 1997) on a serviceable product have concluded that modularity is effective in reducing production volume and therefore maximising the use of resources and minimising the generation of waste while still maintaining economic activity. However, issues such as logistics, customer behaviour, levels of expertise and tooling, product variants as well as laws and regulations may all need to be re-addressed (Eubanks and Ishii 1993; Bor 1994b; Johansen, et al. 1997; Stake 1999). Other adverse implications, which are dealt with by Newcomb, et al. (1998), also need to be considered.

1.5.3 Investigating the domestic refrigerator

In 1991, the worldwide production of refrigerators and fridge-freezers (henceforth, collectively referred to as refrigerators) was 58 million with hundreds of millions being used in the developed world (Kusik, et al. 1991). A staggering increase in production is projected by the year 2010 as developing countries, like India, will utilise 78 million units, up from the 6 million units used in 1989 (Kusik, et al. 1991). In the UK alone, an excess of 81 thousand tonnes of units are discarded annually (DTI 1999). Alternatively, to put the environmental implications of this product in perspective, one may consider that by the year 2010 the projected direct and indirect emissions (Section 1.5.1) of UK greenhouse gases from domestic refrigeration alone will vary from 4.2 to 4.8 million tonnes (Mt) of CO_2 equivalent (DETR 2000). These emissions will result despite the fact that the domestic refrigeration industry in the UK switched from the use of dichlorodifluoromethane (CFC-12) to tetrafluoroethane (HFC-134a) (DOE 1996) and is projected to utilise only 1.8% (DETR 1999) of the total hydrofluorocarbons produced (Section 1.5.1).

For refrigerators, the indirect environmental effects are of a much greater magnitude (30 times greater for the UK scenario (DETR 2000)) when compared to the direct effects (Calm, et al. 1999; March 2000). Given the excellent potential which exists, considerable research efforts have already been underway (Hawkins 1998) to primarily improve the efficiency of this product. These have spanned from the materials used (Guldbrandsen, et al. 1986; Weaver, et al. 1996), cabinet configuration (Reyes-Gavilán, et al. 1996a; Kramer 1999), the mode of operation of the compressor (Guldbrandsen, et al. 1986; Vineyard, et al. 1995; Jacobson 1996) to the pattern of use of the refrigerator (Kryssanov, et al. 1999).

The use of HFC-134a in refrigerators will undoubtedly influence these indirect environmental effects. Although the coefficient of performance (COP) for the CFC-12 and the HFC-134a differ by less than 10% (Jung and Radermacher 1990; Khan and Zubair 1993), the refrigerant is not the only key ingredient that influences energy efficiency, hence these indirect effects. In this study, special consideration is given to the role the lubricant in the hermetic compressor plays. This lubricant, apart from lubricating the mechanical system, cools the compressor mechanism, electrically insulates the motor from the compressor casing, dampens the noise and seals compressor components. About 10% (Kruse and Schroeder 1985) of this bulk lubricant in the compressor is circulated in the refrigeration system as mist with the refrigerant. For this reason, good miscibility must be ensured between the refrigerant and the lubricant and hence ensure good oil return to the compressor. The mineral oil, which formed a highly miscible combination with CFC-12, is immiscible with HFC-134a (Short 1990; Sundaresan and Finkenstadt 1992). The new lubricants developed may reduce system efficiency due to a change in the work done by the compressor as a result of the viscous drag (Reyes-Gavilán, et al. 1996a; Muraki and Sano 2000) or compressor cycling losses (Kusik, et al. 1991). The lubricating medium may also reduce the thermal conductivity at the heat exchangers (Spauschus and Hendersen 1990; Sanvordenker 1991; Reyes-Gavilán, et al. 1997) as it is circulated with the refrigerant. Oil deposits on the inner tube surfaces, as a result of poor miscibility (Kramer 1999) or a change in the condensing and evaporating properties of the refrigerant, due to good solubility (Kruse and Schroeder 1985; Short and Rajewski 1996), may increase the frequency of operation of the compressor (Guldbrandsen, et al. 1986). These implications have been investigated more fully by Reyes-Gavilán, et al. (1996b).

Alternatively, a change in the lubricant and refrigerant combination (which may be collectively referred to as the working fluid throughout this thesis) may influence the *technical lifetime* (OECD 1982) of the product due to a change in lubricity effects (Short and Rajewski 1996). Although a debate exists (Tomiyama, et al. 1997) as to whether refrigerator lifetime should be increased (to reduce the solid waste and material consumption) or reduced (to benefit from any improvements in new technologies) this change in the technical life does not necessarily mean complete product failure and hence a need for replacement. An implication could be that friction and wear may increase the electrical power requirements of the mechanical system (Section 1.3.1). The positive effect that chlorine in the CFCs may have due to the formation of chloride films, which are known to reduce friction and improve wear characteristics (Bowden and Tabor 1950; Muraki 1994; Mizuhara and Tomimoto 1997), may influence this. It is perhaps for this reason that HFC-134a compatible lubricants include additives (Short and Rajewski 1996; Na, et al. 1998; Yamamoto, et al. 1998). These anti-wear or extreme pressure additives (explained in detail by Dizdar and Andersson (1997)) offer better protection to high pressure contacts (Sakurai and Sato 1966; Briscoe, et al. 1973). However, in the case of refrigeration, the behaviour of these additives may be influenced by the refrigerant itself (Kruse and Schroeder 1985) and they too contribute to the total environmental impact (Komatuszaki and Homma 1991). Changes in the working fluid also influence the viscosity (Spauschus and Hendersen 1990) and hence the load carrying capabilities of the lubricating film (de Geer, et al. 1985; Isaksson and Åström 1993) at concentrated contacts. The make of the compressor too may influence such changes since contact pressures as well as other parameters may vary. Furthermore, blockage problems at restrictions (Hewitt, et al. 1994) as a result of wear debris circulating around the system or due to deposits resulting from different lubricant additives (Tazaki, et al. 1998) also reduces this technical life.

1.5.4 Refining the research problem

As explained in the preceding sections, a change in the working fluid influences many parameters. Any of these parameters could have influenced the observed increase (7% maximum) in energy consumption of a refrigerator working with HFC-134a, when compared to one working with CFC-12 (Kusik, et al. 1991). However, how much of this increase is attributed to tribological characteristics is unknown but needs to be characterised given the significance these characteristics have on the environmental impact of a product (Section 1.3.1). In view of this, the ensuing research problem may be refined as outlined in Figure 1.2. Refrigeration (1) is

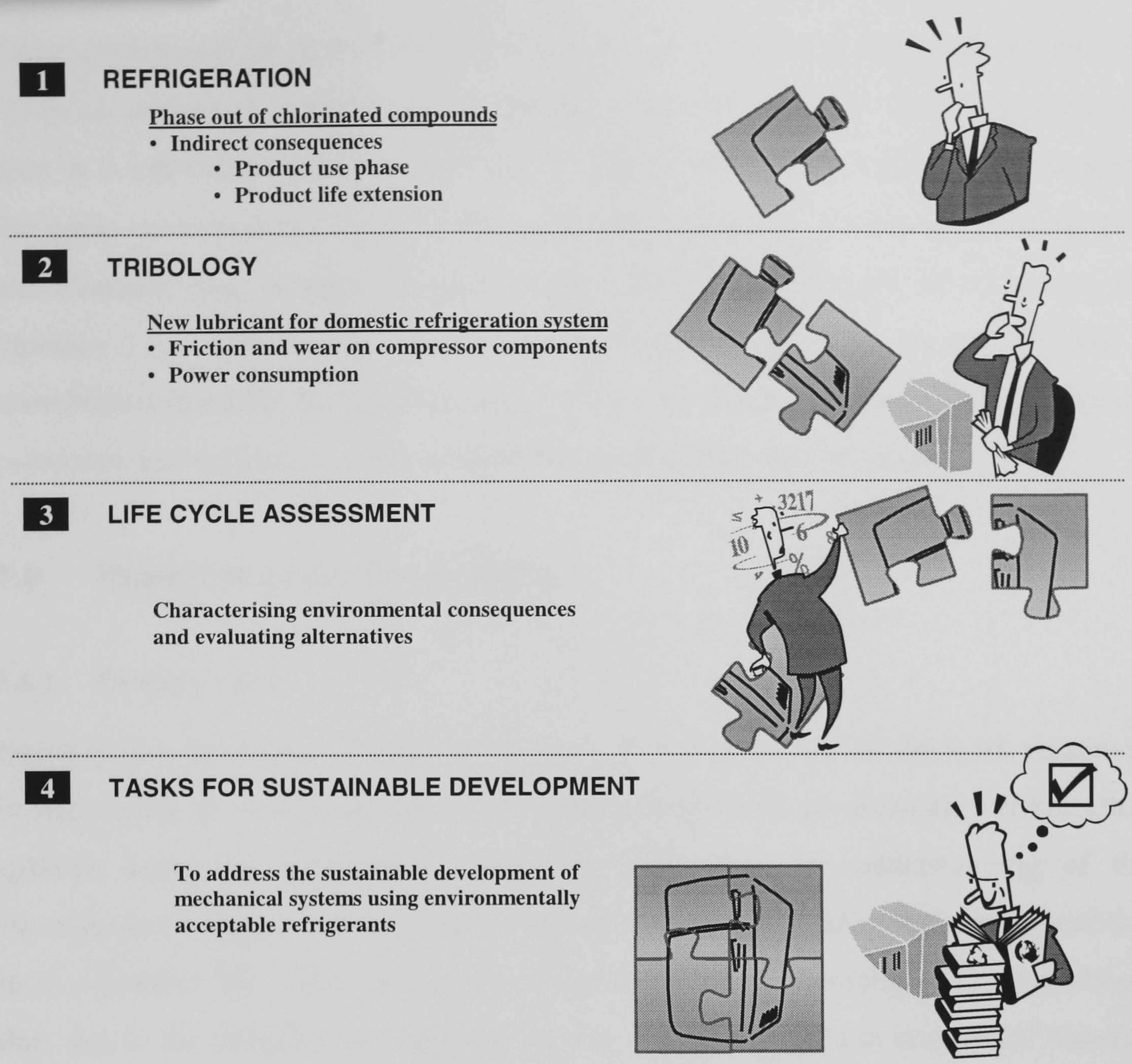


Figure 1.2. Outline of the research problem

currently considered as a sensitive issue in view of the environmentally benign refrigerants being sought (Section 1.5.1). The domestic refrigerator will be focused upon to address the relevant indirect environmental consequences, which may arise as a repercussion of product *failure* due to tribological characteristics (2), as detailed in Section 1.3.1. These may be listed as:

- contributions resulting from the manufacture, transportation and disposal of the refrigerant,
- contributions resulting from the manufacture, transportation and disposal of the lubricant,
- contributions resulting from the manufacture and transportation of the materials of parts making up the product system,
- contributions resulting from the manufacture, transportation, assembly and disposal of parts making up the product system,
- contributions resulting from the in-use electrical power of the compressor.

These environmental consequences need to be assessed using life cycle assessment (3) in an attempt to characterise the problem (Section 1.4). The first three steps are seen as a methodology to develop data to support the understanding of the product life cycle environmental impacts. This will help perform an environmental diagnosis and evaluate new concepts as part of the tasks for sustainable development (4) (Section 1.2). The overall solution to the research problem should provide a contribution towards the growing body of knowledge as to how a new refrigerant compares with its phased out counterpart in performance and reliability.

1.6 Research project description

1.6.1 Research aim

Based on the discussion outlined in Sections 1.1 to 1.5, the aim of the work presented in this thesis is to address the sustainable development of domestic refrigeration systems using the replacement refrigerant HFC-134a. An understanding of the environmental issues and how these are influenced by tribological characteristics from a product life cycle viewpoint is essential. This will investigate the hypothesis that, due to the influence of other engineering disciplines, the environmental benefits of this replacement may not be as great as anticipated.

1.6.2 Research outcomes

Based on the research aim presented in Section 1.6.1, the objectives set to test the research hypothesis are listed as follows:

- design and manufacture a hermetic compressor test rig used for system analyses, including compressor durability and energy consumption, whilst operating with a variety of working fluids
- identify surface wear and frictional characteristics in sliding motion with environmentally acceptable refrigerant and lubricant combinations
- investigate how the outcome of the previous two criteria may be used to promote the sustainable development of systems through life cycle design considerations.

1.6.3 Research milestones

Based on the three research objectives (Section 1.6.2), the milestones include:

<u>Bench testing</u>

(a) Actual hermetic compressor tests

- design a test system and a test programme to simulate the actual lifetime of a hermetic compressor,
- assess a variety of lubricants, compatible with CFC and HFC refrigerator refrigerants, for wear characteristics under different operating scenarios and using two different makes of compressors,
- power monitor two distinct makes of hermetic compressors, working in CFC-12 and HFC-134a environments.

(b) Modified rolling contact machine tests

- test steel ball samples using a rotary tribometer configured as a four-ball machine under extreme sliding contact conditions, in the presence of *clean* and *contaminated* CFC-12 and HFC-134a compatible lubricants, for lubricant degradation.

(c) Life cycle assessment of the product system

- perform an environmental assessment using LCA on the whole product system over the whole life cycle,
- identify the environmental contributions pertaining to the different refrigerants, the manufacture of the hermetic compressor as well as the power monitored from actual compressor tests.

<u>Interpretation of the emerging data</u>

(d) Analyses

- strip the compressor to examine concentrated contact surfaces using a variety of experimental techniques,
- identify prevailing modes of *lubricated wear* mechanisms,
- study friction characteristics during sliding motion in the presence of different working fluids by interpreting trends in the in-use electrical power of the compressor,
- examine the lubricating oils for wear debris,

- interpret the acquired results from an environmental viewpoint to quantify the total indirect consequences using LCA.

Developing a solution to the research problem

(e) Evaluation

- interpret research results obtained to re-evaluate functional and specification requirements of the mechanical system,
- interpret the concept of sustainable development to the design of this product system,
- analyse strengths and weaknesses of this novel approach to sustainable development thus identifying future research requirements.

1.7 Thesis structure

The thesis structure is outlined in Table 1.1. Chapter 1 seeks to lay the foundation to the research work explained throughout the remainder of this thesis. This introductory chapter defined the concept of sustainable development. In so doing, this chapter emphasised the fact that this concept requires a multi-disciplinary approach to address indirect effects, which often go unaccounted for. One particular example, which will be addressed throughout this thesis, is the switch in refrigerant gases and to this effect a product is identified to help characterise any indirect implications.

Foundation to sustainable development
Chapter 1 – Introduction
Requisites to address the research problem
Chapter 2 – Design and manufacture of test system
Chapter 3 – Experimental and analytical methodology
Interpretation of the emerging data
Chapter 4 – Experimental results
Chapter 5 – Analytical results
Developing a solution to the research problem
Chapter 6 – Discussion
Chapter 7 – Conclusions and future directions

Table 1.1. Thesis structure

The next two chapters may be described as the requisites to address the research problem described in Chapter 1. Chapter 2 elaborates on the design and manufacture of a test facility needed to carry out experimental analyses on actual hermetic machines. Chapter 3 explains the procedures for the experimental investigation and the analytical LCA modelling used to evaluate the environmental impacts. The interpretation of the emerging data from the experimental analyses is elaborated upon in Chapter 4 whereas that from the analytical LCA study is given in Chapter 5. In the former chapter the emphasis is on friction and wear and the electrical power characteristics whereas in the latter the emphasis is on the environmental contributions of the individual components, in particular the hermetic compressor, making up the refrigerator. A critical evaluation of the findings disseminated throughout this thesis is found in Chapter 6. This chapter identifies the causes as well as quantifies the indirect environmental consequences pertaining to a change in refrigerant for the product selected. Chapter 6 also validates the work carried out from a sustainable development viewpoint. Finally, Chapter 7 concludes the work and identifies new routes for further development.

2 DESIGN AND MANUFACTURE OF TEST SYSTEM

A test rig was designed and manufactured to evaluate the in-use power requirements of a hermetic compressor operating with a variety of working fluids. Tribological characteristics on concentrated contacts within these tested compressors were then studied to interpret any relationship between friction and wear and fluctuations in the monitored power. This chapter reviews the various mechanical and electrical components of this test system, the calibration of components as well as the commissioning period required. Finally, key decisions made which influenced both the design of the test rig and its limitations are evaluated in order to study their implications on the outcome of the experimental results.

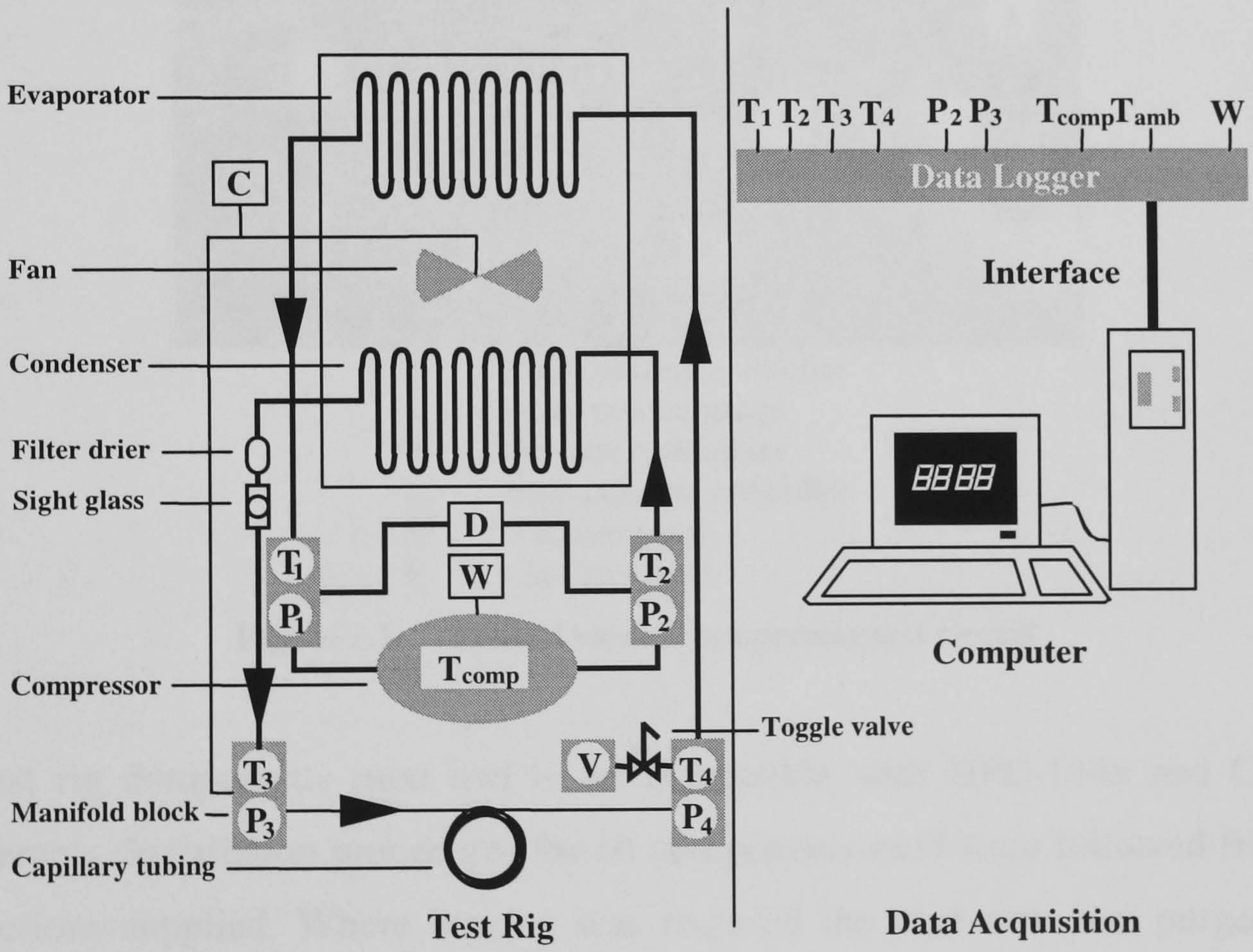
2.1 Overview of hermetic compressor testing

Standard wear tests for actual hermetic compressors (DIN 1973) specify the use of a vapour phase test rig. However, for reasons identified earlier (Section 1.5.3), the operating performance of a hermetic compressor, most notably the electrical power requirements, was the key to this investigation. A liquid/vapour phase test rig allowed a more near-to-reality approach when simulating the vapour compression refrigeration cycle of a domestic refrigeration system. Temperatures and pressures were recorded at strategic points to acquire information on the characteristics of the test system. All data was recorded electronically except for the discharge and suction pressures of the compressor. The in-use electrical power throughout each compressor test was measured and inputted electronically via a power transducer.

2.2 The mechanical system

2.2.1 Overview

The principle of operation of the designed and developed test circuit was to force air over the heat exchangers to help dissipate the heat at the condenser and to maintain the required temperature at the evaporator. In this way, both temperatures and pressures in the vapour and liquid lines of the test circuit were maintained. A schematic of this test circuit is shown in Figure 2.1 with the actual rig shown in Figure 2.2 and Figure 2.3.



C	Fan controller
D	Dual pressure controller
T_1 and P_1	Suction temperature and suction pressure
T_2 and P_2	Discharge temperature and discharge pressure
T_3 and P_3	Condenser temperature and condenser pressure
T_4 and P_4	Evaporator temperature and evaporator pressure
W	Power transducer
T_{comp}	Compressor case temperature
T_{amb}	Ambient temperature
V	Vacuum meter

Figure 2.1. Schematic of the test circuit and a key to the symbols used

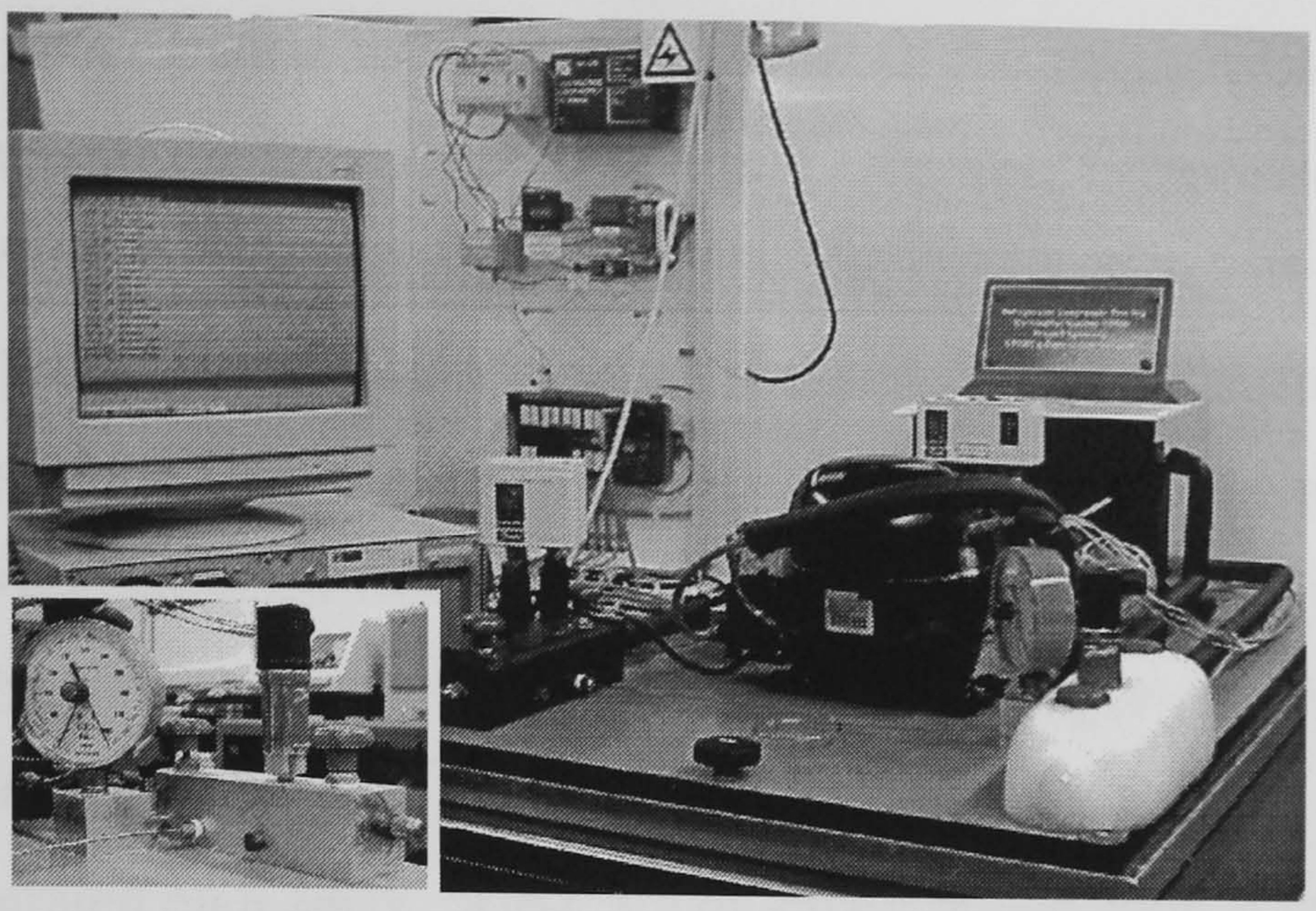
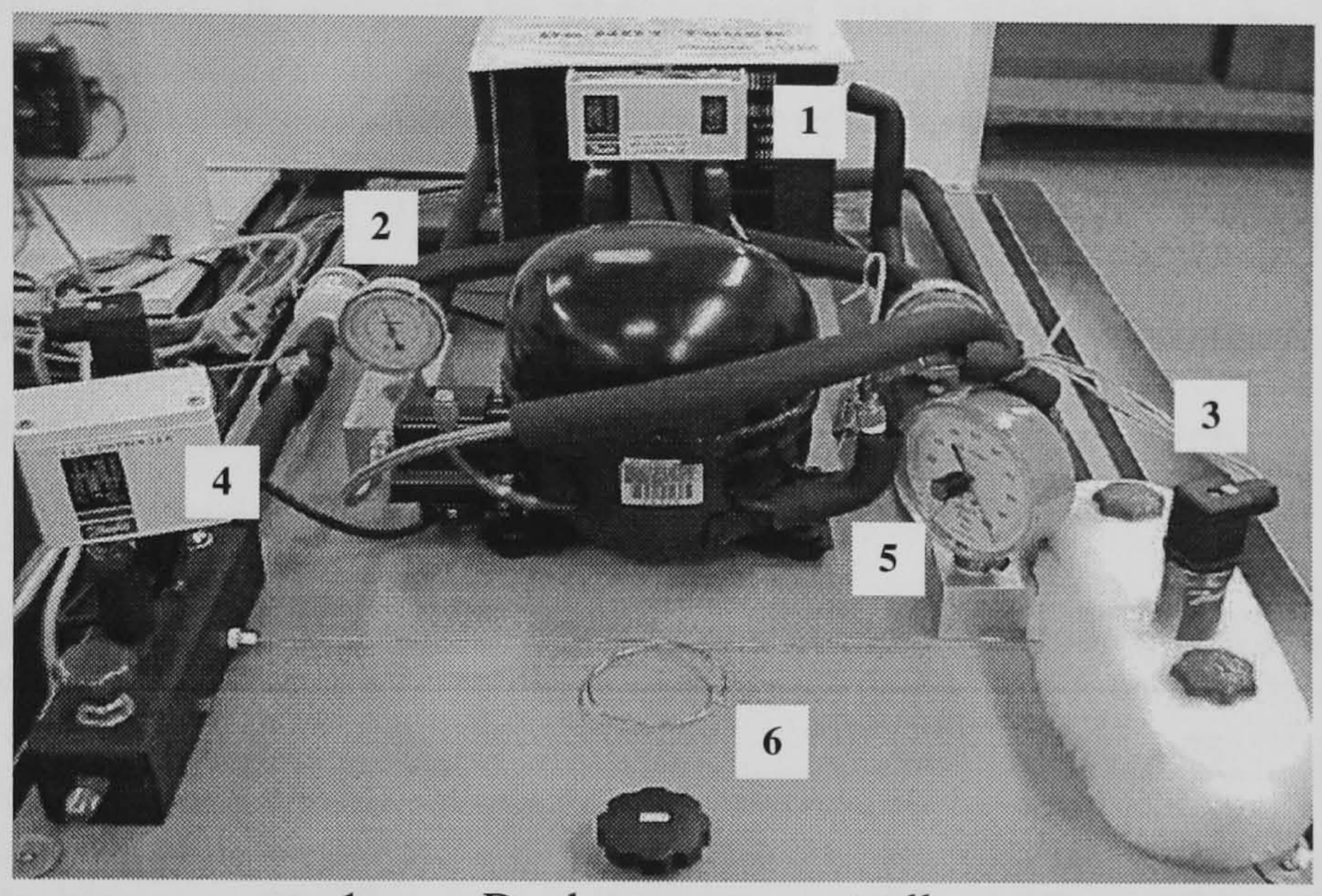


Figure 2.2. General view of the test rig with inset showing the low pressure manifold block



1 Dual pressure controller
2 Dial pressure gauge
3 Pressure transmitter
4 High pressure controller
5 Vacuum gauge
6 Capillary tube

Figure 2.3. Frontal view of compressor test circuit

All test rig components used had to be compatible with HFC-134a and CFC-12 refrigerants. Installation procedures for all components used were followed from the instructions supplied. Where brazing was required the pipework was purged with nitrogen. This is a standard refrigeration procedure that maintains a cool internal surface to the pipework thus minimising the risk of oxidation and scaling. The following sections will detail the different components used on the test rig

2.2.2 The reciprocating compressor

To test the implications the make of the compressor may have on the outcome of this research, two compressor brand names were tested (Section 1.5.3). Both machines were similar in specification to the one mounted on the refrigerator, which will be dealt with throughout the LCA study (Section 3.5ff). This compressor is termed the base unit in Table 2.1. Information supplied by the manufacturer of this refrigerator (Hotpoint 1997) indicates that this base unit is equivalent to a Danfoss NL7F. Table 2.1 gives details of the machines tested based upon their Danfoss equivalent and the values shown were extracted from relevant product catalogues. From this table it is clear that the Type A compressor tested had a slightly larger cooling capacity than the base unit whilst the Type B compressor tested was exactly equivalent. All compressors operated on a 240V, 50Hz, single-phase power supply and were labelled for use with HFC-134a. It should be mentioned that, although labelled for use with this compound, both types of compressors were operated with CFC-12 during this research work (Section 3.2.4). Compressors for use with CFC-12 were not available commercially due to the ban on the refrigerant. This implied that all compressors were optimised for use with HFC-134a and should thus perform best with this refrigerant.

Type	Place of manufacture	Danfoss equivalent	Displacement (cm^3)	Capcaity (W) at evaporating temperature (°C)					
				-35	-30	-25	-20	-15	-10
Base unit	Italy	NL7F	7.3	76	99	134	178	231	292
A	Italy	NL9F	8.35	92	119	157	207	267	337
B	Malaysia	NL7F	7.3	76	99	134	178	231	292

Table 2.1. Specification of compressors

Besides comparing compressor makes (Section 1.5.3), the use of two types of hermetic machines provided another advantage from an experimental viewpoint. Experimental observations could be validated if similar findings were made on two distinct types of compressors.

2.2.3 The heat exchangers

The heat exchangers available commercially and used for the test system described here differ from those mounted on refrigerators, as shown in Table 2.2. To limit the influence the heat exchangers may have on the operation of the test rig two types of heat exchangers, supplied by Hawco, were tested. Initially, the smallest available heat exchanger was used (Table 2.2) but with this STN 6118 type not enough heat was being transferred between the condenser and the evaporator (Section 2.2.1). Operating conditions could not be maintained satisfactorily, with the evaporator *icing* *up* completely. The next higher rating of heat exchangers was tested (Table 2.2). The STN 7127 type, with copper tubes and steel fins, was found to be more appropriate with the transfer of heat seemingly more satisfactory. These heat exchangers were positioned vertically with the intake to the condenser being the uppermost connection and the intake to the evaporator linked to the lowermost connection. This ensured that the refrigerant leaving the condenser was liquid whilst that leaving the evaporator was vapour, as is appropriate in refrigerating circuits.

Type of heat exchanger	Rating with R22 at ΔT 15°K (W)	Air quantity (m^3/h)	Dimensions (mm)		
			width	height	depth
STN 6118	210	260	180	184	30
STN 7121	300	345	210	214	30

Table 2.2. Specification of heat exchangers

2.2.4 The expansion device

Throughout these tests, a capillary tube of 0.6mm internal diameter was used as the expansion device (Figure 2.3). The design of the test rig allowed a change in this capillary tube length whilst preserving the refrigerant charge. This was achieved by isolating the expansion device completely using shut-off bellow valves located on the manifold blocks (Section 2.2.6 and shown in the inset in Figure 2.2). Although capillary tube lengths were maintained identical between respective test conditions (Section 4.1.2), the possibility of altering this length proved to be useful during the commissioning phase (Section 2.5) of this research work. This use was essential until an idea of the tube length for the required pressure differential was obtained. Venting the whole system to change the capillary tube was impractical due to:

- the time taken to recover the refrigerant and recharge the test rig,
- an unaccountable percentage of the oil in the compressor which is lost with the refrigerant when this is recovered (Section 3.2.3).

With the bellows closed, the capillary tube was changed, vacuumed and the refrigerating cycle completed by reopening the bellows. The difficulty with this configuration was that a tight seal removable fitting had to be used to allow for the replacement of the capillary tube. A compression fitting was thought to be the most appropriate. However, the steel olive fittings required were of a very small dimension to be available commercially and therefore PVC olives had to be used.

Unlike the steel, PVC does not grip into the copper capillary tube making it possible for the PVC olives to be reused. The difficulty was that these PVC olives had to be manufactured.

2.2.5 The filter drier

The smallest filter drier available commercially and compatible with both the CFC-12 and HFC-134a compounds was the 0.1 litre, Danfoss DN32 type. This contains a mixture of silicagel and molecular sieves and was installed on the liquid line prior to the expansion device (Figure 2.1). Its main purpose was to limit any debris within the system from reaching the capillary tube and also to ensure that any moisture, particularly with the polyol ester synthetic lubricants (Section 3.2.4), will be reduced. The effectiveness of the use of a filter drier is debatable (Kramer 1999) but was included as an added precaution.

2.2.6 The manifold blocks

An essential design parameter was to monitor the temperature and the pressure of the working fluid at different locations within the system, something that cannot be obtained using a hermetic configuration. All thermocouples and pressure transducers were placed in contact with the working fluid by utilising manifold blocks positioned as shown in Figure 2.1. Engineering drawings for the manufacturing of the blocks are shown in Appendix B. The material chosen was an aluminium alloy due to its ease of machining but this had the added disadvantage of having good heat transfer characteristics. For this reason and due to their large surface areas all manifold blocks on the liquid side of the refrigerating circuit were insulated using standard insulating tape.

Each of the two blocks to which the expansion device was connected (Figure 2.3) incorporated two shut-off bellow valves (SRW 71502) that allowed for the rapid removal of the capillary tube (Section 2.2.4). Pressure transmitters and thermocouples (Section 2.2.8) were mounted to permit pressure and temperature readings just before and after the expansion device (P_3/T_3 and P_4/T_4 respectively in Figure 2.1). A fan controller (Section 2.2.8) was mounted on the high pressure manifold whereas a vacuum gauge (Section 2.2.8) was connected, via a toggle valve, to the low pressure manifold.

Other manifold blocks were incorporated at the suction and discharge sides of the compressor (Figure 2.1). Between these two blocks a dual pressure controller (D in Figure 2.1) was connected. A low pressure gauge (P_1 in Figure 2.1) and a high pressure gauge (P_2 in Figure 2.1) as well as a thermocouple (T_1 and T_2 in Figure 2.1) were also mounted on these suction and discharge manifold blocks respectively. A fifth block (Figure 2.1) was used to mount a vacuum gauge as explained in Section 2.2.8.

2.2.7 The cooling fan

A cooling fan, controlled by a high pressure switch on the liquid side (C in Figure 2.1), was used to maintain the required conditions in the condensing and evaporating sides of the refrigerating circuit. The axial flow fan used was the smallest single-phase device available. The Elco fan motor and propeller had a rotating speed of 1300 rpm and a diameter of 154mm respectively. The frequency of operation of the fan varied between the different experiments carried out and was a function of many variables, most notably the ambient conditions. The electrical design of this refrigerating test circuit (Section 2.3ff) ensured that the power meter did not monitor the power absorbed by the fan. Its start-up current, however, was likely to have caused some interference since all accessories were powered from the same electrical power point.

The cooling fan forced air at ambient temperature over the condenser and onto the evaporator. As the air flowed over the finned tubes of these heat exchangers this caused the condenser to cool and in turn increase the temperature of the evaporator. Forcing air in the opposite direction did not achieve satisfactory conditions since ambient air was used to heat the evaporator whilst the condenser was cooled using cold air from the evaporator. As a result the condenser was cooling down too quickly to allow enough time for the evaporator to defrost and this was thought to influence the results. The heat exchangers and the fan were enclosed in an aluminium sheet chamber to ensure safety from the rotating propeller blades as well as to ensure that all the circulating air was forced over the finned tubes of the heat exchangers.

2.2.8 Ancillaries

Sight glass

An acceptable moisture level had to be ascertained at all times (Section 3.2.4) and hence a sight glass with a moisture indicator (Danfoss SGN) was incorporated on the liquid line (Figure 2.1). This type of sight glass, which is compatible with both CFCs and HFCs, has a colour indicator that does not report an acceptable moisture level within the working fluid (type not available) but simply changes colour with the presence of moisture. As debated by Kramer (1999) the appropriateness of this ancillary is questionable.

Pressure controls

A manual reset, dual pressure controller (D in Figure 2.1) was installed as a safety precaution. Its main task was to interrupt the electrical supply to the compressor once a threshold value of condensing pressure was exceeded, as explained in more detail in Section 2.3.1. The type of dual control used was a Danfoss KP15 and was wired normally closed. A high pressure controller (Danfoss KP5) was also utilised and mounted on the liquid side of the refrigerating circuit (C in Figure 2.1) to trigger the cooling fan when the condensing pressure exceeded its set value (Section 2.2.7). When this set condensing pressure was restored, due to the cooling of the condenser, the high pressure controller interrupted the electrical circuit to the fan automatically.

Vacuum gauge

As explained in Section 3.2.1, the rig had to vacuumed prior to being charged with the appropriate refrigerant. The reasons for this are threefold:

- to allow for the identification of any leaks within the system,
- to remove all the air from the system ensuring no residual moisture content,
- to allow the compressor to be charged with 350ml of oil.

A vacuum gauge (Refco 19801) was connected to the suction line (V in Figure 2.1) via a forged body toggle valve (Whitey SS-0GM2). The gauge could not sustain more than atmospheric pressure so it had to be isolated from the remainder of the circuit. This was achieved with the use of a toggle valve (Figure 2.1) which in turn could not sustain the conditions of the liquid line and hence its positioning on the vapour line.

Pressure transmitters and gauges

The high and low pressure transmitters designated as P_3 and P_4 respectively in Figure 2.1 and shown in Figure 2.3 were of the Danfoss AKS32 type with the following capabilities.

	Operating pressure range	Standard output signal
High pressure transmitter	-1 to 39 bar	(0 to 10)V D.C.
Low pressure transmitter	-1 to 9 bar	(0 to 10)V D.C.

Table 2.3. Pressure transmitter types

Two types of low pressure and high pressure dial gauges designated as P_1 and P_2 respectively in Figure 2.1 and shown in Figure 2.3 were used with either of the refrigerant charge (Table 2.4). The main reason for this was that the CFC-12 compatible type could not sustain a prolonged contact with the HFC-134a refrigerant or its lubricant.

Refrigerant charge	Pressure gauge	Type used
CFC-12	Low pressure	ITE 425 compound gauge
	High pressure	ITE 423 pressure gauge
HFC-134a	Low pressure	Robinair 11726
	High pressure	Robinair 11727

Table 2.4. Pressure dial gauges used

Thermocouples

Two types of thermocouples were used depending on the value of temperature to be recorded (Table 2.5). Each thermocouple was connected to the data logger (Section 2.3.3) via a two flat pin plastic bodied socket and a compensating cable made of copper and copper-nickel conductors appropriate for use in ambient temperatures below 100°C and having a tolerance class of ±100μV (±2.5°C).

Thermocouple type	Continuous temperature range (°C)
K	0 – 1100
T	-185 – 300

Table 2.5. Thermocouples used

Pipework

All copper pipework was of a ¼ inch internal diameter, this being the smallest diameter available commercially. All pipework was appropriately flared and insulated using standard insulating tube. Flexible braided hoses were used to connect the hermetic compressor to the rest of the refrigerating circuit. These hoses allowed for ease of connecting up and also reduced any transfer of vibrations from the compressor onto the pipework. It should be mentioned that the Type B compressor required a braided hose double in length to that used with the Type A machine. The reason was that the rig was designed on the Type A compressor whose suction pipe was on the opposite side to that on the Type B compressor. This extra length of hose is clearly evident in Figure 2.3. The heat transfer from this extra length of pipe was minimised by insulation but no additional refrigerant was added to make up for this extra pipework.

2.3 The electrical system

2.3.1 Mode of operation

Electronic data acquisition of pressures, temperatures and electrical power as well as the operating time of the compressor had to be ascertained to accurately study the characteristics pertaining to the rig. The pressure controls (Section 2.2.8), the compressor (Section 2.2.2) and the elapsed hour meter were wired via a relay. Figure 2.4 is a detailed schematic of the overall electrical installation controlling the test rig, whereas Figure 2.5 shows the actual electrical installation of the system. With reference to Figure 2.4, when the momentary action normally open *START* button was pressed, current flowed through the hour meter (RS 341-547) and the dual pressure controller (D in Figure 2.1). Provided this dual pressure control switch was not disabling the circuit (Section 2.2.8), current flowed onto the coil of the relay (RS 376-874). The energised relay coil then shifted contact (U) from its holding position (W) to position (X), interrupting the supply to the neon and by-passing the *START* button (which was only momentary pressed). Simultaneously, contact (V) was shifted from its normally open position (Y) to position (Z) thus energising the normally open fan controller (C in Figure 2.1) as well as the compressor. The electrical supply to the compressor was via a mechanical timer to start/stop the compressor as required by the experimental schedule (Section 3.2.4). The wiring was such that, whenever this timer interrupted the electrical supply to the compressor, the hour meter could still record the experiment duration. Furthermore, a momentary action start switch was used, so that upon restoration of an electric power failure, neither the compressor nor the hour meter restarted automatically without the computer monitoring the characteristics of the rig.

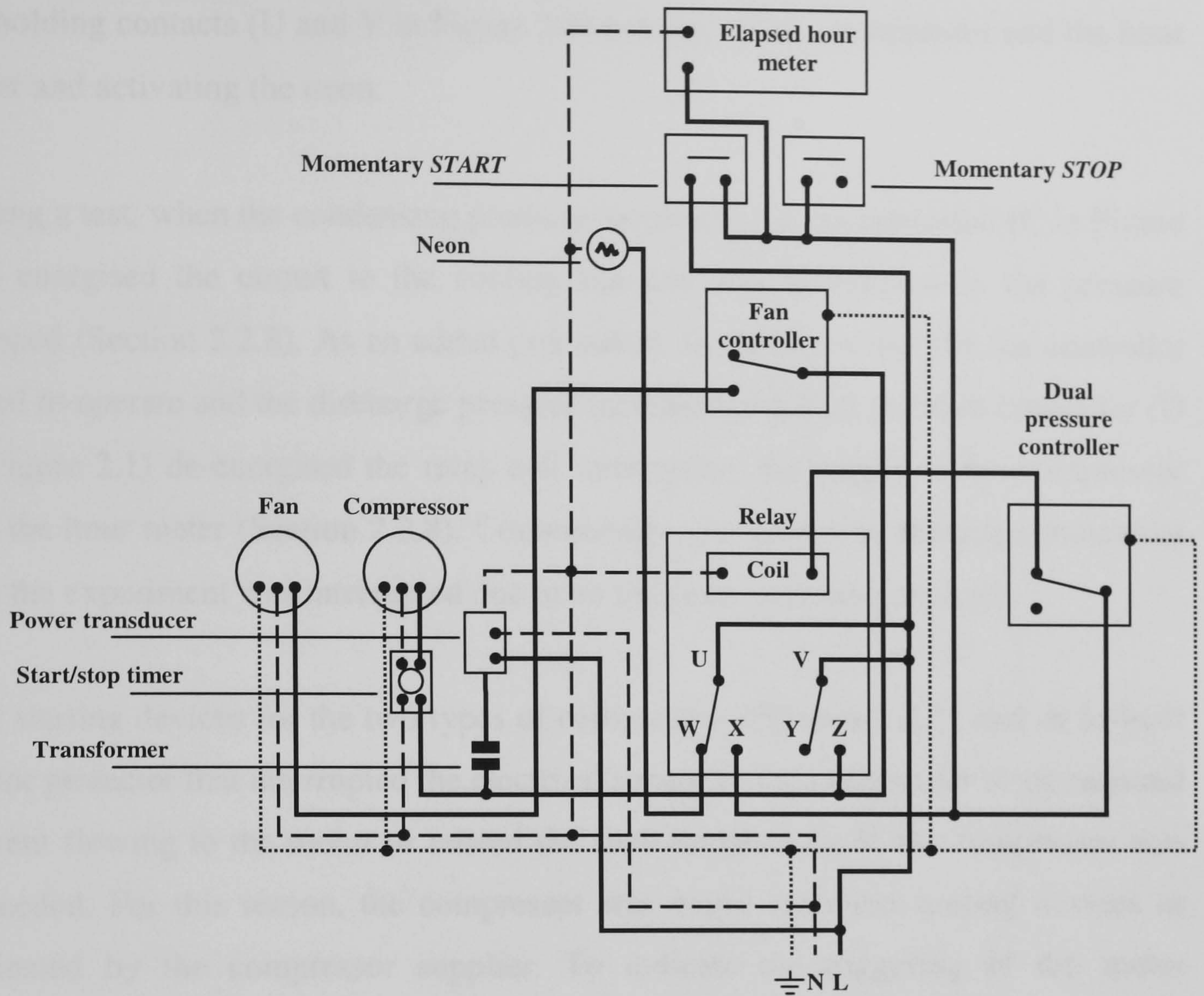
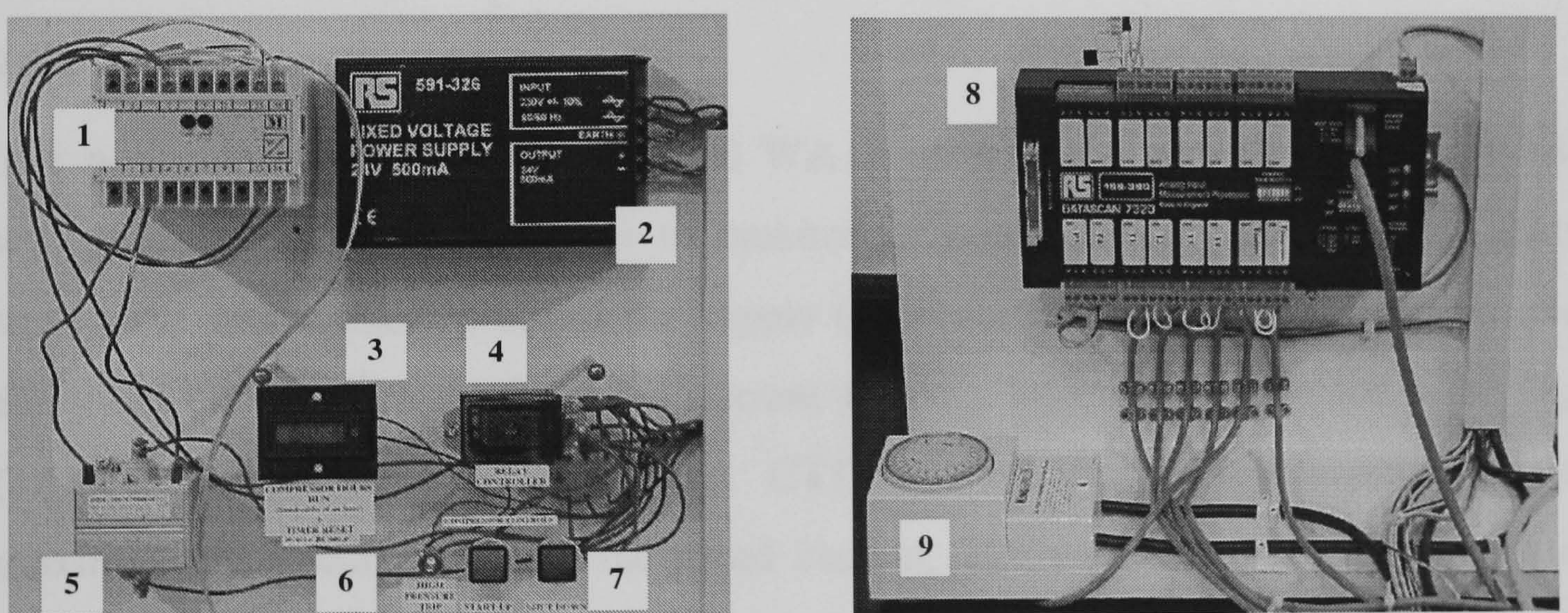


Figure 2.4. Schematic of the electrical installation



1	Power transducer
2	24V fixed voltage power supply
3	Hour meter
4	Relay
5	Step-up transformer
6	Neon
7	Start and stop momentary switches
8	Data logger
9	Mechanical timer

Figure 2.5. The electrical installation controlling the refrigerating circuit

When the momentary action normally closed *STOP* button was pressed, the electrical supply from the dual pressure controller to the relay coil was interrupted. This reset the holding contacts (U and V in Figure 2.4) turning off the compressor and the hour meter and activating the neon.

During a test, when the condensing pressure increased, the fan controller (C in Figure 2.1) energised the circuit to the cooling fan and was interrupted as the pressure dropped (Section 2.2.8). As an added precaution, in the event that the fan controller failed to operate and the discharge pressure increased, the dual pressure controller (D in Figure 2.1) de-energised the relay coil interrupting the supply to the compressor and the hour meter (Section 2.2.8). Consequently, the neon was energised indicating that the experiment was interrupted due to an irregular operating pressure.

The starting devices for the two types of compressors (Section 2.2.2) had an in-built motor protector that interrupted the electrical supply to the compressor if the required current flowing to the motor or indeed the shell temperature of the compressor was exceeded. For this reason, the compressor was wired via these starting devices as indicated by the compressor supplier. To indicate the triggering of the motor protector an LED was wired across the protector switch (not shown).

2.3.2 The power transducer

The power transducer (Multitek M100 WA1), shown schematically in Figure 2.4, was wired across the compressor to monitor its in-use power characteristics. This transducer was connected across the supply to the compressor and the neutral of the electrical circuit. Due to the small current flowing into the compressor a step-up (1A/5A) current transformer (Hobut CT151M1/5-2.5/1 15S) was required to maximise the accuracy of the measured current. The use of this transformer was requested by the manufacturer of the power transducer and is shown schematically in Figure 2.4.

The power transducer generated an analogue D.C. output signal that was compatible with the data logger used, explained in Section 2.3.3 and shown in Figure 2.5. In order not to influence the power reading obtained, this transducer was energised through an auxiliary voltage supply of 240V A.C. Technical specifications of the active power meter are shown in Table 2.6.

Rated value input	5A CT connected
Rated value output	(0 to 5)V
Calibration	(0 to 230)W
Overload (continuous)	4 x rated input
Accuracy	0.18% of full scale output

Table 2.6. Technical specifications of the power transducer

2.3.3 The data logger

The processor module used (Figure 2.5) was the Datascan 7320 appropriate for *realtime* monitoring and data collection. Its 16 direct sensor input channels could be used for thermocouples and D.C. voltages (maximum 10V) as required in this research work. This analogue to digital converter (Figure 2.5) required a fixed voltage power supply of 24V D.C. (RS 591-326) and had an input impedance of 30MΩ. The connecting up between the data logger and the thermocouples and pressure transmitters was carried out as detailed in (Datascan 1995) whilst the connection between the data logger and the power transducer is explained in Section 2.4. Table 2.7 gives the appropriate data logger and *handshake* settings for the successful transfer of data to the supporting interface software.

Channel base address	1 – 7 all OFF
Module configuration	1 and 2 ON, 3 – 8 all OFF
Baud rate	9600
Parity	NONE
Stop bits	1
Data bits	8
End of line	13

Table 2.7. Data logger and PC handshake settings

2.3.4 The interface software

The interface software used to support the data acquisition was Labtech™. This software utilises icons to represent thermocouple connections for temperature readings and analogue connections for voltage readings. In this study, the latter were used to represent values of pressure and power. For a detailed explanation of the setting up of this application the reader is referred to (Labtech 1994). However, it is important to note that the rate at which data was acquired varied between the continuous and the interrupted tests (Section 3.2.4) as summarised in Table 2.8 and explained thereafter.

	Sampling rate	Signal averaging
Continuous test		
0 –1 hour	Once every 60 seconds	Nil
1 – 500 hours	Once every 3600 seconds	5 readings; once every 720 seconds
Start/Stop test		
0 –1 hour	Once every 60 seconds	Nil
1-1000	Once every 300 seconds	5 readings; once every 60 seconds

Table 2.8. Labtech data acquisition settings

For the first 3600 seconds of the continuous tests, the rig had to be monitored rigorously until the specific test conditions were attained. After this the monitoring was relaxed from once every 60 seconds to once every 3600 seconds. This ensured a more accurate data collection (Labtech 1994) and utilisation of smaller electronic files. To further ensure a more reliable data acquisition, after the first hour of operation, five readings were taken during every sampling period and an average of these readings stored to file.

The primary cause for concern in the start/stop test (Section 3.2.4) was the power requirement at start-up. This would assess the influence that the bulk oil temperature within the compressor has on the power characteristics. Unfortunately, for these start/stop experiments, it was impractical to limit the data recorded to when the compressor was in operation and hence for these 1000 hour tests the stored data was doubled compared to the continuous tests (Section 3.2.4). Furthermore, it was difficult to ensure that readings were taken just before and after the mechanical timer triggered the compressor on. To ensure that some indication of this was possible the sampling rate for the start/stop tests were augmented compared to the continuous tests (Table 2.8). This too caused an additional increase in the size of electronic files.

The precision of the sampling rates explained throughout this section depended on the scheduler, which may be affected by the processing capabilities of Microsoft Windows™. Timing reports that quantify this *jitter* (the time differential between the time when a sample was scheduled for collection and the actual collection time) were obtained for all the tests carried out to ensure that sampling rates were maintained. All necessary precautions outlined in (Labtech 1994) were taken to minimise this jitter effect as well as to ensure accurate data collection.

2.4 Equipment calibration

Calibration of the data logger and the thermocouples was not required as the types used were built within the interface software as standard features. As for the pressure transmitters and the power transducer, analogue connections provided on the software were utilised (Section 2.3.4). Settings followed a directly proportional relationship between the instantaneous pressure and power being measured and the simultaneous output D.C. signal being generated. Maximum and minimum values used for calibrating the pressure transmitters and the power transducer are shown in Table 2.3 and Table 2.6 respectively.

In the event that a reading was collected by the data logger at compressor start-up, the input signal from the power transducer to the data logger would have been higher than the maximum acceptable value of 10V (Section 2.3.3). The reason for this being the high starting current drawn by an electrical motor when energised. Apart from damaging the data logger, this over rating of the input signal caused a fault in the data logging thus terminating the data acquisition process. To overcome this problem a *resistor ladder* (Figure 2.6) was used. In this way, the output signal from the power transducer was halved from a range of (0 to 5)V, shown in Table 2.6, to (0 – 2.5)V. This allowed the data logger to accept a reading of power equal to four times the nominal power. This configuration introduced an error of 0.000167% (see following calculation) due to the resistors used and the finite impedance of the data logger (Section 2.3.3) itself.

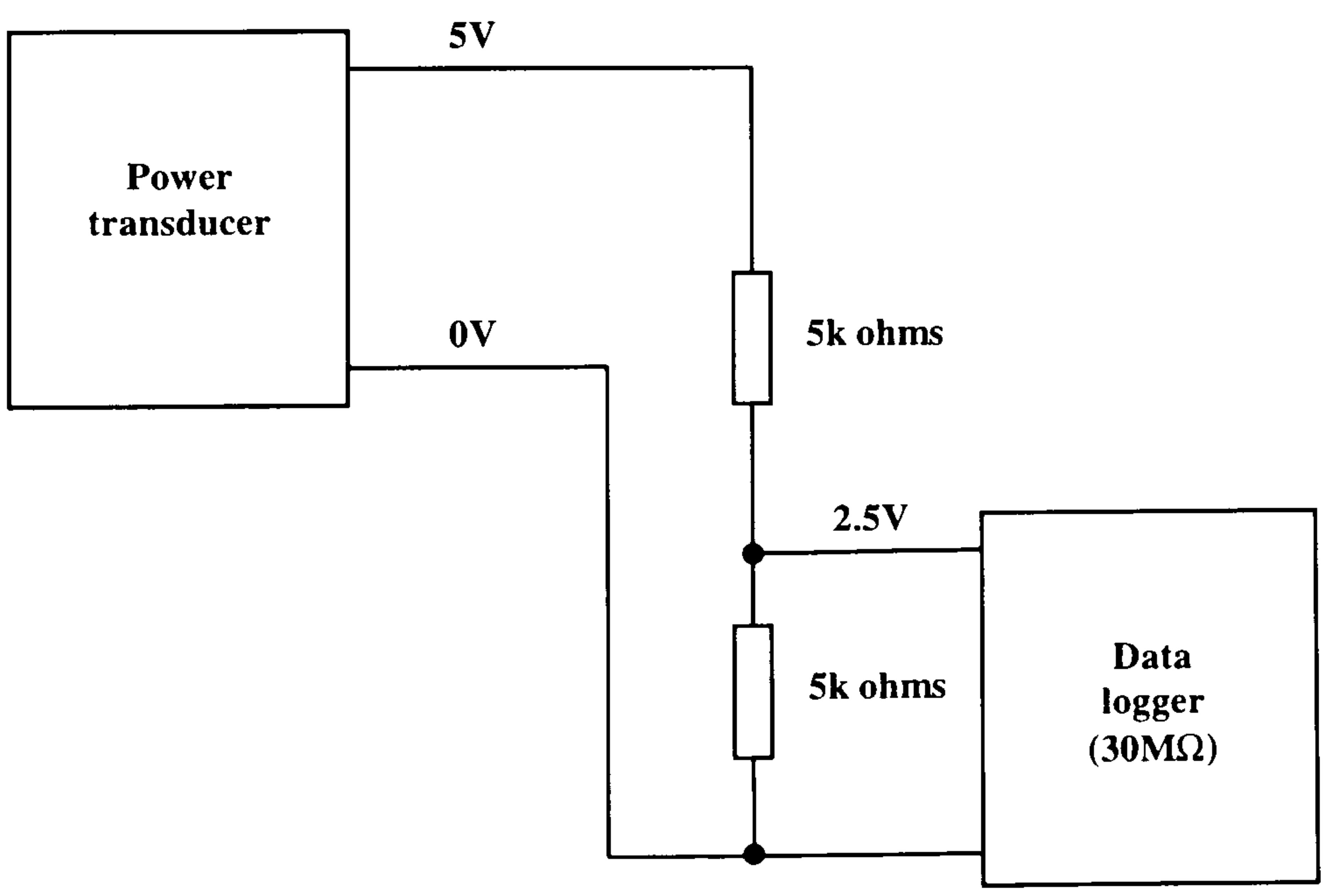


Figure 2.6. Wiring between the transducer and the data logger showing the resistor ladder

To minimise the error from the use of the resistor ladder, the resistors used were of a high precision (RS 201-9898), low tolerance (0.01%) and low temperature coefficient (±5ppm/°C). From Figure 2.6, the total combined resistance of 5kΩ and 30MΩ is:

$$\frac{5000x30x10^{6}}{5000+30x10^{6}}=4999.17\Omega \qquad 2.1$$

The percentage error is therefore equivalent to:

$$\left(\frac{5-4.99917}{5}\right)x100=0.0166\% \qquad 2.2$$

The total error of 0.000167% (0.0166% (Equation 2.2) and 0.01% (tolerance rating)) was considered to be negligible and nonetheless constant throughout this investigation. Hence, no further consideration of this error is given throughout this thesis.

2.5 Commissioning

Prior to performing any actual tests, a commissioning run of approximately 1500 hours (interrupted) was carried out to identify any shortcomings in the development of the experimental rig and to pressure test (30 bar) the system for potential leaks. One of the main concerns was identifying leaks resulting from the connecting up of pipework and accessories and the reliability of the PVC olives for the capillary tube fittings (Section 2.2.4) at test conditions. Another concern was the sizing up of the various components used as explained in Section 2.2.3 and 2.2.4. The length of capillary tube and the mass of refrigerant charge required to attain the operating conditions under different experimental conditions (Section 3.2.4) were determined during this testing phase. The direction of airflow over the heat exchangers, as explained in Section 2.2.7, was also observed here. Furthermore, it had to be ascertained that the handshake between the computer and the data logger (Section 2.3.3) had been achieved successfully and that the acquired information could be processed satisfactorily. It was during this stage that the interruption of data logging due to the high current drawn at compressor start-up (Section 2.4) was noted and rectified.

Throughout this commissioning period a considerable insight into the experimental assembly was acquired and test procedures were formulated, both for the maintenance and for the actual commencement of the experiments (Sections 3.2.1 to 3.2.3). Furthermore, it was found that logging the energy consumed by the compressor (instead of power) as was initially planned, caused a fault in the data logging process as soon as the number of digits exceeded the maximum which could be displayed on the computer screen during *runtime*. Another problem identified was that, due to its moist environment, one thermocouple socket was corroding causing interference during data logging. This was rectified and the pins protected. Finally, moisture from the defrosting of components was causing the resin base plate of the test rig to sag causing bending forces on the pipework. To minimise any possibility of leaks from pipework connections this base plate was appropriately reinforced.

2.6 Design constraints and evaluation

2.6.1 The mechanical system

The test rig described throughout this chapter focused on the technical system of the domestic refrigerator. Based on the theory of technical systems (Hubka and Eder 1988), it is important to mention that the environmental impacts of this product, studied using this apparatus, are a complex interaction between the product, the environment in which the product is operating as well as the unpredictable human behaviour of the person utilising the product (Figure 2.7). With relevance to this thesis, humidity, air circulation, ambient temperature, temperature regulation, defrosting, and type of contents cooled are some of the factors that increase the start/stop frequency of the compressor mounted on a refrigerator. None of these parameters have been addressed throughout this work. Nonetheless, one start/stop frequency was assumed to help shed more light on the influence these parameters have by comparing wear and power characteristics for continuous and interrupted tests (Section 3.2.4).

The copper pipework was of a larger diameter compared to that used on a refrigerator. This, together with the manifold blocks, increased the heat transfer characteristics. Insulation was used on all the pipework and on all the components on

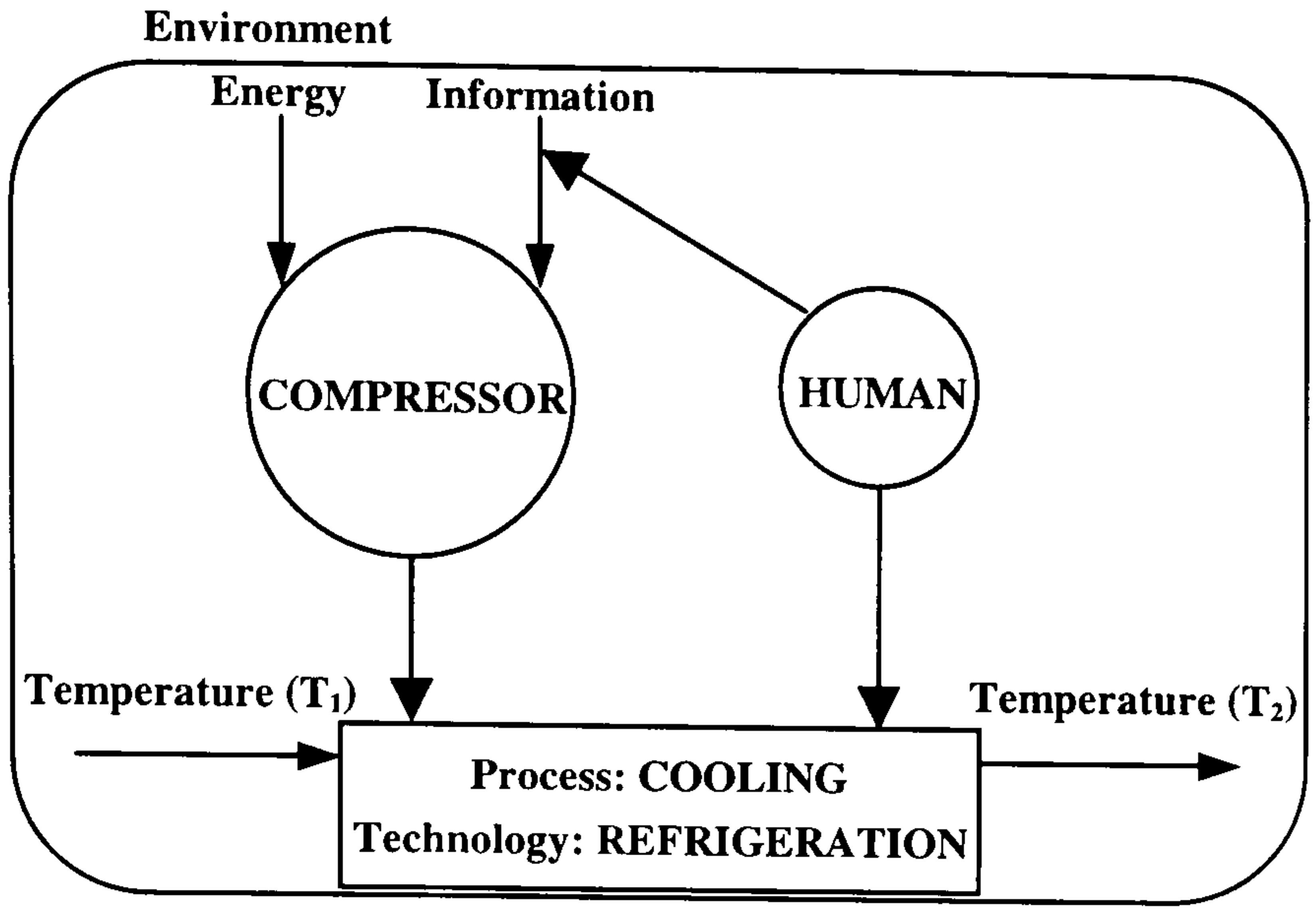


Figure 2.7. Model showing the influences on the compressor

the liquid side of the test circuit but inevitably laboratory conditions played a role in the overall characteristics of each individual test. The manifolds on the low pressure side of the circuit were not insulated and the one at the suction side of the compressor must have influenced the suction vapour superheating. Alternatively, the manifold to which the expansion device was connected *iced up* considerably for the continuous tests compared to the interrupted tests (Section 3.2.4) and this too must have influenced the results. These implications meant that even if an appropriate expansion device for a given operating condition achieved optimisation of the compressor, variations in the ambient conditions influenced the electrical power drawn by the machine. As an example, suction vapour superheating increases the compressor work (for a given refrigerant mass flow rate) but also reduces the vapour density of the circulating fluid thereby reducing the mass flow through the compressor (Atwood and Hughes 1990). This, in turn, reduces the electrical energy consumed. The net effect of superheating was therefore unknown throughout the tests carried out and little control over such variables was possible.

Ambient conditions also influence the temperature of the compressor, which in turn influence the coil winding temperature of the electric motor. Any fluctuations in the compressor shell temperature may influence the viscosity of the lubricant and a change in the temperature of the suction vapour within the compressor. Both of these characteristics influence the electrical energy consumed.

With these hermetic machines it was difficult to ascertain how the cooling capacity of each compressor varied with the evaporating temperature (Table 2.1). The sizing of the heat exchangers (Section 2.2.3) would not have been appropriate for all the different compressors used. This, in turn, influenced the evaporating temperature, hence the suction vapour temperature. This suction vapour condition influences the in-use power of the compressor as was outlined earlier in this section.

Both the refrigerant mass flow rate as well as the pressure differential may benefit or exacerbate mechanical efficiencies. The capillary tube was the only means of control for either of the two but this may not have been fully satisfactory. Nonetheless, if these experimental parameters were maintained identical between respective tests then any error incurred would not vary drastically throughout the experiments performed.

To complete the pressure-enthalpy characteristics plotted (Section 4.3.2) an average reading of the suction and discharge pressures was required (P_1 and P_2 respectively in Figure 2.1). On this test system these were not obtained electronically as an instantaneous reading of these pressures was required during charging and inspection. Electronically this would not have been feasible, as data would need to be collected at much higher frequencies with the ensuing consequences explained in Section 2.3.4. In retrospect, pressure transmitters (Section 2.2.8) should have been fitted in conjunction with the dial gauges. Nonetheless, periodic readings of these pressures were taken manually and average values obtained.

With this design of test facility the energy transferred at the heat exchangers could not be assessed. This made it difficult to obtain compressor performance characteristics as a function of the cooling capacity of the evaporator or the heating capacity of the condenser (Guldbrandsen, et al. 1986). It is likely that such characteristics would have assisted in comparing experimental results.

As explained in Section 3.2.4, during each of the experiments carried out, a pressure for the liquid side of the test circuit had to be set using the mechanical high pressure controller (Section 2.2.8). This controller was graduated at 2 bar intervals which made it difficult to determine any fractional values required (Section 3.2.4). A digital controller would have made these settings more accurate and easier to control.

Nonetheless, the margin of error introduced here is minimal to the outcome of the investigation and was therefore given little consideration.

2.6.2 The electrical system

One of the major concerns of the electrical system was the power transducer as this was purpose built to be able to measure small differences in power. An error was recorded at no load and a personal communication with the supplier identified that:

- the offset error was due to an analogue/digital converter 'hunting' when there was no input,
- the error would never exceed the 1% of full scale output (5V),
- the error diminished to practically zero above about 10% of full scale.

To this effect the instrument was rebuilt using a printed circuit board selected to give a minimum analogue output error at low power. This was measured by the supplier and found to be of an approximate and acceptable value of 0.18% (Table 2.6) compared to the 1% error previously designed for.

The electrical installation was enclosed in a perspex cabinet to minimise the risk of electric shock (Figure 2.2). Also, this allowed the data scanner to be maintained in a draught free environment as specified by the manufacturer (Datascan 1995). Within this compartment the current transformer, the power transducer, the fixed voltage power supply and the relay installation were located in such a way that any influence on the data scanner due to noise or external heating was kept to a minimum.

Initially, a digital timer in place of a mechanical timer was preferred for controlling the start/stop operation of the compressor during the interrupted tests (Section 3.2.4). This was because a digital timer would provide more accurate control, which might influence the results (Section 4.3.1). However, the ones available commercially could not be used since these only had ten settings for every twelve hours. As given in Section 3.2.4, the start/stop tests required twelve settings per twelve hours.

Finally, components like the mechanical timer utilised to start and stop the compressor, the hour meter and the relay were wired in such a way that the value of power recorded by the transducer included the power drawn off by these components. This was overlooked as any error introduced was constant throughout all of the tests carried out.

2.6.3 Evaluation

Some of the constraints explained in the preceding two sections, and in particular those in Section 2.6.1, influenced the operation of the test facility which in turn affected the outcome of the results. However, the objective of the test facility was to acquire knowledge on trends and not provide a solution. It must be emphasised that, although a value for the cooling COP was calculated where appropriate (Section 4.3.2), this thesis does not monitor the efficiency of the compressor or other attributes as given in (DOE 1993). The emphasis is on the power requirement due to friction and wear. The investigation of wear (Chapter 4) will also help shed further light on this so that the basis of discussion will not depend solely on the monitored power.

Due to financial and time constraints under which this Ph.D. research had to be carried out, it would have been inappropriate to test actual domestic refrigerators at the different test conditions performed throughout this study. This test rig was therefore seen as an appropriate alternative. Power characteristics were monitored against pressure and temperature parameters to identify if this could have been drastically influenced by any of these variables (Section 4.3.1). Exceptional care was taken to ensure that test conditions did not vary drastically between the respective tests. Finally, when qualitative rather than quantitative comparisons are sought on variations between working fluid, power, wear and operating time the data obtained should not be interpreted at *face value* due to changes in machines, refrigerants, ambient conditions, etc. Furthermore, the direct use of a power meter implies that the experimental investigation does not rely solely on the pressure-enthalpy characteristics to determine the in-use power of the compressor.

3 EXPERIMENTAL AND ANALYTICAL METHODOLOGY

An experimental and an analytical approach were required to study the environmental implications of a change in the working fluid of a refrigerator by addressing tribological issues within the hermetic compressor. Firstly, this chapter will highlight the experimental approach by providing an overview of the procedures, the samples and the measurement methods used. Secondly, an explanation of the analytical LCA model for the refrigerator, used as a case study, is presented. Decisions made on the product boundaries, data acquisition and assumptions are included and incorporated within the generic model explained.

3.1 Overview of the experimental methodology

Actual hermetic compressors were tested at different operating scenarios using the test facility described in Chapter 2. Throughout these tests the in-use power requirement of each compressor was monitored. Surface characteristics of critical components were studied using light microscopy, Scanning Electron Microscopy (SEM), Energy Dispersive X-ray (EDX) microanalysis and X-ray Photoelectron Spectroscopy (XPS). Mechanical stylus measurements for the aluminium and the steel surfaces were carried out together with post-test oil debris analyses using SEM. Additionally, lubricant bench tests using a rotary tribometer configured as a four-ball machine were performed to assess lubricant degradation. These tests were carried out on unused and used oil samples to determine the extreme pressure performance characteristics of a refrigerant compatible lubricant before and after a compressor test.

3.2 Compressor testing

The following sections will present an overview of the procedures followed for compressor testing. A test schedule and the samples analysed will also be presented. For a step-by-step explanation of the test procedure the reader is referred to Appendix C. Here, an equation for the determination of the coil winding temperature of the compressor (Section 4.3.2) is also presented.

3.2.1 Pre-test procedure

Each hermetic compressor was supplied oil-free and kept under a charge of inert gas to reduce any contamination of the internal parts. With the rubber bungs on the service tube, the suction tube and the discharge tube removed, access fittings were soldered whilst purging with nitrogen gas (Section 2.2.1). The access fittings used here had a schraeder valve to enable a charge of nitrogen to be retained until the compressor was ready for use. It should be noted that, after consultation with the supplier, no cleaning procedure of the compressor was required. This is also the case in a real life scenario where the supplier of the compressor carries out any cleaning required.

Prior to each experiment, a test rig preparation procedure was carried out to remove any residue of working fluid from a previous test and moisture from the air that fills up the circuit when the refrigerant is reclaimed. As will be seen in Section 3.2.4, this moisture may result in a problem. This preparation process is most suitable to the test circuit utilised here (Chapter 2) and was developed after consultation with Castrol International, one of the collaborators of this research project. With the capillary tube, the filter drier and the compressor disconnected, the test rig was purged with petroleum ether solvent (PET spirit) and with dry and clean compressed air. This purging was carried out for three consecutive times, each time making sure to collect the discharged PET spirit in a suitable receptacle. Finally, more compressed air was allowed through the circuit to ensure the removal of any residue of the cleaning solvent.

After cleaning the system, a new compressor (Section 2.2.2), a new capillary tube (Section 2.2.4) and a new filter drier (Section 2.2.5) were installed. The two dial gauges (Section 2.2.8) and the sight glass (Section 2.2.8) were replaced with every change in refrigerant type (Section 3.2.2). When these dual gauges had to be replaced this was done under a regulated continuous flow of compressed air to eliminate any debris from entering the system and before completing the cleaning procedure explained above. An added precaution was that, with the circuit complete, the rig was pressure tested using compressed air to approximately 5 bar. Using soap water all the disturbed connections were tested for leaks. This was done with as little time delay as possible to minimise any risk of moisture deposits. Any leaks identified were rectified and the rig was then vacuumed. During this vacuuming stage, common workshop practice required that the filter drier was heated using a hot air blower to remove any moisture which could have been retained in the silicagel whilst pressure testing the system. Furthermore, to minimise the risk of the presence of moisture, vacuuming was interrupted and the rig was purged with the appropriate refrigerant. When purging was complete, the rig was vacuumed for a further one hour. After this the rig was left overnight under a vacuum to test whether the refrigerating circuit was indeed leak proof.

3.2.2 Experimental procedure

If the vacuum was retained (Section 3.2.1) the circuit was further vacuumed for another 30 minutes to allow the hermetic compressor to be charged with 350ml of an appropriate lubricant. This was done through the service tube using a *quick coupler* fitting that activated the schraeder valve on the access fitting. Lubricant charging was carried out with as little time delay as possible, especially when a synthetic lubricant was used (Section 3.2.4). When oil charging was complete, the compressor was inverted to moisten its internal components with oil and was then mounted on anti-vibration mounts and secured.

After resetting the hour meter (Figure 2.5) and activating the data acquisition software the compressor was run for three minutes in a vacuum to prime the oil system (compressor manufacturer requirement). Charging of the two azeotropic compounds considered (Section 3.2.4) was carried out by automatically transferring a preset weight (Section 2.5) of vapour refrigerant, with an accuracy of approximately 10%, using a full strain gauge bridge electronic charging system (CPS CC-700) (Figure 3.1). The accuracy obtained here was the best that could have been achieved whilst transferring gas at ambient conditions using commercially available equipment. Refrigerant charging was carried out incrementally over a one hour period to allow the equipment to stabilise after each charge. When operating pressures were attained, charging was complete and the rig conditions were monitored closely to ensure that the temperature of the compressor case stabilised around 75°C. It should be noted that, as disclosed by the lubricant manufacturer, this is equivalent to a bulk oil temperature of 90°C and is the ideal operating temperature for these types of compressors. If the required pressure ratio was not attained then the length of capillary tube had to be altered as was done during the commissioning phase of this research work (Section 2.5).

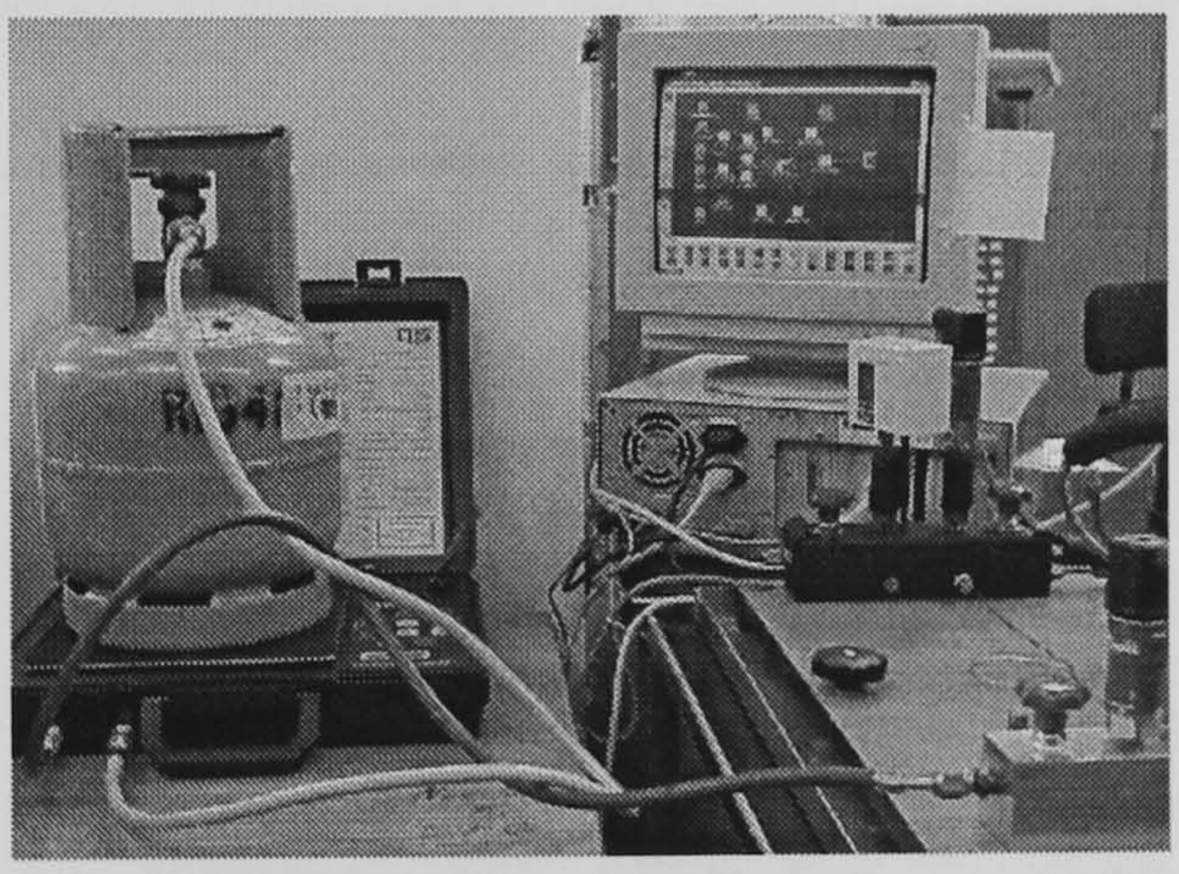


Figure 3.1. Electronic refrigerant charging device

During charging and throughout the test duration leak tests were performed periodically using an electronic leak detector. Any undetected leak would influence the rig characteristics, which would render the outcome of the experiment inappropriate. In the event that a leak was detected the experiment had to be aborted, the refrigerant reclaimed and the test circuit cleaned. Inevitably, an indeterminate quantity of compressor lubricant was lost and this too was likely to influence the experimental outcome. For this reason, a new compressor had to be installed which goes on to emphasise how important it was to ensure a leak proof system prior to starting an experiment.

3.2.3 Post-test procedure

Upon completion of each test, the refrigerant charge was reclaimed. As explained in Section 1.5.3, some of the lubricant in the compressor was present as droplets in the refrigerant. One possibility of ensuring that no gas escaped over the duration of the test was to reweigh the refrigerant prior to it being reclaimed. The charging scales used during charging (Section 3.2.2) were appropriate for this purpose. However, due to the soluble lubricant, readings of the reclaimed refrigerant were always likely to vary and contamination of the charging scales was also considered a possibility. For these reasons, reweighing of the reclaimed refrigerant was not pursued.

Approximately 300ml of lubricant was then reclaimed from the compressor through the service tube, the difference (50ml) being lost with the refrigerant or retained in the circuit and the compressor. The compressor was then milled at the weld that seals the top and the bottom casing together (Figure 3.2). This is a slow operation to minimise any debris from contaminating the samples and also due to the robust and unconformable design of the compressor casing.

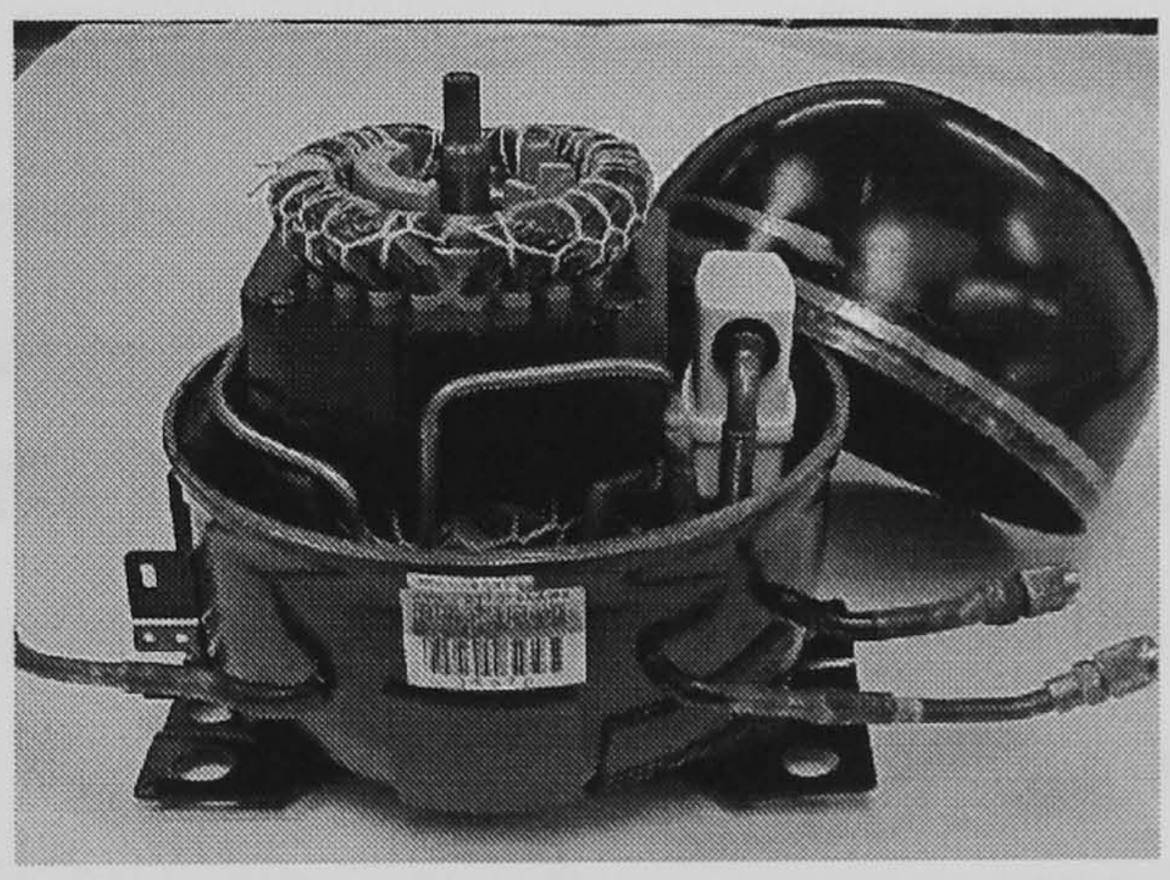


Figure 3.2. Casing of the hermetic compressor milled off

With the compressor stripped open the components to be examined (Section 3.2.5) were obtained and, if required, these were cut to a dimension which made microscopy analyses possible (Section 3.3). All parts to be examined were washed in acetone in an ultrasonic bath for 60 seconds. Each sample was then rinsed with PET spirit, dried under a hot air blower for a further 60 seconds and placed in labelled sample bags. All the remaining parts, which were not to be analysed, including the filter drier and the capillary tube were labelled and retained in case these were needed for analysis later on throughout the investigation.

3.2.4 Details of experiments and test schedule

The two types of compressors (Section 2.2.2) were either tested for a 500 hour duration or for a 1000 hour duration. The 500 hour test was a continuous experiment, chosen to simulate up to 15 years of compressor lifetime (Reyes-Gavilán, et al. 1997), whereas the 1000 hour test was interrupted every 30 minutes and left idle for another 30 minutes. Therefore, throughout these interrupted tests, the actual operating time of the compressor was also 500 hours. It should be emphasised that this value of 30 minutes was chosen arbitrarily but in reality this value is influenced by many factors (Section 2.6.1). Start/stop tests were carried out to allow the bulk oil temperature inside the compressor to drop from its normal operating temperature. This increases the wear effects (Na, et al. 1998) on the samples considered (Section 3.2.5) as well as the power requirements of the compressor (Janssen, et al. 1992).

A schedule for the type of lubricants tested is given in Table 3.1. For the HFC-134a compound, two synthetic lubricants, the polyol ester (POE) type and the polyvinylether (PVE) type, were tested. Previous studies note that POE is unable to form a lubricating film at low speeds (Johnston, et al. 1991) whilst PVE shows improved wear characteristics over POE (Takesue and Tominaga 1998; Yamamoto, et al. 1998). The experiments described throughout this thesis were performed to investigate this further. For the POE type, a low viscosity, an intermediate viscosity and a viscosity corresponding to that normally used with the CFC-12, in this case the SD oil (Table 3.1), was used. The reason for including lower viscosity oils was to study an observation given by Kruse and Schroeder (1985) as to whether these oils may in effect penetrate concentrated contacts better, or lower the environmental impact due to an improved compressor efficiency as noted by Reyes-Gavilán, et al. (1997). For the PVE type, only the higher viscosity grade was tested (Table 3.1) due to availability. It should be noted that for either of these lubricants the chemical structure was not known. This structure differs between blends and influences miscibility, lubricity and viscosity. For the POE, this is studied more thoroughly in (Remigy, et al. 1997).

Lubricant type	Designation	Density[a] (kg/l)	Kinematic viscosity[b] (mm^2/s)	
		@ 15°C	@ 40°C	@ 90°C
Mineral oil	SD	0.879	39	> 4.9[c]
POE of ISO VG 10	POE10	0.991	10.25	3.3
POE of ISO VG 22	POE22	0.997	20.4	5.8
POE of ISO VG 32	POE32	0.999	30.5	7
PVE of ISO VG 32	PVE	0.999	30.5	7

[a] not contaminated by refrigerant and measured as given in (IP 1997c). Typical density characteristics for the synthetic oils at various VG are shown in Appendix D
[b] not contaminated by refrigerant and measured as given in (IP 1997a). Typical viscosity characteristics for the synthetic oils at various VG are shown in Appendix D
[c] this viscosity is at 100°C. A value of viscosity at 90°C was not available

Table 3.1. Density and kinematic viscosity characteristics for the lubricants used

Unlike the SD type oil, both the POE and the PVE are hygroscopic but the esters in the POE are degraded further by water (Sanvordenker 1991; Sundaresan and Finkenstadt 1992) compared to the ether in the PVE (Tazaki, et al. 1998). The presence of any additives, unknown due to a commercial interest, with which both of these synthetic lubricants are characterised (Section 1.5.3) increases this hygroscopic effect further (Reyes-Gavilán, et al. 1997). Any moisture content introduced into the refrigeration system with the lubricant also increases the reactivity with the refrigerant (Mizuhara 1994), which may be detrimental to the interacting surfaces identified in Section 3.2.5 (Kramer 1999). Therefore, necessary precautions were taken to reduce this moisture risk to a minimum (Section 2.2 and 3.2.2). Further typical characteristics of the synthetic lubricants affecting temperature, refrigerant charge, etc. are shown in Appendix D.

One other type of synthetic lubricant, polyalkalyene glycol (PAG), which was initially selected as an ideal candidate for refrigeration applications due to its miscibility with HFCs (Reyes-Gavilán, et al. 1996a), was not considered throughout this study. This is because the synthetic oils in Table 3.1 have recently received increasing attention since PAG oils have a high hygroscopic tendency, are chemically unstable with HFCs and offer reduced protection to interacting surfaces (Short and Cavestri 1992; Yoon, et al. 1998).

Finally, since the operating pressure inside the refrigerator being considered throughout this study is 15 bar (Hotpoint 1997), normal pressure tests and high pressure tests were carried out. For the normal pressure tests the high pressure controller on the test circuit (Section 2.2.8) was set to approximately 14.8 bar and a corresponding low pressure (0.6 bar) on the vapour side of the test circuit was maintained with an appropriate length of expansion device (Section 2.2.4). As for the high pressure test, the high pressure controller was set to 31.5 bar and the increase in pressure was achieved by adding more refrigerant gas to the test circuit. This value of high pressure was selected since it was the maximum pressure the rig components could sustain. For these high pressure tests, the corresponding low pressure was maintained at 1 bar. The test schedule given in Table 3.2 indicates that all operating pressures were allowed to swing by the values given, especially since the high pressure controller used was mechanical and proved difficult to maintain an exact value of the required test pressure (Section 2.2.8).

Test label	Compressor type[a]	Duration (hrs)	Operation[b]	Lubricant type[c]	Pressure (bar)[d]	Analyses[e]					
						P	S	L	D	V	W
A	A	500	Cont.	POE10	31.5/1	✔	✔		✔		
B	A	500	Cont.	POE22	31.5/1	✔	✔		✔		
C	A	500	Cont.	POE32	31.5/1	✔	✔		✔		
D	A	1000	Cont.	POE32	14.8/0.6	✔	✔	✔	✔	✔	
E	A	1000	Cont.	PVE	14.8/0.6	✔	✔	✔	✔	✔	
F	A	500	Cont.	POE32	31.5/1	✔	✔	✔	✔	✔	
G	A	500	Cont.	PVE	31.5/1	✔	✔	✔	✔	✔	
H	A	500	Cont.	POE32	31.5/1	✔	✔	✔	✔	✔	
I	A	500	Cont.	PVE	31.5/1	✔	✔	✔	✔	✔	
1	A	500	Cont.	POE32	14.8/0.6	✔	✔	✔			✔
2	B	500	Cont.	POE32	14.8/0.6	✔	✔	✔			✔
3	A	500	Cont.	SD	14.8/0.6	✔	✔	✔			✔
4	B	500	Cont.	SD	14.8/0.6	✔	✔	✔			✔
5	B	1000	St./Sp.	POE32	14.8/0.6	✔	✔	✔			✔
6	B	1000	St./Sp.	SD	14.8/0.6	✔	✔	✔			✔
7	B	1000	St./Sp.	POE32	14.8/0.6						✔
8	B	1000	St./Sp.	SD	14.8/0.6						✔

[a] more details on the type of compressor are included in Section 2.2.2
[b] Cont. implies that the test was continuous whilst St./Sp. implies that the test was interrupted
[c] Further details in Table 3.1
[d] For the high pressure tests (refered to as 30 bar throughout the thesis) the high pressure was set to 31.5 ± 2 bar and the low pressure was set to 1 ± 0.2 bar, whilst for the normal pressure tests (refered to as 15 bar throughout the thesis) the high pressure was set to 14.8 ± 1.7 bar and the low pressure was set to 0.6 ± 0.1 bar
[e] P – gudgeon pin; S – small end of the connecting rod; L – large end of the connecting rod; D – oil debris; V – valve plate (piston side); W – power monitoring. More details are given in Section 3.2.5

Table 3.2. Test schedule

3.2.5 Identifying the samples to be analysed

The influence tribological concerns have on the in-use power of the compressor were examined by focusing upon the journal bearings of the piston and connecting rod assembly (Figure 3.3). The components within this assembly, upon which this investigation centred, were the die-cast aluminium/silicon alloy connecting rod and the machined steel gudgeon pin. It has been stated that wear by reciprocating sliding is severe due to factors such as heat accumulation, stress reversals and wear debris being trapped, all of which reduce the load bearing capabilities of a reciprocating interface (Somi Reddy, et al. 1995). For these reasons, and other attributes explained in the following sections, this research has concentrated on the wear characteristics of these components.

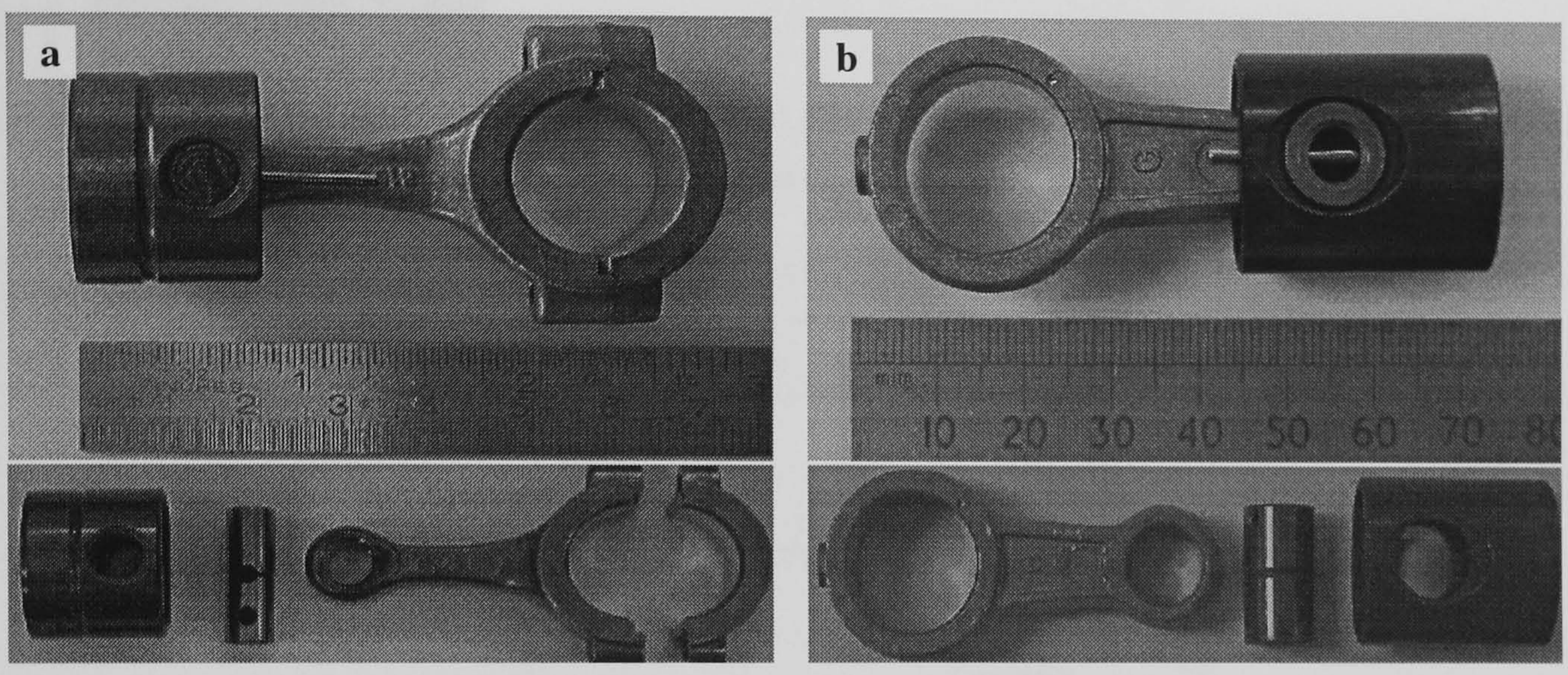


Figure 3.3. Piston and connecting rod assembly; (a) Type A and (b) Type B compressor

<u>*Potential lubrication regimes*</u>

As the connecting rod oscillates relative to the pin, its velocity characteristics (Rio Garcia and Hadfield 2000) are shown in Figure 3.4. In this figure the terminology used for internal combustion engines is adopted. During compression, the surfaces between the pin and the rod (small end) and the rod (large end) and the driveshaft experiencing the greater pressure will be referred to as the *load face* throughout this thesis. The analogy depicted in Figure 3.5 highlights the wear occurring at this load face (small end only) as a function of the connecting rod dynamics.

Increased heat of friction or wear of materials is likely to occur during the transition of the connecting rod from position (4) to position (1) to position (2) due to the rate of change of velocity. Similar conditions are experienced as the rod approaches position (3) from position (2) due to an increase in the cylinder pressure and a decrease in the velocity of the rod relative to the pin. Nonetheless, each transitional phase will be dealt with separately here to explain this further.

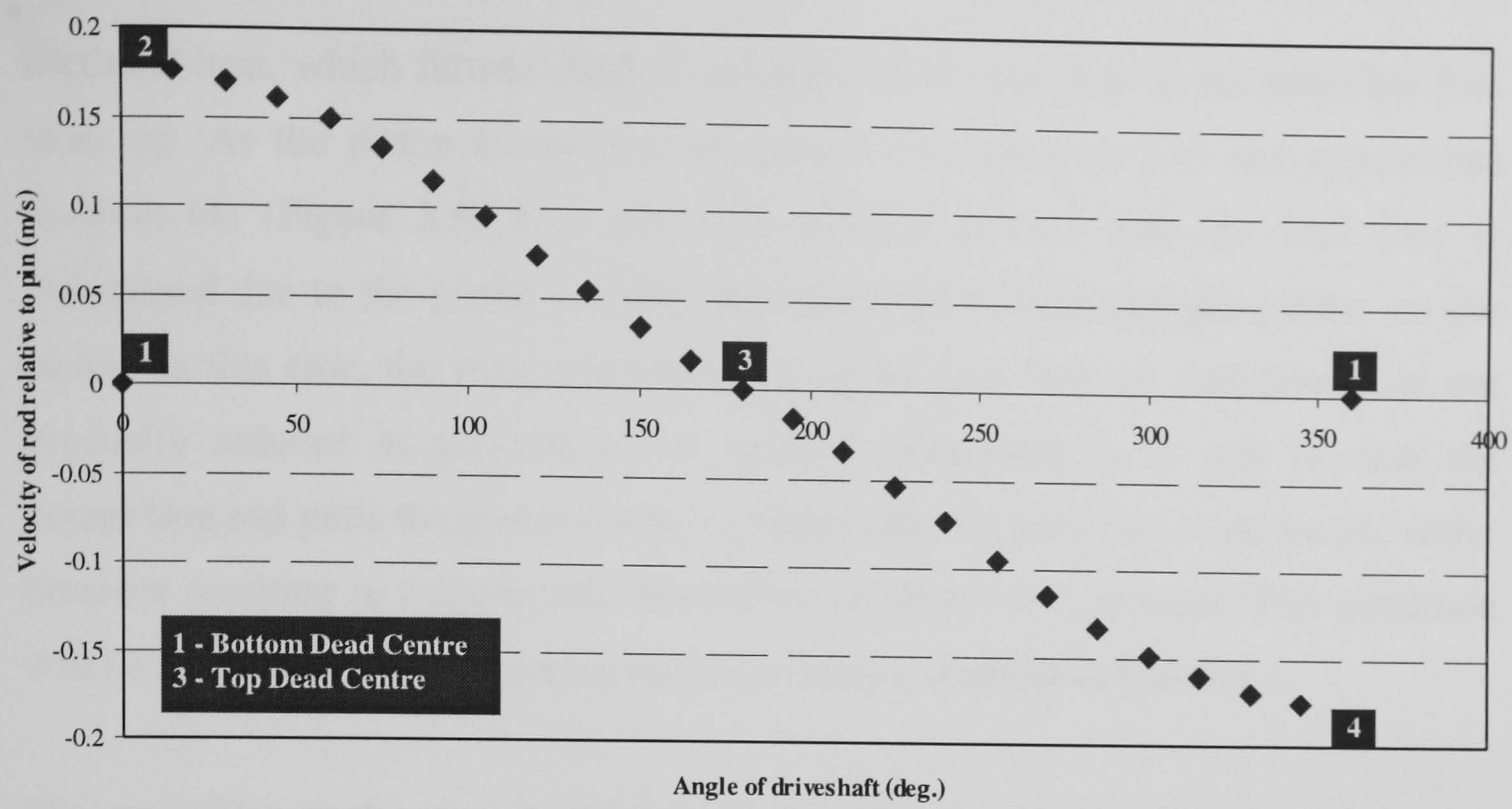


Figure 3.4. Velocity characteristics of rod relative to pin

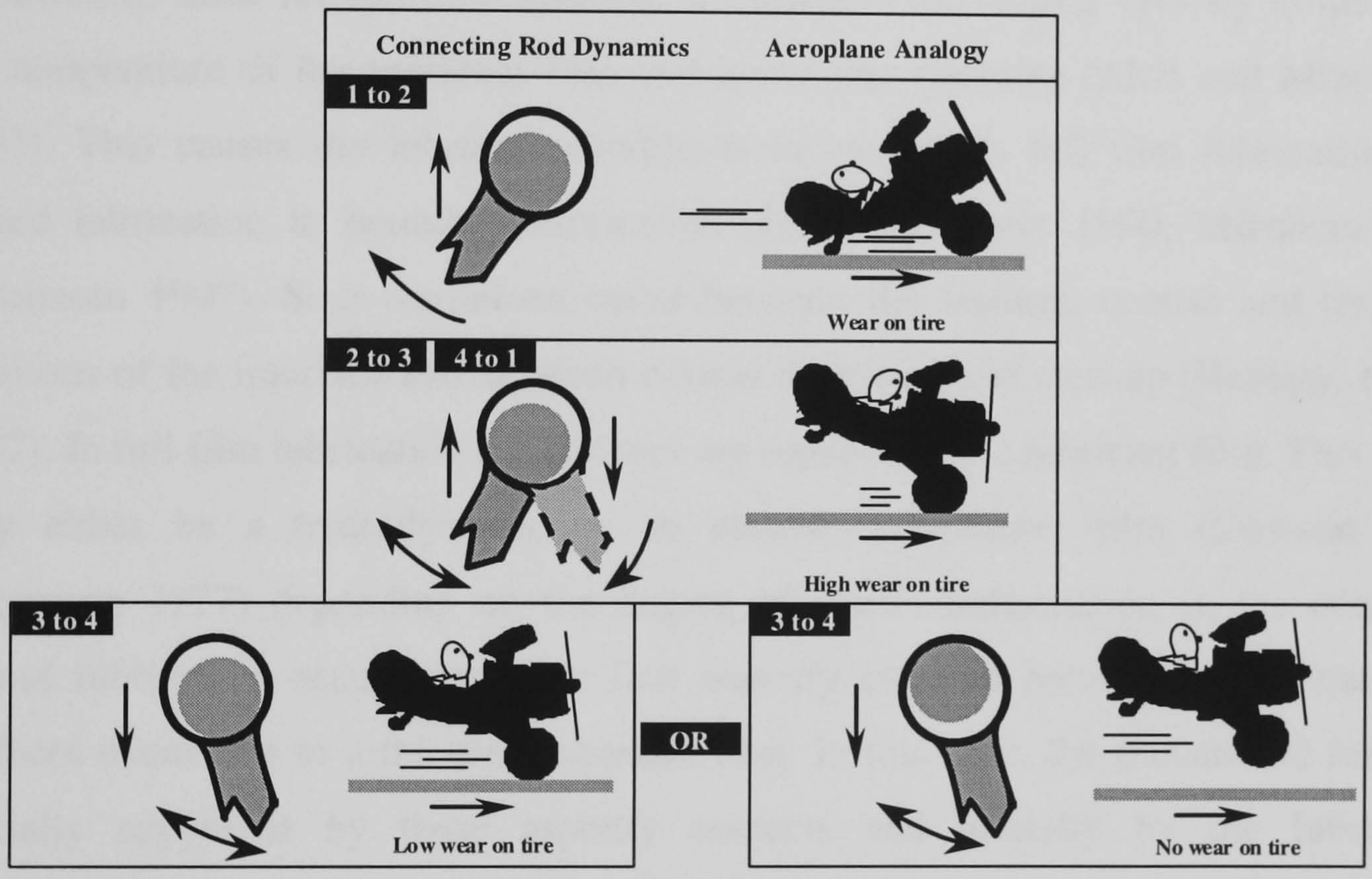


Figure 3.5. Analogy for conditions occurring at the load face as a function of rod dynamics

During the transition of the connecting rod from position (4) to position (1) deceleration of the rod relative to the pin occurs whilst during the transition from position (1) to position (2) acceleration occurs. Despite the low loads, conditions are unfavourable for an adequate film protection due to the low speeds involved (Riahi and Alpas 2000). As the connecting rod moves from position (2) to position (3), the sliding speed drops and the load on the piston increases. These two factors cause the lubrication condition to change and it is during this period of oscillation that the load faces are most likely to experience metallic contact. This causes an increase in the frictional heat, which further changes the lubrication condition as the lubricant film heats up. As the piston leaves the top dead centre (position (3)) and approaches position (4) (Figure 3.5) it is not clear whether contact with the load face is maintained due to the piston pushing the rod as the compressed gas pushes on the piston. In this case, the wear characteristics on the load face are maintained but are gradually reduced as position (4) is reached. Alternatively, it may be that the connecting rod pulls the piston down, in which case the load face is no longer under pressure resulting in a favourable lubricating condition and no wear. This condition will be investigated further during the experimental analysis in Chapter 4.

The preceding explanation highlights the complexities surrounding the lubrication condition of these refrigeration systems. A change in the sliding velocity influences the temperature of the lubricant film and hence the viscosity (Akei and Mizuhara 1997). This causes the lubricant conditions to vary from full film lubrication to mixed lubrication to boundary lubrication (Hess and Soom 1990; Mizuhara and Tomimoto 1997). Such variations occur between the leading, central and trailing positions of the interface and between normal operation and start-up (Remigy, et al. 1997). In full film lubrication the surfaces are separated by a lubricant film. This film may either be a hydrodynamic or an elastohydrodynamic film (Dowson and Higginson 1977) depending on the degree of elastic deformation in the contact. Mixed lubrication occurs when the first asperity contacts between the interacting surfaces occur due to a thinning lubricant film. In this case, the transmitted load is partially supported by these asperity contacts and partially by the lubricant (Andersson and Salas-Russo 1994). The proportion carried by the bulk lubricant increases with speed and viscosity. In boundary lubrication, the total load transmitted is supported by the asperities (Dizdar 1999) and conditions are severe and surface reactions occur (Zhang, et al. 1999). Previous works (Sargent, et al. 1982; Na, et al. 1998) identified that at start-up this latter condition is the prevailing mode in these type of hermetic oscillatory mechanisms but hydrodynamic during normal operation (Reyes-Gavilán, et al. 1996a). All three lubrication conditions depend on the surface roughness (Andersson and Salas-Russo 1994), the lubricant chemistry and viscosity (Na, et al. 1998) as well as the running conditions of the sliding surfaces (Dizdar 1999).

Having identified the various lubrication regimes it is important to mention that the relative velocities mentioned in the preceding paragraph are not the only conditions determining a favourable lubricating film. The bulk oil temperature of the compressor, which is required to be equal to 90°C (Section 3.2.2), as well as the operating pressures play a significant role too. A lower bulk oil temperature may not just increase the lubricant viscosity, hence limiting its presence at concentrated contacts (Section 3.2.4), but also increase the solubility of the refrigerant in the lubricant (Figures D.4 and D.8 for the VG 32 and 22 synthetic oils respectively). In this way, the lubrication regime is affected and it is reported that when a 9% increase (by weight) of refrigerant is added to an ester oil the film thickness reduces by 75% (Jonsson and Höglund 1992). Alternatively, an increase in the bulk oil temperature may reduce the viscosity of the lubricant at a faster rate than it increases it due to the evaporation of the refrigerant from the lubricant. This too minimises the film thickness (as noted by Akei, et al. (1996)), which in turn influences the lubricating regime local to the bearing. Furthermore, the lubricant viscosity (and hence the film thickness) decreases with an increase in pressure (Reyes-Gavilán, et al. 1996a; Muraki and Sano 2000). This drop in viscosity is a characteristic of the solubility of the refrigerant in the lubricant, which increases with an increase in pressure, particularly at lower bulk oil temperatures (Figures D.4 and D.8). This drop in viscosity is also influenced by the concentration of the refrigerant (Isaksson and Åström 1993). It is for these reasons that it must be ensured that an ideal bulk oil temperature and operating pressures need to be maintained in refrigeration systems.

Material hardness

Typical composition values for the steel gudgeon pin and the aluminium alloy connecting rod for the two types of compressors tested are given in Table 3.3. For the Type A compressor these values were obtained from (Safari and Hadfield 1998) whilst for the Type B compressor these values were quantified using EDX (Section 3.3). In both instances values were found to be identical with no differences to be recorded. The Vickers Pyramid Number (VPN), measured as detailed in (BS 1961), is also included (Table 3.3). The use of an aluminium alloy in these applications has advantages due to a low density, high corrosion resistance and a high strength-to-weight ratio but the difference in hardness between the pin and the connecting rod results in a number of wear mechanisms, which are a cause for concern. These

	Material	Typical percentage composition
Gudgeon pin	Iron	97.791
	Chromium	0.99
	Manganese	0.89
	Nickel	0.33
		$VPN_{10} = 715$
Connecting rod	Aluminium	80.713
	Silicon	13.54
	Manganese	0.19
	Iron	0.976
	Nickel	0.167
	Copper	3.090
	Zinc	1.318
		$VPN_5 = 141$

Table 3.3. Materials composition and hardness

mechanisms are studied using a variety of tribotesters and considerable work has been published (Nautiyal and Schey 1990; Somi Reddy, et al. 1994; Yamamoto, et al. 2000). All the alloying elements listed in Table 3.3 enhance the wear and seizure resistance in reciprocating sliding of aluminium against steel (Pramila Bai, et al. 1983). In particular, it should be noted that the silicon content is near-eutectic (12-14% silicon (Higgins 1993)) for best anti-wear performance (Tseregounis 1996; Yoon, et al. 2000). However, it is reported that this is influenced by a number of parameters, including reciprocating speeds (Somi Reddy, et al. 1995), and that higher silicon contents may improve the coefficient of friction but not the wear characteristics (Somi Reddy, et al. 1994).

Finally, it should also be pointed out that the softer metal is likely to experience fatigue wear more than the harder metal. This mechanism may arise due to cyclic changes in velocity at this reciprocating interface. This allows the subsurface stresses to change their sign and the plastic flow in the subsurface to change direction (Somi Reddy, et al. 1995).

