Air Conditioning Faults – An Australian Analysis




Prepared for Refrigerants Australia

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All data used in this analysis was stripped of all customer, supplier and employee details without affecting the nature of the dataset or influencing or altering analytical findings. This was done to ensure client, supplier and vendor confidentiality and to not reveal building or asset locations beyond the States in which buildings reside.

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1 Executive summary

Measures to reduce greenhouse gas emissions and energy use associated with refrigeration and air conditioning (RAC) equipment have to date focused on both higher energy efficiency standards and a reduction in the environmental impact of the refrigerant. Significant improvements have been made in these areas.

Industry contends that significant improvements can be made in the performance of the installed bank of equipment by focusing on correct sizing, installation, service, and repair of equipment and that undertaking these tasks will lead to cost effective energy reductions and greenhouse gas abatement. Indeed, industry believes this may be a useful area for Government policy and programs.

Unfortunately, while intuitively true, to date there is little data to support this analysis. Two fundamental questions need to be answered to make the case.

1. Does poor sizing, installation, service and repair lead to higher energy use and emissions, and by how much?
2. How often do these faults occur?

The answer to the first question has been partially answered in the report *Leaks, maintenance and emissions: Refrigeration and air conditioning equipment*, and is the subject of further research. The second question is the focus of this study.

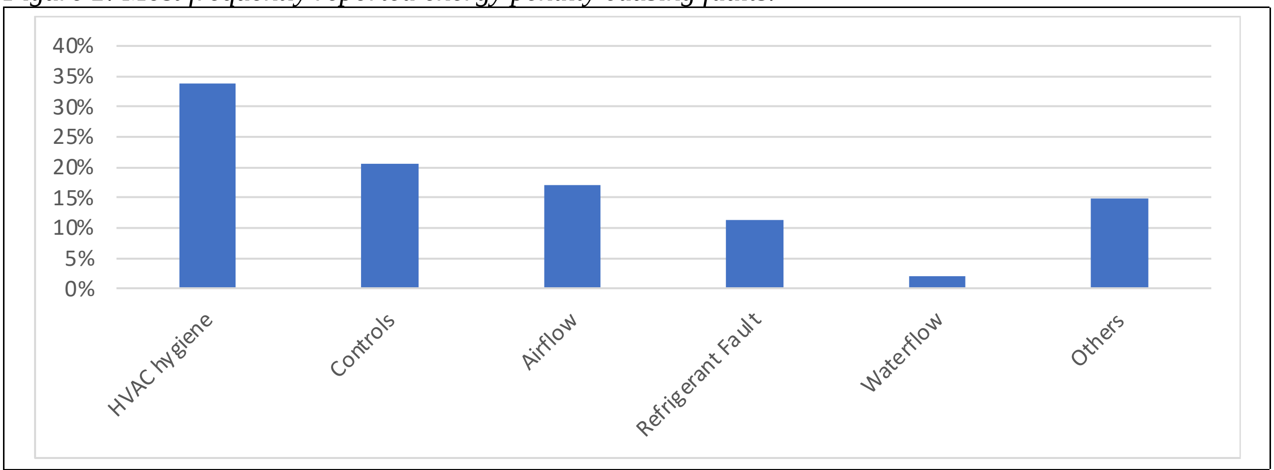
Research for this study involved interrogating one of the most substantial databases of air conditioning (AC) system maintenance and repair work orders in Australia. The data base was established and is run by Grosvenor Engineering Group (GEG) as a central part of their asset management for clients.

The 'repair' work orders underlying the GEG dataset provide a significant record of common AC faults across a large sample of the main equipment categories and strongly support the main findings of earlier analysis that there are common faults that would be expected to incur large and ongoing energy penalties, most of which could be avoided by routine maintenance.

Despite variability in the interpretation and the use of the large number of terms used to describe faults by technicians (the 'Problem Source Codes') the GEG data is a good representation of the frequency of common faults because the dataset is large and statistically relevant in terms of duration of the collection, the number of assets and the type of assets covered in the main equipment categories, and the number of work orders that are searchable in the GEG data.

The analysis reveals a short list of common faults reported across most classes of stationary AC equipment that can cause severe energy penalties for equipment owners.

Figure 1: Most frequently reported energy penalty causing faults.



The results of this analysis are not absolute, and the data is not perfect, but the results provide a good indicator of fault prevalence that result in energy loss or those that simply impose additional costs on equipment owners. The data also allows comparison of fault prevalence between equipment types i.e., the relative levels of particular types of faults across various equipment categories.

This report has three main findings:

1. It confirmed the prevalence of a number of the frequently occurring faults that result in energy penalties to equipment owners, while also providing good insight into the prevalence of faults that do not cause energy penalties but do cause costs to repair and interruptions to service.
2. It revealed the need for the development of standard terminology and application of fault trees in fault reporting.
3. It highlighted the need for more focussed investigations into particular faults and equipment types.

2 Introduction

This study was funded by Refrigerants Australia (RA). RA is the peak body representing the refrigerants industry - importers and wholesalers, as well as several organisations that look after tradespeople and technicians. It also has representation from equipment manufacturers and Refrigerant Reclaim Australia, the industry funded stewardship scheme for recovery and destruction of end-of-life refrigerants.

Refrigerants Australia has been an active participant reforms that reduced emissions of ozone depleting substances and synthetic greenhouse gases in Australia. Refrigerant Reclaim Australia and the refrigerant handling licensing program managed by the Australian Refrigerant Council are direct results of Refrigerant Australia commitment to industry development and product stewardship.

Other opportunities to drive cost effective abatement in the use of refrigerants exist, and Refrigerant Australia believes these should be pursued strongly. The HFC phasedown Australia has committed to under the Kigali Amendment to the Montreal Protocol is driving reductions in the GWP of new equipment, and it is expected this will accelerate through the decade. New equipment is often significantly more efficient than what was sold at the start of the century – using in the best instances less than half the electricity of 20th century equipment. Further improvements in the efficiency of new equipment are expected as a natural process of engineering development and design driven by both regulatory settings and competitive forces.

However, the greatest opportunity to reduce emissions exists in the short term is in existing equipment. Older equipment, some of which will have already been operating for more than a decade, typically contain refrigerant with higher global warming potential, and is innately less efficient and is likely to be regularly operating with faults which further reduce efficiency and increases the likelihood of refrigerant loss.

Faults are typically exacerbated by poor service and maintenance practices. There are a range of policy and program options available to address this issue. But as of the date of this report, there has not been the body of evidence available to demonstrate the validity of this contention.

There are two pieces of information needed:

1. An understanding of the prevalence of faults; and
2. An understanding of the consequence of faults.

The purpose of this report is to resolve the first part of the uncertainty: namely, how often do what faults occur in the installed base of equipment. The Australian Federal Government is undertaking research to determine the consequence of faults. Once we have both sets of data – expected in mid 2022 – a projection of the consequences of poor service and maintenance practices can be made, and policy options considered. This is essential for Refrigerants Australia’s commitment to reduce greenhouse gas emissions from this industry while continuing to support the efficient and cost-effective delivery of the essential services and comfort conditions that the industry provides.

3 Background

The cooling economy, broadly defined as the total of all goods and services that involve employment of vapour compression refrigeration and heat exchange systems, is a significant fraction of the Australian economy. Direct spending on hardware, consumables and energy, plus employment in the sector, is estimated at more than $44 billion, or around 2.2% of Australian gross domestic product (GDP) in 2020.[1] This is an increase of more than 6% over the previous year, a rate of growth significantly greater than general economic growth. A significant portion of the cooling economy is the stationary air conditioning segment providing comfort conditions for almost every building type imaginable, sometimes at huge scale, such as in airport terminals.

For several decades the air conditioning industry has known that a proportion of equipment owners in every sector only call service technicians when a break down occurs, and they tend to invest very little, if anything, in routine preventative maintenance.

Following various research projects into common faults reported by industry in Australia, in 2020 Expert Group were commissioned to undertake an extensive literature review of faults reported in international studies and assess the potential for improved maintenance regimes on RAC equipment, targeting common faults, to deliver meaningful reductions in electricity use, reduced refrigerant leaks and indirect emissions (‘the maintenance study’).

Expert Group was also testing the hypothesis that a relatively small number of common faults are frequently reported across large stocks of RAC equipment and that those common faults cause the great majority of energy penalties.

A wide-ranging survey of the international literature was conducted which confirmed the main findings of previous investigations in Australia about the existence of a relatively small number frequently reported common faults.

Expert Group concluded in the maintenance study that, to be able to evaluate the effect of routine equipment maintenance in the Australian context, both the prevalence and severity of these common faults had to be better understood. Further to quantify and cost the resulting energy penalties caused by common faults, real data from the field was needed.

Expert Group subsequently negotiated access to one of the largest centralised databases of AC maintenance work orders in Australia, developed and maintained by Grosvenor Engineering Group (GEG).

The extensive database, established and run by GEG since 2000, contains millions of assets across tens of thousands of buildings involving in excess of 1,300,000 work orders. The dataset used for this analysis was cleansed of all customer and employee specific information before access by the Expert Group. The dataset also removed building locations other than identifying the State in which the building is located. This ensured customer, building and employee confidentiality was protected at all times. The dataset refined from the GEG data base for the analysis captured more than 260,000 repair work orders reflecting more than a quarter of a billion dollars in repairs on more than 100 air conditioning asset types.

The data was well organised but human behaviour, judgement calls, and the variability/complexity of AC systems needed to be reconciled against the homogenous data schema relevant to this analysis. As such the data underwent a significant amount of additional tagging. This was done to reconcile the wide range of terms used in the field for individual work orders whereby a range of problem sources were recorded. This additional complementary tagging allowed these Work Orders to be categorised against a set of “problem sources” (i.e., fault code) groups pertinent to this analysis whilst enhancing the resolution of the dataset to focus on the air conditioning asset types of most relevance to the study.

After aggregating many commonly used terms into these broader ‘Fault Groups’, a degree of consistency was achieved that allowed analysis of this data and comparisons with the results of previous studies. Because

[1] 5206.0 Australian National Accounts: National Income, Expenditure and Product, Table 3. Expenditure on Gross Domestic Product (GDP), Current prices, Australian Bureau of Statistics, June 2021.

of differences in tagging schemas and some limitations of the fault reporting, analysis of the data was not able to produce a detailed insight into the *severity* of common faults. However, it does provide a screen through which to review findings of prior work into the *prevalence* of common faults in AC equipment. GEG is also currently making alterations to some of its fault analysis methodology to address these limitations for use in any future analysis that may occur.

The Fault Groups identified and frequency of occurrence in the GEG work orders for all years of the data base are set out in Table 4 (Section 4.1) and compared with the prior Expert Group common faults list. The frequency of Fault Group occurrence by the main stationary AC equipment categories is analysed for the years 2015 to 2019.

Subsequent analysis of the most common problem sources reported for particular equipment categories are reported in Section 5. This data was analysed to determine the most prevalent fault groups and the proportion of all faults that result in a system operational energy penalty.

4 The GEG Database

4.1 GEG – The Company

GEG employed more than 850 people in total in 2019 operating across multiple technical disciplines such as Air Conditioning, Fire and Life Safety Protection, Electrical, etc. GEG currently has a workforce of 364 dedicated air conditioning service technicians in the field providing routine AC maintenance and service call outs. As of 2019 Technical assets under management across all technical disciplines is in excess of 1,300,000.

For this analysis the focus was on a subset of the GEG database consisting of an air conditioning asset register totalling more than 178,000 pieces of equipment.

The dataset provided in this report had been pre-prepared by GEG to ensure no client or employee details whatsoever or building locations beyond 'state of building location' were disclosed at any stage.

Figure 2: Grosvenor Engineering Group overview.

4.1.1 GEG's data

The dataset was built on service reports that were completed by technicians during their day-to-day non-scheduled maintenance service work. The database was developed and refined for commercial purposes, not for research. GEG use the database for technical asset resource management and logistics (including work allocation and invoicing) but also for a range of other uses including:

- Providing feedback to system owners and clients regarding likely future failures and future AC replacement expenditures.
- Providing internal feedback on their own technical services for continuous improvement.
- Creating a maintenance and repair history for every asset touched by service staff.
- Benchmarking maintenance performance across the company clients and their portfolios.

The company are also expanding and refining their use of the data to:

- Create automated fault detection diagnosis and technical response systems.
- Identify knowledge and skills gaps within their own organisation to help target training investment.
- Provide life cycle information to owners on request (current state, future work, likely replacement times).
- Encourage a move to 'AC as-a-service' type agreements where suitable to meeting evolving client needs.
- Underpin investment in 'AC as-a-service' using green sustainable financial investment instruments.

Figure 3: Grosvenor have a history of valuing data.

4.1.2 Access to the Database

To access the records, GEG provided dedicated staff members to assist Expert Group researchers to gain secure remote access to their database. At all times, data identifying people, customers and building location were removed so that 3rd party confidentiality was maintained at all times. In the course of interrogating the data, GEG further assisted by developing new queries, search terms and functions, to improve EGs access to the data and the resolution provided into the stock of equipment subject to GEG maintenance.

The data base has been developed over the course of the past 20 years and covers all work generated and undertaken by the company since 01/02/2000.

The primary record of the subset of data from the database used for this analysis is a 'Work Order'.

