

Study of the ozone depletion and global warming potentials associated with fridge recycling operations that involve the manual stripping of polyurethane insulation foam

**14 September 2010
Darmstadt, Germany**

Project sponsor:

RAL–Gütegemeinschaft Rückproduktion von
Kühlgeräten e.V.

Authors:

Günter Dehoust
Dr. Doris Schüler

Öko-Institut e.V.

Freiburg – Headquarters

Postfach 50 02 40
79028 Freiburg, Germany

Physical address

Merzhauser Straße 173
79100 Freiburg, Germany

Tel. +49 (0) 761 - 4 52 95-0

Fax +49 (0) 761 - 4 52 95-88

Darmstadt Office

Rheinstraße 95
64295 Darmstadt, Germany

Tel. +49 (0) 6151 - 81 91-0

Fax +49 (0) 6151 - 81 91-33

Berlin Office

Novalisstraße 10
10115 Berlin, Germany

Tel. +49 (0) 30 – 40 50 85-361

Fax +49 (0) 30 – 40 50 85 - 388

Contents

1	Introduction	1
2	Tests	2
2.1	VersuchskonzeptionTest design	2
2.2	VersuchsdurchführungTest implementation.....	2
2.3	Test analysis methodology.....	3
2.4	VersuchsergebnisseTest results.....	5
2.4.1	Ergebnisse für den KorpusResults from tests carried out on appliance cabinets	5
2.4.2	Results from tests carried out on appliance doors	7
2.4.3	Results for the appliance as a whole	8
2.4.4	Error analysis.....	9
2.4.5	Relationship between appliance size and CFC losses	11
2.4.6	Discussion	12
3	Evaluation of test results.....	14
4	Ozone depletion and global warming potential	16
4.1	Ozone depletion potential.....	16
4.2	Global warming potential	16
5	Practical conclusions for fridge recycling operations	18
6	References.....	19
7	Appendix 1: Photo documentation of the manual dismantling of fridges at a recycling company in the USA	20
8	Appendix 2: Photo documentation of the manual dismantling tests carried out in Limburg on 14– 16 September 2009.....	21

List of Figures

Figure 2.1	Correlation between appliance size and CFC losses	11
------------	---	----

List of Tables

Table 2-1: Results from tests carried out on appliance cabinets	6
Table 2-2: Results from tests carried out on appliance doors	7
Table 2-3: Results from tests carried out on appliance carcasses (cabinets + doors) ...	9
Table 3-1: Test results for the appliance carcasses (cabinets + doors) excluding the results for the three largest appliances	14

1 Introduction

At present, state-of-the-art recycling of waste refrigeration appliances involves treatment in fully encapsulated plants in which the appliances are broken apart and shredded, the secondary raw materials are individually recovered and harmful components or substances are separated for disposal or destruction. If recycling is carried out in accordance with the RAL quality assurance specifications (RAL GZ-728 Quality Assurance and Test Specifications), more than 90% of the particularly harmful CFCs are separated and safely destroyed.

Certain countries that are considering the introduction of a systematic fridge recycling scheme have proposed dispensing with the fully mechanised treatment that corresponds to the current generally accepted state of the art in fridge recycling. The approach suggested involves removing the refrigerant from the cooling circuit of the waste appliance (stage I of the treatment process) and then manually disassembling the appliance and stripping out the insulating foam, which is then sent to landfill for incineration or for treatment in a special degassing facility in which the CFCs are extracted and then liquefied. It should, however, be noted that no detailed plans or practical implementation of the latter processing channel exist at present.

To quantify the (additional) emissions of CFC produced by this approach, the emissions from manually dismantling the appliance and then disposing of the foam in a standard waste incinerator or in a landfill site need to be determined and compared with the emissions arising when state-of-the-art fridge recycling technology is used to treat waste appliances and to dispose of the secondary raw materials and residual materials. The ozone depletion potential and global warming potential associated with these methods must also be determined.

The relatively low levels of CFC emissions associated with state-of-the-art fridge recycling (treatment conforming to the requirements for the award of the RAL GZ-728 quality mark) were calculated and evaluated in a life-cycle assessment (LCA) study conducted by Öko-Institut e.V. on behalf of the RAL Quality Assurance Association for the Demanufacture of Refrigeration Equipment [Öko-Institut 2007]. The LCA study showed that state-of-the-art processing of an average refrigeration appliance (40 kg, 80% of the appliances processed were CFC-containing units) resulted in CFC emissions of about 0.45 kg per appliance (expressed in R11 equivalents). The main source of emissions was identified as the residual CFC still trapped in the degassed polyurethane (PU) foam and that was partially released when the foam was subjected to further processing.

In the present study, the average emissions associated with the manual disassembly of refrigeration appliances were determined solely during the manual dismantling phase. The emissions associated with the subsequent disposal phase will be determined at a later date as part of a separate expert study and assessed in a joint final report.

2 Tests

2.1 Test design

The tests were designed on the basis of reports and documentary photographic and film material dealing with the manual dismantling of refrigeration appliances in the USA (Freep 2009).

2.2 Test implementation

The tests were carried out in the period 14–16 September 2009 at the recycling centre operated by GAB mbH in Limburg, Austria. GAB in Limburg has been active in the environmentally safe treatment of waste electrical and electronic equipment for more than 10 years. The manual dismantling of the appliances was carried out by trained GAB personnel. Weighing and data recording was done by Öko-Institut staff.

