

# **Waste Minimisation at an Air-Conditioning Company**

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By

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# Abstract

Waste minimisation involves reducing waste (emissions, effluent, solid waste) in companies, at source.<sup>3, 7, 8</sup> Its benefits include cost savings, environmental improvement, increased throughput and risk and liability reduction.<sup>7, 8, 13</sup> Through implementation of a structured waste minimisation programme, companies can identify waste minimisation opportunities: broad focus areas that will benefit from a more detailed waste minimisation assessment. More specific waste minimisation solutions can then be identified.

In this study, the waste minimisation opportunity was identified by the company, Ben Booysen, *a priori*. Ben Booysen is a local air-conditioning and refrigeration company in Pietermaritzburg, which services air-conditioner units. They identified the waste minimisation opportunity of optimising the process conditions for cleaning the air-conditioner units. At the time at Ben Booysen, Alukleen, an acid cleaner (RT Chemicals®, RTCM 64), was applied manually (by a paintbrush) at an effective dilution of 1:3 to clean the aluminium air-conditioner coils. Handy Andy and green soap were used to clean the plastic covers of the units. Concerns about the effluent, cost and safety of handling Alukleen led to their identification of this waste minimisation opportunity.

The initial objectives of this project were thus the qualification and quantification of the species present in Alukleen; the quantification of the species present in the Ben Booysen effluent and the subsequent comparison of these values to limits for disposal to stormwater and Darvill. A further objective was the optimisation of the cleaning system with regard to Alukleen concentration and contact (soaking) time.

Wet chemical analysis was employed as a qualitative tool for identification of the components present in Alukleen. This analysis indicated that fluoride, sulfate, sulfide, arsenite and chloride ions are present in Alukleen. Further quantitative analysis using the

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ion chromatograph, the ICP-OES and a fluoride ion selective electrode indicated that only sulfate (152600 ppm) and fluoride (25400 ppm) are present in significant quantities.

Studies were conducted on aluminium coil pieces in which both the contact (soaking) times and Alukleen concentrations were varied. These tests indicated that the effect of soaking time on the cleanliness achieved was negligible. Although a greater amount of dirt was removed when using more concentrated Alukleen solutions, etching of the metal occurred at higher concentrations, resulting in a loss of sheen and malleability of the metal.

Etching of the aluminium air-conditioner coils by Alukleen, as indicated by both digital photography and electron microscopy, resulted in extending the objectives of this project to include the investigation of alternative aluminium cleaners. Hence, the cleaning action of three degreasers was investigated: Powerkleen (RT Chemicals®, RTCM123), Technicians' Choice (Auto Brite (PTY) Ltd.) and Klengine (Auto Brite (PTY) Ltd.). Powerkleen was found to be the most effective degreaser and did not compromise the metal's sheen or malleability. Further studies were then conducted to characterise the major components of Powerkleen and to optimise its use with regard to concentration and contact (soaking) time. The suitability of two methods of application was also tested.


The main component of Powerkleen, determined through the use of ICP-OES, was found to be potassium hydroxide, present at a concentration of 0.711 M. The optimum Powerkleen concentration range for cleaning the aluminium coils was found to be between a 1:20 and 1:40 dilution. Contact (soaking) time of Powerkleen with the aluminium coils was found to have a negligible effect on the mass of dirt removed by the degreaser. Application of the Powerkleen to the aluminium coils by an air gun at a pressure of 4 bars (for units serviced at Ben Booysen) and by a pump bottle (for units serviced in industry) were both found to achieve an acceptable degree of cleanliness of the aluminium.

A feasibility analysis (technical, economical and environmental) indicated that a 1:40 dilution of Powerkleen is a feasible, cost-effective and environmentally compliant alternative to Alukleen. Implementation of the Powerkleen cleaning system would result in a R5030 annual saving with a payback period of 5.9 months and an internal rate of return of 214.9%. It would further eliminate the fluoride effluent problems associated with Alukleen and reduce the quantity of chemical raw materials required for the process from 2100 L/annum to 260 L/annum. In industry, an effective dilution of 1:39 would be used for the sake of easy dilution. A 1:79 dilution of Powerkleen was also found to be a feasible replacement for Handy Andy and green soap in the cleaning of the plastic covers of the units.




# Declaration

I hereby certify that this research is a result of my own investigation, which has not already been accepted in substance for any degree and is not being submitted in candidature for any other degree.

Signed:   
**Paula Ann Blomquist**

I hereby certify that this statement is correct.

Signed:   
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# Table of Contents

Abstract.....	i
Declaration.....	iv
Acknowledgements.....	v
List of Figures.....	xi
List of Tables.....	xviii

## **Chapter 1: Introduction.....1**

1.1 Waste Minimisation as a Waste Management Strategy.....	1
1.2 Waste Minimisation Study at Ben Booyesen.....	4

## **Chapter 2: Literature Review of Waste Minimisation and Aluminium Cleaning Theory.....7**

2.1 Introduction.....	7
2.2 Approaches to Waste Minimisation.....	7
2.3 The Strategy for Waste Minimisation.....	8
2.3.1 Introduction.....	8
2.3.2 Pre-assessment Stage.....	13
2.3.3 Assessment Stage.....	22
2.3.4 Feasibility Analysis.....	29
2.4 The Benefits of Waste Minimisation.....	41
2.4.1 Cost Savings.....	41
2.4.2 Environmental Improvement.....	42
2.4.3 Increased Throughput.....	42
2.4.4 Risk and Liability Reduction.....	43
2.5 The Barriers to Waste Minimisation.....	43
2.6 The Drivers for Waste Minimisation.....	44

<b>2.7</b>	<b>Aluminium Cleaning Theory.....</b>	<b>44</b>
2.7.1	Introduction.....	44
2.7.2	Film Formation.....	45
2.7.3	The Corrosion of Aluminium.....	46
2.7.4	Acid Attack on Aluminium.....	47
2.7.5	Alkali Attack on Aluminium.....	47
2.7.6	The Action of Cleaners.....	50
<b>2.8</b>	<b>Conclusion.....</b>	<b>51</b>
<b>Chapter 3:</b>	<b>Materials and Methods.....</b>	<b>54</b>
<b>3.1</b>	<b>Qualitative Analytical Techniques.....</b>	<b>54</b>
3.1.1	Wet Chemical Analysis.....	54
3.1.2	ICP-OES.....	65
<b>3.2</b>	<b>Quantitative Analytical Techniques.....</b>	<b>65</b>
3.2.1	Ion Chromatography.....	65
3.2.2	Ion Selective Electrode.....	67
3.2.3	Photometry.....	67
3.2.4	C.O.D. Measurement.....	68
3.2.5	pH Titrations.....	69
3.2.6	pH.....	70
3.2.7	Conductivity.....	70
3.2.8	Total Dissolved Solids Measurements.....	70
<b>3.3</b>	<b>Methodologies.....</b>	<b>71</b>
3.3.1	Determination of the most effective Cleaner Type, Concentration and Soaking Time.....	71
3.3.2	Determination of the Suitability of Two Cleaner Application Techniques.....	74

<b>Chapter 4: Results and Discussion – Characterisation of the System.....</b>	<b>76</b>
<b>4.1 Alukleen.....</b>	<b>76</b>
4.1.1 Qualitative Analysis.....	76
4.1.2 Quantitative Analysis.....	88
<b>4.2 Powerkleen.....</b>	<b>88</b>
4.2.1 Quantitative Analysis.....	89
4.2.2 Comparison with Disposal Limits.....	91
<b>4.3 Sampled Effluent.....</b>	<b>92</b>
4.3.1 Quantitative Analysis.....	92
4.3.2 Comparison with Disposal Limits.....	95
<b>4.4 Conclusion.....</b>	<b>97</b>
 <b>Chapter 5: Results and Discussion – Optimisation of System Conditions...99</b>	
<b>5.1 Determination of the most effective Alukleen Concentration and Soaking Time.....</b>	<b>100</b>
5.1.1 Gravimetric Analysis.....	100
5.1.2 Digital Photography.....	104
5.1.3 Electron Microscopy.....	105
<b>5.2 Determination of the Best Cleaning System.....</b>	<b>106</b>
5.2.1 Pre-wash Tests.....	107
5.2.2 Degreaser Tests.....	111
<b>5.3 Optimising the use of Powerkleen.....</b>	<b>115</b>
5.3.1 Determination of the most effective Powerkleen Concentration and Soaking Time.....	115
5.3.2 Assessing the use of Powerkleen as a General Cleaning Agent..	122
<b>5.4 Application Tests.....</b>	<b>123</b>
<b>5.5 Conclusion.....</b>	<b>126</b>

<b>Chapter 6: Feasibility Analysis.....</b>	<b>128</b>
<b>6.1 Technical Evaluation.....</b>	<b>128</b>
6.1.1 Available Technology.....	128
6.1.2 Timescales.....	129
6.1.3 Risks Involved.....	129
6.1.4 Company Culture.....	130
<b>6.2 Economic Evaluation.....</b>	<b>131</b>
6.2.1 Payback Period.....	132
6.2.2 Return on Capital Employed (ROCE).....	132
6.2.3 Net Present Value (NPV).....	133
6.2.4 Internal rate of Return (IRR).....	134
<b>6.3 Environmental Evaluation.....</b>	<b>134</b>
<b>6.4 Conclusion.....</b>	<b>136</b>
 <b>Chapter 7: Conclusions and Recommendations.....</b>	 <b>137</b>
7.1 Conclusions.....	137
7.2 Recommendations.....	141
 <b>Chapter 8: References.....</b>	 <b>142</b>
 <b>Appendix A: Wet Chemical Analysis.....</b>	 <b>150</b>
 <b>Appendix B: Detailed Analytical Methods.....</b>	 <b>155</b>

<b>Appendix C: Quantitative Analysis Results.....</b>	<b>163</b>
C.1    Alukleen.....	164
C.2    Powerkleen.....	178
C.3    Effluent Samples.....	184
 <b>Appendix D: Data for the Optimisation of the Coil Cleaning System.....</b>	 <b>194</b>
D.1    Alukleen System.....	195
D.2    Pre-wash Systems.....	212
D.3    Degreaser Systems.....	214
D.4    Powerkleen System.....	217
D.5    Suitability of Two Cleaner Application Techniques.....	234
 <b>Appendix E: Feasibility Analysis Calculations.....</b>	 <b>240</b>
E.1    Economic Evaluation.....	241
E.2    Environmental Evaluation.....	248

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## List of Figures

Figure 1.1:	Generation of waste in an industrial process.....	2
Figure 1.2:	Waste management hierarchy.....	2
Figure 1.3:	Approaches to waste minimisation.....	3
Figure 2.1:	Schematic diagram for the determination of which solutions are suitable for implementation.....	8
Figure 2.2:	A site process flow diagram for a manufacturing company.....	10
Figure 2.3:	(a) A schematic drawing of a separation process.....	14
	(b) P-graph model for the process in (a).....	14
Figure 2.4:	Bar graph showing the ranking of waste streams for waste minimisation using the waste index system of Kothuis.....	17
Figure 2.5:	Corresponding co-ordinate system for a textile company in South Africa.....	19
Figure 2.6:	Trend graph showing variations in the monthly water consumption.....	26
Figure 2.7:	Scatter plot graph of production as a function of consumption.....	26
Figure 2.8:	Variance graph showing variance as a function of time.....	28
Figure 2.9:	Cusum plot showing rands spent on a particular consumable over a production period.....	28
Figure 3.1:	Schematic illustration of the wet chemical analysis done.....	64
Figure 3.2:	Schematic diagram showing the cutting of a coil into 4 similar pieces....	74
Figure 3.3:	Schematic diagram of the side view of a coil with application point.....	75
Figure 4.1:	Schematic illustration of the wet chemical analysis results.....	80
Figure 4.2:	pH titration of 0.25M H <sub>2</sub> SO <sub>4</sub> with 0.1 M NaOH.....	85
Figure 4.3:	pH titration of Alukleen with 2.040 M NaOH.....	86
Figure 4.4:	pH Titration of Powerkleen with 1.065 M HCl.....	89

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## List of Figures

---

Figure 5.1:	Averaged gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time.....	102
Figure 5.2:	Line graph showing the averaged gravimetric analysis results with standard deviations plotted as y-error bars.....	103
Figure 5.3:	‘Before’ photograph for a soaking time of 2 minutes.....	104
Figure 5.4:	‘After’ photograph for a soaking time of 2 minutes.....	104
Figure 5.5:	Electron Micrographs of the surface of aluminium samples. (a) Control..... (b) Aluminium treated with a 1:3 dilution of Alukleen.....	106 106
Figure 5.6:	Bar graph showing the results of the gravimetric analysis for the pre-wash combinations.....	108
Figure 5.7:	‘Before’ photograph of aluminium pieces treated with various pre-wash combinations (Run 3).....	110
Figure 5.8:	‘After’ photograph of aluminium pieces treated with various pre-wash combinations (Run 3).....	110
Figure 5.9:	Bar graph showing the results of the gravimetric analysis for Powerkleen dilutions of 1:15 and 1:50.....	112
Figure 5.10:	‘Before’ photograph of aluminium pieces treated with various degreasers (Run 2).....	114
Figure 5.11:	‘After’ photograph of aluminium pieces treated with various degreasers (Run 2).....	114
Figure 5.12:	Averaged gravimetric analysis results for the determination of the most effective Powerkleen concentration and soaking time.....	117
Figure 5.13:	Line graph showing the averaged gravimetric analysis results with standard deviations plotted as y-error bars.....	118
Figure 5.14:	‘Before’ photograph for a soaking time of 20 minutes.....	120
Figure 5.15:	‘After’ photograph for a soaking time of 20 minutes.....	120
Figure 5.16:	Electron Micrographs of the surface of aluminium samples. (a) Control..... (b) Aluminium treated with a 1:20 dilution of Powerkleen..... (c) Aluminium treated with a 1:40 dilution of Powerkleen.....	121 121 121

Figure 5.17:	Photographs of a Section of Coil 1 treated with 1:20 or 1:40 Powerkleen for 2 minutes using a pump bottle or an air gun.	
(a) and (b):	'Before' and 'after' photographs: 1 litre of 1:20 Powerkleen using a pump bottle.....	125
(c) and (d):	'Before' and 'after' photographs: 250 ml of 1:20 Powerkleen using an air gun.....	125
(e) and (f):	'Before' and 'after' photographs: 1 litre of 1:40 Powerkleen using a pump bottle.....	125
(g) and (h):	'Before' and 'after' photographs: 250 ml of 1:40 Powerkleen using an air gun.....	125
Figure C.1:	Plot of peak area as a function of sulfate concentration for reproducibility run on the ion chromatograph.....	164
Figure C.2:	Calibration graph for the sulfate determination of Alukleen using ion chromatography.....	166
Figure C.3:	Calibration graph for the chloride determination of Alukleen using ion chromatography.....	168
Figure C.4:	Potential (E) as a function of the fluoride concentration for reproducibility run using the ion selective electrode.....	169
Figure C.5:	Calibration graph for the fluoride determination in Alukleen using an ion selective electrode.....	171
Figure C.6:	Absorbance as a function of sulfide concentration for the reproducibility run on the photometer.....	172
Figure C.7:	Calibration graph for the photometric sulfide determination in Alukleen.....	173
Figure C.8:	Calibration graph for the potassium determination in Powerkleen using the ICP-OES.....	179
Figure C.9:	Calibration graph for the photometric sulfide determination in Powerkleen.....	180
Figure C.10:	Calibration graph for the sulfate determination of the effluent using ion chromatography.....	185

## List of Figures

---

Figure C.11:	Calibration graph for the fluoride determination of the effluent using an ion selective electrode.....	187
Figure C.12:	Calibration graph for the photometric sulfide determination in the effluent samples.....	188
Figure D.1:	‘Before’ photograph for a soaking time of 2 minutes (Run 1).....	205
Figure D.2:	‘After’ photograph for a soaking time of 2 minutes (Run 1).....	205
Figure D.3:	‘Before’ photograph for a soaking time of 4 minutes (Run 1).....	205
Figure D.4:	‘After’ photograph for a soaking time of 4 minutes (Run 1).....	205
Figure D.5:	‘Before’ photograph for a soaking time of 6 minutes (Run 1).....	206
Figure D.6:	‘After’ photograph for a soaking time of 6 minutes (Run 1).....	206
Figure D.7:	‘Before’ photograph for a soaking time of 8 minutes (Run 1).....	206
Figure D.8:	‘After’ photograph for a soaking time of 8 minutes (Run 1).....	206
Figure D.9:	‘Before’ photograph for a soaking time of 10 minutes (Run 1).....	207
Figure D.10:	‘After’ photograph for a soaking time of 10 minutes (Run 1).....	207
Figure D.11:	‘Before’ photograph for a soaking time of 15 minutes (Run 1).....	207
Figure D.12:	‘After’ photograph for a soaking time of 15 minutes (Run 1).....	207
Figure D.13:	‘Before’ photograph for a soaking time of 20 minutes (Run 1).....	208
Figure D.14:	‘After’ photograph for a soaking time of 20 minutes (Run 1).....	208
Figure D.15:	‘Before’ photograph for a soaking time of 2 minutes (Run 2).....	208
Figure D.16:	‘After’ photograph for a soaking time of 2 minutes (Run 2).....	208
Figure D.17:	‘Before’ photograph for a soaking time of 4 minutes (Run 2).....	209
Figure D.18:	‘After’ photograph for a soaking time of 4 minutes (Run 2).....	209
Figure D.19:	‘Before’ photograph for a soaking time of 6 minutes (Run 2).....	209
Figure D.20:	‘After’ photograph for a soaking time of 6 minutes (Run 2).....	209
Figure D.21:	‘Before’ photograph for a soaking time of 8 minutes (Run 2).....	210
Figure D.22:	‘After’ photograph for a soaking time of 8 minutes (Run 2).....	210
Figure D.23:	‘Before’ photograph for a soaking time of 10 minutes (Run 2).....	210
Figure D.24:	‘After’ photograph for a soaking time of 10 minutes (Run 2).....	210
Figure D.25:	‘Before’ photograph for a soaking time of 15 minutes (Run 2).....	211
Figure D.26:	‘After’ photograph for a soaking time of 15 minutes (Run 2).....	211

Figure D.27: ‘Before’ photograph for a soaking time of 20 minutes (Run 2).....	211
Figure D.28: ‘After’ photograph for a soaking time of 20 minutes (Run 2).....	211
Figure D.29: ‘Before’ photograph (Run 1).....	213
Figure D.30: ‘After’ photograph (Run 1).....	213
Figure D.31: ‘Before’ photograph (Run 2).....	213
Figure D.32: ‘After’ photograph (Run 2).....	213
Figure D.33: ‘Before’ photograph (Run 1).....	215
Figure D.34: ‘After’ photograph (Run 1).....	215
Figure D.35: ‘Before’ photograph (Run 3).....	215
Figure D.36: ‘After’ photograph (Run 3).....	215
Figure D.37: ‘Before’ photograph (Run 4).....	216
Figure D.38: ‘After’ photograph (Run 4).....	216
Figure D.39: ‘Before’ photograph for a soaking time of 2 minutes (Run 1).....	231
Figure D.40: ‘After’ photograph for a soaking time of 2 minutes (Run 1).....	231
Figure D.41: ‘Before’ photograph for a soaking time of 4 minutes (Run 1).....	231
Figure D.42: ‘After’ photograph for a soaking time of 4 minutes (Run 1).....	231
Figure D.43: ‘Before’ photograph for a soaking time of 6 minutes (Run 1).....	232
Figure D.44: ‘After’ photograph for a soaking time of 6 minutes (Run 1).....	232
Figure D.45: ‘Before’ photograph for a soaking time of 8 minutes (Run 1).....	232
Figure D.46: ‘After’ photograph for a soaking time of 8 minutes (Run 1).....	232
Figure D.47: ‘Before’ photograph for a soaking time of 10 minutes (Run 1).....	233
Figure D.48: ‘After’ photograph for a soaking time of 10 minutes (Run 1).....	233
Figure D.49: ‘Before’ photograph for a soaking time of 15 minutes (Run 1).....	233
Figure D.50: ‘After’ photograph for a soaking time of 15 minutes (Run 1).....	233
Figure D.51: ‘Before’ photograph for a soaking time of 20 minutes (Run 1).....	234
Figure D.52: ‘After’ photograph for a soaking time of 20 minutes (Run 1).....	234
Figures D.53 and D.54: ‘Before’ and ‘after’ photographs of a section of Coil 1 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes (side view)..	235
Figures D.55 and D.56: ‘Before’ and ‘after’ photographs of a section of Coil 1 that was treated with 250 ml of 1:20 Powerkleen using an air gun for 2 minutes (side view).....	235

Figures D.59 and D.60: 'Before' and 'after' photographs of a section of Coil 1 that was treated with 250 ml of 1:40 Powerkleen using an air gun for 2 minutes (side view).....	235
Figures D.61 and D.62: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes.....	236
Figures D.63 and D.64: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 250 ml of 1:20 Powerkleen using an air gun for 2 minutes.....	236
Figures D.65 and D.66: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 1 litre of 1:40 Powerkleen using a pump bottle for 2 minutes.....	236
Figures D.67 and D.68: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 250 ml of 1:40 Powerkleen using an air gun for 2 minutes.....	236
Figures D.69 and D.70: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes (side view).....	237
Figures D.71 and D.72: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 250 ml of 1:20 Powerkleen using an air gun for 2 minutes (side view).....	237
Figures D.73 and D.74: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 1 litre of 1:40 Powerkleen using a pump bottle for 2 minutes (side view).....	237
Figures D.75 and D.76: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 250 ml of 1:40 Powerkleen using an air gun for 2 minutes (side view).....	237
Figures D.77 and D.78: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes.....	238
Figures D.79 and D.80: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 250 ml of 1:20 Powerkleen using an air gun for 2 minutes.....	238
Figures D.81 and D.82: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 1 litre of 1:40 Powerkleen using a pump bottle for 2 minutes.....	238
Figures D.83 and D.84: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 250 ml of 1:40 Powerkleen using an air gun for 2 minutes.....	238
Figures D.85 and D.86: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes (side view).....	239
Figures D.87 and D.88: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 250 ml of 1:20 Powerkleen using an air gun for 2 minutes (side view).....	239
Figures D.89 and D.90: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 1 litre of 1:40 Powerkleen using a pump bottle for 2 minutes (side view).....	239



## List of Figures

---

Figures D.91 and D.92: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 250 ml of 1:40 Powerkleen using an air gun for 2 minutes (side view).....239

## List of Tables

Table 2.1:	Scope for savings.....	20
Table 2.2:	The limits for effluent disposal to Darvill.....	35
Table 2.3:	Relevant limits for discharging effluent to stormwater.....	36
Table 2.4:	Pollution prevention index of Smith and Khan.....	39
Table 2.5:	Pollution prevention index of Halim and Srinivasan.....	40
Table 4.1:	Results of the wet chemical tests used to determine the chemical species in Alukleen.....	77
Table 4.2:	ICP-OES analysis of Alukleen.....	81
Table 4.3:	Sulfate concentrations in Alukleen determined using ion chromatography.....	83
Table 4.4:	Fluoride concentrations in Alukleen determined using an ion selective electrode.....	84
Table 4.5:	Results from the determination of the sulfide and arsenic concentrations in Alukleen.....	84
Table 4.6:	Results of the measurement of the pH, conductivity and the total dissolved solid content of Alukleen.....	87
Table 4.7:	Results of the measurement of the pH, conductivity and the total dissolved solids concentration of Powerkleen.....	91
Table 4.8:	Comparison of limits for effluent discharge to stormwater and to Darvill with the concentrations of the species present in 1:39 Powerkleen.....	91
Table 4.9:	Sulfate concentrations in the effluent samples determined using ion chromatography.....	93
Table 4.10:	Fluoride concentrations in the effluent samples determined using an ion selective electrode.....	94
Table 4.11:	pH, conductivity and total dissolved solids concentration measurements of the effluent samples.....	95

## List of Tables

---

Table 4.12:	Comparison of limits for effluent discharge to stormwater and to Darvill with the concentrations of the species present in the effluent.....	96
Table 5.1:	Averaged gravimetric data for determining the most effective Alukleen concentration and soaking time.....	101
Table 5.2:	Averaged gravimetric analysis results for the comparison of pre-wash combinations.....	108
Table 5.3:	Averaged gravimetric analysis results for the comparison of Powerkleen dilutions.....	112
Table 5.4:	Averaged gravimetric data for determining the most effective Powerkleen concentration and soaking time.....	116
Table 6.1:	Comparison of the composition of the current effluent, a 1:39 dilution of Powerkleen, the predicted 'new' Powerkleen effluent and the stormwater and Darvill limits.....	135
Table C.1:	Results from the reproducibility run carried out on the ion chromatograph.....	164
Table C.2:	Calculation of the sulfate concentration in Alukleen using ion chromatography.....	165
Table C.3:	Calculation of the chloride concentration in Alukleen using ion chromatography.....	167
Table C.4:	Results from the reproducibility run carried out using the fluoride ion selective electrode.....	169
Table C.5:	Calculation of the fluoride concentration in Alukleen using an ion selective electrode.....	170
Table C.6:	Results from the photometric reproducibility run.....	172
Table C.7:	Photometric measurement of the sulfide concentration in Alukleen.....	173
Table C.8:	pH measurement of Alukleen.....	176
Table C.9:	Conductivity measurement of Alukleen.....	176
Table C.10:	Determination of the suspended solids (S.S.) content of Alukleen.....	177



## List of Tables

---

Table C.11:	Determination of the total solids (T.S.) content of Alukleen.....	177
Table C.12:	Determination of the total dissolved solids (T.D.S.) content of Alukleen.....	177
Table C.13:	Compilation of the total dissolved solids results for Alukleen (9 readings).....	178
Table C.14:	Determination of the potassium concentration in Powerkleen using the ICP-OES.....	178
Table C.15:	Photometric calculation of the sulfide concentration in Powerkleen.....	180
Table C.16:	Results of the measurement of the C.O.D. of 1:39 Powerkleen.....	181
Table C.17:	Results of the measurement of the pH of 1:39 Powerkleen.....	181
Table C.18:	Results of the measurement of the conductivity of neat and 1:39 Powerkleen.....	181
Table C.19:	Determination of the suspended solids (S.S.) content of Powerkleen....	182
Table C.20:	Determination of the total solids (T.S.) content of Powerkleen.....	182
Table C.21:	Determination of the total dissolved solids (T.D.S.) content of Powerkleen.....	183
Table C.22:	Compilation of the total dissolved solids results for Powerkleen (9 readings).....	183
Table C.23:	Calculation of the sulfate concentration in the effluent using ion chromatography.....	184
Table C.24:	Calculation of the fluoride concentration in the effluent using an ion selective electrode.....	186
Table C.25:	Photometric calculation of the sulfide concentration in the effluent samples.....	188
Table C.26:	Results of the pH measurement of the effluent samples.....	189
Table C.27:	Results of the measurement of the conductivity of the effluent samples.....	189
Table C.28:	Determination of the suspended solids (S.S.) content of the effluent (run 1).....	190
Table C.29:	Determination of the total solids (T.S.) content of the effluent (run 1).....	190

## List of Tables

---

Table C.30:	Determination of the total dissolved solids (T.D.S.) content of the effluent (run 1).....	190
Table C.31:	Determination of the suspended solids (S.S.) content of the effluent (run 2).....	191
Table C.32:	Determination of the total solids (T.S.) content of the effluent (run 2).....	191
Table C.33:	Determination of the total dissolved solids (T.D.S.) content of the effluent (run 2).....	191
Table C.34:	Determination of the suspended solids (S.S.) content of the effluent (run 3).....	192
Table C.35:	Determination of the total solids (T.S.) content of the effluent (run 3).....	192
Table C.36:	Determination of the total dissolved solids (T.D.S.) content of the effluent (run 3).....	192
Table C.37:	Compilation of the total dissolved solids results for the effluent samples (9 readings).....	193
Table D.1:	Gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time (run 1).....	195
Table D.2:	Gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time (run 2).....	197
Table D.3:	Gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time (run 3).....	199
Table D.4:	Gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time (run 4).....	201
Table D.5:	Averaged gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time.....	203
Table D.6:	Gravimetric analysis results for the comparison of the pre-wash combinations.....	212
Table D.7:	Gravimetric analysis results for the comparison of Powerkleen concentrations.....	214

Table D.8:	Gravimetric analysis results for the determination of the most effective Powerkleen concentration and soaking time (run 1).....	217
Table D.9:	Gravimetric analysis results for the determination of the most effective Powerkleen concentration and soaking time (run 2).....	220
Table D.10:	Gravimetric analysis results for the determination of the most effective Powerkleen concentration and soaking time (run 3).....	223
Table D.11:	Gravimetric analysis results for the determination of the most effective Powerkleen concentration and soaking time (run 4).....	226
Table D.12:	Compilation of the gravimetric analysis results for the determination of the most effective Powerkleen concentration and soaking time.....	229
Table E.1:	Calculation of the net present value of the Ben Booysen project (replacing Alukleen with Powerkleen).....	246
Table E.2:	Calculation of the internal rate of return of the Ben Booysen project (replacing Alukleen with Powerkleen).....	247

# Chapter 1: Introduction

## 1.1 Waste Minimisation as a Waste Management Strategy

Waste is defined as any material, solid, liquid or gas, that is no longer required by the organism or system that has been using it or producing it.<sup>1</sup> When considering the industrial sector, two distinct sources of waste become clear: waste of energy and waste of matter.<sup>2</sup> Manufacturing processes further produce three classes of waste: process wastes, utility wastes and other wastes (Figure 1.1).<sup>1, 2</sup> Process wastes are defined as the solid, liquid and vapour wastes generated when converting raw materials into products.<sup>2</sup> The necessary raw materials required for production may form part of the generated waste if the correct stoichiometry of reactants is not achieved and if complete conversion does not occur. Secondary raw materials (such as catalysts and solvents), which are necessary for the process to occur but are not converted to product, further contribute to this waste.

Utility wastes are solid, liquid and vapour wastes generated from the utility systems needed to run the process.<sup>2</sup> This waste includes ancillary materials, for example water used as a cooling medium, if it is not effectively recycled. Energy also forms part of this waste if it is not harnessed and used effectively. The broad category of other wastes refers to the waste produced by start-ups and shutdowns of the process, maintenance and housekeeping.<sup>2</sup>

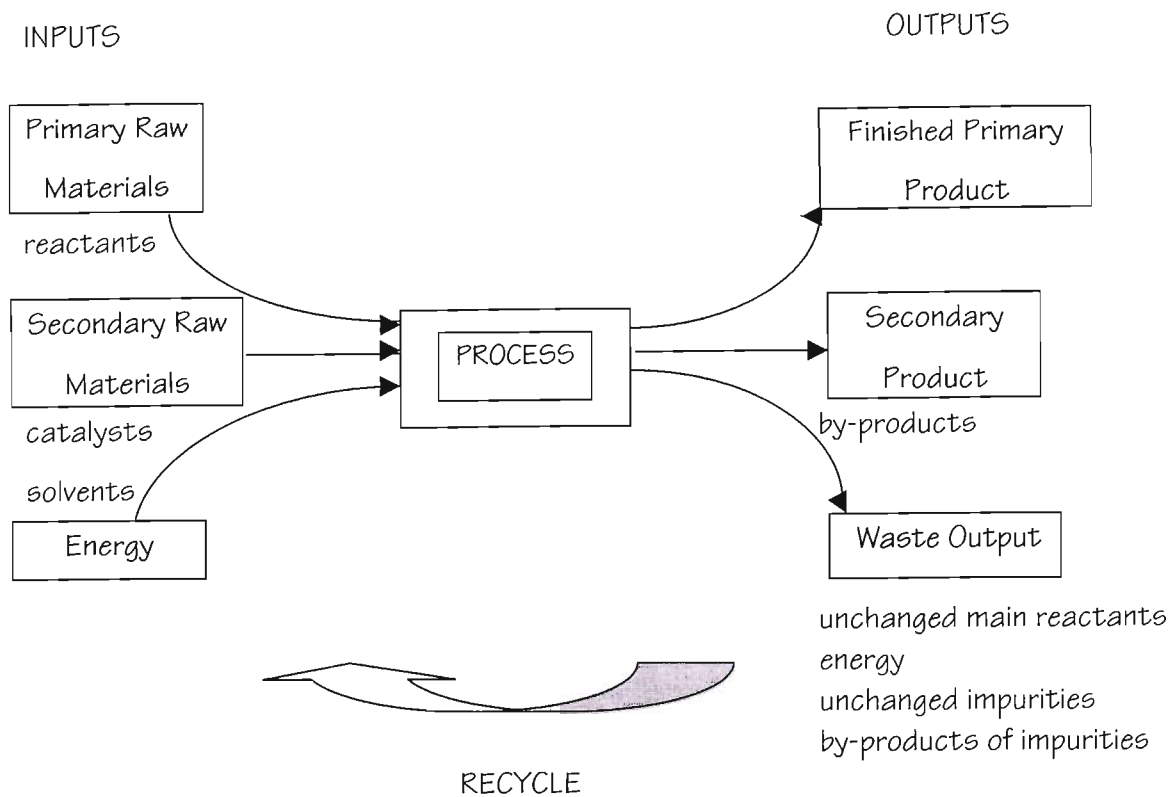


Fig. 1.1: Generation of waste in an industrial process.<sup>1</sup>

Approaches to dealing with waste are illustrated in the following diagram:

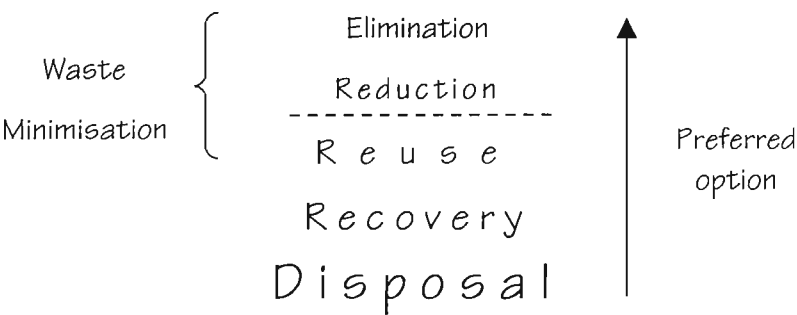


Fig. 1.2: Waste management hierarchy.<sup>3, 4</sup>

The least preferred approach in managing waste is its treatment and disposal. Waste disposal is defined as the destruction of waste materials in such a way that the impact on the environment and society is minimal.<sup>1</sup> Two of the most commonly used techniques include dumping and incineration.<sup>1</sup> Both of these are frequently combined with recovery

and recycling (reuse) to reduce the need for waste disposal. Recovery or reclamation refers to the processing of a waste material such that the valuable constituents are recovered for reuse.<sup>5, 6</sup> Disposal, recovery and reuse are waste hierarchy options that are referred to as 'end of pipe techniques'.<sup>3</sup> They are employed after waste has been produced and are simply a means of managing it effectively.

A more desirable approach to dealing with waste is through the process of waste minimisation (*i.e.*: the reduction or elimination of the generation of waste at source<sup>3, 7, 8</sup> but which can also include the reuse and recycling of waste). Waste minimisation considers raw materials, water and energy consumption and the solid, liquid and gaseous wastes produced.<sup>7</sup> Waste minimisation can be achieved through improved housekeeping, raw material changes, internal recycling, product changes and technological changes, including process changes (Figure 1.3).<sup>8, 9</sup>

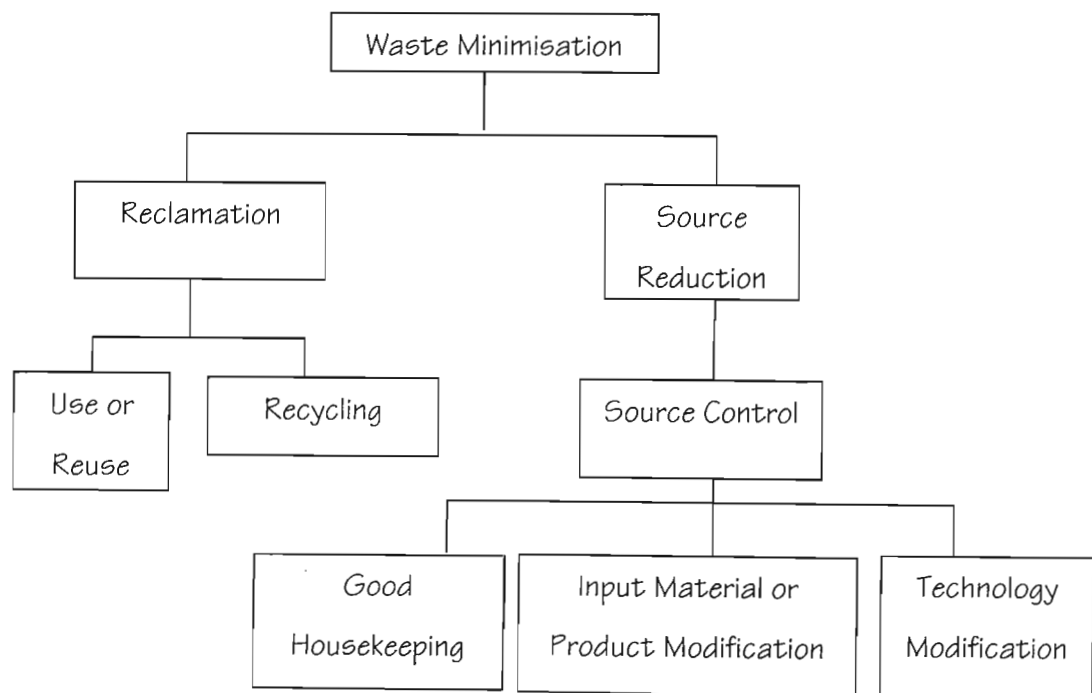


Fig. 1.3: Approaches to waste minimisation.<sup>1</sup>

Implementation of a waste minimisation program in a company has many, far-reaching consequences. The overall aims of a waste minimisation program are the maximisation of business efficiency and the reduction of the company's impact on the environment.<sup>7, 10</sup> Business efficiency is improved through reduced raw materials costs, reduced effluent



treatment costs, reduced waste disposal, reduced utility usage, reduced labour and time costs, regulation compliance and an improved product yield.<sup>3,7</sup> Environmental impact is reduced through a reduced consumption of raw materials and resources, lower emissions and the reduced need for landfill and effluent treatment.<sup>3,7</sup> The above factors result in increased competitiveness, reduced environmental risks and liabilities as well as an improved public image of the company. This is discussed in more detail in Section 2.4. The philosophies and techniques used in waste minimisation are described further in Chapter 2, with particular reference to pre-assessment and assessment techniques. Pre-assessment techniques allow broad focus areas (waste minimisation opportunities) to be identified, which would benefit from a more detailed assessment (*e.g.* improved water flow rate control).<sup>11</sup> The detailed assessment techniques allow specific waste minimisation solutions to be determined (*e.g.* the fixing of water leaks). In this study, the waste minimisation opportunity was determined by the company, Ben Booysen, *a priori*.

## **1.2 Waste Minimisation Study at Ben Booysen**

Ben Booysen is located in Pietermaritzburg and supplies and services a range of refrigeration and air-conditioning products. It employs 75 people and services customers from Richards Bay to Port Shepstone in Kwa-Zulu Natal. The company has been in existence for the last fifty years and, during the last two years, has been a member of the Pietermaritzburg Waste Minimisation Club.

The waste minimisation opportunity identified by Ben Booysen was the optimisation of the process conditions for cleaning air-conditioner units. At the time of this study, Ben Booysen used Alukleen, an acid cleaner, for the cleaning of the aluminium air-conditioner coils. On delivery to Ben Booysen, the Alukleen was diluted with water to an effective dilution of 1:1 by the stores manager and dispensed into one-litre plastic bottles. Technicians diluted this solution further before use to an effective dilution of 1:3. In cleaning the air-conditioner coils, the technicians applied the 1:3 Alukleen to the aluminium coils with a paintbrush, and then rinsed this solution off using a water hose. The plastic casing of the air-conditioner units were cleaned using both Handy Andy and

green soap. At the time of this study, Ben Booyesen's effluent was disposed to stormwater.

In order to optimise the concentration of Alukleen, its composition needed to be quantified. The material safety data sheet of Alukleen<sup>12</sup> only indicated that a blend of inorganic acids and surfactants were present.

Hence the objectives of this study were to:

- qualify and quantify the main chemical species in Alukleen;
- quantify the composition of the company's effluent and subsequently determine whether it complied with the limits for disposal to stormwater and Darvill Wastewater Works; and to
- optimise the Alukleen system with regard to Alukleen concentration and its contact (soaking) time with the coils.

However, during the course of the optimisation of the Alukleen system, it became apparent that Alukleen corroded the surfaces of the aluminium coils. Hence, further objectives of this project were developed. These included the investigation of suitable alternatives to Alukleen, their optimisation with regard to concentration and contact time, and lastly, a feasibility analysis to establish the technical, economic and environmental feasibility of the selected system prior to implementation.

This dissertation begins with a review of the fundamental concepts of waste minimisation and the techniques used in identifying waste minimisation solutions and opportunities (Chapter 2). The chemistry involved in cleaning aluminium metal using acidic and basic cleaners and the relative effectiveness of these cleaners are also reviewed in this chapter.

The wet chemical techniques used in determining the species present in Alukleen are described in Chapter 3. In addition, the instrumentation and analytical techniques used to quantify the species and characterise Alukleen, Powerkleen (the alkaline degreaser) and the effluent of Ben Booyesen are described. Each of the systems was characterised in terms of the concentrations of its main constituents and its pH, conductivity and total



dissolved solids concentration. Lastly, the experimental protocol used to optimise the cleaner systems is discussed in this chapter.

In Chapter 4, the results of the wet chemical techniques are presented, and the characterisation results of the Alukleen, Powerkleen and effluent systems are described. Comparison of the effluent composition to the stormwater and Darvill disposal limits is further made.

Chapter 5 describes the systematic steps taken in investigating the most effective cleaner system for the air-conditioner coils. The results presented in this chapter include those obtained from varying the Alukleen concentration and coil soaking time, the study of the performance of various pre-wash systems and degreasers, the optimisation of the Powerkleen system with regard to cleaner concentration and coil soaking time, and studies on application techniques for Powerkleen.

The feasibility study conducted on the proposed changes at Ben Booysen is detailed in Chapter 6. This analysis includes the technical, economic and environmental evaluations of the selected cleaner system. This chapter thus highlights the potential financial and environmental savings of the proposed changes.

Finally, in Chapter 7, conclusions are drawn from this study and recommendations are made with regard to changing the cleaner chemical, its concentration and application technique.

# **Chapter 2: Literature Review of Waste Minimisation and Aluminium Cleaning Theory**

## **2.1 Introduction**

To set this study in context, the fundamental principles of the concept of waste minimisation are explored in this chapter in detail. The principles include the approach (Section 2.2; page 7), strategy (Section 2.3; page 8), benefits (Section 2.4; page 42), barriers (Section 2.5; page 44) and drivers (Section 2.6; page 45) of waste minimisation in industries. In this review, particular emphasis is placed on the strategy of waste minimisation. Since this waste minimisation project involved the investigation of a process change in the cleaning of air-conditioner coils, the chemistry involved in the cleaning of aluminium metal is reviewed (Section 2.7; page 45). This review includes the effect of both acidic and alkaline solutions on aluminium surfaces.

## **2.2 Approaches to Waste Minimisation**

There are two approaches to the introduction of waste minimisation in a company: the individual approach and the club approach.<sup>13</sup> The individual approach refers to the case where the company hires a consulting company, an academic institution or an expert to assist the company in implementing a waste minimisation program.<sup>14</sup> The club approach, however, describes the situation in which several companies join together to receive the training and support necessary to enable each of the companies to carry out their own waste minimisation programmes.<sup>13, 14</sup> The waste minimisation clubs meet periodically and discuss difficulties and achievements associated with their programmes of waste minimisation. Since this study involves the individual approach, waste minimisation clubs are not reviewed further.

## 2.3 The Strategy for Waste Minimisation

### 2.3.1 Introduction

The sequence of steps involved in the strategy for a waste minimisation programme is commitment to action and organisation of a project team, pre-assessment of the process, detailed assessment, a feasibility analysis of selected solutions and implementation.<sup>7,10,13,15</sup> The latter steps are illustrated in Figure 2.1. Each of these steps is described below.

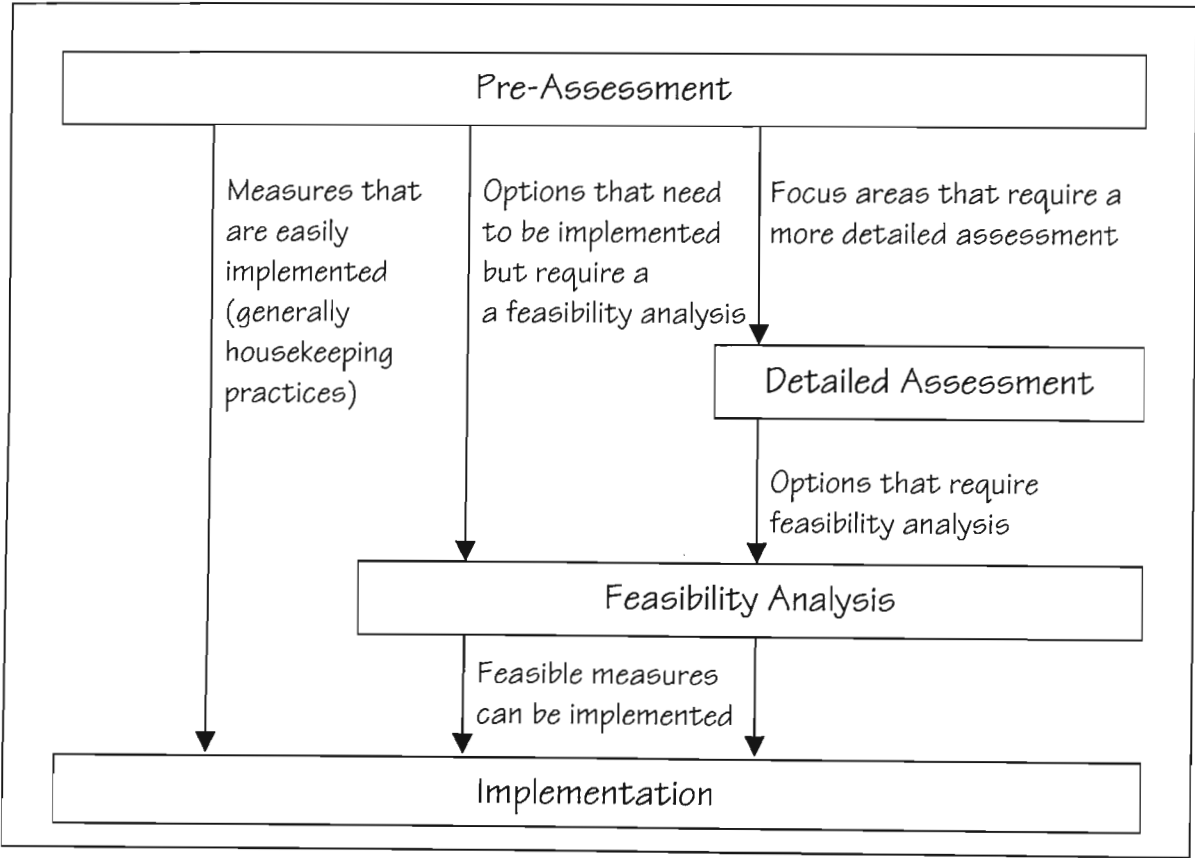


Fig. 2.1: Schematic diagram for the determination of which solutions are suitable for implementation.<sup>16</sup>

### **2.3.1.1 Commitment to Action**

The first step in obtaining the commitment of a company to a waste minimisation programme is obtaining the commitment from senior management. This is essential in that management would be responsible for allocating human resources, facilitating the release of confidential information from departments and for providing financial resources where necessary.<sup>8, 17</sup>

The second step is the selection of a project team from within the company. This should include personnel from all levels of employment and is led by the project champion.<sup>7</sup> The role of the project champion is to attend externally run training sessions, arrange and run meetings within the company during which the progress of the programme is assessed, set goals for the waste minimisation programme and report to management.<sup>10</sup>

### **2.3.1.2 Pre-Assessment Stage**

The pre-assessment stage is the initial stage in conducting a waste minimisation audit (Figure 2.1). The goals of this stage are to identify focus areas (opportunities) and the scope for waste minimisation, to identify the exact sources and causes of wastes and emissions, as well as to prioritise the waste streams for action.<sup>8, 15, 18, 19</sup> This pre-assessment stage in a waste minimisation audit also serves to highlight measures that can be implemented with ease within the company such as good housekeeping measures (Figure 2.1). These initial successes serve to provide motivation for the rest of the waste minimisation programme.<sup>19</sup> This is thus an important stage in a waste minimisation audit.

The pre-assessment stage first involves construction of a process flow diagram, which shows in pictorial form, how materials flow through a process operation (Figure 2.2).<sup>7,8,18,20</sup> Mapping explains where ancillary materials, consumables and energy are used and where known wastes (gas/solid/liquid) are generated.

A process flow diagram is generally constructed for the site as a whole and then for each process in turn.<sup>15</sup> A general site process flow diagram for a manufacturing company is shown below:

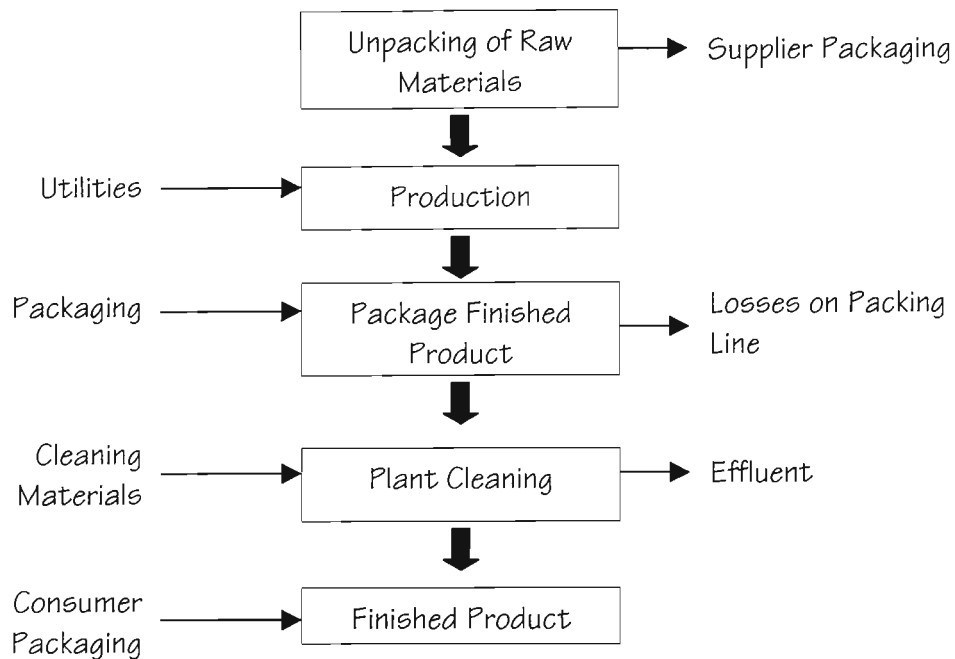


Fig. 2.2: A site process flow diagram for a manufacturing company.<sup>15</sup>

Flow rate, composition and cost data are then collected for each of the input and output streams.<sup>7, 18</sup> Once sources of reliable existing data have been established, including management reports, production statistics, material use reports, by-product and waste disposal reports, effluent analyses and the order sheets of customers and suppliers, the outstanding data can be determined.<sup>15, 17</sup>

The degree of accuracy with which waste minimisation opportunities can be identified in a company using this technique will depend upon the amount of detail and depth on the diagram; these diagrams can be used as a tool for the identification of broad focus areas for improvement such as whole processes or departments or alternatively for the marking of specific areas for optimisation such as process streams or utility use.

Data required are often collected by means of a Proforma, a form in which the data are organised and stored.<sup>7</sup> Several techniques can be used to gather the needed data. The three main categories of data collection are explained below:

### **(a) Measurements**

Measurement of flow rates often necessitates the installation of flow meters at certain points. Meters are also needed to measure energy consumed for heating and power supply. However, simple, cheap techniques are often adequate for obtaining composition and flow rate measurements (*e.g.* pH indicator paper, titrations, the bucket and stopwatch method for measuring flow rates).<sup>7, 15</sup>

### **(b) Informal Interviews and Discussions**

The method of informal interviews and discussions allows the person collecting the data to talk to people who deal intimately with a small part of the process on a daily basis. Their knowledge is often invaluable and through speaking with them, more accurate facts and measurements can be located.

### **(c) Observation of Work Practices**

This seemingly simple method of data collection is often found to be immensely helpful. As workers carry out their tasks on a daily basis, the work tends to become routine. This can be a dangerous situation in that nobody is constantly challenging the system and therefore improving it. For example, a certain reactant may have always been added to a reactor in excess for no particular reason. As it has been done this way for several years, nobody queries it, and yet, it leads to the generation of waste material. An outsider observing this process will query why steps are taken and thus help identify opportunities for waste minimisation within a company.

Several pre-assessment techniques<sup>21, 22, 23, 24</sup>, which use the above data have been developed to assist in identifying waste minimisation focus areas and to prioritise the waste streams for action. These techniques are described in Section 2.3.2 (page 13).

#### **2.3.1.3 Assessment Stage**

The assessment phase in a waste minimisation audit refers to detailed research into focus areas highlighted in the pre-assessment stage as having potential for waste minimisation (Figure 2.1).<sup>8</sup> It involves the collection of further data and its subsequent analysis.

Techniques used in the assessment stage to determine waste minimisation opportunities and solutions are reviewed further in Section 2.3.3 (page 22).

A useful method for generating solutions to waste minimisation opportunities identified through the pre-assessment and assessment stages is brainstorming.<sup>7</sup> With this, a team of personnel from all levels of employment within the company generate as many ideas as possible for the solution of a waste minimisation opportunity.<sup>8, 15</sup> These solutions often have their roots in ideas from operators that have ‘hands-on’ experience and know the process intimately. The solutions then need to be prioritised and selected for implementation (Figure 2.1).<sup>8</sup> Those measures that can be implemented first are generally the simplest and do not require a large capital investment. These are often referred to as ‘good housekeeping’ measures and include those options involving material substitutions if there are no major impacts on production rate or product quality and if no equipment changes are required.<sup>8, 15</sup>

#### **2.3.1.4 Feasibility Analysis**

Those solutions that require a more substantial initial capital investment necessitate a feasibility analysis.<sup>8</sup> The feasibility analysis has three components: technical, economic and environmental evaluations. A solution needs to be pronounced feasible in all three areas prior to implementation in a company. This is discussed in more detail in Section 2.3.4 (page 30).

#### **2.3.1.5 Implementation and Continual Assessment**

Once solutions have been implemented in the company, control systems can be set up to monitor their performance as a quality control measure. The control systems necessitate further data collections and aim to assess the effectiveness of the implemented solutions.<sup>15, 17</sup>

Savings achieved by the company can be quantified in terms of financial and environmental benefits. The financial savings of the company can be determined from the monthly utility and raw materials’ bills. These savings should be analysed with



regard to the amount of product being produced. If the implemented solutions are effective, a decrease in the cost of utilities and raw materials should be noticed with an increased, if not constant, product turnover.<sup>15</sup>

Environmental savings are more difficult to quantify, but an idea of the effectiveness of the solution can be gained through comparison of the concentration of effluent or the colour of any air emissions being released from the process.<sup>8, 15</sup>

Lastly, this stage includes the publication of the waste minimisation results to company employees, directors and shareholders in order that the benefits of their actions can be seen.<sup>7</sup> This serves to boost morale within the company and maintain the momentum of the waste minimisation programme going.

### **2.3.2 Pre-assessment Stage**

The pre-assessment techniques for a process can either be qualitative or quantitative.<sup>7,8,20</sup> These are discussed in more detail below:

#### **2.3.2.1 Qualitative Methods**

This method makes use of qualitative analysis, which prioritises the waste streams for waste minimisation without analysing the relative flow rates or concentrations of the components in the waste stream. This method can be used independently in the pre-assessment stage or as a pre-requisite for quantitative analysis.

The only qualitative method identified through this literature review is the P-graph method of Halim and Srinivasan<sup>21</sup>, which focuses on process wastes. Each material that makes up a stream is classified as useful or useless by referencing it to its function in the overall process. Raw materials, solvents and cooling agents are examples of useful components whilst material impurities and waste by-products are classified as useless. A material should be considered useless only if it serves no function in the process.

The streams and units that contribute to the presence of useful and useless material in each waste stream are then identified using a process graph (P-graph)<sup>21</sup>. In the P-graph, a material stream is represented by a circle, a unit operation by a bar and connections between the material streams and unit operations by directed arrows. An example of a P-graph is shown below:

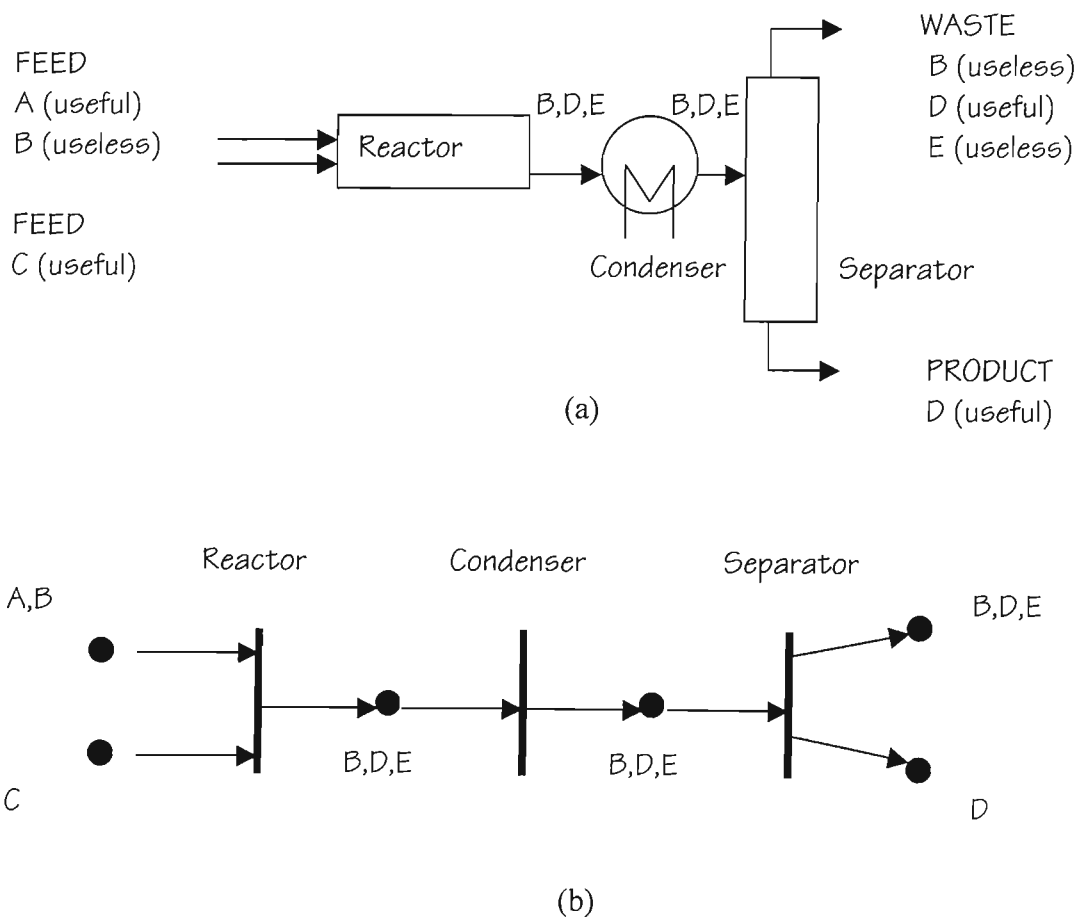


Fig. 2.3: (a) A schematic drawing of a separation process.<sup>21</sup>

(b) P-graph model for the process in (a).<sup>21</sup>

This graph facilitates the identification of opportunities for the separation of the useful material from the waste stream as well as the reduction of useless materials at source. It is a simple method to use in that it does not require the composition of each stream to be known, merely its components.

### 2.3.2.2 Quantitative Methods

These methods use quantitative analysis that serves to establish the relative amount of one or more species or flow rates in numerical terms.<sup>25</sup> The methods below describe various approaches to identifying waste minimisation focus areas (opportunities).

#### (a) DuPont's Method

DuPont developed a waste minimisation methodology for the identification of new process improvement opportunities that reduce/minimise waste. Their methodology is based on the following principles:<sup>22</sup>

- the volumetric flow of an air or gaseous waste stream and the volumetric flow and organic loading of a wastewater stream determine the required end-of-pipe treatment and operating cost;
- manufacturing plant investment and manufacturing costs are influenced by the same gaseous and water flows; and
- end-of-pipe treatment is required only because the streams contain components that have to be abated or removed.

Mulholland and Dyer<sup>2</sup> used DuPont's theory to develop a two-pronged approach for process analysis and waste minimisation. The first phase<sup>2</sup> in identifying waste minimisation opportunities is the *waste stream analysis* of a company. The identified opportunities should eliminate or minimise the waste stream's volumetric flow rate or the components of concern in the waste stream. The *waste stream analysis* involves four steps. The first step is the listing of all components in the waste stream as well as its key parameters. For example, this could include water, inorganic compounds and the pH. The second step involves the identification of the components triggering concern. For example, the concentration of the components present in the stream could be compared to those accepted by the local wastewater treatment plant. The sources of these components should then be determined and waste minimisation options generated for their removal or reduction. Step three is the identification of the highest volume materials (such as diluents, carrier gases or water). Their source in the plant should be determined and, again, waste minimisation options generated. Step four involves

continuous assessment. If the components in Steps two and three have been successfully minimised, the next set of components of concern is considered and options generated for their elimination or reduction.

The second phase<sup>2</sup> of Mulholland and Dyer's method involves *process analysis*. For a plant to operate at zero waste (*i.e.* all raw materials converted into products with no waste of utilities) either the raw materials, intermediates or products must serve the same function as those input streams which later become waste, or the process must be modified to eliminate the latter streams. The *process analysis* phase also consists of four steps. In the first step, all raw materials, including intermediates, are listed ('List 1'). Step two requires the listing of all other materials in the process that do not form saleable products ('List 2'). 'List 2' might include materials like by-products, solvents or water. The third step involves finding ways of using the materials on 'List 1' instead of the compounds on 'List 2', or finding ways to modify the process so that those compounds on 'List 2' are made redundant. Step four looks exclusively at the formation of by-products and asks how the chemistry of the plant can be modified so that the by-products are minimised or eliminated.

The combined use of the waste stream and process analyses should result in a technology plan for driving the process towards minimum waste.<sup>2</sup>

### **(b) Waste Index Methodology**

A number of workers<sup>18, 23, 24, 26</sup> use a Waste Index Method to prioritise waste streams for a more detailed waste minimisation analysis. Each of these waste index methods uses a set of selection criteria for screening the waste streams.

Halim and Srinivasan<sup>23</sup> have suggested criteria such as the quantity and frequency of the waste stream, the cost of managing the existing waste stream, possible regulatory impacts in the future, safety and health risks to the employees and public, ease and cost with which waste minimisation alternatives could be implemented and the demonstrated effectiveness of the solution to be applied. The last two criteria refer more to a feasibility analysis. This method thus combines pre-assessment with aspects of a feasibility analysis. It is however, unlikely that waste minimisation solutions are known when this method is used to identify important waste minimisation streams. Halim and Srinivasan<sup>23</sup>

recommend that each company using this method assign each criterion a weight. Each criterion's index value for a particular waste stream is calculated through the multiplication of the rank (score) of the waste stream by the criterion's weight. The Waste Index value for each waste stream is then calculated by the addition of all the criteria's index values. A criterion considered to be more important to the company involved would thus affect the index more than a lesser criterion. This waste index is thus a general methodology, as it specifies neither the ranking nor weighting system to be used. It is designed to allow the important waste streams to be identified, based on their high index values, and hence to flag those streams that require further, more detailed analysis.<sup>23</sup> To flag the important waste streams, the weights of the feasibility criteria would need to be set to zero so that the feasibility of the generated waste minimisation solution does not detract from the waste stream priority.