Work orders are completed for every reactive breakdown/callout repair and for every quoted repair or 'do & charge' proactive repair made by the company whether such 'repair work' is part of a maintenance contract or some other standalone repair event where there is no scheduled maintenance for the equipment. In most contractual arrangements' automatic agreements for small repairs up to a nominal amount are in place, however for most larger repairs quotes for the work need to be raised and agreed prior to fault correction.

Work orders do not capture any quoted repairs that were not approved by the client. So, the dataset is based on repairs of faults rather than the existence of faults - faults that were reported to the client but that were not repaired are not included in the analysis. Datasets involving faults not actioned are typically reflected in unapproved Quotes. As of 2019 across the 1,300,000 technical assets in the GEG database there are in excess of 40,000 unapproved quotes awaiting approval. This alternate dataset did not form part of this analysis.

The Expert Group were able to access the database through the Work Order Analysis Dashboard.

Dashboard searches could be made by selecting:

- Asset type
- Broad geographical region
- Work order type (focussed on repair work orders tagged as ‘Breakdowns’, “Quoted’ or Do and Charge
- Problem source code
- Building type

Multiple data outputs were provided by the system that included the following:

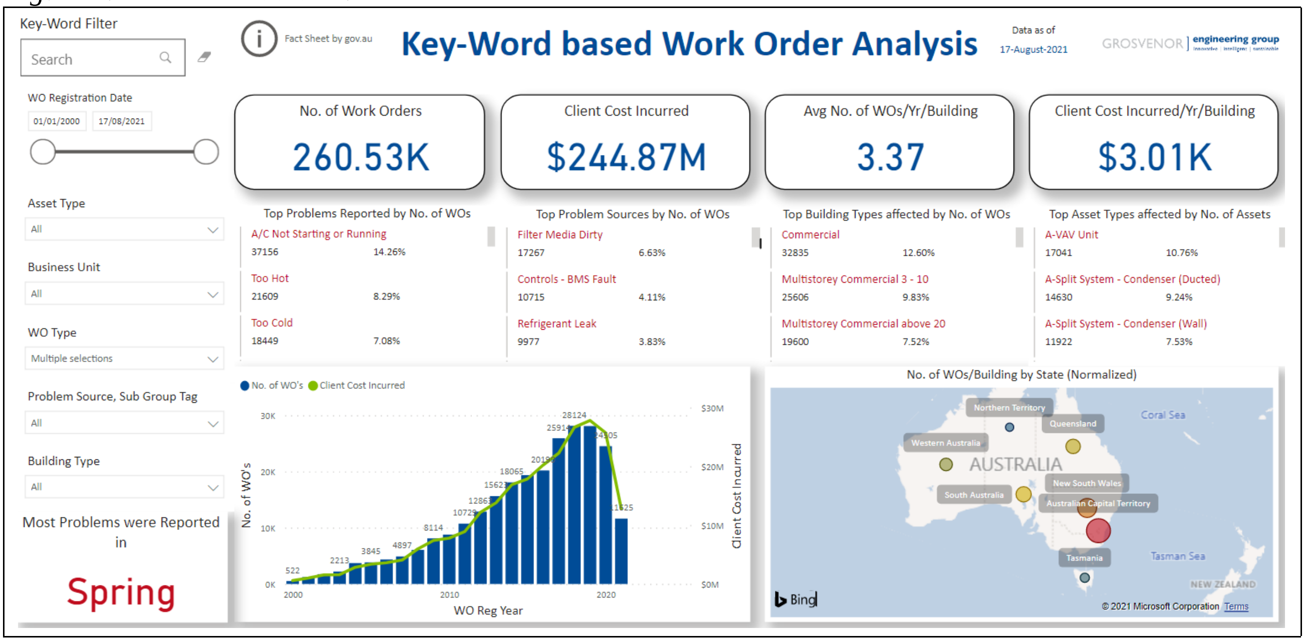
- Number of work orders (for the selected search)
- Total cost incurred in work orders selected
- Average work orders/building
- Average cost/year/building

The dashboard also provided collated lists of the following data:

- Top problems reported (by client but with customer data not disclosed)
- Top problem reported (by technician) – problem source code (but technician name not disclosed)
- Top building types affected
- Top asset types affected

The image of the Dashboard below summarises that part of the dataset from 01/01/2000 to 17/08/2021 that was the basis of this analysis. All data was customer and building agnostic to assure client, employee and supplier confidentiality at all times

Figure 4: Total GEG dataset.



The data includes AC repair services in 14,670 buildings distributed across all states and territories in Australia as set out below in Table 2, illustrating once again the size of the data base and the broad geographical distribution of the equipment underpinning the data base.

Table 1: Geographical distribution of work orders and buildings serviced.

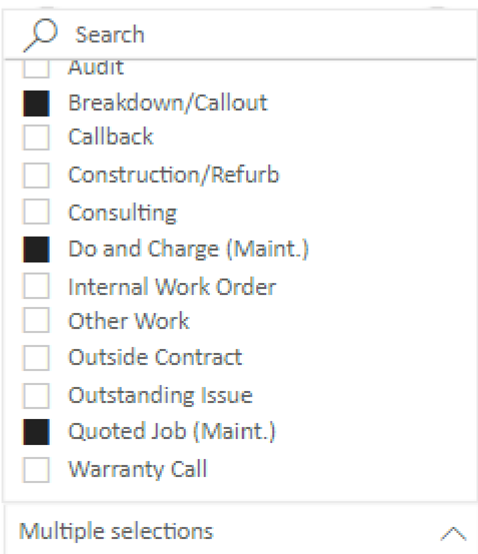
State Name	Count of Work Orders
Australian Capital Territory	8,385
New South Wales	189,568
Northern Territory	287
Queensland	25,708
South Australia	3,992
Tasmania	3,033
Victoria	30,593
Western Australia	4,491
Total	266,059

Every individual asset touched by a service technician is assigned an asset identifier.

There were 178,065 individual AC assets that were identified within the 14,670 buildings that were included in the dataset.

The work orders covered a range of services. Work orders that were associated with the following services we selected.

Figure 5: Maintenance services only.



This excluded the non-repair work including scheduled maintenance, new construction, water and energy audits, NABERS ratings and warranty repairs, all of which other than scheduled maintenance are unrelated to repairs analysed. Scheduled preventative maintenance work (some of which occurred in buildings pertaining to the repairs analysed) did not form part of this dataset given the remit of this analysis.

This reduced the dataset used in the analysis to around 260,000 work orders representing approximately $245 million in repair costs.

4.2 The 5-year dataset

The initial high-level analysis focussed on three-time spans for data analysis:

1. 01/02/2000 to 17/08/2021 – over 20 years of data – the entire dataset available.
2. 01/01/2015 to 31/12/2019 – 5 years of consistent and contemporary data.
3. 01/01/2019 to 31/12/2019 – 1 single year of data.

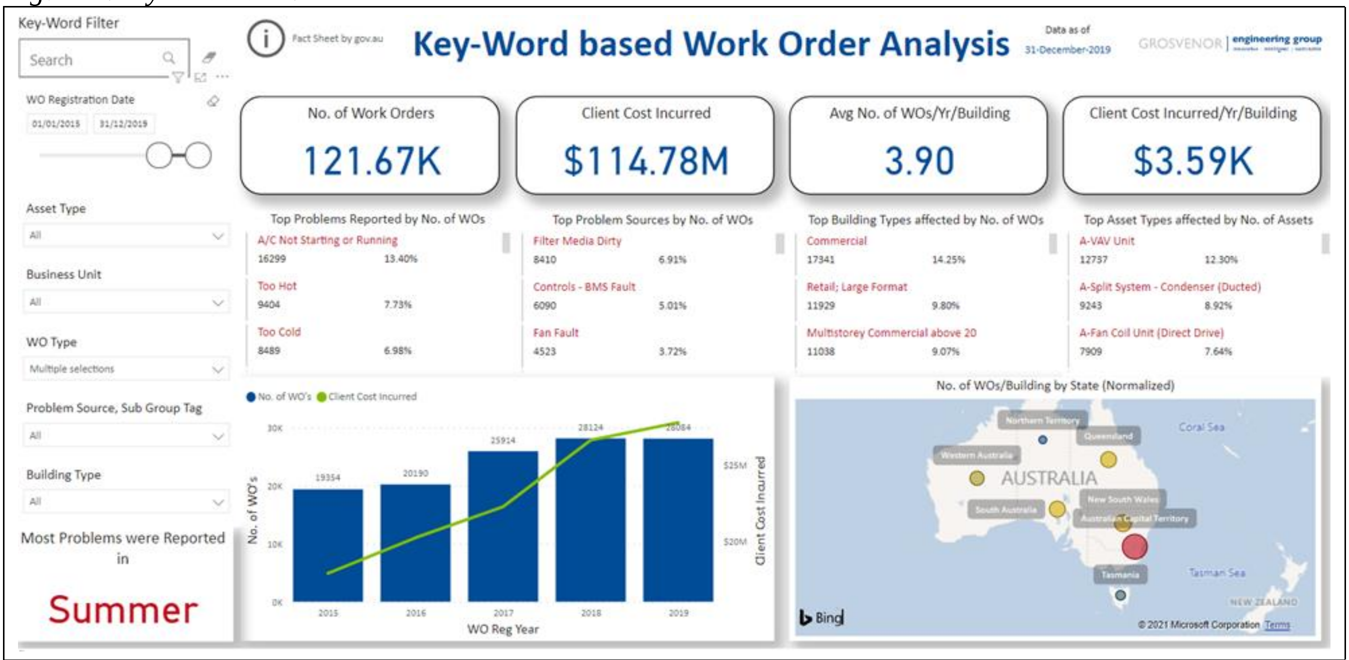
The greater number of data points have been compiled in more recent years (2015 to 2021) and comprise a more consistent collection when assessed in isolation. To avoid capturing impacts of COVID-19 related business changes, data from 2020/2021 was excluded and the five-year period of 2015-2019 was the focus of the detailed analysis of common faults in specific equipment categories.

The 5-year dataset was not only more consistent but is also more representative of contemporary equipment being serviced, skill levels and contractual arrangements in the market today.

As illustration of the dashboard for the 5-year dataset comprised 121,670 individual repairs work orders with a cost incurred of $114 Million is provided in Figure 6. A dissection of repairs work orders is as follows:

1. Breakdown/callout – 67,690 work orders Reactive Repairs: Arising from Tenant Requests.
2. Do and charge – 34,490 work orders Proactive Repairs: Arising from Technician Observations.
3. Quoted job – 19,490 work orders Proactive or Reactive Repairs.

Figure 6: 5-year dataset.



These work orders involved repairs to 103,580 individual AC assets that were identified within 9,765 buildings distributed across the country.

4.3 Data Cleansing

Several steps were undertaken to cleanse the data including removing extraneous work orders that did not relate to AC repair activities (e.g., work on fire protections systems, compliance assessment or audit work). Obvious outliers and data tails that did not fit with or contribute to the analysis were also removed. Other methods used for homogenising the data are set out below.

4.3.1 Categories of asset

There are 111 types of AC assets listed in the GEG database. The assets range from large central plant including chillers and large system components such as cooling towers, pumps and fans, to packaged air handling systems, split system air conditioners and the full range of AC systems typically found in commercial buildings.

There was good correlation between the asset descriptors and major equipment categories used in the Cold Hard Facts equipment taxonomy. The work orders for repairs of AC equipment were able to be sorted into the following 6 major equipment categories for further detailed research:

1. Chillers.
2. Single split ducted.
3. Packaged ducted systems.
4. VRV/VRF systems.
5. Close control (CRAC) systems.
6. Single split non-ducted (i.e., wall hung, cassette, console).

4.3.2 Problem Source Codes

The database was built on the input of individual service technicians across the organisation all using a series of standardised Problem Source Codes. This is a comprehensive list of 258 codes describing faults that could be encountered by a technician.

In order to be able to analyse the data Expert Group aggregated the individual Problem Source Codes into common fault groups. One hundred and fifty-nine of these problem source codes were considered to not be applicable to this analysis. They related to fire services, IT and other work order types that did not relate to the repair of AC systems. The remaining 99 problem source codes were then reviewed and aggregated into 23 common fault groups, (see Table 5).

The Problem Source Codes and the way in which they were aggregated into common fault groups is outlined in Table 5 (See Appendix A).

4.3.3 Categories of Repairs Analyzed

The analysis focussed on three work order types all relating to repairs of AC assets:

1. Breakdown/callout – a request for service due to a perceived system fault reported by a building occupant and repaired as agreed by applicable contract terms. This is considered a “reactive” repair.

2. Do and charge – carrying out minor repairs typically identified by a tradesperson whilst in a building doing other work (i.e., scheduled maintenance) to an agreed upper budget limit. This is considered a 'proactive' repair.

3. Quoted job – identification of asset problems and carrying out repairs thereof as proposed by technician. The technician typically creates a quote as a result of equipment inspections conducted during either of the two work categories above or due to observations made during scheduled maintenance inspections. Quotes nominate an agreed amount (i.e., Quoted Amount) that is then authorized by the client. Upon authorisation/approval the work is executed. This work is typically considered proactive unless it was initiated from a Breakdown/callout work order. Quoted works typically involve major repairs involving larger costs. Hence why such 'repairs' need to be quoted as customers will often seek alternative pricing from other service providers to ensure cost competitiveness for the repairs in question.