Forced feed lubrication

It appears to be difficult to guarantee an adequate oil supply at the load face. As seen in Figure 3.6, the forced feed lubrication technique used in these hermetic systems relies on the operating speed and the oil impeller (1) to transfer oil by cohesion and centrifugal forces into the driveshaft (2). This oil then enters the hollow connecting rod (3), shown in Figure 3.7, to discharge itself onto the pin. This pin is directly connected to the connecting rod. During operation, when the bulk oil temperature is

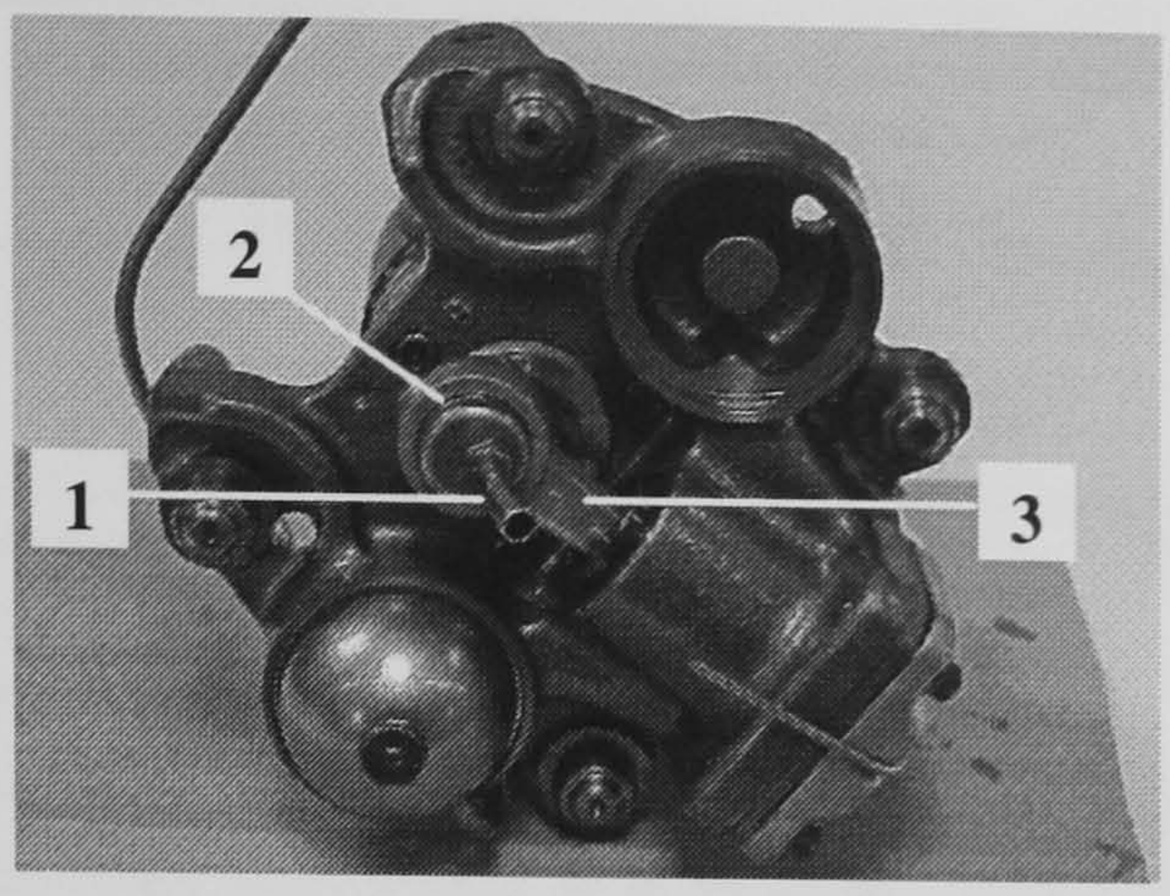


Figure 3.6. Lubrication technique in hermetic compressors

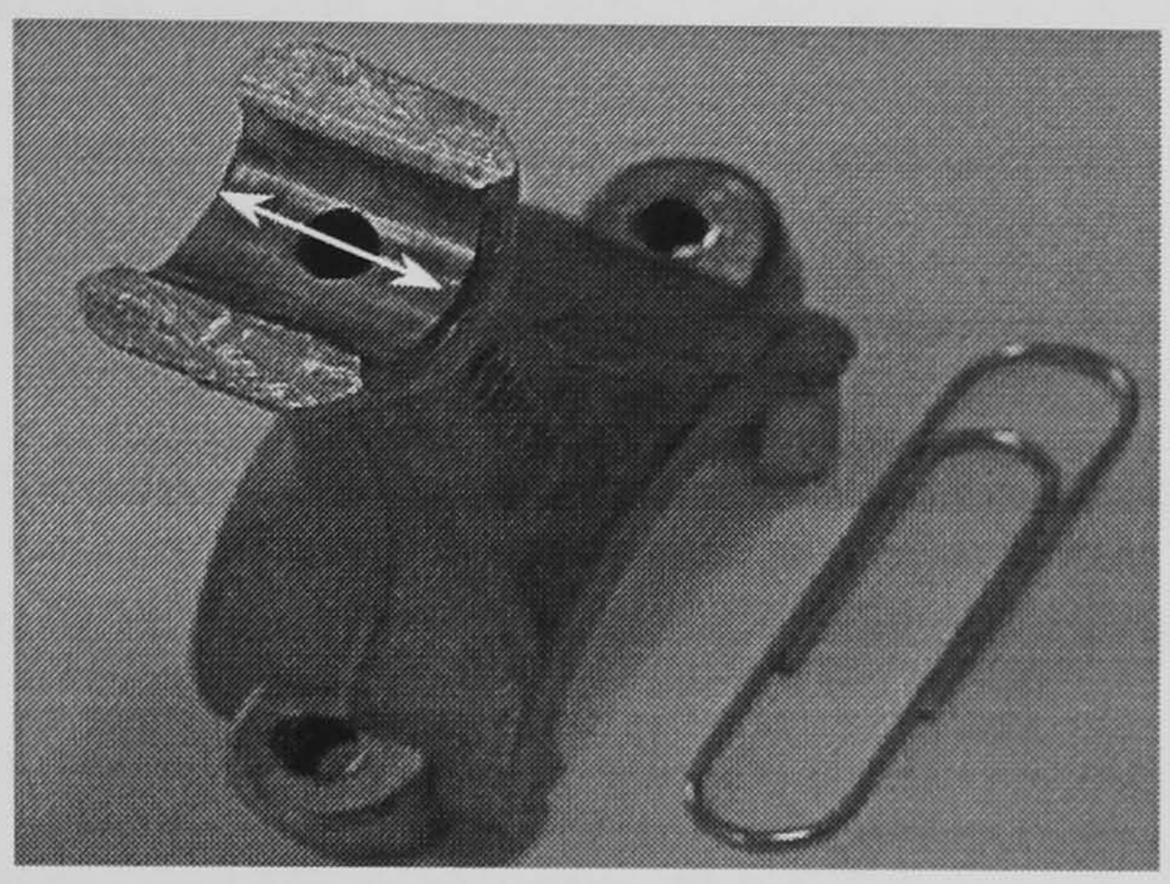


Figure 3.7. Cut connecting rod showing load face at small end

favourable, this lubricating technique is likely to occur but a difficulty may arise at start-up, when the oil temperature is low and viscosity characteristics vary as previously explained.

<u>*Contact conditions*</u>

Finally, the last characteristic that is likely to influence this area of contact, as far as wear is concerned, is the reduced area of contact (compared to the large end of the connecting rod - Figure 3.3). Using the Hertz Theory for a two-dimensional contact of cylindrical bodies (Johnson 1996), the maximum pressure experienced on the load face and the contact area occurring between the rod and the pin of a Type A compressor has been calculated (Appendix E) and is given in Table 3.4.

Despite the fact that the maximum contact pressure (Table 3.4) at this conformal contact was not found to be extreme (Jonsson and Höglund 1993), friction and wear characteristics at the load face were still considered to be a priority for reasons explained in the preceding sections. Furthermore, microscopy analyses around the whole circular contact of these bearings were carried out to identify any additional wear phenomena (Table 3.2).

Discharge pressure (bar)	Force applied on piston face[a] (kN)	Maximum contact pressure[b] (GPa)	Area of contact[b] (mm^2)
30	2.1	1.7	1.58
25	1.75	1.6	1.44
15	1.05	1.2	1.12

[a] this force was applied on a piston face area of $700mm^2$ and transmitted to the pin (no losses were assumed)
[b] calculations based on the following data:
- for pin, radius = 3.568mm, E = 210GPa, ν = 0.3,
- for rod, radius = 3.574mm, E = 80GPa, ν = 0.33,
- line of contact was taken to be equal to the width of the small end of the rod, that is, 8.45mm (indicated by the arrow in Figure 3.7)

Table 3.4. Load face contact conditions according to Hertz Theory

Prior to manually cutting the aluminium samples to accommodate the microscopy analyses (Section 3.2.3), the contacting surfaces were observed for any significant damage or discolourations using the naked eye. This was appropriate since any evidence of wear occurring away from the load face may be eradicated during the cutting operation. Figure 3.7 shows the load face at the small end of a connecting rod after having been cut for analysis.

As the test schedule in Table 3.2 highlights, the piston side of the reed valve plate (Glaeser 1999) was analysed. The purpose of this investigation was to identify any deposits on the plate and hence interpret the increase in the discolourations observed between the plates obtained from the PVE and the POE tests. These discolourations, seen in Figure 3.8 for a PVE plate from a Type A compressor, occurred for both the normal and the high pressure tests.

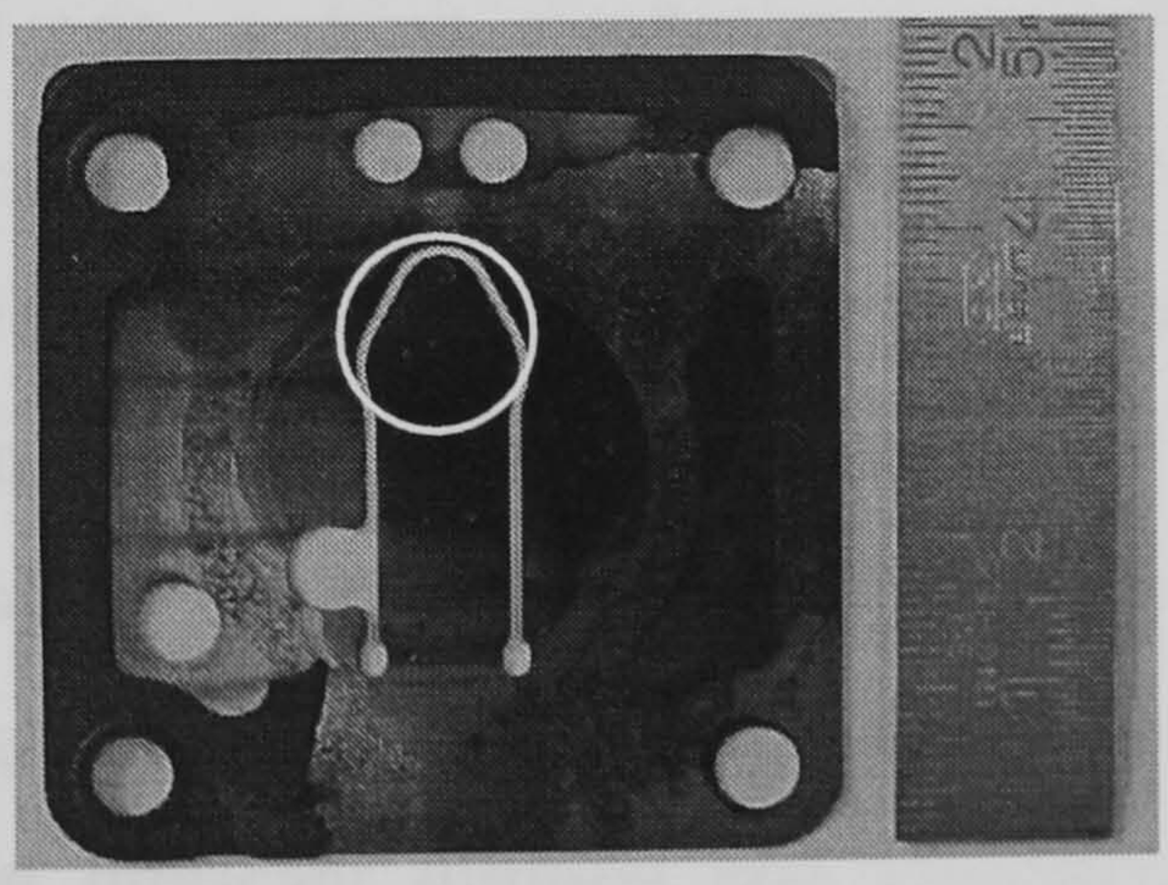


Figure 3.8. Reed valve plate (piston side). Circled region shows area analysed

Finally, oil samples collected from tested compressors were analysed for aluminium and steel debris. The concentration of debris characterises the extent of wear occurring on the rod and the pin whereas the size of the observed particles may shed light on the severity of the wear processes and the extent to which these particles may be transported around the refrigeration system. These oil samples were filtered, under a negative pressure, through a mixed cellulose esters (nitrate and acetate) membrane filter having a pore size of 0.8μm and a disc diameter of 47mm. One typical contaminated filter paper is shown in Figure 3.9 with the circled region (25mm diameter) showing the area analysed using SEM.

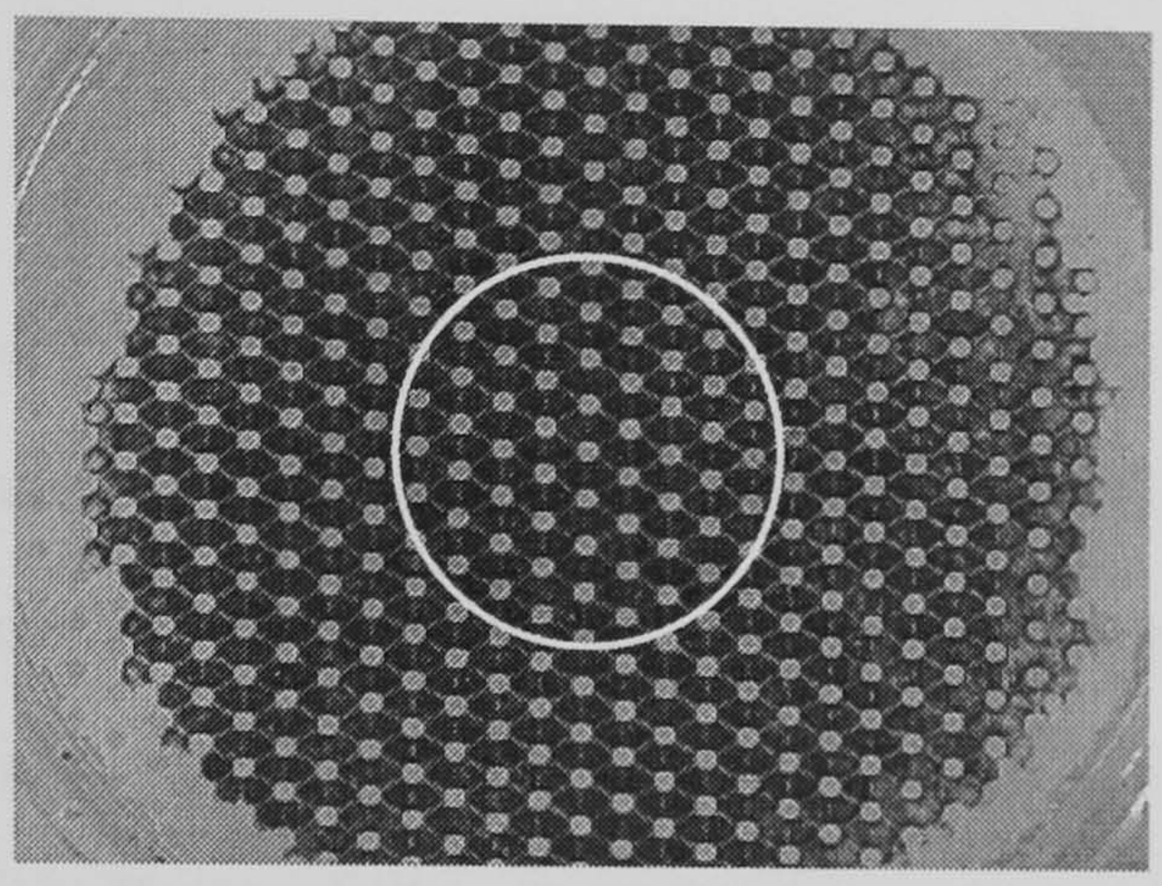


Figure 3.9. Filter membrane for oil debris. Circled region (25mm dia.) shows area analysed

3.2.6 Testing actual compressors

The use of actual hermetic compressors to study friction and wear characteristics addressed issues relating to contact geometries, load, relative motion, velocity, impurities, surface finish and treatment and any generated wear debris. Due to the pre-test procedures employed (Section 3.2.1), a lack of oxygen was present at the rubbing surfaces. Thus, as is likely to happen in reality, a lack of beneficial oxide films were present on the contacting surfaces with the consequent increase in friction and wear noted by Yoon, et al. (1996). Also, with the metallic components investigated (Section 3.2.5), a high dimensional manufacturing precision was unlikely, with the contact not being uniform throughout. This could have resulted in near-point loads of increased contact pressures, wear rates and contact temperatures. Using actual compressors also accounted for near-point loads that could have resulted from the bending on the gudgeon pin due to any yield on the piston walls. Other properties relating to the lubricant in the presence of the refrigerant, such as the relationship between lubricant dilution and viscosity, between viscosity and temperature, between viscosity and pressure, the behaviour of additives and any consequent changes in the materials and the lubricant itself were addressed. The consequences of all these parameters on the power requirements of the compressor were thus accounted for.

Although the effects of friction and wear were studied accurately for a number of parameters, it was difficult to identify initial wear mechanisms and how these developed with time due to the hermetic configuration of the compressors. However, the principal task of this research work was to determine the influence any deterioration on the contact surface between the aluminium alloy connecting rod and the steel pin may have on the power requirements of the compressor. Pre-test or periodical examination of the samples could not be performed and therefore, after the experiment duration, it was not known how mature the observed wear (Chapter 4) was. The hermetic compressor did not allow an examination of parts as a function of time without disturbing the entire experimental conditions, which would have made the power monitoring unrealistic as this is influenced by many parameters within the compressor itself. Furthermore, *in-situ* measurements of viscosity and pressure-viscosity characteristics of the working fluid could not have been done despite the fact that both of these properties have a significant effect on the lubricating film thickness (Section 3.2.5). Finally, results obtained from this type of hermetic compressor do not necessarily relate to other types of machines. However, these may be correlated with other bench tests so that field performances of different refrigeration systems may be improved.

3.3 Measurement methods and preparation

To study the characteristics of the samples obtained (Section 3.2.5), an overview of the measurement techniques used during the analysis stage of this research work is necessary. An optical analysis was carried out using a metallurgical microscope and an SEM. With the optical microscope, fitted with a video imaging display, the observation method was the reflected light, bright field contrast giving an appropriate surface characterisation (Chapter 4) of the samples. SEM was used to study the topography of the surfaces under investigation as well as the morphology of any wear debris present on these sliding surfaces or on the filter paper. Compared with the optical microscope, higher magnifications and improved resolutions are acquired using SEM, which facilitate the detection of characteristic surface features. Unlike its optical counterpart, an SEM uses a focused beam of electrons to *image* the specimen. This beam is accelerated towards the specimen using a positive electrical potential and confined, using metal apertures and magnetic lenses, into a thin focused monochromatic beam. Any interactions occurring within the irradiated sample are detected and transformed into an image. A more specific explanation on the workings of an SEM may be acquired from (Engel and Klingele 1981).

Some of the pin and rod samples were subjected to a mechanical stylus measurement for surface roughness (Bhushan 1999) at the load face. This method uses an instrument that amplifies and records the amplitude parameters, that is, the vertical characteristics of the surface deviations. The profiler used (the Rank Taylor Hobson Talysurf) consists of a stylus measurement head with a stylus tip and a scan mechanism. As the stylus travels along the surface of interest it rises and falls to give vertical displacements corresponding to the surface profile. These movements are converted into an electrical signal and amplified. Surface evaluation for both the pin and the rod was carried out by obtaining a profile using procedures as determined in (BS 1988).

An x-ray analysis of the surfaces or debris in context was also carried out using EDX and XPS. The former acquires the elements and compounds, as well as their relative amounts, at the area of interest up to a dept of 1μm. The latter characterises the surface materials in terms of all their elemental composition and chemical oxidation state up to a depth of (1-3)nm. The principal component of an EDX is a solid state detector that produces an electrical pulse proportional to the energy of each incident x-ray emitted by the specimen on which the electron beam is incident within the SEM. The series of amplified pulses are sorted according to their energy in a multi-channel analyser (Engel and Klingele 1981). In XPS, surface analysis is accomplished by irradiating a sample with monoenergetic soft x-rays and analysing the energy of the electrons emitted. Unlike EDX, these x-rays have penetrating power in a solid, which allows them to interact with the atoms in this surface region and hence causing electrons to be emitted. The kinetic energy of these electrons is detected by an electron spectrometer that records the number of electrons and their energies. For a more detailed overview of the mode of operation of both the EDX and the XPS techniques, the reader is referred to (Engel and Klingele 1981) and (Perkin-Elmer 1979) respectively.

Since all of the samples operated in the presence of a lubricant, an aqueous solution and an ultrasonic bath was used to clean the samples (Section 3.2.3). Unfortunately, such treatment removed loosely attached inclusions but any oil contamination requires such a cleaning procedure. Due to the high carbon content deposited on samples during SEM, any XPS analyses were performed first and once the samples were analysed using SEM this carbon deposit did not allow a re-examination using XPS. Sample handling or direct contact with the skin, which would contaminate the surface with sodium and moisture, was kept to a minimum. Both SEM and XPS work required that the metallic samples be mechanically attached to specimen mounts using carbon tape for sample conductivity. Non-metallic samples, like the filter membrane on which debris were collected, were coated with a gold film of an approximate thickness of 0.12Å using a sputtering technique in a vacuum for 60 seconds. Silver paint was then used at the edges of the sample to ensure an earth connection between the sample and the mount. This coating and earthing prevents non-conducting samples from acquiring a negative charge that would then deflect oncoming electrons causing sample distortion when viewing.

3.4 Lubricant test methodology

To study the effect compressor testing has on some of the lubricants considered (Section 3.2.4), used oils (from the compressor tests) were compared to new oils under extreme pressure conditions using four-ball tests. It was difficult to determine the amount of refrigerant dissolved in the lubricant since most of the refrigerant evaporates at atmospheric conditions or during the extreme pressure test itself. Nonetheless, any deterioration of the base oil or extreme pressure additives (in the case of synthetic lubricants - Section 3.2.4) may still be characterised using this test.

3.4.1 Equipment used

The test equipment used was a Plint™ microprocessor controlled, four-ball rotary tribometer fitted with a clutch drive. The principal mode of operation of this test apparatus is that four balls are arranged in the configuration of an equilateral tetrahedron (Figure 3.10). The upper ball is dead weight-loaded in contact with the three support balls (positioned at an angle of 120° apart) against which it rotates and rubs. The lower balls are clamped in a fixed position using a ball cup. Due to the severity of these extreme pressure tests, a torque transducer is used to interrupt a test once welding occurs between the top and lower balls. For a more detailed overview of this tribotester the reader is referred to (Plint 1998).

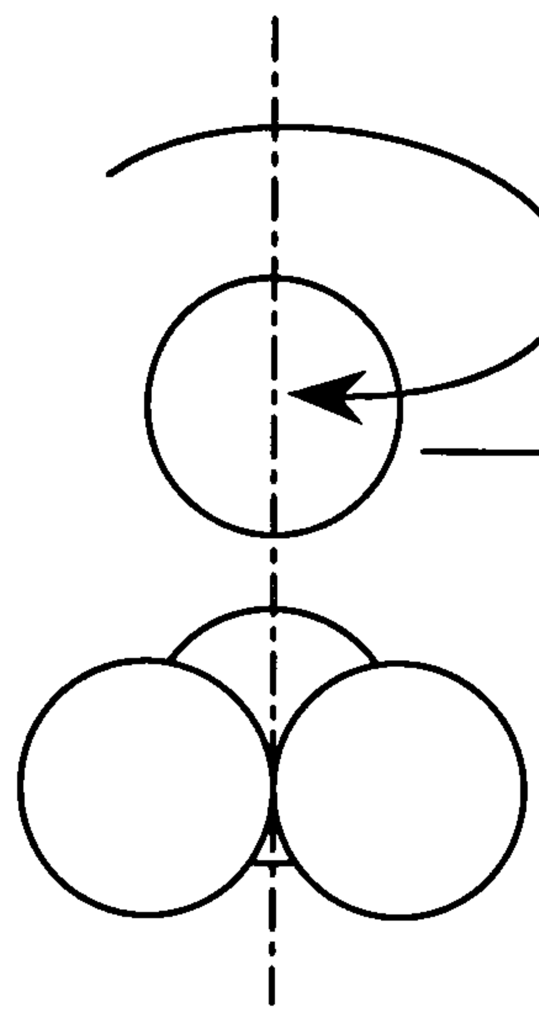


Figure 3.10. Schematic illustration of a four-ball sliding test arrangement

3.4.2 Samples used and experimental procedure

The samples tested during this stage of the investigation were carbon chrome steel balls (material being SAE 52100 bearing steel – equivalent to EN31) having a diameter of 12.7mm. These balls are produced to a very rigid specification and hardened by a carefully controlled heat treatment process, lapped and highly polished. Further specifications of these test balls are included in Table 3.5. Before and after each experiment, these specimens were cleaned in acetone for 60 seconds using an ultrasonic bath. These were then rinsed with PET spirit and dried using a hot air blower for a further 60 seconds. Once mounted in position on the tribometer, 10ml of lubricant was used to completely immerse the lower stationery balls.

Basic composition	Mechanical properties
Carbon: 0.95/1.10%	Hardness: 60 – 66 Rockwell C
Chromium: 1.30/1.60%	Density: 7.83 g/cm^3

Table 3.5. Specification of test balls

A number of methods for the evaluation of lubricants exist (Plint and Alliston-Greiner ; Perez 1996) whilst standard tests (ASTM 1988; ASTM 1994; BS 1996; IP 1997b) have also been developed. Throughout this part of the investigation all the oils tested were subjected to the conditions shown in Table 3.6 and the time taken for a weld of the specimens to occur recorded. This indicates the decomposition and failure of the lubricant and provides a means of comparison. For the 60 seconds tests (EP Test 1) a lighter load was applied compared to the 10 seconds tests (EP Test 2), due to a prolonged test time. The 140kg load was applied for both test durations since, in the unused state, the lubricant could sustain the load for a longer period of time unlike when it was contaminated. For both test durations, the lower loads applied determined the threshold value at which lubricant failure occurred. In the event of a lubricant failure the experiment was repeated for confirmation.

	EP Test 1	EP Test 2
Contact load	100	140
(kg)	112	160
	126	180
	140	

Table 3.6. Contact loads for extreme pressure tests

3.5 Overview of the analytical LCA methodology

Thus far, it has been emphasised that a change in refrigerant needs to be looked at from the overall service provided by the refrigerator. It would be inadequate to look at the environmental impacts of the refrigerant itself if, for example, the energy consumption of the refrigerator is altered by the new working fluid. Alternatively, it would be misleading to look at the energy consumption alone if this new change will alter the life span of the compressor. To help identify the environmental implications and hence to prevent a potential environmental improvement from producing a shift in environmental pollution, LCA was used. From Section 1.4 it is clear that this life cycle approach to assessing choices may be applied with different levels of sophistication. The LCA methodology applied here cannot be identified with any of the three types explained in Section 1.4.2 since formal procedures have not been addressed. Nonetheless, certain basic requirements, which need to be satisfied in order to make the study transparent and comprehensive, are documented here. These include a clear and explicit statement of the purpose of the study, the goal definition, definition of the functional unit, the system boundaries, etc., all of which are elaborated upon throughout the remainder of this chapter. As for the impact assessment and the interpretation of results (Section 1.4.2) these will be addressed fully in Chapter 5 of this thesis.

The software tool used for the LCA study was the Pira Environmental Management System, PEMS 4.5 (Pira 1998). This program compiles data and information obtained from a number of both international and national organisations of materials, processes, transport, etc. The PEMS electronic databases, which were updated regularly, were used to obtain the environmental impacts resulting from the product system. However, with these databases it was not clear how far *back to nature* the individual emissions resulting from materials, chemicals, etc. span, and no attempt was made to try to characterise this throughout this research work. Furthermore, the techniques used for the various stages of this study are also a characteristic of this software. This makes this study distinct in many ways as compared to similar studies carried out with different software tools. This required that the study be documented thoroughly to ensure its repeatability. For an independent evaluation of PEMS, with respect to other LCA tools, the reader is referred to the following publications (SPOLD 1993; SPOLD 1995; Alting and Legarth 1995; Menke, et al. 1996).

3.6 The goal and the scope of the LCA study

The objectives of this study are:

- to apply a scientific methodology in order to *qualitatively* (Weidma 1994) assess the life cycle environmental impacts of a product (domestic refrigerator) system,
- to design LCA models for the refrigerator, the refrigerant and the foam blower as well as for the in-use electrical power requirements of the product under consideration,
- to generate and compare environmental information and hence acquire knowledge on the relative environmental *costs* and *benefits* of a change in refrigerant.

3.6.1 The functional unit

The *functional unit* (BS 1997) is a reference unit that sets the scale for comparison between products and their systems. All data collected in the inventory phase is related to this functional unit. The functional unit chosen here is a fridge-freezer having an approximate weight of 66kg, a total gross volume of 289 litres and a total net volume of 267 litres (Hotpoint 1997). This appliance utilises a hermetic compressor and can maintain, on a mid-range thermostat setting and at an ambient temperature of 20°C, an internal fridge temperature of 5°C. Other secondary qualities include self-defrosting, evaporation of the water from defrosting, shelves and boxes as well as an HFC-134a refrigerant charge of 115g. The average electrical power input to this appliance, including that for the internal light, is 110W.

3.6.2 The product system to be studied

For the product system to be studied it was assumed that some of the parts making up the functional unit were manufactured in-house whilst others were subcontracted and delivered to site. All parts were then assembled into the finished product, which was then packed for delivery. It was also assumed that the functional unit was sold immediately and landfilled at the end of its lifetime. Prior to disposal, the refrigerant and foam blowing compounds were fully reclaimed. Finally, another assumption was that the functional unit was both CFC compliant and HFC compliant. As will be shown, the environmental implications pertaining to the use of the different compounds could thus be assessed.

3.6.3 The product system boundaries

The rationale used to set the system boundaries, as explained throughout the remainder of this chapter, ensured the applicability and interpretation of results. The system boundaries specifically include:

- the production cycle from the extraction of raw materials up to and including the manufacture of the materials of the individual parts, including production and use of fuels and generation of secondary energy,
- the industrial processes for the production of these parts, including the electricity requirements as well as overheads,
- the transport of subcontracted parts,
- the production and recovery of the refrigerant and the foam blowing agent,
- the packaging of the finished product,
- the energy consumption in the use phase.

The system boundaries specifically exclude:

- electricity distribution (impacts due to infrastructure, maintenance, etc.),
- transportation of fuel to electricity generating plants and transport vehicles,
- maintenance of infrastructure (manufacturing plants, power plants, etc.),

- capital equipment and its maintenance as well as administration,
- labelling,
- quality inspection,
- storage, transport and retail of the finished product,
- transportation of CFC and HFC compounds,
- the working environment in contact with the product,
- servicing of the domestic appliance,
- contribution to domestic heating due to the operation of the product,
- transport at end-of-life,
- lower-tier impacts.

All of these exclusions, apart from the contribution to domestic heating, increase the environmental impact. However, many of the overlooked life cycle stages are considered to be of low influence, such as labelling, inspection, storage, etc., when compared to more critical life cycle stages, like manufacturing. Therefore, in this study these exclusions lost in environmental significance and were not expected to affect the results drastically. This is also emphasised by Papasavva and Moomaw (1998) where they argue that the transportation of the CFC and HFC compounds is insignificant compared to their manufacture and disposal. Other exclusions listed were omitted due to the difficulty in filtering out activities that would occur anyway whether or not a product is being manufactured. These include equipment maintenance, administration as well as lower-tier impacts (Hunt, et al. 1992), such as, the impacts resulting from the manufacture of the steel, tyres, etc. required for the vehicles used in the transportation phase. Impacts on the working environment have been overlooked throughout the manufacturing and disposal stages of the functional unit considered. Findings made elsewhere (Wenzel, et al. 1997) identified that these impacts would not have influenced the results obtained very significantly and have therefore not been pursued further due to on-site monitoring requirements, unfeasible within Ph.D. time constraints. It is worth mentioning here that some considerations on human health have been made but these were likely to stem from the production of raw materials and process energies. These will be discussed in Chapter 5 of this thesis. Finally, throughout this work other boundaries were assumed which require to be justified in greater detail. For this reason, these have been excluded from the preceding lists and are treated separately throughout the following paragraphs.

The two types of compressors (Table 2.1) required a 350ml oil charge (Section 3.2.2). The production and recovery of this oil charge should be included in the LCA study if a complete product environmental evaluation is sought. Two major tasks have limited this possibility given the time constraints of this research project. Firstly, oil production is a multiple function that possibly requires complex allocation procedures due to the different by-products per unit of base lubricant produced. Secondly, with the base oil used with the HFC-134a refrigerant, additives are included. These additives were unknown to the author throughout this work (Section 3.2.4) making an environmental evaluation an even more daunting task. However, a recent study on the manufacture of base mineral and ester oils has been published (Våg, et al. 2000) and these findings will be adapted and included in the discussion phase of this thesis (Section 6.2.1).

In the instance when the functional unit was assumed to be CFC compliant both the refrigerant and the rigid polyurethane (PUR) foam blower were assumed to be CFC-12. For the refrigerant, the use of CFC-12 is realistic since the domestic appliance was the principal application for this compound (DOE 1996). For the foam blower this assumption is unrealistic since, in the time when CFC was used, PUR foam was blown using trichloromonofluoromethane (CFC-11) (DOE 1996). From data published by Papasavva and Moomaw (1998) the use of CFC-11 would have reduced the overall GWP (Section 1.5.1). This is because the direct GWP of CFC-11 is less than that of CFC-12 and also the energy required for the synthesis of one gram of CFC-11 is less than that for one gram of CFC-12. It is only in the recovery phase that both compounds have identical energy requirements per unit mass. Hence, this assumption includes a worse case scenario for the environmental impact of the CFC compounds, which is obtained in Section 5.1.5 and evaluated in Section 6.2.1. When the functional unit was assumed to be HFC compliant both the refrigerant and the blowing agent were assumed to be HFC-134a. It should be noted that, as in the case of CFC-12, HFC-134a is not used as a blowing agent but other HFC blends are developed for this purpose (DOE 1996). In view of the lack of information retrieved on the latter, within Ph.D. time constraints, it was thought that such an assumption would provide an appropriate comparison between the HFC and CFC compliant units. Table 3.7 summarises the differences between the two alternative cases.

	Refrigerant charge	Blowing agent for PUR foam
CFC compliant	CFC-12	CFC-12
HFC compliant	HFC-134a	HFC-134a

Table 3.7. The type of refrigerant and blowing agent assumed

During product manufacture and lifetime it was assumed that no emissions of refrigerant or foam blower occurred, a realistic assumption according to (Sand, et al. 1997; DETR 1999). Furthermore, prior to complete product disposal all refrigerant and blowing agent were reclaimed. As shown by a recent study (DETR 1999) this latter assumption was unrealistic. In 1995, the percentage emission of compounds from the disposal of domestic refrigerators was approximately 50% but this is projected to fall to 20% by 2010. Justification of these assumptions was obtained when the study (DETR 1999) projects that in 2010 the percentage of global warming impact related to the direct HFC emissions over the whole product life cycle is only just 3%. The other 97% account for the impact related to the indirect emissions due to the energy use of these appliances. These assumptions of zero direct emissions during the product life cycle ensured that the direct GWP resulting from the CFCs would not overcast the outcome of this study since this environmental impact is approximately 87% higher for CFCs than for HFCs (Papasavva and Moomaw 1998). To accommodate these assumptions, the energy required for the recovery of the refrigerant and the foam blower was included (Section 3.7.2).

The functional unit was completely landfilled at the end of its *first* lifetime. In this study, this lifetime was assumed to be 15 years although in the UK it was found to be less for CFC units (OECD 1982). Due to the relatively recent launch on the market it is still uncertain whether the HFC units would last for this span of time. It was hoped that the experimental tests performed throughout this research work could shed more light on this. Prior to landfilling it was assumed that no materials were recovered. This fact is unrealistic but, as argued in (OECD 1982; Wenzel, et al. 1997), at the end of their useful life refrigerators may become a source of secondary materials but they are unlikely to become a source of primary materials. Moreover, in the UK, recovering and recycling of plastics from white goods, although carried out, is not seen as cost effective (DTI 1999). PUR foams, for example, can only be reused after much processing because they are contaminated with the blowing agent and this too depends on available logistics (Dietrich and McCullough 1996; Weigand and Strobbe 1999).

Environmental problems arising from the landfilling of domestic appliances is the second most problematic matter in landfill use (Johansen, et al. 1997) since any emissions to ground and air are as yet unknown (DTI 1999). Due to these uncertainties, all indirect emissions were overlooked here. It is worth mentioning, however, that a product specific landfill model to evaluate the direct environmental impact of landfilling of domestic refrigerators has been carried out elsewhere (DTI 1999), the implications of which will be discussed in Section 5.2.4 and 6.2.1.

It was assumed that the functional unit was manufactured and marketed primarily in the UK although it is certain that some product parts are imported from different countries, such as, for the case considered here, the compressor. However, to cushion the effects of this, the study was performed relative to the technology of electricity generation used for the production of raw materials, for the manufacturing processes and the use phase of the product. Oil, natural gas and coal, which accounted for approximately 35%, 35% and 18% respectively of the total fuel consumption for the generation of primary energy in the UK in 1998 (BP 1999), were used to environmentally evaluate the manufacture and recovery of the CFC and HFC compounds. A UK mixed fuel scenario, consisting of 50.5% coal, 8.3% oil, 13.5% natural gas, 20.1% nuclear, 4% hydro and 3.6% imported energy (Pira 1998), was also used. Inventories of energy systems, incorporated in the study, were obtained from (Doka 1994) and included in PEMS (Section 3.5). Obtaining environmental information using different electricity generation technologies for the production and recovery of these compounds (Section 5.1.5) should emphasise that the indirect environmental benefits in switching to alternative refrigerants is very much dependent on the appliance manufacturer due to his choice of supplier. For the manufacture and assembly of the parts making up the functional unit a UK mixed fuel scenario was used throughout. Finally, for the use phase of the product, a low voltage electrical supply for the UK (Pira 1998) was adopted.

Finally, it is important to mention that the boundaries emphasised throughout this section are those that specifically relate to this study. Commercial sensitivity as well as time and resource constraints did not permit a full original data acquisition approach and results from previous studies had to be utilised. The boundaries and assumptions set for the databases and the adapted studies used have not been explained for brevity. For further information the reader is instructed to refer to the respective references (Section 3.6.4).

3.6.4 Source of data acquisition

As explained in the preceding section, a synthetic pathway for data acquisition was required to carry out this life cycle assessment. Any data utilised was relatively recent and representative of the processes and technologies applied. Details of data sources are given in Table 3.8. The information required for the inventory of the functional unit was obtained from literature provided by the manufacturer (Hotpoint 1997). All parts pertaining to the product are described in Table F.1 (Appendix F), with some parts being combined for simplicity of presentation and hence designated as *items* henceforth. The information includes type of materials and ancillaries, weight of materials and ancillaries (Section 3.7.1) as well as manufacturing processes. All this information was adapted from relevant literature (Table 3.8). Details of material transportation, which are also included in Table F.1, were assumed using conservative estimates (Section 3.6.5).

3.6.5 Assumptions

In conjunction with the boundaries set (Section 3.6.3), a number of assumptions had to be carried out to make the LCA study complete as well as account for any mass balance considerations (*mass in* equals *mass out* for each process). In order to make this study repeatable, these assumptions are listed in Table 3.9 and some are quantified in Table F.2 (Appendix F).

Apart from listing the assumptions, Table 3.9 also indicates the possible influence each assumption has on the overall study. This was done to assist the reader to judge the implications of these decisions further. Each influence is based purely on the judgement of the author and results from experience gained during the LCA study.

Product system and process type	Data A	Data B	Data source type 1	2	3	4	Source of information
Extraction of raw materials							
Raw materials		✔			✔		• PEMS (Pira 1998)
Production of materials							
Steel		✔			✔		• PEMS (Pira 1998)
Aluminium		✔			✔		• Conservative estimates
Plastic		✔			✔		• Literature (Wenzel, et al.
Others		✔			✔	✔	1997)
Product manufacturing							
Shaping of plastic		✔		✔		✔	• Literature (Wenzel, et al.
Steel processing		✔		✔		✔	1997) and (Papasavva and
Surface treatment		✔		✔		✔	Moomaw 1998)
CFC and HFC compounds	✔				✔		• Conservative estimates
Assembly		✔		✔		✔	
Others		✔		✔		✔	
Use							
Energy consumption	✔		✔				• Lab work (Section 4.3.2)
Lifetime		✔			✔		• Literature (OECD 1982)
Disposal							
Recovery of HFC and CFC compounds	✔				✔		• Literature (Papasavva and Moomaw 1998)
Transport							
Distances and means		✔				✔	• Conservative estimate
Energy consumption and emissions		✔			✔		• PEMS (Pira 1998)
Energy systems							
Consumption and type		✔				✔	• Conservative estimate
Emissions		✔			✔		• PEMS (Pira 1998)

A – Product specific data (specific to the functional unit considered)
B – General data
1 – Measurement
2 – Computations (from mass balance considerations & input data for process in question)
3 – Extrapolation of data from similar type of process or technology
4 – Estimate

Table 3.8. Data sources for the completion of the LCA study

for example, soldering (or brazing) is insignificant to the whole of the study as compared to the welding required to complete the product. Nonetheless, for two of the assumptions listed, that is the process energies and duration as well as transportation, the significance of the environmental impact had to be assessed in more detail. This was done as explained in Chapter 5. On the other hand, Table F.2 assumes the power input and the duration to manufacture each individual item, the type and distance covered by the transportation of the subcontracted and manufactured items as well as the type and value of burdens entering and leaving the manufacturing process of each individual item. It is perhaps opportune to elaborate further on the burdens entering and leaving a manufacturing process by focusing on those listed for the steel cabinet (Table F.2). The input burden of *minor constituents*,

Assumptions	Influence	
• No waste of material; material in equals material out	✔✔	▼
• No rejects	✔	▼
• No tin soldering	✘	
• No brazing	✘	
• No additives to the materials were included	✔	▼
• No wood chippings from the manufacture of the base frame	✘	
• The functional unit was not painted	✔✔	▼
• Inefficiencies in the generation and distribution of electricity in all the product phases have not been accounted for	✔✔	▼
• Brass for compressor was included as copper (Table F.1)	✘	
• Water as an ancillary was completely softened (Table F.1)	✔	▲
• Detergents were replaced by surfactants (Table F.1)	✘	
• Blow nitrogen was replaced by oxygen as an input (Table F.1)	✘	
• Residue of surface treatment was included as waste water (Table F.2)	✔	▼
• Heat removed from processes was included as waste heat (Table F.2)	✘	
• Processed water was included as water (unspecified) (Table F.2)	✔	▲
• Air used was included as air (unspecified) (Table F.2)	✘	
• Phosphoric acid was included as acid (unspecified) (Table F.2)	✔	▲
• Abrasives for industrial tumbling assumed as industrial diamonds and oil (Table F.2)	✘	
• Welding consumables added as minor constituents (Table F.2)	✘	
• For injection moulding, mass of cooling water equals mass of steam and is deducted from waste water (Table F.2)	✘	
• Energy for general use (heating, lighting and ventilation)	✘	
• Waste heat converted from the electric power input (Table F.2)	✘	
• Process type, energy and duration (Table F.2)	✔✔	▲/▼
• Transport of materials and ancillaries (Table F.1) and items (Table F.2)	✔✔	▲/▼
• All transport returned empty after depositing the load	✔	▲

✔✔significant; ✔benign; ✘ insignificant; ▲ increase impact on study; ▼ reduce impact on study

Table 3.9. Assumptions and their influence on the LCA study

for example, refers to consumables used in the welding required for the steel cabinet. PEMS (Section 3.5) does not provide for welding rods, acetylene, etc. and therefore these were grouped together as minor constituents to allocate an environmental impact to them. For mass balance considerations these minor constituents were balanced by *open loop outputs*. Compressed air, which is likely to be used in manufacturing processes (like pneumatics), was included as *air used (unspecified)* in both the input and output burdens. *Water (unspecified)* was included for general use. This could be water used by machine operators, water used for tidying the shop floor, etc. and was balanced by the output burden *waste water*. The *energy for general use* was included by assuming power requirements for heating (8kW), lighting (2kW) and ventilation (4kW) of the shop floor occurring over the duration of the manufacturing process. Unlike mass considerations, energy considerations need not balance. Finally, the output burdens of *salts*, *acid (unspecified)*, *detergent* and *waste water* were all included to balance the ancillaries of the manufacturing processes (Table F.1) with some of the waste water being lost as *steam/water vapour* during the manufacturing process. *Waste heat* was included to account for the heat lost during manufacturing and this was converted directly from the power input of each manufacturing process (Table F.2). For welding 30% of this power input was assumed to be converted into heat, for injection moulding 60% whilst for any other process 20% of the power input was assumed to be converted into heat. Table F.2 also lists and quantifies the burdens assumed for the assembly stages of the product.

3.7 Presentation of the generic LCA model

An LCA model was built using the PEMS software (Section 3.5). Figure G.1 and Figure G.2 (both in Appendix G) provide a generic illustration of how the model was constructed in this study. This model considered the *Manufacture of Item 'X'* (Figure G.1), where X may be any item (Table F.1) making up the functional unit. This model included the materials and ancillaries used during each individual manufacturing process. The transportation of all the materials and the ancillaries, together with the energy required during the manufacturing process of the individual items, were also included.

Once the individual items were manufactured they were either transported for assembly or were directly assembled as shown in the *Assembly for Unit 'Y'* (Figure G.2), where Y may be any *unit* (assembly of a group of items considered to pertain to the same function). Once the functional unit was complete this was combined with the model for the *Production and Recovery of the CFC and HFC Compounds* (Figure G.2) as well as with the model evaluating the power characteristics named *Experimentation* in Figure G.2. In this way, an overall environmental assessment was obtained using a flexible LCA model that could be updated once new product data was retrieved.

3.7.1 The manufacturing and assembly of the individual product items

To complete the values of the bill of materials and ancillaries listed in Table F.1 for the functional unit (designated as FU1 in Figure G.1 and Figure G.2) explained in

Section 3.6.1, a published study on another functional unit, itself a refrigerator, had to be adapted (Wenzel, et al. 1997). Throughout this thesis this functional unit, from which information was acquired, was designated as FU2 (see Figure G.1). Initially, however, it was necessary to increase the mass values obtained from FU2 due to the difference in size of the two appliances. The mass percentage difference assumed was based on the difference in internal volumes as shown in Table 3.10. It is important to note that, by adding this mass percentage difference to the individual items (Table F.1) an overall weight of 68kg was obtained for FU1. This value compares well to the actual weight of this functional unit (Section 3.6.1) and the effect of this slight increase (3%) in weight on the LCA findings was overlooked.

Functional unit	Total net internal volume		
	Fridge	Freezer	Total
FU1	161	106	267
FU2	200	N/A	200
	Percentage difference		33.5%

Table 3.10. Difference between functional units assumed

Reference is made to the generic model of the individual items (Figure G.1 and Figure G.2) where a particular item of FU1 (the compressor) is used to follow the model coherently. The screen shot shown in Figure G.3 helps visualise the construction of this model using PEMS. The compressor is one item that was common both on FU1 and on FU2. However, it was assumed not to be identical and therefore the weight of the compressor from FU2 was increased by 33.5% (Table 3.10) to 9111.38g, as may be verified from Table F.1. From FU2, the materials making up the compressor were steel, copper, aluminium, PVC, brass and rubber. All these materials (except for brass) were available in the PEMS database and therefore the environmental implications for material production were known. As for brass an alternative was assumed and this was taken to be copper (Table 3.9). The weight of the total item had to be apportioned arbitrarily (but similar to FU2) between the different materials making up the compressor (Table 3.11).

Material	Assumed percentage allocation	Weight (grams)
Steel	80% of 9.1kg	7289.1
Copper	15% of 9.1kg	1366.7
Aluminium	2% of 9.1kg	182.2
PVC, brass, rubber	1% each of 9.1kg	91.1

Table 3.11. Assumed allocation of weight of materials in a product item

Ancillary materials, which were known and thought to be of a significant environmental impact, were also included in the assessment (Table F.1). Some of these ancillaries were obtained from FU2 whilst others were included additionally. For the compressor being considered here coating paint was included as an additional ancillary. Ancillaries that were unknown from FU2 and thought to be insignificant to the outcome of the study were overlooked altogether. Transport of materials and ancillaries to the manufacturing company, and hence the distances and means of transportation, were also assumed (Table F.1). It is worth mentioning that the burdens associated with transportation were divided by the useful load of the vehicle. Hence, if the transport of steel is considered as an example, then it is only the burdens associated with the 7289.1g of steel that were included (Figure G.3) and not those for the entire load of the vehicle (Type 1; Table F.1).

Having obtained the type, value and transportation of materials and ancillaries the next step was to determine the manufacturing processes. Whether these processes were known from FU2 or not a value for the electrical power and time duration of these processes was assumed. The unknown manufacturing processes are the ones left blank in Table F.1 as is the case for the compressor. As already explained, the influence of these assumptions was not accurately known but these will be dealt with further in Chapter 5. Finally, burdens for the manufactured processes were included as has already been explained in Section 3.6.5. For the compressor considered here the burdens entering the manufacturing process were minor constituents (which included coolant for machining), water (whose contents could not be specified) and energy for general use (heating, ventilation and lighting).

Next the manufactured items had to be considered for the assembly process. These assembled items are designated as unit (Section 3.7) in Table F.2 and Figure G.2. Table F.2 divides the assembly into five categories depending on the type of items under consideration. Figure G.2 depicts that if a subcontractor manufactures the item then transport for its delivery to the manufacturer of the functional unit had to be assumed. As was done for the manufacture of the individual items, the burdens entering and leaving the assembly process were assumed as was the electrical power and time duration of each process. In the case of the compressor considered throughout this section this was assumed to form part of the refrigeration system assembly (Table F.2). Because this particular item was subcontracted, a means of transportation (Type 2 and 4; Table F.2) had to be assumed prior to the assembly process. Finally, all assemblies were then combined into the boxed fridge (Figure G.2) until the whole of the functional unit was accounted for. It is important to mention that the assembly of the functional unit is unlikely to be carried out in categories as explained here. For simplicity this was overlooked and items pertaining to the same function were grouped together as has just been explained.

3.7.2 The production and recovery of the HFC-134a and CFC-12 compounds

To model the synthesis of refrigerants from their raw materials proved to be unfeasible due to the lack of information on these complex processes on the public domain. However, details on the energy required for raw material extraction, purification and conversion into the HFC-134a and CFC-12 compounds, together with their energy of recovery, were obtained from (Papasavva and Moomaw 1998). This value of energy incorporated the total energy used at the chemical plant and was considered to be the most significant throughout the life cycle of these compounds (Kusik, et al. 1991). Details of interpretation of this value of energy are given in Table 3.12. It should be noted that, in this table, the weight of compound per functional unit was increased by 20% for CFC-12, a worse case scenario as observed from laboratory tests (Section 4.1.2).

Compound	Mass in FU1 (grams)	Molecular weight[a] (g/mole)	Number of moles	Energy of production of one mole[a] (kWh/mole)	Energy of recovery of one mole[a] (kWh/mole)	Total energy of production (MJ)	Total energy of recovery (MJ)
CFC-12							
Refrigerant	138	121	1.14	1.123	0.121	4.61	0.5
Blower[b]	888	121	7.34	1.123	0.121	29.7	3.2
HFC-134a							
Refrigerant	115	101	1.14	1.660	0.101	6.81	0.42
Blower[b]	740	101	7.33	1.660	0.101	43.8	2.67

[a] values obtained from (Papasavva and Moomaw 1998)
[b] values of cabinet insulation and door insulation combined

Table 3.12. Values used for the environmental impact of compounds

The LCA model for the refrigerant production and recovery (Figure G.2) simply incorporated the energy content obtained from Table 3.12 and no burdens were assumed (Table F.2). For the insulation of the functional unit, however, this was treated as an item with the ancillary being HFC-134a or CFC-12 (Figure G.1). The burdens and energy for the manufacturing of the insulation were assumed as given in Table F.2. The value of the power (Table F.2) for the manufacture of the PUR foam was estimated from (Wenzel, et al. 1997) which stated that 4.7kg of PUR foam require approximately 600MJ of energy during manufacture. Given its significance, a sensitivity analysis (Section 5.2.2) will highlight the influence this consideration has on the overall result.

3.7.3 The in-use power obtained from experimentation

Figure G.2 depicts how results obtained from the eight experiments during which power monitoring was carried out (Table 3.2) were utilised. As has been pointed out (Chapter 2), the value of the electrical power obtained was influenced by a number of variables including, ambient temperature, refrigerant charge, compressor characteristics, etc.. Variations in these experimental conditions were inevitable and therefore an average value of the in-use power was of little significance to the LCA. Certification of this are the different values of average power recorded from the experiments (Section 4.1.1) and which they themselves were in the region of three times that of the functional unit (Section 3.6.1). In view of this, power characteristics were investigated and any rates of change in the in-use power became of primal significance. These rates of change were assumed to stabilise after the experiment duration and any rise or fall in the monitored power was extrapolated over the entire product lifetime (15 years). It should be pointed out that this may appear misleading since it has already been stated (Section 3.2.4) that the 500 hour test simulates 15 years of the compressor lifetime. However, this was only assumed from a wear characteristics viewpoint but not for the rate of change in power. The LCA model, therefore, incorporated this percentage increase or decrease in the in-use power as explained in more detail in Section 4.3.2.

4 THE EXPERIMENTAL RESULTS: DIAGNOSIS OF THE COMPRESSOR

Experiments were carried out to simulate the *real life* of a hermetic compressor. The performance of HFC-134a compatible synthetic lubricants in hermetic systems was studied and compared with the performance of a CFC-12/mineral oil combination. This chapter describes these experimental results. Actual hermetic compressors were studied for wear characteristics and power consumption whilst extreme pressure tests helped to assess the performance of the lubricant in the presence of the refrigerant.

4.1 Overview

To fit over 11,500 hours (Table 3.2) of experimental work within Ph.D. research time constraints, preliminary tests had to be carried out using other test rigs supplied by Castrol International (one of the industrial collaborators of this research). These tests helped in the development and improvement of the test rig described in Chapter 2 on which eight final tests were carried out. Furthermore, these preliminary tests also helped in the understanding of wear phenomena under different operating scenarios and allowed the possibility of a larger number of samples to be analysed.

4.1.1 Experimental conditions

Table 4.1 to Table 4.4 give average values (to one decimal place) for the actual

Test label	Pressure (bar) Condenser	Evaporator	Temperature (°C) Condenser	Evaporator	Shell	Ambient	Power (W)	Duration (hrs)
Test A	26.6	0.8	87.4	-14.4	74.6	21.4	N/A	360
Test B	27	1.1	106	-7.5	74.6	21.4	N/A	366
Test C	24.9	0.9	110	-15.1	73.1	21.4	N/A	332

Table 4.1. Preliminary Test 1 – Actual operating and environmental conditions using a liquid/vapour phase, high pressure assembly

Test label	Pressure (bar) Condenser	Evaporator	Temperature (°C) Condenser	Evaporator	Shell	Ambient	Power (W)	Duration (hrs)
Test D	14.9	0.7	50.1	-31.3	101	22.1	N/A	972
Test E	14.8	0.8	50.1	-26.5	101	22.2	N/A	900

Table 4.2. Preliminary Test 2 - Actual operating and environmental conditions using a liquid/vapour phase, normal pressure assembly

Test label	Pressure (bar) Condenser	Evaporator	Temperature (°C) Condenser	Evaporator	Shell	Ambient	Power (W)	Duration (hrs)
Test F	26.9	1.2	94.8	25.9	71.5	22.2	N/A	300
Test G	24.7	1.2	94.4	30.6	71.2	22.2	N/A	300.1
Test H	24.6	1.1	81.7	30.2	69.9	22.6	N/A	311.3
Test I	24	1.3	93.7	31.1	74.3	22.6	N/A	311.3

Table 4.3. Preliminary Test 3 - Actual operating and environmental conditions using a vapour phase only, high pressure assembly

Test label	Pressure (bar)/Temperature (°C) Discharge	Suction	Condenser	Evaporator	Temperature (°C) Shell	Ambient[a]	Power (W)	Duration (hrs)
Test 1	14.1[b]/95	0.6[b]/22.3	13.1/49.6	0.6/-14.9	72.8	19.9 (N/A[c])	392.4	500.9
Test 2	13.1/81.7	0.7/26.8	13.1/48.9	0.8/-12.3	79	23.7 (36-70)	319.5	500.4
Test 3	14.4/100.6	0.5/18.9	13.6/53.2	0.7/-15.2	70.4	20.4 (25-61)	411.3	502.2
Test 4	14.2/79.4	0.6/18.9	13.1/53.7	0.7/-14.1	73.6	20 (31-56)	318.6	500
Test 5	13/62.7	0.6/21.2	12.8/46.3	0.8/-10.9	64.7	21.9 (33-63)	322.3	1004.9
Test 6	13.5/62.06	0.5/17	12/46.1	0.6/-15.6	64.1	19.2 (29-59)	304.3	999.4
Test 7	12.3/58.9	0.3/24	11.7/46.1	0.4/-0.2	62.9	24.7 (35-73)	286.6	1000
Test 8	14/68	0.7/21.6	13.2/48.9	0.9/-11.9	61.7	22.9 (34-75)	337.4	1000

[a] values in brackets are the recorded minimum and maximum relative humidities (in %) reached during each test
[b] values had to be assumed (not measured) but no discrepancies were noted
[c] values not recorded

Table 4.4. Final Test - Actual operating and environmental conditions using the test rig described in Chapter 2

operating and environmental test conditions obtained over the total operating hours of each compressor. For all the tests performed, the condenser and evaporator conditions were measured at position 3 and position 4 respectively (Figure 2.1). Due to the different test rigs used, Test A to Test I did not monitor the suction and discharge conditions (properties at 1 and at 2 respectively in Figure 2.1) as did Test 1 to Test 8. In Table 4.1 the operating pressures and the operating times varied from the set experimental conditions (Table 3.2) and were also different from those in Table 4.3 since these latter tests used a vapour phase rather than a liquid/vapour phase test rig. Pressure variations between Table 4.1 and Table 4.3 and the set conditions (Table 3.2) may be attributed to the fact that doubling the discharge pressure with these hermetic machines is difficult to maintain over the experiment duration. The initial discharge pressure was 30 bar but this receded over time and the values in Table 4.1 and Table 4.3 are average values. The premature failure was due to a failed gasket (Figure 3.8) but this was irrelevant to the outcome of the investigation as all efforts were focused on the compressor components described in Section 3.2.5. In Table 4.2 the evaporator and the shell temperature were higher to the values given in Table 4.4, primarily due to the different test rigs used. The implications of some of the aforementioned variations will be dealt with in the discussion phase of this thesis (Section 6.1).

Due to variations in ambient temperature, some of the temperatures monitored for the final tests varied from set conditions (Table 3.2) whilst other experimental characteristics were maintained (Table 4.4). Apart from these ambient variations, differences between the continuous tests (Test 1 to Test 4) and the interrupted tests (Tests 5 to Test 8) were also due to the compressor operating intermittently (Section 3.2.4). Average values for these last four tests include conditions at start-up when both the pressures and temperatures vary to times when the compressor is in operation. A procedure for selecting and averaging these values will be highlighted in Section 4.3.1. Finally, it has been reported that variations in the discharge temperatures (Table 4.4) influence the viscosity of the refrigerant/lubricant pair (Kruse and Schroeder 1985). Throughout these tests this temperature, as well as other temperatures, was difficult to control and variations were inevitable. Nonetheless, variations between similar tests were not very significant and the analysis which follows overlooked any implications of these temperatures on friction, wear and power trends.

As explained in the preceding paragraph, variations in test conditions occurred, particularly between Preliminary Test 1 (Table 4.1) and Preliminary Test 3 (Table 4.3) and Preliminary Test 2 (Table 4.2) and the Final Test (Table 4.4). To account for these variations, the experimental analysis that follows is determined by the viscosity tests (Test A to Test C), the type of synthetic lubricant tests (Test D to Test I) and the CFC versus the HFC tests with similar viscosity lubricants and power monitoring (Test 1 to Test 8). Thus, within the respective groups, experiments were under similar conditions and hence comparisons could be made between the normal and the high pressure test conditions respectively.

4.1.2 Refrigerant charge and length of capillary

A record of the mass of refrigerant charge and length of capillary tube used throughout the preliminary tests was not acquired. Initially, this was not thought to be necessary since power monitoring was not performed (Table 3.2). Nonetheless, this did not seem to be detrimental to the outcome of the investigation since the operating conditions between respective preliminary tests were similar (Table 4.1 to Table 4.3) and appropriate for wear comparisons. The only discrepancy which, had it occurred, would not have been accounted for was the influence that the solubility of HFC-134a has in the presence of the two synthetic lubricants (POE and PVE) considered. Any discrepancy would have occurred between Test D and Test E and Test F and Test G or Test H and Test I respectively. As reported in Section 3.2.5, this solubility influences the antiwear properties of the working fluid. For the final tests, however, both the mass of the refrigerant charge and the length of capillary tube were recorded (Table 4.5).

Test label	Refrigerant charge (grams)	Length of capillary tube (mm)
Test 1	90	52
Test 2	90	70
Test 3	110	52
Test 4	100	70
Test 5	90	70
Test 6	100	70
Test 7	90	70
Test 8	100	70

Table 4.5. Final Test – Refrigerant charge and length of expansion device

From Table 4.5, two interesting observations are noted. Firstly, for the larger capacity compressors (Type A in Table 2.1) used in Test 1 and Test 3, a shorter length of capillary tube was required to maintain the same pressure ratio as in the remainder of the tests (Table 4.4). Secondly, the CFC-12 refrigerant charge for the larger capacity compressor was 20% higher than the HFC-134a refrigerant charge required for the same operating conditions (Table 3.2). The compressors with the smaller capacity required just a 9% increase in CFC-12. It should be noted that, during the LCA study (Section 3.7.2), a 20% worse case scenario was thus assumed when evaluating the environmental impact of these compounds per domestic refrigerator (Table 3.12). The implications of having a longer capillary tube were overlooked throughout this study. Although the length of this restriction increases the viscous drag (Section 1.5.3) and hence the electrical power monitored, the wear observed on the samples would not have been influenced. As for the monitored power, the focus was not on the actual values but on the rate of change (Section 3.7.3). On the other hand, it was thought that the increase in the refrigerant charge will increase both the wear characteristics (the more the refrigerant the lower the viscosity, the higher the chemical attack, etc.) and the rate of change of power requirements, should a relation between the two exists. These implications will be assessed in Section 4.4 after relevant observations have been described.

4.2 Surface observations

4.2.1 High pressure viscosity tests for one type of synthetic lubricant

The oil viscosity plays an important role in the wear behaviour of sliding contacting surfaces (Section 3.2.4). For this reason, Test A to Test C (Table 3.2) were carried out to study the influence of low, medium and high viscosity POE oils (Table 3.1) on the interface between the steel pin and the aluminium alloy connecting rod (Section 3.2.5).

<u>Test A</u>

With this working fluid combination, a significant transition phase between the machined surface of the gudgeon pin and the surface in contact with the connecting rod was observed as shown in Figure 4.1. The mirror-like regions formed, which indicated the absence of an adequate lubricant film formation, were characterised by very fine scoring marks and very fine material discolourations (not clear in Figure 4.1). These scoring marks were generally found on this pin-face only, as were the surface micro-pits observed (Figure 4.1).

Figure 4.2 indicates that the contact load was not uniformly distributed over the entire surface of the small end of the connecting rod. This resulted in one end of the rod wearing out more significantly than the other. The figure also highlights the

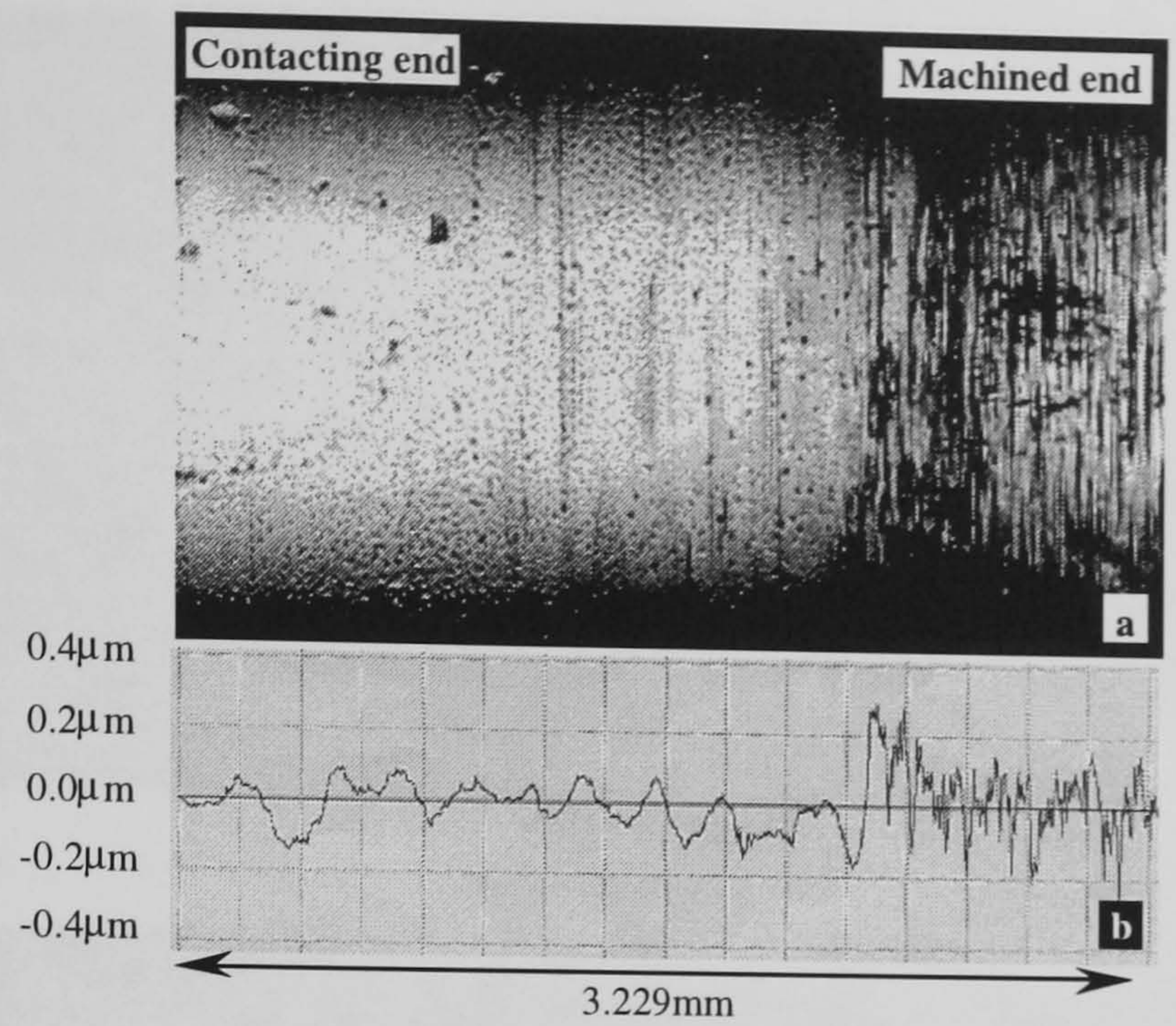


Figure 4.1. **Test A - (a) Formation of mirror-like regions on pin (x52.5), (b) Corresponding Talysurf reading (magnifications: horizontal x47.4, vertical x47400)**

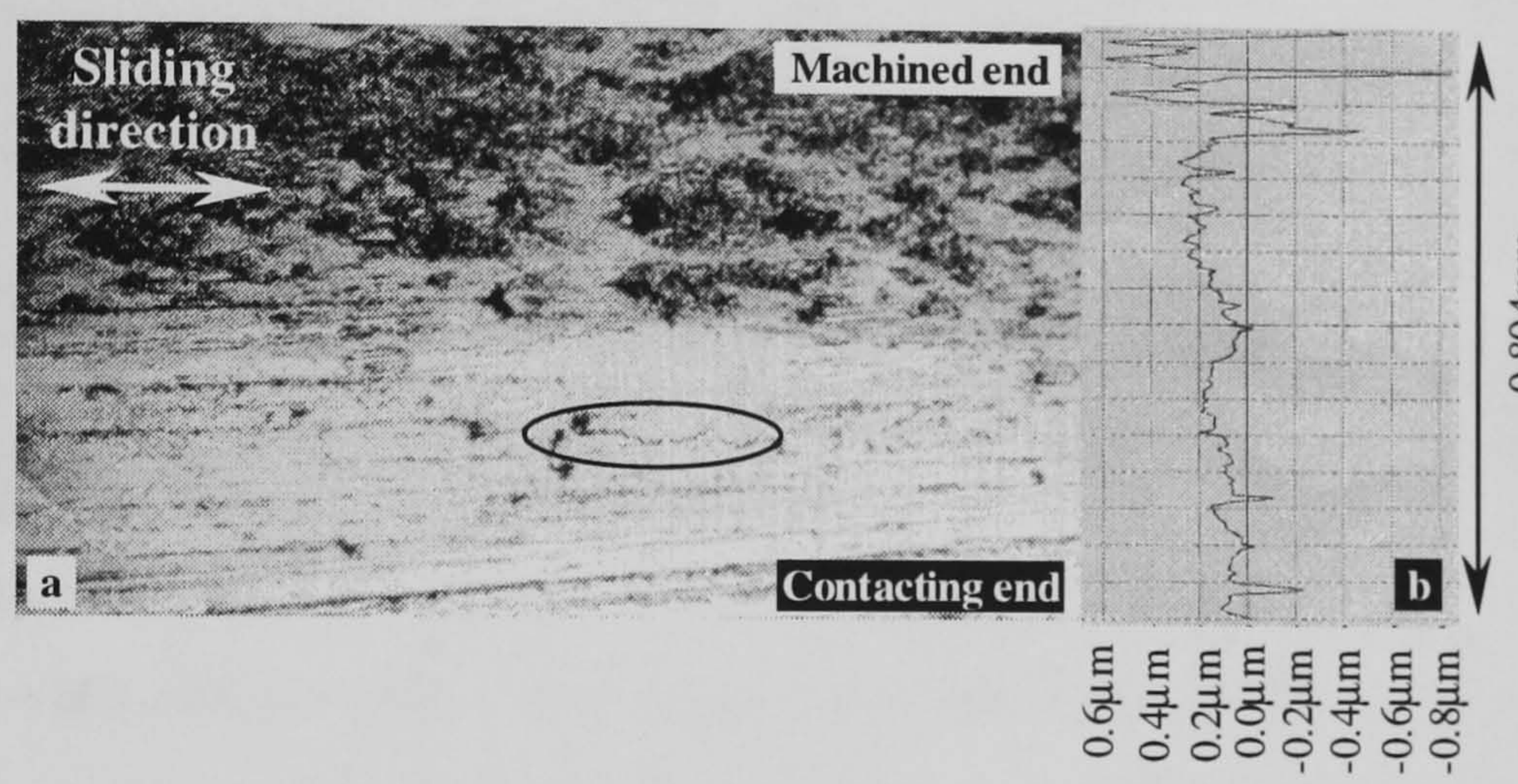


Figure 4.2. **Test A – (a) Wear characteristics on the small end of the connecting rod (x105). Circled region shows area of crack propagation, (b) Corresponding Talysurf reading (magnifications of inverted image: horizontal x47400, vertical x189.6)**

formation of a possible fatigue crack (approximately 0.27mm) developing along the direction of motion and initiating at a surface pit (defect) in the aluminium.

Using SEM, Figure 4.3 and Figure 4.4 were obtained for the gudgeon pin and the connecting rod respectively. Figure 4.3 shows a large number of bundles of material adhered to the surface of the pin. A possible explanation for these bundles could be the transfer of aluminium from the connecting rod that welded on to the steel pin under the contact pressure experienced. The bundles had no special feature related to orientation. Under a higher magnification these bundles consisted of curved cracks (similar to cracks in dried mud) which were opening up to form debris (Figure 4.3(b)). Due to a low number of counts on the specimen it was not possible to obtain a conclusive EDX analysis to determine the exact composition of these bundles. In

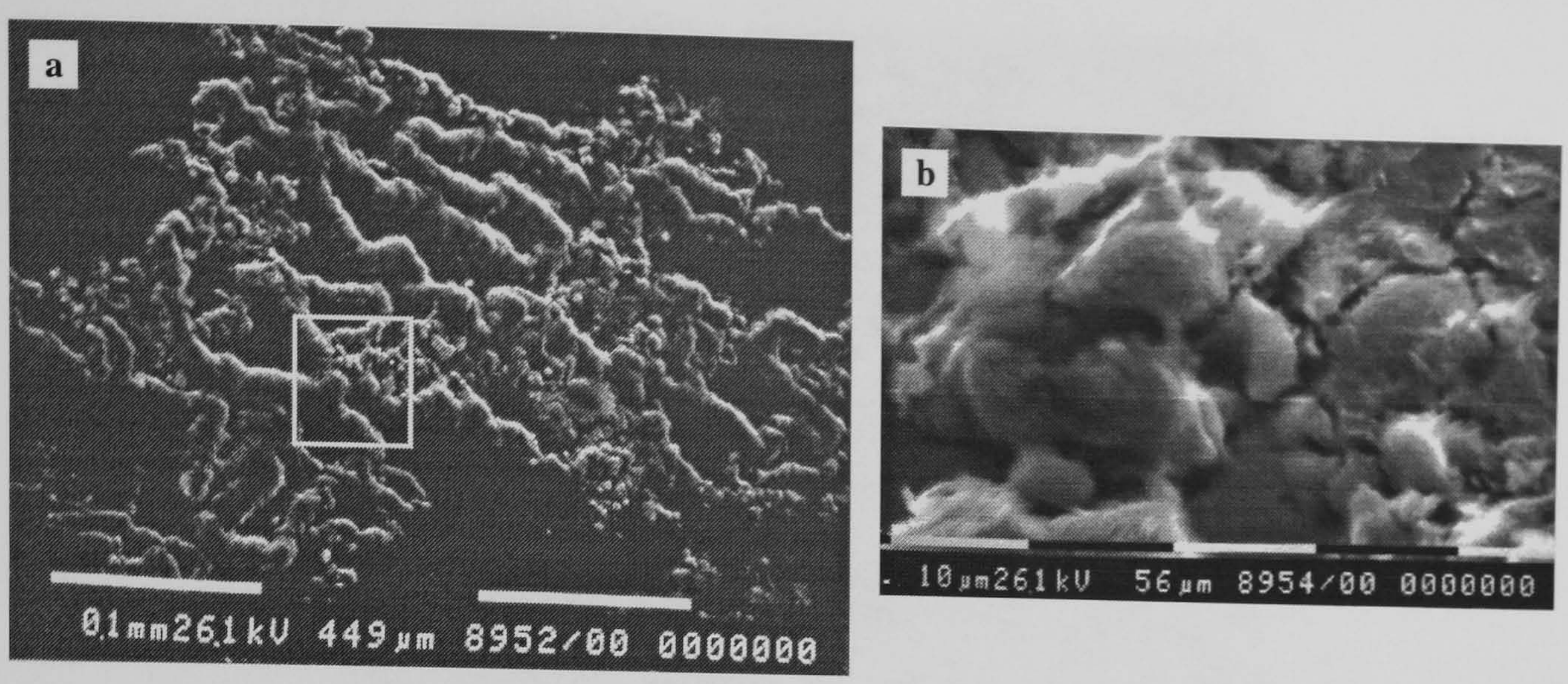


Figure 4.3. Test A – (a) Transfer of material on the pin, (b) Detail of transferred material

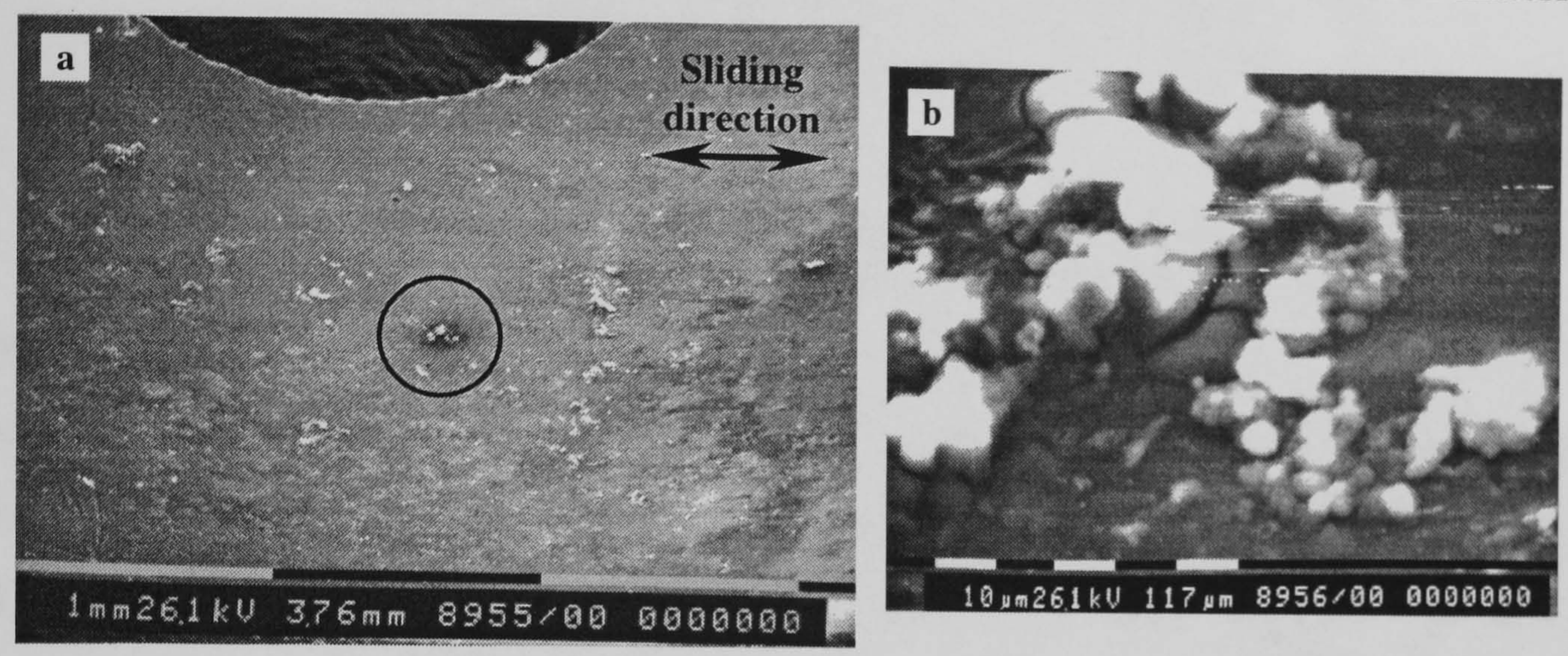


Figure 4.4. Test A – (a) Aluminium torn out of its matrix, (b) Detail of circled region

Figure 4.4 a very similar effect was noticed but this time the bundles were reduced to volcano-like regions, of a typical size of 0.5mm, scattered over the surface of the aluminium rod. A higher magnification (Figure 4.4(b)) revealed similar flake-like material as previously observed on the steel pin indicating the possibility of aluminium being torn out of its matrix.

<u>*Test B*</u>

As observed in Test A, a significant transition phase was evident in the surface texture of the pin using light microscopy. However, this time most of the worn surface consisted of smooth, discoloured strips characterised by fine scoring marks as shown in Figure 4.5. Discolouration was indicative of the formation of films on the steel surface, possibly due to the high temperatures in the region of contact. The results of the SEM analysis were similar to those observed for Test A although the evidence of material transfer from the connecting rod onto the gudgeon pin previously observed was reduced in concentration. For reasons of space no micro-graphs have been included here.

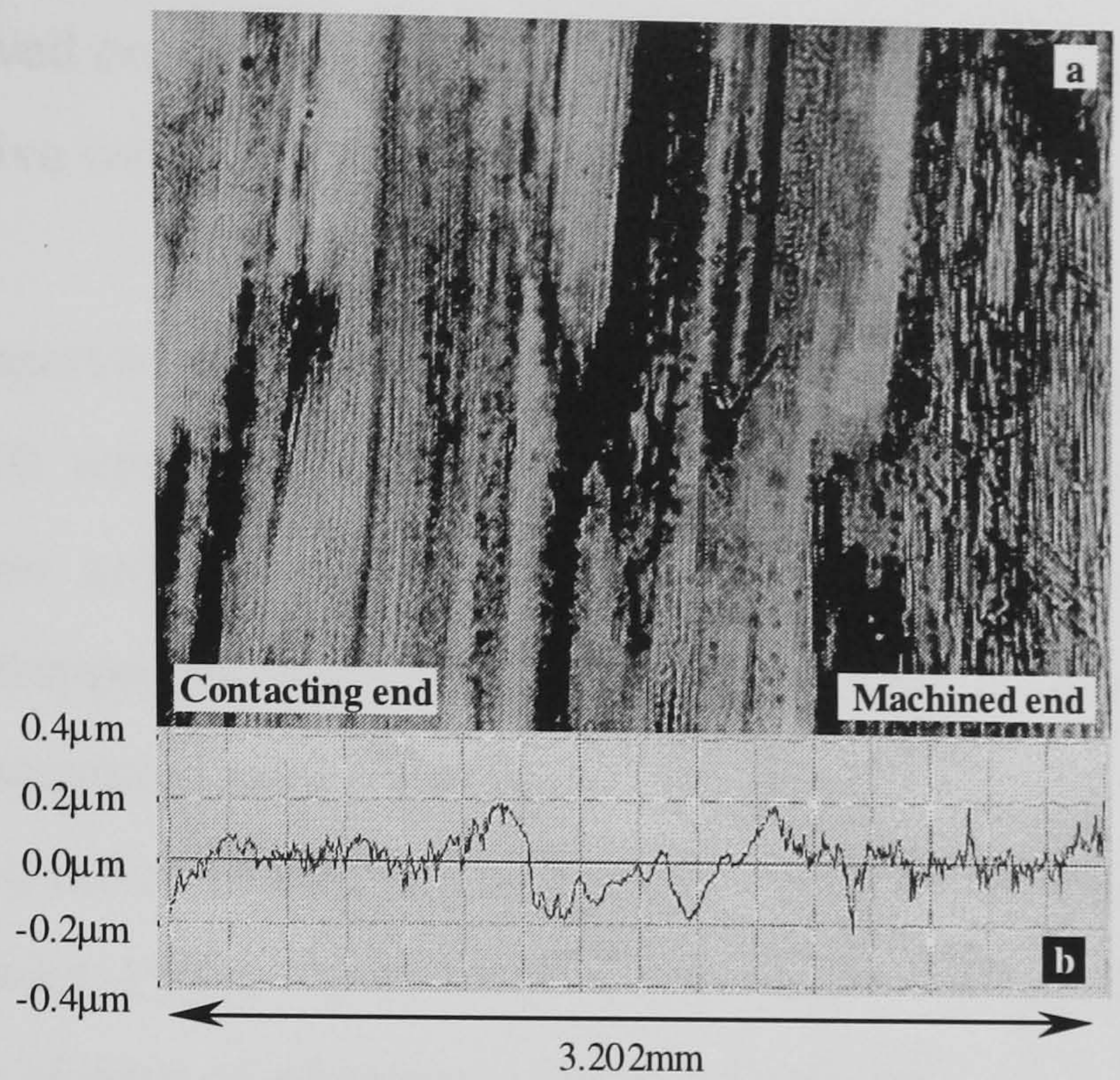


Figure 4.5. **Test B – (a) Discolourations on the gudgeon pin (x105), (b) Corresponding Talysurf reading (magnifications: horizontal x47.4, vertical x47400)**

Test C

The wear marks observed on the pin obtained from this experiment were not as severe as those observed in Test A and Test B. Both the light microscopy and the Talysurf analyses showed very little indication of the transition phase between the machined surface and the surface in contact with the connecting rod (Figure 4.6).

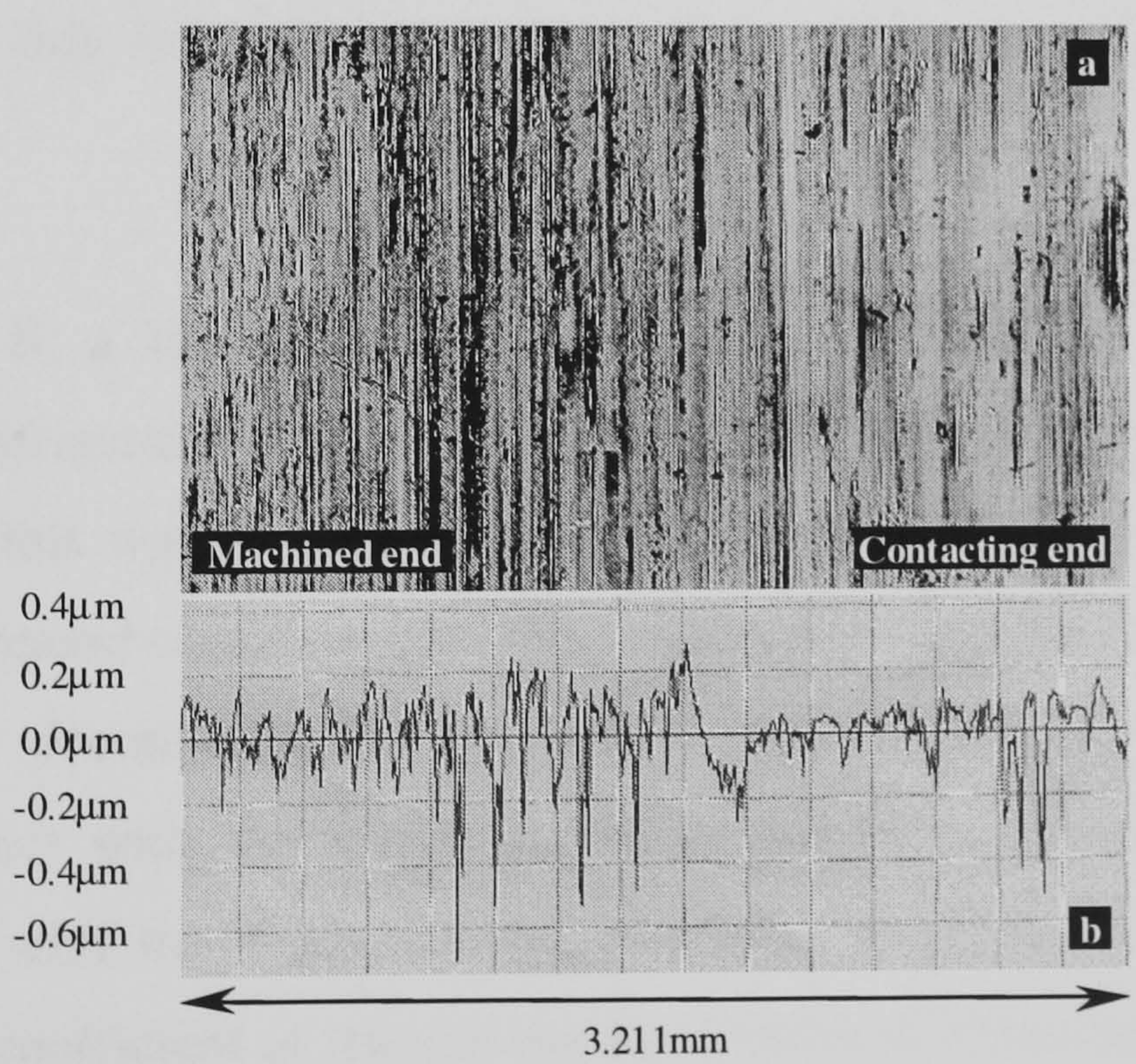


Figure 4.6. **Test C – (a) Wear characteristics on the gudgeon pin (x105), (b) Corresponding Talysurf reading (magnifications: horizontal x47.4, vertical x47400)**

Using light microscopy, the aluminium alloy connecting rod showed no significant wear (not shown). Furthermore, from the SEM analysis carried out no bundle like material was observed on the steel pin (not shown) and generally the surface showed no traces of excessive wear.

From the results observed, a smooth surface on the gudgeon pin was obtained in the presence of POE10 which, although this may improve the *loadability* of these surfaces (Andersson and Salas-Russo 1994), may also limit the presence of a lubricating film entrapped between surface irregularities. One observation pertaining to this latter consequence was that these smooth surfaces provided favourable conditions for the transfer of aluminium from the connecting rod by the process of *adhesion* (Rabinowicz 1965). Apart from the formation of debris, this mechanism also resulted in the sliding of aluminium against aluminium. As noted by Hwang, et al. (1999) and Sargent, et al. (1982) respectively, both the formation of debris and sliding between identical materials increase the heat by friction during sliding. It should be emphasised that the compressors in Test A to Test C had to be cooled externally to maintain operating temperatures. For Test A, however, an increased dissipation of heat was observed compared to Test B and Test C and this increase in friction could have been a contributory factor. During these tests no provision for the quantification of this heat dissipated was made despite its significance to this investigation.

Throughout Test B, a similar process to the one described for Test A occurred. However, some refrigerant/lubricant could have been present between the interface. The evidence for this was the smooth discoloured strips observed (Figure 4.5). It is likely that the increased contact temperature caused the thin lubricant/refrigerant film present to either decompose the refrigerant (Section 6.1.3) or decompose the lubricant in contact with the steel. The latter has been reported in (Kruse and Schroeder 1985) with the discolourations resulting from the formation of soaps, which reduce the coefficient of friction but have not been observed to influence wear (Yamamoto, et al. 2000).

For Test C, the presence of the machining grooves on the steel pin indicated the presence of a lubricating medium. Due to the similarities between surface textures, it was possible that a lubricant film was maintained at this concentrated contact.

Observations made throughout this part of the investigation will be assessed more fully in Section 6.1.

Oil debris analysis for Test A to Test C

Most of the debris consisted of either laminate or string-type particles as already described by other researchers (Pramila Bai, et al. 1983). Although wear mechanisms for Test C were not severe, Figure 4.7 shows a laminate (scale-like) particle resulting from this test and this was measured to be approximately 0.44mm along the arrow (Figure 4.7(a)). An EDX analysis for this particle (Figure 4.7(b)) showed an aluminium content resulting from wear on the connecting rod. A high presence of fluorine (Figure 4.7(b)) was also noted on this particle, possibly resulting from the formation of fluorides due to the refrigerant, as will be explained in (Section 6.1.3). Further observations on the presence of debris in lubricants are described in Section 4.2.2.

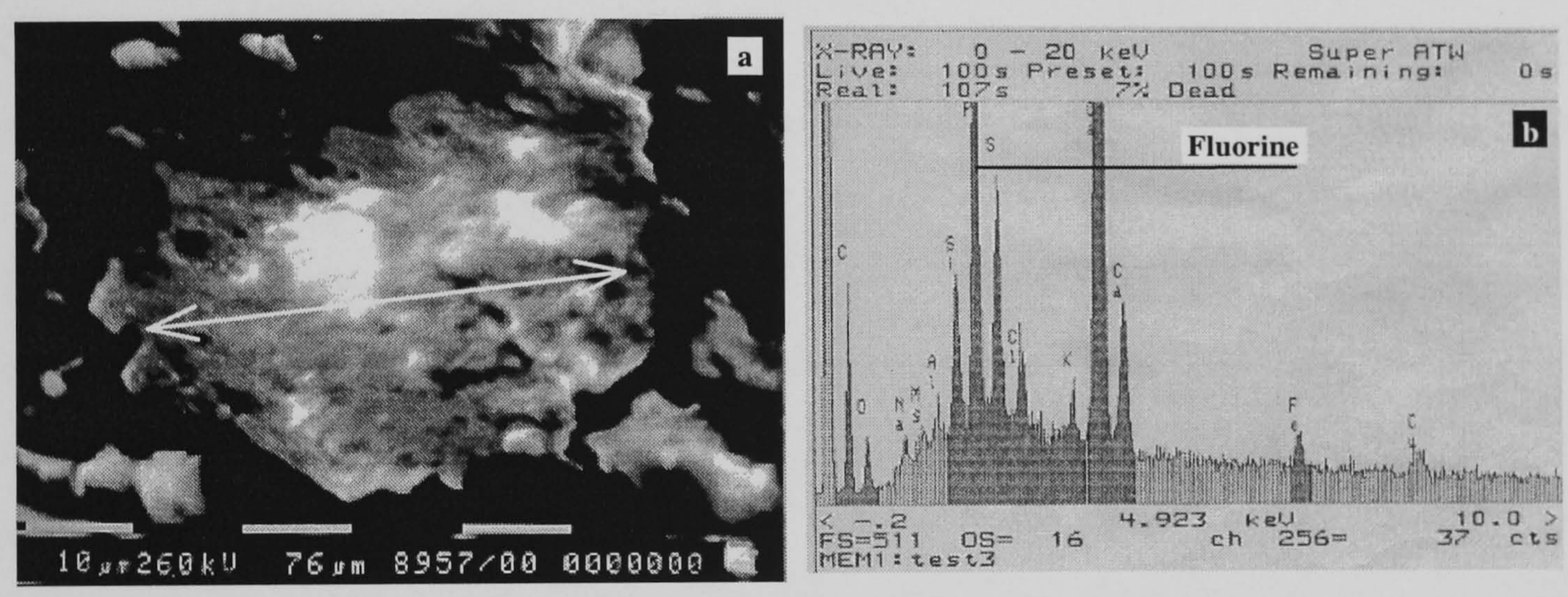


Figure 4.7. (a) Laminate debris, (b) Corresponding EDX analysis

4.2.2 Tests for two types of synthetic lubricants having an identical viscosity

A lower viscosity lubricant may reach contacting surfaces more easily, particularly at start-up and this may help to improve the electrical efficiency of the compressor (Section 3.2.4). Despite both parameters being relevant to this study, the experimental analyses carried out and described throughout the remainder of this chapter were focused on the higher viscosity oil (Table 3.2). This was due to their enhanced performance observed (Section 4.2.1) and to allow a more accurate comparison with the mineral oil used with CFCs (Table 3.1). This section deals with the implications resulting from the use of two types of synthetic lubricants (Section 3.2.4) observed throughout Test D to Test I (Table 3.2). Unlike in Section 4.2.1, this analysis is not carried out per each individual test but the observations have been combined for ease of comparison.

Gudgeon pin and connecting rod analyses for Test D to Test I

Figure 4.8(a) and (b) are two light microscopy slides showing the influence of steel rubbing against the soft aluminium alloy matrix after the completion of Test D and Test E. The deep crevices formed on the surface differed from the aluminium machining marks (Figure 4.8(e)) of an unused connecting rod. It is possible that the machining marks (shown in Figure 4.8(f) for an unused pin) caused this pattern of grooves on the aluminium. At this stage it was not clear whether this pattern of grooves (deep scratches) were formed into the softer material as a result of the run-in of interacting surfaces. It may be that after 1000 hours these grooves may be lessened in depth with the consequent formation of debris and restriction of the presence of the lubricant. This is partially depicted in the observations obtained for Test F to Test G (observations for Test H and Test I are not included in Figure 4.8 for reasons of space but were found to be similar). As the contact pressure increased, the relative movement caused the aluminium surface to become smooth with the consequent formation of mirror-like regions (previously noted in Section 4.2.1). These surfaces comprised large smooth load-bearing areas as shown in Figure 4.8(c) for the POE test and in Figure 4.8(d) for the PVE test (compare to the unused aluminium rod shown in Figure 4.8(e)).

Test D and Test E, that is the normal pressure tests, identified that yet again mirror-like regions on the hard steel surface of the pin were obtained when this slid against the softer aluminium, see Figure 4.8(g) and (h). The machining marks (of which only a few were still visible after the completion of the two tests) may be seen in Figure 4.8(f) for an unused pin. A possible explanation for this is that as the aluminium on the connecting rod wore off (Figure 4.8(a) and (b)) the silicon particles making up the aluminium alloy were exposed. These silicon particles are harder than the steel (Table 3.3) and a resulting machining effect on the steel surface occurred. For Test F to Test I, that is the higher pressure tests, somewhat contradictory results were obtained (again observations for Test H and Test I are not included in Figure 4.8 for reasons of space). The steel surface seemed to be less damaged compared to Test D and Test E as shown in Figure 4.8(i) and (j). The two figures indicate that for the

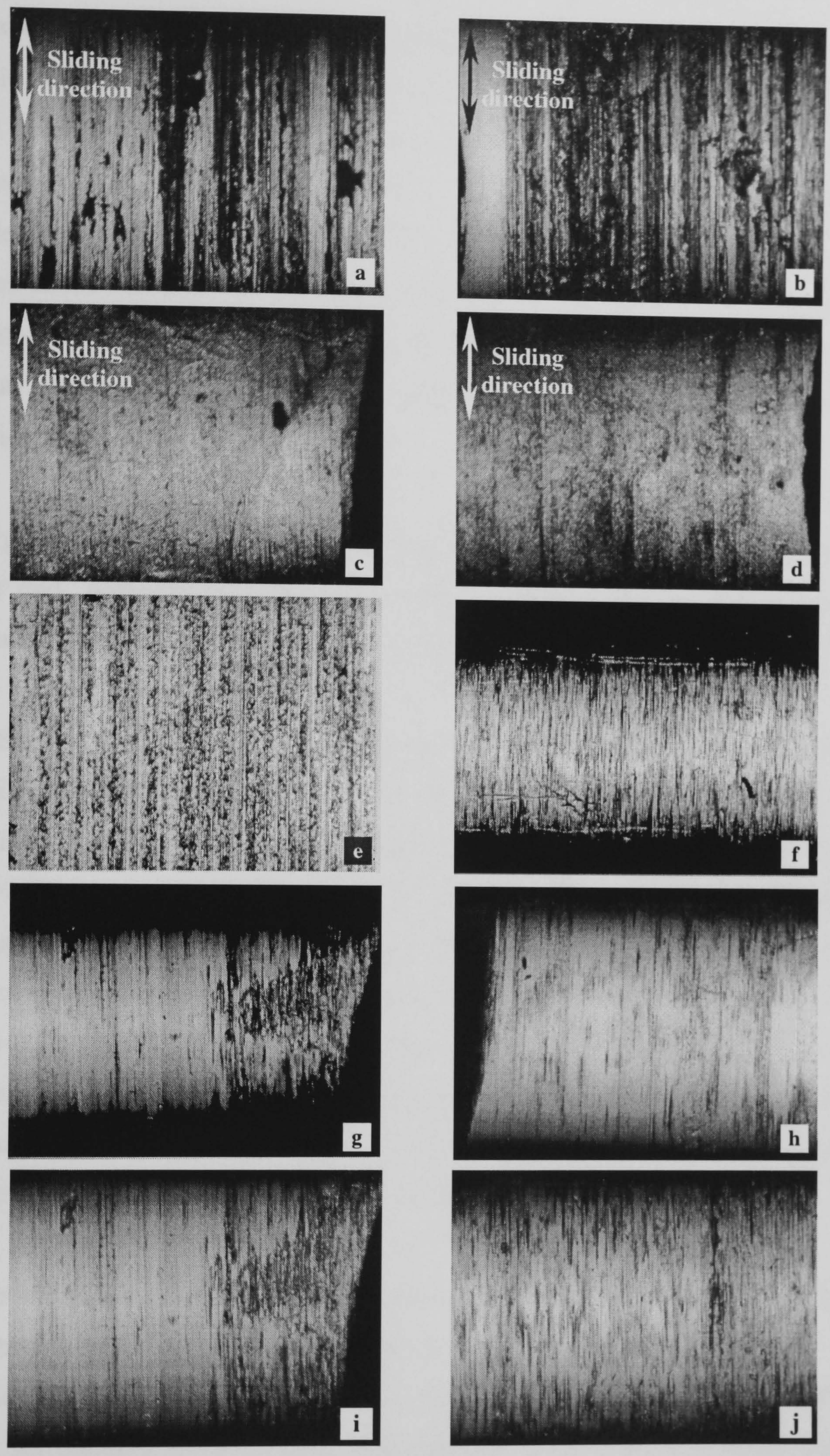


Figure 4.8. Light microscopy analyses on the connecting rod and the gudgeon pin; (a) Test D, normal pressure, POE, small end (x52.5), (b) Test E, normal pressure, PVE, small end (x52.5), (c) Test F, high pressure, POE, small end (x52.5), (d) Test G, high pressure, PVE, small end (x52.5), (e) unused, small end (x52.5), (f) unused, gudgeon pin (x52.5), (g) Test D, normal pressure, POE, gudgeon pin (x52.5), (h) Test E, normal pressure, PVE, gudgeon pin (x52.5), (i) Test F, high pressure, POE, gudgeon pin (x52.5) and (j) Test G, high pressure, PVE, gudgeon pin (x52.5)

POE experiments and the PVE experiments (especially) the machining marks on the steel pin were still visible. An explanation as to why the steel samples from the normal pressure tests (Figure 4.8(g) and (h)) were smoothed out more than the samples from the high pressure test (Figure 4.8(i) and (j)) is difficult to find. It is possible that after approximately 300 hours (Table 4.3) of operation the silicon particles could not degrade the steel surface as occurred after the 900 hour (Table 4.2) tests. Another possibility could result from the increased bulk temperature of the lubricant during the normal pressure tests (Table 4.2). This will be dealt with further in Section 6.1.1.

The large end of the connecting rod showed less evidence of wear compared with the smaller end. Although looked at in detail, using light microscopy analysis, few observations were made that were worth recording here.

Using SEM, micro-pitting was observed on all of the aluminium samples lubricated with either the POE or the PVE oils (Figure 4.9(a) to (c)). Under a higher magnification (Figure 4.9(b)) it is observed that, within these pits, material was broken off to form debris. Characteristics shown in Figure 4.9(c) were identical to findings reported by Pramila Bai, et al. (1983). Although such micro-pitting was observed on the aluminium, their pattern of occurrence made it unlikely that this was as a result of porosity due to the processing of aluminium (Higgins 1993). It seemed that these pits occurred due to the aluminium or silicon particles being torn from their matrix. Another possibility could be the result of a chemical attack from the additives present within the base oil or the refrigerant itself.

Another observation, which resulted in a significant amount of surface degradation on both the small and the large end (the latter being more advanced) of the aluminium connecting rod, is shown in Figure 4.10. Figure 4.10(a) shows dark patches surrounding the lubricating hole through which a mixture of lubricant and refrigerant are forced during compressor operation. These patches seemed to be more evident for samples working in a PVE environment. The micro-graphs shown here are for the high pressure test. A higher magnification (Figure 4.10(b)) reveals how the surface of the aluminium burst open as a result of what appears to be the

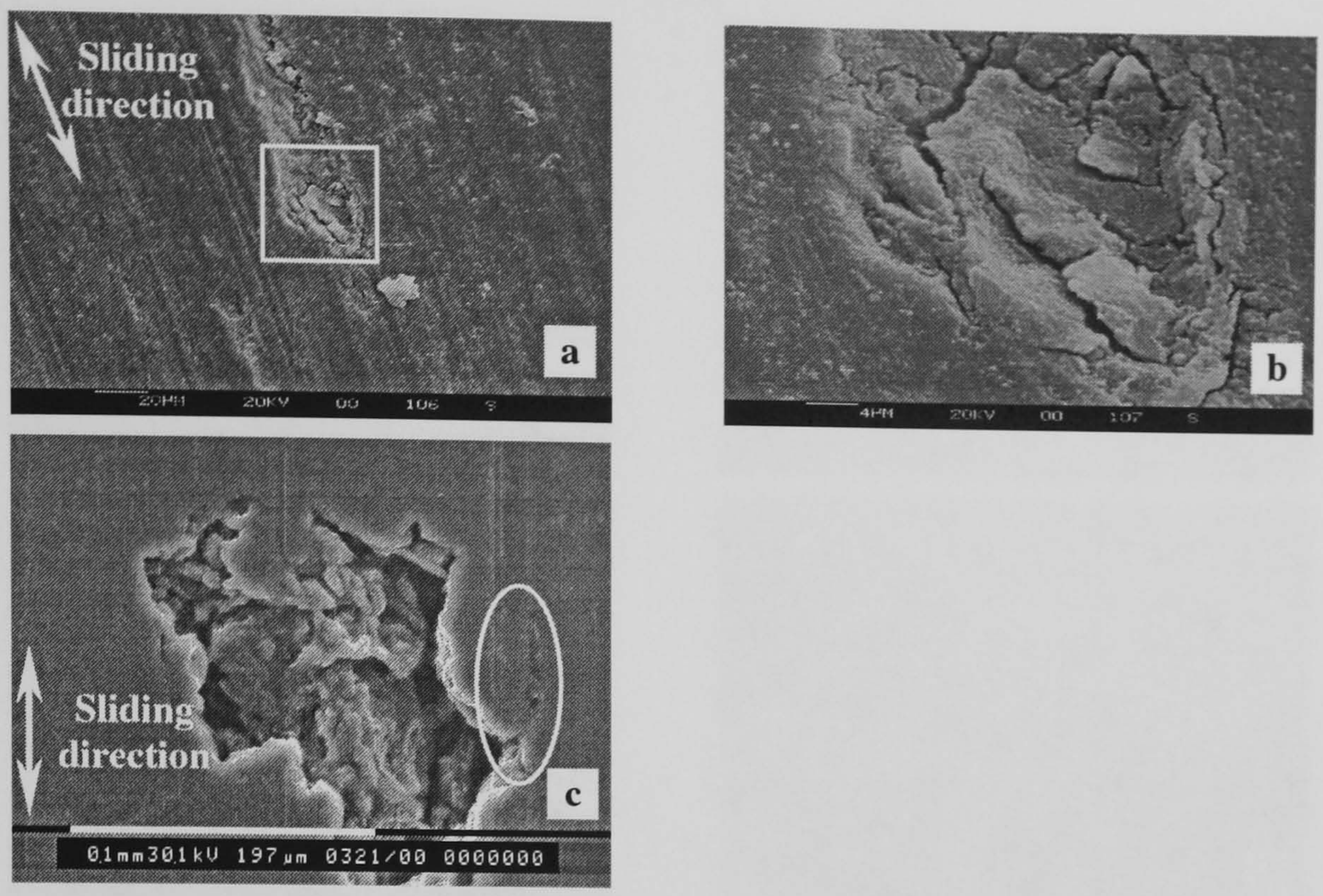


Figure 4.9. Surface pitting of aluminium alloy; (a) Test D, normal pressure, POE, small end, (b) detail of boxed region in (a) showing typical surface texture within pit and (c) Test I, high pressure, PVE, large end (circled region shows crack propagation)

formation of blisters on the aluminium surface. The wrinkling effect within these darkened regions caused the ridges to open with the possible consequence of debris formation (Figure 4.10(c) and (d)). For the samples from the POE experiments this wear mechanism was also observed but was not as well-developed as observed with the PVE samples (Figure 4.10(e)).

The large end of the connecting rod operating under a high pressure in the presence of POE also experienced another form of wear degradation not observed on other samples. Islands were formed on the aluminium surface as shown in Figure 4.10(f). A higher magnification (Figure 4.10(g)) shows the extent of debris formation around these regions. Figure 4.10(h) shows how some of these regions failed to open so that melting points were reached locally due to increased pressures. In this instance, momentary welding followed by plastic separation seemed to occur. One possible explanation for this form of *lubricated wear* could be that any gases entrapped in the cast aluminium expanded due to the high temperatures involved causing the surface deformations observed.

It has already been reported that, for the normal pressure tests (Test D and Test E) under the influence of either of the synthetic lubricants tested, wear tracks in the softer aluminium material were observed using light microscopy. SEM analysis

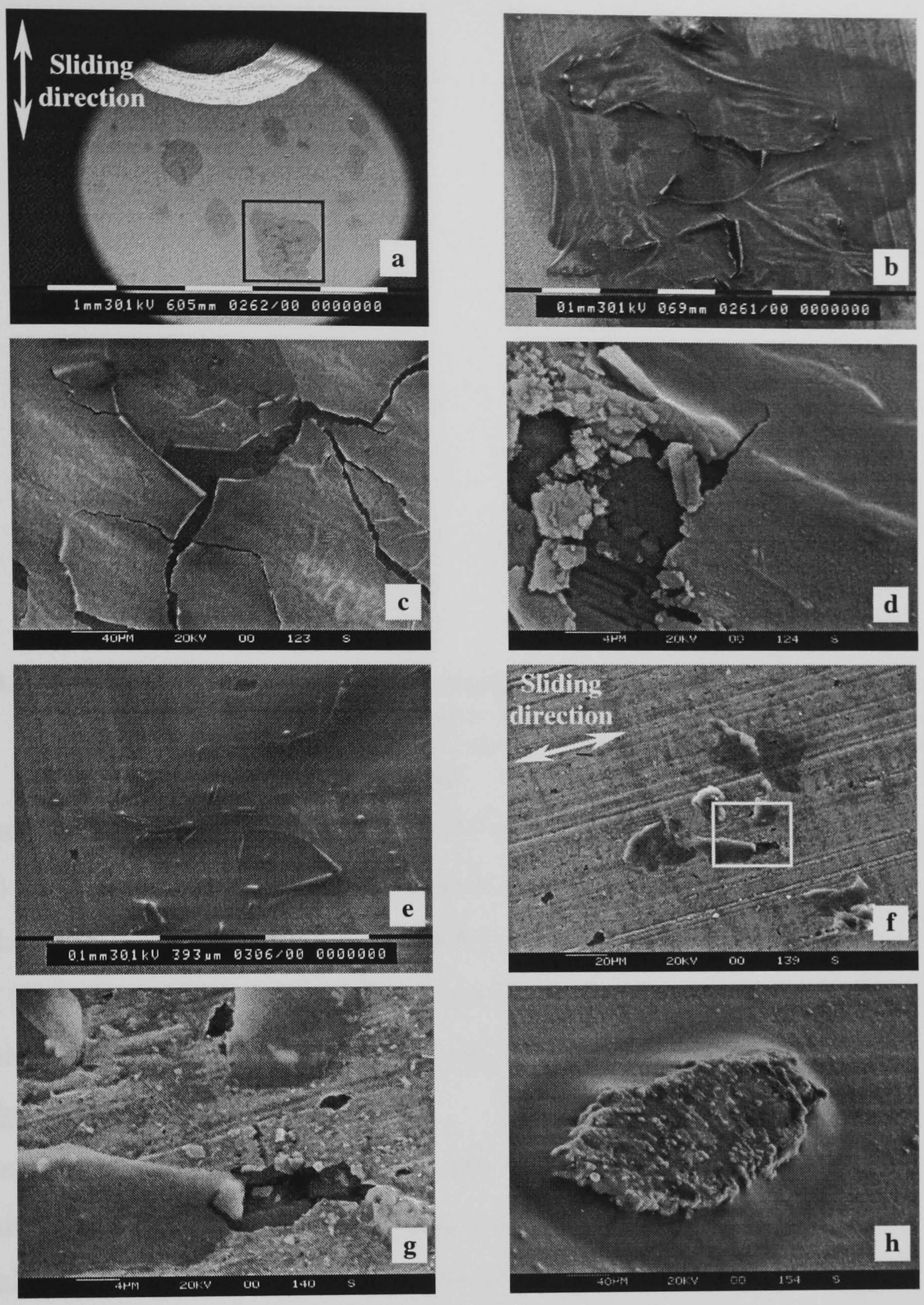


Figure 4.10. Formation of debris on the large end aluminium samples; (a) Test G, high pressure, PVE, large end, (b) magnification of boxed area in (a), (c) magnification of region shown in (b), (d) magnification of region shown in (c), (e) Test H, high pressure, POE, large end, (f) Test F, high pressure, POE, large end, (g) magnification of boxed area in (f) and (h) Test H, high pressure, POE, large end

revealed the formation of grooves in the softer material which, due to oscillatory motion, do not extend around the whole of the small end of the connecting rod (Figure 4.11(a)). Under higher magnification these grooves were ploughed into the softer material resulting in *seizure markings* (Engel and Klingele 1981) as illustrated in Figure 4.11(b) and (c) for the POE and the PVE lubricants respectively. These markings are caused by the oscillatory motion forcing the cracks to open up and scale-like metal flakes to form (as will be observed later). Although light microscopy

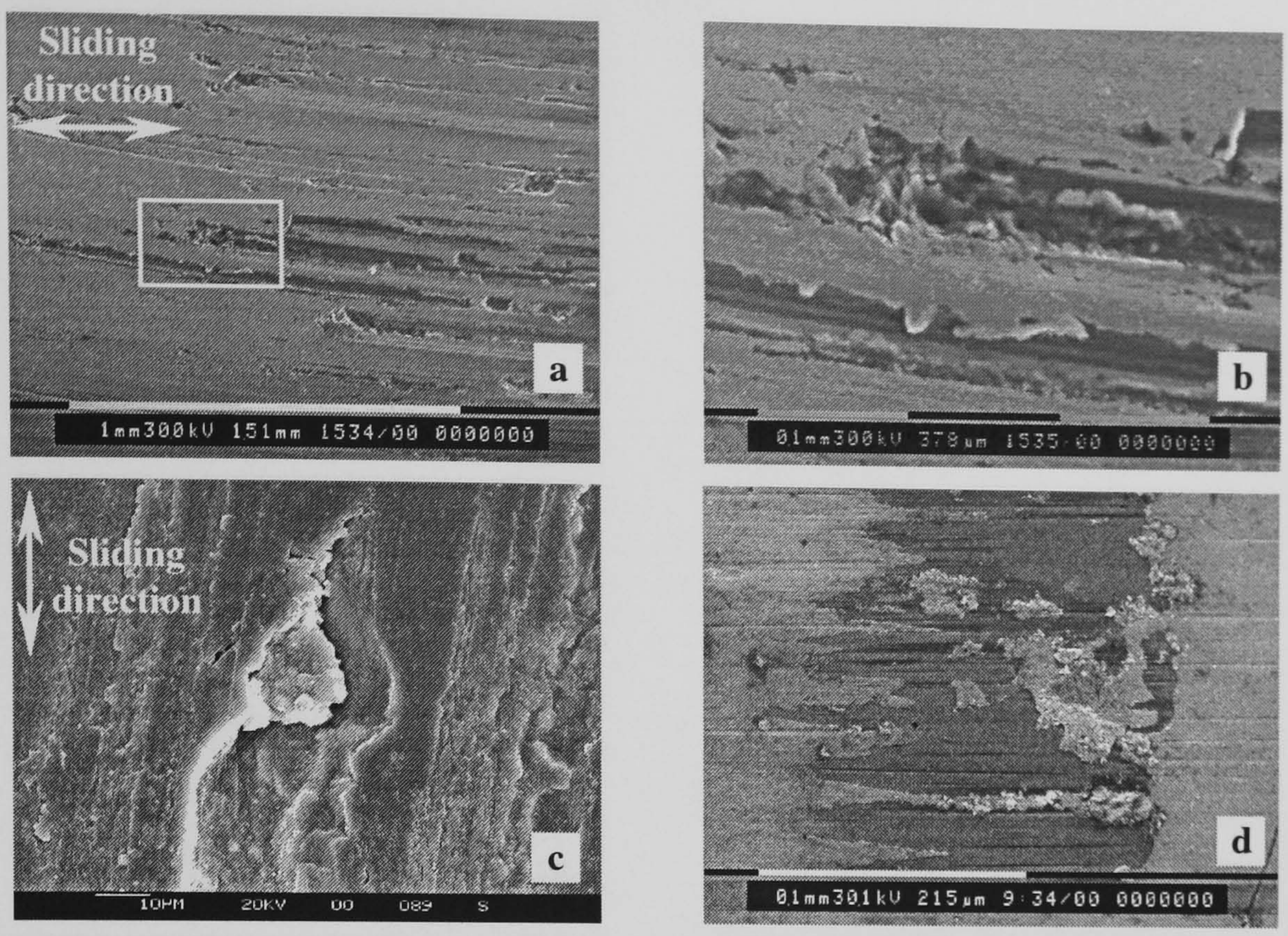


Figure 4.11. Evidence of rubbing between aluminium and steel; (a) Test D, normal pressure, POE, small end, (b) magnification of boxed region in (a) showing typical surface texture of wear track, (c) Test E, normal pressure, PVE, small end and (d) Test H, high pressure, POE, gudgeon pin

revealed that the steel pin was more pitted in the normal pressure tests (Test D and Test E) than in the high pressure ones (Test F to Test I), Figure 4.11(d) revealed that in the latter tests surface degradation on the gudgeon pin also occurred. Pramila Bai, et al. (1983) have published similar findings to those described in this section for aluminium/silicon alloys sliding against steel under dry conditions.

