

CRANFIELD UNIVERSITY

SCHOOL OF MECHANICAL ENGINEERING

Ph.D. THESIS



Academic Year 2000-2001

TARA J. NAYLOR

Development of a pollution prevention methodology for the metalcasting industry.

Supervisor: Paul O'Callaghan

January 2001

ProQuest Number: 10832261

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



ProQuest 10832261

Published by ProQuest LLC (2019). Copyright of the Dissertation is held by Cranfield University.

All rights reserved.

This work is protected against unauthorized copying under Title 17, United States Code
Microform Edition © ProQuest LLC.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

ABSTRACT

The metalcasting industry consists of small businesses that cast a wide variety of metals and use many different casting processes. The metalcasting industry is a large recycler of metal, however, metalcasting is energy intensive and produces significant air, land and water emissions. The industry is vulnerable to the cost of conforming to increasingly stringent environmental regulations. Improving environmental performance while keeping regulatory costs to a minimum is one of the key challenges of the industry.

An adaptable methodology is required that is usable by small manufacturing units in order to comply with environmental regulation in a cost-effective manner.

The processes used in the metalcasting industry were investigated. The available energy, waste, materials consumption data and the industry environmental effects were reviewed and evaluated.

The methodologies used to reduce pollution to a minimum in other industries were evaluated for: applicability to environmental issues, suitability to both high production and jobbing shops, applicability to different casting methods, ease of use by foundry and environmental personnel, data availability. The methods assessed included: preliminary assessment methods, process flowsheets, mass and energy balances, manufacturing process understanding, process integration, pinch methods, exergy analyses, life-cycle assessment and total cost assessment.

The developed methodology is presented in the form of a flowchart that combines an ordered sequence, with appropriate feedback loops, of the selected methods.

The developed methodology was successfully tested at a working non-ferrous metalcasting facility. Fluoride chemicals, added to sand moulds and cores to prevent casting defects, were creating large quantities of hazardous solid waste and air emissions from the sand system. The application of the methodology resulted in the identification of a modified process that added the fluoride chemical in a surface coating only, thus reducing emissions by 99%.

This methodology can be used to reduce waste, material and resource use in the metalcasting industry.

ACKNOWLEDGEMENTS

I wish to thank the people without whom this endeavour would not have been possible.

- ♦ Thank you to the management of Haley Industries Limited for giving me the opportunity to pursue this project.
- ♦ To Paul O'Callaghan who inspired me to undertake this challenge and who gave me advice throughout the thesis.
- ♦ To Dad whose continual advice, encouragement and support have helped me get through the tough times.
- ♦ To Mum and Karen, Shandy, Taffy, Tufty, Walnut and Woffles who have taken care of me each in their own special ways.

CONTENTS

ABSTRACT

ACKNOWLEDGEMENTS

CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

INTRODUCTION	1
1.1 THE METALCASTING INDUSTRY	1
1.2 METALCASTING AND THE ENVIRONMENT	2
1.2.1 <i>Energy use in the metalcasting industry</i>	2
1.2.2 <i>Environmental regulations and the metalcasting industry</i>	4
1.2.3 <i>Metalcasting waste generation</i>	6
1.3 STATEMENT OF NEEDS	9
1.4 THESIS AIMS AND OBJECTIVES	9
2 INTRODUCTION TO METALCASTING PROCESSES	11
2.1 METAL CASTING PROCESSES	11
2.1.1 <i>Pattern Making</i>	16
2.1.2 <i>Mould and Core Preparation</i>	17
2.1.3 <i>Green Sand Moulding</i>	18
2.1.4 <i>Coremaking and dry sand moulding</i>	19
2.1.5 <i>No-bake processes</i>	19
2.1.6 <i>Cold-Box systems</i>	19
2.1.7 <i>Heat cured systems</i>	20
2.1.8 <i>Core and Mould coatings</i>	21
2.1.9 <i>Sands</i>	22
2.1.10 <i>Shakeout, reclamation and reuse of spent sand</i>	22
2.1.11 <i>Expendable patterns</i>	23
2.1.12 <i>Lost foam casting</i>	23
2.1.13 <i>Investment Casting</i>	26
2.1.14 <i>Permanent Mould Processes</i>	29
2.1.15 <i>Permanent Mould Casting</i>	29
2.1.16 <i>Die Casting</i>	30
2.1.17 <i>Melting methods</i>	33
2.1.18 <i>Fluxing</i>	36
2.1.19 <i>Special Note on Magnesium</i>	36
2.2 POSTCASTING OPERATIONS	37
2.2.1 <i>Finishing</i>	37
2.2.2 <i>Cleaning and Trimming</i>	38
2.2.3 <i>Gating and Riser removal</i>	38
2.2.4 <i>Finish Cleaning by Grinding and Filing</i>	38
2.2.5 <i>Heat Treatment</i>	39
2.2.6 <i>Inspections of Castings</i>	39
2.2.7 <i>Non-destructive testing</i>	39
2.2.8 <i>Mechanical and Physical Property Tests</i>	40
2.3 HALEY INDUSTRIES LIMITED CASTING PROCESSES	43
2.3.1 <i>Core Making</i>	46
2.3.2 <i>Mould Making and Assembly</i>	49

2.3.3	<i>Furnace charge, metal melting and pouring</i>	53
2.3.4	<i>Shakeout, cooling and sand handling</i>	58
2.3.5	<i>Finishing and cleaning</i>	61
2.3.6	<i>Heat Treat</i>	63
2.3.7	<i>Welding</i>	67
2.3.8	<i>Non destructive testing</i>	69
2.3.9	<i>Acid Etch</i>	69
2.3.10	<i>Fluorescent penetrant inspection</i>	69
2.3.11	<i>X-ray</i>	70
2.3.12	<i>Chromium Pickle</i>	70
2.3.13	<i>Third Visual Inspection</i>	71
2.3.14	<i>Dimensional Check</i>	71
2.3.15	<i>Rework</i>	71
2.3.16	<i>Pressure Test</i>	71
2.3.17	<i>Final Inspection</i>	72
2.3.18	<i>Release and Quality Control Acceptance</i>	72
2.3.19	<i>Shipping</i>	72
2.4	CONCLUSIONS	75
3	DEVELOPMENT OF THE POLLUTION PREVENTION METHODOLOGY	77
3.1	INTRODUCTION	77
3.2	POLLUTION PREVENTION STRATEGIES	80
3.3	EVALUATION CRITERIA FOR METHODOLOGIES	81
3.4	EXISTING METHODOLOGIES	81
3.5	PRELIMINARY ASSESSMENT	83
3.6	PROCESS FLOWSHEETS	85
3.7	MASS AND ENERGY BALANCE	87
3.8	MANUFACTURING PROCESS UNDERSTANDING	88
3.9	PROCESS INTEGRATION, SYNTHESIS AND DESIGN	91
3.10	PINCH METHODS	93
3.11	EXERGY	95
3.12	ENERGY AND RESOURCE METHODOLOGY	97
3.13	LIFE-CYCLE ASSESSMENT	98
3.14	TOTAL COST ASSESSMENT	101
3.15	POTENTIAL FAILURE MODE AND EFFECTS ANALYSIS (FMEA)	103
3.16	DECISION MAKING	104
3.17	MODELLING AND SIMULATION METHODS/APPROACHES	105
3.18	EVALUATION OF REVIEWED TECHNIQUES	106
3.18.1	<i>Accepted</i>	106
3.18.2	<i>Rejected</i>	106
3.19	DEVELOPMENT OF THE METHODOLOGY	109
3.19.1	<i>Assessment of processes</i>	109
3.19.2	<i>Evaluation of generated options</i>	109
3.19.3	<i>Preliminary assessment</i>	110
3.19.4	<i>Detailed assessment</i>	110
3.19.5	<i>Generation of options</i>	110
3.19.6	<i>Evaluation of options</i>	111
3.19.7	<i>Implementation</i>	111
3.19.8	<i>Maintenance</i>	111
3.20	POLLUTION PREVENTION METHODOLOGY FOR THE METALCASTING INDUSTRY	114
3.20.1	<i>Preliminary assessment</i>	114
3.20.2	<i>Define objectives</i>	114
3.20.3	<i>Develop process flowsheet</i>	114
3.20.4	<i>Identify critical process factors and key production measures</i>	114
3.20.5	<i>Identify data requirements, collect data</i>	114
3.20.6	<i>Completion of mass and energy balance</i>	115
3.20.7	<i>Identify alternate practices</i>	115
3.20.8	<i>Preliminary ranking of options</i>	115