The portions of repair categories of the data analysed (i.e., 5-year period, 121,670 work orders) was as follows:

1. Breakdown/callout 56% – worth $35.20 Million in repair costs – 30.7% of total costs.
2. Do and charge 28% – worth $26.48 Million in repair costs – 23.0% of total costs.
3. Quoted job 16% – worth $53.11 Million in repair costs – 46.3% of total costs.

4.3.4 Operational fault lists

With the 2015-19 dataset relatively homogenised using the data cleansing techniques set out above, Expert Group proceeded to analyse the data to identify the most prevalent faults reported for all AC assets and for specific equipment formats.

This resulted in lists of common operational faults for all AC assets and for specific equipment formats.

These common fault lists were then analysed further to produce a list of faults for each equipment category that caused energy penalties that could be addressed by maintenance.

Top energy penalty fault lists were produced for the following equipment categories:

- Chillers, Section 6.1, Table 7.
- Single split ducted, Section 6.2, Table 8.
- Packaged ducted systems, Section 6.3, Table 9.
- VRV/VRF systems, Section 6.4, Table 10.
- Close control air conditioning systems, Section 6.5, Table 11.
- Single split non-ducted, Section 6.6, Table 12.

5 Common faults and energy penalties

5.1 The common faults

Using the entire 20-year dataset the most commonly encountered faults or fault groups were determined for all asset types. These are listed in Table 2 along with a determination of whether that fault would have an energy impact. This table covers more than 266,000 work orders received between 2000 and 2019.

Table 2: Common fault groups - Prevalence and energy impact.

Rank	Fault Group	Fault description/ Problem source	% of service calls	Energy penalty impact
1	Electrical	Power loss to system or component	16%	No
2	Controls	Faulty sensors, actuators, algorithms, or control settings	16%	Yes
3	Airflow	Fan faults, ductwork blockage, duct leakage, poor air distribution	14%	Yes
4	No fault	Thermal comfort complaint, no fault	8%	No
5	Filter	Dirty air filter	7%	Yes
6	Motor (Fan/Pump)	Fan or pump fault	5%	Yes
7	Refrigerant fault	Refrigerant leak, refrigerant charge too low, refrigerant charge too high	5%	Yes
8	Condensate/Drain	Issues with condensate drainage	5%	No
9	Mechanical	Mechanical component fault/failure	4%	Yes
10	Dirty equipment	Dirty filters, coils, fans and ducts	3%	Yes
11	Pipework	Fault on pipework system	3%	Yes
12	Other	Other miscellaneous faults	3%	Yes
13	Waterflow	Fault on water side distribution, pump faults, strainer faults	3%	Yes
14	Chiller fault	Fault with chiller component	2%	Yes
15	Compressor fault	Fault with compressor component	2%	Yes
16	Design and installation	Fault due to improper design or installation	2%	Yes
17	Coil blockage	Dirty or blocked coil	2%	Yes
18	Line/pressure	Refrigerant line/pressure fault	1%	Yes
19	Poor equipment location	Fault due to improper sensor or component location	1%	Yes
20	Boiler fault	Fault with water heating component	1%	Yes
21	Insulation	Damaged insulation, failed insulation, collapsed insulation	1%	Yes

22	System capacity	Fault due to inadequate capacity in system/component	0.3%	Yes
23	Documentation	Missing or faulty documentation	0.1%	No

The insights gained from this analysis are summarised in Section 5.2.

5.2 Common faults observations

The type of AC equipment problem sources that were included under the common fault groups were judged on whether the fault group would impose an energy penalty on the operating system.

Electrical – Electrical faults are the most common fault. Electrical faults can be a sign or symptom of other faults in the system forcing the system to work too hard or beyond its capacity. Maintenance provides a limited solution. Electrical faults are easily detected by monitoring and can be diagnosed by an Automated Fault Detection and Diagnosis (AFDD) device.

Control – Control faults are a very common fault. These elements of the system are either providing feedback information or telling a component of the system what they should be doing. Control faults are very likely to reduce energy productivity. Control faults can be diagnosed by AFDD.

Airflow – Airflow is generally very important for heat distribution in air-based systems. Airflow faults reduce energy productivity and are easily detected by monitoring and can be diagnosed by AFDD

Waterflow – Waterflow is generally very important for heat distribution in water-based systems. Waterflow faults reduce energy productivity and are easily detected by monitoring and can be diagnosed by AFDD

Refrigerant – Refrigerant fault is a common fault in all equipment formats that contain refrigerant. The prevalence of refrigerant fault tends to increase with increasing system size/pipework complexity. The impact on energy productivity depends on the nature of the fault (i.e., catastrophic leak due to component failure or slow undetected leak leading to reducing charge over an extended time period. Refrigerant overcharge and undercharge can also result from incorrect commissioning or service procedures or lack of system baseline data.

Hygiene – AC hygiene and the cleanliness of filters, coils, trays, airways, fans, heat exchangers, strainers and pumps are a common fault and a fault that can significantly impact system energy productivity. Dirty evaporator and condenser coils for example incur an airflow energy penalty (fans work harder) and a heat transfer energy penalty (surfaces are effectively insulated, diminishing heat transfer), potentially a double penalty to energy productivity. These aspects of AC hygiene can be detected by monitoring however diagnosis generally requires physical inspection.

Mechanical and other faults – AC systems are often complex and made up of equipment with multiple moving and static components. Wear and tear and failures happen for a variety of reasons to a variety of components. The ability to monitor these faults depends on the impact the fault has on the system.

Condensate drainage faults – Cooling coils create condensation when cooling/dehumidifying air which needs to be removed. Volumes of condensate can be high during periods of high temperature and coincident humidity. Condensate failures typically include blocked trays and drainage systems or failed condensate pumps, evidenced by dripping or odours. This fault is not considered to affect system energy productivity.

Line/pressure faults – A refrigerant line/pressure fault includes failures on the refrigerant distribution system pipework, valves and auxiliary components. These faults tend to alter the refrigerant pressure/temperature and can impact on system energy productivity. Line/pressure faults can be detected by monitoring and diagnosed by AFDD although complex algorithms are required.

5.3 Identifying the Top 10 energy penalty faults

To rationalise the common fault list further into the top energy penalty faults, the following additional data processing steps were taken:

- Disaggregate motor (fan/pump) faults into airflow and waterflow.
- Disaggregate pipework faults into refrigerant line/water flow faults.
- Combine filters and coil blockage and dirty equipment into 'AC hygiene'
- Combine capacity, design, installation, and documentation faults into a single fault group.

As the focus of this research is on AC repairs, and the energy impact of faults that necessitated these repairs, the following fault groups were removed from the list to facilitate ranking of energy penalising faults.

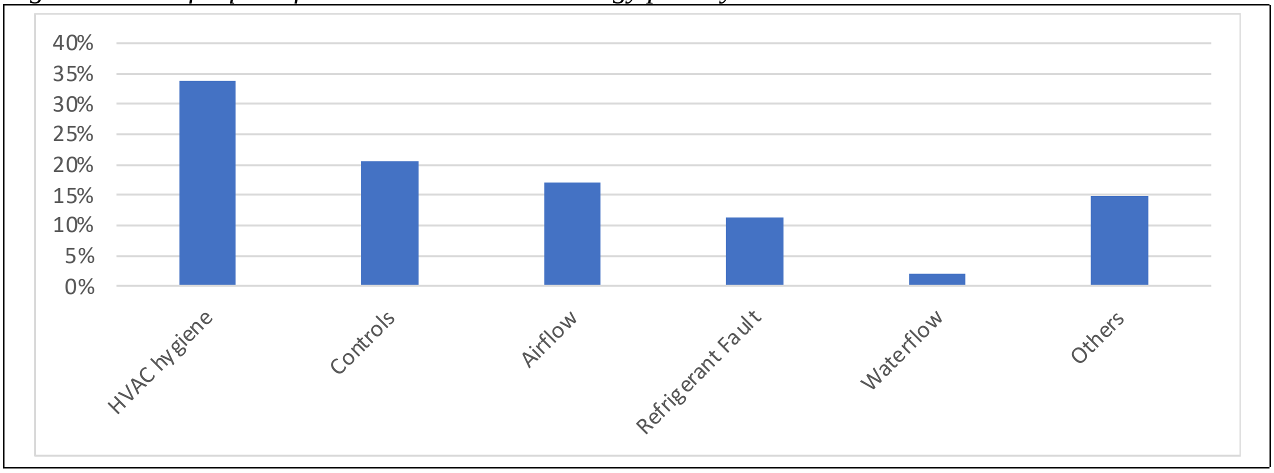
- Electrical fault – as it does not impact energy productivity.
- No fault – as it is does not result in repairs or is addressed by regular maintenance activities.
- Mechanical/other fault – as it does not impact energy productivity.
- Condensate/drainage fault – as it does not impact energy productivity.
- System capacity/design, installation, and documentation – as it is not addressed by maintenance.

This review leaves us with the Top 10 Fault areas that impact energy consumed and energy productivity that can be addressed by maintenance.

5.4 Major Energy Penalty Faults

The top five energy penalty faults account for nearly 90% of all work order/repair activity. The relative frequency of the major energy penalty faults is shown in Figure 6.

Figure 7: Most frequent faults that result in an energy penalty.



This graph is based on the 20-year dataset and covered a wide range of equipment formats across a wide range of building typologies. "Refrigerant Fault" includes leaked, low or high refrigerant charge. "Others" includes Chiller fault, Compressor Fault, Boiler Fault, Insulation Fault. Data tables including percentages are included in Appendix B.

It was not possible to determine the severity of the likely energy penalty, although it is widely recognized that airflow obstructions and the reduced heat exchanger efficiency of dirty equipment can significantly increase energy use. Refrigerant faults can also potentially result in significant energy penalties and tend to be expensive faults to fix.

Refrigerant faults that are catastrophic, i.e., where the entire refrigerant charge is lost in a short period, typically cause the equipment to stop working altogether and do not necessarily cause significant energy penalties. However, where refrigerant faults are slow leaks that take a long time to significantly degrade performance before the problem is identified, can result in significant cumulative energy penalties over long periods of time. The refrigerant fault group in the GEG data contains 3 problem sources; Refrigerant leak, Refrigerant Low (no leak detected), Refrigerant level high.

The most common fault reported in the Refrigerant Fault group (for the entire dataset) is:

- Refrigerant leak – 85%.
- Refrigerant low (no leak detected) – 12%.
- Refrigerant level high – 3%.

Without examining individual work orders in detail, it is not possible to determine what proportion of the 85% refrigerant leak fault discovered were catastrophic leaks and which were slow or partial leaks. Similarly, without examining work orders in detail, it is not possible to determine the charge level for the 12% Refrigerant Low (no leak detected) faults discovered. As such it is impossible at this time to determine what portion of the reported leaks incurred long and accumulating energy penalties. This could be the focus of additional supporting research.

Across all problem sources recorded it appeared that the Refrigerant Fault repair was one of the most expensive faults to correct.

5.5 Comparing with previous fault data

The previous report *Leaks, maintenance and emissions: Refrigeration and air conditioning equipment* ('the maintenance study') was based on analysis of the results of large and small scale audits and research papers of AC systems, conducted in North America, Europe, UK, and Australia.[2] The maintenance study produced a list of common faults (see Appendix D) that were found during the audits of AC systems and that were likely to result in an energy penalty, i.e., a reduction in the energy productivity of the AC asset.

This report is based on the analysis of a large record of fault reporting, repairs and preventative maintenance activity over many years, resulting in operational data collected in a commercial context. This report has also produced a list of common faults that have been found on AC systems and are likely to result in an energy penalty.

To undertake an analysis of the similarities and differences between the GEG derived 'operational' fault list and the earlier 'audit' fault list, the terminology and ranking order between the two lists were aligned, as shown in Table 3.

The similarities between the two lists are self-explanatory and the points where the results of the studies strongly aligned were used to generate the list of overall top ten energy penalty faults discussed above. The areas of difference between the two lists is also informative.

The additional insights gained from this analysis largely relate to non-energy impacts of faults and are discussed in Section 5.9.

[2] *https://www.awe.gov.au/environment/protection/ozone/publications/leaks-maintenance-emissions-refrigeration-air-conditioning-equipment*

Table 3: Comparing common operational faults list to the audit faults list.

Common faults list – GEG Data (This study)	Common faults list – Audit Data (Maintenance study)
Electrical	-
Refrigerant, (sub-optimal charge, over or undercharge, refrigerant leakage)	Refrigerant (sub-optimal charge, over or undercharge, refrigerant leakage)
Airflow: Air distribution, duct sizing, dampers, and fans	Airflow: Air distribution, duct sizing, dampers, and fans
No fault	-
Airflow: Filters	Airflow: Filters
Condensate/Drain	-
Mechanical/Other	-
Control systems, sensors, and wiring issues	Control systems, sensors, and wiring issues
Dirty equipment	Condenser issues (fouling, faulty fan)
Coil blockage (Condenser and evaporator fouling)	Evaporator fouling
System capacity (no heat load, disconnect between owner and designer, safety margins) and mismatched components	System capacity (no heat load, disconnect between owner and designer, safety margins) and mismatched components
-	Refrigerant health and non-condensable
Waterflow	-
Poor equipment location	Poor equipment location
Insulation fault	Duct insulation and leakage
Liquid line issues (including restrictions)	Liquid line issues (including restrictions)
Minimal documentation (i.e., installation, commissioning baseline data, operation, maintenance)	Minimal documentation (i.e., installation, commissioning baseline data, operation, maintenance)
Design and installation	-
Boiler fault	-

It should be noted that faults such as electrical, mechanical and condensate drainage did appear in the results of the previous audit research but were not anywhere near as prevalent as they are in the operational fault data.