Oil debris analysis for Test D to Test I

The task of this wear debris analysis was to determine the presence of steel and aluminium particles present in the lubricant and the extent to which each of these materials was wearing away. Another task of this analysis was an attempt to compare whether the PVE test resulted in more material degradation than the POE test. As shown in Figure 4.12(a) to (l), a number of observations had to be carried out on a variety of debris to investigate these criteria. This study focused on the normal pressure tests (Test D to Test E) although an analysis for the high pressure tests (Test F to Test I) was also carried out. The principal difference between the debris collected for the high and the normal pressure tests was that in the former the debris was generally of a larger dimension. Evidence of this is the 0.8mm aluminium particle collected from the high pressure POE test (Figure 4.12(l)). It should be noted that any particles of an approximate size of 0.15mm indicate severe wear, as noted by Czichos (1978).

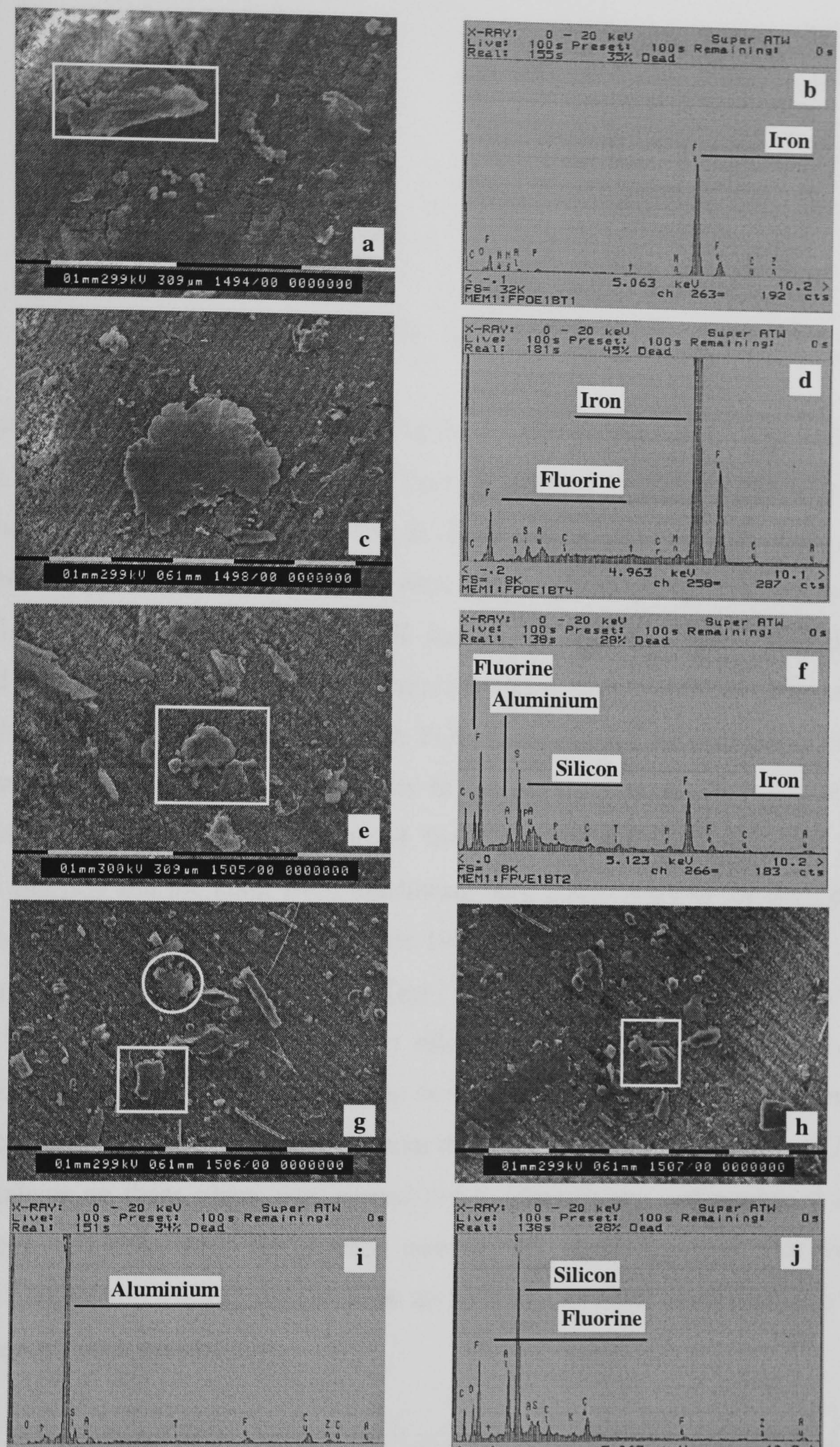


Figure 4.12. Wear debris analyses; (a) Test D, normal pressure, POE, (b) EDX for marked debris in (a), (c) Test D, normal pressure, POE, (d) EDX for debris in (c), (e) Test E, normal pressure, PVE, (f) EDX for boxed debris in (e), (g) Test E, normal pressure, PVE, (h) Test E, normal pressure, PVE, (i) EDX for circled debris in (g), (j) EDX for boxed debris in (g), (k) EDX for boxed debris in (h) and (l) Test H, high pressure, POE

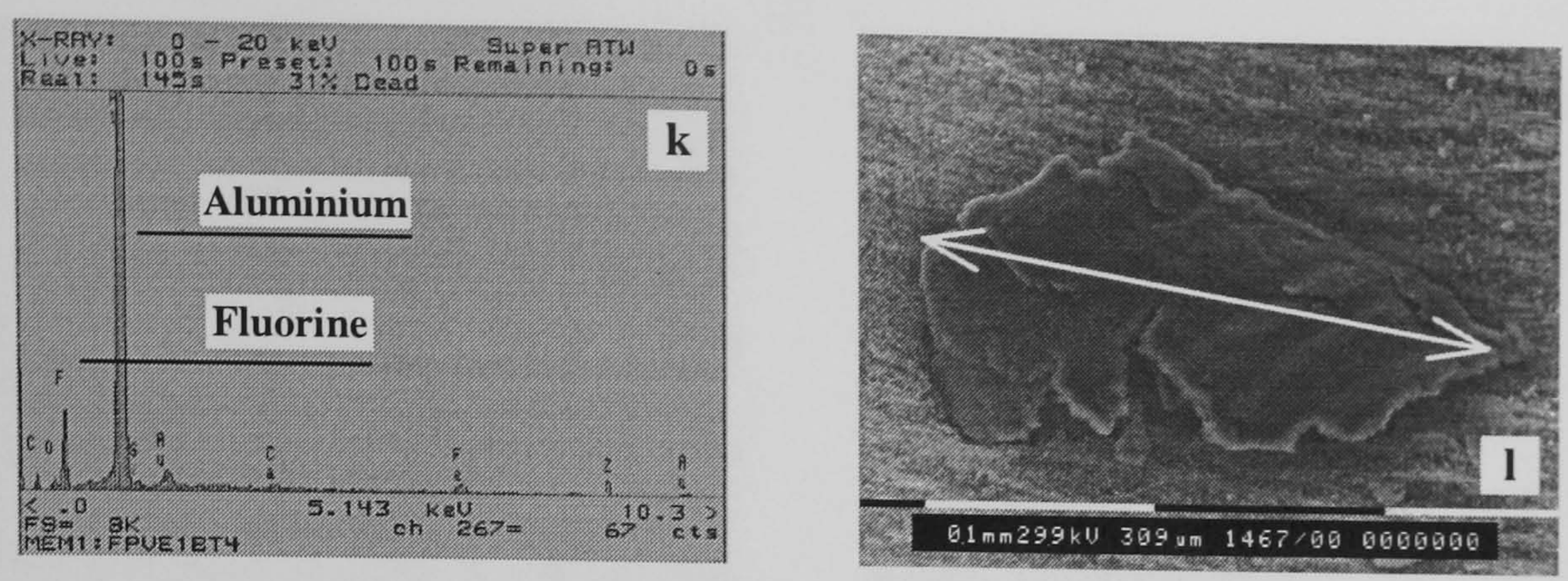


Figure 4.12. (continued)

When comparing Figure 4.12(a) and Figure 4.12(c) to Figure 4.12(g) and Figure 4.12(h), the POE normal pressure test (Test D) resulted in a lower concentration of collected wear debris compared to Test E (PVE normal pressure). Furthermore, the particles collected from the former test were apparently of a larger dimension. From these figures and their respective EDX analysis it was also found that the PVE resulted in a larger concentration of aluminium and silicon content as compared with the higher iron content observed for the POE type. Finally, as previously observed (Section 4.2.1) the debris collected was in the form of scale-like and string-like particles. The former possibly resulted from seizure markings observed (Figure 4.11(b) and (c)) and the latter from machining on a micro-scale of the hard particles on the softer material (Engel and Klingele 1981).

<u>*Reed valve plate analysis for Test F to Test I*</u>

During the post-test analyses the piston side of the exhaust/intake reed valve plate obtained from the PVE experiments was seen to be discoloured to a very deep blue tint as compared to the ones obtained from the POE experiments (Section 3.2.5). An XPS analysis on these plates was carried out to identify any compounds that could have been adsorbed onto the surface causing the discolourations observed (see Section 3.3). Figure 4.13(a) and (b) show an XPS and an EDX analysis for an unused plate used for comparison.

During this analysis, the element zinc was identified on the surface of the plate working in a POE environment (Figure 4.13(c)). This was not the result of a reaction with the substrate material of the valve. The EDX analysis on an unused valve plate did not reveal any presence of zinc (Figure 4.13(b)). One explanation for this detection of zinc could be due to a reaction occurring between the possibly porous

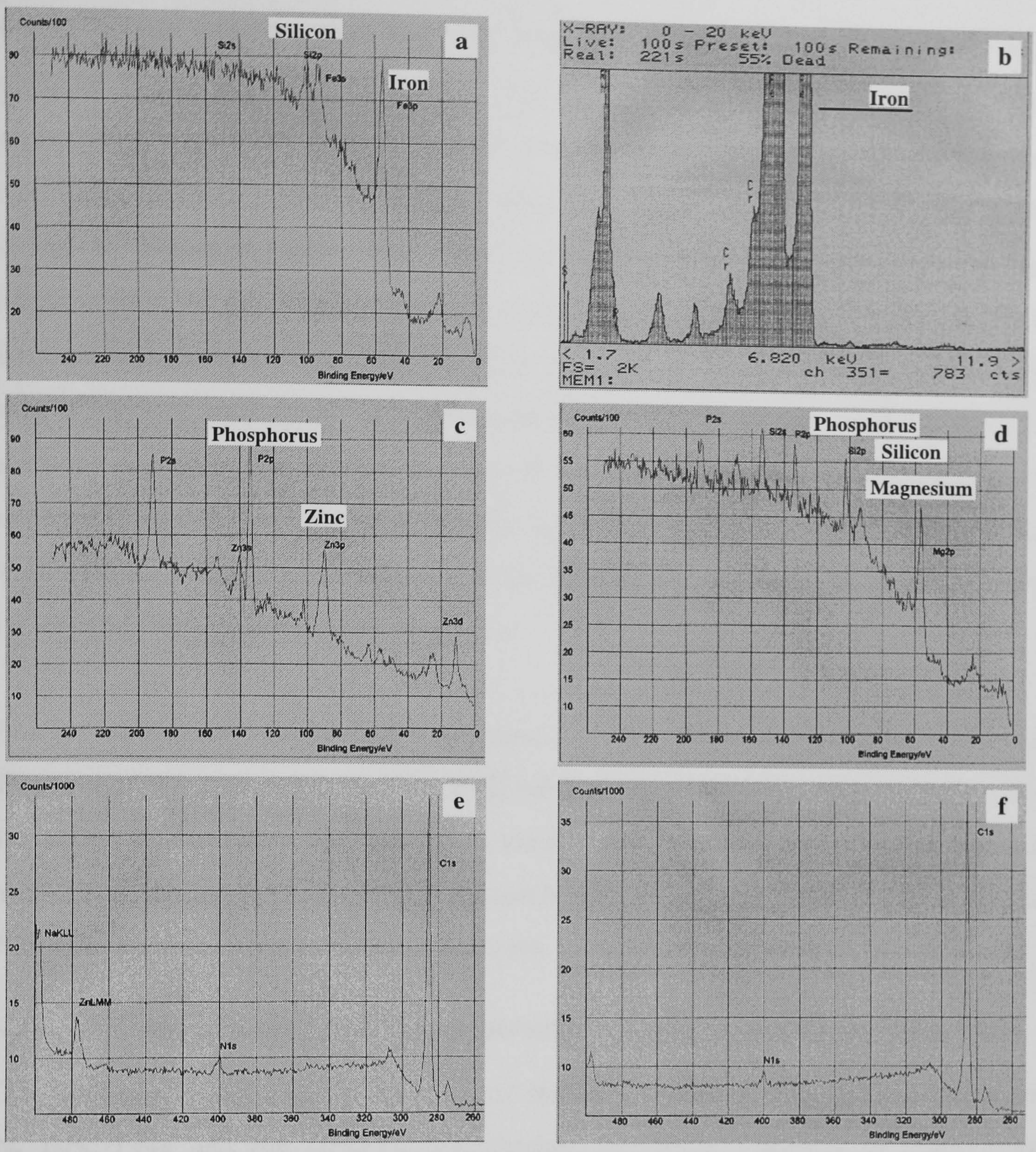


Figure 4.13. Typical reed valve plate analyses; (a) XPS for unused valve plate at a binding energy ranging from 0 - 260eV, (b) EDX for unused valve plate, (c) XPS for POE valve plate at a binding energy ranging from (0 – 260)eV, (d) XPS for PVE valve plate at a binding energy ranging from (0 – 260)eV, (e) XPS for POE valve plate at a binding energy ranging from (260 – 500)eV and (f) XPS for PVE valve plate at a binding energy ranging from (260 – 500)eV

gasket, in which entrapped gases may be present, and the working fluid used. With the PVE, no zinc was observed but the presence of magnesium was noted on the surface (Figure 4.13(d)). This is one possibility that could have increased the PVE valve plate discolouration.

Another interesting observation was that, although discolourations on the valve plate were observed using PVE, the deposited film seemed to be thinner on the plate from the PVE test than that from the POE test. This could be said because the silicon content of the unused valve was still detected on the plate from the PVE test (compare Figure 4.13(a) to Figure 4.13(c) and Figure 4.13(d) for POE and PVE respectively). However, a larger carbon concentration, possibly resulting from the overheating of the oil, was detected on the plate from the PVE test (compare Figure 4.13(e) to Figure 4.13(f)). This could be another possible explanation for the discolouration of the valve. The high temperatures might have caused the PVE lubricant to decompose more than the POE oil although this appears to conflict with what is reported by Takesue and Tominaga (1998) and Yamamoto, et al. (1998). In addition, no carboxylic compounds, which have poor lubricating properties, were recorded for the POE as reported by Takesue and Tominaga (1998) and Yamamoto, et al. (1998). A peak at a binding energy ranging from 280eV to 290eV (Figure 4.13(e) and (f)) would have indicated this.

Finally, considering the surface degradation on the aluminium samples observed (Figure 4.10), it is possible that the PVE lubricant is more chemically active on the interacting surfaces than the POE oil. In view of this, this synthetic lubricant was not considered further throughout this research and all efforts were focused on the POE32 as explained in the following section.

4.2.3 HFC and CFC tests with similar lubricant viscosity at varying operating times

This section will characterise and compare the wear characteristics observed between the HFC-134a and the CFC-12 experiments. A similar viscosity of compressor lubricant was used, that is the POE32 oil and the SD oil (Table 3.1), throughout Test 1 to Test 8 (Table 4.4). Furthermore, this section will identify the influence that start/stop compressor operation has on the wear characteristics and system performance (Section 2.6.1 and 3.2.4). It should be mentioned that throughout the wear analyses for Test 1 to Test 6, the pin and the connecting rod (Figure 4.14) were investigated at different locations around the interface. Evidence of wear, occurring at other locations other than the load face, was thus sought (Section 3.2.5).

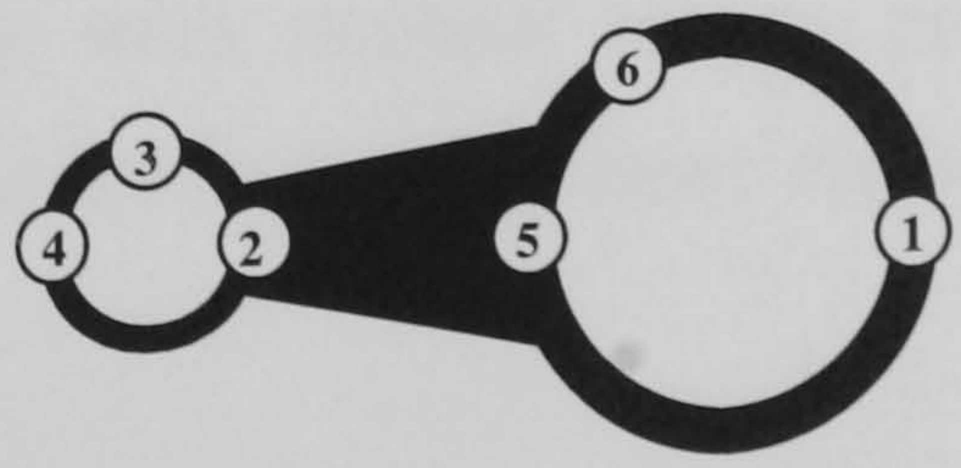


Figure 4.14. Location of microscopy analyses for the connecting rod (Test 1 to Test 6)

<u>*Test 1 and Test 3*</u>

Using optical microscopy for Test 1, similar observations to Test D and Test E (Section 4.2.2) were obtained. Figure 4.15(a), which again identified the transition occurring between the machined end and the contacting end, is evidence of this. The pin obtained from Test 3 (Figure 4.15(b)) showed a reduced extent of wear compared to (Figure 4.15(a)) with some machining marks still evident on the surface.

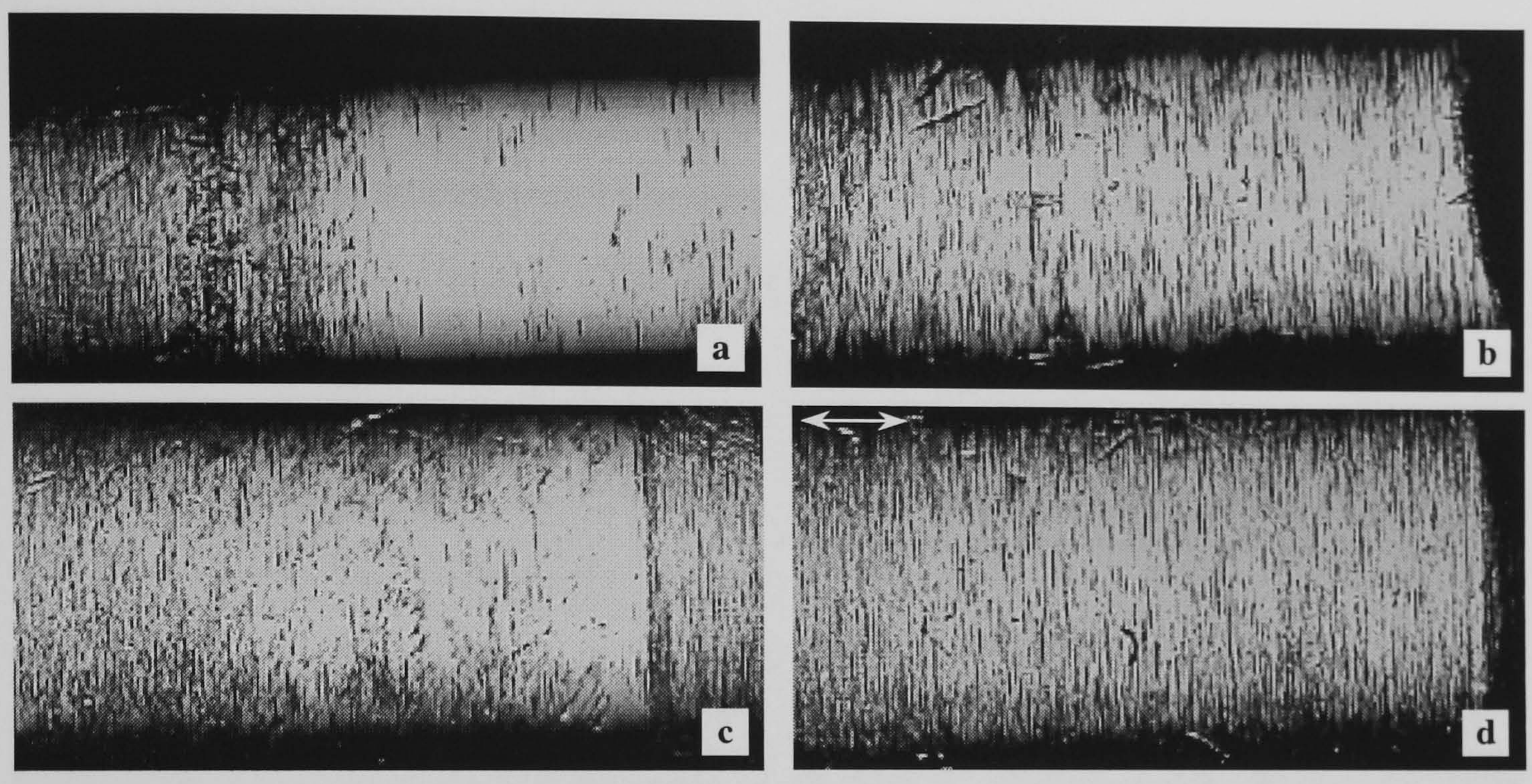


Figure 4.15. Gudgeon pin; (a) load face, Test 1 (x52.5), (b) load face, Test 3 (x52.5), (c) opposite to load face, Test 1 (x52.5) and (d) opposite to load face, Test 3 (x52.5)

To determine whether contact with the load face is maintained during the transition from position (3) to position (4) in Figure 3.5, Figure 4.15(c) and (d) shed some evidence on this. In Figure 4.15(c), it is clear that wear on the pin opposite to the load face occurred implying that during cylinder volume expansion the rod is pulling the piston. This wear is, however, less than that observed in Figure 4.15(a) indicating that the interface at the load face is the most critical. Interestingly, in Figure 4.15(d) the transition between the machined end and the contacting end can just be identified (marked by an arrow) indicating that with the CFC-12 combination much less wear occurred, as was observed on the load face (Figure 4.15(b)). Further analyses were also carried out at 90° to the load face but have not been included here. Wear characteristics on this face were minimal but, as previously observed, the pin working in an HFC environment was slightly more degraded than its counterpart.

Observations on the connecting rod correlate with those made on the pin. It should be noted that the locations of the micro-graphs (Figure 4.16) correspond to the locations shown in Figure 4.14. For the continuous test, the aluminium samples in HFC-134a (Figure 4.14(a)) were scored more significantly than the samples acquired for the CFC-12 continuous test (Figure 4.14(b)). This surface at location 1 is only in contact during cylinder volume expansion. For this reason, the wear is not severe on either of the samples observed (Figure 4.16(a) and (b)) but heavier marks may be seen on the former than on the latter. Some abrasion marks resulted on the samples working in HFC-134a at location 2 (Figure 4.16(c)) compared to the smooth aluminium surface shown in Figure 4.16(d) for a CFC-12 environment. Furthermore, the load face on the large end is heavily scored when operating in HFC-134a (Figure 4.16(e)) as compared to that operating in CFC-12 (Figure 4.16(f)).

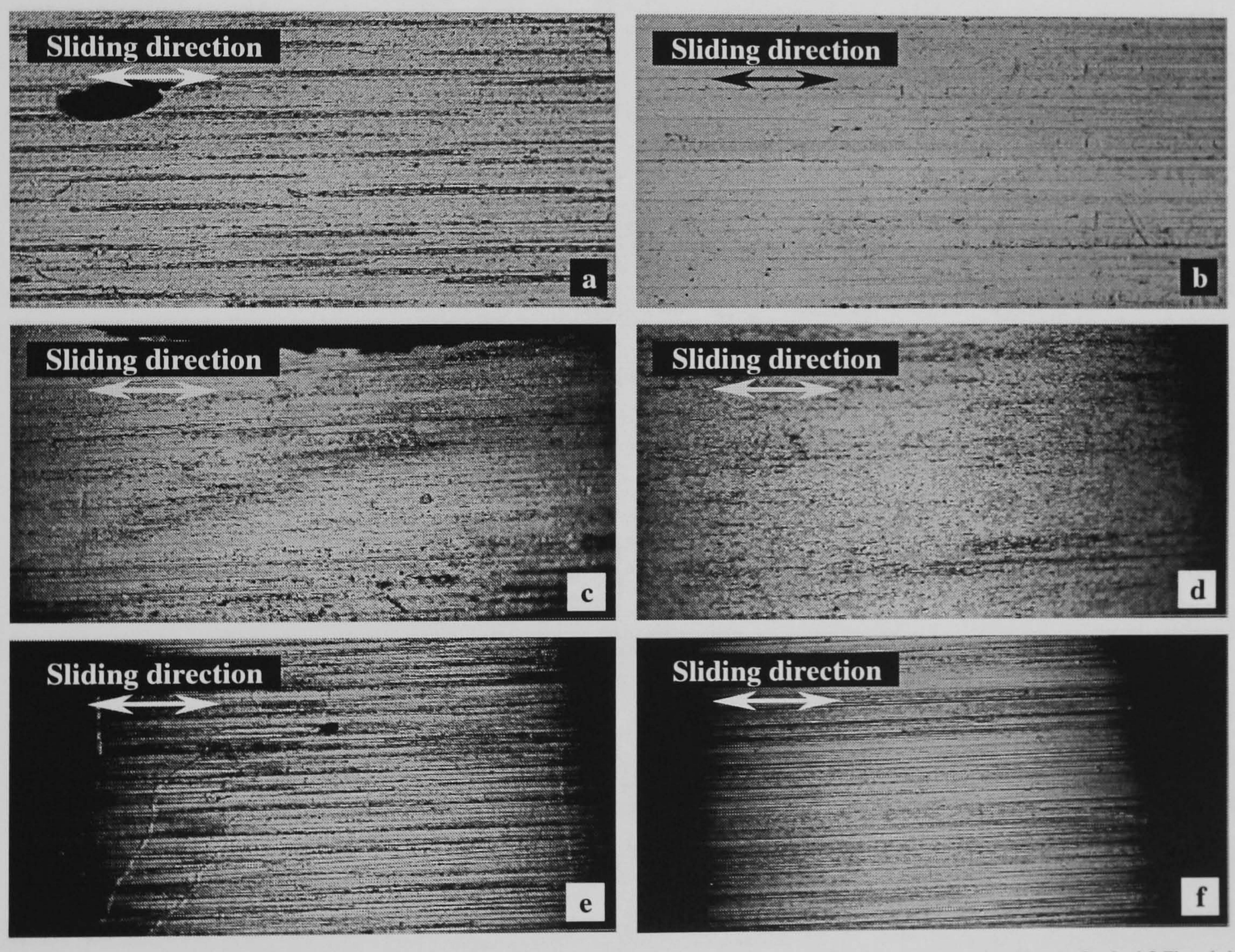


Figure 4.16. Connecting rod; (a) location 1, Test 1 (x105), (b) location 1, Test 3 (x105), (c) location 2, Test 1 (x52.5), (d) location 2, Test 3 (x52.5), (e) location 5, Test 1 (x52.5) and (f) location 5, Test 3 (x52.5)

SEM microscopy did not reveal further insight into the mechanisms or severity of wear on the samples obtained for the HFC-134a (Test 1) and CFC-12 (Test 3) tests. For this reason and for reasons of space no SEM micro-graphs were included here.

Test 2 and Test 4

Both of these tests are identical to Test 1 and Test 3 but this time a different type of compressor was used. At the outset, some interesting observations were made using optical microscopy. Firstly, the transition between the machined end and the contacting end on a pin of a Type B compressor is not as evident as that obtained from a Type A compressor (compare Figure 4.17 to Figure 4.15). This may be due to the larger area of contact at the interface between the pin and rod (Figure 3.3) resulting in lower contact pressures. Secondly, in Figure 4.17, the scoring marks observed on the contacting end are inclined towards the left, unlike as observed for the pin of a Type A compressor. An explanation for this could not be obtained throughout this research work but it may be said that this compressor characteristic did not seem to have any influence on the wear observations made here.

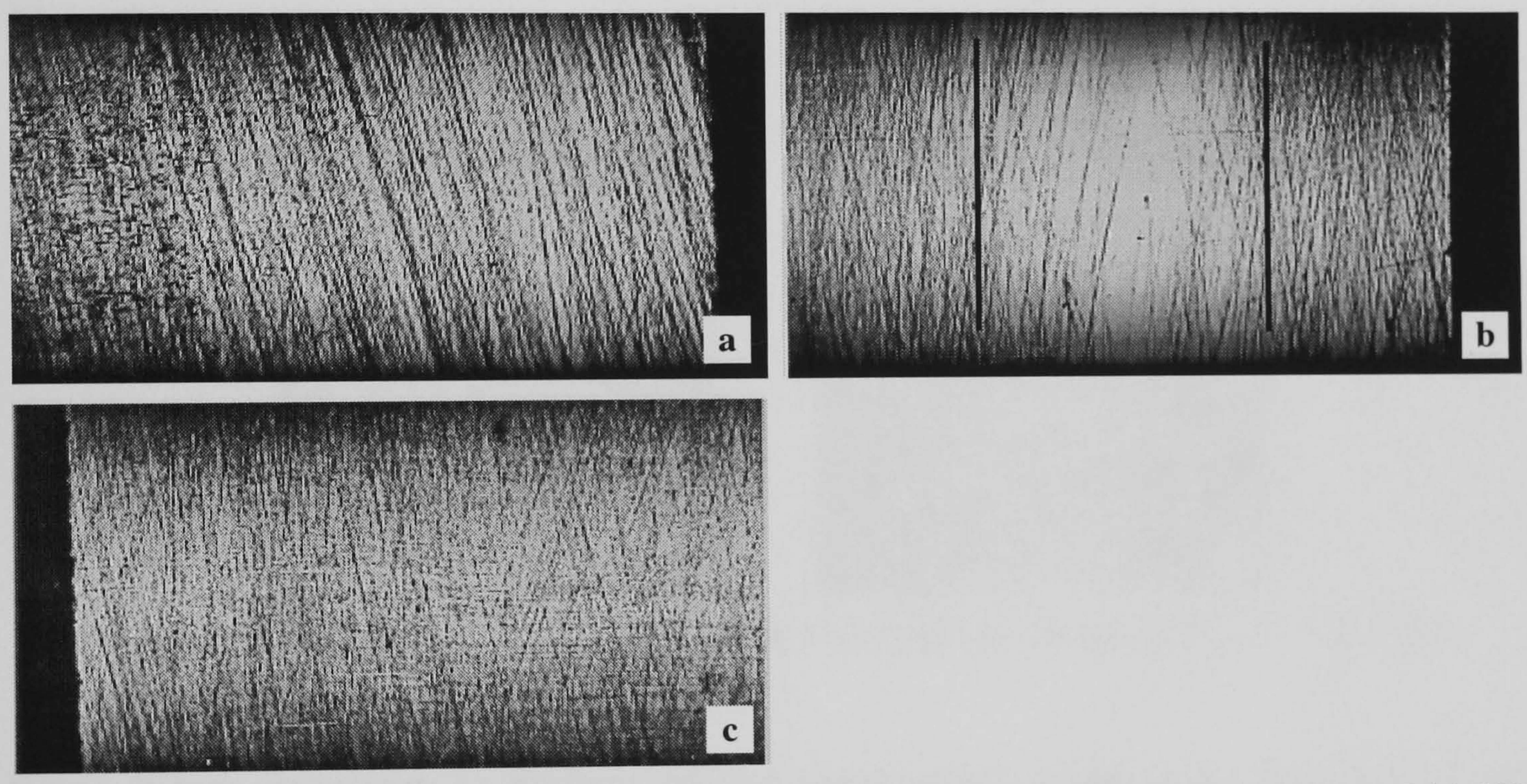


Figure 4.17. Gudgeon pin; (a) load face, Test 2 (x52.5), (b) load face, Test 4 (x52.5), and (c) 90° to load face, Test 2 (x52.5)

Another interesting observation made from Figure 4.17 is that at first glance the pin operating in an HFC-134a environment seemed to be less worn than that operating in a CFC-12 environment, with the latter forming mirror-like regions. This may be said when comparing Figure 4.17(a) to (b) respectively and implies a contradiction to what was noted in Figure 4.15. However, by comparing the surface textures shown in Figure 4.17(c) and Figure 4.17(a) a significant increase in wear tracks may be noted. This is because Figure 4.17(c) is a micro-graph of the side of the pin on which it has already been established that little wear occurred. Hence, Figure 4.17(c) is similar to the machined texture and therefore the scoring marks shown in Figure 4.17(a) are indeed wear tracks. In this instance, no mirror-like regions have formed but the wear was in the form of deep abrasive tracks into the harder material. Another point to be emphasised here is that the region between the hairlines in Figure 4.17(b) indicates non-uniform contact, with the area to the right of the slide not bearing any load. This could have resulted in significant wear in the enclosed region.

Observations on the connecting rod did not back up the findings outlined in the preceding paragraph. Figure 4.18 indicates that the wear on the sample operating in an HFC-134a environment is similar to that obtained from a CFC environment. No other noticeable characteristics were obtained on any location around the connecting rod.

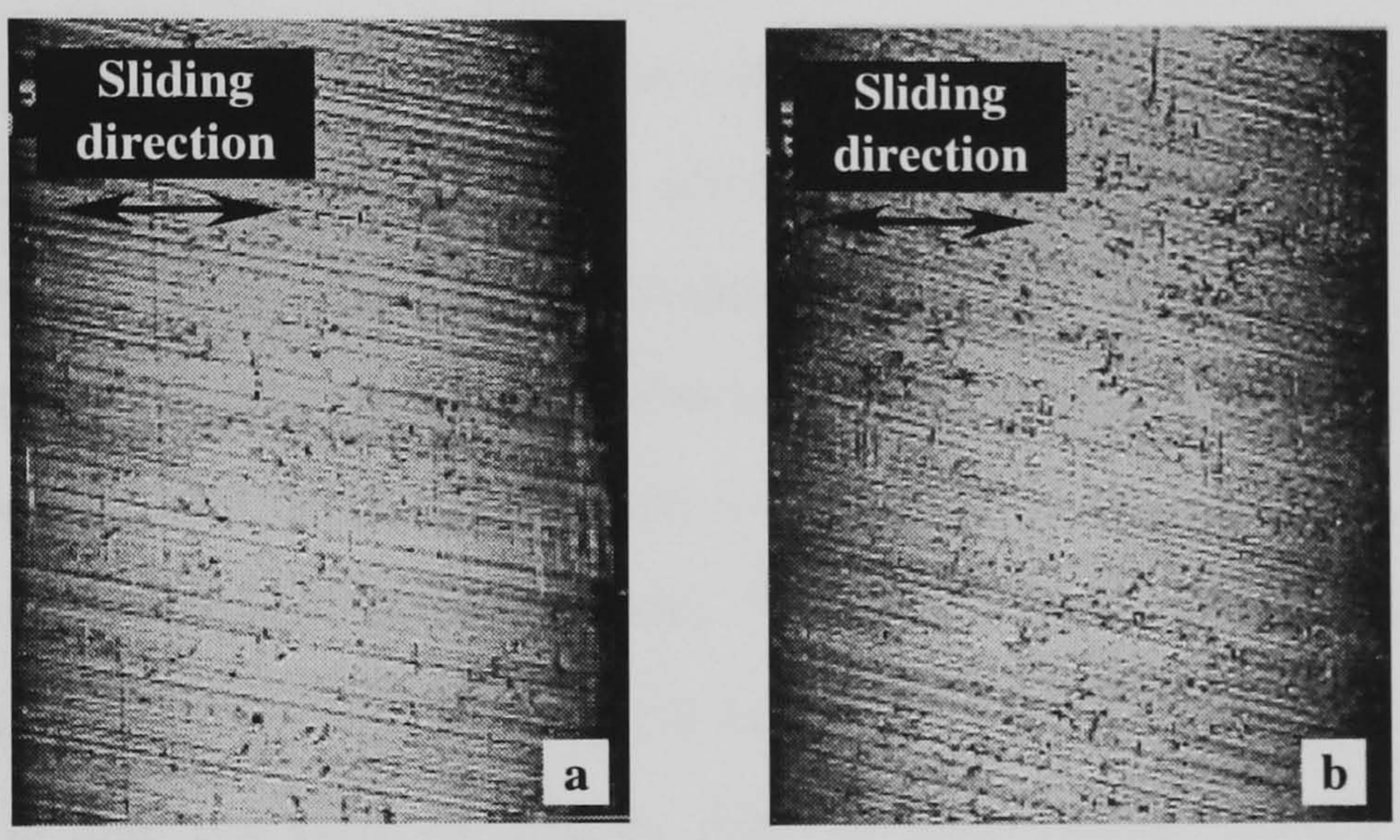


Figure 4.18. Connecting rod; (a) location 2, Test 2 (x52.5), (b) location 2, Test 4 (x52.5)

Since it was necessary to understand the observations made from Figure 4.17, an SEM analysis on an unused pin was carried out as shown in Figure 4.19(a). When comparing the pin from an HFC-134a environment (Figure 4.19(b)) and a pin from a CFC-12 environment (Figure 4.19(c)) to Figure 4.19(a) it may be said that in both instances the pin is showing signs of wear. It is uncertain as to which of the two is in the most advanced state but observations from Figure 4.17(a) and magnified in Figure 4.19(b) clearly show severe wear tracks. It seemed possible that both surfaces were worn to the smooth mirror-like regions previously observed. After continued rubbing, the pin from the HFC test was further worn resulting in the wear tracks shown in Figure 4.19(b) whilst the pin from the CFC test seemed not to be further

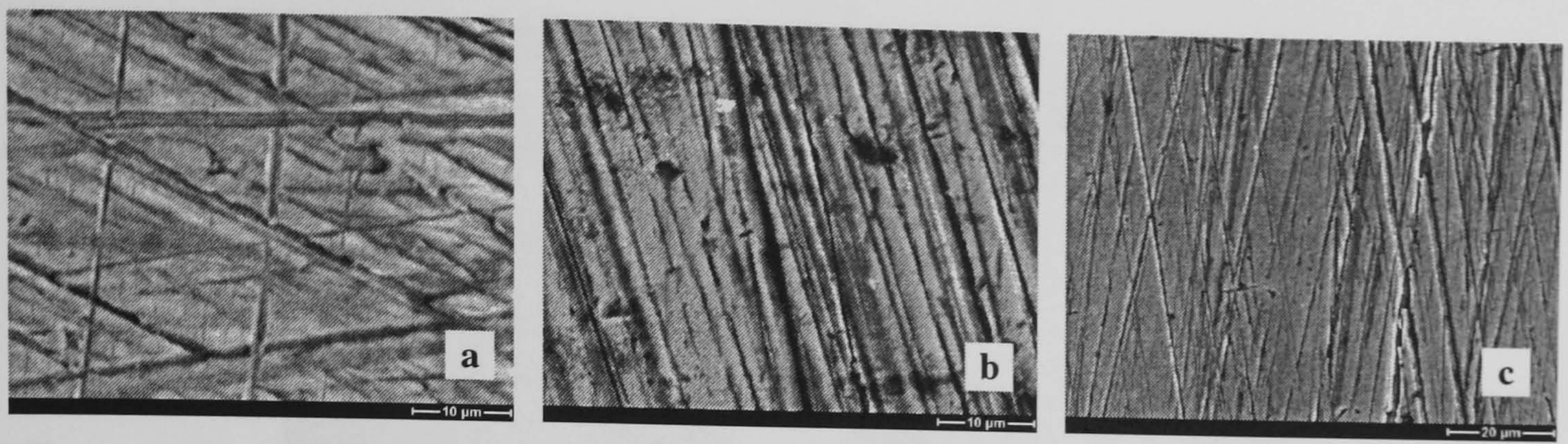


Figure 4.19. Gudgeon pin; (a) load face unused, (b) load face, Test 2 and (c) load face, Test 4

affected (Figure 4.19(c)). The difference in magnification of Figure 4.19(b) and Figure 4.19(c) should be emphasised here.

<u>*Test 5 and Test 6*</u>

During this stage of the investigation an understanding of the wear characteristics for the two types of working fluids operating under a lower bulk oil temperature was sought. Light microscopy on the load face of the two pins (Figure 4.20) revealed that a more severe interaction resulted on the sample working in a CFC-12 environment, with the consequent greater smoothing observed (Figure 4.20(b)). No other distinct observations were made on different regions of the pin. A closer investigation of Figure 4.20 and other micro-graphs, which have not been included for reasons of space, revealed that the wear mechanism here could be more complex. Comparing the extreme left of Figure 4.20(a) with the remainder of the pin, that is the machined surface texture to the contacting surface texture, different surface patterns are clearly evident. This is also the case for Figure 4.20(b) although in this case the extent of surface smoothing seemed to conceal evidence. As done for Test 2 and Test 4, higher magnification using SEM was required to characterise these observations further.

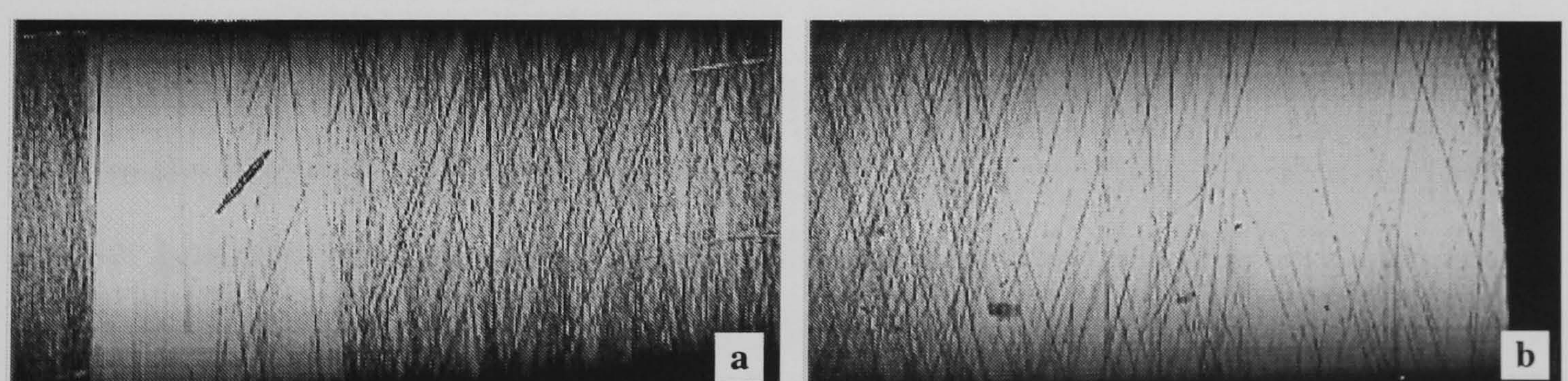


Figure 4.20. Gudgeon pin; (a) load face, Test 5 (x52.5) and (b) load face, Test 6 (x52.5)

Light microscopy analysis on the connecting rod did not reveal any distinctive characteristics between the HFC/synthetic oil and the CFC/mineral oil combinations. This may be seen in Figure 4.21 for location 2 (Figure 4.14), which is the load face of the small end of the connecting rod.

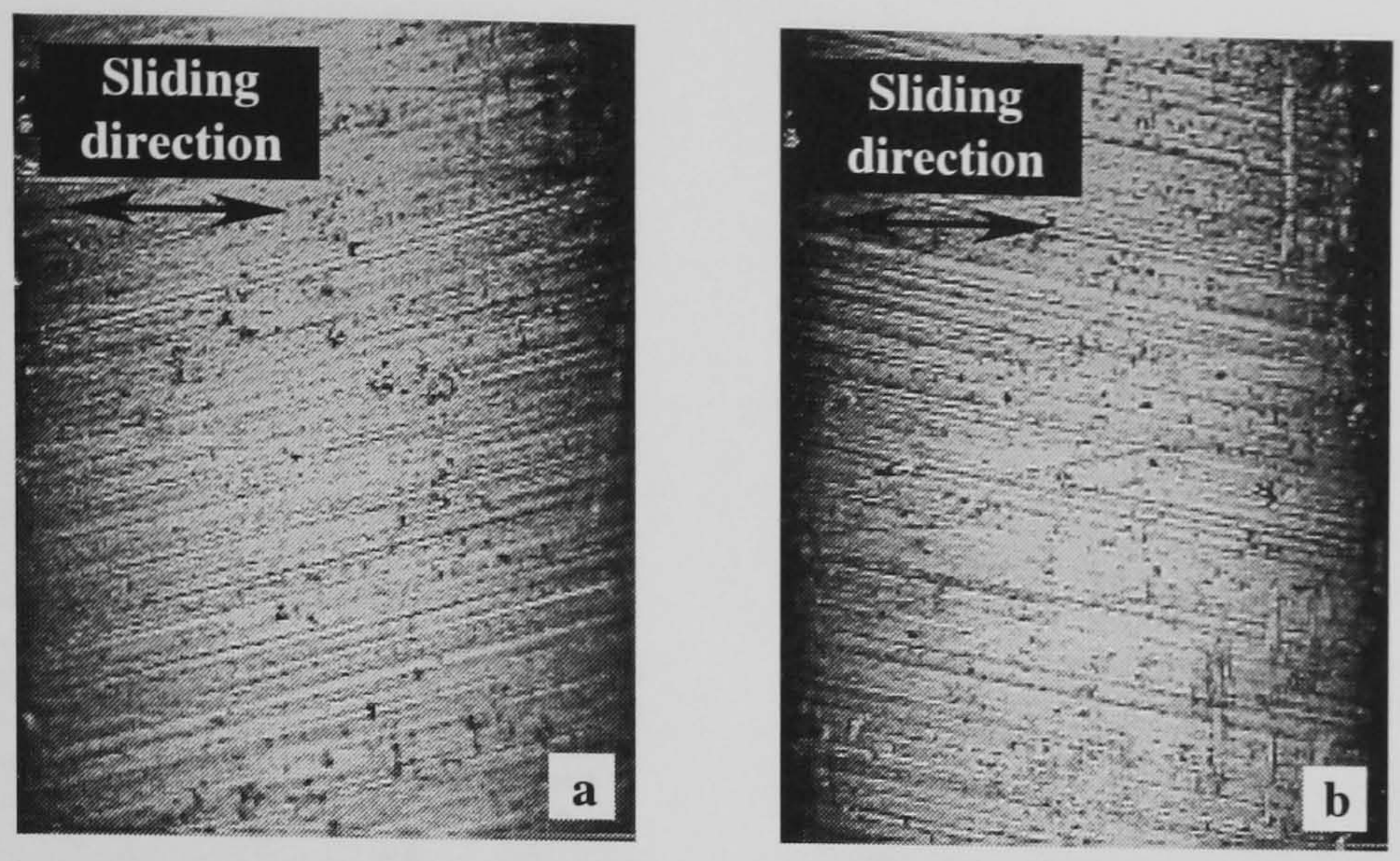


Figure 4.21. Connecting rod; (a) location 2, Test 5 (x52.5), (b) location 2, Test 6 (x52.5)

As already mentioned, to emphasise observations made from Figure 4.20, SEM micro-graphs (Figure 4.22 and Figure 4.23) were used to evaluate the interactions occurring between the pin and the rod. Figure 4.22 shows different locations over the load face of the pins obtained from Test 5 and Test 6. From these slides it is evident that the grooves observed in Figure 4.20 were indeed wear tracks and the distinction from that obtained for the CFC-12 test is also clear. This may be said when comparing the deep wear tracks observed in Figure 4.22(a) and (b) to the unused texture shown in Figure 4.19(a). As for the samples obtained from Test 6 (Figure 4.22(c) and (d)), it is evident that finishing grooves and scratches have been levelled due to the sliding motion, forming small and smooth load bearing surfaces. This too is evidence of wear but that observed in Figure 4.22(a) and (b) is likely to be more advanced as already explained for Test 2 and Test 4.

Observations made on the connecting rod using SEM (Figure 4.23) indicate that, despite the higher magnification in Figure 4.23(a), it is just possible to make out that coarser grooves have developed on the aluminium sample obtained from Test 5. This was indicative throughout this part of the investigation and generally the overall damage of the sample obtained from the HFC-134a experiment was slightly more pronounced than that from the CFC-12 test.

One final microscopy observation made throughout many of these six tests was that steel particles, resulting from debris from the pin or indeed from manufacturing operations, were transferred and embedded into the soft aluminium material. The last

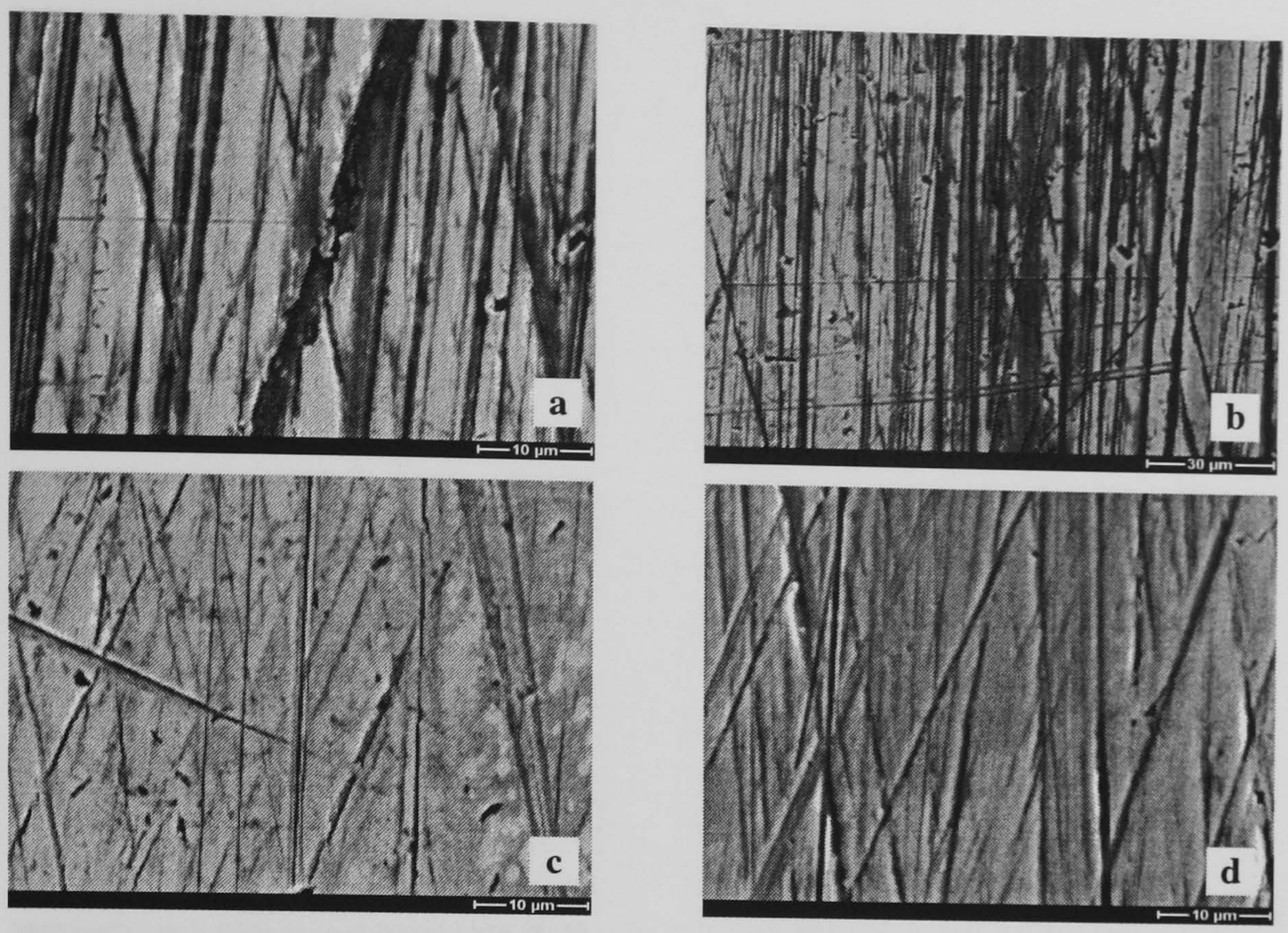


Figure 4.22. Gudgeon pin; (a) and (b) load face, Test 5 while (c) and (d) load face, Test 6

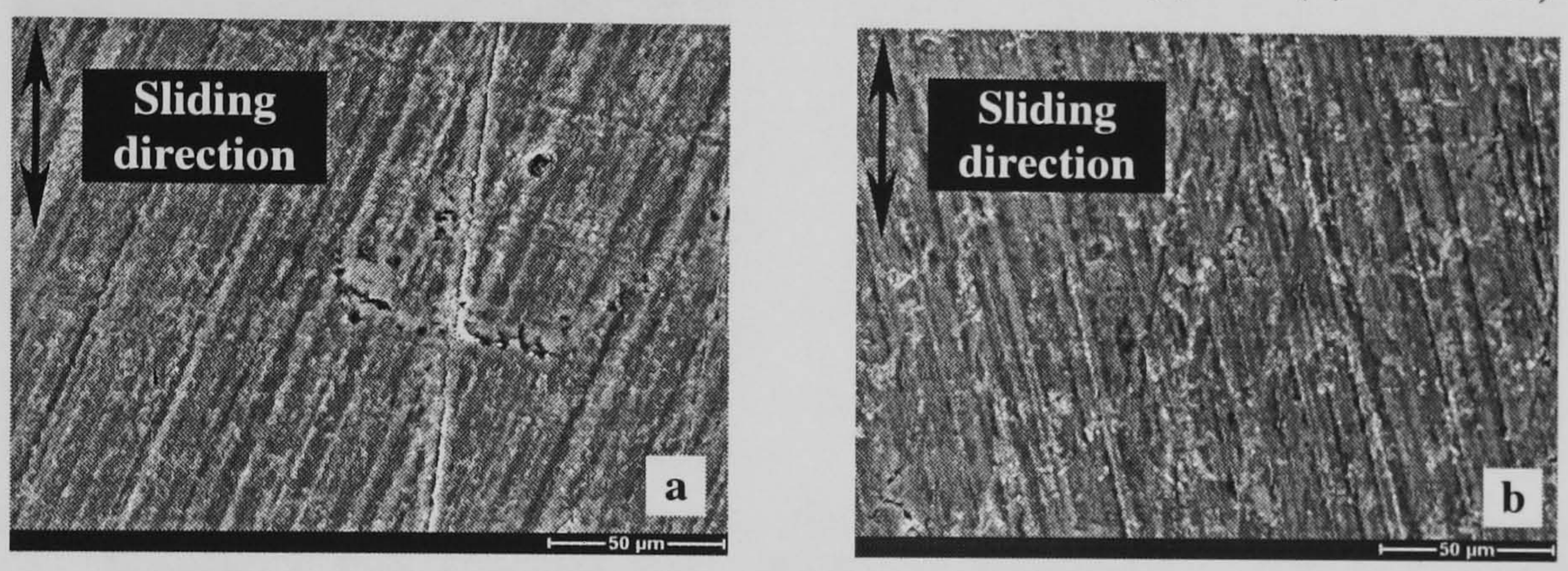


Figure 4.23. Connecting rod; (a) location 2, Test 5 and (b) location 2, Test 6

two experiments showed more evidence of this. As explained in (Engel and Klingele 1981) and noted in Section 4.2.2, this wear mechanism results in machining on a micro-scale with the embedded particle cutting into the steel surface, another form of wear by the process of *abrasion* (Rabinowicz 1965). It must be emphasised that, although less wear was generally observed with the CFC-12 experiment, this latter form of abrasive wear was still evident for these samples indicating that severe wear was difficult to prevent in both instances. The evidence from this observation (Figure 4.24) implies that material transfer does not only occur from the soft to the hard material, as depicted in Figure 4.3, but also viceversa.

From Figure 4.24, although only one EDX profile was included, the difference in micro-structure between the embedded particles and the base material is evident. Both the EDX as well as this difference in micro-structure indicate the presence of iron and the extent of surface damage caused. Figure 4.24(c) indicates how sharp

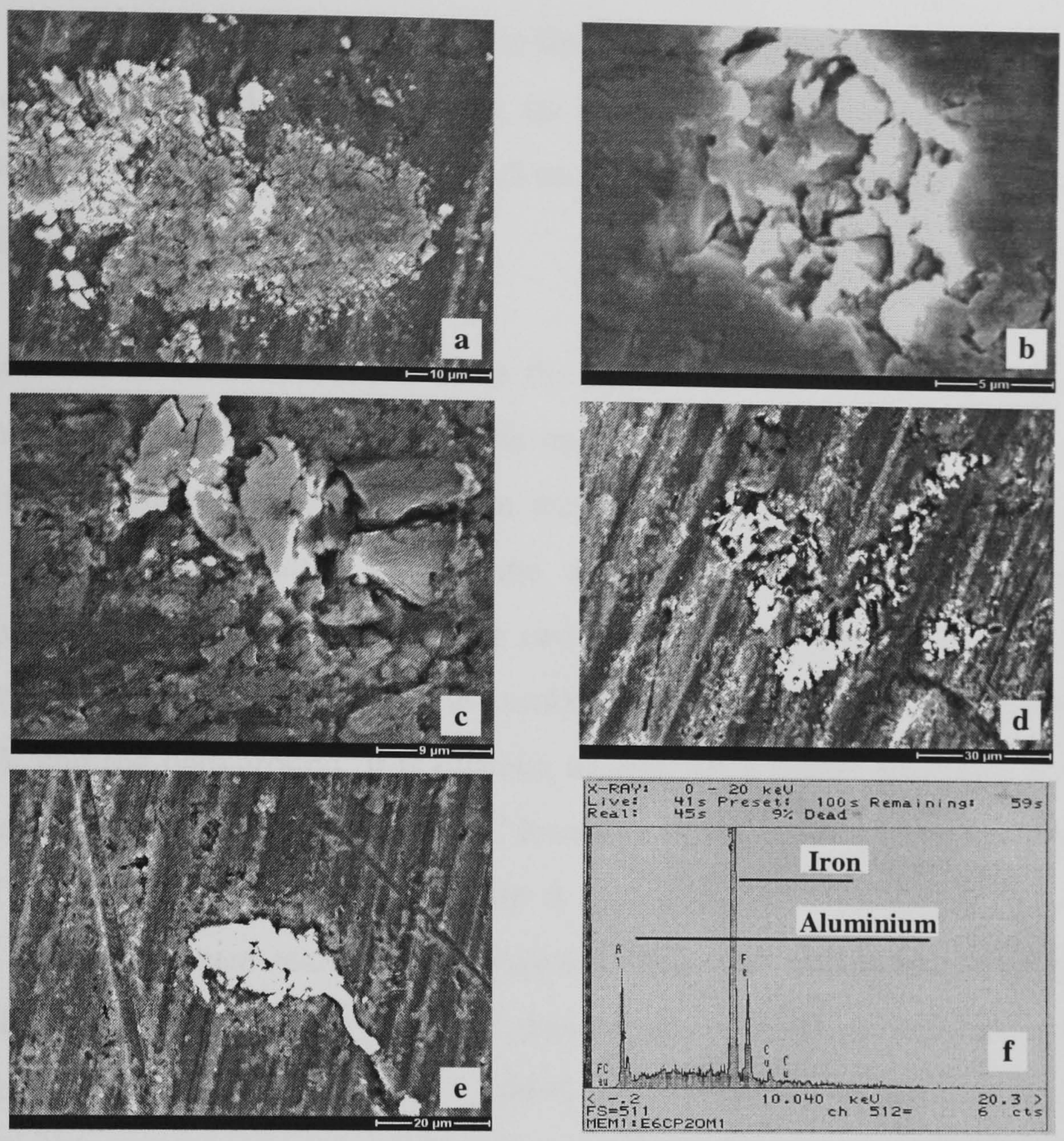


Figure 4.24. Steel particles transferred onto the connecting rod; (a) location 2, Test 2, (b) location 2, Test 3, (c) location 2, Test 4, (d) location 2, Test 5, (e) location 2, Test 6 and (f) EDX of embedded particle in (e)

some of these transferred particles may be and also indicates, together with Figure 4.24(d) and (e), that as these particles machine into the steel surface they become plastically deformed and smoothed out due to the sliding motion. Figure 4.24(b) is particularly interesting because its corresponding EDX (not shown) identifies that the particles within the pit are iron. The possibility of this is that a steel particle, which was embedded into the aluminium, broke off with the consequent formation of a pit and resulting debris. Finally, Figure 4.24(e) is evidence that incipient melting (Engel and Klingele 1981) of the iron resulted due to the high heat of friction which occurs between identical metals (Section 4.2.1).

The final analysis carried out for the tests listed in Table 4.4 was to identify any adsorbed compounds on the aluminium or the steel samples resulting from either the HFC-134a or the CFC-12 refrigerants or the respective lubricants. Due to the difference in porosity between the aluminium and steel (Higgins 1993), both sample batches were analysed using XPS. Due to their lubricating properties (Section 1.5.3), any chlorides identified on the samples for the CFC-12 experiments would be one explanation of the reduced wear observed on these samples compared with their HFC counterparts.

Chloride films were neither detected on the pin nor on the connecting rod samples operating in a CFC-12 environment. The only principal difference occurring on the aluminium samples but not on the pin was that, for the CFC-12 experiments, a slightly higher concentration of fluorine was identified at a binding energy of approximately 685eV, for either of the two types of machines. This may be seen from Figure 4.25 when comparing the number of counts (ordinate) between the peak at 685eV and the background. It is difficult to interpret a higher presence of fluorine on the samples obtained from the CFC tests alone since this element is present in both of the two refrigerants. In passing it should be mentioned that the fluorine content tends to reduce toxicity in refrigerants (Clayton 1967) but also influences flammability and atmospheric lifetimes depending on which element (hydrogen or chlorine) it displaces (McLinden and Didion 1987; Dekleva 1994; Smith and Tufts 1994). Furthermore, it is rather difficult to establish a relation between the presence of fluorine and a reduction in friction and wear. This is because, whilst some research has credited fluorine with the ability to prevent wear (Yamamoto, et al. 2000), other published works have shown that the fluorine does not participate in the lubrication film formation (Komatsuzaki, et al. 1987) and therefore offers little boundary protection to aluminium (Tseregounis 1996; Yoon, et al. 1998). These observations seemed crucial to the overall thesis and Section 6.1 will attempt to discuss why a higher presence of fluorine could be detected on the samples obtained from the CFC tests and how these films may have influenced tribological and electrical power characteristics. Other than this fluoride layer, no more significant observations were made during the course of this part of the investigation and therefore, for reasons of space, no other XPS profiles were included here.

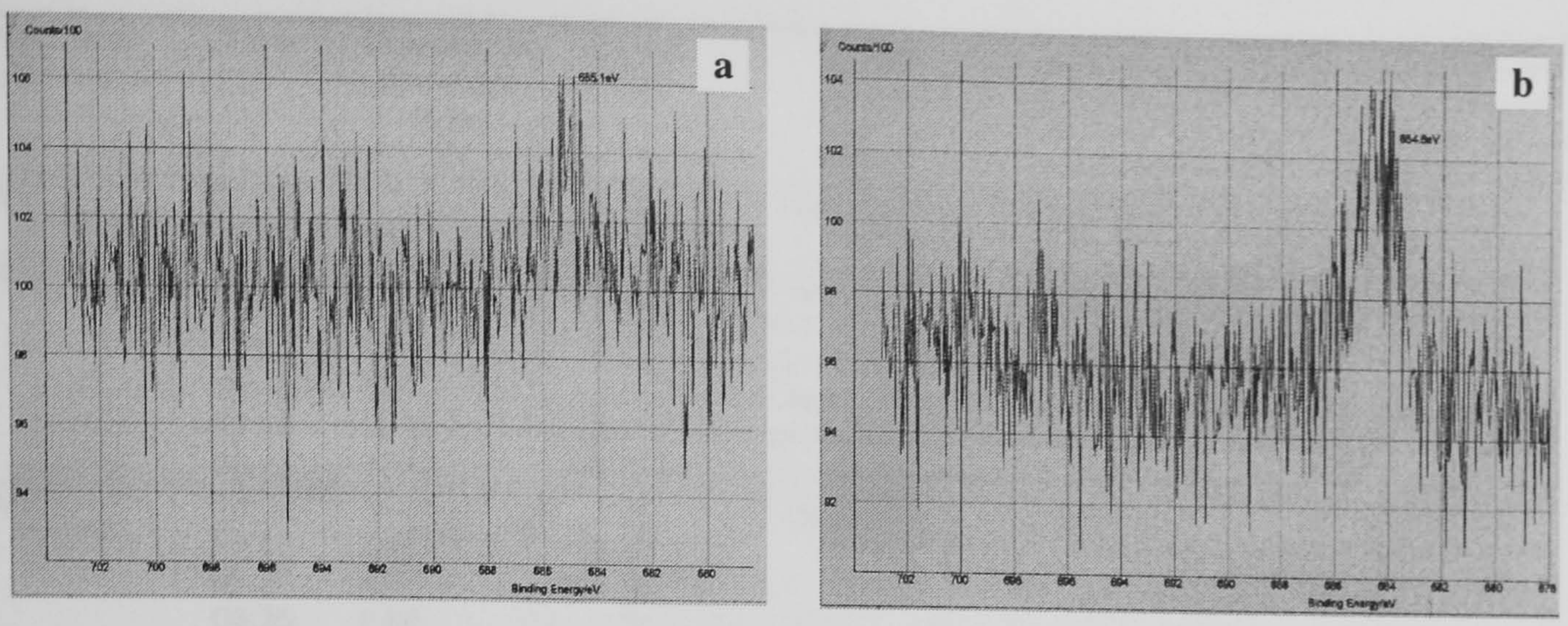


Figure 4.25. XPS on the connecting rod at a binding energy ranging from (680 - 700)eV; (a) location 5, Test 5 and (b) location 5, Test 6

4.3 The in-use power of the compressor

4.3.1 Influence of rig characteristics on the in-use power

Data for the 500 hour and the 1000 hour tests had to be sampled and averaged to obtain plots of rig characteristics for a 500 hour period, which was appropriate for comparison between tests of different duration. For both the continuous tests and the start/stop tests the first hour of compressor operation was discarded to ensure that the rig conditions had stabilised. As shown in Table 2.8, for the 500 hour experiments the data acquisition software recorded an average for the five readings taken every hour of operation. Hence, at the end of the 500 hour experiments, it was these average values that were plotted.

For the 1000 hour tests, due to their start/stop condition, manual data sampling and averaging was required. As detailed in Table 2.8, an average for the five readings taken over a period of 5 minutes was recorded. When selecting the data to be plotted the characteristics of the idle periods of the compressor had to be ignored and the bases for selection was done on the condenser pressure and power (Table 4.6).

When the value of power (Table 4.6) was around 300W this indicated that the compressor was in operation. Values similar to those recorded at time 07:50 and 08:20 (Table 4.6) were ignored because these averages included values of when the compressor was idle and operating. If many of the five readings to be averaged by the data acquisition software (Section 2.3.4) were recorded when the compressor was

Status of compressor	Time	Condenser pressure (bar)	Power (W)	Selection criteria	Condenser pressure Average 30 mins	Condenser pressure Average 60 mins
OFF	07:40	3	1.86	All readings always discarded.		
	07:45	3.1	2.19			
ON	07:50	6.79	178.39	If first condenser pressure reading is		
	07:55	10.6	300.53	less than 8 bar than it is discarded and		
	08:00	11.54	302.03	an average of the remaining values		
	08:05	12.12	304.99	obtained. The first reading is low as it		
	08:10	12.52	307.6	is an average that includes values of		
	08:15	12.88	312.39	when the compressor is off.	11.932	
OFF	08:20	10.26	189	All readings always discarded.		
	08:25	2.62	2.12			
	08:30	2.76	1.52			
	08:35	2.86	1.57			
	08:40	2.95	1.84			
	08:45	3.05	1.95			
ON	08:50	6.74	177.11	If first condenser pressure reading is		
	08:55	10.59	296.42	less than 8 bar than it is discarded and		
	09:00	11.56	301.27	an average of the remaining values		
	09:05	12.12	302.48	obtained. The first reading is low as it		
	09:10	12.52	307.64	is an average that includes values of		
	09:15	12.88	313.97	when the compressor is off.	11.934	11.93
OFF	09:20	11.02	190.91	All readings always discarded		
	09:25	2.68	1.74			

Table 4.6. Sample of recorded data for condenser pressure and power (Test 6) showing data sampling and averaging for condenser pressure

idle then the resulting value (condenser pressure in Table 4.6) would be too low and this would negatively influence the results. However, if the value at 07:50 was greater than 8 bar (arbitrarily chosen) then this was included in the analysis. In this way, values for all the rig parameters to be plotted against a 500 hour duration were sampled and for every two hours of experimental time an average for one hour of compressor operation was obtained (Table 4.6).

Finally, two important aspects related to Table 4.6 are worth mentioning here. Firstly, values of power when the compressor was turned off are not zero. The reasons for this being the error that the power transducer (Section 2.3.2) measured at low load and the power drawn off by the mechanical timer and the hour meter (Section 2.6.2). Secondly, the high power drawn by the electric motor at start-up was overlooked despite all the necessary precautions taken (Section 2.3.4). This was because it could not always be ascertained that the mechanical timer turned on the compressor at exactly the same time (Section 2.6.2). Hence start-up values were merged with different idle readings so that the average recorded value varied significantly. The power drawn at start-up was observed to be four times that obtained during normal operation. It should be mentioned that there seemed to be no reason as to why any rate of change in the power requirements obtained during compressor operation and which are of interest to this study (Section 3.7.3) would be influenced by the omission of this data.

All test rig parameters were plotted against the experiment duration and compared with the power characteristics. One typical curve showing power and condenser pressure plotted against time for Test 1 is shown in Figure 4.26. The remaining curves for Test 1 to Test 8 (Table 4.4) are given in Appendix H. Following are some observations made for each individual test from the plots in Appendix H.

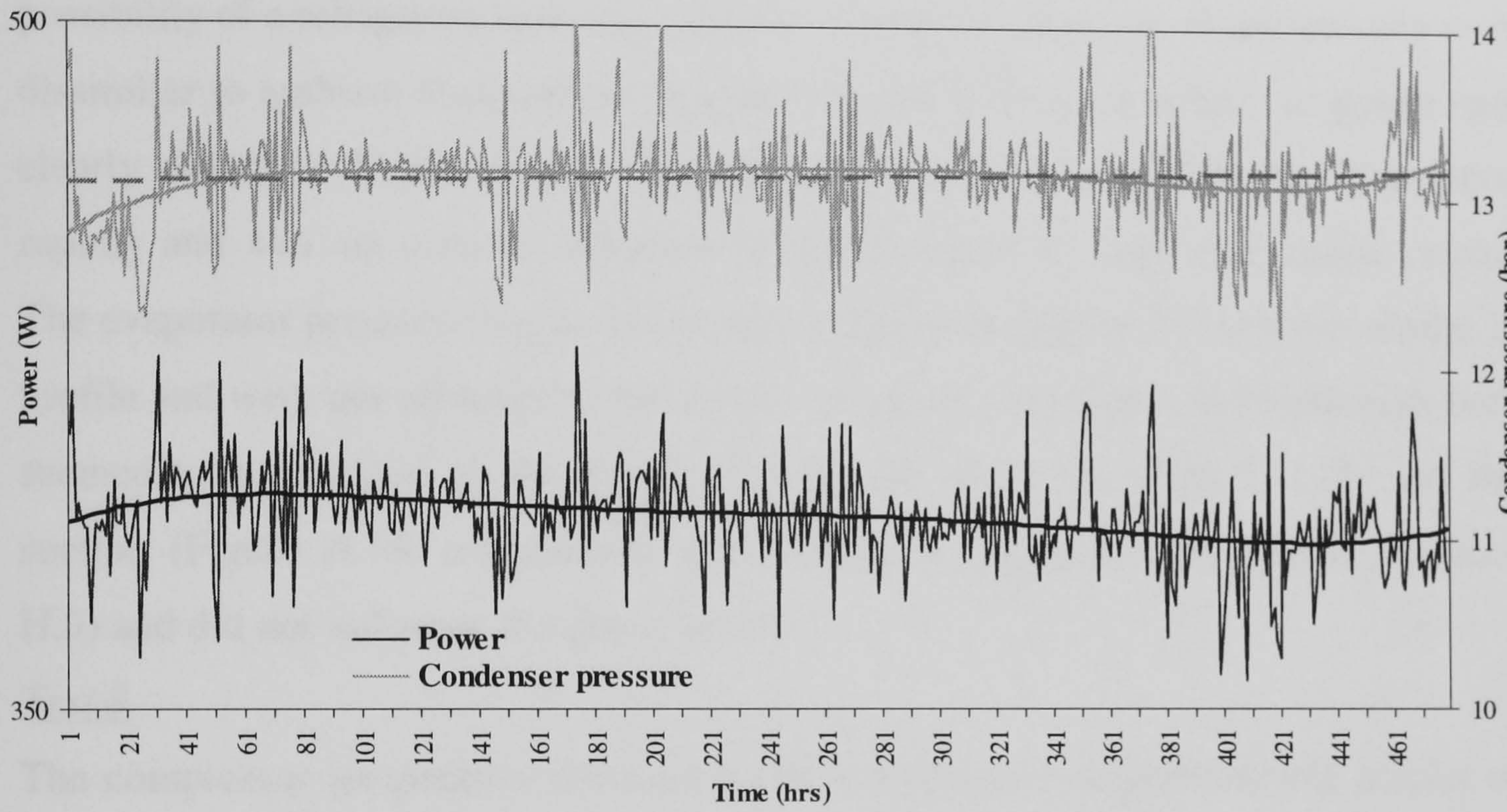


Figure 4.26. Test 1 – Power (W) / Condenser pressure (bar) with Time (hrs)

<u>*Test 1*</u>

The ambient characteristics (Figure H.1) influenced the compressor case temperature (Figure H.2) but it was not clear what influence these latter characteristics had on the electrical power. From the condenser pressure characteristics (Figure H.3) it was evident that as this fluctuated over the experiment duration the power followed its profile. The curves diverged as the power dropped, but not due a refrigerant leak since the condenser pressure was maintained at a fairly constant rate, as shown by the dotted line in Figure H.3 (or indeed in Figure 4.26). The condenser temperature (Figure H.4), which dropped significantly, did not seem to influence the power consumption and was unaffected by the ambient temperature (Figure H.1). Both the evaporator pressure (Figure H.5) and temperature (Figure H.6) fell and both were unaffected by the ambient temperature (Figure H.1). It was not clear whether the evaporator temperature curve was the inverse of the power characteristics but there seemed to be no relation between power and evaporator pressure. Finally, both the discharge (Figure H.7) and suction temperatures (Figure H.8) showed no correlation with the power consumption and were both influenced by ambient conditions.

Test 2

The ambient temperature (Figure H.9) and also the compressor sump temperature (Figure H.10) varied significantly as well as identically. Both these profiles did not seem to influence the power trend. As for Test 1, the condenser pressure (Figure H.11) remained fairly constant throughout the 500 hour duration and therefore the possibility of a refrigerant leak was minimal. Condenser pressure characteristics were dissimilar to ambient temperature (Figure H.9) but were quite similar to power (not clearly evident in Figure H.11). The condenser temperature (Figure H.12) dropped rapidly and was not seen to influence or be influenced by any other characteristic. The evaporator pressure (Figure H.13) and temperature (Figure H.14) were similar in profile and were not affected by the ambient temperature (Figure H.9) although both seemed to be mapped by the power. Finally, the discharge (Figure H.15) and the suction (Figure H.16) temperature were similar to ambient characteristics (Figure H.9) and did not influence the power trend.

Test 3

The compressor temperature fluctuated with the ambient temperature but neither of these characteristics influenced the power significantly ((Figure H.17 and Figure H.18). The condenser pressure characteristics (Figure H.19), which again gave no hint of a refrigerant leak, did not influence the power and nor did the condenser temperature, which fell rapidly with time (Figure H.20). Throughout the duration of this test it was seen that both the evaporator pressure (Figure H.21) and its temperature (Figure H.22) influenced the power with each curve having similar contours and each falling over the test duration. As noted in the previous tests, the ambient temperature (Figure H.17) influenced both the discharge (Figure H.23) and the suction (Figure H.24) temperature but none seemed to influence the power trend.

Test 4

Throughout this test the ambient temperature (Figure H.25) varied significantly and this influenced the sump temperature of the compressor (Figure H.26). Both these characteristics seemed to influence the power profile. The pressure in the condenser (Figure H.27) also seemed to influence the power unlike the condenser temperature

(Figure H.28). Both of these condenser characteristics dropped significantly over time. Based on the explanations for the previous tests, this drop in condenser pressure may imply a loss of refrigerant charge with the consequent reduction in the power consumption (Section 3.2.2). It must be emphasised that this test, like all other experiments, was regularly leak tested using an electronic detector and no evidence of a loss of refrigerant was detected. It must also be emphasised that during this test, unlike in Test 1 to Test 3, the ambient temperature (Figure H.25) influenced the condenser pressure significantly. A possible explanation for this was not possible throughout this research but this could have influenced this drop in condenser pressure. The evaporator pressure (Figure H.29) and temperature (Figure H.30) both varied with ambient temperature (Figure H.25) but it was only the pressure that seemed to influence the power as it dropped over the test duration. Finally, both the discharge temperature (Figure H.31) and the suction temperature (Figure H.32) varied with ambient conditions but again it was only the former that seemed to influence the power.

Test 5

Throughout this test the ambient temperature (Figure H.33) varied significantly. However, although both the compressor temperature (Figure H.34) and the power varied with time they did not follow the ambient characteristics rigidly. As a matter of fact, the power seemed to be the inverse of this ambient temperature. A strong relationship between the condenser pressure (Figure H.35) and the power was observed here. Note, the condenser pressure climbed with time (as did the power), as indicated by the dotted line. Unlike as observed for Test 4, the fluctuating ambient temperature (Figure H.33) did not cause a drop in the condenser pressure and there seemed to be little relationship between the two. However, a possible explanation for the rise in condenser pressure could be the steady increase in ambient temperature after a time of 280 hours. This could have maintained a positive rate of change of condenser pressure with time. This increase in temperature was not experienced throughout Test 4. The condenser temperature (Figure H.36), just like the pressure, was not influenced by the ambient temperature (Figure H.33). Furthermore, the power did not seem to be influenced by the drop in condenser temperature over the experiment duration. Both the evaporator pressure (Figure H.37) and temperature (Figure H.38) followed ambient conditions (Figure H.33) and the two seemed to be the reverse of the power profile. Unlike the discharge temperature (Figure H.39), the suction temperature (Figure H.40) followed ambient conditions rigidly and neither of the two seemed to influence the power characteristics.

Test 6

The ambient conditions (Figure H.41) influenced the compressor sump temperature (Figure H.42) but neither of the two seemed to affect the power characteristics. The condenser pressure (Figure H.43) varied with the ambient temperature (Figure H.41), as did its temperature (Figure H.44). A drop in condenser pressure and a significant drop in condenser temperature are noted over the experiment duration. As for Test 4, fluctuations in the ambient temperature seemed to influence the drop in condenser pressure (interestingly, in both instances, the refrigerant was CFC-12). Again, a justification for this must be found because leak detection did not identify any loss of refrigerant. One possible explanation could stem from the fact that prior to 300 hours (that is, 600 hours of experiment duration due to an interrupted test) condenser pressure conditions remained fairly constant. The drop in ambient temperature around 440 hours (Figure H.41) then seemed to push the profile downwards giving an overall impression of a loss in condensing pressure. The power curve followed the condenser pressure curve quite strictly but not that of the condenser temperature. Furthermore, both the evaporator pressure (Figure H.45) and temperature (Figure H.46) fell over the test duration and both seemed to be influenced by ambient conditions (Figure H.41). Neither of these characteristics seemed to influence the power profile. Finally, as in Test 4, the ambient temperature (Figure H.41) influenced both the discharge (Figure H.47) and the suction (Figure H.48) temperatures but only the latter was mapped by the power. Both of these characteristics dropped over the test time.

Test 7

Throughout this experiment it was evident that the ambient temperature (Figure H.49) influenced both the temperature of the compressor sump (Figure H.50) and the in-use power of the compressor. As shown by the dashed line (Figure H.51), the condenser pressure increased throughout the test duration. The increase in ambient temperature (Figure H.49) around 200 hours may have helped to maintain the condenser pressure constant over the period of time plotted. This, as in Test 5, did not raise any concern of a refrigerant leak. The profile of this pressure, as for the condenser temperature (Figure H.52), followed closely that of the power consumed. A distinct drop in condenser temperature was also observed. Similar to what was observed in the condenser, the profile for the evaporator pressure (Figure H.53) and temperature (Figure H.54) were influenced by the ambient temperature (Figure H.49) and were mapped by that of the power. Finally, the ambient temperature influenced both the discharge (Figure H.55) and the suction temperatures (Figure H.56) and both seemed to be mapped by the power.

Test 8

Ambient conditions (Figure H.57) remained fairly constant over the experiment duration although a notable temperature rise was recorded around the 300 hour mark. The compressor sump temperature (Figure H.58) seemed to follow this ambient temperature profile although variations over the 500 hour period were less evident. The power characteristics did not seem to be affected drastically by any of these minor temperature variations but dropped rapidly over time. Unlike in Test 4 or Test 6, the condenser pressure remained fairly constant as shown by the dotted line in Figure H.59. This may ascertain the fact that the changes in this pressure observed for other tests were indeed due to fluctuations in ambient conditions and not due to a refrigerant leak. Nonetheless, observations made throughout this test maintain that the power profile dropped significantly over the 500 hours plotted despite a nearly constant condenser pressure. Thus, the chances of this drop in power for CFC tests being attributed to a refrigerant leak are minimal. The condenser temperature (Figure H.60) dropped with time as did the evaporator pressure (Figure H.61) and temperature (Figure H.62) but none seemed to influence the power profile. Similarly, the discharge (Figure H.63) and suction (Figure H.64) temperatures did not seem to influence the power characteristics, with the former remaining fairly constant throughout the 500 hour duration. The latter, on the other hand, peaked with the ambient temperature (Figure H.57) around the 300 hour mark.

4.3.2 Comparing the in-use power of the compressors

Included throughout this part of the investigation are values of the coil winding temperature of the compressor (Table 4.7) and the cooling COP of the test rig. It should be mentioned that the coil winding temperature was calculated using the equation in Appendix C after reading off the winding resistance of the coil. For this

Test label	Winding temperature (°C)[a]		
	R_1[b]	ON[c]	OFF[d]
Test 1	9.2	N/A	Not recorded
Test 2	9.9	N/A	148.9[e]
Test 3	9.5	N/A	168[e]
Test 4	9.7	N/A	Not recorded
Test 5	10	46.5[f]	115[f]
Test 6	10	43.6[f]	106.7[f]
Test 7	10	50.6[f]	123.2[f]
Test 8	9.8	62.3[f]	138[f]

[a] at an ambient temperature as given in Table 4.4
[b] value measured prior to test for the coil winding temperature equation (Appendix C)
[c] measured just before the compressor turns on in the start/stop test
[d] measured just after the compressor turns off
[e] measured at end of test
[f] measured periodically during start/stop and an average obtained

Table 4.7. Compressor coil winding temperature

reason, the winding temperature could only be measured when the compressor was idle. These values were included to help study the influence these parameters may have on the overall in-use power requirements of the compressors throughout the final tests (Table 4.4) of the investigation. The coil winding temperature in Table 4.7 is an indication of the internal temperature of the hermetic compressor and the extent to which it varies between when the compressor is operating and when it is turned off (for Test 5 to Test 8). It is also evident that during start/stop conditions this coil winding temperature does not rise to the value recorded for the continuous tests (Test 1 to Test 4), this playing a significant role on the outcome of the investigation (Section 3.2.5 and Section 6.1.1).

The COP values of the test system for Test 1 to Test 8 were compared but have not been included here due to their unreliability. For these COP values, the pressure-enthalpy characteristics were plotted using the data in Table 4.4. It may be said that the refrigerant was assumed to leave the condenser as dry saturated liquid but no assumptions were made for its compression or expansion. This is shown in a typical pressure-enthalpy plot, which was obtained for Test 7, included in Appendix I.

A comparison of the actual in-use power requirement of the compressors tested in Test 1 to Test 8 would have been inconclusive due to the influence minor variations in experimental conditions have had. Section 4.3.1 indicates these variations in the monitored power, as well as other rig characteristics, experienced throughout the course of this investigation. Furthermore, some mechanical systems could not attain the required conditions with an identical refrigerant charge. This may be seen when comparing Test 5 to Test 7 (Table 4.4) in which the power consumption in the former was approximately 12% higher than that of the latter. This did not imply an ineffective compressor but that, for the same amount of refrigerant, the performance of the compressor varied. It is for these reasons that this investigation compared the rate of change (Figure 4.27) in the monitored power over a 500 hour operation for continuous or interrupted tests. A regression curve was obtained for the power profile, the gradient of which was used for comparison (Table 4.8). This gradient was incorporated in a linear relationship where the intercept was the electrical power input to the functional unit (stated to be 110W in Section 3.6.1). Using this relationship, the projected power requirement for the functional unit after the first 500 hours of operation was estimated. Due to the difficulty in understanding what the power profile would do after 500 hours, this value was then assumed to stabilise and used to calculate the overall energy consumption of the functional unit over its estimated lifespan. As explained in Section 3.6.3, this lifespan was taken to be 15 years, with the functional unit assumed to operate for 20% of its lifetime as given by Guldbrandsen, et al. (1986). The percentage difference between the energy consumption, calculated at the rated input of power, and the projected power for the lifetime of the functional unit are shown in Table 4.8. Note that in this in-use power analysis the 500 hour operation, which implies 104 days of functional unit lifetime, have not been deducted from the 15 year lifespan. This was not seen to influence the results since the 104 days are less than 2% of the total product lifetime.

4.3.3 Lubricant degradation

This part of the investigation identifies the time taken for the used and unused lubricants to fail under extreme pressure conditions as explained in the methodology in Section 3.4. The results, summarised in Table 4.9, are averaged values of the welding times since every test was repeated for compatibility (Section 3.4.2).

In Table 4.9, the unused oils were subjected to a higher load than the used ones. The unused HFC compatible lubricant sustained a load for a longer period of time

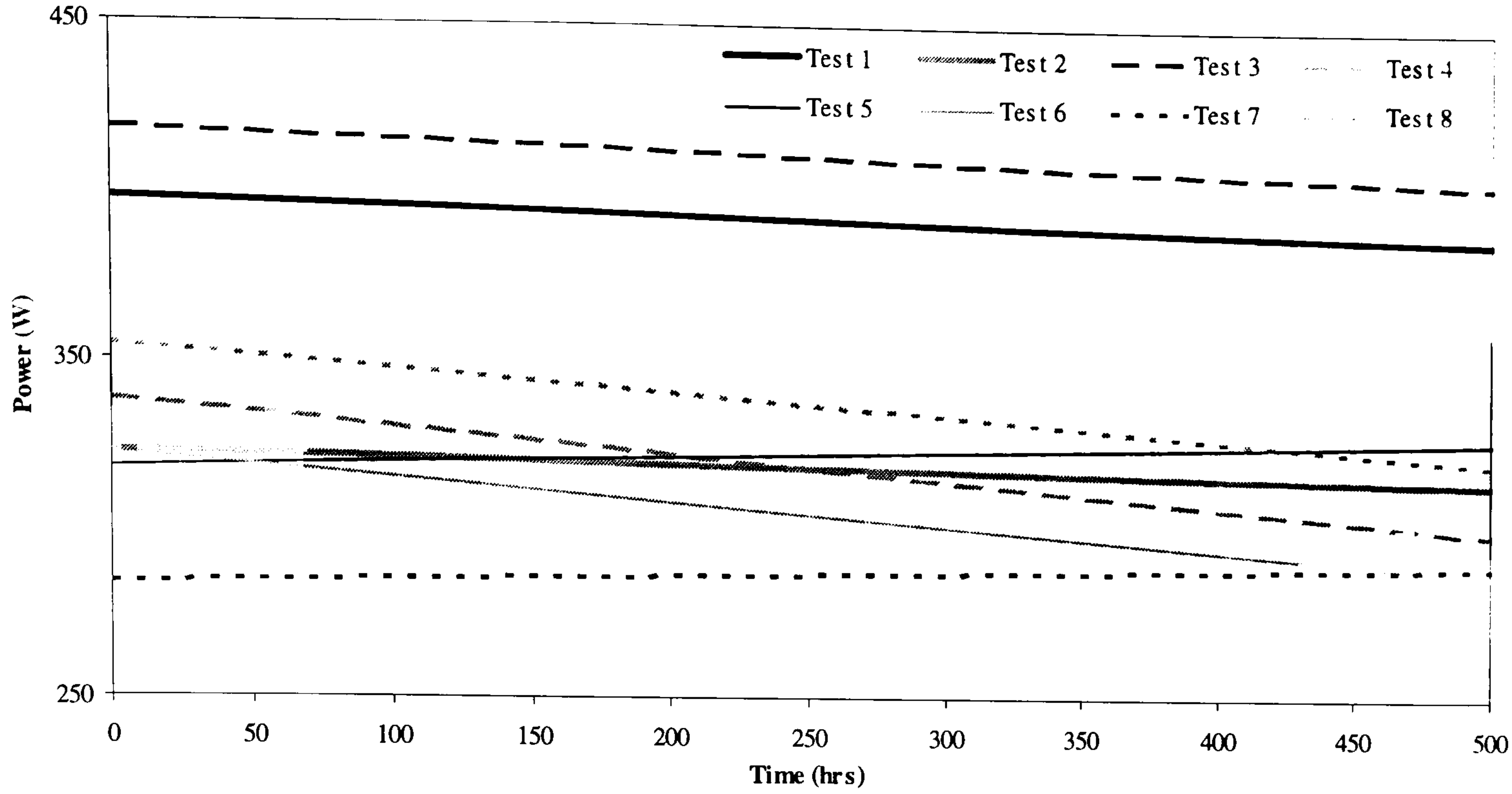


Figure 4.27. Regression analysis of monitored power (Test 1 to Test 8)

Test label	Rate of change of regression curve	Projected power (W) after 500 hours[a]	Lifetime electrical energy consumption[b] (MJ)	Percentage difference between rated and projected values
Test 1	-0.0216	99.2	9385	-9.82 (HFC; Figure H.1 to H.8)
Test 2	-0.0169	101.6	9621	-7.55 (HFC; Figure H.9 to H.16)
Test 3	-0.0293	95.4	9026	-13.27 (CFC; Figure H.17 to H.24)
Test 4	-0.0788	70.6	6679	-35.82 (CFC; Figure H.25 to H.32)
Test 5	0.0058	112.9	10,681	+2.63 (HFC; Figure H.33 to H.40)
Test 6	-0.0703	74.9	7086	-31.91 (CFC; Figure H.41 to H.48)
Test 7	0.0106	115.3	10,908	+4.82 (HFC; Figure H.49 to H.56)
Test 8	-0.0669	76.6	7242	-30.36 (CFC; Figure H.57 to H.64)

[a] assuming a linear relationship (y = mx + c), where:
y is the projected power after 500 hour (experiment duration)
x is the 500 hour duration
c is the stated electrical power input of the functional unit (110W – see Section 3.6.1)
[b] at projected power for (0.2*3600*24*365*15) seconds

Table 4.8. Projection of energy consumption

compared to the unused CFC compatible lubricant. After a compressor test, the performance of the SD type oil improved significantly compared to the POE32 type. It should be noted that the lower viscosity HFC compatible oils (POE10 and POE22) were not included in this analysis as this research work does not consider a CFC compatible counterpart (Table 3.1). However, it is interesting to note that the POE10 (used and unused) can withstand a lighter load (140kg) for a longer period of time compared to its higher viscosity counterpart (POE32). This observation is in contrast to what is reported by Rakic (1999). As the load increases (180kg), the time taken for the POE10 to reach its welding point falls with respect to the POE32. Finally, another observation made during these bench tests was that oil samples coming from the different compressors tested differed in extreme pressure performance. For simplicity, Table 4.9 gives the average time taken for a welding point to be reached

Oil type	Oil condition	Applied load (kg)	Time of test (secs)	Time to weld (secs)
SD	Unused	126	60	43
SD	Unused	140	60	29.5
SD	Unused	160	10	No failure
SD	Unused	180	10	2.6
SD	Used	100	60	32
SD	Used	112	60	24.3
SD	Used	126	60	6.7
SD	Used	140	60	4.9
POE32	Unused	126	60	No failure
POE32	Unused	140	60	35.5
POE32	Unused	160	10	No failure
POE32	Unused	180	10	4.3
POE32	Used	100	60	10.4
POE32	Used	112	60	9
POE32	Used	126	60	3.8
POE32	Used	140	60	3.2
POE10	Unused	140	60	40
POE10	Used	140	60	6
POE10	Unused	180	10	2

Table 4.9. Welding time of steel balls

and does not differentiate between compressors. It has, however, been noted that the time for the lubricants from the higher capacity compressors (Table 2.1) to fail was increased by a minimum of 38% for the continuous tests.

4.4 Comment

As explained in Section 4.1.2, the increase in refrigerant charge was likely to increase both the wear characteristics and the rate of change of power requirements. Observations made throughout this chapter prove that samples from Test 3, which operated at a higher CFC-12 refrigerant charge, did not show any adverse implications as far as wear was concerned, even after comparing them with observations from Test 1 and Test 4. When considering the in-use power, however, Table 4.8 proves that the rate of change of the regression curve for a Type A compressor operating in HFC-134a (Test 1) is double that of a Type B compressor working in the same refrigerant (Test 2). With CFC-12 this is not the case and the difference is actually higher by more than three times for a Type B than for a Type A compressor (compare Test 3 and Test 4 respectively). On the other hand, the difference between the rates of change of Test 6 and Test 8, both Type B compressors working with CFC, was insignificant. An explanation for this could well be the increased refrigerant charge noted in Table 4.5.

5 THE ANALYTICAL RESULTS: EXCHANGES WITH THE ENVIRONMENT

This chapter identifies the potential indirect environmental consequences resulting from a switch in refrigerant in the domestic refrigerator. This it does by assessing the exchanges that occur with the environment throughout the various product life cycle phases using the LCA model elaborated upon in Chapter 3. The most significant potential impacts on the environment were examined on the basis of the criteria within PEMS (Section 3.5) and a critical review of the findings carried out. Simultaneously, the *source* and *location* of these significant contributions in the product system were identified. An emphasis was made on the hermetic compressor, which was found to contribute significantly towards the overall product environmental impact.

5.1 Impact assessment

Impact assessment facilitates the interpretation and aggregation of the inventory data, outlined in the analytical approach explained in Section 3.5ff, to manageable and meaningful forms. According to (ISO 1999), the four main issues to be addressed throughout the impact assessment phase of the LCA study are:

- category definition,
- classification,

- characterisation,
- valuation/weighting.

Similar to the framework of detailed LCA studies (Section 1.4.2), the principal aim of this procedure is to make the methods, assumptions and value-choices of the LCA more transparent and easy to be reviewed. This helps to demonstrate the outcome of these criteria on the LCA. In *category definition*, the impact categories, which describe the environmental impacts caused by the functional unit of the study, are selected. In *classification*, the data generated in the inventory is grouped into the relevant impact categories identified in the category definition. In *characterisation*, the relative contribution of the individual environmental burdens to each impact category is assessed. Finally, in *valuation* (or *weighting*) the contributions of the different impact categories are weighed against each other.

With the PEMS software used (Section 3.5), the *Default Characterisation* method (Pira 1998) was adopted throughout this study. This essentially includes the first three steps of the procedure explained in the preceding paragraph, the impact categories included being described in Appendix A. As for valuation (the final stage of the procedure), a number of techniques were used as will be described throughout this chapter.

To help address the final objective of the LCA study (Section 3.6), the tasks of the impact assessment to be described were:

- to obtain an environmental profile of the product system and compare the hermetic compressor with the remaining items making up the refrigerating unit,
- to environmentally compare the replacement refrigerant (HFC-134a) with the compound it has phased out (CFC-12),
- to interpret any increase in the in-use power of the compressor resulting from the switch in working fluid from an environmental impact viewpoint.

5.1.1 The impact categories of the functional unit

Figure 5.1 shows the environmental impacts in the form of emissions to air, ground and water, which may arise from the extraction of raw materials for the items making up the functional unit up to when the appliance is ready for distribution (Section 3.7). The energy consumption throughout the in-use phase and the end-of-life scenario were not included here. All impacts for the individual items making up the functional unit (Table F.1) have been grouped together in Figure 5.1 for clarity.

It should be noted that whether the actual emissions occur is not known but the assessment gives an indication of the potential problem. It should also be noted that not all of the categories listed in Figure 5.1 are in actual fact impacts. *Extracted Energy* and *Traffic* influence environmental impacts (such as, global warming) but they themselves are not impacts. The reason for them to be included in PEMS is to give an indication of their scale of contribution. Furthermore, *Abiotic Depletion* as an impact should be treated with caution. This issue is controversial since precise quantities on remaining reserves are subjective and heavily dependent on economies, new technologies, discoveries of natural resources, etc. Nonetheless, this was included for completeness but will not be considered further throughout this study.

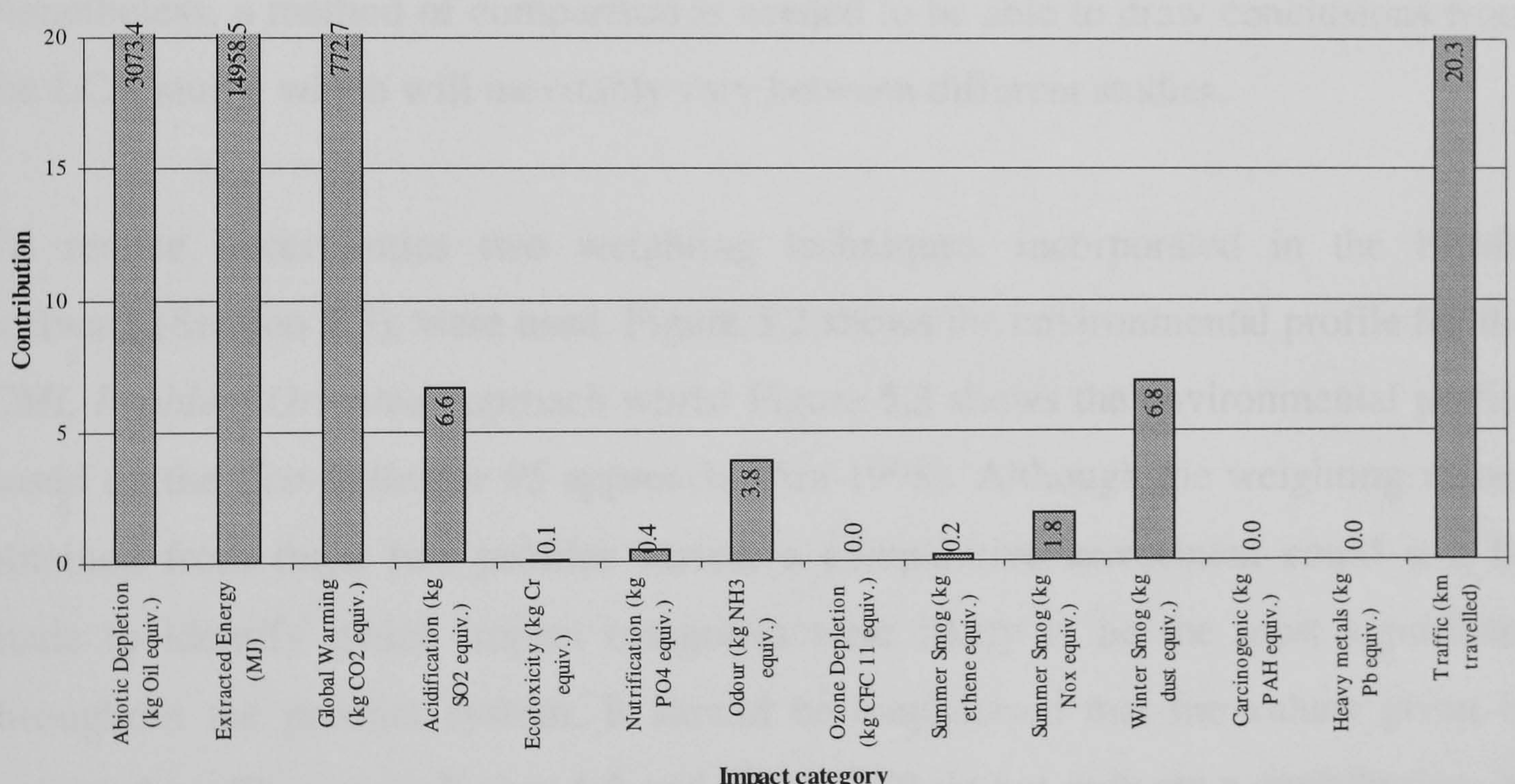


Figure 5.1. The potential impact categories for the functional unit and their contribution

The profile shown in Figure 5.1 lists the inventory data into the relevant impact categories (classification). It also lists the relative contribution (to one decimal place) of the burdens to each impact category, expressed in impact equivalents (characterisation). All burdens known to contribute to the impact potentials of each individual impact category have been added together and included in this profile.

Due to the difference in hazard properties, large quantities do not necessarily imply large environmental impacts. Therefore, from Figure 5.1, it is difficult to determine which potential impacts are the most significant and which are worth focusing upon. To overcome this problem a number of optional processes are outlined in (ISO 1999) but in this study the PEMS (Section 3.5) valuation process was considered.

5.1.2 The most significant impact categories

As explained in (Jensen, et al. 1997), weighting may be either a quantitative or a qualitative step which may not necessarily be based on natural science but on political and ethical values. Undoubtedly, controversies surround this stage within the LCA process and this is perhaps why a number of weighting methods have been developed (Lindeijer 1996). At the time of writing this thesis there was no single standard method to be employed (ISO 1999) and this was not foreseen as happening in the near future (Pira 1998). Due to its lack of scientific backing the desirability of conducting this weighting stage as a basis for decision is seen to be unreliable. Nonetheless, a method of comparison is needed to be able to draw conclusions from the LCA study, which will inevitably vary between different studies.

To reduce uncertainties two weighting techniques, incorporated in the PEMS software (Section 3.5), were used. Figure 5.2 shows the environmental profile for the *CML Problem Oriented* approach whilst Figure 5.3 shows the environmental profile based on the *Eco-indicator 95* approach (Pira 1998). Although the weighting values obtained from these two profiles varied, a comparative assessment could still be made to identify which impact categories were likely to be the most significant throughout the product system. It should be emphasised that the values given in weighted profiles (as in Figure 5.2 and Figure 5.3) do not indicate a contribution, as does Figure 5.1, but only a score appropriate for ranking. It is for this reason that these values are dimensionless.

Both Figure 5.2 and Figure 5.3 identify summer smog, global warming, acidification and nutrification worthy of further investigation. The former profile also identifies human toxicity whilst the latter identifies heavy metals, carcinogens as well as winter smog. It is interesting to note that, as defined in Appendix A, heavy metals,

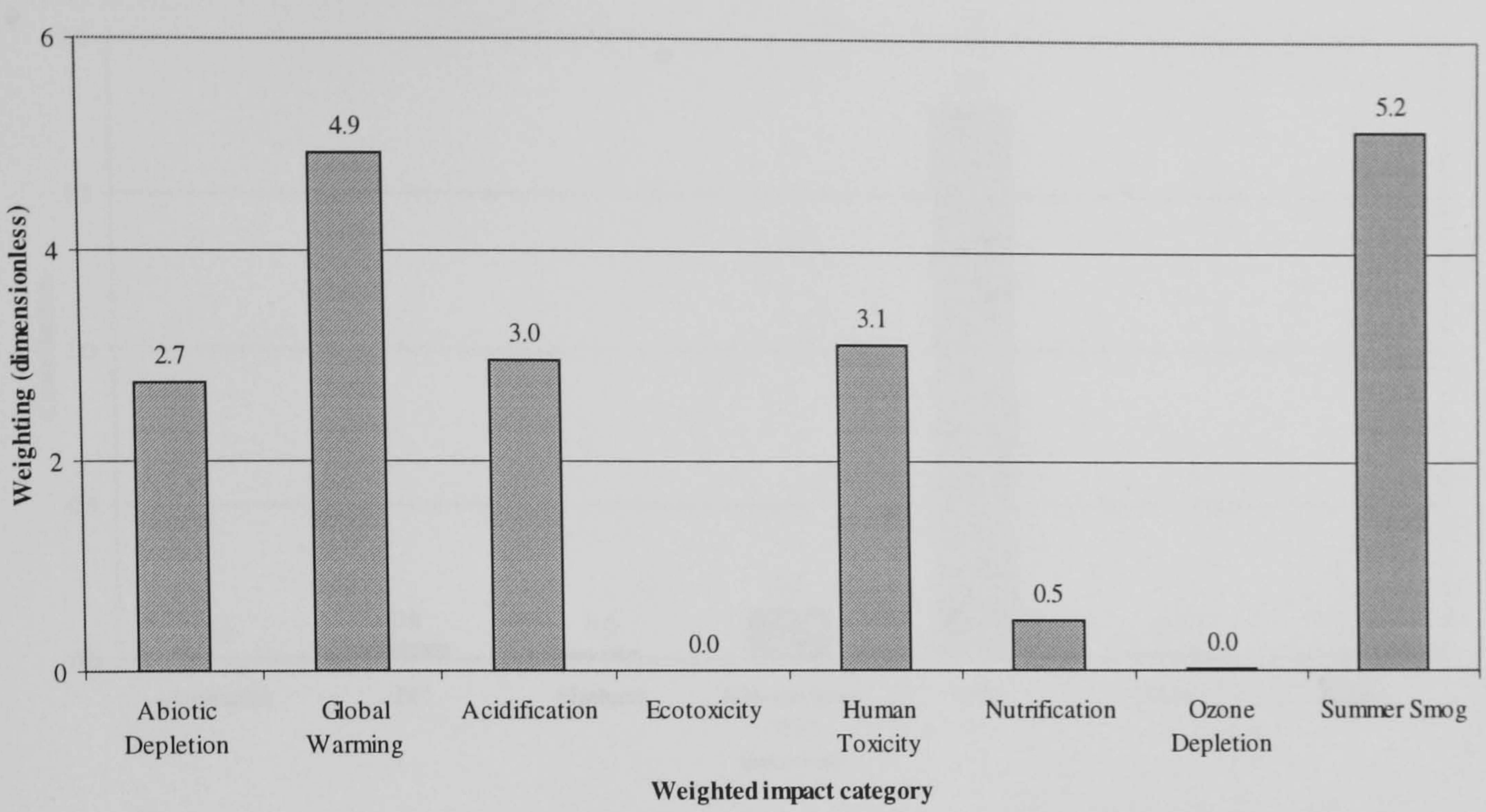


Figure 5.2. Weighted impact categories using the CML Problem Oriented approach

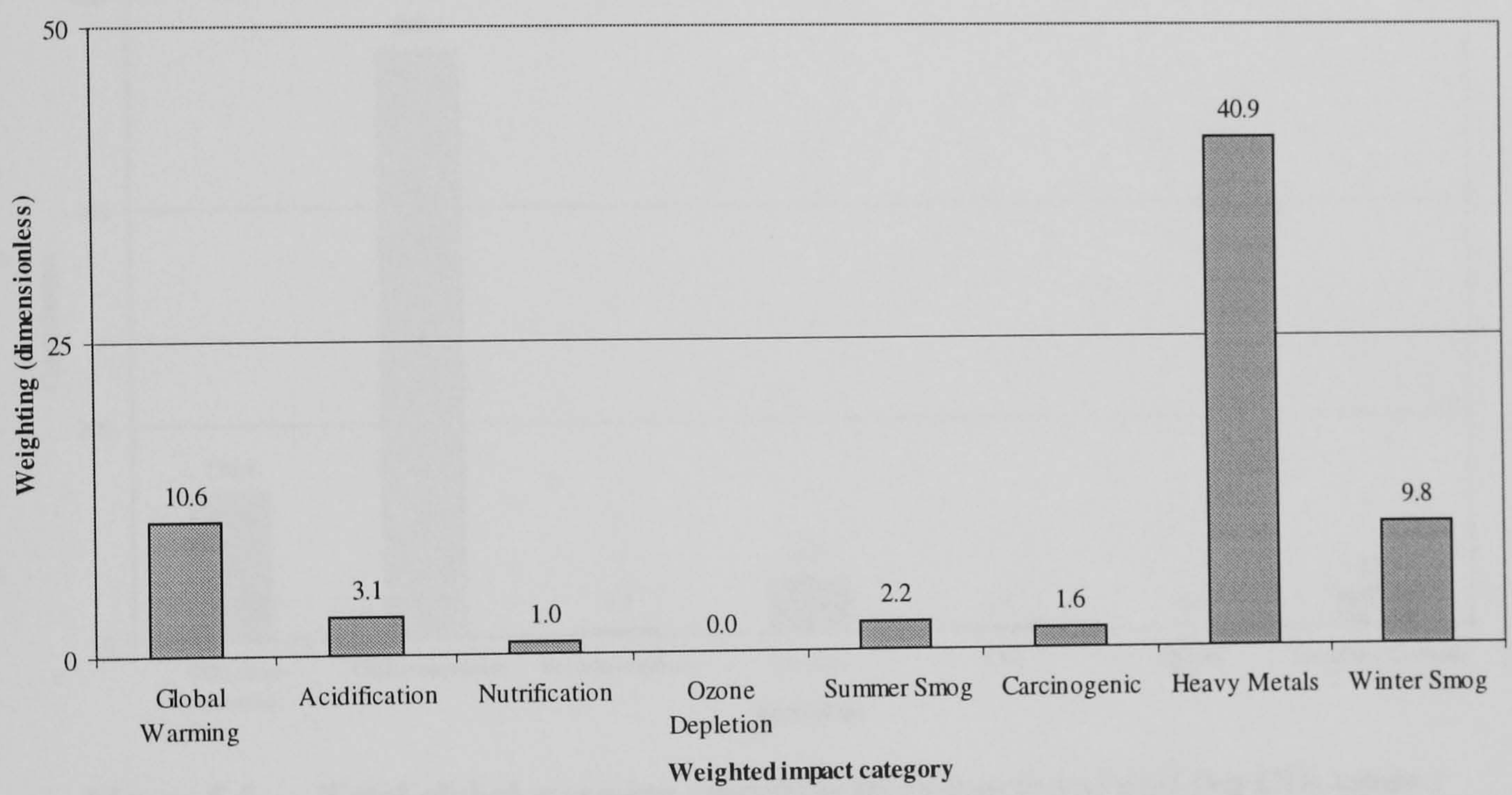


Figure 5.3. Weighted impact categories using the Eco-indicator 95 approach

carcinogens and winter smog mainly influence human toxicity. This implies that the outcome of these impact categories would be similar. Nonetheless, throughout this investigation these categories were analysed separately since these were influenced by different emissions (Section 5.1.3). Finally, all of the impact categories highlighted were investigated in further detail, as explained throughout the remainder of this chapter, to determine their source and location within the product system.

5.1.3 The most significant sources to the impact potentials

To identify from where the contributions to the various impact categories originated, each category was assessed individually using the PEMS tool. In the figures that follow (Figure 5.4 to Figure 5.11) all emissions are labelled to one decimal place.