The initial steps of the manual dismantling work were carried out, as is the case in the USA, using professional power tools, such as a high-quality electric all-purpose saw that can easily cut through the metal and plastic cabinets. Special lever irons and crow bars were also used. A special tool was used to scrape off the PU foam. Tools that would have produced significant quantities of dust, such as angle grinders, were not deployed.

It should be noted that GAB performed the manual dismantling effectively as a pilot operation. It was not possible to determine in this study whether, when carried out as a part of commercial recycling activities, manual dismantling can be conducted as cleanly as was possible in the 'model environment' offered at GAB.

The manual dismantling tests were documented photographically (see Appendix 2).

The following electronic scales were used in this study:

Rhewa table-top scales 833C

weighing range: 0–40 kg; scale division: 1 g; linearity: ± 5 g

The tests were carried out as follows:

1. GAB mbH provided about 20 refrigeration appliances of various sizes and subjected these appliances to stage I processing (vacuum extraction/removal of the CFC R12 and the compressor oil from the cooling circuit and removal of any glass, capacitors, mercury switches, compressors, covers and any loose plastic parts). The doors were unscrewed and removed. The subsequent tests were carried out on these empty appliance cabinets and their separated doors.

2. The masses of nine cabinets and nine doors were then determined. Testing was restricted to those appliances that had polyurethane foam insulation in both the cabinet and the door. Appliances containing polystyrene insulation were not included in the test. After testing, samples of PU foam from each of the nine appliances were analysed in a laboratory to determine their chemical composition. The laboratory confirmed that the CFC R11 was present in each of the nine samples.
3. Cabinets and doors were tested separately. The cabinets and doors were first placed into a large trough. The dismantling procedure used here can be referred to as a coarse foam stripping process typically involving the use of an electric all-purpose saw followed by removal of the foam by hand or separation of the foam using a lever iron. In contrast to the method known to be used in companies in the USA, any small areas of residual foam still adhering to metal or plastic parts of the cabinets or doors was not scraped off. The dismantling process yielded the following material fractions: metal and plastic fraction with some residual PU foam still attached, large coarse chunks of PU foam, and a minor fraction of fine material mainly made up of metal and plastic chippings and shavings. The fines fraction comprised the small particles that had dropped to the bottom of the basin and the material that had been swept up in the vicinity of the basin. Any smallish pieces or chunks of PU foam found at the bottom of the basin or in the sweepings were added to the fraction of PU foam. The weight of each of the fractions (including the fines and the sweepings) was then determined.
4. Finally, the weight of the residual PU foam still adhering to metal and plastic was determined. This was done by scraping the residual PU foam by hand from the cabinet and door parts using bevel-edged chisels, wire brushes and other tools until only minimal quantities remained and then weighing the PU foam scrapings that had been collected.
5. The PU foam fractions from seven of the nine appliances were stored in open sacks and then reweighed after 24 hours. The difference in mass was recorded.
6. The PU foam fractions from four of the nine appliances were also re-weighed after two weeks.

2.3 Test analysis methodology

The test data was analysed separately for the appliance cabinets and the appliance doors. The aim of the analysis was to determine how much CFC escapes into the atmosphere when PU insulating foam is manually stripped from waste refrigeration appliances, how much CFC remains in the adhered PU foam residues, and how much CFC is lost to the atmosphere during the subsequent storage of the PU fraction.

Analysis was based on the following assumptions:

- The average mass fraction of CFC in the PU foam was assumed to be 8.5% for all appliances [UBA 1998].

- It was assumed that any loss of mass during manual foam stripping arose solely from CFC degassing to the atmosphere.
- The amount of CFC present in the residual PU foam still adhering to cabinet and door parts after manual foam stripping was estimated to be 50 % of the foam's original CFC content. This value of 50 % was derived from the following considerations: Standard stage II processing of waste refrigeration appliances (joint treatment of CFC-containing and CFC-free appliances in a single plant) involves the thorough mechanical destruction (shredding/grinding) of the appliance carcass. The CFC content in the PU foam residues on the resulting metal and plastic fractions is about 30 % of that originally present in the foam. [UBA 1998] [Elektrolux 1989] [Iuta 2005]¹. If CFC-containing and CFC-free appliances are processed separately (so-called 'parallel processing'), those appliances thought to be CFC-free are treated directly in a car shredder with the result that the PU foam chunks produced are significantly larger than in joint processing. It has been established that because of inevitable sorting errors in practical recycling operations, some of the appliances identified as CFC-free do in fact contain CFC blowing agent [Öko-Institut 2007]. According to recycling company representatives, the PU foam from such CFC-containing appliances that have been erroneously classified as CFC-free and therefore processed in a car shredder is estimated to contain about 70 % of the CFC originally present in the foam [Öko-Institut 2007]. The CFC-content in the PU foam residues still adhering to metal and plastics following manual disassembly probably lies somewhere between these two values. On the one hand, the PU foam chunks produced by manual foam stripping are not as fine as the PU foam produced in a joint processing plant, on the other hand, the foam residues still adhering to metal and plastic parts are significantly less compact and have a much larger specific surface area compared to the PU chunks found in the PU output fraction from a car shredder. It therefore seems highly plausible that the amount of CFC present in the PU foam residue found after manual disassembly is about 50% of the amount of CFC present in the foam originally (i.e. on average, the mass fraction of CFC in the PU foam residue is about 4.25%).
- It was assumed that the loss in mass of the PU fraction during storage was due solely to CFC degassing from the foam.
- The following four CFC loss channels were considered:
 - o release of CFC into the atmosphere during sawing;

