IEA Heat Pump Programme

Annex 36

Quality Installation / Quality Maintenance Sensitivity Studies

Executive Summary

Operating Agent: United States

2014

HPP-AN36-SUM

PART 1: EXECUTIVE SUMMARY

Introduction to Annex 36

A significant opportunity for improving heat pump operating performance (capacity, efficiency, etc.) is related to how well the cooling and/or heating equipment is installed and subsequently maintained in varied building applications. One challenge in promoting proper installation and maintenance practices is that the marketplace incentivizes ‘cutting corners’ in the collective belief that low first cost is the important driver. This results in poor equipment performance and poor value as received by the end-user. Generally, an underlying cause of this predicament is that the various industry participants (e.g., original equipment manufacturers, equipment distributors, system designers, installers, etc.) – as well as the end users (e.g., building owners, operators, customers) do not appreciate how cumulative small deviations in installation and maintenance impact overall equipment performance.

It is universally recognized that heat pump equipment suffers significant performance loss depending on how well the equipment is designed, installed, and subsequently maintained. Some common deficiencies for heat pumps include:

- oversized equipment,
- improper refrigerant charge,
- incorrect airflow over the coil,
- incorrect water flow through the coil
- leaky air ducts.

However, the heating, ventilation, and air-conditioning (HVAC) industry lacked good quantitative information on the relative value and importance of varied field installation / maintenance practices and the effect that deficiencies may cause. Prior to the undertaking of this Annex activity, it was unclear whether small variances for a given-field-observed practice are significant, whether multiple faults or deficiencies have an additive impact on heat pump performance, and whether some deviations (in various equipment applications and geographical locations) have a larger impact than others. Earlier investigations examined existing equipment in the field and the impact that corrective measures may provide. However, the resulting anecdotal data provided limited quantifiable information on the impact of the various corrective measures on equipment performance.

Annex 36 investigated heat pump faults commonly found in operating equipment, and to assess the relative capacity and efficiency degradations caused by faults. The resultant effort is aimed at positioning stakeholders to better understand how installation and maintenance practices affect heat pump performance.

Objectives

The desired end-product objectives for the Annex 36 work were:

- Develop information for use by key stakeholders in industry (HVACR and construction trades), government (policy makers), and building sector (owners/operators).
- Produce reliable data to position each participating Annex country to evaluate its pertinent industry standards and practices for varied heat pump applications to ensure optimum heat pump performance.
- Reduce usage of energy and emissions of greenhouse gases by encouraging use of quality heat pump installation and maintenance practices.

Target Audience and Benefits

The sectors targeted to benefit from this Annex activity included:

- HVAC practitioners responsible for designing, selecting, installing, and maintaining heat pump systems in varied applications.
- Building owner/operators interested in achieving improved comfort conditioning and efficient performance from their HVACR equipment.

- Entities charged with minimizing energy utilization (i.e., utilities, utility commissions, energy agencies, legislative bodies, etc.) for different types of heat pump applications in varied geographic conditions.

Improved understanding on how quality installation (QI) and quality maintenance (QM) impacts equipment performance will help program managers to focus attention, resources, and effort on the important design, installation, and maintenance parameters that impact their varied programmatic efforts. Application of this improved understanding can help homeowners and building owners / operators appreciate the complete value-to-cost proposition – not merely the "first price" – when making equipment purchasing, installation, and maintenance decisions. Ultimately, discriminating customers will realize enhanced comfort, reduced energy usage, improved occupant productivity, and enhanced occupant safety.

Annex Activities and Time Schedule

Each Annex participant focused their independent efforts on those heat pump types and applications that are in general usage within their residential and commercial building sectors; see Table ES-1. Each country's recognized standards, industry practices, and measurement instrumentation approaches served as the basis for the individual efforts.

Table ES-1: Annex 36 Tasks and Time Schedule

Start Date	End Date	Annex 36 Activities
Nov 2010	Apr 2011	Task 1 – Critical literature survey: Undertake literature review and critical analysis of the results from prior related research to identify QI and QM metrics and to secure quantitative and qualitative impacts of various deviations from the specified levels recommended in industry's relevant QI and QM standards. This may include benchmarking of current QI and QM standards and practices in place in each participating country.
May 2011	Oct 2011	Task 2 – Identify sensitivity parameters: Building on the literature search, and working with pertinent country experts, develop a consensus of the QI and QM elements to be included in the participant's subsequent investigation.
Nov 2011	Jul 2012	Task 3 – Field investigation, Modeling and/or lab-controlled measurements: Field investigations, computer modeling, and/or laboratory-controlled experiments undertaken to verify the results provided by earlier researchers, to fill-in 'holes' in regard to quantifying the impacts of QI and QM vs. non-QI and non-QM applications, and to better understand the singular and additive impacts on equipment effectiveness.
Aug 2012	Apr 2013	Task 4 – Simulations on seasonal impacts: Simulations undertaken to determine the role that seasonal temperature differences have on the varied QI and QM elements and the resultant impact on heat pump performance. This modeling of different geographic temperatures impacts within a country or region (i.e., different outdoor temperature and humidity conditions) help to identify regional effects if any.
May 2013	Nov 2013	Task 5 – Report and information dissemination: Individual country analysis finalized and the individual country reports consolidated into a single Annex 36 volume.

Work Emphasis

Reports from the four participating countries are consolidated in this volume. The specific focus areas and emphasis undertaken by each country are identified in Table ES-2 below.

Table ES-2: Annex 36 Participants' Focus Areas and Work Emphasis

Annex 36 Participants	Focus Area	Work Emphasis
France	EdF – Space heating and water heating applications.	*Field:* Customer feedback survey on heat pump system installations, maintenance, and after-sales service. *Lab*: Water heating performance tests on sensitivity parameters and analysis.
Sweden	SP – Large heat pumps for multi-family and commercial buildings. KTH – Fault detection and diagnoses in heat pump systems.	*Field:* SP – Literature review of operation and maintenance for larger heat pumps. Interviews with real estate companies owning heat pumps. KTH - investigations and statistical analysis of 68,000 heat pump failures. *Modeling/Lab*: Determination of failure modes and analysis of found failures (SP) and failure statistics (KTH).
United Kingdom	DECC – Home heating with ground-to-water, water-to-water, and air-to-water systems.	*Field:* Monitor 83 domestic heat pumps and make modifications to improve performance. *Lab:* Investigate the impact of thermostatic radiator valves on heat pump system performance.
United States (Operating Agent)	NIST – Air-to-air heat pump in residential applications (cooling and heating).	*Lab*: Cooling and heating tests with imposed faults to develop correlations for heat pump performance degradation due to faults. *Modeling*: Seasonal analyses modeling to evaluate the effect of installation faults on heat pump seasonal energy consumption. Include effects of different building types (slab vs. basement foundations, etc.) and climates in the assessment of impact of various faults on heat pump performance.
<u>Participants</u> ACCA → Air Conditioning Contractors of America DECC → Department of Energy and Climate Change (UK) EdF → Electricité de France KTH → Royal Institute of Technology (Sweden) NIST → National Institute of Standards and Technology (US) ORNL → Oak Ridge National Laboratory (US) SP → Technical Research Institute of Sweden		

Country Specific Significant Results and Findings

The individual country reports go into significant details as to the work undertaken, application details, assumptions and constraints used, as well as results and implications of same. However, some significant findings drawn from the country reports are indicated in the balance of this summary.