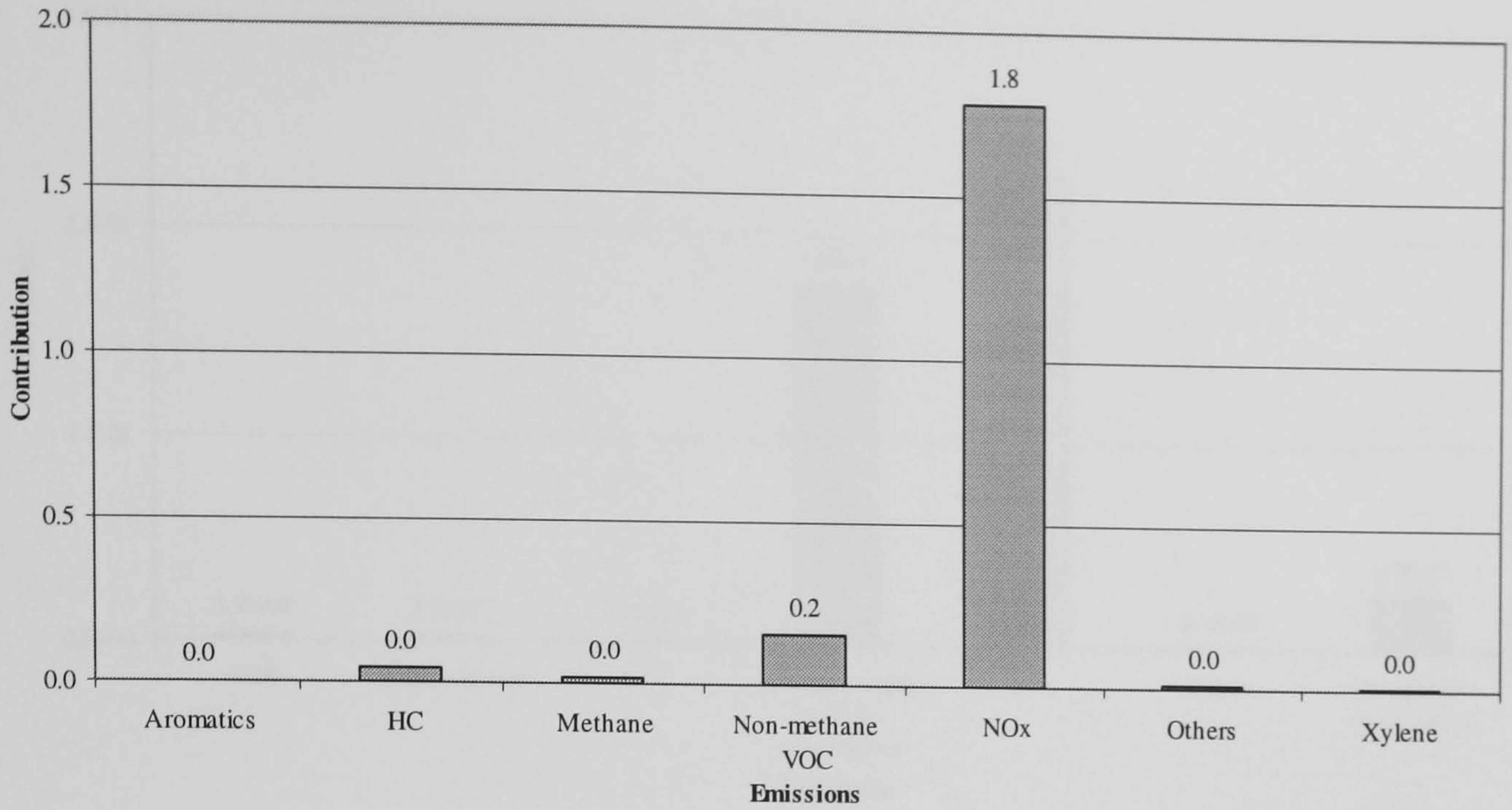


Figure 5.4. Total summer smog emissions from functional unit (kg ethene + NO_x equiv.)

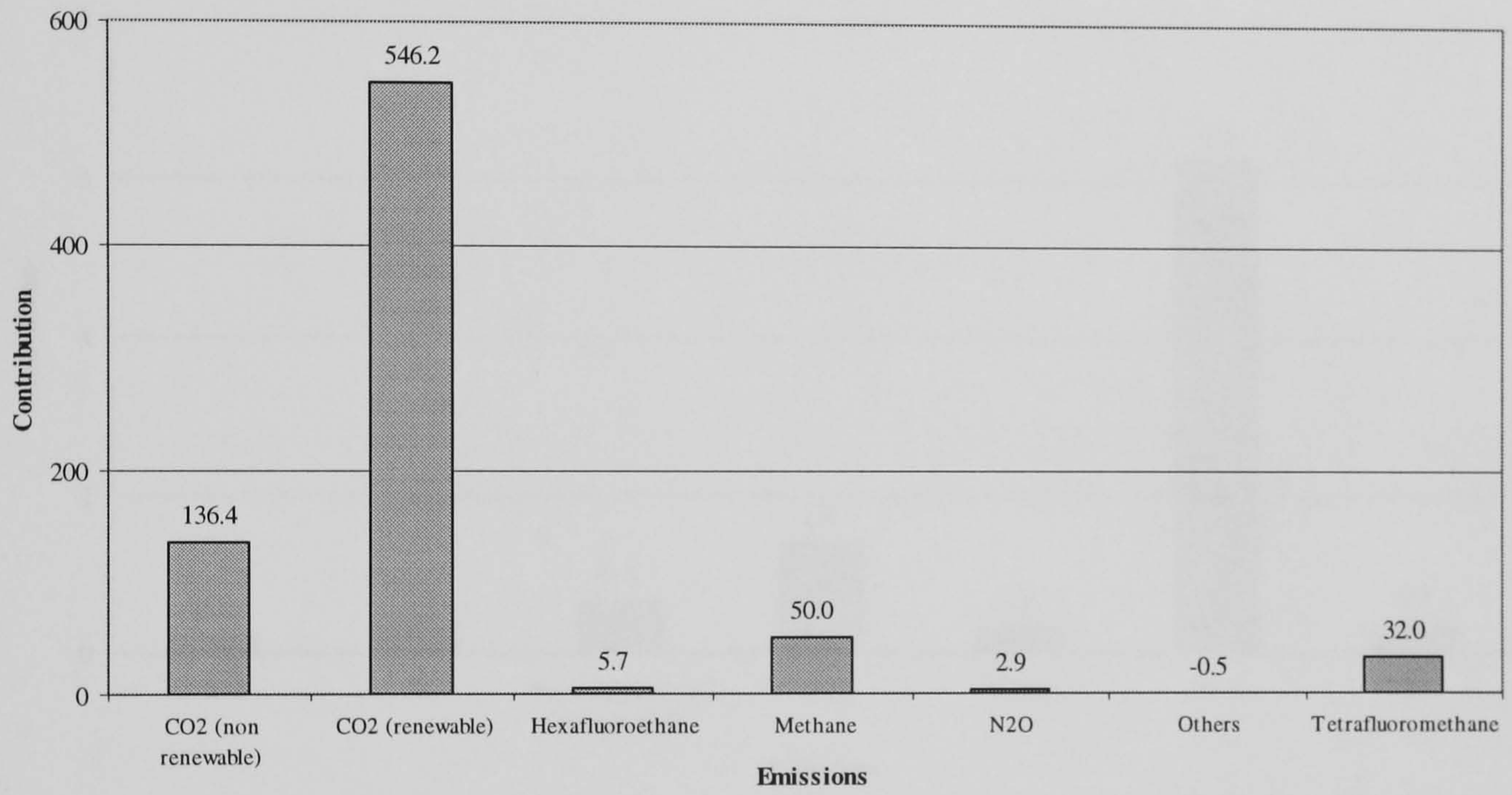


Figure 5.5. Total global warming emissions from functional unit (kg CO_2 equiv.)

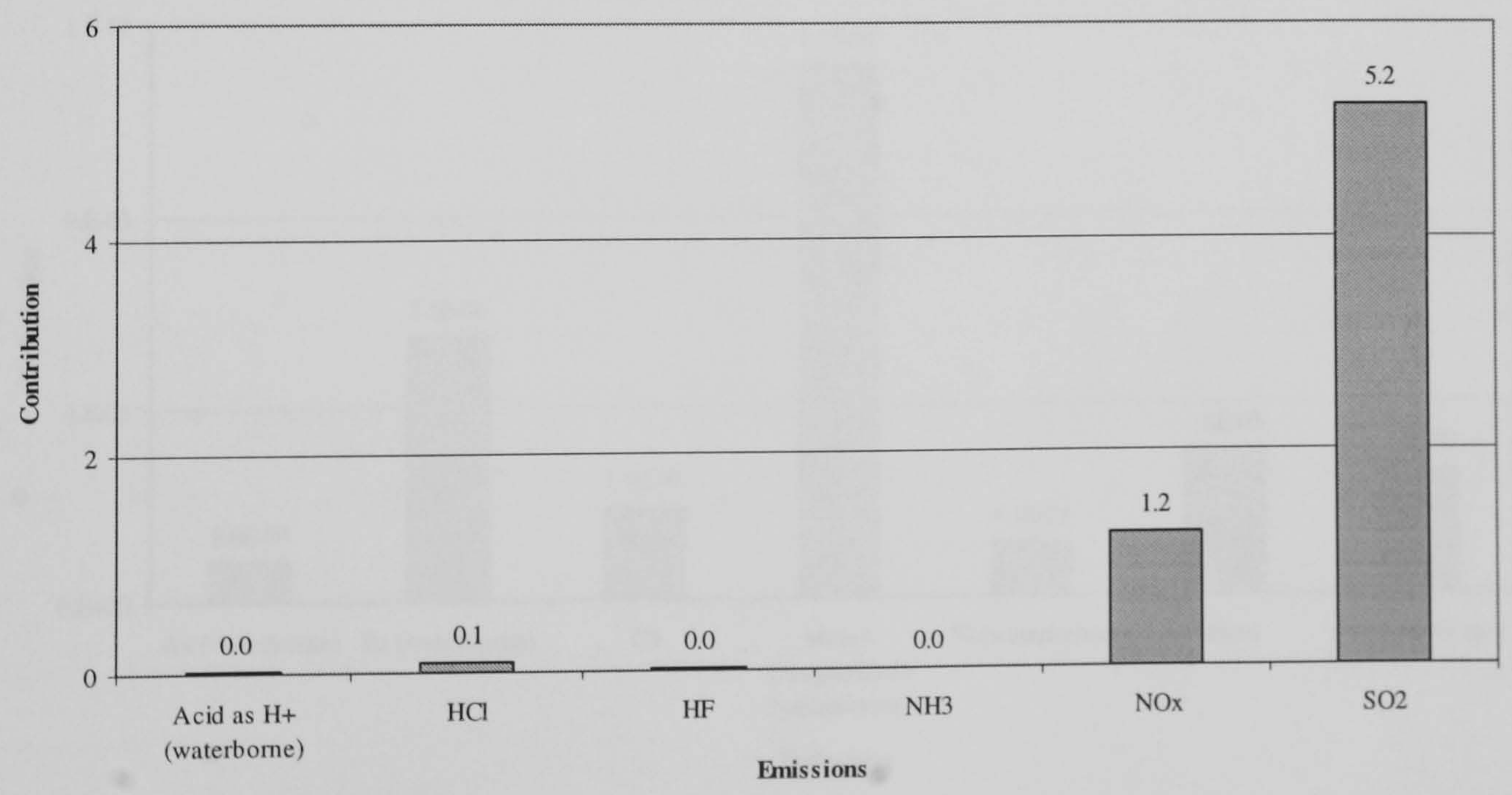


Figure 5.6. Total acidification emissions from functional unit (kg SO_2 equiv.)

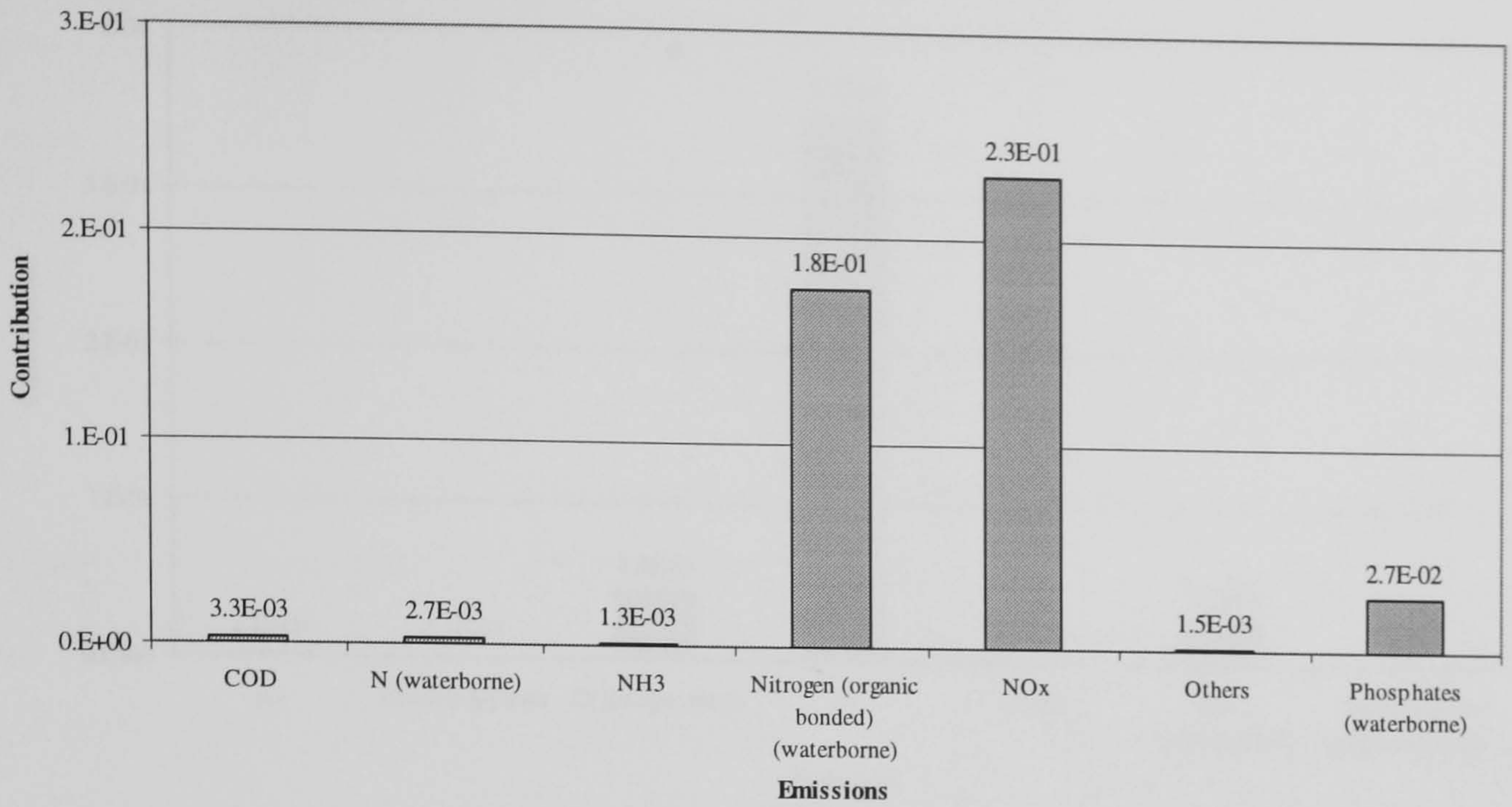


Figure 5.7. Total nutrification emissions from functional unit (kg PO_4 equiv.)

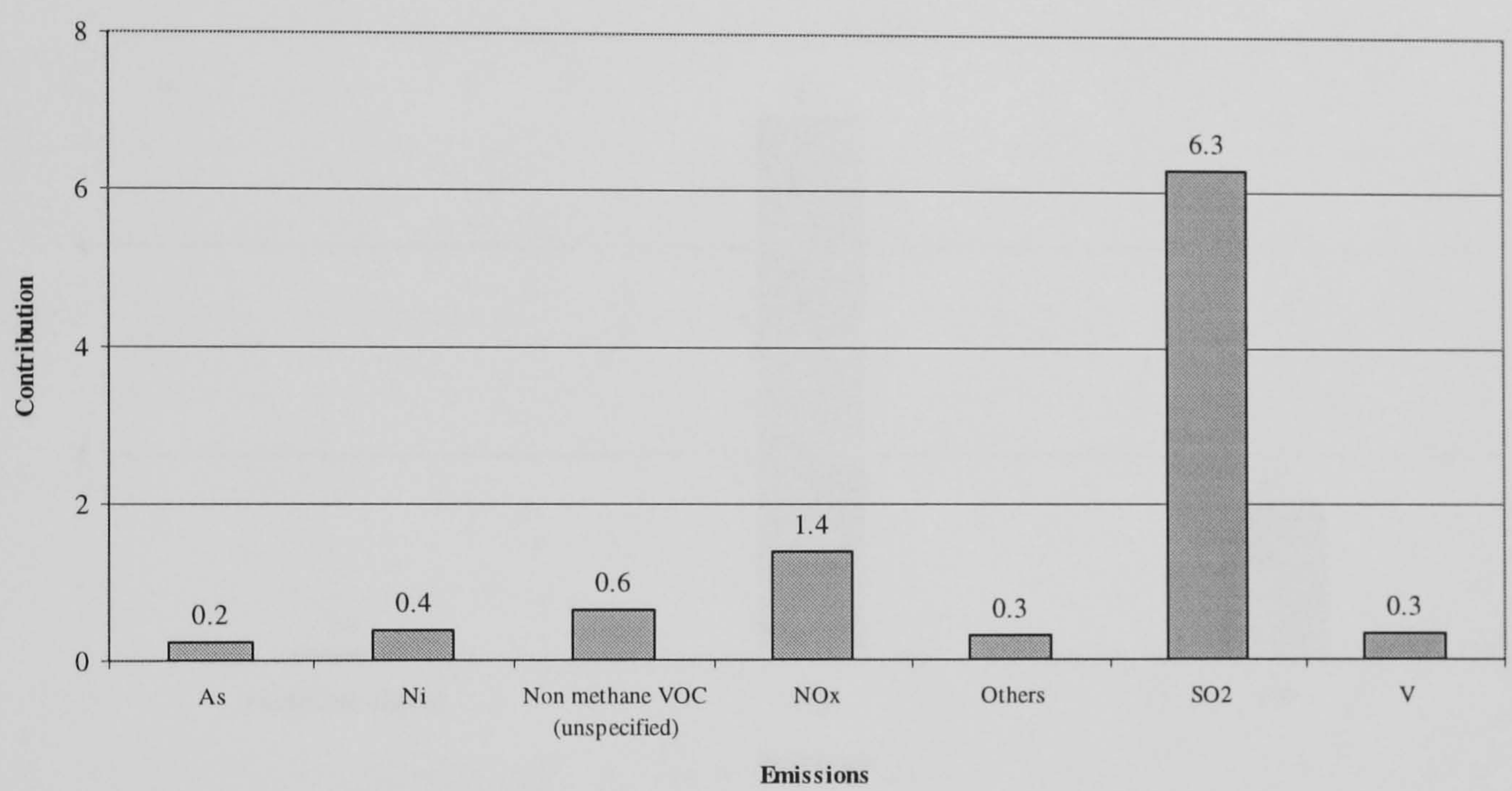


Figure 5.8. Total human toxicity emissions from functional unit (kg/kg equiv.)

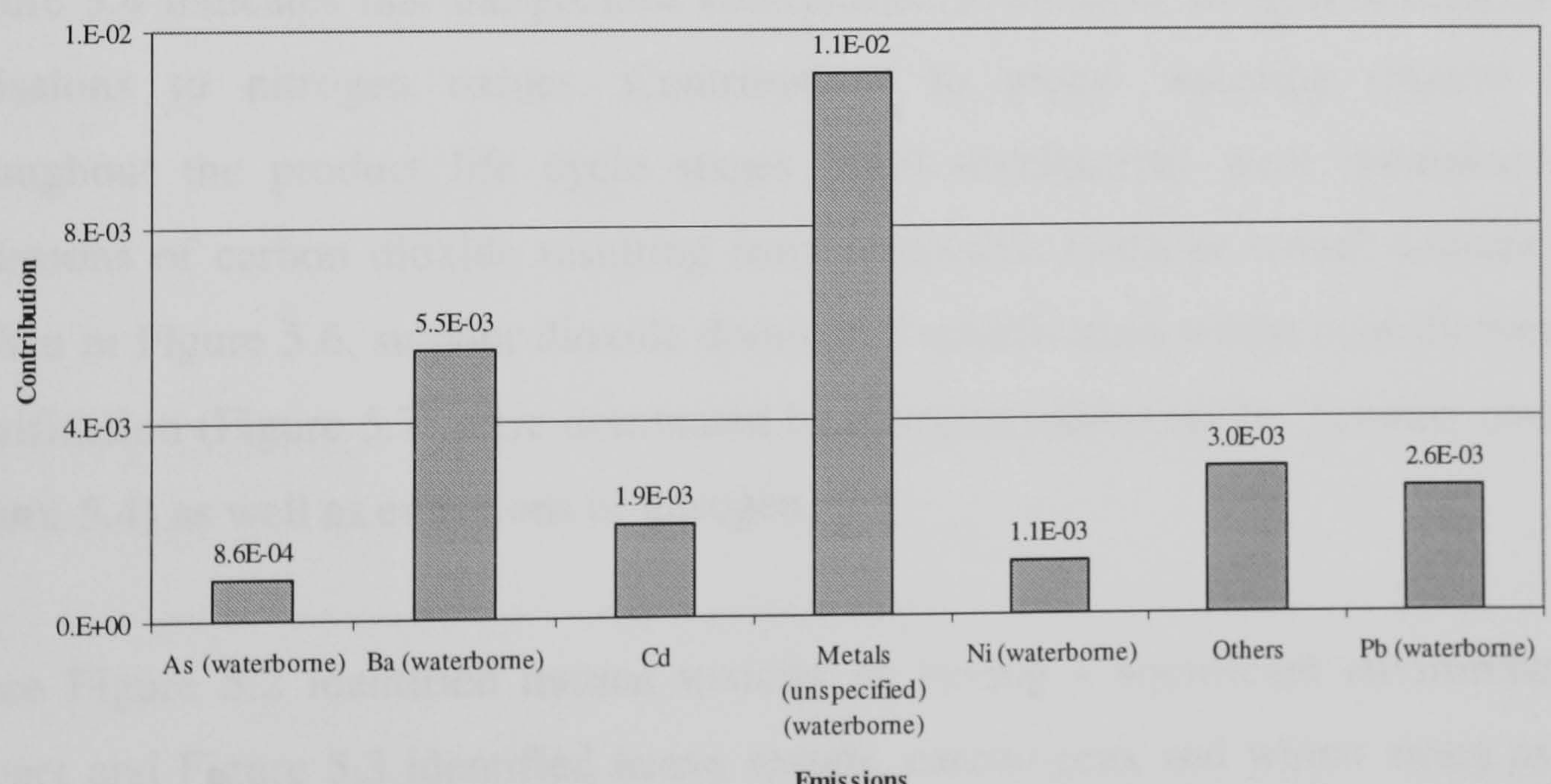


Figure 5.9. Total heavy metals emissions from functional unit (kg Pb equiv.)

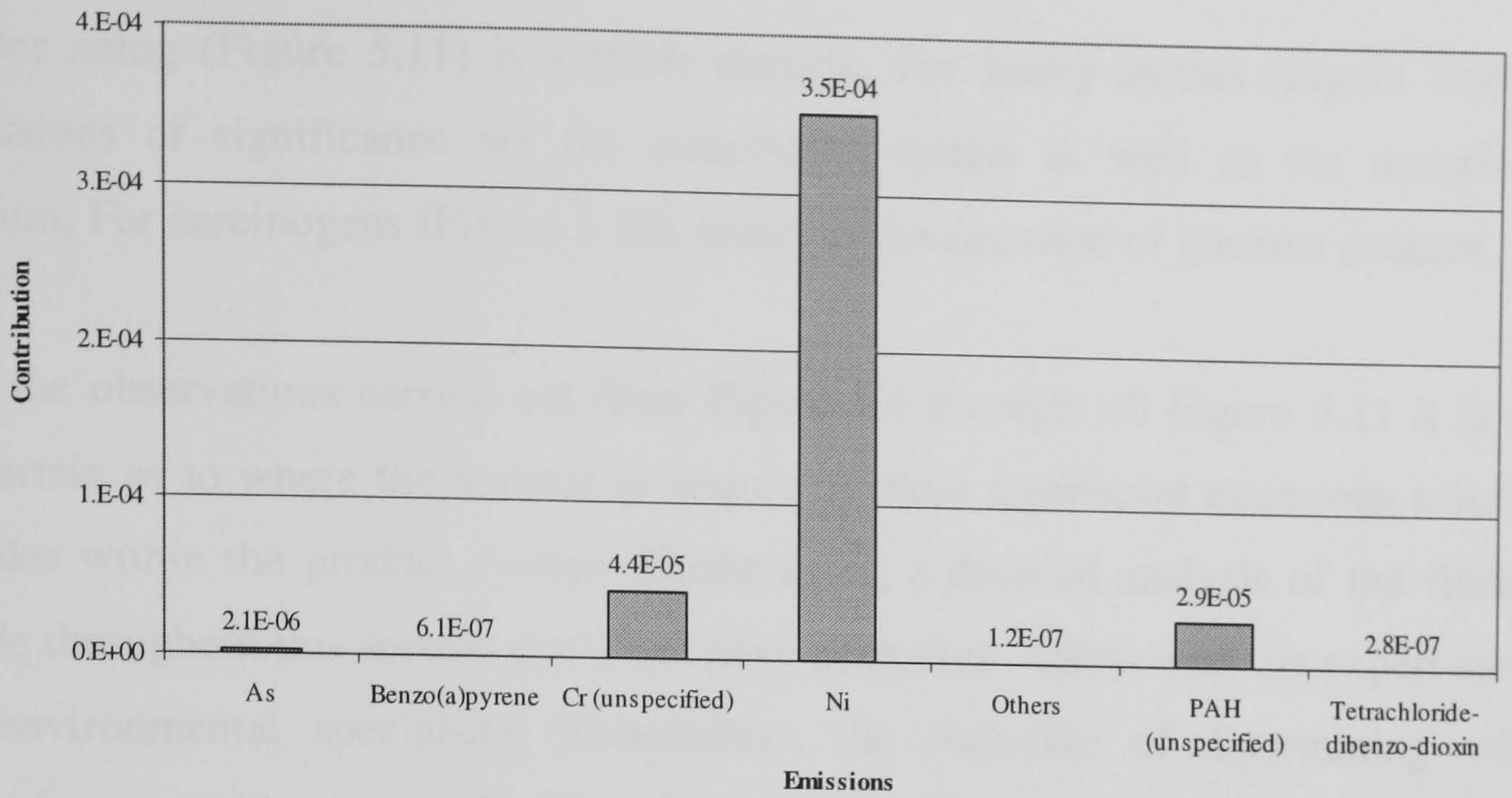


Figure 5.10. Total carcinogen emissions from functional unit (kg PAH equiv.)

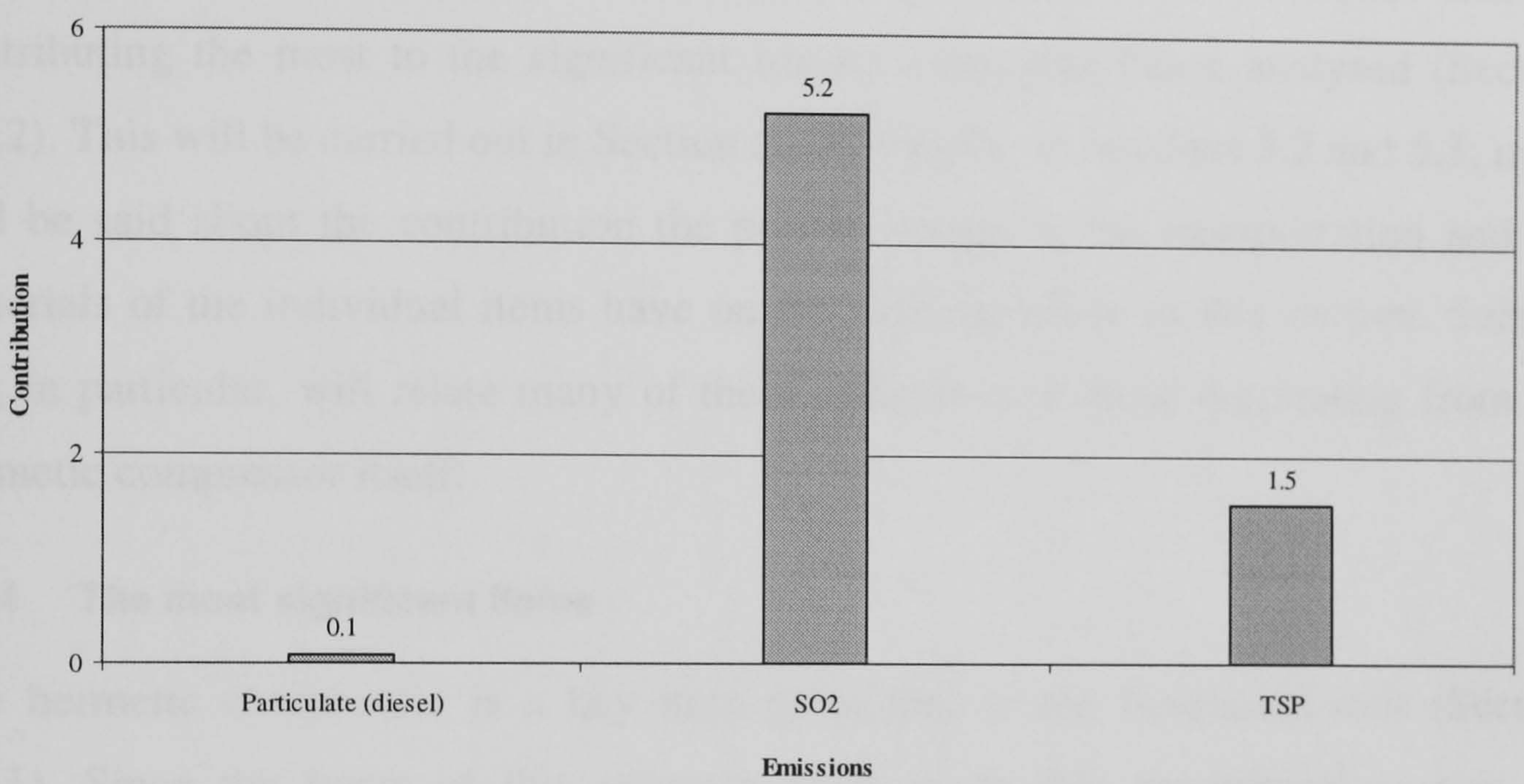


Figure 5.11. Total winter smog emissions from functional unit (kg dust equiv.)

Figure 5.4 indicates that the greatest contribution to summer smog results from the emissions to nitrogen oxides. Contributions to global warming (Figure 5.5) throughout the product life cycle stages (until distribution) were dominated by emissions of carbon dioxide resulting from renewable (such as wood) sources. As shown in Figure 5.6, sulphur dioxide dominated acidification whilst contributions to nutrification (Figure 5.7) were dominated by nitrogen oxides (as for summer smog – Figure 5.4) as well as emissions of nitrogen.

Since Figure 5.2 identified human toxicity as having a significant environmental impact and Figure 5.3 identified heavy metals, carcinogens and winter smog as the most significant these are depicted in Figure 5.8 to Figure 5.10. As for acidification (Figure 5.6), the emission contributing mostly to human toxicity (Figure 5.8) and winter smog (Figure 5.11) is sulphur dioxide. For heavy metals (Figure 5.9) the emissions of significance are the waterborne metals as well as the waterborne barium. For carcinogens (Figure 5.10), nickel is the emission of greatest concern.

For the observations carried out from Figure 5.4 through till Figure 5.11 it is still uncertain as to where the sources or source of these significant emissions reside or resides within the product system. Furthermore, a detailed analysis of the findings made throughout this section could not have been done unless with the expert advice of environmental specialists. Nonetheless, the objective of determining which emissions contribute significantly to the individual impact categories has been attained. The next task would be to know which items in the functional unit are contributing the most to the significant impact categories being analysed (Section 5.1.2). This will be carried out in Section 5.1.4. Finally, in Sections 5.2 and 5.3, more will be said about the contribution the process energies, the transportation and the materials of the individual items have on the findings made in this section. Section 5.3, in particular, will relate many of these emissions to those originating from the hermetic compressor itself.

5.1.4 The most significant items

The hermetic compressor is a key item pertaining to the functional unit (Section 3.6.1). Since the focus of this research work is on this mechanical system, an environmental assessment was carried out on the individual items making up the functional unit. This helped identify the most significant items and in so doing justify the influence the hermetic compressor has over the entire product environmental profile. Figure 5.12 depicts this, by separately assessing all the items within the functional unit, for the most significant impact categories identified in Section 5.1.2.

Apart from showing which items make the biggest impact contributions, Figure 5.12 also indicates the contribution of all the other items which make up the functional unit but which they alone do not contribute much compared to those items that do. The hermetic compressor contributes significantly to the overall environmental profile of the product (Figure 5.12). For this profile, a type and quantity of energy of production and transportation were included (Table F.1 and Table F.2). Due to the

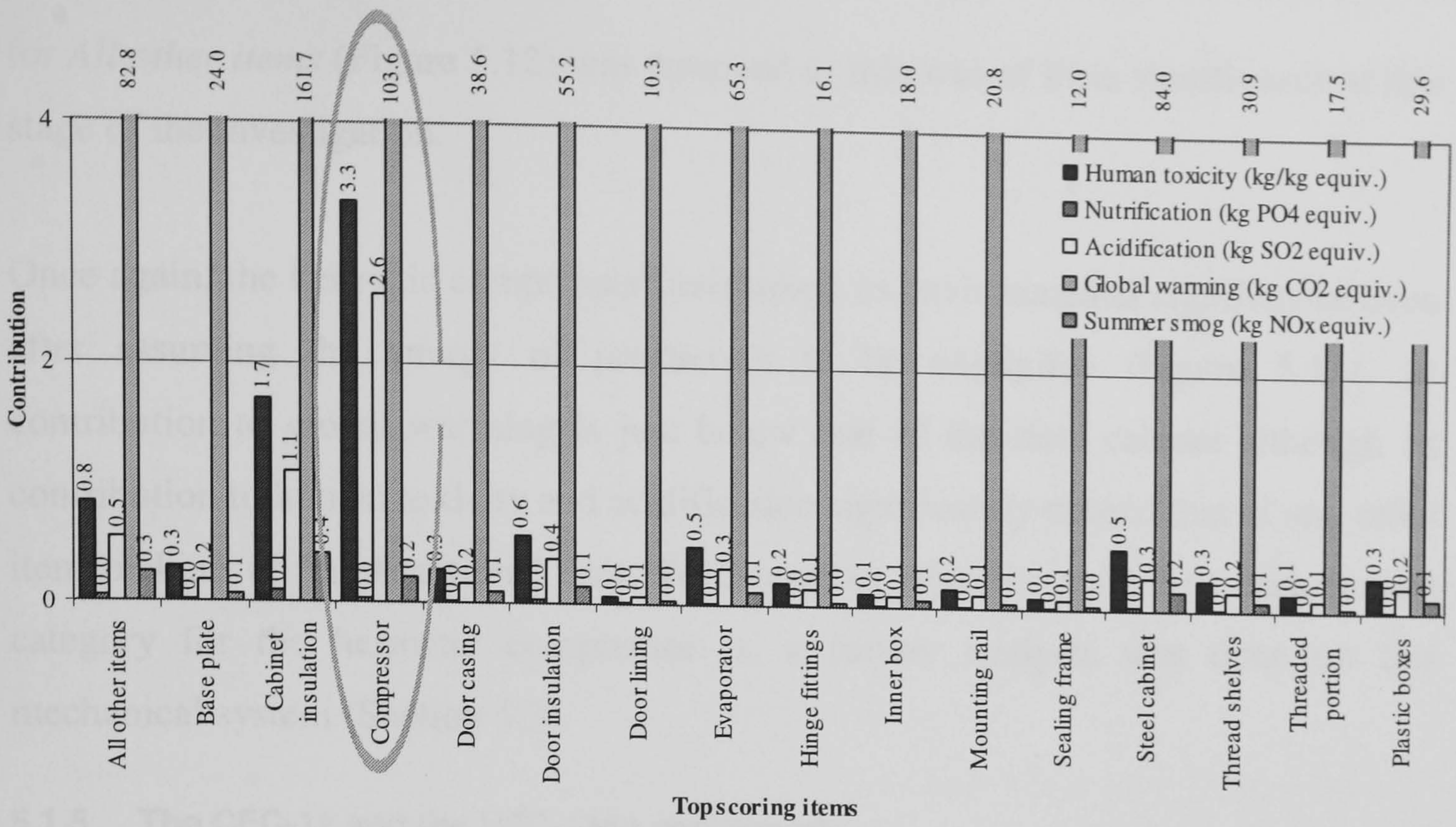


Figure 5.12. The highest scoring functional unit items and their contribution

boundaries and the assumptions set throughout the LCA study (Section 3.6.3 and 3.6.5 respectively) and to provide a holistic picture of the potential consequences on the environment as a choice for solution at item level, this environmental profile was repeated. This time, however, with no energy of production (Figure 5.13).

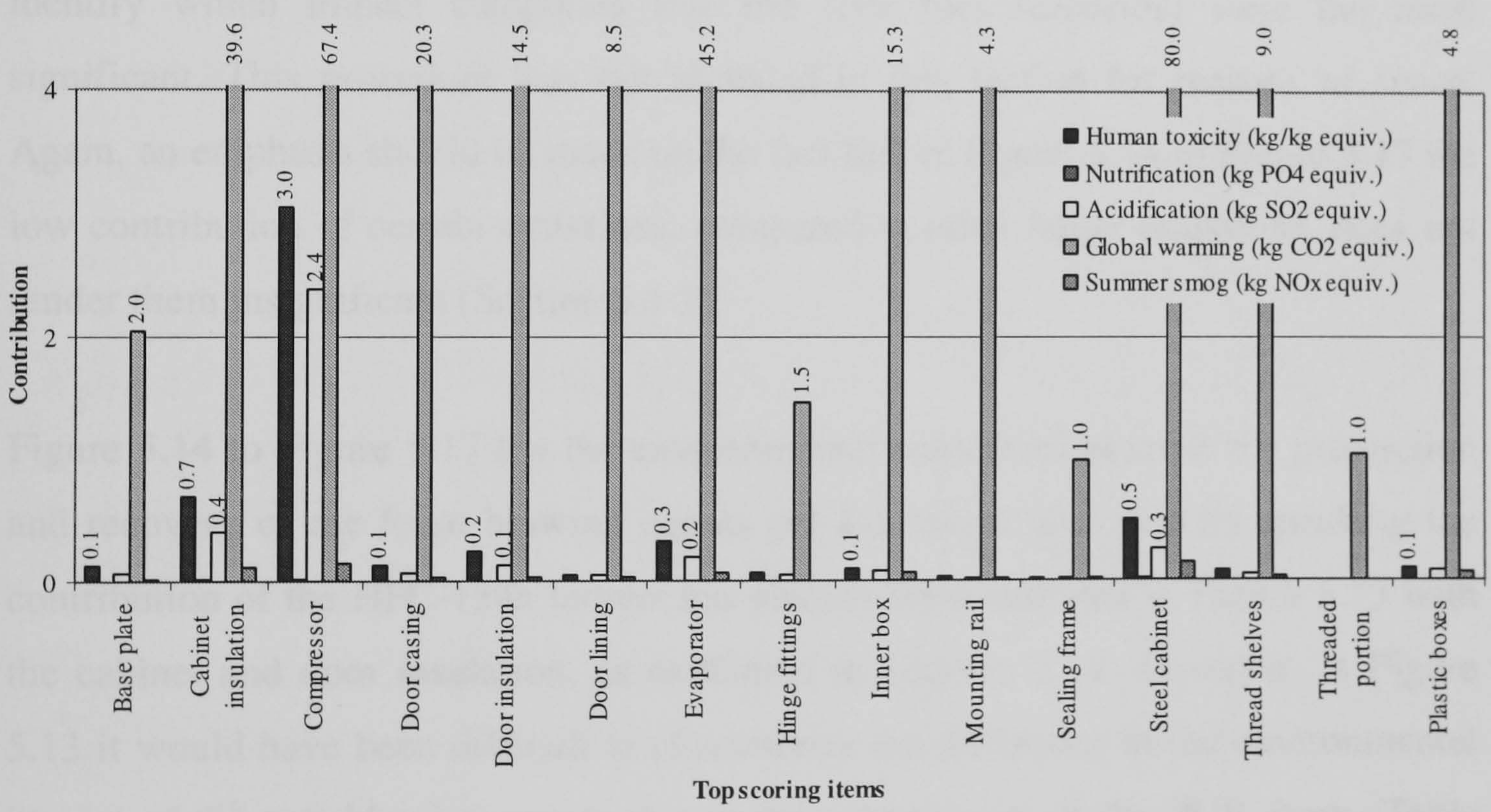


Figure 5.13. The impact of the highest scoring items, assuming no energy of production

In Figure 5.13, as in Figure 5.12 and subsequent profiles, the contribution to summer smog was limited to nitrogen oxides as this was found to be the most significant in Figure 5.1. Also, in Figure 5.13, the impact categories with a potential impact of less than approximately 100g were unlabelled for reasons of clarity. Finally, the profile for *All other items* (Figure 5.12) was removed as this was of little significance at this stage of the investigation.

Once again, the hermetic compressor maintained its environmental significance even after assuming the energy of production to be negligible (Figure 5.13). Its contribution to global warming is just below that of the steel cabinet although its contribution to human toxicity and acidification significantly exceed that of any other item making up the functional unit. To determine what the source of each impact category for the hermetic compressor is, a further analysis was done on this mechanical system (Section 5.3).

5.1.5 The CFC-12 and the HFC-134a compounds

In this section, the most significant impact categories were individually assessed using the Default Characterisation method (Section 5.1) for the production and recovery of these two compounds (Section 3.7.2) under four different fuel scenarios (Section 3.6.3). As done in Section 5.1.1, an impact assessment was carried out to identify which impact categories (for the four fuel scenarios) were the most significant. This procedure was not included in this section for reasons of space. Again, an emphasis should be made on the fact that in Figure 5.14 to Figure 5.17 the low contribution of certain emissions, compared to other larger emissions, does not render them insignificant (Section 5.1.2).

Figure 5.14 to Figure 5.17 list the environmental contributions from the production and recovery of the foam blowing agents per functional unit. Strictly speaking the contribution of the HFC-134a blower has already been included in Figure 5.13 with the cabinet and door insulation, as explained in Section 3.7.2. However, in Figure 5.13 it would have been difficult to characterise the difference in the environmental impact of the two blowing agents due to the contribution of the PUR foam (Table F.1). To emphasise better the significance the two compounds have during production and recovery, despite the fact that both the CFC-12 and the HFC-134a are unlikely to be used as foam blowers (Section 3.6.3), these have been included in this part of the investigation.

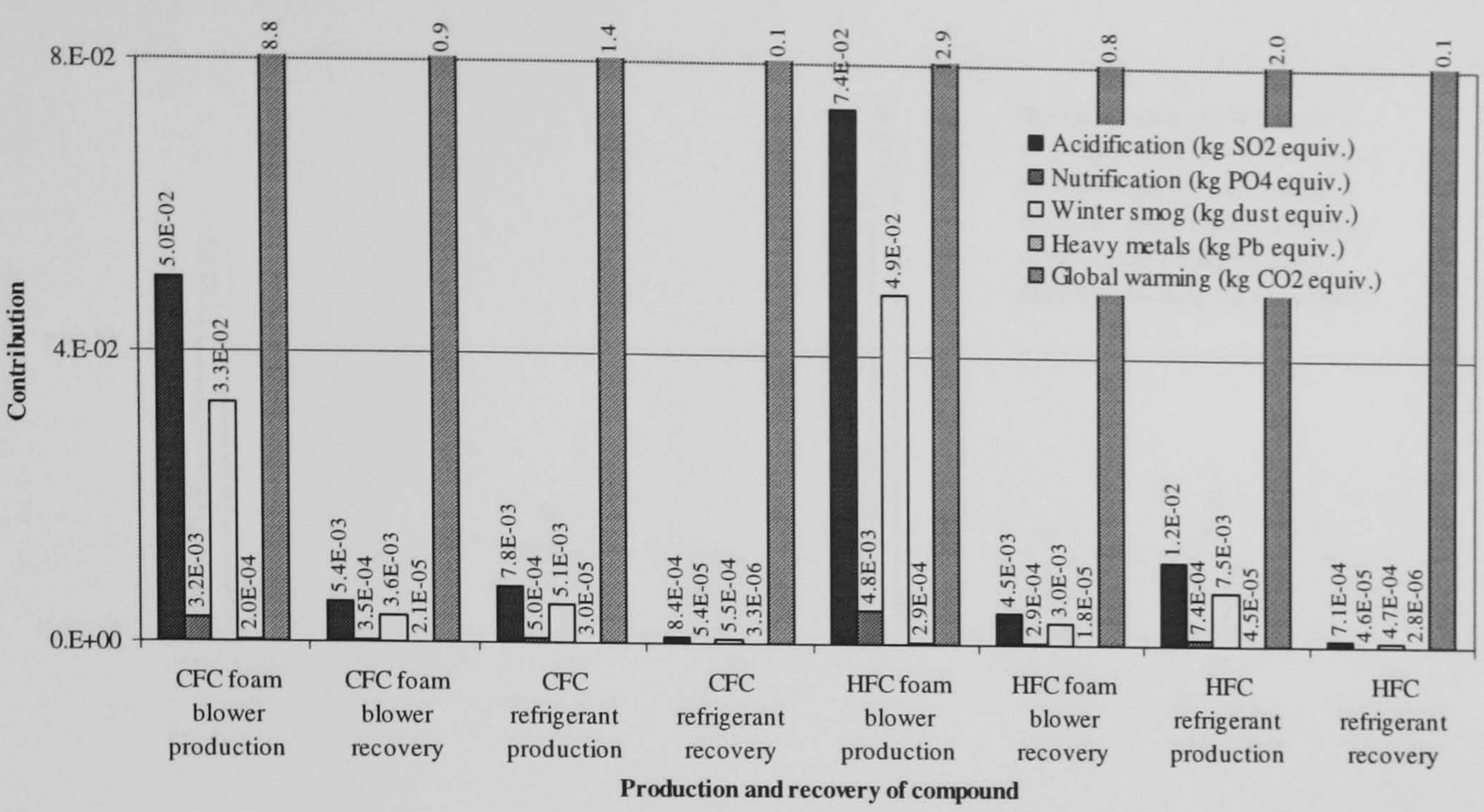


Figure 5.14. Contribution of the production and recovery of compounds; coal fuel scenario

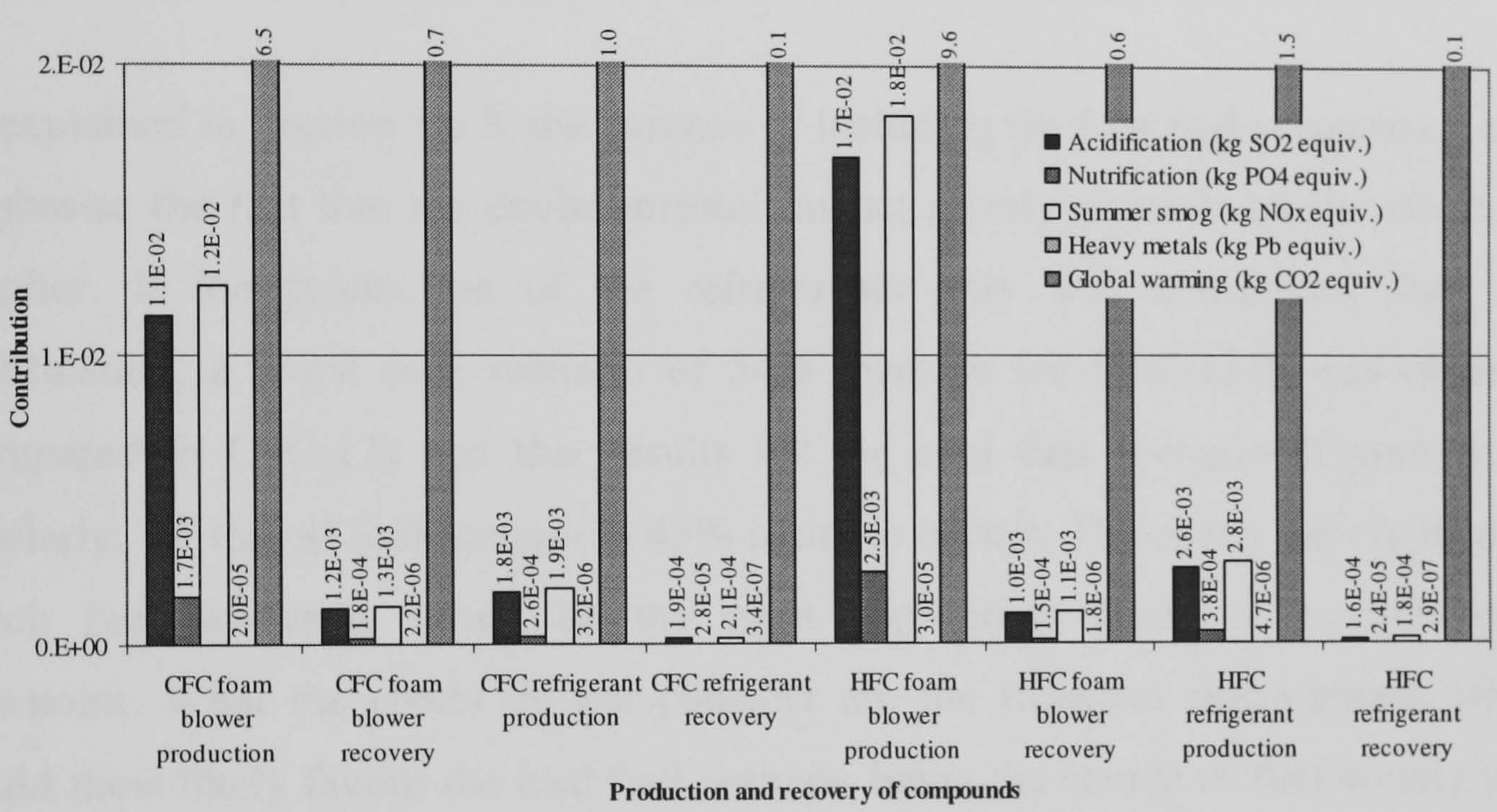


Figure 5.15. Contribution of the production and recovery of compounds; gas fuel scenario

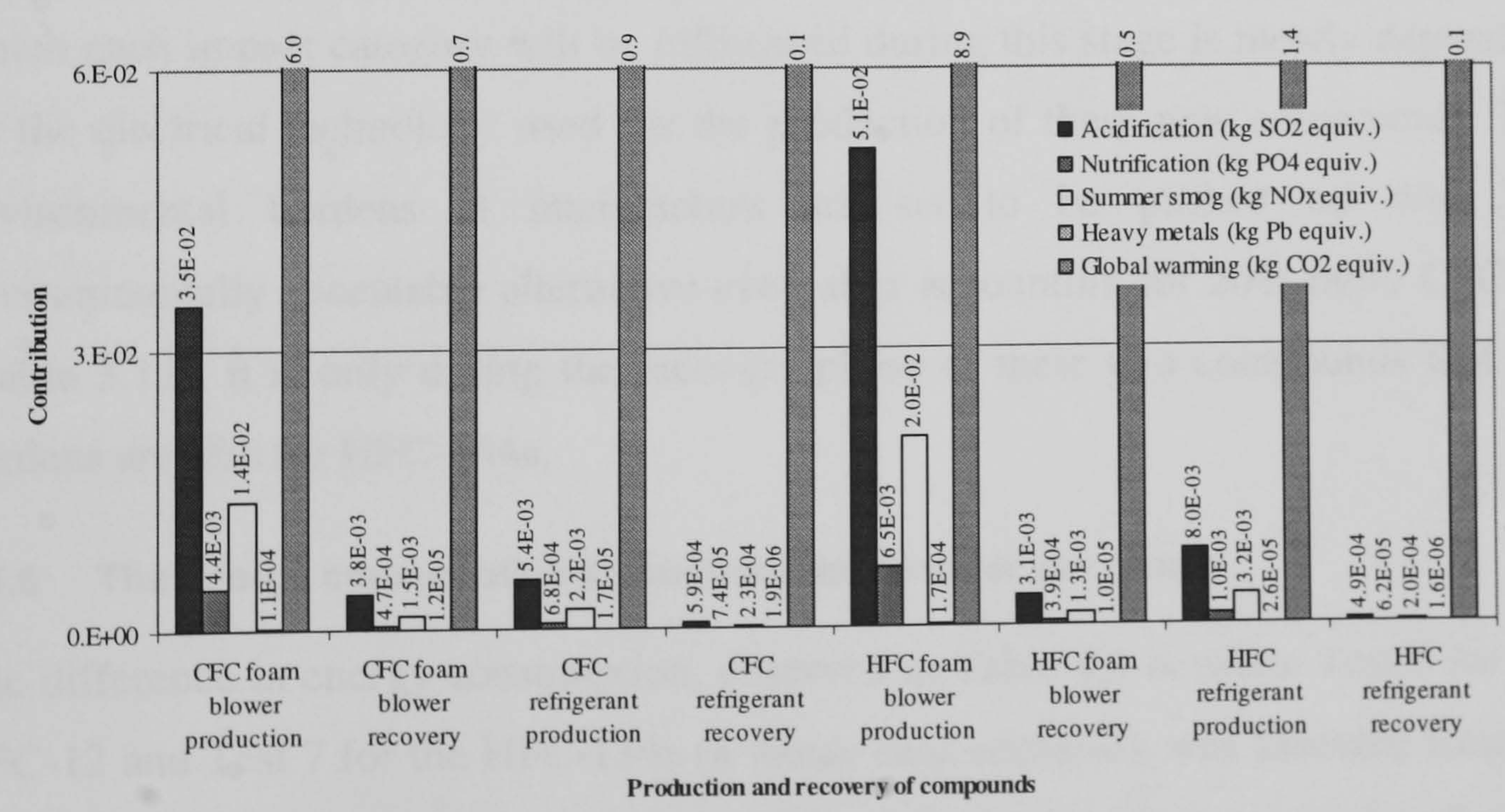


Figure 5.16. Contribution of the production and recovery of compounds; mixed fuel scenario

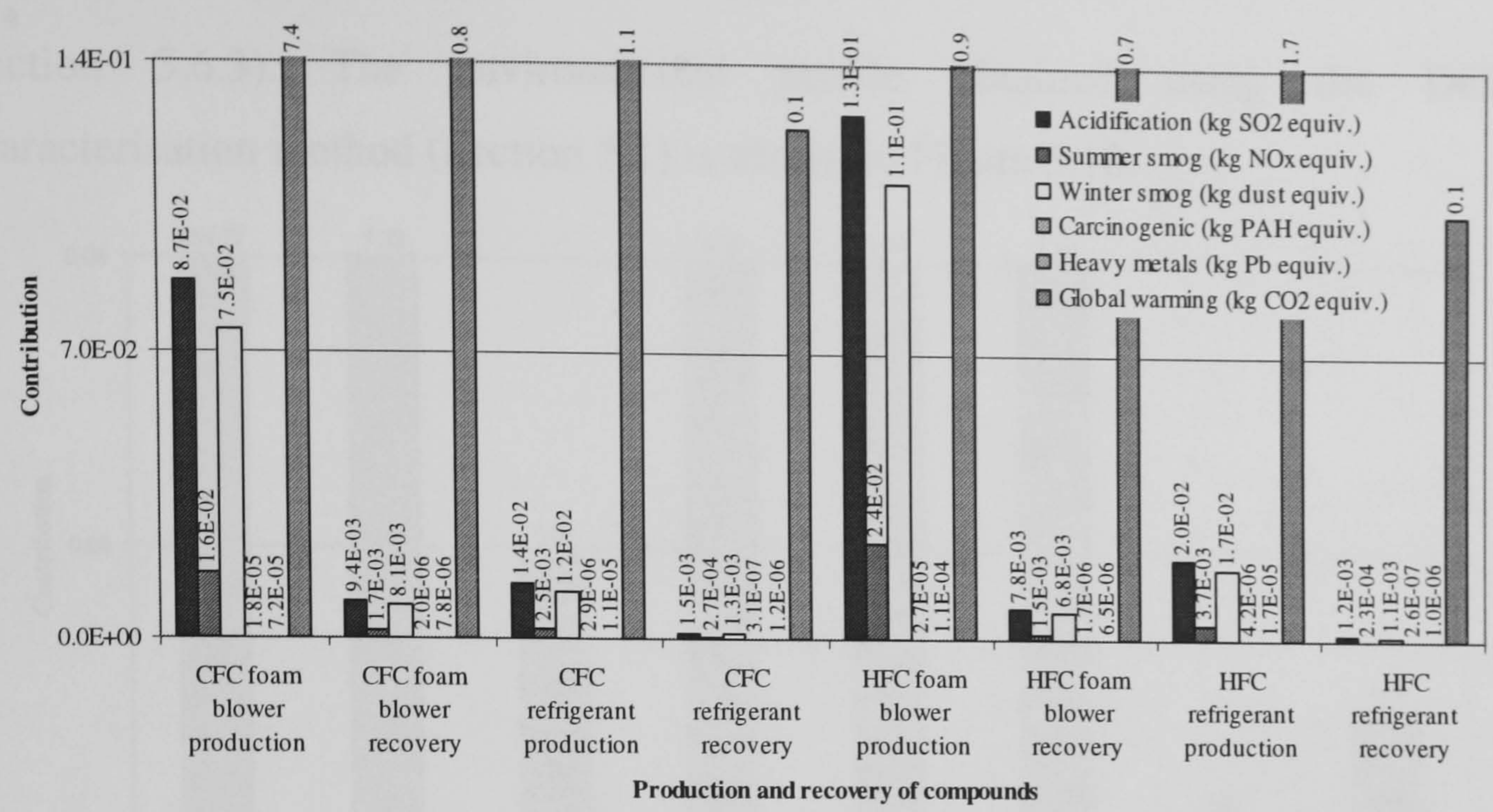


Figure 5.17. Contribution of the production and recovery of compounds; oil fuel scenario

As explained in Section 3.6.3, the purpose of including the four fuel scenarios was to emphasise the fact that the environmental impact greatly depends on the choice of supplier. If the production of the refrigerants only was considered then, for acidification, a worst case scenario of 54% increase for HFC-134a was obtained (compared to CFC-12) and this results for the coal fuel scenario (Figure 5.14). Similarly, for the oil fuel scenario a 43% increase occurs. The charts clearly identify which fuel scenarios would be the most appropriate from an environmental viewpoint. What the charts do not consider are the financial implications, which would most likely favour the coal fuel scenario being the source of fuel widely used in developing countries (Papasavva and Moomaw 1997). Therefore, the extent to which each impact category will be influenced during this stage is mostly dependent on the electrical technology used for the production of these new compounds. The environmental burdens at manufacture are set to be pushed up with the environmentally acceptable alternative even after accounting for 20% more CFC-12 (Table 3.12). It is only during the recovery phase of these two compounds that the burdens are less for HFC-134a.

5.1.6 The energy consumption throughout the product use phase

The difference in energy consumption, observed in Table 4.8 between Test 6 for the CFC-12 and Test 7 for the HFC-134a (a worse case scenario), was assessed from an environmental viewpoint by considering a low voltage electrical supply for the UK

(Section 3.6.3). The environmental profile obtained using the Default Characterisation method (Section 5.1) is shown in Figure 5.18.

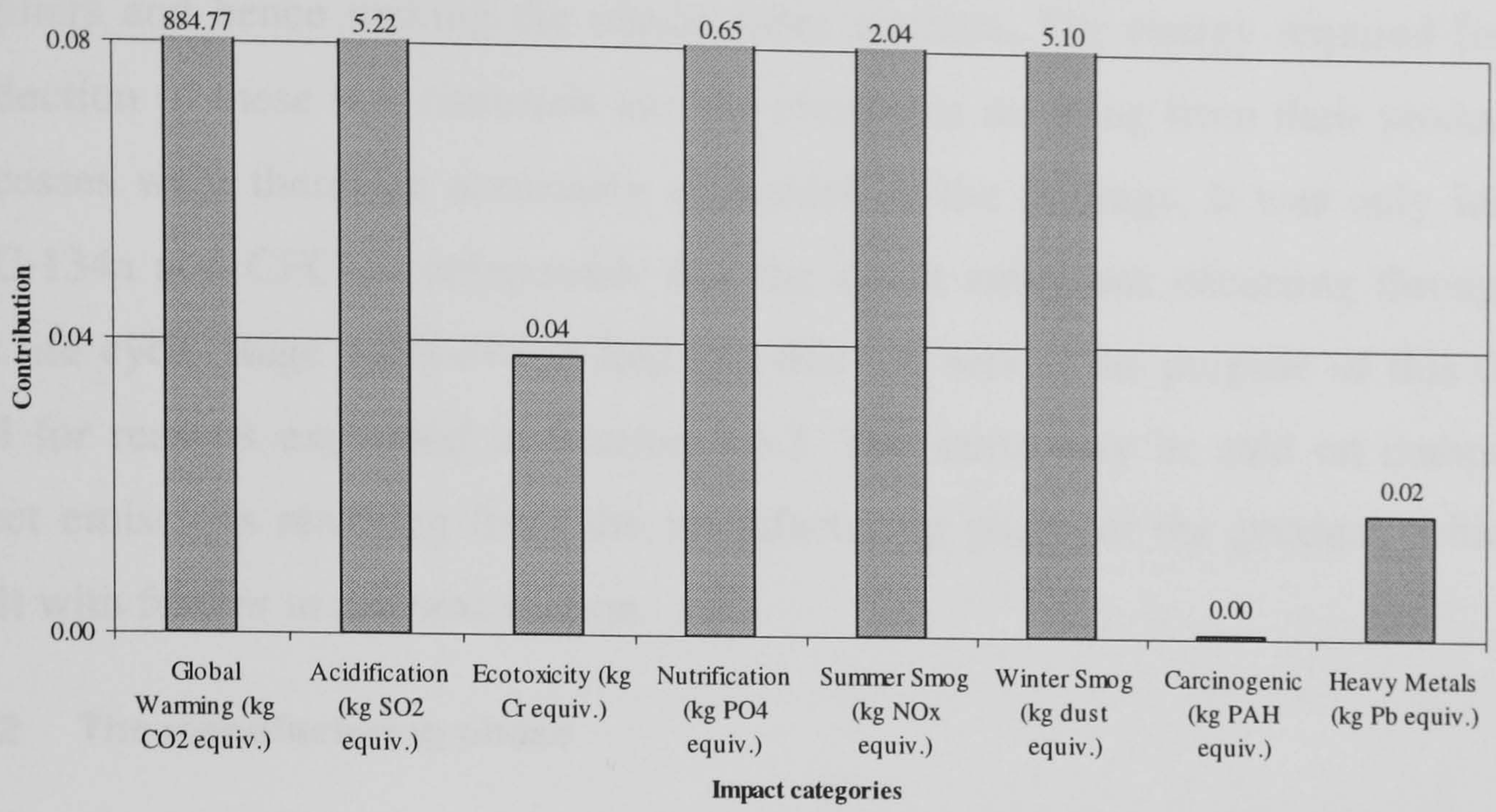


Figure 5.18. The environmental impact as a result of the increase in energy consumption

In this instance, the use of the HFC-134a/POE32 working fluid combination will push the environmental impacts up by more than 850kg of CO_2 equivalent (Figure 5.18). It must be noted that this contribution is just for one functional unit operating at 20% of its 15 year lifespan. This environmentally acceptable refrigerant also augments other impact categories (Figure 5.18), like summer smog and winter smog, which have been identified to be critical in Figure 5.2 and Figure 5.3 respectively.

5.2 Uncertainties and sensitivity analysis

Before proceeding to interpret the results of the LCA study (Chapter 6), a sensitivity analysis was carried out to determine the significance of the lack of information and data uncertainties reported upon in Chapter 3. The tenability of the conclusions reached could thus be strengthened.

5.2.1 The raw material phase

The uncertainties surrounding the emissions resulting from the production of raw materials were unlikely to be very large. These raw materials making up the product inventory (Table F.1) were derived from average data from manufacturers and relevant institutions and incorporated within PEMS (Pira 1998). Data used was not specific to the supplier of the functional unit but average values, collected from various sources, utilised (Table 3.8). This is appropriate since all the raw materials entering the product system considered are likely to be obtained from different suppliers and hence making the results more realistic. The energy required for the production of these raw materials and the emissions resulting from their production processes were therefore accurately embedded in the findings. It was only for the HFC-134a and CFC-12 compounds that the direct emissions occurring throughout this life cycle stage were overlooked and this too served the purpose of this thesis well for reasons explained in Section 3.6.3. The same may be said on compound direct emissions resulting from the manufacturing phase of the product, which is dealt with further in the next section.

5.2.2 The manufacturing phase

During the manufacturing phase uncertainties were high due to the boundaries and assumptions set (Section 3.6.3 and 3.6.5 respectively). The process energies and transport requirements during the manufacture of the individual items making up the functional unit were assumed (Section 3.7.1). Comparing Figure 5.12 to Figure 5.13 characterises the significance the assumptions on the process energies have on a number of product items. Focusing on the compressor, for example, it may be seen that the environmental contribution to human toxicity, nutrification and acidification drop by only 8% whereas global warming and summer smog decreased by approximately 35%. It is clear therefore that the latter two categories are greatly influenced by the type and quantity of electricity. What is of interest to this study is the fact that, with or without energy requirement considerations, the compressor maintains its position as a potential top scorer and will therefore be investigated further in Section 5.3. Such sensitivity studies also shed light on the contribution the energy of production has on findings given in Figure 5.4 and Figure 5.5.

As detailed in Section 3.7.2, the high energy requirement for the manufacture of the insulation was also assessed here (Figure 5.12 and Figure 5.13) to determine its influence on the outcome of the result. The contribution to global warming for the cabinet and door insulation is reduced by 75% if this energy is ignored whilst other impact categories drop by an average of 60%. No more could have been said on what the actual contributions to the individual impact categories were for the insulation since the actual energy requirements for these items was not known. What is emphasised here is that LCA findings should be treated with care and when a priority arises there should be a further analysis of the underlying factors.

The transportation too was assessed to determine its significance on the overall scenario. Due to its reduced significance, findings were not included here for reasons of space. However, as an indication of its contribution, the reader is referred to Section 5.3 where the transportation of the compressor was assessed. This assumption was found to play little or no significance over the outcome of the results and this is in agreement with other published works (Wenzel, et al. 1997). It must be emphasised that this observation was done even after assuming that the steel making up the compressor required a Type 1 vehicle travelling 500km on average road (Table F.1).

5.2.3 The use phase

Data for the use stage was highly reliable since this was recorded from an experimental test rig (Chapter 2) for eight different experiments (Table 3.2). Continuous and interrupted tests were performed to vary the operating scenarios. This may be seen to include a pattern of use for the refrigerator although this pattern is highly dependent on the site and the number of persons utilising the appliance (Figure 2.7). For this reason, as well as the difference in refrigeration systems of the functional unit (Section 3.6.1) and the test rig (Section 2.6), the actual value of instantaneous power varied from the true value (Section 3.7.3). Nonetheless, the percentage differences between the power readings for the individual experiments were highly accurate and it is these differences that were then extrapolated over the lifetime of the functional unit itself (Section 4.3.2). The emissions resulting from the generation of electricity throughout this product life cycle stage was considered to be for the UK (Section 3.6.3) and was retrieved from PEMS (Pira 1998) and therefore considered to be fairly accurate.

Emissions of HFC-134a and CFC-12 compounds throughout the use phase of the product were ignored altogether. The uncertainties resulting from this assumption were unlikely to be significant (Section 3.6.3) given that this research work is involved with quantifying the indirect environmental effects of this change in refrigerant.

A conservative estimate of 15 years (Section 3.6.3) for the lifespan of the refrigerator was chosen. The reason being that the HFC-134a refrigerator has been on the market for a relatively short time, too short indeed to be able to gain an insight into its duration. The accelerated tests carried out throughout this study gave little evidence on this product life expectancy (Section 3.6.3). Should the use phase be longer than 15 years, then the use stage gains a greater environmental significance than that shown in Figure 5.18 whilst the environmental impact occurring from the individual items themselves (Figure 5.13) will reduce in significance. Alternatively, if product durability is reduced, the use phase loses in significance but other life cycle stages gain as more products are produced. This will be emphasised further in Section 6.2.1.

5.2.4 The disposal phase

The importance of the assumption that compounds were recovered at the end-of-life of the product considered (Section 3.6.3) must be emphasised. Any direct release of CFCs into the environment would render the indirect environmental burdens, characterised throughout this thesis, insignificant as chlorinated compounds contribute significantly to the ODP and GWP (Section 1.5.1). The assumption that all HFC-134a and CFC-12 compounds were recovered has other implications, which would have to be considered for completeness. For example, despite assuming 100% recovery, this study overlooks any influences associated with the working environment from the manual handling of these compounds (Section 3.6.3).

Furthermore, for reasons explained in Section 3.6.3 as well as due to the fact that observations made throughout the experimental tests (Chapter 4) gave no hint on the product life expectancy, this study was not involved with assessing the direct and indirect emissions resulting from increased or reduced end-of-life activities. Nonetheless, from the experience gained throughout this project, more insight into the indirect implications resulting from the energy, transportation requirements and similar end-of-life activities are discussed (Section 6.2.1). As explained in Section 3.6.3, for the direct effects resulting from different disposal scenarios of one tonne of refrigerators the reader is referred to (DTI 1999). Table 5.1 is extracted from this study and compares 100% landfilling to the current UK scenario and the proposed EU directive on the treatment of waste from electrical and electronic equipment (*WEEE Directive*). As is evident from Table 5.1, the contributions resulting from 100% landfilling are mostly due to the release of the CFC-11 compound. Since throughout this study it was assumed that compounds were recovered and since the contribution to acidification is fairly identical for any scenario chosen (Table 5.1), then it is almost certain that for the boundaries assumed during this stage no significant direct environmental impacts were overlooked.

Contribution to impact (%)	Acidification	Global warming
Current UK scenario	SO_x (67%)	CO_2 (4%)
	NO_x (31%)	CFC-11 (95%)
100% landfilling	SO_x (77%)	CO_2 (5%)
	NO_x (22%)	CFC-11 (94%)
Proposed WEEE directive	SO_x (65%)	CO_2 (89%)
	NO_x (32%)	CFC-11 (9%)

Table 5.1. Direct contributions at end-of-life of a refrigerator (DTI 1999)

5.3 An environmental analysis for the hermetic compressor

It should be noted that although the hermetic compressor was one of the highest scoring items within the functional unit (Figure 5.13) it might perhaps already be the best solution in environmental terms. However, given its relevance to this study, the significance of the hermetic compressor on the impact assessment (Section 5.1.4) called for further investigation. Throughout this assessment it had to be made clear how much of the significant sources identified in Section 5.1.3 were attributable to the hermetic compressor itself. Therefore, the process energies were completely overlooked, as were all the assembly processes (Table F.2), but the transport requirements were still incorporated. It must also be stressed that during this analysis only the highest scoring items making up the functional unit (Figure 5.13) were grouped together for comparison with the compressor and only the significant sources were included (Figure 5.19 to Figure 5.26). Furthermore, in the previous analyses a high alloy steel was used when assessing the compressor and therefore a plain steel was now included in the LCA model as a matter of discussion to help characterise the effect the choice of material has on this item in particular. Finally, it is important to note that the percentage values calculated and allocated to the

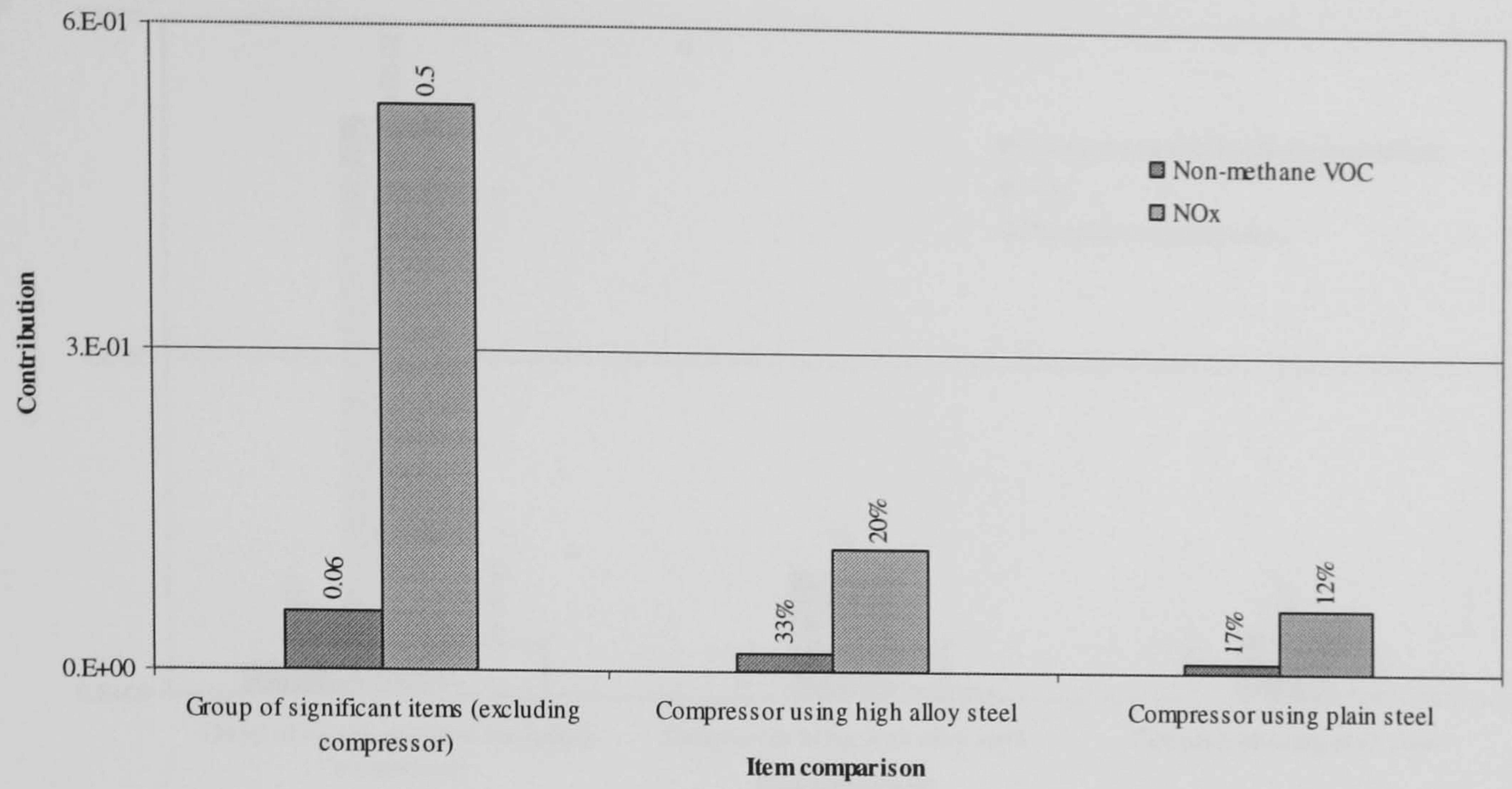


Figure 5.19. Assessing the hermetic compressor for summer smog (kg NO_x equiv.)

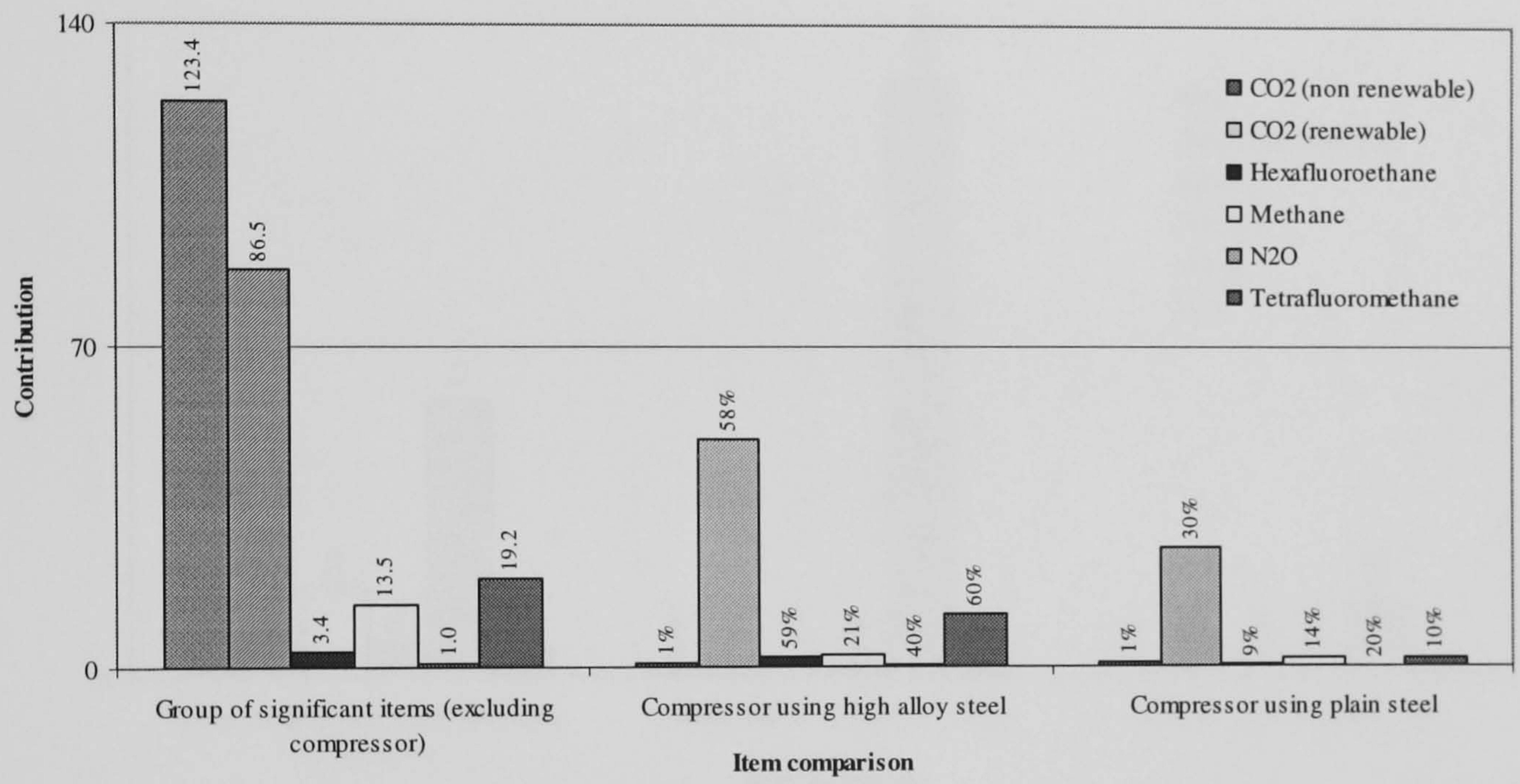


Figure 5.20. Assessing the hermetic compressor for global warming (kg CO_2 equiv.)

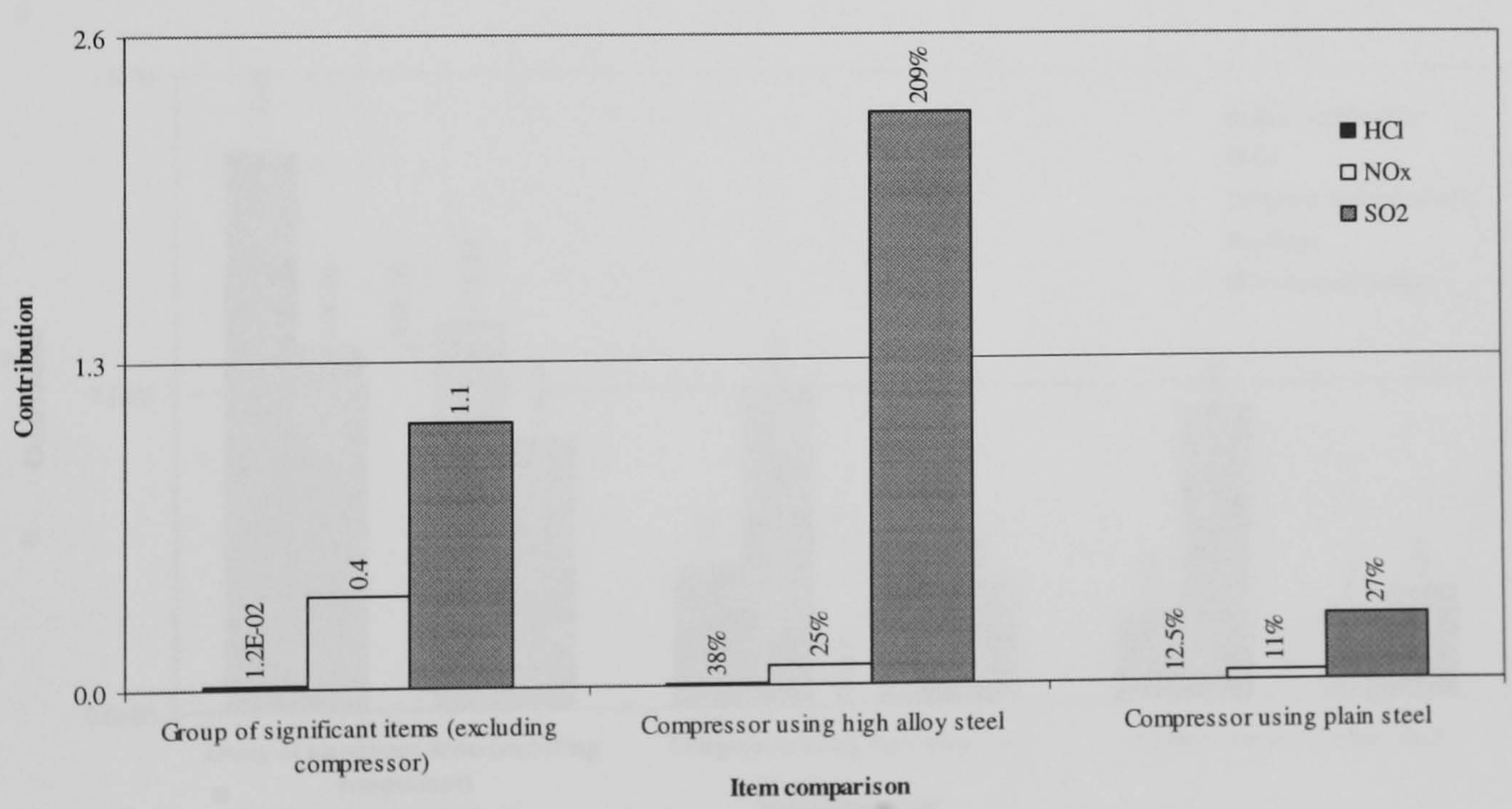


Figure 5.21. Assessing the hermetic compressor for acidification (kg SO_2 equiv.)

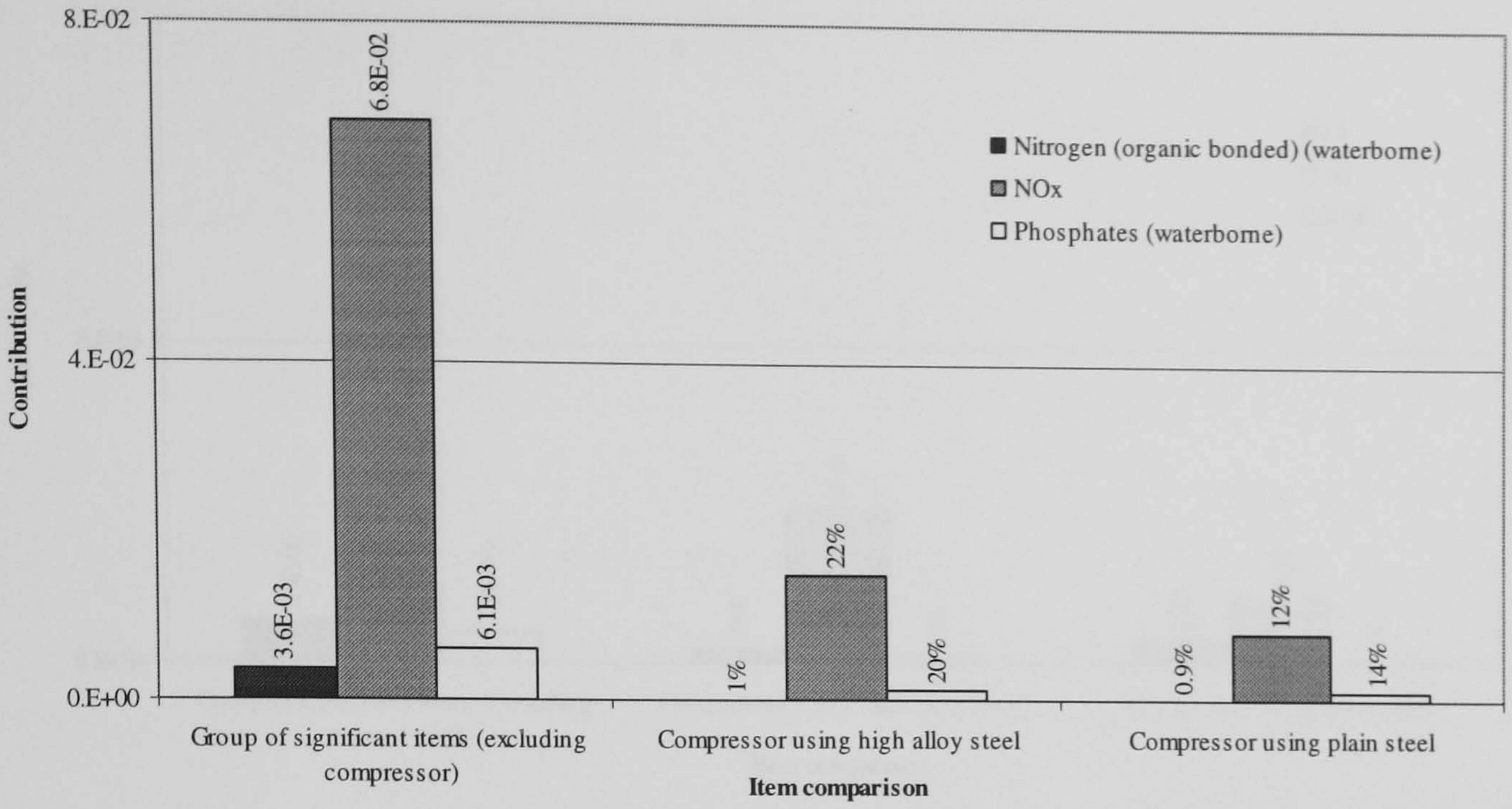


Figure 5.22. Assessing the hermetic compressor for nutrification (kg of PO_4 equiv.)

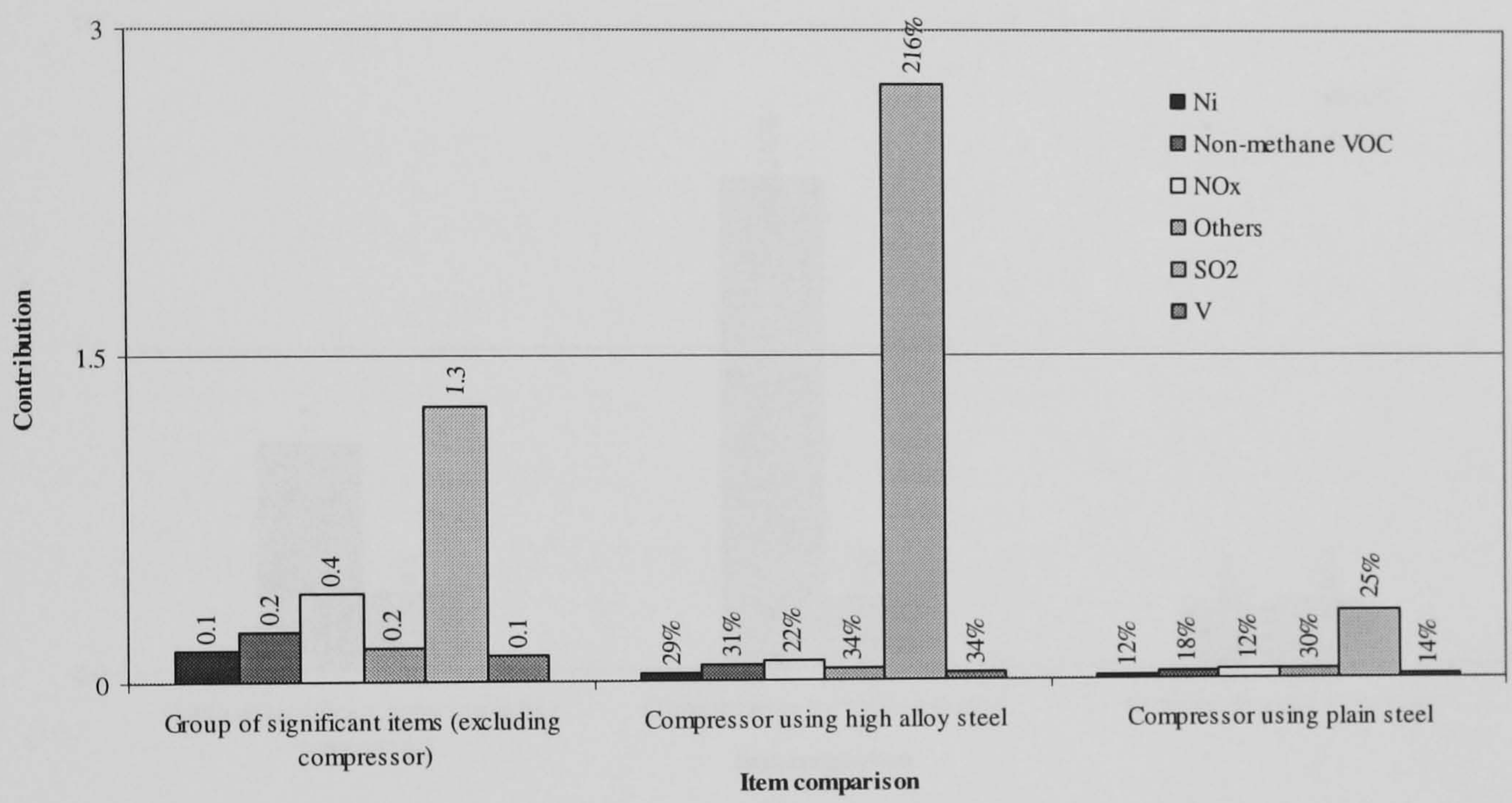


Figure 5.23. Assessing the hermetic compressor for human toxicity (kg/kg equiv.)

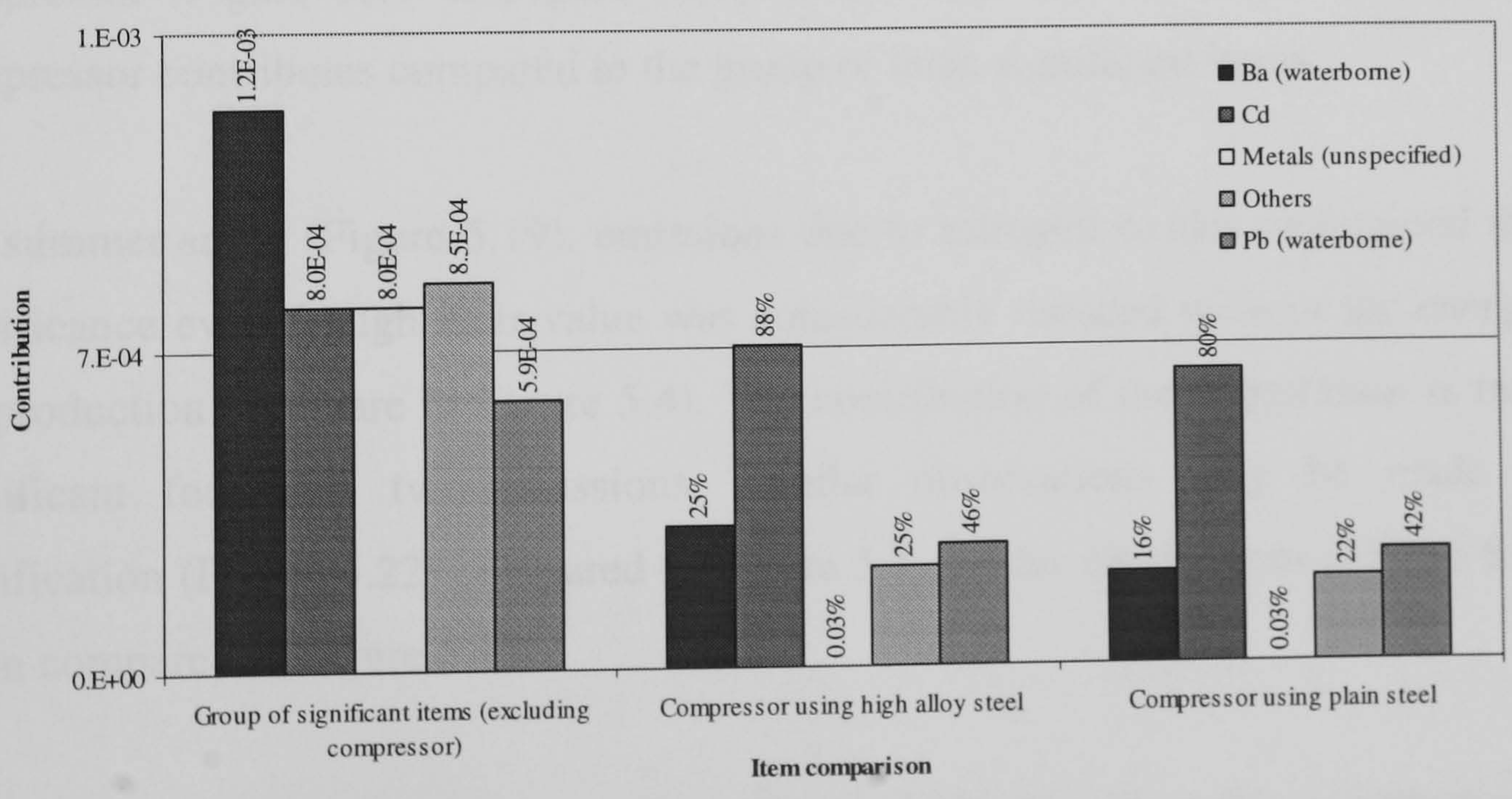


Figure 5.24. Assessing the hermetic compressor for heavy metals (kg of Pb equiv.)

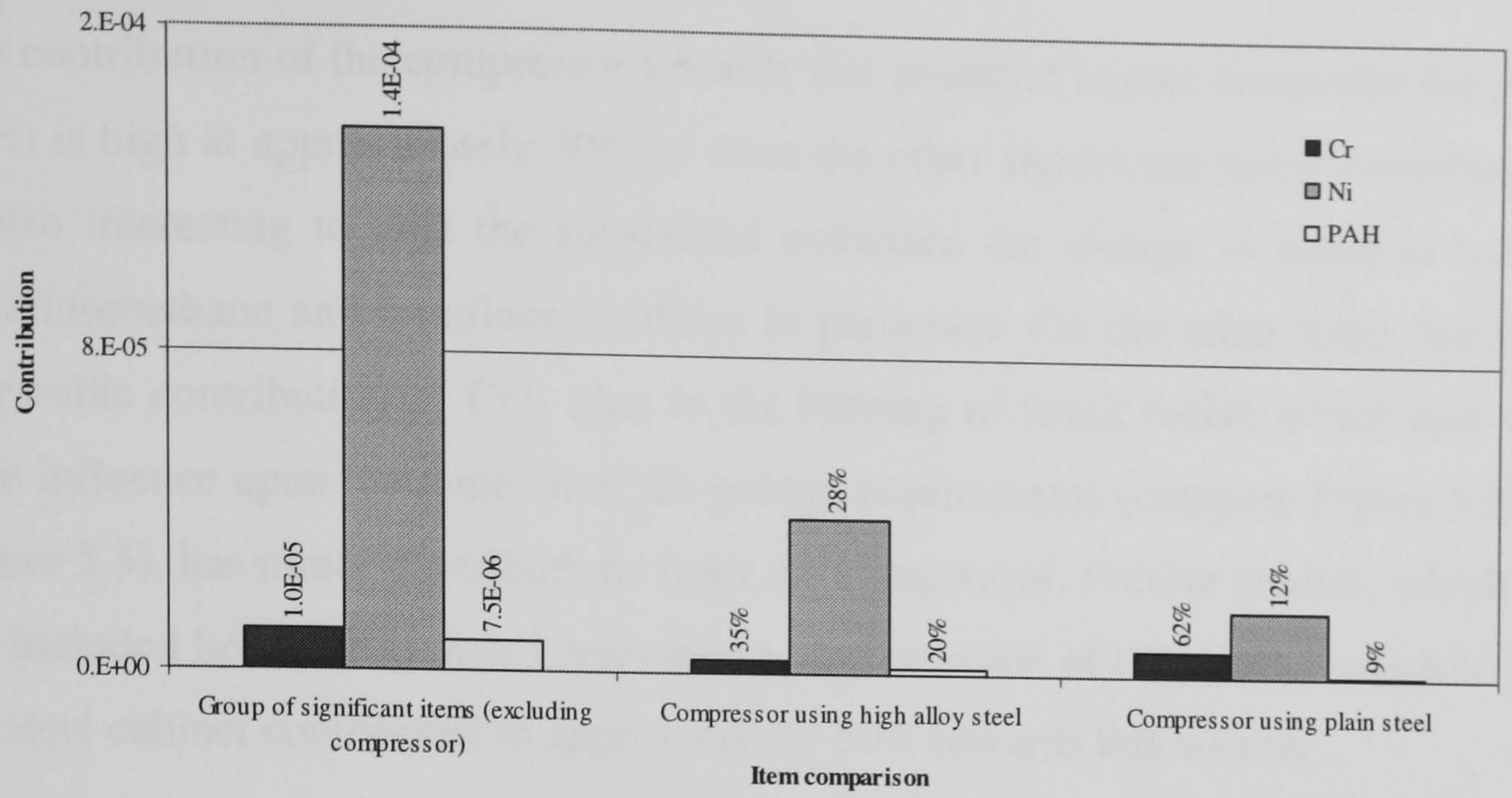


Figure 5.25. Assessing the hermetic compressor for carcinogens (kg of PAH equiv.)

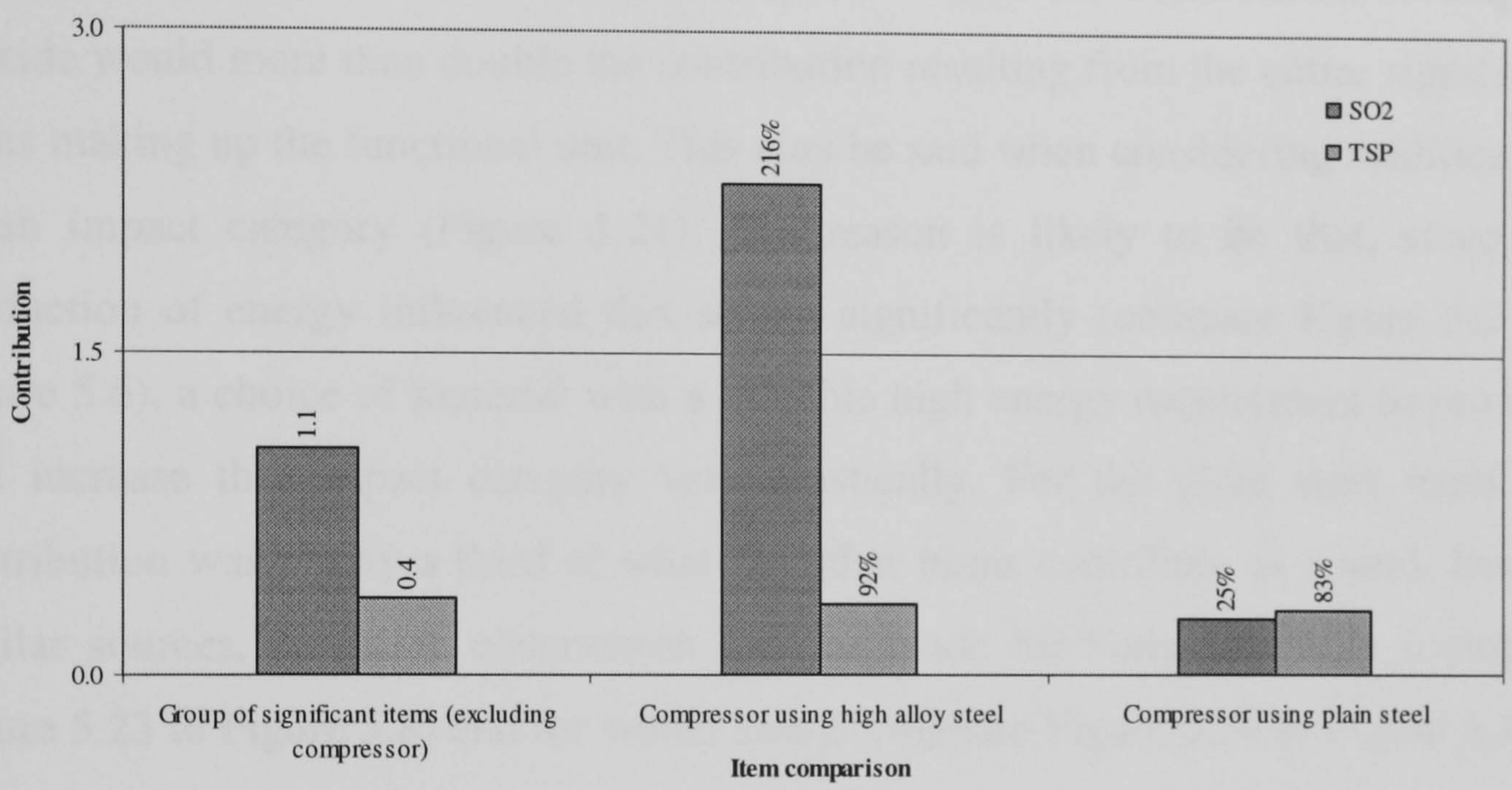


Figure 5.26. Assessing the hermetic compressor for winter smog (kg dust equiv.)

compressor (Figure 5.19 to Figure 5.26) indicate by how much the total for the compressor contributes compared to the group of most significant items.

For summer smog (Figure 5.19), emissions due to nitrogen oxides maintained their significance even though their value was considerably reduced without the energies for production (compare to Figure 5.4). The contribution of the compressor is fairly significant for these two emissions. Similar observations may be made for nutrification (Figure 5.22) compared to Figure 5.7 and for carcinogens (Figure 5.25) when compared to Figure 5.10.

As previously noted, for global warming (Figure 5.20), the renewable contribution to CO_2 drops significantly without the energies for production compared to Figure 5.5.

The contribution of the compressor towards this potential impact (even that for plain steel) is high at approximately 30% of what the other significant items contribute. It is also interesting to note the substantial reduction the change in material has on hexafluoroethane and tetrafluoromethane in particular. On the other hand, the non-renewable contribution of CO_2 (due to the burning of fossil fuels), which had very little influence upon the removal of the energy requirements (compare Figure 5.20 to Figure 5.5), has minor contributions from the compressor. Further studies, which are not included here due to their irrelevance to the outcome of this work, indicated that the steel cabinet contributed to approximately 50% towards this source.

If high alloy steel was used for the compressor then the contribution to sulphur dioxide would more than double the contribution resulting from the entire significant items making up the functional unit. This may be said when considering acidification as an impact category (Figure 5.21). The reason is likely to be that, since the production of energy influenced this source significantly (compare Figure 5.21 to Figure 5.6), a choice of material with a possible high energy requirement to produce will increase this impact category very drastically. For the plain steel itself the contribution was nearly a third of what the other items contribute as a total. Due to similar sources, the same observation may be made for human toxicity (compare Figure 5.23 to Figure 5.8) and for winter smog (compare Figure 5.26 to Figure 5.11).

Another observation made from Figure 5.24 is that for the heavy metals. Whether or not assessing a high alloy or plain steel, the compressor matches the contribution from all the other items making up the functional unit. It is interesting to note that, in Figure 5.9, the waterborne metals were the most significant but the compressor influenced none of these. However, the compressor was responsible for the cadmium and lead contributions identified in Figure 5.9.

To proceed with the investigation, the contributions to summer smog (Figure 5.19), global warming (Figure 5.20), acidification (Figure 5.21) and heavy metals (Figure 5.24) were individually assessed to study the influence that the individual compressor components have towards these critical impact categories (Section 5.1.2). Environmental profiles are shown in Figure 5.27 to Figure 5.30 respectively.

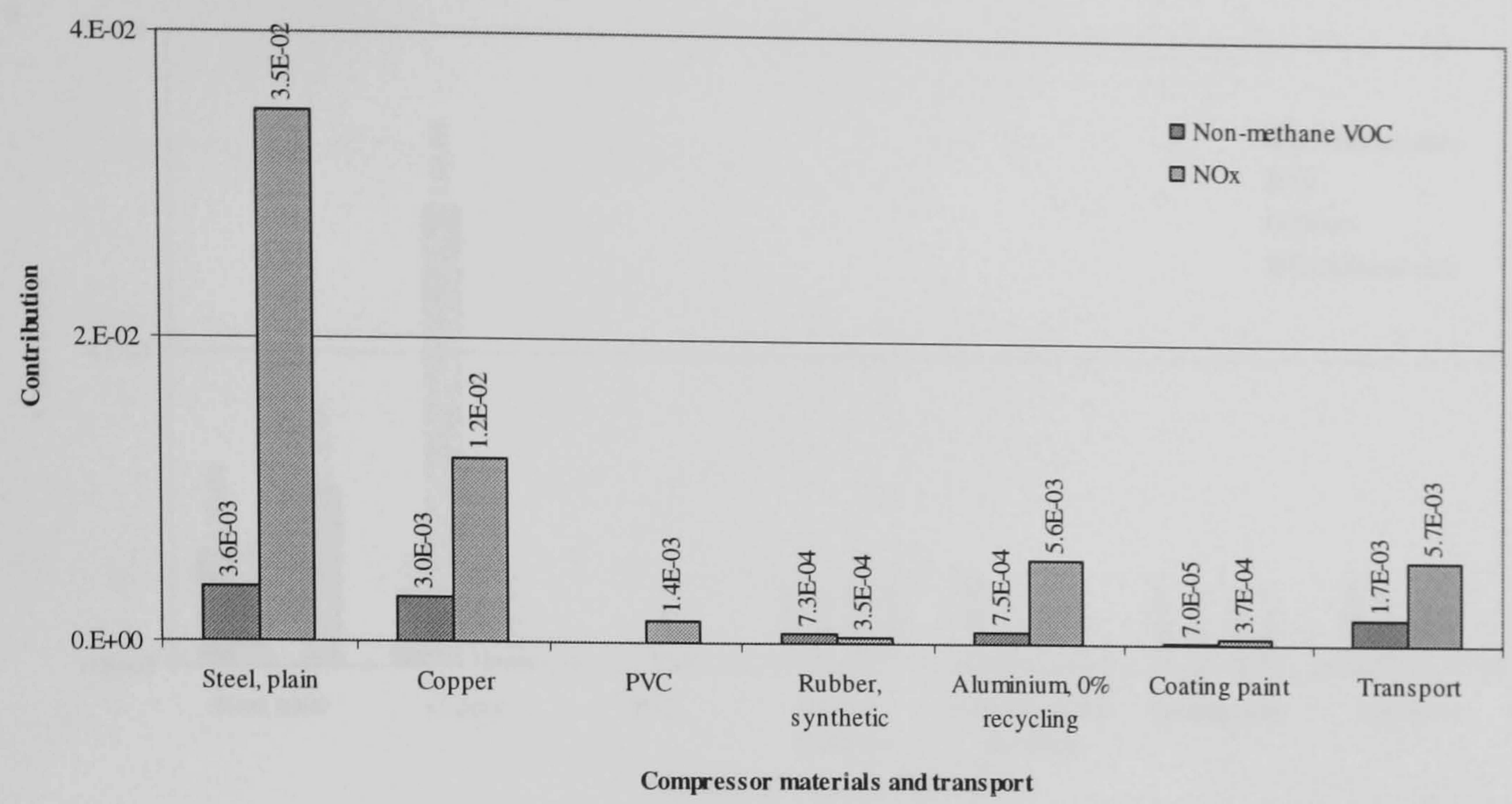


Figure 5.27. Compressor materials and transport on summer smog (kg NO_x equiv.)

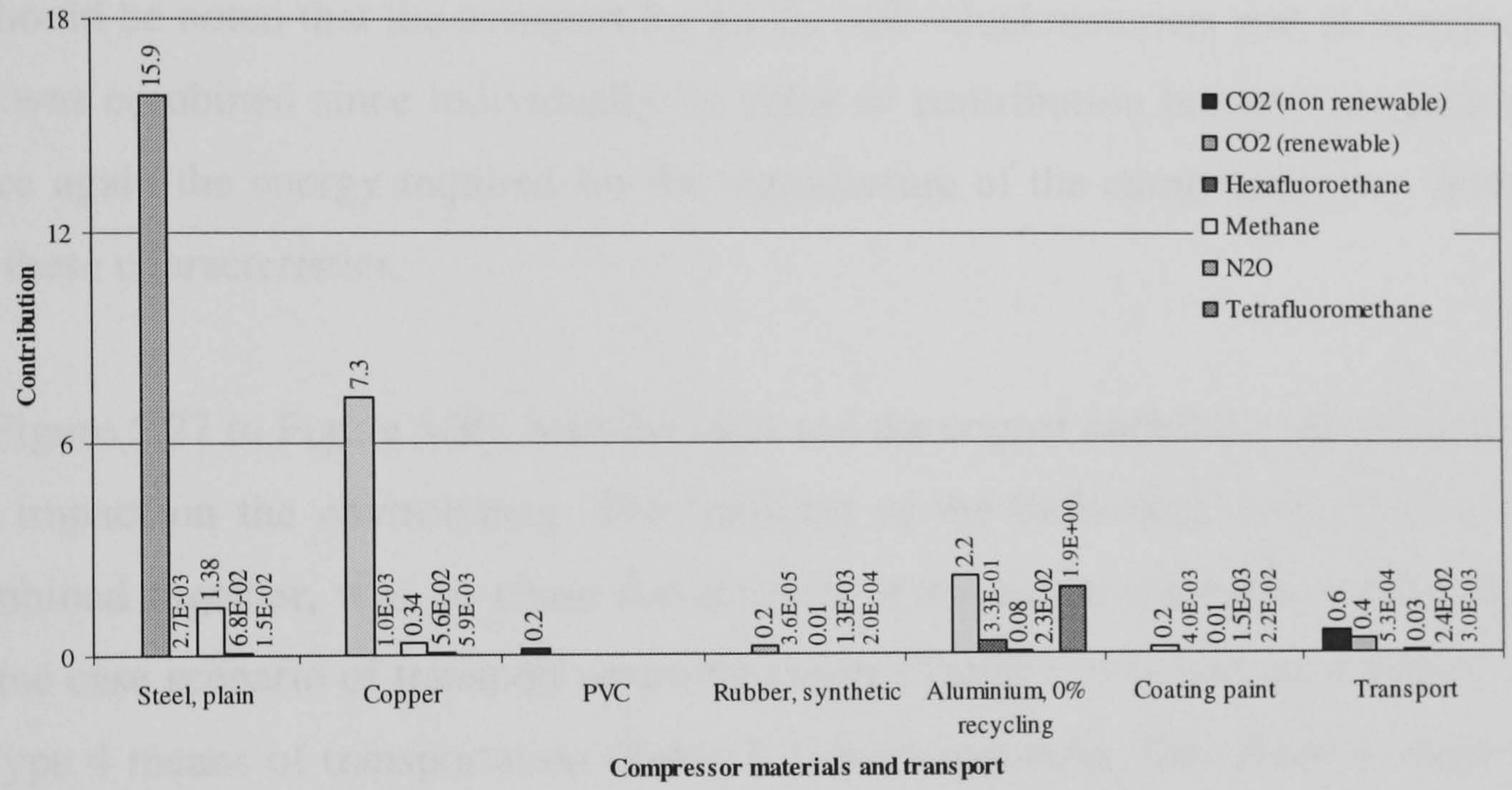


Figure 5.28. Compressor materials and transport on global warming (kg CO_2 equiv.)

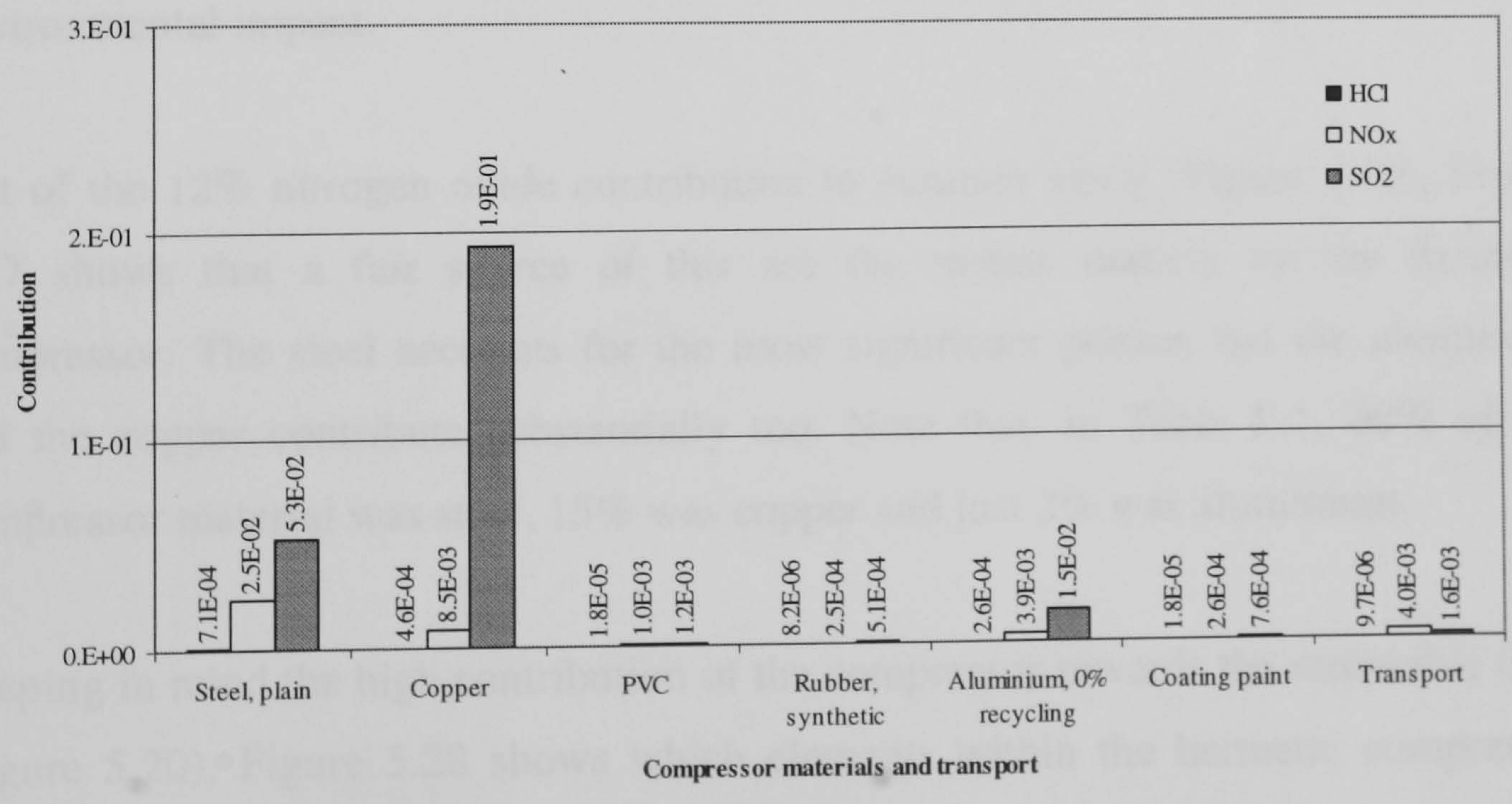


Figure 5.29. Compressor materials and transport on acidification (kg SO_2 equiv.)