5.6 Other fault insights

5.6.1 Electrical faults

The most prevalent common fault group identified in the GEG data across all equipment formats was the Electrical fault group. This fault did not appear highly in the previous audit analysis report. Typically, an electrical fault is a fault somewhere on the electricity supply line to the system or component that interrupts power supply and failure typically stops the system and the service. As the system cannot operate these faults are typically addressed quickly reactively via breakdown callouts.

This fault group did not appear high on the audit fault list and are a group of faults that are typically experienced when the system is operating and often at high capacity, or when the system is initially started (instantaneous failure).

As electrical faults stop the system and are typically repaired relatively quickly, they are not considered an energy penalty fault.

5.6.2 The 'No fault' fault

The fourth most prevalent common fault group across all equipment formats was the fault group called No Fault. This fault group contains two major categories of no fault - *occupant comfort fault* and *no fault found.*

Insights from the current operational dataset showed that about 8% of all work order activity related to these two faults. This represents a significant amount of time and resources by the service provider and a significant cost to the owner/operator for no apparent benefit.

Thermal comfort faults (or complaints) have always been an issue for building/facility managers and AC service companies. Thermal comfort is as much a social and physiological issue as it is an AC performance issue. In these instances, the technician has attended the site in response to a callout and has been unable to find any fault within the system but notes evidence of occupant thermal comfort complaints. The systems are operating correctly but the occupants are not thermally satisfied. Modifications of systems to cater to specific thermal comfort requirements of occupants is an issue beyond the ability of maintenance to address.

The No fault category most likely relates to systems where design and capacity issues (that can't be resolved by a maintenance intervention) lead to the callout. Again, the system is operating correctly but is unable to satisfy the service or demand required, another issue beyond the ability of maintenance to address.

Where multiple or repeated maintenance callouts are occurring due to thermal comfort or other No Fault issues, owners and operators would be best advised to invest some time and money to investigate and address the underlying design and installation problems with the system.

5.6.3 Condensate/Drain fault

The eight most prevalent common fault group across all equipment formats was the fault group called Condensate/Drainage.

Again, this fault group ranks quite high in the operational dataset and does not rank as high in the audit list. Typically, this fault is evidenced by water dripping from the ceiling or pooling on the floor, specifically not adequately draining from the condensate drainage system. A bad odour from the AC is also a common indicator or occupant complaint that leads to this fault discovery.

This fault will typically occur when latent load levels and condensate volumes are high and associated drainage systems are either blocked or reduced, generally, strongly linked to AC hygiene issues.

5.6.4 Mechanical/other faults

The common fault group Mechanical/Other contains a wide range of mechanical fixes plus all other faults that were not captured in another fault group. Individually these faults are not significant but when all aggregated together they do represent a significant number of diverse faults some of which can be expected to at least contribute to an energy penalty in certain circumstances.

5.6.5 Refrigerant health and non-condensable fault

It is also noted that the fault ‘Refrigerant health and non-condensable’ appears high in the audit list but does not feature in the operational list.

The testing of refrigerant health and purity is typically a pro-active maintenance service. Faults resulting from impure or contaminated refrigerant or from non-condensable in the refrigerant circuit could also have been categorised as a compressor fault, a refrigerant/line pressure fault, a mechanical fault or other by the attending technician. There was no GEG problem source allocated to refrigerant health.

6 Results: prevalence of common faults by equipment type

A more detailed examination of data from the period 2015-2019 was undertaken focussing on six main equipment types that make up the vast majority of installed AC equipment. The five year dataset was selected as it was would better reflect the mix of faults in modern equipment.

The six categories selected for specific analysis were:

1. Chillers.
2. Ducted AC (Split).
3. Ducted AC (Packaged).
4. VRV/VRF systems.
5. Close control (CRAC) systems.
6. Single split non-ducted.

This list still leaves a broad group of components listed such as cooling tower faults, fans, pumps, and terminal units that do not fit into CHF taxonomy categories. These equipment categories and components were not subject to this deeper analysis.

When looking into specific equipment formats it was necessary to disaggregate several large and general fault group descriptions to better understand the fault source. For example, approximately 42% of faults associated with chiller systems had simply been identified with a problem source code called Chiller Fault.

In order to disaggregate these large fault groups, the associated work orders were analysed for a range of terms and phrases, which allowed the problem source group to be disaggregated into discrete common faults as follows.

1. **Chiller Fault** – refrigerant fault, water flow, line/pressure, electrical, controls, coil blockage, other.
2. **Compressor fault -** broken down into refrigerant, controls, electrical, line/pressure fault, 15% other.
3. **Dirty equipment** – broken down into filters, coils, fans, duct, condensate/drain, other. Often the dirty equipment problem source would contain systems with several AC hygiene issues with multiple faults such as dirty filters, blocked coils, dirty fans and ductwork.
4. **Coil blockage** – analysed for indoor, outdoor, evaporator or condenser, water or refrigerant (DX), Analysis indicated that coil cleaning activities were roughly evenly distributed as a 50/50 split between indoor and outdoor coils.
5. **Coil fault** (excluding blockage) – broken into coil cleaning, repairing coil damage, coil/condensate drainage issues, other analysis indicated that these coil fault activities were roughly distributed as a 30/70 split between indoor and outdoor coils, indicating that outdoor coils are more susceptible to damage.
6. **Other fault** – this fault group was too diverse and there was limited additional resolution achieved when attempting to disaggregate this fault group with word search/phrase analysis.

A common fault group 'Mechanical/other' was created to contain all of the mechanical fixes and the other faults that could not be disaggregated by the word/phrase analysis and also included 100% of the problem source group 'Other'.

Completion of this analysis provided a ranked list of common fault groups for each equipment category and a Top 10 Energy penalty for list for each category as set out in the following Sections.

Note: As a result of this disaggregation by Expert Group, GEG has adjusted its fault code topology on its primary and mobility software platforms. This will improve future data gathering by AC technicians and enhance future data analysis.

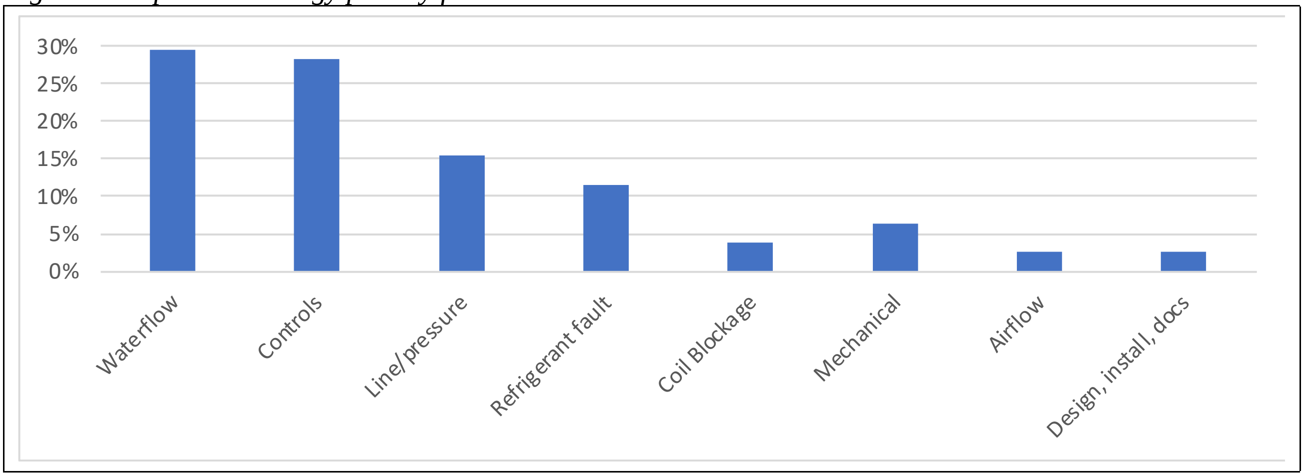
6.1 Chillers

The most prevalent faults in the chiller equipment category were:

1.	Waterflow	23%
2.	Controls	22%
3.	Electrical	16%
4.	Line/pressure	12%
5.	Refrigerant fault	9%
6.	No fault	4%
7.	Coil blockage	3%
8.	Mechanical	3%
9.	Other	2%
10.	Airflow	2%
11.	Design and installation	1%
12.	Documentation	1%

80% of all chiller faults were energy penalty faults. Figure 8 shows the top energy penalty faults in descending order.

Figure 8: Top chiller energy penalty faults.



The most prevalent faults in the chiller equipment category and the energy penalty faults percentages are provided in Appendix B.

6.2 Single split ducted

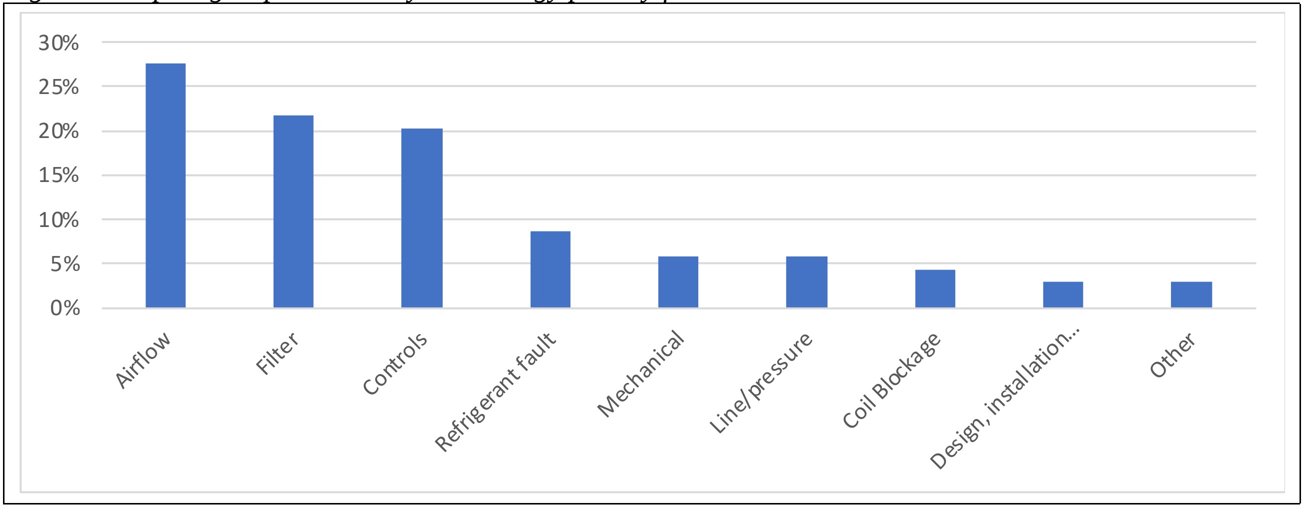
The most prevalent faults in the single split ducted equipment category were as follows:

1.	Airflow	19%
2.	Electrical	17%
3.	Filter	15%
4.	Controls	14%
5.	No fault	7%

6. Refrigerant fault 6%
7. Condensate/Drain 6%
8. Line/pressure 4%
9. Mechanical 4%
10. Coil blockage 3%
11. Other 2%
12. Waterflow 1%
13. Design and installation 1%
14. Poor equipment location 1%
15. Insulation 1%

70% of all split ducted system faults were energy penalty faults. Figure 9 shows the top energy penalty faults in descending order.

Figure 9: Top single split ducted system energy penalty faults.



The most prevalent faults in the single split ducted equipment category and the energy penalty faults percentages are provided in Appendix B.