¹ Cf. UBA Guidelines [UBA 1998], which assume that after shredding 20–30 % of the R11 blowing agent is still present in the shredded foam. A study conducted by a recycling plant operator [Iuta 2005] indicated that after shredding with rotary shears, 28–34 % R11 is still trapped in the foam particles. The investigations detailed in [Electrolux 1989] show that if the size of the PU foam is reduced to a grain size of between 10 mm and 15 mm, 37 % of the R11 remains within the granular PU.

- release of CFC into the atmosphere during subsequent dismantling with lever irons, crowbars and the special tools used for scraping off the PU foam;
- CFC remaining within the residual PU foam adhering to metal and plastic parts (it seems reasonable to assume that the CFC in the foam residue will be almost completely released to the environment when the metal and plastics fractions are subjected to further downstream shredding/grinding processes);
- CFC losses during storage of the PU foam fraction after dismantling.

A discussion of data errors and the results of an error analysis are presented in Sec. 2.4.4.

2.4 Test results

2.4.1 Results from tests carried out on appliance cabinets

Table 2-1 shows the results achieved from tests carried out on the appliance cabinet (appliance carcass without door).

The test numbers refer to the numbering used to identify the 20 appliances that were actually prepared for testing. The appliances finally selected for testing were chosen for their general suitability and to achieve an appropriate distribution of appliance sizes. For example, appliances that, in addition to polyurethane, also contained another insulating material were not selected for testing.

The average mass of the appliance cabinets that were tested was 17 kg. The lightest cabinet had a mass of 9.5 kg, while the heaviest cabinet weighed 34.3 kg.

The appliance cabinets tested contained between 1.6 and 11.6 kg of PU foam; the average amount was 4.4 kg of PU foam per cabinet.

The calculated total amount of the CFC R11 originally present in the cabinets tested ranged from a minimum value of 136 g per cabinet to a maximum of 986 g with the mean average value being 371 g per cabinet.

The CFC losses from the manual foam stripping process were between 12 g and 224 g with the average value being 81 g.

Between 2.4 g and 10 g of CFC were lost (on average 6.8 g per cabinet) because of the CFC still present in the residual PU foam adhering to the dismantled appliance cabinet.

The total loss of CFC from a cabinet during manual dismantling (including CFC retained in adhered PU foam residues) ranged from 15 g to 233 g with the average value being 88 g per cabinet. These figures correspond to percentage losses of between 10% and 33% and an average percentage loss of 23.8%.

As expected, the CFC losses from the manual foam stripping process contribute much more significantly (on average 92%) to total CFC losses than the losses associated with the residual PU foam.

It is particularly interesting to note that significant quantities of CFC degas from the PU foam scrapings during interim storage. Even after 24 hours of storage, a further 1.3% to 5.5% of the CFC originally present in the foam had been lost.

Table 2-1: Results of tests carried out on appliance cabinets

(Note: As the numerical data in the tables have been rounded, there may be a slight imprecision associated with some of the calculated values shown.)

Test No.	Mass of appliance prior to dismantling	Losses during manual foam stripping	Mass of PU foam chunks after foam stripping	Mass of PU foam from scraping off adhered foam residues	Total mass of PU foam originally present (foam from stripping + foam scrapings + losses during stripping)	Ratio of mass of foam scrapings to total mass of foam	Mass of PU foam / mass of appliance
	kg	g	kg	kg	kg	%	%
1	12.6	41	2.5	0.3	2.8	9.5	22.5
2	11.6	36	3.1	0.1	3.2	3.0	27.7
4	11.5	12	1.7	0.1	1.8	7.7	15.9
19	34.3	224	11.0	0.3	11.6	3.0	33.8
20	27.3	171	5.9	0.4	6.4	6.1	23.6
6	9.5	16	1.4	0.2	1.6	12.3	17.2
7	14.7	64	3.0	0.2	3.3	7.3	22.2
8	15.8	78	4.0	0.3	4.4	6.9	28.0
12	15.6	91	3.5	0.4	4.0	9.6	25.7
Min	9.5	11.7	1.4	0.1	1.6	3.0	15.9
Max	34.3	224.0	11.0	0.4	11.6	6.9	33.8
Mean	17.0	81.3	4.0	0.3	4.4	7.3	24.1

Test No.	Mass of CFC in foam prior to dismantling	CFC loss to air during manual foam stripping	CFC in adhered foam residues	CFC in adhered foam residues	CFC losses from manual foam stripping + CFC retained in foam residues <small>relative to amount of CFC originally present</small>	CFC losses from manual foam stripping + CFC retained in foam residues	Further CFC losses after storage for 24 h <small>relative to amount of CFC originally present</small>	Further CFC losses after storage for 2 weeks <small>relative to amount of CFC originally present</small>
	g	%	g	%	%	g	%	%
1	241	17	7	3	19.7	47.6	2.1	
2	272	13	2	1	14.0	38.1	1.5	
4	155	8	4	2	9.8	15.3	1.9	
19	985	23	9	1	23.6	232.9	2.5	0.5
20	547	31	10	2	33.2	181.4	5.5	1.9
6	139	12	5	4	15.4	21.5		
7	279	23	6	2	25.1	69.8	1.8	2.5
8	376	21	8	2	22.7	85.5	1.3	1.2
12	341	27	10	3	29.5	100.5		
Min	155	7.5	2.4	0.9	9.8	15.3	1.3	0.5
Max	985	31.3	10.1	3.7	33.2	232.9	5.5	2.5
Mean	371	21.9	6.8	1.8	23.8	88.1	3.0	1.5

2.4.2 Results from tests carried out on appliance doors

Table 2-2 shows the results achieved from tests carried out on the appliance doors.