Kothuis<sup>18</sup> has suggested that the quantity, cost, environmental impact, waste minimisation potential and general risks involved with the waste stream be used as criteria in prioritising waste streams for waste minimisation. Kothuis suggests the ranking of each of these criteria from 0 to 5 depending on the nature of the waste. This differs from the method of Halim and Srinivasan<sup>23</sup> in that specific criterion ranking values are given. The values for the criteria are then totalled for each waste stream. Kothuis recommends the plotting of a bar graph to illustrate the results (*e.g.* Figure 2.4).

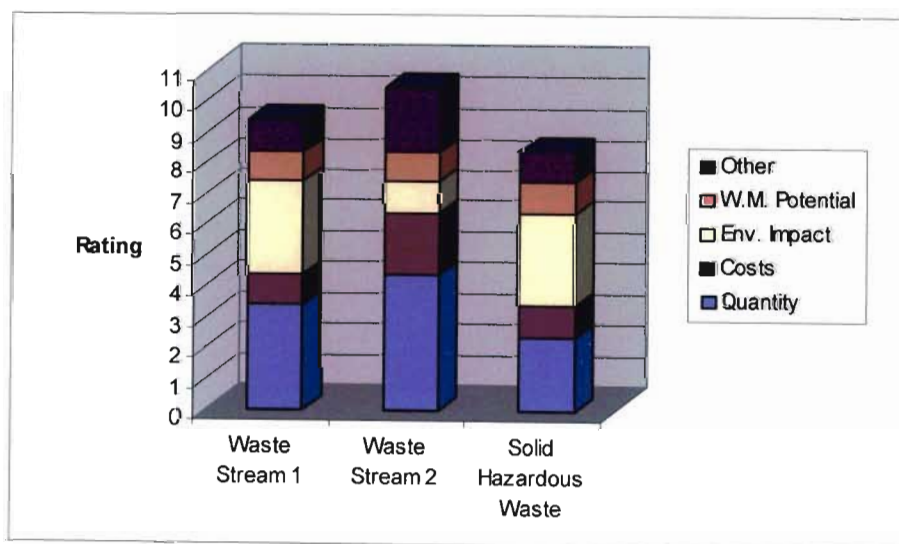


Fig. 2.4: Bar graph showing the ranking of waste streams for waste minimisation using the waste index system of Kothuis.<sup>18</sup>



The bar graph thus shows the contribution of each criterion to the overall waste stream value. A decision can then be made on what stream to prioritise for waste minimisation.

Hawkey<sup>24</sup> has also developed a weighted index system to rank waste minimisation options. Suggested criteria include the amount, cost, toxicity, short-term liability, long-term liability, good management practice and emissions of the waste being considered.<sup>24</sup> The amount (V) of waste is defined as the weight of the waste produced whereas the cost (C) involves all the costs associated with the production and treatment of the waste. The toxicity factor (T) takes into account the type, number and concentration of the toxic constituents of the waste. The short-term liability (ST) looks at the potential risks associated with the transportation of the waste. On the basis of the chosen disposal procedure, the long-term liability (LT) attempts to quantify the life-long responsibility of the producer for the waste. The good management practice variable (GMP) assesses where the current waste treatment fits into the waste management hierarchy. The emissions factor (E) takes into account the amount of material lost by evaporation as well as the cost required to replace the material. As any emission is undesirable, association with its make-up value allows comparison between various waste streams.

Waste stream data for each criterion are then categorised into subgroups of the same order of magnitude. For example, if the cost of all waste streams per year ranges from R10 000 to R80 000, this variable can be divided into 7 subgroups each of R10 000. Each subgroup can then be assigned a whole number value from 1 to 7. The variables ST, LT and GMP are then combined into one total liability value (L); it is merely the sum of the integers that have been assigned to the waste for each of the three variables. Equation 2.1 then gives the appropriate weights to environmental, employee, health, regulatory and business concerns.

$$\text{Rank} = (L + E)[(CV) + T] \quad \text{Equation 2.1}$$

Once calculated, the rank of a waste stream can be used to prioritise the waste streams for waste minimisation efforts.<sup>24</sup>

The South African textile industry uses a score system<sup>26</sup> through which they monitor their pollution potential based on the characteristics of dyes and chemicals used. The environmental impact of all the chemicals and dyes is based on four criteria: the amount of chemical in excess (A), biodegradation (B), bioaccumulation (C) and toxicity (D). Each criterion is given a score of between one and four, with four being the most damaging chemical. Data required for this ranking is obtained from the material safety data sheet of the chemical or dye, the amount of chemical used and the annual wastewater volume produced. An exposure score is calculated as the product of the scores of the criteria, A, B and C ( $A \times B \times C$ ). The exposure score is then plotted against the toxicity score (in fish) (D) for all the chemicals used by the company. On this graph, a diagonal line divides those chemicals of high and low toxicity. A typical graph of this nature is shown below (Figure 2.5):

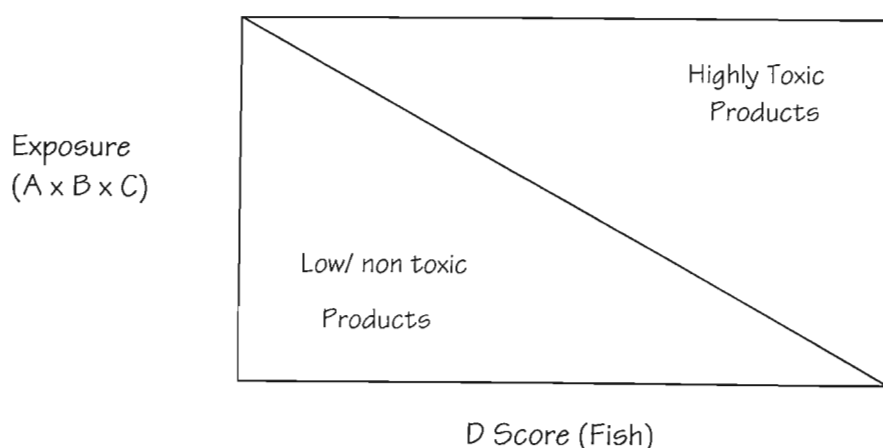


Fig. 2.5: Corresponding co-ordinate system for a textile company in South Africa.<sup>26</sup>

This system allows comparison between the chemicals and dyes used by a company and identifies the highly toxic chemicals or dyes that would form the focus areas of a waste minimisation programme.

### (c) Scoping Audits

The scoping audit involves collecting flow rate and cost data for all input streams, including utilities and all waste streams.<sup>8, 17</sup> The waste streams include solid, liquid, hazardous and general waste; trade waste effluent to sewer, any discharges to storm water drains and gaseous emissions.<sup>20</sup> General guidelines exist as to what savings can be



expected in each area through the implementation of a waste minimisation program (Table 2.1).<sup>8</sup>

Table 2.1: Scope for savings.<sup>8</sup>

Utility	Scope for Saving
Raw materials	1 to 5%
Packaging	10 to 90%
Ancillary materials	5 to 20%
Consumables	10 to 30%
Electricity	5 to 20%
Heat for process and space heating	10 to 30%
Water	20 to 80%
Effluent	20 to 80%
Solid waste	10 to 50%

From the above percentages, the savings in specific areas from implementing a waste minimisation programme can be estimated. In each category, these are calculated through multiplication of the annual cost by the minimum and maximum scope for saving percentage. The respective values generated give the minimum and maximum savings that can be expected for a certain area through the application of waste minimisation principles. From these values, areas for improvement can be identified and ranked according to the maximum scope to save. This gives an indication of potentially important areas for waste minimisation.<sup>8</sup>

It should be noted that the 'scope to save' percentages in Table 2.1 are those calculated for a range of U.K. industries based on the results of previous waste minimisation projects.<sup>11</sup> Previous studies<sup>11, 27</sup> have found that the 'scope to save' in raw materials and waste from implementing waste minimisation solutions is greater in South African industries. This discrepancy could be due to the more stringent environmental legislation present in the U.K.

#### **(d) Calculation of the True Cost of Waste**

Companies often underestimate the true cost of waste since only the cost of disposal (direct cost) is considered. However, the true cost of waste includes both direct and

indirect costs.<sup>3</sup> Direct costs are discussed more in section 2.3.4.3 (page 34). Indirect costs include unconverted raw materials in the waste stream, handling and processing costs (utility and transportation costs as well as employees' time), management and monitoring costs, lost revenue due to reduced capacity, potential liabilities and the cost of any required segregation of waste.<sup>3, 8, 15</sup> It is estimated that the true cost of waste is 5 to 20 times that of the disposal cost.<sup>3</sup>

Calculation of the true cost of waste for each waste stream in a process allows the streams to be prioritised for a more detailed waste minimisation assessment. Although this method ranks the waste streams according to their cost, the quantity, environmental impact and liability of each stream is reflected in its true cost.

Raw water is an expense for industries that needs to be taken into account when calculating the true cost of waste. The costs of raw water in Pietermaritzburg are as follows:<sup>28</sup>

0-400kL	:	R2.95/kL/month
401-1000kL	:	R2.76/kL/month
>1001kL	:	R2.28/kL/month

Calculation of the true cost of waste for each waste stream in a process allows the streams to be prioritised for a more detailed waste minimisation assessment.

#### **(e) Bench-marking**

Bench-marking involves the setting of a desirable consumption level for an operation, process or individual piece of equipment.<sup>8,17</sup> A bench-mark, also called a Key Performance Indicator (KPI), is an indication of the efficiency of a process.<sup>7</sup> Bench-marking also allows comparison of a company's performance with similar companies, on a global scale. This external bench-marking is often co-ordinated through industry associations.<sup>20</sup>

The South African Metal Finishers use a Cleaner Production Bench-marking Tool<sup>29, 30</sup> to assist in identifying waste minimisation opportunities. The Cleaner Production Tool uses eight criteria to fully describe the cleaner production profile in a metal plating facility.

The criteria specified are occupational health and safety, the operational practice of the wastewater treatment plant, chemical savings of the wastewater treatment plant, waste minimisation potential, the state of the rinsing system, required water savings, the maintenance of the process baths and the consumption of process chemicals. The latter three criteria are scored by bench-marking them against built-in goal values representing Best Available Technology (BAT). Hence the company can compare its performance in cleaner production to the best world market performance.<sup>29</sup> The remaining criteria are scored using a waste index scoring system.<sup>30</sup> The resultant scores range between 1 and 100 with 0–20 considered unacceptable, 20–50 considered poor, 50–80 considered fair and 80–100 considered good.<sup>29</sup> Those criteria in a metal finishing plant with the lowest overall scores would be identified as focus areas for a waste minimisation programme.

### 2.3.3 Assessment Stage

The detailed data collection and analysis performed during the assessment stage is project-specific. For example, if it has been ascertained that a raw material change needs to be made, laboratory tests will need to be conducted on the suitability of the specific alternative raw materials. However, two general techniques have been used<sup>8, 15, 31, 32</sup> to identify waste minimisation opportunities and solutions during the assessment stage: mass and energy balances, and monitoring and targeting graphs.

#### 2.3.3.1 Mass and Energy Balances

Any material or energy entering a process as an input *must* come out of the process as an output, in one form or another.<sup>15, 33</sup> This is called the mass/energy balance.

The general mass balance equation is represented below:<sup>33</sup>

$$\text{Input} + \text{Generation} - \text{Output} - \text{Consumption} = \text{Accumulation} \quad \text{Equation 2.2}$$

This is an example of an integral mass balance where the amounts of materials are described in mass units. This mass balance equation can be simplified in three situations,

namely: where the balance is for total mass, the generation and consumption terms become zero; where the balance is being used for non-reactive species, the generation and consumption terms become zero; and lastly, where the system is operating at steady state conditions, the accumulation in material is zero.<sup>33</sup>

The energy balance is a further simplification of Equation 2.2.<sup>33</sup> Since energy can neither be created nor destroyed, the generation and consumption terms are eliminated yielding the energy balance equation as:

$$\text{Accumulation} = \text{Input} - \text{Output} \qquad \text{Equation 2.3}$$

A primary use of mass balance equations is that they allow parts of the process to be identified where raw materials are converted into waste (effluent, solid waste or emissions) and not into useful product.<sup>8, 17</sup> Losses from the site are categorised as either captured or uncaptured losses. Examples of uncaptured losses include emissions (to the atmosphere) or leaks and spills. Captured losses are quantifiable such as solid waste.<sup>7</sup> Identification of these losses allows waste minimisation opportunities to be identified. Mass balance calculations should account for stock gains and losses; hence a period between two successive stock takes is recommended for the mass balance.<sup>34</sup>

The mass balance generated will not be a precise representation of the company's activities; it will merely be a representation of the material balance.<sup>8</sup> This lack of precision is due to several factors such as the lack of precision in industrial measurements, the reliance on the human factor in the acquisition of data and the unavailability of certain data and its subsequent estimation.<sup>33</sup>

A further important use of mass balances is in the validation of data. Quantitative data are applied to the process flow diagram and balances are used to establish whether the total input and output stream masses are equal. If they do not tally, then data validation techniques can be used to investigate the differences.<sup>20</sup>

Mass balance calculations also allow calculation of two indicators of a company's performance: the mass balance yield (MBY) and the first-time yield (FTY).<sup>34</sup> These

indicators would find application in the pre-assessment stage of the waste minimisation programme. The MBY is calculated according to the following equation:

$$\text{MBY} = \frac{\text{Production (tons)}}{\text{Raw materials (tons)}} \quad \text{Equation 2.4}$$

This is a good indicator of a company's performance as it can be increased only by converting more of the raw materials into finished products.<sup>34</sup> The FTY is a measure of how much product is produced 'right first time'. It is calculated as follows:

$$\text{FTY} = \frac{\text{Production (tons)}}{\text{Total inputs (tons)}} \quad \text{Equation 2.5}$$

The total inputs should include all material that is reworked. The FTY can be increased by reducing recycling within a process or increasing the MBY. The goal state is  $\text{MBY} = \text{FTY}$  (*i.e.* no need to recycle or rework material)<sup>34</sup> These indicators allow comparison between companies in the same field and hence highlight the need for waste minimisation in a company.

Associated with the above-mentioned indicators are two costs that serve to quantify the cost of the waste being produced: the MBY cost and the FTY cost.<sup>34</sup> The MBY cost is calculated from the MBY (expressed as a percentage) and the annual cost of materials:<sup>34</sup>

$$\text{MBY cost} = \frac{(100 - \text{MBY}) \times \text{Annual cost of materials}}{100} \quad \text{Equation 2.6}$$

The FTY cost includes the cost of processing the material up to the point when it leaves the process. It is calculated from the FTY (expressed as a percentage) and the annual cost of running the process:<sup>34</sup>

$$\text{FTY cost} = \frac{(100 - \text{FTY}) \times \text{Annual cost of running the process}}{100} \quad \text{Equation 2.7}$$



Mass balance techniques thus allow a process to be kept in tight control; they serve to act as an indicator of the process's performance and highlight streams that would benefit from a waste minimisation analysis.

Energy balances in industry are useful in that they allow calculation of the energy efficiencies of equipment such as boilers, compressors and refrigeration systems. The calculation of such efficiencies furthers the prioritisation of waste streams for action. Barclay and Buckley have reviewed these energy efficiency calculations in the form of proforma tables in detail.<sup>8</sup>

### **2.3.3.2 Monitoring and Targeting Graphs**

Monitoring and targeting involves the measurement of the consumption of raw materials and utilities such as water and energy as a function of time and is a useful technique for determining waste minimisation opportunities where there is a variable target, such as energy consumption.<sup>7, 8</sup> Further steps involved in monitoring and targeting include the determination of the performance levels of a company, setting obtainable targets or goals for the consumption of a particular resource and the ongoing monitoring and feedback of progress made.<sup>3</sup>

To obtain the measurements, it is necessary to have some kind of metering available to ensure the readings are taken on a regular basis.<sup>3, 8</sup> Performance levels are reflected graphically and in this way, process inconsistencies are easily identified. There are a number of graphical representations of monitoring and targeting results: trend graphs, XY scatter plots, variance graphs and cusum plots.

#### **(a) Trend Graphs**

A trend graph (*e.g.* Figure 2.6) shows the actual material consumption over a period of time. Comparison between time periods shows seasonal variations in the raw material and utility consumption.<sup>7, 8</sup> A shortcoming of this plot, however, is that it shows no measure of performance; it does not take into account fluctuations in the consumption of resources due to variations in production levels.<sup>8</sup>

Target consumption can also be included on the trend graph, located below the actual production. The target is the desired/expected consumption for a process.<sup>7</sup> Through the process of attaining this target, waste minimisation opportunities are identified.

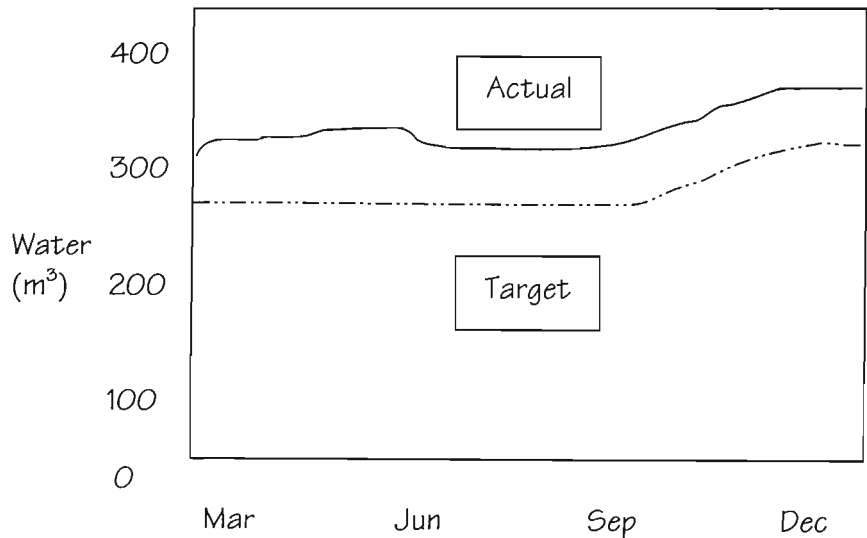


Fig. 2.6: Trend graph showing variations in the monthly water consumption.<sup>7</sup>

**(b) XY Scatter Plots**

These plots allow comparison of the raw material and utility consumption to a relevant production variable (*i.e.* performance). For example, the consumption of electricity can be plotted against the mass of product manufactured over the same time period.<sup>8, 15</sup>

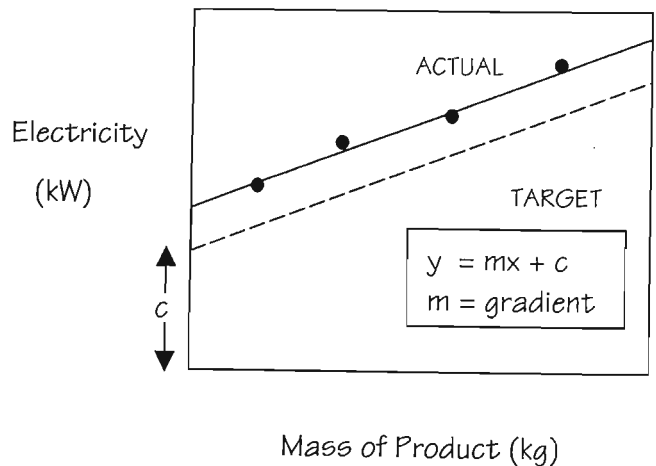


Fig. 2.7: Scatter plot graph of production as a function of consumption.<sup>7, 15</sup>



A 'best fit' linear regression can be used to highlight several features of the process:<sup>8,10,15</sup>

- the base load (the amount consumed at zero production) of the process is given by the y-intercept (c);
- the running efficiency of the plant is given by the slope (m) of the line; and
- the spread of points indicates how tightly controlled the process is.

The values of c and m would ideally be minimised through the course of a waste minimisation programme (*i.e.* the base-load of a process would be reduced and the efficiency with which it was running would increase). Determining the reasons for the scatter of points and the large magnitude of the y-intercept and slope further leads to the identification of waste minimisation opportunities.<sup>15</sup>

A target can then be set for future production to improve the efficiency of the process. This target is then included in the XY scatter plot (*e.g.* Figure 2.7)<sup>8, 10</sup> and is representative of the desired consumption of the resource related to production. The practicality of this target should be verified through the use of a mass balance. Setting a consumption target allows monitoring and targeting to be used as a management-lead approach.<sup>7</sup>

### **(c) Variance Graphs**

In a variance graph, the variance is calculated as the difference between the actual consumption and the target consumption.<sup>7</sup> This graph shows where a change in performance has occurred (*e.g.* Figure 2.8).

This graphical representation thus illustrates when a unit operation in a plant is exceeding the desired consumption (indicated by positive variance values on the graph). This would then serve to highlight the need for waste minimisation solutions for that unit operation.

Variance (000's KWh/wk)

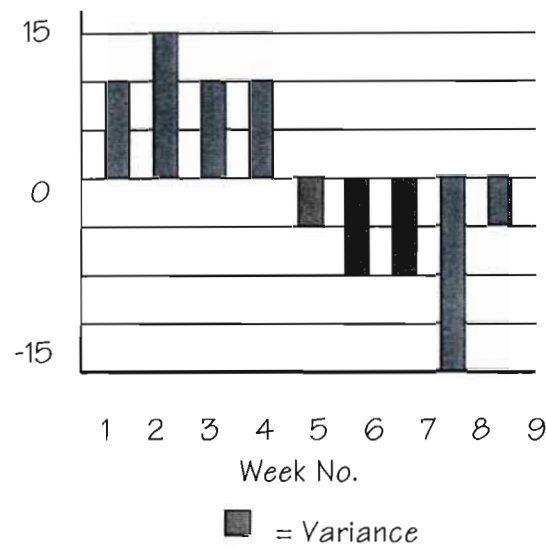


Fig. 2.8: Variance graph showing variance as a function of time.<sup>7</sup>

**(d) Cusum Plots**

Another way to show variance from a target is a cusum plot.<sup>7, 8</sup> The cumulative sum is calculated by adding variances over the time period analysed and has proven a useful method of plotting what is happening on a plant (*e.g.* Figure 2.9).<sup>7</sup>

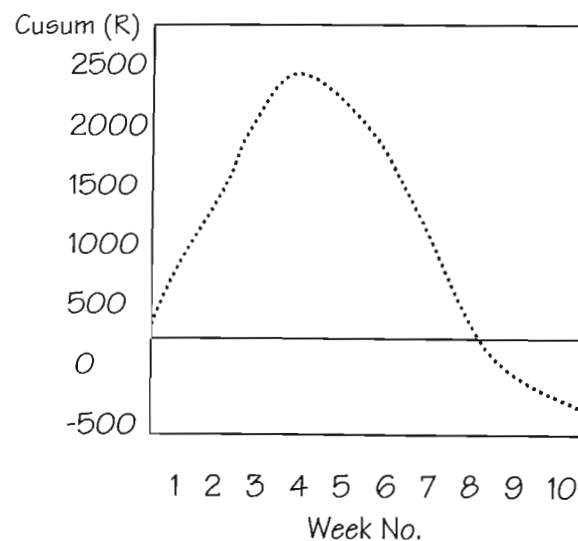


Fig. 2.9: Cusum plot showing rands spent on a particular consumable over a production period.<sup>7</sup>

This type of graph illustrates various performance measures:

- a positive gradient of this graph indicates that the unit operation is operating at above target consumption;
- a negative gradient of this graph indicates that the unit operation is operating below target consumption;
- the x-intercept of this graph indicates the time required for the unit operation to obtain an average consumption corresponding to the target consumption of a resource; and
- the points below the x-axis show that the unit operation is averaging below target consumption for the entire time period being investigated.

This type of graph thus serves to highlight the unit operations that are out of control and the need for identifying waste minimisation solutions for them.

### **2.3.4 Feasibility Analysis**

Waste minimisation solutions that require process and/or equipment changes are more expensive and hence require an in-depth feasibility analysis prior to implementation (Figure 2.1).<sup>8, 19</sup> The feasibility analysis has three components: the technical, economic and environmental evaluations. As discussed in Section 2.3.1.4 (page 12), the generated solution to a waste minimisation problem needs to be feasible in all three of the above areas to be viable for implementation in a company. These areas can be evaluated individually for a solution or a combination approach<sup>23, 35</sup> can be used to determine each solution's feasibility.

#### **2.3.4.1 Technical Evaluation**

The technical evaluation of a project assesses the feasibility of a solution in terms of the technology, timescales, risks involved and company culture.<sup>7, 8, 17, 19</sup>

In evaluating the technology of a solution, the first aspect that needs to be considered is whether it is possible. Some solutions are not appropriate for a specific company and the necessary technology may not be available.<sup>7, 8, 19</sup> It must be considered whether the solution is solving the waste problem or merely masking it. For example, a solution that identifies a recycle route for waste merely deals with the waste; it does not reduce or eliminate it. The feasibility of implementing a solution must also be considered and this includes the physical work required for implementation.<sup>7, 8</sup>

The effect on the short- and long-term project outcome, if the supplier were to cease trading, should be assessed. If the project's success is dependent upon the supplier either because it is the sole supplier or for technical support, the financial stability of the supplier should be analysed and a new supplier chosen if necessary.<sup>7, 8</sup>

Timescale is an important factor affecting a project's technical feasibility. Some solutions take longer to achieve results than others. If there is time pressure on a waste problem, then the solution chosen is that which would solve the problem within the time limit. Examples of time-pressured problems are those where action needs to be taken for compliance reasons in order to avoid a financial penalty; where training is required in order for the project to be successful, or to reduce the time taken before the full benefits of the project are realised. In these situations, it may be preferable to implement a short-term solution. This can then later be replaced with a longer-term solution.<sup>7, 8</sup>

Another area involved in the technical evaluation is the risk associated with a particular solution in terms of whether the technology to be used is 'watertight' and whether the production might suffer initially as a result of the project's implementation.<sup>17</sup> If a project is too risky and success cannot be guaranteed then other possible solutions to the problem can be sought.<sup>7, 8</sup>

With any prospective project, it is important to consider whether the changes involved will be accepted by the organisation's culture. If rejected, the success of the project could be undermined, reducing the benefits achieved, or, at worst, result in the project not being implemented.<sup>7, 8</sup>

Procedures that should be followed for a complete technical evaluation include: reviews of technical literature, visits to existing installations and bench- or pilot-scale demonstration.<sup>8</sup> If it is found that the solution generated initially does not stand up to the technical evaluation, then it may be that the problem was not properly defined in the first instance. Re-visiting the problem-solving stage may yield better solutions.<sup>7, 8</sup> Once solutions are deemed to be technically acceptable, they must be assessed for economic feasibility.

#### 2.3.4.2 Economic Evaluation

Economic evaluation is an objective method a company can use to choose which waste minimisation solutions to invest in.<sup>7, 8, 19</sup> An economic evaluation has three objectives: to determine which investments make the best use of the organisation's money, to ensure minimum financial risk to the enterprise and to provide a basis for the subsequent analysis of the performance of each investment.<sup>7, 8, 15</sup>

The economic evaluation is carried out using standard methods of determining profitability, such as payback period, return on capital employed (ROCE), net present value (NPV) and internal rate of return (IRR).<sup>7, 8</sup> Both capital and operating costs are considered in these methods. If a waste minimisation solution has no significant capital costs, then its profitability can be determined by whether there is a saving or not in operating costs. If there is a reduction in operating costs, then the option should be implemented as soon as practically possible.<sup>8</sup>

The above methods can be classified as either non-discounting (payback period, ROCE) or discounting techniques (NPV, IRR). Only discounting techniques take into account that money will not have the same value in future and therefore cash flows at different points in time are not comparable. In order to enable evaluation and comparison between options, cash flows are converted into equivalent values using a discounting factor:<sup>36, 37</sup>

$$\text{Discount factor} = \frac{1}{(1 + r)^n} \quad \text{Equation 2.8}$$

Where  $r$  is the interest rate of the loan (as a fraction) that is being used to finance the project and  $n$  is the number of years.<sup>36, 37</sup>

### (a) Payback Period

The payback period is the length of time it takes to recover the initial cash outlay on the project. It is determined from the ratio of the capital investment that is required, to the annual operating savings that can be achieved:<sup>7, 36, 37</sup>

$$\text{Payback period} = \frac{\text{Capital costs}}{\text{Net savings}} \quad \text{Equation 2.9}$$

When deciding between two or more projects, the usual decision is to accept the one with the shortest payback period.<sup>37</sup> However, payback is a rough measure of cash flow, not of profitability since it does not account for profitability after the payback period.<sup>8, 37</sup> It is best used for initial screening of several options.<sup>8</sup>

### (b) Return on Capital Employed

The return on capital investment (ROCE), defined as the overall profit over the project lifetime divided by the capital employed, is often used as a measure of the financial success of a company or project. ROCE indicates whether projects will generate profits and which project appears to generate a higher rate of return.<sup>8, 37</sup> However, this technique also does not account for the time value of money.<sup>7</sup>

$$\text{Gross ROCE} = \frac{\text{Total Cost Savings}}{\text{Capital}} \times 100\% \quad \text{Equation 2.10}$$

$$\text{Net ROCE} = \frac{\text{Total Cost Savings} - \text{Capital}}{\text{Capital}} \times 100\% \quad \text{Equation 2.11}$$

$$\text{Gross Annual Rate of Return} = \frac{\text{Gross ROCE}}{\text{Project Life}} \% \quad \text{Equation 2.12}$$

$$\text{Net Annual Rate of Return} = \frac{\text{Net ROCE}}{\text{Project Life}} \% \quad \text{Equation 2.13}$$

**(c) Net Present Value**

The net present value (NPV) is an estimation, in today's terms, of the value of future cash flows generated from a project. Annual cash flow is discounted based on an assumed interest rate or the cost of capital. The sum of the discounted cash flows over the lifetime of the project is the NPV.<sup>7</sup> The higher the NPV of a project, the more appealing the investment is to a company.<sup>37</sup>

NPV accounts for both the size of cash flows after the payback period as well as the time value of money.<sup>7, 36</sup> Where payback, return on capital employed and NPV calculations produce conflicting conclusions, the project with the highest NPV should be chosen because this will add more financial value to the company.<sup>7</sup>

Dantus and High<sup>38</sup> have adapted the NPV definition to calculate an annual equivalent profit (AEP) for a particular investment. The AEP measures a project's profitability over its lifetime,  $N_y$ :<sup>38</sup>

$$\text{AEP} = \left[ \sum_{n=0}^{N_y} \frac{F_n}{(1 + i_r)^n} \right] \left[ \frac{i_r (1 + 1)^{N_y}}{(1 + i_r)^{N_y} - 1} \right] \quad \text{Equation 2.14}$$

Here, the cash flow,  $F$ , is calculated from the cash inflow and cash outflow and  $i_r$  is the annual interest rate.<sup>38</sup> The higher the value of the AEP, the more desirable the waste minimisation solution.

**(d) Internal Rate of Return**

The Internal Rate of Return (IRR) represents the rate of interest that money would have to earn outside or elsewhere in the organisation to be a better investment. The higher the IRR, the more financially rewarding the project. If capital were not restricted, all projects with an IRR greater than the cost of capital should be pursued.<sup>7, 36</sup>

IRR is defined as the discount rate at which the NPV of the project reduces to zero (*i.e.* the discount rate at which the sum of all the discounted cash flows equals the initial capital investment).<sup>7, 36, 37</sup>



### 2.3.4.3 Environmental Evaluation

Where possible, an environmental assessment of the selected solutions should be conducted, even if some of the benefits cannot be quantified.<sup>17</sup> In most cases, the environmental advantage is apparent; some effects to be noted are those on wastewater toxicity and volume, reduced generation of solid wastes and improved working conditions (compliance with the local health and safety regulations).<sup>8</sup>

For those companies undertaking a waste minimisation programme in order to induce environmental legislative compliance, solutions need to be analysed so as to ascertain whether they will be effective in bringing the produced waste into compliance. Knowledge of both local bylaws and national environmental legislation is thus required.

#### (a) Local Bylaws

As the waste dealt with in this project was of a liquid nature (effluent), only bylaws pertaining to effluent discharge to the local Darvill Wastewater Works and stormwater are reviewed.

#### (i) Wastewater Treatment

This area of waste treatment is covered by the Industrial Effluent Bylaws<sup>39, 40</sup>, published in 1988. The wastewater from industries in Pietermaritzburg is treated by Darvill Wastewater Works, which is a subsidiary of Umgeni Water. The cost (in cents per kiloliter) of the treatment that Darvill provides is calculated according to the following formula:

$$C = (V \times X) + [V \times 0.28 (\text{COD} - 350) Y] \quad \text{Equation 2.15}$$

where V is the volume of effluent (kL) and X accounts for the fixed costs associated with the volume of effluent discharged (cents/kL/month) (Refer to Section 2.3.2.2(d); page 20). The term COD refers to the chemical oxygen demand ( $\text{mgO}_2/\text{L}$ ) of the effluent and is a measure of how polluted the water is. Equation 2.15 indicates that each company is charged for the amount that their wastewater exceeds a COD of 350. Wastewater with a COD of below 350 is categorised as domestic wastewater and is

treated free of charge. Companies that pre-treat their wastewater prior to sending it to Darvill are thus charged less. Y is a phasing-in factor that is gradually increasing to 1. Its current value is 0.66.

Table 2.2 outlines the effluent limits for disposal to Darvill Wastewater Treatment Plant.

Table 2.2: The limits for effluent disposal to Darvill.<sup>40</sup>

Description	Units	Limit
Temperature	°C	45
pH		$6.5 < x < 9.5$
Electrical conductivity	mS/m	400
Total dissolved solids	mg/L	5000
Solids in suspension	mg/L	400
Mineral oils and grease	mg/L	50
Soap oil and grease	mg/L	250
Sulfates in solution (expressed as SO <sub>4</sub> )	mg/L	250
Total sulfides (expressed as S)	mg/L	25
Soluble reactive phosphate (expressed as P)	mg/L	20
Free and saline ammonia (expressed as N)	mg/L	80
Total Kjeldhal nitrogen	mg/L	100
Chloride (expressed as Cl)	mg/L	not specified
Fluoride (expressed as F)	mg/L	5
Hydrocyanic acid and cyanides (expressed as HCN)	mg/L	10
Sodium (expressed as Na)	mg/L	not specified
Copper (expressed as Cu)	mg/L	5
Zinc (expressed as Zn)	mg/L	5
Lead (expressed as Pb)	mg/L	5
Cadmium (expressed as Cd)	mg/L	1
Total chromium (expressed as Cr(III))	mg/L	25
Cromium(VI) (expressed as Cr(VI))	mg/L	0
Mercury (expressed as Hg)	mg/L	1
Arsenic (expressed as As)	mg/L	1
Selenium (expressed as Se)	mg/L	1
Nickel (expressed as Ni)	mg/L	5
Boron (expressed as B)	mg/L	5
Cobalt (expressed as Co)	mg/L	5
Molybdenum (expressed as Mo)	mg/L	1

The Industrial Effluent Bylaws further serve to highlight that no industrial effluent may be discharged elsewhere but in a sewer and that the City Engineer must grant permission for this discharge.<sup>40</sup> All effluent that is sent to the wastewater treatment plant must be within the specifications of Table 2.2. Consequently, if damage is caused to the wastewater treatment plant as a result of a company's effluent, the company is liable for the costs of the necessary repairs.<sup>40</sup> A shortcoming in the Industrial Effluent Bylaws is the low fines charged when a person contravenes them. Fines of up to R500 and R1000 are charged for the first and second contraventions respectively. These can be accompanied by respective prison sentences of up to 6 and 12 months.<sup>40</sup> The financial penalties require review.

Companies sometimes use stormwater drains as a means of disposal of effluent. There are very stringent limits for disposal of effluent to stormwater as illustrated in Table 2.3.

Table 2.3: Relevant limits for discharging effluent to stormwater.<sup>41</sup>

Component	Limit
Aluminium	< 5 µg/l
Arsenic	< 10 µg/l
Chlorine	< 0.2 µg/l
Fluorine	< 750 µg/l
Inorganic Nitrogen	< 0.5 mg/l
Total Suspended Solids	< 10 mg/l
Electrical Conductivity	400 mS/m
pH	6.5 < x < 9.5

### **(b) National Legislation**

Since 1996, two Acts and one White Paper have been passed that deal with environmental management of effluent. These are the National Water Act (No. 36 of 1998), the National Environmental Management Act (No. 107 of 1998) and the White Paper on Integrated Pollution and Waste Management for South Africa (2000).<sup>8, 14</sup> The details of these documents that deal with effluent discharge and its liability are given below.

**(i) The National Water Act (No. 36 of 1998)**

The National Water Act deals with how pollution impacts on a water source. It states that “the person who owns, controls, occupies or uses the land in question is responsible for taking measures to prevent pollution of water resources. If these measures are not taken, the catchment management agency concerned may itself do whatever is necessary to prevent the pollution or to remedy its effects, and to recover all reasonable costs from the persons responsible for the pollution.”<sup>42</sup>

**(ii) The National Environmental Management Act (No. 107 of 1998)**

The National Environmental Management Act deals with three areas of environmental concern namely resource conservation and exploitation; pollution control and waste management; and land-use planning and development. The essential points of this document are:

- waste must be avoided or, if not possible, minimised, reused, recycled or disposed of responsibly;
- the polluter responsible for environmental degradation and/or the ill-health of people, is responsible for the payment of the measures required to remedy and control the pollution (‘polluter pays’ principle);
- an employer may not take action against an employee who refuses to do a certain type of work if, in the employee’s opinion, it would cause a serious threat to the environment;
- any person may have legal standing if they allege that there is a breach of any law pertaining to the protection of the environment; and
- the director of a company that has been found not to have taken all the reasonable steps to prevent pollution occurring, can be held legally accountable in a private capacity.<sup>43</sup>

**(iii) The White Paper on Integrated Pollution and Waste Management for South Africa (2000)**

The White Paper on Integrated Pollution and Waste Management for South Africa is a document of paramount importance with regard to waste minimisation. One of the important points in this document is that of ‘cradle to grave’ responsibility. This concept

recognises that pollution is the responsibility of the producer from the cradle to the grave inclusive of generation, collection, transportation, treatment and final disposal.<sup>44</sup>

Compliance with the terms of the above-mentioned pieces of legislation would thus form a large part of the environmental evaluation in a feasibility analysis.

#### **2.3.4.4 A Combination Approach**

Smith and Khan<sup>35</sup> proposed a combination approach which assesses a project's overall feasibility. They generated a table of eight weighted factors that are used in an indexing procedure to screen and rank the waste minimisation solutions. The proposed waste minimisation solutions are referenced (Table 2.4) using the following criteria: priority in the waste minimisation hierarchy (source reduction, recycling, waste treatment), ease of implementation of the solution (EI), percentage of waste reduction that can be achieved (PR), capital-cost requirements (CC), payback period (PB), and the depth of investigation for the solution reported (DS).

Table 2.4 can be adapted to company and industry-specific solutions.

The weights in Table 2.4 indicate the relative importance of the criteria in Smith and Khan's<sup>35</sup> model. The index values weight the different possibility for each criterion. In the EI category, a procedural change is easiest to implement and thus is assigned the highest index value. Similarly, retrofitting is simpler than adding new equipment. Hence the former is assigned a higher index value. Lower capital cost requirements further receive higher index values. The indexes used for the percentage of waste reduction (PR) and payback period (PB) correspond to the actual values of these criteria. In the DS category, a company case study, followed by an EPA case study are the most preferred because they are most likely to be credible as a result of their actual implementation in a real process plant.<sup>35</sup>



Table 2.4: Pollution prevention index of Smith and Khan.<sup>35</sup>

Criteria	Weight	Activity	Index value
Pollution Prevention Type:			
Source reduction (SR)	$10^{11}$		1
Recycling (R)	$10^{10}$		1
Waste treatment (WT)	$10^9$		1
Ease of Implementation (EI)	$10^8$	Procedure change	5
		Retrofit equipment	4
		New equipment	3
		Higher purity solvent	2
		Material substitution	1
Percentage of waste Reduction (PR)	$10^5$	0-100%	
Capital Cost (CC)	$10^4$	No cost	5
		Low (<\$15,000)	4
		Moderate (\$15,000<cost<\$50,000)	3
		High (\$50,000<cost<\$150,000)	2
		Very high (>\$150,000)	1
Payback (PB)	$10^3$	0-9 years	
Depth of Solution (DS)	1	Company case study	1000
		EPA case study	100
		Consultation report	10
		Other option	1

Smith and Khan used a waste minimisation index (WI) to calculate the overall feasibility of a waste minimisation solution. The WI value of each solution was calculated through the weighted sum of the individual criterion values (represented by the letters in Equation 2.16) assigned to the stream. A waste minimisation solution would usually only encompass one of either source reduction, recycling or waste treatment.

**Waste minimisation index (WI):**<sup>35</sup>

$$\text{WI} = \text{SR} \times 10^{11} + \text{R} \times 10^{10} + \text{WT} \times 10^9 + \text{EI} \times 10^8 + \text{PR} \times 10^5 + \text{CC} \times 10^4 + (9 - \text{PB}) \times 10^3 + \text{DS}$$

Equation 2.16

Halim and Srinivasan<sup>26</sup> have further modified Smith and Khan's waste index (Table 2.4). Their modifications were suggested in an attempt to rectify what they saw as shortcomings associated with the initial ranking procedure. These included the subjective assignment of weights and indexes to each criterion, which can influence results to a great extent. They further considered the assignment of index values not to be clear for intermediate cases, which were neither the best nor the worst possible solution. Their modifications included the elimination of the waste treatment criterion, since this should not be included in the ranking of waste minimisation solutions, and the elimination of the depth of solution category. Interestingly, they changed neither the weights nor the index values of Smith and Khan's model<sup>35</sup> when they developed their Waste Minimisation Index (WMI) (Equation 2.17, Table 2.5).

Table 2.5: Pollution prevention index of Halim and Srinivasan.<sup>23</sup>

Criteria	Weight	Activity	Index value
Pollution Prevention Type:			
Source reduction (SR)	$10^{11}$		1
Recycling (R)	$10^{10}$		1
Ease of Implementation (EI)	$10^8$	Procedure change	5
		Retrofit equipment	4
		New equipment	3
		Higher purity solvent	2
		Material substitution	1
Percentage of waste Reduction (PR)	$10^5$	0-100%	
Capital Cost (CC)	$10^4$	No cost	5
		Low (<\$15,000)	4
		Moderate (\$15,000<cost<\$50,000)	3
		High (\$50,000<cost<\$150,000)	2
		Very high (>\$150,000)	1
Payback (PB)	$10^3$	0-9 years	

**Waste minimisation index (WMI):<sup>26</sup>**

$$\text{WMI} = \text{SR} \times 10^{11} + \text{R} \times 10^{10} + \text{EI} \times 10^8 + \text{PR} \times 10^5 + \text{CC} \times 10^4 + (9 - \text{PB}) \times 10^3 \quad \text{Equation 2.17}$$



In both of these indexes, the most feasible waste minimisation solutions can be identified by their high index values.

A further rating mechanism that uses a combination approach has been developed by Envirowise<sup>15</sup> to assess the overall feasibility of a project. Their model involves awarding points from 1 – 5 for the position that the solution occupies in the waste management hierarchy, the ease of its implementation, the proposed degree of change and the cost of the solution. The structure of this method is shown below:<sup>15</sup>

<b>Waste management hierarchy</b>	5 = reduction/elimination at source 1 = disposal
<b>Implementation potential</b>	5 = can be implemented immediately 1 = not feasible
<b>Type of option</b>	5 = good housekeeping 1 = new technology
<b>Cost of option</b>	5 = no cost 1 = outside limits of budget

The points for each option are then added up to produce a total score and the option with the highest score is considered the most feasible.<sup>15</sup>

## 2.4 The Benefits of Waste Minimisation

### 2.4.1 Cost Savings

In implementing a waste minimisation program and hence reducing the quantity of waste, considerable amounts of money have been saved.<sup>27, 45, 46, 47</sup> The first waste minimisation club run in the United Kingdom reported savings in the area of £3 million.<sup>45</sup> It was a cross-sectoral club consisting of 11 members. Other waste minimisation clubs in the United Kingdom that have had financial gains include the Ayrshire Textiles Waste Minimisation Club and the East of Scotland Waste

Minimisation Project.<sup>48</sup> These clubs have reported savings of £538 000 and £3.8 million per annum respectively.<sup>48</sup> A waste minimisation club for the metal finishing sector, run in Kwa-Zulu Natal, reported a total annual savings of over R2 million for its 15 members.<sup>27</sup> Other waste minimisation clubs in the country, which have run to completion, include the Hammarsdale club (Kwa-Zulu Natal) and the Waste Minimisation Club for Larger Industries (Western Cape).<sup>49</sup> These cross-sectoral clubs of 8 and 7 members have reported savings of over R10 million and R7 million per annum respectively.<sup>49</sup>

Savings result from the reduction of effluent treatment and waste disposal costs, improved product yield, the reduced need for capital to be spent on pollution control facilities as well as the reduced requirement for purchased materials.<sup>8, 10, 15</sup> Overall, the increased operating efficiency that results through the implementation of waste minimisation techniques leads to fundamental financial improvement.<sup>13, 15</sup>

#### **2.4.2 Environmental Improvement**

A significant environmental improvement is noticed upon the implementation of a waste minimisation program.<sup>7</sup> These benefits are due to the reduction of the consumption of materials and natural resources. By reducing waste at source, companies reduce their emissions, effluent and solid waste, although this is not always quantified.<sup>8,9</sup> This reduction in environmental impact leads to improved compliance with environmental regulations and legislation.<sup>7</sup> This, in turn, leads to an enhanced company image.<sup>7, 8, 13</sup>

#### **2.4.3 Increased Throughput**

If employees are trained to make more productive use of their time and of the materials used, more product can be made at a faster rate with the same amount of available equipment.<sup>7, 15</sup> Thus process intensification occurs which, in turn, leads to decreased capital expenditure.<sup>15</sup> This intensification of the resources available is a definite benefit of a waste minimisation programme in a company.

#### **2.4.4 Risk and Liability Reduction**

This benefit may not be one of the major reasons to implement a waste minimisation program but it is an advantage of it.<sup>7, 15</sup> Due to the minimisation of the waste from a process, the associated environmental risk and liability in the workplace and the natural environment are simultaneously reduced. The risk of dealing with hazardous wastes is reduced as well as the liability for the correct management of controlled wastes and potential environmental damage. There is therefore a better understanding, control and management of present risks and future liabilities.<sup>13, 15</sup>

### **2.5 The Barriers to Waste Minimisation**

The barriers to the implementation of waste minimisation in a company are usually a result of a lack of understanding or a lack of resources.<sup>13, 50, 51</sup> A further barrier is the commonly held belief that waste minimisation techniques are only applicable to large companies or manufacturing industries.<sup>50</sup>

Many employees are reluctant to take time out of their already rushed day to implement waste minimisation procedures.<sup>51, 52</sup> This could be due to their not being made fully aware of the financial and environmental benefits. This lack of awareness and understanding of waste minimisation can lead to a hostile response from employees towards additional tasks and responsibilities, perception of the implementation being onerous and hostility towards the 'management' initiative.<sup>4</sup> In addition, many small-medium enterprises (SMEs) do not have a dedicated environmental or health and safety officer. Managers in these companies often do not have the time to oversee a waste minimisation programme personally.<sup>51</sup>

Additional barriers that have been identified by businesses and industry include the need to use fewer resources to meet demands, the need for innovative requirements to create higher quality products or processes, and stakeholder and customer pressures and demands.<sup>4</sup> Resistance to change, the disbelief of payback periods, the lack of technical

knowledge, conflicting priorities, lack of motivation as well as the slow implementation of ideas have also been identified as further barriers that need to be overcome.<sup>51, 52</sup>

## **2.6 The Drivers for Waste Minimisation**

There are many drivers that motivate companies to use waste minimisation measures. The main driver is improved competitiveness resulting from reduced direct charges for waste disposal and effluent treatment, improved process efficiency and reduced utility and raw material costs.<sup>7, 13, 50, 51</sup> Environmental improvement is another important driver that results from reduced emissions to land, air and water. Sustainable development is also promoted through implementation of a waste minimisation programme in a company. Waste minimisation not only reduces the amount of waste generated, but also reduces consumption of raw materials, energy and water, thus making it important to those companies with an interest in sustainable development. Another key driver is the reduced demand on resources. This reduction in demand on raw materials and on the plant itself, serves to extend their lifetimes.<sup>13</sup>

Other drivers that have been identified include direct pressure from customers to improve company performance, the fact that compliance with environmental regulations and a competitive product price lead to an enhanced public image, and the fact that improved utilisation of the plant as a whole leads to a higher degree of efficiency being attained. These cascading benefits are all drivers that push companies towards waste minimisation.<sup>7, 13, 50, 51</sup>

## **2.7 Aluminium Cleaning Theory**

### **2.7.1 Introduction**

In the past 100 years aluminium has found widespread use in a range of industrial and consumer good markets.<sup>53</sup> An increasing proportion of commercial aluminium-based

products are either surface-coated or composed of various materials. In all cases, interface structure and composition are of great importance to the properties and qualities of the products.<sup>54</sup> Failure during service life is often related to interfacial reactions affecting the qualities and properties of the multi-material products or the adhesion of surface coatings. Although this problem has been found to compromise the aluminium products in decorative rather than functional aspects, the damage is potentially very large.<sup>54</sup> Problems are often related, for example, to oxidation, surface and interface corrosion, adhesion and wear.<sup>53</sup>

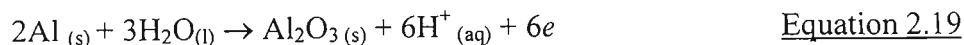
### 2.7.2 Film Formation

When a fresh aluminium surface is exposed to dry air, a dense, thin and protective amorphous oxide coating (100-200Å thick) forms. In moist atmospheres, the oxide coating grows thicker.<sup>55</sup> However, film-forming reactions usually slow down as the film thickens.<sup>56</sup> The oxide coating consists of one, dense protective barrier layer next to the metal and one outer more permeable bulk layer.<sup>55</sup>

The oxide coating enables metals, such as aluminium, to survive in destructive environments. In the case of aluminium, this natural film is known to form during the rolling or annealing process. The main factors governing the composition of the oxide film and hence, the interfacial properties, are the metal composition, rolling lubricant quality and annealing conditions.<sup>54</sup>

#### 2.7.2.1 The Chemistry of Film Formation

A solid oxide or hydroxide forms through precipitation from aqueous solution when its solubility product is exceeded. However, when there are no metal ions in solution (as is the case in outdoor corrosion of aluminium), and conditions such as potential and pH are appropriate, the metal most likely converts to the oxide through *electrochemical* oxidation since oxygen is a powerful cathodic reactant.<sup>57</sup>



The oxidation reaction (Equation 2.19) continues until electrical resistance offered by the film itself slows growth.<sup>57</sup> There is some thickening of the film over a long period (several days), but the most important period is the first few minutes, when the thickness attains a few atomic layers.<sup>57</sup>

### 2.7.3 The Corrosion of Aluminium

The term ‘corrosion’ is used to cover all transformations in which a metal passes from the elementary to the combined condition.<sup>56</sup> The following compounds have been identified in corrosion products formed on atmospheric corrosion of aluminium under outdoor conditions: amorphous  $\text{Al}(\text{OH})_3$ ,  $\alpha\text{-Al}(\text{OH})_3$  (bayerite), and  $\gamma\text{-Al}_2\text{O}_3$ , the latter with varying amounts of water in the lattice.<sup>55</sup>

In heterogeneous surface films (such as formed on aluminium upon exposure to air), chemical variations in the underlying metal occur, for example at segregated grain boundaries and in weld decay. In addition, scratch lines, inclusions and sheared edges, which are likely to introduce internal stresses on the film, exist on the metal surface. There are, therefore, a number of points (pores) in the film where it is less thick, less strong or more permeable than elsewhere. The metal may therefore start corroding at these sensitive points when it is exposed to chemical species. There are three possible results of this corrosion:

- either the film prevents further corrosion by growing again at the pores;
- or film breakdown causes localised corrosion at the exposed, bare metal (a type of corrosion known as pitting); or
- general attack occurs during which breakdown expands sideways from the pores until there is no film left.<sup>57</sup>



The factors causing one or other of these outcomes are the solubility of the oxide, the anion concentration, the chemical potential and the pH.<sup>57</sup>

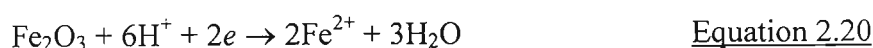
Anions such as  $\text{SO}_4^{2-}$  or  $\text{Cl}^-$  deposited on the oxide surface may react with the oxide resulting in the formation of water-soluble salts, *e.g.*  $\text{Al}_2(\text{SO}_4)_3$ .<sup>55</sup> The anions may also be incorporated into the lattice to form a variety of basic salts and complexes. The oxide coating is protective in urban atmospheres with  $\text{SO}_2$  pollution, which produces a relatively low pH value in the moisture film. High  $\text{SO}_2$  concentrations, however, cause a very low pH value in the moisture film, leading to dissolution of the protective coating.<sup>55</sup>

In the presence of chloride, the oxide coating is more permeable to ions. The chloride ions are believed to migrate into the oxide layer and lower its resistance to the outward migration of  $\text{Al}^{3+}$ .<sup>55</sup> In the presence of chloride ions, pitting is also initiated. In the propagation stage, aluminium is dissolved anodically to  $\text{Al}^{3+}$  ions within the pit. The cathodic reaction takes place either outside the pit, close to its mouth or inside the pit and consists of the reduction of oxygen or  $\text{H}^+$  ions respectively. By hydrolysis of the  $\text{Al}^{3+}$  ions, acid conditions are created within the pit and a cap of  $\text{Al}(\text{OH})_3$  and/or  $\text{Al}_2\text{O}_3$  is formed over its mouth; the corrosion products finally block the operation of the pit.<sup>55</sup>

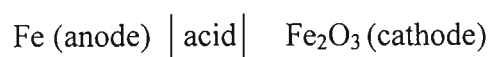
Thus, in clean outdoor atmospheres, aluminium will retain its shiny appearance for years, even under tropical conditions; however, in polluted outdoor atmospheres, corrosion of the metal is initiated.<sup>55</sup> A low penetration rate of the oxide layer and shallow pitting do not generally influence the mechanical properties of aluminium structures, except in excessively polluted atmospheres. The shiny metal appearance will, however, gradually disappear and the surface will roughen under the formation of corrosion products.<sup>55</sup>

#### **2.7.4 Acid Attack on Aluminium**

It has been found that sesquioxides ( $\text{M}_2\text{O}_3$ ) are only very slowly corroded through direct attack by acids.<sup>56</sup> With ferric oxide ( $\text{Fe}_2\text{O}_3$ ), for example, direct dissolution is slow but the reductive dissolution at any point where the oxide is made a cathode in acid proceeds rapidly and quantitatively according to the equation:<sup>56</sup>



Thus when iron carries an iron oxide film, which at any point is 'leaky' due to actual cracks or to lattice defects penetrating the thickness, the cell



is established, and the film will be destroyed around the leak point.<sup>56</sup> Passing into the liquid as the ferrous ion, the initially small gap in the film will become extensive, and the iron, left unprotected, will quickly be attacked.<sup>56</sup>

The 'reductive dissolution', which causes a rapid destruction of ferric oxide films, cannot affect aluminium films since aluminium exists in one oxidation state only.<sup>56</sup> Consequently aluminium, introduced into acid after air-exposure, exhibits a period of induction where no corrosion of the metal occurs due to the slow dissolution of aluminium. For very pure aluminium, the induction period may be measured in days; on the impure metal, it is much shorter, possibly because the sites of impurities constitute the defects in the film (Section 2.7.3; page 46). If pure aluminium is etched in concentrated hydrochloric acid and then placed in dilute hydrochloric acid, there is no period of induction since the stronger acid destroys the film.<sup>56</sup>

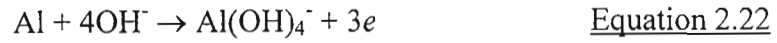
### 2.7.5 Alkali Attack on Aluminium

Aluminium is attacked by caustic alkali without the induction period found in acids, although the final attack is slower.<sup>56</sup> A possible reason for the fast destruction of the protective film by alkalis is the positive adsorption of  $\text{OH}^-$  ions.<sup>56</sup>

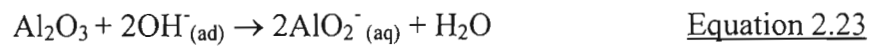
Armstrong and Braham<sup>58</sup> have identified two electrochemical half reactions that occur in the alkali attack on aluminium. The first is the following cathodic reaction:<sup>58</sup>



The reduction of water in these circumstances results in hydrogen evolution and hydroxide ion formation at the surface of the aluminium. The overall anodic reaction in the alkaline corrosion of aluminium is:<sup>58</sup>

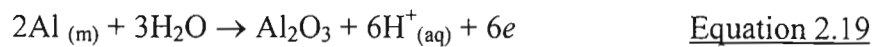


This is the slow step in the mechanism of corrosion.<sup>58</sup> Moon and Pyun<sup>59</sup>, however, established that the following reaction is responsible for the dissolution of the surface oxide film.



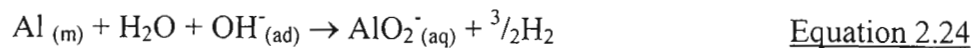
where  $\text{OH}^-_{(\text{ad})}$  is the adsorbed hydroxide ion and  $\text{AlO}_2^-_{(\text{aq})}$  is the aluminate ion in aqueous solution.

They further found that the formation and dissolution of the oxide film on aluminium are in dynamic equilibrium.<sup>59</sup> The oxide film formation at the aluminium/oxide interface proceeds by the movement of oxygen vacancies towards the oxide/electrolyte interface and subsequent reaction with water to form oxygen ions in the oxygen lattice.<sup>59</sup>



where m is the normal aluminium atom in the metal site.

The dissolution reaction of pure aluminium can be obtained by combining the electrochemical oxide formation and the chemical dissolution reactions of the surface oxide film (Equations 2.19 and 2.23):<sup>59</sup>



The electrons produced will be consumed immediately by the evolution of hydrogen (Equation 2.21).<sup>59</sup>

## 2.7.6 The Action of Cleaners

Cleaning is defined as the removal of soil and of unwanted matter (including moisture) from a surface to which it clings.<sup>60</sup> This can be achieved by mechanical action (wiping, brushing, spraying, machining or abrading); by solution (the soil is dissolved in the solvent); by chemical reactions (soluble or non-interfering products are formed by chelation, saponification, *etc.*), or by detergency (*i.e.* lifting the soil from the surface by displacing it with surface-active materials that have a greater affinity for the surface than the soil).<sup>60</sup>

### 2.7.6.1 Acid Cleaners

Acid cleaners are used to remove rust and scale and to clean aluminium and zinc-metals susceptible to etching when exposed to strong alkaline cleaners. Acid cleaners contain mineral acids (nitric, phosphoric, sulfuric and hydrofluoric), chromic acid, or organic acids (acetic and oxalic), in addition to chelating agents, detergents, and small amounts of water-miscible solvents.<sup>60</sup>

### 2.7.6.2 Alkaline Cleaners

Alkaline cleaners vary in their degree of alkalinity.<sup>61</sup> Generally, the more alkaline the solution, the more rapid the cleaning achieved. Factors influencing the cleaning effectiveness of an alkaline cleaner include the type of metal, the type and concentration of the cleaner, the cleaner temperature, the time of immersion and the condition of use.<sup>61</sup> For the non-etch cleaning of aluminium, a solution having a low free alkalinity must be used. Soak cleaning is recommended.<sup>61</sup>

A good alkaline cleaning material must have the following properties:<sup>53</sup>

- solubility in water to enable wetting of the surface of the metal being cleaned;
- the ability to wet and penetrate any soil for removal;
- the ability to dissolve or saponify animal and vegetable oils and greases or temporarily emulsify or suspend the insoluble solid dirt particles;

- the ability to rinse freely;
- the ability to prevent attack or tarnish of the metal surface; and
- the ability to form no excessive foam or suds in the cleaning and rinsing operations.<sup>53</sup>

Soaps and synthetic detergents in various combinations are added to cleaning compounds to decrease surface and interfacial tensions, emulsify oil and suspend dirt particles in the solution. Dirt and other solid particles are bound to the metal surface by oils and greases and are removed when the binding material is dislodged from the surface. The most widely used surface-active agents in metal cleaning are the sodium linear alkylate sulfonates and the oxyethylated alcohol type of non-ionics in soak cleaners.<sup>53</sup>

Agitation of the cleaning solution is desired since it speeds up the wetting and emulsification of oils and greases.<sup>53</sup> The mechanical force of the moving solution is helpful in dislodging the dirt as well as constantly exposing the metal being cleaned to fresh cleaning agent.<sup>53</sup>

It is not clear from the reviewed literature whether acidic or alkaline cleaners are favoured for the cleaning of aluminium metal; both kinds of cleaners are responsible for the corrosion of the metal.<sup>55, 56, 60, 61</sup> However, it appears that acidic cleaners etch the metal surface less than strong alkaline cleaners;<sup>60, 61</sup> a benefit of alkaline cleaners is that they clean the metal surface more rapidly.<sup>56</sup>

## **2.8 Conclusion**

This literature review has shown that implementation of a waste minimisation programme in a company can limit its production of waste, save the company time and money as well as reduce the impact the company has on the environment.



To place this study in context, the strategy of a waste minimisation programme was reviewed. This included the available pre-assessment and assessment techniques used in the identification of waste minimisation opportunities and in prioritising waste streams for action. The available pre-assessment techniques are diverse and include both qualitative and quantitative methods. Several of the techniques are general methodologies (P-graph method<sup>21</sup>, Du Pont's method<sup>2</sup>, waste index methods<sup>18, 23, 24</sup>, true cost of waste assessment<sup>8, 15</sup>). Other tools have been developed for particular sectors in South African industry (score system of the South African textile industry<sup>26</sup>, the Cleaner Production Bench-marking Tool of the South African Metal Finishers<sup>29, 30</sup>). However, the scoping audit<sup>7</sup> method has been developed for UK industry and requires modification for application to South African industry.<sup>11</sup>

Waste minimisation opportunities that require further investigation are studied during the assessment stage.<sup>8</sup> Although the techniques used are often project-specific, the literature review indicated two general techniques: mass and energy balances<sup>33, 34</sup> and monitoring and targeting.<sup>7, 8</sup>

Since this study involved a feasibility analysis, the technical, economic and environmental aspects of a feasibility analysis were reviewed in this chapter. The technical evaluation<sup>7, 8, 17</sup> assesses the proposed waste minimisation solution in terms of technology, timescales, associated risks and the company culture. The economic evaluation<sup>7, 36, 37</sup> involves calculation of four financial indicators (payback period, return on capital employed, net present value and the internal rate of return) to ensure minimum risk to the company. The environmental aspect evaluates the proposed solution for legislative compliance. Hence local bylaws<sup>40</sup> and national legislation<sup>42, 43, 45</sup> pertaining to effluent discharge were reviewed. The latter highlights areas such as the responsibility of the producer of the waste from 'cradle to grave' and the 'polluter pays' principle.