3.20.9	<i>Feasibility analysis</i>	115
3.20.10	<i>Environmental analysis</i>	116
3.20.11	<i>Economic analysis</i>	116
3.20.12	<i>Optimisation</i>	117
3.20.13	<i>Reporting and evaluation</i>	117
3.20.14	<i>Implementation</i>	117
3.20.15	<i>Maintain process control</i>	117
3.20.16	<i>Compare results to initial objectives</i>	117
3.20.17	<i>Continuous improvement of implemented processes</i>	117
3.20.18	<i>Start on next process as identified in the preliminary assessment</i>	118
3.21	CONCLUSIONS	118
4	AUDIT OF A WORKING METALCASTING FACILITY	120
4.1	INTRODUCTION	120
4.2	SITE ENVIRONMENTAL ISSUES	120
4.2.2	<i>Environmental Regulation</i>	122
4.2.3	<i>Federal</i>	122
4.2.4	<i>Provincial (Ontario)</i>	123
4.2.5	<i>Costs and Penalties for Non-Compliance</i>	123
4.2.6	<i>Compliance audit 1998</i>	124
4.3	ENERGY AND AIR EMISSIONS	126
4.3.1	<i>Site and scope of audit</i>	126
4.3.2	<i>Overall energy use</i>	126
4.3.3	<i>Thermal and energy use changes</i>	129
4.3.4	<i>Building Services: Heating Ventilation and Air Conditioning</i>	139
4.3.5	<i>Energy Output Analysis</i>	140
4.3.6	<i>Energy outputs</i>	143
4.3.7	<i>Energy Balance Sheet</i>	143
4.3.8	<i>Energy Throughput Analysis</i>	144
4.3.9	<i>Compressor Use</i>	145
4.3.10	<i>Options for energy savings</i>	147
4.3.11	<i>Conclusions</i>	147
4.4	MATERIALS AND WASTE AUDIT	148
4.4.1	<i>Site and Scope of Audit</i>	148
4.4.2	<i>Material Input Analysis</i>	148
4.4.3	<i>Material Output Analysis</i>	153
4.4.4	<i>Waste disposal alternatives</i>	158
4.4.5	<i>Summary</i>	159
4.4.6	<i>Conclusions</i>	159
4.5	WATER ANALYSIS.....	160
4.5.1	<i>Water Input Analysis</i>	160
4.5.2	<i>Water Output Analysis</i>	163
4.5.3	<i>Water Throughput Analysis</i>	164
4.5.4	<i>Water conservation and money saving opportunities:</i>	166
4.5.5	<i>Summary</i>	167
4.6	SUMMARY OF AUDIT FINDINGS.....	167
5	APPLICATION OF THE POLLUTION PREVENTION METHODOLOGY TO HALEY INDUSTRIES LIMITED	168
5.1	PRELIMINARY ASSESSMENT.....	168
5.1.1	<i>Identification of problem to be studied</i>	170
5.2	OBJECTIVES	170
5.3	PROCESS FLOWSHEETS.....	170
5.3.1	<i>Sand system flowchart, silos to shotblast</i>	170
5.3.2	<i>Sand system flowchart, shotblast to silos</i>	171
5.3.3	<i>Sand binder flowchart</i>	172
5.3.4	<i>Sodium silicofluoride flowchart</i>	173
5.4	CRITICAL PROCESS FACTORS AND KEY PRODUCTION MEASURES	174

5.4.1	<i>Metal, sand and binder systems in use at Haley Industries Ltd.</i>	174
5.4.2	<i>Critical process variables</i>	175
5.4.3	<i>Chemical binders</i>	176
5.4.4	<i>Sand and binder mixing</i>	176
5.4.5	<i>Pouring emissions</i>	177
5.4.6	<i>Sand processing, reuse and recycling</i>	178
5.4.7	<i>Sand and waste yields</i>	181
5.4.8	<i>Cost Factors</i>	183
5.4.9	<i>Inhibitors for magnesium alloys</i>	183
5.4.10	<i>Haley Industries Ltd. sand system</i>	184
5.5	DATA REQUIREMENTS	186
5.5.1	<i>Sand data</i>	186
5.5.2	<i>Fluoride data</i>	186
5.5.3	<i>Binder data</i>	186
5.5.4	<i>Data collection</i>	187
5.6	MASS AND ENERGY BALANCES	187
5.6.1	<i>Assumptions</i>	187
5.6.2	<i>Equations</i>	187
5.6.3	<i>Conclusions</i>	188
5.7	ALTERNATE PRACTICES	188
5.8	PRELIMINARY RANKING OF OPTIONS	189
5.9	FEASIBILITY ANALYSIS	189
5.9.1	<i>Option 1: Use of alternate inhibitors</i>	190
5.9.2	<i>Option 2: Treatment of solid waste and air emissions</i>	193
5.9.3	<i>Option 3: Recycle waste dust and treat air emissions</i>	195
5.9.4	<i>Option 4: Eliminate the use of Na₂ SiF₆ in aluminium moulds and cores</i>	197
5.9.5	<i>Option 5: Reduce the percentage of Na₂ SiF₆ used in magnesium castings and eliminate its use in aluminium castings</i>	200
5.9.6	<i>Option 6: Use inhibitor in alcohol based mould and core coating</i>	202
5.9.7	<i>Option 7: Use inhibitor in water based mould and core coating</i>	204
5.10	OPTIMISATION	206
5.11	REPORTING AND EVALUATION	208
5.12	IMPLEMENTATION	211
5.13	PROCESS CONTROL	211
5.14	COMPARE RESULTS TO INITIAL OBJECTIVES	211
5.15	CONCLUSIONS	211
6	DISCUSSION	213
7	CONCLUSIONS	218
	REFERENCES	219
APPENDIX A	SUMMARY OF ENVIROMENTAL EFFECTS	A
APPENDIX B	WATER MASS BALANCE AND EFFULENT RESULTS	B
APPENDIX C	PROCESS FLOWSHEETS	C
APPENDIX D	FOUNDRY CHEMICALS AND COLLECTED DATA	D
APPENDIX E	SAND MASS BALANCE	E
APPENDIX F	REDUCED INHIBITOR CASTING TRIALS	F
APPENDIX G	ALCOHOL BASED COATING TRIALS	G
APPENDIX H	WATER BASED CASTING TRIALS	H