The average mass of the appliance doors that were tested was 6.7 kg. The lightest door had a mass of 3.6 kg, while the heaviest door weighed 15.6 kg.

Table 2-2: Results of tests carried out on appliance doors

(Note: As the numerical data in the tables have been rounded, there may be a slight imprecision associated with some of the calculated values shown.)

Test No.	Mass of appliance prior to dismantling	Losses during manual foam stripping	Mass of PU foam chunks after foam stripping	Mass of PU foam from scraping off adhered foam residues	Total mass of PU foam originally present (foam from stripping + foam scrapings + losses during stripping)	Ratio of mass of foam scrapings to total mass of foam	Mass of PU foam / mass of appliance
	kg	g	kg	kg	kg	%	%
1	4.4	1	0.3	0.0	0.3	0.0	6.0
2	4.2	12	0.8	0.1	0.9	12.9	21.0
4	3.6	6	0.3	0.1	0.4	21.9	9.8
19	7.1	8	1.6	0.1	1.7	5.4	24.7
20	10.3	6	1.0	0.2	1.3	17.1	12.2
6	4.3	2	0.2	0.1	0.2	22.4	5.7
7	4.2	6	0.4	0.2	0.6	25.7	14.2
8	6.5	4	0.3	0.1	0.4	29.2	5.9
12	15.6	9	0.7	0.1	0.8	10.0	5.1
Min	3.6	1	0.2	0.0	0.2	0.0	5.1
Max	15.6	12	1.6	0.2	1.7	29.2	24.7
Mean	6.7	6	0.6	0.1	0.7	16.0	11.6

Test No.	Mass of CFC in foam prior to dismantling	CFC loss to air during manual foam stripping	CFC in adhered foam residues	CFC in adhered foam residues	CFC losses from manual foam stripping + CFC retained in foam residues relative to amount of CFC originally present	CFC losses from manual foam stripping + CFC retained in foam residues
	g	%	g	%	%	g
1	23	6	0	0	5.8	1.3
2	75	16	5	6	22.3	16.7
4	30	21	3	11	32.4	9.7
19	149	6	4	3	8.3	12.3
20	107	6	9	9	14.5	15.5
6	21	11	2	11	22.4	4.7
7	50	13	6	13	25.4	12.8
8	33	13	5	15	27.9	9.1
12	68	14	3	5	18.7	12.7
Min	21	5.6	2.3	0.0	5.8	1.3
Max	149	21.4	9.1	14.6	27.9	15.5
Mean	62	10.2	4.2	6.9	17.1	10.5

The appliance doors tested contained between 0.2 and 1.7 kg of PU foam; the average amount was 0.7 kg of PU foam per door.

The calculated total amount of the CFC R11 originally present in the doors prior to testing ranged from a minimum value of 21 g to a maximum of 149 g per door, with the mean average value being 62 g.

The CFC losses from manually stripping foam from the doors were between 1 g and 12 g, with the average value being 6 g.

Between 2.3 g and 9 g of CFC were lost (on average 4 g per door) because of the CFC still present in the residual PU foam adhering to the dismantled appliance door.

The total loss of CFC per door during the manual dismantling of the appliance doors (including CFC retained in adhered PU foam residues) ranged from 1.3 g to 15.5 g, with the average value being 10.5 g per appliance door. These figures correspond to percentage losses of between 6% and 28% and an average percentage loss of 17%.

On average, the manual foam stripping process is responsible for about 60% of total CFC losses. The CFC losses associated with the residual CFC foam still adhering to the dismantled door parts are therefore substantially greater than was the case with the appliance cabinets.

2.4.3 Results for the appliance as a whole

The following table shows the test results for the appliance cabinets with doors (carcass).

The average mass of the appliance carcasses tested was 23.7 kg. The lightest carcass had a mass of 13.8 kg, while the heaviest weighed 41.4 kg.

The appliance carcasses tested contained between 1.9 and 13.3 kg of PU foam; the average amount was 5.1 kg of PU foam per carcass.

The calculated total amount of CFC R11 originally present in the appliances prior to testing ranged from a minimum value of 160 g to a maximum of 1134 g per carcass with the mean average value being 432 g

Table 2-3: Results of tests carried out on appliance carcasses (cabinets + doors)

(Note: As the numerical data in the tables have been rounded, there may be a slight imprecision associated with some of the calculated values shown.)