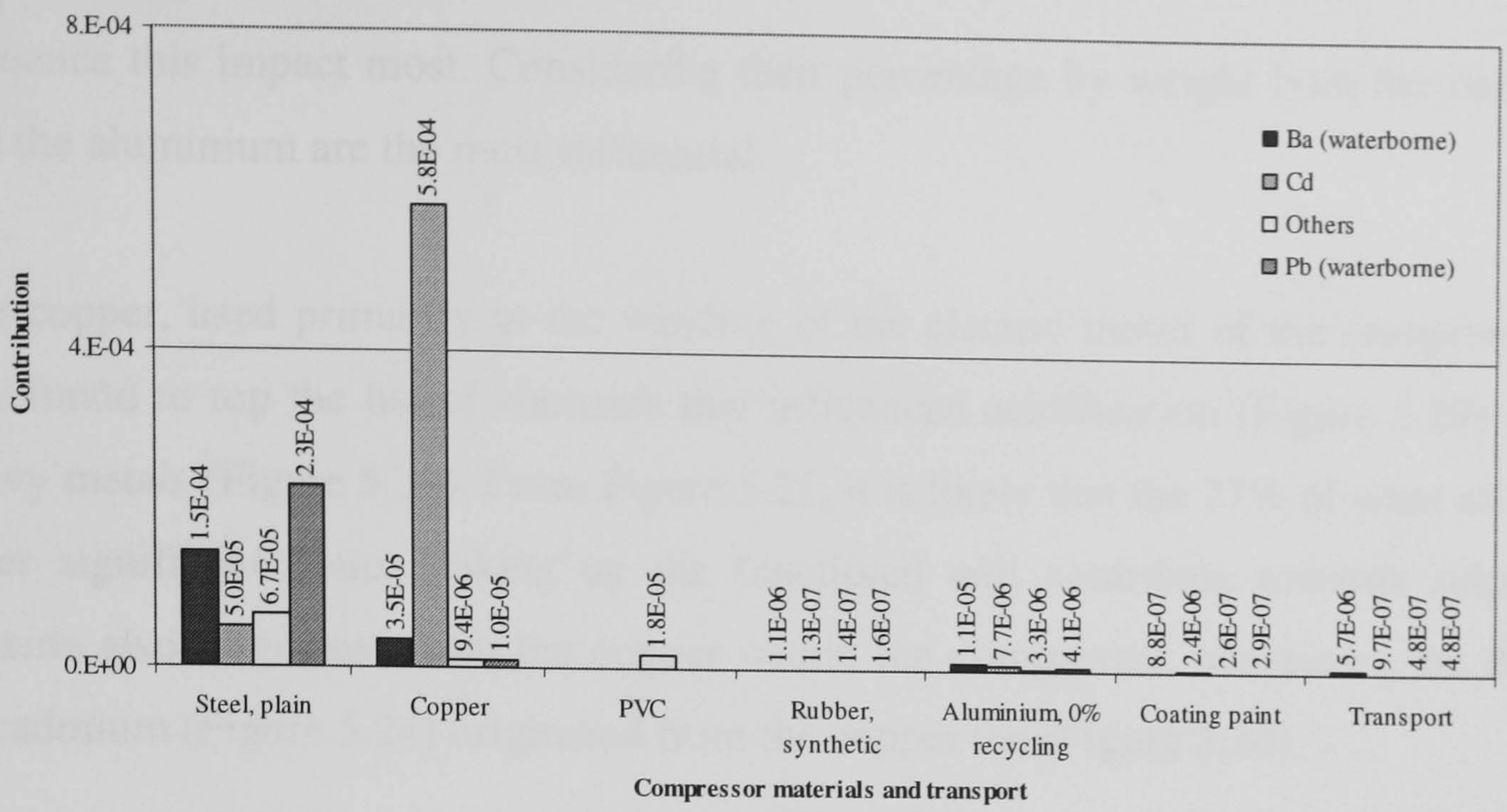


Figure 5.30. Compressor materials and transport on heavy metals (kg Pb equiv.)

It should be noted that the transport for all the individual materials was also included but was combined since individually its value of contribution became insignificant. Once again the energy required for the manufacture of the compressor was ignored for these characteristics.

In Figure 5.27 to Figure 5.30, both the steel and the copper contribute significantly to the impact on the environment. The transport of the individual items, even when combined together, was no cause for concern. It should be emphasised here that a worse case scenario of transport returning empty (Table 3.9) as well as a Type 2 and a Type 4 means of transportation (Table F.2) were assumed. This justifies what was said in Section 5.2.2 about the low significance of transportation on the overall environmental impact.

Out of the 12% nitrogen oxide contribution to summer smog (Figure 5.19), Figure 5.27 shows that a fair source of this are the metals making up the hermetic compressor. The steel accounts for the most significant portion but the aluminium and the copper contribute substantially too. Note that, in Table F.1, 80% of the compressor material was steel, 15% was copper and just 2% was aluminium.

Keeping in mind the high contribution of the compressor towards the renewable CO_2 (Figure 5.20), Figure 5.28 shows which elements within the hermetic compressor influence this impact most. Considering their percentage by weight both the copper and the aluminium are the most influential.

The copper, used primarily in the winding of the electric motor of the compressor, was found to top the list of elements that influenced acidification (Figure 5.29) and heavy metals (Figure 5.30). From Figure 5.21, it is likely that the 27% of what all the other significant items making up the functional unit contribute towards sulphur dioxide also originated from the copper within the compressor. Moreover, the 80% of cadmium (Figure 5.24) originated from the copper too (Figure 5.30).

As may be seen there is no end to such assessments, in particularly because different studies seek different results whilst different LCA practitioners may seek to follow different assessment routes. Different LCA software tools may also focus on different impact categories than those addressed here. Nonetheless, the LCA objectives set out in this study (Section 3.6) have been addressed and the results obtained sufficiently (although not exhaustively) satisfy the requirements of this LCA study.

6 DISCUSSING IMPLICATIONS OF HFC-134a TO REDUCE ENVIRONMENTAL RISKS

This chapter discusses findings made throughout this research in relation to the concept of sustainable development. HFC-134a was found to increase tribological characteristics on compressor components as well as the in-use power of the compressor (Chapter 4). The hermetic compressor itself was found to contribute significantly to the total environmental impact of a refrigerator and a number of contributory factors were identified (Chapter 5). This chapter discusses the relation these tribological characteristics and LCA findings have by quantifying the actual potential environmental impact of a switch in refrigerant. In an attempt to minimise this impact, design alternatives are addressed and improvement potentials towards the sustainable development of mechanical systems working with CFC alternatives identified.

6.1 Influences on product performance

Prior to discussing experimental observations (Chapter 4), it is appropriate to discuss the influence the actual operating conditions (Section 4.1.1) and the choice of lubricant viscosity (Section 4.2.2ff) have had on the results. The consequences of both these influential experimental parameters must be explained to follow this discussion coherently.

6.1.1 Operating conditions

To maintain a bulk oil temperature of 90°C, a compressor shell temperature of 75°C was sought throughout the preliminary and final tests of this research (Section 3.2.2). However, Test D and Test E (Table 4.2) were operating at a higher sump temperature whilst the interrupted 1000 hour tests were operating at a lower temperature due to the cooling off period (Table 4.4). Under both of these conditions wear characteristics seemed to be the most severe (Figure 4.8 and Figure 4.22 respectively). The influence of the operating temperature on lubricity and how this is strongly connected to solubility properties of the lubricant have already been explained in Section 3.2.5. This might explain observations made in Section 4.2.2, where the normal pressure tests seemed to wear out components more than the high pressure tests (Figure 4.8). A possible explanation could be that the high bulk oil temperature at normal pressures reduced the thickness of the protecting film with the ensuing increase in wear characteristics. Seemingly, the lower bulk oil temperature for the interrupted tests (Test 5 and Test 6) influenced the lubricating regime just as the high temperature did. The wear tracks shown in Figure 4.22(a) and (b) were a clear evidence of severe wear interactions that also affected the hard steel. Again, a possible explanation for this may be that a drop in the bulk oil temperature does not simply increase the viscosity of the oil but reduces it more rapidly due to an increase in the solubility of the refrigerant in the lubricant (Section 3.2.5). Both characteristics could have influenced the lubricating film. Clearly, an ideal lubricant temperature must be maintained with these mechanical systems but which cannot be guaranteed under normal start/stop operation.

Another interesting fact, which does not corroborate observations made in the preceding paragraph, is that at higher operating pressures the lubricant viscosity decreases due to the presence of the refrigerant (Section 3.2.5). This should have influenced the wear characteristics of the high pressure tests (Section 4.2.2) more severely compared to those of the normal pressure tests. This was not observed and a possible explanation could be that the bulk oil temperature has a higher influence on the solubility characteristics of a synthetic lubricant than the operating pressure. This may be signified in Figure D.4 for a synthetic lubricant of VG 32. Nonetheless, findings pertaining to a high operating pressure in domestic refrigeration systems are unlikely to attract attention because of a consequent increase in the electrical energy consumed.

6.1.2 Lubricant viscosity

It may be argued that, given the potential benefits of a lower viscosity oil (Section 3.2.4), the CFC compatible oil should have been assessed against POE10 or POE22 (Table 3.1) to obtain a better indication of the performance at start/stop conditions and on the in-use power of the compressor. After all, this work also identified that the POE10 could withstand a load of 140kg for a longer period of time than the POE32 (Section 4.3.3). This 140kg load is actually higher than the load experienced between the connecting rod and the pin at normal compressor operation (Table 3.4). However, the wear tests performed to assess lubricant viscosity (Test A to Test C) identified that the POE32 performed relatively better than the lower viscosity oils (Section 4.2.1). Therefore, generalisations of improved performance with lower viscosity oils must be made with caution. At 30 bar, (a pressure double to that experienced in a domestic refrigeration system) contact conditions were severe and reminiscent of start-up, where a possibility exists that low viscosity lubricants perform better. However, Test A to Test C show otherwise, with the higher viscosity oil performing better than either the POE22 or the POE10. On the other hand, when compared to the CFC/mineral oil combination, the POE32 showed degrading performance both from tribological and monitored power characteristics (Test 1 to Test 6). Therefore, given their similar viscosities (Table 3.1), the power increase observed for the POE32 compared to the SD type oil was not as a result of the viscosity of the bulk lubricant but as a result of friction and wear. As argued, there is reason to believe that this friction and wear would have been augmented if a lower viscosity synthetic ester was used. This justified the fact why lower viscosity synthetic oils were not compared to the CFC/mineral oil combination. This argument might imply that a higher viscosity than that of POE32 would have improved tribological and perhaps power characteristics even further. From the work recorded here it is not possible to determine this but, whatever the outcome, oils with a viscosity higher than that of POE32 are found to be detrimental to the evaporator performance of small refrigeration systems (Short and Cavestri 1992) and hence not recommended for use in refrigerators.

The preceding argument may be corroborated by investigating the typical viscosity charts (Appendix D) for a synthetic lubricant and considering that a minimum viscosity of (5-10)mm^2/s is necessary to separate reciprocating surfaces, as is reported by Kruse and Schroeder (1985) and Short (1990). From the charts, only the lubricant with a VG 32 guarantees a viscosity equal to 6mm^2/s and this after assuming that the temperature at the interface is 100°C and any refrigerant soluble in the lubricant was evaporated. The first assumption is somewhat unrealistic since calculations of the coil winding temperature (Table 4.7) indicate that the temperature at the conforming interface may well be above 100°C, but these charts do not include temperatures beyond this value and 100°C was therefore assumed. The second assumption is seemingly more realistic since at 100°C, or more, much of the refrigerant dissolved in the lubricant is likely to evaporate (Jonsson and Höglund 1993). Here it is interesting to note that, from the viscosity chart of a synthetic lubricant of VG 32 (Figure D.3), a 10% dissolution of refrigerant in oil is comparable to a temperature drop of 30°C.

6.1.3 Protection of contact surface

From a wear viewpoint, the HFC working fluid combination performed less favourable than the CFC/mineral oil combination for either of the two types of machines tested (Section 4.2.3), even though all compressors were optimised for operating in an HFC-134a environment (Section 2.2.2). This was interpreted as a validation of the observations made (Section 2.2.2). One important observation differing between the HFC and CFC experiments, for either of the two types of machines, was the concentration of fluorine on the aluminium alloy (Section 4.2.3). It is most likely that the fluorine present on the aluminium samples working in a CFC-12 environment resulted from the refrigerant since the mineral oil used had no additives (Section 3.2.4). On the other hand, the lesser concentration of fluorine on the aluminium samples working in an HFC-134a environment could have resulted from either the refrigerant or any of the unknown additives present in the lubricant.

The influence of this concentration on differing characteristics observed for the HFC-134a/POE32 and the CFC-12/SD combinations had to be determined.

There appeared to be two possibilities for the difference in concentration of fluorine on samples in contact with HFC-134a and CFC-12. One possibility could be that any films formed on rubbing surfaces would be removed by *fresh* HFC-134a refrigerant as it was carried to the contact area with the oil. However, this was not found to be the case by Yamamoto, et al. (2000) and therefore it was overlooked here. The other possibility was based on the fact that Mizuhara (1994) reported that the CFC-12 decomposes at a temperature equal to 497°C and the HFC-134a decomposes at a temperature equal to 897°C, both of which require the presence of worn surfaces to decompose. This difference in decomposition temperature of the two compounds, which may only occur at asperities due to frictional heat, may well explain the difference in concentration of fluorine on the aluminium alloy samples from the CFC and HFC tests (Section 4.2.3). Given the high decomposition temperature of HFC-134a, it is likely that any presence of fluorine on samples obtained for the HFC tests was due to additives in the base oil and not due to the refrigerant. This could not have been ascertained throughout this research but given the observations made it is important that the remainder of this discussion will focus on the potential effect of fluorine rather than its source in the HFC/synthetic lubricant combination. On the other hand, the presence of the fluorine on samples obtained from the CFC tests indicated refrigerant decomposition and that the asperity contact temperature (better known as the flash temperature) of these small hermetic systems is well above the coil winding temperature listed in Table 4.7. It should be mentioned that, despite its significance to the outcome of this investigation, no attempt was made to calculate this flash temperature. The exclusivity of the variables influencing the conditions experienced throughout these tests make it impractical to attempt this temperature calculation when in effect the presence of the fluorine has been ascertained using XPS. It may be said that a high flash temperature for a small capacity compressor has also been observed in (Padhy and Scheldorf 1994), albeit for a rolling piston type machine.

It has been reported that, apart from this fluoride layer, metal chlorides also form under CFC conditions but these are less likely to react readily with either of the steel or aluminium metals (Mizuhara 1994) and hence the failure in detecting them with XPS. This may also explain why the fluorides were only detected on the aluminium but not on the steel. One explanation for this could be that, as with the chlorides, the fluorides react less readily with the steel. Alternatively, the higher porosity of the aluminium compared to the steel (Section 4.2.3) could have influenced their presence on the former material but not on the latter. Oku, et al. (1989) describe the mechanisms that could have led to the release of this fluoride and chloride for sliding surfaces working in a CFC environment.

The presence of this fluorine was not observed with all the tests carried out (Section 4.1.1). From the samples observed for Test A to Test C wear was severe and no fluorine was observed for the lower viscosity oils with distinct discolourations observed for the POE22 lubricant (Figure 4.5). In Section 4.2.1, these discolourations were associated with either the decomposition of the lubricant or the refrigerant. Given the high decomposition temperature of HFC-134a (see preceding paragraphs) and that discolourations for the POE10 (Test A) were not as evident as for POE22 (Test B), then it may be possible that the discolourations on the samples working in an HFC-134a/POE22 combination were due to lubricant decomposition. This is reported to be around 350°C for POE by Padhy and Scheldorf (1994). It is likely that despite the high dissipation of heat for Test A, there was no film to be decomposed and therefore there were no discolourations to be observed and no fluoride layer formed. Alternatively, for Test B, the presence of an inadequate protecting film decomposed the lubricant before the refrigerant. This could have degraded the lubricant additives resulting in the formation of soaps (Section 4.2.1) but no fluoride layer. It is important to note that this fluoride layer was not characterised by any distinctive marks when observed on the CFC samples, for example. For Test C, some fluorine was observed, as depicted by Figure 4.7. Similar to the final tests, the presence of this fluorine could have resulted in the improved wear characteristics as compared with the previous lower viscosity tests. Test D to Test I also showed severe wear characteristics for normal operation but reduced wear for high operating pressures. As explained (Section 6.1.1), this severe wear was likely to be due to a higher bulk oil temperature at normal pressure, which might have overshadowed the positive influence of any fluoride layer. Alternatively, for the higher operating pressures but an appropriate bulk oil temperature, the presence of fluorine could have accounted for improving the wear characteristics as noted for other high viscosity experiments. Evidence of the presence of fluorine throughout Test D to Test I were found on some of the debris collected (Figure 4.12). It should be noted that the reed valve plate analysis revealed no fluorine at 680eV (not shown in Figure 4.13) but these plates must have experienced different operating conditions to those experienced at the steel and aluminium interface.

Therefore, from the above observations it is likely that for inadequate lubricating films formed by low viscosity POEs the flash temperatures are high enough to decompose the lubricant but not the refrigerant. This does not allow the formation of fluorides. As the POE lubricating film increases, the lubricant does not decompose and therefore a fluoride layer, resulting from the lubricant additives, forms. From observations described in Chapter 4, this layer was not found to be as effective, from a wear and energy consumption viewpoint, as the fluoride layer that forms when the CFC-12 refrigerant decomposes in CFC-12/mineral oil combinations.

The presence of these layers may best be depicted with a cross-section of a lubricated metallic surface with magnified layers, as explained by Dizdar (1999) and shown in Figure 6.1. The outer layers are mainly non-metallic and are affected by the operating conditions and chemicals present within the lubricant and the refrigerant. The thin contaminant layer is most likely where the presence of fluorine, identified on the aluminium alloy samples, is located given that the XPS analyses surfaces at a maximum depth of 3nm (Section 3.3). From the results obtained throughout this research work it is difficult to determine in what concentration these layers occur, how quickly they form *in-situ*, how they fail or regenerate and whether they may be pre-formed on a surface. What is clear, though, is that when these layers are depleted direct metal-to-metal contact occurred, influencing friction, wear and the electrical power required by the compressor. For a detailed explanation of the mechanisms

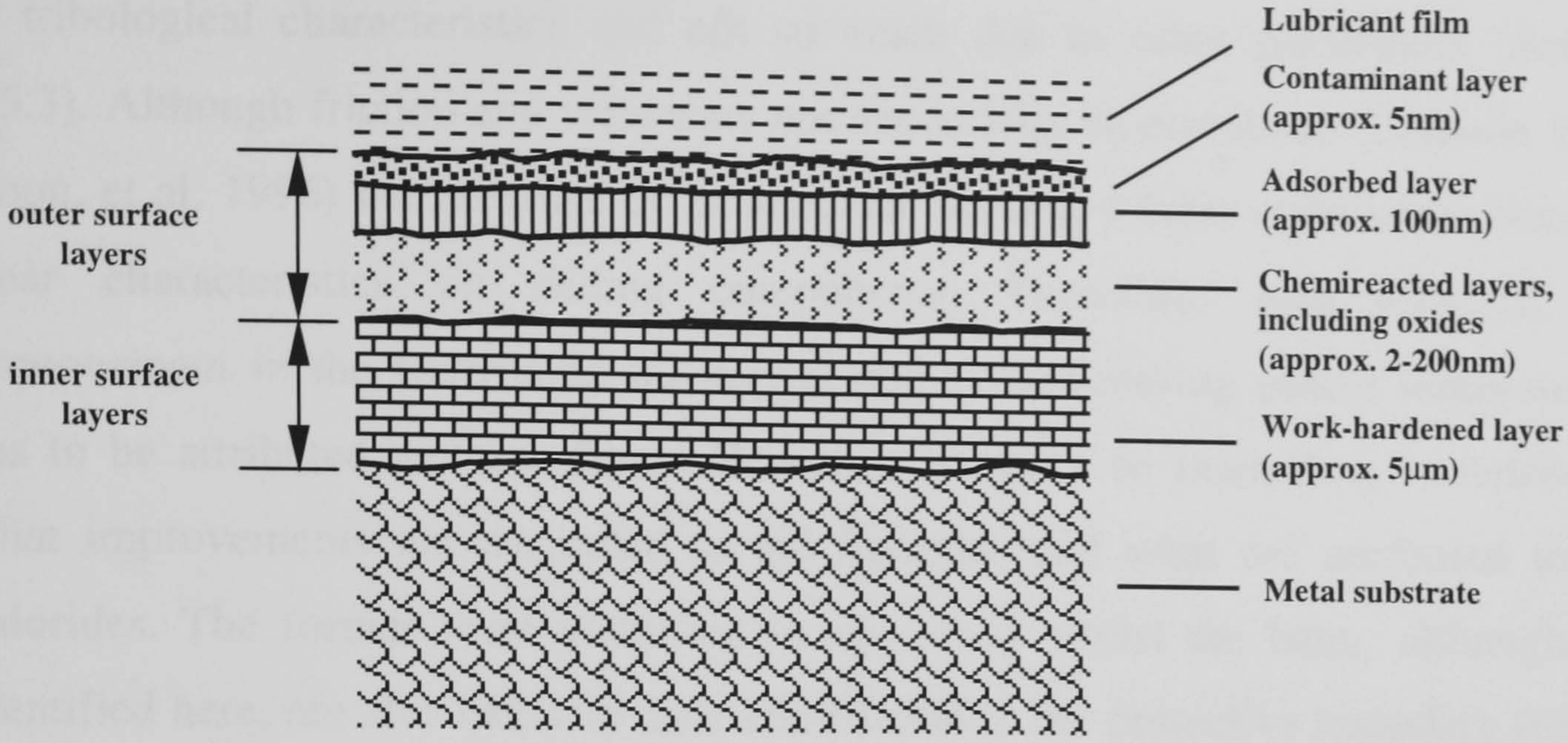


Figure 6.1. Schematic of a lubricated surface with boundary layers (Dizdar 1999)

influencing the formation of protective boundary films the reader is referred to (Czichos 1978).

Findings made throughout this work require that more is to be learnt about the additives within the synthetic lubricants and the role they play in making the HFC/synthetic lubricant combination less efficient than the CFC/mineral oil combination. In an attempt to shed light on this, attention must be focused on the extreme pressure experiments between the synthetic and mineral oils of corresponding viscosities (Section 4.3.3). The outcome of these experiments showed that the synthetic lubricant performed better than the mineral oil in its unused state but the additives in the POE32 were either depleted or degraded after a compressor test. However, it must also be said that the presence of wear debris, which were observed for all the synthetic oil tests throughout Test A to Test I, significantly increases the coefficient of friction at a sliding interface (Section 4.2.1). This could also have contributed to the degrading of these synthetic lubricants under extreme pressure conditions. If this is the case then, although wear debris for CFC environments were not collected throughout this research, the very fact that sufficient wear particles were present to affect failure of the HFC-134a combination is also an indication of inadequacy on behalf of the CFC substitutes.

From the foregoing discussion it seems likely that the increase in the in-use power requirements of the compressor operating in an HFC-134a environment, observed throughout this work (Section 4.3.2) and reported elsewhere (Section 1.5.4), was due to tribological characteristics and not so much due to other parameters (Section 1.5.3). Although friction and wear may not necessarily be correlated (Ludema 1995; Yoon, et al. 1996) the presence of an adequate boundary layer reduced friction and wear characteristics on sliding components. Therefore, with CFC-12, the improvement in the environmental impact due to diminishing power requirements has to be attributed to these films. However, it would be interesting to determine what improvements are attributed to the fluorides and what are attributed to the chlorides. The former were identified in this study whilst the latter, although not identified here, are also likely to have contributed to the protective boundary film. If the fluorides alone were accountable for most of the diminishing power requirements of the compressor then a refrigerant that decomposes at a lower temperature than HFC-134a may provide an ideal environmentally friendly alternative. It would seem a delusion to tackle the direct influence of chlorine on the environment by penalising the benefits of these fluorides due to a higher decomposition temperature. These layers, which are not being sufficiently formed with HFC-134a/synthetic lubricant combinations, are required to form from the refrigerant by decomposing at a lower temperature than that of HFC-134a and hence maintain the indirect environmental benefits of CFC-12. Therefore, it is almost certain that the problem at hand is not simply due to the synthetic lubricants, known to provide greater flexibility for more efficient systems, the emphasis must be on the refrigerant itself.

6.2 Tasks for the sustainable development of refrigerators

Having carried out a thorough investigation of the experimental characteristics, quantification of the overall indirect environmental impact is required to attain the tasks for sustainable development (Figure 1.2). This will be carried out using the LCA findings (Chapter 5) by focusing on CO_2 (a significant greenhouse gas) contributions. This will help identify how a shift in refrigerants must be accommodated so as to address the environmental problems more fully. Component redesign is seen as one possible solution now that chlorinated refrigerants have been replaced and compressor durability may no longer be guaranteed.

6.2.1 Quantifying the indirect environmental impact from a CO_2 perspective

From this research it has been difficult to determine whether product lifetime will be reduced due to a change in the working fluid (Section 5.2.3). Nonetheless, an extension in product lifetime as a result of this change is definitely contradictory due to the increase in the electrical power requirements observed (Table 4.8). Table 6.1 lists the CO_2 contribution for the life cycle of the functional unit up to the end of its technical lifetime (Section 3.6.3), after which no end-of-life activities are accounted for (Section 5.2.4). The table also assumes that the HFC compliant unit fails after 10 years, again assuming no end-of-life activities. This 10 year period is an arbitrary value used to study the implications of premature product retirement and help highlight the fact that for a shorter product lifetime the environmental impact in the use phase drops but all other impacts gain in significance (Section 5.2.3). This value was conveniently chosen to correspond to the projected direct and indirect CO_2 emissions resulting from domestic refrigeration in the UK by 2010 (4.8Mt of CO_2 equivalent – Section 1.5.3). Hence, a percentage contribution towards these projections, as a result of a deterioration of power requirements or premature product failure, was calculated. From the value of discarded units (Section 1.5.3) it was necessary, for calculation purposes, to assume that 1.2 million HFC-134a units are sold in the UK in the year 2000. Details of how the values in Table 6.1 were obtained are given in Appendix J.

For the completion of Table 6.1, four considerations were made. Firstly, it is important to note that the impact for the mineral and synthetic lubricants was included for completeness (Section 3.6.3). This value assumes the production of the base oil alone and no consideration to the unknown additives in the POE was made. Therefore, this value is inaccurate but was included as it does not increase the results significantly and it is appropriate for comparison. Secondly, for the contribution throughout the use phase, the compressor electrical requirements for Test 6 and Test 7 were considered and these were assumed to stabilise just after 1000 hours of operation (Table 4.8). From observations made throughout this work, no indication of this assumption was given and therefore it is possible that the lifetime contributions will actually increase further for HFC-134a. Thirdly, during the time

	HFC-134a compliant (kg equiv.)	CFC-12 compliant (kg equiv.)	Increase in contribution for HFC unit[a] (kg equiv.)	Contribution towards 2010 projections for CO_2 equiv. emissions[b]
Items[c] making up the functional unit[d]	666.8	663.9		
Compressor[d]	103.6	103.6		
Refrigerant production[e]	1.4	0.9		
Lubricant production[f]	0.8	1.2		
Lifetime of functional unit[g]: 15 years	2525.1	1640.3	887.8	15%
10 years	1683.9	1093.6	849.8	21%

[a] if premature failure of the unit does not occur, then the increase is due to the energy consumption plus the difference in dissimilar contributions at manufacturing. If failure occurs, then the contribution from the increased production of the individual items must be accounted for together with the increase in contribution due to the energy consumption over the 10 year lifetime. The values obtained are explained in Appendix J

[b] based on the projected UK greenhouse gas emissions from domestic refrigeration (4.8Mt – Section 1.5.3). Value calculated as in Appendix J

[c] compressor not included and foam blower assumed to be CFC-12 (worse case scenario)

[d] assuming a mixed fuel scenario for the manufacture and assembly of parts (Section 3.6.3). Values obtained from Figure 5.12 and detailed in Appendix J

[e] assuming a mixed fuel scenario (Figure 5.16) as detailed in Appendix J

[f] values obtained as detailed in Section 3.6.3 and in Appendix J

[g] for interrupted tests and assuming a low voltage electrical supply for the UK (Section 5.1.6). Calculations of energy consumption and CO_2 contribution were calculated as in Table 4.8 and Section 5.1.6 respectively. Note, neither of these two calculations are shown in this thesis but more is said in Appendix J

Table 6.1. Refrigerator CO_2 contributions and its increase on 2010 projections

this research was carried out not enough information was obtained regarding the indirect effects of the disposal phase of a refrigerator (Section 5.2.4). Undoubtedly, this would have augmented the percentages in Table 6.1. Finally, the percentage value obtained, albeit indicatory, does not account for any HFC-134a units manufactured prior and after the base year assumed (the year 2000) and therefore the contribution itself may be even higher.

Findings in Table 6.1 emphasise the importance a detailed LCA study has. Although influenced by the boundaries and assumptions set (Section 3.5ff.), this table should justify the use of the life cycle concept in quantifying the environmental burdens resulting from the use of a CFC substitute. By considering and comparing the CO_2 equivalent emissions to projected emissions, this table identified a significant setback to the efforts being made by the UK (and other countries) to reduce greenhouse gas emissions from the domestic sector as a result of the Kyoto Protocol (DETR 2000). It is only through the use of this life cycle concept that the significance of such a contribution may be measured. Findings made here also emphasise the fact that, although shortening product lifetime increases the emissions pertaining to manufacturing, the environmental impact resulting from increased energy consumption is high enough to render a shorter product lifetime attractive, should new products become more efficient. Of course, this study does not account for indirect emissions resulting from end-of-life activities, which would increase if shorter lifetimes were experienced. Nonetheless, the slight difference in percentage values obtained calls for further consideration.

6.2.2 Linking refrigerator design considerations to sustainability

Despite the fact that much research efforts are focused on improving refrigerator performance (Section 1.5.3), at the time this thesis was written it was apparent to the author that improvements for this product had reached a point of diminishing returns. Furthermore, much of the emphasis seemed to be directed away from the small hermetic compressor studied here. Little change had been made to this type of compressor from the simple and successful (albeit inefficient) mechanical system that operated with CFCs to the one operating with HFCs. In view of this, it is hoped that the outcome of this investigation will stimulate new ideas for new developments to be encouraged. This is essential at a time when, although emissions per capita are falling (Calm, et al. 1999), the rise in population growth, improved standards of living and a deterioration in the supply of power requirements are likely to increase the indirect environmental impact pertaining to this product. The remainder of this chapter will seek to highlight these new opportunities.

The systems-based approach (Section 1.1) applied throughout this research work identified no indirect benefits to be gained by switching to non chlorinated refrigerants and this after addressing just one of the many issues likely to be influenced (Section 1.5.3). The use of HFC-134a lessens compressor performance and this alone does not make the refrigerant or the refrigerator operating with this compound environmentally acceptable. What makes it worse is that if direct emissions of HFC-134a are further restrained (Section 1.5.1) then, for the refrigerator at least (for reasons of negligible direct effects – Section 1.5.3), restraining CFC-12 rather than banning it would have resulted in a greater environmental benefit. This highlights the complexities that govern the environmental criterion on products indicating the unintended consequences that arise. For the case discussed here, focusing on the ODP or GWP of a refrigerant compound as a *command and control* indicator is ineffectual, especially since legislatory targets, or indeed the GWP indicator itself (Calm 1999), are continuously changing. Indicators limit the number of available alternatives, which indeed are a prerequisite to the concept of sustainability (Section 1.1).

Addressing sustainability for domestic refrigerators may not necessarily depend on the development of a new refrigerant (Section 6.1.3). Furthermore, shortening product lifetime to address findings made in Table 6.1 does not seem to address sustainability either, due to the additional resources required. A means to accommodate both considerations is to focus on the hermetic compressor itself, identified to contribute significantly towards the overall environmental impact of the refrigerator (Figure 5.13) and whose performance is deteriorating with the shift in refrigerant. Due to the different materials used, disassembly of electric motors has always been problematic (Legarth and Nilsson 1997; Caspersen 1998) and the hermetic compressor is unlikely to make this any easier. The *resolution* (Pahl and Beitz 1995) of this mechanical system is very low, due to its steel enclosure, making it impossible to maintain, upgrade and reuse any of its internal components. Even if 100% recycling of these machines is possible this should still be considered unsatisfactory for sustainability due to the amount of materials used and its robust design. It should be mentioned that at the time this thesis was written no evidence of compressor recycling was found for the UK, whilst for other EU countries this is reported to be approximately 40% (Hansen and Gustafsson 1994). Nonetheless, the environmental impacts identified in Figure 5.13 should motivate the immediate reuse of components in the development of new compressors; recycling laws simply do not suffice.

A change in perspective, which should not be restricted by financial considerations, is therefore required if issues of sustainability are to be attained. The hermetic compressor needs to be re-addressed to ensure that once system performance deteriorates this may be maintained/upgraded with ease and product durability ensured. This is also seen to conform to the concept of extended producer responsibility (Section 1.5.2). However, rather than designing for a longer life by making the product more robust using more resources, life extension for the compressor, and hence the refrigerator, should be attained through serviceability. This concept is seen by many as an important life cycle issue (Eubanks and Ishii 1993; Marks, et al. 1993). Coatings on the bearing studied here would reduce the friction and wear effects observed, as noted in (Padhy and Scheldorf 1994; Dearnley, et al. 1999; Rosemann, et al. 2000) but this too is a manufacturing process with consequent financial and environmental implications. Furthermore, the protecting layers noted in Section 6.1.3 may also be forming on other rotating components including the armature, the driveshaft, etc., on which friction will also be reduced. The highly competitive compressor market may not sustain additional costs required for serviceability but this may be made attractive to companies if maintenance fees are introduced and customer satisfaction enhanced. Unfortunately, although modular refrigerators have been studied, an example of which is described by Remich Jr. (1992), the hermetic compressor has always featured as a complete component that satisfies a functional requirement with little attention to maintenance, malfunction diagnosis and repair. If such operations are carried out with ease they will have a significant impact on customer satisfaction and environmental costs, hence increasing added value to the overall product (Section 1.5.2). If ever there was a chance to exploit new technologies that can improve quality and performance of the compressor it has never been as opportune as it is today given the shift in refrigerant gases.

This concept of serviceability is also of significant importance if refrigerators are cascaded onto second hand markets, usually with little maintenance on the compressor being carried out (OECD 1982). This requires that system performance be optimal even at this stage of the product life cycle, particularly if these second hand products are exported to developing countries (Tomiyama 1997). Generally speaking, environmental legislation is less stringent in these countries (not covered by the Kyoto Protocol (Campbell and McCulloch 1998)), climates are warmer and the use of coal as a fuel for electricity generation is also a possibility.

To extend product lifetime it must be ensured that the cost of serviceability compares well with the overall cost of a new product, which at present is too low for any incentive to be realised. If a new compressor is on the market, an old compressor may be replaced without having to discard the whole refrigerator. Alternatively, the energy consumption of the compressor may be periodically monitored to identify when its performance deteriorates. In both instances, the ageing compressor is compulsory traded-in, the component itself or indeed subcomponents of it, should be fairly evaluated for any remaining value and depending on the outcome will be either refurbished or reused. Such a growth-sustaining product (Section 1.5.2) requires specialised tooling and personnel due to the use of the refrigerant gas and the potential for leaks as well as any contaminants entering the system. However, with a collection infrastructure (Section 1.5.2) as advanced as that of product distribution, such maintenance might be done within a service company where the product is returned for upgrading. Providing a service industry to physically and functionally upgrade products (these may also be leased) may still provide satisfactory company profits. Although life cycle costs need to be accurately known, sales figures are set to increase with a drastic reduction in waste figures, as shown by the maintenance centred product life cycle simulation already performed by others (Section 1.5.2). Maintaining a compromise between ecology and economics through the environmentally oriented concept discussed here is seen as one way towards optimising and supporting the competitive strength of this product.

From findings described in Section 4.3.2, another option worth investigating is that continuous compressor operation may provide an overall environmental benefit. Reducing the start/stop frequency and hence maintaining a favourable bulk oil temperature (Section 6.1.1) may prove to be beneficial in the long term. This may perhaps be achieved by allowing the speed of the compressor to vary by evolving new electronic controls capable of sensing any changes in the demands of the system.

Further discussion on sustainability, based on the findings made throughout this thesis, will have no end. Dwelling on resource consumption, for example, would focus on the 1.7kg of copper used in the functional unit considered (Table F.1). This was found to have a significant environmental impact (Section 5.3) and its worldwide availability is not for certain either. Premature product failure will consume more of these raw materials, drastically impeding sustainability. As given in Section 5.1.5, focus may also be made on the choice of subcontractors. The environmental impact resulting from the technology for the production of electricity around the various regions of the world vary significantly and a shorter product lifetime will further increase any arising impacts. Finally, although the definition of sustainability pertaining to this thesis does not allow it (Section 1.2), focus may also be made on the financial costs of the product life cycle, an example of which is described by Veefkind (1999). Rather than focusing on the environmental burdens one may choose to focus on the economics of this switch in refrigerant. Premature product failure increases process, transport, production as well as other life cycle costings, hindering the financial dimension of sustainable development (Section 1.2).

6.2.3 Establishing sustainable development

Having characterised the environmental impact resulting from the experimental observations made and having identified possible alternative routes to curb or minimise this impact, the final task of this research is to synchronise and conform these findings to the sustainable development framework explained in Section 1.2.2. This does not only highlight one possible alternative to attaining the sustainable development of the system studied here, but also identifies a possibility of generalising research findings. Indeed refrigeration systems vary remarkably but a possibility exists that these too may gain from the findings made throughout this research.

Figure 6.2 demonstrates how the framework in Section 1.2.2 is applied to refrigerant use in addressing the sustainable development of these mechanical systems. The outcome of this research was essentially a working fluid assessment, employing a multi-dimensional view (Section 1.1) by addressing traditional technological and life cycle viewpoints. Indeed, there are other issues influenced by a change in the working fluid, which have to be addressed (Section 1.5.3) and which may alter the findings made here. Nonetheless, making these and similar findings available for discussion and for identifying alternatives is the next important step towards sustainable development. In the same way that it is essential that this knowledge is rapidly acquired (Olesen and Keldmann 1994), it is also essential for this knowledge to be shared (EPSRC 2000), reused (Tomiyama, et al. 1995) or even *traded* (Frank

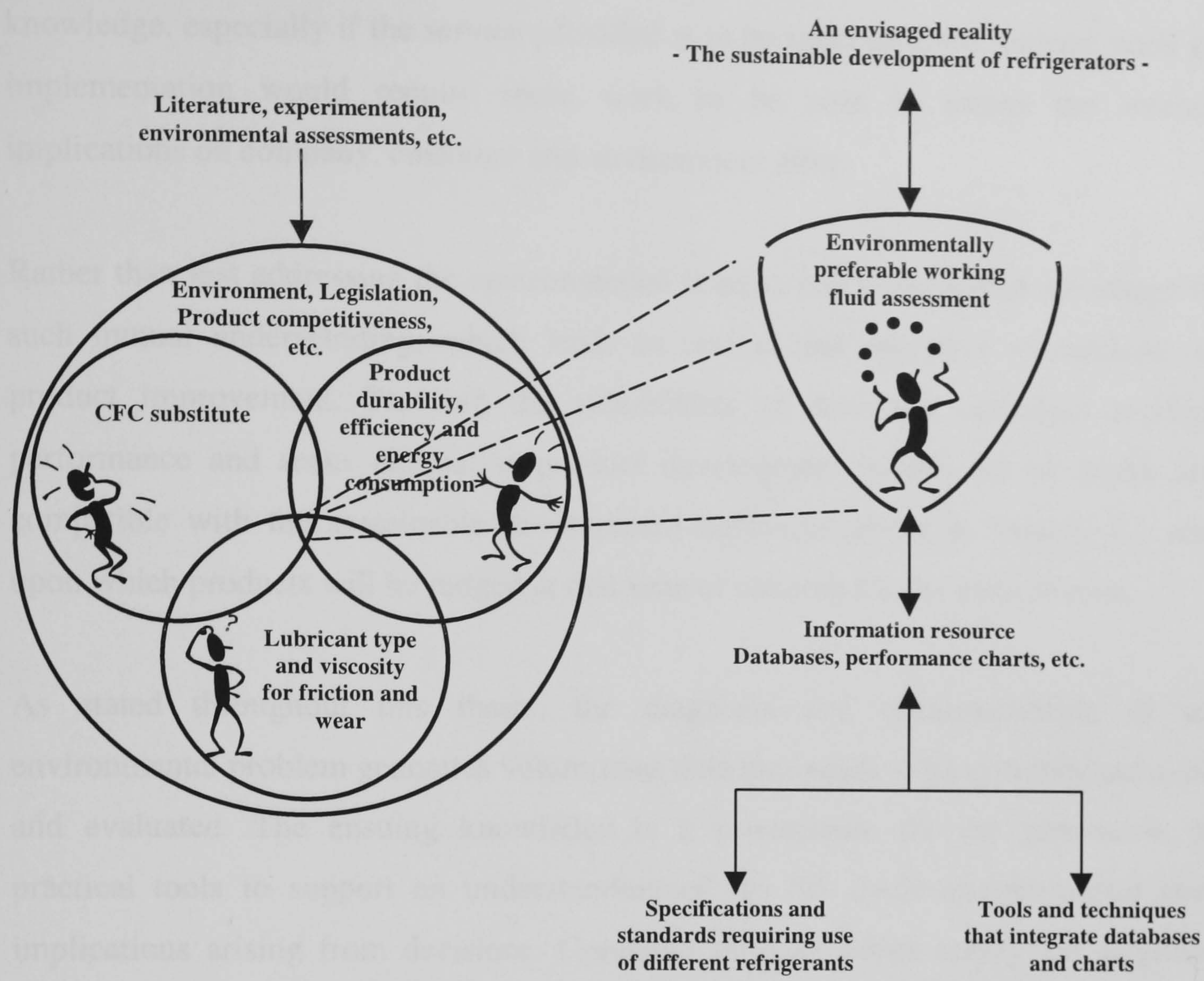


Figure 6.2. The components of sustainable development applied to the use of an environmentally preferable refrigerant

1999) in value creating processes that address the environment. This life cycle knowledge permits choice and facilitates communication among decision-makers but must first be translated for interpretation by the different stakeholders who not only influence decisions but also influence unknown consequences. This is essential for moving away from the so called environmental indicators that have proved to be both environmentally and economically inadequate so far. The final component shown in Figure 6.2 is more concerned with the implementation of this translated knowledge. This may take the form of specifications and standards in the immediate term whilst tools and techniques are more of a long term development. For the case study considered here, the specification and standards would require that refrigerants be evaluated on their direct and indirect implications rather than on their direct effects alone. The design changes highlighted in Section 6.2.2 will, on the other hand, be more relevant to tools and techniques and highly specific to the type of industry considered here. Intensifying the service industry for domestic refrigerators (Section 6.2.2) or other sectors also requires the optimal use and management of this knowledge, especially if the service provided is to be subcontracted. Indeed, such an implementation would require more work to be able to assess the overall implications on company, customer and environment alike.

Rather than just addressing the environmental impact, one unperceived advantage to such mutual understanding, which leads to critical and objective evaluations, is product improvement. Tackling the side-effects of decisions optimises product performance and seeks alternative product development targets, all of which are compatible with the sustainable development definition given in Section 1.2 and upon which products will be judged at this time of concern for the environment.

As stated throughout this thesis, the diagnosis and characterisation of an environmental problem generates voluminous data that needs to be critically assessed and evaluated. The ensuing knowledge is a prerequisite for the generation of practical tools to support an understanding of the life cycle environmental cost implications arising from decisions. Computer models, which codify the acquired knowledge, may be used in existing systems and industrial cultures to embed this knowledge into the economic system. It is imperative that the environmental and energy costs be assessed to minimise the negative impact on society of the tribological criteria studied here. Such tribological options are at present unknown to stakeholders not so much from an economic viewpoint, but rather from a life cycle environmental cost perspective. Acquiring knowledge of technical issues, which would otherwise be beyond the domain of a non-specialist, is a positive attempt to attain the envisaged reality of a product, that is, sustainable development.

7 CONCLUSIONS AND FUTURE WORK

This research identified potential environmental problems arising from the use of HFC-134a in the domestic refrigeration industry. This was done by evaluating the indirect environmental implications of this replacement refrigerant against those of CFC-12. Tribological properties within the hermetic compressor, for which the chlorine in the CFC is a good candidate, were focused upon. This chapter will identify key conclusions that highlight these unforeseen consequences and reveal possible avenues to be explored.

7.1 Conclusions

The findings presented within this thesis were possible due to an experimental refrigeration test system that was designed and manufactured by the author. Detailed LCA modelling work evaluated these findings from an environmental viewpoint. This assisted in an understanding towards the development of sustainable mechanical systems using replacement refrigerants. The main research conclusions are categorised below.

(1) The use of HFC-134a, as a CFC-12 refrigerant substitute in domestic refrigerators, will increase the indirect environmental impact of this product.

This work has shown that this impact accounts to a substantial contribution towards emissions from the domestic sector in the UK.

(2) Since the compressor itself contributes significantly towards the overall environmental impact of a refrigerator, new design considerations for the compressor are essential at a time when new refrigerant gases have been introduced. Some considerations have been identified as potential solutions in ensuring the sustainable development of the system studied.

(3) Experimental work identified that the electrical energy consumption of the compressor improved substantially with CFC-12, as compared with HFC-134a, over the first 500 hours tested. For mechanical systems working with HFC-134a, this energy consumption was influenced by the bulk oil temperature of the compressor.

(4) Observations on the aluminium alloy connecting rod and the steel gudgeon pin revealed enhanced wear characteristics for samples working in an HFC-134a environment as compared with samples operating in a CFC-12 environment.

(5) Using four-ball bench tests on oil samples before and after a compressor test, the extreme pressure performance of a synthetic lubricant was found to deteriorate more than that of the mineral oil.

7.2 Future work

It is inevitable that other issues will influence the findings made throughout this research. Nonetheless, the increase in indirect environmental effects identified due to the use of HFC-134a in domestic refrigerators is unlikely to be reduced even if other considerations are studied. However, in view of the significant findings made here, more needs to be done to understand unintended environmental consequences. Furthermore, this work has only focused on the use of HFC-134a but other CFC substitutes are in contention. The following lists the future research potentials that need to be exploited to comprehend the indirect effects of phasing out CFCs.

(1) Synthetic lubricant additives were unknown throughout this work but the experience gained thus far identified their potential contribution to the findings made here. These additives need to be studied to quantify their environmental impact and to learn more on the influence both the refrigerant and the operating conditions have on their performance. This will help capitalise on the potential benefits additives in synthetic lubricants for the HFC-134a refrigerant have as far as friction, wear and power characteristics are concerned.

(2) Simulation tests, using the four-ball configuration with identical materials and operating conditions as experienced in a hermetic system, need to be performed. These will help identify initial wear mechanisms as well as understand more fully the properties of the protecting layers formed with CFCs and their behaviour under different conditions.

(3) It is desirable to test hydrocarbon refrigerants for wear on compressor components and power monitoring using the test system designed. Since hydrocarbons operate at lower pressure ratios than HFC-134a or even CFC-12 and may be used with either synthetic or mineral lubricants, these tests will help in understanding further the issues of operating conditions and lubricant types identified in this study. Furthermore, these tests will also help in understanding the environmental implications of these natural substances from a life cycle perspective.

(4) This work suggests that servicing and extending the life of the hermetic compressor, as well as its start/stop operating frequency, all play an important contribution towards environmental considerations. More tests are required, including coupling the rig to a domestic refrigerator, to study the influence these attributes have on these considerations.

(5) Finally, a better understanding of the end-of-life of refrigerators is required with particular emphasis on the hermetic compressor. This not only helps to evaluate other indirect environmental impacts but also helps to study the design considerations discussed to attain the sustainable development of this product.

APPENDIX A

This appendix provides some explanation on some of the environmental impact categories dealt with throughout this thesis. These definitions are not exhaustive and have not been checked against scientific atmospheric studies. Nonetheless, their inclusion seems appropriate to assist the reader in the coherent interpretation of this work. Explanations have been derived from (Pira 1998).

Global Warming

The gases involved in the greenhouse effect all have the property of absorbing energy and emitting thermal infrared radiation. Therefore, an increase in the atmospheric concentration of greenhouse gases will change the absorption of infrared radiation in the atmosphere, known as radiative forcing. This may lead to changes in climatic patterns as well as higher global temperatures. The gases thought to be involved in the greenhouse effect differ considerably in their atmospheric lifetime and their absorption properties and therefore in their potential contribution to radiative forcing. Global warming is referenced to carbon dioxide, a significant greenhouse gas.

Ozone Depletion

Changes in stratospheric ozone will permit an increase in the amount of harmful ultraviolet radiation penetrating the atmosphere of the earth with potentially adverse effects on human health and ecosystems. Reductions in stratospheric ozone concentrations have been linked to anthropogenic chlorine and bromine compounds. Indicators used to express the potential contribution of substances towards ozone depletion are referenced to trichloromonofluoromethane (CFC-11).

Acidification

Acidification results from the deposition of acids in the environment. This leads to a decrease in the internal pH content of the soil and increased concentrations of potentially toxic elements in the soil solution. These effects are caused by the phenomena known as acid rain and the major gaseous pollutants associated with this impact category are sulphur dioxide and nitrogen oxides. These are dissolved in the rain-water and are then transformed or deposited. The effect of acid deposition is very site specific and the impact may be classified into either regional or local. The potential to cause acidification is calculated on the basis of the number of H+ ions that can be produced per mole of substance using sulphur dioxide as the reference substance.

Nutrification

This impact category is caused by the addition of nutrients to a soil or water system that leads to an increase in biomass. Any nutrient can have a nutrifying effect, however, nitrogen and phosphorus are the most important. Substances that have the potential for causing nutrification are compared to phosphate. As for acidification, this impact is very site specific.

Summer Smog

The formation of photochemical oxidant smog is the result of complex reactions between nitrogen oxides and volatile organic carbon under the action of sunlight (ultraviolet radiation). This leads to the formation of ozone in the troposphere, which although harmful when depleted in the stratosphere (ozone depletion), is also harmful when generated at lower altitudes. The contribution of nitrogen oxides in the atmosphere may be a very important factor in the formation of photochemical smog compared to volatile organic compounds. For this reason separate categories are included in this study.

Winter Smog

Winter smog primarily constitutes particulates and their influence on human health. This impact category measures contributions arising from these particulates and from aerosol production.

Human Toxicity

Human toxicity is a measure of the effect atmosphere, water and soil emissions have on humans. This impact category is assessed by comparing emissions to maximum daily intakes or concentrations considered acceptable to humans. This results in the definition of human toxicological classification factors that depend on the substance and the environmental medium concerned. The unit of comparison is that of body weight (in kg) exposed to the emission (in kg). Two significant contributors towards this impact category are carcinogens and heavy metals. The former measures the potential that compounds have to cause cancer and is measured in polycyclic aromatic hydrocarbon equivalents. The latter measures the toxic effects heavy metals and lead have on humans and these are compared to lead equivalent.

Appendix B

This appendix details the engineering drawings of the *as fitted* manifold blocks used on the test system described in detail in Chapter 2.

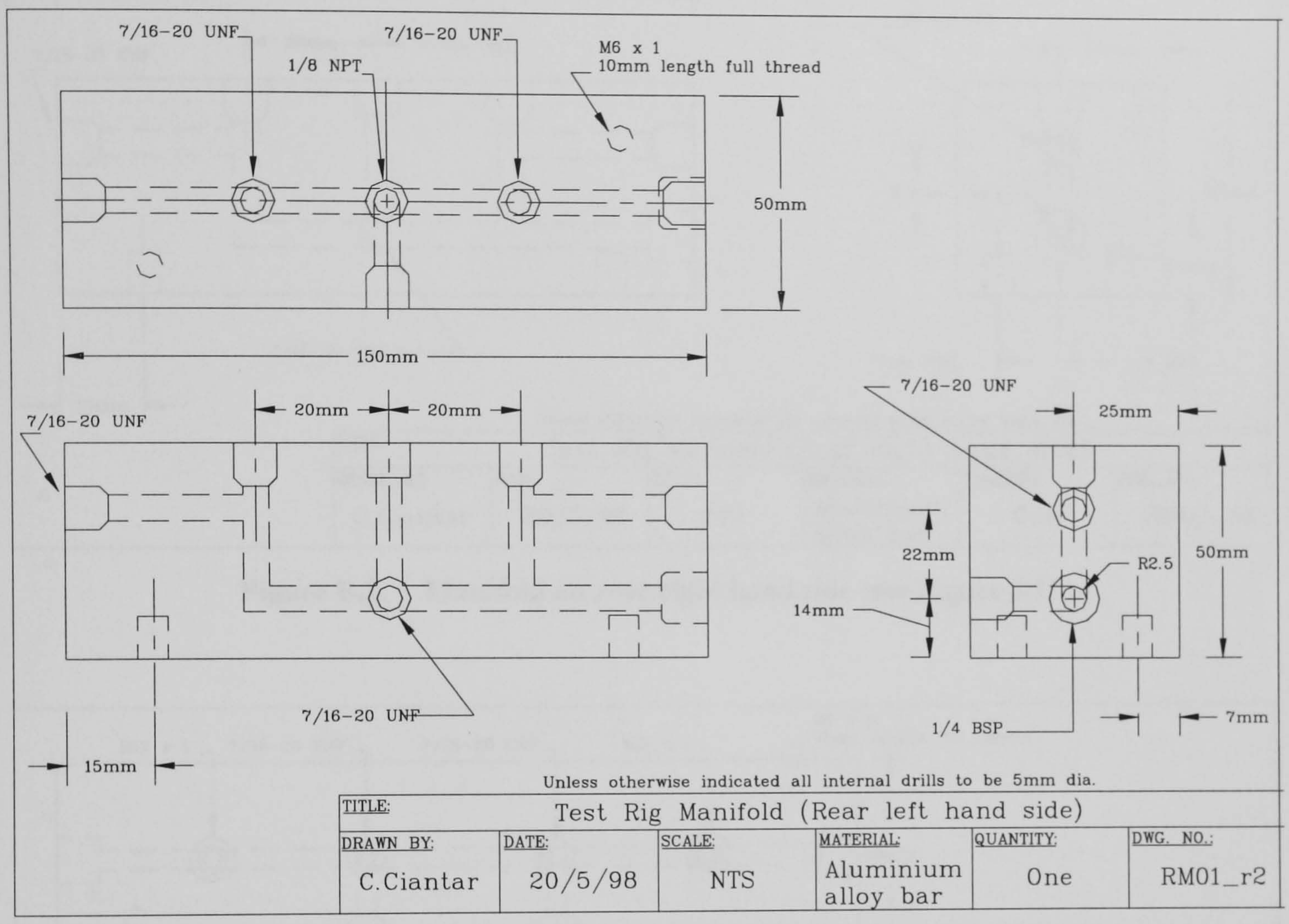


Figure B.1. Manifold on rear left hand side (see Figure 2.1)

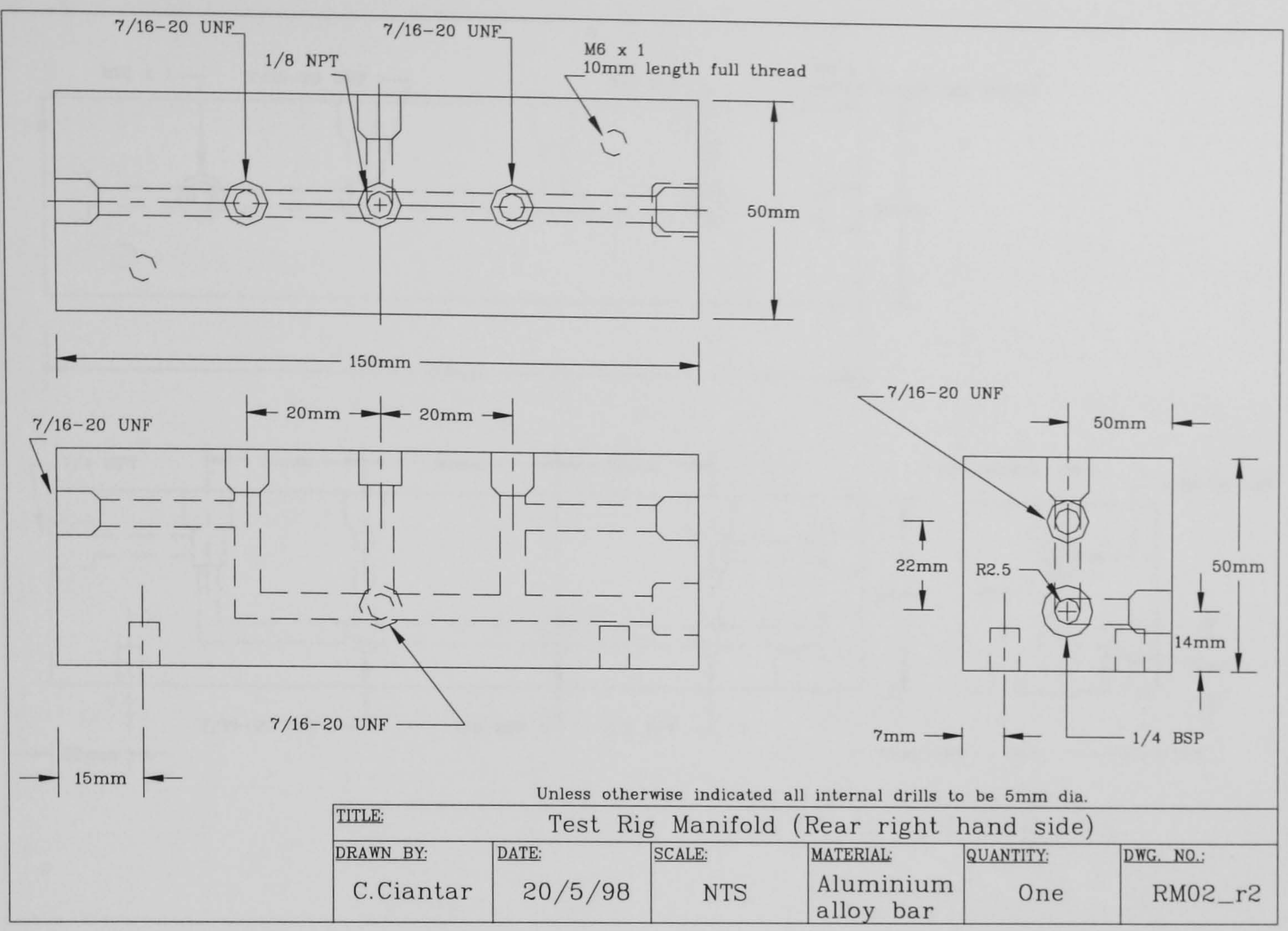


Figure B.2. Manifold on rear right hand side (see Figure 2.1)

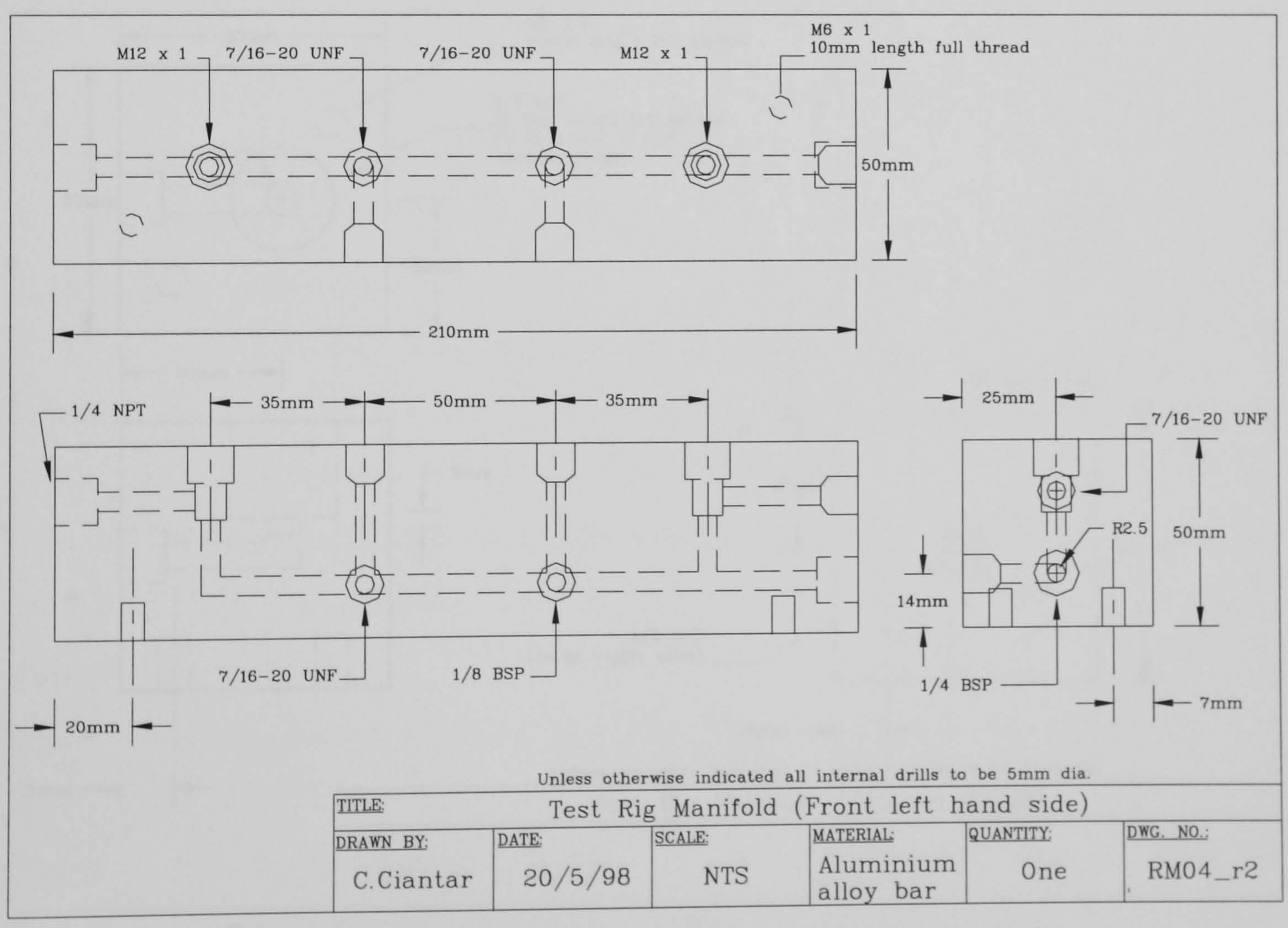


Figure B.3. Manifold on front left hand side (see Figure 2.1)

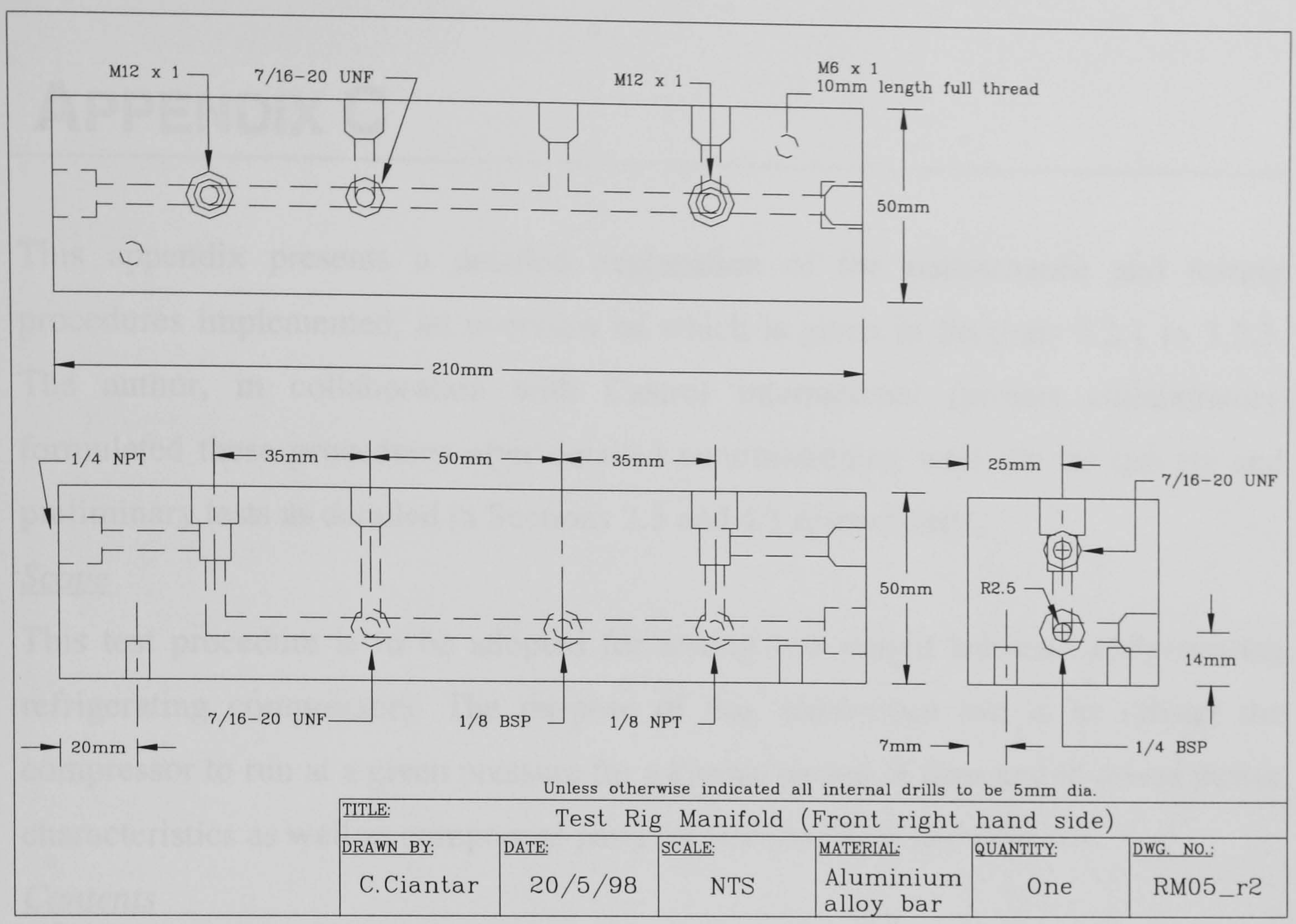


Figure B.4. Manifold on front right hand side (see Figure 2.1)

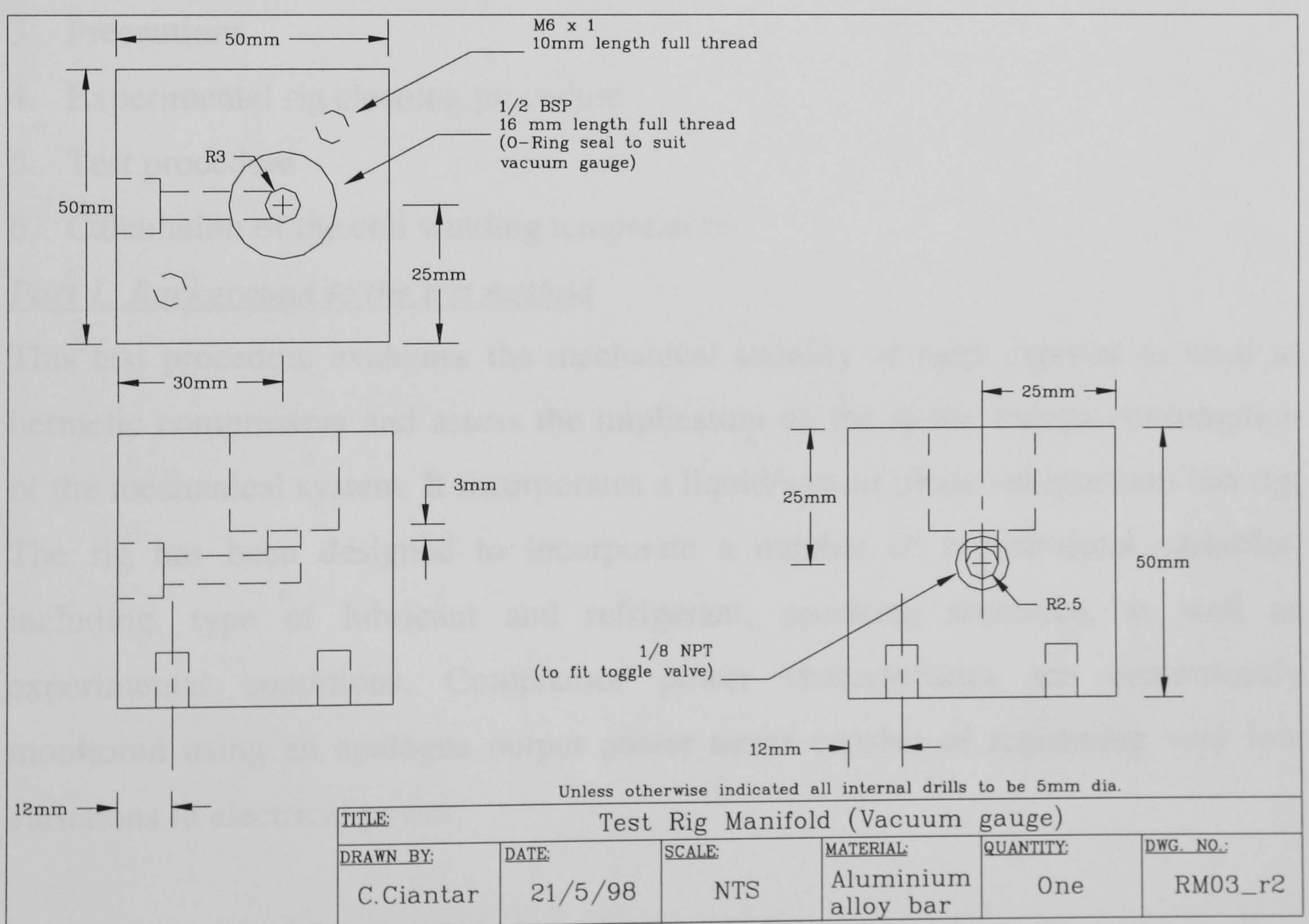


Figure B.5. Manifold for vacuum gauge (see Figure 2.1)

APPENDIX C

This appendix presents a detailed explanation of the maintenance and testing procedures implemented, an overview of which is given in Sections 3.2.1 to 3.2.3. The author, in collaboration with Castrol International (project collaborator), formulated these procedures after detailed commissioning work on the test rig and preliminary tests as detailed in Sections 2.5 and 4.1 respectively.

Scope

This test procedure is to be adopted for testing low output hermetic reciprocating refrigerating compressors. The purpose of this accelerated test is to subject the compressor to run at a given pressure for a known period of time and to assess power characteristics as well as component parts for friction, wear and deposits.

Contents

1. Background to the test method
2. Test specifications and conditions
3. Precautions
4. Experimental rig cleaning procedure
5. Test procedure
6. Calculation of the coil winding temperature

Part 1: Background to the test method

This test procedure evaluates the mechanical stability of parts exposed to wear in hermetic compressors and assess the implication on the in-use energy consumption of the mechanical system. It incorporates a liquid/vapour phase refrigeration test rig. The rig has been designed to incorporate a number of experimental variables, including, type of lubricant and refrigerant, operating scenarios, as well as experimental conditions. Compressor power characteristics are continuously monitored using an analogue output power meter capable of registering very low variations in electrical power.

It is of paramount importance to keep in mind that external heat sources as well as ambient conditions effect the test rig developed. It must also be operated in extreme clean conditions.

Part 2: Test specifications and conditions

Compressor model:	approximate capacity at –15°C is 230W
Power supply:	240V, A.C., 50 Hz
Refrigerant:	R134a or CFC-12 with identical filter drier
Oil charge:	350cc
Test duration:	500 or 1000 hours
Capillary specification:	0.6mm inside diameter and of an approximate length of 70mm for a 15 bar pressure test
Discharge pressure:	15 or 30 bar
Suction pressure:	0.6 or 1 bar
Sump temperature:	75°C

Part 3: Precautions

Throughout the maintenance and test procedures outlined below safety glasses and disposable gloves should be worn at all times. Respiratory protection is also advisable. These precautions are a requirement to minimise direct contact with the solvent or refrigerant and any possible inhalation of vapours as the solvent is purged through the rig or during refrigerant purging and charging. Due to the pressures involved the safety glasses are a requirement. Whilst carrying out either the maintenance or test procedures the area is to be adequately ventilated.

Part 4: Experimental rig cleaning procedure

1. If the compressor is mounted on the rig, disconnect it from the flexible pipes and let the flexible pipes loose.
2. Open the capillary tube connections and disconnect the tube so that any debris may be discharged and not block the capillary tube.
3. Open all shut-off valves on the manifold blocks.
4. Disconnect the filter drier and the sight glass.
5. Replace the low and high pressure dial gauges with ones compatible with the type of lubricant/refrigerant to be used. To minimise the inclusion of debris into the system this operation is to be carried out under a regulated flow of compressed air.
6. Once all components have been removed from the rig the flushing process may begin. The rig should be flushed through with clean petroleum ether solvent (PET spirit) and purged with clean shop air. Since components are disconnected and

the refrigeration circuit is not complete then flushing must take place on every section of the rig.

7. PET spirit must be poured in through the flexible hoses as well as through the access fittings on the front manifold blocks. This ensures that all the components of the rig are reached.
8. Allow the PET spirit to set for some minutes and then purge the solvent from the rig using clean shop air. Ensure that the purged spirit is collected in a suitable receptacle.
9. Steps 6 to 8 are to be performed for three consecutive times.
10. Leave the rig evacuated for a minimum period of twelve hours before compressor testing may commence.

Part 5: Test procedure

1. Obtain a new compressor, appropriately flared and flushed clean (the compressor cleaning procedure is not outlined here, it is normal that this is carried out by the supplier of the compressor). Connect the suction and discharge flexible hoses to the suction and discharge pipes of the compressor (see drawings supplied by the manufacturer of the compressor). Prior to connecting up, be sure to remove the schraeder valves on the access fittings on these compressor pipes and to include copper flares. The schraeder valves are necessary to maintain the compressor under a charge of nitrogen when stored whilst the copper flares allow a tight seal between the steel of the braided hose and the brass fitting.
2. Connect a new filter drier. An arrow indicates the direction in which the filter is to be connected.
3. Attach the capillary tube coil to the rig.
4. Pressure test the rig (approximately 5 bar) using compressed air (or nitrogen) and soap water to identify any leaks from disturbed connections.
5. Set the pressure switches (the dual pressure controller and the fan controller) to the appropriate pressure levels depending on the test to be performed. The high pressure setting on the dual pressure controller must be set slightly higher (approximately 2 bar) than that of the fan controller.
6. Apply a vacuum to the compressor test rig for about half an hour using the access fittings on the front manifold on the low pressure side. Ensure that the vacuum gauge toggle valve is open whilst vacuuming the rig.

NOTE: A vacuum gauge is fitted on the low pressure side of the rig. This gauge is isolated by a manual valve to avoid damage due to over pressure. This valve must only be opened when the suction pressure is below 1 bar. **This valve must never be left open** during pressure testing the rig or during compressor testing since on shut down the pressure in the suction side will rise to approximately 3 bar.

7. Using a hot air blower, heat the filter drier whilst vacuuming the rig to ensure that any absorbed moisture in the filter evaporates
8. To ensure the complete removal of air, allow some refrigerant gas into the rig (approximately 1 bar). Then continue vacuuming the rig from this refrigerant vapour for about one hour. The minimum vacuum to be achieved should be approximately 2 Torr (2mmHg, 2.67mbar).
9. Ensure that the vacuum is maintained overnight to minimise the possibility of potential leak problems.
10. If no leaks are present, continue vacuuming the rig for another 30 minutes.
11. During this vacuuming period, charge the compressor with the appropriate lubricant through the service pipe on the compressor (see drawings supplied by the manufacturer). This service pipe is fitted with a schraeder valve and therefore the use of a quick release coupler is necessary. **The lubricant charging must be carried out with as minimum delay as possible. Synthetic lubricants are hygroscopic and should not be allowed to stand open to the atmosphere.**
12. Prior to fastening the compressor to the base plate of the rig, momentarily interrupt the vacuuming and invert the compressor. This will ensure that the oil within the compressor wets all the internal components of the compressor. Mount the compressor on the test rig bolting it on rubber mountings. Continue the vacuuming operation until 30 minutes have elapsed.
13. Connect the electrical starting device to the compressor as shown in the wiring diagram. Both the starting device and the wiring diagram are to be supplied by the manufacturer of the compressor.
14. With the compressor turned off, measure and note the winding resistance of the motor by connecting a resistance meter across the live and neutral supply of the compressor. Attach the K-type thermocouple to the compressor casing in the region of the oil sump.

15. When vacuuming is complete, disconnect the vacuum pump and connect the refrigerant cylinder to the access fitting on the low pressure side of the test system via the electronic charging scales. Purge all charging hoses with vapour refrigerant to ensure that no air is in the charging lines. This is done by following the procedure highlighted on the charging scales.
16. Reset the elapsed hour meter.
17. Check that the mechanical timer is not activated.
18. Activate the data acquisition software.
19. Start the compressor by pushing the green button on the compressor control panel. The compressor should be allowed to run in a vacuum for approximately 3 minutes to prime the oil system.
20. Slowly add in refrigerant vapour. Allow 30 grams (arbitrary) of refrigerant each time the rig is charged and leave to settle for approximately 15 minutes.
21. When charging is complete, check all pipework and joints for any refrigerant leaks using an electronic leak detector, particularly on the high pressure side of the rig. If an interrupted test is being run be sure to test for leaks on the low pressure side of the rig when the compressor is turned off.
22. The capillary tube length may need to be altered to achieve the required test pressure differential. (For a set high pressure, if the low pressure is high than the capillary tube needs to be lengthened whilst if the low pressure is low the capillary tube needs to be shortened). The design of the rig allows this to be carried out without having to discharge the whole of the refrigerant. The compressor must be switched off (by pressing the blue button on the compressor control panel) and the appropriate shut-off below valves (located on the front manifold blocks) closed to completely isolate the capillary tube.

NOTE: The starting device to which the compressor is connected requires the off cycle period of the compressor to be longer than five minutes. If an attempt is made to restart the compressor prior to the elapse of this time it will NOT operate.

23. With an adjusted length of new capillary tube fitted, a vacuum needs to be reapplied to the capillary tube from the low pressure access valve. After applying the vacuum for about 10 minutes, the refrigeration circuit is completed by reopening the shut-off below valves. Restart the compressor.

24. Allow the compressor to stabilise at test conditions prior to the actual start of the test (this usually takes about 1½ hours from the starting of the compressor). Test conditions as well as electronic leak detection must be monitored continuously. Check that the condenser fan is cycling as appropriate to maintain the operating conditions. Check that the discharge and the suction pressures are oscillating about their respective set points. It must also be ensured that, during this initial phase of the experiment, the compressor casing temperature is maintained at 75°C. The expansion device must be hot at the high pressure side and cold at the low pressure side. This indicates gas flow. In the absence of a flow, the compressor will overheat and will shut down due to the compressor over temperature switch.
25. The red light on the compressor control panel indicates that a high pressure interruption has occurred. The LED on the compressor connection box indicates that the motor protector of the compressor has been activated either due to an over current or due to an over temperature. Neither of these indicators should be on at this, or any other, stage of the experiment.
26. If the test is interrupted then an indication for the interruption must be recorded together with the test conditions.
27. When conditions have stabilised, the mechanical start/stop timer is activated when performing an interrupted test.
28. For a continuous test, the winding resistance must be recorded just when the compressor is turned off. For an interrupted test, periodic readings of this winding resistance are obtained just before the compressor turns on and just after it turns off.
29. Periodic readings of the suction and discharge pressures must be taken as manual gauges (compared to electronic transmitters) are used here.
30. Periodically (at least twice a week) monitor the test system for leaks using the electronic leak detector.
31. When the test duration expires, the experiment is terminated by pressing the blue button on the control panel. Data from the data acquisition software must be appropriately stored.
32. With the test rig allowed to cool, the refrigerant vapour is reclaimed in the recovery cylinders provided for appropriate disposal.

33. The used filter drier, the compressor, the dial gauges (if appropriate) and the capillary tube are removed from the rig and marked with the test number. These are appropriately stored for analysis if required.
34. Drain and collect the compressor oil from the compressor service pipe and label the oil sample appropriately.
35. Maintain the compressor for stripping and analysis.
36. Once all the appropriate components have been removed from the rig the flushing process, described in Part 4, is repeated.

NOTE: In case of **EMERGENCY** only, the rig may be turned off by disconnecting the mains supply

Part 6: Calculation of the coil winding temperature

The following equation has been adopted to calculate the coil winding temperature from the metered winding resistance. Unfortunately, no appropriate scientific background was found to support its validity but the following equation is used extensively in industry. For this reason, it has been used throughout this research work for appropriate indication and comparative purposes.

The coil winding temperature may be calculated by the following equation:

$$t_2 = \frac{(234.5 + t_1) \times R_2}{R_1} - 234.5$$

where: t_1 is the temperature in °C for R_1 (ambient)

t_2 is the temperature in °C for R_2

R_1 is the main winding resistance in Ohms (at t_1) measured prior to commencing of test

R_2 is the main winding resistance in Ohms (at t_2) measured immediately before or after the compressor starts or stops

APPENDIX D

This appendix disseminates typical characteristics of the synthetic lubricants utilised throughout this research. These figures are to be used for indication purposes only.

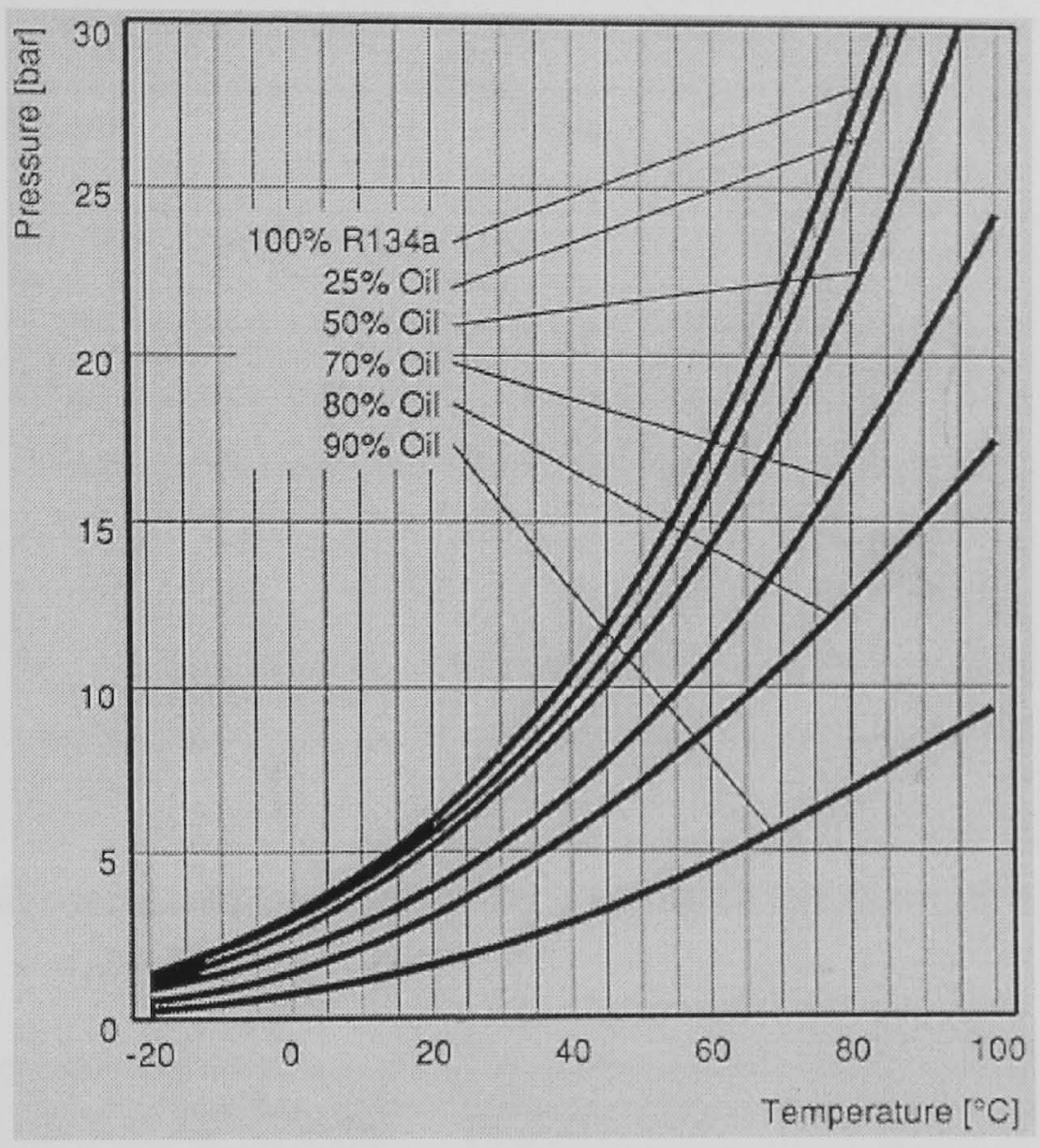


Figure D.1. Pressure-temperature diagram for a synthetic lubricant of VG 32 with HFC-134a

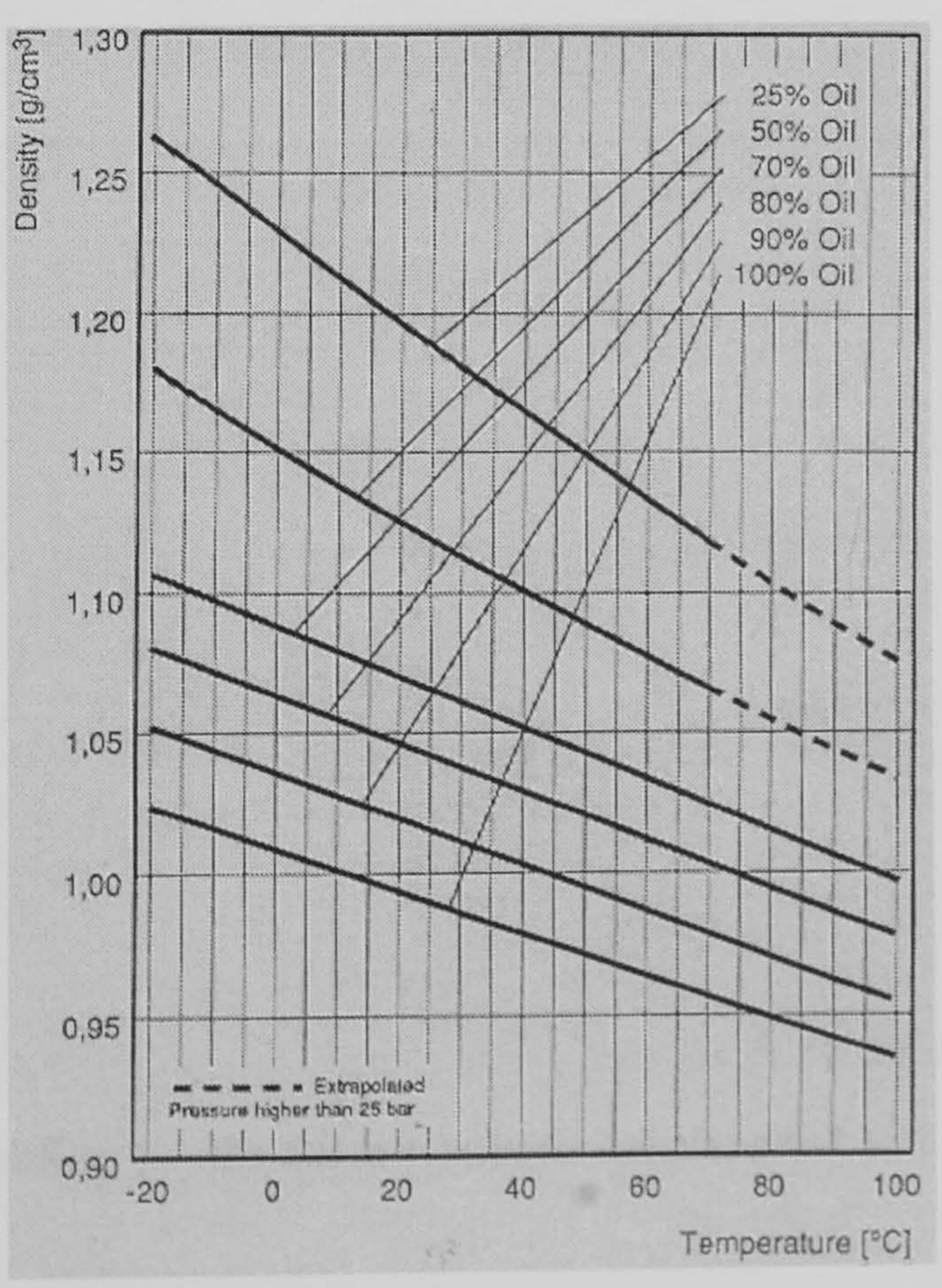


Figure D.2. Density-temperature diagram for a synthetic lubricant of VG 32 with HFC-134a

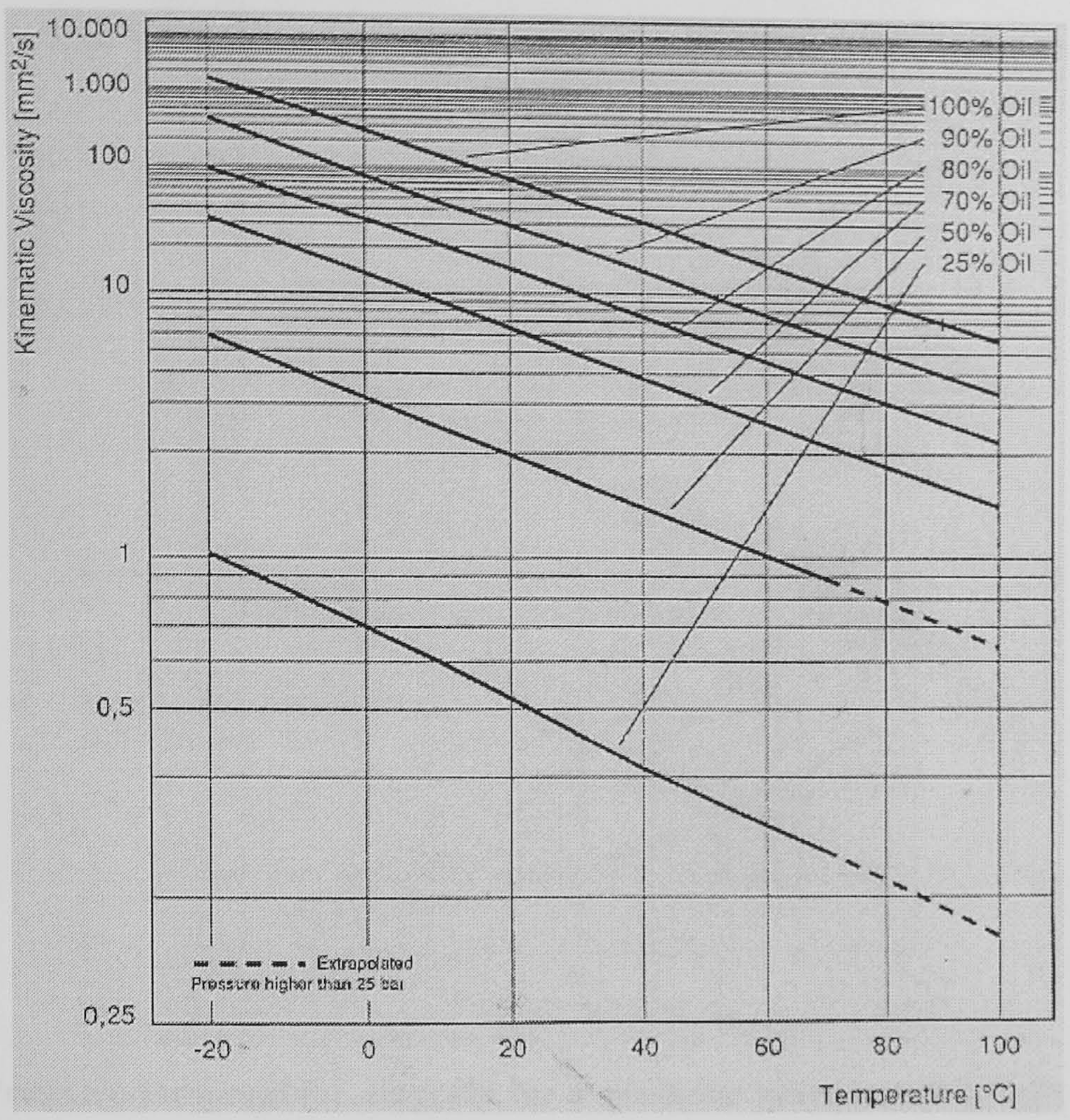


Figure D.3. Viscosity-temperature diagram for a synthetic lubricant of VG 32 with HFC-134a

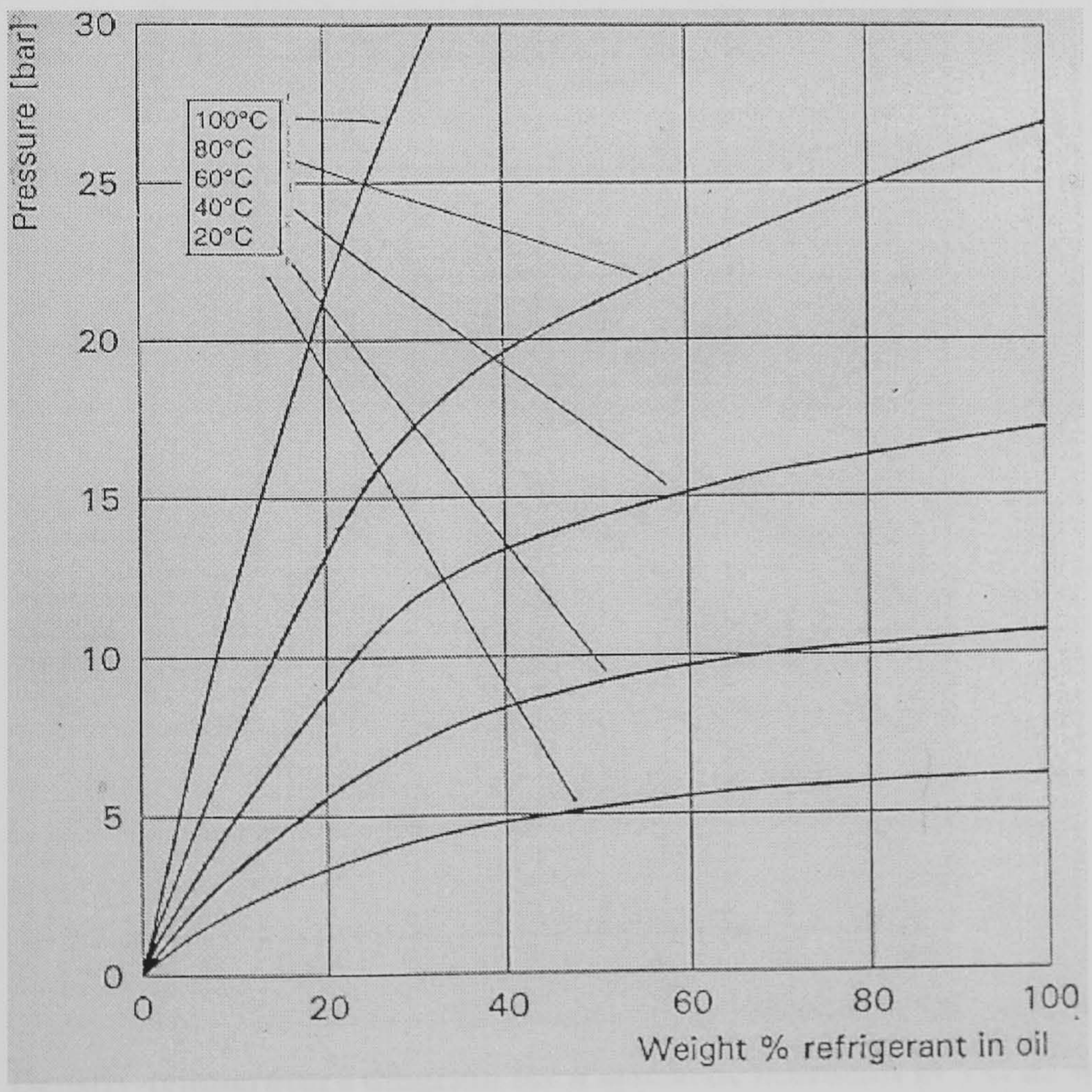


Figure D.4. Solubility profile for a synthetic lubricant of VG 32 with HFC-134a

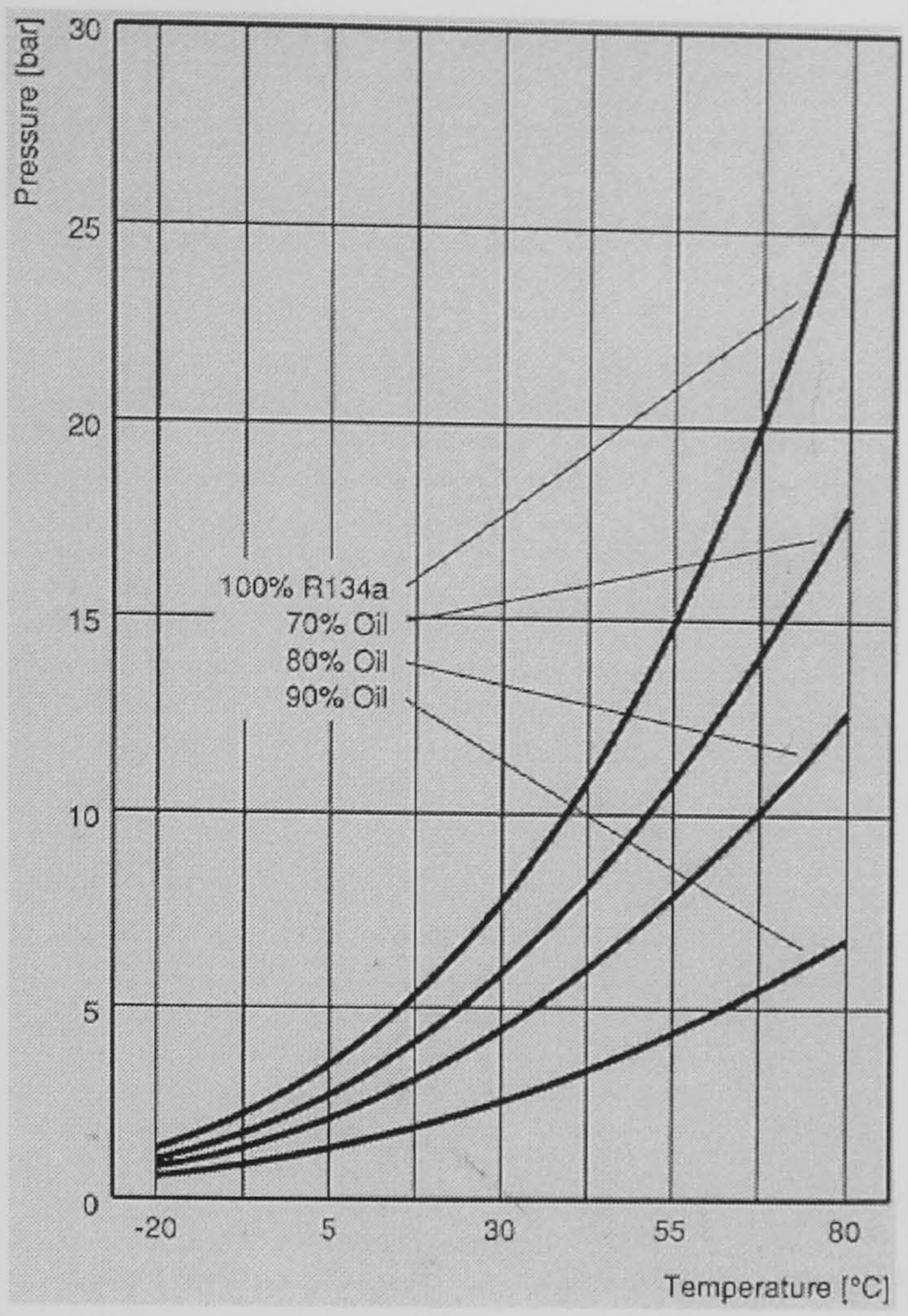


Figure D.5. Pressure-temperature diagram for a synthetic lubricant of VG 22 with HFC-134a

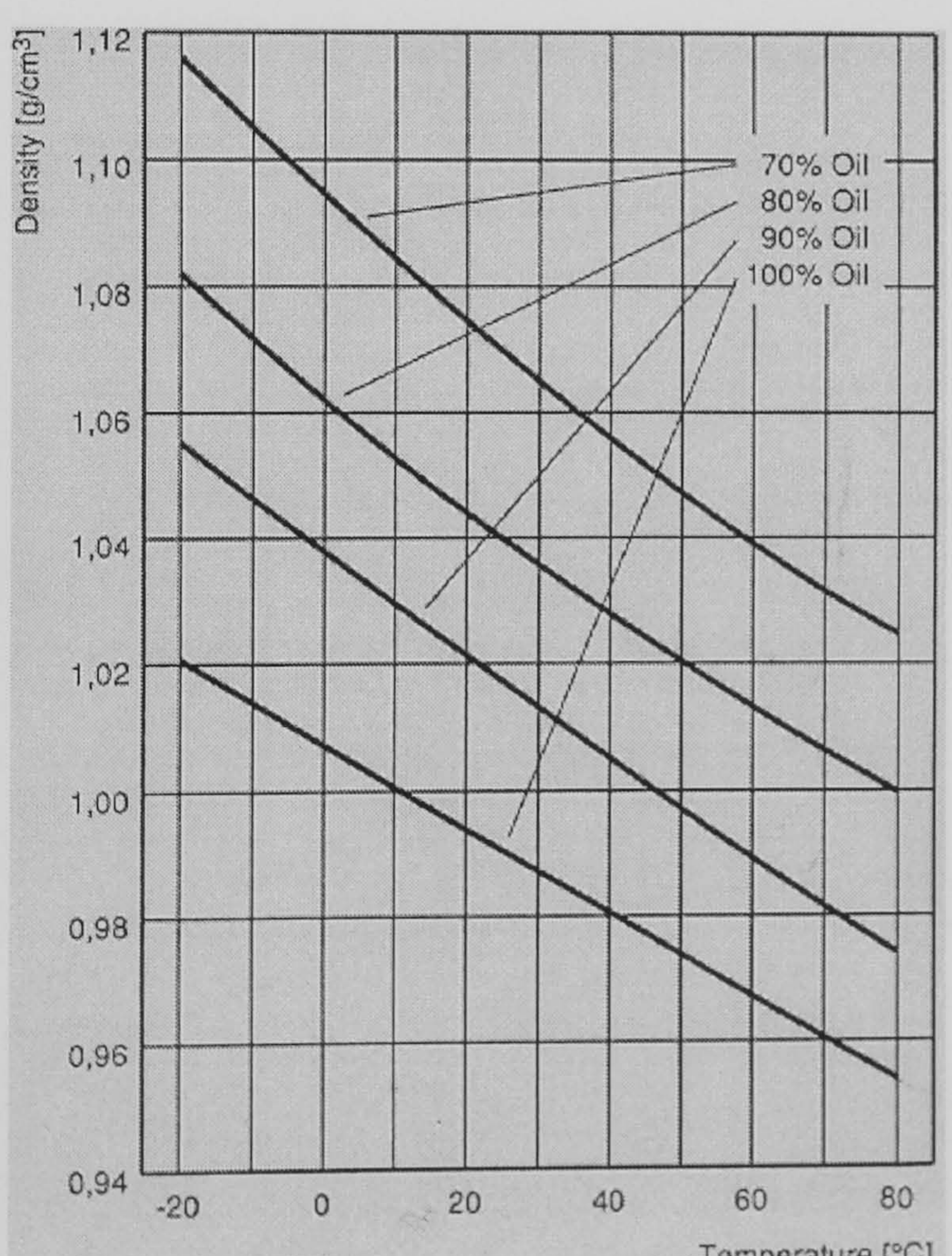


Figure D.6. Density-temperature diagram for a synthetic lubricant of VG 22 with HFC-134a

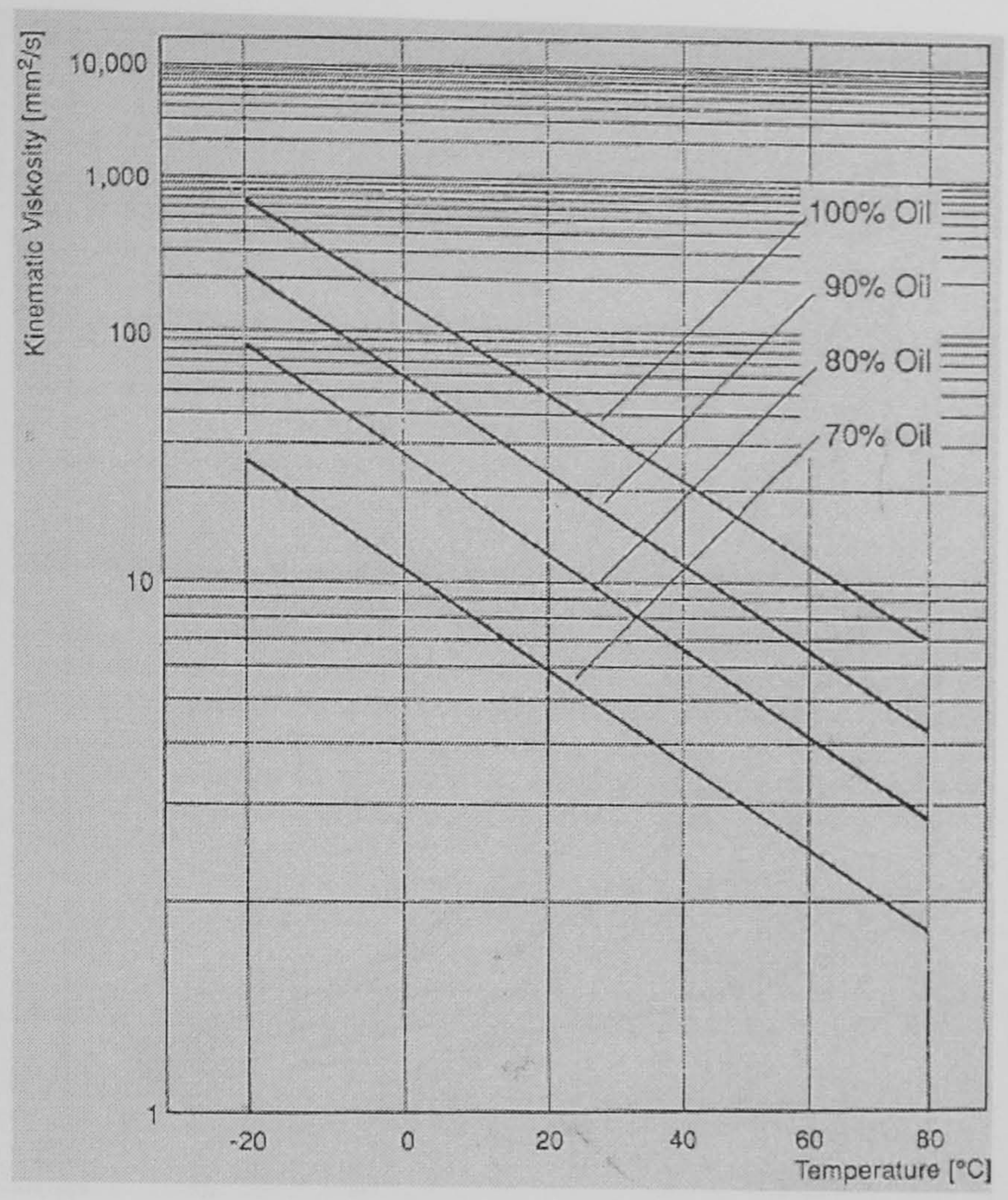


Figure D.7. Viscosity-temperature diagram for a synthetic lubricant of VG 22 with HFC-134a

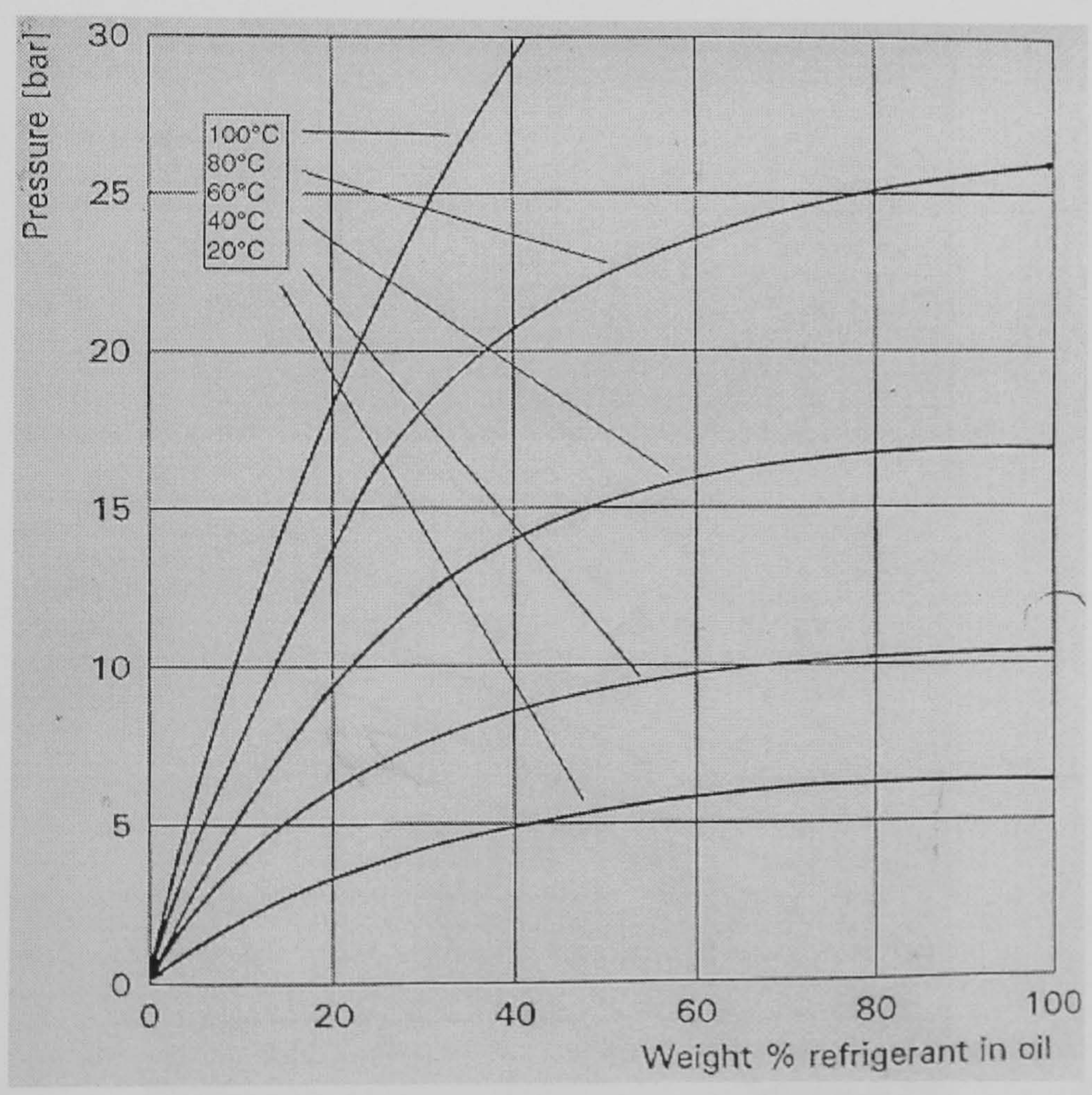


Figure D.8. Solubility profile for a synthetic lubricant of VG 22 with HFC-134a

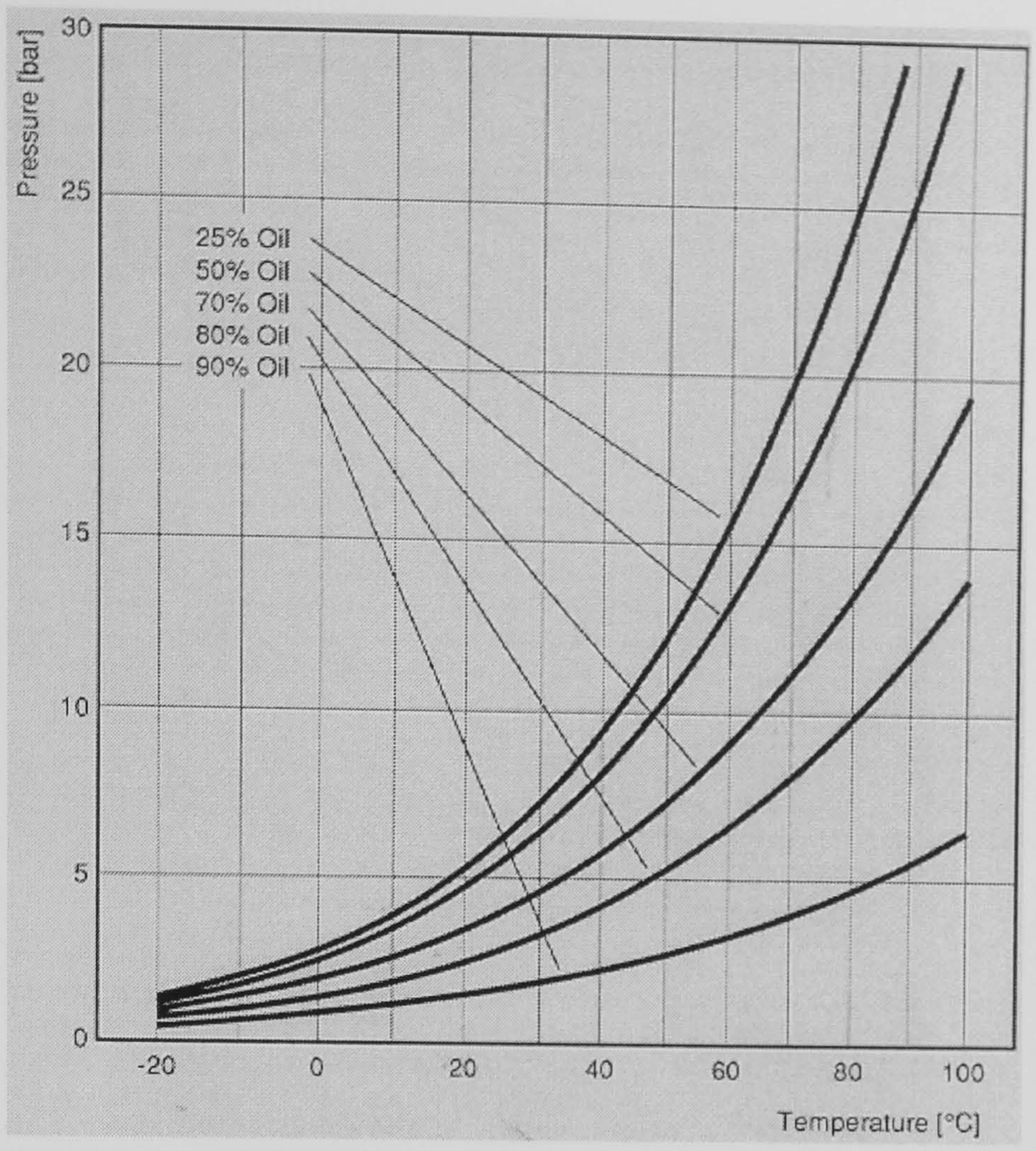


Figure D.9. Pressure-temperature diagram for a synthetic lubricant of VG 10 with HFC-134a

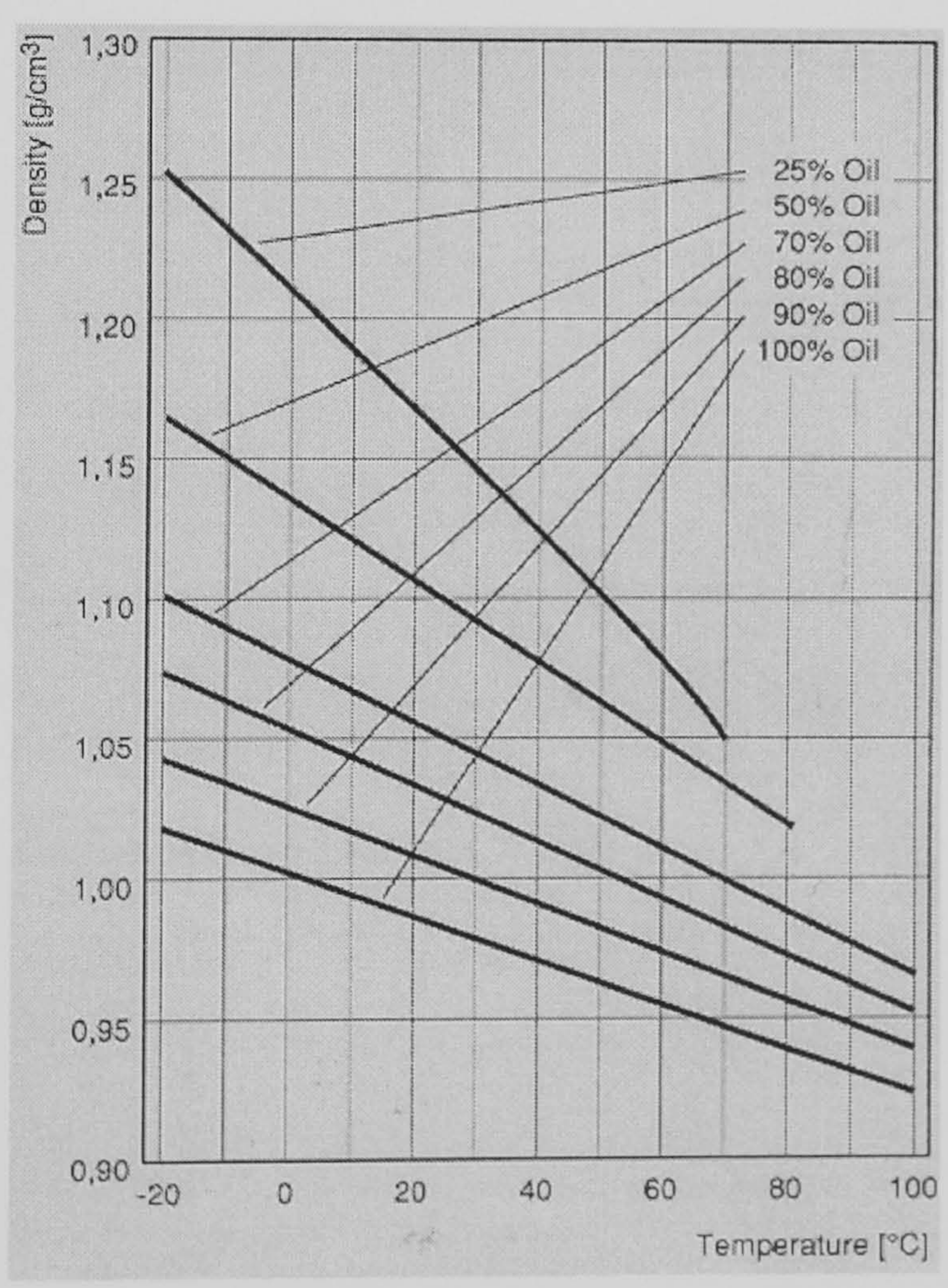


Figure D.10. Density-temperature diagram for a synthetic lubricant of VG 10 with HFC-134a

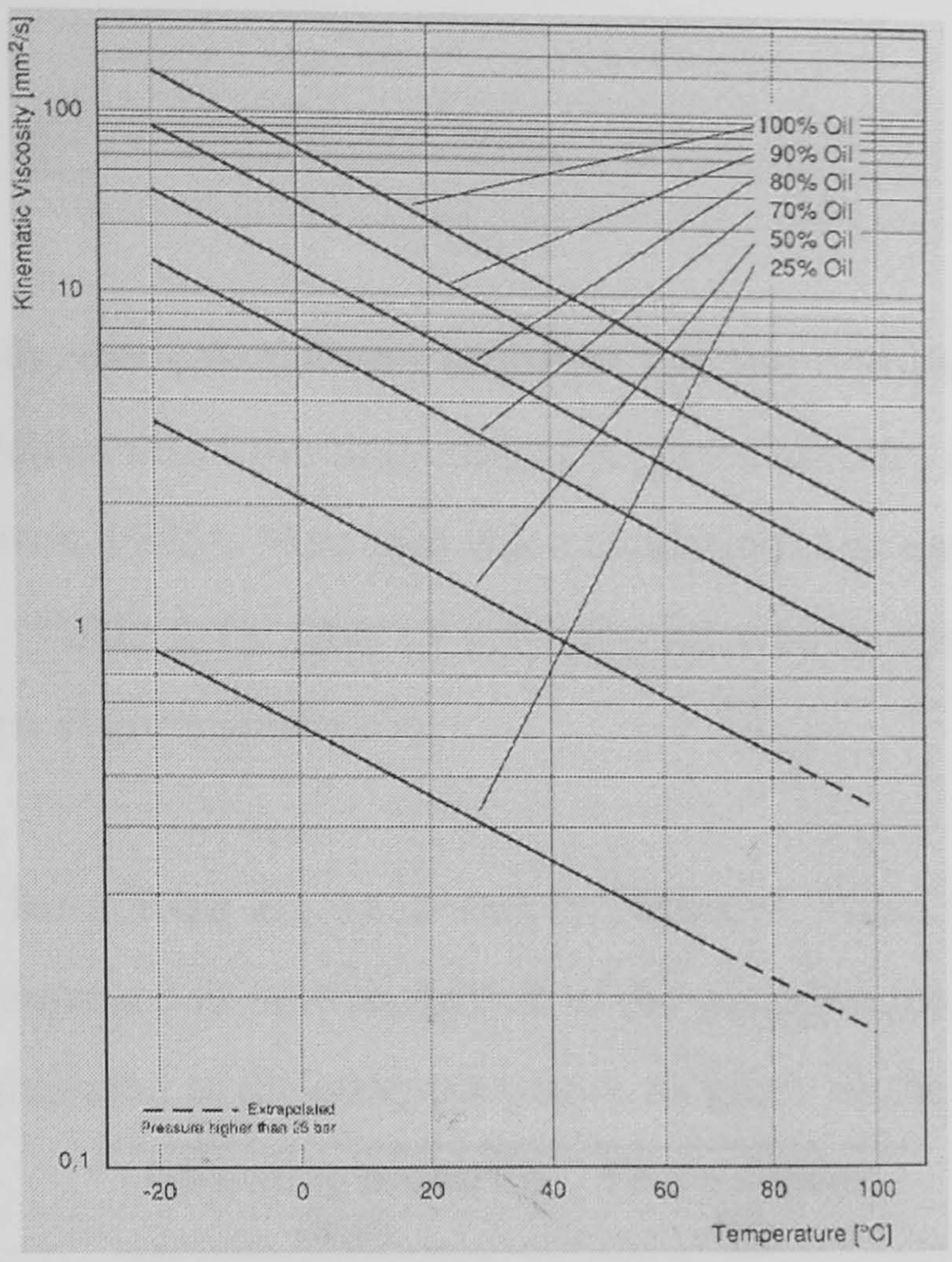


Figure D.11. Viscosity-temperature diagram for a synthetic lubricant of VG 10 with HFC-134a

APPENDIX E

This appendix details the calculations required for the completion of Table 3.4. Formulas for the calculation of the line contact pressure and the area of contact were obtained from (Johnson 1996). Note that this calculation was carried out for a Type A compressor only (Table 2.1). Due to very similar characteristics, the values are indicative of the Type B compressor too.