LIST OF TABLES

Table 1 Top 10 Metalcasting Countries in 1997 (AFS, 1998).	1
Table 2 Major markets served by industry in 1994 (CMC, 1998).	2
Table 3 Breakdown of different metals cast and their relative tonnages and values (CMC, 1998).....	2
Table 4 Breakdown of Process Energy Costs (Bates, 1997).	3
Table 5 Energy Use Mix for Gray and Ductile Iron Foundries in 1994 (US DOE, 1997).	3
Table 6 UK foundry energy consumption for 1992-93 (ETSU, 1995).	3
Table 7 1995 Toxics Release Inventory Data for Metalcasting (US EPA, 1997).	7
Table 8 1995 Air Pollutant Releases in the US Metalcasting Industry (US EPA, 1997).	7
Table 9 1995 Toxic Release Inventory Breakdown by Release (US EPA, 1997).	7
Table 10 1995 Toxic Release Inventory Breakdown by Transfer (EPA, 1997).	7
Table 11 Key Energy and Environmental Facts: Mouldmaking and Coremaking.	17
Table 12 Key Energy and Environmental Facts – Lost Foam Casting.	23
Table 13 Key Energy and Environmental Facts: Investment Casting.	26
Table 14 Key Energy and Environmental Facts: Die Casting.	30
Table 15 Key Energy and Environmental Facts: Cupola Melting.	33
Table 16 Key Energy and Environmental Facts: Electric Melting Furnaces.	34
Table 17 Key Energy and Environmental Facts: Gas-Fired Melting Furnaces.	35
Table 18 Key Energy and Environmental Facts: Refining, Pouring, and Cooling (Energetics, 1999).	36
Table 19 Key Energy and Environmental Facts: Cleaning and Finishing.	37
Table 20 Summary of Environmental Effects from Metalcasting Processes (US EPA, 1997).	41
Table 21 Cost Categories for the Three Approaches to TCA (Kennedy, 1997)	103
Table 22 Summary of pros and cons of evaluated methods.	107
Table 23 Electricity, natural gas and climate data for 1997.	127
Table 24 Electricity, natural gas and climate data for 1998.	128
Table 25 Heat Treat Furnaces.	145
Table 26 Compressor Energy Consumption 1997.	145
Table 27 Foundry materials, 1996-97.	150
Table 28 Melting and pouring materials 1996-97.	151
Table 29 Casting processing and auxiliary materials 1996-97.	152
Table 30 Potable water conservation opportunities.	166
Table 31 Process water conservation opportunities.	166
Table 32 Pollutant concentration on American elm foliage adjacent to Haley Industries production plant (Gizyn, 2000).	168
Table 33 Emission Rate Summary (CTI, 2000).	169
Table 34 Physical Exhaust Gas Parameter Summary (CTI, 2000).	169
Table 35 Point of Impingement Summary (CTI, 2000).	169
Table 36 Main alloys poured at Haley Industries Ltd.	174
Table 37 Comparison of three options that meet environmental criteria.	207
Table 38 Summary of Technical and Environmental Feasibility Criteria.	209

LIST OF FIGURES

Figure 1 Expendable Mould Processes.....	13
Figure 2 Permanent Mould Processes.	14
Figure 3 Flow chart of a typical foundry operation (ASM, 1988).	15
Figure 4 Schematic of a sand mould (Voigt, 1988).....	16
Figure 5 Typical inputs and outputs of the mouldmaking and coremaking process (Energetics, 1999).....	17
Figure 6 Pouring green sand moulds at Presto Castings.	18
Figure 7 Cold box coremaking process (Piwonka, 1988).	20
Figure 8 Various cold-box and no-bake cores.....	21
Figure 9 Typical inputs and outputs of the lost foam process (Energetics, 1999).	23
Figure 10 Manufacture of foam pattern (Inmetalna, 2000).....	24
Figure 11, Figure 12 Assembly and coating of pattern (Inmetalna, 2000).....	24
Figure 13 Placing pattern in the flask (Inmetalna, 2000).	25
Figure 14 Pouring metal into the mould (Inmetalna, 2000).	25
Figure 15 Removal of casting from moulding material (Inmetalna, 2000).....	25
Figure 16 Typical inputs and outputs of the investment casting process (Energetics, 1999).....	26
Figure 17 Investment casting process steps (Piwonka, 1988).....	28
Figure 18 Typical inputs and outputs of the die casting process (Energetics, 1999).....	30
Figure 19 Cold-chamber diecasting plant.....	32
Figure 20 Typical inputs and outputs for cupola furnaces (Energetics, 1999).....	33
Figure 21 Typical inputs and outputs of electric furnaces (Energetics, 1999).....	34
Figure 22 Typical inputs and outputs of fuel-fired melting furnaces (Energetics, 1999).....	34
Figure 23 Typical inputs and outputs of refining, pouring and cooling (Energetics, 1999).....	36
Figure 24 Typical inputs and outputs of cleaning and finishing (Energetics, 1999).....	37
Figure 25 Haley process flow chart.....	44
Figure 26 Haley Industries Limited plant layout.....	45
Figure 27 Cold box coremaking machines.....	48
Figure 28 No-bake sand mixing and core making.....	48
Figure 29 Pattern box preparation.	51
Figure 30 Mould packing.	51
Figure 31 Mould assembly.	52
Figure 32 Close-up of mould assembly.....	52
Figure 33 Lifting a crucible of magnesium from the furnace.	55
Figure 34 Lowering crucible into pouring lift-truck.	55
Figure 35 Magnesium pouring.	56
Figure 36 Moulds after pouring.....	56
Figure 37 Aluminium large casting pouring.	57
Figure 38 Shot-blast unit for sand removal from casting.	59
Figure 39 Thermal reclaimer.....	59
Figure 40 Dust storage, thermal reclaimer building and sand silos.	60
Figure 41 Manual sand removal (blow-out).....	60
Figure 42 Riser cut-off saw.	64
Figure 43 Gating cut-off.....	64
Figure 44 CNC milling.....	65

Figure 45 Casting clean-up (chipping).....	65
Figure 46 Disk sanding a casting.....	66
Figure 47 Casting clean-up (fettling).	66
Figure 48 Welding a casting.....	68
Figure 49 Acid etching castings before inspection.....	73
Figure 50 Draining fluorescent penetrant oil from casting.	73
Figure 51 X-ray inspection of a casting.	74
Figure 52 Dimensional inspection of castings.....	74
Figure 53 Final inspection prior to shipping.	75
Figure 54 Flowchart of a typical foundry operation with Haley processes highlighted.	76
Figure 55 Graphical representation of an industrial process (Boustead, 1979).....	85
Figure 56 A system for drawing process flowsheets (Freeman, 1997).	86
Figure 57 Flowchart of unit-of-product analysis (Malkin, 1997).....	90
Figure 58 Composite curves and the pinch in a T-H diagram (Wall, 1996).	94
Figure 59 Life Cycle Stages (Office of Enforcement, 1995)	98
Figure 60 Technical Framework for LCA (Rhodes, 1997).	99
Figure 61 Schematic of the decision analysis process (Huang, 1995).	104
Figure 62 Methodology for waste minimisation in process industries (Petek, 1996).	112
Figure 63 Pollution prevention planning overview (Ontario, 1993).	113
Figure 64 Haley Industries Limited site plan.	121
Figure 65 Site Layout Diagram	125
Figure 66 Total energy delivered, 1997-98	131
Figure 67 Energy used per kg of casting poured vs. outside air temperature.	132
Figure 68 Electricity delivered, 1997-98.....	133
Figure 69 Electricity maximum demand, 1997-98.....	134
Figure 70 Electricity used per kg of casting poured vs. outside air temperature.	135
Figure 71 Electricity Use vs. Poured Metal.....	136
Figure 72 Natural gas usage, 1997-98.....	137
Figure 73 Natural gas usage vs. mean monthly temperatures.	138
Figure 74 Haley Industries Ltd. ventilation and make-up air.....	142
Figure 75 Drain locations	162
Figure 76 Reclamation flow chart (ETSU, 1998b).	179
Figure 77 Burning on magnesium casting made without an inhibitor.	184
Figure 78 Helicopter main transmission casting.	189
Figure 79 Graph to show relative quantities of aluminium and magnesium poured.	198
Figure 80 Comparison of Case Study Steps to Developed Methodology	213