The main drivers identified for the implementation of a waste minimisation programme in a company were the savings resulting from improved process efficiency and the reduced environmental impact. The main barriers to its implementation include a lack of understanding and a lack of resources, especially time, within a company.<sup>50, 51</sup>



Since this project concerns the optimisation of the method used for cleaning the aluminium coils on air-conditioner units, the literature on the corrosion and cleaning of aluminium metal was surveyed. The literature indicates that virgin aluminium, upon exposure to air, forms a dense, protective oxide coating.<sup>55</sup> Oxidation is rapid but slows down as the film forms. It was shown that the film forms as a result of an electrochemical reaction in which oxygen is the powerful cathodic reagent.<sup>57</sup>

Pores (points on the metal surface where the film is thinner) can result from scratch lines, inclusions or weld decay. The pores are permeable and result in the dissolution of the metal at these points. Whether corrosion continues from these points or whether the film repairs itself, is dependent upon the solubility of the oxide, the anion concentration, the chemical potential and the pH. However, due to aluminium's low penetration rate and formation of only shallow pits, its mechanical properties are largely unaffected by corrosion.<sup>57</sup>

The literature review further indicated that alumina ( $\text{Al}_2\text{O}_3$ ) is only very slowly dissolved through direct attack by acids.<sup>56</sup> Aluminium is also attacked by caustic alkali. Although the final attack is slower than that of acid solutions, alkalis seem to destroy the protective film quickly, possibly because the metal positively adsorbs  $\text{OH}^-$  ions.<sup>59</sup>

The literature did not specify which type of cleaner, acid or alkaline, was preferable for aluminium metal. Acid cleaners tend to etch the surface of the metal less than strong alkaline cleaners<sup>60, 61</sup> whilst alkaline cleaners are known to work more rapidly.<sup>61</sup>

## **Chapter 3: Materials and Methods**

In this chapter, the materials and methods used in the qualification (Section 3.1; page 54) and quantification (Section 3.2; page 65) of the chemical species present in Alukleen (the acid cleaning agent), Powerkleen (the alkaline degreaser) and the effluent samples taken from Ben Booyesen are discussed. Further quantitative techniques used in measuring the chemical oxygen demand (COD), pH, conductivity, and total dissolved solids content in samples are described in Section 3.2. The methods used in determining the most effective cleaning system (cleaner type, concentration and soaking time) for the air-conditioner coils and in investigating two application techniques are described in Section 3.3 (page 71).

### **3.1 Qualitative Analytical Techniques**

Quantitative analysis of the concentrations of the chemical species in Alukleen first required their identification. The material safety data sheet<sup>12</sup> indicated the presence of a blend of inorganic acids and surfactants. In order to determine their identity more precisely, wet chemical analysis and Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP – OES) were used as the qualitative analytical techniques.

#### **3.1.1 Wet Chemical Analysis**

In wet chemical analysis, the identification of chemical species is based on the conversion of the substance of interest through chemical reaction into a new compound, having distinguishing characteristics.<sup>62</sup> The following section describes the steps taken to identify the main species present in Alukleen. The steps taken are schematically illustrated in Figure 3.1 and are detailed in Appendix A (page 150).

The wet chemical analysis is divided into two categories: those tests which yield positive results for the group of ions or specific ion that they are testing for are termed positive tests. Negative tests eliminated the possibility of a specific ion or group of ions being present. Negative tests are used once a group of ions with similar properties is identified.

Qualitative analysis was not required for the elucidation of Powerkleen's composition since its Material Safety Data Sheet<sup>63</sup> indicated the presence of a single strong base, potassium hydroxide, as the active ingredient along with compounds such as butyl oxitol and sodium xylene sulfonate. Butyl oxitol is a solvent included in the make-up of cleaning agents in order to improve gloss and levelling for surface coat formulation. Sodium xylene sulfonate is a hydrotropic solvent commonly found in detergents.<sup>64</sup>

### 3.1.1.1 Calcium Chloride Test

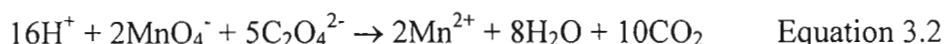
The calcium chloride test<sup>62, 65</sup> (detailed in Appendix A; page 151) uses calcium chloride ( $\text{CaCl}_2$ ) to confirm the presence of fluoride ( $\text{F}^-$ ), oxalate ( $\text{C}_2\text{O}_4^{2-}$ ), phosphate ( $\text{PO}_4^{3-}$ ), arsenate ( $\text{AsO}_4^{3-}$ ) or tartrate ( $\text{C}_4\text{H}_4\text{O}_6^{2-}$ ) ions in the sample. The formation of a white precipitate indicates the presence of one or more of the above-mentioned ions. For example, the formation of the precipitate, calcium fluoride ( $\text{CaF}_2$ ), is governed by the following equation:<sup>62, 65</sup>



The solubility of the precipitate is then tested in dilute acetic acid ( $\text{CH}_3\text{COOH}$ ). A soluble precipitate indicates the presence of phosphate, arsenate or tartrate ions<sup>62, 65</sup> whilst an insoluble precipitate indicates the presence of either fluoride or oxalate ions.<sup>62, 65</sup>

The insoluble precipitate is then dissolved with sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and treated with potassium permanganate ( $\text{KMnO}_4$ ). If no bleaching of the potassium permanganate

occurs, fluoride is the ion present in the sample.<sup>62,65</sup> Oxalate ( $\text{C}_2\text{O}_4^{2-}$ ) bleaches permanganate because of the redox reaction:<sup>66</sup>



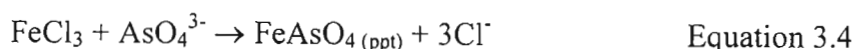
### 3.1.1.2 Ferric Chloride Test

The ferric chloride test uses ferric chloride ( $\text{FeCl}_3$ ) as a reagent to induce either colouration of the solution or precipitation.<sup>62, 65</sup> The formation of a yellow to brown precipitate indicates the presence of phosphate ( $\text{PO}_4^{3-}$ ) and/or arsenate ( $\text{AsO}_4^{3-}$ ); a blue precipitate with a reddish-brown colouration indicates the presence of acetate ( $\text{C}_2\text{H}_3\text{O}_2^-$ ), a blood-red colouration indicates the presence of thiocyanate ( $\text{CNS}^-$ ) and lastly, a reddish-purple colouration which vanishes on warming is indicative of the presence of thiosulfate ( $\text{S}_2\text{O}_3^{2-}$ ). The reactions that occur upon the addition of ferric chloride are governed by the following equations:<sup>62, 65</sup>

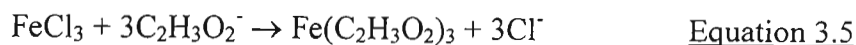
$\text{PO}_4^{3-}$ :



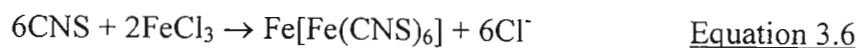
$\text{AsO}_4^{3-}$ :



$\text{C}_2\text{H}_3\text{O}_2^-$ :



$\text{CNS}^-$ :



$\text{S}_2\text{O}_3^{2-}$ :



### 3.1.1.3 Barium Chloride Test

The barium chloride test was a preliminary test conducted to confirm the presence of sulfate ( $\text{SO}_4^{2-}$ ), thiosulfate ( $\text{S}_2\text{O}_3^{2-}$ ) or sulfite ( $\text{SO}_3^{2-}$ ) ions. The test involves the addition of barium chloride ( $\text{BaCl}_2$ ) to the sample (detailed in Appendix A; page 151). The formation of a white precipitate indicates the presence of the above-mentioned ions and is governed by one or more of the following equations:<sup>62, 65</sup>

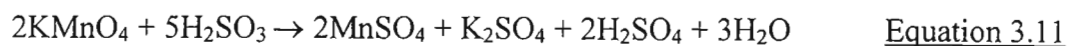


The ferric chloride test (Section 3.1.1.2; page 56) and potassium dichromate test (Section 3.1.1.6; page 59) were run in conjunction with this test to further identify the ion responsible for the precipitate formation.

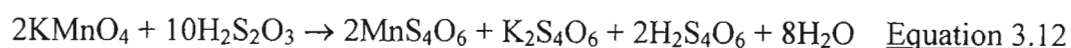
### 3.1.1.4 Reducing Agent Test

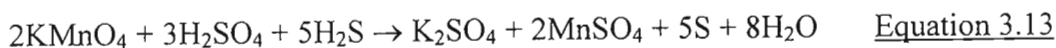
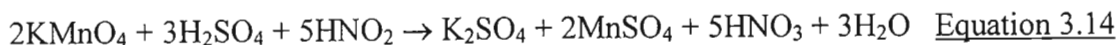
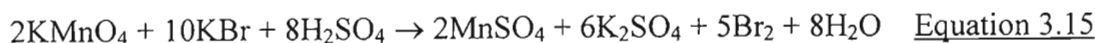
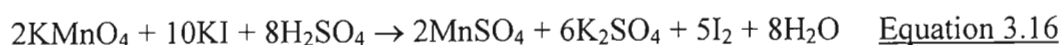
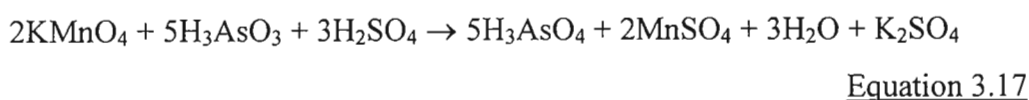
This test served as confirmation of the presence of one or more of the following ions: sulfite ( $\text{SO}_3^{2-}$ ), thiosulfate ( $\text{S}_2\text{O}_3^{2-}$ ), sulfide ( $\text{S}^{2-}$ ), nitrite ( $\text{NO}_2^-$ ), bromide ( $\text{Br}^-$ ), iodide ( $\text{I}^-$ ) or arsenite ( $\text{AsO}_3^{3-}$ ). The sample is acidified with dilute sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and treated with potassium permanganate ( $\text{KMnO}_4$ ) (detailed in Appendix A; page 151). If bleaching of the sample occurs, the test is positive for one or more of the above-mentioned ions since these ions have the capacity to act as a reducing agent. This bleaching would occur according to the following equations:<sup>62, 65</sup>

$\text{SO}_3^{2-}$ :



$\text{S}_2\text{O}_3^{2-}$ :

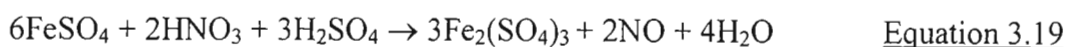


**S<sup>2-</sup>:****NO<sub>2</sub><sup>-</sup>:****Br<sup>-</sup>:****I<sup>-</sup>:****AsO<sub>3</sub><sup>3-</sup>:**

The ferric chloride test (Section 3.1.1.2; page 56), brown ring test (Section 3.1.1.5; page 58) and potassium dichromate test (Section 3.1.1.6; page 59) are negative tests for the reducing agent test since they eliminate the possibility of specific ions being present.

### 3.1.1.5 Brown Ring Test

This test was used for the confirmation of the presence of nitrate (NO<sub>3</sub><sup>-</sup>) and/or nitrite (NO<sub>2</sub><sup>-</sup>) ions. Ferrous sulfate (FeSO<sub>4</sub>) and concentrated sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) are the reagents used. The formation of a brown ring in the test tube at the interface of the solution and H<sub>2</sub>SO<sub>4</sub> layers confirms the presence of NO<sub>3</sub><sup>-</sup> or NO<sub>2</sub><sup>-</sup>, and is due to the formation of the compound [Fe(NO)SO<sub>4</sub>]. The equations below illustrate how the brown ring is formed in a solution of sodium nitrate (NaNO<sub>3</sub>).<sup>62, 65</sup>

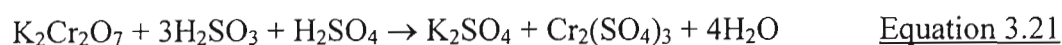






### 3.1.1.6 Potassium Dichromate Test

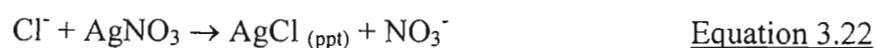
The potassium dichromate test uses potassium dichromate ( $\text{K}_2\text{Cr}_2\text{O}_7$ ) to confirm the presence of sulfite ions ( $\text{SO}_3^{2-}$ ). A green solution forms upon the addition of  $\text{K}_2\text{Cr}_2\text{O}_7$  to  $\text{SO}_3^{2-}$  ions according to the following equation:<sup>62, 65</sup>



### 3.1.1.7 Silver Nitrate Test

The silver nitrate test is a multi-step test that uses silver nitrate ( $\text{AgNO}_3$ ) to separate possible anions into three groups (Figure 3.1; page 64). The methods for each of these tests are briefly described below and are detailed in Appendix A (page 152)

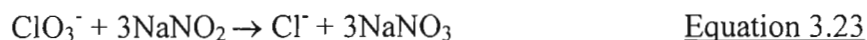
The first test involves the addition of concentrated nitric acid ( $\text{HNO}_3$ ) to the sample followed by silver nitrate ( $\text{AgNO}_3$ ) solution. These additions are made to precipitate iodide, bromide, chloride, iodate and thiocyanate ions from solution completely. Precipitation is favoured in dilute nitric acid solution (approximately 1.5 M) at a pH of about 0.2. A white precipitate results from the formation of silver iodide ( $\text{AgI}$ ), silver bromide ( $\text{AgBr}$ ), silver chloride ( $\text{AgCl}$ ), silver iodate ( $\text{AgIO}_3$ ) or silver thiocyanate ( $\text{AgCNS}$ ) respectively.<sup>62, 65</sup> For example, the formation of the  $\text{AgCl}$  precipitate is described by the following equation:<sup>62, 65</sup>



The displacement (Section 3.1.1.8; page 61) and precipitate (Section 3.1.1.9; page 62) tests were subsequently run to ascertain which ion was responsible for the formation of the white precipitate.

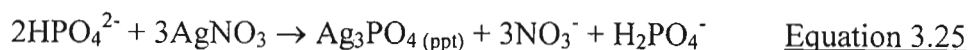
In the test for the second group of anions, silver nitrate ( $\text{AgNO}_3$ ) and sodium nitrite ( $\text{NaNO}_2$ ) solutions are added to the filtrate from Test 1 until precipitation is complete.

At this stage, precipitation of silver chloride (AgCl) or silver bromide (AgBr) occurs if chlorate or bromate ions are present in the sample. The following equations illustrate how, in the presence of sodium nitrite and more silver nitrate, chlorate ions reduce to chloride ions prior to precipitating with  $\text{Ag}^+$  ions.<sup>62</sup>

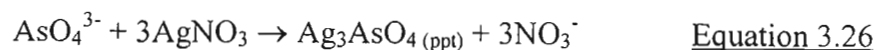


If no precipitate forms in Test 2, the same solution is used to test for Group 3 anions. However, if a precipitate does form, its filtrate is used for Test 3. Dilute acetic acid ( $\text{CH}_3\text{COOH}$ ) and the silver nitrate ( $\text{AgNO}_3$ ) solution are then used to induce precipitation. Precipitation of phosphate ( $\text{PO}_4^{3-}$ ), arsenate ( $\text{AsO}_4^{3-}$ ), arsenite ( $\text{AsO}_3^{3-}$ ), oxalate ( $\text{C}_2\text{O}_4^{2-}$ ) and possibly other organic acids by silver nitrate is favoured by a pH of around 5.<sup>62</sup> Arsenite is unlikely to be found in this procedure due to its oxidation to arsenate by the dilute nitric acid treatment of the prepared sample.<sup>62</sup> Identification of the precipitate can be elucidated by virtue of its colour: silver phosphate ( $\text{Ag}_3\text{PO}_4$ ) is yellow, silver arsenate ( $\text{Ag}_3\text{AsO}_4$ ) is reddish brown and silver oxalate ( $\text{Ag}_2\text{C}_2\text{O}_4$ ) is white.<sup>62, 65</sup>

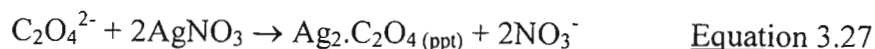
**$\text{PO}_4^{3-}$ :**



**$\text{AsO}_4^{3-}$ :**



**$\text{C}_2\text{O}_4^{2-}$ :**

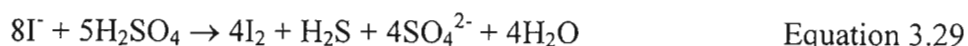
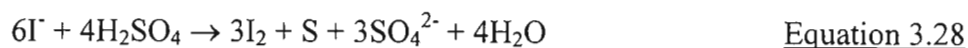


The nature of the precipitate is further elucidated through an additional ferric chloride test (Section 3.1.1.2; page 56).

### 3.1.1.8 Displacement Tests

These tests identify whether iodide, iodate or bromide ions are present in the first precipitate from the silver nitrate test (Figure 3.1; page 64). Details of the methods used are presented in Appendix A (page 153).

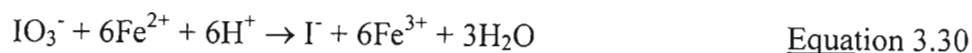
To establish whether iodide ions are present, the precipitate is heated and granulated zinc and dilute sulfuric acid ( $\text{H}_2\text{SO}_4$ ) are added. The Iodide ( $\text{I}^-$ ) ions will reduce the sulfuric acid to hydrogen sulfide ( $\text{H}_2\text{S}$ ) and sulfur ( $\text{S}$ ) (Equations 3.28 and 3.29), the relative proportions of which depend upon the concentrations of the reagents.<sup>65</sup> Simultaneously, the iodide ions are oxidised to elemental iodine.



The solution is filtered, the precipitate is washed with dilute sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and the filtrate is divided into two equal volumes for the following tests, which establish whether iodate or bromide ions are present.

#### (a) Iodide Test

Ferrous sulfate ( $\text{FeSO}_4$ ) is added for the rapid reduction of iodate ( $\text{IO}_3^-$ ) ions to iodide ( $\text{I}^-$ ) ions.<sup>65</sup>



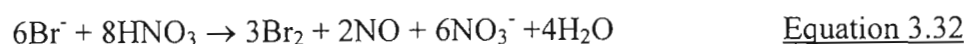
If the iodate ions are in excess, iodine is formed due to the interaction of iodate and iodide ions:<sup>65</sup>



Carbon tetrachloride (CCl<sub>4</sub>) is used to form an organic layer. A purple or violet colouration of the CCl<sub>4</sub> layer is indicative of the presence of iodine and hence iodide (I<sup>-</sup>) or iodate (IO<sub>3</sub><sup>-</sup>) ions.<sup>62</sup>

### **(b) Bromide Test**

Concentrated nitric acid (HNO<sub>3</sub>) is added to the sample followed by carbon tetrachloride (CCl<sub>4</sub>). The nitric acid is added to ensure oxidation of the bromide (Br<sup>-</sup>) ions to elemental bromine (Br<sub>2</sub>) as shown below:<sup>65</sup>

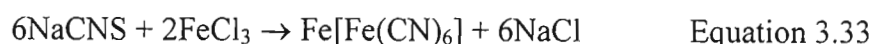


A yellow or brown colouration of the CCl<sub>4</sub> layer indicates the presence of bromine and hence bromide ions.<sup>62</sup>

### **3.1.1.9 Precipitate Test**

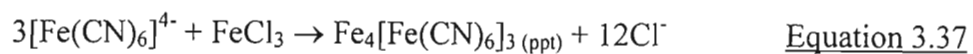
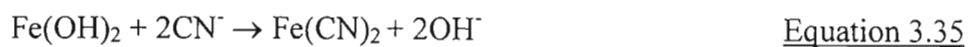
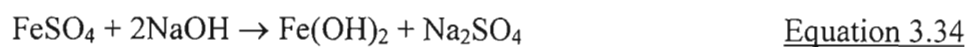
The Precipitate Test was carried out on the first precipitate isolated from the silver nitrate test (Figure 3.1; page 64). The formation of the latter precipitate indicates the presence of chloride (Cl<sup>-</sup>), bromide (Br<sup>-</sup>), iodide (I<sup>-</sup>), iodide (IO<sub>3</sub><sup>-</sup>) or thiocyanate (CNS<sup>-</sup>) ions. The Precipitate Test allows the presence of thiocyanate (CNS<sup>-</sup>) ions to be confirmed. Details of the method are presented in Appendix A (page 154).

The precipitate is heated and treated with sodium chloride (NaCl) solution to convert silver thiocyanate (AgCNS) to the soluble sodium thiocyanate (NaCNS). After any remaining precipitate has settled, the supernatant liquid is treated with dilute hydrochloric acid (HCl) and ferric chloride (FeCl<sub>3</sub>). A red colouration indicates the presence of thiocyanate ions. The colour arises as a result of the formation of ferric ferri-thiocyanate (Fe[Fe(CN)<sub>6</sub>]), according to the following equation:<sup>62, 65</sup>



**3.1.1.10 Prussian Blue Test**

This test was used to determine whether cyanide (CN<sup>-</sup>) ions were present in Alukleen. The sample is rendered strongly alkaline after which a saturated solution of ferrous sulfate (FeSO<sub>4</sub>) is added and the sample is boiled. In the presence of cyanide ions, ferrocyanide ( [Fe(CN)<sub>6</sub>]<sup>4-</sup> ) forms, which, upon acidification and the addition of ferric chloride, forms a clear solution with a pale blue precipitate known as Prussian blue. This occurs according to the following reactions:<sup>62, 65</sup>



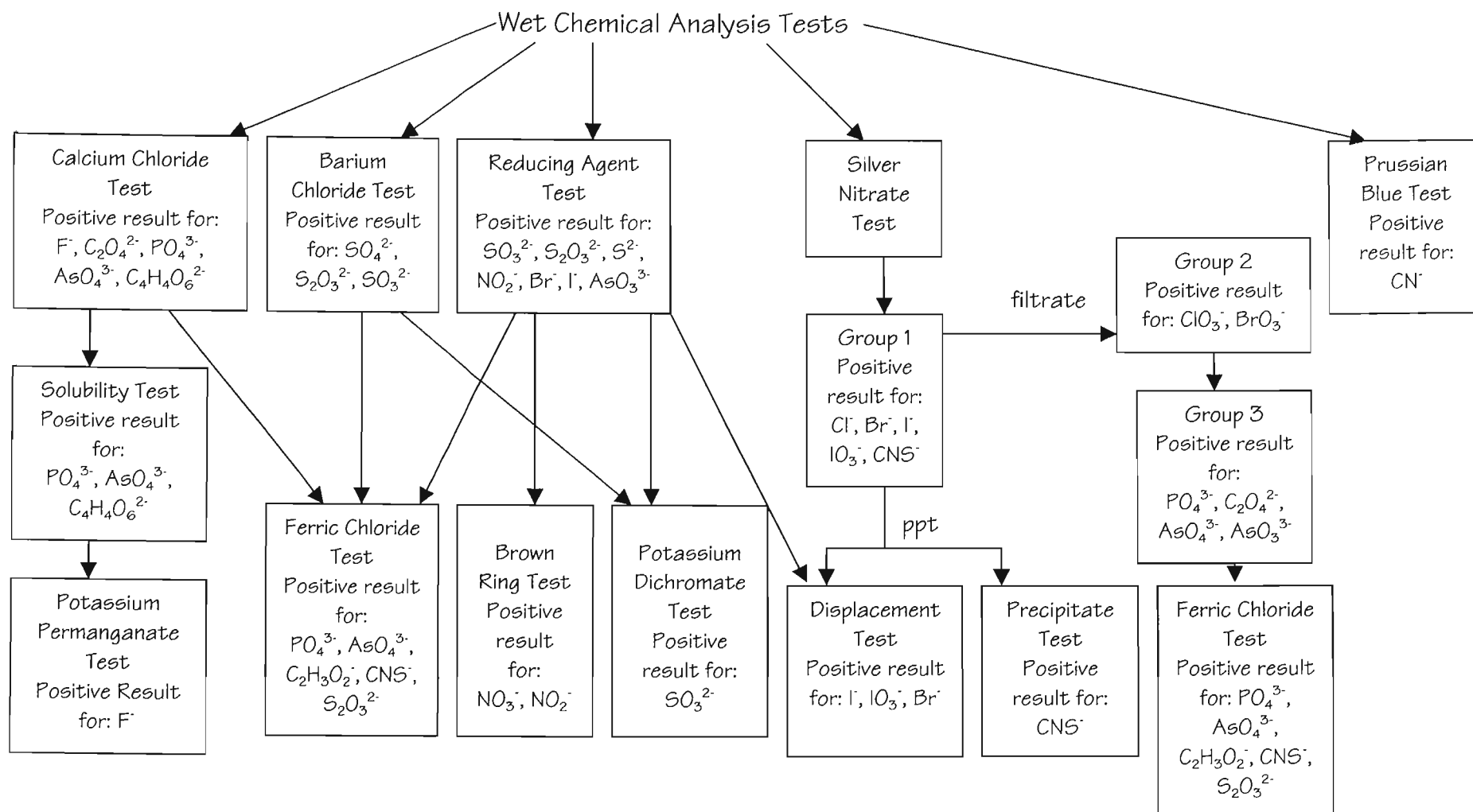


Fig. 3.1: Schematic illustration of the wet chemical analysis done.<sup>62, 65</sup>



### **3.1.2 Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES)**

The ICP–OES is largely a quantitative instrument and is a powerful analytical tool for the determination of trace elements in a variety of sample matrices.<sup>67</sup> An ICP-OES (Varian Liberty 150 AX Turbo) was used in this study in the initial characterisation of the components in Alukleen: a wave scan was run to determine the species present in the acid cleaner. It was also used later to determine the concentration of potassium ( $K^+$ ) in the alkaline degreaser, Powerkleen.

In the ICP-OES, liquid samples are nebulized and injected into a radio frequency (RF)-induced plasma source. A spontaneous emission of photons occurs from atoms and ions that have been excited in the RF discharge. The emitted photons have characteristic energies determined by the quantized energy level structure for the atoms or ions. Thus the wavelength of the photons can be used to identify the elements from which they originated. The total number of photons is directly proportional to the concentration of the element in the sample.<sup>67</sup>

Quantitative measurements of the potassium in Powerkleen were made in triplicate. The coefficient of variation of these measurements was below 5% (Appendix C; page 178). The method used is detailed in Appendix B (page 156) and a calibration graph from five standard measurements is shown in Appendix C (page 179).

## **3.2 Quantitative Analytical Techniques**

### **3.2.1 Ion Chromatography**

Ion chromatography is a separation and detection strategy applied to the determination of inorganic and organic analyte cations and anions.<sup>68</sup> In this study, an Ion Chromatograph (Waters 590 programmable HPLC pump, Waters 430

conductivity detector, 4.6 x 50mm HPLC column (anion) part no: 07355) was used to quantify the concentrations of anions present in Alukleen and in the effluent sampled from Ben Booysen ( $\text{SO}_4^{2-}$ ,  $\text{F}^-$  and  $\text{Cl}^-$ ; Appendix B; page 156).

Differences exist in the way that the individual analyte ions and electrolyte ions of similar charge in the sample (mobile phase) compete electrostatically for the ion-exchange sites on the ion-exchanger.<sup>68</sup> Once adsorption of the solute of the ion-exchanger (stationary phase) is complete, a solvent (eluent) is passed through the column to desorb the solutes.<sup>25</sup> The retention time is the time between the injection of a sample and the appearance of a solute peak at the detector of a chromatographic column. Differences in the retention times of various solutes occur because of the different affinities of the solutes for the ion-exchange sites.<sup>25</sup> Hence components of the sample separate into bands along the length of the column, which results in the formation of clean chromatographic peaks used in the identification and quantification of the species. Quantitative analysis is facilitated since peak area and peak height on the chromatogram are proportional to the solute concentrations.<sup>68</sup>

Since interference of the fluoride and system peaks occurred, the fluoride peak underwent baseline distortion. Since this distortion compromised the accuracy of the fluoride measurements, it was decided to use an ion selective electrode for fluoride analysis (Section 3.2.2; page 67).

Five standards of different sulfate concentrations were run on the instrument in order to determine a calibration graph. The standards were run both before and after the samples to compensate for any drift present in the instrument's readings. Each sample was run in triplicate. Four standards of different chloride concentrations were also run before and after the samples, which were also run in triplicate.

Sample and eluent (2 mM p-hydroxybenzoate in 2.5% methanol) preparation is detailed in Appendix B (page 156). The calibration graph obtained is shown in Appendix C (page 166). The coefficient of variation for these results was typically below 10% and always below 14% (Appendix C; page 165).

### 3.2.2 Ion Selective Electrode

An ion selective electrode (Fluoride Selectrode, F1052F, Radiometer Copenhagen) was used for the determination of the free fluoride concentration in Alukleen and the effluent samples. The fluoride ion selective electrode is an electrochemical sensor based on a thin film or selective membrane as a recognition element.<sup>69</sup> The membrane is equivalent to a half-cell in electrochemistry although it may contain a second electrode as an 'internal' reference electrode. One surface of this membrane is in contact with the bulk phase. Ideally the membrane is specific for only fluoride ions although it can be selective for a small set of ions (electrode interferences). In addition, chemical interferences can disguise the fluoride ions or change the surface of the membrane so it is no longer sensitive to the fluoride ion.<sup>25</sup>

The samples that were run were 500-fold dilutions of 1:1 Alukleen (*i.e.*: an effective 1000-fold dilution) and 1.05-fold dilutions of effluent. 5 ml of a total ionic strength adjustment buffer (TISAB) was added to each sample since this volume, which brought the sample into the required pH range of between 4.5 and 5. TISAB is required for fluoride ion selective electrode measurements to adjust all solutions to the same ionic strength and to prevent chemical interferences.<sup>25</sup>

The electrode was calibrated before analysis using a set of 5 standards (Appendix B; page 157). The resultant calibration graph is shown in Appendix C (page 171). A reproducibility run was performed to determine whether the instrument was subject to drift and to calculate the coefficient of variance (Appendix C; page 170). This was accomplished through five measurements each of 5 standard solutions. The coefficient of variation of the measurements (in mV) was typically less than 4% and always less than 6%.

### 3.2.3 Photometry

A photometer (Photometer SQ 200, Merck) was used for the determination of  $S^{2-}$  in Alukleen, Powerkleen and the effluent samples (Appendix B; page 158). The visible

light transmitted by photometers is absorbed by molecules in one or more electronic absorption bands, each of which is made up of numerous closely packed but discrete lines. Each line arises from the transition of an electron from the ground state to one of the many vibrational and rotational energy states associated with each excited electronic energy state.<sup>25</sup>

For monochromatic radiation, absorbance is directly proportional to the path length through the medium (b) and concentration of the absorbing species (c):<sup>25</sup>

$$A = \epsilon bc \qquad \text{Equation 3.38}$$

where  $\epsilon$  is a proportionality constant called the molar absorptivity ( $\text{L}\cdot\text{mol}^{-1}\cdot\text{cm}^{-1}$ ).

In this study, reagents from a sulfide test kit (Merck Sulfide Spectroquant® Testing Kit no. 1.14779.0001) were added to the samples before the absorbance was measured in triplicate at 665nm (Appendix B; page 158). Five standards were run to allow the plotting of a calibration graph (Appendix C; page 173). A reproducibility run, in which three measurements each of five standard solutions were made, allowed calculation of coefficients of variation. The latter were less than 3% for all measurements (Appendix C; page 172).

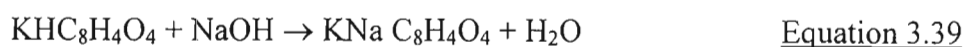
### 3.2.4 COD Measurement

The Material Safety Data Sheet indicated that Powerkleen contained both butyl oxitol and sodium xylene sulfonate.<sup>63</sup> Hence the chemical oxygen demand (COD) of a Powerkleen sample was measured using back titration of potassium dichromate with ferrous ammonium sulfate after digestion of the sample using microwave radiation. Umgeni Water carried out this analysis.<sup>70</sup>

### 3.2.5 pH Titrations

#### 3.2.5.1 Alukleen

A pH titration (Crison pH meter, cat. no. 52-03) was carried out to determine the quantities of strong and weak inorganic acids in Alukleen (Appendix B; page 158). NaOH (2.040 M) was used as the titrant. The NaOH solution was first standardised with a standard solution of potassium hydrogen phthalate ( $\text{KHC}_8\text{H}_4\text{O}_4$ ) (0.21006 M), using phenolphthalein as the indicator (Appendix B; page 158).



For comparison, a second qualitative titration between NaOH (~0.1 M) and  $\text{H}_2\text{SO}_4$  (~0.25 M) was carried out (Appendix B; page 158) to investigate whether there was a significant difference between the points at which the two protons of  $\text{H}_2\text{SO}_4$  were removed. Sulfuric acid is a significant constituent of Alukleen (see Section 4.1.2.1; page 82).

#### 3.2.5.2 Powerkleen

The Powerkleen Material Safety Data Sheet<sup>63</sup> indicated that KOH was present. However the presence of weak bases was unclear. Hence Powerkleen was titrated with HCl (1.065 M, Appendix B; page 159). The HCl was standardised through titration with a 2-fold dilution of the 2.040 M NaOH, using phenolphthalein as the indicator (Appendix B; page 159).



### 3.2.6 pH

The hand-held pH meter (Yellow Springs Instrument, model no. 63/10FT) was used to measure the pH of a 20-fold dilution of Alukleen, a 1:39 dilution of Powerkleen and the effluent samples. The meter was calibrated before each use with three standard pH solutions (Merck, pH 4.00, pH 7.02 and pH 10.00). The coefficients of variation for all measurements made with this instrument were found to be below 3% (Appendix C; page 176).

### 3.2.7 Conductivity

A hand-held conductivity meter (Yellow Springs Instrument, model no. 63/10FT) was used for the measurement of the conductivity of a 1000-fold dilution of Alukleen, Powerkleen (neat and a dilution of 1:39) and the effluent (neat). The conductivity meter was calibrated before use with a standard conductivity solution (Hanna Instruments, 1413  $\mu\text{S}/\text{cm}$ ). The coefficient of variation for the measurements (in  $\mu\text{S}/\text{cm}$ ) was always below 2% (Appendix C; page 176).

### 3.2.8 Total Dissolved Solids Measurements

The total dissolved solids concentration of Alukleen, Powerkleen and the effluent samples were measured since the local sewage works (Darvill) specifies a limit (Section 2.3.4.3; page 34). These measurements were made based on the equation:

$$\text{Total Dissolved Solids} = \text{Total Solids} - \text{Suspended Solids} \quad \text{Equation 3.39}$$

Measurements of the total and suspended solids were made gravimetrically (Appendix B; page 159). Large coefficients of variation (< 54%) were noted for this technique, particularly for the Alukleen measurements. As the mean total dissolved solids



concentration in Alukleen was found to be very low (0.12 g/L), a seemingly large coefficient of variation was obtained through division of the standard deviation of the measurements (0.06 g/L) by the mean.

### **3.3 Methodologies**

In this section, the gravimetric, photographic and the electron microscope methodologies used to investigate the most effective cleaner type, concentration and soaking time are described. Soaking time was investigated to allow the optimum contact time with the cleaner solution to be determined. Methodologies used to establish the suitability of two cleaner application techniques are also described.

#### **3.3.1 Determination of most effective Cleaner Type, Concentration and Soaking Time**

##### **3.3.1.1 Gravimetric Analysis**

Aluminium coils from air-conditioner units no longer in use were used for this study. Aluminium fins were isolated from air-conditioner units' coils and cut into pieces approximately 5 cm x 5 cm. Pieces of approximately the same level of dirtiness were used in a given experiment.

The aluminium pieces were each submerged in a weighing boat containing cleaner solution at a given concentration and soaking time (Appendix B; page 160). Cleaners investigated included Alukleen, several pre-wash systems, three degreasers, and Powerkleen (the selected degreaser). The effectiveness of each cleaner was assessed in terms of the mass of dirt removed from the aluminium. The latter was determined gravimetrically (Mettler AJ100 analytical balance).

**(a) Alukleen**

Alukleen (RT Chemicals®, RTCM 64) dilutions of 1:1, 1:3, 1:9, 1:14 and 1:19 were used. For each dilution, soaking times of 2, 4, 6, 8, 10, 15 and 20 minutes were assessed. The method used for the gravimetric analysis is detailed in Appendix B (page 160). Each experiment was performed four times on pieces of aluminium of roughly the same level of dirtiness. Difficulty was experienced in replicating the same level of dirtiness in all the pieces of aluminium. Furthermore, since many air-conditioner units were used to obtain the aluminium pieces, the type of dirt varied as well. The amount of dirt removed by the cleaner depended on whether the dirt was oily or dry, old or recently layered. Furthermore, the mass of dirt removed was small (around 0.05 g), leading to relatively large measurement errors with the four decimal place balance. Hence the reproducibility of these tests was low with an average coefficient of variation of 196%.

**(b) Pre-wash Systems**

The possibility of a pre-wash system was investigated through the determination of whether either green soap or Alukleen (1:9 and 1:19 dilutions) could be implemented as a pre-wash prior to the main wash of Alukleen (1:9 and 1:19 dilutions). A soaking time of 5 minutes was used for both the pre-wash and the main wash of Alukleen (Appendix B; page 161). Each experiment was performed in triplicate. As with Alukleen, high coefficients of variance of between 68.4 and 93.8% were obtained.

**(c) Degreasers**

Three degreasers were investigated: Powerkleen (RT Chemicals®, RTCM123), Technicians' Choice (Auto Brite (PTY) Ltd.) and Klengine (Auto Brite (PTY) Ltd.). Technicians' Choice and Klengine degreasers were tested neat whilst Powerkleen was tested at dilutions of 1:15 and 1:50.<sup>63</sup> A standard soaking time of 5 minutes was used (Appendix B; page 161). Each experiment was performed in triplicate. Coefficients of variation of between 17% and 30% were obtained. Reasons for these high values were discussed in (a).

#### **(d) Powerkleen**

The selected degreaser, Powerkleen, was tested at dilutions of 1:15, 1:20, 1:30, 1:40, 1:50 and 1:60 each at soaking times of 2, 4, 6, 8, 10, 15 and 20 minutes (Appendix B; page 160). Each experiment was repeated four times. As with the Alukleen tests, the reproducibility of these tests was low with an average coefficient of variance of 89%.

#### **3.3.1.2 Digital Photography**

Digital photography was used in conjunction with the gravimetric analysis to determine the most effective cleaning system for the aluminium. Photographs were taken before and after soaking the aluminium piece in the cleaner. This analysis illustrated both the amount of dirt removed by the cleaner and the degree of etching that occurred on the aluminium surface.

#### **3.3.1.3 Electron Microscopy**

The surface appearances of five pieces of aluminium (50 mm x 50 mm x 1 mm) were studied using scanning electron microscopy (Phillips XL30, Environmental Scanning Electron Microscope). Four of the pieces of the virgin metal were exposed to different cleaners and concentrations: 1:3 and 1:9 dilutions of Alukleen, and 1:20 and 1:40 dilutions of Powerkleen. The remaining piece of aluminium was left untreated and acted as a control.

Analytical electron microscopy is based on the effects of elastic and inelastic scattering of an accelerated electron beam upon interaction with atoms and electrons of the material. Scanning electron microscopy monitors secondary (reflected) electrons and generates surface topography images.<sup>71</sup>

The pieces of aluminium that were treated were soaked in their respective solutions for 5 minutes before being allowed standing time to dry. The Centre for Electron Microscopy at the University of Natal, Pietermaritzburg, performed the electron microscopy at a magnification of 5000X.

### 3.3.2. Determination of the Suitability of Two Cleaner Application Techniques

Two application methods of the cleaner were studied: application by a pressurised pump bottle and by an air gun operated at a pressure of 4 bars (Appendix B; page 162). A pressure of 4 bars was used since this was the pressure available on-site at Ben Booyesen. A pressurised pump bottle was chosen since this application technique was the closest simulation of the on-site conditions for those technicians working in the field. Two concentrations of Powerkleen (1:20 and 1:40), identified as optimum concentrations in Section 5.3 (page 115), were used in these tests.

Each air-conditioner coil was divided into 4 equal pieces (Figure 3.2) for application by each of the four combinations, namely: 1:20 and 1:40 Powerkleen applied each by the pump bottle and air gun. The Powerkleen solutions were applied directly to real air-conditioner coils that had not been stripped.

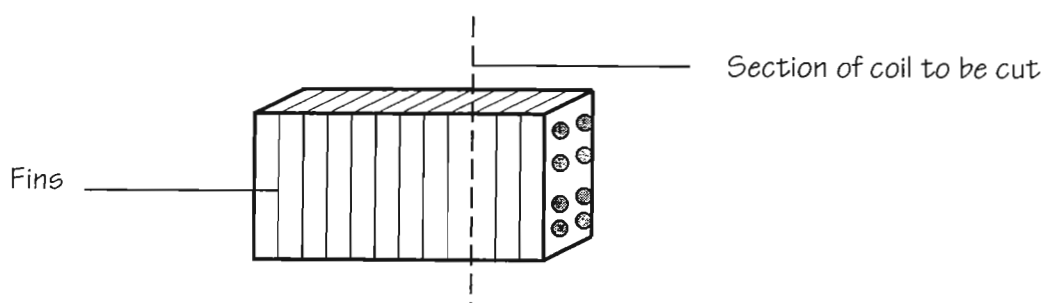


Fig. 3.2: Schematic diagram showing the cutting of a coil into 4 similar pieces.

It was initially intended that cleaner would be applied until saturation of the coil piece occurred. However, due to the lack of pressure in the pump bottle, the top corner of the coil piece never saturated (Figure 3.3). Hence, the cleaner was applied for a standard time of two minutes. The coils were then allowed to stand for 5 minutes (soaking time) before they were rinsed with water using a hose. The cleanliness of the coil was assessed by cutting the coils in half to enable the fins to be inspected.

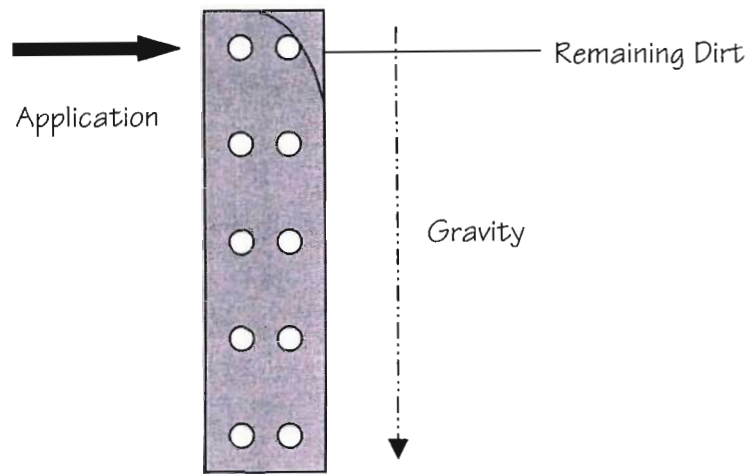


Fig. 3.3: Schematic diagram of the side view of a coil with application point.

The initial intention was to measure the penetration distance on the fins to determine the most effective application technique. However, as penetration was not uniform along the length of the fins, this was not possible. Instead, digital photographs were used to record the degree of cleanliness achieved using each application technique and cleaner concentration.

Each test was repeated three times to account for variance in the dirtiness of the coils.

# **Chapter 4: Results and Discussion**

## **– Characterisation of the System**

This chapter discusses the initial characterisation of the chemicals studied for cleaning the air-conditioner coils. The characterisation involves the identification and quantification of the components present in the acid cleaner (Alukleen) and the quantification of the species present in the alkaline degreaser (Powerkleen) and the effluent from Ben Booyesen.

The qualitative analysis of Alukleen was accomplished through the use of wet chemical analysis and ICP-OES (Section 3.1; page 54) whereas the quantitative analysis of Alukleen, Powerkleen and the effluent was achieved through the use of ion chromatography, ion selective electrodes, photometry, titrations, ICP-OES, pH, conductivity and total dissolved solids measurements (Section 3.2; page 65).

### **4.1 Alukleen**

#### **4.1.1 Qualitative Analysis**

##### **4.1.1.1 Wet Chemical Analysis**

The results of each of the wet chemical analysis positive and negative tests are summarised in Table 4.1 and Figure 4.1. The wet chemical analysis confirmed the presence of fluoride and chloride ions and indicated the possible presence of sulfate, sulfide and arsenite ions in Alukleen. The tests for sulfate, sulfide and arsenite ions were not conclusive: the positive result for the reducing agent test could have been due to sulfide or arsenite ions; and the positive result for the barium chloride test could have been due to sulfate or sulfide ions (Table 4.1). The presence of these ions was established through quantitative techniques (Section 4.1.2; page 82).



Table 4.1: Results of the wet chemical tests used to determine the chemical species in Alukleen.

Ion	Positive Test (Test Confirmed By)	Observation	Negative Test (Test Eliminated By)	Observation	Ions Present in Alukleen
Acetate ( $C_2H_3O_2^-$ )			Ferric Chloride Test	no colour change or precipitation occurred	No
Arsenate ( $AsO_4^{3-}$ )	Calcium Chloride Test	white precipitate formed	Solubility Test	insoluble in acetic acid	No
	Silver Nitrate Test (Group 3)	reddish-brown precipitate formed	Ferric Chloride Test	no colour change or precipitation occurred	
Arsenite ( $AsO_3^{3-}$ )	Reducing Agent Test	bleaching of $KMnO_4$ occurred			Yes - ppt could also be due to $S^{2-}$
Bromate ( $BrO_3^-$ )			Silver Nitrate Test (Group 2)	no precipitate formed	No
Bromide ( $Br^-$ )	Reducing Agent Test	bleaching of $KMnO_4$ occurred	Displacement Tests	no brown colouration of the $CCl_4$ layer occurred	No
	Silver Nitrate Test (Group 1)	white precipitate formed			
Chlorate ( $ClO_3^-$ )			Silver Nitrate Test (Group 2)	no precipitate formed	No
Chloride ( $Cl^-$ )	Silver Nitrate Test (Group 1)	white precipitate formed			Yes

Table 4.1: continued.

Ion	Positive Test (Test Confirmed By)	Observation	Negative Test (Test Eliminated By)	Observation	Ions Present in Alukleen
Cyanide (CN <sup>-</sup> )			Prussian Blue Test	no precipitate formed	No
Fluoride (F <sup>-</sup> )	Calcium Chloride Test	white precipitate formed			Yes
	Solubility Test	soluble in acetic acid			
	Potassium Permanganate Test	no bleaching of KMnO <sub>4</sub> occurred			
Iodate (IO <sub>3</sub> <sup>-</sup> )	Silver Nitrate Test (Group 1)	white precipitate formed	Displacement Tests	no purple colouration of the CCl <sub>4</sub> layer occurred	No
Iodide (I <sup>-</sup> )	Reducing Agent Test	bleaching of KMnO <sub>4</sub> occurred	Displacement Tests	no purple colouration of the CCl <sub>4</sub> layer occurred	No
	Silver Nitrate Test (Group 1)	white precipitate formed			
Nitrate (NO <sub>3</sub> <sup>-</sup> )			Brown Ring Test	no brown ring formed	No
Nitrite (NO <sub>2</sub> <sup>-</sup> )	Reducing Agent Test	bleaching of KMnO <sub>4</sub> occurred	Brown Ring Test	no brown ring formed	No
Oxalate (C <sub>2</sub> O <sub>4</sub> <sup>2-</sup> )	Calcium Chloride Test	white precipitate formed	Potassium Permanganate Test	no bleaching of the KMnO <sub>4</sub> occurred	No
	Solubility Test	insoluble in acetic acid			

Table 4.1: continued.

Ion	Positive Test (Test Confirmed By)	Observation	Negative Test (Test Eliminated By)	Observation	Ions Present in Alukleen
Phosphate ( $\text{PO}_4^{3-}$ )	Calcium Chloride Test	white precipitate formed	Solubility Test	insoluble in acetic acid	No
	Silver Nitrate Test (Group 3)	reddish-brown precipitate formed	Ferric Chloride Test	no colour change or precipitation occurred	
Sulfate ( $\text{SO}_4^{2-}$ )	Barium Chloride Test	white precipitate formed			Yes - ppt could also be due to $\text{S}^{2-}$
Sulfide ( $\text{S}^{2-}$ )	Barium Chloride Test	white precipitate formed			Yes - ppt could also be due to $\text{SO}_4^{2-}$
	Reducing Agent Test	bleaching of $\text{KMnO}_4$ occurred			Yes - ppt could also be due to $\text{AsO}_3^{3-}$
Sulfite ( $\text{SO}_3^{2-}$ )	Reducing Agent Test	bleaching of $\text{KMnO}_4$ occurred	Potassium Dichromate Test	no green solution of chromic salts formed	No
Tartrate ( $\text{C}_4\text{H}_4\text{O}_6^{2-}$ )	Calcium Chloride Test	white precipitate formed	Solubility Test	insoluble in acetic acid	No
Thiocyanate ( $\text{CNS}^-$ )	Silver Nitrate Test (Group 1)	white precipitate formed	Precipitate Test	no red colouration of the solution occurred	No
			Ferric Chloride Test	no colour change or precipitation occurred	
Thiosulfate ( $\text{S}_2\text{O}_3^{2-}$ )	Barium Chloride Test	white precipitate formed	Ferric Chloride Test	no colour change or precipitation occurred	No
	Reducing Agent Test	bleaching of $\text{KMnO}_4$ occurred			



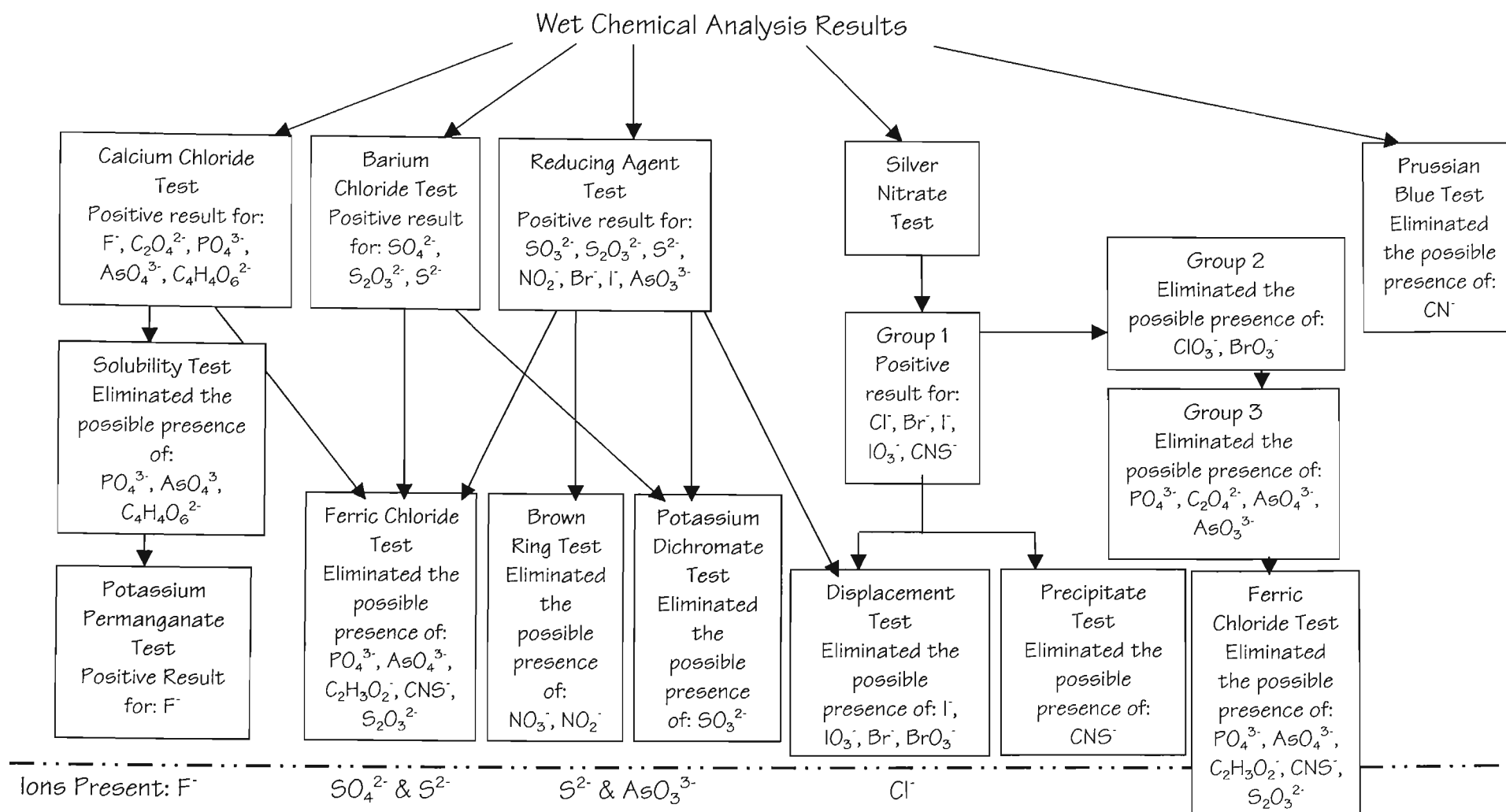


Fig. 4.1: Schematic illustration of the wet chemical analysis results.<sup>62</sup>

4.1.1.2 ICP-OES

The ICP-OES wave scan on a sample of Alukleen was used to detect elements present and hence validate the wet chemical analysis results. The results of the wave scan are shown below along with the limit of detection (L.O.D.) for the ICP-OES using a pneumatic nebulizer. The limit of detection for an element is usually defined as the analyte concentration that produces an analytical signal equivalent to three times the standard deviation observed for 16 measurements of a blank solution.<sup>67</sup>

Table 4.2: ICP-OES analysis of Alukleen.

Element	L.O.D. (µg/L) with a Pneumatic Nebulizer	Present	Comment
As			Does not detect
Br			Does not detect
Ca	14.5	Yes	
Cl			Does not detect
Cr	1.6	Yes	
F			Does not detect
Fe	2.5	Yes	
I	12.8	No	
K	152	Yes	
Mg	24.8	Yes	
Mn	0.61	Yes	
N			Does not detect
Na	11.7	Yes	
P	34.2	No	
Pb	10.7	Yes	Not a good peak
S			Does not detect
Zn	1.5	Yes	

As seen in Table 4.2, the ICP-OES is incapable of detecting arsenic, bromine, chlorine, fluorine, nitrogen and sulfur. Fluorine is undetectable along with hydrogen, oxygen and inert gases.<sup>67</sup> Arsenic, chlorine and sulfur require large excitation energies. As a result, the photon emitted has a small wavelength that falls into the part of the ultra violet – visible spectrum that is obscured by the atmosphere<sup>67</sup>. Thus the

wave scan could not be used as confirmation of the above elements in Alukleen. It did, however, confirm the absence of phosphorous and iodine in Alukleen. The metals listed in Table 4.2 are possibly associated with the surfactants<sup>12</sup> in Alukleen.

### **4.1.2 Quantitative Analysis**

Ion chromatography, ion selective electrodes, photometry and titrations were the respective methods used to quantify  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$ ,  $\text{F}^-$ ,  $\text{S}^{2-}$  and  $\text{H}^+$  ions present in Alukleen. Arsenic analysis was performed by Umgeni Water. Further characterisation of the Alukleen system was achieved through measurement of the pH, conductivity and total dissolved solids.

#### **4.1.2.1 Ion Chromatography**

At Ben Booysen, the Alukleen is dispensed to the technicians as a pre-mixed 1:1 stock solution. By measuring the sulfate concentration in three Alukleen 1:1 stock solutions as well as in Alukleen prior to dilution by Ben Booysen, the presence of sulfate in Alukleen was confirmed and an indication of the accuracy of the initial 1:1 dilution was obtained.

The samples of 1:1 Alukleen were taken from Ben Booysen on the 8<sup>th</sup> August, 20<sup>th</sup> August and the 26<sup>th</sup> August 2002. Average results for each of these samples and the concentrated Alukleen solution are summarised in Table 4.3. Appendix C (page 164) includes the calibration graph, all measurements, mean values, standard deviations and coefficients of variance. Calculation of the dilution factors of the stock solutions is also presented in Appendix C.



Table 4.3: Sulfate concentrations in Alukleen determined using ion chromatography.

Sample	[SO <sub>4</sub> <sup>2-</sup> ] (ppm)	Calculated Dilution Factor for the Stock Solution
1:499 dilution of Sample 1 (8th August 2002)	108.1 ± 2.9	2.822-fold
1:499 dilution of Sample 2 (20th August 2002)	104.6 ± 9.2	2.917-fold
1:499 dilution of Sample 3 (26th August 2002)	143.9 ± 5.2	2.122-fold
1:999 dilution of concentrated Alukleen	152.6 ± 7.4	

The average sulfate concentration in neat Alukleen was determined as 152600 ppm (Appendix C, Table 4.3), indicating that a significant amount of sulfuric acid is present in Alukleen. Variation of the dilution factor of the Alukleen stock solution from approximately 2.1 to 2.9 (Table 4.3) suggests that the stores manager at Ben Booyesen did not always carry out the pre-dilution of Alukleen accurately. This can lead to variations in the degree of cleaning and the amount of etching on the air-conditioner coils (refer to Section 5.1 for the effect of Alukleen concentration on the aluminium pieces; page 100).

Chloride was found to be present in concentrations lower than the limit of detection of the ion chromatograph (0.1 ppm, Appendix C; page 167). It was thus assumed that chloride ions were present in Alukleen in insignificant concentrations.

#### 4.1.2.2 Ion Selective Electrode

The three 1:1 stock solutions of Alukleen and the concentrated Alukleen solution were analysed for their fluoride concentration. Table 4.4 shows the average fluoride concentrations of each of these samples as well as the calculated dilution factors. The calibration graph and all measurements, means, standard deviations and coefficients of variance are presented in Appendix C (page 169).

Table 4.4: Fluoride concentrations in Alukleen determined using an ion selective electrode.

Sample	[F] (ppm)	Calculated Dilution Factor for the Stock Solution
1:499 dilution of Sample 1 (8th August 2002)	20.8 ± 0.2	2.44-fold
1:499 dilution of Sample 2 (20th August 2002)	20.5 ± 0.1	2.47-fold
1:499 dilution of Sample 3 (26th August 2002)	24.4 ± 0.2	2.08-fold
1:999 dilution of concentrated Alukleen	25.4 ± 0.3	

The above table illustrates that concentrated Alukleen has an average fluoride concentration of 25400 ppm, thus indicating a significant hydrofluoric acid concentration. Sulfuric acid however, is present in much larger quantities (152600 ppm; Section 4.1.2.1; page 82) and is thus the major constituent of Alukleen.

There is a discrepancy in the dilution factors calculated using the ion chromatography measurements (Table 4.3) and the ion selective electrode (ISE) measurements (Table 4.4), however, both techniques indicate the same trend in results: the first two samples have larger dilution factors than the third.

#### 4.1.2.3 Further Measurements of the Alukleen Composition

The sulfide concentration in Alukleen was determined using photometry whilst Umgeni Water determined the arsenic concentration through measurement of its hydride (Section 3.2.4; page 68). The results from these analyses are summarised in Table 4.5:

Table 4.5: Results from the determination of the sulfide and arsenic concentrations in Alukleen.

Species	Concentration (ppm)
Sulfide (S <sup>2-</sup> )	0.091 (< L.O.D; 0.5 ppm) <sup>#</sup>
Arsenic (As)	< L.O.D.(0.002 ppm)

<sup>#</sup> The sulfide values account for absorbance by the blank.

The sulfide concentration in Alukleen was calculated as 0.091 ppm. This value is lower than the limit of detection for the instrument (0.5 ppm) however. The above table thus shows that the concentrations of sulfide and arsenic in Alukleen are negligible. Hence the main inorganic acids<sup>12</sup> in Alukleen are sulfuric and hydrofluoric acids.

#### 4.1.2.4 Titrations

A pH titration of Alukleen was carried out to verify the quantities of both strong ( $\text{H}_2\text{SO}_4$ ) and weak (HF) acids present. It was anticipated that only one endpoint would be observed for  $\text{H}_2\text{SO}_4$  since the diprotic acid is strong and its  $K_{a2}$  value is  $1.20 \times 10^{-2}$ .<sup>25</sup> To confirm this,  $\text{H}_2\text{SO}_4$  was first titrated with sodium hydroxide (Figure 4.2). The result was a single endpoint, corresponding to the reaction of NaOH with both  $\text{H}_2\text{SO}_4$  protons.

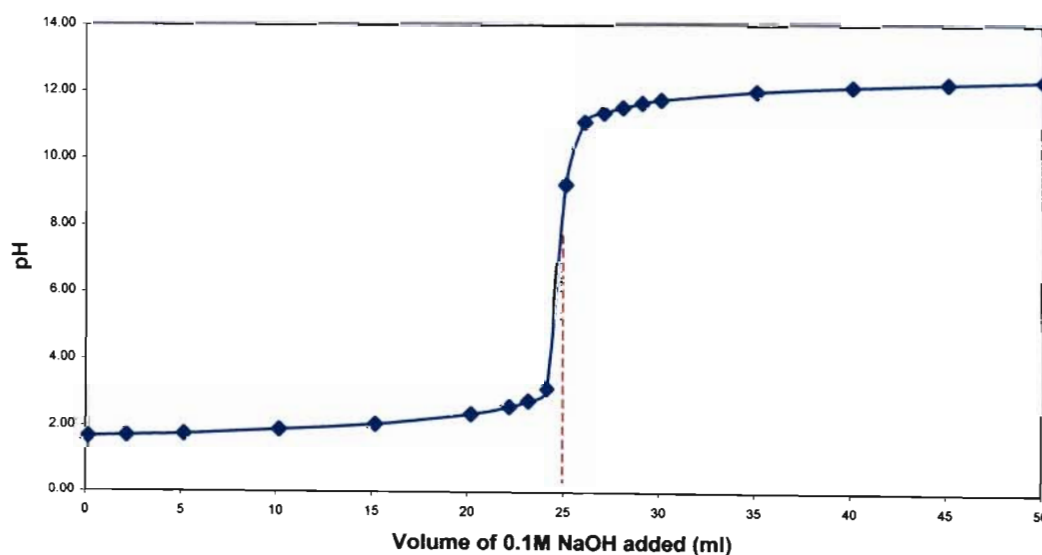


Fig. 4.2: pH titration of 0.25 M  $\text{H}_2\text{SO}_4$  with 0.1 M NaOH.

A stock solution of Alukleen (1:1 dilution) was then titrated with sodium hydroxide to determine the amounts of strong and weak acids (Figure 4.3). The concentration of NaOH was determined as 2.040 M through titration with potassium hydrogen phthalate (a primary standard; Appendix B; page 159).

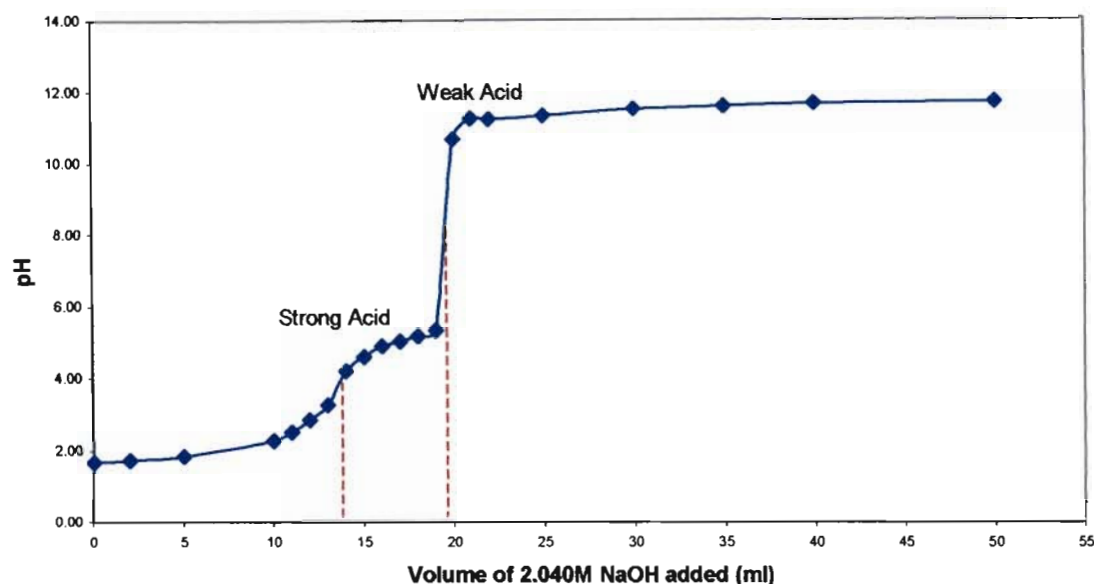
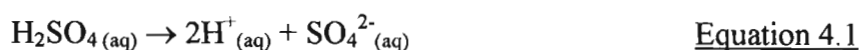


Fig. 4.3: pH titration of Alukleen with 2.040 M NaOH.

The first endpoint was assigned to the neutralisation of sulfuric acid since the complete dissociation of sulfuric acid (Equation 4.1) inhibits the dissociation of the weak HF (Equation 4.2).



As sodium hydroxide is added to the solution of the Alukleen and the  $\text{H}_2\text{SO}_4$  protons are reacted, the dissociation of HF shifts more to the right, according to Le Chatelier's principle. Hence the second endpoint in Figure 4.3 was assigned to the reaction of HF with sodium hydroxide.