6.3 Packaged ducted systems

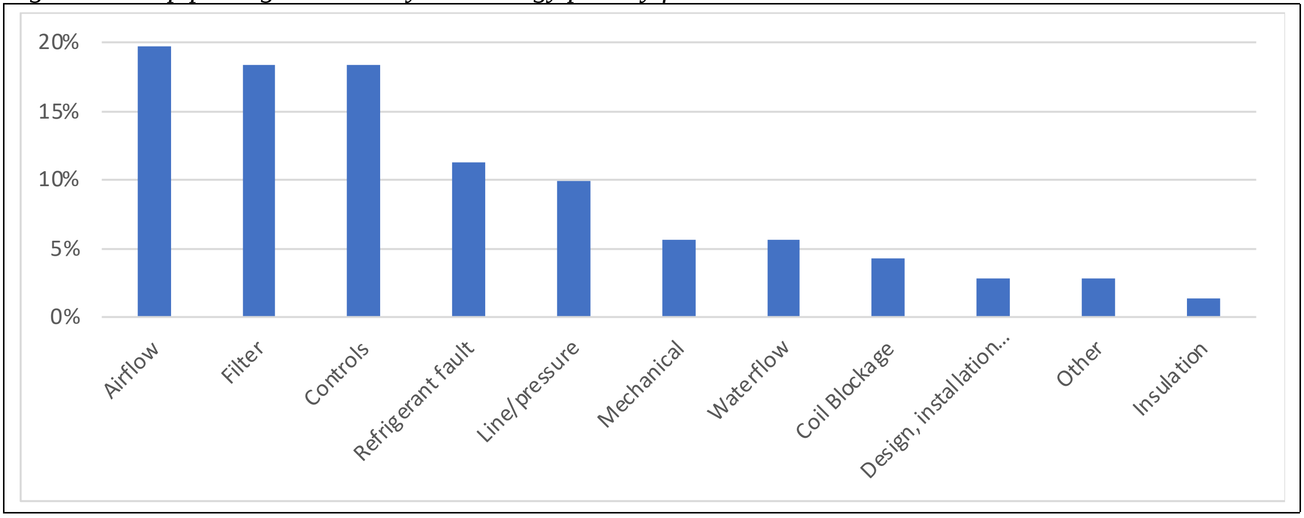
The most prevalent faults in the packaged ducted equipment category were as follows:

1. Electrical 19%
2. Airflow 14%
3. Filter 13%
4. Controls 13%
5. Refrigerant fault 8%
6. No fault 7%
7. Condensate/Drain 5%
8. Waterflow 6%
9. Mechanical 4%

10. Coil blockage 3%
11. Line/pressure 3%
12. Other 2%
13. Design and installation 1%
14. Poor equipment location 1%
15. Insulation 1%

69% of all packaged ducted system faults were energy penalty faults. Figure 10 shows the top energy penalty faults in descending order.

Figure 10: Top packaged ducted system energy penalty faults.



The most prevalent faults in the packaged/ducted equipment category and the energy penalty faults percentages are provided in Appendix B.

6.4 VRV/VRF systems

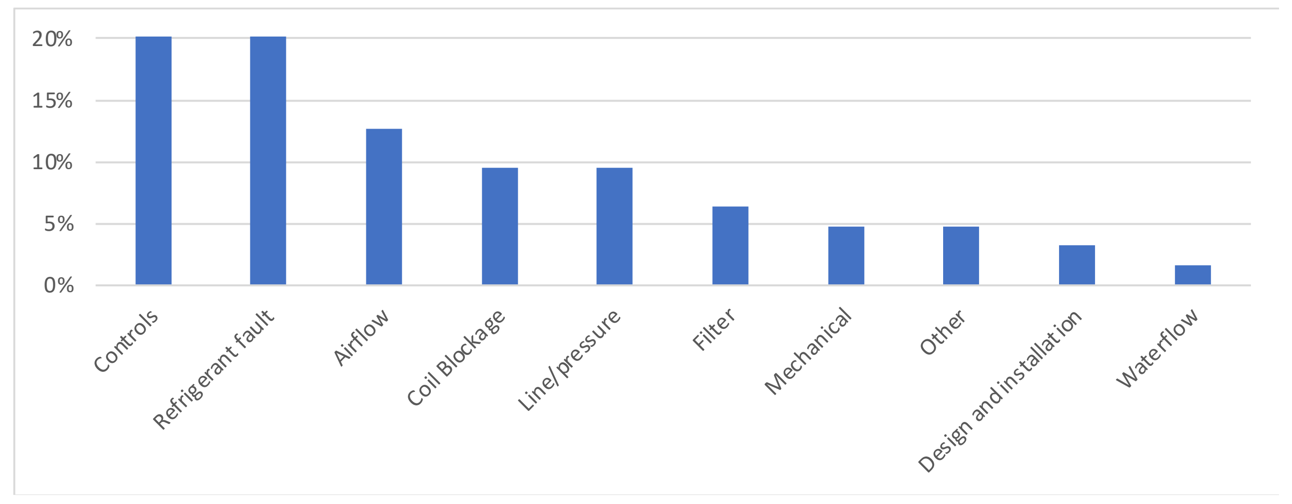
The most prevalent faults in the VRV/VRF system equipment category were as follows:

1. Electrical 26%
2. Controls 17%
3. Refrigerant fault 13%
4. Airflow 8%
5. No fault 8%
6. Coil blockage 6%
7. Line/pressure 6%
8. Filter 4%
9. Condensate/Drain 3%
10. Mechanical 3%
11. Other 3%
12. Design and installation 2%

13. Waterflow 1%

63% of all VRV/VRF system faults were energy penalty faults. Figure 11 shows the top energy penalty faults in descending order.

Figure 11: Top VRV/VRF system energy penalty faults.



The most prevalent faults in the VRV/VRF equipment category and the energy penalty faults percentages are provided in Appendix B.

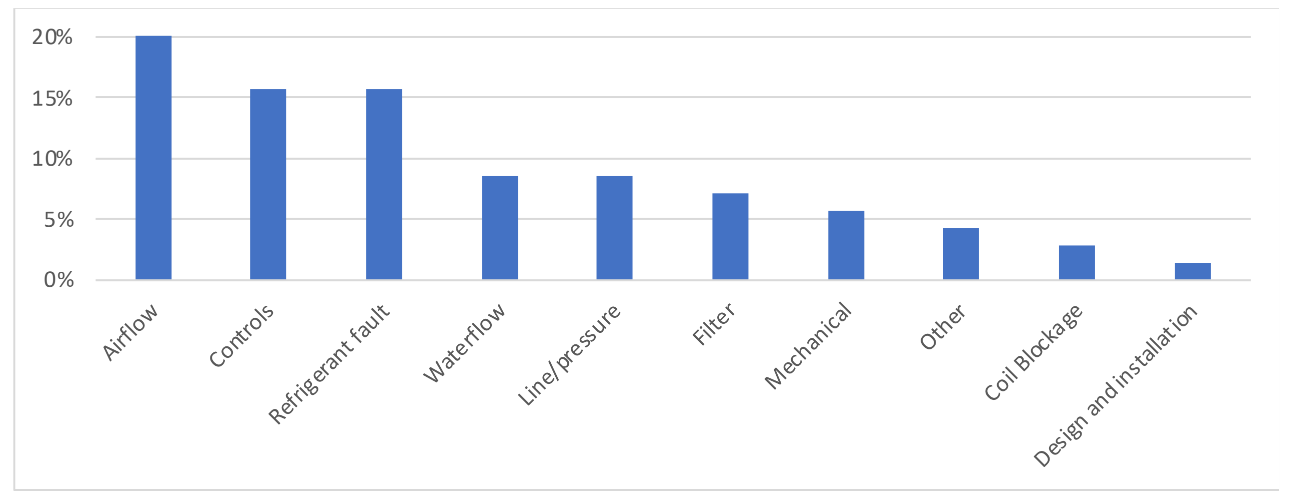
6.5 Close control air conditioners

The most prevalent faults in the close control air conditioner (CRAC) equipment category were as follows:

1. Airflow 21%
2. Electrical 18%
3. Controls 11%
4. Refrigerant fault 11%
5. No fault 7%
6. Waterflow 6%
7. Line/pressure 6%
8. Filter 5%
9. Condensate/Drain 4%
10. Mechanical 4%
11. Other 3%
12. Coil blockage 2%
13. Design and installation 1%

69% of all CRAC system faults were energy penalty faults. Figure 12 shows the top energy penalty faults in descending order.

Figure 12: Top close control air conditioner energy penalty faults.



The most prevalent faults in the CRAC equipment category and the energy penalty faults percentages are provided in Appendix B.

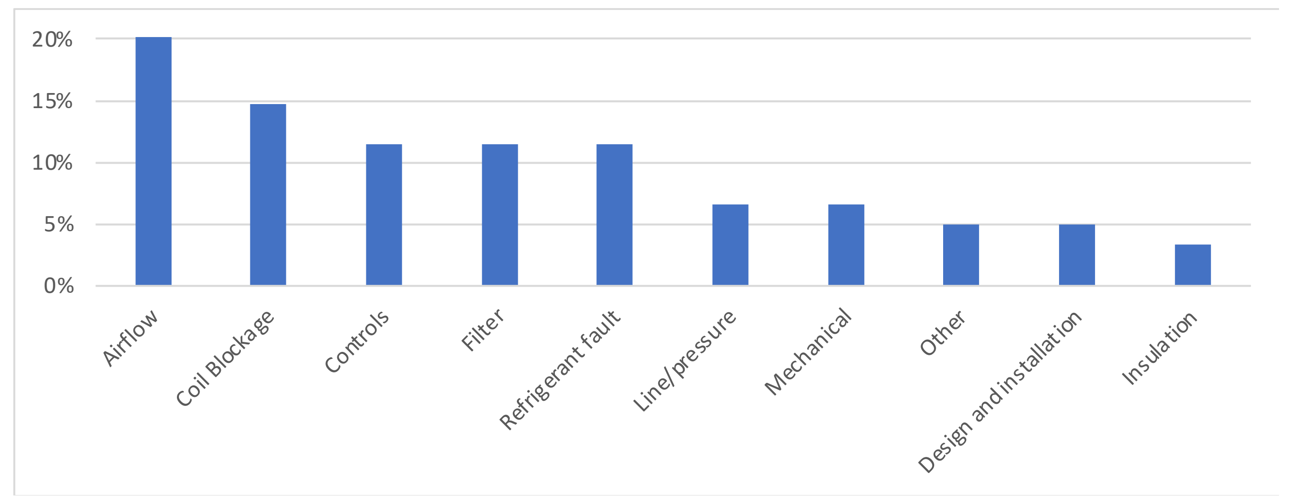
6.6 Single split non-ducted

The most prevalent faults in the Single split non-ducted air conditioner equipment category were as follows:

1. Electrical 18%
2. Condensate/drain 15%
3. Airflow 15%
4. Coil blockage 9%
5. Controls 7%
6. Filter 7%
7. Refrigerant fault 7%
8. No fault 6%
9. Line/pressure 4%
10. Mechanical 4%
11. Other 3%
12. Design and installation 3%
13. Insulation 2%

61% of all Single split non-ducted air conditioner system faults were energy penalty faults. Figure 13 shows the top energy penalty faults in descending order.

Figure 13: Top single split non-ducted air conditioner system energy penalty faults.



The most prevalent faults in the split non-ducted air conditioner equipment category and the energy penalty faults percentages are provided in Appendix B.

6.7 Top Energy Penalty faults by equipment format

Following disaggregation of generalised problem sources into the common fault groups the Top Energy Penalty faults by equipment format were identified as follows.

Table 4: Top ten energy penalty faults by equipment format.

Summary – Top Ten Energy Penalty faults by equipment format						
Rank	Chiller	Ducted AC (Split)	Ducted AC (Packaged)	VRV/VRF systems	Close control (CRAC) systems	Single split non-ducted
1	Waterflow	Airflow	Airflow	Controls	Airflow	Airflow
2	Controls	Filter	Filter	Refrigerant	Controls	Coil blockage
3	Line/pressure	Controls	Controls	Airflow	Refrigerant	Controls
4	Refrigerant	Refrigerant	Refrigerant	Coil blockage	Waterflow	Filter
5	Coil blockage	Mechanical	Line/pressure	Line/pressure	Line/pressure	Refrigerant
6	Mechanical	Line/pressure	Mechanical	Filter	Filter	Line/pressure
7	Airflow	Coil blockage	Waterflow	Mechanical	Mechanical	Mechanical
8	Design and installation	Design and installation	Coil blockage	Other	Other	Other
9	Other	Other	Design and installation	Design and installation	Coil blockage	Design and installation
10		Insulation	Other	Waterflow	Design and installation	Insulation

The distribution of the common Energy Penalty faults across different equipment formats also provides some useful insights. Notable similarities across the various categories analysed include:

- **Airflow/Waterflow** – The Airflow fault group is always in the top 3 for all equipment categories, except for chillers where the most common fault group, Waterflow, is the equivalent of the Airflow fault in other equipment categories. Waterflow is also an Energy Penalty fault in those equipment categories where systems are applied in water-cooled formats or rely on water-based heating coils (i.e., CRAC, Packaged AC and some VRV/VRF systems). Airflow and waterflow faults impact the heat transfer and heat distribution within these systems, directly impacting energy productivity. Proactive maintenance that routinely inspects and cleans air flow and water flow components of AC systems (and refrigeration systems) would almost certainly avoid energy waste attributed to these faults.
- **Controls** – The Controls fault group is also always in the top 3. The Controls fault group contains a lot of different problem source groups, and these faults impact the feedback into and outputs from the system control elements. These faults tend to cloud or disable the system intelligence and its sensors, reducing a system's ability to react correctly to the environment being controlled. Some controls faults (e.g.,

simultaneous heating and cooling) can be intensely energy wasteful. Additional analysis of the GEG work orders to better understand the implications of Control Faults for energy consumption, and the potential for proactive maintenance to avoid these faults is recommended.

- **Refrigerant Fault** – The Refrigerant fault group is always in the top 5 most common faults, and in the case of VRV/VRF systems is the number 2 fault. The vast majority of refrigerant faults (over 85%) relate to refrigerant leakage and either operation on low charges or catastrophic loss of all refrigerants. Further work is required to better analyse the thousands of reports of refrigerant faults to identify the proportion of catastrophic loss (which will result in equipment ceasing to operate and thus not incur any further energy penalty) and those that were reported due to a longer term leaks. ‘
- **Design, installation, equipment location and documentation faults** are always in the lower rankings but are consistent across equipment formats. A certain proportion of all systems contain inherent design and installation faults that are typically more difficult to address than simple maintenance.