FRANCE – *FOCUSED PROJECTS ON HEAT PUMP SPACE HEATING AND WATER HEATING*

The country report details work in four independent areas of interest:

1. Customer study aimed at determining the satisfaction level of heat pump end users,
2. Field analysis of an in-situ heat pump to explore how various attributes impact COP,
3. Sensitivity analysis of refrigerant charge on air-to-air heat pump performance,
4. In-situ field trials in ten residential homes of a Japanese thermodynamic ECS (Ecocute program) water heater to ascertain what technology transfer was necessary to adapt them to the European market.

Some of these efforts were commenced starting as early as 2005, others commenced in 2012.

Customer Survey

The customer survey was aimed at ascertaining the satisfaction level of the user of heat pump systems based on: heating system by type of heat pump, ease of maintenance, and the repair process. Feedback was collected from 202 owners of houses equipped with a thermodynamic heating system. Heat pumps were installed between January 2005 and October 2008 in four geographical regions: PACA, Midi-Pyrénées, Bretagne and north-eastern France. The information was collected in June and July 2009 based on telephone interviews. The distribution of heat pump types involved in the survey activity are shown in Table ES-3.

Table ES-3: Distribution of Heat Pump Types in French Literature Survey

Type of Heat pump	Distribution (%)
Air/water (heating only)	26
Air/water (additional heating)	28
Air/air	23
Geothermal	22

Among the air/water heat pumps, approximately two-thirds (2/3) are an outdoor single piece. In most cases, the heat pump manages the heating of the entire accommodation (94%), a little less for the air/air heat pumps (85%). As far as air/water and geothermal heat pumps are concerned, the emitters are mainly hot water radiators (71%). Even so, the heating floors represent one-fourth of the installations. In one-third of the cases, the heat pumps produce domestic hot water in addition to heating. One-third of heat pumps also provide air conditioning, but heat pumps meeting all three uses (heating, air conditioning, and domestic hot water) are rare. The average reported price of a heat pump installation, over the entire sample, is 13,500 Euros (€).

As can be seen in Table ES-4 below, the maintenance frequency for most heat pumps is usually carried out once a year. A guarantee of the proper operation of the installation and peace of mind for the customer are the main motives for signing a maintenance contract. Maintenance contracts come in a wide range of prices ranging from 80 € to 350 € with an average value of 144 €. Yet, there is no significant difference between the types of heat pumps.

Table ES-4: Frequency of Heat Pump Maintenance

Twice a year	5%
Once a year	89%
Once every two years	1%
As and when required	1%
No opinion	3%

One-fourth of field-surveyed heat pump owners had encountered technical incidents or heat pump failures (see Table ES-5 for frequency by failure mode). In most cases, it is the heating function that is affected by the incident. In nearly two-thirds of the cases, the incident resulted in the system failing to operate. However, in more than half the cases, the incident is regarded as "minor" by the customer.

The main conclusions that emerged from this survey were:

- One-third of heat pump owners indicated that a maintenance contract is not useful.
- Only 38% of heat pump owners had a maintenance contract, which was most often contracted at the time of installation. The average value of a maintenance contract was 144 €.
- The comfort provided by the heat pumps was considered to be good.
- The identified weak points were minor; but, equipment noise level was identified as an important issue.
- There were a rather large number of incidents; one-fourth of heat pump owners experienced problems.
- Apart from the investment cost, the consumption and maintenance costs were affordable.
- The main improvements expected by customers concern the reduction in the noise level and comfort control.
- Improvements expected by the customers concern: reduction in the installation cost, reduction in the noise level, comfort control, more explanations from the installers, and improvement of efficiencies for energy saving or for comfort.

Table ES-5: Failure Occurrences by Failure Mode

Incident	% of total occurrences	Incident	% of total occurrences
Water or liquid leak	16%	Filter clogged, obstructed	4%
Installation error, electrical connection error	12%	Circulator failure	2%
Refrigerant leak	8%	Compressor failure	2%
Adjustment problem	8%	Fan failure	2%
Frost, ice on fan	8%	Failure of a heat pump component	2%
Manufacturing defect on the heat pump	6%	Scale deposit	2%
Failure of the electronic board	6%	Difficulty in restarting the heat pump	2%
Shut down of the heat pump	6%	Air bubbles in the system	2%
Electrical problems: Circuit breaker "trips"	6%	Heat pump overheating	2%
Insufficient domestic hot water	4%	Need to redo the drilling	2%

Field Analysis and Modeling of an In-situ Heat Pump

A centralized air-to-air type heat pump monitored for a winter period (October 2011 - February 2012) by EDF R&D shows satisfactory performance levels over the examined period; an average COP of 3.3 is obtained. The selected instrumentation was simpler to set up on this centralized installation than on a multi-split.

A simple air/air heat pump model was created in order to estimate the impact of certain parameters, such as the rated COP or the sizing, on the seasonal COP. This model was developed from the SIMFAST calculation core used at the ENERBAT department and on a simple heat pump model developed in Excel based on data from a heat pump manufacturer. In spite of strong hypotheses (particularly an identical heating season for all regions compared), the conclusions of this preliminary work show that:

- Sizing the heat pump at 100% of requirements does not lead to an energy optimum, all the more so as the base temperature at which the calculations are performed is rarely attained with this model, which is based on a thirty-year weather forecast. The standby consumption significantly degrades the seasonal COP, particularly when heating requirements are low and spread out over time.

- The machine's load factor, particularly for newly built homes, has an impact on homes with low-load requirements; and thus the importance of proper sizing and control for this equipment type.

The causes for the lowered performance levels were combined in a family, classified according to possibilities of action: design, sizing rules, installation rules, and maintenance. The degradation of the COP is due to objective factors such as: non-optimized regulation for the on-site performance; standby consumption appreciably degrading the seasonal COP; non-optimized sizing. Additionally, there are subjective factors such as the occupant's choice of the temperature setting and in particular the comfort perception.

Specific installation and maintenance malfunction causes were explored in laboratory tests aimed at understanding the influence of low refrigerant charge on equipment performance.

Impact of Low Refrigerant Charge on Air-to-Air Heat Pump Performance

Another part of the EDF work involved the performance of air-to-air heat pumps and particularly, the causes for the lack of performance of this equipment. Evaluation on the performance differences between the field reality, and those measured in the laboratory, was carried out on air-to-air heat pumps starting in 2011 and carried through 2013.

An air-to-air, ductless, variable-speed heat pump, containing R-410A, was tested in the laboratory at the normative points of +7°C, +2°C, -7°C (44.6°F, 35.6°F, 19.4°F) for low refrigerant charge. The main objective of these tests was to demonstrate the influence of a low-refrigerant fault on the COP calculation and on the power output for similar conditions. Since the air-to-air machine has integrated controls, the investigation included comparing varied output parameters such as compressor speed (or frequency), electrical input power, condensation and evaporation temperatures, pressure (suction and discharge), and discharge temperature.

It was found that at low thermal loads the heat pump performance was affected by low refrigerant charge. For a lack of 40% of refrigerant, with respect to the rated load, the COP drops by 18% at a test condition of +7°C/20°C (44.6°F/68°F). At this condition, the impact is not as much on the compression rate or the evaporation pressure as it is on the compressor load (i.e., rotational speed). The performance degradation is weaker for lower operating temperatures (at which the COP is lower); however, the actual field required thermal load of the machine becomes greater. The rotational frequencies adopted by the machine are already very high for a load of -48% and -52% of the rated load; thus, the system could not provide the entire demand.

Prototyping of ECS Thermodynamic Water Heaters

Starting in 2009, EdF undertook in-situ field trials (in ten residential homes) of a Japanese thermodynamic ECS (Ecocute programme) water heater to ascertain what technology transfer was necessary to adapt them to the European market. The objectives of the on-site testing were to:

- adapt the machine as best as possible to "French" use of domestic hot water,
- measure the Coefficient of Performance over one year,
- participate in setting up a commercial offer,
- assess with the selected installer, the possible implementation difficulties for heat pumps,
- work on the product design by including an Eco-design dimension.