Figure 4.3 thus allowed the calculation of the concentration of  $\text{H}_2\text{SO}_4$  and HF acids in the Alukleen stock solution as 0.6885 M and 0.610 M respectively. These values correspond to  $\text{H}_2\text{SO}_4$  and HF concentrations of 1.71 M and 1.51 M respectively in neat Alukleen. Details of these calculations are shown in Appendix C (page 174).

These values were compared to the  $\text{H}_2\text{SO}_4$  and HF concentrations determined from ion chromatography and ion selective electrode measurements. Ion chromatography yielded a  $\text{SO}_4^{2-}$  concentration of 152600 ppm in neat Alukleen (Section 4.1.2.1; page 82), which equates to a  $\text{H}_2\text{SO}_4$  concentration of 1.556 M. A difference of 9.01% is noted when this value is compared to the  $\text{H}_2\text{SO}_4$  concentration of 1.71 M, calculated from the first endpoint of the pH titration of Alukleen.

Measurements made on the ion selective electrode produced a fluoride ion concentration of 25400 ppm or an HF concentration of 1.33 M in neat Alukleen. An 11.9% difference between this value and that calculated from the pH titration of Alukleen (1.51 M) is apparent.

#### 4.1.2.5 Further Measurements Characterising Alukleen

The average pH, conductivity and total dissolved solids measurements taken for Alukleen are summarised in Table 4.6. All measurements are presented in Appendix C (page 176).

Table 4.6: Results of the measurement of the pH, conductivity and the total dissolved solid content of Alukleen.

Measurement	Alukleen Dilution	Average Reading	Extrapolated to neat Alukleen
pH	1:19	$3.01 \pm 0.05$	
Conductivity ( $\mu\text{S}/\text{cm}$ )	1:999	$185.0 \pm 2.8$	$1850 \times 10^2 \pm 2.8 \times 10^3$
Total Dissolved Solids (g/25ml)			$0.0031 \pm 0.0014$

Since the pH of concentrated Alukleen was found to be below the range of the pH meter (Merck Indicator Strips registered a pH of 1), the pH of a 20-fold dilution of the acid cleaner was measured. Similarly, the conductivity of concentrated Alukleen was found to be above the range of the equipment (999 mS/cm). A 1000-fold dilution of Alukleen was analysed and the readings extrapolated to neat Alukleen. The total dissolved solid content of Alukleen was calculated to be 0.12 g/L. The negative



masses, obtained for the suspended solids measurements (Appendix C; page 177), can probably be attributed to moisture loss from the filter paper during drying. This indicates that the mass of suspended solids in Alukleen is negligible.

The workers at Ben Booyesen handle a 1:3 solution of Alukleen (Section 1.2; page 4). The pH of this solution would be lower than 3 (Table 4.6). Hence a 1:3 Alukleen solution can give rise to acid burns when contacted with skin.<sup>12</sup> The occupational safety concerns associated with Alukleen were one of the factors that motivated Ben Booyesen to optimise its concentration. The environmental compliance of Alukleen is discussed in Section 4.3.2 (page 95).

## **4.2 Powerkleen**

Since Powerkleen was found to be a viable alternative to Alukleen in cleaning the aluminium coils (Section 5.2; page 106), studies were conducted to quantify the species present in Powerkleen (Section 4.2.1). Since the material safety data<sup>63</sup> sheet of Powerkleen defined its active components, no qualitative analysis was necessary as it was for Alukleen. Furthermore, Darvill specifies no limits for the cations that would be associated with the bases in Powerkleen. Hence a qualitative analysis to identify these cations was not needed. In Section 4.2.2 (page 91) the quantitative measurements are compared to stormwater and Darvill disposal limits to establish whether the use of Powerkleen would reduce Ben Booyesen's environmental impact.

The studies were conducted on neat Powerkleen as well as on a dilution of 1:39 Powerkleen. This Powerkleen dilution was chosen for analysis since studies in Section 5.3 (page 115) suggest that this concentration is optimum.



### 4.2.1 Quantitative Analysis

The material safety data sheet<sup>63</sup> indicated that the main species in Powerkleen were potassium hydroxide, butyl oxitol and sodium xylene sulfonate. In determining the concentrations of species, titrations, the ICP-OES and photometry were used. Further measurements included the chemical oxygen demand (COD), pH, conductivity and total dissolved solids concentration.

#### 4.2.1.1 Titrations

Since the Powerkleen material safety data sheet indicated that the main alkali present was potassium hydroxide (KOH), a pH titration was carried out to determine its concentration. Powerkleen was titrated with HCl (Appendix B; page 159) and Figure 4.4 was obtained. The concentration of HCl was determined through standardisation with NaOH of a known concentration and was found to be 1.065 M (Appendix B; page 159).

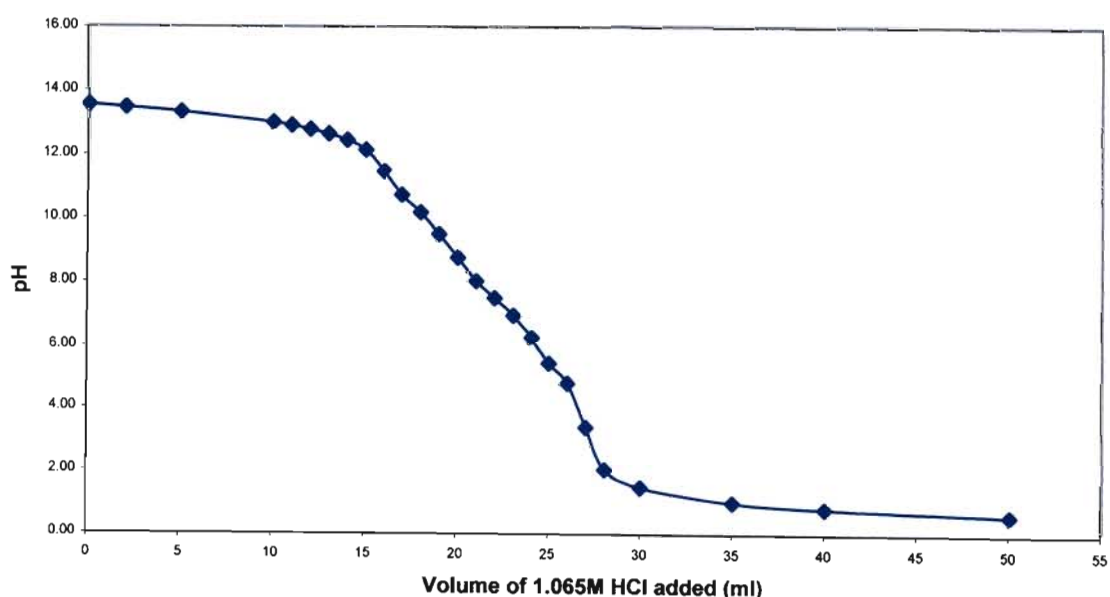


Fig. 4.4: pH Titration of Powerkleen with 1.065 M HCl.

Figure 4.4 shows that no clear endpoint was obtained for this titration. This could be due to the presence of weak bases that prevent the possibility of attaining a clear,

sharp endpoint. Hence the concentration of KOH could not be determined through this method. Instead the ICP-OES was used to quantify the concentration of potassium as a means of estimating the concentration of KOH.

#### **4.2.1.2 ICP-OES**

The average concentration of potassium in Powerkleen was measured as 27800 ppm with a standard deviation of 153 ppm. All measurements, including calculation of the mean, standard deviation and coefficient of variation, are presented in Appendix C (page 178). Assuming that all the potassium present is present as potassium hydroxide, the KOH concentration was calculated as 0.711 M (Appendix C; page 179).

#### **4.2.1.3 Photometry**

The sulfide determination of Powerkleen was accomplished photometrically (Section 3.2.3; page 67). Powerkleen was found to have a negligible sulfide concentration (less than the limit of detection of 0.5 ppm). The measurements for this determination are presented in Appendix C (page 180).

#### **4.2.1.4 Chemical Oxygen Demand Measurement**

Umgeni Water determined the chemical oxygen demand (COD) of 1:39 Powerkleen as  $6431 \text{ mgO}_2/\text{L} \pm 13.00 \text{ mgO}_2/\text{L}$ . The measurements are presented in Appendix C (page 181) and this value is compared in Section 4.2.2 (page 91) with the limits for discharge to Darvill.

#### **4.2.1.5 Further Measurements Characterising Powerkleen**

The average pH, conductivity and total dissolved solids concentration measurements for Powerkleen are presented in Table 4.7. Detailed results are shown in Appendix C.

Table 4.7: Results of the measurement of the pH, conductivity and the total dissolved solids concentration of Powerkleen.

Measurement	Powerkleen Dilution	Reading	Neat Powerkleen
pH	1:39	12.11 ± 0.11	
Conductivity (µS/cm)			$8.81 \times 10^4 \pm 721$
Total Dissolved Solids (g/25ml)			4.7293 ± 0.9185

The pH of neat Powerkleen was found to be greater than the range of the pH-meter (Merck Indicator Strips registered a pH of 14). The pH was thus measured for a 1:39 dilution of the degreaser. The mean total dissolved solids concentration of Powerkleen was found to be 189.17 g/L.

#### 4.2.2 Comparison with Disposal Limits

The quantitative analysis in Section 4.2.1 (page 88) allowed a rough estimation of the effluent composition if Powerkleen were to replace Alukleen as the cleaner used by Ben Booysen. It is shown in Section 5.3.2 (page 122) that Powerkleen could replace the use of green soap and Handy Andy. Hence, the effluent generated would consist mainly of further diluted 1:39 Powerkleen. In comparing the Powerkleen effluent composition to the disposal limits (Table 4.8), the composition of 1:39 Powerkleen was used to give an upper-limit to the effluent's composition.

Table 4.8: Comparison of limits for effluent discharge to stormwater and to Darvill with the concentrations of the species present in 1:39 Powerkleen.

Component	1:39 Powerkleen	Limits (Stormwater) <sup>41</sup>	Limits (Darvill) <sup>40</sup>
Conductivity	462 mS/m	400 mS/m	400 mS/m
pH	12.11	$6.5 < x < 9.5$	$6.5 < x < 9.5$
Potassium	695 ppm		
Total Dissolved Solids	4729.3 ppm		5000 ppm
Chemical Oxygen Demand	6431 mgO <sub>2</sub> /L		< 350 mgO <sub>2</sub> /L

Table 4.8 highlights that the pH, conductivity and chemical oxygen demand of 1:39 Powerkleen are too high for disposal to either stormwater or Darvill. However, the effluent would never be pure 1:39 Powerkleen since further dilution of Powerkleen would occur from rinsing water, water from the floor and vehicle washing, and rainwater. As estimate of this dilution effect is made in Section 6.3 (page 134). Based on this estimate, it is shown that the diluted Powerkleen effluent complies with all stormwater and Darvill disposal criteria.<sup>40, 41</sup>

### **4.3 Sampled Effluent**

Samples of Ben Booyesen's effluent were taken on three random days over a four week period for quantitative analysis: the 18<sup>th</sup> September, 25<sup>th</sup> September and 7<sup>th</sup> October 2002. Samples were taken from a sump from where the effluent is drained to stormwater. This sump is uncovered and, as a result, is exposed to the elements.

The cleaning agents used by Ben Booyesen included Alukleen, green soap and Handy Andy. Hence the effluent was a dilute mixture of these cleaning agents because of dilution with rain water and water used to rinse the air-conditioner units, hose down the concrete floors, and wash vehicles.

#### **4.3.1 Quantitative Analysis**

Because of the presence of Alukleen in the effluent, sulfate, fluoride and sulfide concentrations were measured (Section 4.3.1.1 – 4.3.1.3). The pH, conductivities and total dissolved solids concentrations of the effluent samples were further measured since Ben Booyesen had previously been sending its effluent to stormwater. Quantitative analysis thus allowed comparison with the stormwater disposal limits and discharge limits to Darvill wastewater treatment plant (Section 4.3.2; page 95). The results obtained are discussed below.

### 4.3.1.1 Ion Chromatography

Ion chromatography was used to measure the sulfate concentrations in the effluent samples. Mean results and standard deviations for each of the samples are presented in Table 4.9. All measurements are presented in Appendix C (page 184).

Table 4.9: Sulfate concentrations in the effluent samples determined using ion chromatography.

Sample	Mean [SO <sub>4</sub> <sup>2-</sup> ] (ppm)
Effluent 1	66.42 ± 3.22
Effluent 2	187.8 ± 13.2
Effluent 3	54.85 ± 1.26
Mean	103.0 ± 64.2

Table 4.9 shows a significant difference between the sulfate concentrations of the effluent samples. This can be attributed to the effluent being sampled on different days and consequently under different conditions. The number of air-conditioner units serviced each day varied. Furthermore, 15 technicians manually serviced the air-conditioner units and the quantities of the chemicals used by each technician was not standardised. Hence the quantities of chemicals sent to drain varied. In addition, since the sampling point was uncovered, the effluent was subject to dilution with water from many sources including rainwater. The dilution was thus not constant from day to day.

### 4.3.1.2 Ion Selective Electrode

A fluoride ion selective electrode was used to measure the fluoride concentration in the effluent samples. Table 4.10 shows the mean values and standard deviations obtained for each of the effluent samples. Appendix C shows all measurements made (page 186).



Table 4.10: Fluoride concentrations in the effluent samples determined using an ion selective electrode.

Sample	Mean [F] (ppm)
Effluent 1	20.0 ± 0.2
Effluent 2	23.5 ± 0.1
Effluent 3	16.3 ± 0.1
Mean	17.2 ± 1.5

The fluoride concentration in the effluent samples is also variable due to the reasons mentioned in Section 4.3.1.1 (page 93). Similar trends in the fluoride and sulfate concentrations were observed for the effluent samples. (Tables 4.9 and 4.10).

#### **4.3.1.3 Photometry**

The sulfide concentration in the effluent samples was measured using photometry. The effluent samples were found to have a sulfide concentration lower than the limit of detection for the instrument (0.5 ppm; Appendix C; page 188). This result was expected since the average sulfide concentration in Alukleen prior to dilution was lower than the limit of detection (Section 4.1.2.3; page 84).

#### **4.3.1.4 Further Measurements Characterising the Effluent Samples**

The average pH, conductivity and total dissolved solids measurements of the effluent samples are summarised in Table 4.11. All measurements, means, standard deviations and coefficients of variance are presented in Appendix C (page 189).



Table 4.11: pH, conductivity and total dissolved solids concentration measurements of the effluent samples.

Sample	Mean pH	Mean Conductivity ( $\mu\text{S}/\text{cm}$ )	Mean Total Dissolved Solids (g/25ml)
Effluent 1	$4.34 \pm 0.12$	$390.2 \pm 1.8$	$0.0366 \pm 0.0028$
Effluent 2	$3.88 \pm 0.06$	$647.0 \pm 2.9$	$0.0251 \pm 0.0061$
Effluent 3	$6.44 \pm 0.02$	$193.6 \pm 2.0$	$0.0151 \pm 0.0050$
Mean	$4.89 \pm 1.18$	$410.3 \pm 196.9$	$0.0256 \pm 0.0101$

As anticipated, the average pH of the effluent samples is higher than that measured for pure Alukleen (Section 4.1.2.5; page 87). Similarly, the average conductivity of the effluent is lower than that of pure Alukleen. This is a result of the dilution of the Alukleen stock solution with water from miscellaneous sources. However, the mean total dissolved solids concentration of the effluent samples (0.0256 g/25ml or 1.02g/L) is approximately 8 times higher than pure Alukleen (0.12 g/L; Section 4.1.2.5; page 87). This can probably be attributed to the corrosive action of Alukleen on the air-conditioner coils (Section 5.1; page 100). In addition, the green soap and Handy Andy, used by Ben Booyesen to clean the plastic casings of the air-conditioner units, could contribute further to the high total dissolved solids concentration of the effluent.

Ranges of 39.8%, 70.1% and 58.7% are observed in the pH, conductivity and total dissolved solids measurements respectively. These variations in values can also be attributed to the unique mix of detergents and water on each sampling day.

### 4.3.2 Comparison with Disposal Limits

Quantification of the key species present in the effluent samples allowed comparison with the stormwater and Darvill disposal limits (Table 4.12). The concentrations presented are the average of the three effluent samples.

Table 4.12: Comparison of limits for effluent discharge to stormwater and to Darvill with the concentrations of the species present in the effluent.

Component	Mean Concentration in Effluent	Maximum Measured Concentration in Effluent	Limits (Stormwater) <sup>41</sup>	Limits (Darvill) <sup>40</sup>
Conductivity	41.03 mS/m	64.70 mS/m	400 mS/m	400 mS/m
pH	4.89	3.88 (minimum)	6.5 < x < 9.5	6.5 < x < 9.5
Fluoride	17.2 ppm	23.5 ppm	0.750 ppm	5 ppm
Sulfates (aq)	103.0 ppm	187.8 ppm		250 ppm
Total Dissolved Solids	1020 ppm	1464 ppm		5000 ppm
Total Sulfides	< 0.5 ppm	< 0.5 ppm		25 ppm
COD				350 mgO <sub>2</sub> /L

The maximum values shown in Table 4.12 are included as indicators for the *worst-case scenario* for the effluent's composition. In evaluating the compliance of the effluent with the disposal limits, these values need to be considered with the average values. For example, although the average sulfate concentration of the effluent is far lower (59%) than the discharge limit to Darvill, the maximum concentration of the sulfate in the three samples (187.8 ppm) is only 25% lower than the 250 ppm limit. The maximum values observed for the electrical conductivity, sulfate, total dissolved solids and total sulfide concentrations in Alukleen comply with the disposal limits.

Table 4.12 highlights two problem areas: the average and maximum values of the effluent's pH are too low and the fluoride concentrations are too high for discharge to either Darvill or stormwater. Since the effluent composition varies depending on workload, amount of rinsing done and the amount of rainfall received, these values serve only as a guideline. However, they do serve to illustrate potential problem areas. These results motivated investigation into other, less environmentally harmful cleaners for use at Ben Booyesen.

## 4.4 Conclusion

In this chapter, the results obtained from the qualification of the species present in Alukleen and the quantification of the species present in Alukleen, Powerkleen and the sampled effluent were discussed.

Through the use of wet chemical analysis, the presence of fluoride and chloride ions in Alukleen was confirmed, and the possible presence of sulfate, sulfide and arsenite ions was indicated. An ICP-OES wave scan further verified the absence of phosphorous and iodine in Alukleen. Measurement of the ions was achieved using an ion chromatograph, an ion selective electrode and a photometer. The results indicated that only sulfate and fluoride were present in Alukleen in significant quantities with respective average concentrations of 152600 ppm and 25400 ppm in the neat solution. A further result was the variable pre-dilution factor of Alukleen, indicating that control is required in Ben Booyesen's stores in the initial dilution of the Alukleen.

A pH titration of Alukleen provided an alternate means of calculating the sulfuric and hydrofluoric acid concentrations. These methods of calculation correlated with the ion chromatography and titration measurements yielding sulfuric acid concentrations of 1.556 M and 1.71 M respectively (a difference of 9.01%) and the ion selective electrode and titration measurements yielding hydrofluoric acid concentrations of 1.33 M and 1.51 M respectively (a difference of 11.9%).

Alukleen was further characterised in terms of its pH, conductivity and total dissolved solids concentration. The low average pH measurement (3.01) of a 1:19 dilution of Alukleen indicates that workers' handling the cleaner is an occupational hazard. This was one reason that motivated the investigation into alternative cleaners for the aluminium coils.

Powerkleen was then characterised to determine whether an environmental improvement would occur upon its implementation. Both neat Powerkleen and a 1:39 Powerkleen solution (the dilution of choice) were analysed for their potassium hydroxide (KOH) concentration, chemical oxygen demand, pH, conductivity and total

dissolved solids concentration. Since a clear endpoint in the titration of Powerkleen with 1.065 M HCl was absent, the ICP-OES was used to determine the potassium and hence KOH concentration (0.711 M).

The measured properties of 1:39 Powerkleen were then compared with the stormwater and Darvill disposal limits. The concentrations of 1:39 Powerkleen are an upper limit since any effluent generated from its use would be further diluted. Although three potentially problematic areas were identified through the comparison (a pH of 12.11, a conductivity of 462 mS/m and a COD of 6431 mgO<sub>2</sub>/L) is far higher than the limit set for domestic wastewater (350 mgO<sub>2</sub>/L), it is shown in Section 6.3 (page 134) that dilution of the effluent by rinse, wash and rainwater should result in the effluent complying with all stormwater and Darvill disposal criteria.

Three effluent samples from Ben Booysen were analysed for their sulfate, fluoride and sulfide concentrations as well as their pH, conductivity and total dissolved solids concentration. A large variation in the results obtained from the three effluent samples was observed. This variation in concentration of key species and the effluent's parameters was attributed to daily variations in the number of air-conditioner units serviced, the quantities of detergents used and the amount of water contributed by rinsing, vehicle and floor washing, and rainwater.

Since Ben Booysen had previously been discharging its effluent to stormwater, the effluent parameters were compared to stormwater and Darvill disposal limits. The comparison indicated that the average pH of the effluent (4.89) is below the pH range of 6.5 – 9.5 of the disposal limits. In addition, the average fluoride concentration (17.2 ppm) exceeds the limits for both disposal to stormwater or Darvill.



## **Chapter 5: Results and Discussion – Optimisation of System Parameters**

In this chapter, the optimisation of the system used for cleaning the air-conditioner units is discussed. The optimisation of the cleaning system was four-fold. Firstly, the current system was optimised, *i.e.* the most effective concentration of Alukleen as well as the most effective soaking (contact) time for the coil were determined (Section 5.1; page 100). Secondly, the use of Alukleen with various pre-washes was studied (Section 5.2.1; page 107). Observation that even the optimum Alukleen concentration and soak time caused etching, and hence deterioration of the air-conditioner coils, motivated an investigation into feasible alternatives to Alukleen. This part of the study was further motivated by the environmental and handling problems associated with Alukleen (Section 4.3.2; page 95). Hence the cleaning capacity of various degreasers was investigated (Section 5.2.2; page 111). Thirdly, the selected degreaser system (Powerkleen) was optimised with regard to cleaner concentration and soaking time (Section 5.3.1; page 115). Powerkleen was further studied to establish whether it could replace green soap and Handy Andy in cleaning the plastic components of the air-conditioner units (Section 5.3.2; page 122). The final optimisation stage involved investigating the suitability of two methods for applying the cleaner to the air-conditioner coils (Section 5.4; page 123).

The optimisation of system conditions was accomplished using gravimetric analysis, digital photography and electron microscopy (Section 3.3.1; page 71). The gravimetric analysis was used as a means of measuring the amount of dirt removed from the aluminium whilst digital photography was used to capture ‘before’ and ‘after’ photographs of the aluminium during cleaning. Electron microscopy was used to assess the damage caused by Alukleen and Powerkleen to the aluminium coil.

## **5.1 Determination of the most effective Alukleen Concentration and Soaking Time**

### **5.1.1 Gravimetric Analysis**

For this analysis (as described in Section 3.3.1.1; page 71), pieces of aluminium coils were treated with varying dilutions of Alukleen in tap water (1:1, 1:3, 1:9, 1:14 and 1:19) each at soaking times of 2, 4, 6, 8, 10, 15 and 20 minutes. Soaking times of more than 20 minutes per coil were considered unfeasible in terms of the productivity of the company. The dirt removed during each run was collected and dried on pre-weighed filter paper. The mass of dirt removed was thus used as a means of comparing the effectiveness of each Alukleen concentration and soaking time.

The raw data from the replicated runs are shown in Appendix D (page 195). Table 5.1 shows the averaged data. As described in Section 3.3.1.1 (page 71), coefficients of variation as high as 2000% were observed as a result of the difficulty in replicating the level and nature of dirtiness in each of the aluminium pieces used. To minimise this variation, each test was repeated four times. Negative values were also obtained for the mass of dirt removed using some of the dilute Alukleen solutions. This was attributed to negligible amounts of dirt being removed by these cleaner concentrations and loss of moisture from the filter paper during drying. Correction was not made for this loss of moisture from the filter paper since, on average, the error incurred is less than the standard deviation in the measurements.



Table 5.1: Averaged gravimetric data for determining the most effective Alukleen concentration and soaking time.

Soaking Time (mins)	Alukleen Dilution	Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
2	1:1	0.0775	0.0203	26.2
	1:3	0.0321	0.0330	103
	1:9	0.0071	0.0057	81
	1:14	0.0038	0.0053	140
	1:19	0.0011	0.0105	950
4	1:1	0.0661	0.0097	15
	1:3	0.0263	0.0150	57.1
	1:9	0.0062	0.0138	220
	1:14	0.0010	0.0086	870
	1:19	-0.0069	0.0090	130
6	1:1	0.0580	0.0096	17
	1:3	0.0331	0.0138	41.8
	1:9	0.0097	0.0107	110
	1:14	0.0055	0.0136	250
	1:19	-0.0004	0.0069	2000
8	1:1	0.0610	0.0210	34.4
	1:3	0.0335	0.0106	31.8
	1:9	0.0124	0.0101	81.8
	1:14	0.0055	0.0048	87
	1:19	-0.0003	0.0070	2000
10	1:1	0.0908	0.0212	23.3
	1:3	0.0524	0.0081	16
	1:9	0.0219	0.0150	68.3
	1:14	0.0243	0.0099	41
	1:19	0.0143	0.0116	81.6

Table 5.1 continued.

Soaking Time (mins)	Alukleen Dilution	Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
15	1:1	0.0740	0.0071	9.6
	1:3	0.0555	0.0118	21.3
	1:9	0.0096	0.0106	110
	1:14	0.0108	0.0073	68
	1:19	0.0047	0.0114	240
20	1:1	0.0798	0.0159	20.0
	1:3	0.0376	0.0122	32.6
	1:9	0.0245	0.0141	57.6
	1:14	0.0156	0.0184	118
	1:19	0.0019	0.0245	1300

Trends in the results are more clearly illustrated in Figures 5.1 and 5.2.

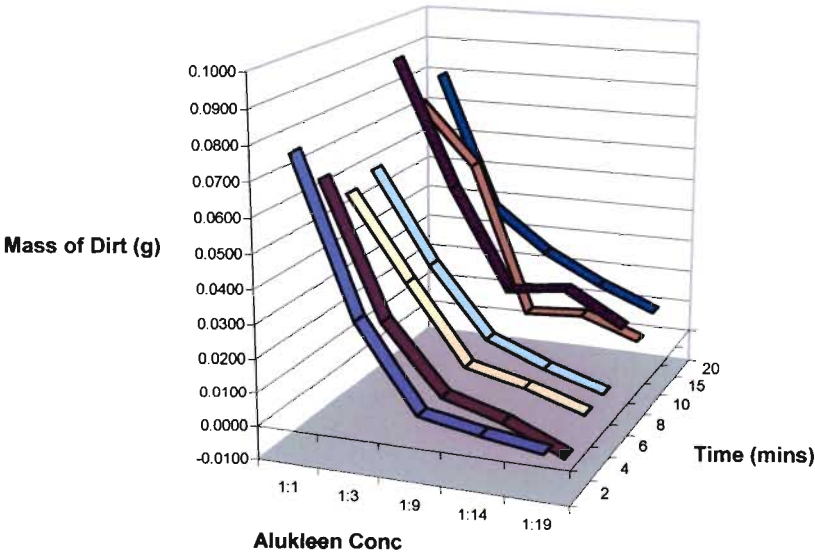


Fig. 5.1: Averaged gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time.

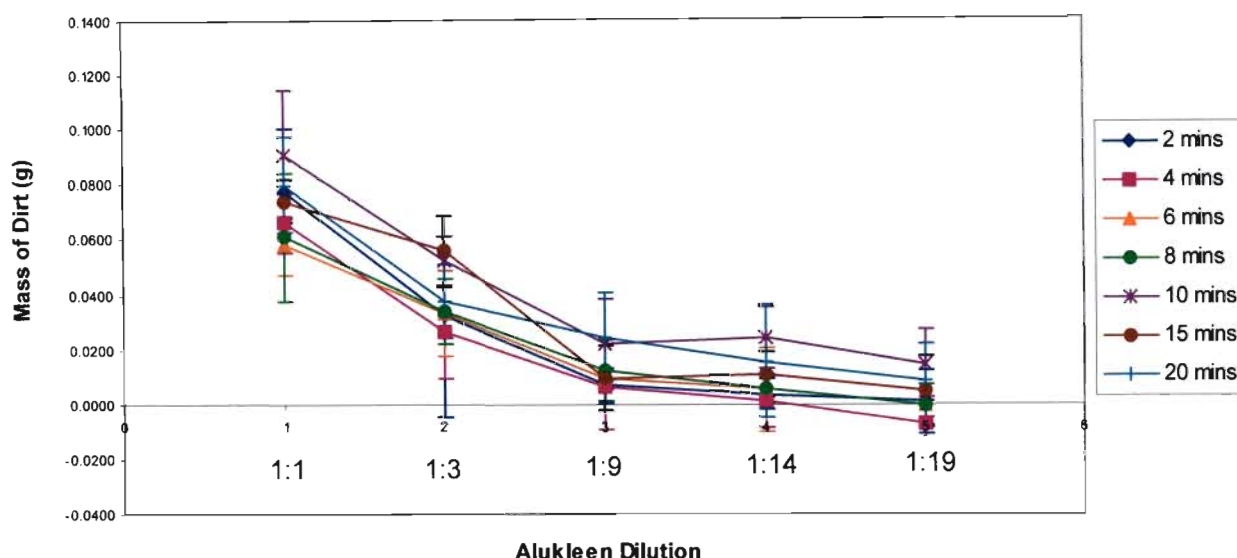


Fig. 5.2: Line graph showing the averaged gravimetric analysis results with standard deviations plotted as y-error bars.

The Alukleen dilutions of 1:1 and 1:3 remove 4 –7 times more ‘dirt’ than the dilutions of 1:9, 1:14 and 1:19. A possible explanation is that the stronger concentrations of Alukleen are etching the aluminium in addition to removing surface dirt. This theory is explored further in Sections 5.1.2 and 5.1.3 (pages 104 and 105).

It can be seen from Figure 5.2 that at a fixed Alukleen concentration, the y-error bars (indicating the standard deviation in measurements) overlap for many of the soaking times. The standard deviations are thus greater than any differences in mass of dirt removed by the respective soaking times. It can thus be concluded that the increase in soaking time does not significantly influence the amount of dirt removed from the aluminium.

### 5.1.2 Digital Photography

Digital photographs were taken of the aluminium pieces used for these tests (described in Section 5.1.1; page 100) before and after cleaning. This method provided a means of capturing the visual effects of etching caused by the stronger concentrations of Alukleen. The ‘before’ and ‘after’ photographs are all shown in Appendix D (page 205). Figures 5.3 and 5.4 below show these photographs for a soaking time of 2 minutes.

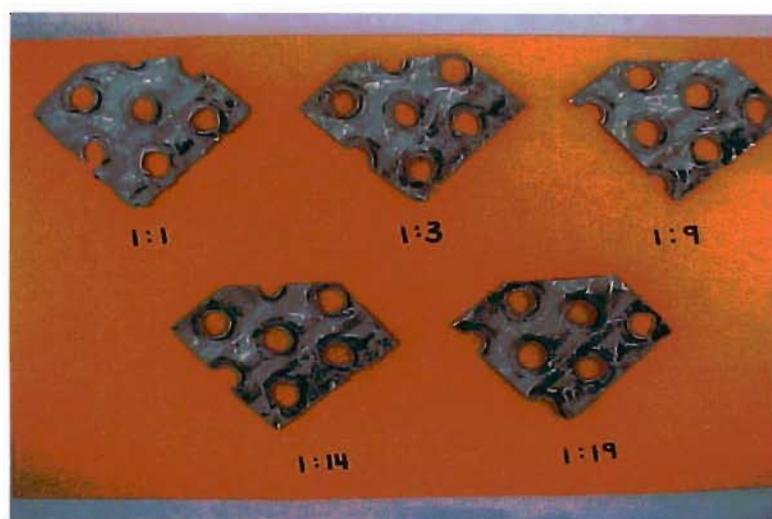


Fig. 5.3: ‘Before’ photograph for a soaking time of 2 minutes. \*

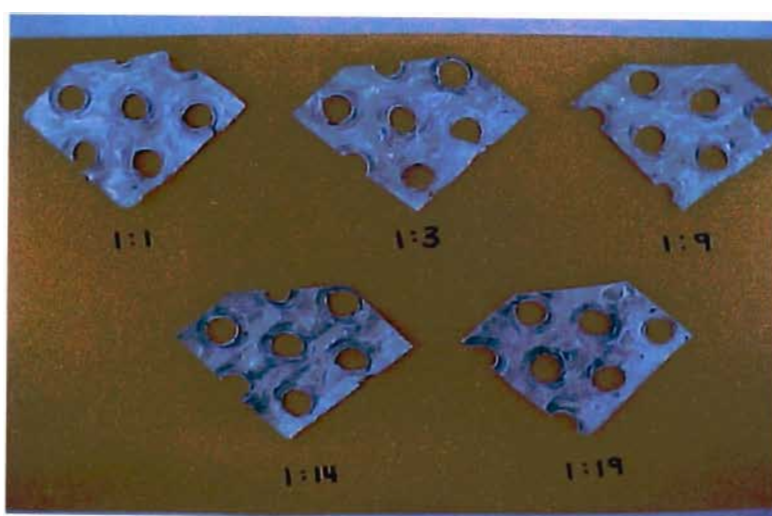


Fig. 5.4: ‘After’ photograph for a soaking time of 2 minutes. \*

\* The numbers below the aluminium pieces refer to the dilutions of Alukleen in tap water.

The etching of the aluminium pieces appears as a whitening of the metal with a loss of the metal's sheen and malleability. As can be seen in the above photographs, the aluminium is etched by Alukleen dilutions of 1:1, 1:3 and 1:9 at soaking times as short as 2 minutes. Aluminium soaked in dilutions of 1:14 and 1:19 partially retained its natural gloss but showed a small degree of etching at the corners of the metal pieces. This is considerably less than the damage caused by the more concentrated Alukleen. Hence this study indicates that an effective dilution of between 1:9 and 1:19 would be optimal for Alukleen.

The technicians at Ben Booyesen use Alukleen at an effective dilution of 1:3 (Section 1.2; page 4). The photographs above illustrate the damage this dilution is causing. As well as destroying the aluminium's natural sheen, it is shortening its working lifespan by reducing its malleability. The damage caused by the 1:3 Alukleen to the aluminium pieces was further investigated through electron microscopy.

### **5.1.3 Electron Microscopy**

For the electron microscopy analysis, two pieces of virgin aluminium were studied: an untreated control piece and a piece that had been soaked for 5 minutes in a 1:3 dilution of Alukleen (Section 3.3.1.3; page 73). A dilution of 1:3 was used to match the effective dilution used by Ben Booyesen technicians. The results of this study are presented in Figure 5.5.



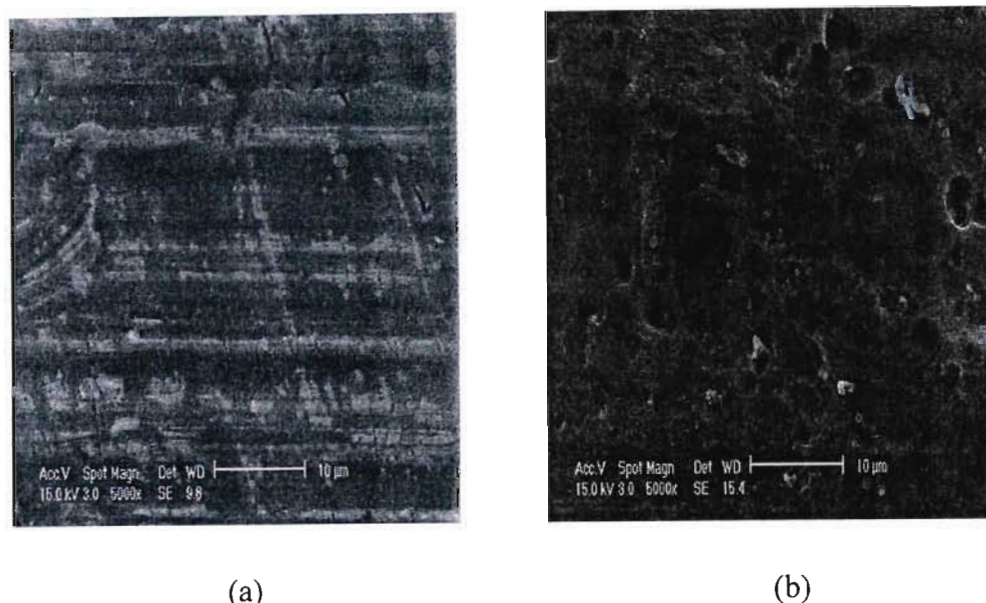


Fig. 5.5: Electron Micrographs of the surface of aluminium samples.

Scanning Electron Microscope (Phillips XL 30); magnification of 5000X.

(a) Control.

(b) Aluminium treated with a 1:3 dilution of Alukleen.

In Figure 5.5(a), annealing marks are evident on the surface of the aluminium employed as a control. These marks are a result of the finishing stages of the production of the metal.<sup>72</sup> However, Figure 5.5(b) clearly illustrates pitting, the initiation of corrosion as a result of its submergence in Alukleen (Section 2.7.3; page 46). This analysis thus confirms the unsuitability of Alukleen at a 1:3 dilution for the cleaning of the aluminium coils.

## 5.2 Determination of the Best Cleaning System

In investigating the best cleaning system, two types of tests were conducted. Initially, the investigation focussed on retaining dilute Alukleen (1:9, 1:19) as the cleaner and using a pre-wash to facilitate removal of the dirt from the aluminium pieces (Section 5.2.1; page 107). Alukleen dilutions of 1:9 and 1:19 were considered in this study since these were the two limits identified in the Alukleen optimisation study (Section



5.1; page 100). The results from the pre-wash tests were compared to the cleaning action of three degreasers, used without a pre-wash (Section 5.2.2; page 111).

### 5.2.1 Pre-wash Tests

The pre-wash testing combined various pre-washes with the two Alukleen dilutions (1:9 or 1:19). This was an attempt to determine whether Alukleen could be retained as the cleaner but its performance enhanced through use of a pre-wash and its etching action reduced through use of a more dilute solution. This would eliminate the need to change the entire system that Ben Booysen was using.

Ben Booysen already employed the use of green soap for the cleaning of the air-conditioner units' covers. Testing was thus carried out to ascertain whether a pre-wash of green soap prior to washing with the optimum dilution of Alukleen (1:9 or 1:19) would improve the level of cleanliness attained by the aluminium coil. In addition, the effectiveness of two washes with the dilute Alukleen solutions (1:9 or 1:19) was investigated. This was based on the hypothesis that a pre-wash and subsequent wash would bring more virgin cleaner into contact with the aluminium surface as well as exposing the aluminium surface to an increased volume of *moving fluid*, thus enabling more cleaning to occur.

The combinations used in the pre-wash test were thus green soap followed by 1:9 Alukleen, green soap followed by 1:19 Alukleen, 1:9 Alukleen followed by 1:9 Alukleen, and lastly, 1:19 Alukleen followed by 1:19 Alukleen. The results were quantified using gravimetric analysis and digital photography.

#### 5.2.1.1 Gravimetric Analysis

All results from the gravimetric analysis are shown in Appendix D (page 212). Average data for each run are shown in Table 5.2.

Table 5.2: Averaged gravimetric analysis results for the comparison of pre-wash combinations.

Pre- wash	Alukleen Dilution	Mass of Dirt (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		Run 1	Run 2	Run 3			
Green soap	1:9	0.0346	0.0098	0.0754	0.0399	0.0287	71.7
Green soap	1:19	0.0225	-0.0034	0.0228	0.0140	0.0130	93.1
Alukleen (1:9)	1:9	0.0442	0.0096	0.0800	0.0446	0.0305	68.4
Alukleen (1:19)	1:19	0.0386	0.0011	0.1028	0.0475	0.0446	93.8

A negative value was obtained in Run 2 for the mass of dirt removed by the green soap and Alukleen 1:19 combination. The reasons for this observation and the large coefficients of variation are the same as those detailed in Section 5.1.1 (page 100). The data is further illustrated in Figure 5.6.

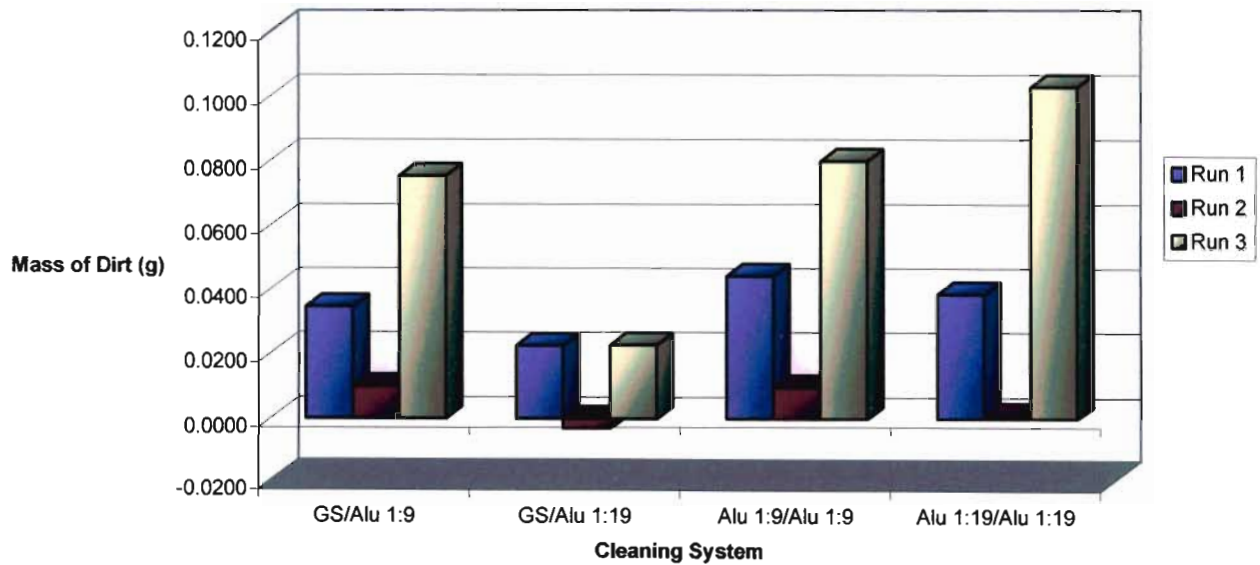


Fig. 5.6: Bar graph showing the results of the gravimetric analysis for the pre-wash combinations.

‘Alu’ refers to Alukleen; ‘GS’ refers to green soap.

The pieces of aluminium used in each run were of roughly the same level of dirtiness. It is clear from Figure 5.6 that the aluminium used for Run 2 was cleaner than that used for Runs 1 and 3 since less dirt was removed using each of the treatments.

Figure 5.6 indicates that the least effective cleaning system was the green soap – 1:19 Alukleen combination. It is difficult to compare the relative effectiveness of the remaining cleaning systems because of the relatively large standard deviations in the measurements (Appendix D; page 212). Hence digital photography was used to investigate these cleaning systems further.

#### **5.2.1.2 Digital Photography**

Figures 5.7 and 5.8 are ‘before’ and ‘after’ photographs of the aluminium pieces in Run 3. Photographs for Runs 1 and 2 are included in Appendix D (page 213). The photographs include a piece of aluminium that was treated with a 1:15 dilution of Powerkleen (Section 5.2.2; page 111). This enabled comparison between the pre-wash combinations and the use of a degreaser.

The combinations that included the use of green soap as a pre-wash were left with a coating of residual ‘dirt’, not removed by the cleaning process. This observation served to eliminate the possibility of green soap being used as a pre-wash. The double wash of Alukleen 1:9 was, visually, the most effective system for aluminium cleaning. However, the combinations that involved the use of Alukleen (1:9 or 1:19) *do* show a degree of etching. This etching is not evident with the use of the degreaser (D). Treatment of the aluminium with Powerkleen resulted in the metal retaining its sheen and malleability. Hence the use of degreasers, as an alternative to Alukleen, was investigated.

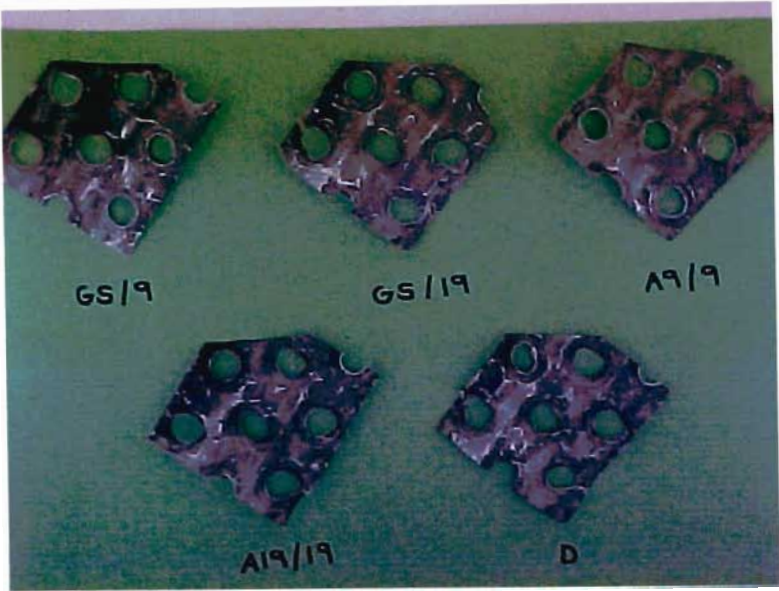


Fig. 5.7: ‘Before’ photograph of aluminium pieces treated with various pre-wash combinations (Run 3). \*

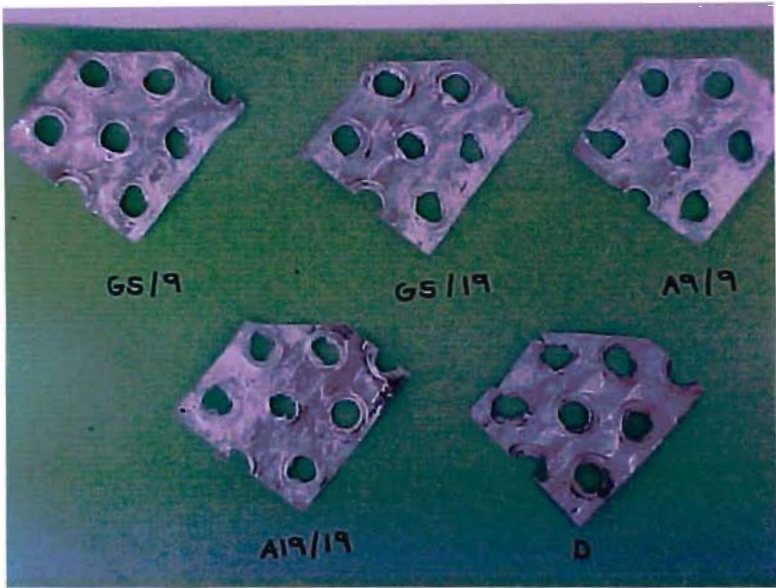


Fig. 5.8: ‘After’ photograph of aluminium pieces treated with various pre-wash combinations (Run 3). \*

\* ‘G.S/9’ refers to green soap followed by 1:9 Alukleen; ‘G.S/ 19’ refers to green soap followed by 1:19 Alukleen; ‘A9/9’ refers to a double wash of 1:9 Alukleen; ‘A19/19’ refers to a double wash of 1:19 Alukleen; and ‘D’ refers to a once-off wash with 1:15 Powerkleen.



### 5.2.2 Degreaser Tests

Three degreasers were compared in this study: Powerkleen, Technicians' Choice and Klengine. All three degreasers were recommended for use in industry.<sup>73</sup> The methodology for this testing was the same as that for the Alukleen optimisation (Section 5.1.1; page 100) with the exception that, in this preliminary study, all pieces of aluminium were soaked for a standard time of 5 minutes.

Both Technicians' Choice and Klengine had no recommended dilution factors and, as a result, were tested neat. The supplier of Powerkleen, RT Chemicals®, recommended dilution of Powerkleen from 1:15 for heavy degreasing to 1:50 for the degreasing of stoves and refrigerators.<sup>63</sup> Both 1:15 and 1:50 dilutions of Powerkleen were tested in this study.

#### 5.2.2.1 Gravimetric Analysis

Gravimetric analyses were only performed on Powerkleen (1:15, 1:50) since Klengine and Technicians' Choice could not be analysed in this way. Klengine is a paraffin-based degreaser which, when mixed with water, forms a cloudy suspension. This suspension was deposited on the filter paper and skewed the gravimetric analysis results. Technicians' Choice is a very viscous degreaser. Filtration of the solution of Technicians' Choice left a residue on the filter paper, which also inflated the gravimetric analysis results. The cleaning effectiveness of Klengine and Technicians' Choice degreasers was thus assessed using digital photography (Section 5.2.2.2; page 113).

Use of Klengine and Technicians' Choice would lead to processing difficulties in industry: addition of water to Klengine upon rinsing, and formation of the resulting suspension would lead to an effluent with a high suspended solids content. The viscous nature of Technicians' Choice does not allow sufficient cleaner to come into contact with the metal surface and, as a result, its cleaning capacity is diminished. Dilution of Technicians' Choice would, however, reduce its viscosity.

Results from the replicate experiments performed using Powerkleen (1:15, 1:50) are presented in Appendix D (page 214). Averaged results are summarised in Table 5.3 and illustrated in Figure 5.9.

Table 5.3: Averaged gravimetric analysis results for the comparison of Powerkleen dilutions.

Mass of Dirt (g)					Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
Dilution	Run 1	Run 2	Run 3	Run 4			
1:15	0.0226	0.0305	0.0203	0.0276	0.0253	0.0042	17
1:50	0.0091	0.0044	0.0091	0.0105	0.0083	0.0025	30

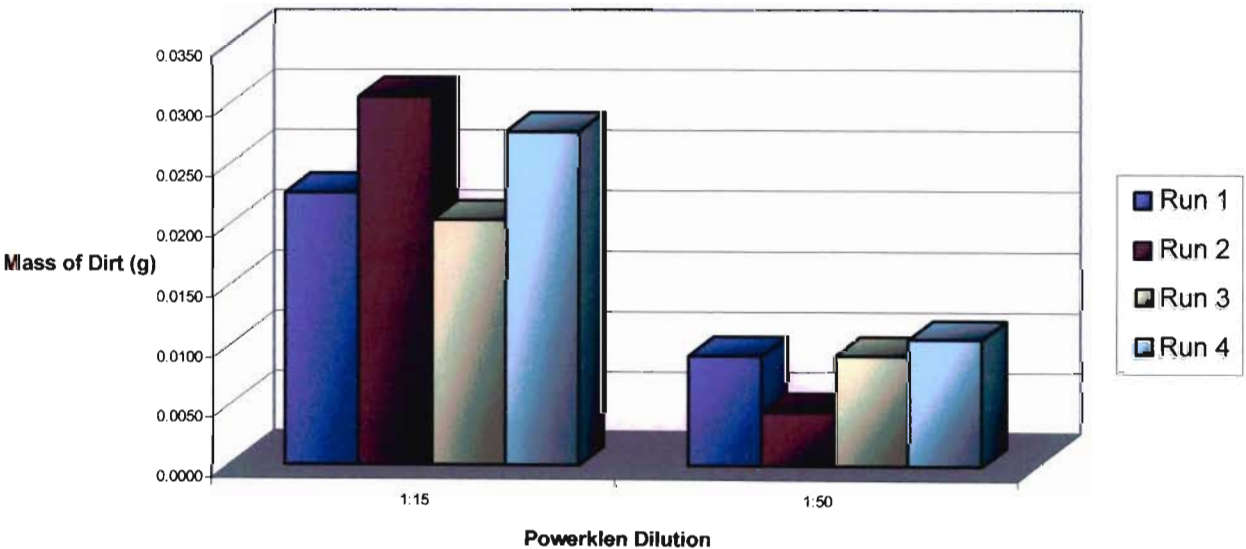


Fig. 5.9: Bar graph showing the results of the gravimetric analysis for Powerkleen dilutions of 1:15 and 1:50.

Table 5.3 and Figure 5.9 both indicate that 1:15 Powerkleen removes approximately 3 times the mass of dirt compared to the 1:50 dilution. In Section 5.3.1.3 (page 121), verification is given that this mass is dirt and that it does not result from etching of the aluminium. Hence 1:15 Powerkleen is a more suitable cleaner of the aluminium coils than 1:50 Powerkleen.



### 5.2.2.2 Digital Photography

Digital photographs were used to record the degree of cleanliness and degree of etching caused by each cleaning system. Figures 5.10 and 5.11 show ‘before’ and ‘after’ photographs for treatment of the aluminium pieces with the two Powerkleen dilutions (1:15, 1:50), Klengine and Technicians’ Choice degreasers. Photographs from Runs 1, 3 and 4 are included in Appendix D (page 215).

The photographs clearly indicate that the highest degree of cleanliness was obtained using Powerkleen and more specifically, using 1:15 Powerkleen. Etching of the aluminium as a result of the use of degreasers was not as noticeable as it had been when using Alukleen (see Figures 5.4 and 5.8). Furthermore, use of the degreasers did not appear to compromise the malleability and sheen of the metal. The action of Alukleen and Powerkleen on aluminium are further compared in Section 5.3.1.3 (page 121).

From this study, it was concluded that 1:15 Powerkleen was a feasible alternative to Alukleen for removing dirt and grease from aluminium. Studies were then performed on Powerkleen in order to optimise its concentration and soaking time for cleaning aluminium coils (Section 5.3; page 115).

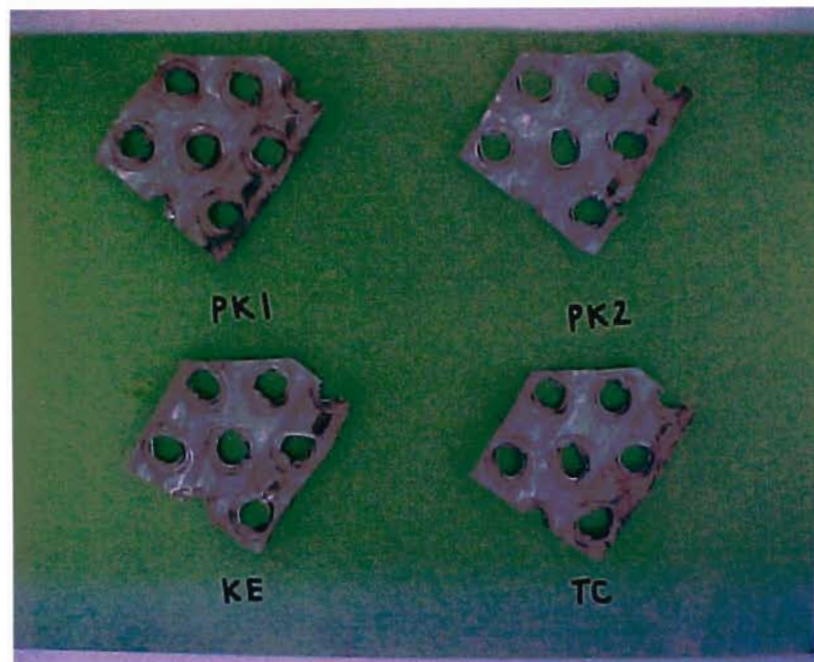


Fig. 5.10: 'Before' photograph of aluminium pieces treated with various degreasers (Run 2). \*

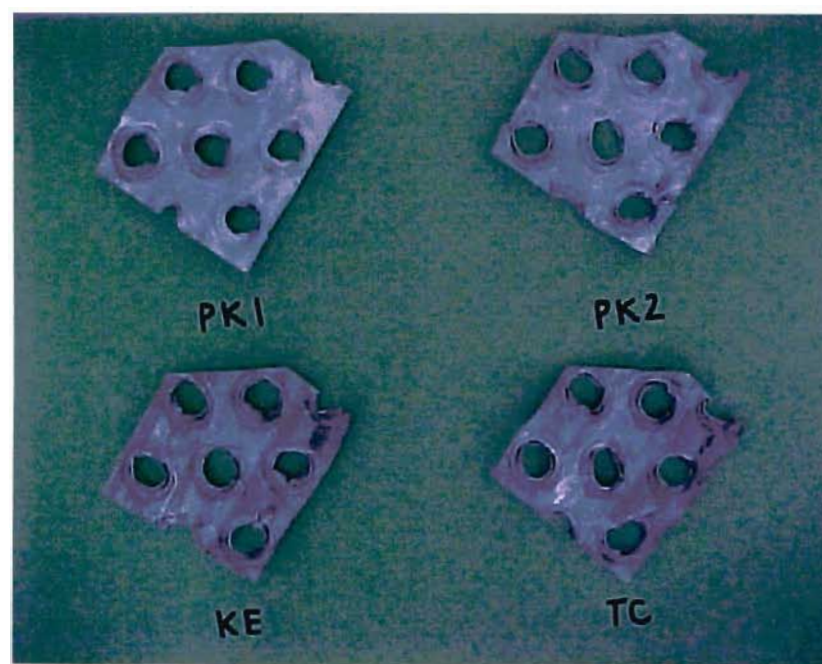


Fig. 5.11: 'After' photograph of aluminium pieces treated with various degreasers (Run 2). \*

\* PK1 indicates treatment with 1:15 Powerkleen; PK2 indicates treatment with 1:50 Powerkleen; KE indicates treatment with Klengine; and TC indicates treatment with Technicians' Choice Degreaser.

## **5.3 Optimising the Use of Powerkleen**

### **5.3.1 Determination of the most effective Powerkleen Concentration and Soaking Time**

Gravimetric analysis, digital photography and electron microscopy were used to quantify the results of this study.

#### **5.3.1.1 Gravimetric Analysis**

The gravimetric analysis was carried out in a similar manner to that of the optimisation studies conducted on Alukleen (Section 5.1.1; page 100). In this study, soaking times of 2, 4, 6, 8, 10, 15 and 20 minutes were used and Powerkleen dilutions of 1:15, 1:20, 1:30, 1:40, 1:50 and 1:60 were investigated. Each experiment was repeated four times to minimise the effects of variations in the level and nature of the dirt found on the aluminium pieces. All measurements are presented in Appendix D (page 217) and the averaged results are shown in Table 5.4.

Negative masses of dirt were obtained in several runs at high dilutions of Powerkleen (Appendix D). In addition, coefficients of variance as high as 200% were obtained. Reasons for these observations are the same as those detailed in Section 5.1.1 (page 100). The data in Table 5.4 is better illustrated in Figures 5.12 and 5.13 (pages 117 and 118).

Table 5.4: Averaged gravimetric data for determining the most effective Powerkleen concentration and soaking time.

Soaking Time (mins)	Powerkleen Dilution	Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
2	1:15	0.0526	0.0447	85.0
	1:20	0.0349	0.0249	71.4
	1:30	0.0257	0.0202	78.6
	1:40	0.0221	0.0202	91.5
	1:50	0.0157	0.0220	140.0
	1:60	0.0097	0.0175	180
4	1:15	0.0747	0.0503	67.4
	1:20	0.0425	0.0251	59.1
	1:30	0.0212	0.0144	68.3
	1:40	0.0212	0.0204	96.0
	1:50	0.0156	0.0255	163.0
	1:60	0.0116	0.0226	194
6	1:15	0.0951	0.0499	52.4
	1:20	0.0571	0.0365	64.0
	1:30	0.0491	0.0435	88.5
	1:40	0.0332	0.0240	72.1
	1:50	0.0195	0.0332	170
	1:60	0.0216	0.0204	94.6
8	1:15	0.0839	0.0313	37.3
	1:20	0.0496	0.0311	62.7
	1:30	0.0381	0.0286	75.2
	1:40	0.0238	0.0259	109
	1:50	0.0148	0.0228	155
	1:60	0.0141	0.0243	172

Table 5.4 continued.

Soaking Time (mins)	Powerkleen Dilution	Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
10	1:15	0.0817	0.0186	22.8
	1:20	0.0528	0.0240	45.5
	1:30	0.0326	0.0171	52.5
	1:40	0.0277	0.0144	52.0
	1:50	0.0191	0.0199	104
	1:60	0.0153	0.0204	133
15	1:15	0.0729	0.0275	37.7
	1:20	0.0456	0.0282	61.8
	1:30	0.0285	0.0218	76.6
	1:40	0.0340	0.0264	77.7
	1:50	0.0300	0.0321	107
	1:60	0.0204	0.0345	169
20	1:15	0.1057	0.0367	34.7
	1:20	0.0812	0.0416	51.2
	1:30	0.0722	0.0483	66.9
	1:40	0.0711	0.0359	50.6
	1:50	0.0443	0.0350	79.0
	1:60	0.0392	0.0320	81.4

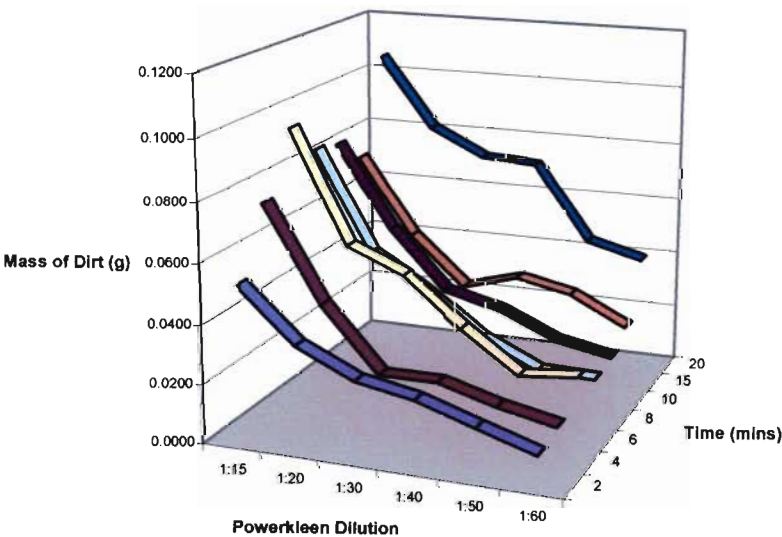


Fig. 5.12: Averaged gravimetric analysis results for the determination of the most effective Powerkleen concentration and soaking time.



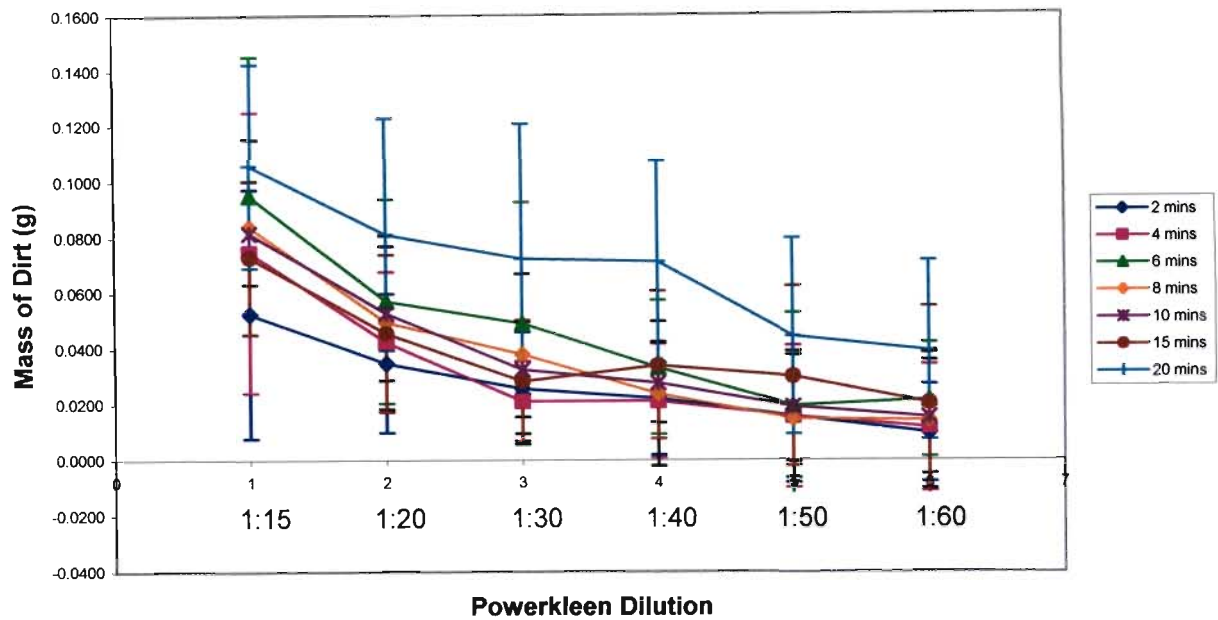


Fig. 5.13: Line graph showing the averaged gravimetric analysis results with standard deviations plotted as y-error bars.