It is also informative to look at the differences in characteristics of individual equipment formats:

- **Chillers –** Waterflow is the dominant fault group for these water-cooling devices, followed closely by faults with controls, then refrigerant line issues and refrigerant (charge) faults. Coil blockage is the 5th most prevalent fault indicating how important surface cleanliness is to heat exchange process within these systems. Airflow also features in the top chiller results which generally relates to the heat rejection elements, where applicable. Proactive maintenance that routinely inspects and cleans water flow and air flow components of chiller systems and verifies correct refrigerant charge would almost certainly avoid energy waste in the majority of instances.
- **Ducted split and packaged –** Given that these are largely air-based systems (i.e., they rely on air for heat transfer and heat distribution) it is not surprising that Airflow faults are the most prevalent fault followed closely by the related Filter fault. As noted previously filter faults impact airflow and AC hygiene which can both reduce energy productivity of the system. These two system formats also exhibit very similar fault patterns, with the exceptions that condensate drainage faults appearing to be higher in split systems and with the waterflow fault appearing higher in packaged ducted systems, possibly relating to the heat rejection side of these systems.
- **VRV/VRF systems –** The Controls fault group is the most prevalent fault for this equipment format with refrigerant fault in second rank. This may be explained by the tendency of these equipment formats to have higher level/complexity of controls and refrigerant distribution pipework than many other equipment formats. Airflow and coil hygiene are also top faults in this category. Waterflow also features because some of the equipment in this format are water cooled.
- **CRAC** – These close control IT applications exhibit a lower prevalence of Filter and Coil blockage faults which may be because of the generally low-density occupation and cleaner nature of the computer room/data centre environments when compared to other occupancies. Refrigerant fault group is higher than average and line/pressure faults are common, again reflecting the sometimes-extensive refrigerant pipework involved in these systems. Mechanical faults also ranked highest in the CRAC category perhaps indicative of the 24/7 operation mode of many of these systems.
- **Single split non-ducted** – It is noted that condensate drainage is a top fault in this category, the only equipment category that exhibits this characteristic. These systems tend to be located within the occupancy rather than tucked away in a plantroom or plant cupboard and are either visible dripping or a drainage problem that rapidly becomes visible. The use of condensate pumps that have relatively short lifespans is also possibly contributing to this. The most important faults in terms of energy penalty ranking are Airflow, Coil blockage, Controls, Filter, Refrigerant.

7 Insights into equipment owner maintenance behaviour

7.1 Maintenance delivery - reactive or proactive?

Generally, all of the breakdown/callout work orders (by far the largest portion of work orders at 56% of the work orders in the 5-year set) are considered to be reactive repairs. When technicians are attending a site, they may also inspect other AC assets operated by the owner/client. Additional reports, quotes and work orders may be generated following these additional inspections.

It should be noted that where faults and equipment deterioration are noted, and a report or quote generated to address the fault, it is the owner/operator decision whether to action the issue in a proactive or reactive manner.

The dataset analysed did not include the work orders associated with any scheduled maintenance work carried out by the organisation.

AC maintenance service delivery is a highly competitive business in Australia, with owners and operators generally looking for a lowest cost solution. The vast majority of clients adopt a reactive-only approach to maintenance – fix it when it breaks. Some clients do adopt a scheduled approach to inspections and minor maintenance work, and it is only very few clients that adopt a truly pro-active approach to maintenance.

Analysis by GEG has shown that for specific sites and specific portfolio owners that move to a pro-active and automated approach to maintenance service will, in the medium term, reduce the overall costs of ownership of the system. However due to the low number of clients that actually adopt this approach, the research was unable to test this hypothesis for a significant large representative group of buildings within a typology or of system types.

7.2 System diagnosticians

7.2.1 Owners and operators

One of the interesting opportunities offered in the dataset was a comparison between the problem reported and the problem discovered.

One of the insights from this analysis is that owners and operators of AC systems are generally not good diagnosticians of the systems. Work orders for breakdowns/callouts contain both the problem reported to the service company by the operator and the problem recorded by the attending service technician. With the exception of the report “System not working” there was generally poor alignment between the problem reported and the problem discovered. Operators can tell when the system does not work but for any further detail, they are typically not reliable diagnosticians for AC (and nor should they be expected to be). This lends significant argument for the installation or incorporation of automated electronic monitoring and metering to AC systems and equipment, to enable automated fault detection and potentially automated fault diagnosis.

This would provide several potential benefits:

- Early administrative clarity for a service company on a likely No fault/thermal comfort complaint scenario.
- Remote diagnosis of likely problem source (prior to callout).
- Pre-diagnosis of likely problem source, prior to attendance at site.
- Targeting technician specialist skills to particular problem sources.
- In some cases, remote fault correction or fault patches.

Faults that would lend themselves to monitoring and AFDD would include:

- Electrical (Current monitoring and system power consumption).
- Airflow/waterflow fault (Flow presence and volume sensors and AFDD algorithms).
- Refrigerant Fault (Specialised sensors and AFDD algorithms).
- Controls (Specialised sensors and AFDD algorithms).

Inexpensive sensors and in particular sensors with IoT capabilities have enabled automated monitoring at a much lower cost than ever before.

To avoid issues with sensor calibration any critical control sensors (temperature, airflow, etc.) can be easily and cost effectively duplicated and used to monitor each other's accuracy.

7.2.2 Digitalisation of diagnostics

For owners willing to extend their maintenance scope beyond simple reactive repairs the combination of digital monitoring, fault detection and analysis and digital-ready service providers can provide a new and cost-effective offering in proactive approaches to AC maintenance.

In the absence of a digital approach to pro-active maintenance the next best approach is delivery of a scheduled periodic asset inspection and assessment process.

In all cases of diagnostics, the fault detection process must run through a selection of inputs and elimination of possibilities to determine, first the source and then the cause of the fault, and ultimately the corrective action to be taken. Categorising faults helps with the diagnostics process.

7.2.3 Fault severity based on need to repair

The dataset available did not assign a severity level to faults. For example, we don't know how much a coil was blocked or the how low a refrigerant charge was or the extent the airflow had been reduced by the fault.

There are many indicators that in most cases, by the time the fault was reported and repaired, the fault had reached severe levels. Given that over 50% of the repairs derive from breakdowns/callout (i.e., emergency repairs) in many of these cases the system was either not working at all or was working but clearly unable to perform the required function. While many of these breakdown faults relate to electric faults or mechanical failures all other common fault groups are also represented in the data.

- Dirty filters had to be replaced.
- Coils that were blocked had to be physically cleaned.
- Control systems had to be reset or recalibrated.
- Fans and pumps, ducts and pipework had to be corrected.

To return the system to correct function repairs had to be made. In these systems characterised by breakdown faults there is also evidence of multiple faults in a single system. The fault is logged as a single problem source but in reality, the work order/repair work can cover multiple faults or repairs to multiple components.

As evidenced in the maintenance report, multiple faults can only compound the energy productivity and system performance problems.

7.2.4 Fault severity based on energy impact

If one way of looking at "severity" relates to the ongoing energy impact of the fault, the reduction in energy productivity, then 'severe' faults are those faults that allow the system to keep operating but waste ever increasing amounts of energy until the systems reached a point where it no longer provides the service intended, and a service callout is initiated.

This report has provided significant insight and understanding into fault prevalence but due to the nature of the data and the purpose of the data base analysed, we can still only make informed guesses as to fault severity, and its actual energy impact and therefore the cost incurred to equipment owners from energy waste.

8 Conclusions

The work orders underlying the GEG dataset provide a significant record of common AC faults across a large sample of the main equipment categories.

Analysis for this report required a considerable effort, facilitated by GEG, to clean and manipulate the data.

One particularly informative finding is that the single most frequently reported problem source in GEG repair work orders are ‘Electrical’ faults, with more than 16% of all work orders (42,201) reporting an electrical fault requiring action. In prior studies Expert Group had concluded that electrical faults were a relatively small cause of problems, rating electrical faults at 13th in the list of most common faults.

Another surprising finding was the number of work orders reporting ‘No Fault’ (19,902 - 8% of all work orders). These ‘No Fault’ records were the fourth most common reported in the GEG work orders, as compared to prior research that ranked maintenance call outs that found no fault at 15th.

Controls, Airflow and Filters ranked 2, 3 and 5 respectively in the GEG data fault analysis aligning well with previous Expert Group rankings of these commonly reported faults.

The findings strongly support the main findings of earlier analysis that there are common faults that would be expected to incur large and ongoing energy penalties most of which could be avoided by routine maintenance.

Additional benefits of routine maintenance would be avoided service (i.e., occupant comfort) and business interruptions.

Further work is recommended, building on the effort that has been invested in making the GEG data base more accessible for analytical purposes.

Programs of work that could be considered include.

1. Detailed analysis of all ‘refrigerant faults’ to determine the frequency of catastrophic losses versus faults resulting from gradual leaks.
2. Analyse the cost and detail of completed repairs under a set of selected Problem Source Codes to build an informed model of common fault severity, allowing informed estimates of energy penalties and estimates of the cost savings of routine maintenance versus reactive maintenance.
3. Work with GEG to develop refined fault tree systems that would facilitate more immediate on-site diagnosis of complex, multi-source faults and establish cleaner data capture directly form work orders, quotes and repairs and maintenance reports.
4. To quantify benefits from different approaches to maintenance, work with GEG/Industry to define separate sets or portfolios of Buildings/HVAC asset groups within the data base, where (1) no scheduled maintenance has been applied and (2) where scheduled maintenance has been applied and potentially (3) where digital monitoring/proactive maintenance has been applied.

Appendix A: Fault groups and problem source descriptions

Table 5: GEG Problem source descriptions and Expert Group maintenance study common fault groups.

#	Fault group	GEG Problem source descriptions
1	Refrigerant	Refrigerant Leak, Refrigerant Level Low (No Leak Detected), Refrigerant Level Excessive, Refrigeration System Leak
2	Airflow	Fan Fault, Air Flow Fault - General, Air Flow Fault - Supply Air, Ductwork Fault, Damper Fault, VAV Fault, Air Flow Fault - Return Air, Humidifier Unit Fault
3	Filter	Filter Media Dirty
4	Dirty Equipment	Dirty Equipment
5	Controls	Controls - BMS Fault, Electrical Fault - Control Circuit, No Fault - Occupant Temp. Adjustment, Electrical Fault - Time Clock, Sensor - Calibration Fault, Actuator Fault, Sensor - Setpoint Fault, Electrical Fault - VSD, DO NOT USE!!! Sensor - Temperature, Pneumatic Air System Fault
6	Coil Blockage	Coil Blockage
7	Condensate/Drain	Drain - Condensate Fault, Drain - Other (excl. condens.) Fault, Blocked Drain
8	Capacity	No Fault - System Capacity Exceeded
9	Poor equipment location	Sensor - Incorrect Location, Location Incorrect - AC Equipment
10	Insulation	Insulation Related Fault
11	Liquid line	Refrigeration Circuit Fault, Valve - TX Fault, Liquid Line Dryer/Valve Fault
12	Documentation	No Fault - Design Documentation
13	Electrical	Electrical Fault - Printed Circuit Board, Electrical Fault - Motor, Electrical Fault - Other, Electrical Fault - Contactor, Electrical Fault - Wiring, Electrical Fault - Circuit Breaker, Electrical Fault - Switch, Electrical Fault - Overload, Electric Element or Duct Heater Fault, Electrical Fault - Relay, Electrical Fault - Power Failure, Electrical Fault - Connection, Electrical Fault - Fuse, Electrical Fault - Capacitor, Electrical Fault - Light/Globes, Electrical Fault - Solenoid Coil, Electrical Fault - Sump/Crank Case Heater, Switchboard Access Not Restricted, E- Power switching / Control, E- Switchboard, E-Cabling, E- RCD/CB Fault, E- AS/NZS 3000 Non Compliance, Pump Has No Power
14	Design and installation	Construction/Refurb/Fitout, Design &/or Compliance Problem, Tenancy Fitout Related Fault, Building Structure Fault, Commissioning Fault, Pipework Design Issue
15	No fault	No Fault - Occupant Comfort Complaint, No Fault Found, Reset, Problem Not Identified
16	Chiller fault	Chiller Fault
17	Compressor Fault	Compressor Fault
18	Waterflow	Pump Fault, Cooling Tower Fault, Faulty Pump
19	Boiler	Boiler Fault
20	Mechanical	Mechanical Wear & Tear, Pulley Fault, End of Useful Life, Excessive Corrosion, Coil Fault (excl. blockage), Equipment Malfunction, Energy-Saving Device Fault, Pressure Switch Faulty
21	Fan/Pump	Vee Belt Fault, Motor Fault, Bearings Worn
22	Pipework	Valve - General Fault, Pipework Fault, Strainer - Fault (Dirty, Blocked etc), Flow Switch Fault, Mechanical Seal Fault, Pipework Cracked/ Damaged, Damaged Pipework, Check Valve Faulty, Pipework Faulty