GLOSSARY

acid demand	A measurement by titration of the acid requirements of a base or system sand. The ADV is expressed as the number of milliequivalents (meq) of 0.1N HCl which is used or reacted with the sand being tested.
activated carbon	Charcoal to absorb contaminants, used in filters and for clarifying liquids.
additive	Any material added to moulding sand for reasons other than bonding.
ADV	Acid demand value.
AFS	American Foundrymen's Society.
aging	In metal or alloy, a change in properties occurring, generally slowly, at room temperatures and more rapidly (artificial aging) at higher temperatures.
AIChE	American Institute of Chemical Engineers.
alloy	A substance having metallic properties and composed of two or more chemical elements of which at least one is a metal.
batch	An amount of core or mould sand or other material prepared at one time
bentonite	A plastic, adhesive type of clay that swells when wet. It is derived from decomposed volcanic ash, and is used for bonding moulding sand.
binder	A material used to hold the grains of sand together in molds or cores. It may be cereal, oil, or natural or organic resins.
blackening	Carbonaceous materials such as graphite, powdered carbon, or soot from acetylene smoke used to improve metal fluidity or surface finish.
blasting or blast cleaning	A process for cleaning or finishing metal objects with an air blast or centrifugal wheel that throws abrasive particles against the surface of the workpiece. Small irregular particles are used as the abrasive in grit-blasting; sand, in sandblasting; and steel balls, in shotblasting.

blow	A term that describes the trapping of gas in castings causing voids in the metal.
blow shoot	Holes in the top of the corebox where the sand enters the corebox.
blowhole	A void or large pore that may occur because of entrapped air, gas, or shrinkage; usually evident in heavy sections.
BOD	Biochemical oxygen demand
boss	A short protrusion or projection from the surface of a casting, often cylindrical in shape. Usually intended for drilling and tapping for attaching parts.
bottom board	A flat base for holding the flask in making sand moulds.
CAD	Computer aided design.
calcining	The preparatory heat treatment given raw refractory materials to remove volatile substances.
CAM	Computer aided manufacturing.
casting	Metal object cast to the required shape by pouring or otherwise injecting liquid metal into a mould, as distinct from one shaped by mechanical process.
casting yield	The weight of a casting divided by the total weight of metal poured into the mould, expressed as a percentage.
CFC	chlorofluorocarbons
charge	1) The total ore, ingot, metal, scrap introduced into a melting furnace for the production of a single heat. 2) Casting placed in a heat treating furnace.
cheek	Intermediate section of flask inserted between cope and drag to decrease the difficulty of moulding unusual shapes or to fill a need for more than one parting line.
chill	Any material with high heat capacity and/or conductivity placed in the mould to increase the cooling rate at that point; also improves microstructure where parts are required to be hard.

chipping	1) Removing seams and other surface imperfections in metals manually with a chisel or gouge, or by a continuous machine, before further processing. 2) Similarly, removing excessive metal.
CHP	Combined heat and power.
chrome pickle	1) Producing a chromate conversion coating on magnesium for temporary protection or as a paint base. 2) The solution that produces the conversion coating.
CMC	Cast Metals Coalition.
CMM	Co-ordinate Measuring Machine.
CNC	Computer Numerical Control machining.
cold box process	A two part organic resin binder system mixed in conventional mixers and blown into shell or solid core shapes at room temperature. A vapour mixed with air is blown into the core, permitting instant setting and immediate pouring of metal around it.
cold chamber machine	A diecasting machine where the metal chamber and plunger are not immersed in hot metal.
cold shut	A discontinuity that appears on the surface of cast metal as a result of two streams of a liquid meeting and failing to unite.
continuous mixer	A mixer in which sand, binder and additive are continuously metered into a mixing trough or chamber that contains revolving mixers of various designs, and prepared sand is discharged.
cope	The upper or topmost section of a flask, mould or pattern.
core	A specially formed material inserted in a mould to shape the interior of another part of a casting which cannot be shaped easily by the pattern.
core assembly	An assembly made from a number of cores.
core blower	A machine for making cores by blowing sand into the core box by means of compressed air. The air escapes from the core box through finely slotted or screened openings.

core box	A box in which a sand core is formed. The wood, metal, or plastic structure contains a shaped cavity into which sand is packed to make a core.
core paste	A prepared adhesive for joining cores, and setting core into moulds.
core print	1) Recess or seating formed in a mould in which the ends of cores are set. 2) Projections on a pattern that form and locate prints in the mould.
core vents	Holes made in the core for escape of gas.
crucible	A vessel or pot, made of a refractory substance or of a metal with a high melting point, used for melting metals or other substances.
crucible furnace	A melting or holding furnace in which the molten metal is contained in a pot-shaped shell. Electric heaters or fuel-fired burners outside the shell generate the heat that passes through the crucible to the molten metal.
cupola	A cylindrical straight shaft furnace usually lined with refractories, for melting metal in direct contact with coke by forcing air under pressure through openings near its base.
cut off saw	A circular saw used to remove gating or risers from a casting.
degas	Usually a chemical reaction resulting from a compound added to molten metal to remove gases from the metal.
degaser	A material employed for removing gases from molten metals or alloys.
degassing	Removing gases from liquids or solids.
degating	Removal of gating system from rough casting.
developer (penetrant)	A finely divided material applied over the surface of a part to help bring out penetrant indications.
developer (radiographic)	A chemical solution which reduces exposed silver halide crystals to metallic silver.
die	A metal block used in forming materials by casting, moulding, stamping, threading or extruding.

die casting	<ol style="list-style-type: none"> 1) A casting made in a die 2) A casting process in which molten metal is forced under high pressure into the cavity of a metal mould.
die lubricant	In diecasting also known as a release agent. Forms an impenetrable barrier or film between molten metal and die metal.
directional solidification	Solidification of molten metal in such a manner that feed metal is always available for that portion which is just solidifying.
double-pass firing	Commonly used in reverberatory furnaces, it consists of a luminous or semi-luminous flame that is relatively high in the combustion chamber so that heat is radiated to the refractory walls and roof. The flue is located on the same wall as the burners so that on the return path, convective heat transfer from the combustion gases is used.
downsprue	The first channel, usually vertical, which the molten metal enters; so-called because it conducts metal down into the mould.
draft	An angle or taper on the surface of a pattern, core box, punch, or die that facilitates removal of the parts from a mould or die cavity, or a core from a casting.
drag	The bottom section of a flask, mould, or pattern.
dragout	Solution carried out of a bath by the work and its associated handling equipment
draw	To remove pattern from the mould.
dross	<ol style="list-style-type: none"> 1) The scum that forms on the surface of molten metal because of oxidation or the rising impurities to the surface. 2) Waste resulting from (1) plus spillage and separated foreign matter.
exhaust system	The arrangement of ducts or pipes and fans for removing objectionable dust, heat and pollutants from one or more points or from a process and discharging them into the atmosphere.
facing sand	A special sand mixture placed against the pattern which produces the surface in contact with the molten metal. Is backed up by sand.

feed metal	The volume of liquid metal that passes from the risers to the casting to make up for shrink.
fettle	Trim or clean the rough edge of a metal casting.
fin	Metal on a casting caused by an imperfect joint in the mould or die.
fines	1) A particle size classification of non-metallic materials in a sand mixture with equivalent diameters of 74 to 20 microns. 2) Those sand grains substantially smaller than the predominating grain size.
finish	Surface condition, quality or appearance of a metal.
fixer	A chemical solution which dissolves unexposed silver halide crystals from developed film emulsions.
flash	A thin section or fin of metal formed at the mould, core, or die joint or parting in a casting due to the cope and drag not matching completely or where core and core print do not match.
flask	Metal or wood frame without top and without fixed bottom used to hold the sand of which a mould is formed.
fluorescent penetrant inspection	A nondestructive test for detection of surface discontinuities with fluorescent material viewed under black (ultraviolet) light.
fluoroscope	An instrument with a fluorescent screen on which x-ray images may be viewed without taking and developing x-ray photographs.
flux	In metal refining, a material used to remove undesirable substances, such as sand, ash, dirt, as a molten mixture. It is also used as a protective covering for certain molten metal baths. A fusible salt mixture or gas used to purify molten metal by removing suspended oxides or dissolved gas.
FMEA	Failure Mode and Effects Analysis.
foundry	A commercial establishment or building where metal castings are produced.