Based on the resulting operating data, an extrapolation using a weather forecast file for the Paris region resulted in an average annual COP in the order of 2.5; this value was appreciably lower than that which EDF initially identified as a desired objective. However, the most critical requirements were met, including during the winter period when the outside air temperature was approximately -11°C (12.2°F)!

The analysis of operating parameters identified the items to be improved, such as: the insulation of the tank, temperature stratification, and software management. Modifications were made to attain the ambitious objective of an average effective COP of 3, which subsequently positioned this equipment to favorably compare to other equipment options.

SWEDEN (KTH) – *A COMPREHENSIVE ANALYSIS OF FAULTS IN SWEDISH HEAT PUMP SYSTEMS*

The project 'Smart Fault Detection and Diagnosis (SFDD) for heat pump systems,' was undertaken in the energy department of the Royal Institute of Technology (KTH) in cooperation with Folksam (one of the largest insurance companies in Sweden), and also with some of the main Swedish heat pump manufacturers. The project was aimed at improving the performance of the systems while reducing maintenance times and costs.
The project was organized in several steps:

- *Literature survey*: Aimed at analyzing the available fault detection and diagnosis (FDD) techniques. Attention was placed on those techniques, which have been applied, or had influence in developing fault detection and/or diagnosis tools for heat pump systems.
- *Building a comprehensive database*: Identifying the most common faults occurring in domestic heat pump systems, which became the basis for the developing of the FDD system.
- *Design of fault detection system.*

The project objectives were:

- Build a reference database which includes the most common faults occurring in modern heat pump systems.
- Design a smart fault detection and diagnosis system at three different phases: commissioning, operation, and maintenance.

Review of FDD Techniques

The first part of the project studied the different techniques applied in FDD in general systems, and more in detail about heat pump systems. Fault detection of heat pumps can be performed with different methods. The most applied are indicated in Table ES-6.

Fault detection and diagnosis is a discipline that has been widely applied in different industries, for example in nuclear power plants, though it is still in its infancy for heat pump applications. Fault detection refers to the automatic process of determining whether a fault has occurred in the system. The next step, known as fault diagnosis, aims at determining the exact location, time, and magnitude of the fault. The aim of a fault detection and diagnosis system is to help the technician repair the fault by making the process more efficient and effective; thus, reducing repair and time costs.

Table ES-6: FDD Advantages and Disadvantages

FDD Methods	***Advantages***	***Disadvantages***
Data-driven methods	• They are well suited for problems in which the theoretical knowledge is poor or in systems where analytical models are complex and time consuming to develop. • They do not need a physical understanding of the system. • They are useful in systems where training data are easy to collect. • The computational effort required is generally manageable.	• A large number of data is needed, representing both normal and faulty operation. • The derived models cannot be used to draw conclusions beyond the range of training data. • The models are specific to the system for which they are trained.
Analytical methods	• They are based on physical principles; so, if the model is well formulated, they can provide the most accurate description of the system. • They can model both normal and faulty operation; therefore, fault conditions can be identified without having to run the system.	• They can be complex and time consuming to develop. • They can be computational intensive, therefore, not suitable for online FDD. • Models can require inputs that can be difficult to get.
Knowledge-based methods	• They are simple to develop and apply. • They can be useful when a large number of data and knowledge about failure of the system is available. • They are well suited when a deep knowledge about the system is lacking. • Their way of reasoning is transparent therefore easy to verify.	• They become more and more complicated and difficult to apply for complex system. • They are specific to a system or a process. • Their resolution can be approximate and strongly dependent on the expertise knowledge available.

Faults Database

To create an efficient FDD tool, it is fundamental to have a preliminary knowledge about faults, and about the most common faults that occur in heat pumps systems. Using the data provided by the Swedish insurance company Folksam, and the main Swedish heat pump manufacturers, statistics have been assembled that reveal the most common types of faults and problems occurring in installed Swedish residential heat pumps. The procedure of analysis was as follows:

- Data were categorized according to the different types of heat pumps (i.e., air-to-air, air-to-water, brine-to-water, exhaust air).
- Data where grouped into different categories by fault or a reason of failure.
- The most frequent and costliest faults reported to the insurance company and the heat pump manufacturers were determined.
- Meetings with heat pump manufactures were held in order to review the analysis and to investigate the root cause of the faults reported.

The Folksam database tabulated 13,993 faults and included fault data from 2001 to 2011; due to an error in the data files, data from year 2007 could not be included in the statistics. After removing wrong data, and data not including the model or the type of heat pump, the number of faults included in the analysis shrunk to 8,659. The same methodology was applied to the data coming from the heat pump manufacturers. There were about 37,000 faults field-reported to the heat pump manufacturers from beginning of 2010 to the end of 2012 (three years). These reports include the fault or complaints (e.g. about the noise in the system). The breakdown of faults, by equipment type, from the two sources are shown in Table ES-7:

Table ES-7: Fault Breakout by Equipment Type

Equipment Type	***Folksam Study***	***OEM Study***
Brine-to-water heat pump faults	41%	31%
Air-to-air heat pump faults	31%	8%
Air-to-water heat pump faults	15%	56%
Exhaust air heat pump faults	13%	5%

Table ES-8a is a summary of the results after processing the faults data provided by the insurance company, Folksam and Table ES-8b illustrates similar from the OEM-provided data.

Table ES-8a: Summary of Heat Pump Faults in the Folksam Study

	Type of Heat Pump (HP)			
	Air-to-Air HP	Air-to-Water HP	Brine-to-Water HP	Exhaust Air HP
The most common faults	Compressor (30%)	Compressor (52%)	Shuttle valve (22%)	Compressor (40%)
	Fan (19%)	Evaporator (6%)	Compressor (19%)	Control and Electronics (15%)
	Control and Electronics (13%)	Control and Electronics (4%)	Control and Electronics (14%)	Evaporator (11%)
The costliest faults	Compressor (46%)	Compressor (52%)	Compressor (49%)	Compressor (56%)
	Control and Electronics (12%)	Evaporator (6%)	Shuttle valve (9%)	Evaporator (15%)
	Fan (8%)	Refrigerant Leakage (5%)	Control and Electronics (9%)	Control and Electronics (9%)

Table ES-8b: Summary of Heat Pump Faults in the OEM Study

	Type of Heat Pump (HP)			
	Air-to-Air HP	Air-to-Water HP	Brine-to-Water HP	Exhaust Air HP
The most common faults	Fan (26%)	Pressure switch (44%)	Control and Electronics (31%)	Control and Electronics (32%)
	Control and Electronics (25%)	Control and Electronics (25%)	Shuttle valve (19%)	Shunt valve/motor (19%)
	Temperature Sensors (16%)	Temperature sensors (10%)	Liquid pumps (17%)	Temperature sensors (11%)
The costliest Faults	Control and Electronics (23%)	Pressure switch (25%)	Control and Electronics (28%)	Control and Electronics (24%)
	Refrigerant Leakage (17%)	Control and Electronics (21%)	Liquid pumps (18%)	Refrigerant leakage (17%)
	Fan (15%)	Compressor (19%)	Shuttle valve (12%)	Domestic Hot Water tank (13%)

Findings

When a good system model is available, fault detection approaches based on analytical models outperform the other cited techniques. Although some reported data were incomplete, the resulting inconsistencies were compensated for by a large amount of collected data that leads to more valuable statistical analysis. The categorized heat pump faults – based on the type of system (air-to-air, air-to-water, brine-to-water, exhaust air) and reported failure modes – highlighted the most problematic components.