23	Other		Other, Problem Source To Be Confirmed
99		NA	No Fault - Scheduled Maintenance, Evap Cooler - Fault (Excl. Dirty Pads), No Fault - Site Inspection, No Fault - Spare Parts Supplied, Fire Trip Initiated Fault, No Fault - Fire Test Certification, No Fault - Equip. Manually Isolated, Evap Cooler - Dirty Pads, No Fault - Decommission Equipment, Portable AC, F-Fault, F-FIP Fault - General, Vandalism or Wilful Damage, Building Inspection, F-Fire Extinguisher Fault, Energy Efficiency Upgrades, F-No Fault - Fire Test Certification, F-Exit/EML Fault, F-Design &/or Compliance Problem, EEO Audit, Gas Heater Fault, F-Sensor - Incorrect Location, Water Audit - Level 1, F-FIP - Isolate/Deisolate, zIT - Server Software Config, F-Non Compliance to BCA &/or AS, E- Fault Other, Human Error, NABERS Energy and Water Rating, F-Dirty Room, zIT - Internet Link Down, OT-Power supply failure, Water Filter Dirty, zIT - Internet DSL Modem Hardware, Valve Shut, E- Switchboard Control, F-Fire Door Fault, NABERS Energy Rating, F-Fire Sprinkler Fault, Inverter Board Fault, Sewer Blocked, E- RCD/CB Trip, Product Sales, zIT - Internet Router Hardware, Ceiling Tile Fault, F-EWIS Issue/Fault, F-Fire Drill, Sprinkler Leak, zIT - Internet Router Config, E-Faulty Apparatus, NABERS Water Rating, OT-Power outage, Blocked Gutter-Debrities, E- Cable Termination, E- Fault in cable, F-Fire Diesel Pump Fault, F-Fire Equipment Vandalaised/Damaged, F-Fire Hose Reel Fault, F-Fire Hydrant Fault, F-Fire Sprinkler Leak, Gasket Fault, zIT - DHCP Server Scope, zIT - Internet ISP, Compactor Inoperative, E- Lamp LED, Gas Tripped, High Water Pressure, Blocked Water Main, Compactor Damaged, E - Starter, Energy Audit - Level 1, F-Fire Electric Pump Fault, Faulty Tank Float, Gate Valve Damaged, Tap Washer Faulty, zIT - Email Mail Routing Config, zIT - End User Incorrect Use, zIT - UPS Capacity, BEEC, Compactor Blocked, E- Faulty Appliance, E- Lighting Control / Switch, E- Network Device, E- Socket outlet/GPO, Energy Audit - Level 3, F-Diesel Pump - Low Fuel, F-Fire Water Supply Tank Fault, F-Location Incorrect - Fire Equipment, Faulty Pressure Reducing Valve, Pump Undersized, zIT - Active Directory AD Database Corruption, zIT - Citrix/Term Servic Application Compatibility, zIT - Desktop Software Config, zIT - Email Server Hardware, zIT - IIS Permissions /ACL, zIT - Other, zIT - Printing Hardware, zIT - SQL Permissions/ACL, Blocked Toilet-Debrities, E- Ballast/Driver, E- Cable Reticulation, E- Generator, E- Grid failure, E- Lamp other, E- Tube, EWIS Issue/Fault, F-FIP Alarm - Environmental, F-FIP Fault - Field Device, F-Fire Hydrant Leak, F-Passive Repairs, Faulty Relief Valve, Gate Valve Seized, OT-Unauthorised cabling change, Pump Running, Water Audit - Level 2, Water Audit - Level 3, zIT - Active Directory AD Configuration, zIT - Backup Configuration, zIT - Citrix/Terminal Services TS Profile, zIT - Desktop Hardware, zIT - DHCP Server Outage, zIT - DNS Database Corruption, zIT - DNS Cache Flush, zIT - DNS Zone Config, zIT - Domain Controller Security, zIT - Email Client Config, zIT - Email POP3 Config, zIT - Email Server Config, zIT - Email SMTP Config, zIT - IIS Virtual Directory Config, zIT - LAN Cabling, zIT - Network Drives Mapping, zIT - No fault found, zIT - Printing Server Print Spooler, zIT - Security Firewall Breach, zIT - Security Policy Configuration, zIT - Security Spam, zIT - SMS/Fax Messaging Service Providor, E-Cabling, E-Cable Termination, E-Fault Other, E-RCD/CB Fault, E-Ballast/Driver, E-Cable Reticulation, E-Faulty Apparatus, E-Tube, E-Power switching / Control, E-Switchboard, E-Starter, E-Fault in cable, E-RCD/CB Trip, Bldg - Door Defects, E-Faulty Appliance, E-Generator, E-Grid failure, E-Lamp LED, E-Network Device, OT-Faulty cabling, E-Switchboard Control

Appendix B: Cold Hard Facts stock of air conditioners in 2020

The stocks of equipment that are the subject of this study are highlighted in Table 6.

Table 6: Cold Hard Facts stock of air conditioners by equipment type in 2020.

Item no	Segment	Application	Category code	Product category	Stock 2020
1	AC1: Small AC: Self-contained	Window/wall	AC1-1	Non-Ducted: Unitary 0-10 kWr	1,119,000
2		Portable AC	AC1-2	Portable AC: 0-10 kWr	953,000
3	AC2: Small AC: Split	Single split: non-ducted	AC2-1	Single split system: Non-ducted: 1-phase	10,890,000
4		Single split: non-ducted	AC2-2	Single split system: Non-ducted: 3-phase	
5	AC3: Medium AC: Ducted & light commercial	Domestic & light commercial	AC3-1	Single split system: Ducted: 1-phase	2,173,000
6		Domestic & light commercial	AC3-2	Single split system: Ducted: 3-phase	
7		Light commercial	AC3-3	RT Packaged ducted systems	130,000
8		Domestic & light commercial	AC3-4	Multi split	467,000
9		Light commercial	AC3-5	VRV/VRF split systems	161,000
10	AC3: Medium AC: Ducted & light commercial	Light commercial	AC3-6	Close control	24,000
11		Light commercial	AC3-7	HW heat pump: commercial	2,600
12		Domestic & light commercial	AC3-8	Pool heat pump	47,000
13	AC4: Large AC: Chillers	Chillers	AC4-1	<350 kWr	9,700
14		Chillers	AC4-2	>350 & <500 kWr	4,300
15		Chillers	AC4-3	>500 & <1000 kWr	7,800
16		Chillers	AC4-4	>1000 kWr	3,700
17	AC5: Other	HW Heat pump	AC5-1	HW heat pump: domestic	296,000
18		Heat pump clothes dryers	AC5-2	Heat pump clothes dryers	210,000

Appendix C: Most prevalent faults in major equipment categories

This Appendix contains the data tables most prevalent faults and top ten energy penalty faults for six CHF equipment categories that were subject to the 5-year data analysis from 2015 to 2019.

Table 7: Chiller fault analysis.

Most prevalent chiller faults			Top 9 Chiller energy penalty faults		
Rank	Fault group name	% WO for this Fault	Rank	Fault group name	% WO for this Fault
1	Waterflow	23%	1	Waterflow	23%
2	Controls	22%	2	Controls	22%
3	Electrical	16%	3	Line/pressure	12%
4	Line/pressure	12%	4	Refrigerant fault	9%
5	Refrigerant fault	9%	5	Coil blockage	3%
6	No fault	4%	6	Mechanical	5%
7	Coil blockage	3%	7	Airflow	2%
8	Mechanical	3%	8	Other	2%
9	Other	2%	9	Design, installation, and Documentation	2%
10	Airflow	2%			
11	Design and installation	1%			
12	Documentation	1%			

Figure 14: Most prevalent chiller faults.

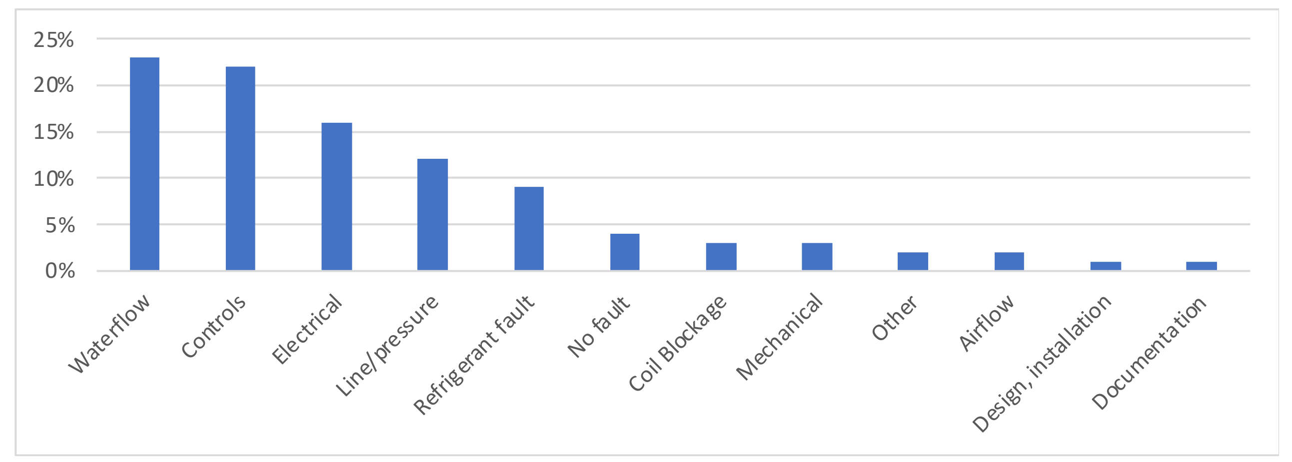


Table 8: Single split ducted system faults.

Most prevalent single split ducted system faults			**Top 10 Energy penalty faults single split ducted system**		
Rank	Fault group name	% WO for this Fault	Rank	Fault group name	% WO for this Fault
1	Airflow	19%	1	Airflow	19%
2	Electrical	17%	2	Filter	15%
3	Filter	15%	3	Controls	14%
4	Controls	14%	4	Refrigerant fault	6%
5	No fault	7%	5	Mechanical	4%
6	Refrigerant fault	6%	6	Line/pressure	4%
7	Condensate/Drain	6%	7	Coil blockage	3%
8	Line/pressure	4%	8	Design, installation equipment location	2%
9	Mechanical	4%	9	Other	2%
10	Coil blockage	3%	10	Waterflow	1%

11	Other	2%	11	Insulation	1%
12	Waterflow	1%			
13	Design and installation	1%			
14	Poor equipment location	1%			
15	Insulation	1%			

Figure 15: Most prevalent single split ducted system faults.

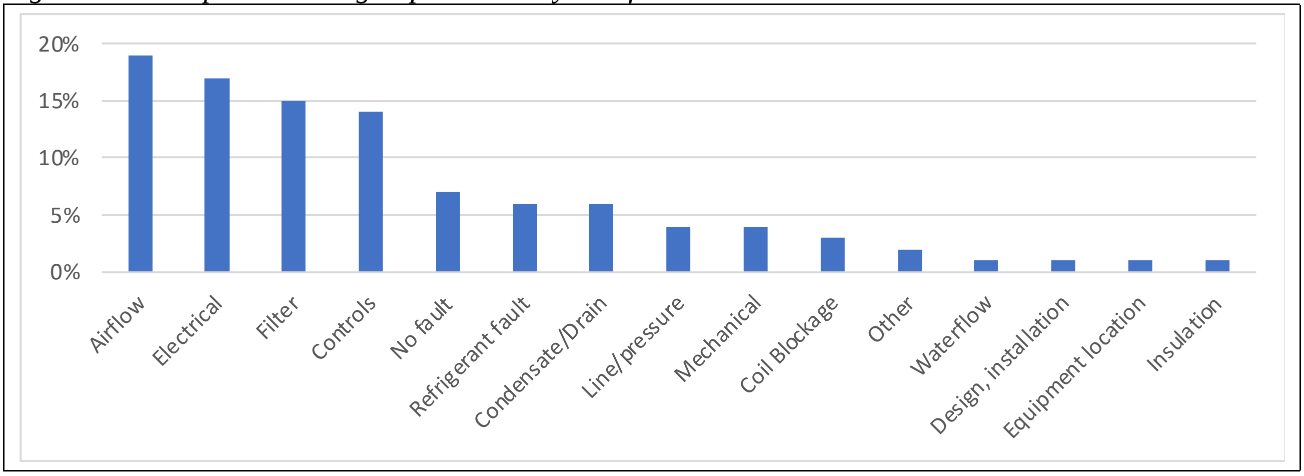


Table 9: Packaged ducted system faults.

Most prevalent packaged ducted systems faults			**Top 10 Energy Penalty faults packaged ducted systems**		
Rank	Fault group name	% WO for this Fault	Rank	Fault group name	% WO for this Fault
1	Electrical	19%	1	Airflow	14%
2	Airflow	14%	2	Filter	13%
3	Filter	13%	3	Controls	13%
4	Controls	13%	4	Refrigerant fault	8%
5	Refrigerant fault	8%	5	Line/pressure	7%

6	No fault	7%	6	Mechanical	4%
7	Condensate/Drain	5%	7	Waterflow	4%
8	Waterflow	4%	8	Coil blockage	3%
9	Mechanical	4%	9	Design, installation equipment location	2%
10	Coil blockage	3%	10	Other	2%
11	Line/pressure	3%	11	Insulation	1%
12	Other	2%			
143	Design and installation	1%			
14	Poor equipment location	1%			
16	Insulation	1%			

Figure 16: Most prevalent packaged ducted system faults.