Figures 5.12 and 5.13 are similar in appearance to those generated for the Alukleen optimisation process (Figures 5.1 and 5.2; pages 102 and 103). The more concentrated solutions are seen to remove more dirt: 1:15 Powerkleen removes approximately 3.5 times the mass of dirt removed by 1:60 Powerkleen. The average mass of dirt removed by 1:1 Alukleen (0.0725 g) is a similar amount to that removed by 1:15 Powerkleen (0.0809 g). However, it appears that some of the mass removed by Alukleen is due to etching of the aluminium (Sections 5.1.2 and 5.1.3; pages 104 and 105) whereas little etching of the aluminium occurs using Powerkleen (Section 5.3.1.3; page 119). Another observation is that, on average, 1:60 Powerkleen removes approximately 12 times the mass of dirt removed by 1:19 Alukleen. These are clear indications that large cost and environmental savings could be achieved if Powerkleen were to replace Alukleen as the cleaner at Ben Booyesen.

As with the Alukleen optimisation, the y-error bars (indicating the standard deviation of each soaking time) are greater than the difference in mass of dirt removed by sequential soaking times, including the 20 minute soaking time. This illustrates that at a fixed Powerkleen concentration, the soaking times do not significantly influence the



mass of dirt removed. A standard soaking time of 5 minutes was thus used in all further tests.

### **5.3.1.2 Digital Photography**

Digital photographs were taken of the aluminium pieces before and after their treatment with Powerkleen. These photographs are shown in Appendix D (page 231). Figures 5.14 and 5.15 are the ‘before’ and ‘after’ photographs of the aluminium pieces soaked in the various dilutions (1:15, 1:20, 1:30, 1:40, 1:50, 1:60) of Powerkleen for 20 minutes.

Figures 5.14 and 5.15 show that a good level of cleanliness is achieved through use of Powerkleen dilutions of 1:15, 1:20, 1:30 and 1:40. Furthermore, these photographs serve to illustrate that even for a soaking time of 20 minutes with a Powerkleen dilution of 1:15, no etching of the aluminium occurs. The aluminium pieces emerge considerably cleaner with no loss of sheen or malleability. The effect of Powerkleen on the surface of the aluminium coils was further investigated using electron microscopy (Section 5.3.1.3; page 121).

Hence it was decided that 1:20, 1:30 or 1:40 were feasible, cost-effective dilutions of Powerkleen to use in cleaning the aluminium coils. Powerkleen dilutions of 1:20 and 1:40 were thus used in all further testing since they represent the limits of suitable Powerkleen dilutions. In the laboratory tests, cleaning was achieved through soaking with little or no pressure from rinse water. In industry, the cleaner and the rinse water would be applied at pressure. This pressurised application would increase the level of cleanliness achieved.

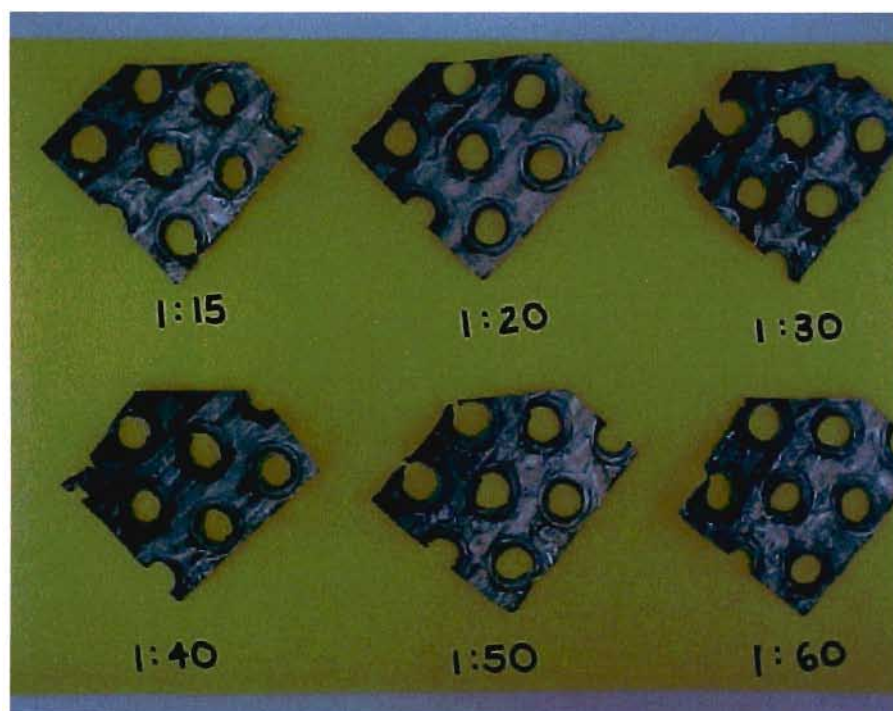


Fig. 5.14: 'Before' photograph for a soaking time of 20 minutes. \*

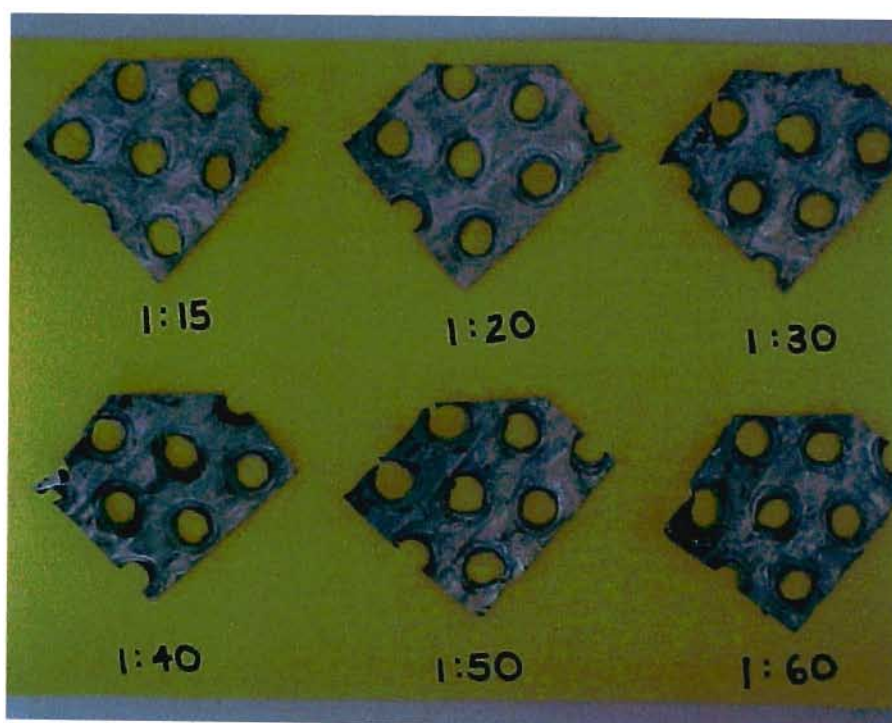


Fig. 5.15: 'After' photograph for a soaking time of 20 minutes. \*

\* The numbers below the aluminium pieces refer to the dilutions of Powerkleen in tap water.

### 5.3.1.3 Electron Microscopy Results

As in Section 5.1.3 (page 105), electron microscopy was used to assess whether damage to the surface of the aluminium coils was occurring upon treatment with Powerkleen. As before, a virgin piece of aluminium was run as a control along with two other pieces of aluminium that had been treated with 1:20 and 1:40 Powerkleen (the feasible concentration limits) respectively. The results of this study are presented in Figure 5.16.

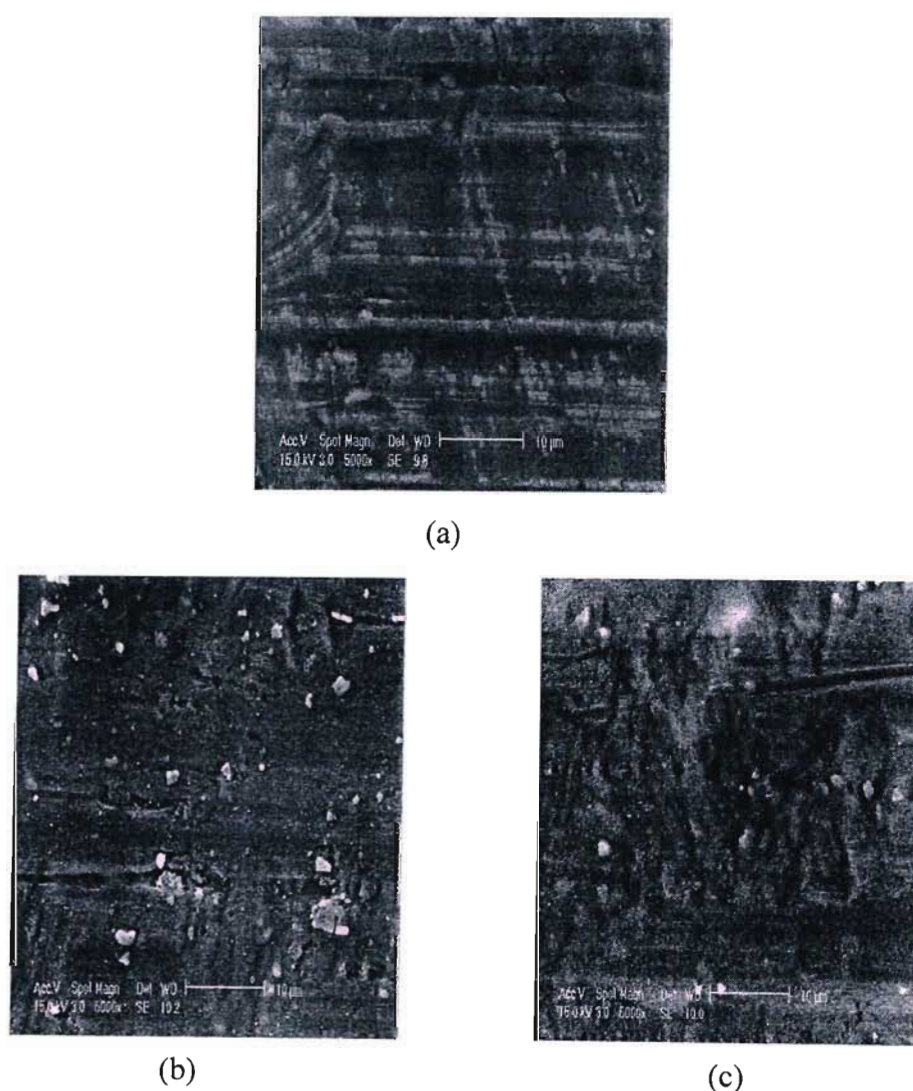


Fig. 5.16: Electron Micrographs of the surface of aluminium samples.

Scanning Electron Microscope (Phillips XL 30); magnification of 5000X.

(a) Control.

(b) Aluminium treated with a 1:20 dilution of Powerkleen.

(c) Aluminium treated with a 1:40 dilution of Powerkleen.

A small degree of pitting is evident in Figures 5.16(b) and (c) which is significantly reduced when compared to the pitting that occurred on treatment of the aluminium with 1:3 Alukleen (Figure 5.5; page 106). The reduced corrosion of aluminium using Powerkleen is further supported by the retained sheen malleability of the metal (Figures 5.8 and 5.15; pages 110 and 120).

Foecke<sup>60</sup> and Tromans<sup>61</sup> indicated that acidic cleaners etch the aluminium surfaces less than strong alkaline cleaners (Section 2.7.6; page 50). The reviewed literature thus appears to contradict the findings in this study. However, in this study, the alkaline cleaner Powerkleen, was far more dilute (0.711 M) than the acidic cleaner, Alukleen (1.556 M H<sub>2</sub>SO<sub>4</sub>; 1.51 M HF). This may explain why Powerkleen corroded the aluminium less.

### **5.3.2 Assessing the Use of Powerkleen as a General Cleaning Agent**

Powerkleen was further investigated to establish whether it could be used to clean the plastic components of the air-conditioner units and hence replace the green soap and Handy Andy currently used at Ben Booysen. Through reducing the number of cleaning agents, the cleaning process would be simpler.

The plastic body and cover of a number of air-conditioner units that were being serviced by Ben Booysen were washed with a 1:80 dilution of Powerkleen. An increase in the cleanliness of the cover and body of the unit was observed which was comparable to that achieved using green soap and Handy Andy. Approximately 200 millilitres of the dilution were used per unit.

It is more convenient to use a dilution of 1:79 than 1:80 in industry. Thus 12.5 litres of neat Powerkleen could be diluted to 1000 litres with tap water in the Ben Booysen stores to obtain a 1:79 Powerkleen solution.



## 5.4 Application Tests

Once it had been ascertained that Powerkleen could replace Alukleen in the cleaning of the aluminium coils, studies were conducted to assess the effectiveness of the two proposed application techniques: a pump bottle and an air gun operated at a pressure of 4 bars. The pump bottle would be used for the air-conditioner units serviced on-site in industry where a pressure source would not be available whereas the air gun would be used for units sent to Ben Booysen for servicing.

Two Powerkleen dilutions (1:20, 1:40) were used for this testing. Four combinations were compared:

- 1:20 Powerkleen applied with the air gun;
- 1:40 Powerkleen applied with the air gun;
- 1:20 Powerkleen applied with the pump bottle; and
- 1:40 Powerkleen applied with the pump bottle.

The results achieved from this study were largely qualitative in nature. Figure 5.17 includes ‘before’ and ‘after’ photographs of coils treated with either 1:20 or 1:40 Powerkleen using either the pump bottle or the air gun. Photographs from the other two runs can be seen in Appendix D (page 234). Photographs were taken from both a side and front view.

Figure 5.17 indicates that application of the Powerkleen by the air gun led to the greatest penetration and degree of cleanliness. This was the expected result as the air gun was operated at a pressure of 4 bars whilst pressure was created manually through pump action in the pump bottle. The gun’s effectiveness could be further enhanced through the fine-tuning of its nozzle width (which determines the volume of cleaner dispensed) and pressure. It was further found that for an average two-minute application, the pump bottle used approximately 1 litre of the cleaner whereas the air gun used only approximately 250 millilitres. The greater volume dispensed by the pump bottle served to dislodge a comparable amount of dirt from the coil to that

removed by the air gun. Hence both the air gun and pump bottle are suitable application techniques.

Figure 5.17 also confirms that the difference in the cleaning action of the 1:20 and 1:40 Powerkleen solutions is relatively small. A 1:40 dilution was chosen for use at Ben Booyesen because it is more cost-effective.

As the above tests were all conducted on a quarter of a standard-sized coil, the volumes of cleaner used needed to be extrapolated to a whole coil. Hence, 4 litres and 1 litre would be needed by the pump bottle and air gun respectively. These volumes are for a standard sized coil (approximately 300 mm x 290 mm x 60 mm) and would need to be adjusted accordingly for larger or smaller coils.

Although the experimental work was conducted using a dilution of 1:40, the Powerkleen dilution of choice in industry would be 1:39. By slightly strengthening the concentration of the Powerkleen, a 25-litre drum of Powerkleen can be diluted easily to a volume of 1000 litres using tap water.



**Before Photographs:**



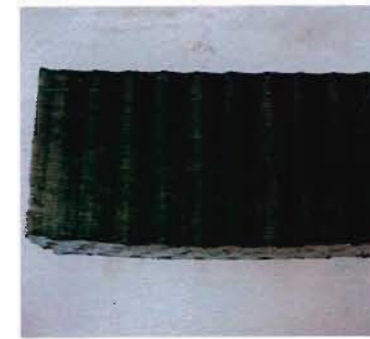
(a)



(c)



(e)



(g)

**After Photographs:**



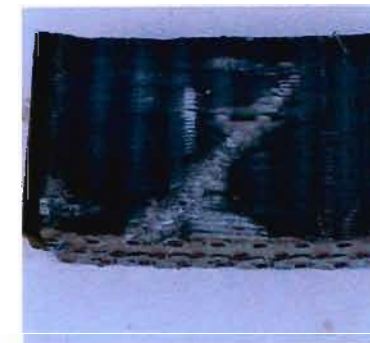
(b)



(d)



(f)



(h)

Fig. 5.17: Photographs of a Section of Coil 1 treated with 1:20 or 1:40 Powerkleen for 2 minutes using a pump bottle or an air gun.

(a) and (b): 'Before' and 'after' photographs: 1 litre of 1:20 Powerkleen using a pump bottle.

(c) and (d): 'Before' and 'after' photographs: 250 ml of 1:20 Powerkleen using an air gun.

(e) and (f): 'Before' and 'after' photographs: 1 litre of 1:40 Powerkleen using a pump bottle.

(g) and (h): 'Before' and 'after' photographs: 250 ml of 1:40 Powerkleen using an air gun.

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## 5.5 Conclusion

In this chapter, the optimisation of the system parameters pertaining to the cleaning the aluminium coils from air-conditioner units was discussed. This initially involved optimisation of the concentration and soaking time used for Alukleen, and then the investigation of alternatives to Alukleen and their subsequent optimisation.

Tests on the Alukleen system indicated that the soaking time did not significantly influence the degree of cleanliness achieved by the aluminium pieces. It was further found that dilutions of 1:1 and 1:3 of Alukleen in tap water removed 4 - 7 times the mass of dirt removed by dilutions of 1:9, 1:14 and 1:19. The hypothesis that the greater mass of dirt removed resulted from etching of the aluminium in addition to dirt removal was confirmed through digital photographs. Etching occurred where pieces of aluminium were soaked in Alukleen dilutions of 1:1, 1:3 and 1:9 for soaking times of even 2 minutes. Electron microscopy further indicated the occurrence of pitting and hence damage to the aluminium pieces treated with 1:3 Alukleen (the effective dilution currently used by Ben Booysen). Hence an Alukleen dilution of between 1:9 and 1:19 is most suitable for cleaning the aluminium coils.

The investigation then focused on retaining dilute Alukleen (1:9 or 1:19) as the cleaner and using a pre-wash of green soap to facilitate removal of dirt from the aluminium pieces. The effectiveness of two washes with the dilute Alukleen solutions (1:9 or 1:19) was also investigated. The relatively large standard deviations in the gravimetric measurements made comparison of the effectiveness of the cleaning systems difficult. However, digital photographs indicated that a double wash of a 1:9 dilution of Alukleen was the most effective. Etching of the aluminium still occurred at these Alukleen dilutions (1:9, 1:19). Visual comparison of these results to the aluminium pieces treated with a 1:15 dilution of the degreaser, Powerkleen, suggested that the use of degreasers be further investigated.

In the degreaser tests, three degreasers were compared, namely: Technicians' Choice, Klengine and Powerkleen (at dilutions of 1:15 and 1:50). Gravimetric analysis could only be performed for Powerkleen because of the suspended solids and viscous nature

of Klengine and Technicians' Choice degreasers respectively. The Powerkleen dilution of 1:15 removed approximately three times the mass of dirt compared to the 1:50 dilution. Digital photographs showed that the best cleaning system was achieved using Powerkleen at a 1:15 dilution. Use of this degreaser did not compromise the malleability and sheen of the metal. Hence Powerkleen is a feasible alternative to Alukleen for cleaning the aluminium air conditioner coils.

Optimisation tests of the Powerkleen system indicated that soaking time did not significantly influence the mass of dirt removed. In addition, Powerkleen dilutions of 1:20 – 1:40 achieved good cleaning of the aluminium coils. The comparable average masses of dirt removed by 1:15 Powerkleen and 1:1 Alukleen suggest that financial and environmental savings could be achieved if Powerkleen were to replace Alukleen. Environmental savings would result from sending a reduced quantity of chemicals to drain. Digital photography showed that little etching of the aluminium pieces occurred even at a soaking time of 20 minutes in a 1:15 Powerkleen dilution. Electron microscopy further confirmed only a small amount of pitting of the aluminium when using 1:20 Powerkleen.

Finally, application tests were conducted to assess the effectiveness of the two proposed cleaner application techniques: a pump bottle for on-site use in industry, and an air gun operated at a pressure of 4 bars for use at Ben Booysen. It was found that the difference in the cleaning action of the 1:20 and 1:40 Powerkleen solutions is relatively small. A 1:39 dilution was chosen for use because of its cost-effectiveness and ease of preparation. Furthermore, it was concluded that for a standard sized coil (approximately 300 mm x 290 mm x 60 mm), 1 litre of 1:39 Powerkleen is required for the air gun whereas 4 litres of 1:39 Powerkleen are needed for the pump bottle. Although the best cleaning and penetration of the coil are achieved using the air gun, the pump bottle also yields good cleaning results, which were confirmed through the use of digital photography.

In addition, it was found that a dilute solution of Powerkleen (1:79) could replace green soap and Handy Andy in the cleaning of the plastic air-conditioner unit covers, thus simplifying the servicing process. Studies indicated that 200 millilitres of this dilution are required per unit.

# Chapter 6: Feasibility Analysis

In this chapter, the feasibility of using Powerkleen to clean the air-conditioner coils is discussed in terms of a technical (Section 6.1), economic (Section 6.2; page 131) and environmental (Section 6.3; page 134) evaluation. A waste minimisation solution needs to be feasible in all of the above three areas prior to implementation in a company.<sup>8</sup> Each of the evaluations is discussed in more detail below.

## 6.1 Technical Evaluation

As discussed in Section 2.3.4.1 (page 29), the technical evaluation considers whether the necessary technology is available in the company, and whether the timescales of the project are suitable for the desired short-term and long-term company goals. The technical evaluation further assesses the risks involved in the implementation of the project and whether the company culture is able to withstand and facilitate the necessary changes.<sup>7, 8, 17</sup>

### 6.1.1 Available Technology

To change from Alukleen to Powerkleen, only slight equipment changes would have to be made. Currently the Alukleen that arrives at Ben Booysen is diluted to a 1:1 solution with tap water and dispensed for use in plastic 1-litre bottles. This solution is further diluted to 1:3 by the technicians and is applied to the air-conditioner coils using a paintbrush.

The proposed process changes include the pre-dilution of the neat Powerkleen to 1:39 and 1:79 solutions and their subsequent storage in 1000-litre tanks. Technicians would have access to these tanks and would decant the solutions into plastic bottles as required for on-site use in industry or for use at Ben Booysen. 1:39 Powerkleen would be applied to the air-conditioner units using an air gun connected to a 4 bar pressure

source (at Ben Booysen), or a 2-litre pump bottle (in the field). The plastic bottles of 1:39 Powerkleen would thus be used to fill up the air guns or pump bottles. After 5 minutes of soaking time, the air-conditioner units would be rinsed using a water hose. The new equipment needed would thus be two 1000-litre tanks, two air guns, and one pump bottle for the demonstration of its use (technicians would then have to purchase their own pump bottles for field work). This equipment was priced and is locally available (Appendix E; page 244).

### **6.1.2 Timescales**

The year taken to research and optimise the cleaner system for the air-conditioner coils did not hamper the short-term servicing of air-conditioner units at Ben Booysen since the Alukleen system was already in place.

It is estimated that installation of the Powerkleen system does not require more than a day. Installation of the two 1000-litre tanks and connection of the two air guns to the pressure source would be carried out by a Ben Booysen employee who is normally responsible for the running repairs of the existing equipment. Hence, the capital cost of this project will not include any installation costs.

A further time-related matter for this project is the training of the technicians. It is estimated that only half a day will be required and thus training should not delay implementation of the project. The short time-scales required for implementation are thus highly suitable for both the short-term goal (servicing air-conditioner units timeously) and the long-term goal of Ben Booysen (increasing the efficiency and decreasing the environmental impact and cost of the servicing process).

### **6.1.3 Risks Involved**

The risks involved in the implementation of a project in a company are two-fold:<sup>7, 8</sup>

- whether the technology to be implemented is ‘watertight’, and
- whether its implementation will initially adversely affect production.

The risks involved with implementing the Powerkleen system are negligible. The technology has proved effective in the laboratory and pilot-scale demonstrations discussed in Chapter 5. Since installation of the equipment should take no more than a day and training less than half a day, the rate of production would not be significantly compromised.

The stability of the supplier also needs to be considered when a project is dependent on the supplier for technical support or the supplier is the sole-supplier of the chemical.<sup>7, 8</sup> No technical support is required for Powerkleen. Although RT Chemicals® is the sole supplier of Powerkleen, since the same supplier manufactures both Alukleen and Powerkleen, no greater risk is encountered in changing the cleaner to Powerkleen.

#### **6.1.4 Company Culture**

Determining whether the project is acceptable to the company culture is a factor that is often linked to the health and safety regulations of a company.<sup>7, 8</sup> If the project under consideration leads to improved working conditions in terms of health and safety, resistance to its implementation is usually minimal.<sup>7, 8</sup>

Use of Powerkleen 1:39 and 1:79 solutions eliminates the handling problems associated with the hydrofluoric and sulfuric acids present in Alukleen. Since Alukleen was previously dispensed as a 1:1 solution, the danger to technicians from acid burns, inhalation and ingestion<sup>12</sup> was high. The alternative, Powerkleen, is both non-toxic and non-corrosive. In its concentrated form, Powerkleen may cause alkaline burns if exposed to skin.<sup>63</sup> This danger, however, will be considerably reduced as a result of its dilution to 1:39 and 1:79 solutions by the stores-manager on-site. The technicians will only be exposed to these dilute solutions.

Application of the 1:39 Powerkleen using an air gun or pump bottle, as opposed to manual application using a paintbrush, decreases the technicians' skin contact with the cleaner. However, a fine spray of the Powerkleen solutions will result from the



nebulizing action of the air gun and pump bottle. Inhalation of this dilute Powerkleen solution can be avoided through the use of dust masks whilst the coils are being cleaned.<sup>63</sup> It is also recommended that the technicians wear safety glasses to prevent the fine spray from contacting their eyes.

As a result of the general improvement in the technicians' health and safety, it is anticipated that there will be no resistance to use of Powerkleen instead of Alukleen. Hence Powerkleen should be acceptable to the company culture.

The above considerations indicate that each of the requirements of the technical evaluation is met. In the following section, use of Powerkleen is evaluated in terms of the economic component of the feasibility analysis.

## **6.2 Economic Evaluation**

The economic evaluation uses four key parameters to determine whether a solution is suitable for implementation in a company: *i.e.* payback period, return on capital employed (ROCE), net present value and the internal rate of return.<sup>7, 8</sup> Each of these indicators is discussed below. All calculations are detailed in Appendix E (page 241).

In the calculations, the project lifetime refers to the lifespan of the equipment (storage tanks, air guns and pump bottle), which was estimated as 10 years. This estimation was based on the assumption that the air guns would probably need replacing after this time period. These calculations are further based on a before-tax basis and the capital employed is original capital investment. The required rate of return for Ben Booyesen is 20%.<sup>73</sup> Inflation has been taken as the national inflation value (12%).<sup>74</sup>

### 6.2.1 Payback Period

The payback period is defined as the time period needed to recover the initial capital outlay for a project.<sup>7, 37</sup> The initial capital expenditure was calculated as R2480 and the annual proposed savings from using Powerkleen were calculated as R5030 (Appendix E; page 243). Hence a 5.9-month payback period is needed (Appendix E; page 244).

A payback period of less than a year for a 10-year project lifetime is favourable and indicates that there is capacity for savings to be made. As discussed in Section 2.3.4.2 (page 31), this measure does not give any indication of the profitability of the project after the payback period. Hence the ROCE of the project was calculated.

### 6.2.2 Return on Capital Employed (ROCE)

The return on capital employed calculates the rate of return on the capital invested in a certain project.<sup>8, 37</sup> Four indicators are used in this area:<sup>8, 37</sup>

$$\text{Gross ROCE} = \frac{\text{Total Cost Savings}}{\text{Capital}} \times 100\% \quad \text{Equation 6.1}$$

$$\text{Net ROCE} = \frac{\text{Total Cost Savings} - \text{Capital}}{\text{Capital}} \times 100\% \quad \text{Equation 6.2}$$

$$\text{Gross Annual Rate of Return} = \frac{\text{Gross ROCE}}{\text{Project Life}} \% \quad \text{Equation 6.3}$$

$$\text{Net Annual Rate of Return} = \frac{\text{Net ROCE}}{\text{Project Life}} \% \quad \text{Equation 6.4}$$

For the project solution of replacing Alukleen with Powerkleen, the gross return on capital employed was calculated as 2030%. Through dividing this percentage by the project lifetime, the gross annual rate of return was calculated as 203%. This effectively means that a return of 203% can be expected on the original investment every year of the project excluding the year of the initial capital outlay.<sup>37</sup> The net return on capital employed and the net annual rate of return were calculated as 1930% and 193% respectively. Details of these calculations are shown in Appendix E (page 244).

These rates of return are significantly higher than Ben Booysen's required rate of return of 20%, indicating that changing the cleaner to Powerkleen would be financially beneficial. However, the return on capital employed does not take annual inflation or the time value of money into account.<sup>7</sup> Net present value calculations were thus performed to account for these factors in determining the economic feasibility of using Powerkleen.

### **6.2.3 Net Present Value (NPV)**

In the calculation of the net present value, a discount rate of 20% was used since this is Ben Booysen's required rate of return.<sup>73</sup> The cash flow for each year of the project was calculated, taking into account annual inflation of 12%.<sup>74</sup> The discounted cash flow was then determined, accounting for the required rate of return, and was totalled to yield a net present value of R28 860. Details of this calculation are shown in Appendix E (page 246).

This net present value is an indication of what the project savings would be worth in today's terms.<sup>37</sup> This value is 11.6 times larger than the initial capital outlay, indicating that use of Powerkleen is financially viable.

The final economic parameter calculated was the internal rate of return.

### 6.2.4 Internal Rate of Return (IRR)

The internal rate of return (IRR) represents the rate the company's money would have to earn elsewhere in order to be a better investment.<sup>7, 36</sup> It is determined through calculating the discount rate at which the net present value of a project reduces to zero.<sup>7</sup>

The IRR for the Powerkleen project was calculated as 214.9% (Appendix E; page 247). Since this is approximately 11 times greater than Ben Booysen's required rate of return (20%), the Powerkleen project is clearly economically feasible.

The calculation of the payback period, return on capital employed, net present value and internal rate of return all serve to indicate that this waste minimisation solution is financially viable. Since the project is both technically and economically feasible, the Powerkleen project was evaluated in terms of its environmental feasibility (Section 6.3).

## 6.3 Environmental Evaluation

The environmental evaluation is less quantifiable than the financial evaluation.<sup>17</sup> An indication of the potential environmental improvement from the Powerkleen project can be gained through comparison of the present effluent quality and the predicted 'new' effluent quality.

As discussed in Section 4.2.2 (page 91), the composition of 1:39 Powerkleen can be used to give an upper limit of the proposed effluent's composition. The effluent produced would be further diluted as a result of addition of 1:79 Powerkleen (used for cleaning the air-conditioners' covers) and water from rinsing, rain, and vehicle and floor washing. The dilution factor for 1:39 Powerkleen in the effluent was estimated by using the sulfate concentrations of the Alukleen stock solution and the actual effluent to calculate the volume of water in the actual effluent (Appendix E.2; page 248). Assuming the same volume of water would be added to Powerkleen from

rinsing, washing and rain water, a dilution factor of  $9.4 \times 10^{-3}$  was determined (Appendix E.2; page 248). Hence the concentrations of key components in the 'new' Powerkleen effluent could be estimated. These values are compared to the Alukleen effluent, 1:39 Powerkleen and the stormwater and Darvill disposal limits in Table 6.1.

Table 6.1: Comparison of the composition of the current effluent, a 1:39 dilution of Powerkleen, the predicted 'new' Powerkleen effluent and the stormwater and Darvill limits.

Component	Mean Concentration in Sampled Effluent	Mean Concentration in 1:39 Powerkleen	Predicted Concentration in 'new' Powerkleen Effluent	Limits (Stormwater) <sup>41</sup>	Limits (Darvill) <sup>40</sup>
Conductivity	41.03 mS/m	462 mS/m	4.4 mS/m	400 mS/m	400 mS/m
pH	4.89	12.11		$6.5 < x < 9.5$	$6.5 < x < 9.5$
Potassium		695 ppm	6.5 ppm		
Total Dissolved Solids	1020 ppm	4729.3 ppm	44 ppm		5000 ppm
COD		6431 mgO <sub>2</sub> /L	61 mgO <sub>2</sub> /L		350 mgO <sub>2</sub> /L
Fluoride	17.2 ppm			0.750 ppm	5 ppm
Sulfate	103.0 ppm				250 ppm

Table 6.1 indicates that the predicted 'new' effluent complies with the conductivity, potassium, total dissolved solids and chemical oxygen demand limits. Addition of the estimated 1048 kL of wastewater (generated through wash, rinse and rain water) to the 10400 L of 1:39 Powerkleen would significantly reduce the pH of 1:39 Powerkleen.

An environmental improvement in changing to Powerkleen would be the elimination of the fluoride ions from the effluent. As discussed in Section 4.3.2 (page 95), the concentration of fluoride in the Alukleen effluent exceeds both the stormwater and Darvill discharge limits of 0.750 ppm and 5 ppm respectively.

A further environmental improvement in changing to Powerkleen would be the reduction in the quantities of chemicals sent to drain. Approximately 260 L of Powerkleen are required per annum whereas the Alukleen system requires 900 L of Alukleen, 600 L of green soap and 600 L of Handy Andy per annum.

## **6.4 Conclusion**

It has thus been shown that the proposed waste minimisation solution is technically, economically and environmentally feasible and can hence be implemented. The feasibility study has not yielded any problematic areas that would cause the project to return to its formative stage. As a result, implementation of this project can proceed to the benefit of the company's efficiency and environmental impact.



# Chapter 7: Conclusions and Recommendations

## 7.1 Conclusions

This waste minimisation research project involved optimising the process for cleaning air-conditioner coils at Ben Booysen, a local air-conditioning and refrigeration company. This company made use of Alukleen, an acidic cleaner, at an effective dilution of 1:3 for cleaning the aluminium air-conditioner coils. The strongly acidic and corrosive nature of Alukleen motivated the investigation into the possible use of Alukleen at greater dilutions, hence reducing both the environmental impact and occupational hazards associated with it.

To place the study in context, the strategy of a waste minimisation programme was reviewed. The review (Section 2.4; page 41) indicated the availability of various pre-assessment and assessment techniques for the identification of waste minimisation opportunities and solutions. This review served to highlight that the techniques are either general methodologies, tools developed for specific sectors in South African Industry, or tools developed for the UK industry, which require modification for application to South African industry. In this study, however, the waste minimisation opportunity (*i.e.* optimising the coil cleaning process for air-conditioners) was defined by Ben Booysen *a priori*. This study thus involved a more detailed assessment to establish specific waste minimisation solutions. Rather than apply the production-orientated assessment techniques described in Section 2.3.3 (page 22), a more fundamental study was performed in which the chemical effects and cleaning ability of various cleaners was assessed.

Literature on the cleaning of aluminium metal (Section 2.7; page 44) was reviewed to gain insight into the cleaning action and corrosion caused by acidic and basic cleaners. There was no indication in the literature as to which type of cleaner was

preferable although the literature<sup>60, 61</sup> indicated that acid cleaners tend to etch the surface of aluminium less than strong alkaline cleaners.

The Alukleen system was characterised through the use of both qualitative and quantitative analyses. Wet chemical techniques (Section 4.1.1.1; page 76) confirmed the presence of fluoride and chloride ions and indicated the possible presence of sulfate, sulfide and arsenite ions in Alukleen. Subsequent quantitative analysis (Section 4.1.2; page 82) showed that only fluoride (25400 ppm) and sulfate (152 600 ppm) ions were present in detectable quantities. The Alukleen system was further characterised through measurement of its pH, conductivity, free and total acid (pH titrations), and total dissolved solids concentrations. Furthermore, measurement of the sulfate and fluoride concentrations in both the stock and concentrated Alukleen allowed calculation of the pre-dilution factors. Variation in these pre-dilution factors indicated that more control was required in Ben Booysen's stores in this initial dilution of the Alukleen.

Three samples of the Alukleen effluent produced by Ben Booysen were taken. The effluent was characterised in terms of the sulfate and fluoride concentrations and the pH, conductivity and total dissolved solids concentration (Section 4.3.1; page 92). The purpose of these measurements was two-fold: firstly, to ascertain whether Ben Booysen was in compliance with the local bylaws for disposal and secondly, to obtain base-line data that would allow any improvement in effluent quality to be quantified. The effluent contained both fluoride (17.2 ppm) and sulfate (103.0 ppm) ions. Comparison of the measurements with disposal limits indicated that the effluent's pH (4.89) was too low and its fluoride concentration too high for disposal to either stormwater or to Darvill.

The first part of the optimisation study involved optimising the Alukleen concentration and contact (soaking) time with the coil (Section 5.1; page 100). Gravimetric analyses indicated that soaking time had a negligible effect on the cleanliness attained by the aluminium. A 4 – 7 fold greater mass of dirt was removed at Alukleen dilutions of 1:1 and 1:3 compared to dilutions between 1:9 and 1:19. The hypothesis that this resulted from etching of the aluminium was confirmed through

the use of digital photography and electron microscopy. It was hence concluded that Alukleen should be used at a dilution of between 1:9 and 1:19.

The effectiveness of a green soap wash prior to an Alukleen (1:9, 1:19) main wash and an Alukleen double wash (1:9 or 1:19) was then investigated (Section 5.2.1; page 107). The result of this trial was that green soap was found to be ineffective in the cleaning of the aluminium pieces and the Alukleen double wash resulted in etching of the aluminium. Visual comparison of the cleaning achieved to that achieved by the degreaser, Powerkleen (1:15), indicated the need to investigate the cleaning action of degreasers further.

In the degreaser trial (Section 5.2.2; page 111), three degreasers were tested on the aluminium coil: Powerkleen (1:15, 1:50), Technicians' Choice (neat) and Klengine (neat). Since the high viscosity and paraffin-based nature of Technicians' Choice and Klengine respectively disallowed comparison by gravimetric analysis, digital photography was used to assess the degree of cleanliness achieved by each degreaser. From this study, it was found that 1:15 Powerkleen was the most effective cleaner. Furthermore, it did not appear to compromise the metal's sheen or malleability.

Characterisation of the Powerkleen system (Section 4.2; page 88) indicated that potassium hydroxide (0.711 M) was the active ingredient. The chemical oxygen demand, pH, conductivity and total dissolved solids concentration of Powerkleen were also measured.

The Powerkleen system was optimised with respect to its contact (soaking) time with the coil and its concentration (Section 5.3; page 115). Gravimetric analyses showed that soaking time had a negligible effect on the cleanliness of the aluminium. In addition, it was found that 1:15 Powerkleen removed approximately 3.5-times more dirt than did the 1:60 dilution. It was further found that 1:15 Powerkleen removed a mass of dirt comparable to that removed by 1:1 Alukleen, although, as discussed, some of the mass removed by Alukleen is likely to be due to etching of the aluminium. Digital photography showed that Powerkleen dilutions of 1:15, 1:20, 1:30 and 1:40 all produced an acceptable level of cleanliness of the aluminium.

Furthermore, digital photography and electron microscopy indicated that relatively little etching of the aluminium resulted even at soaking times of 20 minutes.

The two methods investigated for applying Powerkleen to the air-conditioner coils included a pump bottle (for on-site application in industry) and an air gun at a pressure of 4 bars (for application at Ben Booyesen) (Section 5.4; page 123). A relatively small difference in the cleaning action of 1:20 and 1:40 Powerkleen solutions was found. A 1:39 dilution was chosen for use because of its cost-effectiveness and ease of preparation. Although better penetration and cleanliness was observed using the air gun, good cleaning action was also achieved using the pump bottle. The pump bottle required approximately 4 times the volume of Powerkleen used by the air gun (1 L). In addition, it was ascertained that a dilution of 1:79 Powerkleen could replace green soap and Handy Andy in the cleaning and general degreasing of the cases of the air-conditioner units (Section 5.3.2; page 122).

A feasibility study was then conducted on the replacement of Alukleen, green soap and Handy Andy with Powerkleen. The feasibility study involved technical, economic and environmental evaluations. The technical evaluation (Section 6.1; page 128) determined that the required technology was available, the timescales were appropriate, the involved risks were negligible and the company culture would be amenable to the implementation of the Powerkleen system. Calculation of the financial indicators (Section 6.2; page 131): the payback period (5.9 months), the net annual rate of return on capital employed (193%), the net present value of the project (R28 860) and the internal rate of return (214.9%) strongly indicated the economic feasibility of the project.

Finally, the environmental evaluation (Section 6.3; page 134) required an estimation of the dilution factor for the 'new' Powerkleen effluent. Estimation of this dilution factor, using the sulfate concentrations of the Alukleen stock solution and actual effluent, allowed prediction of the concentrations of key components in the 'new' effluent. All parameters of this predicted Powerkleen effluent complied with Darvill and stormwater disposal limits. A further environmental improvement in changing to Powerkleen would be the elimination of fluoride and sulfate from the effluent, and a reduction in the use of chemical raw materials from 2100 L per annum to 260 L per

annum. Hence this study shows that the replacement of Alukleen with Powerkleen is technically, economically and environmentally feasible.

## **7.2 Recommendations**

As a result of the findings in this waste minimisation study, the following changes are recommended within Ben Booyesen:

- The replacement of 1:3 Alukleen with a 1:39 dilution of Powerkleen as the cleaning agent for the aluminium coils;
- the replacement of green soap and Handy Andy with a 1:79 dilution of Powerkleen as the cleaning agent for the plastic casing of the air-conditioner units;
- the application of the Powerkleen using an air-gun for units serviced at Ben Booyesen, and using a pump bottle for units serviced in the field; and lastly,
- the immediate and accurate dilution of Powerkleen to a dilution of 1:39 and 1:79 by the stores manager upon the delivery of Powerkleen to Ben Booyesen. Centralising the dilution factor will prevent further variations in the Powerkleen concentration, and will ensure that all air-conditioner units are treated with the same Powerkleen concentration.



## Chapter 8: References

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<sup>61</sup>B.Tromans, D.Probert and F.Essex, *The Canning Handbook – Surface Finishing Technology*, W.Canning, London, 1982.

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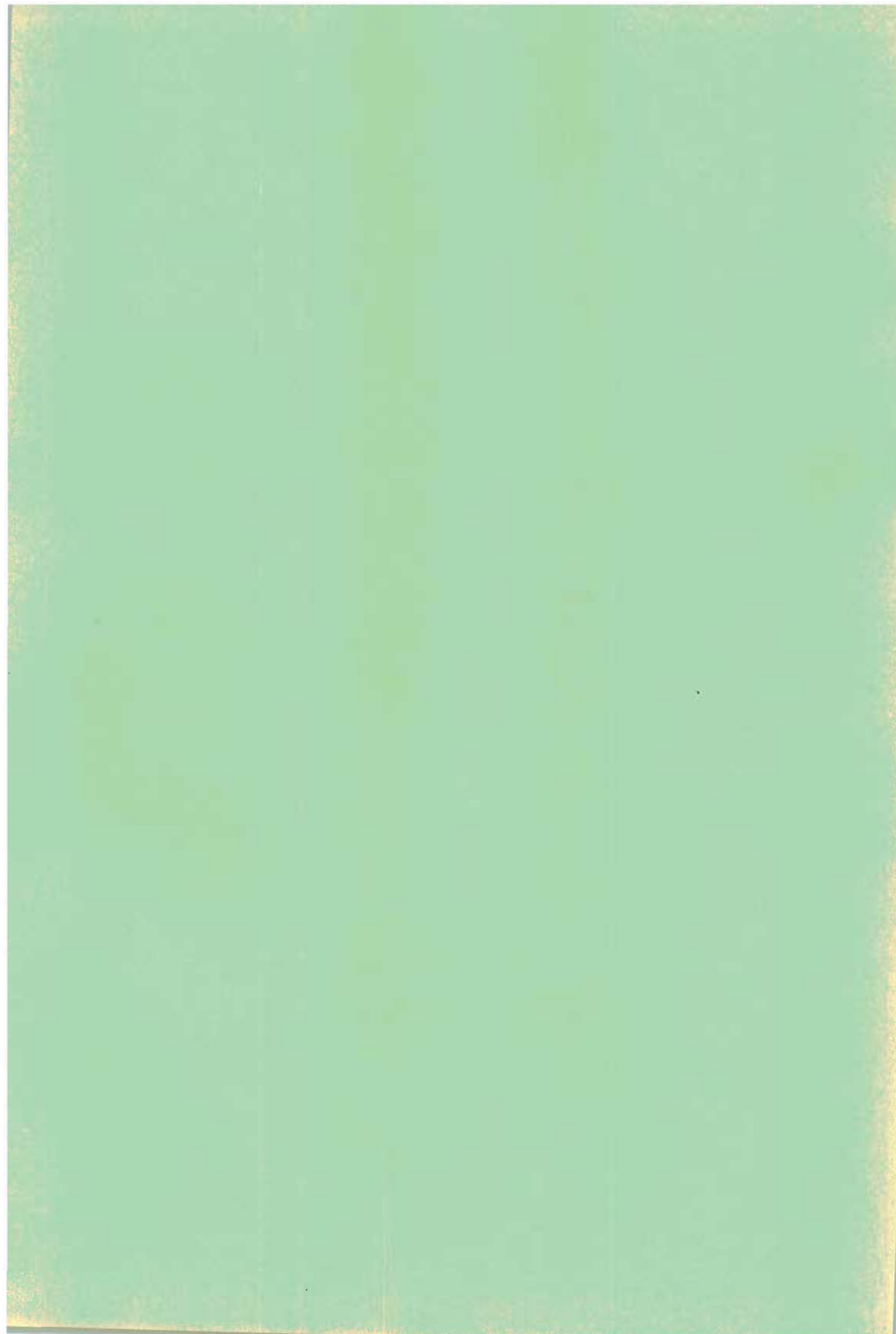
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Tel: 0832696240, (24<sup>th</sup> February 2002).

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Tel: (033) 3956286, (7<sup>th</sup> February 2003).

<sup>73</sup>Personal communication with Tony Brooking, Ben Booyesen, Tel: (033) 3424911,  
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# Appendix A

In this Appendix, details of all the wet chemical analysis conducted to determine the chemical species present in Alukleen are given. The tests detailed are those described in Section 3.1.1 (page 54).

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### ***Calcium Chloride Test:***

Neutralise 3 ml of the original sample with 5 M ammonium hydroxide ( $\text{NH}_4\text{OH}$ ) solution and boil to expel any excess ammonia. Add 3 ml of 0.5 M calcium chloride ( $\text{CaCl}_2$ ) solution and allow the solution to stand for several minutes whilst precipitation occurs. Test the precipitate for solubility in dilute (5 M) acetic acid. Dissolve an insoluble precipitate with hot dilute (5 M) sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and test with a few drops of 0.1 M potassium permanganate ( $\text{KMnO}_4$ ).

### ***Ferric Chloride Test:***

Neutralise 3 ml of the sample with 5 M ammonium hydroxide ( $\text{NH}_4\text{OH}$ ) solution and boil to expel any excess ammonia. Treat the solution with aqueous ferric chloride ( $\text{FeCl}_3$ ) drop by drop until no further change occurs.

### ***Barium Chloride Test:***

To 3 ml of the sample add 5 M hydrochloric acid ( $\text{HCl}$ ) until acidic and then add 2 ml in excess. Boil for 1 – 2 minutes to expel any carbon dioxide. Add 1 ml of 0.5 M barium chloride ( $\text{BaCl}_2$ ) solution to induce precipitation.

### ***Reducing Agent Test:***

Acidify 3 ml of the sample with 5 M sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and add 1 ml in excess. Add 3 – 4 drops of 0.02 M potassium permanganate ( $\text{KMnO}_4$ ) to the solution with a dropper and observe if bleaching of the potassium permanganate occurs.

### ***Brown Ring Test:***

Add 3 ml of freshly prepared saturated ferrous sulfate ( $\text{FeSO}_4$ ) to 2 ml of the sample. Then slowly add 3 – 5 ml of concentrated (36 M) sulfuric acid ( $\text{H}_2\text{SO}_4$ ) down the side of the test-tube so that the acid forms a layer beneath the mixture. The formation of a brown ring at the liquid interface indicates the presence of nitrate ( $\text{NO}_3^-$ ) or nitrite ( $\text{NO}_2^-$ ) ions.

### ***Potassium Dichromate Test:***

Acidify the sample with dilute sulfuric acid ( $\text{H}_2\text{SO}_4$ ); add a spatula-tip full of potassium dichromate to the solution and stir.

### ***Silver Nitrate Test:***

#### **a) Test for Group 1 Anions**

Acidify 10 ml of the sample with 5 M nitric acid and add 1 ml in excess. Add 1 ml concentrated (16 M) nitric acid ( $\text{HNO}_3$ ) to the sample followed, slowly and with stirring, by the addition of 0.1 M silver nitrate ( $\text{AgNO}_3$ ) solution until precipitation is complete. Filter and wash the white precipitate that forms at this stage with very dilute (1:20) nitric acid ( $\text{HNO}_3$ ). Then use the Displacement and Precipitate Tests to confirm further the presence of these ions.

#### **b) Test for Group 2 Anions**

To the filtrate from (a), add 1 ml of  $\text{AgNO}_3$  solution and then 20% sodium nitrite ( $\text{NaNO}_2$ ) solution until the precipitation is complete. If no precipitation occurs, do not add more than 0.5 ml  $\text{NaNO}_2$ .

**c) Test for Group 3 Anions**

To the solution from (b), or to the filtrate should a precipitate form, add 5 M sodium hydroxide (NaOH) solution drop-wise until a neutral pH is obtained. Then add 0.5 ml of 5 M acetic acid ( $\text{CH}_3\text{COOH}$ ) and 1 ml of silver nitrate ( $\text{AgNO}_3$ ) solution and heat the mixture to about  $80^\circ\text{C}$ . Continue to add more silver nitrate until the precipitation is complete. Filter and wash the precipitate with hot water.

***Displacement Tests:***

To the remaining two-thirds of the precipitate from the first silver nitrate test, add 1 – 2 g of granulated zinc and 5 – 10 ml of dilute (5 M) sulfuric acid ( $\text{H}_2\text{SO}_4$ ). Allow the reduction to proceed for 10 minutes with frequent stirring. Filter and wash the precipitate with a little dilute (5 M) sulfuric acid ( $\text{H}_2\text{SO}_4$ ). Divide the filtrate in two for the following two tests:

**a) Iodide Test**

Add 1 ml carbon tetrachloride ( $\text{CCl}_4$ ) and 3 ml of 25% ferrous sulfate ( $\text{FeSO}_4$ ) solution to half of the filtrate formed above. Shake the solution vigorously and allow to settle.

**b) Bromide Test**

Use the second half of the filtrate for this test. To the sample, add concentrated nitric acid ( $\text{HNO}_3$ ) equal in volume to the sample. Stand the test-tube containing the reagents in a beaker of boiling water for 2 minutes. Allow the test-tube to cool to room temperature. Add 1 – 2 ml carbon tetrachloride ( $\text{CCl}_4$ ) to the sample and stir vigorously with a glass rod.



***Precipitate Test:***

Heat one-third of the precipitate from the Silver Nitrate Test for Group 1 Anions for 3 – 4 minutes with 5% sodium chloride (NaCl) solution; allow the solution to cool and the precipitate to settle. Treat the supernatant liquid with dilute (5 M) hydrochloric acid (HCl) and a few drops of 0.5 M ferric chloride ( $\text{FeCl}_3$ ).

***Prussian Blue Test:***

Render the sample strongly alkaline with 5 M sodium hydroxide (NaOH). Add a few ml of freshly prepared 0.5 M ferrous sulfate ( $\text{FeSO}_4$ ) solution and then boil the mixture. Acidify the solution with 5 M hydrochloric acid (HCl) and add a few ml of 0.5 M ferric chloride ( $\text{FeCl}_3$ ) solution in order to initiate precipitation.

## **Appendix B**

Details of the analytical methods used for the quantification of the chemical species found in Alukleen, Powerkleen and the effluent sampled from Ben Booysen are given in this appendix. The analytical methods described are for the determination of potassium, sulfate, chloride, fluoride and sulfide concentrations as well as the methods used for pH titrations (strong and weak acids), measurement of the total dissolved solids concentration and gravimetric analysis. Experimental protocols used to determine the most effective cleaning system for the aluminium coils, and the suitability of two cleaner application techniques are also included.

**Potassium:**

**Equipment:** Inductively Coupled Plasma - Optical Emission Spectrometer (Varian Liberty 150 AX Turbo).

**Sample:** 10-000 fold dilution of Powerkleen.

**Standards:** 1.00 ppm, 2.00 ppm, 5.00 ppm, 7.00 ppm and 10.0 ppm  $K^+$  standards made from potassium fluoride (KF) with distilled water.

**Sulfate:**

**Equipment:** ion chromatograph (Waters 590 Programmable HPLC pump, Waters 430 conductivity detector, 4.6 x 50 mm HPLC column (anion) part no: 07355).

**Sample:** Run 1000-fold dilutions of Alukleen and neat effluent samples.

**Sample preparation:** Filter each sample through an assembly containing a filter paper holder (Swinnex), filter paper (Swinnex, 25 mm, nylon, 0.45  $\mu m$ ), an Accell SEP-PAK cartridge and an Accell C-18 SEP-PAK cartridge. The cartridges remove any dissolved organics and suspended solids in the sample. Flush the entire filtration assembly first with ultrapure water and then with air before and after each filtration. The sample's conductivity must be less than 200  $\mu S/cm$  to run the chromatography column.

**Standards:** 50.00 ppm, 100.0 ppm, 150.0 ppm, 200.0 ppm and 400.0 ppm  $SO_4^{2-}$  standards made from potassium sulfate ( $K_2SO_4$ ) with ultrapure water.

**Eluent:** 2 millimolar p-hydroxybenoate in 2.5% methanol by volume, adjusted to a pH of approximately 9.3. Degas the eluent by filtration and allow to stabilise in the instrument before measurement.

**Procedure:** Run 5 standards before and after the set of samples and run each sample in triplicate.

***Chloride:***

**Equipment:** ion chromatograph (Waters 590 Programmable HPLC pump, Waters 430 conductivity detector, 4.6 x 50 mm HPLC column (anion) part no: 07355).

**Sample:** Run 1000-fold dilutions of Alukleen.

**Sample preparation:** Filter each sample as for sulfate determination.

**Standards:** 0.100 ppm, 0.300 ppm, 0.500 ppm and 1.00 ppm  $\text{Cl}^-$  standards made from potassium chloride (KCl) with ultrapure water.

**Eluent:** 2 millimolar p-hydroxybenoate in 2.5% methanol by volume, adjusted to a pH of approximately 9.3. Degas the eluent by filtration and allow to stabilise in the instrument before measurement.

**Procedure:** Run 4 standards before and after the set of samples and run each sample in triplicate.

***Fluoride:***

**Equipment:** Ion selective electrode (Fluoride Selectrode, F1052F, Radiometer Copenhagen).

**Sample:** 500-fold dilution of 1:1 stock Alukleen; 1000-fold dilution of neat Alukleen; 1.05-fold dilution of effluent. All samples include 5 ml of TISAB.

**Standards:** 5.00 ppm, 10.0 ppm, 15.0 ppm, 25.0 ppm and 50.0 ppm

F<sup>-</sup> standards are made from potassium fluoride (KF) with distilled water and include 5 ml of TISAB.

### ***Sulfide:***

**Equipment:** photometer (Photometer SQ 200, Merck).

**Sample:** 5 ml of concentrated Alukleen or effluent.

**Standards:** 0.500 ppm, 1.00 ppm, 1.50 ppm, 2.00 ppm and 3.00 ppm S<sup>2-</sup> standards made from sodium sulfide (Na<sub>2</sub>S) with distilled water.

**Procedure:** Add 5 ml of the standard or sample to the cuvette. Add 1 drop of reagent A, 5 drops of reagent B and 5 drops of reagent C from the sulfide test kit (Merck Sulfide Spectroquant® Testing Kit no. 1.14779.0001). Mix contents of curvette through inversion and measure against a blank at 665 nm.

### ***pH Titrations:***

**Equipment:** pH probe (Crison pH meter, cat. no. 52-03, Crison microPH 2000)

**Titration of H<sub>2</sub>SO<sub>4</sub> with NaOH:** titrate 5.00 ml of ~ 0.25 M H<sub>2</sub>SO<sub>4</sub>, made up to 50.0 ml with distilled water, with ~ 0.1 M NaOH.

**Titration of Alukleen with NaOH:** titrate 20.00 ml of 1:1 Alukleen (sample from the 20<sup>th</sup> August 2002), made up to 50.0 ml with distilled water, with 2.040 M NaOH.

**Titration of Powerkleen with HCl:** titrate 25.00 ml of concentrated Powerkleen made up to 50.0 ml with distilled water, with 1.065 M HCl.

**Procedure:** Titrate the sample with the titrant in the burette, taking measurements with the pH probe initially at 5 ml intervals and then at more frequent intervals as the end points are approached.

### ***Standardisation Titrations:***

**Standardisation of the NaOH:** titrate 25.00ml of 0.21006 M  $\text{KHC}_8\text{H}_4\text{O}_4$  with a 10-fold dilution of  $\sim 2.1$  M NaOH using phenolphthalein as the indicator. The first persistent pink colour indicates the end-point.

**Standardisation of the HCl:** titrate 25.00ml of a 2-fold dilution of the 2.040 M NaOH with  $\sim 1.0$  M HCl, using phenolphthalein as the indicator. The change of the solution to colourless indicates the end-point.

### ***Total Dissolved Solids:***

**Samples:** concentrated Alukleen, Powerkleen and the effluent sampled from Ben Booyesen.

**Suspended solids:** determine gravimetrically. Pre-weigh filter paper (Whatman No. 1) in triplicate, filter sample under gravity and allow filter paper to dry in a drying oven at  $105^\circ\text{C}$  overnight. The difference in filter paper weights is the mass of the suspended solids.

**Total solids:** determine gravimetrically. Put sample into a pre-weighed crucible and evaporate the solution until dryness. Allow the crucible's contents to dry overnight at



105°C. The difference in the crucible's masses is the weight of the total solids in the sample.

**Total dissolved solids:** determine from the difference of the above two masses according to Equation 3.39.

***Gravimetric Analysis for the Determination of the most effective Cleaning System with regard to Cleaner Concentration and Soaking Time:***

**Aluminium samples:** 5 x 5 cm pieces from the aluminium fins (air-conditioner).

**Alukleen dilutions:** 1:1, 1:3, 1:9, 1:14 and 1:19.

**Powerkleen dilutions:** 1:15, 1:20, 1:30, 1:40, 1:50 and 1:60.

**Soaking times for each dilution:** 2, 4, 6, 8, 10, 15 and 20 minutes.

**Procedure:** Submerge the pieces of aluminium in 50 ml of the appropriate dilution and allow to soak for the required amount of time. Rinse the samples with distilled water. Collect the runoffs from the rinsing in the vessel in which the pieces have been submerged. Pre-weigh Whatman no. 1 filter paper in triplicate for the gravimetric analysis. Filter the cleaner solution and residue from each vessel under gravity and collect the solid residue on the filter paper. Dry the pieces of filter paper in a drying oven (set at 80°C) overnight and re-weigh in triplicate the following day.

### ***Gravimetric Analysis for the Investigation of a Pre-wash System:***

**Aluminium samples:** 5 x 5 cm pieces from the aluminium fins (air-conditioner).

**Pre-washes:** green soap (neat) and Alukleen (1:9 and 1:19).

**Main washes:** Alukleen (1:9 and 1:19).

**Procedure:** Submerge the pieces of aluminium in 50 ml of the appropriate pre-wash (green soap, 1:9 Alukleen or 1:19 Alukleen) and allow to soak for 5 minutes. Rinse the samples with distilled water. Collect the runoffs from the rinsing in the vessel in which the pieces have been submerged. Submerge the pieces of aluminium in 50 ml of the appropriate main wash (1:9 Alukleen or 1:19 Alukleen) and allow to soak for a further 5 minutes. Again, rinse the samples with distilled water and collect the runoffs in which the pieces have been submerged. Pre-weigh Whatman no. 1 filter paper in triplicate for the gravimetric analysis. Combine the pre-wash and main wash solutions from each trial combination and filter the solution and residue from each vessel under gravity. Collect the solid residue on the filter paper. Dry the pieces of filter paper in a drying oven (set at 80°C) overnight and re-weigh in triplicate the following day.

### ***Gravimetric Analysis for the Investigation of Degreasers:***

**Aluminium samples:** 5 x 5 cm pieces from the aluminium fins (air-conditioner).

**Degreasers:** Powerkleen (1:15 and 1:50), Technicians' Choice (neat) and Klengine (neat).

**Procedure:** Submerge the pieces of aluminium in 50 ml of the degreaser solution under investigation and allow to soak for 5 minutes. Rinse the samples with distilled water. Collect the runoffs from the rinsing in the vessel in which the pieces have been

submerged. Pre-weigh Whatman no. 1 filter paper in triplicate for the gravimetric analysis. Collect the solid residue on the filter paper. Dry the pieces of filter paper in a drying oven (set at 80°C) overnight and re-weigh in triplicate the following day.

***Determination of the Suitability of Two Cleaner Application Techniques:***

**Aluminium samples:** Air-conditioner's coils cut into 4 equal pieces (Figure 3.2).

**Powerkleen dilutions:** 1:20 and 1:40.

**Procedure:** Position the coil in such a way that the fins of the coil run from top to bottom. This positioning facilitates the Powerkleen solution constantly coming into contact with a cleaner metal surface. Apply the Powerkleen to the entire surface of the coil for 2 minutes, using the pump bottle or the air gun connected to a pressure source of 4 bars. Allow the coil to stand for 5 minutes before rinsing with water from a hose. Allow the coil pieces to dry. Cut each coil piece in half to enable the distance of penetration on the fins to be noted and photographed.

## **Appendix C**

In this appendix, the quantitative analyses of Alukleen, Powerkleen and the effluent samples are presented. These analyses include ion chromatography, ion selective electrode measurements, photometry, titrations and the measurement of pH, conductivity and the total dissolved solids content of each of the three types of samples. Potassium measurements of Powerkleen, determined using the ICP-OES, are also included.

C.1 Alukleen

Sulfate Determination:

Table C.1: Results from the reproducibility run carried out on the ion chromatograph.

Standard	[SO <sub>4</sub> <sup>2-</sup> ] (ppm)	Peak Area			Mean Peak Area	Std. Deviation	Coeff. of Variation (%)
		1	2	3			
1	50.00	796603	795080	795864	795849	762	0.0957
2	100.0	1637101	1552289	1722030	1637140	84871	5.1841
3	150.0	2340796	2545784	2442702	2443094	102495	4.19528
4	200.0	3400505	3191708.5	2982306	3191507	209100	6.55175
5	400.0	6175112	7378444.5	6776731	6776763	601666	8.87837

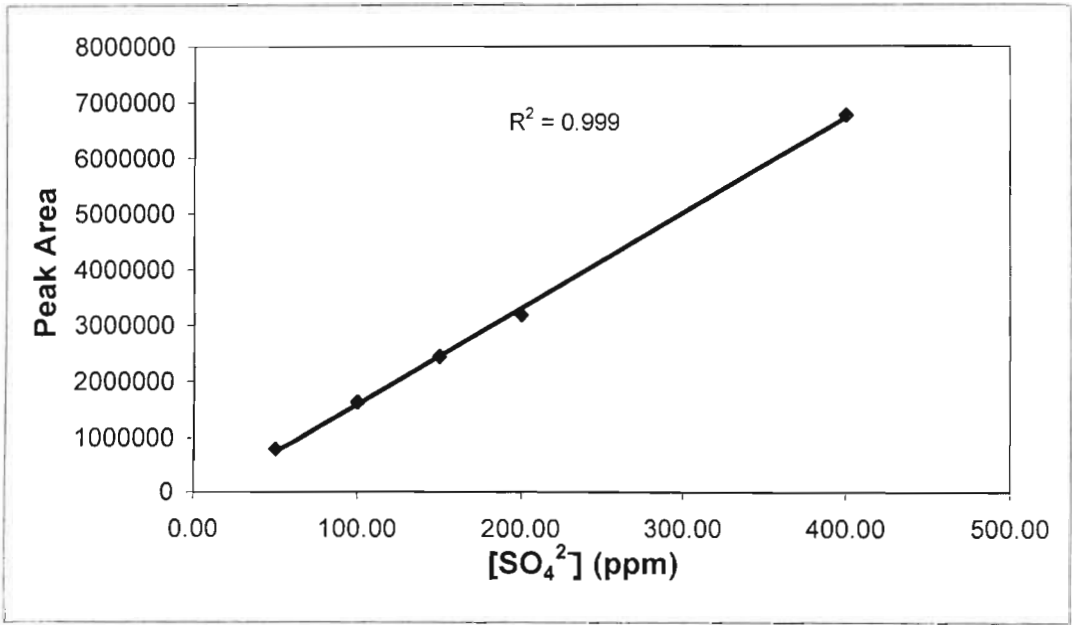


Fig. C.1: Plot of peak area as a function of sulfate concentration for reproducibility run on the ion chromatograph.