Area of piston face for a Type A compressor is 700mm². Thus, the force applied on the piston face and assumed to be transmitted to the gudgeon pin and connecting rod assembly may be calculated at different pressures, as given in the following table:

Operating pressure (bar)	Force applied (N)
30	2100
25	1750
15	1050

Table E.1. Pressure and corresponding force applied on pin and rod assembly

From the Hertz Theory of line contacts:

- Maximum contact pressure:

$$P_0 = \left(\frac{PE*}{\pi \mathrm{Re}}\right)^{\frac{1}{2}} \qquad E.1$$

- Semi-contact width:

$$a = \left(\frac{4P\mathrm{Re}}{\pi E*}\right)^{\frac{1}{2}} \qquad E.2$$

where: P is the applied force per unit length, the length being the width of the small end of the connecting rod (8.45mm as indicated by the arrow in Figure 3.7)

E* is the contact modulus and is calculated using Equation E.3

Re is the effective curvature and is calculated using Equation E.4

$$E^* = \left(\frac{1-\upsilon^2}{E_1} + \frac{1-\upsilon_2^2}{E_2} \right)^{-1} \qquad E.3$$

$$\mathrm{Re} = \left(\frac{1}{R_1} + \frac{1}{R_2} \right)^{-1} \qquad E.4$$

where: E_1 is the Young's modulus of the steel pin, assumed to be equal to 210GPa

E_2 is the Young's modulus of the aluminium alloy, assumed to be equal to 80GPa

R_1 is the radius of the steel pin, measured to be equal to 3.568mm

R_2 is the radius of the small end of the connecting rod, measured to be equal to 3.574mm

υ_1 is the Poisson's ratio of the steel pin, assumed to be equal to 0.3

υ_2 is the Poisson's ratio of the aluminium alloy, assumed to be equal to 0.33

After determining values for E* and Re, using Equation E.3 and E.4 respectively, these values are substituted into Equation E.1 and E.2 to obtain values of the maximum contact pressure (P_0) and the semi-contact width (a) respectively. Calculated values are listed in Table E.2, where the area of contact is calculated by doubling the semi-contact width (a) and multiplying the result to the width of the small end of the connecting rod.

Force/unit length (kN/m)	P_0 (GPa)	a (mm)	area of contact (mm^2)
248.5	1.7	0.0935	1.58
207.1	1.6	0.0853	1.44
124.3	1.2	0.0661	1.12

Table E.2. Calculated values

APPENDIX F

This appendix lists the details of the functional unit described in Section 3.6.1. This functional unit was a refrigerator and was used as a case study on which an LCA was performed. The LCA study helped to quantify the indirect environmental implications arising due to a change in refrigerant. A bill of materials obtained from literature supplied by the manufacturer of the refrigerator is given in Table F.1. Note that this table spans over two separate pages. This table also lists details of the total weight of materials and their individual transportation assumed. The ancillary materials required for the manufacture of the different items are also included together with their separate weights and the manufacturing processes assumed. As explained in Section 3.6.4, details for the completion of this table was retrieved using numerous resources.

On the other hand, Table F.2 (this table spans over four separate pages) lists assumptions of the energy requirements of the manufacturing processes, transportation details for the subcontracted items as well as the burdens entering and leaving each manufacturing process. Further details and explanations regarding this table may be obtained from Sections 3.6.5 and 3.7ff.

Item	Material[a]	Total weight (grams)	Transportation type/distance covered (km[b])	Manufacturing processes included[c]	Ancillary substances[d]	Weight of ancillary (grams)
Cabinet						
Steel cabinet	Steel, plain Epoxy resin	23,478.65 659.5	1/300 2/250	Punching, welding, surface treatment, etc.	Electrodes Water Salt Detergent Phosphoric acid	 26,766.76 30 50 4
Inner box	ABS sheet	4,432.2	1/300	Vacuum forming		
Compressor box	ABS sheet	559.4	1/300	Vacuum forming and treatment		
PUR foam	Polyurethane	6,242.46	1/150	Foaming	HFC-134a[e] or CFC-12[e]	452.9 543.5
Compressor with accessories (subcontract)	Steel Copper Aluminium PVC, brass, rubber	7,289.1 1,366.7 182.2 91.1	1/500 3/150 3/150 3/150		Coating paint	100
Pipes for compressor (subcontract)	Copper pipe	13.35	2/150	Blow through, cutting	Nitrogen	500
Refrigerant	HFC-134a[e] or CFC-12[e]	115 138	Assumed identical for both	Filling		
Evaporator (subcontract)	Aluminium	1,788.9	1/300			
Condenser (subcontract)	Steel pipe	484.6	2/300	Bending, plugging		
Pipe for condenser (subcontract)	Copper pipe	26.7	2/150	Blowing, cutting, bending	Nitrogen	500
Drying filter (subcontract)	Copper Zeolite	37.25 4.14	2/300			
Thermostat (subcontract)	Steel Plastics	56.75 56.75	3/150 2/300			
Sensor / thermostat	PVC pipe	33.38	3/150	Cutting		
Wiring (subcontract)	Copper PVC Steel Brass	243.84 93.79 18.76 18.76	2/150 2/200 2/200 2/150			
Lamp panel	ABS	126.83	1/300	Injection moulding	Water	747.6
Lamp screen	PVC	29.37	2/300	Injection moulding	Water	226.95
Lamp socket (subcontract)	Steel Plastic	18.02 6.01	3/150 3/150			
Light bulb (subcontract)	Glass Brass	13.89 3.47	3/150 3/150			
Hinge fittings (subcontract)	Stainless steel	173.55	2/300	Punching, tumbling, etc	Water Abrasives	106.8 2.67
Hinge fitting threaded portion (subcontract)	Steel	272.34	2/300	Punching, tumbling, etc	Water Abrasives	3,337.5 1.34
Mounting rail	Steel, plain	1,628.7	1/300		Water	3337.5
Base plate	Galvanised steel	237.63	1/300	Cutting, punching		
Door						
Door casing	Steel sheet Epoxy resin	5,673.75 209.6	1/300 2/250	Punching, welding, surface treatment	Acetylene, oxygen Salt Detergent Phosphoric acid Water	 8 16 0.267 10,680

Table F.1. Bill of materials for the functional unit (FU1) and transportation details – Part A

Item	Material[a]	Total weight (grams)	Transportation type/distance covered (km[b])	Manufacturing processes included[c]	Ancillary substances[d]	Weight of ancillary (grams)
Door lining	ABS sheet	2,403	1/300	Vacuum forming		
PUR foam	Polyurethane	1,969.125	1/150	Foaming	HFC-134a[e] or CFC-12[e]	287.03 344.5
Seal frame (subcontract)	PVC	440.55	1/250			
Handle	PVC	300	2/300	Injection moulding	Water	2500
Accessories						
Thread shelves	Steel Epoxy powder	3,204 106.8	2/300 2/250	Cutting, spot welding, surface treatment	Salt Detergent Phosphoric acid Water	5 8.5 0.9 8,343.75
Coverplate	PVC	124.7	2/250	Cutting, punching bending		
Front rim	PVC	182.9	2/250			
Glass shelf	Glass	500	2/200			
Various plastic boxes	PVC	2,213	2/300	Injection moulding	Water	1,305
Packaging						
Packaging	Corrugated cardboard	4,872.75	2/300	Stapling		
Plastic bag (subcontract)	Polyethylene	140.2	2/250			
Door support	Expanded polystyrene	18.69	3/50	Cutting		
Base frame	Wood	2,136	2/300	Manual fitting		
Miscellaneous						
Other steel items (subcontract)	Steel	26.7	2/300			
Rubber items (subcontract)	Rubber	20.03	2/100			
Other ABS items	ABS granulate	87.84	1/300	Injection moulding	Water	523.32
Nylon items (subcontract)	Nylon	8.01	2/100	Injection moulding	Water	53.4
Adhesive tape (subcontract)	LDPE, film	18.69	2/100			
Lupolene items	PVC	5.34	2/300	Injection moulding	Water	40.05
Acetal items	PVC	53.4	2/300	Injection moulding	Water	400.5
Other small items	Steel	232.29	1/300			

[a] Material retrieved from available sources may differ from the type used in the product

[b] Transportation details for different materials: Type 1 – truck > 25 tonnes, average road
Type 2 – truck > 7.5 tonnes, average road
Type 3 – van < 3.5 tonnes, average road

[c] Only manufacturing processes where the use of ancillary substances were necessary are included

[d] Transportation details for ancillary substances, although considered, are not shown

[e] Laboratory experience identified a 20% (by weight) increase in CFC-12 as compared to HFC-134a due to a change in the specific volume of the two compounds. Values obtained from Table 3.12

Table F.1. Bill of materials for the functional unit (FU1) and transportation details – Part B

Item	Power (kW)/duration (mins) for manufacturing process Transportation type/distance (km[b])	Burdens IN[a]	Burdens OUT[a]	Value of burden
		Cabinet		
Steel cabinet	22/15 N/A	Minor constituents Air used (unspecified) Water(unspecified) Energy for general use	Open loop outputs Air used (unspecified) Waste water Salts Acid(unspecified) Detergent Steam/water vapour Waste water Waste heat	50g 15kg 6kg for general use 12.6MJ 30g 4g 50g 600g 26.12kg 9.9MJ
Inner box	15/15 N/A	Water(unspecified) Energy for general use	Waste water Waste heat	6kg 12.6MJ 2.7MJ
Compressor box	15/5 N/A	Water(unspecified) Energy for general use	Waste water Waste heat	6kg 12.6MJ 0.9MJ
PUR foam	111/90 N/A	Water(unspecified) Energy for general use	Waste water Waste heat	10kg 75.6MJ 120MJ
Compressor with accessories (subcontract)	50/60 2/154 4/60	Minor constituents (inc. coolant for machining) Water(unspecified) Energy for general use	Open loop outputs Waste water Waste heat (inc. casting)	1.25kg 10kg 50.4MJ 90MJ
Pipes for compressor (subcontract)	22/5 2/75	Minor constituents Water(unspecified) Oxygen Energy for general use	Open loop outputs Waste water Nitrogen Waste heat	50g 6kg 0.5kg 12.6MJ 1.32MJ
Refrigerant[b] (subcontract)	N/A 1/200	See Table 3.12		
Evaporator (subcontract)	55/30 2/100	Water(unspecified) Energy for general use	Waste water Waste heat	6kg for general use 25.2MJ 19.8MJ
Condenser (subcontract)	25/30 2/100	Water(unspecified) Energy for general use	Waste water Waste heat	6kg for general use 25.2MJ 9MJ
Pipe for condenser (subcontract)	22/15 2/75	Minor constituents Water(unspecified) Oxygen Energy for general use	Open loop outputs Waste water Nitrogen Waste heat	50g 6kg 0.5kg 21MJ 3.96MJ
Drying filter (subcontract)	20/30 2/50	Water(unspecified) Energy for general use	Zeolite Waste water Waste heat	4.14g 6kg for general use 25.2MJ 5.4MJ
Thermostat (subcontract)	10/45 3/100	Water(unspecified) Energy for general use	Waste water Waste heat	6kg for general use 37.8MJ 5.4MJ
Sensor / thermostat (subcontract)	10/10 3/100	Water(unspecified) Energy for general use	Waste water Waste heat	2kg for general use 8.4MJ 1.2MJ
Wiring (subcontract)	10/25 3/75	Water(unspecified) Energy for general use	Waste water Waste heat	5kg for general use 21MJ 3MJ
Lamp panel	30/15	Air used (unspecified) Water(unspecified) Energy for general use	Air used (unspecified) Waste water Steam/water vapour Waste water Waste heat	1kg 6kg for general use 16.8MJ 0.26kg 0.49kg 21.6MJ

Table F.2. Assumptions to processes – Part A

Item	Power (kW)/duration (mins) for manufacturing process / Transportation type/distance (km[b])	Burdens IN[a]	Burdens OUT[a]	Value of burden
Lamp screen	30/15 N/A	Air used (unspecified) Water(unspecified) Energy for general use	Air used (unspecified) Waste water Steam/water vapour Waste water Waste heat	1kg 6kg for general use 16.8MJ 0.1kg 0.13kg 21.6MJ
Lamp socket (subcontract)	2/10 3/75	Water(unspecified) Energy for general use	Waste water Waste heat	3kg for general use 8.4MJ 0.24MJ
Light bulb (subcontract)	20/10 3/75	Water(unspecified) Energy for general use	Waste water Waste heat	3kg for general use 8.4MJ 2.4MJ
Hinge fittings (subcontract)	40/30 3/175	Industrial diamonds Oil Air used (unspecified) Water(unspecified) Energy for general use	Mineral oil (inc. industrial diamonds) Air used (unspecified) Waste water Waste water Waste heat	1g 2g 10kg 6kg 29.4MJ 106.8g 14.4MJ
Hinge fitting threaded portion (subcontract)	45/30 3/175	Industrial diamonds Oil Air used (unspecified) Water(unspecified) Energy for general use	Mineral oil (inc. industrial diamonds) Air used (unspecified) Waste water Waste water Waste heat	1g 2g 10kg 6kg 29.4MJ 3.4kg 16.2MJ
Mounting rail	30/45 N/A	Water(unspecified) Energy for general use	Waste water Steam/water vapour Waste water Waste heat	6kg for general use 37.8MJ 0.8kg 2.54kg 16.2MJ
Base plate	15/20 N/A	Air used (unspecified) Water(unspecified) Energy for general use	Air used (unspecified) Waste water Waste heat (inc. galvanising)	2kg 5kg for general use 16.8MJ 18+2.7MJ
Door				
Door casing	20/15 N/A	Minor constituents Air used (unspecified) Water(unspecified) Energy for general use	Open loop outputs Air used (unspecified) Waste water Salts Acid(unspecified) Detergent Steam/water vapour Waste water Waste heat	200g 10kg 5kg for general use 12.6MJ 8g 0.3g 16g 300g 10.38kg 8MJ
Door lining	15/10 N/A	Water(unspecified) Energy for general use	Waste water Waste heat	5kg for general use 12.6MJ 1.8MJ
PUR foam	111/30 N/A	Water(unspecified) Energy for general use	Waste water Waste heat	8kg 25.2MJ 39.96MJ
Seal frame (subcontract)	20/45 2/100	Water(unspecified) Energy for general use	Waste water Waste heat	5kg for general use 46.2MJ 10.8MJ
Handle	30/15 N/A	Air used (unspecified) Water(unspecified) Energy for general use	Air used (unspecified) Waste water Steam/water vapour Waste water Waste heat	1kg 5kg for general use 16.8MJ 0.5kg 2kg 21.6MJ

Table F.2. Assumptions to processes – Part B

Item	Power (kW)/duration (mins) for manufacturing process Transportation type/distance (km[b])	Burdens IN[a]	Burdens OUT[a]	Value of burden
Accessories				
Thread shelves	40/45 N/A	Water(unspecified) Energy for general use	Waste water Salts Acid(unspecified) Detergent Steam/water vapour Waste water Waste heat	6kg for general use 42MJ 5g 0.9g 8.5g 300g 8kg 54MJ
Coverplate	15/15 N/A	Air used (unspecified) Water(unspecified) Energy for general use	Air used (unspecified) Waste water Waste heat	4kg 4kg for general use 16.8MJ 2.7MJ
Front rim	15/10 N/A	Water(unspecified) Energy for general use	Waste water Waste heat	2kg for general use 12.6MJ 1.8MJ
Glass shelf	0.5/15 N/A	Water(unspecified) Energy for general use	Waste water Waste heat	0.5kg for general use 12.6MJ 0.09MJ
Various plastic boxes	45/45 N/A	Air used (unspecified) Water(unspecified) Energy for general use	Air used (unspecified) Waste water Steam/water vapour Waste water Waste heat	10kg 5kg for general use 46.2MJ 100g 1.2kg 97.2MJ
Packaging				
Packaging	5/20 N/A	Air used (unspecified) Water(unspecified) Energy for general use	Air used (unspecified) Waste water Waste heat	1kg 3kg for general use 21MJ 1.2MJ
Plastic bag (subcontract)	15/15 3/100	Water(unspecified) Energy for general use	Waste water Waste heat	2kg for general use 12.6MJ 0.24MJ
Door support	0.5/5 N/A	Water(unspecified) Energy for general use	Waste water Waste heat	1kg for general use 8.4MJ 0.03MJ
Base frame	0.5/30 N/A	Air used (unspecified) Energy for general use	Air used (unspecified) Waste heat	5kg 29.4MJ 0.18MJ
Miscellaneous				
Other steel items (subcontract)	5/10 3/50	Water(unspecified) Energy for general use	Waste water Waste heat	2kg for general use 12.6MJ 0.6MJ
Rubber items (subcontract)	20/10 3/75	Water(unspecified) Energy for general use	Waste water Waste heat	2kg for general use 12.6MJ 2.4MJ
Other ABS items	30/10 N/A	Air used (unspecified) Water(unspecified) Energy for general use	Air used (unspecified) Waste water Steam/water vapour Waste water Waste heat	1kg 2kg for general use 12.6MJ 0.2kg 0.32kg 14.4MJ
Nylon items (subcontract)	5/5 3/50	Air used (unspecified) Water(unspecified) Energy for general use	Air used (unspecified) Waste water Steam/water vapour Waste water Waste heat	1kg 1kg for general use 8.4MJ 3g 50.4g 1.2MJ
Adhesive tape (subcontract)	0.2/30 3/50	Water(unspecified) Energy for general use	Waste water Waste heat	1kg for general use 96MJ 0.072MJ

Table F.2. Assumptions to processes – Part C

Item	Power (kW)/duration (mins) for manufacturing process Transportation type/distance (km[b])	Burdens IN[a]	Burdens OUT[a]	Value of burden
Lupolene items	30/5 N/A	Air used (unspecified) Water (unspecified) Energy for general use	Air used (unspecified) Waste water Steam/water vapour Waste water Waste heat	1kg 2kg 8.4MJ 10g 30.05g 7.2MJ
Acetal items	30/10 N/A	Air used (unspecified) Water (unspecified) Energy for general use	Air used (unspecified) Waste water Steam/water vapour Waste water Waste heat	1kg 2kg for general use 12.6MJ 100.5g 300g 14.4MJ
Other small items	0.5/10 N/A	Water(unspecified) Energy for general use	Waste water Waste heat	0.5kg for general use 12.6MJ 0.06MJ
Assembly				
Assembly of cabinet items (designated as unit)	5/60 N/A	Air used (unspecified) Water (unspecified) Energy for general use	Air used (unspecified) Waste water Waste heat	25kg for pneumatics 10kg for general use 63MJ 3.6MJ
Assembly of refrigerating system items (designated as unit)	20/60 N/A	Minor constituents Air used (unspecified) Water (unspecified) Oxygen Energy for general use	Open loop outputs Air used (unspecified) Waste water Nitrogen Waste heat	0.5kg for brazing 25kg for pneumatics 7kg for general use 10kg 50.4MJ 18MJ
Assembly of all accessories (designated as unit)	2/30 N/A	Air used (unspecified) Water (unspecified) Energy for general use	Air used (unspecified) Waste water	10kg for pneumatics 5kg for general use 25.2MJ
Assembly of door items (designated as unit)	5/20 N/A	Air used (unspecified) Water (unspecified) Energy for general use	Air used (unspecified) Waste water Waste heat	15kg for pneumatics 5kg for general use 16.8MJ 1.2MJ
Assembly of all misc. items (designated as unit)	2/20 N/A	Air used (unspecified) Water (unspecified) Energy for general use	Air used (unspecified) Waste water Waste heat	10kg for pneumatics 5kg for general use 16.8MJ 0.48MJ
Boxing of fridge (designated as unit)	2/15 N/A	Air used (unspecified) Water (unspecified) Energy for general use	Air used (unspecified) Waste water Waste heat	5kg for stapling 5kg for general use 12.6MJ 0.36MJ

[a] Burdens IN and OUT may not necessarily balance since some burdens are inputted as materials

[b] Transportation details for subcontracted items: Type 1 – truck > 25 tonnes, average road
Type 2 – truck > 7.5 tonnes, average road
Type 3 – van < 3.5 tonnes, average road
Type 4 – freighter, inland waters

Table F.2. Assumptions to processes – Part D

APPENDIX G

This appendix presents the LCA generic model in flow chart format. It is important that these charts be read in conjunction with explanations given in Section 3.7ff. Figure G.1 deals with the model until the manufacturing process for *item 'X'* is considered. Alternatively, Figure G.2 deals with the remainder of the product manufacturing stage. The functional unit (FU1) is then assembled and the overall environmental impact pertaining to its manufacture may thus be determined. Figure G.2 also details the LCA models for the synthesis of the HFC-134a and the CFC-12 compounds based on the total energy of production. The outcome of this model is either inputted into the manufacturing process (Figure G.1) as an ancillary for the manufacture of the cabinet or door insulation or, in the case of the refrigerant, treated separately and the environmental impact from the manufacture of this refrigerant determined. This figure also details the LCA model used to determine the environmental impact from the rates of change in the in-use power observed from the experimentation carried out.

Finally, Figure G.3 gives an indication of how the relevant data is inputted into the LCA software. The figure shows the manufacture of the compressor. All the materials and their respective transport details as well as the electrical requirements are linked to the process node *Compressor*. The output of this node, that is the environmental impact, may thus be calculated separately or linked to the whole of the functional unit. Process browsers for the compressor showing the weights of the input materials, for the transport of the steel showing the type and distance travelled as well as for the electrical supply have also been included.

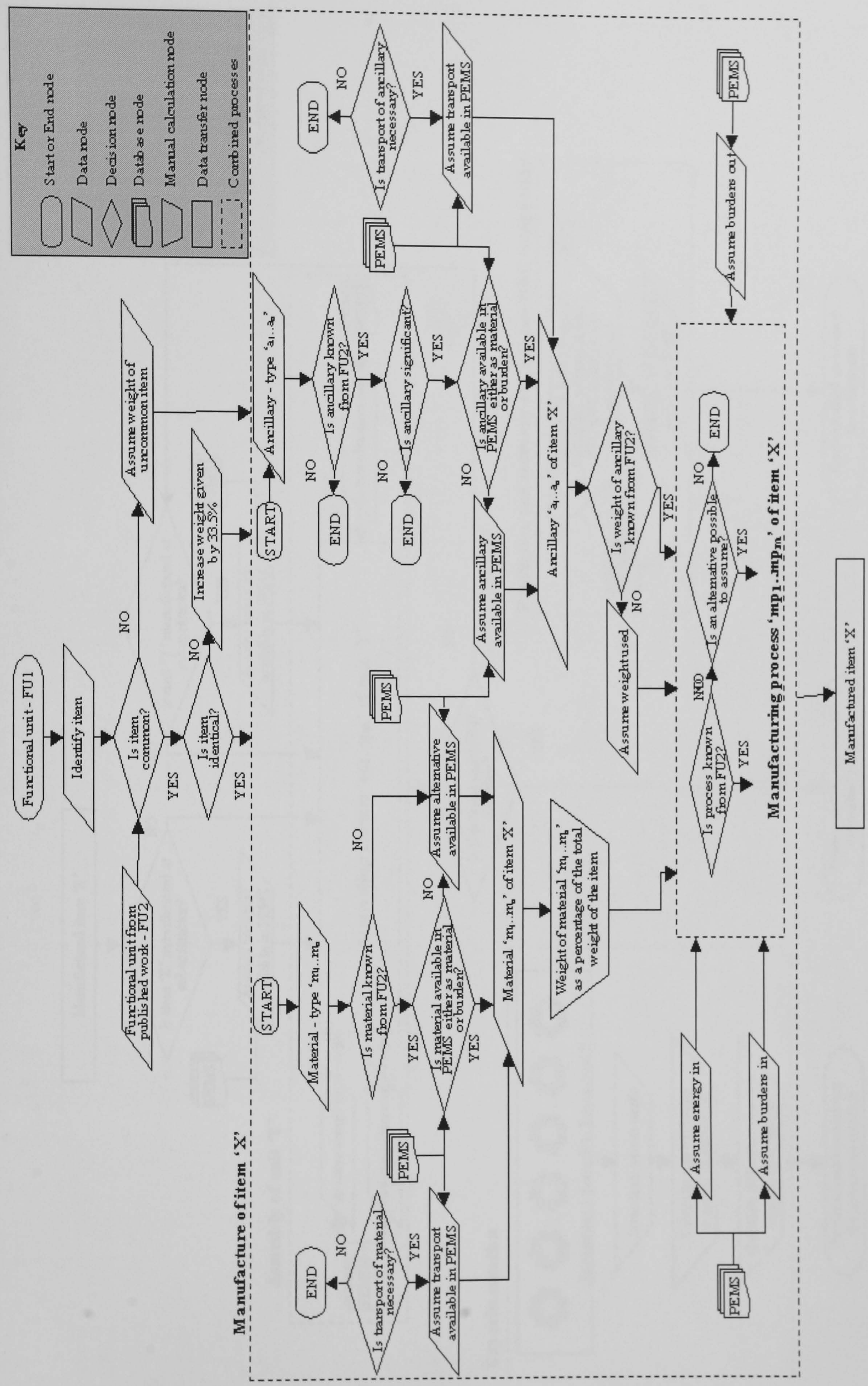


Figure G.1. **LCA model till manufacture of product item**

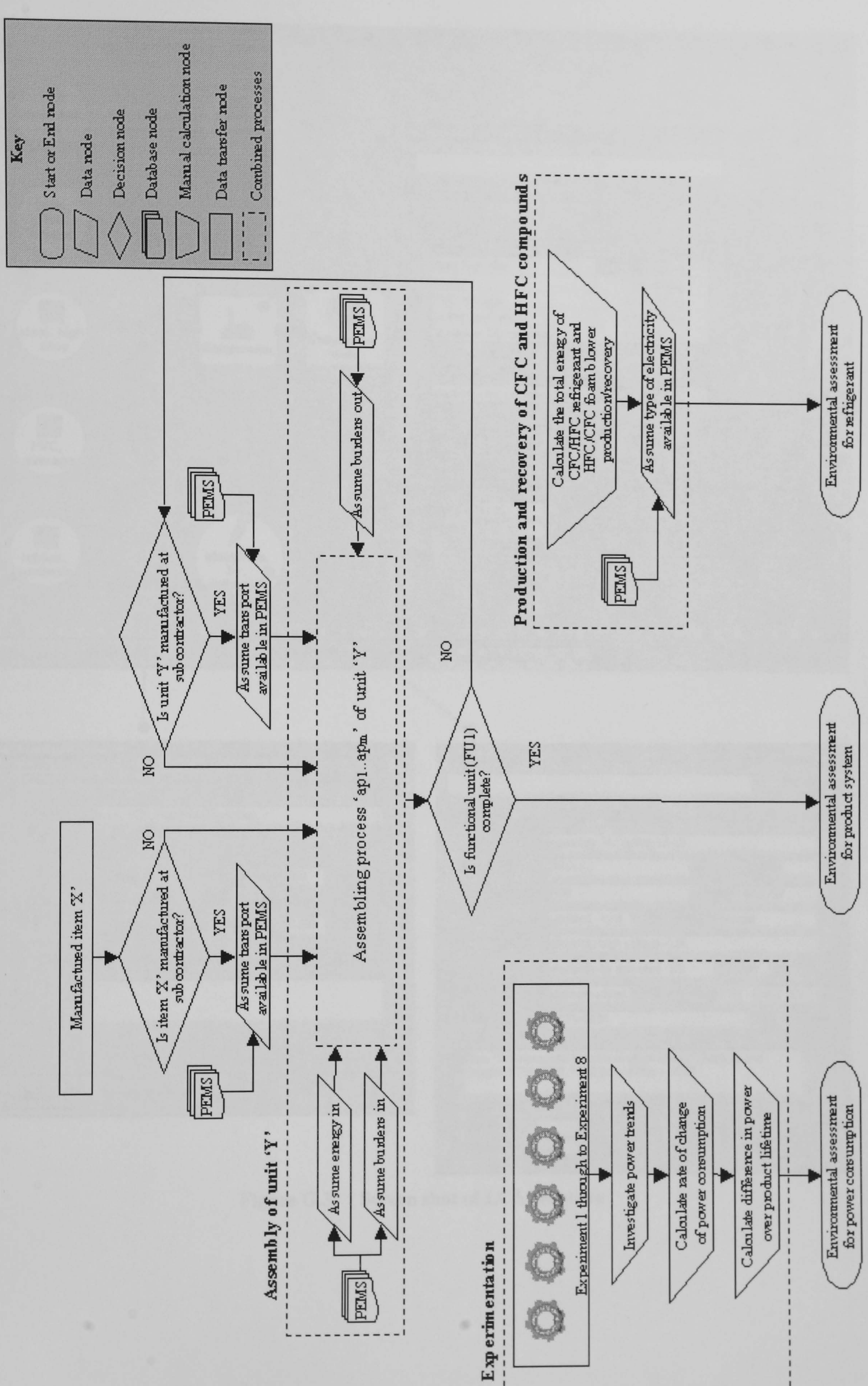


Figure G.2. Remaining LCA models

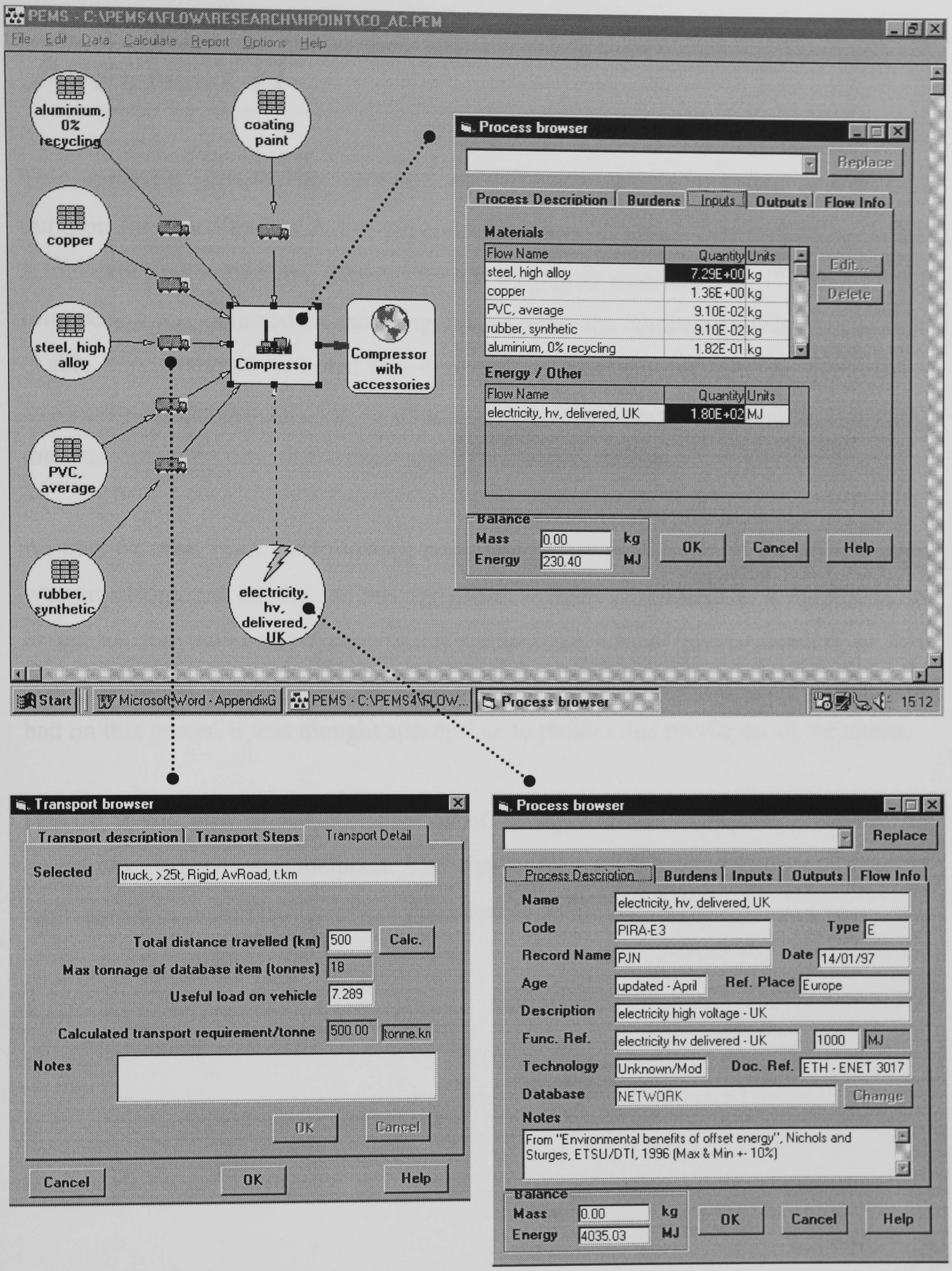


Figure G.3. Screen shot of LCA software

APPENDIX H

This appendix presents the different rig characteristics plotted over a 500 hour duration for Test 1 to Test 8. For the continuous tests (Table 3.2) this 500 hour is the actual experiment duration, whereas for the 1000 hour start/stop tests (Table 3.2) this time period was obtained by sampling data of when the compressor was in operation (Table 4.6). It should be noted that during these latter type of tests the compressor was operating periodically for 30 minutes every 30 minutes. Therefore, in this case, the total operating time of the compressor was also 500 hours.

As may be seen from the following plots, the power profile for all the experiments was superimposed on the various rig characteristics monitored. It is important to emphasis that the in-use power of the compressor was of primal concern to this study. However, to determine the influence other experimental conditions may have had on this power, it was thought appropriate to present this profile on all the charts.

Finally, it will also be noted that for all of the eight tests a regression curve for the condenser pressure was included. The significance of this is given in the detailed explanation of these characteristics presented in Section 4.3.1.

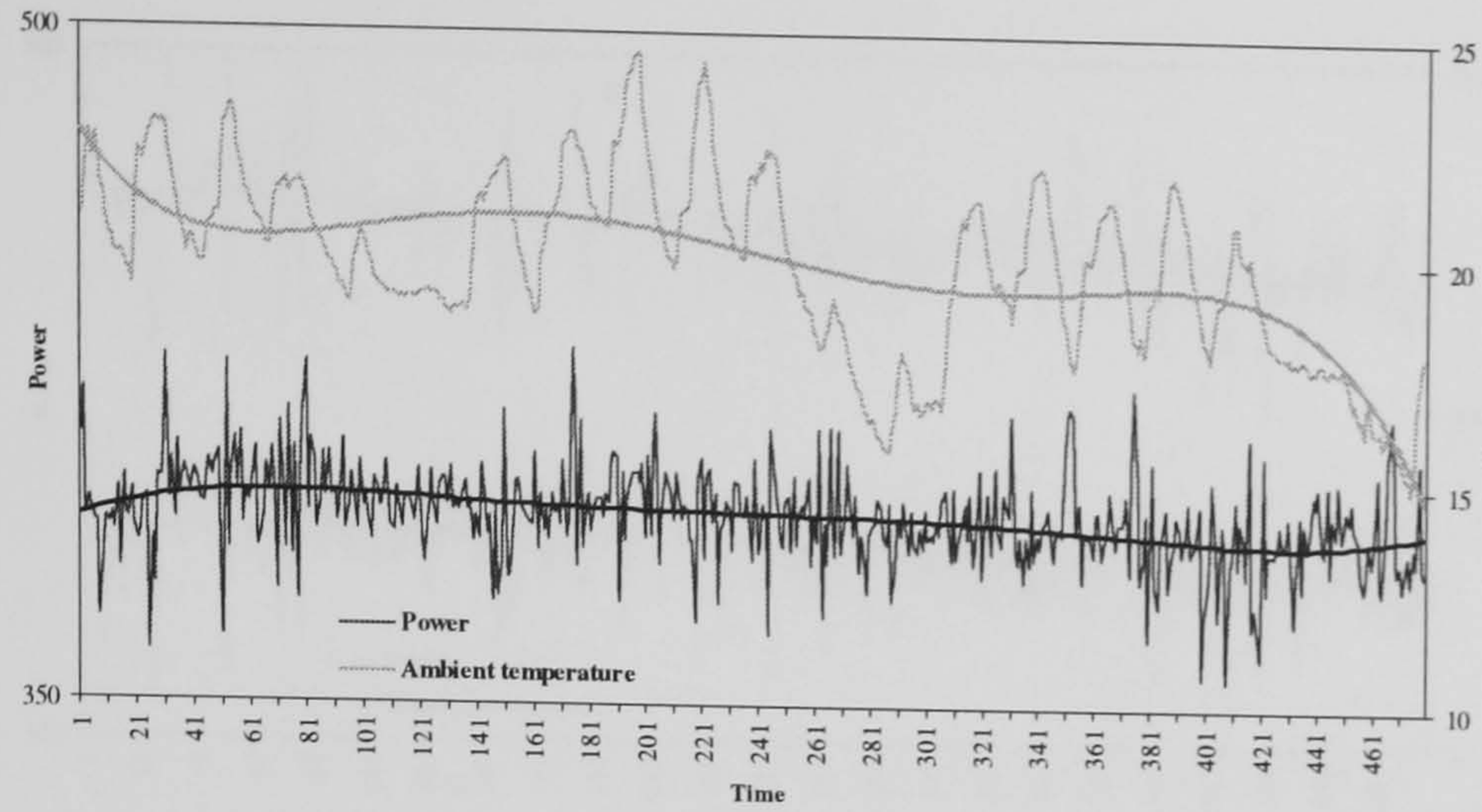


Figure H.1. Test 1 – Power (W) / Ambient temperature (°C) with Time (hrs)

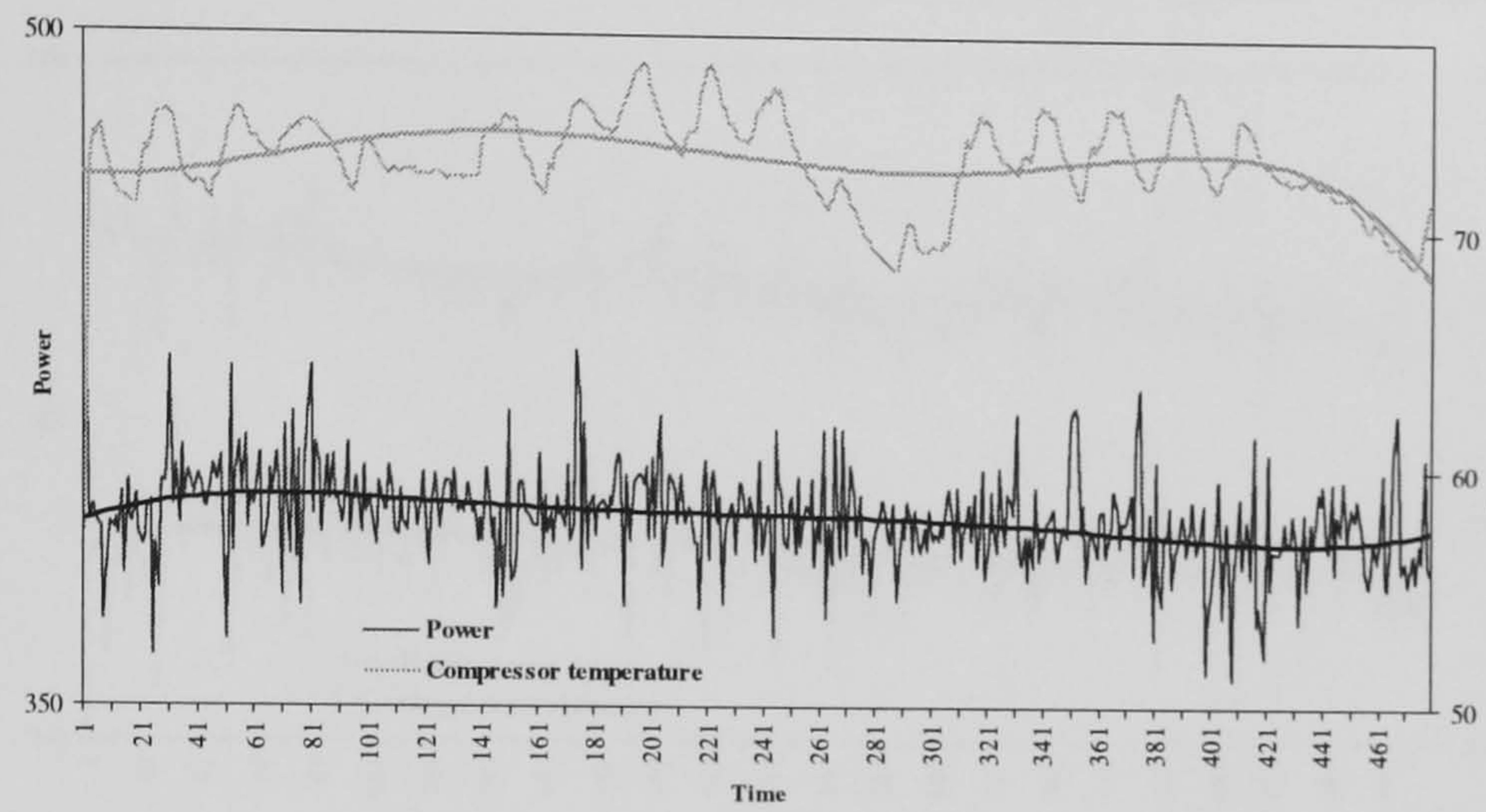


Figure H.2. Test 1 - Power (W) / Compressor temperature (°C) with Time (hrs)

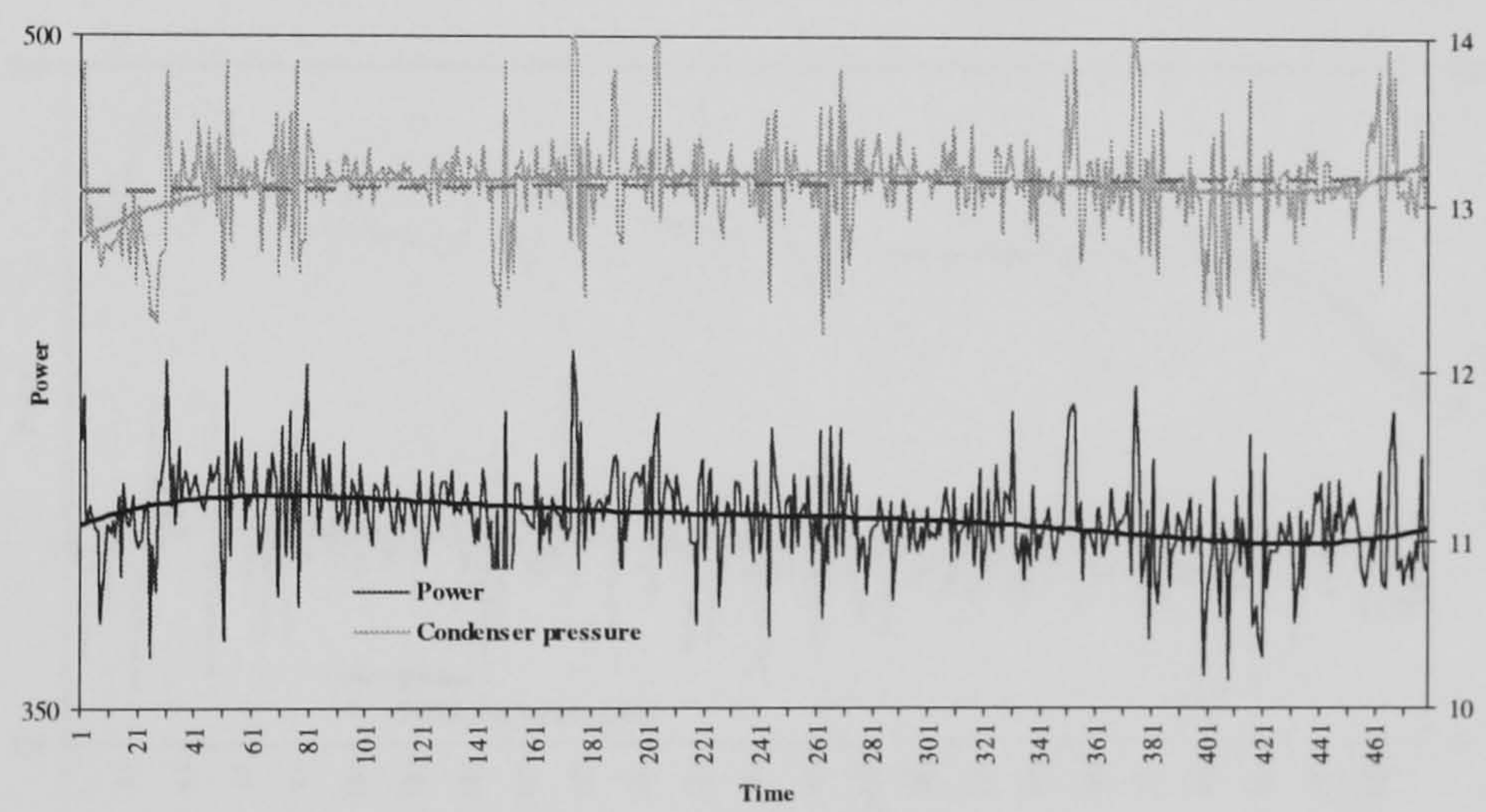


Figure H.3. Test 1 - Power (W) / Condenser pressure (bar) with Time (hrs)

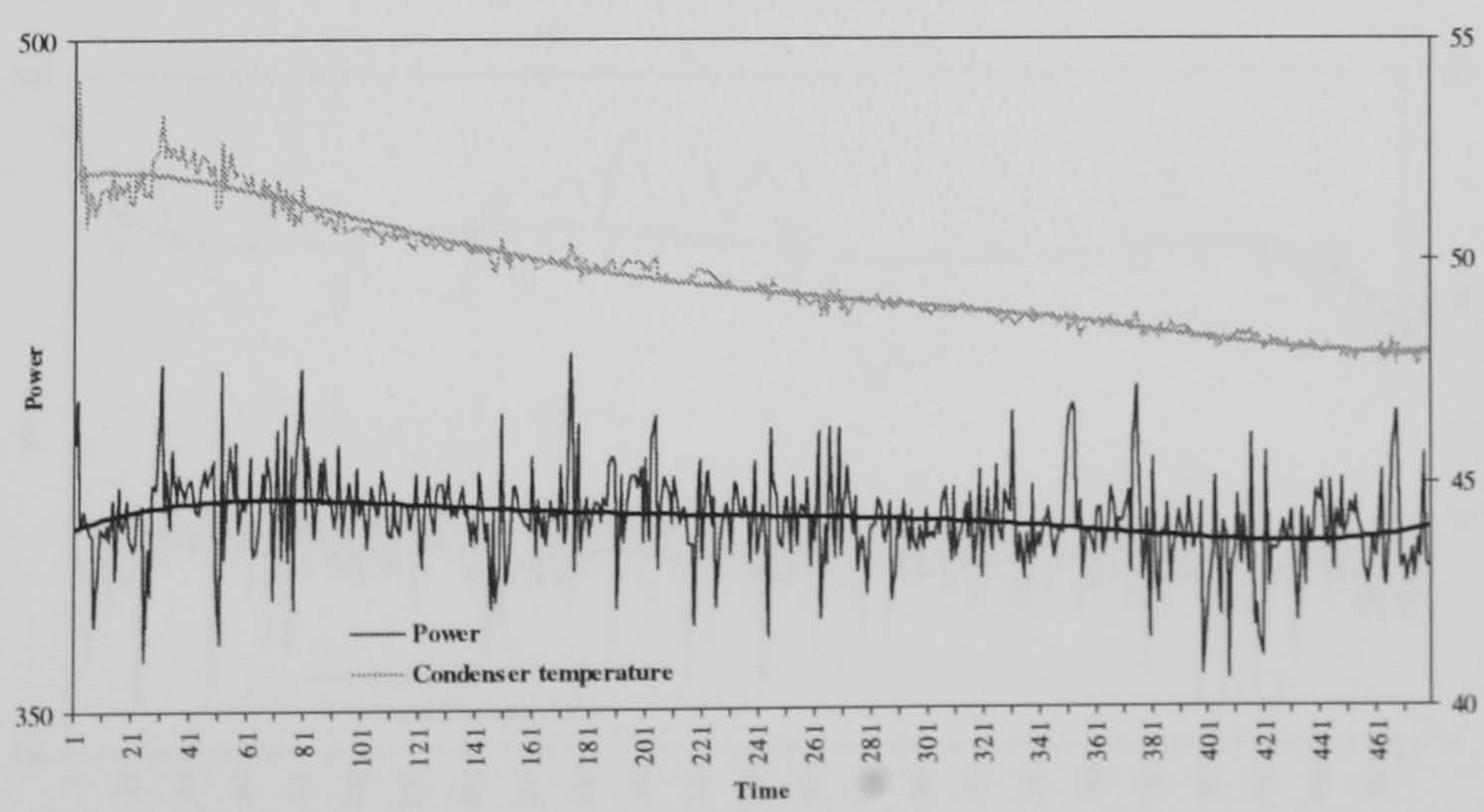


Figure H.4. Test 1 - Power (W) / Condenser temperature (°C) with Time (hrs)

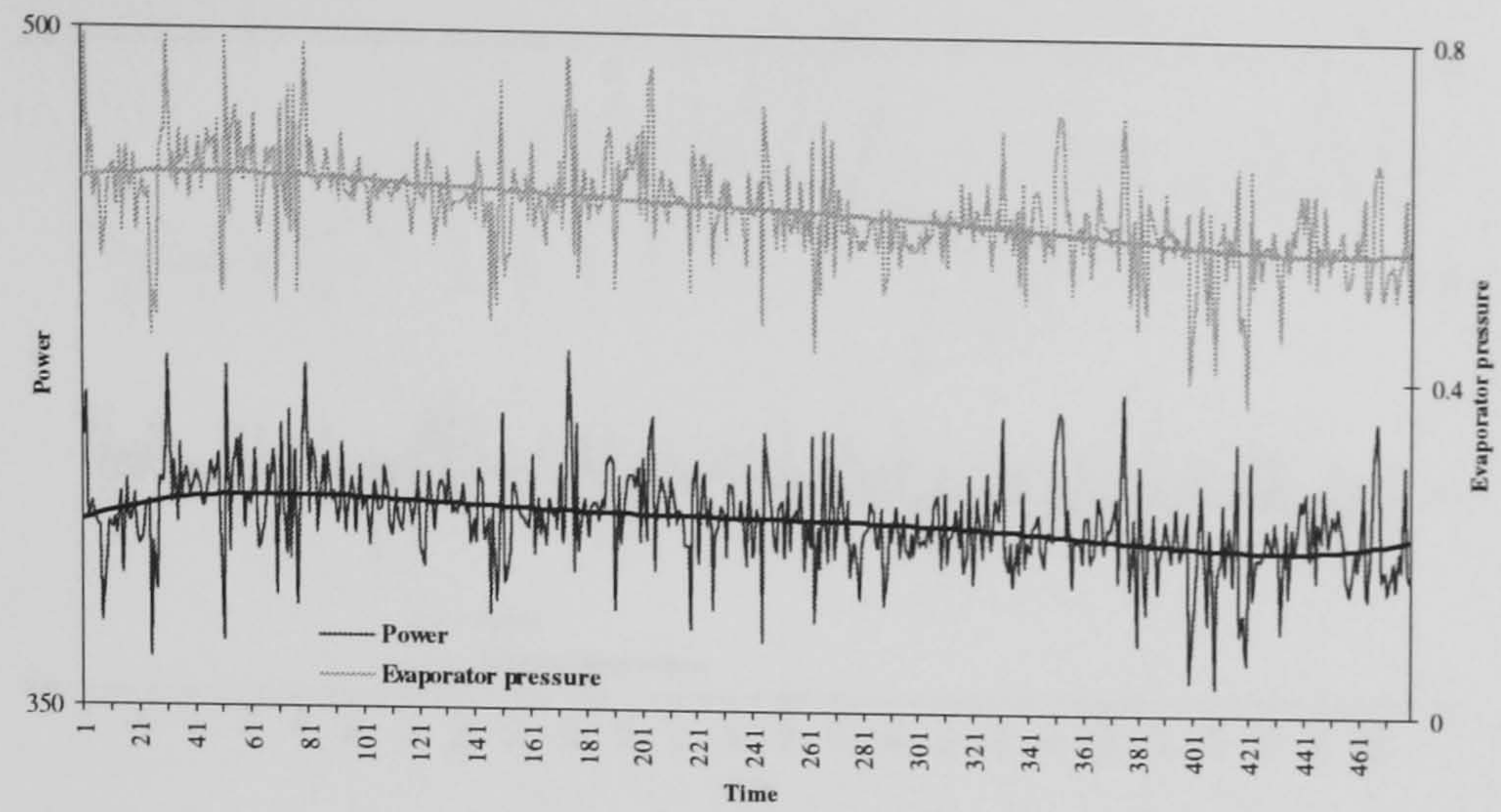


Figure H.5. Test 1 - Power (W) / Evaporator pressure (bar) with Time (hrs)

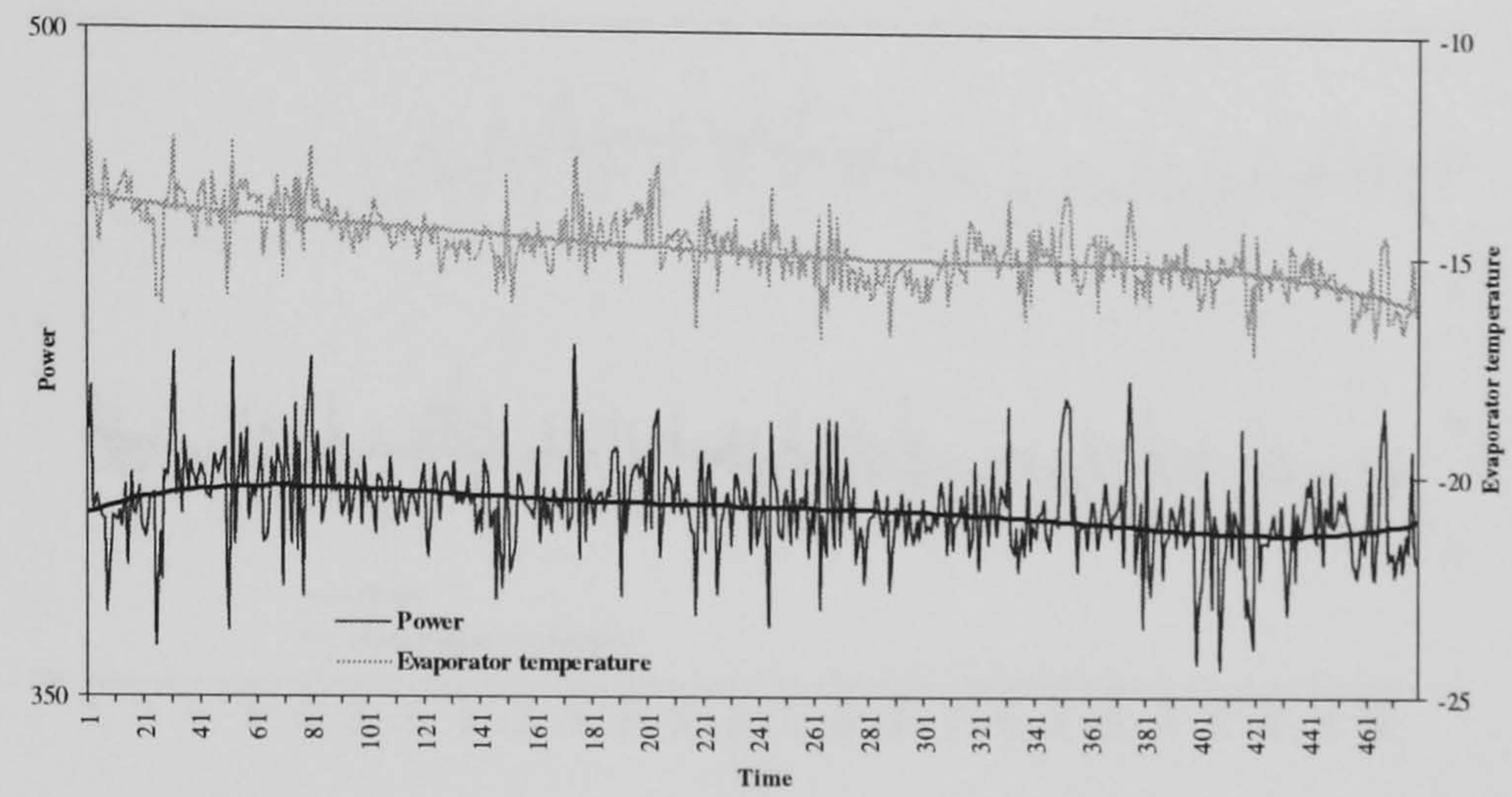


Figure H.6. Test 1 - Power (W) / Evaporator temperature (°C) with Time (hrs)

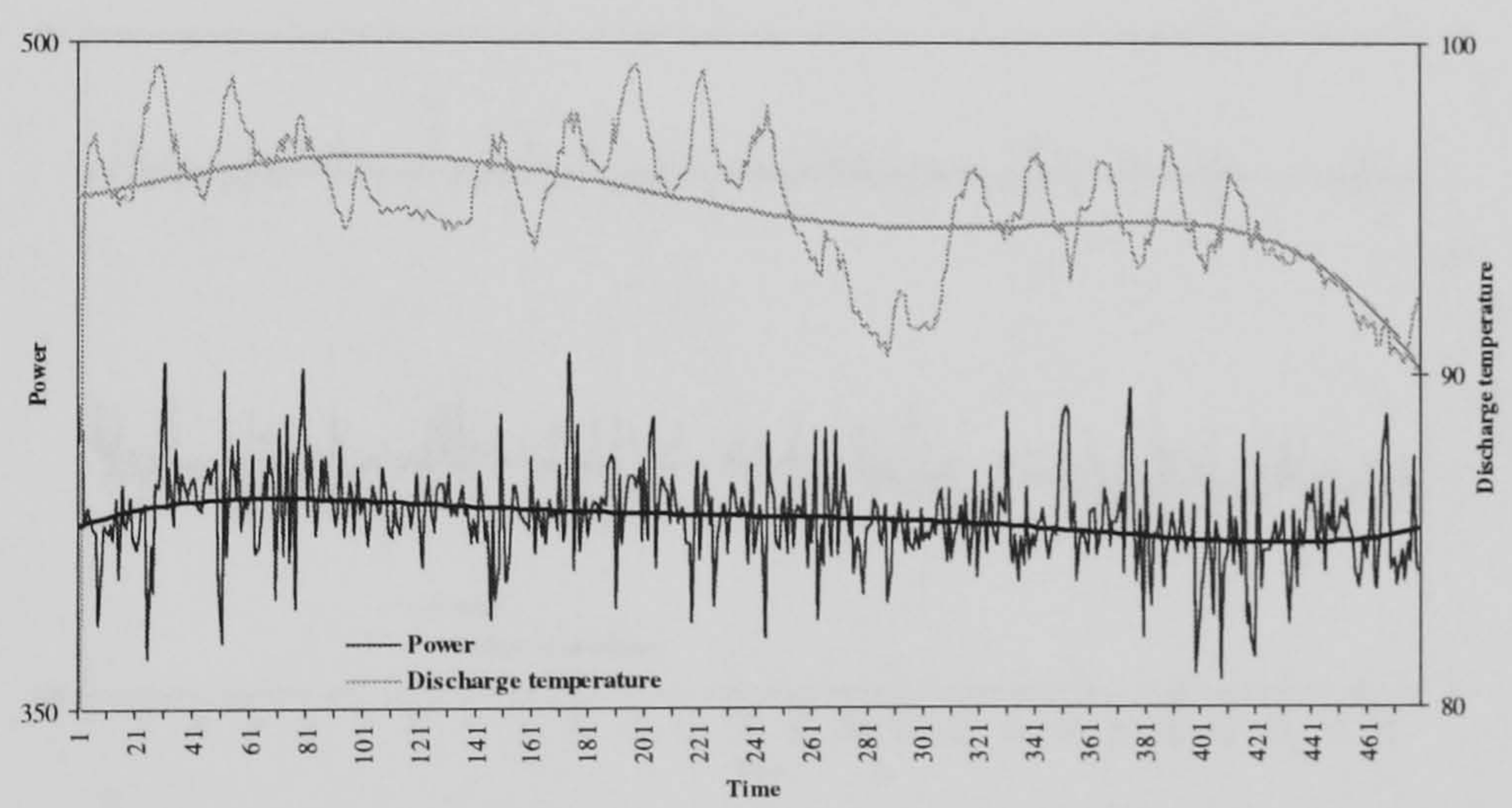


Figure H.7. Test 1 - Power (W) / Discharge temperature (°C) with Time (hrs)

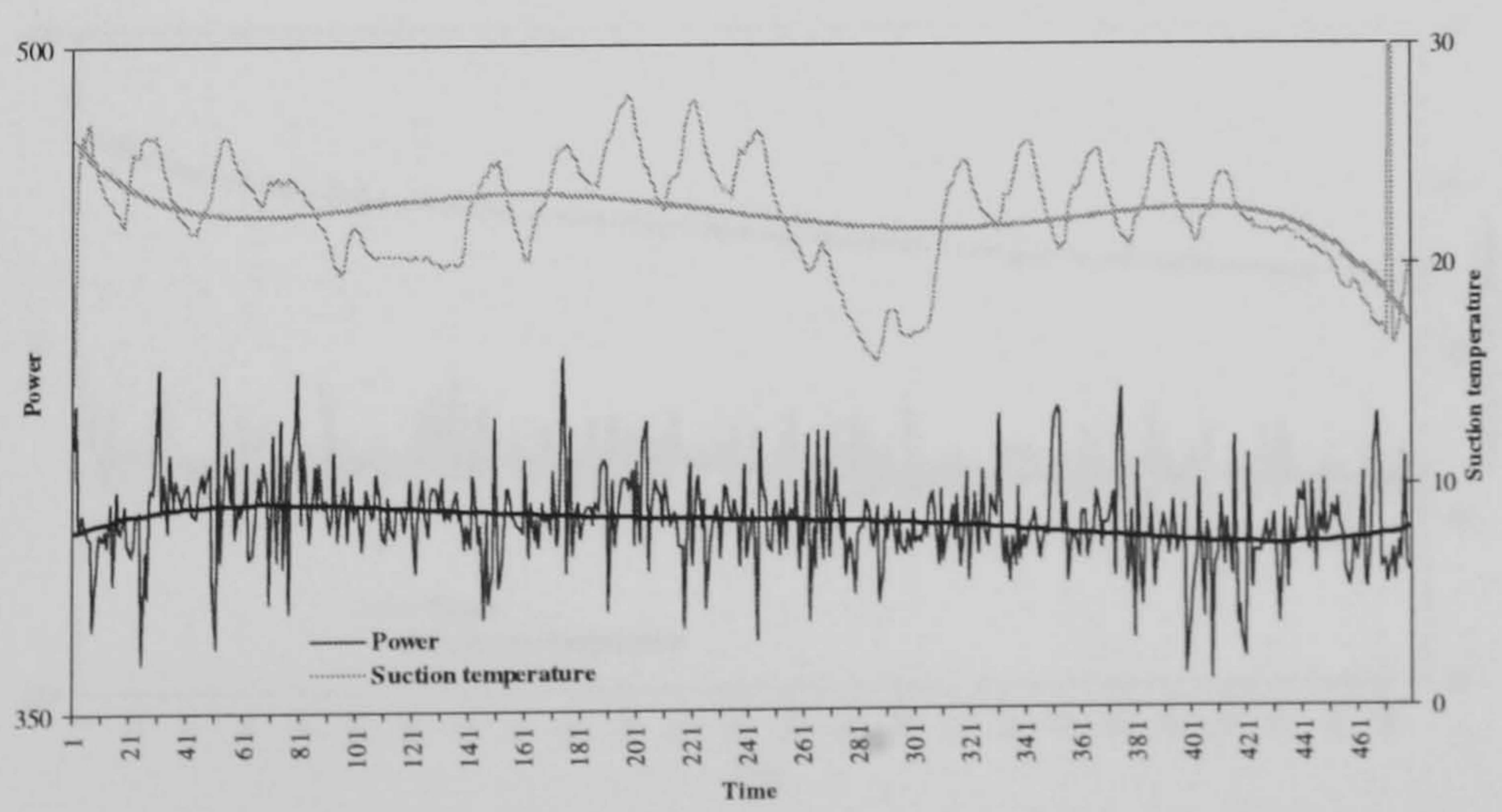


Figure H.8. Test 1 - Power (W) / Suction temperature (°C) with Time (hrs)

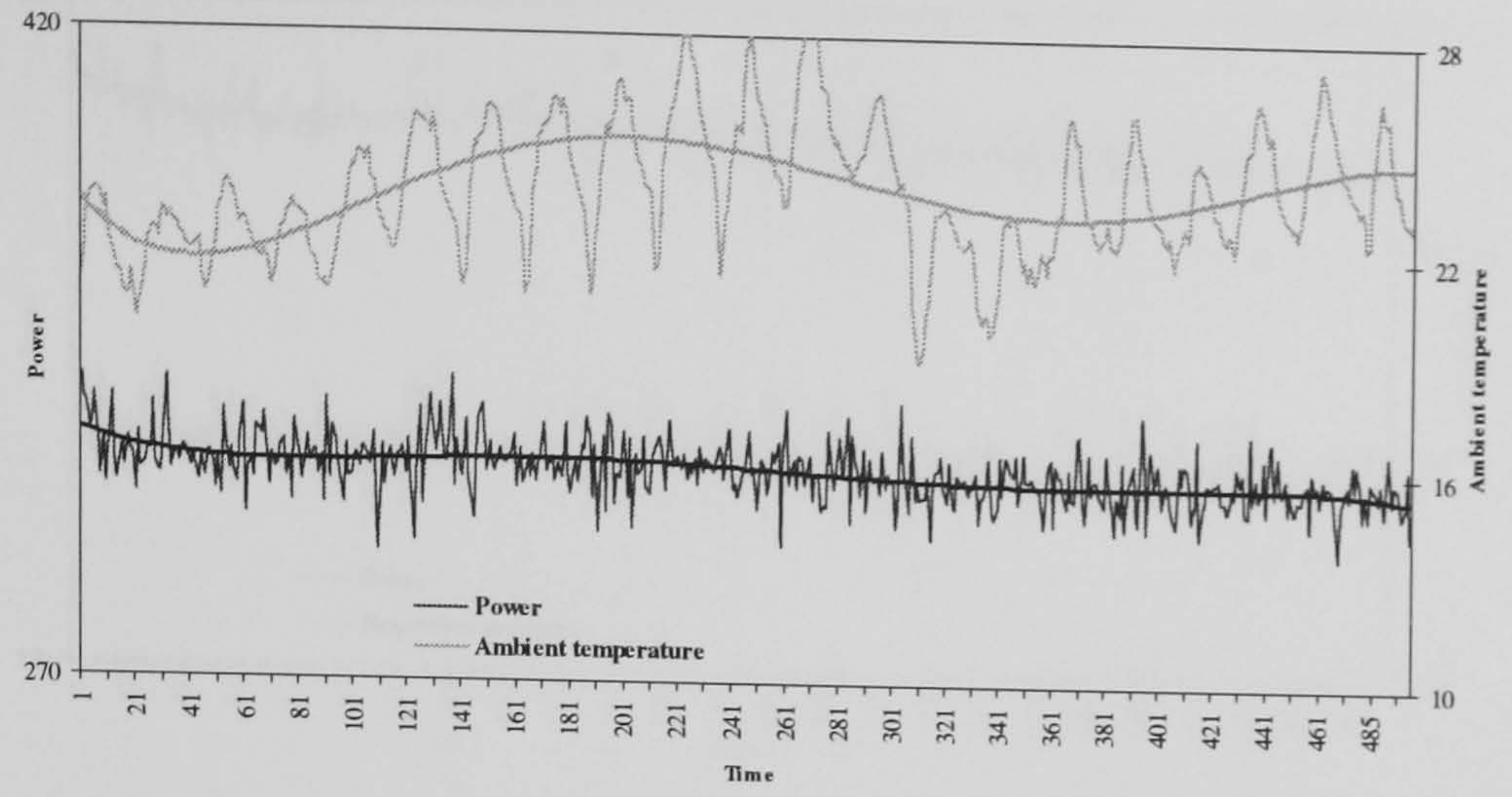


Figure H.9. Test 2 - Power (W) / Ambient temperature (°C) with Time (hrs)

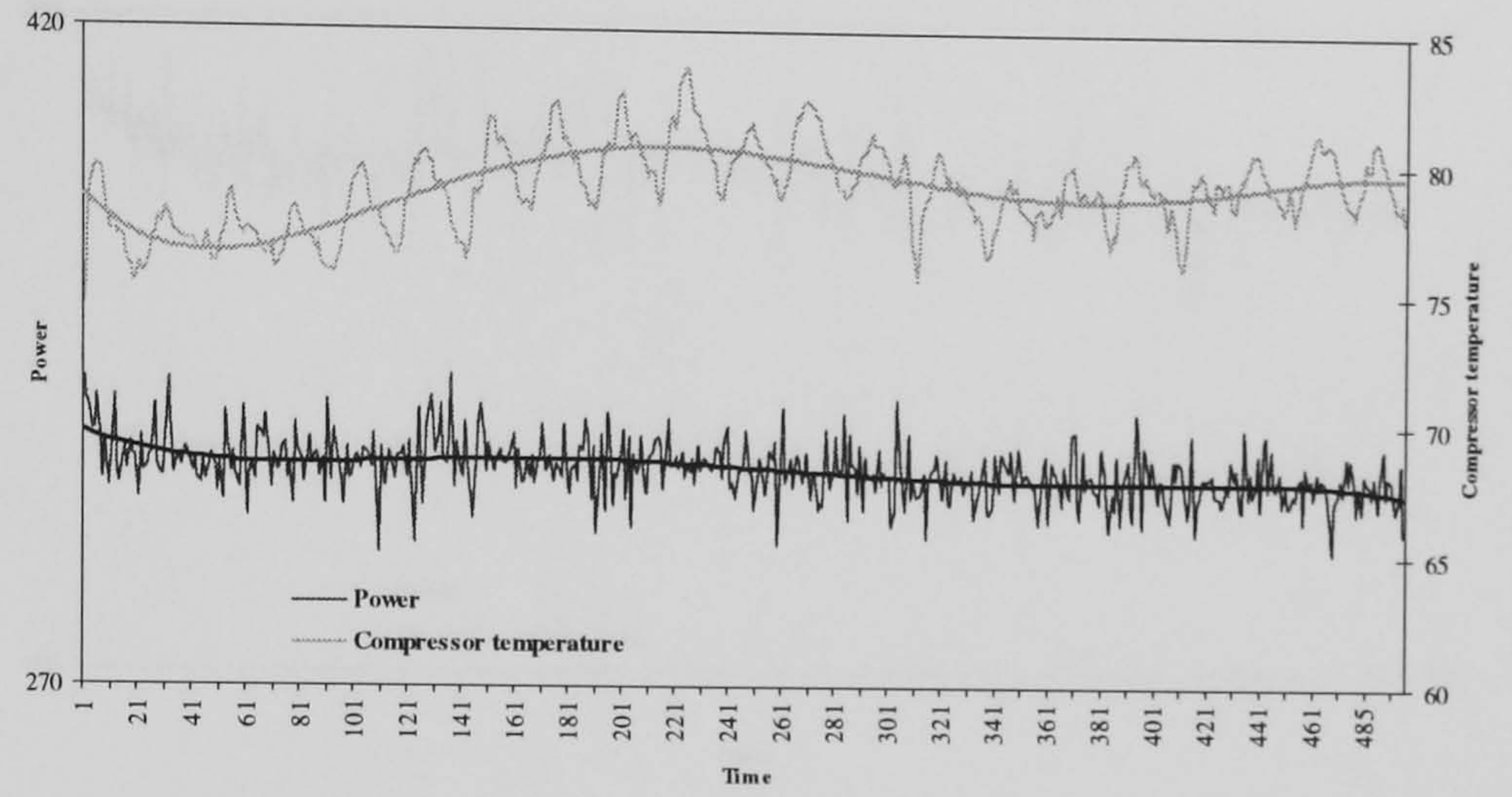


Figure H.10. Test 2 - Power (W) / Compressor temperature (°C) with Time (hrs)

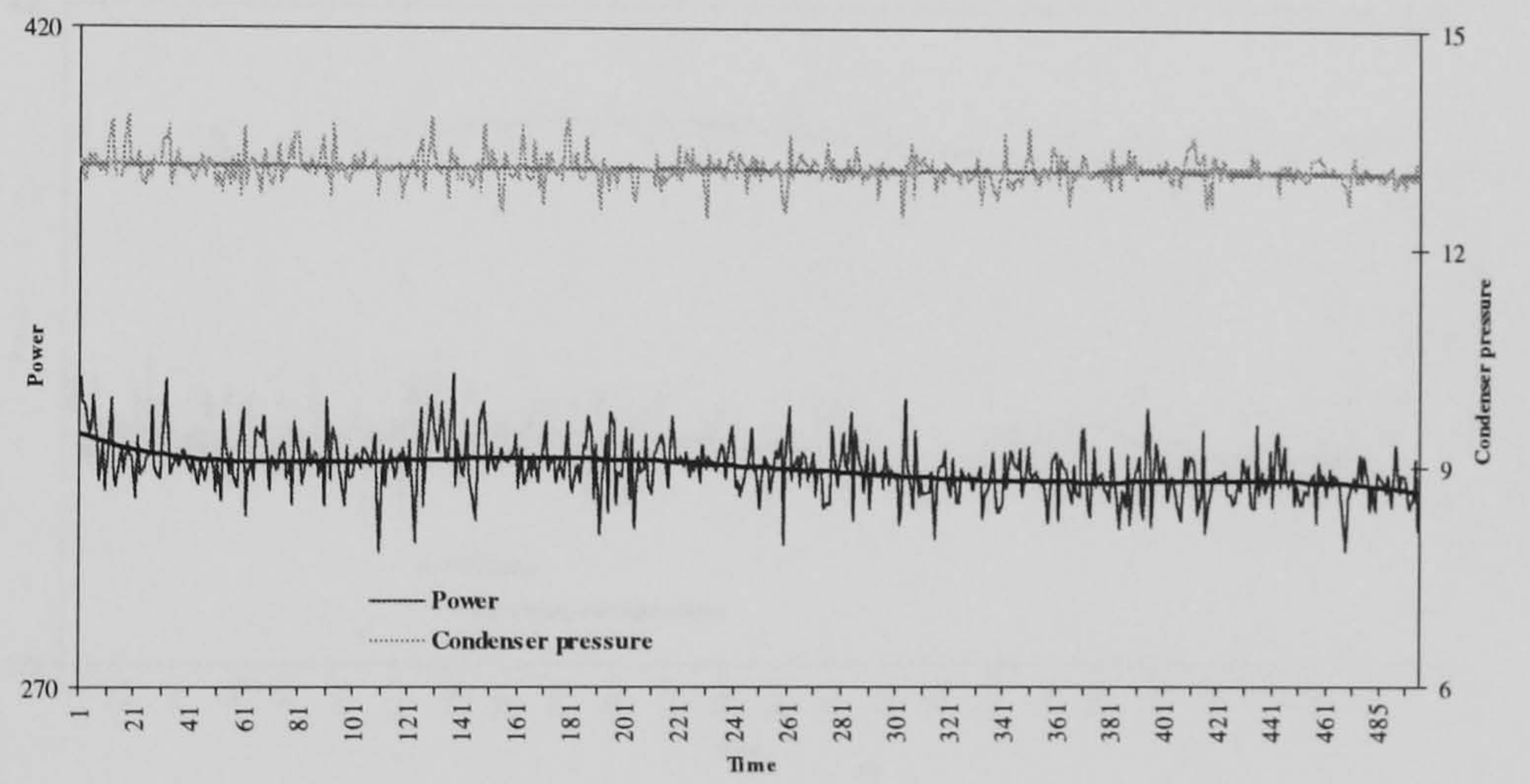


Figure H.11. Test 2 - Power (W) / Condenser pressure (bar) with Time (hrs)

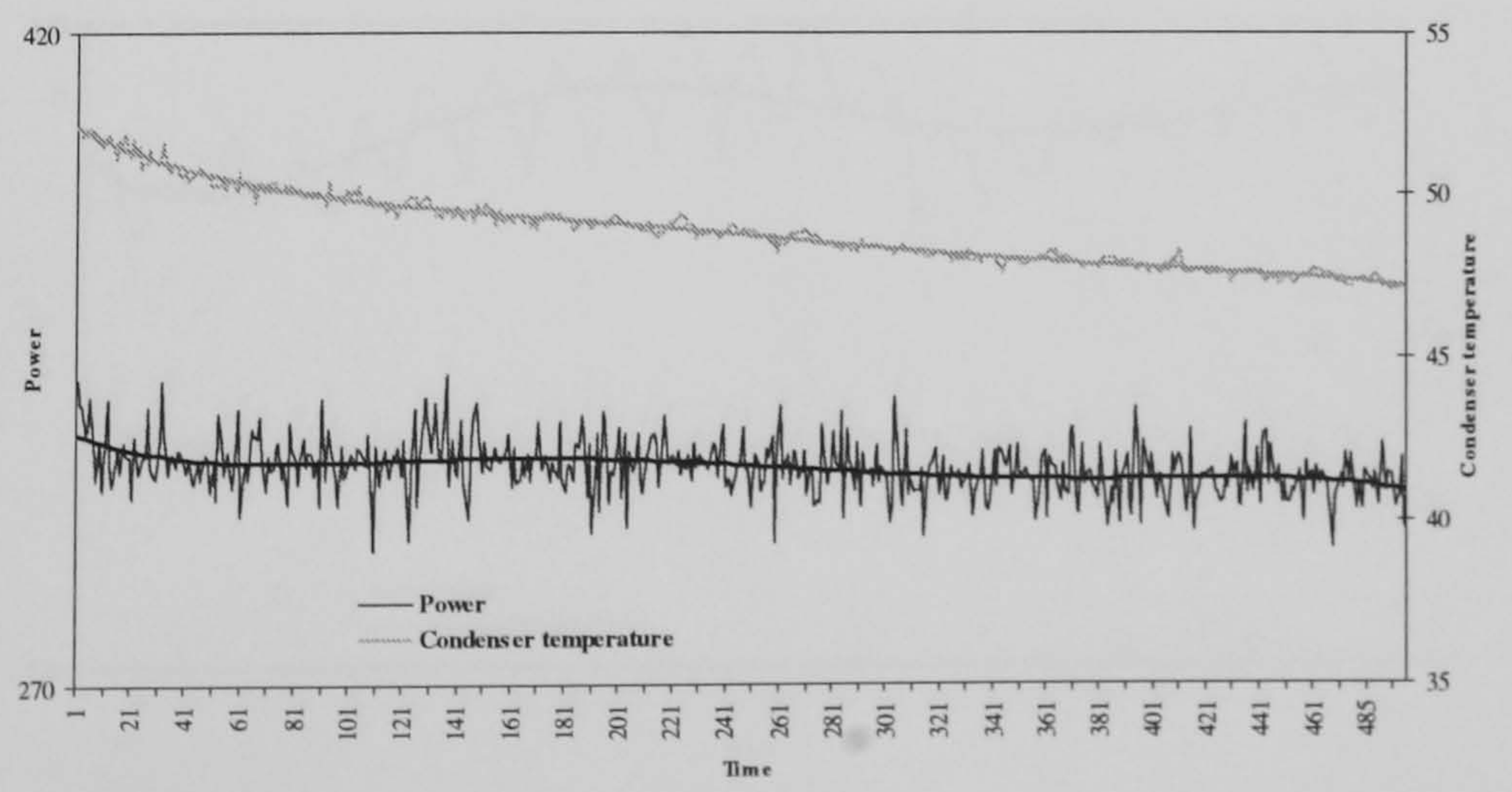


Figure H.12. Test 2 - Power (W) / Condenser temperature (°C) with Time (hrs)

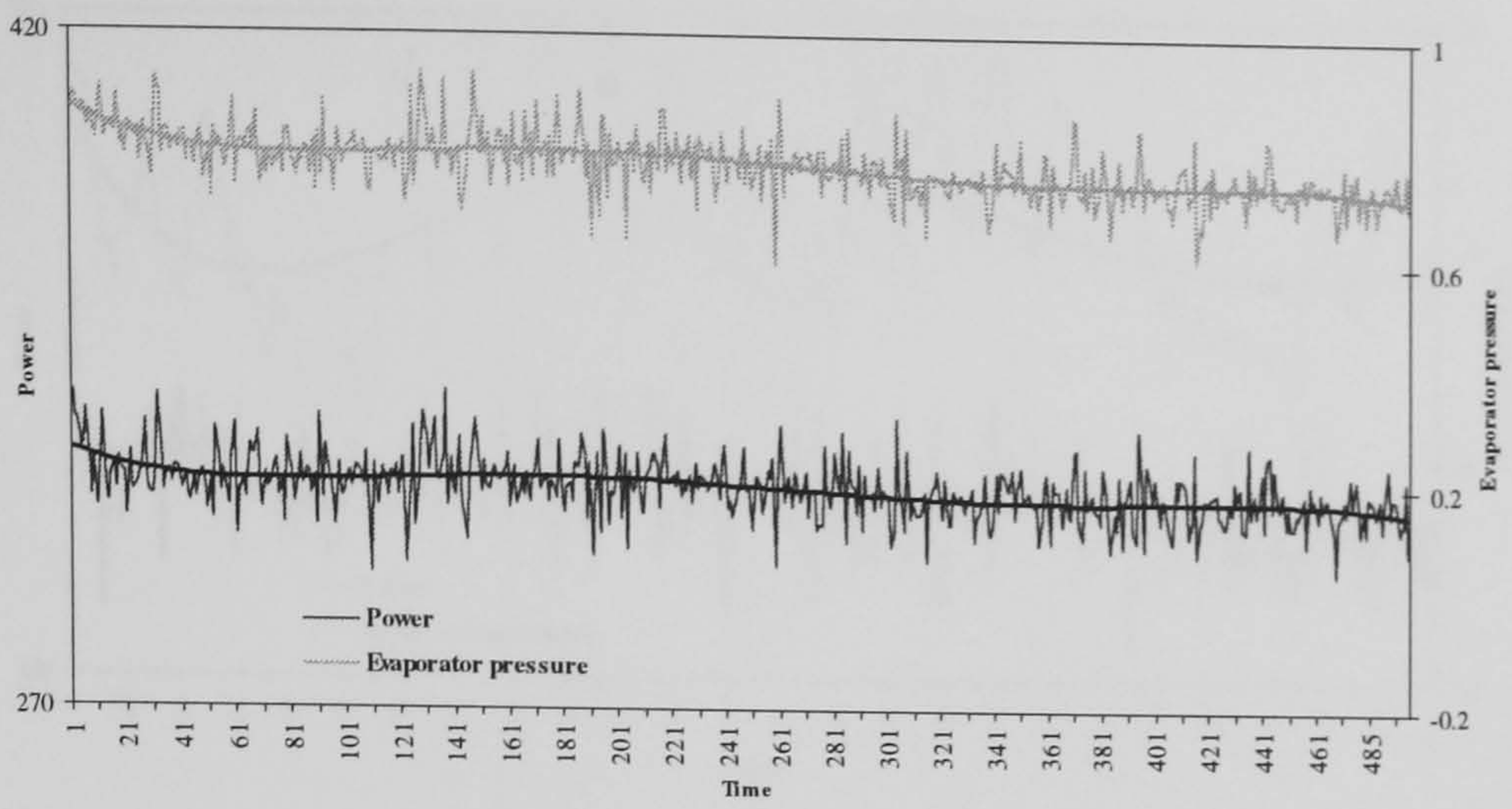


Figure H.13. Test 2 - Power (W) / Evaporator pressure (bar) with Time (hrs)

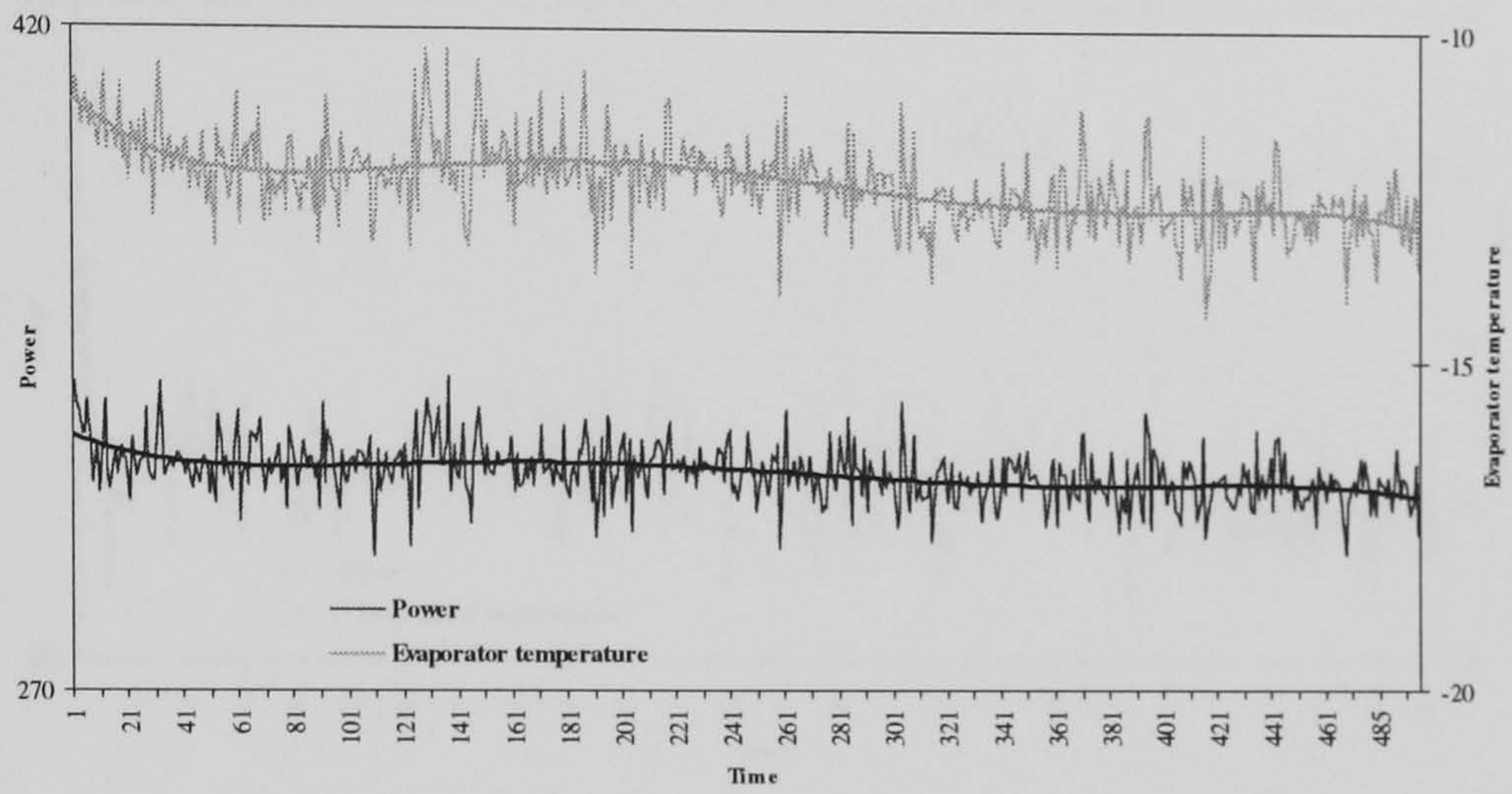


Figure H.14. Test 2 - Power (W) / Evaporator temperature (°C) with Time (hrs)

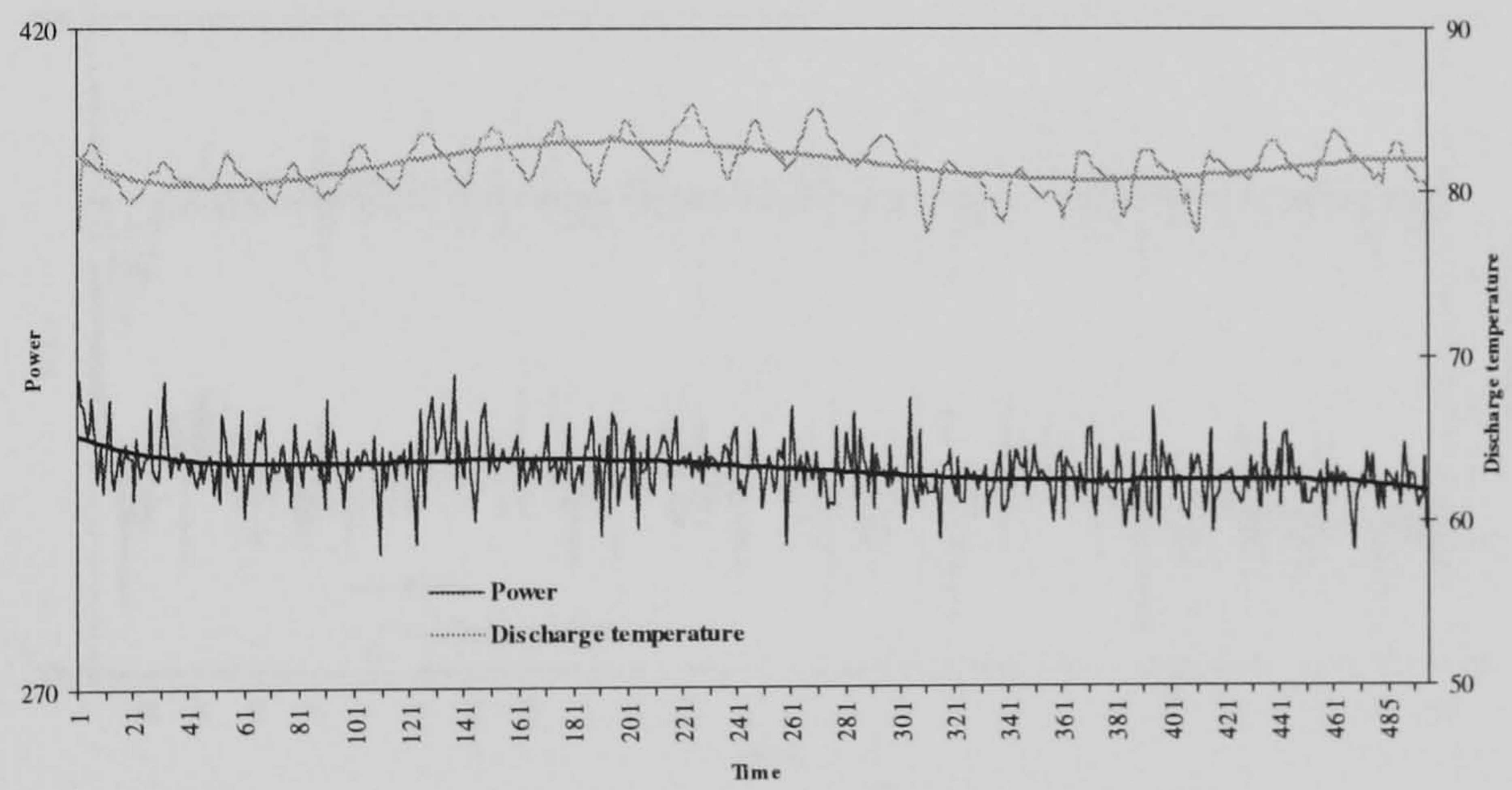


Figure H.15. Test 2 - Power (W) / Discharge temperature (°C) with Time (hrs)

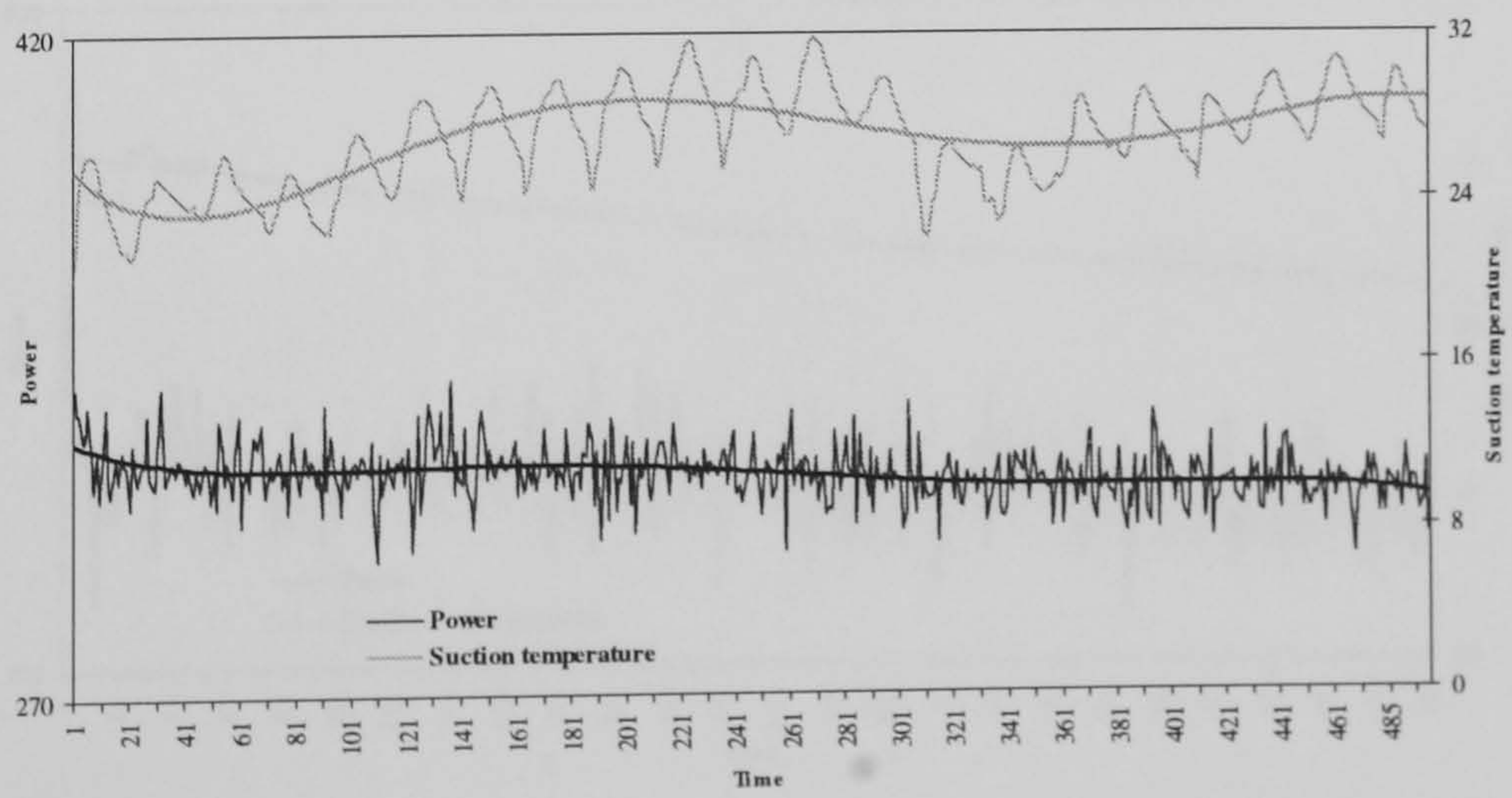


Figure H.16. Test 2 - Power (W) / Suction temperature (°C) with Time (hrs)

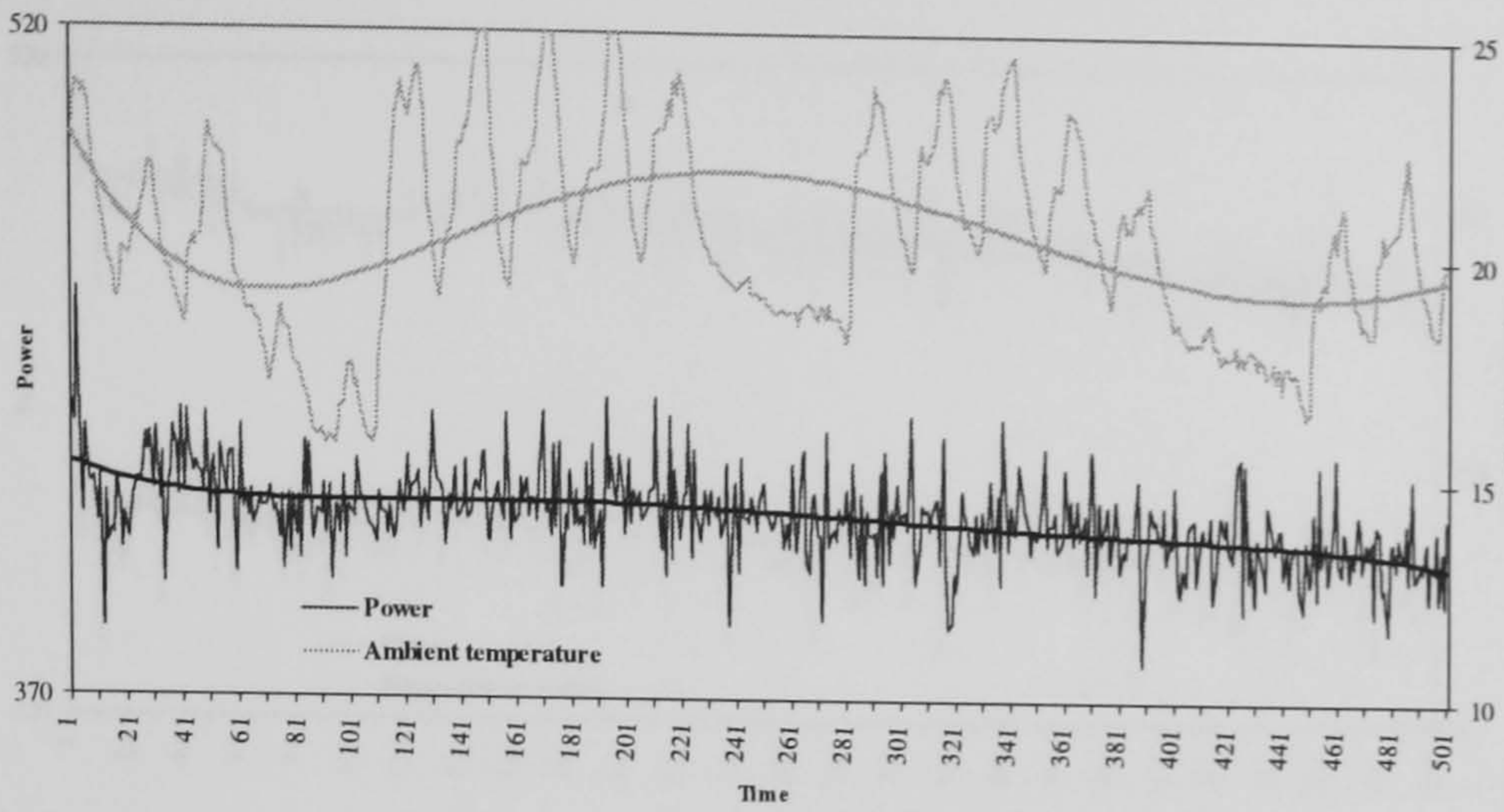


Figure H.17. Test 3 - Power (W) / Ambient temperature (°C) with Time (hrs)

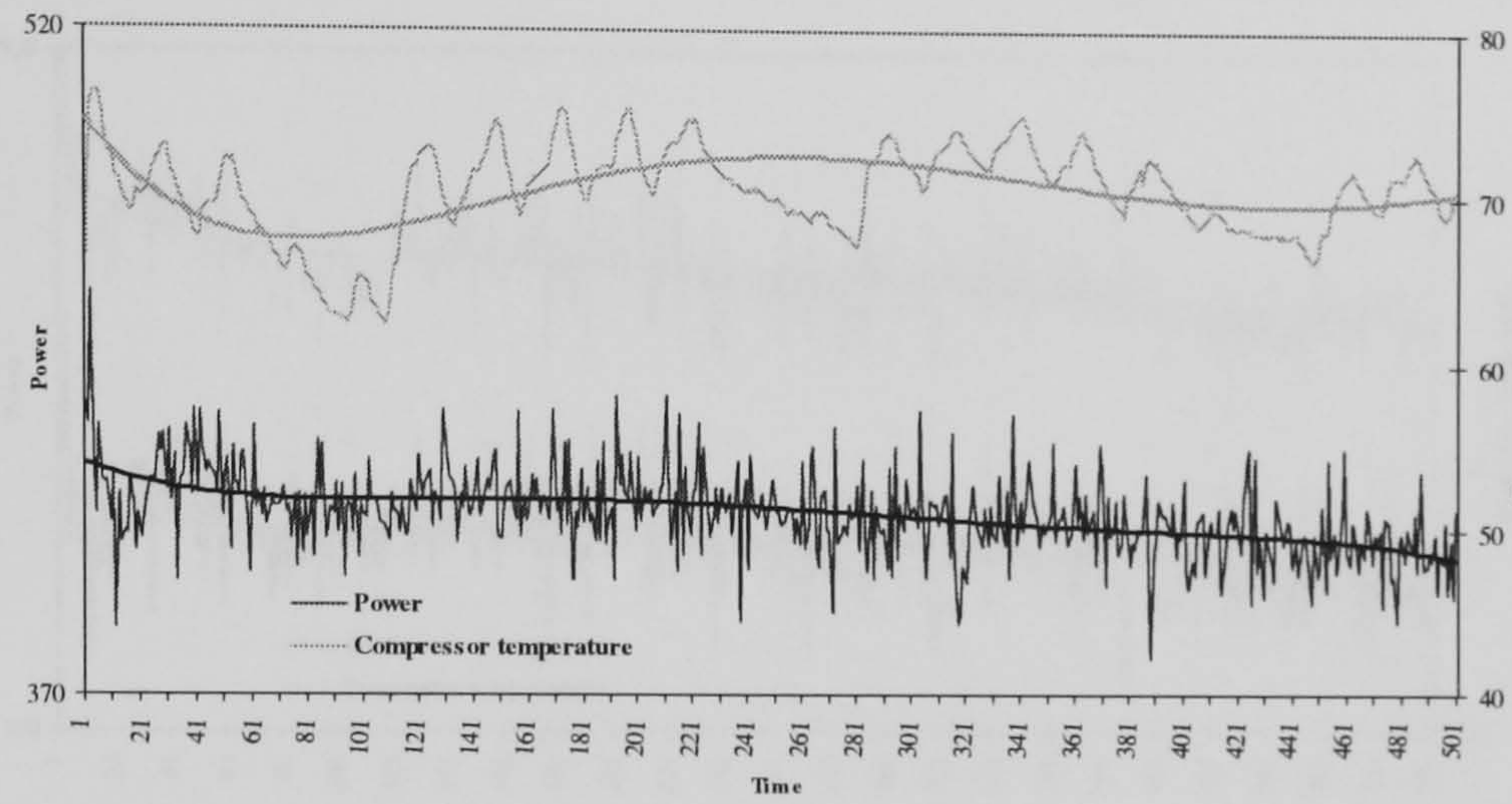


Figure H.18. Test 3 - Power (W) / Compressor temperature (°C) with Time (hrs)