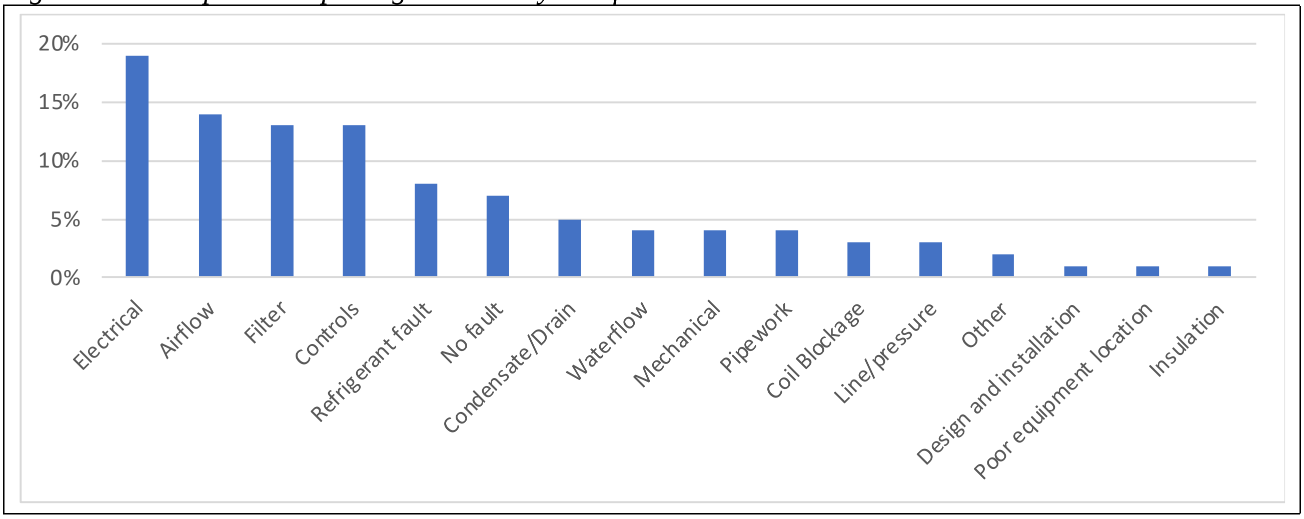


Table 10: VRV/VRF system faults.

Most prevalent VRV/VRF system Faults			Top 10 Energy Penalty faults VRV/VRF systems		
Rank	Fault group name	% WO for this Fault	Rank	Fault group name	% WO for this Fault
1	Electrical	26%	1	Controls	17%
2	Controls	17%	2	Refrigerant fault	13%
3	Refrigerant fault	13%	3	Airflow	8%
4	Airflow	8%	4	Coil blockage	6%
5	No fault	8%	5	Line/pressure	6%
6	Coil blockage	6%	6	Filter	4%
7	Line/pressure	6%	7	Mechanical	3%
8	Filter	4%	8	Other	3%
9	Condensate/Drain	3%	9	Design and installation	2%
10	Mechanical	3%	10	Waterflow	1%
11	Other	3%			
12	Design and installation	2%			
13	Waterflow	1%			

Figure 17: Most prevalent VRV/VRF system faults.

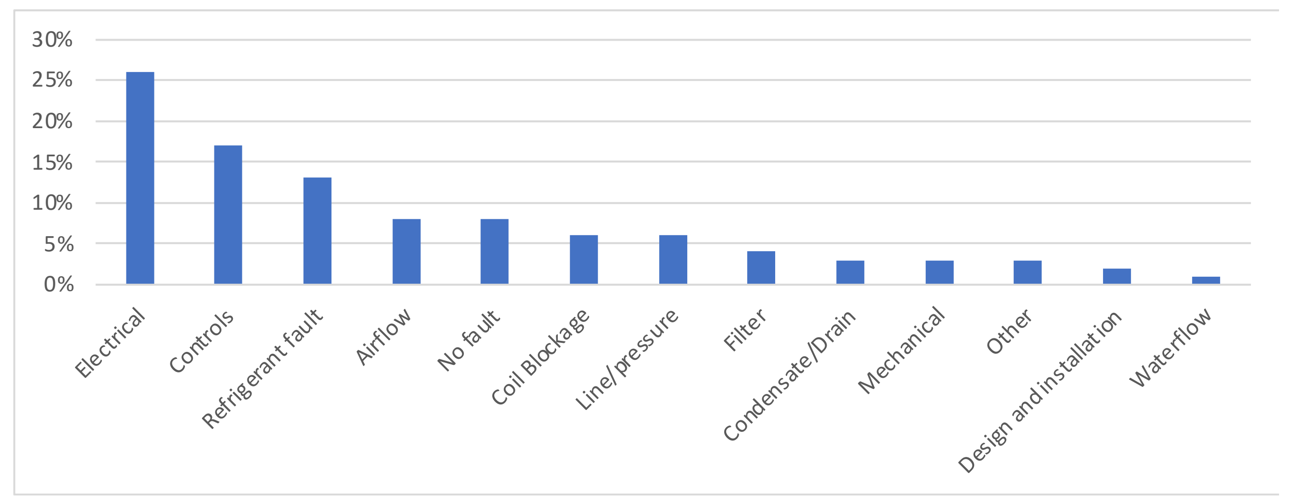


Table 11: Close control air conditioning system faults.

Most prevalent CRAC system faults			Top 10 Energy Penalty faults CRAC system		
Rank	Fault group name	% WO for this Fault	Rank	Fault group name	% WO for this Fault
1	Airflow	21%	1	Airflow	21%
2	Electrical	18%	2	Controls	11%
3	Controls	11%	3	Refrigerant fault	11%
4	Refrigerant fault	11%	4	Waterflow	6%
5	No fault	7%	5	Line/pressure	6%
6	Waterflow	6%	6	Filter	5%
7	Line/pressure	6%	7	Mechanical	4%
8	Filter	5%	8	Other	3%
9	Condensate/Drain	4%	9	Coil blockage	2%
10	Mechanical	4%	10	Design and installation	1%

11	Other	3%			
12	Coil blockage	2%			
13	Design and installation	1%			

Figure 18: Most prevalent close control air conditioning system faults.

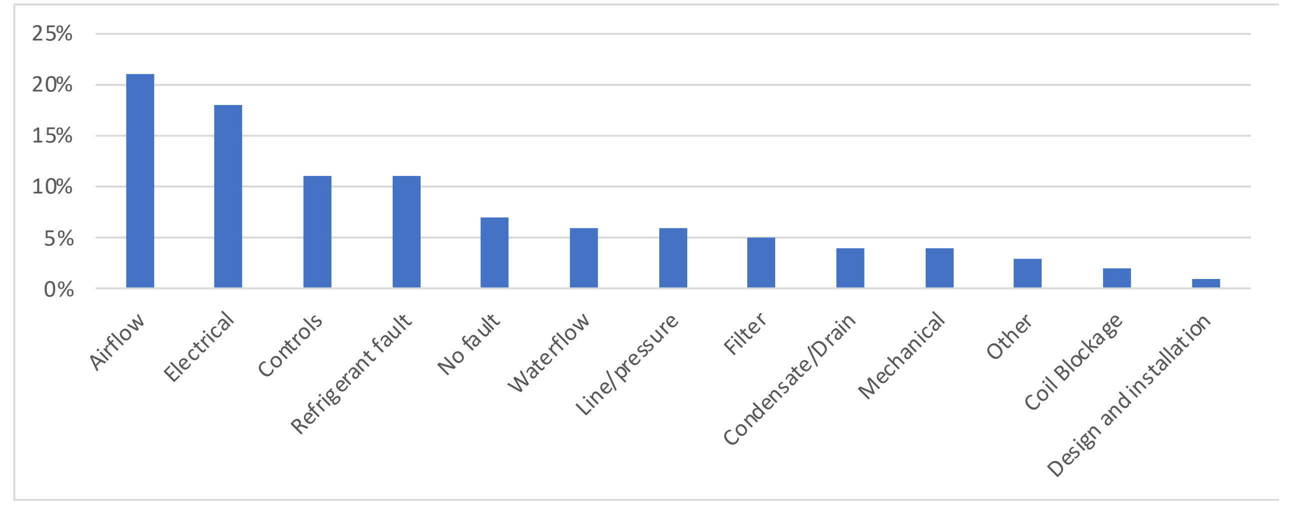
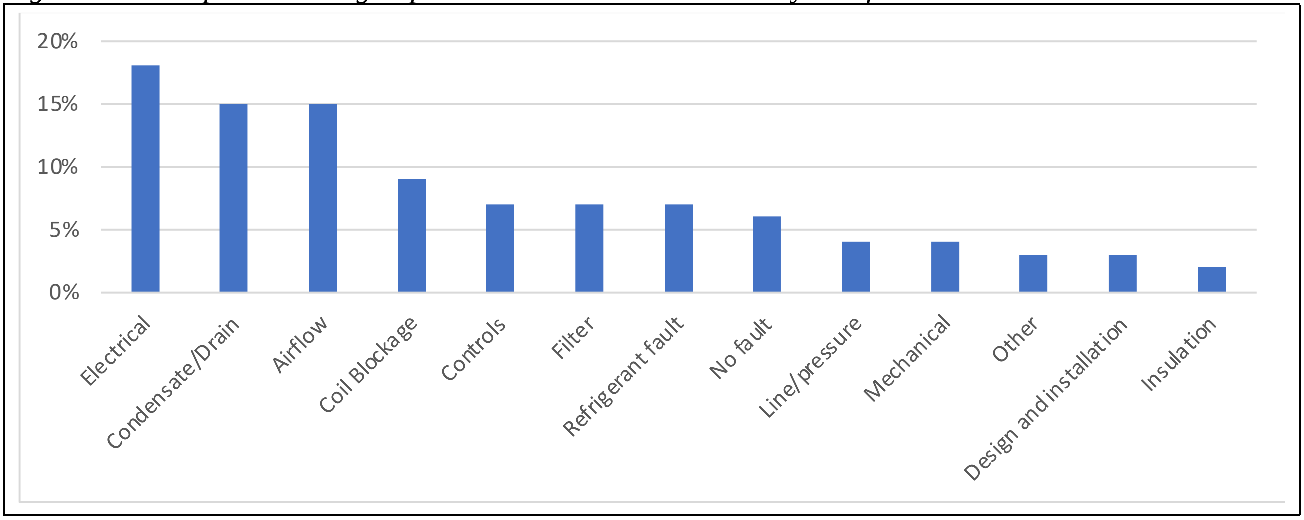


Table 12: Single split non-ducted air conditioner system faults.

Most prevalent Single split non-ducted air conditioner system Faults			**Top 10 Energy Penalty faults Single split non-ducted air conditioner system**		
Rank	Fault group name	% WO for this Fault	Rank	Fault group name	% WO for this Fault
1	Electrical	18%	1	Airflow	15%
2	Condensate/Drain	15%	2	Coil blockage	9%
3	Airflow	15%	3	Controls	7%
4	Coil blockage	9%	4	Filter	7%
5	Controls	7%	5	Refrigerant fault	7%
6	Filter	7%	6	Line/pressure	4%

7	Refrigerant fault	7%	7	Mechanical	4%
8	No fault	6%	8	Other	3%
9	Line/pressure	4%	9	Design and installation	3%
10	Mechanical	4%	10	Insulation	2%
11	Other	3%			
12	Design and installation	3%			
13	Insulation	2%			

Figure 19: Most prevalent single split non-ducted air conditioner system faults.



Appendix D: Common faults in air conditioning equipment from audits

Common faults in air conditioning equipment and systems from *Leaks, maintenance and emissions: Refrigeration and air conditioning equipment* ('the maintenance study').

Table 4: Common faults in air conditioning equipment and systems.

Fault		Split AC (Non-ducted)	Ducted AC (Split and package)	Central Plant (Chillers)	Installation related fault	Maintenance related fault	Opportunity/ priority	Section
1	Refrigerant (sub-optimal charge, over or undercharge, refrigerant leakage)	Y	Y	Y	Y	Y	1	4.1 and 4.2
2	Airflow: Air distribution, duct sizing, dampers and fans	N	Y	Y	Y	S	1	4.11.1
3	Airflow: Filters	Y	Y	Y	N	Y	1	4.11.2
4	Control systems, sensors, and wiring issues	N	Y	Y	Y	Y	1	4.6
5	Condenser issues (fouling, faulty fan)	Y	Y	Y	S	Y	2	4.3
6	Evaporator fouling	Y	Y	Y	N	Y	2	4.4
7	System capacity (no heat load, disconnect between owner and designer, safety margins) and mismatched components	N	Y	Y	Y	N	2	4.5
8	Refrigerant health and non-condensables	S	Y	Y	Y	Y	3	4.9
9	Poor equipment location	N	Y	S	Y	N	3	4.7
10	Duct insulation and leakage	N	Y	Y	Y	N	3	4.11.3
11	Liquid line issues (including restrictions)	S	Y	Y	Y	Y	4	4.8
12	Minimal documentation (i.e. installation, commissioning baseline data, operation, maintenance)	Y	Y	Y	Y	Y	4	4.10

Notes:

S = Some applications or circumstances.