Table C.2: Calculation of the sulfate concentration in Alukleen using ion chromatography.

Sample	[SO <sub>4</sub> <sup>2-</sup> ] (ppm)	Mean [SO <sub>4</sub> <sup>2-</sup> ] (ppm)	Peak Area	Mean Peak Area	Std. Deviation	Coeff. of Variation (%)
Standard 1	50.00		904442	853237	72415	8.4871
			802032			
Standard 2	100.0		1901151	1786718	161833	9.05758
			1672284			
Standard 3	150.0		2659146	2803003	203444	7.25807
			2946859			
Standard 4	200.0		3739885	3757799	25334	0.67418
			3775713			
Standard 5	400.0		8401077	7758652	908527	11.7099
			7116226			
Sample 1	104.8	108.1	1904183	1970171	57235	2.9051
	109.6		2000001			
	110.0		2006330			
Converted to 1:1 stock Alukleen	52400	54070				
	54820					
	54980					
Sample 2	94.51	104.6	1700683	1900873	174736	9.19242
	110.8		2022780			
	108.6		1979155			
Converted to 1:1 stock Alukleen	47260	52320				
	55400					
	54300					
Sample 3	146.9	143.9	2737789	2677339	102619	3.83288
	137.9		2558853			
	146.8		2735376			
Converted to 1:1 stock Alukleen	73470	71920				
	68890					
	73410					
Sample 4	144.1	152.6	2680777	2848921	145922	5.12202
	156.3		2923564			
	157.3		2942423			
Converted to neat Alukleen	72030	76280				
	78170					
	78640					



**Note:** 'Stock Alukleen' refers to a 1:1 dilution of Alukleen made by the stores manager of Ben Booysen whilst 'neat Alukleen' refers to undiluted Alukleen.

All measurements were made on the same day; therefore only one set of standards was run, before and after the set of samples.

Sample 1 refers to a 1:499 dilution of 1:1 Alukleen stock that was sampled on the 8<sup>th</sup> August 2002; sample 2 refers to a 1:499 dilution of 1:1 Alukleen stock that was sampled on the 20<sup>th</sup> August 2002 and sample 3 refers to a 1:499 dilution of 1:1 Alukleen stock that was sampled on the 26<sup>th</sup> August 2002. Sample 4 refers to a 1:999 dilution of neat Alukleen. These dilutions were made in order that the samples run on the ion chromatograph were within its correct range.

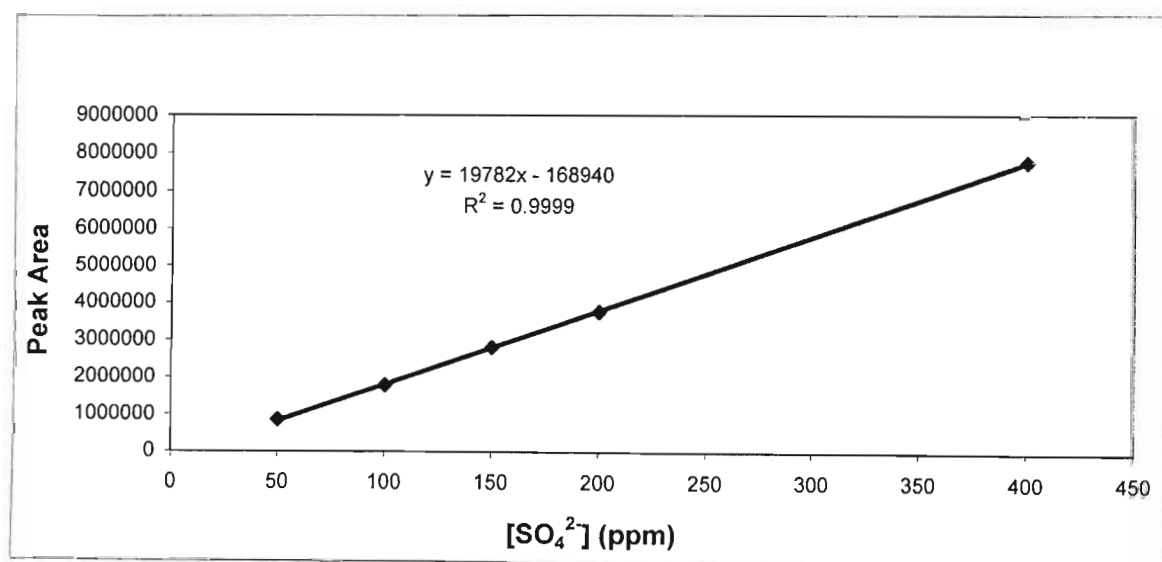


Fig. C.2: Calibration graph for the sulfate determination of Alukleen using ion chromatography.

$$\text{Peak Area} = 19782[\text{SO}_4^{2-}] - 168940$$

$$\therefore [\text{SO}_4^{2-}] = \frac{\text{Peak Area} + 168940}{19782}$$

**Calculation of the Dilution Factors of the Stock Solutions:**

$[\text{SO}_4^{2-}]$  (neat Alukleen) = 152600 ppm (Table C.1)

∴ Sample 1 ( $[\text{SO}_4^{2-}] = 54070$  ppm) is a 2.822-fold dilution

and Sample 2 ( $[\text{SO}_4^{2-}] = 52320$  ppm) is a 2.917-fold dilution

and Sample 3 ( $[\text{SO}_4^{2-}] = 71920$  ppm) is a 2.122-fold dilution

**Chloride Determination:**

Table C.3: Calculation of the chloride concentration in Alukleen using ion chromatography.

Sample	[Cl] (ppm)	Peak Area	Mean Peak Area	Std. Deviation	Coeff. of Variation (%)
Standard 1	0.100	98916	105501	9313	8.827
		112086			
Standard 2	0.300	179806	173059	9542	5.514
		166312			
Standard 3	0.500	248713	250910	3107	1.238
		253107			
Standard 4	1.00	437661	430956	9482	2.200
		424251			
Sample 1	< L.O.D.	*			
Sample 2	< L.O.D.	*			
Sample 3	< L.O.D.	*			
Sample 4	< L.O.D.	*			

**Note:** The samples are named according to the note after Table C.2.

\* refers to the fact that no chloride peak area was obtained for these Alukleen samples.

< L.O.D. indicates that the chloride concentration of the samples run were lower than the limit of detection of the instrument.

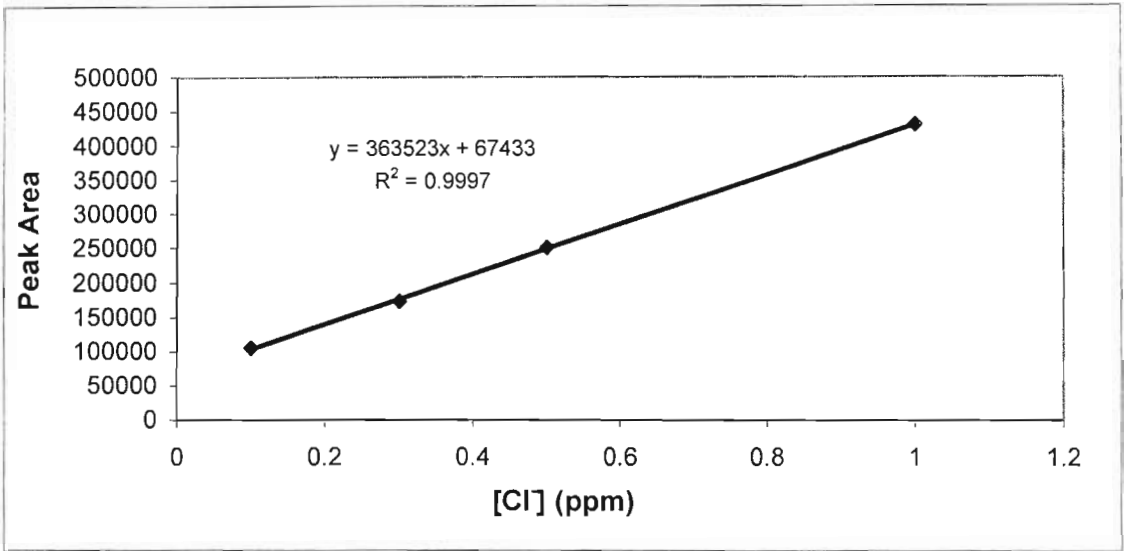


Fig. C.3: Calibration graph for the chloride determination of Alukleen using ion chromatography.

$$\text{Peak Area} = 363523 [\text{Cl}^-] + 67433$$

$$\therefore [\text{Cl}^-] = \frac{\text{Peak Area} - 67433}{363523}$$

**Fluoride Determination:**

Table C.4: Results from the reproducibility run carried out using the fluoride ion selective electrode.

Sample	[F] (ppm)	E (mV)					Mean (mV)	Std. Deviation (mV)	Coeff. of Variation (%)
		1	2	3	4	5			
Standard 1	5.00	228.4	241.3	242.9	242.1	238.6	238.7	6.0	2.5
Standard 2	10.0	132.7	128.2	127.9	124.6	120.5	126.8	4.5	3.6
Standard 3	15.0	34.1	33.6	33.4	31.1	31.8	32.8	1.3	3.9
Standard 4	25.0	-58.2	-56.1	-51.9	-53.3	-53.9	-54.7	2.5	4.5
Standard 5	50.0	-150.5	-148.4	-151.5	-153.3	-154.1	-151.6	2.3	1.5

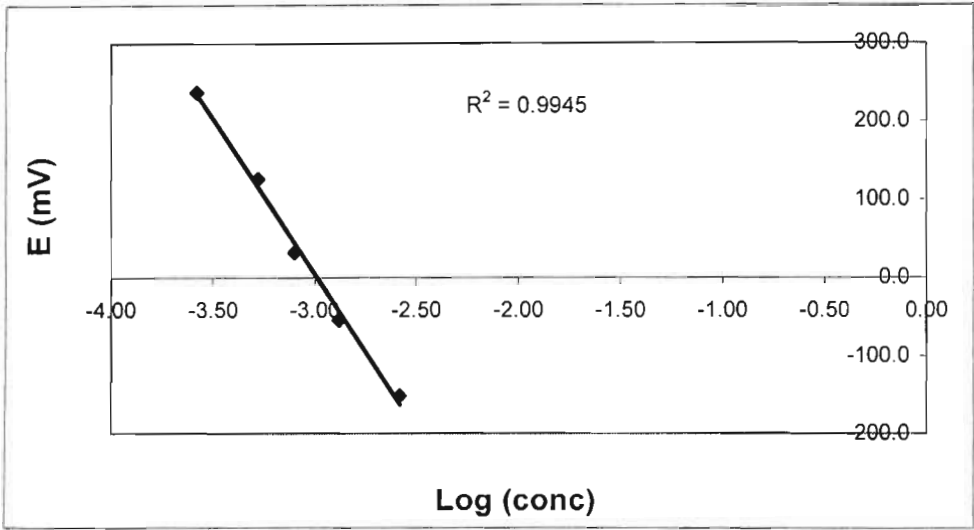


Fig. C.4: Potential (E) as a function of the fluoride concentration for reproducibility run using the ion selective electrode.

Table C.5: Calculation of the fluoride concentration in Alukleen using an ion selective electrode.

Sample	[F] (ppm)	[F] (M)	Log (conc)	E (mV)			Mean (mV)	Std. Deviation (mV)	Coeff. of Variation (%)
				1	2	3			
Standard 1	5.00	$2.63 \times 10^{-4}$	-3.58	228.4	241.3	242.9	237.5	8.0	3.3
Standard 2	10.0	$5.26 \times 10^{-4}$	-3.28	132.7	128.2	127.9	129.6	2.7	2.1
Standard 3	15.0	$7.90 \times 10^{-4}$	-3.10	34.1	33.6	33.4	33.7	0.4	1.1
Standard 4	25.0	$1.32 \times 10^{-3}$	-2.88	-58.2	-56.1	-51.9	-55.4	3.2	5.8
Standard 5	50.0	$2.63 \times 10^{-3}$	-2.58	-150.5	-148.4	-151.5	-150.1	1.6	1.1
Sample 1	20.8	$1.09 \times 10^{-3}$	-2.96	-7.8	-10.5	-11.1	-9.8	1.8	17.9
Converted to 1:1 stock Alukleen	10400	0.545							
Sample 2	20.5	$1.08 \times 10^{-3}$	-2.96	-8.9	-7.6	-7.3	-7.9	0.9	10.7
Converted to 1:1 stock Alukleen	10300	0.540							
Sample 3	24.4	$1.29 \times 10^{-3}$	-2.89	-37.8	-35.5	-37.1	-36.8	1.2	3.2
Converted to 1:1 stock Alukleen	12200	0.645							
Sample 4	25.4	$1.33 \times 10^{-3}$	-2.87	-43.9	-46.4	-42.3	-44.2	2.1	4.7
Converted to neat Alukleen	25400	1.33							

**Note:** The samples are named according to the note after Table C.2.

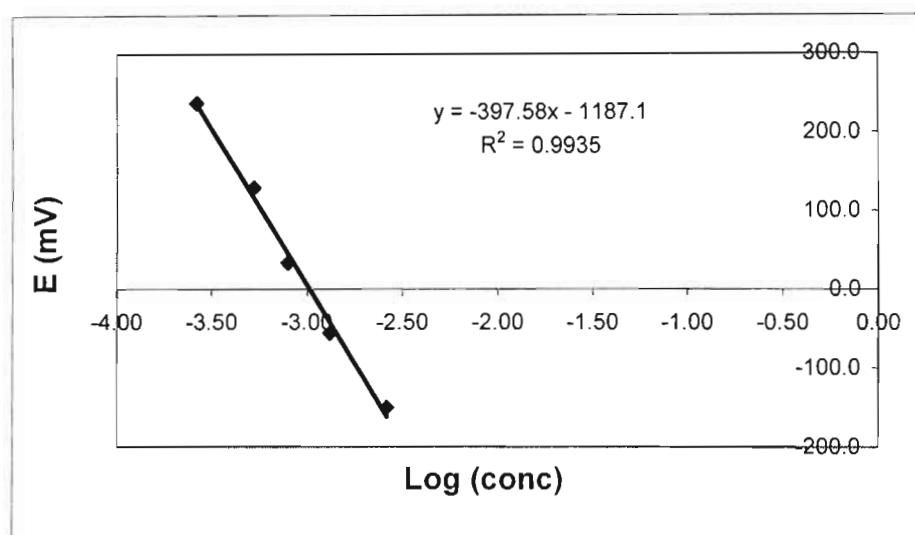


Fig. C.5: Calibration graph for the fluoride determination in Alukleen using an ion selective electrode.

$$E = -397.58(\log [F^- (M)]) - 1187.1$$

$$\therefore \log [F^- (M)] = \frac{E + 1187.1}{-397.58}$$

$$\therefore [F^- (M)] = \text{alog} \left( \frac{E + 1187.1}{-397.58} \right)$$

#### Calculation of the Dilution Factors for the Stock Solutions:

$[F^-]$  (neat Alukleen) = 25400 ppm (Table C.4)

$\therefore$  Sample 1 ( $[F^-] = 10400$  ppm) is a 2.44-fold dilution

and Sample 2 ( $[F^-] = 10300$  ppm) is a 2.47-fold dilution

and Sample 3 ( $[F^-] = 12200$  ppm) is a 2.08-fold dilution.



**Sulfide Determination:**

Table C.6: Results from the photometric reproducibility run.

Sample	[S <sup>2-</sup> ] (ppm)	Absorbance			Mean	Std. Deviation	Coeff. of Variation (%)
		1	2	3			
Blank	0.0	0.000	0.001	0.000	0.000	0.001	
Standard 1	0.5	0.193	0.194	0.197	0.195	0.002	1.1
Standard 2	1.0	0.440	0.416	0.433	0.430	0.012	2.9
Standard 3	1.5	0.556	0.549	0.543	0.549	0.007	1.2
Standard 4	2.0	0.734	0.728	0.731	0.731	0.003	0.4
Standard 5	3.0	0.799	0.787	0.794	0.793	0.006	0.8

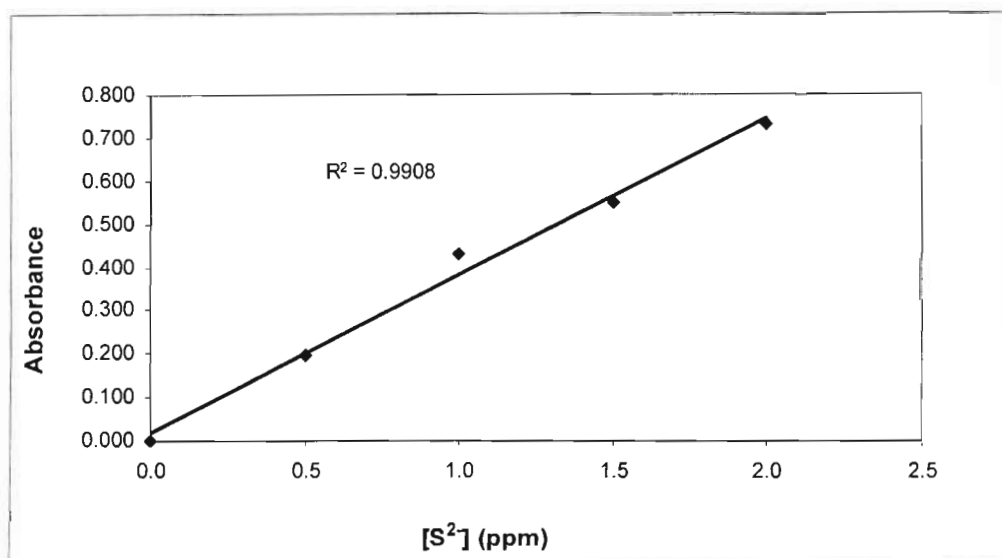


Fig. C.6: Absorbance as a function of sulfide concentration for the reproducibility run on the photometer.

Table C.7: Photometric measurement of the sulfide concentration in Alukleen.

Sample	[S <sup>2-</sup> ] (ppm)	Absorbance			Mean	Std. Deviation	Coeff. of Variation (%)
		1	2	3			
Blank	0.000	0.001	0.000	0.001	0.001	0.001	58
Standard 1	0.500	0.263	0.269	0.268	0.267	0.003	1.2
Standard 2	1.00	0.540	0.541	0.531	0.537	0.006	1.0
Standard 3	1.50	0.678	0.678	0.683	0.680	0.003	0.4
Standard 4	2.00	0.850	0.844	0.842	0.845	0.004	0.5
Standard 5	3.00	1.393	1.398	1.380	1.390	0.009	0.7
Alukleen	0.091	0.067	0.067	0.072	0.069	0.003	4.2

**Note:** Absorbance readings for all standards and samples are adjusted for the absorbance reading of the blank.

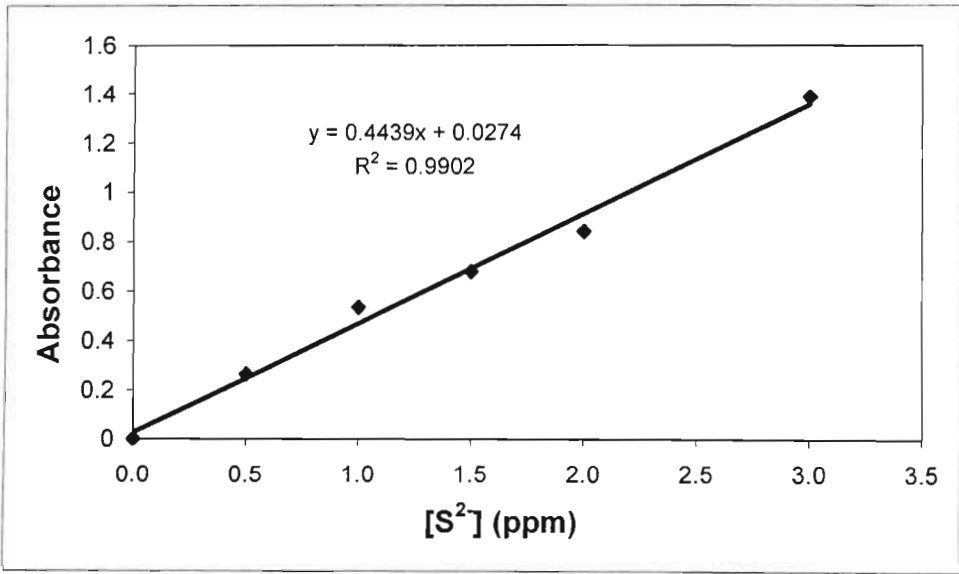
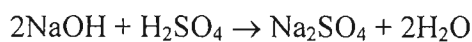


Fig. C.7: Calibration graph for the photometric sulfide determination in Alukleen.

$$\text{Absorbance} = 0.4439[\text{S}^{2-}] + 0.0274$$

$$\therefore [\text{S}^{2-}] = \frac{\text{Absorbance} - 0.0274}{0.4439}$$

**Determination of the Free and Total Acid Content:****Endpoint 1 (strong acid):**

$$[\text{NaOH}] = 2.040 \text{ M}$$

$$v(\text{NaOH}) = 0.01350 \text{ dm}^3$$

$$n(\text{NaOH}) = (2.040 \text{ M})(0.01350 \text{ dm}^3)$$

$$= 0.02754 \text{ mol}$$

$$\therefore n(\text{H}_2\text{SO}_4) = 0.01377 \text{ mol}$$

$$v(\text{Alukleen}) = 0.02000 \text{ dm}^3 \text{ (Appendix B)}$$

$$\therefore [\text{H}_2\text{SO}_4] = (0.01377 \text{ mol})/(0.02000 \text{ dm}^3)$$

$$= 0.6885 \text{ M}$$

But this is a stock solution of Alukleen,

$$\therefore [\text{H}_2\text{SO}_4] = (0.6885 \text{ M})(\text{the average dilution factor from the } \text{SO}_4^{2-} \text{ and } \text{F}^- \text{ measurements})$$

$$= (0.6885 \text{ M})(2.48)$$

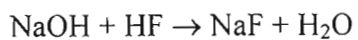
$$= 1.71 \text{ M}$$

$$\therefore [\text{H}^+] \text{ for strong acid:}$$

$$= (0.6885 \text{ M} \times 2)(2.48)$$

$$= (1.377 \text{ M})(2.48)$$

$$= \underline{3.41 \text{ M}}$$

**Endpoint 2 (weak acid):**

$$[\text{NaOH}] = 2.040 \text{ M}$$

$$\begin{aligned} v(\text{NaOH}) &= 0.01950 \text{ dm}^3 - 0.01350 \text{ dm}^3 \\ &= 0.00600 \text{ dm}^3 \end{aligned}$$

$$\begin{aligned} n(\text{NaOH}) &= (2.040 \text{ M})(0.00600 \text{ dm}^3) \\ &= 0.0122 \text{ mol} \end{aligned}$$

$$\therefore n(\text{HF}) = 0.0122 \text{ mol}$$

$$v(\text{Alukleen}) = 0.02000 \text{ dm}^3 \text{ (Appendix B)}$$

$$\begin{aligned} \therefore [\text{HF}] &= (0.0122 \text{ mol}) / (0.02000 \text{ dm}^3) \\ &= 0.610 \text{ M} \end{aligned}$$

But this is a stock solution of Alukleen,

$$\begin{aligned} \therefore [\text{HF}] &= (0.610 \text{ M})(\text{the average dilution factor from the } \text{SO}_4^{2-} \text{ and } \text{F}^- \text{ measurements}) \\ &= (0.610 \text{ M})(2.48) \\ &= 1.51 \text{ M} \\ &= [\text{H}^+] \text{ for weak acid.} \end{aligned}$$

**pH Measurement:**

Table C.8: pH measurement of Alukleen.

pH				Mean	Std. Deviation	Coeff. of Variation (%)
Sample	1	2	3			
1:19 dilution of Alukleen	2.95	3.03	3.04	3.01	0.05	1.6

**Conductivity Measurement:**

Table C.9: Conductivity measurement of Alukleen.

Conductivity (µS/cm)				Mean (µS/cm)	Std. Deviation (µS/cm)	Coeff. of Variation (%)
Sample	1	2	3			
1:999 dilution of Alukleen	182.6	184.4	188.1	185.0	2.8	1.5
Concentrated Alukleen	1826x10 <sup>2</sup>	1844x10 <sup>2</sup>	1881x10 <sup>2</sup>	1850x10 <sup>2</sup>		

**Total Dissolved Solids Determination:**

Table C.10: Determination of the suspended solids (S.S.) content of Alukleen.

Run No.	Mass before filtration (g)			Mass after filtration (g)			Mass of S.S. (g/25ml)		
	1	2	3	1	2	3	1	2	3
1	0.8145	0.8145	0.8147	0.8103	0.8102	0.8104	-0.0042	-0.0043	-0.0043
2	0.8333	0.8336	0.8334	0.8297	0.8299	0.8299	-0.0036	-0.0037	-0.0035
3	0.8247	0.8250	0.8251	0.8222	0.8228	0.8227	-0.0025	-0.0022	-0.0024

Table C.11: Determination of the total solids (T.S.) content of Alukleen.

Run No.	Mass before use (g)			Mass after use (g)			Mass of T.S. (g/25ml)		
	1	2	3	1	2	3	1	2	3
1	63.8452	63.8452	63.8453	63.8480	63.8478	63.8479	0.0028	0.0026	0.0026
2	54.7186	54.7185	54.7184	54.7198	54.7204	54.7203	0.0012	0.0019	0.0019
3	50.1119	50.1118	50.1119	50.1169	50.1167	50.1167	0.0050	0.0049	0.0048

Table C.12: Determination of the total dissolved solids (T.D.S.) content of Alukleen.

Run No.	Mass of S.S. (g/25ml)			Mass of T.S. (g/25ml)			Mass of T.D.S. (g/25ml)			Mean (g/25ml)	Std. Deviation (g/25ml)	Coeff. of Variation (%)
	1	2	3	1	2	3	1	2	3			
1	0.0000	0.0000	0.0000	0.0028	0.0026	0.0026	0.0028	0.0026	0.0026	0.0027	0.0001	4
2	0.0000	0.0000	0.0000	0.0012	0.0019	0.0019	0.0012	0.0019	0.0019	0.0017	0.0004	24
3	0.0000	0.0000	0.0000	0.0050	0.0049	0.0048	0.0050	0.0049	0.0048	0.0049	0.0001	2



Table C.13: Compilation of the total dissolved solids results for Alukleen (9 readings).

Total Dissolved Solids (g/25ml)												
Sample	1	2	3	4	5	6	7	8	9	Mean	Std. Deviation (g/25ml)	Coeff. of Variation (%)
Alukleen	0.0028	0.0026	0.0026	0.0012	0.0019	0.0019	0.0050	0.0049	0.0048	0.0031	0.0014	47

## C.2 Powerkleen

### Potassium Determination:

Table C.14: Determination of the potassium concentration in Powerkleen using the ICP-OES.

		Intensity			Mean	Std. Deviation	Coeff. of Variation (%)
Sample	[K <sup>+</sup> ] (ppm)	1	2	3			
Blank	0.00	12780	11780	12340	12300	501	4.07
Standard 1	1.00	349000	359400	374400	360933	12769	3.5378
Standard 2	2.00	694600	683200	708400	695400	12619	1.8146
Standard 3	5.00	1583000	1559000	1583000	1575000	13856	0.87977
Standard 4	7.00	2128000	2170000	2095000	2131000	37590	1.7640
Standard 5	10.0	2776000	2817000	2764000	2785666	27791	0.99764
1:9999 dilution of Powerkleen	2.78	878800	869800	873800	874133	4509	0.5159

**Note:** Intensity values in the above table take into account the intensity of the blank.

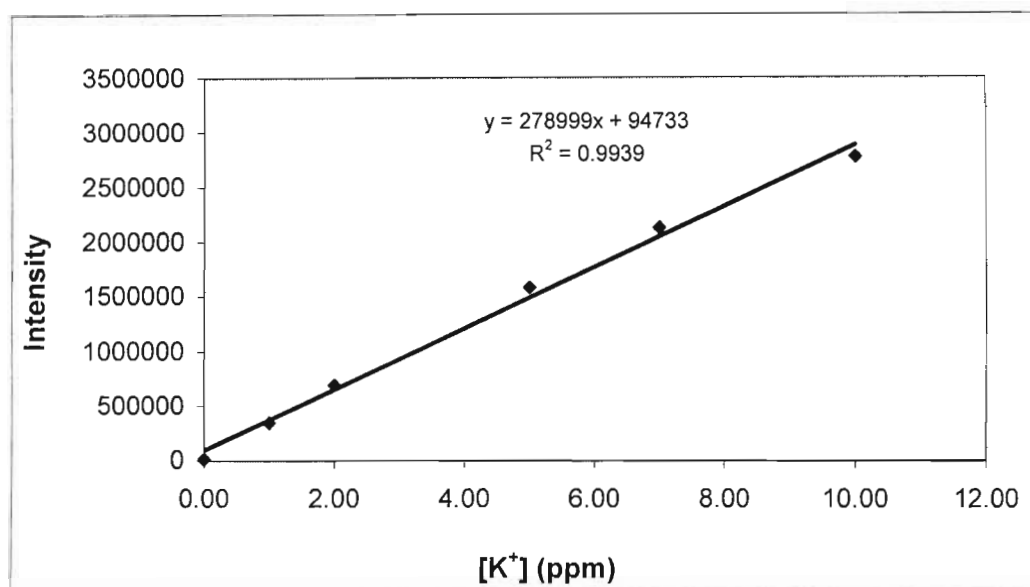


Fig. C.8: Calibration graph for the potassium determination in Powerkleen using the ICP-OES.

$$\text{Intensity} = 278999[\text{K}^+] + 94733$$

$$\therefore [\text{K}^+] = \frac{\text{Intensity} - 94733}{278999}$$

#### Calculation of Free Alkalinity of Powerkleen:

$$\begin{aligned}
 [\text{K}^+] &= 27\,800 \text{ ppm} \\
 &= 27\,800 \text{ mg/L} \\
 &= 27.8 \text{ g/L} \\
 &= (27.8 \text{ g/L}) / (39.10 \text{ g/mol}) \\
 &= 0.711 \text{ M}
 \end{aligned}$$

Assuming the alkalinity in Powerkleen arises from:  $\text{KOH} \rightarrow \text{K}^+ + \text{OH}^-$

$$\therefore [\text{OH}^-] = 0.711 \text{ M}$$

**Sulfide Determination:**

Table C.15: Photometric calculation of the sulfide concentration in Powerkleen.

Sample	[S <sup>2-</sup> ] (ppm)	Absorbance			Mean	Std. Deviation	Coeff. of Variation (%)
		1	2	3			
Blank	0.000	0.001	0.000	0.001	0.001	0.001	58
Standard 1	0.500	0.263	0.269	0.268	0.267	0.003	1.2
Standard 2	1.00	0.540	0.541	0.531	0.537	0.006	1.0
Standard 3	1.50	0.678	0.678	0.683	0.680	0.003	0.4
Standard 4	2.00	0.850	0.844	0.842	0.845	0.004	0.5
Standard 5	3.00	1.393	1.398	1.380	1.390	0.009	0.7
Powerkleen	*	0.000	0.000	0.000	0.000	0.000	0.0

\* = below the limit of detection for the instrument (0.5 ppm)

**Note:** Absorbance readings for all standards and samples are adjusted for the absorbance reading of the blank.

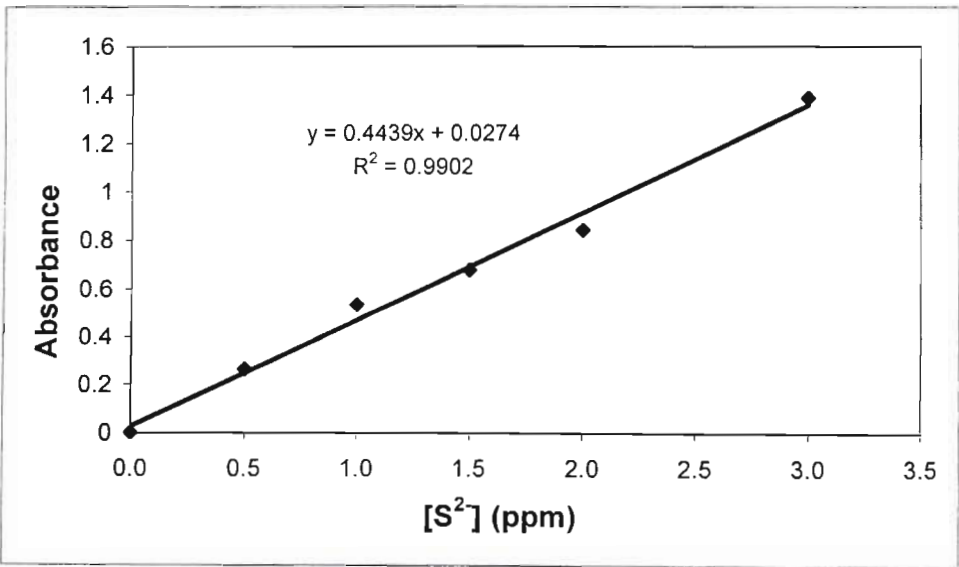


Fig. C.9: Calibration graph for the photometric sulfide determination in Powerkleen.

$$\text{Absorbance} = 0.4439[S^{2-}] + 0.0274$$

$$\therefore [S^{2-}] = \frac{\text{Absorbance} - 0.0274}{0.4439}$$

C.O.D. Determination:

Table C.16: Results of the measurement of the C.O.D. of 1:39 Powerkleen.

C.O.D. (mgO <sub>2</sub> /L)				Mean (mgO <sub>2</sub> /L)	Std. Deviation (mgO <sub>2</sub> /L)	Coeff. of Variation (%)
Sample	1	2	3			
1:39 Powerkleen	6444	6418	6431	6431	13	0.20

pH Measurement:

Table C.17: Results of the measurement of the pH of 1:39 Powerkleen.

pH				Mean	Std. Deviation	Coeff. of Variation (%)
Sample	1	2	3			
1:39 Powerkleen	12.13	12.00	12.21	12.11	0.11	0.91

Conductivity Measurement:

Table C.18: Results of the measurement of the conductivity of neat and 1:39 Powerkleen.

Conductivity (μS/cm)				Mean (μS/cm)	Std. Deviation (μS/cm)	Coeff. of Variation (%)
Sample	1	2	3			
Powerkleen	*8.79x10 <sup>4</sup>	*8.89x10 <sup>4</sup>	*8.75x10 <sup>4</sup>	8.81x10 <sup>4</sup>	721	0.818
Powerkleen (1:39)	4.62x10 <sup>3</sup>	4.63x10 <sup>3</sup>	4.62x10 <sup>3</sup>	4.62 x10 <sup>3</sup>	4	0.1

Note: \* These results are within the range of the instrument.

**Total Dissolved Solids Determination:**

Table C.19: Determination of the suspended solids (S.S.) content of Powerkleen.

Run No.	Mass before filtration (g)			Mass after filtration (g)			Mass of S.S. (g/25ml)		
	1	2	3	1	2	3	1	2	3
1	0.8140	0.8138	0.8143	0.8099	0.8098	0.8100	-0.0041	-0.0040	-0.0043
2	0.8427	0.8430	0.8430	0.8325	0.8326	0.8328	-0.0102	-0.0104	-0.0102
3	0.8332	0.8333	0.8335	0.8307	0.8305	0.8305	-0.0025	-0.0028	-0.0030

Table C.20: Determination of the total solids (T.S.) content of Powerkleen.

Run No.	Mass before use (g)			Mass after use (g)			Mass of T.S. (g/25ml)		
	1	2	3	1	2	3	1	2	3
1	0.8711	0.8711	0.8713	5.1776	5.1782	5.1799	4.3065	4.3071	4.3086
2	0.8270	0.8273	0.8273	4.7717	4.7717	4.7719	3.9447	3.9444	3.9446
3	0.8357	0.8360	0.8359	6.7718	6.7717	6.7718	5.9361	5.9357	5.9359



Table C.21: Determination of the total dissolved solids (T.D.S.) content of Powerkleen.

Run No.	Mass of S.S. (g/25ml)			Mass of T.S. (g/25ml)			Mass of T.D.S. (g/25ml)			Mean (g/25ml)	Std. Deviation (g/25ml)	Coeff. of Variation (%)
	1	2	3	1	2	3	1	2	3			
1	0.0000	0.0000	0.0000	4.3065	4.3071	4.3086	4.3065	4.3071	4.3086	4.3074	0.0011	0.0
2	0.0000	0.0000	0.0000	3.9447	3.9444	3.9446	3.9447	3.9444	3.9446	3.9446	0.0002	0.0
3	0.0000	0.0000	0.0000	5.9361	5.9357	5.9359	5.9361	5.9357	5.9359	5.9359	0.0002	0.0

Table C.22: Compilation of the total dissolved solids results for Powerkleen (9 readings).

Sample	Total Dissolved Solids (g/25ml)									Mean	Std. Deviation (g/25ml)	Coeff. of Variation (%)
	1	2	3	4	5	6	7	8	9			
Powerkleen	4.3065	4.3071	4.3086	3.9447	3.9444	3.9446	5.9361	5.9357	5.9359	4.7293	0.9185	19.42



C.3 Effluent Samples

Sulfate Determination:

Table C.23: Calculation of the sulfate concentration in the effluent using ion chromatography.

Sample	[SO <sub>4</sub> <sup>2-</sup> ] (ppm)	Mean [SO <sub>4</sub> <sup>2-</sup> ] (ppm)	Peak Area	Mean Peak Area	Std. Deviation	Coeff. of Variation (%)
Standard 1	50.00		261099	285519	34535	12.096
			309939			
Standard 2	100.0		1352257	1484447	186944	12.5935
			1616636			
Standard 3	150.0		1921434	2115945	275079	13.0003
			2310455			
Standard 4	200.0		2927540	2902620	35242	1.2142
			2877700			
Standard 5	400.0		7658370	8183829	743111	9.08023
			8709287			
Effluent 1	62.72	66.42	475296	559038	72886	13.038
	67.94		593640			
	68.59		608178			
Effluent 2	172.7	187.8	2965205	3308227	298719	9.02957
	194.0		3448356			
	196.8		3511120			
Effluent 3	56.03	54.85	324022	295703	40050	13.544
	53.53		267383			
	54.98		300204			

**Note:** All measurements were made on the same day; therefore only one set of standards was run, before and after the set of samples.

Effluent 1 refers to an effluent sample that was taken on the 18<sup>th</sup> September 2002; effluent 2 refers to an effluent sample that was taken on the 25<sup>th</sup> September 2002 and effluent 3 refers to an effluent sample that was taken on the 7<sup>th</sup> October 2002.

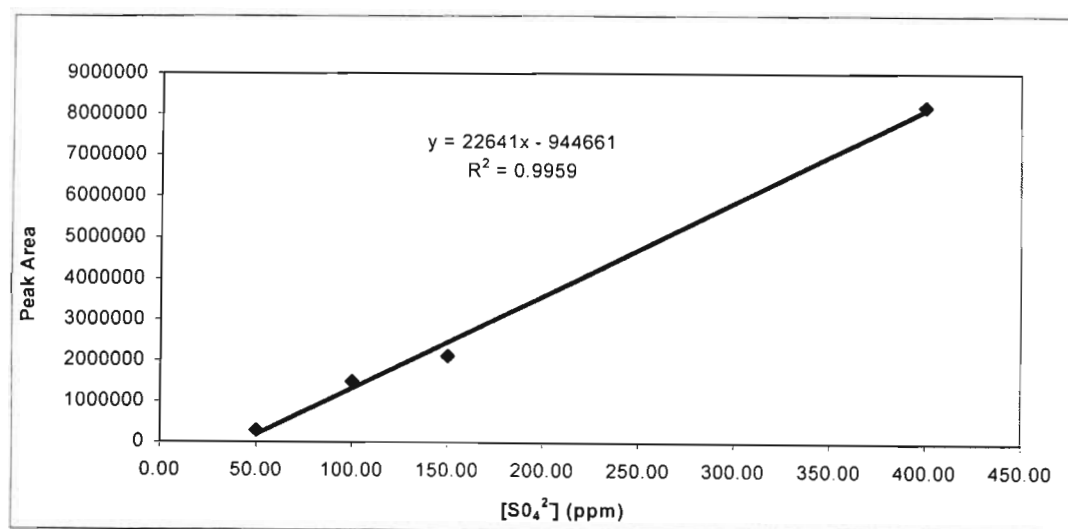


Fig. C.10: Calibration graph for the sulfate determination of the effluent using ion chromatography.

$$\text{Peak Area} = 22641[\text{SO}_4^{2-}] - 994461$$

$$\therefore [\text{SO}_4^{2-}] = \frac{\text{Peak Area} + 994461}{22641}$$

**Fluoride Determination:**

Table C.24: Calculation of the fluoride concentration in the effluent using an ion selective electrode.

Sample	[F] (ppm)	[F] (M)	Log (conc)	E (mV)			Mean (mV)	Std. Deviation (mV)	Coeff. of Variation (%)
				1	2	3			
Standard 1	5.00	$2.63 \times 10^{-4}$	-3.58	228.4	241.3	242.9	237.5	8.0	3.3
Standard 2	10.0	$5.26 \times 10^{-4}$	-3.28	132.7	128.2	127.9	129.6	2.7	2.1
Standard 3	15.0	$7.90 \times 10^{-4}$	-3.10	34.1	33.6	33.4	33.7	0.4	1.1
Standard 4	25.0	$1.32 \times 10^{-3}$	-2.88	-58.2	-56.1	-51.9	-55.4	3.2	5.8
Standard 5	50.0	$2.63 \times 10^{-3}$	-2.58	-150.5	-148.4	-151.5	-150.1	1.6	1.1
Sample 1	19.0	$1.00 \times 10^{-3}$	-3.00	4.7	7.3	4.5	5.5	1.6	28.4
Converted to Effluent 1	20.0								
Sample 2	22.3	$1.17 \times 10^{-3}$	-2.93	-21.0	-22.9	-22.6	-22.2	1.0	4.6
Converted to Effluent 2	23.5								
Sample 3	15.5	$8.16 \times 10^{-4}$	-3.09	40.5	42.7	41.1	41.4	1.1	2.7
Converted to Effluent 3	16.3								

**Note:** All measurements were made on the same day; therefore only one set of standards was run.

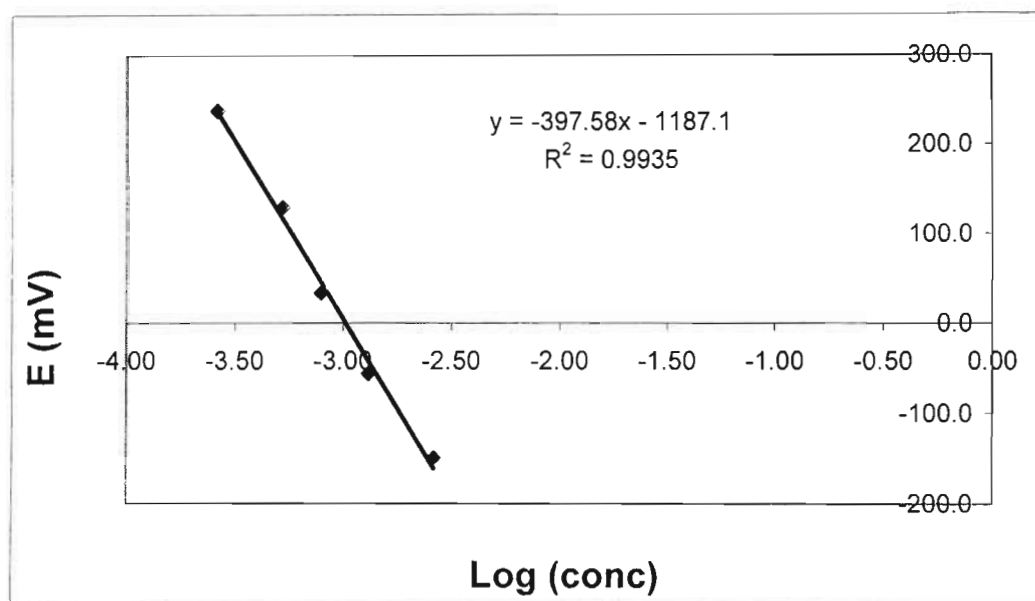


Fig. C.11: Calibration graph for the fluoride determination of the effluent using an ion selective electrode.

$$E = -397.58(\log [F^- (M)]) - 1187.1$$

$$\therefore \log [F^- (M)] = \frac{E + 1187.1}{-397.58}$$

$$\therefore [F^- (M)] = \text{alog} \left( \frac{E + 1187.1}{-397.58} \right)$$

**Sulfide Determination:**

Table C.25: Photometric calculation of the sulfide concentration in the effluent samples.

Sample	[S <sup>2-</sup> ] (ppm)	Absorbance			Mean	Std. Deviation	Coeff. of Variation (%)
		1	2	3			
Blank	0.000	0.001	0.000	0.001	0.001	0.001	58
Standard 1	0.500	0.263	0.269	0.268	0.267	0.003	1.2
Standard 2	1.00	0.540	0.541	0.531	0.537	0.006	1.0
Standard 3	1.50	0.678	0.678	0.683	0.680	0.003	0.4
Standard 4	2.00	0.850	0.844	0.842	0.845	0.004	0.5
Standard 5	3.00	1.393	1.398	1.380	1.390	0.009	0.7
Effluent 1	*	0.000	0.001	0.000	0.000	0.001	0.0
Effluent 2	*	0.000	0.000	0.000	0.000	0.000	0.0
Effluent 3	*	0.000	0.000	0.000	0.000	0.000	0.0

\* = below the limit of detection for the instrument (0.5 ppm)

**Note:** Absorbance readings for all standards and samples are adjusted for the absorbance reading of the blank.

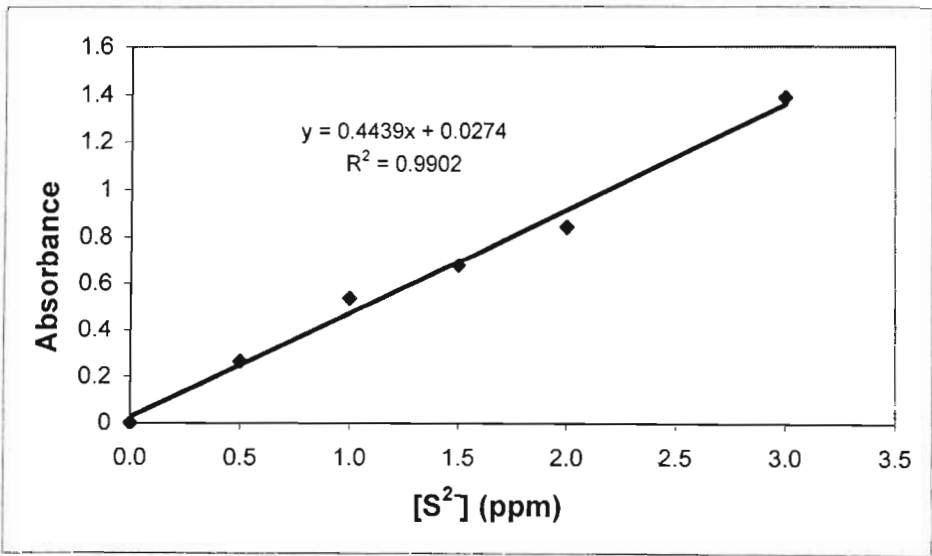


Fig. C.12: Calibration graph for the photometric sulfide determination in the effluent samples.

$$\text{Absorbance} = 0.4439[\text{S}^{2-}] + 0.0274$$

$$\therefore [\text{S}^{2-}] = \frac{\text{Absorbance} - 0.0274}{0.4439}$$

**pH Measurement:**

Table C.26: Results of the pH measurement of the effluent samples.

	pH					
Sample	1	2	3	Mean	Std. Deviation	Coeff. of Variation (%)
Effluent 1	4.44	4.21	4.36	4.34	0.12	2.7
Effluent 2	3.86	3.84	3.95	3.88	0.06	1.5
Effluent 3	6.41	6.45	6.45	6.44	0.02	0.4

**Conductivity Measurement:**

Table C.27: Results of the measurement of the conductivity of the effluent samples.

	Conductivity (μS/cm)					
Sample	1	2	3	Mean (μS/cm)	Std. Deviation (μS/cm)	Coeff. of Variation (%)
Effluent 1	388.2	391.7	390.8	390.2	1.8	0.46
Effluent 2	643.8	649.3	648.0	647.0	2.9	0.45
Effluent 3	195.1	194.3	191.3	193.6	2.0	1.03

**Total Dissolved Solids Determination:**

The tables below show the results of the three sets of gravimetric analysis done to determine the total dissolved solids concentration of the effluent.



Table C.28: Determination of the suspended solids (S.S.) content of the effluent (run 1).

Sample	Mass before filtration (g)			Mass after filtration (g)			Mass of S.S. (g/25ml)		
	1	2	3	1	2	3	1	2	3
Effluent 1	0.8044	0.8045	0.8044	0.7966	0.7971	0.7983	-0.0078	-0.0074	-0.0061
Effluent 2	0.8136	0.8136	0.8136	0.8043	0.8046	0.8049	-0.0093	-0.009	-0.0087
Effluent 3	0.8672	0.8674	0.8675	0.8874	0.8877	0.8879	0.0202	0.0203	0.0204

Table C.29: Determination of the total solids (T.S.) content of the effluent (run 1).

Sample	Mass before filtration (g)			Mass after filtration (g)			Mass of T.S. (g/25ml)		
	1	2	3	1	2	3	1	2	3
Effluent 1	63.8933	63.8929	63.8928	63.9301	63.9287	63.9290	0.0368	0.0358	0.0362
Effluent 2	50.8047	50.8047	50.8048	50.8268	50.8264	50.8265	0.0221	0.0217	0.0217
Effluent 3	52.8215	52.8214	52.8214	52.8503	52.8500	52.8501	0.0288	0.0286	0.0287

Table C.30: Determination of the total dissolved solids (T.D.S.) content of the effluent (run 1).

Sample	Mass of S.S. (g/25ml)			Mass of T.S. (g/25ml)			Mass of T.D.S. (g/25ml)			Mean (g/25ml)	Std. Deviation (g/25ml)	Coeff. of Variation (%)
	1	2	3	1	2	3	1	2	3			
Effluent 1	0.0000	0.0000	0.0000	0.0368	0.0358	0.0362	0.0368	0.0358	0.0362	0.0363	0.0005	1.4
Effluent 2	0.0000	0.0000	0.0000	0.0221	0.0217	0.0217	0.0221	0.0217	0.0217	0.0218	0.0002	1.1
Effluent 3	0.0202	0.0203	0.0204	0.0288	0.0286	0.0287	0.0086	0.0083	0.0083	0.0084	0.0002	2.1

Table C.31: Determination of the suspended solids (S.S.) content of the effluent (run 2).

Sample	Mass before filtration (g)			Mass after filtration (g)			Mass of S.S. (g/25ml)		
	1	2	3	1	2	3	1	2	3
Effluent 1	0.8433	0.8430	0.8430	0.8535	0.8535	0.8536	0.0102	0.0105	0.0106
Effluent 2	0.8204	0.8203	0.8205	0.8176	0.8178	0.8179	-0.0028	-0.0025	-0.0026
Effluent 3	0.8375	0.8378	0.8380	0.8535	0.8534	0.8534	0.0160	0.0156	0.0154

Table C.32: Determination of the total solids (T.S.) content of the effluent (run 2).

Sample	Mass before filtration (g)			Mass after filtration (g)			Mass of T.S. (g/25ml)		
	1	2	3	1	2	3	1	2	3
Effluent 1	63.8805	63.8805	63.8807	63.9254	63.9242	63.9242	0.0449	0.0437	0.0435
Effluent 2	50.7967	50.7966	50.7967	50.8170	50.8167	50.8170	0.0203	0.0201	0.0203
Effluent 3	36.9352	36.9353	36.9354	36.9697	36.9695	36.9695	0.0345	0.0342	0.0341

Table C.33: Determination of the total dissolved solids (T.D.S.) content of the effluent (run 2).

Sample	Mass of S.S. (g/25ml)			Mass of T.S. (g/25ml)			Mass of T.D.S. (g/25ml)			Mean (g/25ml)	Std. Deviation (g/25ml)	Coeff. of Variation (%)
	1	2	3	1	2	3	1	2	3			
Effluent 1	0.0102	0.0105	0.0106	0.0449	0.0437	0.0435	0.0347	0.0332	0.0329	0.0336	0.0010	2.9
Effluent 2	0.0000	0.0000	0.0000	0.0203	0.0201	0.0203	0.0203	0.0201	0.0203	0.0202	0.0001	0.6
Effluent 3	0.0160	0.0156	0.0154	0.0345	0.0342	0.0341	0.0185	0.0186	0.0187	0.0186	0.0001	0.5

Table C.34: Determination of the suspended solids (S.S.) content of the effluent (run 3).

Sample	Mass before filtration (g)			Mass after filtration (g)			Mass of S.S. (g/25ml)		
	1	2	3	1	2	3	1	2	3
Effluent 1	0.8608	0.8609	0.8606	0.8687	0.8688	0.8688	0.0079	0.0079	0.0082
Effluent 2	0.8388	0.8390	0.8390	0.8319	0.8320	0.8320	-0.0069	-0.0070	-0.0070
Effluent 3	0.8181	0.8179	0.8178	0.8268	0.8269	0.8274	0.0087	0.0090	0.0096

Table C.35: Determination of the total solids (T.S.) content of the effluent (run 3).

Sample	Mass before filtration (g)			Mass after filtration (g)			Mass of T.S. (g/25ml)		
	1	2	3	1	2	3	1	2	3
Effluent 1	43.4927	43.4926	43.4926	43.5408	43.5406	43.5402	0.0481	0.0480	0.0476
Effluent 2	17.7381	17.7381	17.7382	17.7714	17.7713	17.7712	0.0333	0.0332	0.0330
Effluent 3	20.9745	20.9744	20.9742	21.0017	21.0018	21.0019	0.0272	0.0274	0.0277

Table C.36: Determination of the total dissolved solids (T.D.S.) content of the effluent (run 3).

Sample	Mass of S.S. (g/25ml)			Mass of T.S. (g/25ml)			Mass of T.D.S. (g/25ml)			Mean (g/25ml)	Std. Deviation (g/25ml)	Coeff. of Variation (%)
	1	2	3	1	2	3	1	2	3			
Effluent 1	0.0079	0.0079	0.0082	0.0481	0.0480	0.0476	0.0402	0.0401	0.0394	0.0399	0.0004	1.1
Effluent 2	0.0000	0.0000	0.0000	0.0333	0.0332	0.0330	0.0333	0.0332	0.0330	0.0332	0.0002	0.5
Effluent 3	0.0087	0.0090	0.0096	0.0272	0.0274	0.0277	0.0185	0.0184	0.0181	0.0183	0.0002	1.1

Table C.37: Compilation of the total dissolved solids results for the effluent samples (9 readings).

Sample	Total Dissolved Solids (g/25ml)									Mean	Std. Deviation	Coeff. of Variation (%)
	1	2	3	4	5	6	7	8	9			
Effluent 1	0.0368	0.0358	0.0362	0.0347	0.0332	0.0329	0.0402	0.0401	0.0394	0.0366	0.0028	7.65
Effluent 2	0.0221	0.0217	0.0217	0.0203	0.0201	0.0203	0.0333	0.0332	0.0330	0.0251	0.0061	24.36
Effluent 3	0.0086	0.0083	0.0083	0.0185	0.0186	0.0187	0.0185	0.0184	0.0181	0.0151	0.0050	33.33

# Appendix D

In this appendix, data collected for the optimisation of the coil cleaning system is presented. This includes data from the gravimetric analyses for the Alukleen, pre-wash, general degreaser and Powerkleen systems as well as photographs used to ascertain the degree of cleanliness and etching afforded by each of the above-mentioned systems.



## D.1 Alukleen System

### Gravimetric Analysis Results for the Optimisation of the Alukleen System:

Table D.1: Gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time (run 1).

Soaking Time (mins)	Alukleen Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
2	1:1	0.8292	0.8291	0.8286	0.9101	0.9103	0.9110	0.0809	0.0812	0.0824	0.0815	0.0008	1
	1:3	0.8230	0.8227	0.8226	0.8821	0.8845	0.8857	0.0591	0.0618	0.0631	0.0613	0.0020	3.3
	1:9	0.8130	0.8130	0.8131	0.8245	0.8252	0.8263	0.0115	0.0122	0.0132	0.0123	0.0009	7
	1:14	0.8272	0.8269	0.8267	0.8315	0.8316	0.8321	0.0043	0.0047	0.0054	0.0048	0.0006	10
	1:19	0.8221	0.8222	0.8220	0.8213	0.8219	0.8222	-0.0008	-0.0003	0.0002	-0.0003	0.0005	200
4	1:1	0.8390	0.8387	0.8384	0.8919	0.8924	0.8930	0.0529	0.0537	0.0546	0.0537	0.0009	2
	1:3	0.8218	0.8214	0.8213	0.8635	0.8651	0.8660	0.0417	0.0437	0.0447	0.0434	0.0015	3.5
	1:9	0.8221	0.8218	0.8214	0.8400	0.8401	0.8402	0.0179	0.0183	0.0188	0.0183	0.0005	2
	1:14	0.8204	0.8201	0.8202	0.8300	0.8301	0.8302	0.0096	0.0100	0.0100	0.0099	0.0002	2
	1:19	0.8280	0.8279	0.8278	0.8345	0.8347	0.8350	0.0065	0.0068	0.0072	0.0068	0.0004	5
6	1:1	0.8319	0.8321	0.8322	0.8824	0.8828	0.8835	0.0505	0.0507	0.0513	0.0508	0.0004	0.8
	1:3	0.8182	0.8179	0.8179	0.8603	0.8604	0.8610	0.0421	0.0425	0.0431	0.0426	0.0005	1
	1:9	0.8288	0.8286	0.8285	0.8415	0.8419	0.8423	0.0127	0.0133	0.0138	0.0133	0.0006	4
	1:14	0.8200	0.8199	0.8201	0.8282	0.8219	0.8299	0.0082	0.0020	0.0098	0.0067	0.0041	62
	1:19	0.8230	0.8229	0.8228	0.8295	0.8299	0.8298	0.0065	0.0070	0.0070	0.0068	0.0003	4



Table D.1 continued.

Soaking Time (mins)	Alukleen Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
8	1:1	0.8213	0.8213	0.8211	0.8599	0.8604	0.8615	0.0386	0.0391	0.0404	0.0394	0.0009	2
	1:3	0.8288	0.8287	0.8288	0.8669	0.8676	0.8679	0.0381	0.0389	0.0391	0.0387	0.0005	1
	1:9	0.8233	0.8231	0.8231	0.8349	0.8356	0.8357	0.0116	0.0125	0.0126	0.0122	0.0006	5
	1:14	0.8208	0.8208	0.8207	0.8225	0.8221	0.8228	0.0017	0.0013	0.0021	0.0017	0.0004	20
	1:19	0.8270	0.8267	0.8269	0.8171	0.8178	0.8186	-0.0099	-0.0089	-0.0083	-0.0090	0.0008	9
10	1:1	0.8327	0.8324	0.8326	0.8980	0.8985	0.9004	0.0653	0.0661	0.0678	0.0664	0.0013	1.9
	1:3	0.8276	0.8272	0.8271	0.8704	0.8709	0.8712	0.0428	0.0437	0.0441	0.0435	0.0007	2
	1:9	0.8294	0.8287	0.8288	0.8291	0.8301	0.8313	-0.0003	0.0014	0.0025	0.0012	0.0014	120
	1:14	0.8244	0.8246	0.8244	0.8403	0.8416	0.8422	0.0159	0.0170	0.0178	0.0169	0.0010	5.6
	1:19	0.8285	0.8285	0.8284	0.8253	0.8260	0.8270	-0.0032	-0.0025	-0.0014	-0.0024	0.0009	40
15	1:1	0.8248	0.8246	0.8247	0.9068	0.9098	0.9104	0.0820	0.0852	0.0857	0.0843	0.0020	2.4
	1:3	0.8374	0.8375	0.8377	0.8941	0.8943	0.8958	0.0567	0.0568	0.0581	0.0572	0.0008	1
	1:9	0.8322	0.8322	0.8320	0.8412	0.8420	0.8439	0.0090	0.0098	0.0119	0.0102	0.0015	15
	1:14	0.8028	0.8029	0.8030	0.8027	0.8030	0.8036	-0.0001	0.0001	0.0006	0.0002	0.0004	200
	1:19	0.8178	0.8173	0.8180	0.8221	0.8221	0.8224	0.0043	0.0048	0.0044	0.0045	0.0003	6
20	1:1	0.8080	0.8078	0.8077	0.8686	0.8694	0.8703	0.0606	0.0616	0.0626	0.0616	0.0010	1.6
	1:3	0.8189	0.8186	0.8185	0.8375	0.8378	0.8381	0.0186	0.0192	0.0196	0.0191	0.0005	3
	1:9	0.8216	0.8217	0.8213	0.8323	0.8332	0.8340	0.0107	0.0115	0.0127	0.0116	0.0010	8.7
	1:14	0.8213	0.8215	0.8214	0.8216	0.8225	0.8233	0.0003	0.0010	0.0019	0.0011	0.0008	80
	1:19	0.8211	0.8210	0.8209	0.8137	0.8140	0.8147	-0.0074	-0.0070	-0.0062	-0.0069	0.0006	9

Table D.2: Gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time (run 2).

Soaking Time (mins)	Alukleen Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
2	1:1	0.8405	0.8404	0.8402	0.8942	0.8951	0.8950	0.0537	0.0547	0.0548	0.0544	0.0006	1
	1:3	0.9024	0.9021	0.9022	0.9360	0.9376	0.9380	0.0336	0.0355	0.0358	0.0350	0.0012	3.4
	1:9	0.8602	0.8600	0.8600	0.8593	0.8602	0.8613	-0.0009	0.0002	0.0013	0.0002	0.0011	550
	1:14	0.8523	0.8521	0.8500	0.8483	0.8491	0.8490	-0.0040	-0.0030	-0.0010	-0.0027	0.0015	57
	1:19	0.9230	0.9233	0.9232	0.9180	0.9185	0.9187	-0.0050	-0.0048	-0.0045	-0.0048	0.0003	5
4	1:1	0.8363	0.8364	0.8362	0.9064	0.9063	0.9071	0.0701	0.0699	0.0709	0.0703	0.0005	0.8
	1:3	0.8427	0.8427	0.8425	0.8515	0.8512	0.8512	0.0088	0.0085	0.0087	0.0087	0.0002	2
	1:9	0.9281	0.9276	0.9276	0.9136	0.9141	0.9143	-0.0145	-0.0135	-0.0133	-0.0138	0.0006	5
	1:14	0.8666	0.8668	0.8666	0.8552	0.8566	0.8570	-0.0114	-0.0102	-0.0096	-0.0104	0.0009	9
	1:19	0.8695	0.8694	0.8692	0.8523	0.8524	0.8535	-0.0172	-0.0170	-0.0157	-0.0166	0.0008	5
6	1:1	0.9014	0.9018	0.9015	0.9511	0.9514	0.9526	0.0497	0.0496	0.0511	0.0501	0.0008	2
	1:3	0.8859	0.8854	0.8852	0.8962	0.8962	0.8964	0.0103	0.0108	0.0112	0.0108	0.0005	4
	1:9	0.8447	0.8449	0.8450	0.8374	0.8379	0.8383	-0.0073	-0.0070	-0.0067	-0.0070	0.0003	4
	1:14	0.9205	0.9211	0.9214	0.9066	0.9067	0.9071	-0.0139	-0.0144	-0.0143	-0.0142	0.0003	2
	1:19	0.8594	0.8594	0.8593	0.8479	0.8482	0.8485	-0.0115	-0.0112	-0.0108	-0.0112	0.0004	3

Table D.2 continued.