fugitive air emissions	Air emissions associated with an area rather than a specific point.
gas porosity	Fine holes or pores within a metal that are caused by entrapped gas or by the evolution of dissolved gas during solidification.
gassing	Cure by applying gas to sand mould or cores.
gate (ingate)	That portion of the runner in a mould where molten metal enters the casting or moulding cavity; sometimes applied to entire assembly of connected chambers, to the pattern parts which form them or to the metal which fills them, and sometimes restricted to mean the first or main channel.
gating system	The complete assembly of sprues, runners, and gates in a mould through which metal flows to enter the casting cavity. The term is also applied to equivalent portions of the pattern.
gfn	grain fineness number
grain fineness number	The screen number which would correspond with the empirically calculated average screen size of the sample.
grain refiner	Any material added to a liquid metal for producing a finer grain size in the subsequent casting.
green sand	A naturally-bonded sand or a compounded moulding sand mixture which has been tempered with water for use while it is still in the damp or wet condition.
HAPs	Hazardous Air Pollutants as defined by the US Clean Air Act.
hardener (master alloy)	An alloy rich in one or more alloying elements that is added to a melt to permit closer control of composition than is possible by the addition of pure metals, or to introduce refractory elements not readily alloyed with the base metal. Sometimes called a master alloy.
Hazardous Air Pollutants	Chemicals that cause serious health and environmental effects. Health effects include, cancer, birth defects, nervous system problems and death due to massive accidental release.

heat treatment	A combination of heating or cooling operations timed and applied to a metal or alloy in the solid state in a manner which will produce desired properties.
HIL	Haley Industries Limited.
hot chamber machine	A diecasting machine in which the metal chamber is immersed in the molten metal in a built-in furnace. The chamber itself is called a gooseneck from its appearance.
inhibitor	A material such as fluoride, boric acid or sulphur, used to prevent burning of molten magnesium alloys, or one for restraining an undesirable chemical reaction.
insulating sleeves	Insulating material used to lower the rate of solidification. As sleeves on open risers, they are used to keep the metal liquid, thus increasing the feeding efficiency.
LCA	Life cycle assessment or analysis.
LCI	Life cycle inventory.
locators	Plastic inserts that are inserted into moulds and cores to position the mould/core within a specified tolerance.
LOI	Loss on ignition.
loose piece	1) Core box; part of a core box which remains embedded in the core, and is removed after lifting off the core box. 2) Pattern; laterally-projecting part of a pattern so attached that it remains in the mould until the body of the pattern is drawn.
loss on ignition	The total amount of material in a sand mixture which is capable of burning at high temperature in the presence of air.
macrograph	A graphic reproduction of the surface of a prepared specimen that has been magnified not more than ten diameters.
master alloy	An alloy, rich in one or more desired addition elements, that is added to a melt to raise the percentage of a desired constituent.
melting loss	Loss of metal in the charge during the operation of melting, usually due to oxidation or volatilisation.

metalcasting	Pouring molten metal into a mould to solidify, the shape of the solidified object being determined by the shape of the mould cavity.
micrograph	A graphic reproduction of the structure of a prepared sample of metal or alloy as observed at a magnification of more than 10 diameters.
micron	A linear distance of one millionth (10^{-6} m) of a meter.
misrun	Denotes an irregularity of the casting surface caused by incomplete filling of the mould due to low pouring temperatures, gas back pressure from inadequate venting of the mould, and inadequate gating.
mould	Normally consists of a top and bottom form, made of sand, metal, or any other investment material which contains a cavity into which molten metal is poured to produce a casting of definite shape and outline.
mould coating	Coating to prevent surface defects i.e. metal penetration and improved metal finish. Usually an aqueous suspension containing various compounds such as graphite, silica flour and the like, used to coat the surface of the cavity in the casting mould.
MSDS	Material Safety Data Sheets
muller	A machine designed to mix foundry green sand. It mixes the sand and clay particles by compressing with a heavy roller and involves a kneading as well as a stirring motion.
NDT	Nondestructive testing.
no-bake binder	A synthetic liquid resin sand binder that hardens completely at room temperature, generally no requiring baking.
nondestructive testing (NDT)	Testing to detect internal and concealed defects in materials using techniques that do not damage or destroy the items being tested.
nucleant	A chemical additive to the molten metal that can provide nuclei for grain growth, used for grain refining.
parting line	1) A line on a pattern or casting corresponding to the separation between the cope and drag portions of the sand mould. 2) The mark left on a casting at die joint.

patching sand	Sand that is used to patch or fill voids on cores to produce a smooth finish.
pattern (sand casting)	A form of wood, metal or other materials, around which moulding material is placed to make a mould for casting metals.
penetrant	This is the fluid that is caused to enter the discontinuity in order to produce an indication at the flaw.
pig	An ingot of virgin or secondary metal (as rejected castings or scrap) to be remelted for use.
PJ	10^{15} Joules.
PM₁₀	Particulate matter less than or equal to 10 micrometers (μm) in aerodynamic diameter.
point air emissions	Air emissions originating from a stack or distinct point.
pot	A vessel for holding molten metal.
POTW	Publicly Owned Treatment Works, wastewater treatment.
PT	Total particulate.
Q	heat (kJ)
quenching	A process of rapid cooling from an elevated temperature by contact with liquids, gases or solids.
radiography	A nondestructive method of internal examination in which metal objects are exposed to a beam of x-ray or gamma radiation. Differences in thickness, density or absorption, caused by internal defects or inclusions, are apparent in the shadow image either on a fluorescent screen or on a photographic film placed behind the object.
ramming	<ol style="list-style-type: none"> 1) Packing sand, refractory, or other material into a compact mass. 2) The compacting of moulding sand in forming a mould.
refractory	A material of very high melting point with properties that make it suitable for such uses as furnace lining and kiln construction.

release agent	A material, such as silicone, stearate, oil or wax for lubricating a die pattern or core box to facilitate easy removal of a casting, mould or core.
riser	A reservoir of molten metal connected to the casting to provide additional metal to the casting, required as the result of shrinkage before and during solidification. Risers allow gas to escape as the metal rises in the mould and indicates when the mould is full.
riser sleeves	A liner that goes between the sand and the molten metal, it is made of an insulating fabric to keep the metal molten for longer.
rolling over	The operation of reversing the position of the mould/flask. If the drag part of the pattern has been rammed with the parting surface downward, it is rolled over 180° to allow core setting and placement of cope.
rollover machine	A moulding machine with which the flask/mould is rolled over before the pattern is drawn from the mould.
runner	1) A channel through which molten metal flows from one receptacle to another. (2) The portion of the gate assembly of a casting that connects the sprue with the gates. (3) Parts of patterns and finished casting corresponding to the portion of the gate assembly described in (2).
sand	In metalcasting, a loose granular material, high in SiO ₂ resulting from the disintegration of rock. The name sand refers to the size of grain and not to mineral composition. Diameter of the individual grains can vary from approximately 6 to 270 mesh.
sand holes	Cavities of irregular shape and size, the inner surfaces of which plainly show the imprint of a granular material or the inclusion of sand particles.
sand reclamation	Processing of used foundry sand by thermal, air, or hydraulic methods so that it can be used in place of new sand without substantially changing the foundry sand process.
sandblasting	Abrasive blasting with sand.

scrap	1) Defective product not suitable for sale. 2) Discarded metallic material from whatever source that may be reclaimed through melting and refining.
SF₆	Sulphur hexafluoride.
shakeout	1) The operation of removing castings from the mould. 2) A mechanical unit for separating the moulding materials from the solidified casting.
shotblasting	Casting cleaning process employing a metal abrasive (grit or shot) propelled by centrifugal or air force.
shrinkage defects	Formed if there is a region of liquid metal which is trapped in the casting with no open feed paths to a source of hot replenishment metal, and this region continues to contract, forming a void.
snagging	Removal of stubs, fins, parting lines, other surplus material and rough spots from a casting are removed by abrasive wheels, belts or discs.
solution heat treat	A process in which an alloy is heated to a suitable temperature, held at this temperature long enough to allow a certain constituent to enter into solid solution and is then cooled rapidly to hold the constituent in solution. The metal is left in a supersaturated, unstable state and may subsequently exhibit age hardening.
spectrograph	An optical instrument for determining the presence or concentration of minor metallic constituents in a material by indicating the presence and intensity of specific wavelengths of radiation when the material is thermally or electrically excited.
sprue	The mould channel that connects the pouring basin with the runner or, in the absence of a pouring basin, directly into which the molten metal is poured. Sometimes referred to as a downsprue or downgate.
strike-off	Operation of removing excess sand from the top or core or pattern box.
TCA	Total Cost Assessment.
tex vent	A vent placed in a mould or core so that gases can escape during the pouring process.