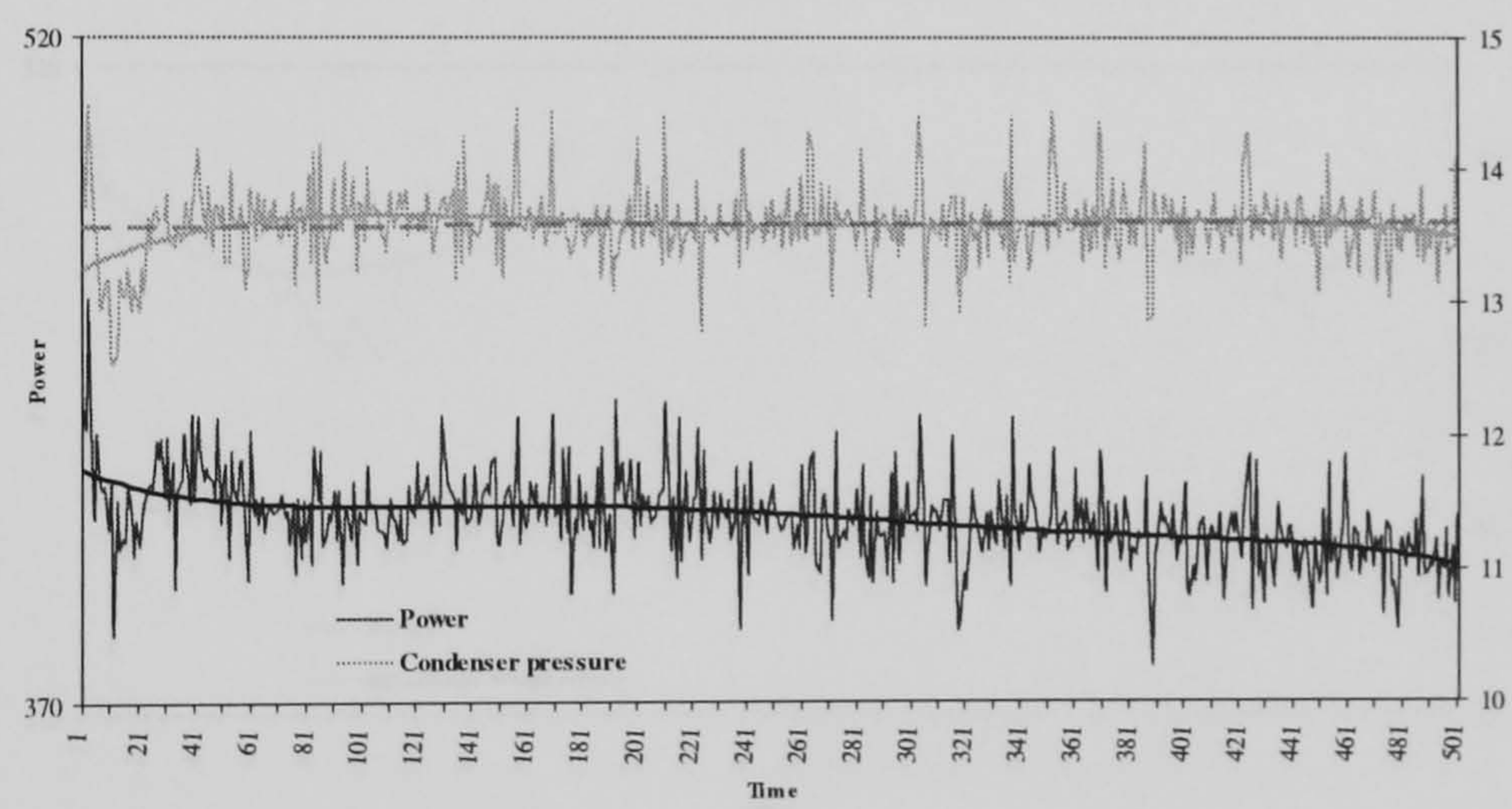


Figure H.19. Test 3 - Power (W) / Condenser pressure (bar) with Time (hrs)

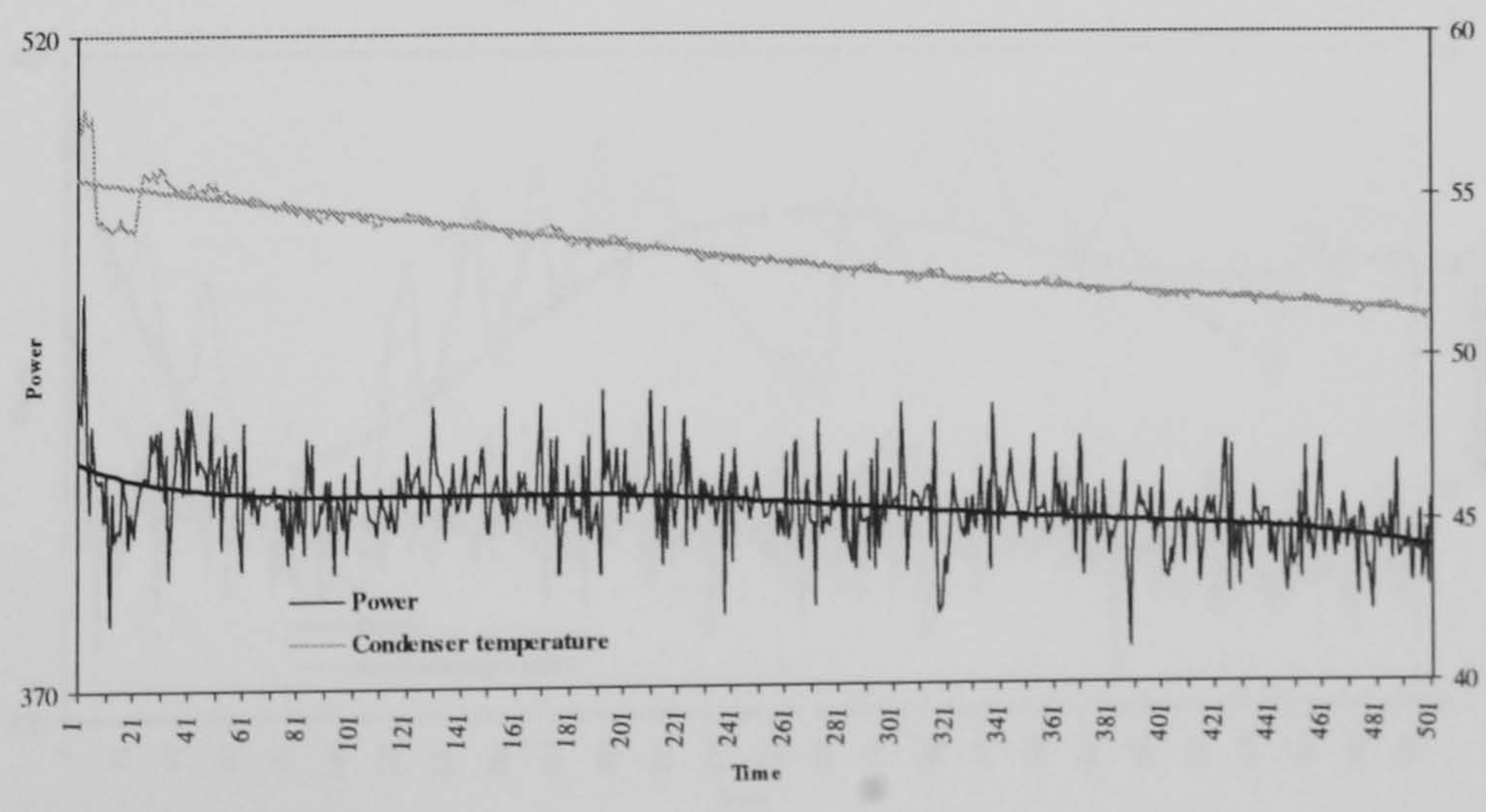


Figure H.20. Test 3 - Power (W) / Condenser temperature (°C) with Time (hrs)

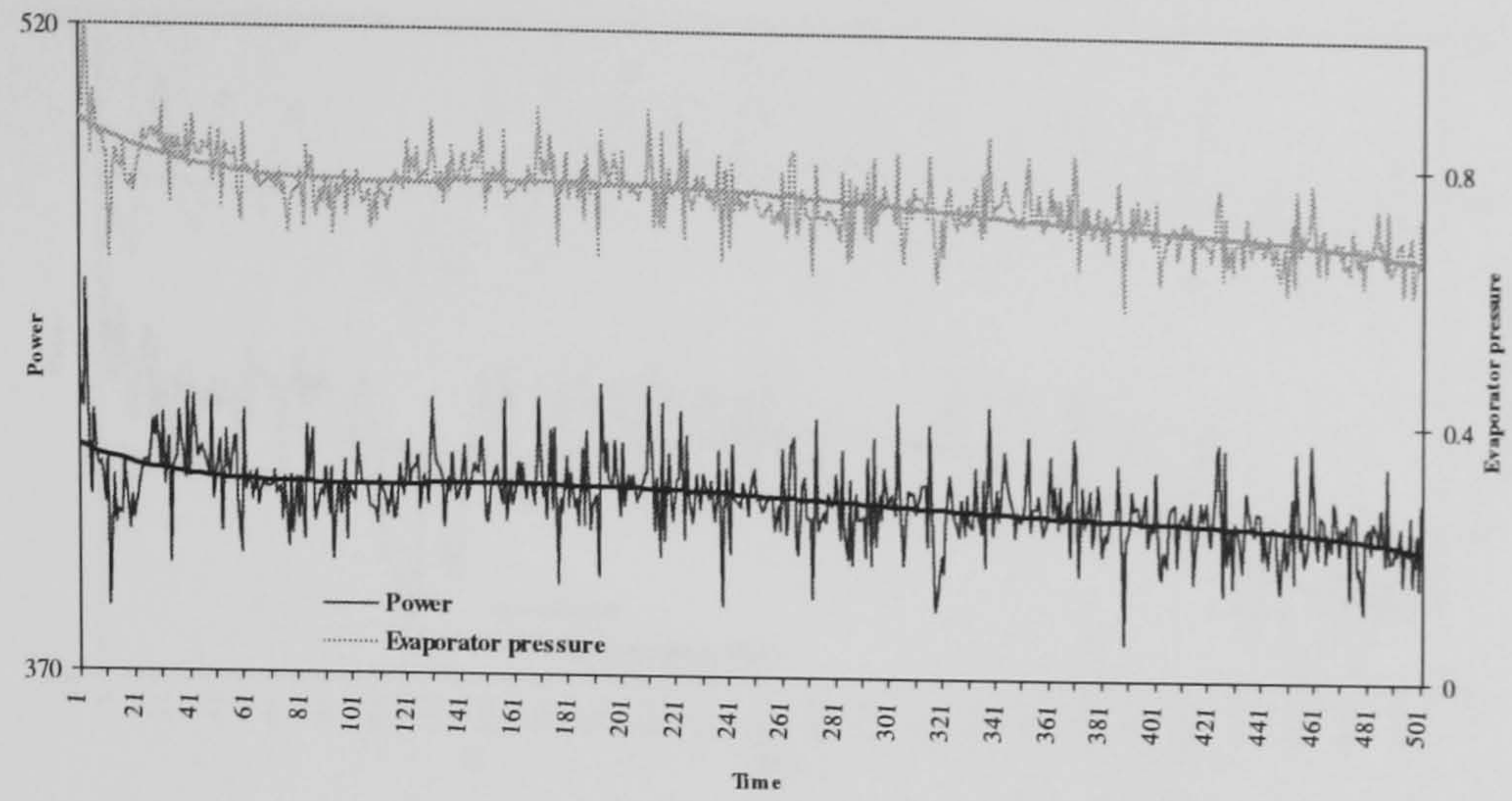


Figure H.21. Test 3 - Power (W) / Evaporator pressure (bar) with Time (hrs)

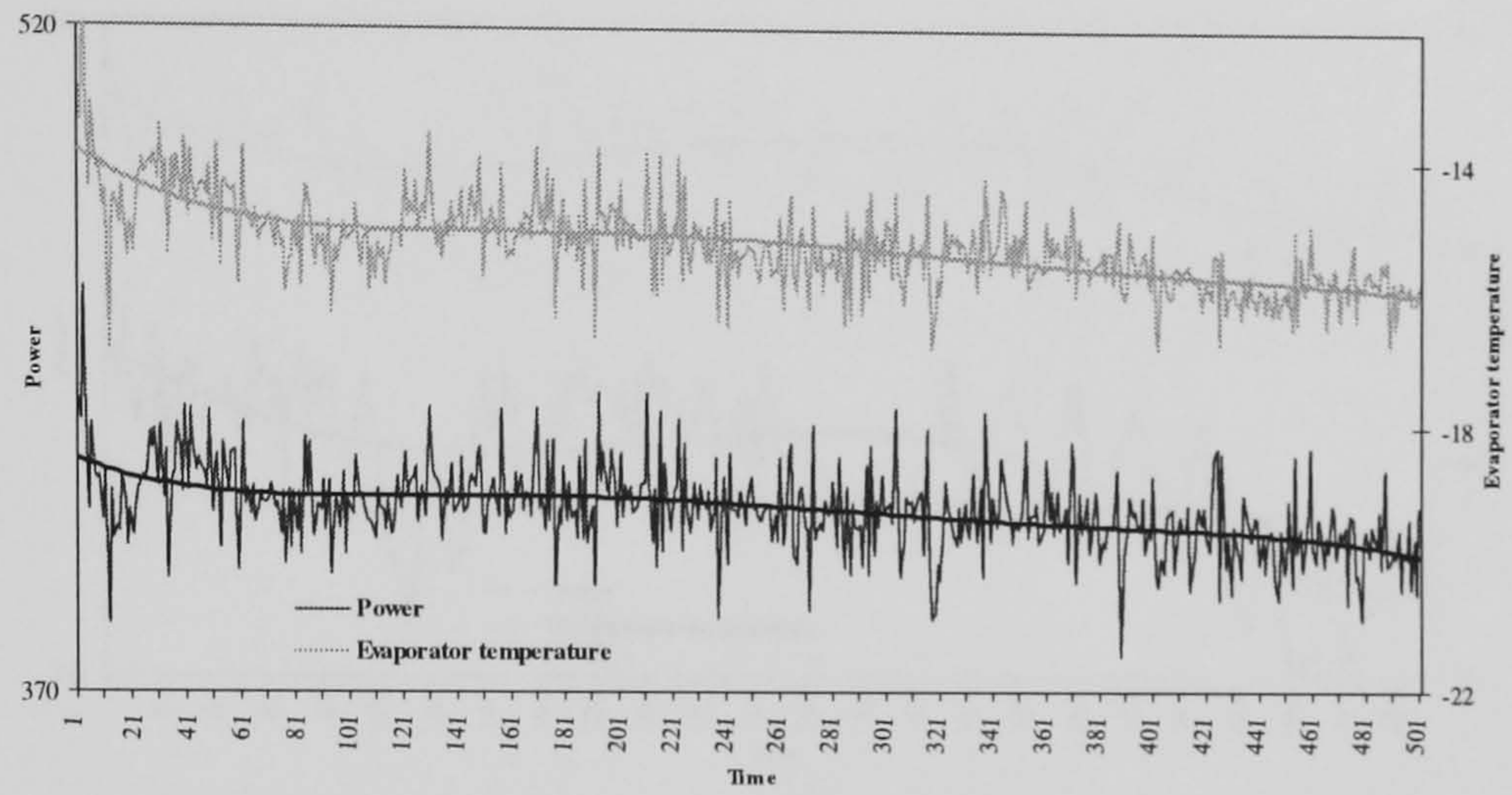


Figure H.22. Test 3 - Power (W) / Evaporator temperature (°C) with Time (hrs)

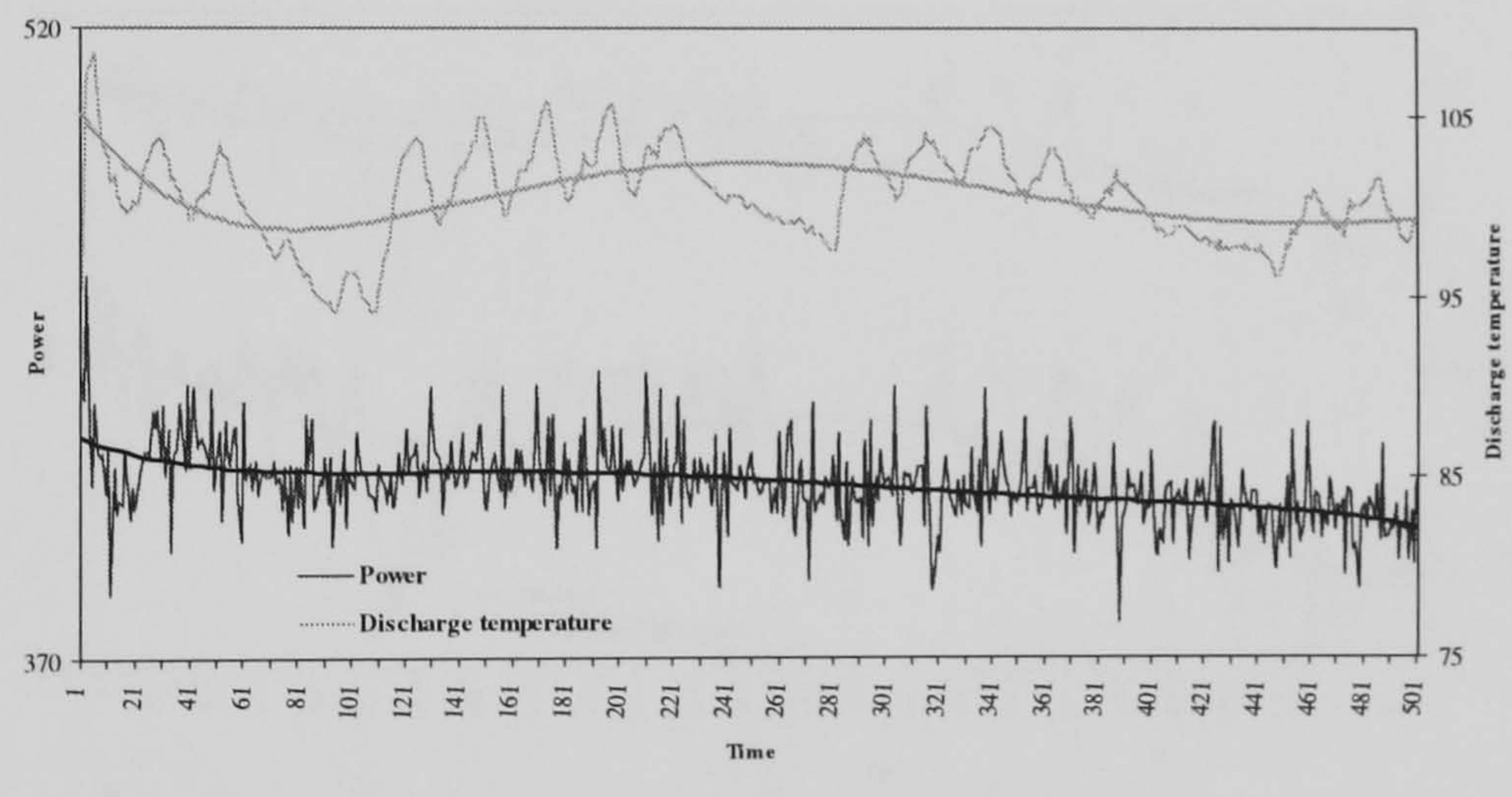


Figure H.23. Test 3 - Power (W) / Discharge temperature (°C) with Time (hrs)

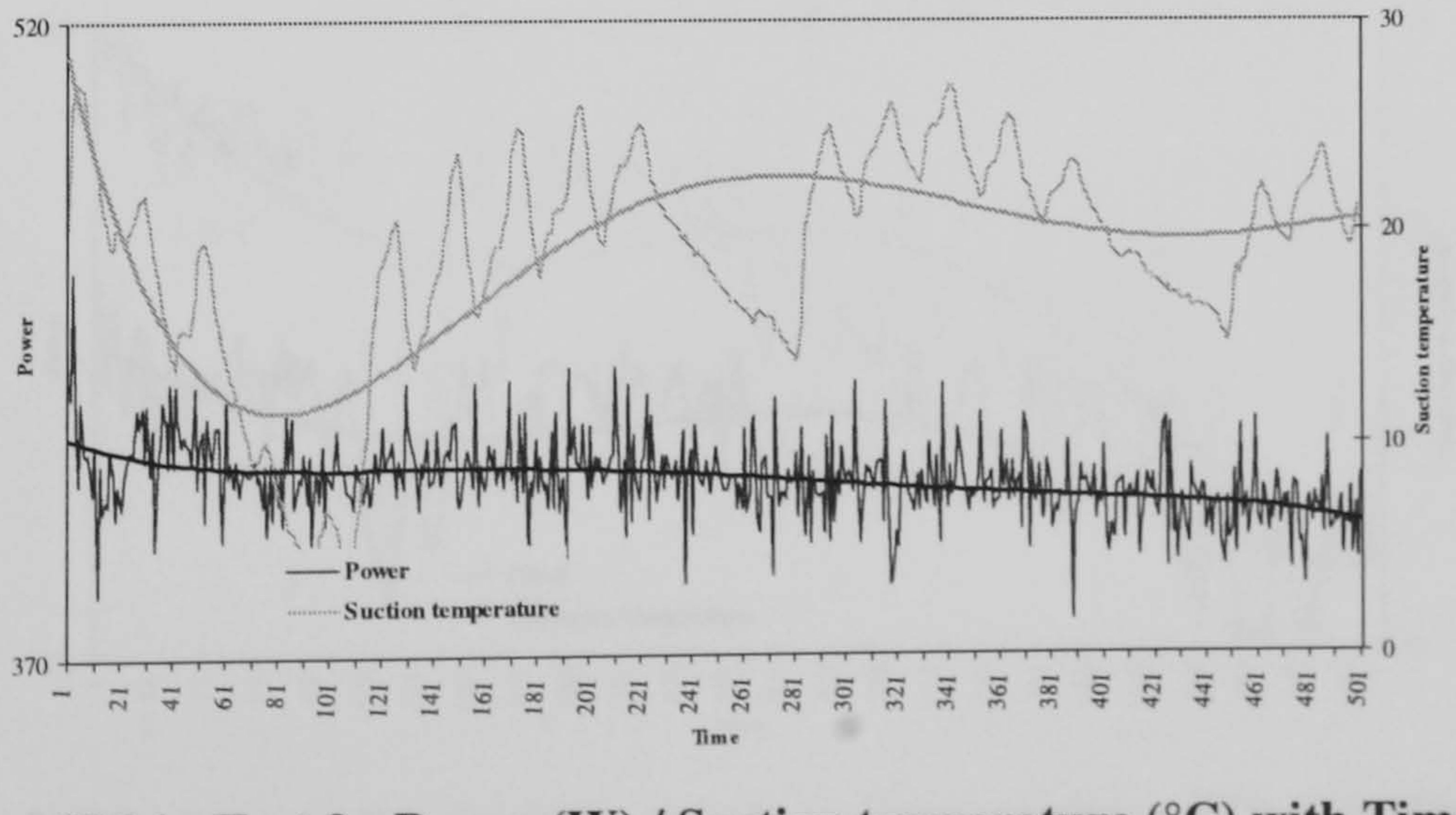


Figure H.24. Test 3 - Power (W) / Suction temperature (°C) with Time (hrs)

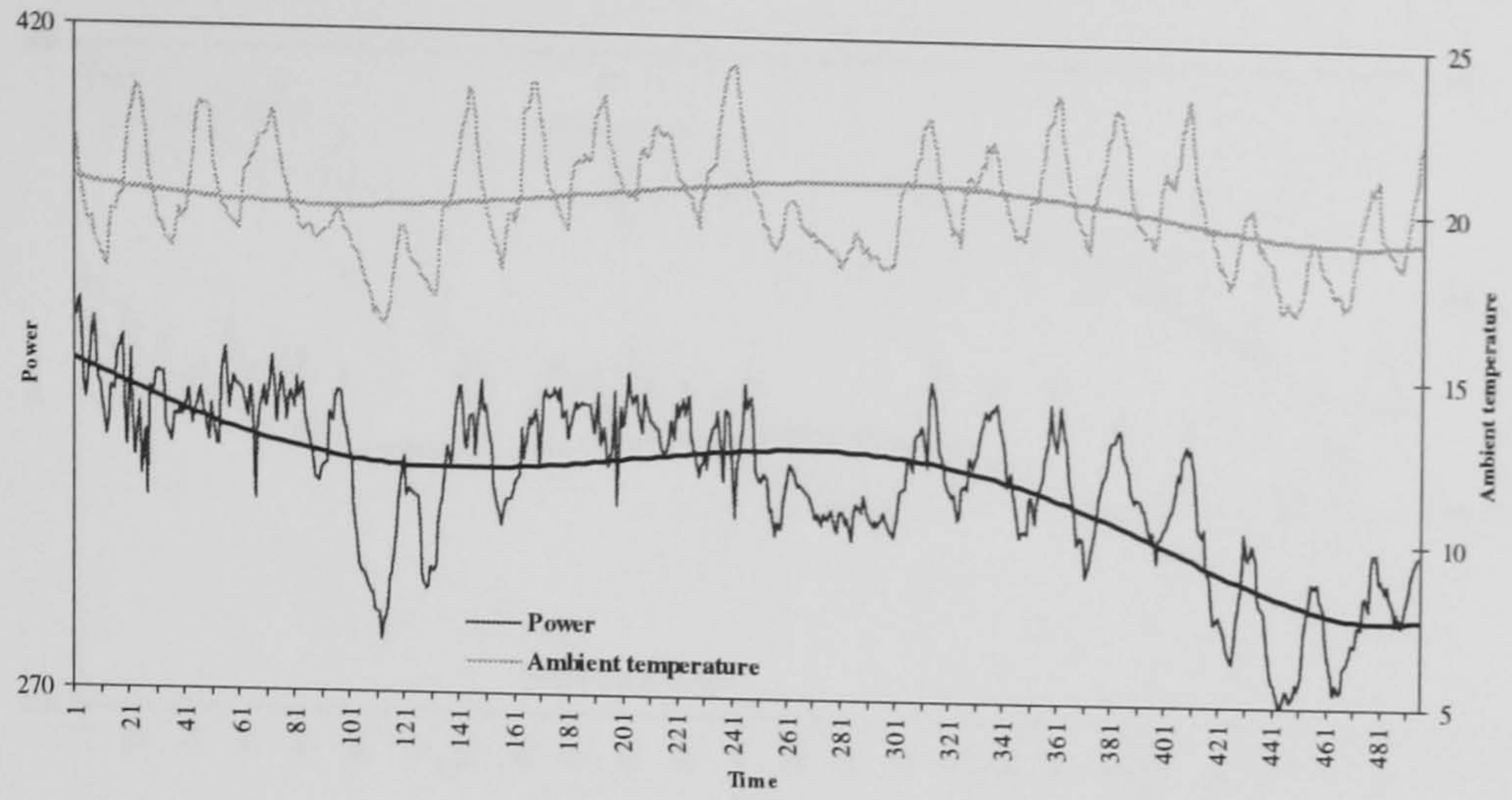


Figure H.25. Test 4 - Power (W) / Ambient temperature (°C) with Time (hrs)

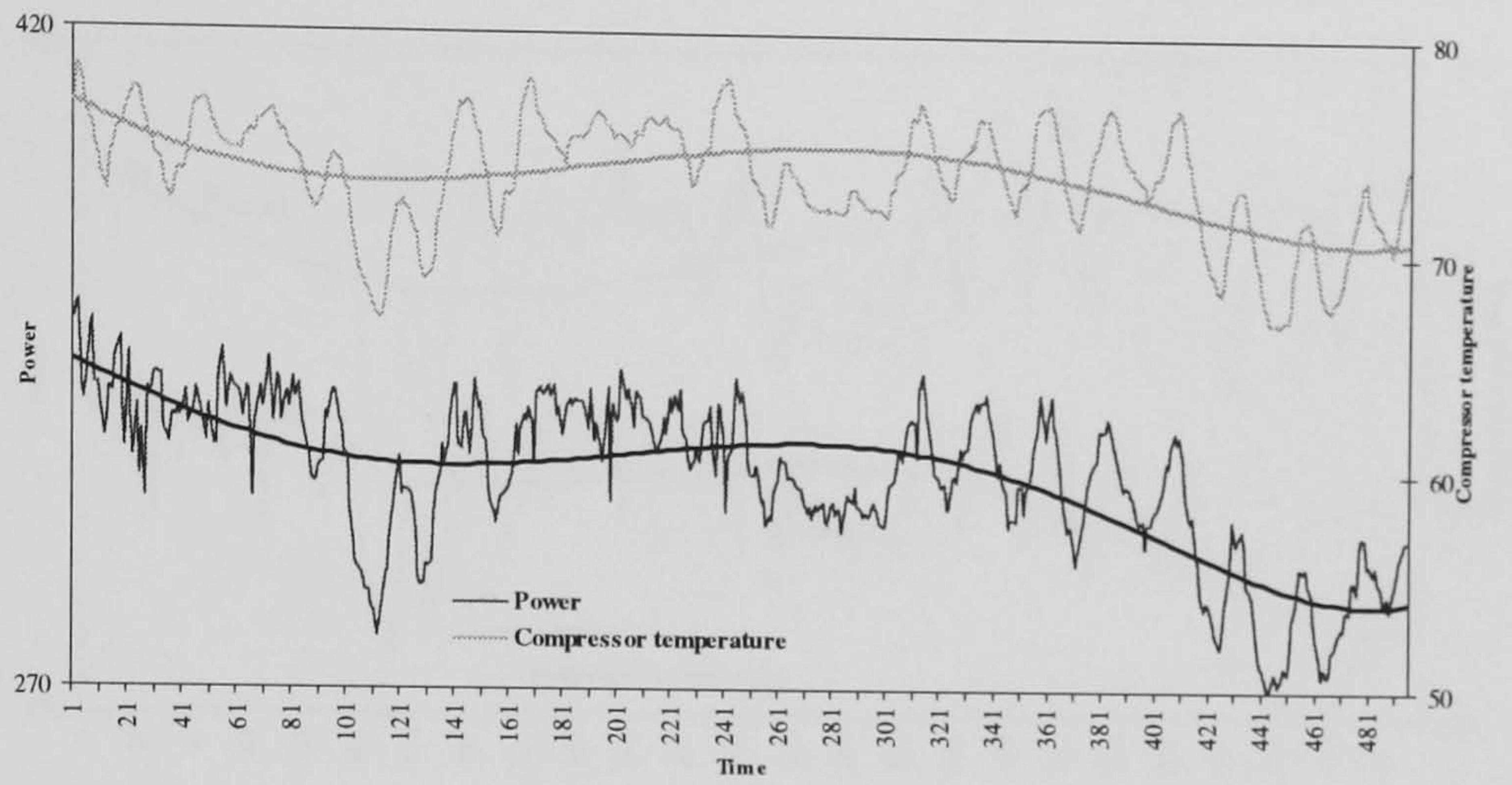


Figure H.26. Test 4 - Power (W) / Compressor temperature (°C) with Time (hrs)

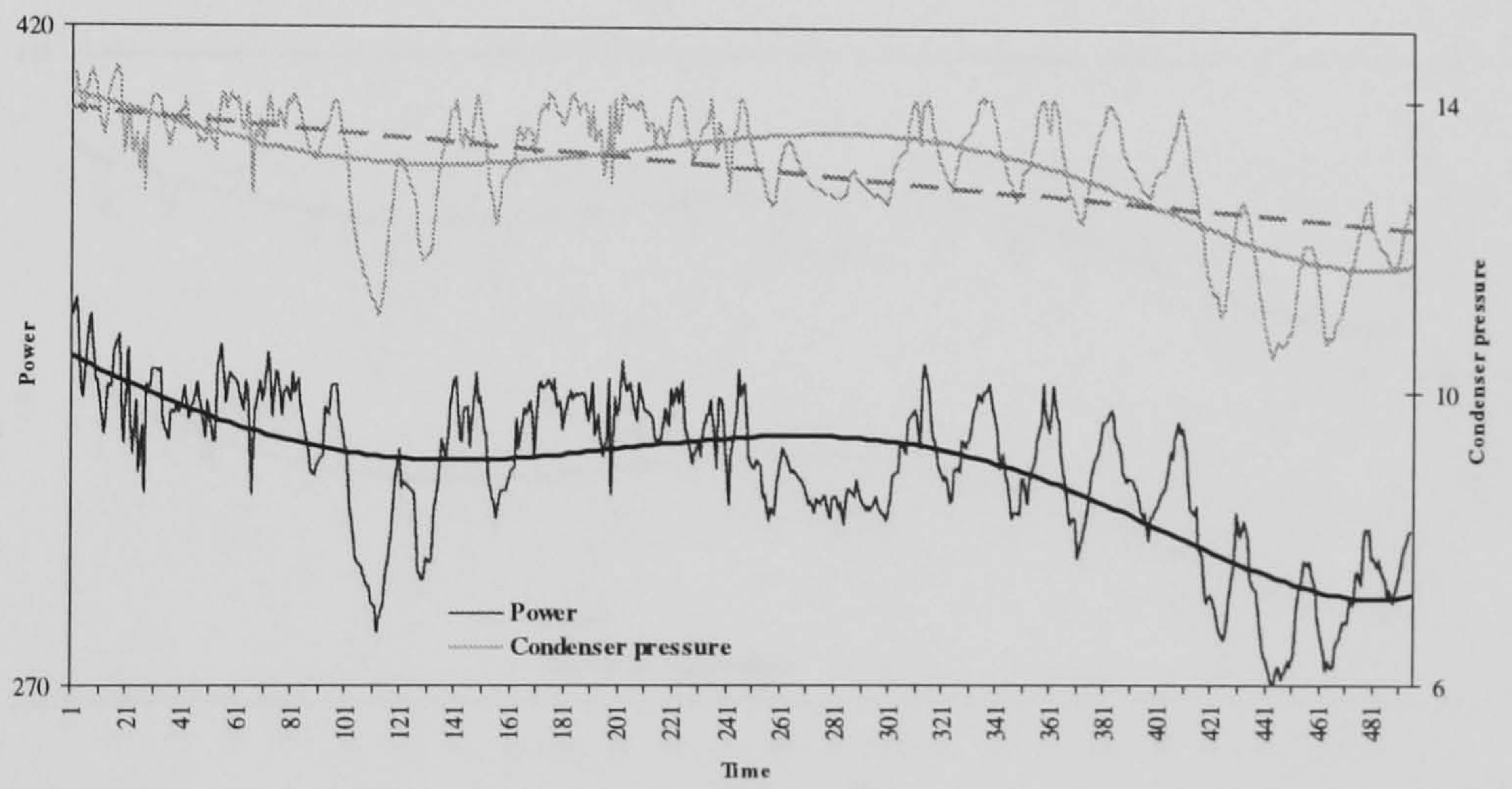


Figure H.27. Test 4 - Power (W) / Condenser pressure (bar) with Time (hrs)

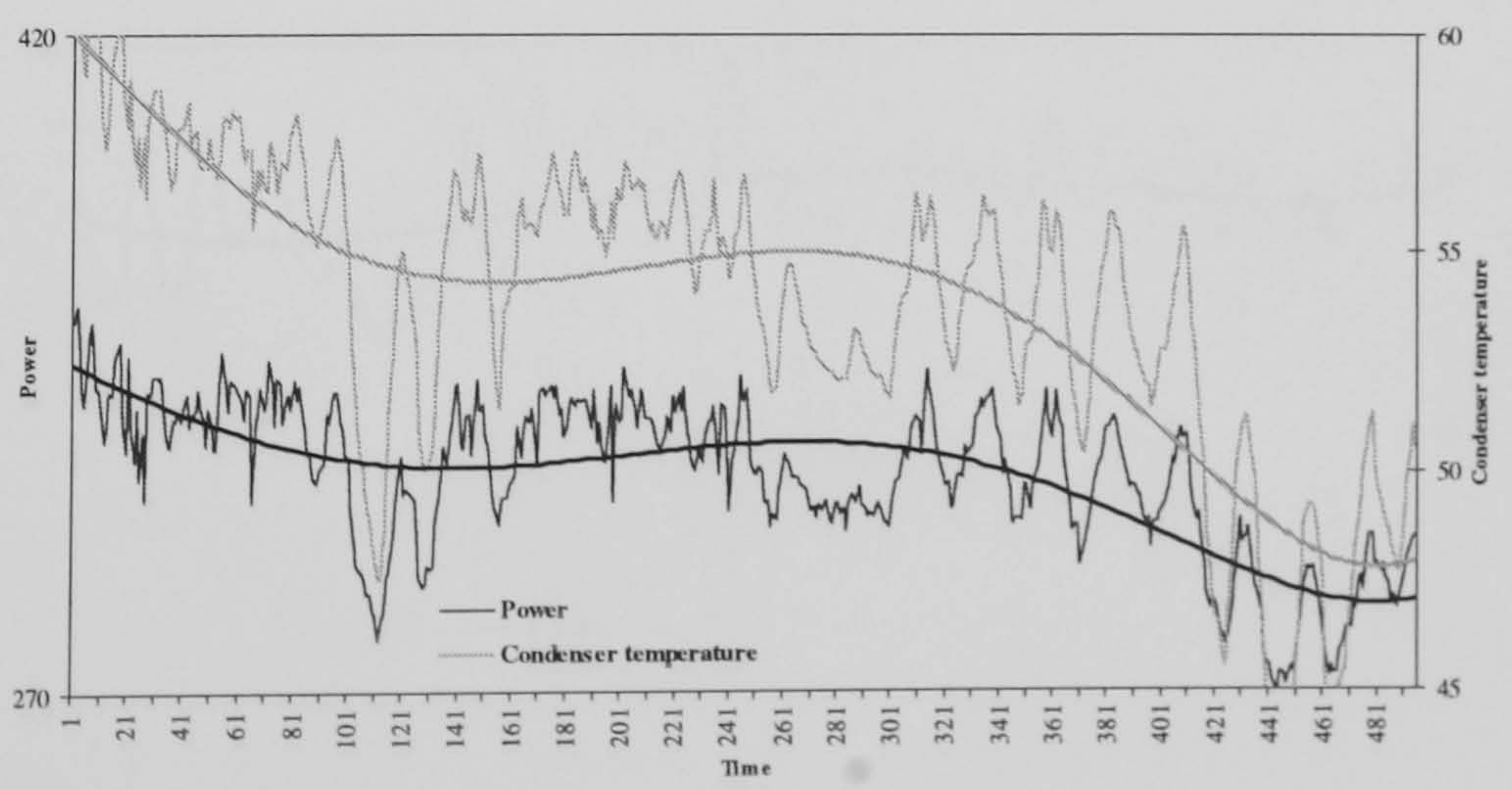


Figure H.28. Test 4 - Power (W) / Condenser temperature (°C) with Time (hrs)

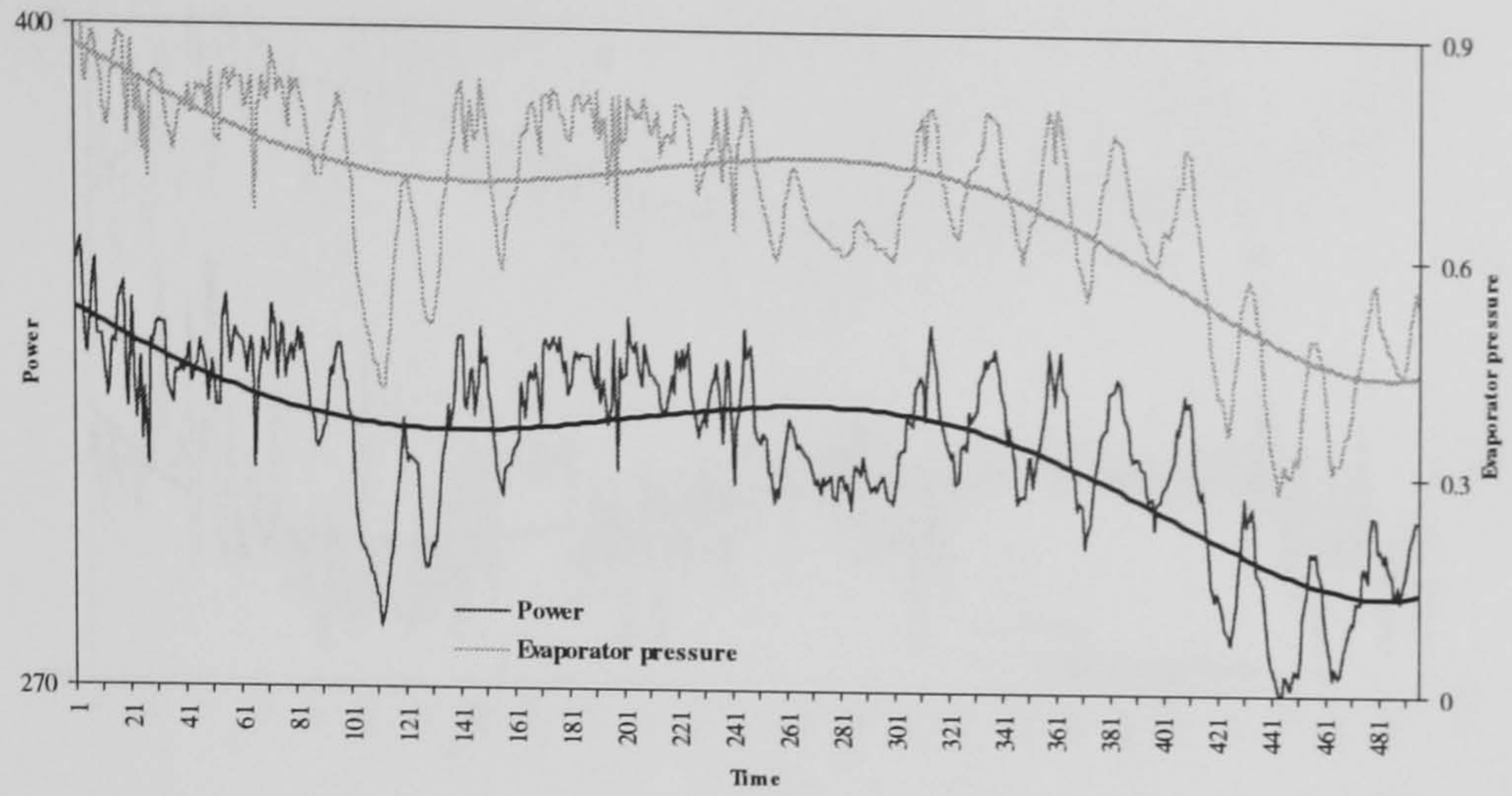


Figure H.29. Test 4 - Power (W) / Evaporator pressure (bar) with Time (hrs)

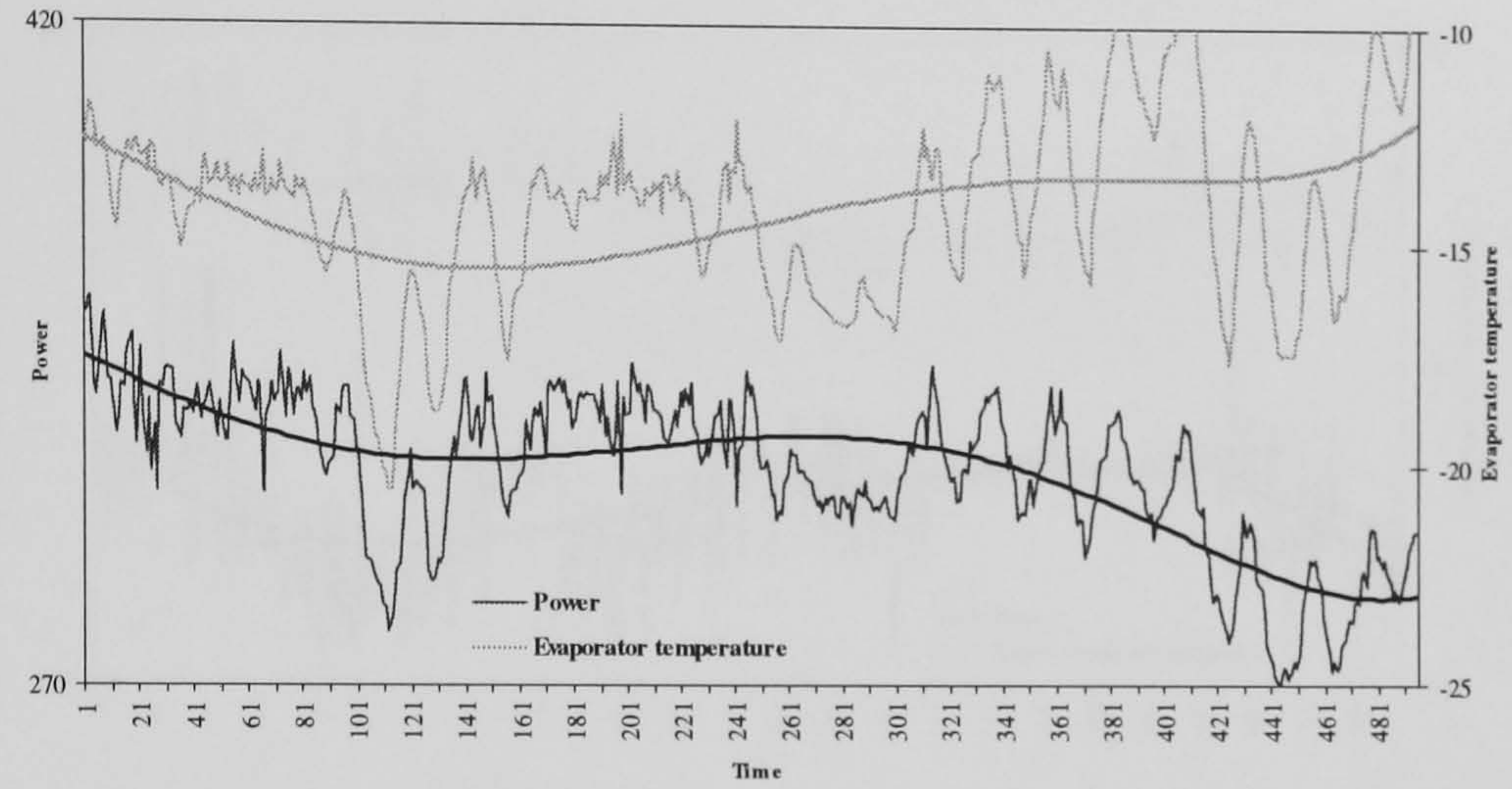


Figure H.30. Test 4 - Power (W) / Evaporator temperature (°C) with Time (hrs)

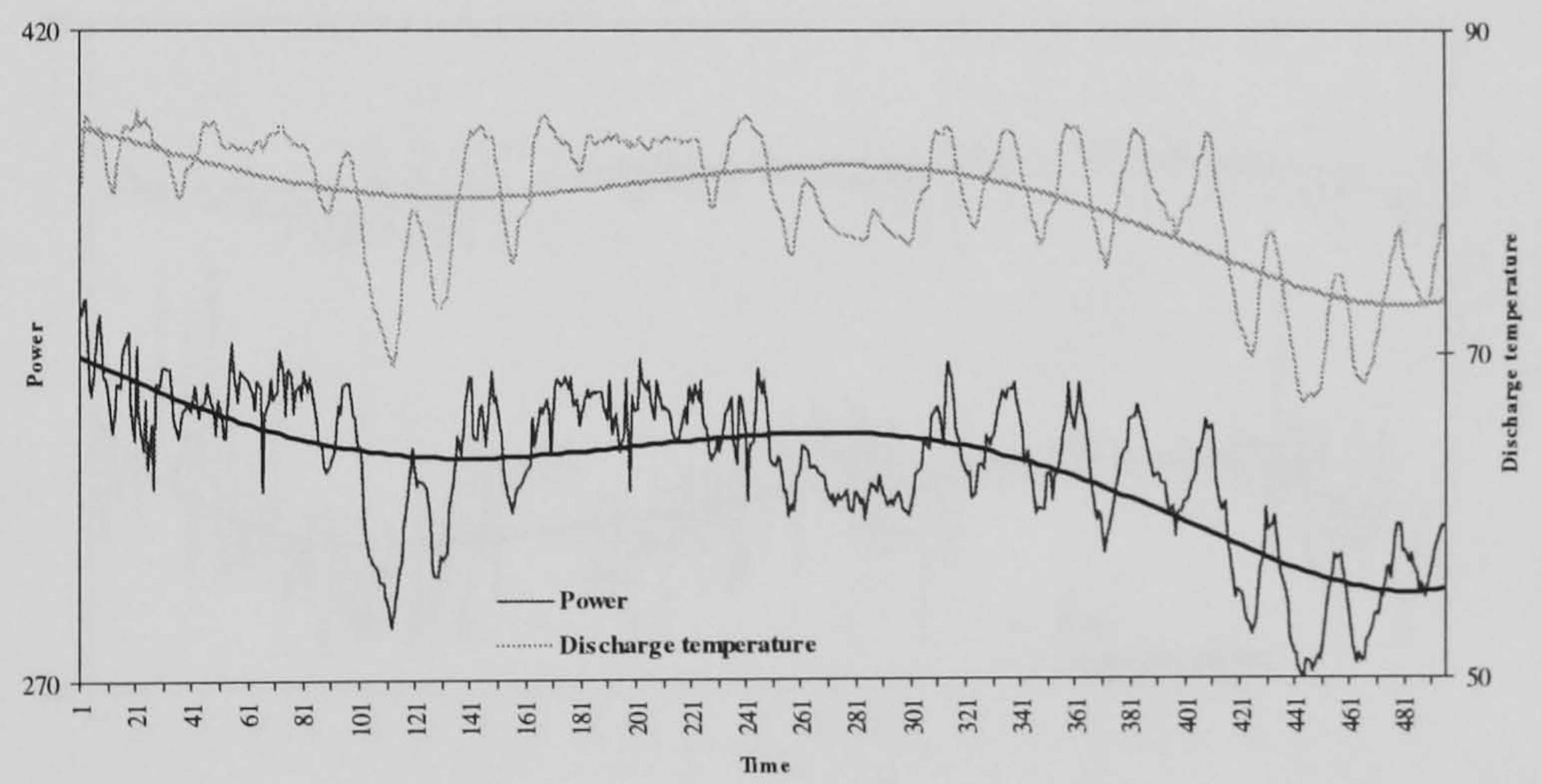


Figure H.31. Test 4 - Power (W) / Discharge temperature (°C) with Time (hrs)

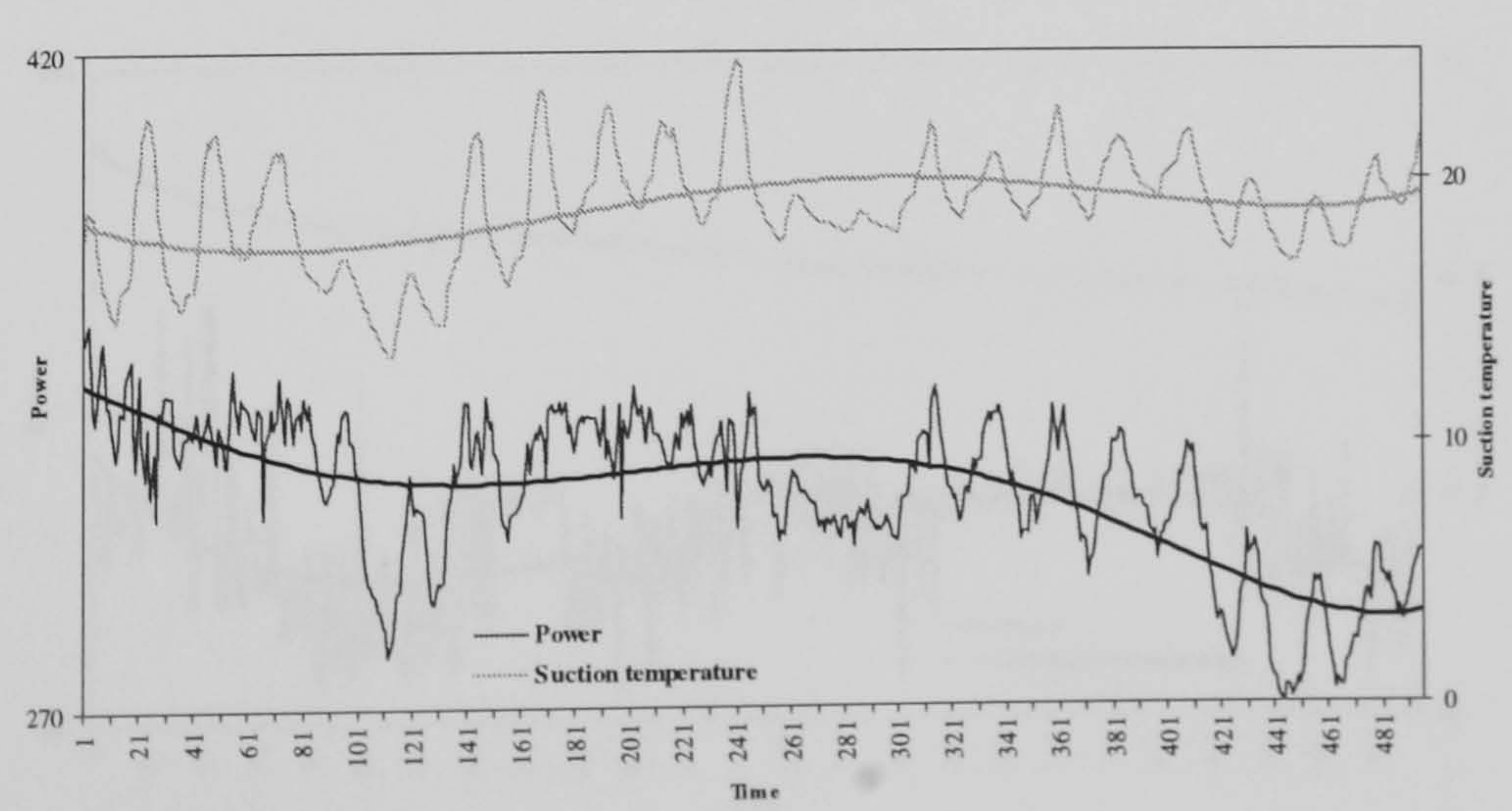


Figure H.32. Test 4 - Power (W) / Suction temperature (°C) with Time (hrs)

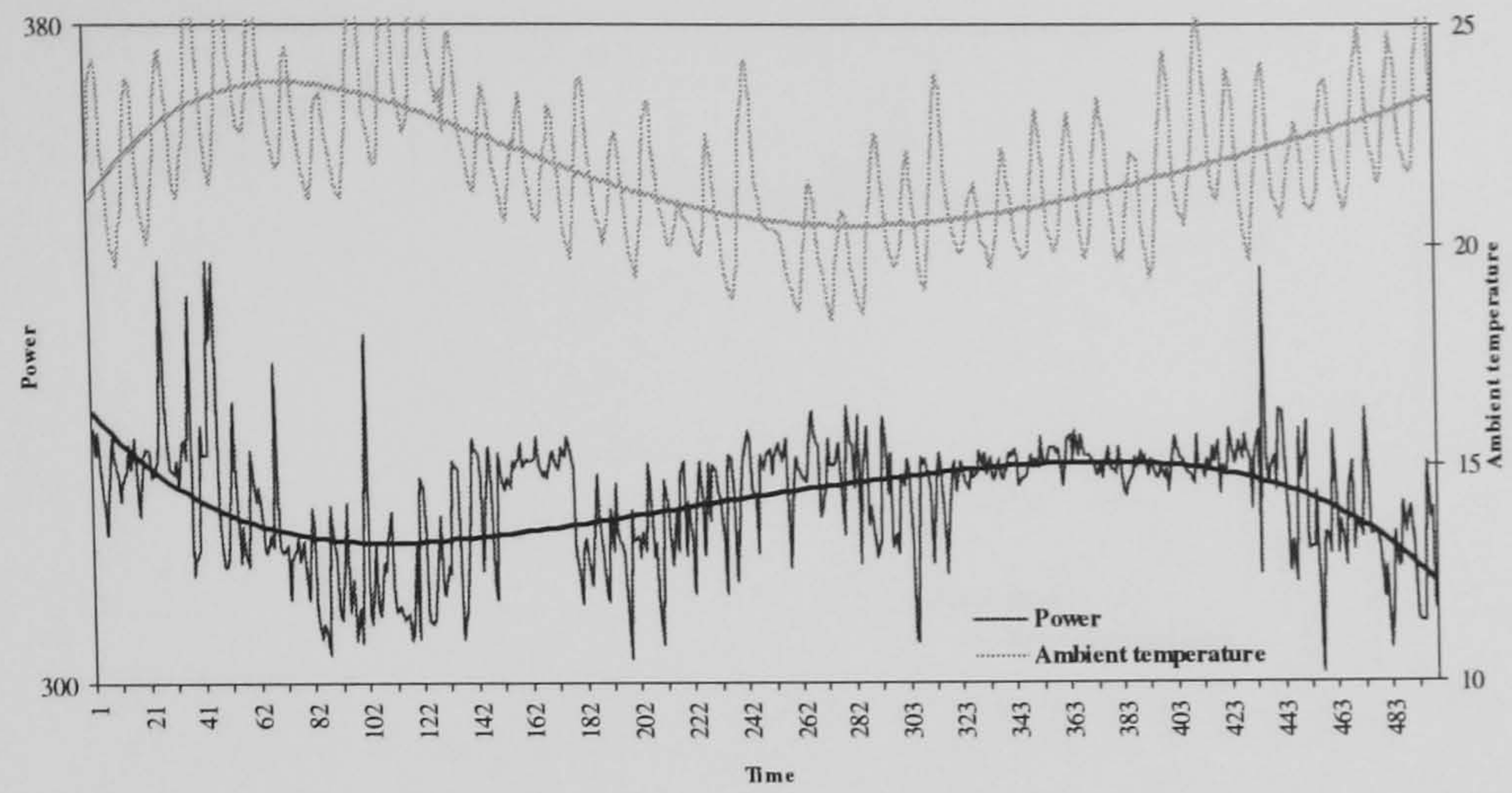


Figure H.33. Test 5 - Power (W) / Ambient temperature (°C) with Time (hrs)

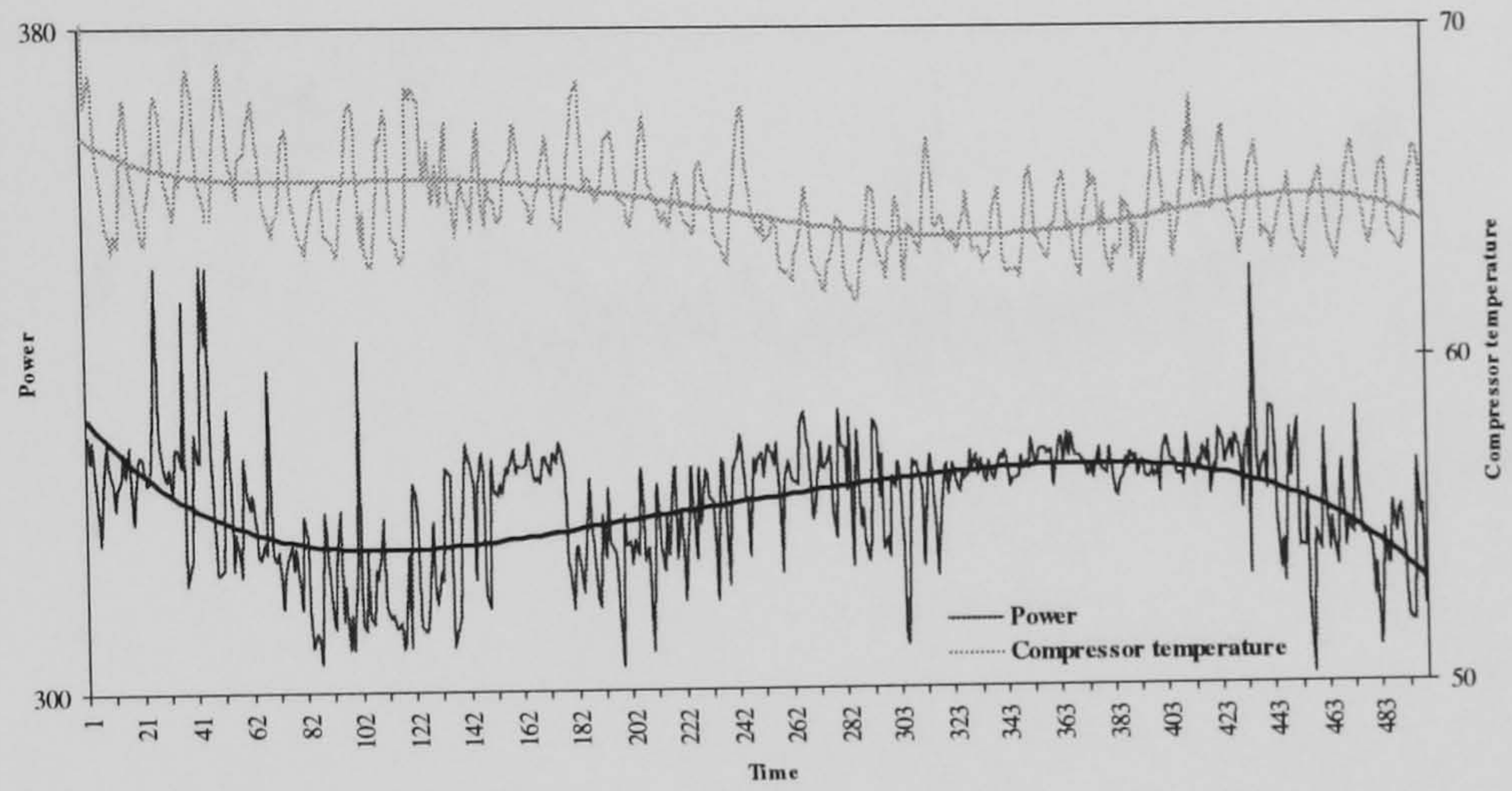


Figure H.34. Test 5 - Power (W) / Compressor temperature (°C) with Time (hrs)

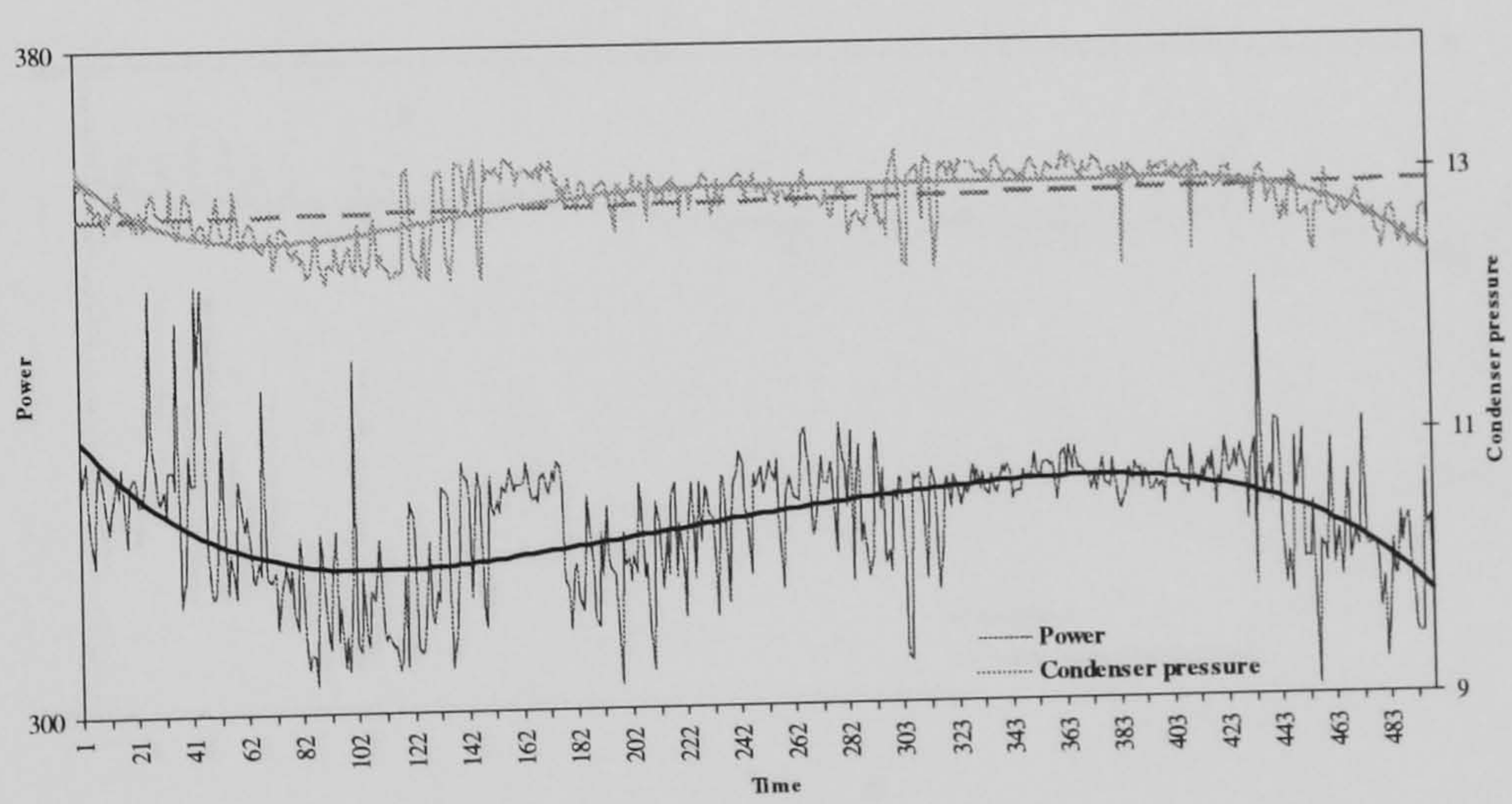


Figure H.35. Test 5 - Power (W) / Condenser pressure (bar) with Time (hrs)

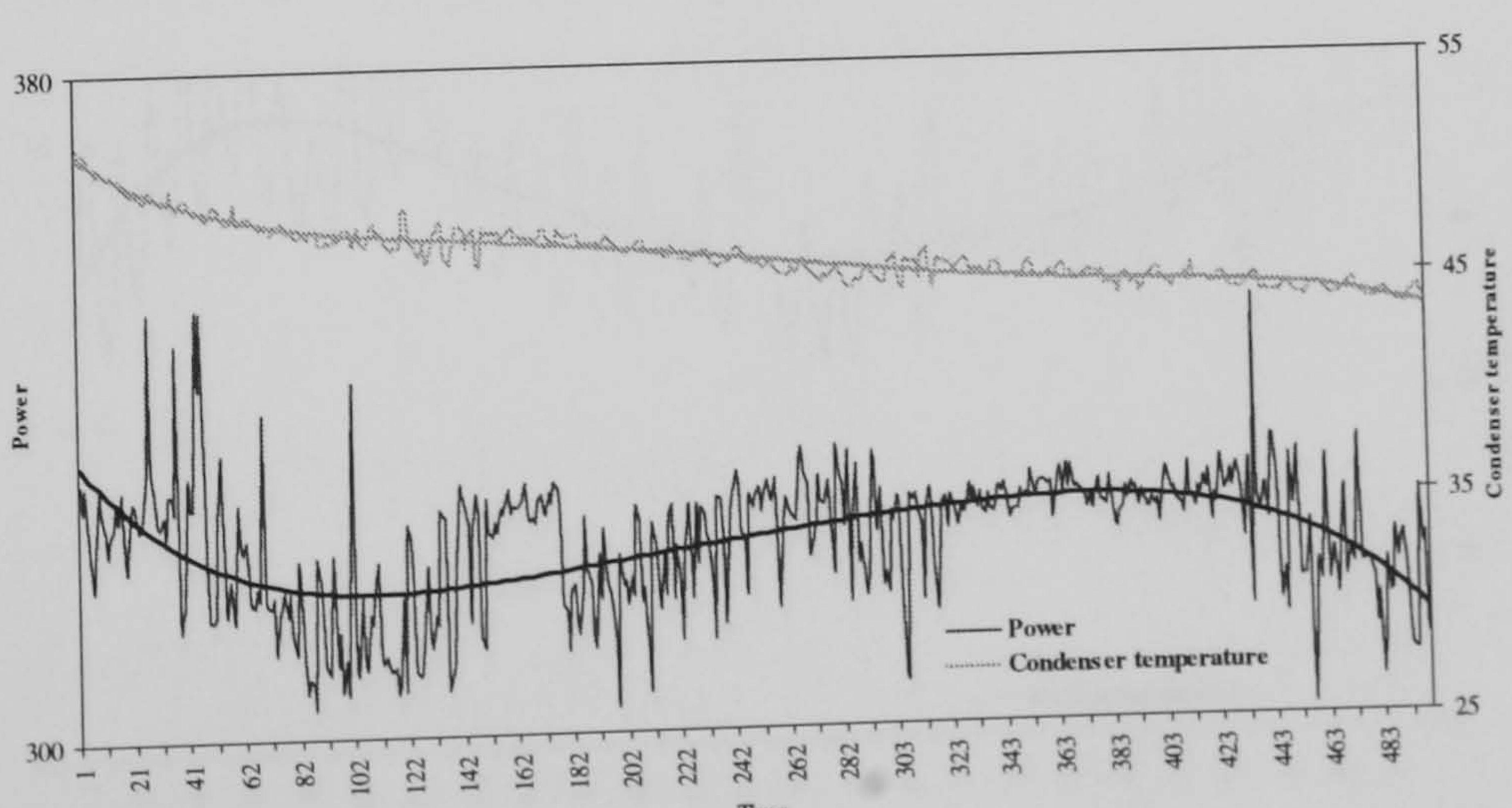


Figure H.36. Test 5 - Power (W) / Condenser temperature (°C) with Time (hrs)

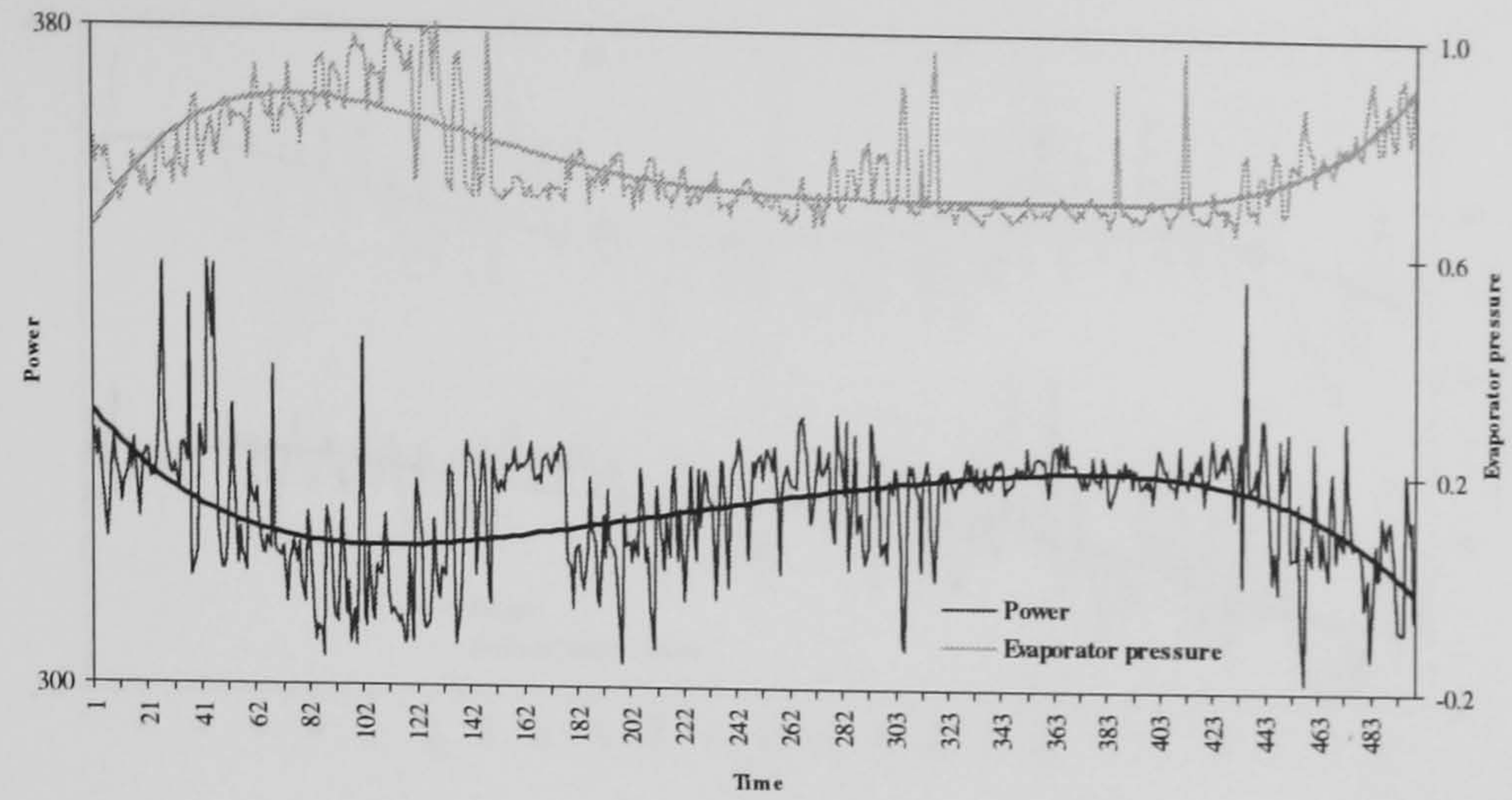


Figure H.37. Test 5 - Power (W) / Evaporator pressure (bar) with Time (hrs)

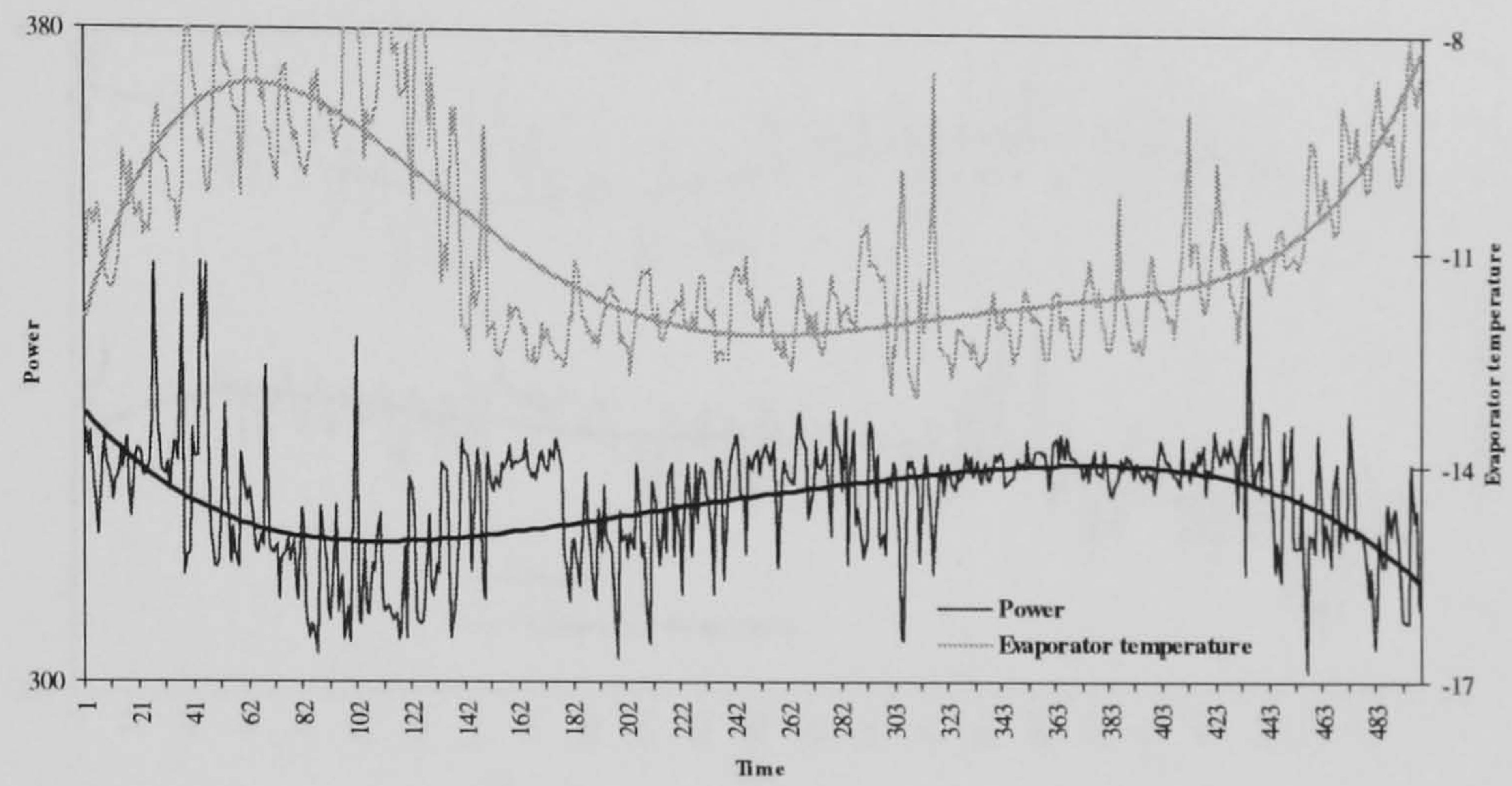


Figure H.38. Test 5 - Power (W) / Evaporator temperature (°C) with Time (hrs)

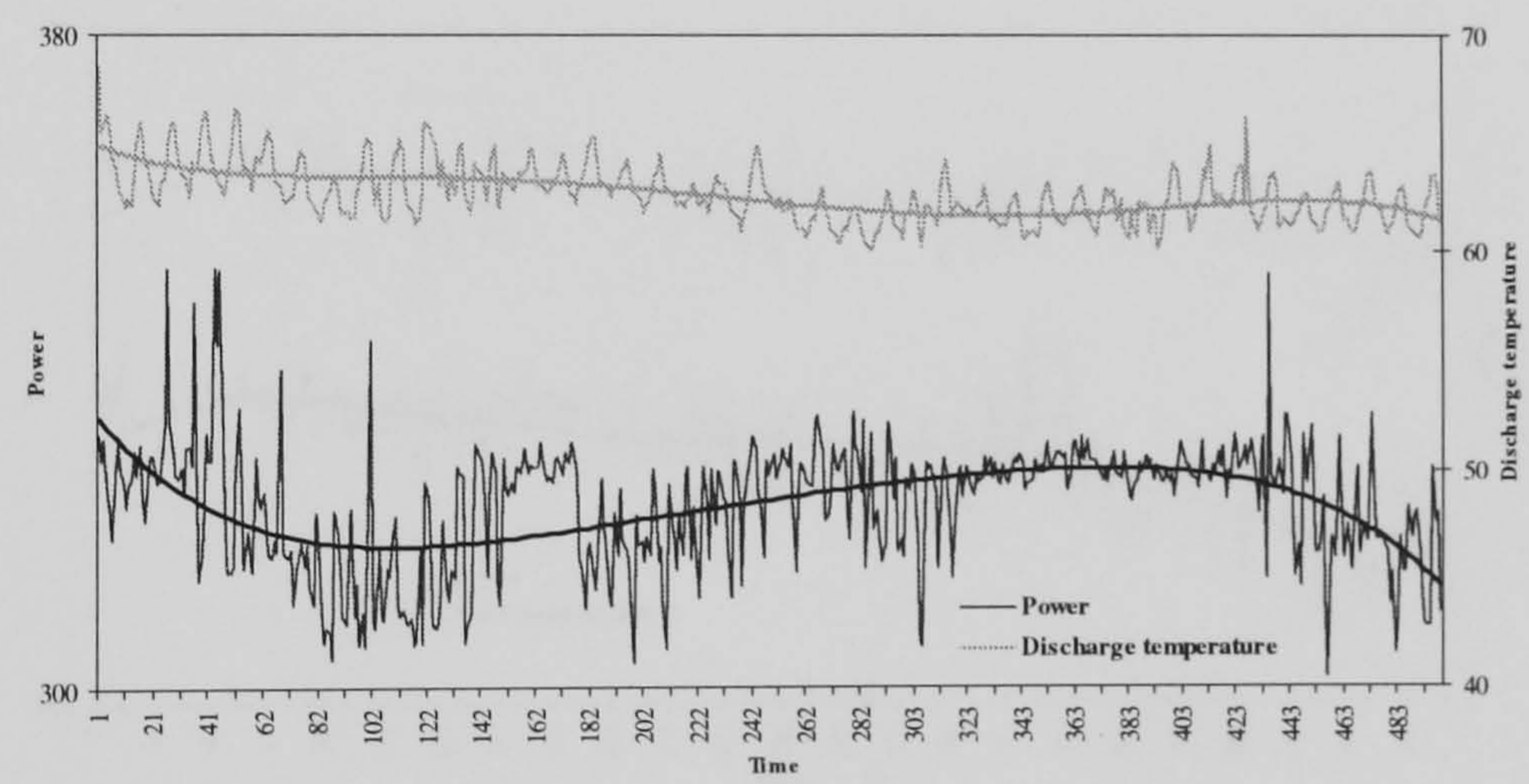


Figure H.39. Test 5 - Power (W) / Discharge temperature (°C) with Time (hrs)

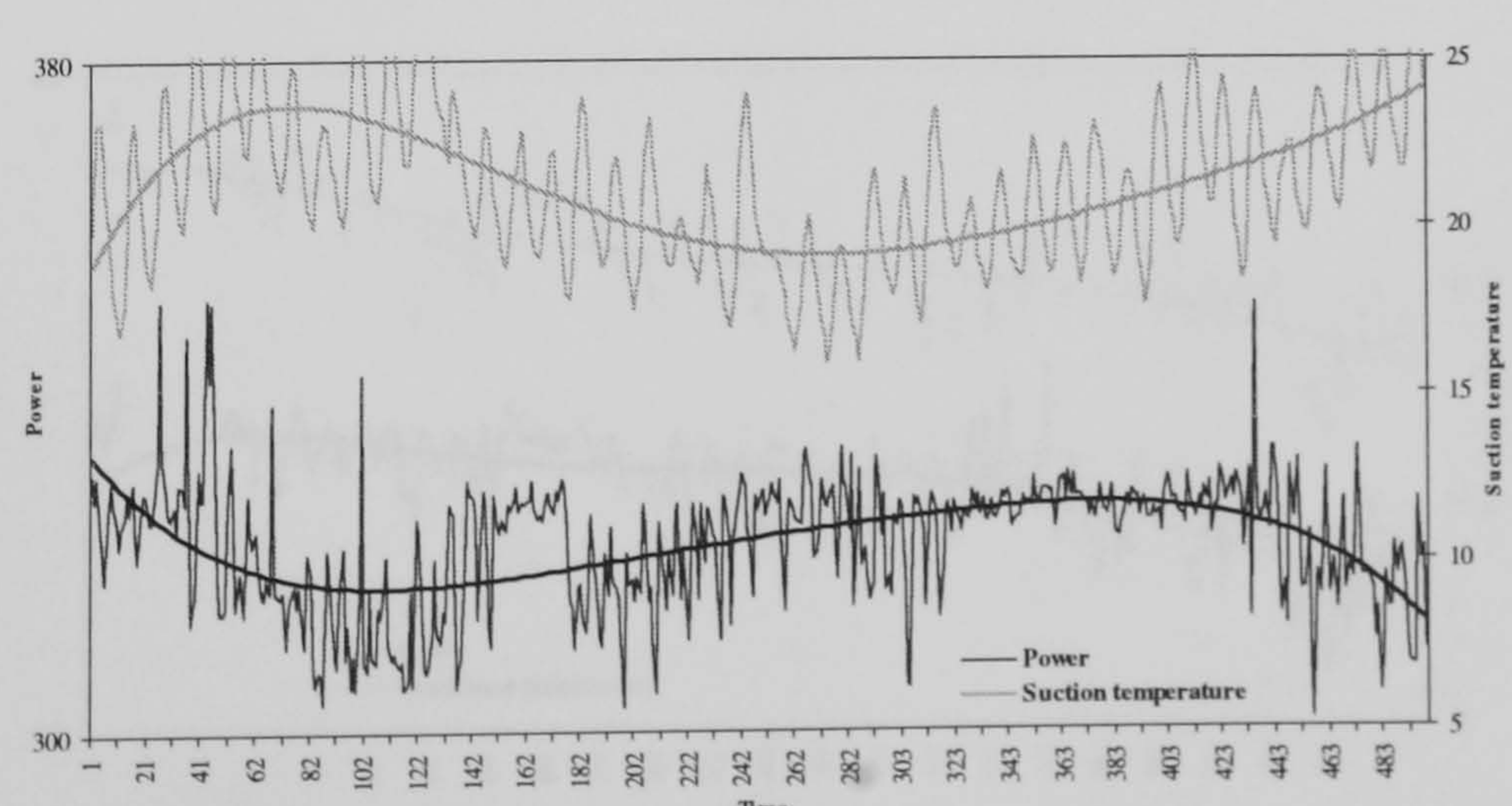


Figure H.40. Test 5 - Power (W) / Suction temperature (°C) with Time (hrs)

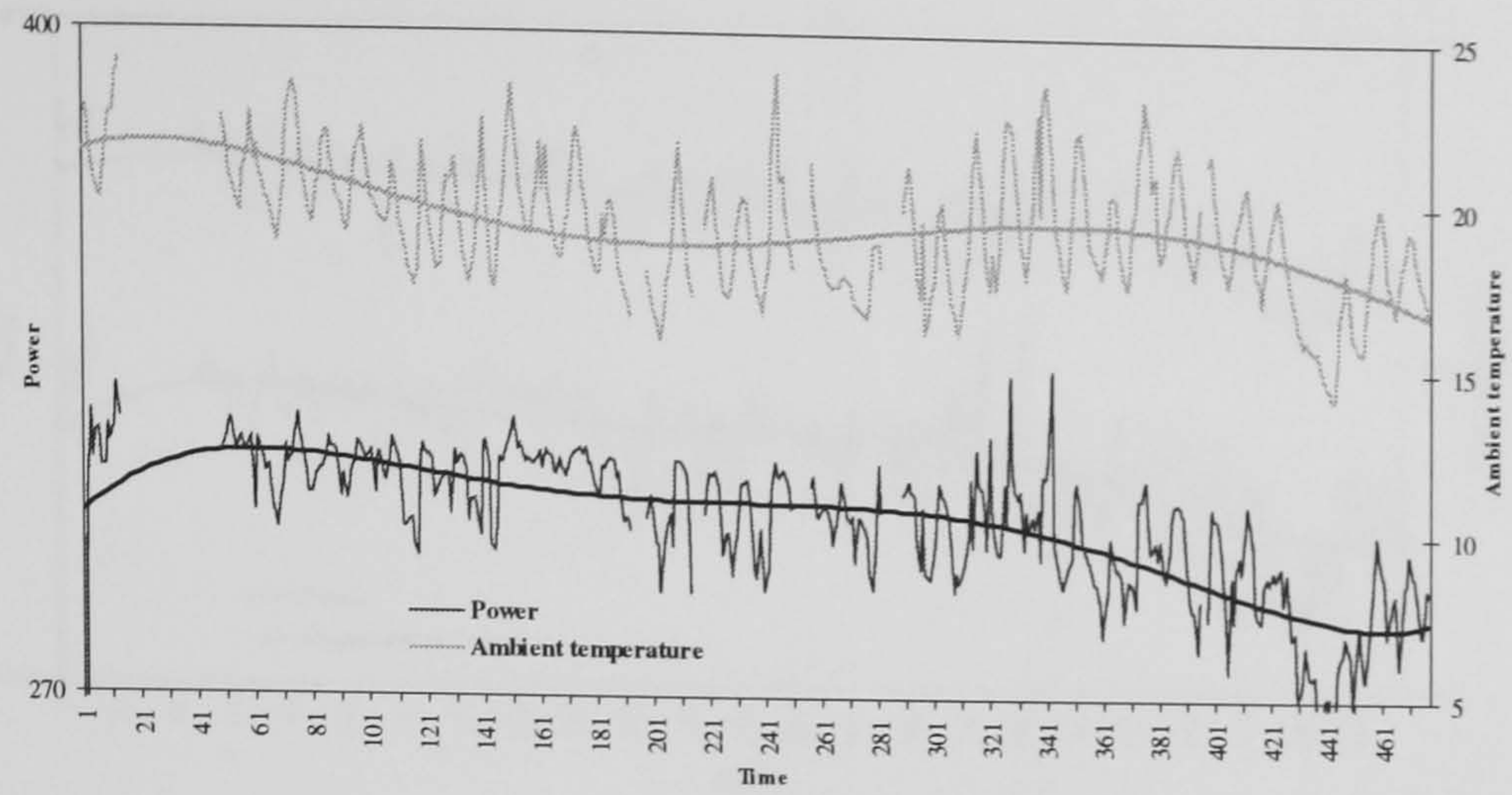


Figure H.41. Test 6 - Power (W) / Ambient temperature (°C) with Time (hrs)

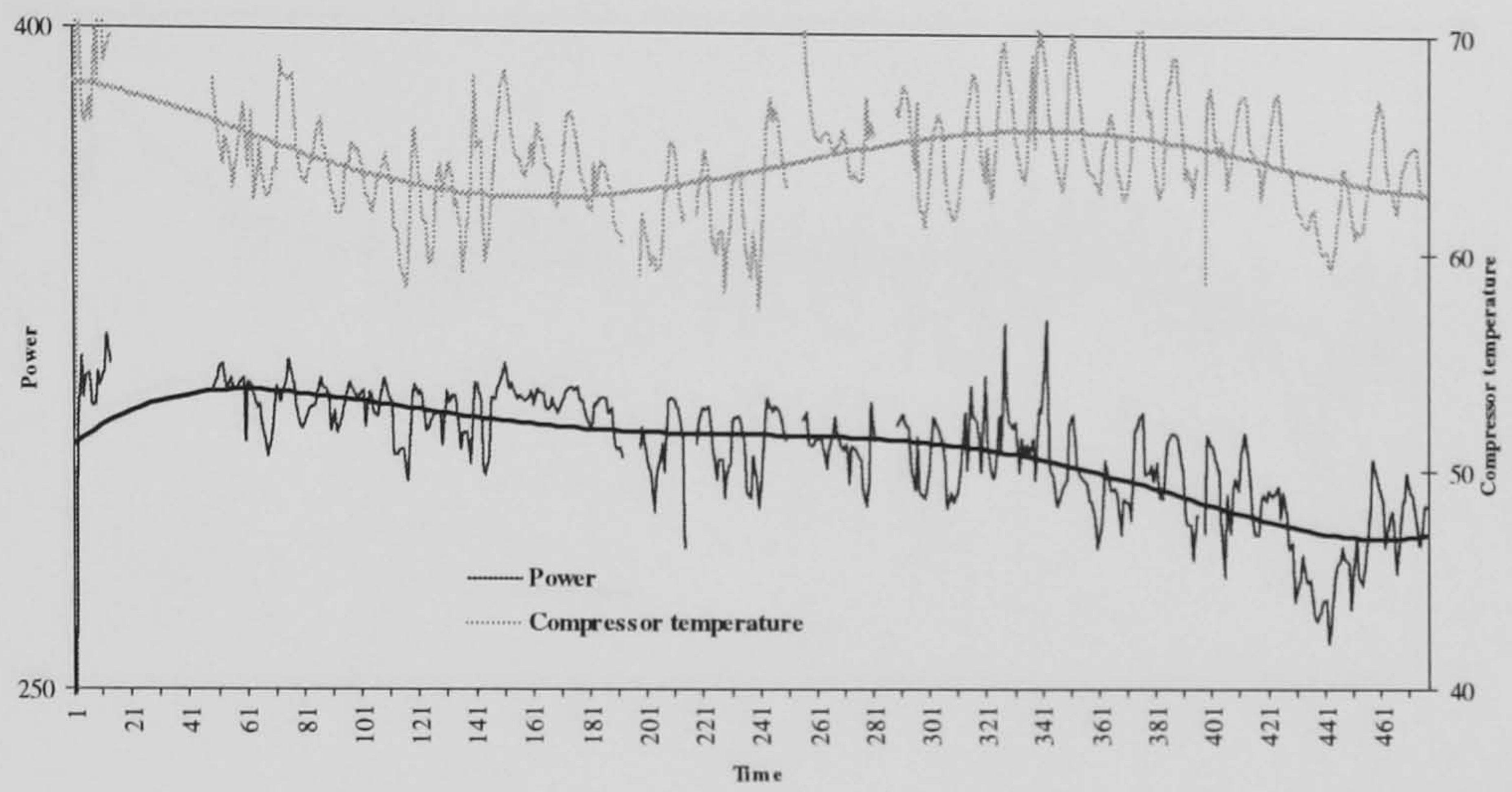


Figure H.42. Test 6 - Power (W) / Compressor temperature (°C) with Time (hrs)

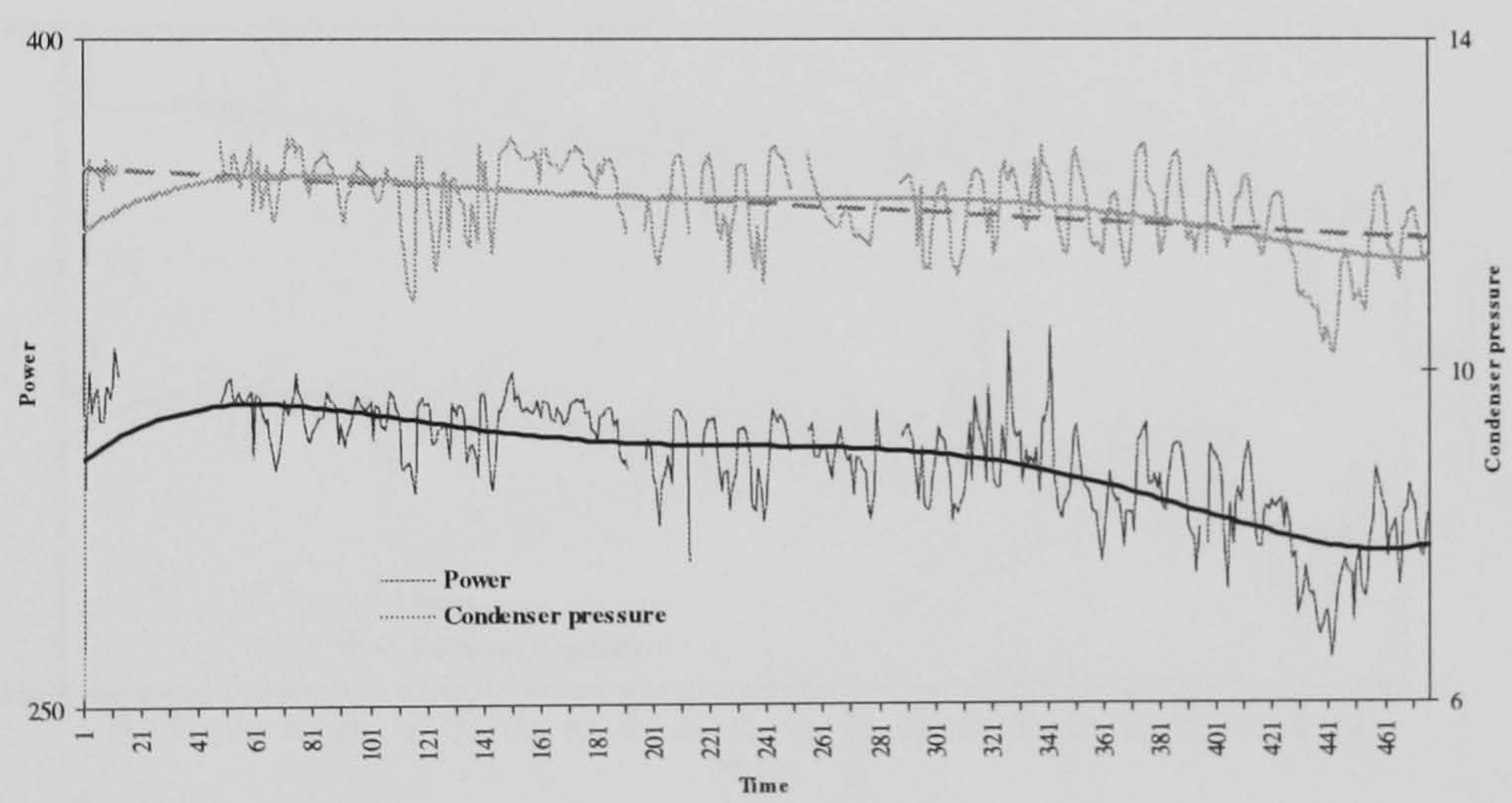


Figure H.43. Test 6 - Power (W) / Condenser pressure (bar) with Time (hrs)

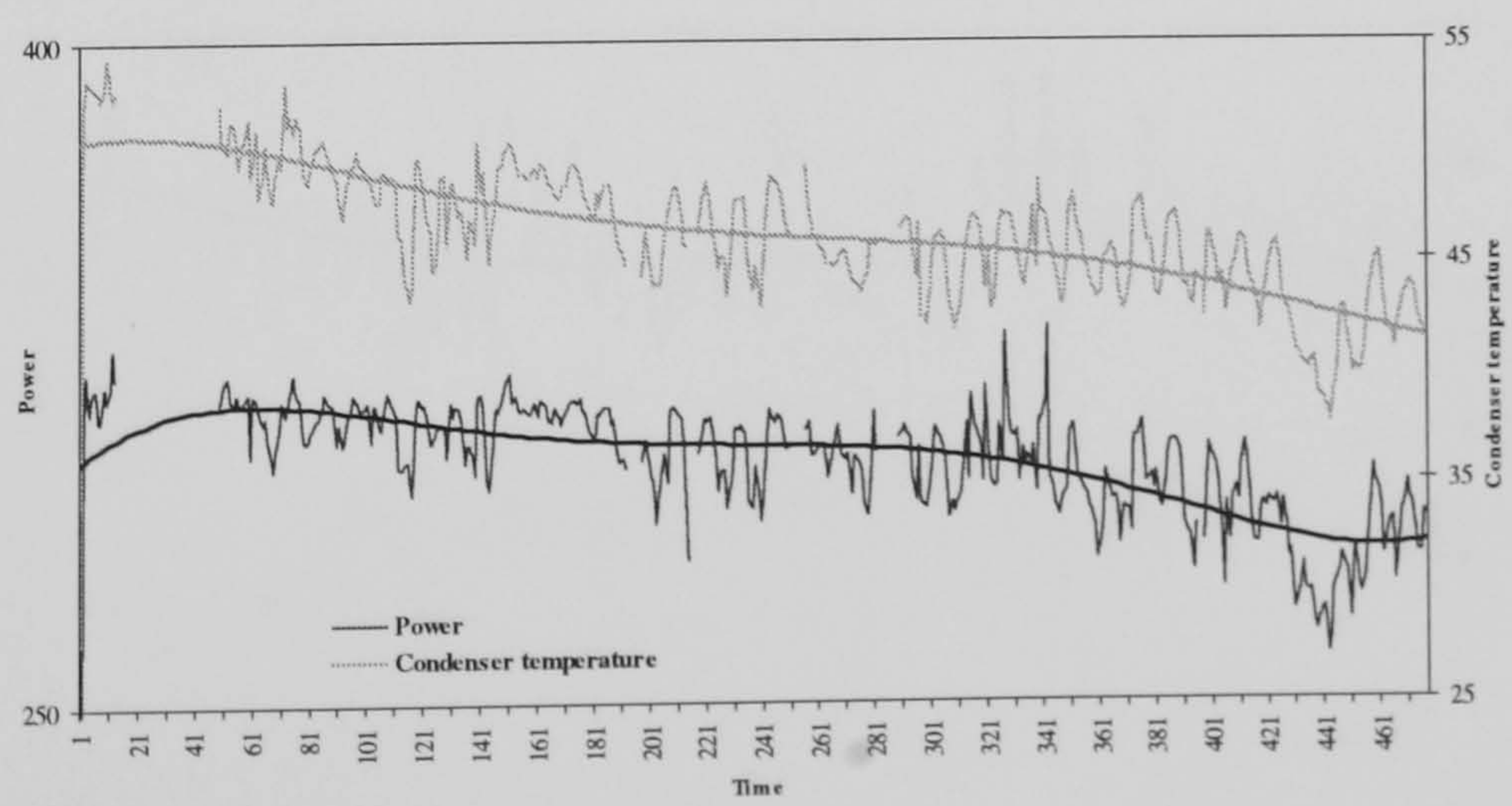


Figure H.44. Test 6 - Power (W) / Condenser temperature (°C) with Time (hrs)

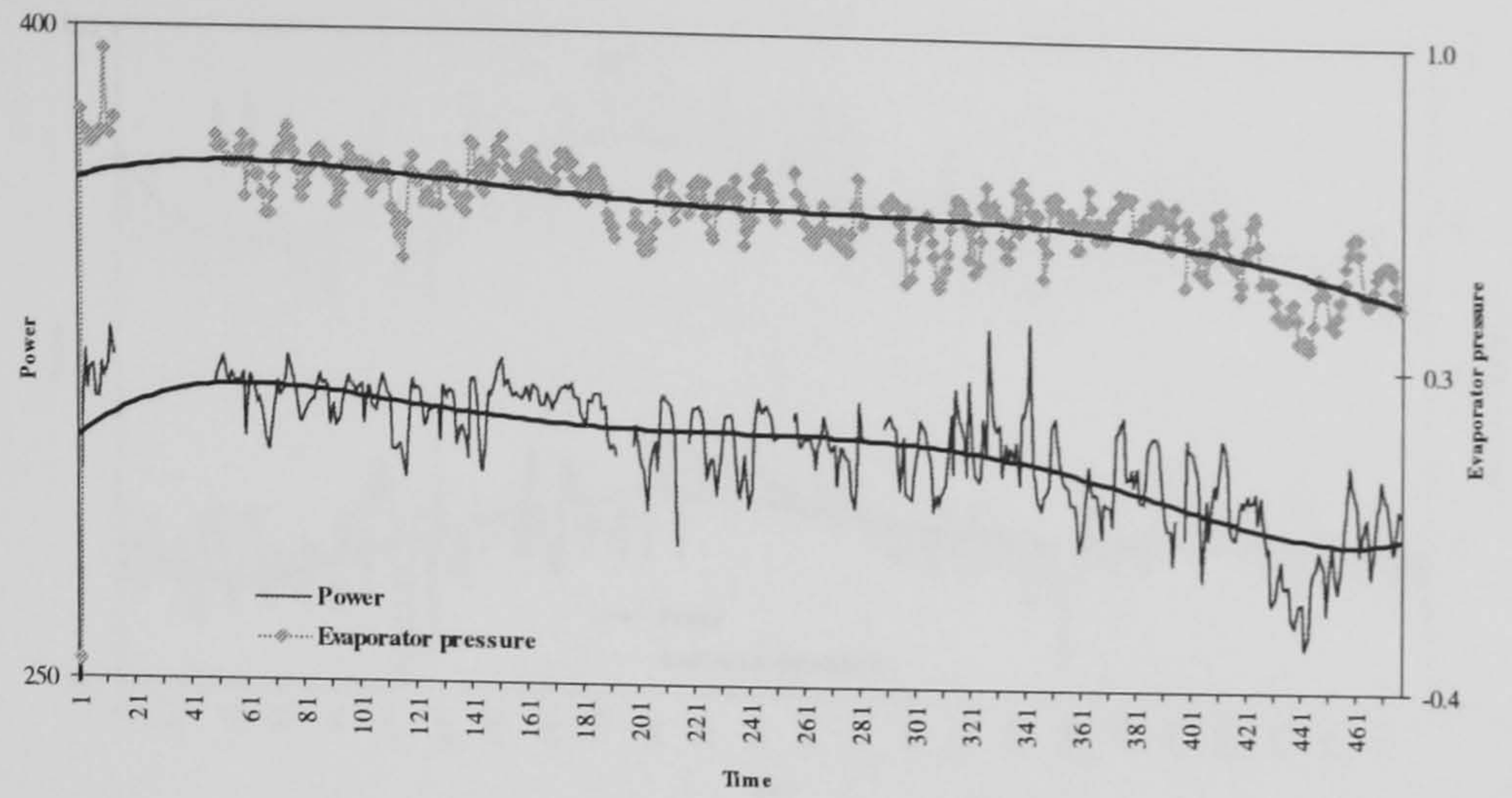


Figure H.45. Test 6 - Power (W) / Evaporator pressure (bar) with Time (hrs)

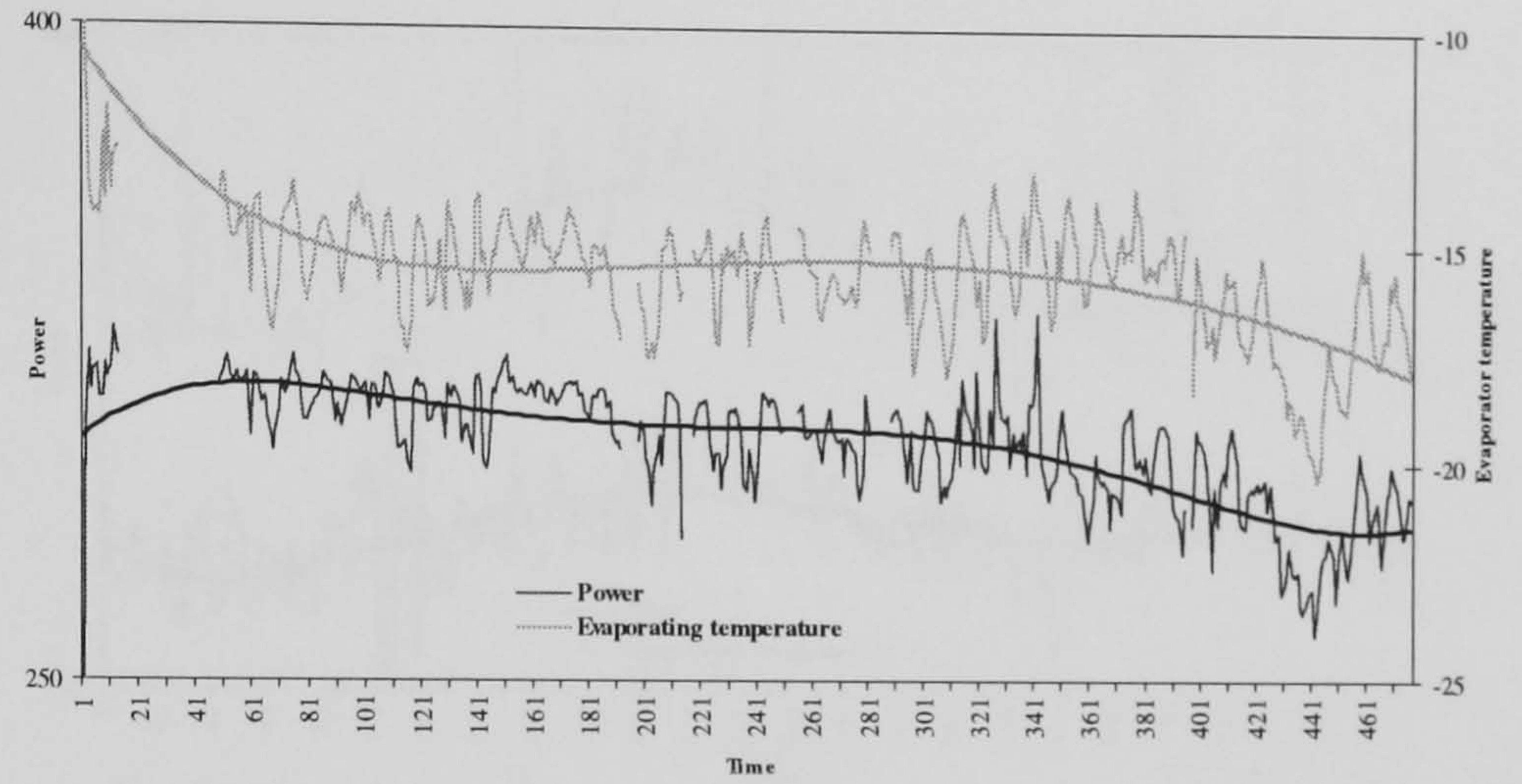


Figure H.46. Test 6 - Power (W) / Evaporator temperature (°C) with Time (hrs)

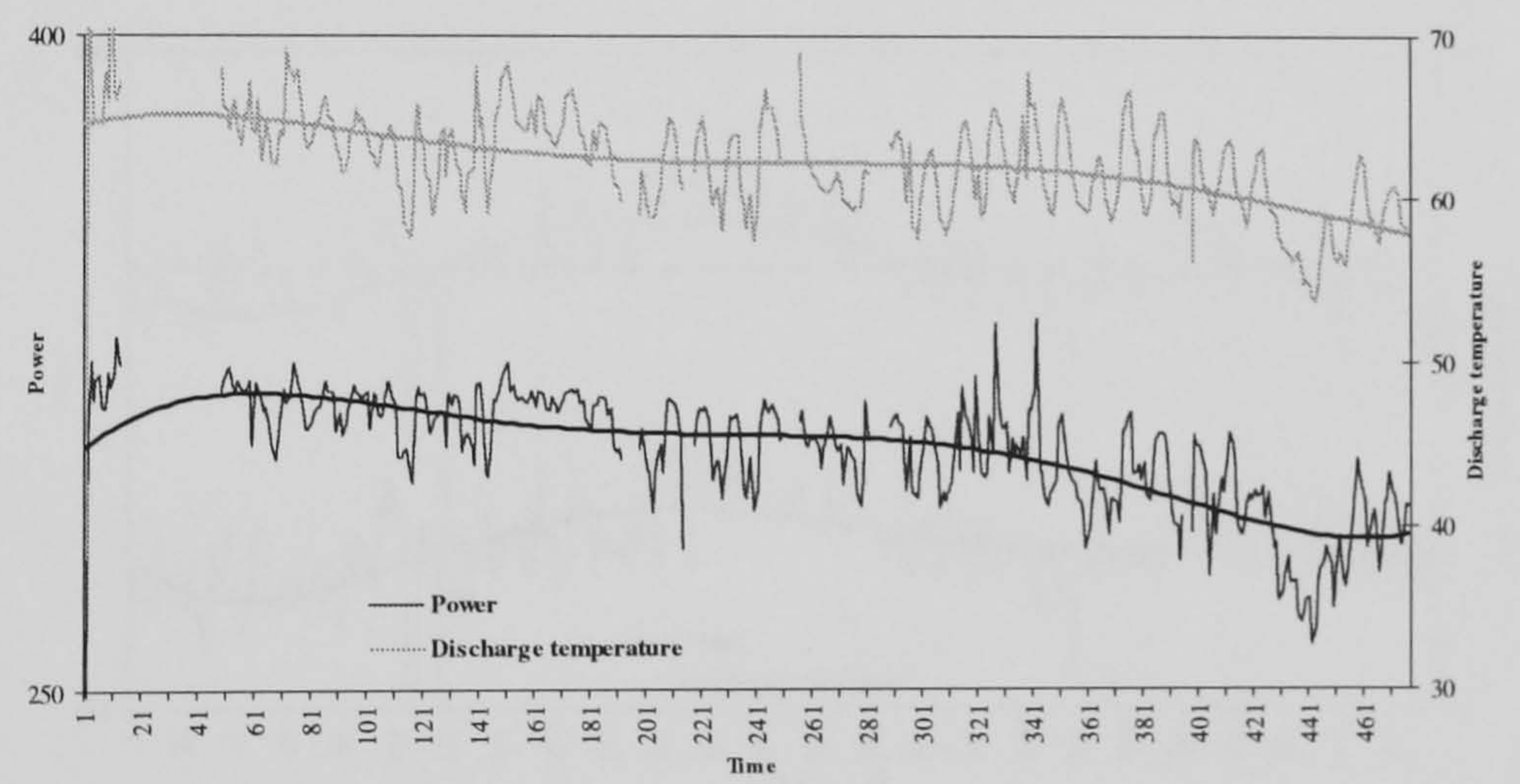


Figure H.47. Test 6 - Power (W) / Discharge temperature (°C) with Time (hrs)

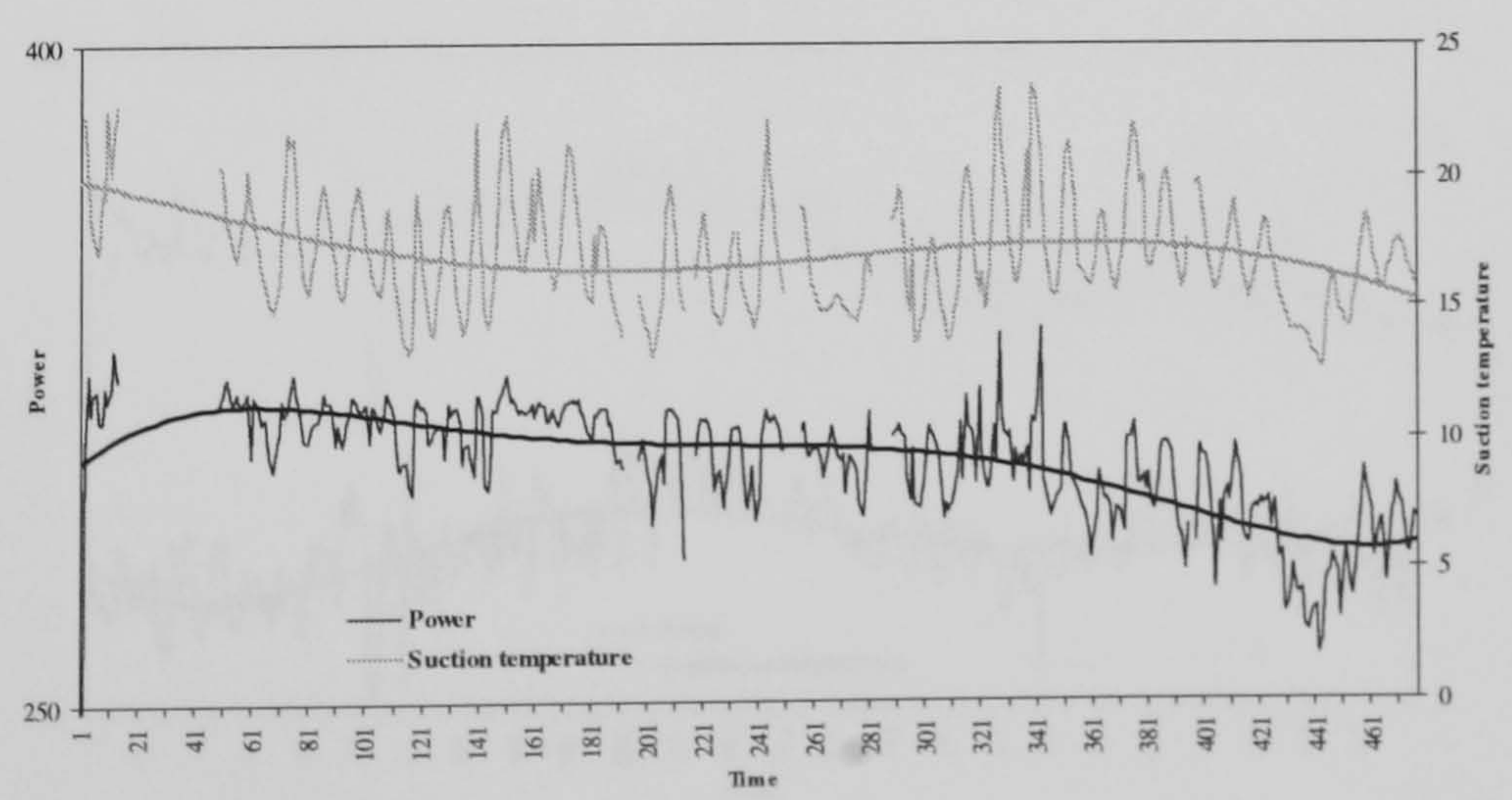


Figure H.48. Test 6 - Power (W) / Suction temperature (°C) with Time (hrs)