Soaking Time (mins)	Alukleen Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
8	1:1	0.8560	0.8557	0.8555	0.9007	0.9007	0.9010	0.0447	0.0450	0.0455	0.0451	0.0004	0.9
	1:3	0.9083	0.9077	0.9079	0.9231	0.9240	0.9243	0.0148	0.0163	0.0164	0.0158	0.0009	6
	1:9	0.8758	0.8763	0.8761	0.8764	0.8768	0.8765	0.0006	0.0005	0.0004	0.0005	0.0001	20
	1:14	0.8297	0.8295	0.8297	0.8296	0.8299	0.8302	-0.0001	0.0004	0.0005	0.0003	0.0003	100
	1:19	0.8458	0.8457	0.8456	0.8413	0.8414	0.8419	-0.0045	-0.0043	-0.0037	-0.0042	0.0004	10
10	1:1	0.9135	0.9137	0.9135	1.0285	1.0284	1.0288	0.1150	0.1147	0.1153	0.1150	0.0003	0.3
	1:3	0.8577	0.8575	0.8578	0.9150	0.9152	0.9149	0.0573	0.0577	0.0571	0.0574	0.0003	0.5
	1:9	0.8425	0.8425	0.8423	0.8632	0.8629	0.8630	0.0207	0.0204	0.0207	0.0206	0.0002	0.8
	1:14	0.8947	0.8945	0.8946	0.9080	0.9078	0.9078	0.0133	0.0133	0.0132	0.0133	0.0001	0.4
	1:19	0.8851	0.8853	0.8854	0.9022	0.9012	0.9016	0.0171	0.0159	0.0162	0.0164	0.0006	4
15	1:1	0.8241	0.8243	0.8241	0.8976	0.8992	0.8994	0.0735	0.0749	0.0753	0.0746	0.0009	1
	1:3	0.9317	0.9317	0.9316	0.9868	0.9873	0.9874	0.0551	0.0556	0.0558	0.0555	0.0004	0.6
	1:9	0.8541	0.8540	0.8541	0.8590	0.8591	0.8593	0.0049	0.0051	0.0052	0.0051	0.0002	3
	1:14	0.8500	0.8499	0.8496	0.8589	0.8592	0.8597	0.0089	0.0093	0.0101	0.0094	0.0006	6
	1:19	0.8928	0.8928	0.8926	0.8912	0.8918	0.8923	-0.0016	-0.0010	-0.0003	-0.0010	0.0007	70
20	1:1	0.8677	0.8671	0.8668	0.9489	0.9495	0.9499	0.0812	0.0824	0.0831	0.0822	0.0010	1.2
	1:3	0.8404	0.8406	0.8402	0.8800	0.8801	0.8804	0.0396	0.0395	0.0402	0.0398	0.0004	1
	1:9	0.9205	0.9202	0.9201	0.9341	0.9342	0.9344	0.0136	0.0140	0.0143	0.0140	0.0004	3
	1:14	0.8850	0.8851	0.8850	0.8828	0.8834	0.8835	-0.0022	-0.0017	-0.0015	-0.0018	0.0004	20
	1:19	0.8304	0.8305	0.8305	0.8332	0.8333	0.8334	0.0028	0.0028	0.0029	0.0028	0.0001	2



Table D.3: Gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time (run 3).

Soaking Time (mins)	Alukleen Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
2	1:1	0.9222	0.9211	0.9208	0.9892	0.9887	0.9884	0.0670	0.0676	0.0676	0.0674	0.0003	0.5
	1:3	0.8668	0.8666	0.8665	0.8458	0.8466	0.8473	-0.0210	-0.0200	-0.0192	-0.0201	0.0009	4
	1:9	0.9006	0.9004	0.9003	0.9129	0.9128	0.9129	0.0123	0.0124	0.0126	0.0124	0.0002	1
	1:14	0.8438	0.8435	0.8435	0.8552	0.8547	0.8547	0.0114	0.0112	0.0112	0.0113	0.0001	1
	1:19	0.9085	0.9082	0.9083	0.9264	0.9260	0.9259	0.0179	0.0178	0.0176	0.0178	0.0002	0.9
4	1:1	0.8619	0.8617	0.8613	0.9236	0.9232	0.9232	0.0617	0.0615	0.0619	0.0617	0.0002	0.3
	1:3	0.8466	0.8461	0.8461	0.8625	0.8623	0.8622	0.0159	0.0162	0.0161	0.0161	0.0002	1
	1:9	0.9150	0.9146	0.9144	0.9168	0.9167	0.9170	0.0018	0.0021	0.0026	0.0022	0.0004	20
	1:14	0.8619	0.8620	0.8619	0.8588	0.8586	0.8587	-0.0031	-0.0034	-0.0032	-0.0032	0.0002	5
	1:19	0.8300	0.8294	0.8295	0.8225	0.8223	0.8224	-0.0075	-0.0071	-0.0071	-0.0072	0.0002	3
6	1:1	0.8949	0.8945	0.8944	0.9677	0.9676	0.9676	0.0728	0.0731	0.0732	0.0730	0.0002	0.3
	1:3	0.8748	0.8746	0.8747	0.9104	0.9101	0.9101	0.0356	0.0355	0.0354	0.0355	0.0001	0.3
	1:9	0.8281	0.8279	0.8277	0.8489	0.8486	0.8484	0.0208	0.0207	0.0207	0.0207	0.0001	0.3
	1:14	0.9117	0.9117	0.9115	0.9334	0.9338	0.9341	0.0217	0.0221	0.0226	0.0221	0.0005	2
	1:19	0.8732	0.8728	0.8728	0.8743	0.8743	0.8741	0.0011	0.0015	0.0013	0.0013	0.0002	20

Table D.3 continued.

Soaking Time (mins)	Alukleen Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
8	1:1	0.8581	0.8579	0.8578	0.9278	0.9280	0.9281	0.0697	0.0701	0.0703	0.0700	0.0003	0.4
	1:3	0.9134	0.9133	0.9130	0.9530	0.9528	0.9528	0.0396	0.0395	0.0398	0.0396	0.0002	0.4
	1:9	0.8722	0.8715	0.8714	0.8808	0.8812	0.8814	0.0086	0.0097	0.0100	0.0094	0.0007	8
	1:14	0.8293	0.8291	0.8290	0.8389	0.8388	0.8390	0.0096	0.0097	0.0100	0.0098	0.0002	2
	1:19	0.9010	0.9007	0.9004	0.9042	0.9044	0.9045	0.0032	0.0037	0.0041	0.0037	0.0005	10
10	1:1	0.8594	0.8587	0.8584	0.9343	0.9345	0.9350	0.0749	0.0758	0.0766	0.0758	0.0009	1
	1:3	0.8274	0.8271	0.8268	0.8732	0.8734	0.8737	0.0458	0.0463	0.0469	0.0463	0.0006	1
	1:9	0.9173	0.9175	0.9171	0.9415	0.9416	0.9418	0.0242	0.0241	0.0247	0.0243	0.0003	1
	1:14	0.8648	0.8639	0.8639	0.8954	0.8950	0.8950	0.0306	0.0311	0.0311	0.0309	0.0003	0.9
	1:19	0.8424	0.8418	0.8415	0.8561	0.8559	0.8560	0.0137	0.0141	0.0145	0.0141	0.0004	3
15	1:1	0.9013	0.9009	0.9007	0.9670	0.9669	0.9668	0.0657	0.0660	0.0661	0.0659	0.0002	0.3
	1:3	0.8347	0.8345	0.8343	0.8732	0.8732	0.8734	0.0385	0.0387	0.0391	0.0388	0.0003	0.8
	1:9	0.8387	0.8386	0.8385	0.8641	0.8638	0.8638	0.0254	0.0252	0.0253	0.0253	0.0001	0.4
	1:14	0.8934	0.8932	0.8933	0.9078	0.9080	0.9080	0.0144	0.0148	0.0147	0.0146	0.0002	1
	1:19	0.8705	0.8701	0.8698	0.8925	0.8922	0.8920	0.0220	0.0221	0.0222	0.0221	0.0001	0.5
20	1:1	0.8346	0.8345	0.8335	0.9374	0.9372	0.9370	0.1028	0.1027	0.1035	0.1030	0.0004	0.4
	1:3	0.9096	0.9104	0.9101	0.9618	0.9620	0.9615	0.0522	0.0516	0.0514	0.0517	0.0004	0.8
	1:9	0.8788	0.8786	0.8782	0.9245	0.9240	0.9243	0.0457	0.0454	0.0461	0.0457	0.0004	0.8
	1:14	0.8380	0.8384	0.8382	0.8801	0.8803	0.8804	0.0421	0.0419	0.0422	0.0421	0.0002	0.4
	1:19	0.9077	0.9075	0.9071	0.9310	0.9311	0.9311	0.0233	0.0236	0.0240	0.0236	0.0004	1

Table D.4: Gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time (run 4).

Soaking Time (mins)	Alukleen Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
2	1:1	0.8164	0.8159	0.8156	0.9224	0.9226	0.9231	0.1060	0.1067	0.1075	0.1067	0.0008	0.7
	1:3	0.8590	0.8589	0.8587	0.9102	0.9111	0.9114	0.0512	0.0522	0.0527	0.0520	0.0008	1
	1:9	0.8468	0.8466	0.8466	0.8498	0.8497	0.8504	0.0030	0.0031	0.0038	0.0033	0.0004	10
	1:14	0.8130	0.8126	0.8124	0.8155	0.8142	0.8141	0.0025	0.0016	0.0017	0.0019	0.0005	30
	1:19	0.8487	0.8487	0.8486	0.8402	0.8406	0.8403	-0.0085	-0.0081	-0.0083	-0.0083	0.0002	2
4	1:1	0.8429	0.8427	0.8427	0.9212	0.9213	0.9212	0.0783	0.0786	0.0785	0.0785	0.0002	0.2
	1:3	0.8190	0.8187	0.8188	0.8562	0.8559	0.8561	0.0372	0.0372	0.0373	0.0372	0.0001	0.2
	1:9	0.8332	0.8329	0.8326	0.8506	0.8509	0.8511	0.0174	0.0180	0.0185	0.0180	0.0006	3
	1:14	0.8380	0.8381	0.8379	0.8459	0.8458	0.8455	0.0079	0.0077	0.0076	0.0077	0.0002	2
	1:19	0.8245	0.8246	0.8243	0.8139	0.8139	0.8143	-0.0106	-0.0107	-0.0100	-0.0104	0.0004	4
6	1:1	0.8419	0.8418	0.8415	0.8996	0.8995	0.8996	0.0577	0.0577	0.0581	0.0578	0.0002	0.4
	1:3	0.8382	0.8380	0.8377	0.8815	0.8812	0.8815	0.0433	0.0432	0.0438	0.0434	0.0003	0.7
	1:9	0.8128	0.8134	0.8130	0.8250	0.8251	0.8248	0.0122	0.0117	0.0118	0.0119	0.0003	2
	1:14	0.8491	0.8492	0.8492	0.8559	0.8565	0.8570	0.0068	0.0073	0.0078	0.0073	0.0005	7
	1:19	0.8388	0.8384	0.8380	0.8400	0.8396	0.8397	0.0012	0.0012	0.0017	0.0014	0.0003	20



Table D.4 continued.

Soaking Time (mins)	Alukleen Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
8	1:1	0.8206	0.8204	0.8200	0.9094	0.9098	0.9100	0.0888	0.0894	0.0900	0.0894	0.0006	0.7
	1:3	0.8447	0.8448	0.8446	0.8843	0.8843	0.8845	0.0396	0.0395	0.0399	0.0397	0.0002	0.5
	1:9	0.8409	0.8412	0.8413	0.8688	0.8684	0.8685	0.0279	0.0272	0.0272	0.0274	0.0004	1
	1:14	0.8199	0.8200	0.8198	0.8303	0.8302	0.8305	0.0104	0.0102	0.0107	0.0104	0.0003	2
	1:19	0.8674	0.8672	0.8671	0.8753	0.8754	0.8754	0.0079	0.0082	0.0083	0.0081	0.0002	3
10	1:1	0.8405	0.8408	0.8406	0.9467	0.9468	0.9468	0.1062	0.1060	0.1062	0.1061	0.0001	0.1
	1:3	0.9107	0.9105	0.9104	0.9729	0.9730	0.9732	0.0622	0.0625	0.0628	0.0625	0.0003	0.5
	1:9	0.8673	0.8674	0.8669	0.9086	0.9086	0.9088	0.0413	0.0412	0.0419	0.0415	0.0004	0.9
	1:14	0.8269	0.8264	0.8262	0.8625	0.8626	0.8628	0.0356	0.0362	0.0366	0.0361	0.0005	1
	1:19	0.8810	0.8807	0.8807	0.9098	0.9096	0.9096	0.0288	0.0289	0.0289	0.0289	0.0001	0.2
15	1:1	0.8545	0.8544	0.8542	0.9253	0.9256	0.9253	0.0708	0.0712	0.0711	0.0710	0.0002	0.3
	1:3	0.8308	0.8310	0.8306	0.9012	0.9017	0.9016	0.0704	0.0707	0.0710	0.0707	0.0003	0.4
	1:9	0.9041	0.9039	0.9040	0.9017	0.9017	0.9015	-0.0024	-0.0022	-0.0025	-0.0024	0.0002	6
	1:14	0.8747	0.8745	0.8747	0.8937	0.8937	0.8936	0.0190	0.0192	0.0189	0.0190	0.0002	0.8
	1:19	0.8301	0.8298	0.8296	0.8228	0.8227	0.8229	-0.0073	-0.0071	-0.0067	-0.0070	0.0003	4
20	1:1	0.9095	0.9095	0.9092	0.9817	0.9817	0.9819	0.0722	0.0722	0.0727	0.0724	0.0003	0
	1:3	0.8649	0.8651	0.8648	0.9044	0.9046	0.9046	0.0395	0.0395	0.0398	0.0396	0.0002	0
	1:9	0.8291	0.8289	0.8289	0.8558	0.8558	0.8558	0.0267	0.0269	0.0269	0.0268	0.0001	0
	1:14	0.9106	0.9105	0.9101	0.9313	0.9313	0.9315	0.0207	0.0208	0.0214	0.0210	0.0004	2
	1:19	0.8659	0.8657	0.8650	0.8000	0.8800	0.8801	-0.0659	0.0143	0.0151	-0.0122	0.0465	382

Table D.5: Averaged gravimetric analysis results for the determination of the most effective Alukleen concentration and soaking time.

		Mass of Dirt Removed (g)														
		Run 1			Run 2			Run 3			Run 4					
Soaking Time (mins)	Alukleen Dilution	1	2	3	1	2	3	1	2	3	1	2	3	Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
2	1:1	0.0809	0.0812	0.0824	0.0537	0.0547	0.0548	0.0670	0.0676	0.0676	0.1060	0.1067	0.1075	0.0775	0.0203	26.2
	1:3	0.0591	0.0618	0.0631	0.0336	0.0355	0.0358	-0.0210	-0.0200	-0.0192	0.0512	0.0522	0.0527	0.0321	0.0330	103
	1:9	0.0115	0.0122	0.0132	-0.0009	0.0002	0.0013	0.0123	0.0124	0.0126	0.0030	0.0031	0.0038	0.0071	0.0057	81
	1:14	0.0043	0.0047	0.0054	-0.0040	-0.0030	-0.0010	0.0114	0.0112	0.0112	0.0025	0.0016	0.0017	0.0038	0.0053	140
	1:19	-0.0008	-0.0003	0.0002	-0.0050	-0.0048	-0.0045	0.0179	0.0178	0.0176	-0.0085	-0.0081	-0.0083	0.0011	0.0105	950
4	1:1	0.0529	0.0537	0.0546	0.0701	0.0699	0.0709	0.0617	0.0615	0.0619	0.0783	0.0786	0.0785	0.0661	0.0097	15
	1:3	0.0417	0.0437	0.0447	0.0088	0.0085	0.0087	0.0159	0.0162	0.0161	0.0372	0.0372	0.0373	0.0263	0.0150	57.1
	1:9	0.0179	0.0183	0.0188	-0.0145	-0.0135	-0.0133	0.0018	0.0021	0.0026	0.0174	0.0180	0.0185	0.0062	0.0138	220
	1:14	0.0096	0.0100	0.0100	-0.0114	-0.0102	-0.0096	-0.0031	-0.0034	-0.0032	0.0079	0.0077	0.0076	0.0010	0.0086	870
	1:19	0.0065	0.0068	0.0072	-0.0172	-0.0170	-0.0157	-0.0075	-0.0071	-0.0071	-0.0106	-0.0107	-0.0100	-0.0069	0.0090	130
6	1:1	0.0505	0.0507	0.0513	0.0497	0.0496	0.0511	0.0728	0.0731	0.0732	0.0577	0.0577	0.0581	0.0580	0.0096	17
	1:3	0.0421	0.0425	0.0431	0.0103	0.0108	0.0112	0.0356	0.0355	0.0354	0.0433	0.0432	0.0438	0.0331	0.0138	41.8
	1:9	0.0127	0.0133	0.0138	-0.0073	-0.0070	-0.0067	0.0208	0.0207	0.0207	0.0122	0.0117	0.0118	0.0097	0.0107	110
	1:14	0.0082	0.0020	0.0098	-0.0139	-0.0144	-0.0143	0.0217	0.0221	0.0226	0.0068	0.0073	0.0078	0.0055	0.0136	250
	1:19	0.0065	0.0070	0.0070	-0.0115	-0.0112	-0.0108	0.0011	0.0015	0.0013	0.0012	0.0012	0.0017	-0.0004	0.0069	2000

Table D.5 continued.

		Mass of Dirt Removed (g)														
		Run 1			Run 2			Run 3			Run 4					
Soaking Time (mins)	Alukleen Dilution	1	2	3	1	2	3	1	2	3	1	2	3	Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
8	1:1	0.0386	0.0391	0.0404	0.0447	0.0450	0.0455	0.0697	0.0701	0.0703	0.0888	0.0894	0.0900	0.0610	0.0210	34.4
	1:3	0.0381	0.0389	0.0391	0.0148	0.0163	0.0164	0.0396	0.0395	0.0398	0.0396	0.0395	0.0399	0.0335	0.0106	31.8
	1:9	0.0116	0.0125	0.0126	0.0006	0.0005	0.0004	0.0086	0.0097	0.0100	0.0279	0.0272	0.0272	0.0124	0.0101	81.8
	1:14	0.0017	0.0013	0.0021	-0.0001	0.0004	0.0005	0.0096	0.0097	0.0100	0.0104	0.0102	0.0107	0.0055	0.0048	87
	1:19	-0.0099	-0.0089	-0.0083	-0.0045	-0.0043	-0.0037	0.0032	0.0037	0.0041	0.0079	0.0082	0.0083	-0.0003	0.0070	2000
10	1:1	0.0653	0.0661	0.0678	0.1150	0.1147	0.1153	0.0749	0.0758	0.0766	0.1062	0.1060	0.1062	0.0908	0.0212	23.3
	1:3	0.0428	0.0437	0.0441	0.0573	0.0577	0.0571	0.0458	0.0463	0.0469	0.0622	0.0625	0.0628	0.0524	0.0081	16
	1:9	-0.0003	0.0014	0.0025	0.0207	0.0204	0.0207	0.0242	0.0241	0.0247	0.0413	0.0412	0.0419	0.0219	0.0150	68.3
	1:14	0.0159	0.0170	0.0178	0.0133	0.0133	0.0132	0.0306	0.0311	0.0311	0.0356	0.0362	0.0366	0.0243	0.0099	41
	1:19	-0.0032	-0.0025	-0.0014	0.0171	0.0159	0.0162	0.0137	0.0141	0.0145	0.0288	0.0289	0.0289	0.0143	0.0116	81.6
15	1:1	0.0820	0.0852	0.0857	0.0735	0.0749	0.0753	0.0657	0.0660	0.0661	0.0708	0.0712	0.0711	0.0740	0.0071	9.6
	1:3	0.0567	0.0568	0.0581	0.0551	0.0556	0.0558	0.0385	0.0387	0.0391	0.0704	0.0707	0.0710	0.0555	0.0118	21.3
	1:9	0.0090	0.0098	0.0119	0.0049	0.0051	0.0052	0.0254	0.0252	0.0253	-0.0024	-0.0022	-0.0025	0.0096	0.0106	110
	1:14	-0.0001	0.0001	0.0006	0.0089	0.0093	0.0101	0.0144	0.0148	0.0147	0.0190	0.0192	0.0189	0.0108	0.0073	68
	1:19	0.0043	0.0048	0.0044	-0.0016	-0.0010	-0.0003	0.0220	0.0221	0.0222	-0.0073	-0.0071	-0.0067	0.0047	0.0114	240
20	1:1	0.0606	0.0616	0.0626	0.0812	0.0824	0.0831	0.1028	0.1027	0.1035	0.0722	0.0722	0.0727	0.0798	0.0159	20.0
	1:3	0.0186	0.0192	0.0196	0.0396	0.0395	0.0402	0.0522	0.0516	0.0514	0.0395	0.0395	0.0398	0.0376	0.0122	32.6
	1:9	0.0107	0.0115	0.0127	0.0136	0.0140	0.0143	0.0457	0.0454	0.0461	0.0267	0.0269	0.0269	0.0245	0.0141	57.6
	1:14	0.0003	0.0010	0.0019	-0.0022	-0.0017	-0.0015	0.0421	0.0419	0.0422	0.0207	0.0208	0.0214	0.0156	0.0184	118
	1:19	-0.0074	-0.0070	-0.0062	0.0028	0.0028	0.0029	0.0233	0.0236	0.0240	-0.0659	0.0143	0.0151	0.0019	0.0245	1300



**Photographic Results for the Optimisation of the Alukleen System:**

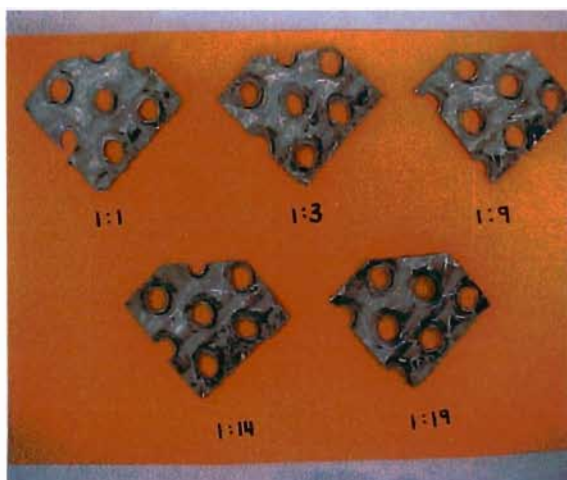


Fig.D.1

Fig. D.1: 'Before' photograph for a soaking time of 2 minutes (Run 1). \*

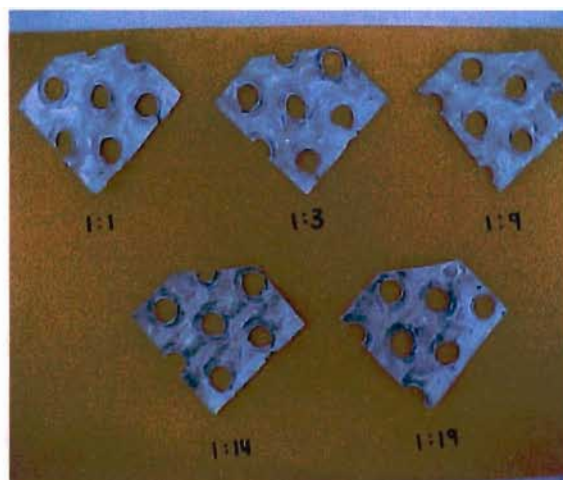


Fig.D.2

Fig. D.2: 'After' photograph for a soaking time of 2 minutes (Run 1). \*

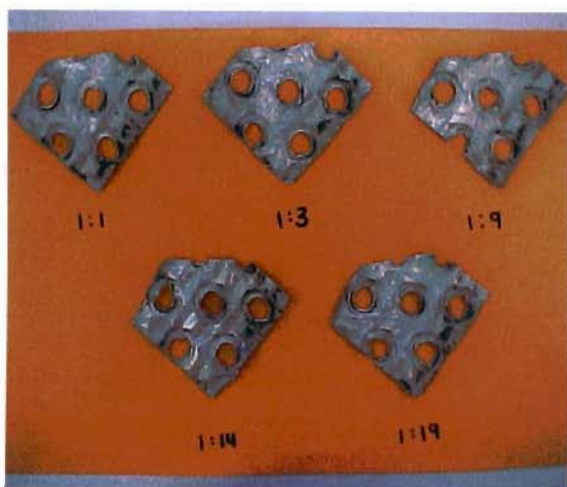


Fig.D.3

Fig. D.3: 'Before' photograph for a soaking time of 4 minutes (Run 1). \*

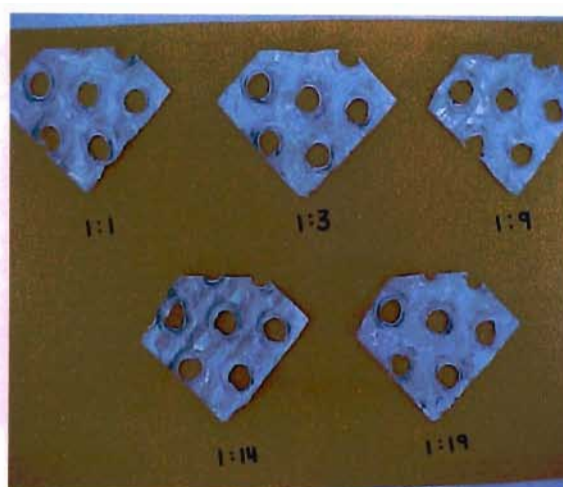


Fig.D.4

Fig. D.4: 'After' photograph for a soaking time of 4 minutes (Run 1). \*

\* The numbers below the aluminium pieces refer to the dilutions of Alukleen in tap water.

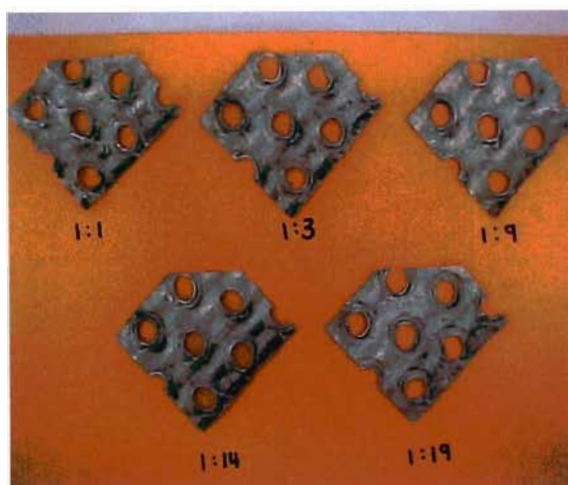


Fig. D.5

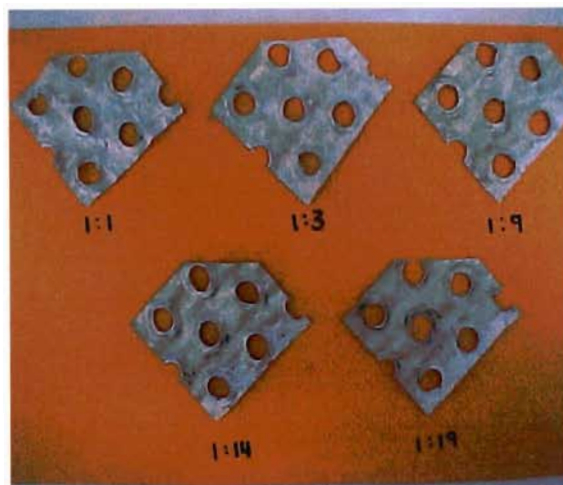


Fig.D.6

Fig. D.5: 'Before' photograph for a soaking time of 6 minutes (Run 1). \*

Fig. D.6: 'After' photograph for a soaking time of 6 minutes (Run 1). \*

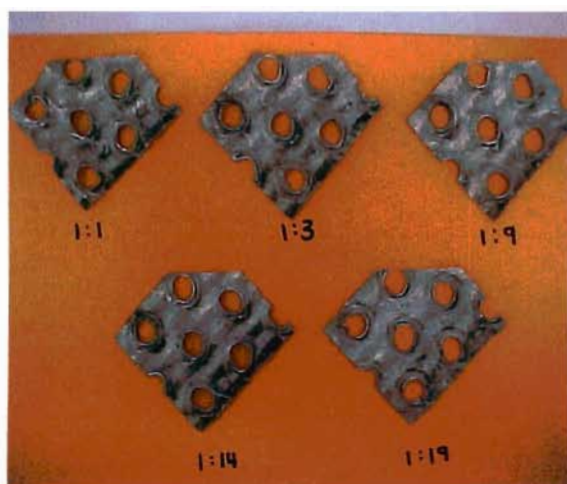


Fig. D.7

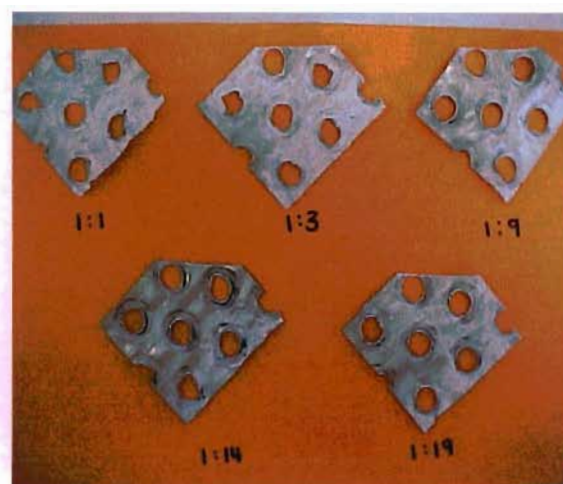


Fig.D.8

Fig. D.7: 'Before' photograph for a soaking time of 8 minutes (Run 1). \*

Fig. D.8: 'After' photograph for a soaking time of 8 minutes (Run 1). \*

\* The numbers below the aluminium pieces refer to the dilutions of Alukleen in tap water.



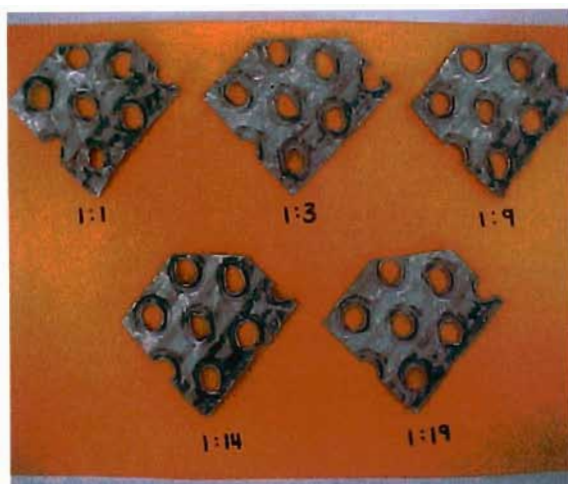


Fig. D.9

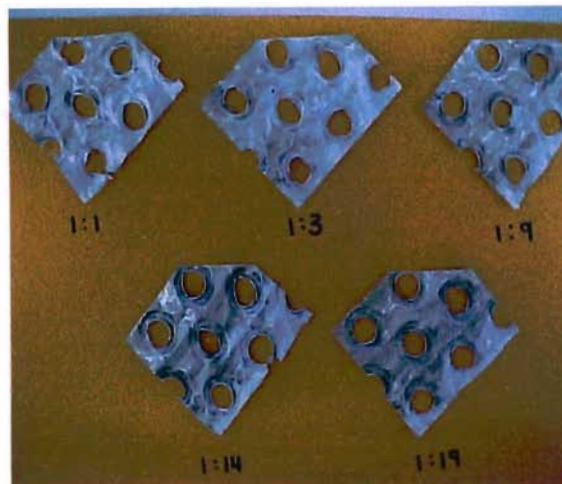


Fig. D.10

Fig. D.9: 'Before' photograph for a soaking time of 10 minutes (Run 1). \*

Fig. D.10: 'After' photograph for a soaking time of 10 minutes (Run 1). \*



Fig.D.11

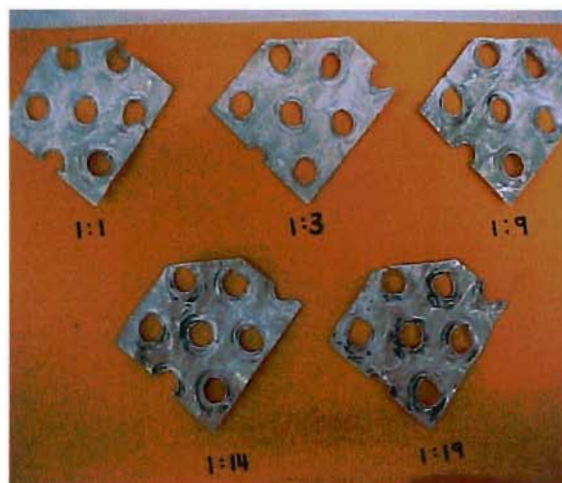


Fig.D.12

Fig. D.11: 'Before' photograph for a soaking time of 15 minutes (Run 1). \*

Fig. D.12: 'After' photograph for a soaking time of 15 minutes (Run 1). \*

\* The numbers below the aluminium pieces refer to the dilutions of Alukleen in tap water.



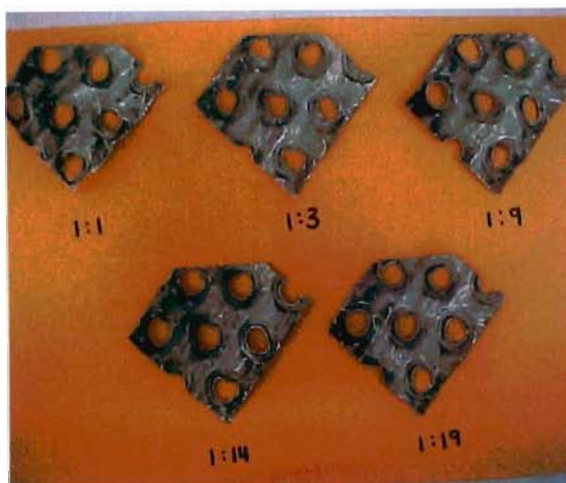


Fig. D.13

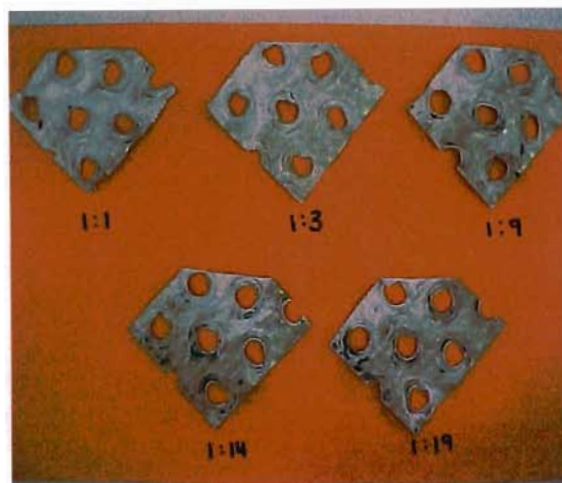


Fig. D.14

Fig. D.13: 'Before' photograph for a soaking time of 20 minutes (Run 1). \*

Fig. D.14: 'After' photograph for a soaking time of 20 minutes (Run 1). \*

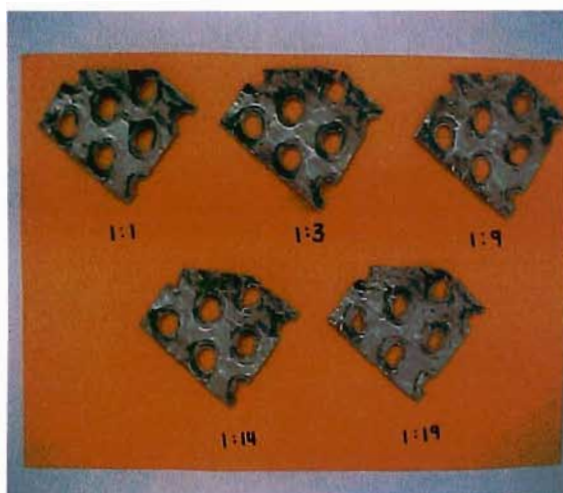


Fig. D.15

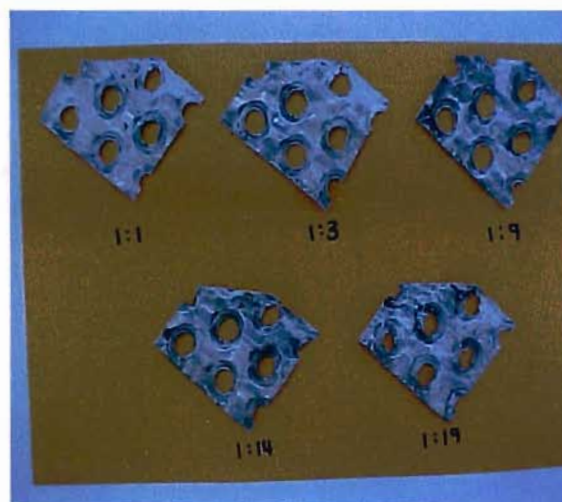


Fig. D.16

Fig. D.15: 'Before' photograph for a soaking time of 2 minutes (Run 2). \*

Fig. D.16: 'After' photograph for a soaking time of 2 minutes (Run 2). \*

\* The numbers below the aluminium pieces refer to the dilutions of Alukleen in tap water.



Fig. D.17

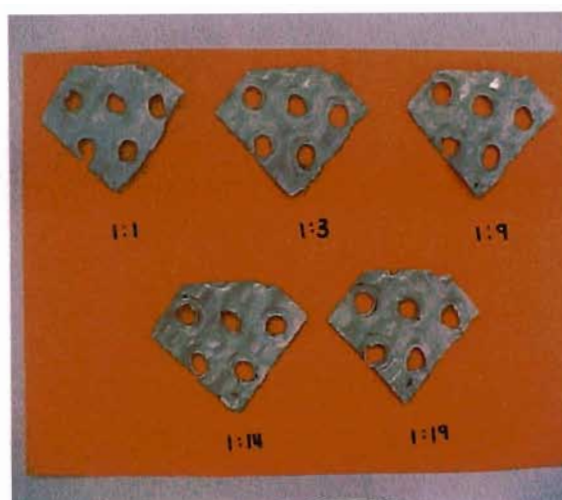


Fig. D.18

Fig. D.17: 'Before' photograph for a soaking time of 4 minutes (Run 2). \*

Fig. D.18: 'After' photograph for a soaking time of 4 minutes (Run 2). \*



Fig. D.19



Fig. D.20

Fig. D.19: 'Before' photograph for a soaking time of 6 minutes (Run 2). \*

Fig. D.20: 'After' photograph for a soaking time of 6 minutes (Run 2). \*

\* The numbers below the aluminium pieces refer to the dilutions of Alukleen in tap water.



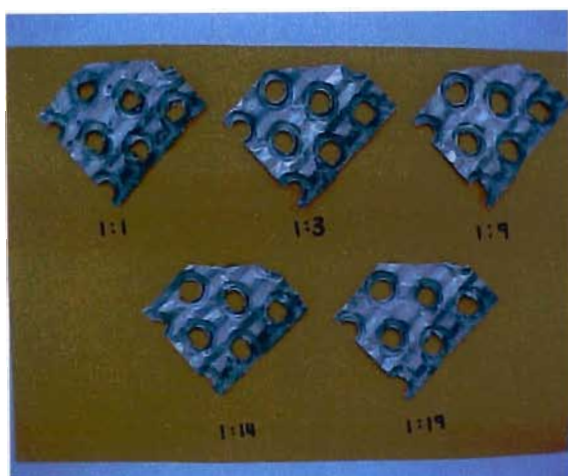


Fig. D.21

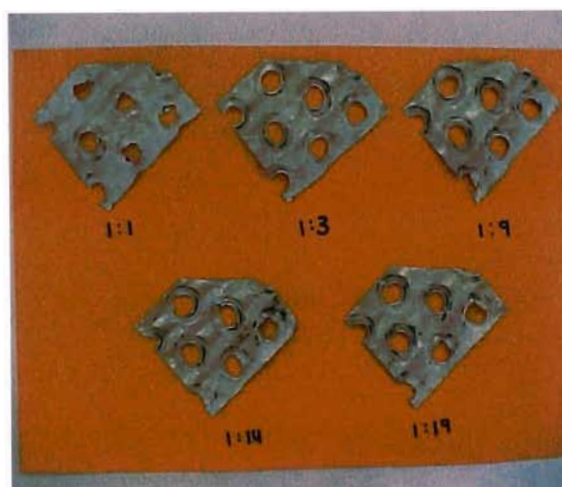


Fig. D.22

Fig. D.21: 'Before' photograph for a soaking time of 8 minutes (Run 2). \*

Fig. D.22: 'After' photograph for a soaking time of 8 minutes (Run 2). \*

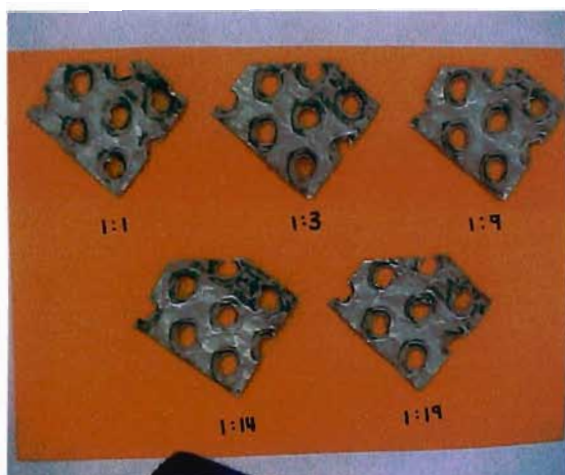


Fig. D.23

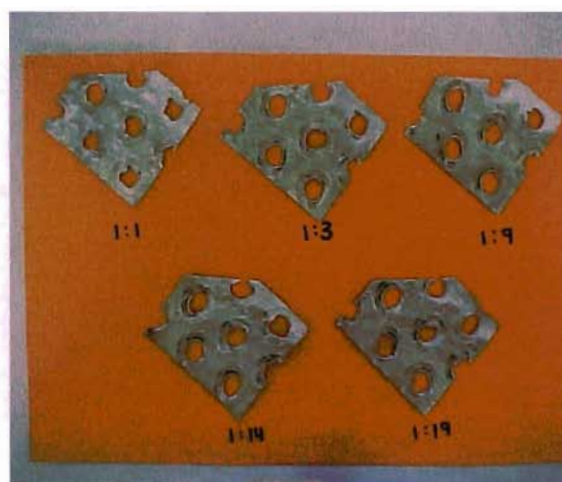


Fig. D.24

Fig. D.23: 'Before' photograph for a soaking time of 10 minutes (Run 2). \*

Fig. D.24: 'After' photograph for a soaking time of 10 minutes (Run 2). \*

\* The numbers below the aluminium pieces refer to the dilutions of Alukleen in tap water.

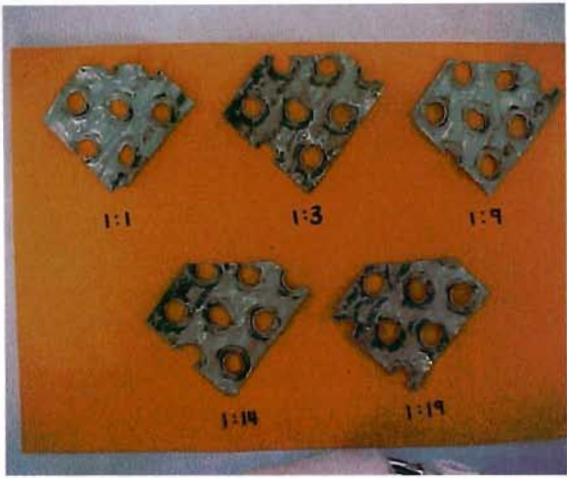


Fig. D.25

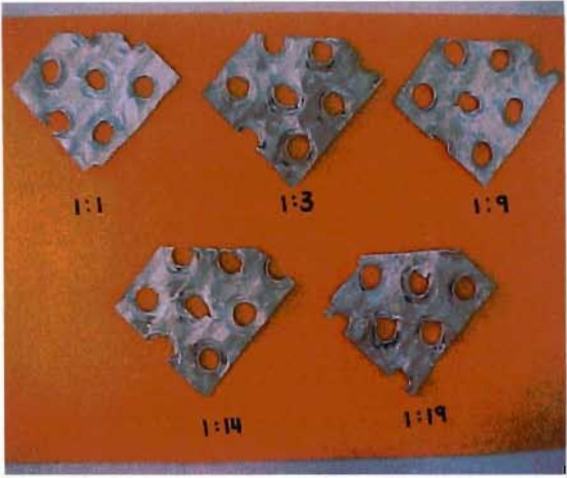


Fig. D.26

Fig. D.25: ‘Before’ photograph for a soaking time of 15 minutes (Run 2). \*  
Fig. D.26: ‘After’ photograph for a soaking time of 15 minutes (Run 2). \*

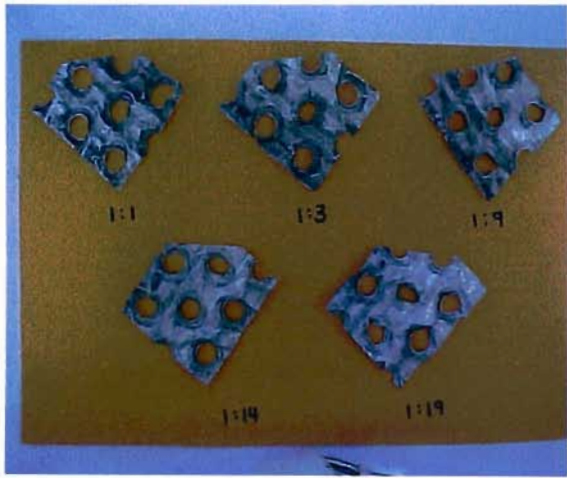


Fig. D.27

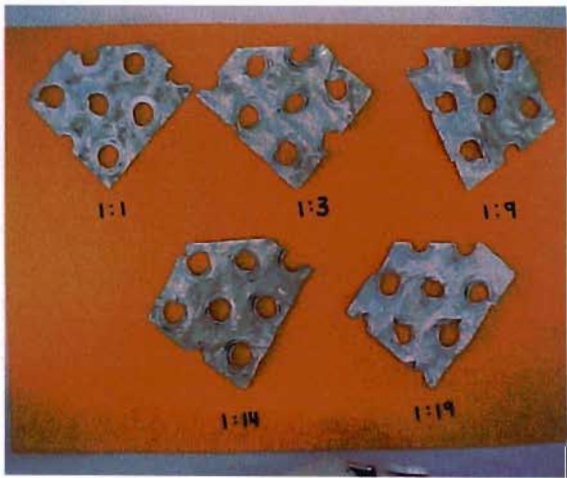


Fig. D.28

Fig. D.27: ‘Before’ photograph for a soaking time of 20 minutes (Run 2). \*  
Fig. D.28: ‘After’ photograph for a soaking time of 20 minutes (Run 2). \*

\* The numbers below the aluminium pieces refer to the dilutions of Alukleen in tap water.

## D.2 Pre-wash Systems

### Gravimetric Analysis Results for the Comparison of Pre-wash Combinations:

Table D.6: Gravimetric analysis results for the comparison of the pre-wash combinations.

Run No.	Pre-wash	Alukleen Dilution	Mass Before Use (g)			Mass After Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
			1	2	3	1	2	3	1	2	3			
1	Green soap	1:9	0.8240	0.8241	0.8240	0.8583	0.8588	0.8589	0.0343	0.0347	0.0349	0.0399	0.0287	71.7
2			0.8078	0.8081	0.8084	0.8179	0.8178	0.8181	0.0101	0.0097	0.0097			
3			0.8449	0.8449	0.8449	0.9202	0.9203	0.9203	0.0753	0.0754	0.0754			
1	Green soap	1:19	0.8455	0.8457	0.8456	0.8678	0.8682	0.8684	0.0223	0.0225	0.0228	0.0140	0.0130	93.1
2			0.8438	0.8439	0.8438	0.8404	0.8405	0.8405	-0.0034	-0.0034	-0.0033			
3			0.8128	0.8129	0.8129	0.8355	0.8356	0.8358	0.0227	0.0227	0.0229			
1	Alukleen (1:9)	Alukleen (1:9)	0.8174	0.8171	0.8172	0.8608	0.8618	0.8618	0.0434	0.0447	0.0446	0.0446	0.0305	68.4
2			0.8543	0.8541	0.8539	0.8632	0.8638	0.8640	0.0089	0.0097	0.0101			
3			0.8382	0.8380	0.8382	0.9180	0.9181	0.9183	0.0798	0.0801	0.0801			
1	Alukleen (1:19)	Alukleen (1:19)	0.8504	0.8504	0.8504	0.8888	0.8890	0.8891	0.0384	0.0386	0.0387	0.0475	0.0446	93.8
2			0.8214	0.8213	0.8216	0.8222	0.8227	0.8227	0.0008	0.0014	0.0011			
3			0.8508	0.8507	0.8509	0.9535	0.9536	0.9538	0.1027	0.1029	0.1029			



**Photographic Results for the Comparison of Pre-wash Systems:**



Fig. D.29

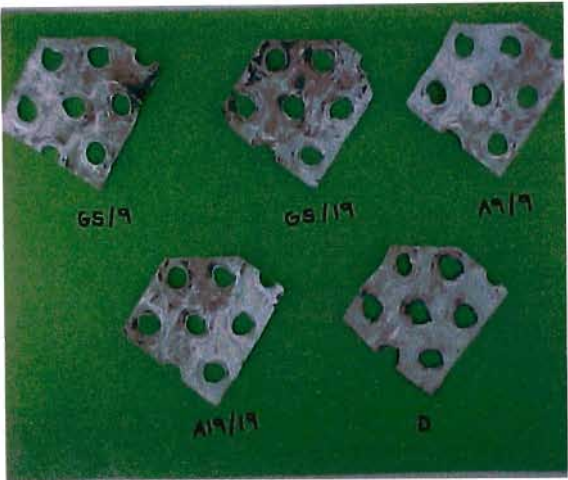


Fig. D.30

Fig. D.29: 'Before' photograph (Run 1). \*

Fig. D.30: 'After' photograph (Run 1). \*

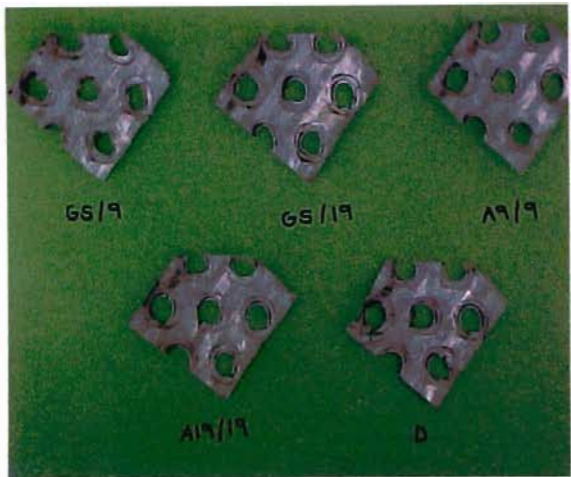


Fig. D.31

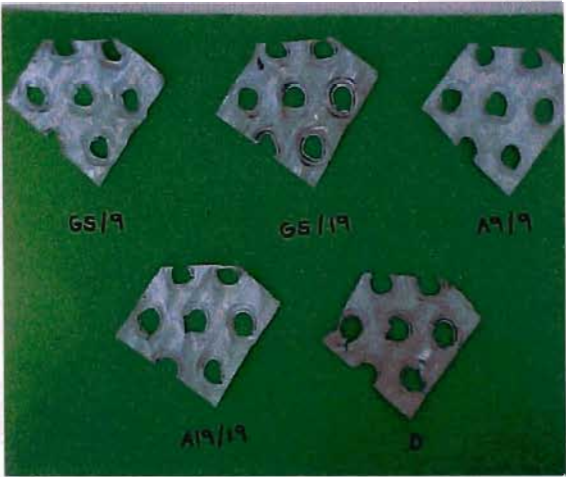


Fig. D.32

Fig. D.31: 'Before' photograph (Run 2). \*

Fig. D.32: 'After' photograph (Run 2). \*

\* The codes below the aluminium pieces refer to the combination used in the pre-wash cleaning system: 'G.S/9' refers to green soap followed by 1:9 Alukleen; 'G.S/ 19' refers to green soap followed by 1:19 Alukleen; 'A9/9' refers to a double wash of 1:9 Alukleen; 'A19/19' refers to a double wash of 1:19 Alukleen; and 'D' refers to a once-off wash with 1:15 Powerkleen.



### D.3 Degreaser Systems

#### Gravimetric Analysis Results for the Comparison of Degreasers:

Table D.7: Gravimetric analysis results for the comparison of Powerkleen concentrations.

Run No.	Dilution	Mass Before Use (g)			Mass After Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
1	1:15	0.8537	0.8537	0.8535	0.8762	0.8761	0.8764	0.0225	0.0224	0.0229	0.0253	0.0042	17
2		0.8344	0.8342	0.8341	0.8643	0.8649	0.8651	0.0299	0.0307	0.031			
3		0.8511	0.8512	0.8512	0.8712	0.8714	0.8719	0.0201	0.0202	0.0207			
4		0.8359	0.8358	0.8357	0.8633	0.8634	0.8636	0.0274	0.0276	0.0279			
1	1:50	0.8408	0.8411	0.841	0.8492	0.8503	0.8508	0.0084	0.0092	0.0098	0.0083	0.0025	30
2		0.8503	0.8506	0.8504	0.8539	0.8549	0.8558	0.0036	0.0043	0.0054			
3		0.8379	0.8379	0.8378	0.8461	0.8472	0.8477	0.0082	0.0093	0.0099			
4		0.8468	0.8467	0.8468	0.8572	0.8572	0.8574	0.0104	0.0105	0.0106			

**Photographic Results for the Comparison of Degreasers:**

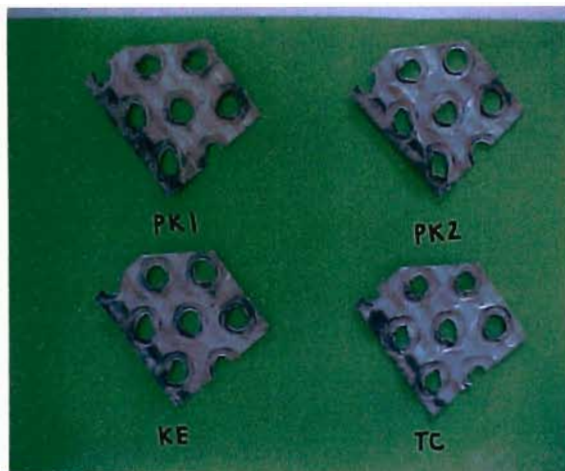


Fig. D.33

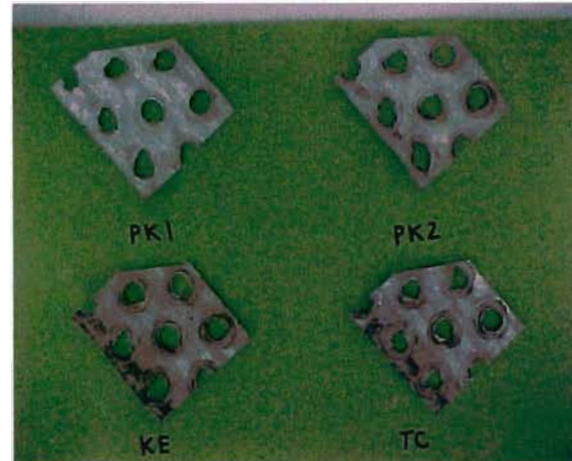


Fig. D.34

Fig. D.33: 'Before' photograph (Run 1). \*

Fig. D.34: 'After' photograph (Run 1). \*



Fig. D.35

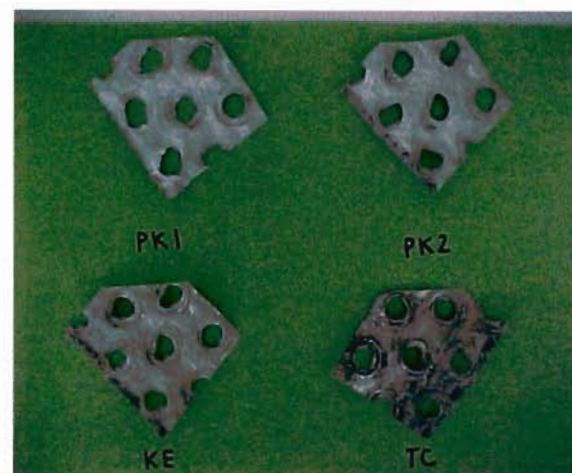


Fig. D.36

Fig. D.35: 'Before' photograph (Run 3). \*

Fig. D.36: 'After' photograph (Run 3). \*

\* PK1 indicates treatment with 1:15 Powerkleen; PK2 indicates treatment with 1:50 Powerkleen; KE indicates treatment with Klengine; and TC indicates treatment with Technicians' Choice Degreaser.

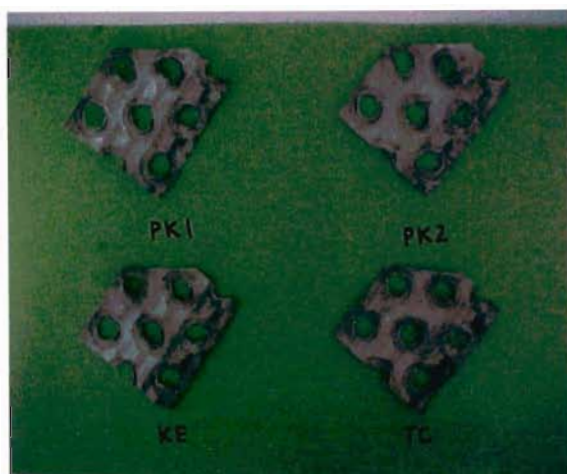


Fig. D.37

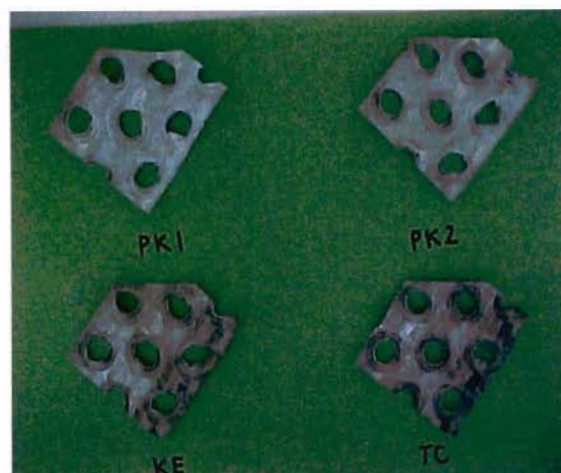


Fig. D.38

Fig. D.37: 'Before' photograph (Run 4). \*

Fig. D.38: 'After' photograph (Run 4). \*

\* PK1 indicates treatment with 1:15 Powerkleen; PK2 indicates treatment with 1:50 Powerkleen; KE indicates treatment with Klengine; and TC indicates treatment with Technicians' Choice Degreaser.

## D.4 Powerkleen System

### Gravimetric Analysis Results for the Optimisation of the Powerkleen System:

Table D.8: Gravimetric analysis results for the determination of the most effective Powerkleen concentration and soaking time (run 1).

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
2	1:15	0.8483	0.8481	0.8480	0.8950	0.8949	0.8948	0.0467	0.0468	0.0468	0.0468	0.0001	0.1
	1:20	0.8367	0.8366	0.8365	0.8759	0.8756	0.8756	0.0392	0.0390	0.0391	0.0391	0.0001	0.3
	1:30	0.8459	0.8459	0.8459	0.8881	0.8883	0.8883	0.0422	0.0424	0.0424	0.0423	0.0001	0.3
	1:40	0.8282	0.8283	0.8284	0.8551	0.8550	0.8549	0.0269	0.0267	0.0265	0.0267	0.0002	0.7
	1:50	0.8500	0.8503	0.8503	0.8838	0.8835	0.8834	0.0338	0.0332	0.0331	0.0334	0.0004	1
	1:60	0.8611	0.8612	0.8611	0.8869	0.8867	0.8867	0.0258	0.0255	0.0256	0.0256	0.0002	0.6
4	1:15	0.8290	0.8290	0.8288	0.8796	0.8794	0.8794	0.0506	0.0504	0.0506	0.0505	0.0001	0.2
	1:20	0.8530	0.8528	0.8528	0.9191	0.9191	0.9191	0.0661	0.0663	0.0663	0.0662	0.0001	0.2
	1:30	0.8579	0.8578	0.8578	0.8878	0.8877	0.8876	0.0299	0.0299	0.0298	0.0299	0.0001	0.2
	1:40	0.8280	0.8283	0.8283	0.8728	0.8727	0.8725	0.0448	0.0444	0.0442	0.0445	0.0003	0.7
	1:50	0.8626	0.8623	0.8622	0.9120	0.9118	0.9119	0.0494	0.0495	0.0497	0.0495	0.0002	0.3
	1:60	0.8464	0.8465	0.8466	0.8873	0.8870	0.8870	0.0409	0.0405	0.0404	0.0406	0.0003	0.7



Table D.8 continued.

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
6	1:15	0.8310	0.8310	0.8308	0.9419	0.9419	0.9418	0.1109	0.1109	0.1110	0.1109	0.0001	0.05
	1:20	0.8524	0.8527	0.8527	0.9423	0.9426	0.9427	0.0899	0.0899	0.0900	0.0899	0.0001	0.06
	1:30	0.8409	0.8409	0.8409	0.9475	0.9476	0.9475	0.1066	0.1067	0.1066	0.1066	0.0001	0.05
	1:40	0.8233	0.8235	0.8235	0.8881	0.8882	0.8880	0.0648	0.0647	0.0645	0.0647	0.0002	0.2
	1:50	0.8464	0.8464	0.8464	0.9137	0.9137	0.9137	0.0673	0.0673	0.0673	0.0673	0.0000	0.00
	1:60	0.8528	0.8528	0.8529	0.9021	0.9021	0.9022	0.0493	0.0493	0.0493	0.0493	0.0000	0.00
8	1:15	0.8136	0.8138	0.8139	0.9287	0.9288	0.9287	0.1151	0.1150	0.1148	0.1150	0.0002	0.1
	1:20	0.8543	0.8543	0.8545	0.9503	0.9502	0.9502	0.0960	0.0959	0.0957	0.0959	0.0002	0.2
	1:30	0.8478	0.8479	0.8480	0.9280	0.9281	0.9278	0.0802	0.0802	0.0798	0.0801	0.0002	0.3
	1:40	0.8221	0.8221	0.8222	0.8841	0.8843	0.8845	0.0620	0.0622	0.0623	0.0622	0.0002	0.2
	1:50	0.8488	0.8489	0.8489	0.8978	0.8977	0.8979	0.0490	0.0488	0.0490	0.0489	0.0001	0.2
	1:60	0.8587	0.8588	0.8589	0.9054	0.9055	0.9054	0.0467	0.0467	0.0465	0.0466	0.0001	0.2
10	1:15	0.8679	0.8680	0.8681	0.9373	0.9374	0.9374	0.0694	0.0694	0.0693	0.0694	0.0001	0.08
	1:20	0.8219	0.8225	0.8226	0.9029	0.9031	0.9029	0.0810	0.0806	0.0803	0.0806	0.0004	0.4
	1:30	0.8551	0.8549	0.8550	0.9100	0.9104	0.9103	0.0549	0.0555	0.0553	0.0552	0.0003	0.6
	1:40	0.8369	0.8372	0.8373	0.8786	0.8787	0.8787	0.0417	0.0415	0.0414	0.0415	0.0002	0.4
	1:50	0.8200	0.8200	0.8201	0.8592	0.8592	0.8592	0.0392	0.0392	0.0391	0.0392	0.0001	0.1
	1:60	0.8537	0.8538	0.8540	0.8795	0.8797	0.8798	0.0258	0.0259	0.0258	0.0258	0.0001	0.2

Table D.8 continued.