Test No.	Mass of appliance prior to dismantling kg	Total mass of PU foam originally present (foam from stripping + foam scrapings + losses during stripping) kg	Mass of CFC in foam prior to dismantling g	CFC loss to air during foam stripping g	CFC loss to air during foam stripping %	CFC in adhered foam residues g	CFC in adhered foam residues %	CFC losses from manual foam stripping + CFC retained in foam residues relative to amount of CFC originally present %	CFC losses from manual foam stripping + CFC retained in foam residues g
1	17.0	3.1	264	42	15.9	7	3	18.5	48.9
2	15.8	4.1	348	48	13.7	7	2	15.8	54.8
4	15.1	2.2	185	18	9.8	7	4	13.5	24.9
19	41.4	13.3	1.134	232	20.5	13	1	21.6	245.2
20	37.6	7.7	654	178	27.2	19	3	30.1	196.9
6	13.8	1.9	160	19	11.7	7	5	16.3	26.1
7	18.9	3.9	329	70	21.3	13	4	25.1	82.6
8	22.2	4.8	408	82	20.1	13	3	23.2	94.6
12	31.2	4.8	410	100	24.4	13	3	27.7	113.2
Min	13.8	1.9	160	18	9.8	7.3	1.1	15.8	24.9
Max	41.4	13.3	1.134	232	27.2	19.2	4.7	30.1	245.2
Mean	23.7	5.1	432	88	18.3	11.0	2.5	22.8	98.6

The CFC losses from the manual foam stripping of the carcasses (cabinets plus doors) were between 18 g and 232 g with the average value being 88 g.

Between 7 g and 19 g of CFC were lost (on average 11 g per carcass) because of the CFC still present in the residual PU foam adhering to the dismantled appliance carcass.

The total loss of CFC per carcass during manual dismantling (including CFC retained in adhered PU foam residues) ranged from 25 g to 245 g with the average value being 98.6 g per appliance carcass. These figures correspond to percentage losses of between 16 % and 30 % and an average percentage loss of 23 %.

On average, the manual foam stripping process is responsible for about 89 % of total CFC losses.

2.4.4 Error analysis

The following sources of error were considered when assessing the results of the tests:

1. It is conceivable that the PU foam takes up moisture from the air during the testing period. If this were the case, the CFC losses calculated from the test results would be too low. However, it can be assumed that the effects of this possible source of error are small, as measurements made after storage showed that the weight of the PU foam continued to decrease. If any water

uptake had occurred to any relevant degree, it seems probable that an increase in weight would have been observed in some batches.

2. It is equally conceivable that the PU foam released moisture to the air during the testing period. If this were the case, the CFC losses calculated from the test results would be too high. Moisture was identified during manual foam stripping in only one appliance cabinet (cabinet no. 8). However, the calculated CFC loss from this appliance during manual dismantling was very close to the mean average value from all tests and the further reduction in mass observed during post-test storage was in fact below the average value. It can therefore be assumed that the release of moisture into the air takes place so slowly that it has only a negligibly small influence on the test results.
3. The original CFC content in the PU foam, which was assumed to be 8.5%, is not constant for all CFC-blown foams and can vary within a range that cannot be defined exactly. Determining the original CFC content in a specific appliance is both time and cost intensive as the very process of removing a sample for laboratory analysis will result in the loss of an unknown amount of CFC from the foam. A sensitivity analysis in which the mass fraction of CFC in the untreated PU foam was reduced from 8.5% to 7% showed that the resulting CFC losses during manual dismantling (incl. losses due to PU foam residues) changed only marginally (97 g instead of 99 g).
4. The CFC content in the residual adhering foam was estimated to be 50% of the foam's original CFC content. The rationale underlying this assumption was discussed earlier. As the amount of residual PU foam adhering to metal and plastic parts represents on average only about 7% of the total quantity of PU foam, this parameter only has a minor effect on the overall result. This was confirmed by the following sensitivity analysis. Reducing the CFC content in the residual adhering foam from 50% to 40% resulted in only a slight change (98 g instead of 99 g) in the CFC losses calculated for the manual dismantling process (incl. losses due to CFC in the PU foam residues).
5. The linearity of the balance was ± 5 g. This imprecision primarily effects the calculation of the CFC released into the air during manual dismantling and also, though to a far lesser extent, the CFC losses associated with the residual adhering foam.
6. A further source of test data uncertainty can arise from the loss of fine dust-like abraded material or from the input of dust from the surrounding work environment. The amount of fine material swept up and collected after manually stripping foam from the cabinets was between 5 g and 77 g; the average value was 28 g. A further 12 g was collected by re-sweeping the floor area after completing all tests on the first day of testing (14 September).

Summary of error analysis:

Compared to the last two sources of error discussed above, the first four sources of error have only a minor influence on the test results. The linearity of the electronic scales and the data uncertainty associated with the loss of fine material on the

workplace floor or the inclusion of additional fine material from neighbouring areas influence the accuracy of the calculated CFC losses to air during manual dismantling. The estimated maximum uncertainty associated with these two sources errors is $\pm 20\%$. The maximum data uncertainty for the overall result 'CFC losses from manual foam stripping and from CFC retained in adhered foam residues' is therefore $\pm 18\%$. The average CFC loss from an appliance carcass (cabinet and door) can therefore be given as $(21.3 \pm 3.8)\%$ plus additional losses of the order of 4% during a two-week period of storage.

2.4.5 Relationship between appliance size and CFC losses

The following diagram shows the CFC losses determined for the entire appliance carcass (cabinet plus door) plotted as a function of appliance weight prior to manual foam stripping.