- Although the results were slightly different between the Folksam and the heat pump manufacturers sources, somewhat similar results were obtained in terms of common fault identification and relative costs to correct the fault or faulty components.
- Based on the database provided by Folksam, the faults related to compressor, control and electronics, fans, and shuttle valves are the most frequent and also the costliest faults which were reported to the insurance company during the ten-year period.

SWEDEN (SP) – *OPERATION AND MAINTENANCE OF HEAT PUMPS IN APARTMENT BUILDINGS OWNED BY SMALLER PROPERTY COMPANIES*

The SP's programme of work was aimed at improving the quality of installation and maintenance of heat pump systems in Sweden. It focused on heat pumps serving apartment buildings in Sweden, where heat pumps are used mainly for space heating and domestic hot water heating. The full SP report describes three studies:

1. That part of the EFFSYS+ project "Operation and Maintenance of Refrigeration and Heat Pump Systems" focusing on heat pumps installed in Swedish apartment buildings and non-residential premises.
2. An English summary of a study focusing on experience from operation and maintenance of larger heat pumps and research in the heat pump field in Sweden during the 1980s.
3. The study "Improved Reliability of Residential Heat Pumps" made on behalf of the research fund of Länsförsäkringsbolagen, focused on heat pumps installed in Swedish single-family houses.

Operating and Maintenance of Refrigeration and Heat Pumps System

A main contribution of SP is the project "Operation and Maintenance of Refrigeration and Heat Pumps System" with the scope to maintain the installed capacity and efficiency of the heat pumps by applying maintenance methods, not to modify the installations.

The principle task was to identify the 3-to-5 most common problems with heat pump installations and suggest maintenance methods to prevent them. The first part of the project analysed conventional operation and maintenance principles and identified concepts that can be applied on heat pumps to prevent common failures. The second part in the project examined common and expensive failures of heat pumps servicing apartment buildings and non-residential premises in Sweden. An indirect expense was related to the use of back-up heating systems when the heat pumps were unable to operate properly because of failures and poor adjustments. The third part was to recommend cost-effective maintenance methods to prevent three of the identified failures.

The method used to find common failures and problems was to interview personnel working with heat pumps at property companies. A reference group of representatives from property companies, interest groups, and designers was also a part of the project. The main result of the interviews was that heat pumps themselves are seen as reliable; that is, in terms of providing space heating and domestic hot water heating. However, the main difficulties were:

- Lack of knowledge by building service personnel of proper purchasing, design and commissioning of heat pump systems; the ability to identify the requirements and to apply a heat pump system that suits the building.
- Lack of adjustment and functional control of the whole building system at heat pump start-up.
- Lack of knowledge on how to survey and control the heat pump system during operation.

It is more difficult for very small property companies (less than ten apartments and/or premises) to gather this knowledge than it is for larger companies with greater resources and more heat pumps installed in their buildings. It was therefore decided to focus on small property companies and to create a manual on operation and maintenance of heat pumps for apartment buildings. The outcome of this task was the creation of a maintenance manual for owners of heat pumps in multi-family houses. The resultant manual addresses problems associated with:

- Procurements competences – knowledge about heat pumps in the owners' purchasing group
- Heat pump system design for an existing building.
- Coordinator at design and commissioning – somebody with a responsibility of the whole building services system.
- Communication between the designer of the heat pump and the software engineer.
- Systems descriptions and manuals for operation and maintenance.
- An effective interface of the control and/or surveillance system.

Large Heat Pump – Research and Development During the 1980’s in Sweden

A literature review of operational experiences of large heat pumps and research from the 1980’s identified marketplace difficulties and best operating procedures for heat pump systems. But one difficulty was, and still is, to convince the owner that purchasing of operation and maintenance services will lead to economical profits.

To achieve better operational results at existing heat pump plants, five interventions for operation and maintenance were identified (and are valid still today):
1) Reducing the temperature of the supply flow from the heat pump condenser and making better use of its capacity.
2) Better tools for monitoring heat pump performance and related adjustments to achieve maximum performance.
3) Operation and maintenance readiness for maximum availability.
4) Supervisory and alarm equipment.
5) Training, particularly including practical tests, for operating personnel, service companies, consultants etc., concerning the above measures. This could help poorly performing units to achieve more profitable operation. Ideas for improving components, design, and supervisory and control equipment would also benefit from better knowledge.

It was estimated that, if the measures described above were realised on existing heat pumps at the time, an energy saving of 10 % could be achieved. It was opined that the cost for introducing the measures would be recouped by the value of one year’s energy savings.

Improved Reliability of Swedish Residential Heat Pumps

Heat pump heating systems are common in Swedish single-family houses. Many owners are pleased with their installation, but statistics show that a certain number of heat pumps break every year, resulting in high costs for both insurance companies and owners. On behalf of the research fund of Länsförsäkringsbolagen, SP studied the cause of the most common failures for residential heat pumps. The objective of the study was to identify measures to reduce the number of failures, (i.e., improving the reliability of heat pumps). The approach used was analysis of (1) publicly-available information on failure and sale statistics, and (2) interviews with heat pump manufacturers, installers, service representatives and insurance assessors. The interviews resulted in categorizing the most common failures based on whether they:
- could have been prevented by better operation and maintenance,
- were caused by a poorly performed installation,
- could have been prevented if certain parameters had been measured, recorded and followed up,
- were due to poor quality of components or systems.

The interviews indicated that failures on residential heat pumps are probably often caused by poor installation, neglected maintenance and monitoring, poor quality of standard components, or components that are used outside their declared operating range. Furthermore, many of the common failures can be caused by several of these categories and different types of measures must be taken to improve system reliability. Current focus is mainly on the energy efficiency of the heat pump and questions regarding lifetime and reliability may be neglected at purchasing. In order to improve the reliability of heat pumps installed in single-family houses, and reduce the costs for the insurance companies, there must be incentives for people to choose a product with good quality while engaging the best installers and service technicians. Many failures and costs are due to lack of knowledge. In addition, the heat pump owner must be informed to maintain the heat pump to ensure it functions as well as possible. In order to create these incentives, communication and cooperation between the stakeholders in the heat pump industry is needed.

UK – *IMPROVEMENTS TO DESIGN AND INSTALLATION STANDARDS OF DOMESTIC HEAT PUMP SYSTEMS*

The UK's programme of work was aimed at improving the quality of installation and maintenance of heat pump systems in the UK. It focused on the residential sector, where heat pumps are used for space and water heating, but are typically not used for cooling. The work comprised five main projects:

1) A literature review of issues relating to installation and maintenance, including, reviews of consumer protection, training courses, insurance, standards and field trials.
2) Analysing the performance of real systems and making interventions to improve performance in field trials.
3) Laboratory experiments to analyse the effect on heat pumps from cycling, water buffer tanks and the efficiency of hot water tanks.
4) Improvements to standards for design and installation.
5) Dissemination of improvements to standards through UK-wide roadshows for heat pump installers and social housing providers.

The comprehensive field trials carried out by the Energy Saving Trust, and analysed by DECC, have resulted in an update in the UK's standards for design and installation of heat pumps. DECC subsidised a series of road shows to inform installers and social housing landlords about these revisions.

Field Trails

In 2007, the Department of Energy and Climate Change (DECC) identified the lack of reliable field trial data as a major problem for the nascent UK heat pump industry. Working with both the public and private sectors, EST, funded by DECC and the UK heat pump industry, set up the first large scale field trial of domestic heat pumps in the UK. Eighty-three (83) heat pumps, located throughout the UK were monitored for one year (April 2009 to March 2010). Out of these, reliable data were obtained for 71 sites. The most common configuration was a ground-source heat pump supplying radiators and domestic hot water.