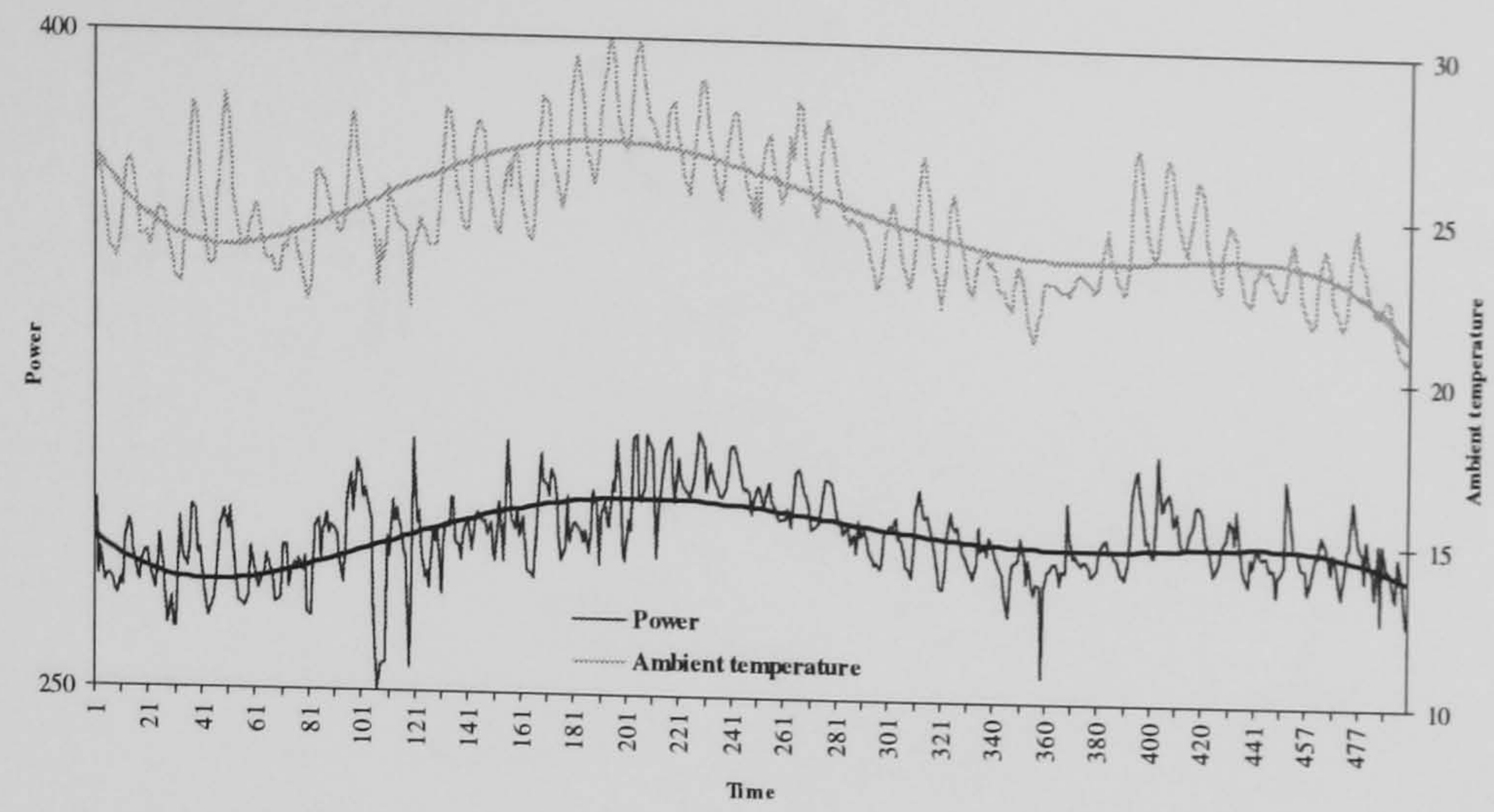


Figure H.49. Test 7 - Power (W) / Ambient temperature (°C) with Time (hrs)

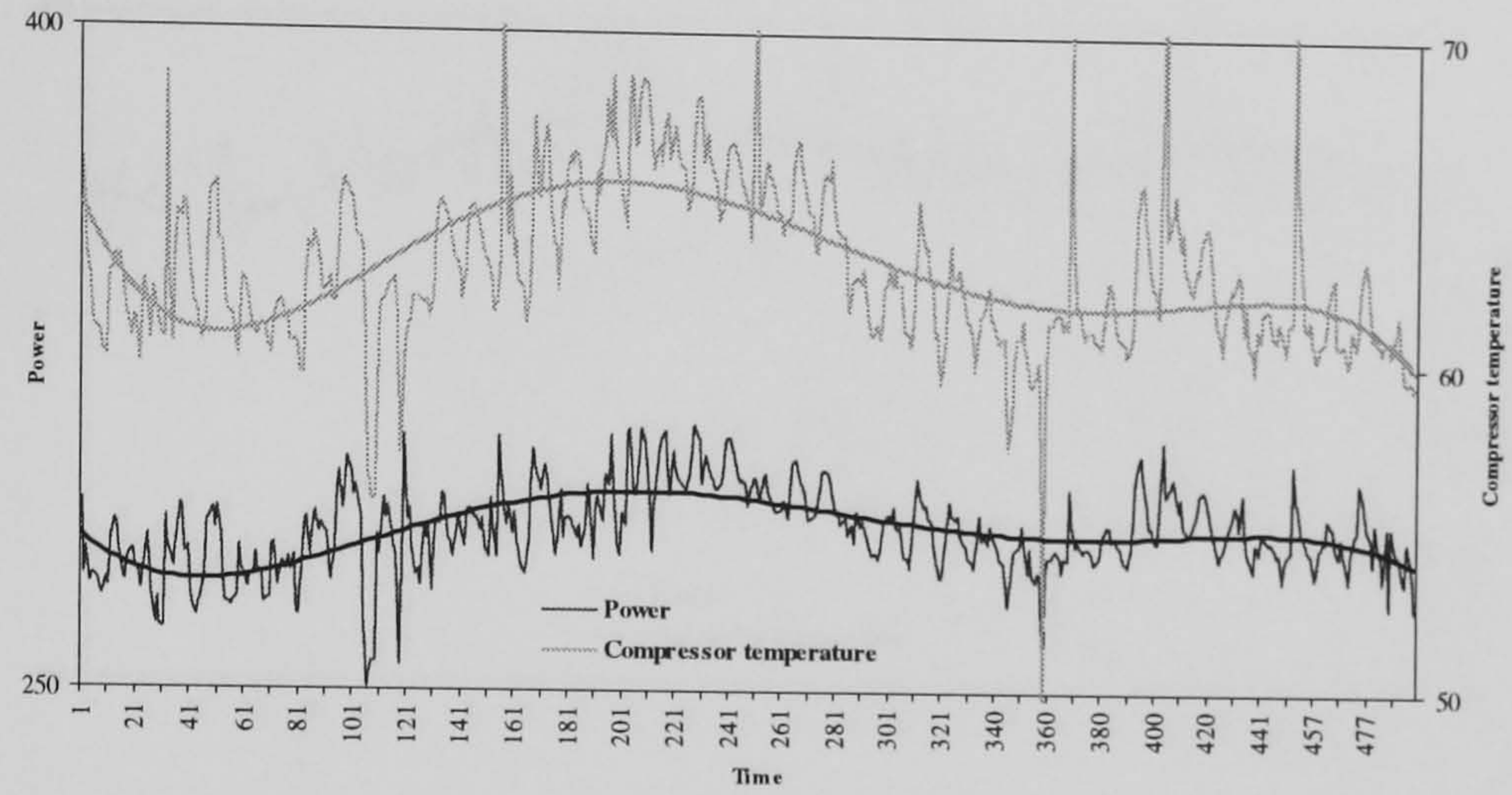


Figure H.50. Test 7 - Power (W) / Compressor temperature (°C) with Time (hrs)

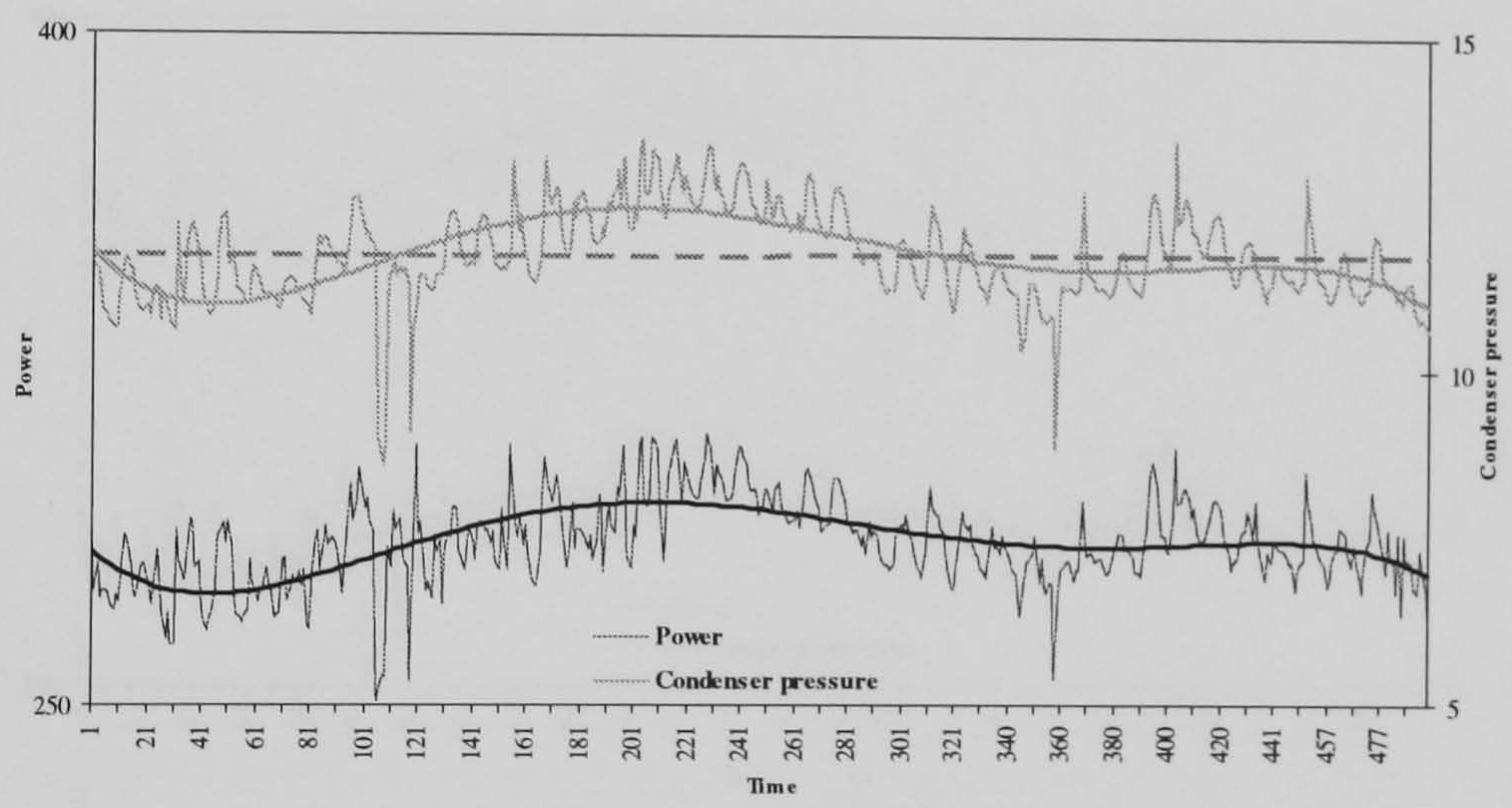


Figure H.51. Test 7 - Power (W) / Condenser pressure (bar) with Time (hrs)

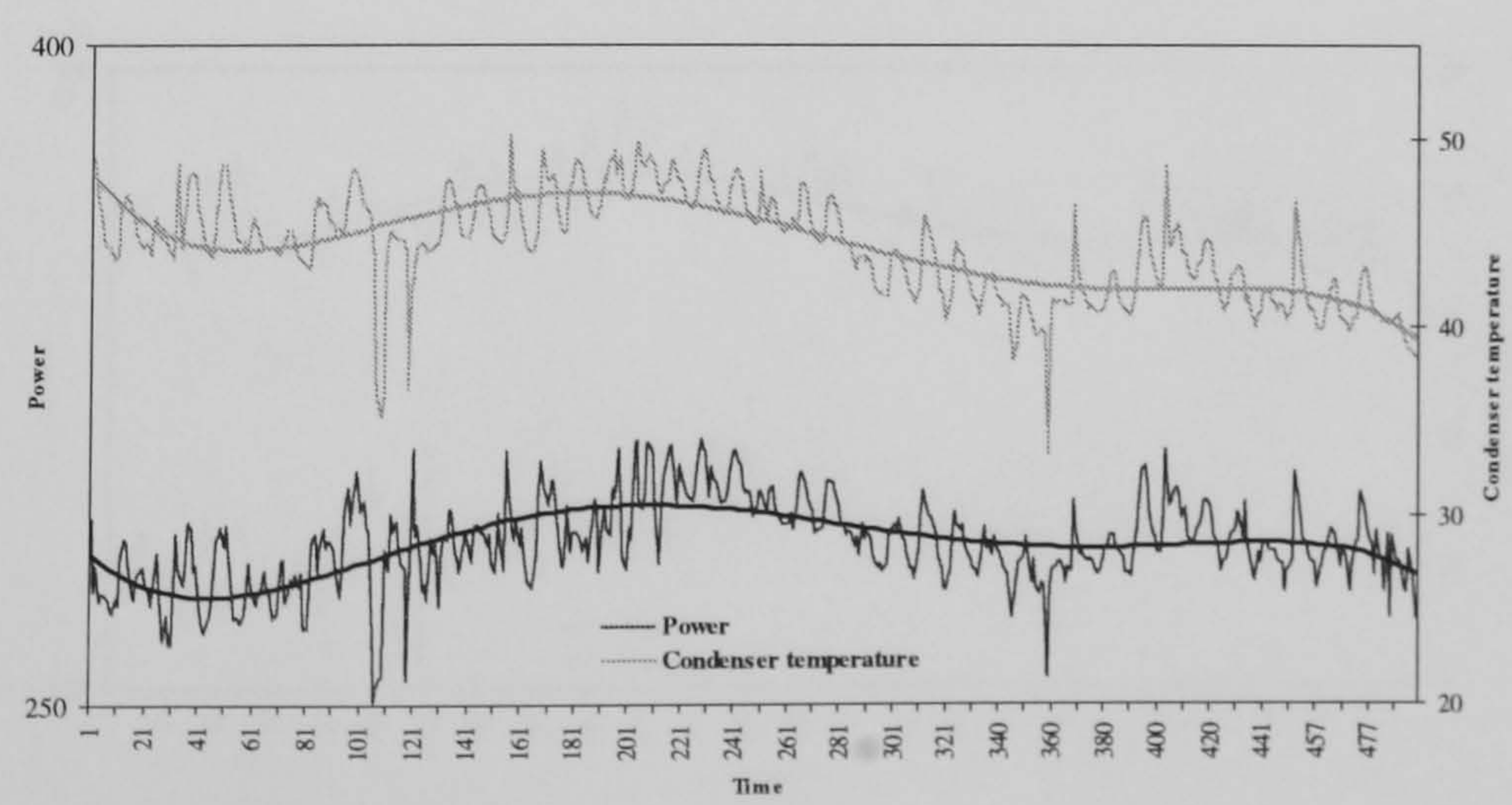


Figure H.52. Test 7 - Power (W) / Condenser temperature (°C) with Time (hrs)

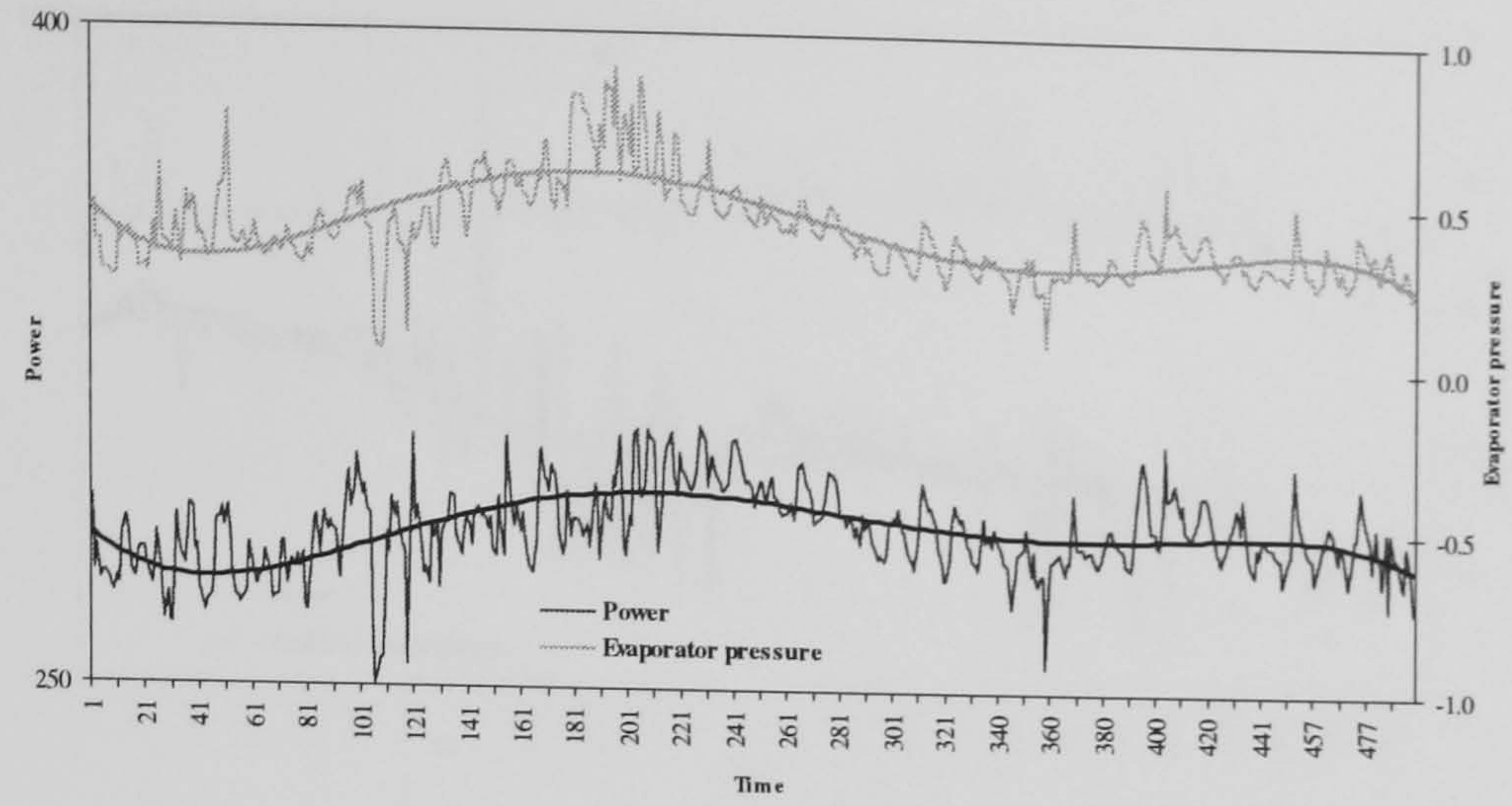


Figure H.53. Test 7 - Power (W) / Evaporator pressure (bar) with Time (hrs)

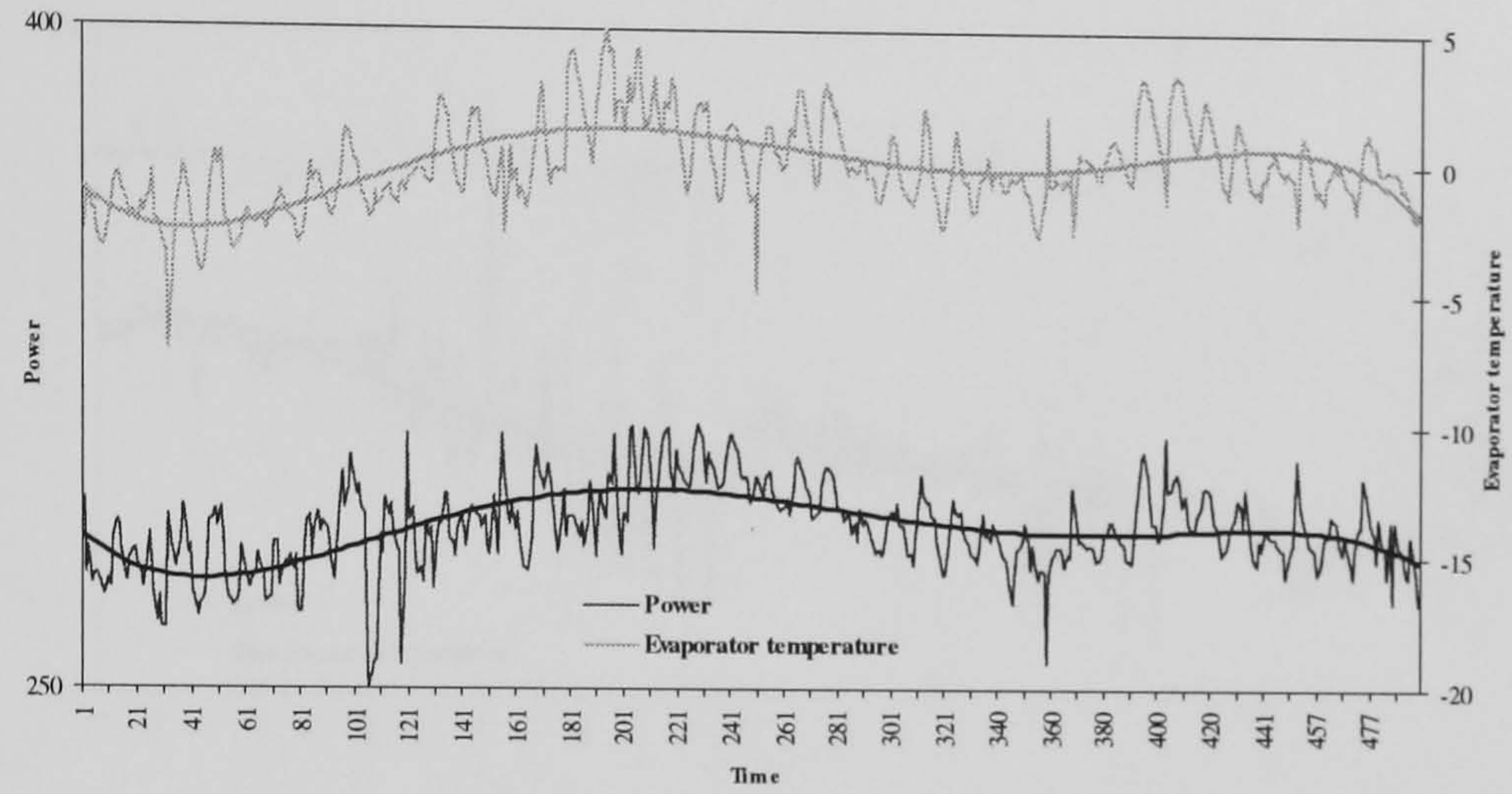


Figure H.54. Test 7 - Power (W) / Evaporator temperature (°C) with Time (hrs)

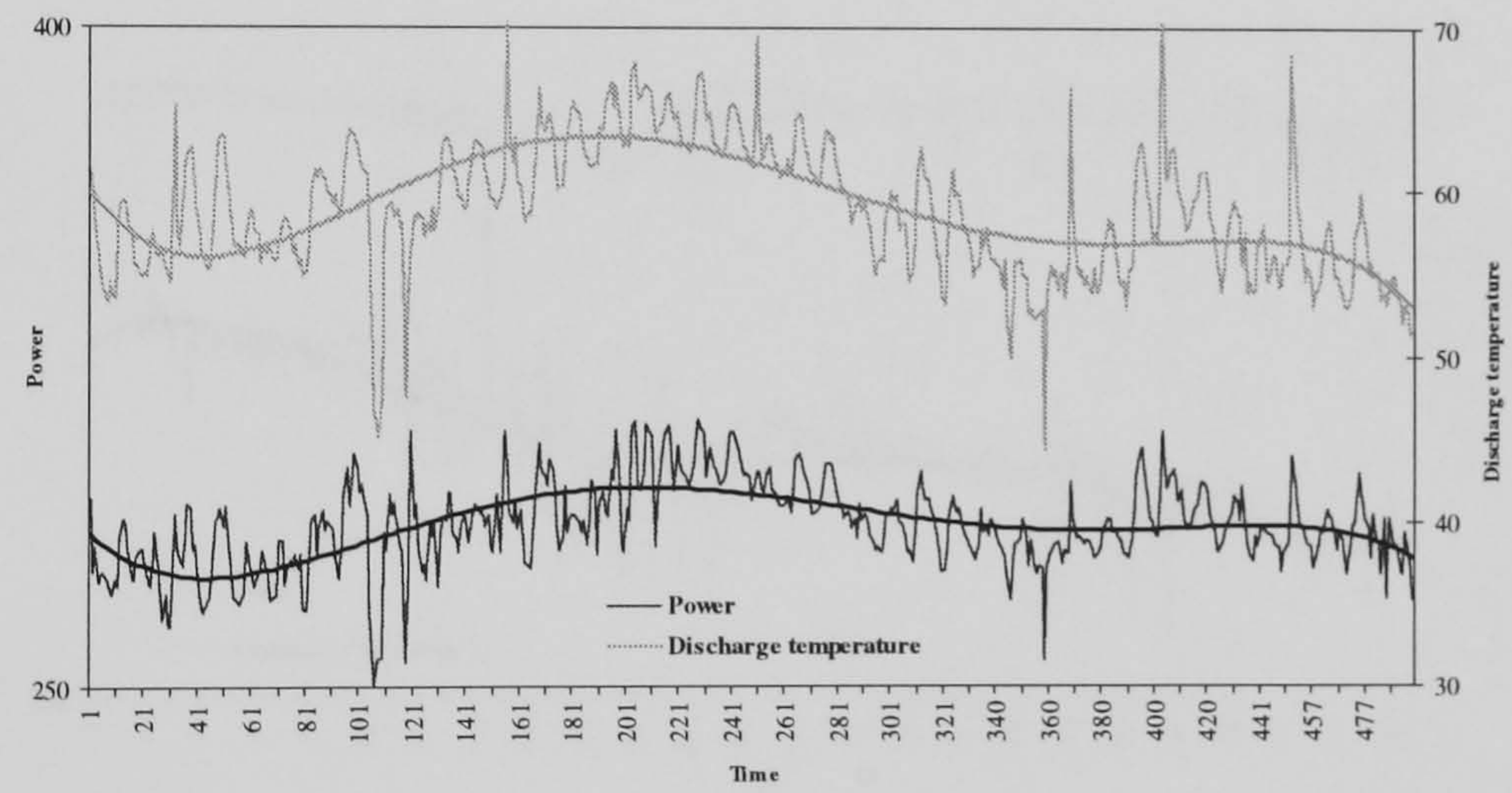


Figure H.55. Test 7 - Power (W) / Discharge temperature (°C) with Time (hrs)

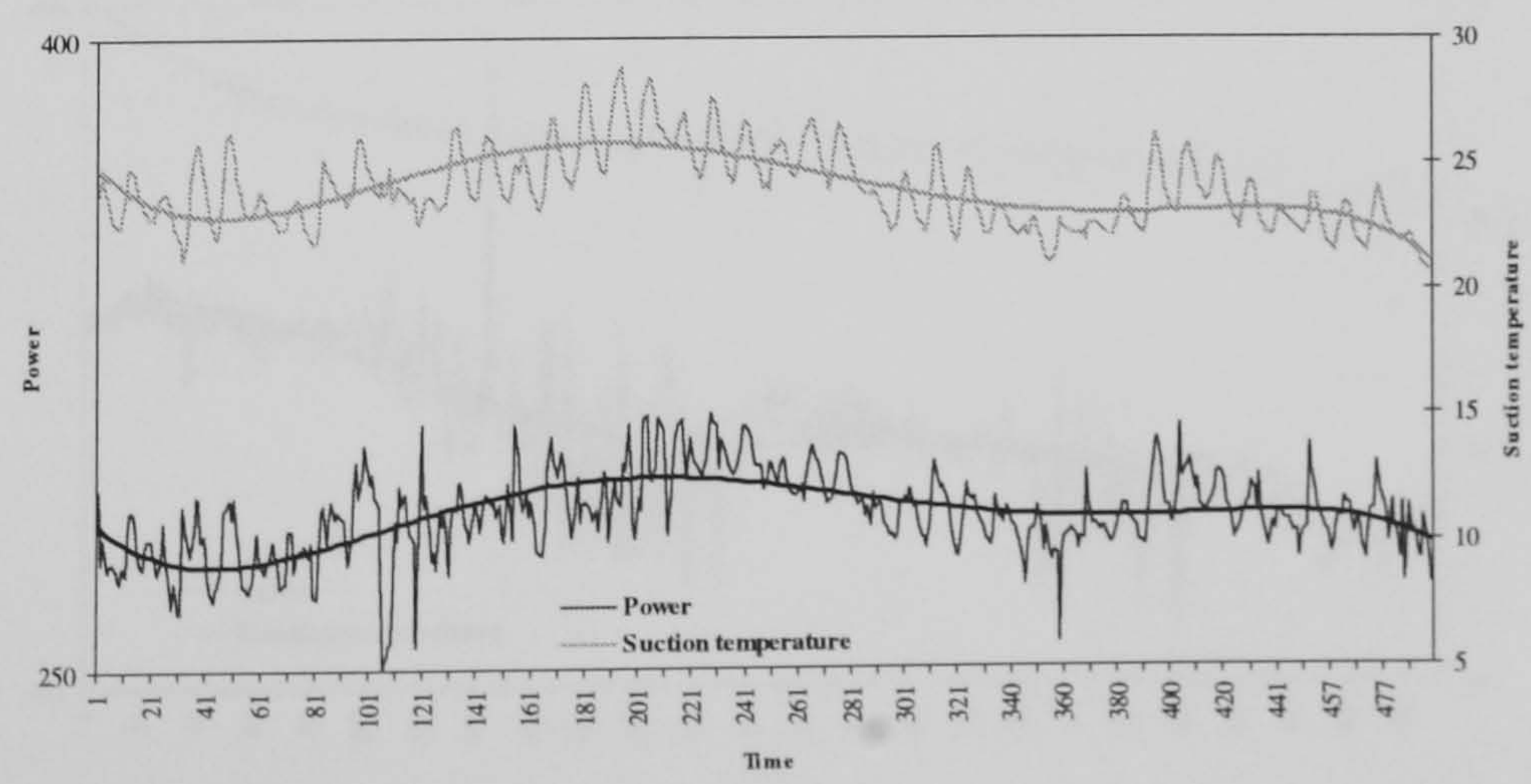


Figure H.56. Test 7 - Power (W) / Suction temperature (°C) with Time (hrs)

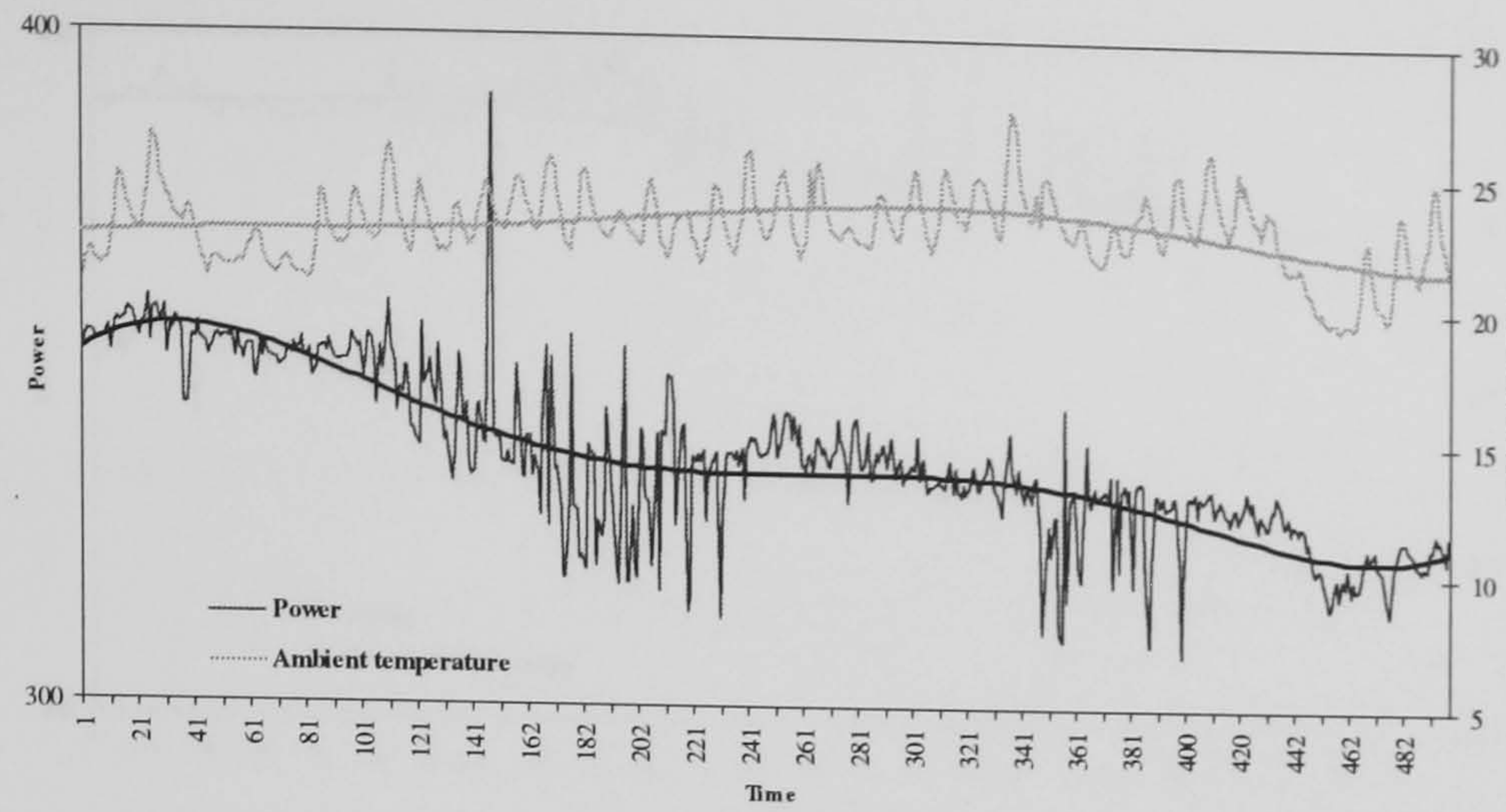


Figure H.57. Test 8 - Power (W) / Ambient temperature (°C) with Time (hrs)

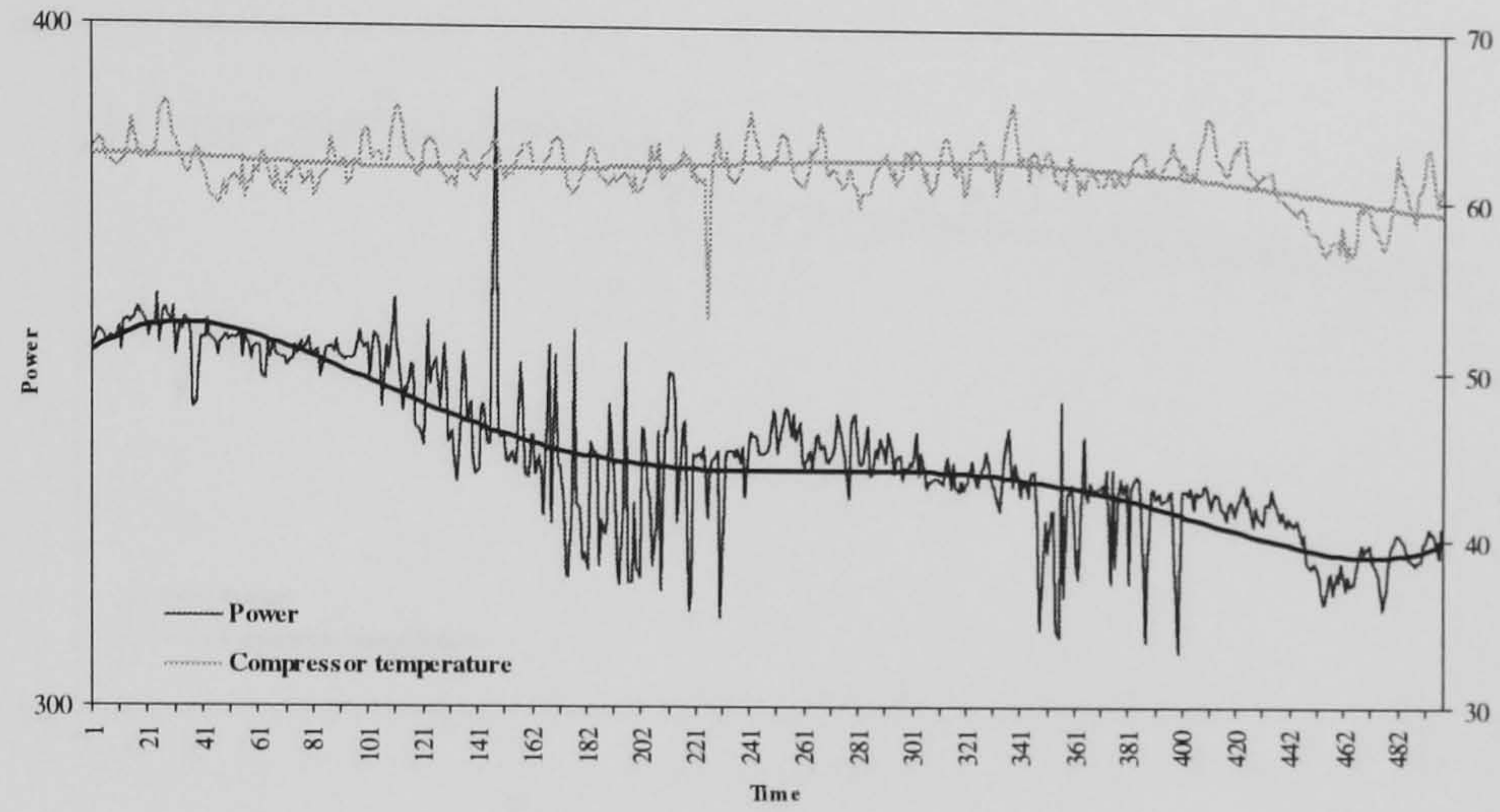


Figure H.58. Test 8 - Power (W) / Compressor temperature (°C) with Time (hrs)

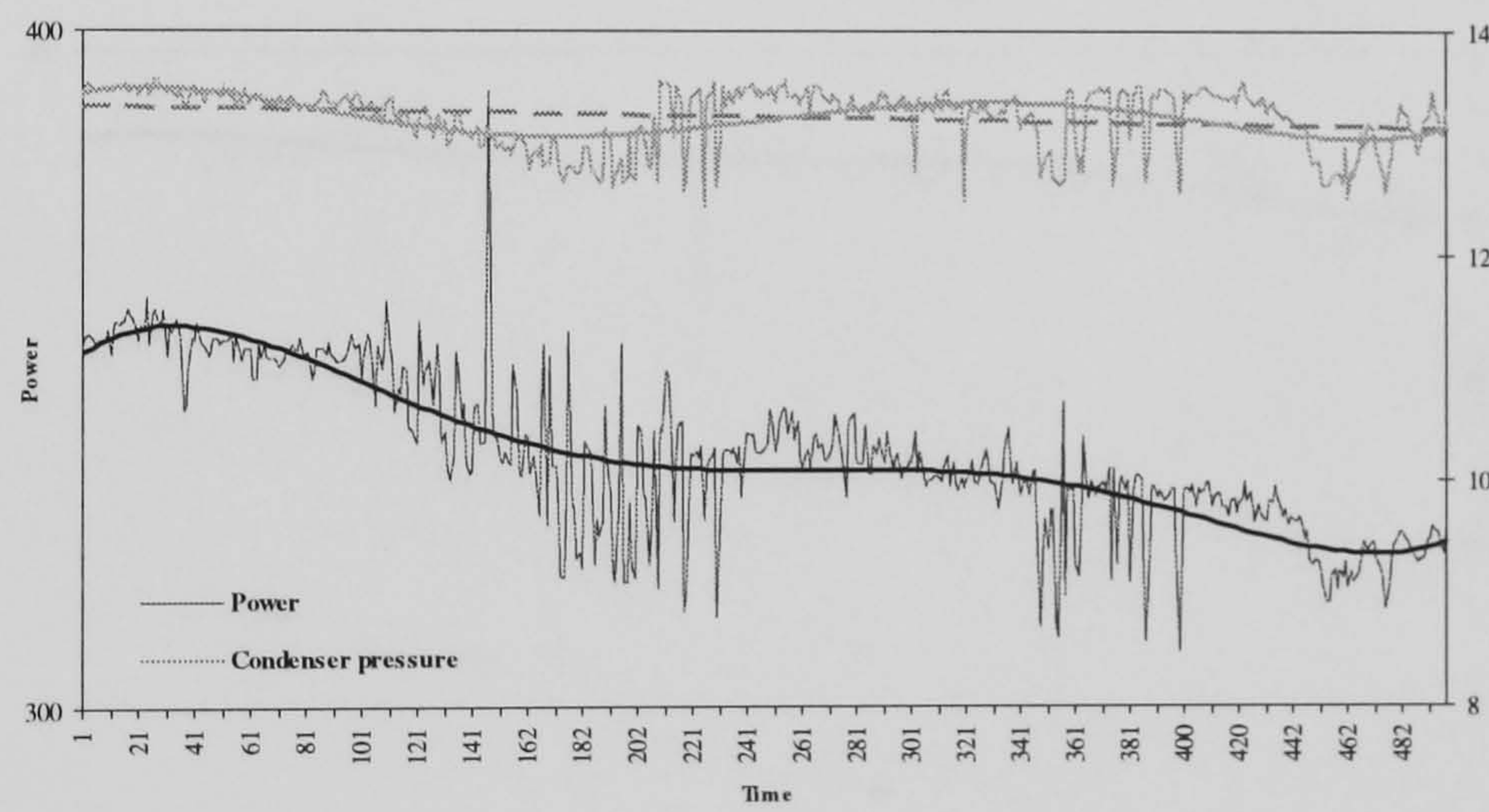


Figure H.59. Test 8 - Power (W) / Condenser pressure (bar) with Time (hrs)

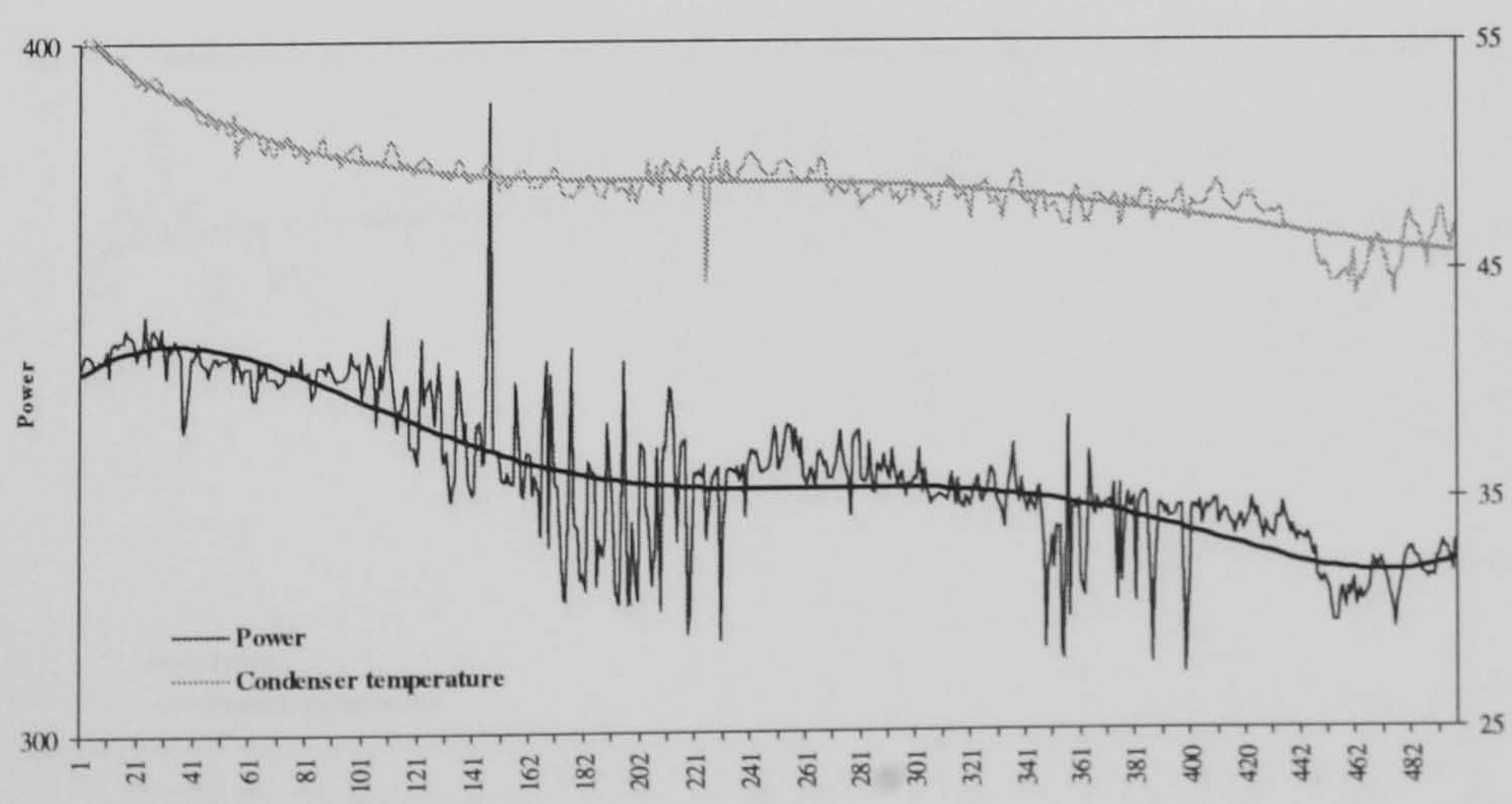


Figure H.60. Test 8 - Power (W) / Condenser temperature (°C) with Time (hrs)

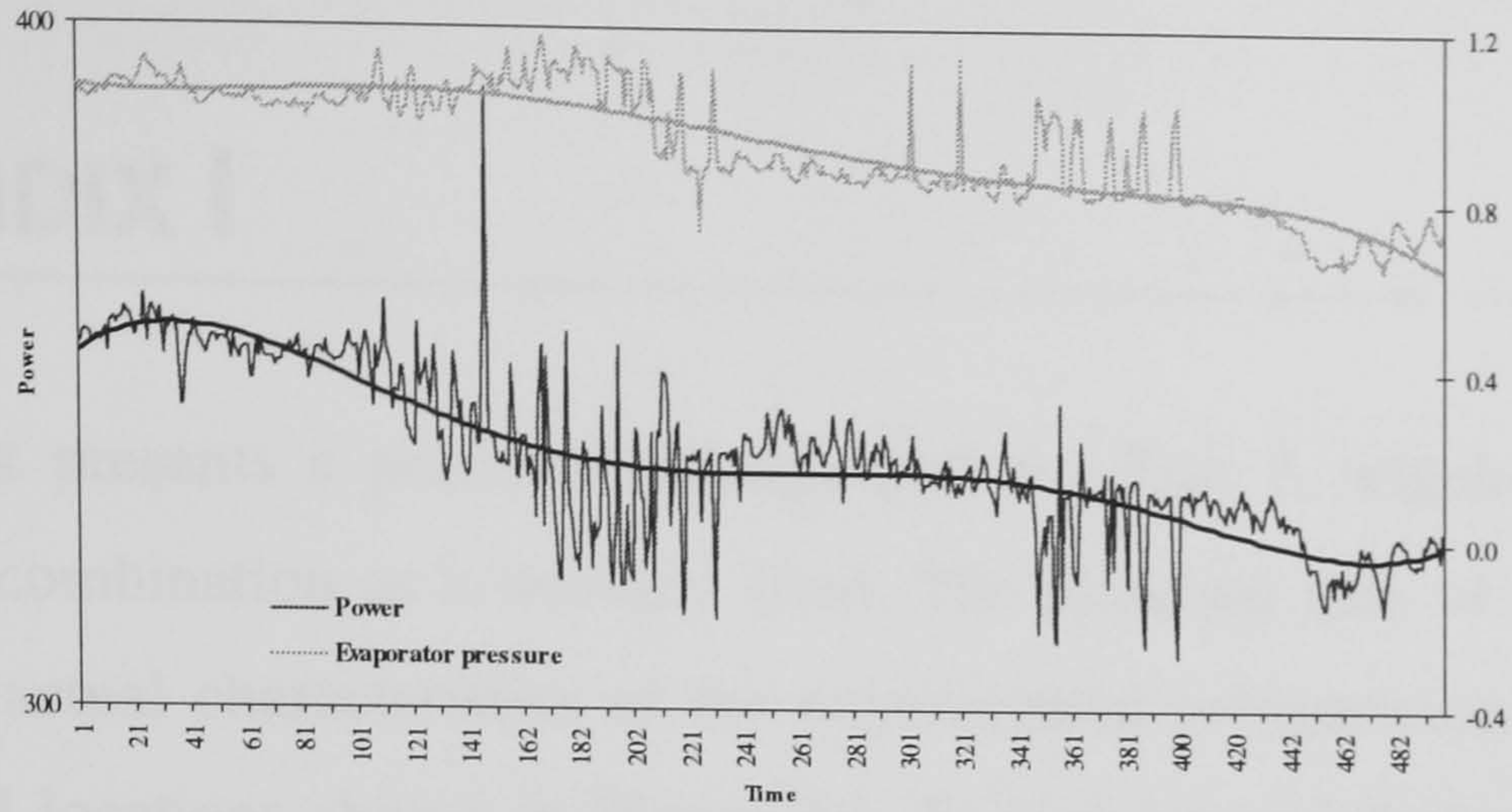


Figure H.61. Test 8 - Power (W) / Evaporator pressure (bar) with Time (hrs)

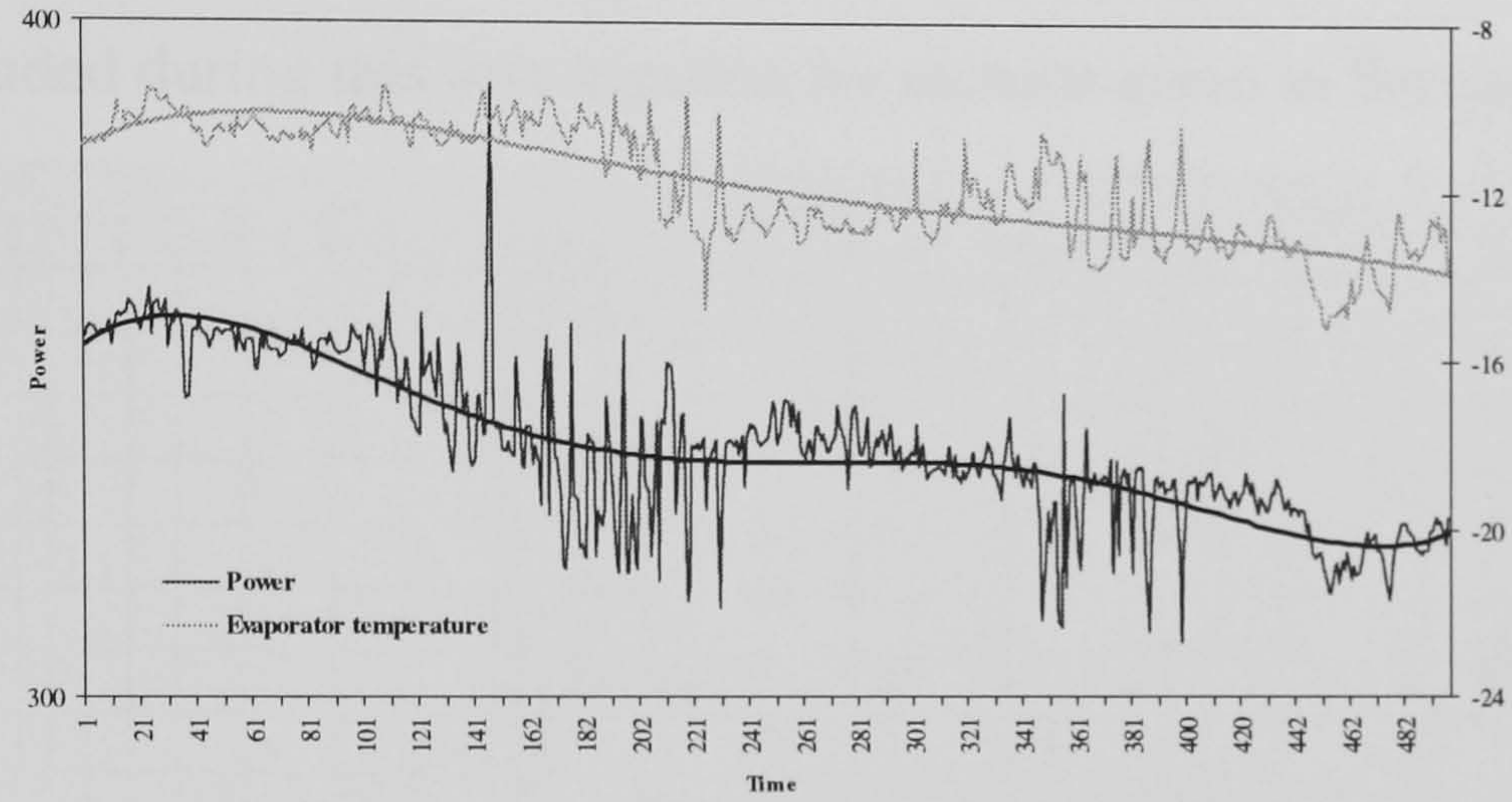


Figure H.62. Test 8 - Power (W) / Evaporator temperature (°C) with Time (hrs)

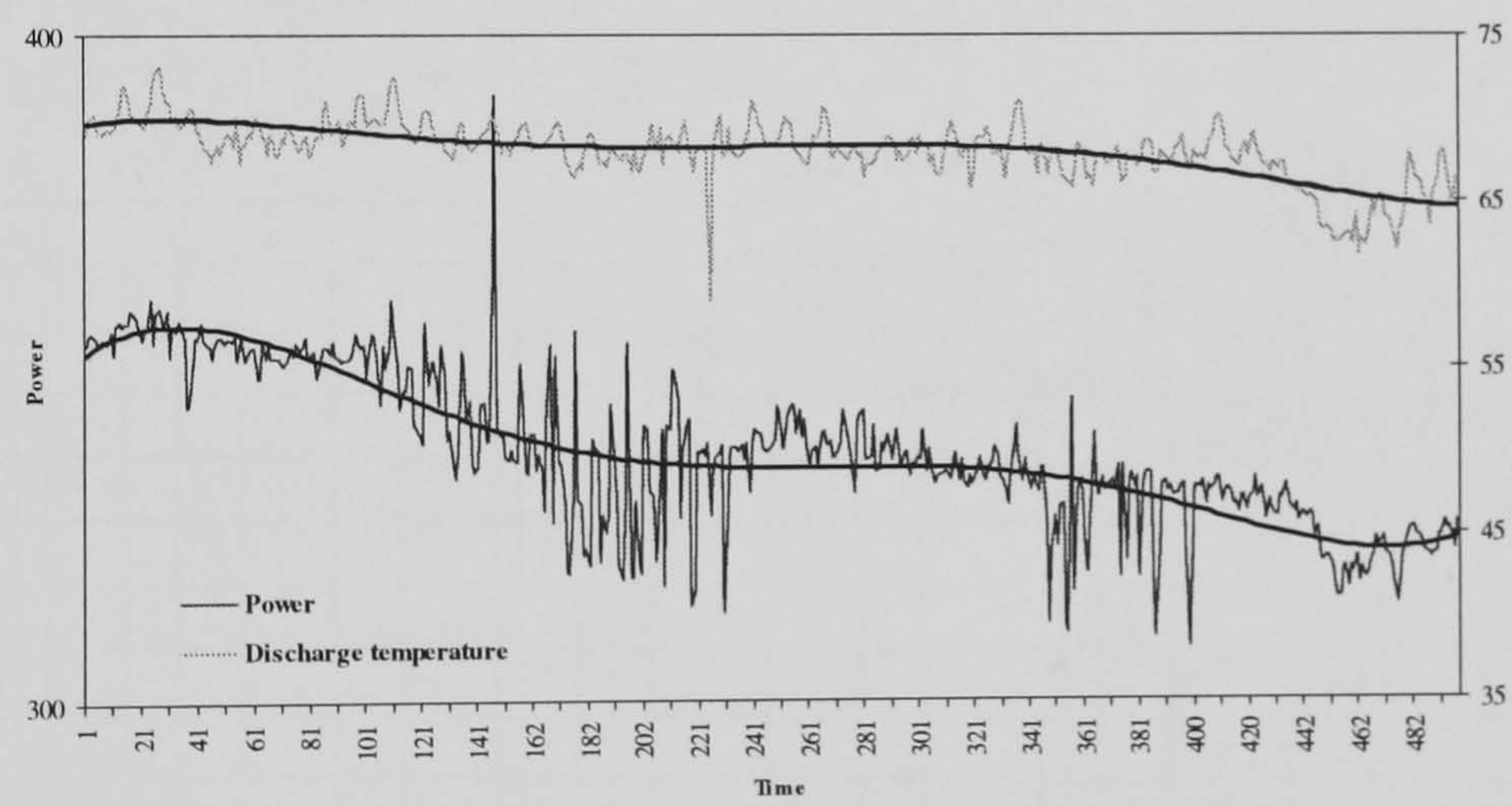


Figure H.63. Test 8 - Power (W) / Discharge temperature (°C) with Time (hrs)

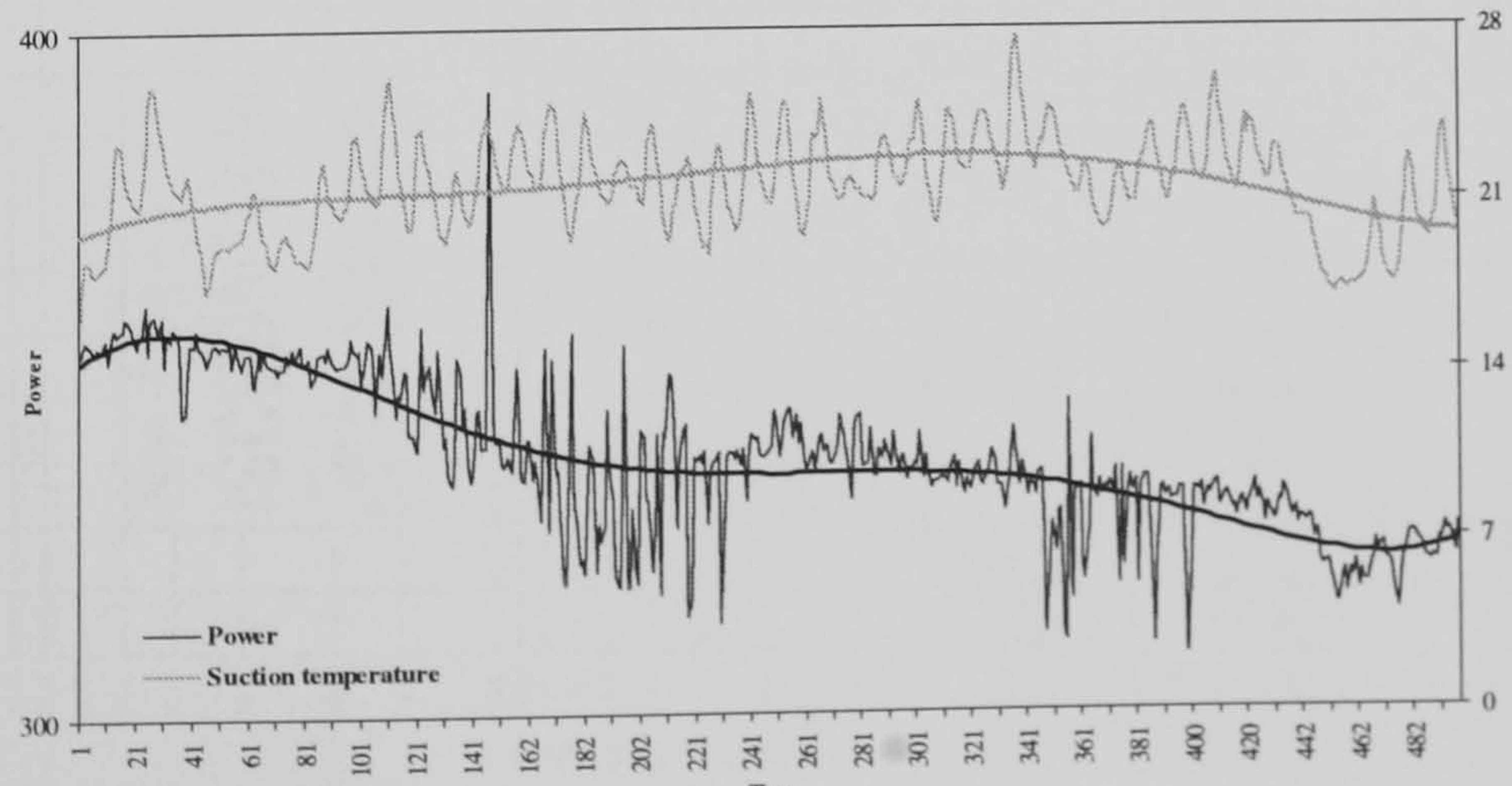


Figure H.64. Test 8 - Power (W) / Suction temperature (°C) with Time (hrs)

APPENDIX I

This appendix presents a pressure-enthalpy plot for Test 7, which used an HFC-134a/POE32 combination as a working fluid. The principal task of Figure I.1 is to highlight the actual characteristics of the experimental refrigeration system around the monitored locations shown in Figure 2.1. It must be said that although similar characteristics were obtained, the cooling COPs obtained for Test 1 to Test 8 have not been included during this investigation for reasons given in Section 4.3.2.

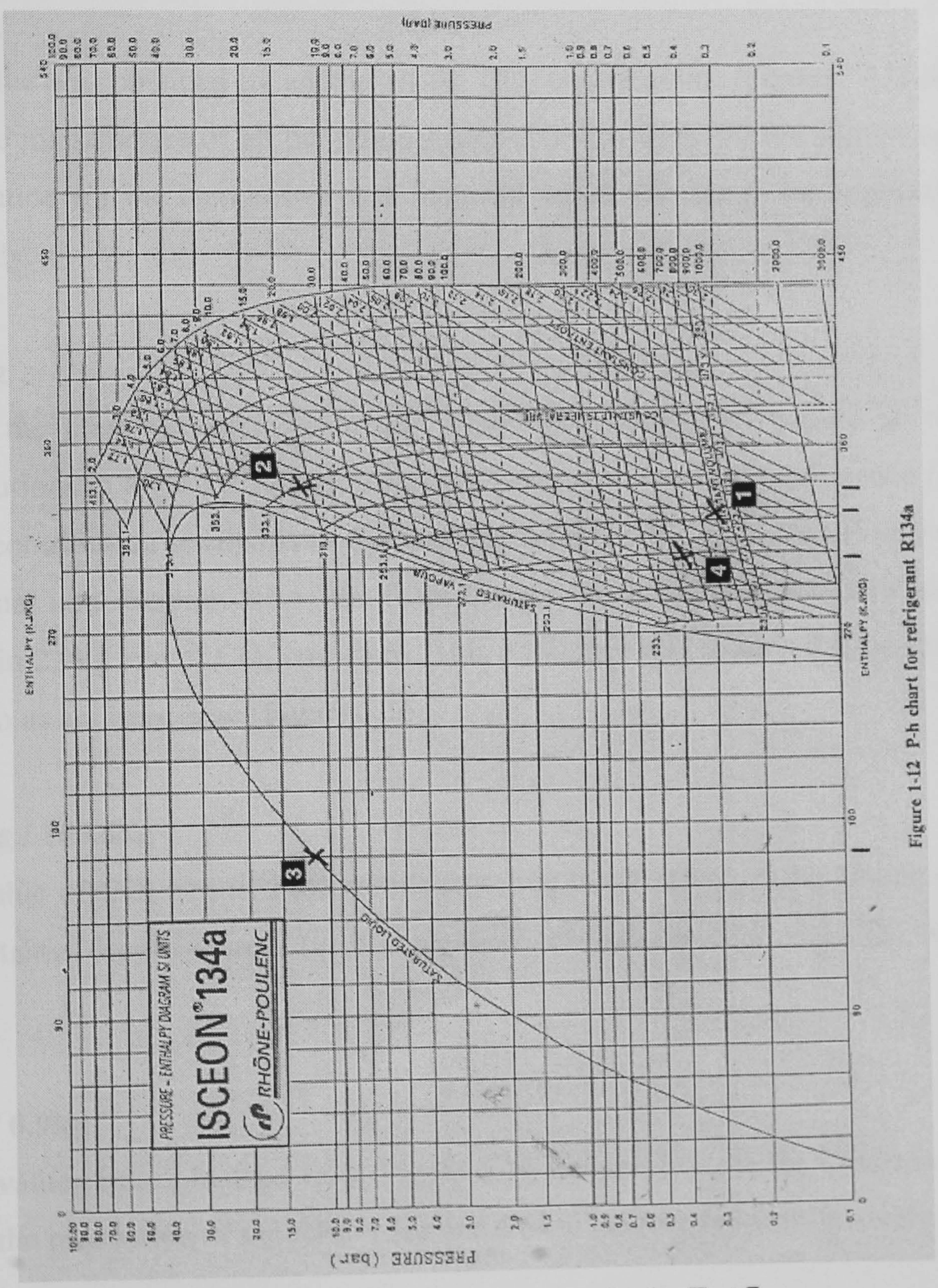


Figure I.1. Pressure-enthalpy plot for Test 7

APPENDIX J

This appendix explains how the values listed in Table 6.1 were obtained. Given the relevance of this table to the overall research work, each value is dealt with separately here. The CO_2 burdens given include the contribution of emissions known to contribute to global warming and referenced to carbon dioxide, hence CO_2 equivalent (Figure 5.5).

666.8kg

This value was obtained by adding all the CO_2 contributions (Figure 5.12) resulting from the manufacture of all the product items, except those for the compressor. The contribution for the compressor was included separately due to its implications on this study.

663.9kg

As for the previous contribution this value was obtained by adding all the CO_2 contributions in Figure 5.12 (not including the compressor). The difference from the above contribution results from the fact that for the CFC compliant (Section 3.6.3) functional unit (Section 3.6.1) the foam blower for the cabinet and door insulation results in 2.9kg less of CO_2 emissions. This difference was observed for a mixed fuel scenario as assumed here (Figure 5.16).

103.6kg / 103.6kg

This value of CO_2 contribution results from the manufacture of the compressor and was obtained from Figure 5.12. It is identical for both the HFC and CFC compliant units.

1.4kg / 0.9kg

These values were obtained from Figure 5.16 and result from the CO_2 contribution due to the production of the HFC-134a and CFC-12 refrigerants respectively.

0.8kg / 1.2kg

This value was extrapolated from (Våg, et al. 2000) and results from the production of the base ester and mineral oils respectively. Contributions from additives required for synthetic lubricants were not included here but it is likely that these would have increased the contribution for ester oils.

2525.1kg

This value of CO_2 contribution was obtained from the value of product lifetime energy consumption for Test 7. This value of energy was chosen to be the worse case scenario obtained from all the HFC-134a interrupted tests and was equal to 10,908MJ in Table 4.8. The LCA model used, in which this energy value was incorporated, was similar to that used for the calculation of the emissions given in Section 5.1.6.

1640.3kg

This CO_2 contribution was obtained from the value of product lifetime energy consumption for Test 6, as done for the preceding contribution. The value of energy consumption incorporated in the LCA model was equal to 7086MJ in Table 4.8.

887.8kg

This CO_2 contribution is equal to the difference in contribution due to the energy consumption throughout the 15 year lifetime of a unit operating with HFC-134a and a unit operating with CFC-12 (Contribution A) plus any differences in contribution during the manufacturing stage (Contribution B).

Contribution A

This is the difference between 2525.1kg and 1640.3kg and is identical to the CO_2 contribution obtained in Figure 5.18. This difference is equal to 884.8kg.

Contribution B

This results from the difference between the total emissions during the manufacturing of an HFC compliant unit (772.6kg) and the total emissions during the manufacturing of a CFC compliant unit (769.6kg). This difference is equal to 3kg.

1683.9kg

This value of CO_2 contribution was obtained from the value of a 10 year product lifetime energy consumption for Test 7. Again, the LCA model used was similar to that used for the calculation of the emissions given in Section 5.1.6. The value of energy chosen was the worse case scenario obtained from all the HFC-134a interrupted tests. This value of energy consumption was equal to 7272MJ and was calculated thus: 115.3*(0.2*3600*24*365*10).

1093.6kg

This value of CO_2 contribution was obtained from the value of a 10 year product lifetime energy consumption for Test 6, as done for the preceding contribution. This value of energy consumption was equal to 4724MJ and was calculated thus: 74.9*(0.2*3600*24*365*10).

849.8kg

This CO_2 contribution is equivalent to the difference in contribution resulting from a 10 year consumption of electricity (Contribution C) plus the contribution resulting from increased product manufacture (Contribution D). Note that in this calculation we overlook the fact that a new HFC-134a unit would require more or less energy to operate than the HFC-134a unit which failed after 10 years.

<u>Contribution C</u>

This is the difference between 1683.9kg and 1093.6kg. This difference is equal to 590.3kg.

<u>Contribution D</u>

The best way to visualise this, given the timeframes chosen, is to assume a 30 year period. During this time, three HFC-134a units are required for every two CFC-12 units. As previously mentioned, the former unit contributes 772.6kg of CO_2 emissions whereas the latter unit contributes 769.6kg of CO_2 emissions. Hence, from the manufacturing of the units, the total contribution during these 30 years is equal to the difference between (3*772.6kg) and (2*769.6kg), that is, 778.6kg. Over a 10 year period, this contribution is equivalent to 259.5kg.

15% / 21%

In Section 1.5.3 it was mentioned that the CO_2 emissions from domestic refrigeration will increase to a maximum of 4.8Mt equivalent by the year 2010. These emissions result from the direct and indirect effects but it should be emphasised that the former is insignificant compared to the latter in domestic refrigeration (Section 1.5.3). It would be interesting to calculate by how much the values of increased contribution, obtained in Table 6.1, account towards this projected rise.

Since 81 thousand tonnes of units are discarded annually in the UK (Section 1.5.3) and assuming that each of these units weighs as much as the functional unit (66kg) described in Section 3.6.1, then approximately 1.2 million units are sold annually in the UK. In so doing, it is assumed that all units discarded are replaced and that no new units are bought without discarding another.

Assuming that the number of units mentioned in the preceding paragraph are the only units operating over the next 15 years, at which time both units fail, then the total CO_2 contribution is 1.06Mt (887.8*1.2E06). Therefore, over a 10 year period, this contribution is equivalent to 0.71Mt. This 0.71Mt equates to approximately 15% of the total projected contributions for 2010.

If it is assumed that the same number of units are the only units operating over the next 10 years, at which time only the HFC unit fails, then the total CO_2 contribution is 1.02Mt (849.9*1.2E06), which is approximately equal to 21% of the total projected contributions for 2010.

REFERENCES

Akei, M. and Mizuhara, K. 1997. The elastohydrodynamic properties of lubricants in refrigeration environments. *Tribology Transactions.* 40 (1), pp. 1-10.

Akei, M., Mizuhara, K. and Yamamoto, T. 1996. Evaluation of film-forming capability of refrigeration lubricants in pressurized refrigerant atmosphere. *Wear.* 196 (1-2), pp. 180-187.

Allenby, B.R. 1999a. Industrial ecology and design for the environment. In: Yoshikawa, H., Yamamoto, R., Kimura, F., Suga, T. and Umeda, Y., (eds.) *Proceedings of the First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, Tokyo, pp. 2-10.

Allenby, B.R. 1999b. *Industrial Ecology. Policy Framework and Implementation.* New Jersey, Prantice Hall.

Alting, L. 1995. Sustainable industrial production. Environmental issues in product development. In: Jansen, H. and Krause, F.-L., (eds.) *Proceedings of the IFIP WG5.3 International Conference on Life Cycle Modeling for Innovative Products and Processes*, Berlin, Chapman & Hall, pp. 31-42.

Alting, L., Hauschild, M. and Wenzel, H. 1997. Elements in a new sustainable industrial culture: environmental assessment in product development. In: Wright, T., Rudolph, M., Hanna, V., Gillingwater, D. and Burns, N., (eds.) *Managing Enterprises - Stakeholders, Engineering, Logistics and Achievement*, Loughborough, Mechanical Engineering Publications Ltd., pp. 523-531.

Alting, L., Hauschild, M. and Wenzel, H. 1998. Elements in a new sustainable industrial culture; environmental assessment in product development. *Robotics and Computer Integrated Manufacture.* 14, pp. 429-439.

Alting, L. and Legarth, J.B. 1995. Life cycle engineering and design. *Annals of the CIRP.* 44 (2), pp. 569-580.

Andersson, S. and Salas-Russo, E. 1994. The influence of surface roughness and oil viscosity on the transitions in mixed lubricated sliding steel contacts. *Wear.* 174, pp. 71-79.

Anon 1998. CFCs still widely used despite ban on production. *ASHRAE Journal.* 40 (6), p. 26.

ASME 1977. *Strategy for Energy Conservation through Tribology.* New York, The American Society of Mechanical Engineers.

ASTM 1988. *D 2783 - 88. Standard test method for measurement of extreme-pressure properties of lubricating fluids (four-ball method).* New York, American Society for Testing and Materials.

ASTM 1994. *D 4172 - 94. Standard test method for wear preventive characteristics of lubricating fluid (four-ball method).* New York, American Society for Testing and Materials.

Atwood, T. and Hughes, H.M. 1990. Refrigerants and energy efficiency. In: *Proceedings of the 1990 USNC/11R-Purdue Refrigeration Conference and ASHRAE-Purdue CFC Conference*, West Lafayette, Purdue University, pp. 80-89.

Bey, N., Lenau, T. and Larsen, M.H. 1999. Oil points - life cycle evaluations without the data problem. In: Lindenmann, U., Birkhofer, H., Meerkamm, H. and Vajna, S., (eds.) *Proceedings of the 12th International Conference on Engineering Design,* Vol. 1, Munich, Technische Universität München, pp. 469-472.

Bhushan, B. 1999. *Principles and Applications of Tribology.* John Wiley and Sons.

Bor, J.M. 1994a. Environmental product development becomes business. *Journal of Engineering Design.* 5 (1), pp. 55-63.

Bor, J.M. 1994b. The influence of waste strategies on product design. *Materials and Design.* 15 (4), pp. 219-224.

Boustead, I. 1999. Eco-labels and eco-indices do they make sense? In: *Proceedings of the Fourth Ryder Transpak Conference*, Brussels.

Bowden, F.P. and Tabor, D. 1950. *The Friction and Lubrication of Solids.* London, Oxford University Press.

BP 1999. *Statistical Review of World Energy.* UK, BP Amoco.

Bretz, R. 1998. SETAC LCA Workgroup: data availability and data quality. *International Journal of Life Cycle Assessment.* 3 (3), pp. 121-123.

Briscoe, B.J., Scruton, B. and Willis, F.R. 1973. The shear strength of thin lubricant film. In: *Proceedings of the Royal Society,* Vol. 333, pp. 99-114.

BS 1961. *BS 427: Part 1. Method for Vickers Hardness test.* London, British Standards Institution.

BS 1988. *BS 1134: Part 1. Assessment of surface texture. Methods and instrumentation.* London, British Standards Institution.

BS 1996. *96/122613 DC. Petroleum products and lubricants. Determination of extreme pressure properties of lubricating greases. Four-ball method (ISO/CD 11008), draft copy*. London, British Standards Institution.

BS 1997. *BS EN ISO 14040. Environmental management: Life cycle assessment - principles and framework*. London, British Standards Institution.

BS 1998. BS EN ISO 14041. Environmental management: Life cycle assessment - goal and scope definition and inventory analysis. London, British Standards Institution.

Calm, J.A. and Didion, D.A. 1997. Trade-offs in refrigerant selections: Past, Present and Future. In: *Proceedings of the ASHRAE/NIST Refrigerants Conference on Refrigerants for the 21st Century*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, pp. 6-19.

Calm, J.M. 1993. Global warming impacts of chillers. *Heating, Piping and AirConditioning Engineering* (February).

Calm, J.M. 1999. Emissions and environmental impacts from air-conditioning and refrigeration systems. In: *Proceedings of the Joint IPCC/TEAP Expert Meeting*, Petten.

Calm, J.M., Wuebbles, D.J. and Jain, A.K. 1999. Impacts on global ozone and climate from use and emission of 2,2-Dichloro-1,1,1-Trifluoroethane (HCFC-123). *Journal of Climatic Change*. 42, pp. 439-474.

Campbell, N.J. and McCulloch, A. 1998. The climate change implications of manufacturing refrigerants. A calculation of 'production' energy contents of some common refrigerants. *Transactions of the IChemE*. 76 (B), pp. 239-244.

Caspersen, N. 1998. LCA used in design of electric motors - influence of allocation procedure. In: *Proceedings of the Fifth International Seminar on Life Cycle Engineering*, Stockholm, Royal Institute of Technology, KTH, pp. 171-180.

Clayton, J.W., Jr. 1967. Fluorocarbon toxicity and biological action. *Fluorine Chemistry Reviews*. 1, pp. 197-252.

Coulon, R., Camobreco, V., Teulon, H. and Besnainou, J. 1997. Data quality and uncertainty in LCI. *International Journal of Life Cycle Assessment*. 2 (3), pp. 178-182.

Czichos, H. 1978. *Tribology - A Systems Approach to the Science and Technology of Friction, Lubrication and Wear*. Elsevier.

Dahlman, S. 1998. Sustainability from a human point of view. In: *Proceedings of the Fifth International Seminar on Life Cycle Engineering*, Stockholm, Royal Institute of Technology, KTH, pp. 1-11.

Dannheim, F., Schott, H. and Birkhofer, H. 1997. The significance of the product's usage phase for design for the environment. In: *Proceedings of the 11th International Conference on Engineering Design, ICED 97,* Vol. 2, Tampere, pp. 641-646.

Datascan 1995. *Datascan Technology Installation and User Guide.* UK, Datascan Technology.

de Geer, A.W.J., Begelinger, A. and Salomon, G. 1985. Failure mechanism in sliding lubricated contacts. In: Dowson, D., Taylor, C.M., Godet, M. and Berthe, D., (eds.) *Proceedings of the 11th Leeds-Lyon Symposium on Tribology; Mixed Lubrication and Wear*, Elsevier, pp. 105-116.

Dearnley, P.A., Gummersbach, J., Weiss, H., Ogwu, A.A. and Davies, T.J. 1999. The sliding wear resistance and frictional characteristics of surface modified aluminium alloys under extreme pressure. In: Hutchings, I., (ed.) *Proceedings of the 12 the International Conference on Wear of Materials,* Vol. 225-229, Atlanta, Elsevier, pp. 127-134.

Dekleva, T.W. 1994. Presentation 2.5 - Flammability testing: Observations related to HFC systems. In: *Proceedings of the ARI Flammability Workshop*, Arlington, VA, Air-Conditioning and Refrigeration Institute.

DeSimone, L. and Popoff, F. 1997. Eco-efficiency: the business link to sustainable development. *MIT Press.*

DETR 1998. *Sustainable development: Opportunities for change. Consultation paper on a revised UK strategy.* UK, Department of the Environment, Transport and the Regions.

DETR 1999. *UK emissions of HFCs, PFCs and SF_6 and potential emission reduction options.* UK, Department of the Environment, Transport and the Regions.

DETR 2000. *Climate change draft UK programme.* London, Department of the Environment, Transport and the Regions.

Dietrich, K.W. and McCullough, D.W. 1996. Method for making insulating materials from recycled rigid polyurethane foam. *Utech'96*, pp. 64.1-64.10.

DIN 1973. *DIN 8978: Wear test for refrigerant compressors - translation.* Berlin, Deutsches Institut fur Normung, pp. 1-8.

Dizdar, S. 1999. *Formation and failure of chemireacted boundary layers in lubricated steel contacts.* Sweden, Ph.D. dissertation, Royal Institute of Technology.

Dizdar, S. and Andersson, S. 1997. Influence of pre-formed boundary layers on wear transition in sliding lubricated contacts. *Wear.* 213, pp. 117-122.

DOE 1993. *Good Practice Guide 59; Energy efficient design and operation of refrigeration compressors*. UK, Department of the Environment.

DOE 1996. *UK use and emissions of selected halocarbons*. UK, Department of the Environment.

Doka, G. 1994. *Environmental Life-Cycle Inventories of Energy Systems*. Switzerland, Swiss Federal Energy Office.

Dowson, D. and Higginson, G.R. 1977. *Elasto-hydrodynamic Lubrication. SI Edition*. Pergamon Press.

DTI 1999. *Life cycle assessment and life cycle financial analysis of the proposal for a directive on waste from electrical and electronic equipment*. London, Department of Trade and Industry.

DTI 2000. *Foresight: Industrial minerals - A life cycle approach*. London, Department of Trade and Industry.

Duffy, A.H.B. and O'Donnell, F.J. 1998. A design research approach. In: *Workshop on Research Methods in AI in Design,* Lisbon.

Eekels, J. 1994. The engineer as designer and as a morally responsible individual. *Journal of Engineering Design.* 5 (1), pp. 7-23.

Engel, L. and Klingele, H. 1981. *An Atlas of Metal Damage*. Munich, Wolfe Publishing Ltd.

EPA 1995. *Summary of the report of the refrigeration, air conditioning and heat pumps technical options committee*. USA, Environmental Protection Agency, pp. 95-110.

EPSRC 2000. *Report of a sustainable development community meeting*. UK, Engineering and Physical Science Research Council.

Eubanks, C.F. and Ishii, K. 1993. AI methods for life-cycle serviceability design of mechanical systems. *Artificial Intelligence in Engineering.* 8, pp. 127-140.

FF 2000. *The Engineer of the 21st Century Inquiry*. UK, Forum for the Future.

Frank, D. 1999. The importance of knowledge management for BMW. In: Lindenmann, U., Birkhofer, H., Meerkamm, H. and Vajna, S., (eds.) *Proceedings of the 12th International Conference on Engineering Design,* Vol. 1, Munich, Technische Universität München, pp. 33-40.

Glaeser, W.A. 1999. Failure mechanisms of reed valves in refrigeration compressors. In: Hutchings, I., (ed.) *Proceedings of the 12 the International Conference on Wear of Materials,* Vol. 225-229, Atlanta, Elsevier, pp. 918-924.

Gu, P., Hashemian, M. and Sosale, S. 1997. An integrated modular design methodology for life-cycle engineering. *Annals of the CIRP*. 46 (1), pp. 71-74.

Guldbrandsen, T., Heebøll, J., Mehlsen, K. and Nørgård, J. 1986. *Development of energy efficient electrical household appliances. Part One: Refrigerators. Report EUR 10449 EN*. Brussels, Commission of the European Communities.

Hansen, P.E. and Gustafsson, V. 1994. Total environmental impact of a small hermetic compressor. In: *Proceedings of the 1994 International Compressor Engineering Conference*, West Lafayette, Purdue University.

Hanssen, O.J. 1995. Preventive environmental strategies for product systems. *Journal of Cleaner Production*. 3 (4), pp. 181-187.

Hawken, P., Lovins, A.B. and Lovins, L.H. 1999. *Natural Capitalism. The Next Industrial Revolution*. Earthscan Publications.

Hawkins, D.J. 1998. Critical review of recent developments in domestic refrigeration. *International Appliance Manufacturing 1998* (2), pp. 24-29.

Heijungs, R. 1996. Identification of key issues for further investigation in improving the reliability of life-cycle assessments. *Journal of Cleaner Production*. 4 (3-4), pp. 159-166.

Hess, D.P. and Soom, A. 1990. Friction at a lubricated line contact operating at oscillating sliding velocities. *Transactions of ASME, Journal of Tribology*. 112, pp. 147-152.

Hewitt, N.J., McMullan, J.T. and Mongey, B. 1994. The replacement of HCFC 22 in refrigeration systems. In: Editoriali, SG, (ed.) *CFCs, The Day After*, Padova, International Institute of Refrigeration, pp. 231-237.

Higgins, R.A. 1993. *Engineering Metallurgy - Part 1*. London, Edward Arnold.

Hotpoint 1997. *Service Information Issue 3; Fridge Freezer Combination*. UK, Hotpoint Ltd.

Hubka, V. and Eder, W.E. 1988. *Theory of Technical Systems*. Springer-Verlag.

Hunt, R.G., Sellers, J.D. and Franklin, W.E. 1992. Resource and environmental profile analysis: a life cycle environmental assessment for products and procedures. *Environmental Impact Assessment Review*. 12, pp. 245-269.

Hwang, D.H., Kim, D.E. and Lee, S.J. 1999. Influence of wear particle interaction in the sliding interface on friction of metals. In: Hutchings, I., (ed.) *Proceedings of the 12 the International Conference on Wear of Materials*, Vol. 225-229, Atlanta, Elsevier, pp. 427-439.

IP 1997a. *IP 71 Section 1: Kinematic viscosity and calculation of dynamic viscosity*. London, Institute of Petroleum.

IP 1997b. *IP 239: Determination of extreme pressure and antiwear properties of lubricants - Four-ball machine method*. London, Institute of Petroleum.

IP 1997c. *IP 365: Density - Oscillating U-tube method*. London. Institute of Petroleum.

IPCC 1996. *Climate Change 1995 - Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. UK, Cambridge University Press.

Isaksson, O. and Åström, H. 1993. Pressure-viscosity coefficient of a refrigerant-oil mixture. *International Journal of Refrigeration*. 16 (2), pp. 139-142.

Ishii, K. 1995. Life-cycle engineering design. *Transactions of the ASME*. 117 (June), pp. 42-47.

Ishii, K. 1998. Design for environment and recycling: overview of research in the United States. In: *Proceedings of the Fifth International Seminar on Life Cycle Engineering*, Stockholm, Royal Institute of Technology, KTH, pp. 191-200.

Ishii, K., Eubanks, C.F. and Di Marco, P. 1994. Design for product retirement and material life-cycle. *Materials and Design*. 15 (4), pp. 225-233.

ISO 1997. *ISO/CD 14043: Environmental management: Life cycle assessment - life cycle interpretation*. International Organisation of Standardisation.

ISO 1999. *ISO/DIS 14042: Environmental management: Life cycle assessment - life cycle impact assessment*. International Organisation for Standardisation.

Jackson, A.R.W. and Jackson, J.M. 1996. *Environmental Science*. Singapore, Longman.

Jacobson, B. 1996. Ball bearing lubrication in refrigeration compressors. In: *Proceedings of the 1996 International Compressor Engineering Conference*, West Lafayette, Purdue University, pp. 103-108.

Jakobsen, M.M. and Støren, S. 1999. Improving the eco-efficiency of product systems. In: Lindenmann, U., Birkhofer, H., Meerkamm, H. and Vajna, S., (eds.) *Proceedings of the 12th International Conference on Engineering Design*, Vol. 3, Munich, Technische Universität München, pp. 1477-1482.

Janssen, M.J., de Wit, J.A. and Kuijpers, L.J.M. 1992. Cycling losses in domestic appliances: an experimental and theoretical analysis. *International Journal of Refrigeration*. 15 (3), pp. 152-158.

Jensen, A.A., Elkington, J., Christiansen, K., Hoffmann, L., Møller, B.T., Schmidt, A. and van Dajk, F. 1997. *Life Cycle Assessment (LCA). A guide to approaches, experiences and information sources - final report.* Denmark. dk-TEKNIK.

Johansen, M., Umeda, Y. and Tomiyama, T. 1997. Life cycle simulation for verifying sustainable model of products. In: Camarinha-Matos, L.M., (ed.) *Re-Engineering for Sustainable Industrial Production*, London. Chapman and Hall, pp. 247-258.

Johnson, K.L. 1996. *Contact Mechanics.* UK, Cambridge University Press.

Johnston, G.J., Wayte, R. and Spikes, H.A. 1991. The measurement and study of very thin lubricant films in concentrated contacts. *Tribology Transactions.* 34 (2), pp. 187-194.

Jonsson, U. and Höglund, E. 1992. The influence of refrigerants on the high pressure properties of lubricating oil. In: *Proceedings Nordtrib,* Vol. 3, pp. 89-96.

Jonsson, U. and Höglund, E. 1993. Determination of viscosities of oil-refrigerant mixtures at equilibrium by means of film thickness measurements. *ASHRAE Transactions.* 99 (2), pp. 1129-1136.

Jost, H.P. 1966. *Lubrication (Tribology).* London, Department of Education and Science.

Jost, H.P. 1981. Tribology's big bonus. *Industrial Lubrication and Tribology.* 33 (6), pp. 216-226.

Jung, D.S. and Radermacher, R. 1990. Performance evaluation of pure and mixed refrigerants in domestic refrigerators: Drop-in replacement of R12. In: *Proceedings of the 1990 USNC/IIR-Purdue Refrigeration Conference and the ASHRAE-Purdue CFC Conference*, West Lafayette, Purdue University, pp. 177-189.

Keoleian, G.A. 1993. The application of life cycle assessment to design. *Journal of Cleaner Production.* 1 (3-4), pp. 143-149.

Keoleian, G.A. and Menerey, D. 1994. Sustainable development by design: review of life cycle design and related approaches. *Air & Waste.* 44, pp. 645-668.

Khan, S.H. and Zubair, S.M. 1993. Thermodynamic analyses of the CFC-12 and HFC-134a refrigeration cycles. *Energy.* 18 (7), pp. 717-726.

Klöcker, S. and Müller, D.H. 1999. Ecological classification and risk analysis to evaluate environmental impact of new products. In: Lindenmann, U., Birkhofer, H., Meerkamm, H. and Vajna, S., (eds.) *Proceedings of the 12th International Conference on Engineering Design,* Vol. 3, Munich, Technische Universität München, pp. 1483-1488.

Komatsuzaki, S., Tomobe, T. and Hon-ma, Y. 1987. Additive effects on lubricity and thermal stability of refrigerator oils. *Lubrication Engineering.* 43 (1), pp. 31-36.

Komatuszaki, S. and Homma, Y. 1991. Antiseizure and antiwear properties of lubricating oils under refrigerant gas environments. *Journal of STLE.* 47 (3), pp. 193-198.

Kramer, D.E. 1999. Why not mineral oil? In: *ASHRAE Practical Guide,* Vol. 41, ASHRAE, pp. 55-61.

Kruse, H.H. and Schroeder, M. 1985. Fundamentals of lubrication in refrigerating systems and heat pumps. *International Journal of Refrigeration.* 8, pp. 347-355.

Kryssanov, V.V., Tamaki, H. and Ueda, K. 1999. Agents for assessing requirements in dynamic environments to support evolutionary design. In: Jeswiet, J., Moore, T.N. and Oosthuizen, P.H., (eds.) *Proceedings of the 6th International Seminar on Life Cycle Engineering*, Ontario, Queen's University, pp. 151-160.

Kurakawa, K. and Kiriyama, T. 1999. Life cycle design support based on environmental information sharing. In: Yoshikawa, H., Yamamoto, R., Kimura, F., Suga, T. and Umeda, Y., (eds.) *Proceedings of the First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, Tokyo, pp. 138-142.

Kurakawa, K., Kiriyama, T. and Baba, Y. 1997. The Green Browser: an internet-based information sharing tool for product life cycle design. In: Krause, F.-L. and Seliger, G., (eds.) *Annals of the CIRP*, Chapman and Hall, pp. 454-466.

Kusik, C.L., Dieckmann, J.T., McMahon, E.M., Hobday, N., Fischer, S.K., Hughes, P.J. and Fairchild, P.D. 1991. *Energy and global warming impact of CFC alternative technologies.* U.S. Department of Energy, (AFEAS) Alternative Fluorocarbons Environmental Acceptability Study.

Labtech 1994. *Labtech.* USA, Laboratory Technologies Corporation.

Legarth, J.B., Åkesson, S., Ashkin, A. and Imrell, A.-M. 2000. A screening level life cycle assessment of the ABB EU 2000 air handling unit. *International Journal of Life Cycle Assessment.* 5 (1), pp. 47-58.

Legarth, J.B. and Alting, L. 1995. Demands on industry in sustainable use of metal resources. *Manufacturing Science and Engineering.* MED-Vol.2.2/MH-Vol.3.2, pp. 883-894.

Legarth, J.B. and Nilsson, J. 1997. Re-design of electromechanical products for re-use and recycling - a European initiative. In: *Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment*, San Francisco, pp. 1-6.

Lindeijer, E. 1996. Part VI: normalisation and valuation. In: de Haes, U., (ed.) *Towards a methodology for life cycle impact assessment.* Brussels, Society of Environmental Toxicology and Chemistry (SETAC).

Lindfors, L.-G., Christiansen, K., Hoffmann, L., Virtanen, Y., Hanssen, O.J., Ronning, A., Ekvall, T. and Finnveden, G. 1995. *Nordic Guidelines on Life Cycle Assessment. Nord 1995:20.* Copenhagen, Nordic Council of Ministers.

Ludema, K.C. 1995. Lubricated sliding - a review of chemical and physical effects. In: Dowson, D., (ed.) *Lubricants and Lubrication, Proceedings of the 21st Leeds-Lyon Symposium on Tribology,* Elsevier, pp. 383-398.

March 2000. *Refrigeration and global warming. An independent review of the role of hydrofluorocarbon (HFC) refrigerants.* UK, March Consulting Group.

Marks, M., Eubanks, C. and Ishii, K. 1993. Life-cycle clumping of product designs for ownership and retirement. In: *Proceedings of the ASME Design Theory and Methodology Conference,* Vol. 53, Albuquerque.

McLinden, M.O. and Didion, D.A. 1987. Quest for alternatives. *ASHRAE Journal.* 29 (12), pp. 32-36, 38, 40 and 42.

Menke, D.M., Davis, G.A. and Vignon, W. 1996. *Evaluation of life cycle assessment tools,* Hazardous Waste Branch Environment Canada.

Mizuhara, K. 1994. The friction and wear behaviour in controlled alternative refrigerant atmosphere. *Tribology Transactions.* 37, pp. 120-128.

Mizuhara, K. and Tomimoto, M. 1997. The effect of refrigerants in the mixed lubrication regime. In: Totten, G.E., Kling, G.H. and Smolenski, D.J., (eds.) *Proceedings of the 1995 Symposium in Tribology of Hydraulic Pump Testing. ASTM STP 1310,* American Society for Testing and Materials, pp. 38-48.

Mueller, K.G., Court, A.W. and Besant, C.B. 1998. A strategy for energy life cycle design. In: Sivaloganathan, S. and Shahin, T.M.M., (eds.) *Proceedings of the Engineering Design Conference'98 on Design Reuse,* London, Professional Engineering, pp. 321-328.

Muraki, M. 1994. Refrigeration lubricants based on polyolester for alternative refrigerants. In: *Proceedings of the International Symposium R22 and R502 Alternative Refrigerants,* Japan, pp. 101-106.

Muraki, M. and Sano, T. 2000. Determination of film thickness and traction of polyol ester under an EHD contact in some refrigerant environments. *Tribology Transaction.* 43 (1), pp. 15-20.

Muys, B., Wouters, G. and Spirinckx, C. 1997. *Cleaner Production: a guide to information sources.* European Environment Agency.

Na, B.C., Chun, K.J. and Han, D.-C. 1998. A tribological study of refrigeration oils under HFC-134a environment. *Tribology International.* 30 (9), pp. 707-716.

Nautiyal, P.C. and Schey, J.A. 1990. Transfer of aluminium to steel in sliding contact: Effects of lubricant. *ASME Journal of Tribology.* 112 (April), pp. 282-287.

Navinchandra, D. 1994. The recovery problem in product design. *Journal of Engineering Design.* 5 (1), pp. 65-86.

Newcomb, P.J., Bras, B. and Rosen, D.W. 1998. Implications of modularity on product design for the life cycle. *Journal of Mechanical Design.* 120 (3), pp. 483-490.

Nonomura, A., Tomiyama, T. and Umeda, Y. 1999. Life cycle simulation for inverse manufacturing. In: Jeswiet, J., Moore, T.N. and Oosthuizen, P.H., (eds.) *Proceedings of the 6th International Seminar on Life Cycle Engineering*, Ontario, Queen's University, pp. 304-313.

OECD 1982. *Product durability and life extension: their contribution to solid waste management.* Paris, Organisation for Economic Co-operation and Development.

Oku, A., Kimura, K. and Sato, M. 1989. Complete destruction of chlorofluorocarbons by reductive dehalogenation using sodium naphthalenide. *Industrial Engineering Chemical Research.* 28 (7), pp. 1055-1059.

Olesen, J. and Keldmann, T. 1994. Design for the environment - a framework. *Journal of Engineering Design.* 5 (1), pp. 45-54.

Padhy, S.K. and Scheldorf, G.O. 1994. Wear and tribodynamics of a rolling piston rotary compressor. In: *Proceedings of the 1994 International Compressor Engineering Conference*, West Lafayette, Purdue University, pp. 79-84.

Pahl, G. and Beitz, W. 1995. *Engineering Design. A Systematic Approach.* London, Springer.

Papasavva, S. 1997. *Reducing the risk of global warming from CFC alternatives: a scientific basis for policy options.* USA, Ph.D. dissertation, Tufts University.

Papasavva, S. and Moomaw, W.R. 1997. Adverse implications of the Montreal Protocol Grace Period for developing countries. *International Environmental Affairs.* 9 (3), pp. 219-231.

Papasavva, S. and Moomaw, W.R. 1998. Life-cycle global warming impact of CFCs and CFC-substitutes for refrigeration. *Journal of Industrial Ecology.* 1 (4), pp. 71-91.

Perkin-Elmer 1979. *Handbook of X-Ray Photoelectrons Spectroscopy.* Perkin-Elmer Corporation. Physical Electronics Division.

Perez, J.M. 1996. A review of four-ball methods for the evaluation of lubricants. In: Totten, G.E., Kling, G.H. and Smolenski, D.J., (eds.) *Tribology of Hydraulic Pump Testing, ASTM STP 1310,* American Society for Testing and Materials.

Pine II, B.J., Victor, B. and Boynton, A.C. 1993. Making mass customisation work. *Harvard Business Review* (Sept/Oct), pp. 108-119.

Pira 1998. *PEMS Version 4 - user manual.* UK, Pira International.

Plint, M.A. and Alliston-Greiner, A.F. Extreme pressure and anti-wear properties of lubricants: a critical study of current test methods and suggestions for the future. In: *Technical Publications by Users of Plint Tribology Products,* Paper 32, UK, Plint and Partners.

Plint 1998. *TE92/HS Microprocessor Controlled Rotary Tribometer.* UK, Plint and Partners Ltd.

Pramila Bai, B.N., Biswas, S.K. and Kumtekar, N.N. 1983. Scanning electron microscopy study of worn Al-Si alloy surfaces. *Wear.* 87, pp. 237-249.

Rabinowicz, E. 1965. *Friction and Wear of Materials.* New York, John Wiley and Sons.

Rakic, R. 1999. The influence of tribological properties of lubricating oils on the reliability of gears. *Industrial Lubrication and Tribology.* 51 (4), pp. 170-178.

Remich Jr., N.C. 1992. 'Green Frost': a recyclable refrigerator. *Appliance Manufacturer,* p. 69.

Remigy, J.-C., Nakache, E. and Brechot, P.D. 1997. Structure effect of refrigeration polyolester oils for use in HFC-134a compressors. *Journal of Synthetic Lubrication.* 14 (3), pp. 237-247.

Reyes-Gavilán, J., Eckard, A., Flak, T. and Tritcak, T. 1996a. A review of lubrication and performance issues in refrigeration systems using an HFC (R-134a) refrigerant. *Lubrication Engineering.* 52 (4), pp. 317-322.

Reyes-Gavilán, J.L., Flak, G.T. and Tritcak, T.R. 1996b. Lubricant return comparisons of naphthenic and polyol ester oils in R-134a household refrigerator applications. *ASHRAE Transactions.* 102 (2), pp. 180-185.

Reyes-Gavilán, J.L., Flak, G.T., Tritcak, T.R. and Barbour, C.B. 1997. Enhanced naphthenic refrigeration oils for household refrigerator systems. *ASHRAE Transactions.* 103 (1), pp. 95-106.

Riahi, A.R. and Alpas, A.T. 2000. Wear mechanisms in a graphitic metal matrix composite A356 Al-10%SiC-4%Gr. In: Hadfield, M. and Ciantar, C., (eds.) *Proceedings of the First International Conference on Tribology in Environmental Design*, UK, Professional Engineering Publishing, pp. 317-327.

Rio Garcia, P. and Hadfield, M. 2000. *Lubricant characterisation using extreme pressure experiments*. UK, Bachelor's dissertation, Bournemouth University.

Rosemann, B., Schaufler, C. and Meerkamm, H. 2000. Design for tribology and design for the environment - two goals, one way. In: Hadfield, M. and Ciantar, C., (eds.) *Proceedings of the First International Conference on Tribology in Environmental Design*, Bournemouth, Professional Engineering Publishing.

Rowledge, L.R., Barton, R.S. and Brady, K.S. 1999. *Mapping the Journey. Case Studies in Strategy and Action Towards Sustainable Development*. Greenleaf Publishing.

Safari, S. and Hadfield, M. 1998. Wear behaviour of the piston/gudgeon pin in a hermetic compressor with replacement CFC refrigerants. *Wear*. 219 (1), pp. 8-15.

Sakurai, T. and Sato, K. 1966. Study of corrosivity and correlation between chemical reactivity and load-carrying capacity of oil containing extreme pressure agents. *ASLE Transactions*. 9, pp. 77-87.

Sand, J.R., Fischer, S.K. and Baxter, V.D. 1997. Energy and global warming impacts of HFC refrigerants and emerging technologies. In: *Proceedings of the International Conference on Climate Change*, Baltimore, Oak Ridge National Laboratory.

Sanvordenker, K.S. 1991. Durability of HFC-134a compressors - The role of the lubricant. In: *International Appliance Technical Conference*, Madison, pp. 37-50.

Sargent, L.B., Jr., Milz, W.C. and Atkinson, R.E. 1982. The effect of aluminium transfer upon friction between aluminium alloys and steel. *Lubrication Engineering*. 39 (11), pp. 706-711.

Short, G.D. 1990. Synthetic lubricants and their refrigeration applications. *Lubrication Engineering*. 46 (4), pp. 239-247.

Short, G.D. and Cavestri, R.C. 1992. High-viscosity ester lubricants for alternative refrigerants. *ASHRAE Transactions*. 5 (2), pp. 789-795.

Short, G.D. and Rajewski, T.E. 1996. Lubricants for use with HFC based refrigerants the current state of the art. In: *Proceedings of the International Conference on Energy and the Environment*, Shanghai, pp. 321-330.

Smith, N.D. and Tufts, M.W. 1994. Presentation 2.2 - Flammable properties of HFC refrigerants - some fundamental considerations. In: *Proceedings of the ARI Flammability Workshop*, Arlington, VA, Air-Conditioning and Refrigeration Institute.

Solem, K.E. and Brattebo, H. 1999. Industrial Ecology and Design for the Environment. In: Yoshikawa, H., Yamamoto, R., Kimura, F., Suga, T. and Umeda, Y., (eds.) *Proceedings of the First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, Tokyo, pp. 178-183.

Somi Reddy, A., Murthy, K.S.S. and Biswas, S.K. 1995. Wear and seizure of aluminium silicon piston alloys in reciprocating motion against steel. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology.* 209 (4), pp. 287-296.

Somi Reddy, A., Pramila Bai, B.N., Murthy, K.S.S. and Biswas, S.K. 1994. Wear and seizure of binary Al-Si alloys. *Wear.* 171, pp. 115-127.

Spauschus, H.O. and Hendersen, D.R. 1990. New methods of determining viscosity and pressure of refrigerant/lubricant mixtures. In: *Proceedings of the 1990 USNC/IIR-Purdue Refrigeration Conference and the ASHRAE-Purdue CFC Conference*, West Lafayette, Purdue University, pp. 173-176.

SPOLD 1993. *The LCA Sourcebook.* London, SustainAbility, Society for the Promotion of LCA Development and Business in the Environment.

SPOLD 1995. *Directory of Life Cycle Inventory Data Sources*, Brussels, Society for the Promotion of LCA Development.

Stake, R.B. 1999. A hierarchical classification of the reasons for modularity. In: Lindenmann, U., Birkhofer, H., Meerkamm, H. and Vajna, S., (eds.) *Proceedings of the 12th International Conference on Engineering Design,* Vol. 2, Munich, Technische Universität München, pp. 1135-1138.

Stevels, A., Brezet, H. and Rombouts, J. 1999. Application of LCA in eco-design: a critical review. *The Journal of Sustainable Product Design*, pp. 20-26.

Sundaresan, S.G. and Finkenstadt, W.R. 1992. Polyalkalylene glycol and polyolester lubricant candidates for use with HFC-134a in refrigeration compressors. *ASHRAE Transactions.* 5 (3), pp. 796-803.

Takesue, M. and Tominaga, S. 1998. Wear and scuffing characteristics of polyvinylether in an HFC atmosphere. In: *Proceedings of the 1998 International Compressor Engineering Conference*, West Lafayette, Purdue University, pp. 379-384.

Tazaki, T., Konishi, T. and Nagamatsu, N. 1998. Development of polyvinylether refrigeration oil for hydrofluorocarbon air-conditioning systems. *ASHRAE Transactions*. 104 (1B), pp. 1341-1346.

Teulon, H.P. 1997. Life cycle assessment: a tool for design for the environment. *Society of Automotive Engineers Special Publications*. 126, pp. 145-151.

Thurston, D.L. 1994. Environmental design trade-offs. *Journal of Engineering Design*. 5 (1), pp. 25-36.

Tillman, A.-M. 2000. Significance of decision-making for LCA methodology. *Environmental Impact Assessment Review*. 20 (1), pp. 113-123.

Tipnis, V.A. 1993. Evolving issues in product life cycle design. *Annals of the CIRP*. 42 (1), pp. 169-173.

Tipnis, V.A. 1995. Towards a comprehensive life cycle modelling for innovative strategy, systems, processes and product/services. In: Jansen, H. and Krause, F.-L., (eds.) *Proceedings of the IFIP WG5.3 International Conference on Life Cycle Modeling for Innovative Products and Processes*, Berlin, Chapman & Hall, pp. 43-55.

Tomiyama, T. 1997. A manufacturing paradigm toward the 21st Century. *Integrated Computer Aided Engineering*. 4, pp. 159-178.

Tomiyama, T. 1999. The post mass production paradigm. In: Yoshikawa, H., Yamamoto, R., Kimura, F., Suga, T. and Umeda, Y., (eds.) *Proceedings of the First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, Tokyo, pp. 162-167.

Tomiyama, T. and Umeda, Y. 1997. Life cycle design for the post mass production paradigm. In: Jin, Y. and Lu, S., (eds.) *Proceedings of the CIRP 1997 International Design Seminar on Multimedia Technologies for Collaborative Design and Manufacturing*, Los Angeles, University of Southern California, pp. 117-125.

Tomiyama, T., Umeda, Y., Ishii, M., Yoshioka, M. and Kiriyama, T. 1995. Knowledge systemization for a knowledge intensive engineering framework. In: Tomiyama, T., Mäntylä, M. and Finger, S., (eds.) *Proceedings of the First IFIP WG 5.2 Workshop on Knowledge Intensive CAD*, Finland, Chapman and Hall.

Tomiyama, T., Umeda, Y. and Wallace, D.R. 1997. A holistic approach to life cycle design. In: Krause, F.-L. and Seliger, G., (eds.) *Life Cycle Networks*, London, Chapman and Hall, pp. 92-103.

Tseregounis, S.I. 1996. Wear and galling of 356-T6 aluminium-on-steel in low amplitude reciprocating sliding in the presence of synthetic lubricants in HFC-134a atmosphere. *Tribology Transactions*. 39 (1), pp. 1-12.

Turner, E. and Little, A. 1999. Measuring corporate progress towards sustainability. *ENDS Report 296.* 78, pp. 21-24.

UN 1997. *Kyoto Protocol to the United Nations Framework Convention of Climate Change.* New York, United Nations.

Våg, C., Marby, A., Kopp, M., Furberg, L. and Norrby, T. 2000. A comparative life cycle assessment (LCA) of the manufacturing of base fluids for lubricants. In: *Proceedings of the 12th International Colloquium Tribology 2000-Plus.*

van der Horst, T.J.J. and Zweers, A. 1994. Environmentally oriented product development - various approaches to success. *Journal of Engineering Design.* 5 (1), pp. 37-44.

Veefkind, M. 1999. Assessment of business effectiveness of green design options. In: Lindenmann, U., Birkhofer, H., Meerkamm, H. and Vajna, S., (eds.) *Proceedings of the 12th International Conference on Engineering Design,* Vol. 2, Munich, Technische Universität München, pp. 1077-1080.

Vesilind, P.A., Pierce, J.J. and Weiner, R.F. 1990. *Environmental Pollution and Control,* Butterworth-Heinemann.

Vigon, B.W., Tolle, D.A., Cornaby, B.W., Latham, H.C., Harrison, C.L., Boguski, T.L., Hunt, R.G. and Sellers, J.D. 1994. *Life-Cycle Assessment. Inventory guidelines and principles.* Boca Raton, Lewis Publishers.

Vineyard, E.A., Sand, J.R. and Bohman, R.H. 1995. Evaluation of design options for improving the energy efficiency of an environmentally safe domestic refrigerator-freezer. *ASHRAE Transactions.* 24 (2), pp. 1422-1430.

Wade, S., Hossell, J., Hough, M. and Fenn, C. 1999. The impacts of climate change in the south east. WS Atkins, Epsom.

WCED 1987. *Our Common Future.* UK, World Commission on Environment and Development.

Weaver, P.M., Ashby, M.F., Burgess, S. and Shibaike, N. 1996. Selection of materials to reduce environmental impact: a case study on refrigerator insulation. *Materials & Design.* 17 (1), pp. 11-17.

Weidma, B.P. 1994. Qualitative and quantitative parameters in product impact assessment. In: de Haes, U., (ed.) *Proceedings of the LCA Symposium held at the 4th SETAC-Europe Congress. Integrating Impact Assessment into LCA,* Brussels, pp. 29-35.

Weigand, E. and Strobbe, G. 1999. Polyurethanes recycling in Europe. *Polymer Recycling.* 3 (4), pp. 311-323.

Wellburn, A. 1994. *Air Pollution and Climate Change*. Longman Scientific and Technical.

Wenzel, H., Hauschild, M. and Alting, L. 1997. *Environmental Assessment of Products*. London, Chapman & Hall.

Wigley, T.M.L. and Raper, S.C.B. 1992. Implications for climate change and sea level of revised IPCC emissions scenarios. *Nature*. 357 (6376), pp. 293-300.

Wuebbles, D.J. and Calm, J.M. 1997. An environmental rationale for retention of endangered chemicals. *Science*. 278, pp. 1090-1091.

Yamamoto, Y., Gondo, S. and Kim, J. 1998. Friction and wear performance of polyvinylether (PVE) in bound lubrication regime as a lubricant for an alternative refrigerant. In: *Proceedings of the 1998 International Compressor Engineering Conference*, West Lafayette, Purdue University, pp. 367-372.

Yamamoto, Y., Gondo, S. and Kim, J. 2000. Wear characteristics of aluminium silicon against steel in HFC-134a. *Lubrication Engineering*. 56 (3), pp. 32-39.

Yoon, H., Sheiretov, T. and Cusano, C. 1998. Tribological evaluation of some aluminium-based materials in lubricant/refrigerant mixtures. *Wear*. 218 (1), pp. 54-65.

Yoon, H., Sheiretov, T. and Cusano, C. 2000. Scuffing behaviour of 390 aluminium against steel under starved lubrication conditions. *Wear*. 237, pp. 163-175.

Yoon, H.K., Poppe, C.H. and Cusano, C. 1996. Predicting lubricant performance in refrigerant compressors: a comparison between component testing and benchtesters. *ASHRAE Transactions*. 102 (1), pp. 86-95.

Zhang, J., Yang, L., Liu, W. and Xue, Q. 1999. The effect of poly[hexanedioic acid-1,2-propylene-glycol] ester on the wear of steel. *Wear*. 232 (1), pp. 61-66.

Züst, R. and Caduff, G. 1995. Methods for continual improvement of products and processes. In: Jansen, H. and Krause, F.-L., (eds.) *Proceedings of the IFIP WG5.3 International Conference on Life Cycle Modeling for Innovative Products and Processes*, Berlin, Chapman & Hall, pp. 420-431.