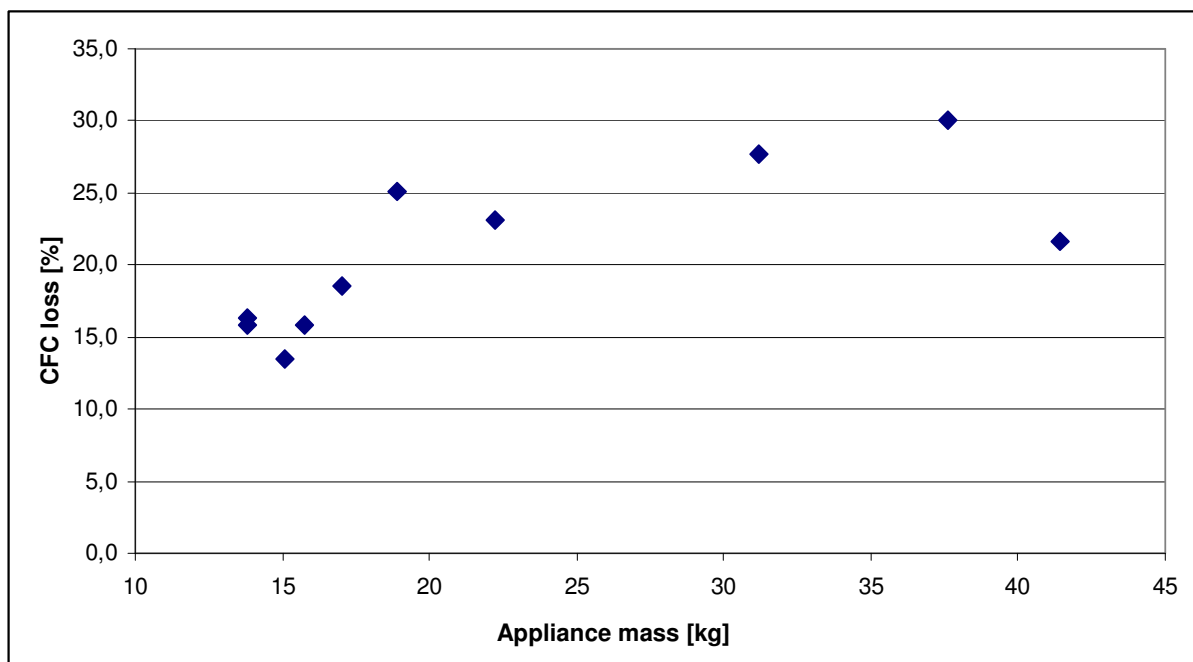


Figure 2.1 Correlation between appliance mass and CFC losses

The diagram indicates that heavier appliances exhibit significantly higher CFC loss levels. Whereas the CFC losses of 15% are found for appliances weighing around 15 kg, the three appliances with weights of over 30 kg show significantly higher losses (up to 30%).

Because of the small number of appliances in each weight class it is not possible to establish whether or not this is a general trend. A correlation between CFC loss and the average quantity of PU foam recovered from the manual dismantling process would

seem more probable. However, in the tests performed the amounts of PU foam recovered from each appliance were all in the same approximate weight range.

2.4.6 Discussion

The test results show a certain degree of scattering which is not surprising given the range of appliance sizes used in the test. Error analysis showed that, on a conservative estimate, the average uncertainty in the test data is $\pm 18\%$. This level of data uncertainty lies within the range of experimental scatter and is therefore acceptable given that the main objective of the study was to estimate potential CFC losses from manual dismantling of waste refrigeration appliances.

In summary, analysis of nine tests conducted on appliances of varying size has shown that the CFC losses associated with the manual stripping of foam insulation and the CFC retained in adhered PU foam residues are between 25 g and 245 g of CFC per appliance (average value: 99 g per appliance). As the appliances used in testing were of different size, it is more meaningful to consider percentage rather than absolute values. Relative to the amount of CFC originally present in the untreated **appliance carcass (cabinet and door)**, manual disassembly resulted in losses of between 16% and 30% by weight (**mean average: 23 %** of the mass of CFC originally present).

The following CFC losses were found for appliance **cabinets (carcass without door)**:
absolute values: 15–233 g; average 88 g.
percentage values: 5–33% ; **average 24 %**.

The following CFC losses were determined for the **doors**:
absolute values: 1–17 g; average 11 g.
percentage values: 6–28% ; **average 17 %**.

The CFC losses for the entire appliance carcass (cabinet + door) are therefore:
absolute Werte: 25 – 245 g; average 99 g.
percentage values: 16–30% ; average 23 %.

Additional CFC emissions might also arise at existing fridge treatment plants if the appliance doors, which contain PU foam insulation, are not disassembled to remove the foam. Examples of recycling practice (e.g. in the USA) have been reported in which the untreated PU/CFC-containing doors are sent straight to scrap dealers because manual dismantling of the doors is considered to be much more involved and therefore too cost-intensive. In the appliances tested, around 14% of the total PU foam (and therefore CFC blowing agent) within the appliance was contained in the doors. The greater effort required to manually strip the foam from the doors was confirmed in the present study. In the worst-case scenario, CFC losses of up to 47% could occur if the

doors are not properly dismantled and the foam-containing doors are simply sent for metal processing in a car shredder.