TQM	Total Quality Management.
tramp metal	Small pieces of metal, flashing that gets into the sand after shakeout.
TRI	Toxic Release Inventory (United States).
ultrasonic testing	A non-destructive method of testing metal for flaws based on the fact that ultrasonic waves are reflected and refracted at the boundaries of a solid medium.
US DOE	United States Department of Energy.
US EPA	United States Environmental Protection Agency.
vent	A small opening or passage in a mould or core to facilitate the escape of gases when the mould is poured.
VOCs	Volatile Organic Compounds.
yield	Comparison of casting weight to total weight of metal poured into the mould.

1 INTRODUCTION

1.1 The Metalcasting Industry

The term ‘metalcasting’ applies to the entire industry of melting metal, and pouring molten metal into a mould for the purpose of achieving a desired shape. The term ‘foundry’ is applied to all but diecasting operations (CMC, 1995).

The earliest evidence of metalcasting dated between 5000 and 3000 B.C. Metalcasting at that time was used to make objects such as axes and jewellery (Goodway, 1988). Today, more than 90% of all manufactured, durable goods, and 100% of all manufacturing machinery contain metal castings. In 1996 USA metal casting industry shipments totalled about 12.2 million tonnes with a value exceeding \$23 billion (US dollars) (CMC, 1998). Table 1 shows the top ten metalcasting countries in 1997. Globally, 1997 metalcasting shipments were approximately 60.8 million tonnes (Modern Casting, 1998).

Table 1 Top 10 Metalcasting Countries in 1997 (AFS, 1998).

Country	Shipments (million tonnes)	Number of Foundries
U.S.	13.0	2,950
China	10.1	10,997
Japan	6.3	1,357
Germany	3.7	710
India	3.0	6,000
France	2.2	477
Italy	2.0	398
Korea	1.4	740
U.K.	1.3	786
Mexico	1.1	227

Note: Brazil and Taiwan did not report in 1997 but were in the top ten in 1996.

The metalcasting industry employed nearly 217,000 people in the U.S. in 1997 although it is an industry dominated by small business. Of the approximately 3100 metalcasting establishments in the country, 79% employ fewer than 100 people, only 4% having greater than 250 employees (CMC, 1998). In 1997 there were approximately 127,000 persons employed by ferrous foundries and 90,000 employed by non-ferrous foundries (US DOE, 1997). Due to the small business nature of the industry, the wide variety of processes used and metals cast, the metalcasting industry is highly segmented and diverse.

The American Foundrymen’s Society has described 38 methods for producing a metal casting. Each process offers distinct advantages that are familiar to and exploited by casting designers and specialists (Energetics, 1999). Table 2 shows the diverse markets served by the industry. Metalcastings are important to designers and specifiers of components because (CMC, 1995):

- ♦ Cast components are net or near-net shape.
- ♦ Almost all metals and alloys can be cast.
- ♦ There are almost no restrictions on part weight or size.
- ♦ Intricate parts can be produced as single cast components
- ♦ Castings can be manufactured to include complex interior cavities.
- ♦ All the industry's products are made from fully recyclable materials.

Table 2 Major markets served by industry in 1994 (CMC, 1998).

Market	Ferrous (%)	Non-Ferrous (%)
Motor Vehicles	28	43
Ingot Moulds	20	0
Pipe	20	0
Industrial Machinery	14	15
Farm Equipment	9	0
Railroad	5	0
Construction	4	5
Transportation	0	13
Electric Power	0	24
TOTAL	100	100

Table 3 shows the breakdown of different metals cast and their relative tonnages and values. Although non-ferrous castings make up only 19% of the tonnage of castings, they represent 48% of casting value (AFS, 1998). The most common casting processes are sand casting, permanent mould casting, die casting, and investment mould casting (DOE, 1997). A description of these processes follows.

Table 3 Breakdown of different metals cast and their relative tonnages and values (CMC, 1998).

Metal	% of Tonnage	% of Value
Iron Castings	73%	35%
Steel Castings	9%	14%
Aluminum Castings	13%	28%
Copper Alloy Castings	2%	5%
Other Nonferrous Castings	4%	15%

1.2 Metalcasting and the Environment

1.2.1 Energy use in the metalcasting industry

Metalcasting is among the most energy-intensive industries in the United States, with 15-25% of production costs being related to the use of energy. The range is due to the type of metal and melting method (OIT, 2000). Industry wide process energy consumption is estimated to be 211-264 PJ (Energetics, 1999 and OIT, 2000), Table 4 shows a breakdown of the main energy consuming processes. Metalcasting

products have the potential to effect higher energy consumption and potential savings because the main end use is transportation (OIT, 2000).

Table 4 Breakdown of Process Energy Costs (Bates, 1997).

Process Step	% of Total Costs
Coremaking	8
Mouldmaking	12
Melting	55
Heat Treatment	6
Post Cast	7
Other	12
Total	100

Table 5 Energy Use Mix for Gray and Ductile Iron Foundries in 1994 (US DOE, 1997).

Fuel	Percentage Use
Natural Gas	21.4
Electricity	19.5
Electricity Losses	39.0
Coke and Breeze	18.9
LPG	0.6

In 1992-93 a total of 22.7 PJ delivered energy was consumed in the United Kingdom metalcasting industry (ETSU, 1995). The breakdown of this consumption by metal cast is shown in Table 6.

Table 6 UK foundry energy consumption for 1992-93 (ETSU, 1995).

Sector	Casting Output (t/yr)	Total delivered energy consumption (PJ)
Iron	1,300,000	15.5
Steel	100,000	2.5
Non-Ferrous	190,000	4.7
Total	1,590,000	22.7

In the UK it is estimated that foundry services such as motors, drives, compressed air, lighting, space heating etc. account for 20 – 50% of the total energy consumption, with an average of about 35%. (ETSU, 1995).

In the transportation sector the trend is to lower the weight of cars to increase their fuel efficiency. This has resulted in a decrease in the use of gray iron and an increase in the use of light metals (such as aluminium and magnesium) and ductile iron (Energetics, 1999). Generally, light metals require less energy to melt a similar volume of metal.

Targets have been set for the US metalcasting industry (CMC, 1998). These are:

- ♦ Reduce the amount of energy consumed per unit value of shipments by 20% by 2020.
- ♦ Interim targets are to reduce energy consumption 3 to 5% within five years.

Although the Metalcasting Industry Roadmap (CMC, 1998) lists the barriers to reducing energy consumption in the industry, there is not a specific plan to reduce energy consumption in the industry.

1.2.2 Environmental regulations and the metalcasting industry

“Metalcasting produces a number of gaseous, liquid and solid waste streams, many of which could have an adverse effect on the environment. Waste products from casting operations include waste gases from moulding and core making, melting, moulding, and shakeout; contaminated and unusable spent sand from casting shakeout; slag from melting; and particulate from melting, shakeout, and cleaning. Air-borne pollutants and contaminants also present a major environmental issue for all metalcasters. These include dust, particulates, off-gases, fumes and gases from furnaces, and other by-product gases and fugitive emissions. Metalcasting also produces some very positive impacts on the environment by preventing the landfilling of large amounts of scrap metal.”(AFS, 1998).