The overall system efficiencies were low; between 1.2 and 2.2 COPs for the air-source heat pumps, and between 1.8 and 3.4 for the ground-source heat pumps. The mean values were 1.8 ± 0.06 for the air-source heat pumps, and 2.39 ± 0.06 for the ground-source heat pumps. Six additional air-source heat pumps, selected by a manufacturer instead of being selected at random, were also monitored and showed better system efficiencies (between 2.4 and 3.0), demonstrating that good performance can be achieved with heat pumps that are designed, installed and configured correctly. [Note: It should be remembered the "system efficiency", as defined here, is strongly influenced by the householders' use of domestic hot water and by the heat losses from the domestic hot water cylinder.]

For this investigation, detailed analysis was carried out on a site-by-site basis to ascertain the reasons for low performance. The main design and installation issues were:

- Over-use of the electric backup heat. This may be caused by under-sizing of the heat pump or poor control strategies.
- Under-sizing of the ground loop.
- High central heating flow temperatures, leading to poor performance.
- High consumption of electricity by circulation pumps on the central heating side.
- Incorrectly sized domestic hot water tanks, leading to overuse of the electric immersion, or alternatively, wasting energy if more water is heated than the householder can use.
- Excessive use of defrosting (for air-source heat pumps).

As a result of these findings, two steps were taken. First, a number of heat pumps were selected for interventions to improve performance, and monitored for an additional year. Secondly, the Microgeneration Certification Standard MIS 3005 was updated to address these issues.

For the resultant Phase II field trials, 38 heat pumps were selected for interventions to improve performance, plus six OEM heat pumps were added to the sample. The interventions were classified into four categories:

1) Major: requiring the input of a heat pump specialist (e.g. replacing the heat pump, repairing the ground loop, refilling the refrigerant) (12 heat pumps).
2) Medium: requiring the input of a plumber (e.g. refilling the ground loop, adding a buffer tank, replacing a domestic hot water tank, replacing flap valves, replacing radiators, replacing circulation pumps) (9 heat pumps).
3) Minor: altering controls, disabling the auxiliary direct electric heater, switching off unnecessary circulation pumps (11 heat pumps).
4) None (6 heat pumps).

Figure ES-1 below compares system efficiencies that resulted from Phases I and II of the trial. These have been corrected to take account of the difference in degree-day heating requirements for the two phases of monitoring (winter 2009-10 was colder than winter 2011-12).

Nine (9) out of twelve (12) heat pumps with major modifications showed improvements in system efficiency from Phase I to Phase II. Of these, eight showed an improvement of ≥0.3. For two of the three sites for which system efficiency was reduced in Phase II, the reason was increased immersion consumption for domestic hot water.

Eight (8) out of nine (9) heat pumps that received medium interventions showed improved system efficiencies in Phase II. In five cases, the improvement was ≥0.3. The greatest improvement, from 2.31 to 3.29, was at a site where software was altered to reduce the use of the auxiliary heater. The remaining heat pump in this category developed a fault during the second phase.

These substantial improvements in system efficiency indicate that a majority of the problems were rectified.

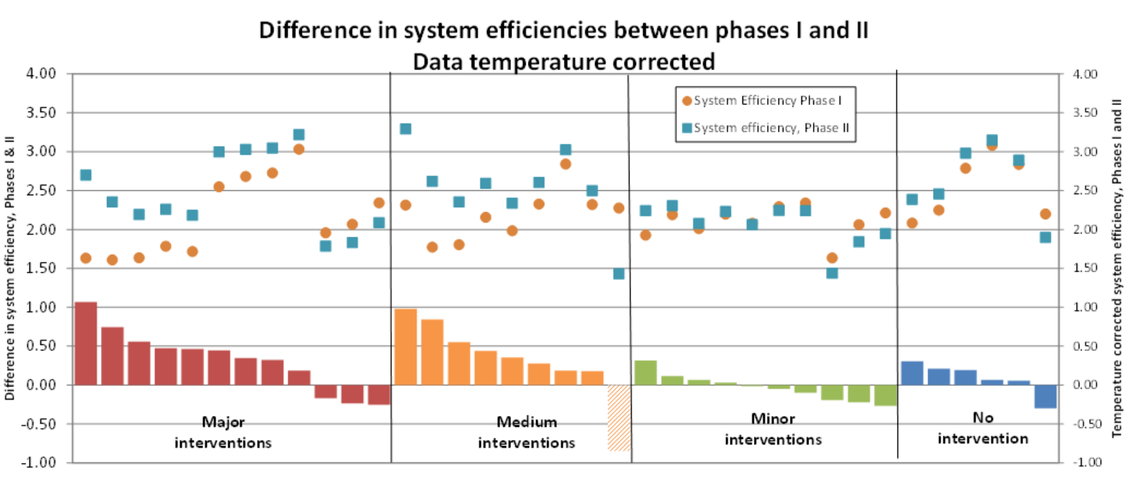

Figure ES-1: Difference in Temperature-Corrected System Efficiencies Between Phases I and II of the Energy Saving Trust Heat Pump Field Trials

Laboratory Experiments – Effect of Cycling on Heat Pump Efficiency

Heat pumps with fixed-speed compressors may cycle rapidly (i.e., short cycle) in warm weather, when the house does not require the full heat output of the heat pump. Heat pumps with variable-speed compressors are less likely to be affected. Short cycling can adversely affect the lifetime of the compressor and other components and may also reduce efficiency. In addition, the spike in current draw-off when the compressor starts up can have adverse effects on the grid. As a result of laboratory experiments, it was found that:

- *For air-sourced heat pumps*: As the operating runtime fraction decreases, the heat pump efficiency goes down dramatically.

- *For ground-source heat pumps*: For short runtimes, ground-source heat pump efficiency is reduced; but, the effect is less marked than for air-source heat pumps. (This is because the ground temperature does not cool as rapidly when the runtime is short.)

One way of reducing cycling is to include a buffer tank in the central heating circuit. This may be a two-pipe system (i.e. situated either in the flow or return pipes), or a four-pipe system (through which both the flow and return pipes flow). There are two, counter-prevailing principles at work when buffer tanks are incorporated into the water circuit:

1) The heat pump is more efficient when the return temperature is lower (i.e., the case with no buffer tanks).
2) Yet, inclusion of a buffer tank results in a larger hysteresis, which means that the heat pump will cycle less.

Experiments were carried out using a large heating volume (7 radiators), a medium heating volume (4 radiators) and a small heating volume (1 radiator). For the 7 and 4 radiator cases, ground-source heat pumps were relatively unaffected by the choice of configuration (2-3% performance change when the return temperature changed from 40 to 41°C (104 - 105°F)). While the performance of air-source heat pumps was improved when a buffer tank (of any configuration) was inserted, or when the hysteresis was increased for the case of no buffer tank. It is concluded that buffer tanks are not necessary in all heat pump circuits. Although they may be useful either when the volume of water heated is insufficient to avoid cycling or, alternatively, when heat pumps are operated on a cheap tariff and heat storage is necessary. If installed, a 2-pipe configuration in the return pipe is the preferred arrangement.