For a number of appliances, we also estimated how much CFC escapes when the PU output fraction from each appliance is stored in open sacks. Seven of the sacks were weighed after 24 hours and four of them were also weighed again after 14 days. It was assumed that the difference in weight was completely attributable to CFC outgassing. After storing for 24 hours, the average CFC loss was 3%. After storing for 14 days, a further 1.5 % of CFC was lost on average (all figures relative to the original amount of CFC in the appliance).

3 Evaluation of test results

In order to relate the results of this study to the CFC emissions calculated in an earlier report [Öko-Institut 2007], it needs to be recalled that in the earlier life cycle assessment study large appliances were not included in the study. To compare data from appliances of comparable size (i.e. containing comparable amounts of PU foam and CFC blowing agent) and to establish a conservative basis for data evaluation, only data from the six smaller appliances tested in this study are assessed here.

Table 3-1: Test results for the appliance carcasses (cabinets + doors) excluding the results for the three largest appliances

(Note: As the numerical data in the tables have been rounded, there may be a slight imprecision associated with some of the calculated values shown.)

Test No.	Mass of appliance prior to dismantling kg	Total mass of PU foam originally present (foam from stripping + foam scrapings + losses during stripping) kg	Mass of CFC in foam prior to dismantling g	CFC losses from manual foam stripping + CFC retained in foam relative to amount of CFC originally present %	CFC losses from manual foam stripping + CFC retained in foam relative to amount of CFC originally present g
1	17.0	3.1	264	18.5	49
2	15.8	4.1	348	15.8	55
4	15.1	2.2	185	13.5	25
6	13.8	1.9	160	16.3	26
7	18.9	3.9	329	25.1	83
8	22.2	4.8	408	23.2	95
Min	13.8	1.9	160	15.8	25
Max	22.2	4.8	408	25.1	95
Mean	17.1	3.3	282	19.6	55

It should also be noted that in the life-cycle assessment study performed in 2007, the CFC emission levels related to fridge treatment plants that deployed state-of-the-art recycling technology and where the appliance input mix comprised 80% appliances with CFC as the blowing agent and 20% appliances with a VOC foam blowing agent. The average CFC emission level of 0.45 g per appliance in the LCA study (expressed as R11 equivalents) therefore has to be revised to a value of 0.54 g per appliance.

It should also be taken into account that in the LCA study the emissions from the entire waste treatment path were included and that more than half of total emissions arose from the treatment of the degassed PU foams and from the residual PU foam still adhering to metal and plastic fractions. This phase of the waste treatment process was not considered in the present study. However, emissions from stage I processing,

which were included in the earlier LCA report but were not part of the present study, can be neglected as they contribute less than 3 % to total emissions.

Other important parameters for a comparative assessment are the amounts of PU foam and R11 blowing agent recovered per appliance. In the LCA study in 2007, it was assumed that on average 4.0 kg of PU foam and 340 g of R11 were recoverable per appliance.

The tests on the six smaller appliances yielded average values of 4.4 kg of PU foam and 282 g of R11 per appliance (cf. Table 3-1).

The manual dismantling of the six smaller appliances produced average emissions of 55 g of CFC per appliance, which is about 100 times greater than the emissions expected if the appliance had been treated in a state-of-the-art fridge recycling plant. The minimum emission level recorded (25 g of CFC per appliance) is about 46 times greater, while the maximum recorded emission level (99 g of CFC per appliance) is about 175 times more than would be expected in an advanced fridge recycling plant.

If the degassing from the PU foam during a 24-hour storage period after foam removal (prior to final treatment of the foam to recover/destroy the CFC blowing agent) is also taken into account, the CFC emissions associated with the manual foam stripping and foam storage for the six smaller appliances increase to an average value of 62 g of CFC per appliance, which is about 115 times greater than the emissions expected if the appliance had been treated in a state-of-the-art fridge recycling plant.

The consensus among experts in the field is that, not only in Europe but worldwide, a common recipe/formulation was used to manufacture the PU foams used in the production of refrigeration equipment. Although minor differences in the foam ageing process cannot be ruled out, there is unanimous agreement among experts that, within Europe at least (and for sure in the rest of the world), the end-of-life refrigeration appliances in the waste disposal market all contain approximately the same amount of CFC blowing agent in the polyurethane foam (85 grams CFC per kilogram of PU foam). In the opinion of the authors, the results obtained in the present study can therefore be confidently transferred to the situation in both European and non-European countries.

4 Ozone depletion and global warming potential

4.1 Ozone depletion potential

The potential to deplete the earth's ozone layer (ODP: ozone depletion potential) describes the ability of a substance to reduce ozone concentrations in the stratosphere, i.e. at altitudes of between 15 and 40 km above the surface of the earth. Stratospheric ozone is damaged by long-lived chlorinated, brominated and fluorinated hydrocarbons. Of particular relevance in this regard are the chlorofluorocarbons (CFC). Increased ozone depletion is accompanied by an increase in UV-B radiation at the surface of the earth, as the stratospheric ozone layer filters out a large part of the incident UV-B radiation. An increase in UV-B radiation at the earth's surface can lead to a greater incidence of skin and eye disease in humans and can impair the human immune system. Even a relatively small increase in the average UV-B radiation flux is expected to cause damage to ecosystems and to have a long-term influence on the food chain [UBA 2006]. The ozone depletion potential is expressed in kg of R11 equivalents.