The financial stability of the metalcasting industry is vulnerable to the cost of increasingly stringent environmental and occupational regulations. These, coupled with changing market conditions and increased global competition, have resulted in the annual loss of about 100 metalcasting establishments in the United States during the last two decades (CMC, 1995).

The waste streams produced by metalcasting are subject to compliance with a number of environmental regulations governing air, water, and solid waste effluents. The US federal legislation that pertains to the metalcasting industry (Energetic, 1999 and US EPA, 1997) is:

- ♦ Clean Air Act and Clean Air Act Amendments of 1990
The Act and amendments are designed to protect and enhance the nation’s air resources so as to “promote the public health and welfare and the productive capacity of the population”.
- ♦ Federal Water Pollution Control Act (commonly known as the Clean Water Act)
The primary objective of this Act is to restore and maintain the chemical, physical, and biological integrity of the nation’s surface waters.
- ♦ Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980
This law is also known as Superfund, it authorises the Environmental Protection Agency to respond to releases, or threatened releases of hazardous substances that may endanger public health, welfare, or the environment.
- ♦ Superfund Amendments and Reauthorization Act
This Act revised some sections of CERCLA and extends taxing authority for Superfund and created EPCRA.
- ♦ Pollution Prevention Act (PPA) of 1990
The Pollution Prevention Act established a national policy of managing wastes through source reduction. It also established as national policy a

hierarchy of waste management options for situations in which source reduction cannot be implemented feasibly. The Pollution Prevention Act (PPA) requires facilities to report information about the management of Toxic Release Inventory (TRI) chemicals in waste and efforts made to eliminate or reduce those quantities.

- ♦ Emergency Planning and Community Right-to-Know Act (EPCRA)

This statute is designed to improve community access to information about chemical hazards and to facilitate the development of chemical emergency response plans by State and local governments. Specifies reporting obligations for facilities which store or manage specified chemicals.

- ♦ Resource Conservation and Recovery Act

This Act addresses solid and hazardous waste management activities.

The US foundry industry spends over \$1.25 billion (US dollars) per year to comply with regulations. About 40% of compliance costs are used for control, treatment, and disposal of air pollutants and related sludges. Solid and hazardous waste disposal, mostly sands and slags, account for about 33% of compliance costs. In terms of new capital expenditures, it has been estimated that environmental expenditures consume as much as 30 to 60% of total annual spending for the foundry industry (CMC, 1998). A recent survey of North American foundries found that 66% planned to change one or more processes in the next three years to ensure environmental compliance (Laitar, 1996).

In the UK, the industry is also subject to regulation. Environmental legislation affecting the foundry industry in the UK falls under the following Acts (Envirowise, 2000):

- ♦ Environmental Protection Act 1990

EPA 1990 introduced new controls on all aspects of industrial and other sources of pollution. There has been considerable environmental legislation introduced under the auspices of this Act. This Act, regulations and guides have designated foundries as “prescribed processes”. Foundries must be authorised to operate the process by their relevant regulatory body. Foundries must also meet their “Duty of Care” obligations in regards to their waste management.

- ♦ Pollution Prevention and Control Act 1999

This Act provides the primary legislation for implementation of the EC Directive on Integrated Pollution Prevention and Control (IPPC). This legislation will not be fully implemented until 2007. Processes prescribed under IPPC will be subject to IPPC permits based on the use of Best Available Techniques (BAT). These permits will control: emissions to air, land and water; prevention of noise and vibration nuisance; minimisation of resource, energy and utilities consumption; prevention of land contamination.

- ♦ Clean Air Act 1993

The Act imposes restrictions on the emissions of dark and black smoke from chimneys. Foundries must ensure that no black smoke is emitted from any chimney or activity on the site.

- ♦ Air Quality Regulations 1997

These regulations require local authorities to ensure that Air Quality Standards for seven polluting substances are achieved in all areas of the UK by 2005.

- ♦ Water Industry Act 1991
This Act established the control regime for the discharge of trade effluents.
- ♦ Water Resource Act 1991
Introduced controls to prevent pollution of controlled waters and to restrict abstraction.
- ♦ Groundwater Regulations 1998
This legislation is applicable for discharges to ground, an authorisation is required for any such activities at a site.

From the above lists of regulations affecting the metalcasting industry in both the United States and the United Kingdom it is clear that the industry has many regulatory obligations. Additional regulatory constraints are continually being added to manufacturing facilities. This has frequently led to additional costs in the manufacturing process.

1.2.3 Metalcasting waste generation

The metalcasting industry is the largest recycler in North America, saving about 13.6-18.1 million tonnes of scrap metal from disposal to landfills and junk yards each year and using this waste as a source of raw materials to produce useful products. (OIT, 2000). Although the metalcasting industry is renowned for using recycled metal to produce new goods, 75% of its own by-products could be easily recycled, but instead end up in landfills or are released into the air or water (Reuland, 1997).

The various forms of sand casting account for a combined total of 60% of U.S. castings by weight. Permanent mould and die casting combined together account for another 20% of the total, while investment casting has increased to about 7% of the total (Energetics, 1999).

For a sand casting foundry wastes fall into four major categories: sand, slag, dusts, and other. Waste sand may account for nearly 70% of an individual foundry's waste stream, depending on how much can be recycled on site. Slag typically comprises 20% to 25% of a foundry's by-products. Cupola ash and refractories may contribute to the residual slag that forms. Dusts can comprise 10% or more of the total wastes, and other wastes fall into a number of categories (Energetics, 1999).

The largest material stream used in foundries is sand. Over 93% is recycled within foundries. The remaining 7% account for 6.3 to 7.3 million tonnes annually in the United States and leave the foundries as spent sand. (Leidel, 1994). The UK foundry industry currently spends nearly 35 million pounds per year on purchasing and disposing of over one million tonnes of new and used sand. (ETSU, 1998). Reducing sand use, increasing the amount of sand recycled or redirecting sand from landfill is one of the key challenges for foundries now and in the future.

Most of the data available about foundry releases to the environment comes from the US Toxic Release Inventory (TRI). The TRI includes self-reported facility release and transfer data for over 600 toxic chemicals. Facilities that are required to report

have more than 10 employees, and are above weight-based reporting thresholds for on-site releases and off-site transfers (US EPA, 1997). Toxic Release Inventory data for the metalcasting industry in 1995 is shown in Table 7 to Table 10.

Table 7 1995 Toxics Release Inventory Data for Metalcasting (US EPA, 1997).

# facilities.	TRI	Total Releases (million kg)	Total Transfers (million kg)	Total Releases and Transfers (million kg)	Average Releases & Transfers per facility
654		16.3	33.5	49.8	76,147 kg

Table 8 1995 Air Pollutant Releases in the US Metalcasting Industry (US EPA, 1997).

CO (tonnes/yr)	NO ₂ (t/yr)	PM ₁₀ (Particulate) (t/yr)	PT (t/yr)	SO ₂ (t/yr)	VOC (t/yr)
105700	10803	9972	19023	5907	17261

Table 9 1995 Toxic Release Inventory Breakdown by Release (US EPA, 1997).

Industry	No. Facilities	Fugitive Air (kg)	Point Air (kg)	Water Discharges (kg)	Land Disposal (kg)	Total Releases (kg)
Foundries	664	2549247	2088333	25722	11664084	16327385
Die casting	100	27967	205210	727	1458	235362

Table 10 1995 Toxic Release Inventory Breakdown by Transfer (EPA, 1997).