Additional experiments were undertaken to determine the most efficient way to heat domestic hot water with a heat pump, using a range of cylinder sizes, storage temperatures, heating patterns, sterilization patterns and tapping patterns. The study investigated the heat losses from the cylinder as a function of storage temperature, at low, medium, and high consumption levels. In all cases, cylinder losses increased by at least 20 percentage points as the storage temperature increases from 45˚C to 55˚C (113°F to 131°F). This would be compounded by a reduced efficiency of the heat pump when operating at higher temperatures (from the Heat Emitter Guide, the seasonal performance factor – SPF4 – for an air-source heat pump would be reduced from 3.0 at a flow temperature of 45˚C (113°F) to 2.4 at 55˚C (131°F)). For these reasons, the study recommends:

- For optimum efficiency, the storage temperature should be slightly lower than the flow temperature of the heat pump.
- Where usage is low, the cylinder should not be heated continuously.
- Weekly sterilization to 60˚C (140°F) should be carried out during periods of low use (e.g., at night).
- Heat pumps typically heat domestic hot water with a flow temperature of 45-50˚C (113°F to 131°F) and flow rate of 0.4 ls^{-1} (6.3 gpm). In order to transfer the heat to the water, a coil with a large surface area is required.
- Current kW ratings for heating coils in domestic hot water cylinders are calculated according to standard BS EN 12897, which applies to an 80˚C (176°F) flow temperature and a flow rate of 0.25 ls^{-1} (4 gpm). This is not appropriate for heat pumps and therefore a new system of rating is required.

Changes to UK Standards

Following the findings of the first phase of the Energy Saving Trust Field Trials, DECC, the Energy Saving Trust and the UK heat pump industry worked together to improve the design and installation standards for small scale heat pumps (< 45 kWth). As a result, the MCS MIS 3005 Issue 3.1 Standard came into force in March 2012. The principal differences between this standard and its predecessor are:

- *New sizing requirements*: A heat pump must be able to supply the steady-state space heating requirement of the house for 99% of the hours of a typical year without recourse to the electric auxiliary heater. In order to size the heat pump correctly, the installer must carry out a room-by-room calculation of heat loss. Additionally, for air-source heat pumps, the reduction in capacity as the temperature falls must be taken into account.

- *New guidance on heat emitter design*: The Heat Emitter Guide for Domestic Heat Pumps was revised to allow the installer to size and design the heat emitters correctly. It assigns an efficiency rating based on the flow temperature at the design ambient temperature for the location. As part of the handover process, the installer must show the householder this efficiency rating, which is displayed as 1 to 6 stars (6 being the most efficient). For good performance, low flow temperatures are required; guidance is given on the appropriate spacing of pipes in underfloor systems and the appropriate sizing of radiators.
- *New guidance on designing ground loops and boreholes:* The Ground Heat Exchanger Look-up Tables specify the power that can be extracted per meter of ground loop (or borehole) as a function of full time equivalent run hours, mean annual ground temperature, and ground conductivity.

The new standards also provide guidance on the sizing of domestic hot water cylinders and re-iterated the need to insulate all pipes and tanks thoroughly, and to sterilize the domestic hot water cylinder once per week to protect against Legionella and other bacteria.

US – SENSITIVITY ANALYSIS OF INSTALLATION FAULTS ON HEAT PUMP PERFORMANCE

The US investigation explores the impact that installation errors (e.g., improper refrigerant charge, incorrect air flow, oversized equipment, leaky ducts faults, etc.) have on the performance of a single-speed, 8.8 kW (2.5-ton), ducted, split-system heat pump having rated seasonal cooling and heating efficiencies of 3.81 SPFc and 2.26 SPFh, respectively (13 SEER and 7.7 HSPF) in a single-family, single-zone house. The laboratory/modeling project combined building, equipment, and climate effects in a comprehensive evaluation of the impact of installation faults on heat pump annual energy consumption via seasonal simulations of the house/heat pump system. Addressed was the significance of specific operational deviations (faults), whether the deviations (when combined) have an additive effect on equipment performance, and whether some deviations are more greatly impacted by climatic conditions than others. The parameters for the effort (see Table ES-9) were based on the requirements in the ANSI/ACCA 5 QI – 2010 Standard (*HVAC Quality Installation Specification*) with two additional items added as a result of the literature survey: (1) excessive liquid line refrigerant subcooling and (2) undersized thermal expansion valve (TXV).

The results from the critical literature survey are included in the country report in three sections; the identified publications are related to:

- air conditioner and heat pump installation and maintenance issues,
- heat pump oversizing/undersizing and cycling loses,
- heat pump fault detection and diagnostics.

Table ES-9: Parameters included in the investigation

Effects	***Varied parameters***
Building subsystem	– Duct leakage (unconditioned space)
Residential split, air-to-air heat pump equipped with a thermostatic expansion valve (TXV)	– Equipment sizing – Indoor coil airflow – Refrigerant charge – Presence of non-condensable gases – Electrical voltage – TXV undersizing – Excessive liquid line subcooling
U.S. Climates (cooling and heating)	– Hot and humid – Hot and dry – Mixed – Heating dominated – Very cold

Single-family houses (the structures representative for the geographic area)	– House on a slab (air ducts in unconditioned attic) – House with a basement (ducts in conditioned basement)

Laboratory Analysis

The laboratory analysis, using the same heat pump and test apparatus, expanded on prior work undertaken at NIST related to heat pump faults. Specifically added to the new work are: improper electric line voltage, TXV undersizing, and improper liquid line subcooling. The goal of the laboratory work was to develop the correlations that characterize heat pump performance that operate with varied faults. Table ES-10 lists nine (9) studied faults, including their definitions and studied ranges. The first seven (7) were included in the laboratory testing and subsequent modeling, the last two (2) faults were modeled only.

Table ES-10: Studied faults, definitions, and fault ranges

Fault name	Symbol	Definition of fault level	Fault Levels (%)
Improper indoor airflow rate	AF	% above or below correct airflow rate	CM: -36, -15, +7, +28 HM: -36, -15, +7, +28
Refrigerant undercharge	UC	% mass below correct (no-fault) charge	CM: -10, -20, -30 HM: -10, -20, -30
Refrigerant overcharge	OC	% mass above correct (no-fault) charge	CM: +10, +20, +30 HM: +10, +20, +30
Excessive liquid line refrigerant subcooling (indication of improper refrigerant charge)	SC	% above the no-fault subcooling value	CM: +100, +200 HM: none
Presence of non-condensable gases	NC	% of pressure in evacuated indoor section and line set, due to non-condensable gas, with respect to atmospheric pressure	CM: +10, +20 HM: +10, +20
Improper electric line voltage	VOL	% above or below 208 V	CM: -8, +8, +25 HM: -8, +8, +25
TXV undersizing	TXV	% below the nominal cooling capacity	CM: -60, -40, -20 HM: none
Duct leakage	DUCT	% of total equipment airflow that leaks out of the duct distribution system (60% supply leakage, 40% return leakage).	CM: +0, +10, +20, +30, +40, +50 HM: +0, +10, +20, +30, +40, +50
Heat pump sizing	SIZ	% above or below optimum heat pump capacity	CM: -20, +25, +50, +75, +100 HM: -20, +25, +50, +75, +100
Notes: CM = Cooling Mode HM = Heating Mode			

Simulations of Building / Heat Pump Systems with Installation Faults

The full report details simulations of annual energy consumption (combined heating and cooling) of a heat pump operating under various levels of different installation faults. The simulations focused strictly on performance issues of the house/heat pump systems related to heat pump capacity and heat pump energy consumption; heating and cooling energy consumption is delineated. The effect of the installation faults on occupant comfort was not the main focus of the study, and the effort did not seek to quantify any impacts on indoor air quality or noise generation (e.g., airflow noise from air moving through restricted ducts). Additionally, the study did not address the effects that installation faults have on equipment reliability/robustness (number of starts/stops, etc.), maintainability (e.g., access issues), or costs of initial installation and ongoing maintenance.