As the overall test results in Section 2.4 (expressed in kilograms) refer only to losses of the CFC R11 and because R11 has a scaling factor of 1 (in R11 equivalents), the results listed are therefore also equal to the relevant ODP values.

4.2 Global warming potential

The calculation of global warming potential (GWP) in terms of CO₂ equivalents is an established and generally recognized procedure. The Intergovernmental Panel of Climate Change (IPCC) is an international committee of experts that updates the method used to compute GWP and calculates the parameters for all climatically relevant substances. As the residence time of a gas in the troposphere is taken into account when calculating its GWP, the question arises as to which time horizon should be used for the purposes of a life cycle assessment study. The German Federal Environmental Agency (UBA) recommends modelling on the basis of a time horizon of 100 years, as this best reflects the long-term impact of the greenhouse effect. R11 has a GWP of 4680. That means that 1 kg of R11 has the same global warming potential as 4680 kg of CO₂ [IPCC 2005].

The calculated R11 emissions from the manual dismantling of a refrigeration appliance range from 25 g to 245 g correspond to a GWP per appliance of between approximately 120 kg and 1150 kg CO₂ equivalents. On average, 99 g of R11 was released per appliance, which corresponds an average GWP of 460 kg CO₂ equivalents.

At present, emissions from an average sized car are currently estimated to be about 180 g of CO₂ per kilometre. Based on this value, the average CFC emission level from the manual dismantling of a waste fridge corresponds to the carbon dioxide emissions from an average-sized car travelling more than 1600 miles (2600 km).

Assuming an average mileage of about 8100 miles (13000 km) per year [see www.kba.de], an average car can be driven for more than ten weeks before its CO₂

emissions have equalled those from the manual dismantling of a single average-sized fridge.

5 Practical conclusions for fridge recycling operations

The CFC emissions identified in the tests and the ozone depletion and global warming potential of these emissions lead us to conclude that manual dismantling of CFC-containing refrigeration appliances to recover PU insulating foams cannot be recommended.

The conditions under which the testing was carried out in Limburg were ideal. The workers at GAB who were assigned the task of dismantling the waste appliances were highly motivated, performed their work conscientiously and, most importantly, no time limits were set for completion of the work. It is doubtful whether the working conditions in daily recycling practice would produce the same results as the Limburg tests. It is far more likely that a lower level of motivation coupled with tight scheduling and productivity requirements would lead to higher CFC emissions. It is also unlikely that the specifications regarding the size of the PU foam chunks to be recovered will be met in day-to-day recycling operations. Such specifications will prove to be particularly infeasible in the case of the very involved process of manually dismantling fridge doors.

As the end-of-life refrigeration appliances in the worlds waste disposal markets all contain approximately the same amount of CFC blowing agent in the polyurethane foam (85 grams CFC per kilogram of PU foam) it is the opinion of the authors, that the results obtained in the present study can be confidently transferred to the situation in both European and non-European countries.

In our view, there is no alternative but to shred the entire appliance carcasses (cabinet + door) in encapsulated shredders. This is applicable for all countries in the world.

6 References

- Electrolux 1989 Holmberg, B.: Förklaring till CFC-Analys på kylskapsisolering [*Information on the analysis of CFCs from refrigerator insulation materials*], Electrolux Industrial Systems, 1989
- Freep 2009 www.freep.com
- IPCC 2005 Intergovernmental Panel on Climatic Change (IPCC): Special Report on Safeguarding the Ozone Layer and the Global Climate System; Issues related to Hydrofluorocarbons and Perfluorocarbons; Chapter 2: Chemical and Radiative Effects of Halocarbons and Their Replacement Compounds, 23rd Session at Addis Ababa, April 2005
- iuta 2005 Institut für Energie- und Umwelttechnik e.V., Duisburg: Analysenbericht zu drei Proben von PUR-Schaum nach der Vorzerkleinerung mit einer Rotorschere [*Report on the analysis of three samples of PU foam after preliminary shredding with rotary shears*], 2005
- KBA 2009 Kraftfahrt-Bundesamt [*German Federal Office of Motor Vehicles*]: www.kba.de
- Öko-Institut 2007 Dehoust, G.; Schüler, D.: Ökobilanzielle Untersuchung zur Verwertung von FCKW- und KW-haltigen Kühlgeräten [*Life cycle assessment of the treatment and recycling of refrigeration equipment containing CFCs and hydrocarbons*], Darmstadt 2007
- UBA 1998a Umweltbundesamt, FG III 3.2: Leitfaden zur Entsorgung von Kältegeräten [*UBA (German Federal Environmental Agency): Guidelines on the Disposal of Refrigeration Equipment*], January 1998
- UBA 2006d Umweltbundesamt: Schutz der Ozonschicht - FCKW und Halone [*UBA (German Federal Environmental Agency): Protecting the Ozone Layer – CFCs and Halons*]; Downloadable from: <http://www.umweltbundesamt.de/uba-info-daten/daten/fckw/halone.htm>, 18 July 2006

7 Appendix 1: Photo documentation of the manual dismantling of fridges at a recycling company in the USA

The following photographs document the manual disassembly of refrigeration appliances in the USA (www.freep.com).



8 Appendix 2: Photo documentation of the manual dismantling tests carried out in Limburg on 14–16 September 2009