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
15	1:15	0.8426	0.8427	0.8426	0.9364	0.9366	0.9366	0.0938	0.0939	0.0940	0.0939	0.0001	0.1
	1:20	0.8325	0.8326	0.8327	0.9093	0.9095	0.9094	0.0768	0.0769	0.0767	0.0768	0.0001	0.1
	1:30	0.8358	0.8359	0.8361	0.8967	0.8965	0.8964	0.0609	0.0606	0.0603	0.0606	0.0003	0.5
	1:40	0.8441	0.8445	0.8446	0.9155	0.9156	0.9153	0.0714	0.0711	0.0707	0.0711	0.0004	0.5
	1:50	0.8273	0.8280	0.8281	0.9019	0.9018	0.9017	0.0746	0.0738	0.0736	0.0740	0.0005	0.7
	1:60	0.8456	0.8457	0.8458	0.9064	0.9065	0.9064	0.0608	0.0608	0.0606	0.0607	0.0001	0.2
20	1:15	0.8374	0.8376	0.8378	0.9000	0.8999	0.8998	0.0626	0.0623	0.0620	0.0623	0.0003	0.5
	1:20	0.8230	0.8228	0.8229	0.8873	0.8871	0.8870	0.0643	0.0643	0.0641	0.0642	0.0001	0.2
	1:30	0.8439	0.8440	0.8441	0.9318	0.9317	0.9317	0.0879	0.0877	0.0876	0.0877	0.0002	0.2
	1:40	0.8497	0.8499	0.8500	0.9193	0.9193	0.9192	0.0696	0.0694	0.0692	0.0694	0.0002	0.3
	1:50	0.8128	0.8129	0.8130	0.8857	0.8857	0.8857	0.0729	0.0728	0.0727	0.0728	0.0001	0.1
	1:60	0.8421	0.8418	0.8419	0.8904	0.8904	0.8903	0.0483	0.0486	0.0484	0.0484	0.0002	0.3



Table D.9: Gravimetric analysis results for the determination of the most effective Powerleen concentration and soaking time (run 2).

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
2	1:15	0.8249	0.8248	0.8249	0.8280	0.8283	0.8283	0.0031	0.0035	0.0034	0.0033	0.0002	6
	1:20	0.8873	0.8876	0.8876	0.8874	0.8876	0.8877	0.0001	0.0000	0.0001	0.0001	0.0001	90
	1:30	0.8305	0.8307	0.8310	0.8309	0.8308	0.8308	0.0004	0.0001	-0.0002	0.0001	0.0003	300
	1:40	0.8207	0.8211	0.8212	0.8149	0.8149	0.8149	-0.0058	-0.0062	-0.0063	-0.0061	0.0003	4
	1:50	0.8308	0.8308	0.8310	0.8251	0.8251	0.8254	-0.0057	-0.0057	-0.0056	-0.0057	0.0001	1
	1:60	0.8772	0.8772	0.8772	0.8674	0.8677	0.8679	-0.0098	-0.0095	-0.0093	-0.0095	0.0003	3
4	1:15	0.8393	0.8392	0.8394	0.8553	0.8559	0.8559	0.0160	0.0167	0.0165	0.0164	0.0004	2
	1:20	0.8252	0.8254	0.8257	0.8339	0.8337	0.8339	0.0087	0.0083	0.0082	0.0084	0.0003	3
	1:30	0.8109	0.8113	0.8115	0.8116	0.8119	0.8120	0.0007	0.0006	0.0005	0.0006	0.0001	20
	1:40	0.8576	0.8578	0.8579	0.8546	0.8551	0.8552	-0.0030	-0.0027	-0.0027	-0.0028	0.0002	6
	1:50	0.8331	0.8330	0.8330	0.8281	0.8282	0.8281	-0.0050	-0.0048	-0.0049	-0.0049	0.0001	2
	1:60	0.8266	0.8269	0.8272	0.8211	0.8209	0.8210	-0.0055	-0.0060	-0.0062	-0.0059	0.0004	6

Table D.9 continued.

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
6	1:15	0.7919	0.7921	0.7920	0.8335	0.8336	0.8337	0.0416	0.0415	0.0417	0.0416	0.0001	0.2
	1:20	0.8600	0.8598	0.8598	0.8649	0.8649	0.8650	0.0049	0.0051	0.0052	0.0051	0.0002	3
	1:30	0.8440	0.8440	0.8441	0.8473	0.8476	0.8473	0.0033	0.0036	0.0032	0.0034	0.0002	6
	1:40	0.8096	0.8102	0.8103	0.8164	0.8165	0.8167	0.0068	0.0063	0.0064	0.0065	0.0003	4
	1:50	0.8096	0.8093	0.8092	0.8036	0.8038	0.8038	-0.0060	-0.0055	-0.0054	-0.0056	0.0003	6
	1:60	0.8874	0.8873	0.8873	0.8875	0.8880	0.8882	0.0001	0.0007	0.0009	0.0006	0.0004	70
8	1:15	0.8409	0.8409	0.8409	0.8814	0.8816	0.8814	0.0405	0.0407	0.0405	0.0406	0.0001	0.3
	1:20	0.8096	0.8099	0.8100	0.8386	0.8390	0.8389	0.0290	0.0291	0.0289	0.0290	0.0001	0.3
	1:30	0.8275	0.8276	0.8276	0.8600	0.8604	0.8605	0.0325	0.0328	0.0329	0.0327	0.0002	0.6
	1:40	0.8627	0.8631	0.8633	0.8698	0.8696	0.8695	0.0071	0.0065	0.0062	0.0066	0.0005	7
	1:50	0.8267	0.8273	0.8276	0.8321	0.8321	0.8321	0.0054	0.0048	0.0045	0.0049	0.0005	9
	1:60	0.8211	0.8213	0.8214	0.8399	0.8400	0.8399	0.0188	0.0187	0.0185	0.0187	0.0002	0.8
10	1:15	0.8051	0.8052	0.8053	0.8672	0.8674	0.8675	0.0621	0.0622	0.0622	0.0622	0.0001	0.09
	1:20	0.8783	0.8781	0.8782	0.9210	0.9213	0.9213	0.0427	0.0432	0.0431	0.0430	0.0003	0.6
	1:30	0.8421	0.8422	0.8423	0.8692	0.8693	0.8694	0.0271	0.0271	0.0271	0.0271	0.0000	0.00
	1:40	0.8222	0.8223	0.8222	0.8607	0.8608	0.8609	0.0385	0.0385	0.0387	0.0386	0.0001	0.3
	1:50	0.8189	0.8188	0.8188	0.8517	0.8515	0.8512	0.0328	0.0327	0.0324	0.0326	0.0002	0.6
	1:60	0.8672	0.8672	0.8673	0.9064	0.9061	0.9059	0.0392	0.0389	0.0386	0.0389	0.0003	0.8

Table D.9 continued.

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
15	1:15	0.8270	0.8270	0.8270	0.8595	0.8596	0.8595	0.0325	0.0326	0.0325	0.0325	0.0001	0.2
	1:20	0.8227	0.8230	0.8232	0.8356	0.8356	0.8357	0.0129	0.0126	0.0125	0.0127	0.0002	2
	1:30	0.8206	0.8207	0.8205	0.8409	0.8409	0.8410	0.0203	0.0202	0.0205	0.0203	0.0002	0.8
	1:40	0.8819	0.8820	0.8821	0.9169	0.9168	0.9168	0.0350	0.0348	0.0347	0.0348	0.0002	0.4
	1:50	0.8167	0.8170	0.8167	0.8496	0.8496	0.8497	0.0329	0.0326	0.0330	0.0328	0.0002	0.6
	1:60	0.8453	0.8450	0.8451	0.8742	0.8743	0.8742	0.0289	0.0293	0.0291	0.0291	0.0002	0.7
20	1:15	0.8125	0.8123	0.8124	0.9376	0.9374	0.9373	0.1251	0.1251	0.1249	0.1250	0.0001	0.09
	1:20	0.8760	0.8760	0.8759	1.0104	1.0105	1.0104	0.1344	0.1345	0.1345	0.1345	0.0001	0.04
	1:30	0.8191	0.8193	0.8193	0.9479	0.9476	0.9474	0.1288	0.1283	0.1281	0.1284	0.0004	0.3
	1:40	0.8200	0.8197	0.8199	0.9155	0.9155	0.9154	0.0955	0.0958	0.0955	0.0956	0.0002	0.2
	1:50	0.8133	0.8133	0.8135	0.8833	0.8834	0.8833	0.0700	0.0701	0.0698	0.0700	0.0002	0.2
	1:60	0.8814	0.8816	0.8816	0.9580	0.9557	0.9556	0.0766	0.0741	0.0740	0.0749	0.0015	2.0



Table D.10: Gravimetric analysis results for the determination of the most effective Powerkleen concentration and soaking time (run 3).

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
2	1:15	0.8319	0.8317	0.8314	0.8801	0.8800	0.8801	0.0482	0.0483	0.0487	0.0484	0.0003	0.5
	1:20	0.8054	0.8052	0.8051	0.8464	0.8462	0.8466	0.0410	0.0410	0.0415	0.0412	0.0003	0.7
	1:30	0.8303	0.8302	0.8301	0.8489	0.8491	0.8495	0.0186	0.0189	0.0194	0.0190	0.0004	2
	1:40	0.8689	0.8688	0.8689	0.8943	0.8946	0.8949	0.0254	0.0258	0.0260	0.0257	0.0003	1
	1:50	0.8242	0.8241	0.8241	0.8222	0.8236	0.8242	-0.0020	-0.0005	0.0001	-0.0008	0.0011	140
	1:60	0.8148	0.8148	0.8147	0.8138	0.8141	0.8147	-0.0010	-0.0007	0.0000	-0.0006	0.0005	90
4	1:15	0.8146	0.8149	0.8147	0.9404	0.9411	0.9415	0.1258	0.1262	0.1268	0.1263	0.0005	0.4
	1:20	0.8521	0.8521	0.8521	0.8916	0.8925	0.8927	0.0395	0.0404	0.0406	0.0402	0.0006	1
	1:30	0.8276	0.8277	0.8275	0.8487	0.8494	0.8499	0.0211	0.0217	0.0224	0.0217	0.0007	3
	1:40	0.8112	0.8109	0.8107	0.8240	0.8245	0.8251	0.0128	0.0136	0.0144	0.0136	0.0008	6
	1:50	0.7967	0.7965	0.7962	0.7930	0.7934	0.7939	-0.0037	-0.0031	-0.0023	-0.0030	0.0007	20
	1:60	0.8552	0.8548	0.8547	0.8477	0.8483	0.8486	-0.0075	-0.0065	-0.0061	-0.0067	0.0007	10

Table D.10 continued.

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
6	1:15	0.8303	0.8306	0.8303	0.9013	0.9019	0.9022	0.0710	0.0713	0.0719	0.0714	0.0005	0.6
	1:20	0.8089	0.8090	0.8086	0.8710	0.8713	0.8716	0.0621	0.0623	0.0630	0.0625	0.0005	0.8
	1:30	0.8272	0.8269	0.8268	0.8597	0.8604	0.8609	0.0325	0.0335	0.0341	0.0334	0.0008	2
	1:40	0.8547	0.8544	0.8543	0.8829	0.8834	0.8837	0.0282	0.0290	0.0294	0.0289	0.0006	2
	1:50	0.8467	0.8468	0.8467	0.8625	0.8631	0.8636	0.0158	0.0163	0.0169	0.0163	0.0006	3
	1:60	0.8321	0.8322	0.8321	0.8470	0.8471	0.8479	0.0149	0.0149	0.0158	0.0152	0.0005	3
8	1:15	0.8029	0.8030	0.8028	0.8892	0.8897	0.8902	0.0863	0.0867	0.0874	0.0868	0.0006	0.6
	1:20	0.8635	0.8638	0.8635	0.8997	0.9001	0.9005	0.0362	0.0363	0.0370	0.0365	0.0004	1
	1:30	0.8309	0.8309	0.8309	0.8500	0.8507	0.8512	0.0191	0.0198	0.0203	0.0197	0.0006	3
	1:40	0.8137	0.8134	0.8133	0.8227	0.8232	0.8236	0.0090	0.0098	0.0103	0.0097	0.0007	7
	1:50	0.7989	0.7988	0.7988	0.7999	0.8006	0.8012	0.0010	0.0018	0.0024	0.0017	0.0007	40
	1:60	0.8572	0.8571	0.8570	0.8512	0.8519	0.8524	-0.0060	-0.0052	-0.0046	-0.0053	0.0007	10
10	1:15	0.8251	0.8250	0.8249	0.9214	0.9222	0.9225	0.0963	0.0972	0.0976	0.0970	0.0007	0.7
	1:20	0.8131	0.8131	0.8129	0.8750	0.8755	0.8759	0.0619	0.0624	0.0630	0.0624	0.0006	0.9
	1:30	0.8009	0.8005	0.8004	0.8340	0.8344	0.8347	0.0331	0.0339	0.0343	0.0338	0.0006	2
	1:40	0.8650	0.8648	0.8647	0.8784	0.8785	0.8794	0.0134	0.0137	0.0147	0.0139	0.0007	5
	1:50	0.8280	0.8278	0.8277	0.8253	0.8260	0.8263	-0.0027	-0.0018	-0.0014	-0.0020	0.0007	30
	1:60	0.7910	0.7914	0.7910	0.7906	0.7913	0.7917	-0.0004	-0.0001	0.0007	0.0001	0.0006	900



Table D.10 continued.

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
15	1:15	0.8150	0.8148	0.8147	0.8989	0.8992	0.8997	0.0839	0.0844	0.0850	0.0844	0.0006	0.7
	1:20	0.8458	0.8459	0.8456	0.8791	0.8795	0.8798	0.0333	0.0336	0.0342	0.0337	0.0005	1
	1:30	0.8070	0.8071	0.8069	0.8185	0.8191	0.8196	0.0115	0.0120	0.0127	0.0121	0.0006	5
	1:40	0.8040	0.8039	0.8038	0.8182	0.8188	0.8193	0.0142	0.0149	0.0155	0.0149	0.0007	4
	1:50	0.8013	0.8012	0.8010	0.8020	0.8023	0.8026	0.0007	0.0011	0.0016	0.0011	0.0005	40
	1:60	0.8581	0.8580	0.8579	0.8503	0.8057	0.8512	-0.0078	-0.0523	-0.0067	-0.0223	0.0260	117
20	1:15	0.8208	0.8209	0.8207	0.9660	0.9658	0.9657	0.1452	0.1449	0.1450	0.1450	0.0002	0.1
	1:20	0.8151	0.8154	0.8152	0.9047	0.9045	0.9044	0.0896	0.0891	0.0892	0.0893	0.0003	0.3
	1:30	0.8105	0.8104	0.8103	0.8697	0.8697	0.8696	0.0592	0.0593	0.0593	0.0593	0.0001	0.1
	1:40	0.8717	0.8718	0.8718	0.9702	0.9702	0.9702	0.0985	0.0984	0.0984	0.0984	0.0001	0.06
	1:50	0.8120	0.8120	0.8120	0.8486	0.8487	0.8486	0.0366	0.0367	0.0366	0.0366	0.0001	0.2
	1:60	0.8117	0.8114	0.8114	0.8471	0.8471	0.8471	0.0354	0.0357	0.0357	0.0356	0.0002	0.5

Table D.11: Gravimetric analysis results for the determination of the most effective Powerleen concentration and soaking time (run 4).

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
2	1:15	0.8203	0.8203	0.8202	0.9322	0.9321	0.9321	0.1119	0.1118	0.1119	0.1119	0.0001	0.05
	1:20	0.8802	0.8800	0.8798	0.9394	0.9390	0.9390	0.0592	0.0590	0.0592	0.0591	0.0001	0.2
	1:30	0.8560	0.8558	0.8555	0.8974	0.8974	0.8973	0.0414	0.0416	0.0418	0.0416	0.0002	0.5
	1:40	0.8311	0.8310	0.8310	0.8734	0.8729	0.8729	0.0423	0.0419	0.0419	0.0420	0.0002	0.5
	1:50	0.8307	0.8307	0.8304	0.8665	0.8664	0.8664	0.0358	0.0357	0.0360	0.0358	0.0002	0.4
	1:60	0.8882	0.8880	0.8882	0.9115	0.9114	0.9115	0.0233	0.0234	0.0233	0.0233	0.0001	0.2
4	1:15	0.8467	0.8461	0.8461	0.9519	0.9519	0.9519	0.1052	0.1058	0.1058	0.1056	0.0003	0.3
	1:20	0.8159	0.8159	0.8158	0.8714	0.8711	0.8709	0.0555	0.0552	0.0551	0.0553	0.0002	0.4
	1:30	0.8014	0.8014	0.8012	0.8339	0.8336	0.8337	0.0325	0.0322	0.0325	0.0324	0.0002	0.5
	1:40	0.8779	0.8780	0.8778	0.9076	0.9076	0.9075	0.0297	0.0296	0.0297	0.0297	0.0001	0.2
	1:50	0.8555	0.8564	0.8565	0.8772	0.8770	0.8769	0.0217	0.0206	0.0204	0.0209	0.0007	3
	1:60	0.8284	0.8287	0.8287	0.8475	0.8471	0.8469	0.0191	0.0184	0.0182	0.0186	0.0005	3

Table D.11 continued.

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
6	1:15	0.8166	0.8132	0.8131	0.9709	0.9709	0.9709	0.1543	0.1577	0.1578	0.1566	0.0020	1.3
	1:20	0.8830	0.8830	0.8830	0.9542	0.9540	0.9537	0.0712	0.0710	0.0707	0.0710	0.0003	0.4
	1:30	0.8305	0.8307	0.8305	0.8836	0.8835	0.8835	0.0531	0.0528	0.0530	0.0530	0.0002	0.3
	1:40	0.8243	0.8240	0.8240	0.8572	0.8569	0.8568	0.0329	0.0329	0.0328	0.0329	0.0001	0.2
	1:50	0.8075	0.8074	0.8703	0.8285	0.8284	0.8283	0.0210	0.0210	-0.0420	0.0000	0.0364	0.00
	1:60	0.8720	0.8720	0.8719	0.8933	0.8931	0.8932	0.0213	0.0211	0.0213	0.0212	0.0001	0.5
8	1:15	0.8468	0.8468	0.8468	0.9401	0.9403	0.9403	0.0933	0.0935	0.0935	0.0934	0.0001	0.1
	1:20	0.8240	0.8234	0.8234	0.8604	0.8604	0.8605	0.0364	0.0370	0.0371	0.0368	0.0004	1
	1:30	0.8282	0.8281	0.8282	0.8477	0.8481	0.8482	0.0195	0.0200	0.0200	0.0198	0.0003	1
	1:40	0.8778	0.8775	0.8775	0.8942	0.8943	0.8943	0.0164	0.0168	0.0168	0.0167	0.0002	1
	1:50	0.8378	0.8375	0.8376	0.8410	0.8411	0.8412	0.0032	0.0036	0.0036	0.0035	0.0002	7
	1:60	0.8334	0.8334	0.8331	0.8296	0.8298	0.8299	-0.0038	-0.0036	-0.0032	-0.0035	0.0003	9
10	1:15	0.7982	0.7983	0.7983	0.8963	0.8963	0.8963	0.0981	0.0980	0.0980	0.0980	0.0001	0.06
	1:20	0.8775	0.8778	0.8777	0.9026	0.9028	0.9029	0.0251	0.0250	0.0252	0.0251	0.0001	0.4
	1:30	0.8743	0.8434	0.8434	0.8681	0.8679	0.8680	-0.0062	0.0245	0.0246	0.0143	0.0178	124
	1:40	0.8212	0.8212	0.8212	0.8376	0.8379	0.8380	0.0164	0.0167	0.0168	0.0166	0.0002	1
	1:50	0.8201	0.8199	0.8198	0.8267	0.8267	0.8266	0.0066	0.0068	0.0068	0.0067	0.0001	2
	1:60	0.8878	0.8875	0.8876	0.8840	0.8841	0.8844	-0.0038	-0.0034	-0.0032	-0.0035	0.0003	9

Table D.11 continued.

Soaking Time (mins)	Dilution	Mass before Use (g)			Mass after Use (g)			Mass of Dirt Removed (g)			Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		1	2	3	1	2	3	1	2	3			
15	1:15	0.8478	0.8479	0.8477	0.9282	0.9285	0.9285	0.0804	0.0806	0.0808	0.0806	0.0002	0.2
	1:20	0.8179	0.8176	0.8176	0.8769	0.8769	0.8771	0.0590	0.0593	0.0595	0.0593	0.0003	0.4
	1:30	0.8137	0.8138	0.8138	0.8344	0.8346	0.8349	0.0207	0.0208	0.0211	0.0209	0.0002	1
	1:40	0.8614	0.8616	0.8616	0.8764	0.8768	0.8770	0.0150	0.0152	0.0154	0.0152	0.0002	1
	1:50	0.8461	0.8467	0.8467	0.8589	0.8586	0.8585	0.0128	0.0119	0.0118	0.0122	0.0006	5
	1:60	0.8186	0.8183	0.8182	0.8320	0.8324	0.8324	0.0134	0.0141	0.0142	0.0139	0.0004	3
20	1:15	0.8237	0.8242	0.8242	0.9143	0.9144	0.9149	0.0906	0.0902	0.0907	0.0905	0.0003	0.3
	1:20	0.8766	0.8761	0.8760	0.9123	0.9130	0.9132	0.0357	0.0369	0.0372	0.0366	0.0008	2
	1:30	0.8379	0.8376	0.8374	0.8506	0.8513	0.8517	0.0127	0.0137	0.0143	0.0136	0.0008	6
	1:40	0.8060	0.8060	0.8060	0.8269	0.8269	0.8268	0.0209	0.0209	0.0208	0.0209	0.0001	0.3
	1:50	0.8143	0.8140	0.8140	0.8116	0.8121	0.8123	-0.0027	-0.0019	-0.0017	-0.0021	0.0005	30
	1:60	0.8734	0.8735	0.8735	0.8716	0.8714	0.8716	-0.0018	-0.0021	-0.0019	-0.0019	0.0002	8



Table D.12: Compilation of the gravimetric analysis results for the determination of the most effective Powerkleen concentration and soaking time.

Soaking Time (mins)	Powerkleen Dilution	Mass of Dirt (g)				Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		Run 1	Run 2	Run 3	Run 4			
2	1:15	0.0468	0.0033	0.0484	0.1119	0.0526	0.0447	85.0
	1:20	0.0391	0.0001	0.0412	0.0591	0.0349	0.0249	71.4
	1:30	0.0423	0.0001	0.0190	0.0416	0.0258	0.0202	78.6
	1:40	0.0267	-0.0061	0.0257	0.0420	0.0221	0.0202	91.5
	1:50	0.0334	-0.0057	-0.0008	0.0358	0.0157	0.0220	140
	1:60	0.0256	-0.0095	-0.0006	0.0233	0.0097	0.0175	180
4	1:15	0.0505	0.0164	0.1263	0.1056	0.0747	0.0503	67.4
	1:20	0.0662	0.0084	0.0402	0.0553	0.0425	0.0251	59.1
	1:30	0.0299	0.0006	0.0217	0.0324	0.0212	0.0144	68.3
	1:40	0.0445	-0.0028	0.0136	0.0297	0.0212	0.0204	96.0
	1:50	0.0495	-0.0049	-0.0030	0.0209	0.0156	0.0255	163
	1:60	0.0406	-0.0059	-0.0067	0.0186	0.0116	0.0226	194
6	1:15	0.1109	0.0416	0.0714	0.1566	0.0951	0.0499	52.4
	1:20	0.0899	0.0051	0.0625	0.0710	0.0571	0.0365	64.0
	1:30	0.1066	0.0034	0.0334	0.0530	0.0491	0.0435	88.5
	1:40	0.0647	0.0065	0.0289	0.0329	0.0332	0.0240	72.1
	1:50	0.0673	-0.0056	0.0163	0.0000	0.0195	0.0332	170
	1:60	0.0493	0.0006	0.0152	0.0212	0.0216	0.0204	94.6
8	1:15	0.1150	0.0406	0.0868	0.0934	0.0839	0.0313	37.3
	1:20	0.0959	0.0290	0.0365	0.0368	0.0496	0.0311	62.7
	1:30	0.0801	0.0327	0.0197	0.0198	0.0381	0.0286	75.2
	1:40	0.0622	0.0066	0.0097	0.0167	0.0238	0.0259	109
	1:50	0.0489	0.0049	0.0017	0.0035	0.0148	0.0228	155
	1:60	0.0466	0.0187	-0.0053	-0.0035	0.0141	0.0243	172



Table D.12 continued.

Soaking Time (mins)	Powerkleen Dilution	Mass of Dirt (g)				Mean (g)	Std. Deviation (g)	Coeff. of Variation (%)
		Run 1	Run 2	Run 3	Run 4			
10	1:15	0.0694	0.0622	0.0970	0.0980	0.0817	0.0186	22.8
	1:20	0.0806	0.0430	0.0624	0.0251	0.0528	0.0240	45.5
	1:30	0.0552	0.0271	0.0338	0.0143	0.0326	0.0171	52.5
	1:40	0.0415	0.0386	0.0139	0.0166	0.0277	0.0144	52.0
	1:50	0.0392	0.0326	-0.0020	0.0067	0.0191	0.0199	104
	1:60	0.0258	0.0389	0.0001	-0.0035	0.0153	0.0204	133
15	1:15	0.0939	0.0325	0.0844	0.0806	0.0729	0.0275	37.7
	1:20	0.0768	0.0127	0.0337	0.0593	0.0456	0.0282	61.8
	1:30	0.0606	0.0203	0.0121	0.0209	0.0285	0.0218	76.6
	1:40	0.0711	0.0348	0.0149	0.0152	0.0340	0.0264	77.7
	1:50	0.0740	0.0328	0.0011	0.0122	0.0300	0.0321	107
	1:60	0.0607	0.0291	-0.0223	0.0139	0.0204	0.0345	169
20	1:15	0.0623	0.1250	0.1450	0.0905	0.1057	0.0367	34.7
	1:20	0.0642	0.1345	0.0893	0.0366	0.0812	0.0416	51.2
	1:30	0.0877	0.1284	0.0593	0.0136	0.0722	0.0483	66.9
	1:40	0.0694	0.0956	0.0984	0.0209	0.0711	0.0359	50.6
	1:50	0.0728	0.0700	0.0366	-0.0021	0.0443	0.0350	79.1
	1:60	0.0484	0.0749	0.0356	-0.002	0.0393	0.0320	81.4

**Photographic Results for the Optimisation of the Powerkleen System:**

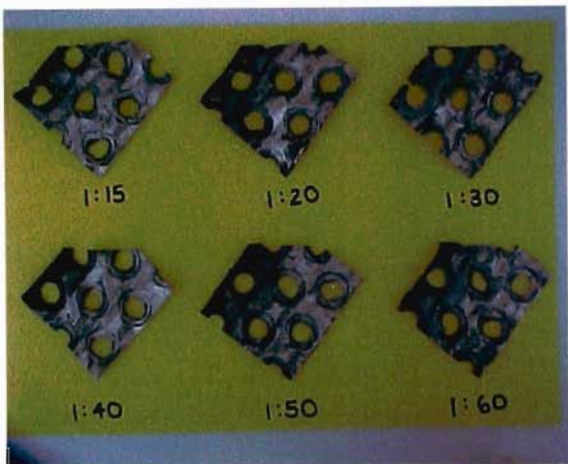


Fig. D.39

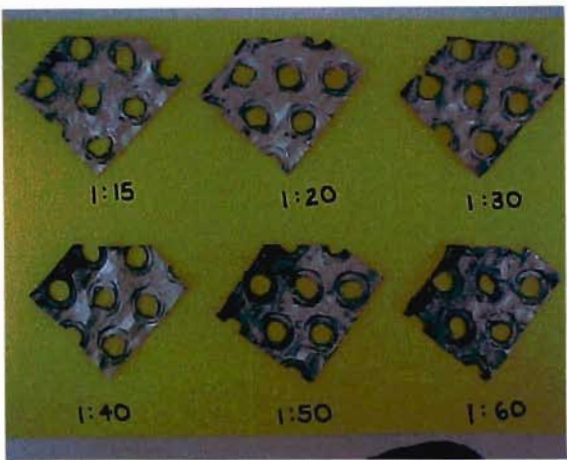


Fig. D.40

Fig. D.39: 'Before' photograph for a soaking time of 2 minutes (Run 1). \*

Fig. D.40: 'After' photograph for a soaking time of 2 minutes (Run 1). \*

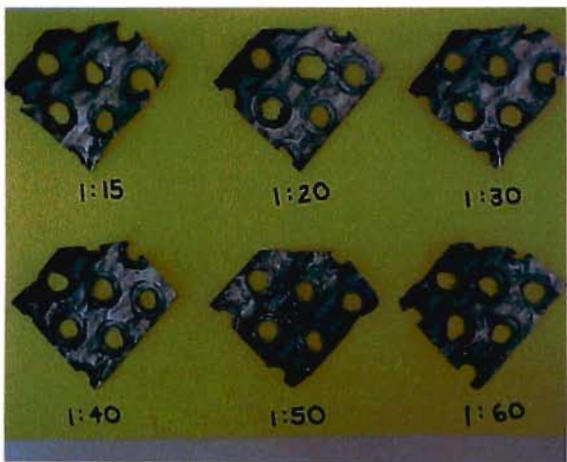


Fig. D.41

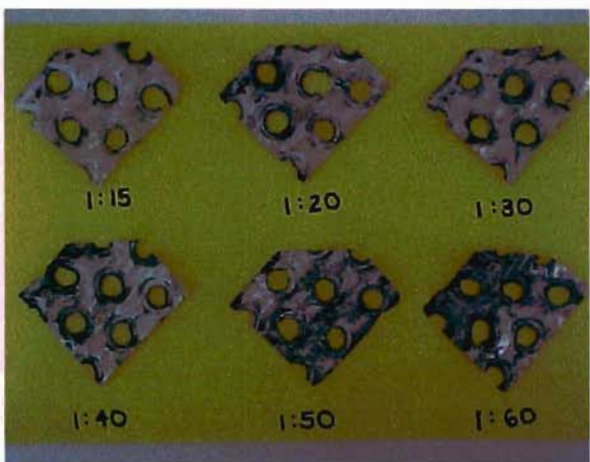


Fig. D.42

Fig. D.41: 'Before' photograph for a soaking time of 4 minutes (Run 1). \*

Fig. D.42: 'After' photograph for a soaking time of 4 minutes (Run 1). \*

\* The numbers below the aluminium pieces refer to the dilutions of Powerkleen in tap water.



Fig. D.43

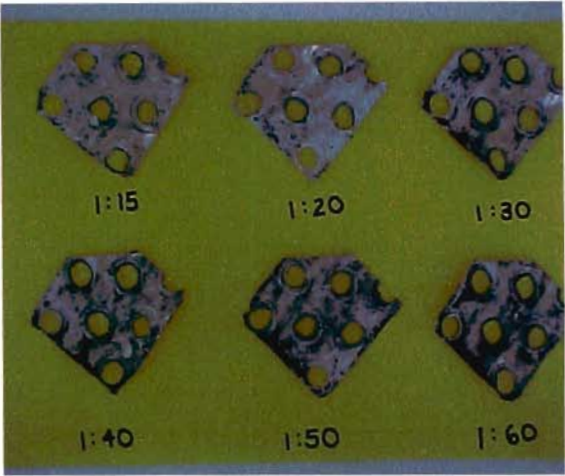


Fig. D.44

Fig. D.43: 'Before' photograph for a soaking time of 6 minutes (Run 1). \*

Fig. D.44: 'After' photograph for a soaking time of 6 minutes (Run 1). \*

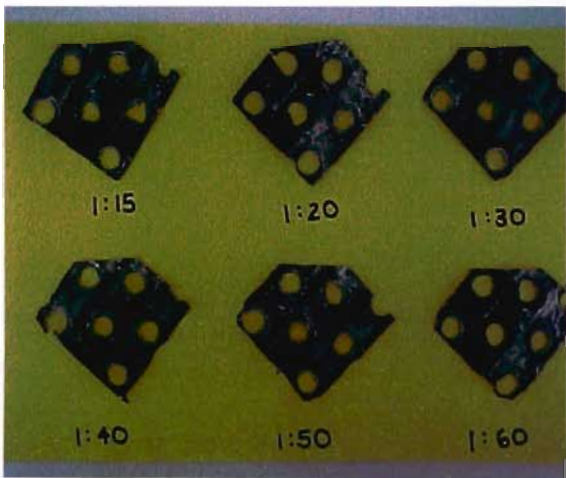


Fig. D.45

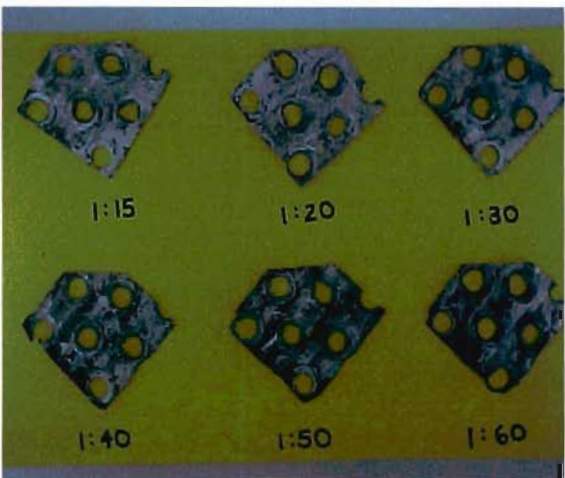


Fig. D.46

Fig. D.45: 'Before' photograph for a soaking time of 8 minutes (Run 1). \*

Fig. D.46: 'After' photograph for a soaking time of 8 minutes (Run 1). \*

\* The numbers below the aluminium pieces refer to the dilutions of Powerkleen in tap water.



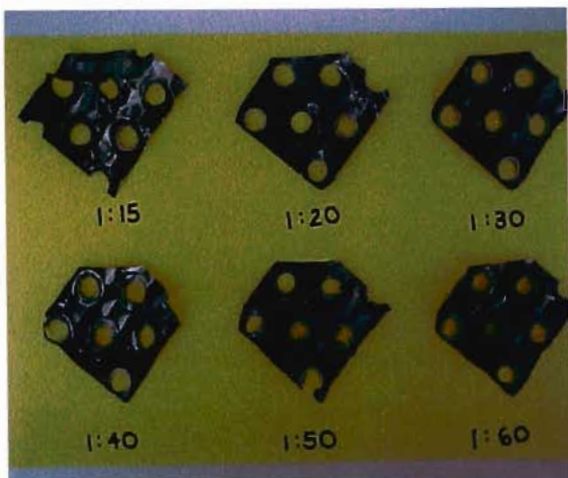


Fig. D.47



Fig. D.48

Fig. D.47: ‘Before’ photograph for a soaking time of 10 minutes (Run 1). \*  
Fig. D.48: ‘After’ photograph for a soaking time of 10 minutes (Run 1). \*



Fig. D.49

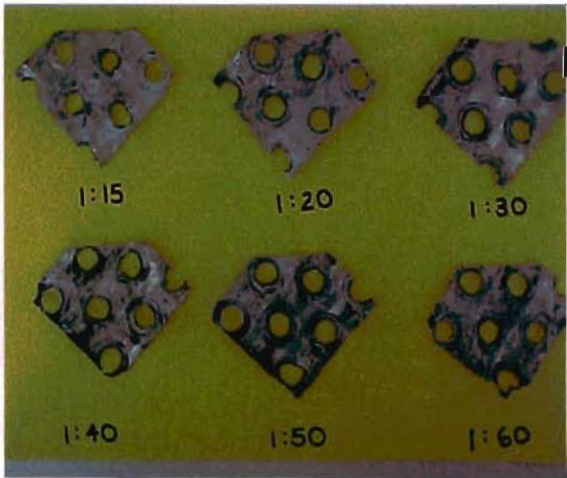


Fig. D.50

Fig. D.49: ‘Before’ photograph for a soaking time of 15 minutes (Run 1). \*  
Fig. D.50: ‘After’ photograph for a soaking time of 15 minutes (Run 1). \*

\* The numbers below the aluminium pieces refer to the dilutions of Powerkleen in tap water.

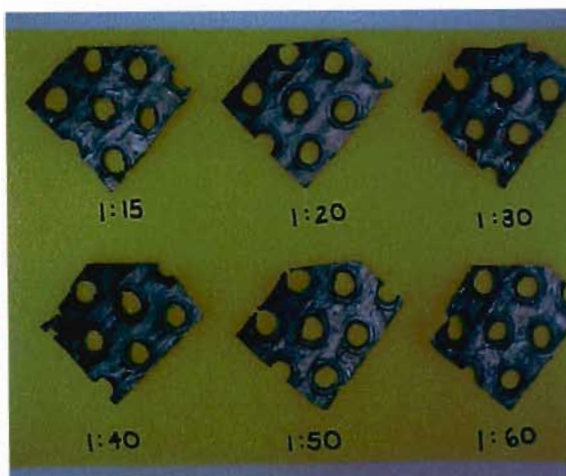


Fig. D.51

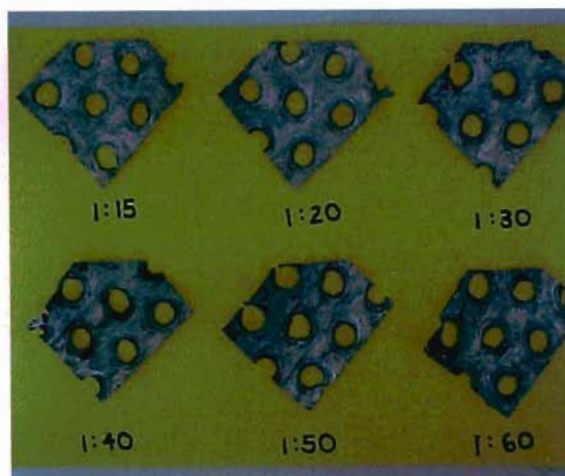


Fig. D.52

Fig. D.51: 'Before' photograph for a soaking time of 20 minutes (Run 1). \*

Fig. D.52: 'After' photograph for a soaking time of 20 minutes (Run 1). \*

\* The numbers below the aluminium pieces refer to the dilutions of Powerkleen in tap water.

## **D.5 Suitability of Two Cleaner Application Techniques**

### ***Photographic Results for the Powerkleen Application Tests:***

Below, the digital photographs used for the determination of the most effective cleaner application technique are shown. These include 'before' and 'after' photographs of the dissected coil pieces in both side and front view.



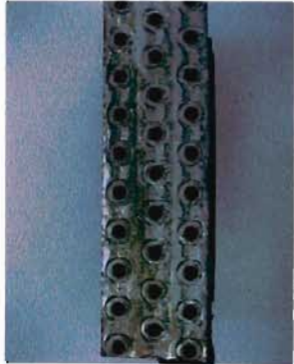


Fig. D.53



Fig. D.55



Fig. D.57

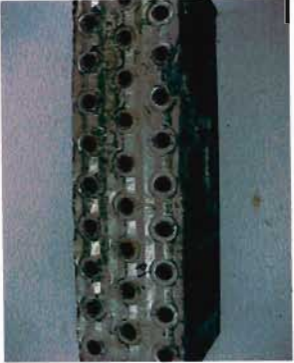


Fig. D.59

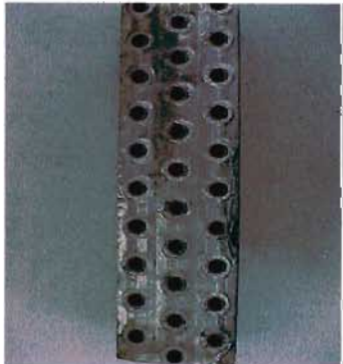


Fig. D.54

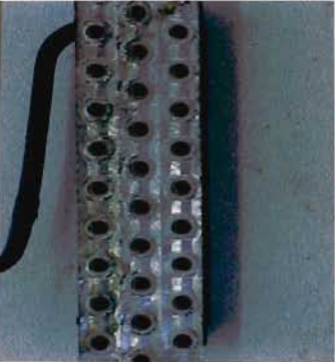


Fig. D.56

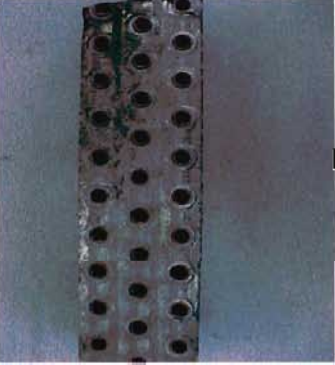


Fig. D.58



Fig. D.60

Figs. D.53 and D.54: 'Before' and 'after' photographs of a section of Coil 1 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes (side view).

Figs. D.55 and D.56: 'Before' and 'after' photographs of a section of Coil 1 that was treated with 250 ml of 1:20 Powerkleen using an air gun for 2 minutes (side view).

Figs. D.57 and D.58: 'Before' and 'after' photographs of a section of Coil 1 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes (side view).

Figs. D.59 and D.60: 'Before' and 'after' photographs of a section of Coil 1 that was treated with 250 ml of 1:40 Powerkleen using an air gun for 2 minutes (side view).

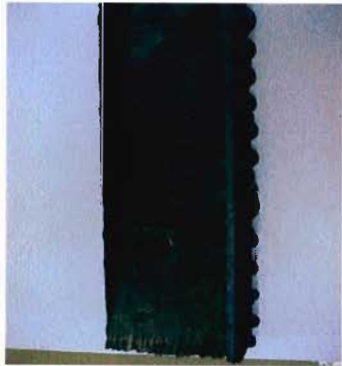


Fig. D.61

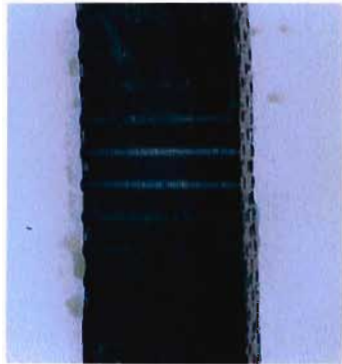


Fig. D.63



Fig. D.65



Fig. D.67

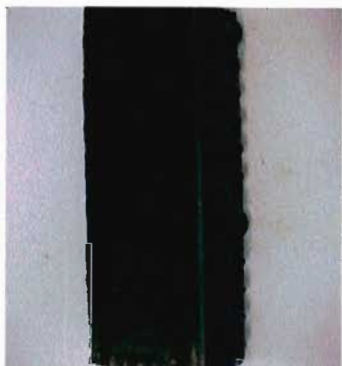


Fig. D.62

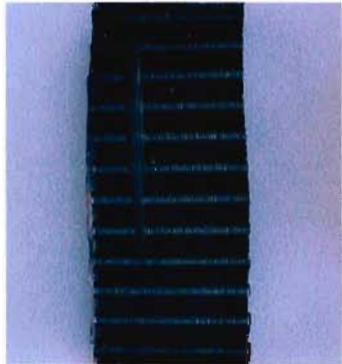


Fig. D.64



Fig. D.66

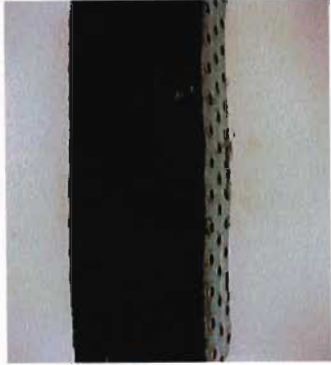


Fig. D.68

Figs. D.61 and D.62: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes.

Figs. D.63 and D.64: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 250 ml of 1:20 Powerkleen using an air gun for 2 minutes.  
Figs. D.65 and D.66: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 1 litre of 1:40 Powerkleen using a pump bottle for 2 minutes.

Figs. D.67 and D.68: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 250 ml of 1:40 Powerkleen using an air gun for 2 minutes.



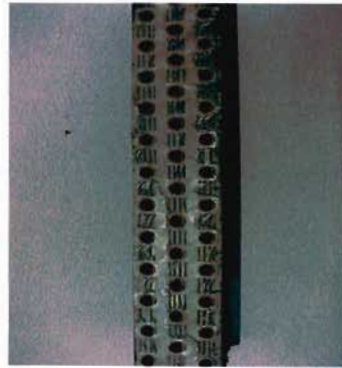


Fig. D.69

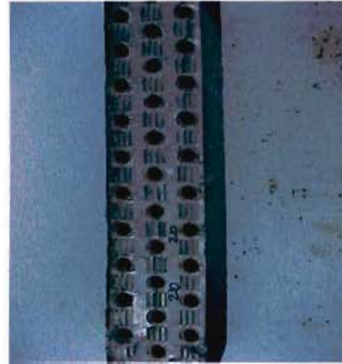


Fig. D.71



Fig. D.73

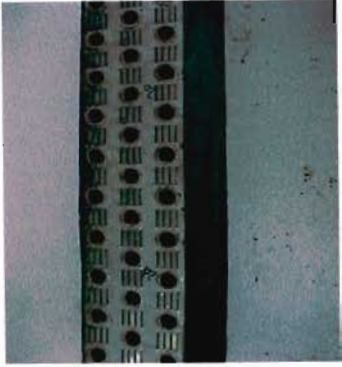


Fig. D.75

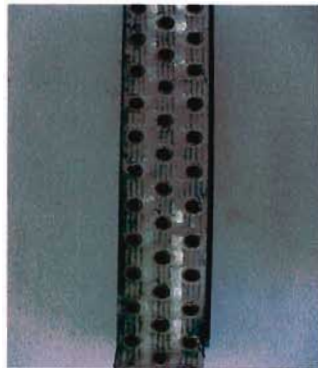


Fig. D.70

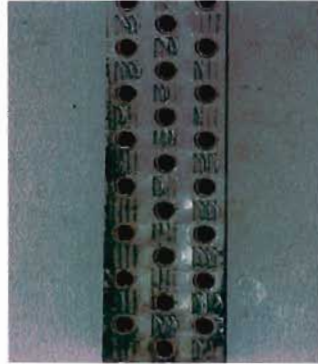


Fig. D.72

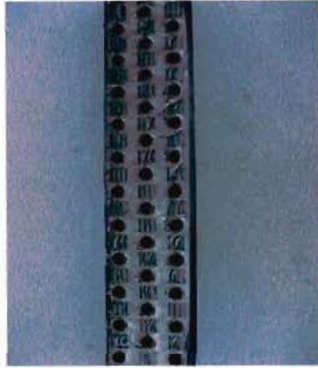


Fig. D.74

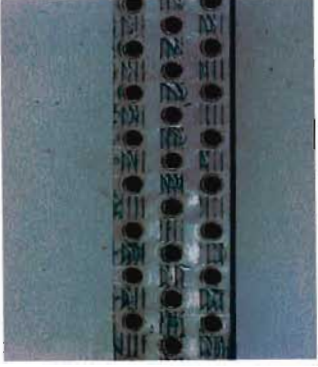


Fig. D.76

Figs. D.69 and D.70: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes (side view).

Figs. D.71 and D.72: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 250 ml of 1:20 Powerkleen using an air gun for 2 minutes (side view).

Figs. D.73 and D.74: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 1 litre of 1:40 Powerkleen using a pump bottle for 2 minutes (side view).

Figs. D.75 and D.76: 'Before' and 'after' photographs of a section of Coil 2 that was treated with 250 ml of 1:40 Powerkleen using an air gun for 2 minutes (side view).

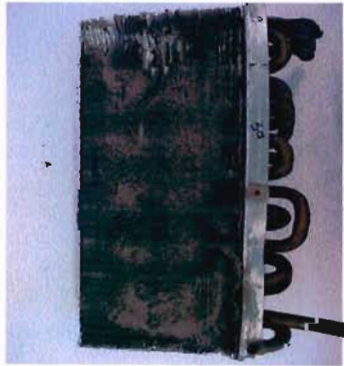


Fig. D.77

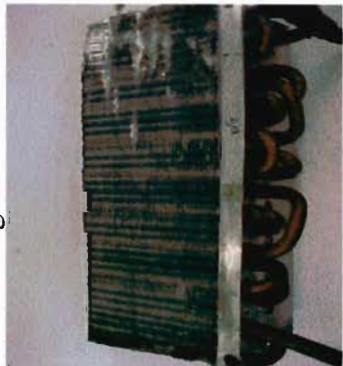


Fig. D.78

Figs. D.77 and D.78: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes.



Fig. D.79

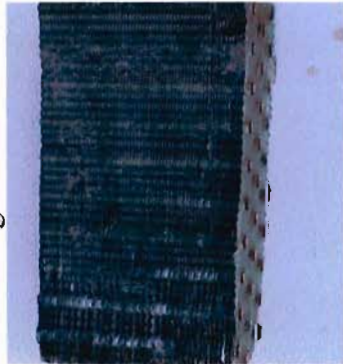


Fig. D.80

Figs. D.79 and D.80: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 250 ml of 1:20 Powerkleen using an air gun for 2 minutes.

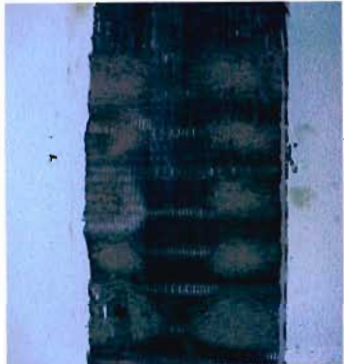


Fig. D.81

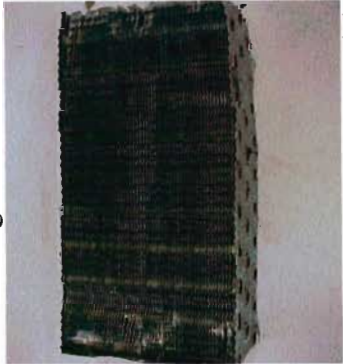


Fig. D.82

Figs. D.81 and D.82: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 1 litre of 1:40 Powerkleen using a pump bottle for 2 minutes.



Fig. D.83

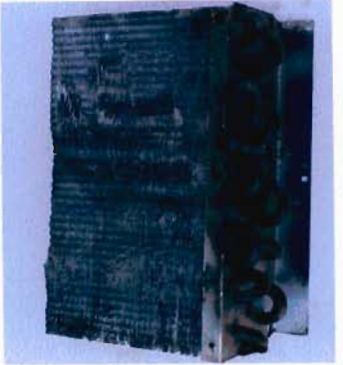


Fig. D.84

Figs. D.83 and D.84: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 250 ml of 1:40 Powerkleen using an air gun for 2 minutes.





Fig. D.85

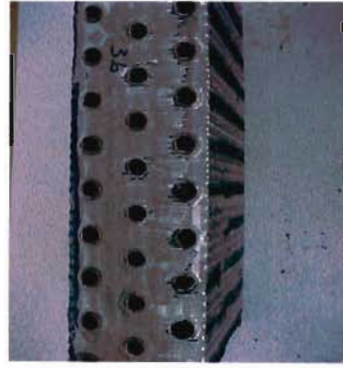


Fig. D.87

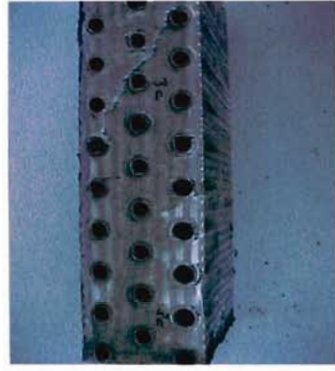


Fig. D.89



Fig. D.91

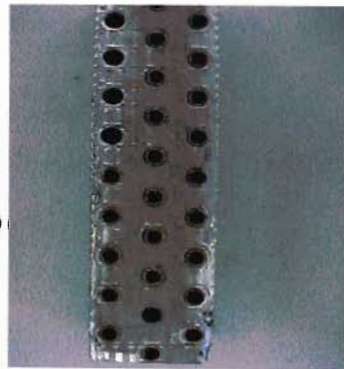


Fig. D.86

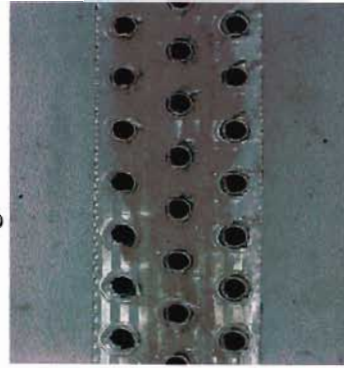


Fig. D.88

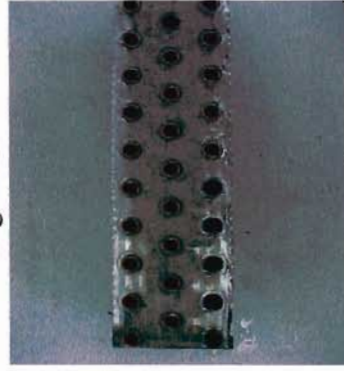


Fig. D.90

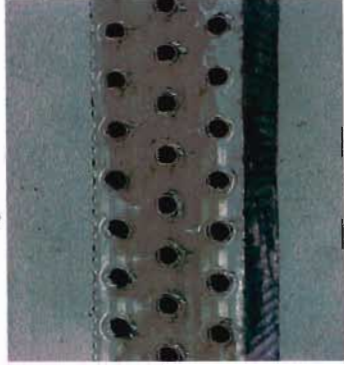


Fig. D.92

Figs. D.85 and D.86: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 1 litre of 1:20 Powerkleen using a pump bottle for 2 minutes (side view).

Figs. D.87 and D.88: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 250 ml of 1:20 Powerkleen using an air gun for 2 minutes (side view).

Figs. D.89 and D.90: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 1 litre of 1:40 Powerkleen using a pump bottle for 2 minutes (side view).

Figs. D.91 and D.92: 'Before' and 'after' photographs of a section of Coil 3 that was treated with 250 ml of 1:40 Powerkleen using an air gun for 2 minutes (side view).



# Appendix E

In this appendix, the calculations are shown for the economic and environmental evaluations of the feasibility analysis for Powerkleen. The economic evaluation includes the calculation of financial parameters such as payback period, return on capital employed, net present value and the internal rate of return.

## **E.1 Economic Evaluation**

### ***Calculation of Current Running Costs:***

#### **Alukleen and Water Combination (dispensed as a 1:1 dilution):**

~ 4500 air conditioning units are serviced / year<sup>71</sup> = 375 units / month

75 L of concentrated Alukleen are used / month<sup>71</sup> = 150 L of 1:1 dilution used / month

1800 L of 1:1 Alukleen used / year and 0.4 L of 1:1 Alukleen are used / unit

Cost of Alukleen = R5.42 / L (incl. vat)<sup>71</sup>

Cost of water = 0.44 c / L<sup>71</sup>

Therefore, cost of 1:1 Alukleen = (0.5 x R5.42/L) + (0.5 x R0.0044/L) = R2.71 / L

Therefore cost / unit = (0.4 L/unit x R2.71/L) = R1.08 / unit

Therefore cost / year = (R1.08 x 4500) = R4881.96

= R4880

#### **Green Soap (dispensed neat):**

50 L of green soap are used / month<sup>71</sup> = 0.13 L of green soap used / unit

Therefore, 600 L of green soap are used / year.

Cost of Green Soap = R4.43 / litre (incl. vat)<sup>71</sup>

Therefore, cost / unit = (0.13 L/unit x R4.43/L) = R0.59 / unit

Therefore, cost / year = (R0.59 x 4500) = R2658.00

= R2660

#### **Handy Andy (dispensed neat):**

50 L of Handy Andy are used / month<sup>71</sup> = 0.13 L of Handy Andy used / unit

Therefore, 600 L of Handy Andy are used / year

Cost of Handy Andy = R3.04 / L (incl. vat)<sup>71</sup>

Therefore, cost / unit = (0.13 L/unit x R3.04/L) = R0.41 / unit

Therefore, cost / year = (R0.41 x 4500) = R1824.00

= R1820

### ***Calculation of Proposed Running Costs:***

#### **Coil Cleaning (Powerkleen Dilution of 1:39):**

Of the 4500 units serviced / year, approximately 60% (2700) are serviced at Ben Booysen and approximately 40% (1800) are serviced on-site at the industry.<sup>71</sup>

Volume of 1:39 Powerkleen needed per standard-sized unit for application with pump bottle = 4 L (Section 5.4)

Volume of 1:39 Powerkleen needed per standard-sized unit for application with air gun = 1 L (Section 5.4)

Therefore, annual requirements for 1:39 Powerkleen are:

(2700 x 1 L) + (1800 x 4 L) = 9900 L

Cost of Powerkleen = R16.53 / L (incl. vat)<sup>71</sup>

Of the 9900 L of the 1:39 dilution required, 248 L are Powerkleen and 9652 L are water.

Therefore cost / year of 1:39 Powerkleen

= (248 L x R16.53/L) + (9652 L x R0.0044/L)

= R4141.90

= R4140

**Case Cleaning (Powerkleen Dilution of 1:79):**

Volume of 1:79 Powerkleen needed per standard sized unit for general cleaning = 0.2 L  
(Section 5.3.2)

Therefore, annual requirements for 1:79 Powerkleen are:

$$(0.2 \text{ L} \times 4500) = 900 \text{ L}$$

Cost of Powerkleen = R16.53 / L (incl. vat)

Of the 900 L of the 1:79 dilution required, 11 L are Powerkleen and 889 L are water.

Therefore, cost / year of 1:79 Powerkleen

$$= (11 \text{ L} \times \text{R}16.53/\text{L}) + (889 \text{ L} \times \text{R}0.0044\text{L})$$

$$= \underline{\text{R}185.74}$$

$$= \underline{\text{R}190}$$

***Calculation of Proposed Annual Savings:***

Previous annual operating costs

$$= (\text{annual cost of 1:1 Alukleen} + \text{annual cost of green soap} + \text{annual cost of Handy Andy})$$

$$= (\text{R}4880 + \text{R}2660 + \text{R}1820)$$

$$= \underline{\text{R}9360}$$

Proposed annual operating costs

$$= (\text{annual cost of 1:39 Powerkleen} + \text{annual cost of 1:79 Powerkleen})$$

$$= (\text{R}4140 + \text{R}190)$$

$$= \underline{\text{R}4330}$$

Projected Annual Savings

$$= (\text{previous annual operating costs} - \text{proposed annual operating costs})$$

$$= \text{R}9360 - \text{R}4330$$

$$= \underline{\text{R}5030}$$

**Calculation of Capital Costs Required for the Solution:**

2 x 1000 litre tanks @ R1049.60 each =	R2099.20
2 x air guns @ R149 each =	R298.00
1 x pump bottle (2 litre) @ R80 each =	<u>R80.00</u>
<b>Total</b>	<u>R2477.20</u>
	<u>= R2480</u>

**Calculation of the Payback Period:**

Payback period	= capital costs / net savings
	= <u>R2480</u>
	R5030
	= 0.493 years
	= <u>5.9 months</u>

**Calculation of the Return on Capital Employed (ROCE):**

Gross ROCE	= (total cost savings / capital) x 100%
Equipment Life Span	= 10 years
Total cost savings	= (R5030x 10 years)
	= R50300
Therefore Gross ROCE	= <u>R50300 x 100%</u>
	R2480
	= <u>2030%</u>



$$\begin{aligned}\text{Net ROCE} &= \frac{(\text{total cost savings} - \text{capital}) \times 100\%}{\text{Capital}} \\ &= \frac{(\text{R50300} - \text{R2480}) \times 100\%}{\text{R2480}} \\ &= \underline{1930\%}\end{aligned}$$

$$\begin{aligned}\text{Gross Annual Rate of Return} &= \frac{\text{Gross ROCE \%}}{\text{Project Life}} \\ &= \frac{2030\%}{10 \text{ years}} \\ &= \underline{203\%}\end{aligned}$$

$$\begin{aligned}\text{Net Annual Rate of Return} &= \frac{\text{Net ROCE \%}}{\text{Project Life}} \\ &= \frac{1930\%}{10 \text{ years}} \\ &= \underline{193\%}\end{aligned}$$

**Calculation of the Net Present Value:**

Table E.1: Calculation of the net present value of the Ben Booysen project  
(replacing Alukleen with Powerkleen).

Years	Discount Factor	Capital Expenditure	Saving	Cash Flow	Discounted Cash Flow
0	1.000	R 2,480	R 0.00	-R 2,480	-R 2,480
1	0.833	R 0	R 5,030	R 5,030	R 4,192
2	0.694	R 0	R 5,030	R 5,634	R 3,912
3	0.579	R 0	R 5,030	R 6,310	R 3,651
4	0.482	R 0	R 5,030	R 7,067	R 3,408
5	0.402	R 0	R 5,030	R 7,915	R 3,181
6	0.335	R 0	R 5,030	R 8,865	R 2,969
7	0.279	R 0	R 5,030	R 9,928	R 2,771
8	0.233	R 0	R 5,030	R 11,120	R 2,586
9	0.194	R 0	R 5,030	R 12,454	R 2,414
10	0.162	R 0	R 5,030	R 13,949	R 2,253
				Total	R 28,856

**Calculation of the Internal Rate of Return:**

Table E.2: Calculation of the internal rate of return of the Ben Booyesen project  
(replacing Alukleen with Powerkleen).

Years	Discount Factor	Capital Expenditure	Saving	Cash Flow	Discounted Cash Flow
0	1.000	R 2,480	R 0.00	-R 2,480	-R 2,480
1	0.318	R 0	R 5,030	R 5,030	R 1,598
2	0.101	R 0	R 5,030	R 5,634	R 568
3	0.032	R 0	R 5,030	R 6,310	R 202
4	0.010	R 0	R 5,030	R 7,067	R 72
5	0.003	R 0	R 5,030	R 7,915	R 26
6	0.001	R 0	R 5,030	R 8,865	R 9
7	0.000	R 0	R 5,030	R 9,928	R 3
8	0.000	R 0	R 5,030	R 11,120	R 1
9	0.000	R 0	R 5,030	R 12,454	R 0
10	0.000	R 0	R 5,030	R 13,949	R 0
				<b>Total</b>	<b>R 0</b>

Using the above table and the solver function in Microsoft® Excel 2000, the internal rate of return was calculated as 214.9%.

## E.2 Environmental Evaluation

### *Calculation of Dilution Factor for the 'new' Powerkleen Effluent:*

$$[\text{SO}_4^{2-} \text{ (Average Alukleen stock solution)}] = \frac{54050 \text{ ppm} + 52300 \text{ ppm} + 71950 \text{ ppm}}{3}$$

$$= 59430 \text{ ppm}$$

$$[\text{SO}_4^{2-} \text{ (Average Alukleen effluent)}] = 103.0 \text{ ppm}$$

$$[\text{SO}_4^{2-} \text{ (Alukleen stock solution)}] \times (\text{annual volume of 1:1 Alukleen used})$$

$$= [\text{SO}_4^{2-} \text{ (Alukleen effluent)}] \times (\text{annual volume of the effluent})$$

$$\therefore (59430 \text{ ppm}) (1800 \text{ L}) = (103.0 \text{ ppm}) (\text{annual volume of effluent})$$

$$\therefore \text{annual volume of effluent} = 1039 \text{ kL} \approx \text{volume of water (since } 1800 \text{ L} \ll 1039 \text{ kL)}$$

Assuming the same volume of dilution water for Powerkleen,

$$\begin{aligned} \text{annual volume of effluent} &= (\text{volume of 1:39 Powerkleen}) + (\text{volume of dilution water}) \\ &= (9900 \text{ L}) + (1039 \text{ kL}) \\ &= 1048 \text{ kL} \end{aligned}$$

$$\begin{aligned} \therefore \text{Dilution Factor} &= \frac{9900 \text{ L}}{1048 \times 10^3 \text{ L}} \\ &= \underline{9.4 \times 10^{-3}} \end{aligned}$$

(volume of 1:79 Powerkleen is  $\sim 900 \text{ L}$  which is negligible)

For example, using data in Table 6.1:

$$\begin{aligned} \text{an estimate of the COD of the final Powerkleen effluent} &= \frac{9900 \text{ L}}{1048 \times 10^3 \text{ L}} \times 6431 \text{ mgO}_2/\text{L} \\ &= 61 \text{ mgO}_2/\text{L} \end{aligned}$$