Impact of Single Installation Faults on Heat Pump Performance

Table ES-11 shows representative examples of annual energy used by a heat pump installed with different installation faults. The increase in energy consumption, for each fault type, is presented on a relative base as an isolated fault on an otherwise fault-free installed system. The table data was extracted from simulation results presented in the full U.S. report. It is anticipated that the selected levels of individual faults reflect an installation condition which might not be noticed by a poorly-trained, or inattentive, technician.

Table ES-11: Annual energy use by a heat pump resulting from single-fault installation, referenced to a fault-free installation

Fault type	***Fault level***	***Relative energy use (%)*** ***[100 is baseline]***								
		Slab-on-grade house installation (Air ducts located in unconditioned attic)					Basement house installation (Air ducts in conditioned basement)			
	%	HOU	LV	WAS	CHI	MIN	LV	WAS	CHI	MIN
AF	- 36	112	113	114	113	111	111	112	112	110
UC	- 30	121	122	123	120	117	120	121	119	117
OC	+ 30	110	110	114	113	112	111	116	115	113
SC	+ 200	118	116	119	118	116	118	120	120	119
NC	+ 10	102	102	101	101	101	102	101	101	101
VOL	+ 8	102	101	102	102	101	101	102	102	102
TXV	- 40	114	110	107	105	107	109	105	103	102
DUCT	+ 30	118	117	124	126	126	100*	100*	100*	100*
SIZ (2)	+ 50	115	113	105	101	99	114	108	104	102
	U.S. cities included in the study: **HOU** → Houston, TX **LV** → Las Vegas, NV **WAS** → Washington, DC **CHI** → Chicago, IL **MIN** → Minneapolis * It is assumed that duct leakage into basements have no energy impact (inside thermal boundary) (2) Oversize scenario (2) described in Section 5.5.5 of the US report.									

Tables ES-11 indicates that there are no drastic differences in the effect of installation faults on energy use in a slab-on-grade house and a basement house, except for the duct leakage fault (DUCT). For the slab-on-grade house, duct leakage has the potential to result in a higher increase in energy use than any other fault. The impact of this fault is higher for the heating dominated climate (Chicago and Minneapolis, 26 %) than for the cooling dominated climate (Houston, 18 %). Obviously, duct leakage will also result in some increase of energy use for the basement house; however, the modeling approach employed could not discern this increase.

The next most influential faults were refrigerant undercharge (UC), refrigerant overcharge (OC), and improper airflow across the indoor coil (AF). For the 30% undercharge fault (UC) level, the energy use increase is of the order of 20%, irrespective of the climate and building type. Refrigerant overcharge (OC) can also result in a significant increase in energy use, 10 - 16% at the 30% overcharge fault level. Improper indoor airflow (AF) can affect similar performance degradation. [Note: Excessive refrigerant subcooling (SC) correlates to refrigerant overcharge (OC); 100% subcooling is approximately equivalent to 20% refrigerant overcharge.]

Equipping a house with an oversized heat pump (SIZ) has a small effect if the air duct is oversized accordingly (which may be the case with a new construction). However, if the air duct is undersized or otherwise too restrictive, and the nominal indoor airflow is maintained by adjusting the fan speed (scenario 2), 15% increase in energy use for the house in Houston is predicted. The full report notes that there are latent issues associated with varied fault conditions and that the number of hours at or greater than an indoor relative humidity (RH) of 55% is dramatically impacted.

The undersized cooling TXV fault (TXV) also has the potential to significantly increase the energy use. The effect of this fault will be most pronounced in localities with a high number of cooling mode operating hours. The cooling mode TXV, undersized by 40%, results in 14% more energy consumption in Houston as compared to 5% in Chicago.

The impact of the remaining faults – non-condensables (NC) and improper voltage (VOL) – is under 4%. The non-condensables and improper voltage faults, however, represent a substantial risk for durability of equipment and are very important to be diagnosed during a heat pump installation.

Impact of Dual Installation Faults on Heat Pump Performance

The combination of two faults, A and B, were considered in the following four combinations as listed in Table ES-12 below:

Table ES-12: Combinations of studied faults

Fault combination case	Level of fault A	Level of fault B
a	moderate	moderate
b	moderate	worst
c	worst	moderate
d	worst	worst

The 'moderate level' is the value at the middle of the range, while the 'worst level' is the highest (or lowest) probable level of the fault value (see Table ES-10). Table ES-13 presents specific fault sets for the combined annual heating and cooling cases (sets 1 – 11) and cooling only case (sets 12 – 14). The furthest right-hand column in the table shows the effect of the combined faults on energy use: the faults' effect on increased energy consumption may be additive (A+B), less than additive (<A+B), or greater than additive (>A+B).

Table ES-13: Dual fault sets considered in annual simulations (heating and cooling) and their approximate collective effect on annual energy use

Multiple fault set #	Fault A (moderate & worst level) [(a)]	Fault B (moderate & worst level) [(a)]	Effect on Energy Use
1	Duct leakage (20%, 40%)	Oversize[(b)] (25%, 50%)	A + B
2	Duct leakage (20%, 40%)	Indoor coil airflow (-15%, -36%)	< A + B
3	Duct leakage (20%, 40%)	UC (-15%, -30%)	A + B or > A+ B
4	Duct leakage (20%, 40%)	OC (15%, 30%)	A + B
5	Duct leakage (20%, 40%)	NC (10%, 20%)	A + B
6	Oversize [(b)] (25%, 50%)	UC (-15%, -30%)	A + B
7	Oversize[(b)] (25%, 50%)	OC (15%, 30%)	A + B
8	Oversize (25%, 50%)	NC (10%, 20%)	A + B
9	Indoor coil airflow (-15%, -36%)	UC (-15%, -30%)	A + B
10	Indoor coil airflow (-15%, -36%)	OC (15%, 30%)	< A + B
11	Indoor coil airflow (-15%, -36%)	NC (10%, 20%)	< A + B
12	Duct leakage (20%, 40%)	TXV undersizing[(c)] (-20%, -60%)	A + B
13	Oversize (25%, 50%)	TXV undersizing[(c)] (-20%, -60%)	A + B
14	Indoor coil airflow (-15%, -36%)	TXV undersizing[(c)] (-20%, -60%)	< A + B

Notes:
(a) – Moderate = mid-level value, worst = lowest/highest level value.
(b) – Oversize scenario (2) was selected because it covers the prevalent field bias (undersized ducts).
(c) – TXV undersizing only impacts cooling; faults listed as Fault A exist in cooling and heating (applies to Sets 12, 13, 14).

Faults effects may be additive (A+B), less than additive (<A+B), or greater than additive (>A+B).

Simulations were performed for 14 dual fault sets (refer to Table ES-13), with four (4) fault combinations per set, in the 9 house/climate combinations for a total of 504 runs. The relative impact on annual energy use is shown in Figure ES-2 and Figure ES-3.

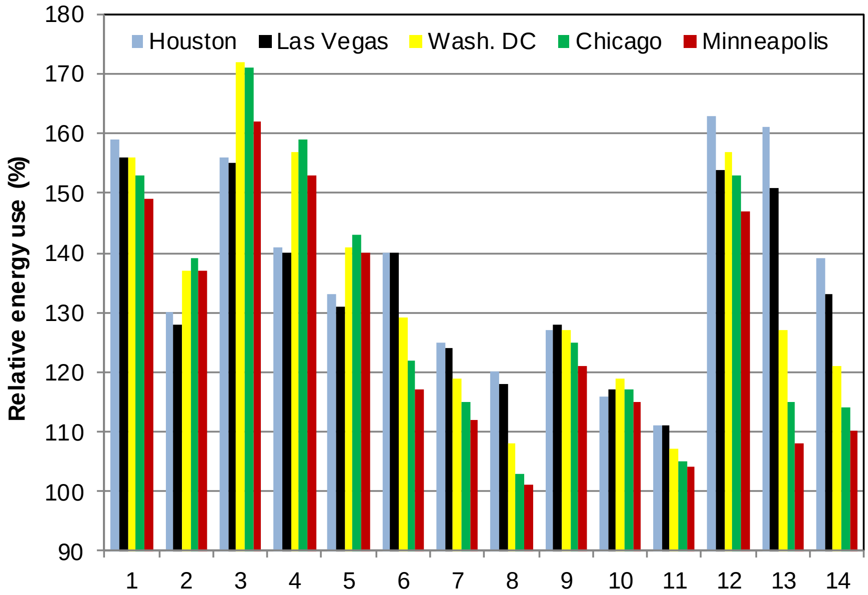

Figure ES-2: Annual energy use for ducts located in unconditioned attics with 14 dual-faults relative to the energy use for the houses with fault-free installations (Faults defined in Table ES-13; Table ES-12 case d, worst level for both faults; 100 is baseline).

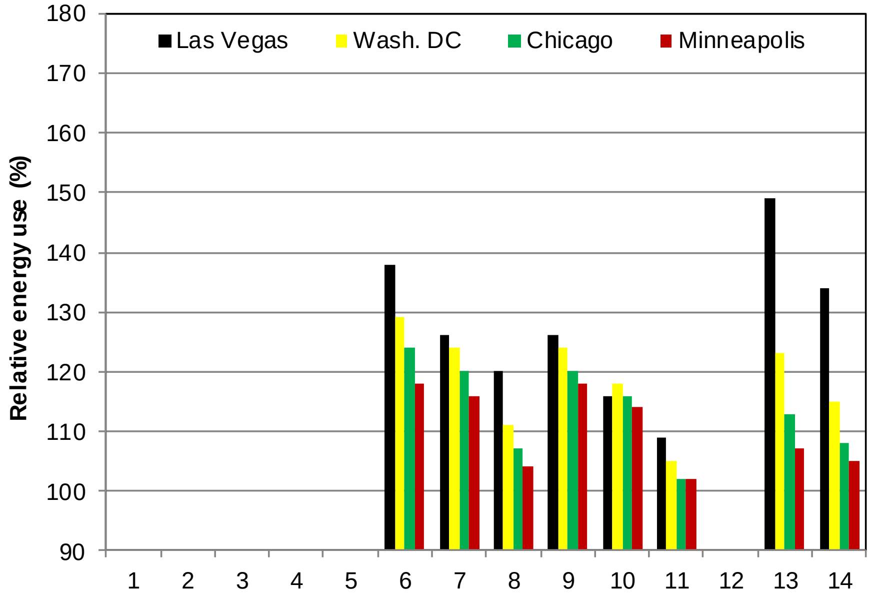

Figure ES-3: Annual energy use for ducts located in conditioned basements with 8 dual-fault installations referenced to the energy use for the houses with fault-free installations (Faults defined in Table ES-13, Table ES-12 case d; worst level for both faults; the omitted dual faults involve duct leakage, which was not considered in houses with basement; 100 is baseline).

Effects of Triple Faults

Triple faults were not simulated in this study. Nevertheless, the occurrence of three simultaneous faults is plausible, particularly for the most common faults such as refrigerant undercharge, improper indoor airflow, or duct leakage. The report notes that it is reasonable to assume that the effect of a triple fault will be as least as high as that of any of the possible three fault pairs considered individually; however, the effect of the third fault can increase the effect of the other two faults in an additive manner.

Findings

Extensive simulations of house/heat pump systems in five U.S. climatic zones lead to the following conclusions:

- The study found that duct leakage, refrigerant undercharge, oversized heat pump with undersized ductwork, low indoor airflow due to undersized ductwork, and refrigerant overcharge have the most potential for causing significant performance degradation and increased annual energy consumption.
- Effect of different installation faults on annual energy use is similar for a slab-on-grade house (ducts located in the unconditioned attic) and a basement house (ducts located in the semi-conditioned basement), except for the duct leakage fault.
- Effect of different installation faults is similar in different climates except for the following cases:
  - Duct leakage: significant increase in the indoor relative humidity for an installation in a hot and humid climate.
  - Heat pump oversizing with undersized air ducts: in heating-dominated climates, heat pump oversizing reduces the use of backup heat, which may compensate for the increased indoor fan energy use associated with overcoming the higher external static pressure.
  - Undersized cooling mode TXV: little effect in heating-dominated climates, while a significant increase of energy use is possible in cooling-dominated climates.
- The report notes that a significant increase in annual energy use can be caused by lowering the thermostat in the cooling mode to improve indoor comfort in cases of excessive indoor humidity levels. As an example, for Houston, TX, lowering the thermostat setting by 1.1°C (2.0°F) increased the annual energy use by 20%, and the energy use increase rate is even higher due to further lowering the setting (the effect is not linear).
- The effect of simultaneous faults can be additive (e.g., duct leakage and non-condensable gases), little changed relative to the single fault condition (e.g., low indoor airflow and refrigerant undercharge), or well-beyond additive (duct leakage and refrigerant undercharge).
- The report authors contend that the laboratory and modeling results from this fault analysis on a 8.8 kW (2.5 ton) heat pump are representative of all unitary equipment, including commercial split-systems and single package units (e.g., roof top units).

Annex 36 Future Research Needs

As can be observed in the above summary, the type of investigations undertaken by the participating countries were very different, and the studied equipment applications were broad. However, there are a number of cross-cutting needs that universally accrue to all and are in need of future exploration:

1) Determine the effect of simultaneous, multiple faults / deficiencies (at different severity levels) through rigorous laboratory measurements.
2) Relatedly, there is need to collect and analyze in field fault data (type, frequency, degree of severity) to quantify the impact that heat pump inefficiency on a national level.
3) Determine the effect of installation / operational faults on energy use of energy-efficient heat pumps installed in energy-efficient buildings; combination of laboratory measurements and building/heat pump simulations.
4) Development of open communication protocols for heat pump commissioning and re-commissioning; entails a common set of error codes as well as a universal access port/method to retrieve the error codes.
5) Effort is needed to improve cold-climate efficiency and reliability of heat pump technologies.
6) Need to quantify the effect that installation and maintenance deficiencies have on occupant comfort / health, equipment reliability / robustness / maintainability, and operational / maintenance costs.
7) Reliable, cost-effective, in-situ means to measure heat pump capacity (delivered kW/hr or BTU/hr) versus operating efficiency (delivered capacity divided by total energy input).
8) Investigate methods for controlling bacteria such as Legionella in domestic hot water applications.
9) Information on installation rules and maintenance procedures needs to be created and provided in a manner that installers and service personnel can easily understand and implement.
10) Approaches to improve communications and cooperation among the various stakeholders (manufacturers, distributors, customers, insurance companies, efficiency programs, etc.) to ensure that incentives, encouragements, and rewards result in quality equipment being purchased with installations and maintenance undertaken by trained, qualified service personal.

IEA Heat Pump Programme
Heat Pump Centre
c/o SP Technical Research Institute of Sweden
PO Box 857
SE-501 15 BORÅS
Sweden
Tel: +46 10 516 5512
E-mail: hpc@heatpumpcentre.org
www.heatpumpcentre.org

HPP-AN36-SUM