Industry	No. Facilities	POTW transfers (kg)	Disposal transfers (kg)	Recycling transfers (kg)	Treatment transfers (kg)	Energy Recovery (kg)	Total Transfers (kg)
Foundries	554	57904	12309486	20338004	718800	96251	33521852
Die casting	100	517	144022	5514440	17121	0	5676100

Although the metalcasting industry is a large recycler of metal it produces significant air, land and water emissions. These emissions have frequently been controlled by purchasing a system to capture pollutants without preventing the creation of the pollutants at source. This approach is not sustainable in the long term as high quality raw materials purchased at a cost are degraded to low quality materials or wastes that often have a cost associated with treatment or disposal. The best way to stop toxic substances from entering the environment is not to produce them. As it can be seen from the above regulations, regulators are starting to use source reduction/pollution prevention (Archer, 1994).

“Improving environmental performance while keeping regulatory compliance costs at a minimum is one of the key challenges affecting the future competitiveness of metalcasters. How well the industry copes with increasingly stringent controls on emissions to the environment will have dramatic impacts on production costs as well as industry growth.” (CMC, 1998)

In order to address some of these and other issues facing the industry the Cast Metals Coalition was formed. In 1995 a document called “Beyond 2000: A vision for the American metalcasting industry” (CMC, 1995) was released. The document was an evaluation of the state of American metalcasting and a vision for its future. With respect to environmental issues the Cast Metals Coalition stated that “Metalcasting will find ways to enhance the cleanliness of its processes, increase both pre- and post-consumer recycling, and explore ways to reduce, and eventually eliminate its waste streams.” A subsequent document was released in 1998 (CMC, 1998), the “Technology Roadmap” detailed the technology milestones and presented a detailed research portfolio. Several areas of research pertaining to environmental issues were identified, including: complete characterization of waste streams allowing for process modification, advance waste treatment technologies, alternative processes or materials for reduced waste generation (CMC, 1998).

The 1992 World Foundry Congress (Dorfmueller, 1992) defined the concept of Producing More with Less as: analysing the environmental impact of all energy, materials and processes involved in metalcasting and resolving at their source any use and disposal problems inherent in each. It was also stated that “end of pipe strategy always costs money, but new approaches to process control and materials reuse have the potential eventually to lower costs through energy savings, materials conservation and lower capital investment”

The way of the future has been described by the “Technology Roadmap” (CMC, 1998) as eliminate and reduce waste streams. This is the pollution prevention approach. “Pollution prevention seeks to eliminate pollution problems by not creating potential pollutants at all or, if their creation cannot be avoided, by not letting them reach the end of the pipe if this can be reasonably be avoided.” (Rossiter, 1995). Experience in the United States and other countries has demonstrated that, in the long run, pollution prevention, through activities such as waste minimisation and cleaner production, is more cost effective than many pollution control methods. The industry visionaries and leaders are all advocating pollution prevention approaches to environmental issues. Yet articles are still appearing in industry journals advocating the old approach, for example (McDermott, 1999): “Environmental control represents the broad range of methods that are currently available to foundrymen to integrate into their daily operations to help meet the various environmental standards and regulations that have been set forth by federal, state, and local laws.” In that same article pollution control equipment was ranked as “the number one item on foundry executives’ equipment purchase plans for 1999.”

Obviously pollution prevention techniques have many benefits for the industry including potentially lowering material purchases as well as reducing the pollutants

that need to be controlled and treated. However, this is not necessarily a simple undertaking in an industry consisting of small businesses and a large variety of processes. Long term solutions to some environmental issues requires research and development, investments and information gathering, and financial investment. This has been difficult for many foundries, most of which are small businesses with limited funds for capital expenditures or research of any kind. Those businesses that do have innovative solutions may not be willing to share their competitive advantage. Pollution prevention can mean altering fundamental manufacturing processes. The new processes may be patentable and/or be a valuable financial asset to the company. Radical changes to an industry nearly always creates strong resistance from those that have been accustomed to the previous modes of operation.

Metalcasting as an industry has a high scrap rate, at least 10% of all castings made are scrapped in the foundry or rejected by its customers (ETSU, 1994). However, much of the technological development of the last fifty years concentrated on how to increase production and how to salvage defective castings by developing technology for shotblasting, automated grinding, welding etc. and relatively little effort has been extended to improving process control i.e. making the casting right the first time (Leidel, 1996). The result of this is waste, unnecessary energy used to repair castings while simultaneously causing pollution. A current barrier to environmental improvement is a relatively high industry scrap rate. A near-term research priority for the industry is scrap analysis methods and reduction strategies (DOE, 1997). Reducing defective material not only reduces manufacturing costs but also reduces pollution. According to the American Foundrymen's Society (AFS, 1995) "It is estimated that in-process control of key points in production could avoid over 90% of the defects that cause casting scrap". Sustainable manufacturing may be defined as a process of creating harmony between economic goals and social/ecological concerns at every step of industrial activity. This means that the risk associated with material use throughout the entire life-cycle should be considered (Ghosh, 1993). The main issue is that limited resources can prevent metalcasters from defining the limits of process control and implementing these control strategies.

1.3 Statement of Needs

The chief drivers of environmental performance goals are regulation and economics. Regulations are continually reducing permissible emissions. A control strategy that meets standards today may not meet future standards. The issues of environmental controls have to be faced, in spite of the many difficulties, if the metalcasting industry is to have a viable future. A methodology needs to be developed that can be used by a diverse industry made up of small units. These units need individual solutions to particular local problems, at a cost that allows the companies to continue profitable operations, with continued improvements on quality on a long term basis.

1.4 Thesis Aims and Objectives

- ♦ Evaluate the processes used in the metalcasting industry.
- ♦ Evaluate energy, water and materials consumption.

- ♦ Evaluate the environmental effects of the metalcasting industry.
- ♦ Investigate methodologies used to reduce pollution to a minimum in other industries.
- ♦ Evaluate the applicability of the methodologies to the metalcasting industry.
- ♦ Examine in depth the environmental issues at Haley Industries Limited.
- ♦ Develop and apply an ordered methodology to complete a pollution prevention assessment at Haley Industries Limited.
- ♦ Develop an ordered methodology to complete pollution prevention assessments at metalcasting facilities.
- ♦ Estimate the effects if the methodology is applied at all metalcasting operations.

2 INTRODUCTION TO METALCASTING PROCESSES

This chapter is divided into two sections. The first section introduces the most commonly used metalcasting processes. The second section reviews the processes used at the case study site.

2.1 Metal Casting Processes

The metal casting process consists of pouring molten metal into a mould containing a cavity of the desired shape of the casting. Metal casting processes can be classified either by the type of mould and pattern, or by the pressure or force used to fill the mould with molten metal (Kotzin, 1981).

The following classifies foundry processes based on mould type:

Expendable Mould Processes

Permanent Patterns

- Clay/water bonds (green sand moulding)
- Heat cured resin binder processes
- Cold box resin binder processes
- No-bake resin binder processes
- Silicate and phosphate bonds
- Plaster bonds
- No bond
- Other bonding systems

Expendable patterns

- Foamed patterns
- Wax patterns (investment casting)

Permanent Mould Processes

- Die casting
- Centrifugal casting
- Hybrid processes

Figure 1 shows a chart of expendable mould processes and how they relate to one another. Figure 2 shows a chart of permanent mould processes and how they relate to one another.

The type of process chosen to make a casting is dependent on many variables, the main ones being those listed below (AFS, 1988):

- ♦ Quantity of castings required
- ♦ Design of the casting
- ♦ Tolerances required
- ♦ Complexity
- ♦ Metal specification
- ♦ Surface finish required
- ♦ Tooling costs

- ♦ Economics of machining versus casting costs
- ♦ Financial limits on capital costs
- ♦ Delivery requirements

A basic description of most of these processes will be given. However the focus will be on permanent pattern and die casting processes. The materials used and the environmental effects of the processes are shown in Table 20.

Figure 1 Expendable Mould Processes.

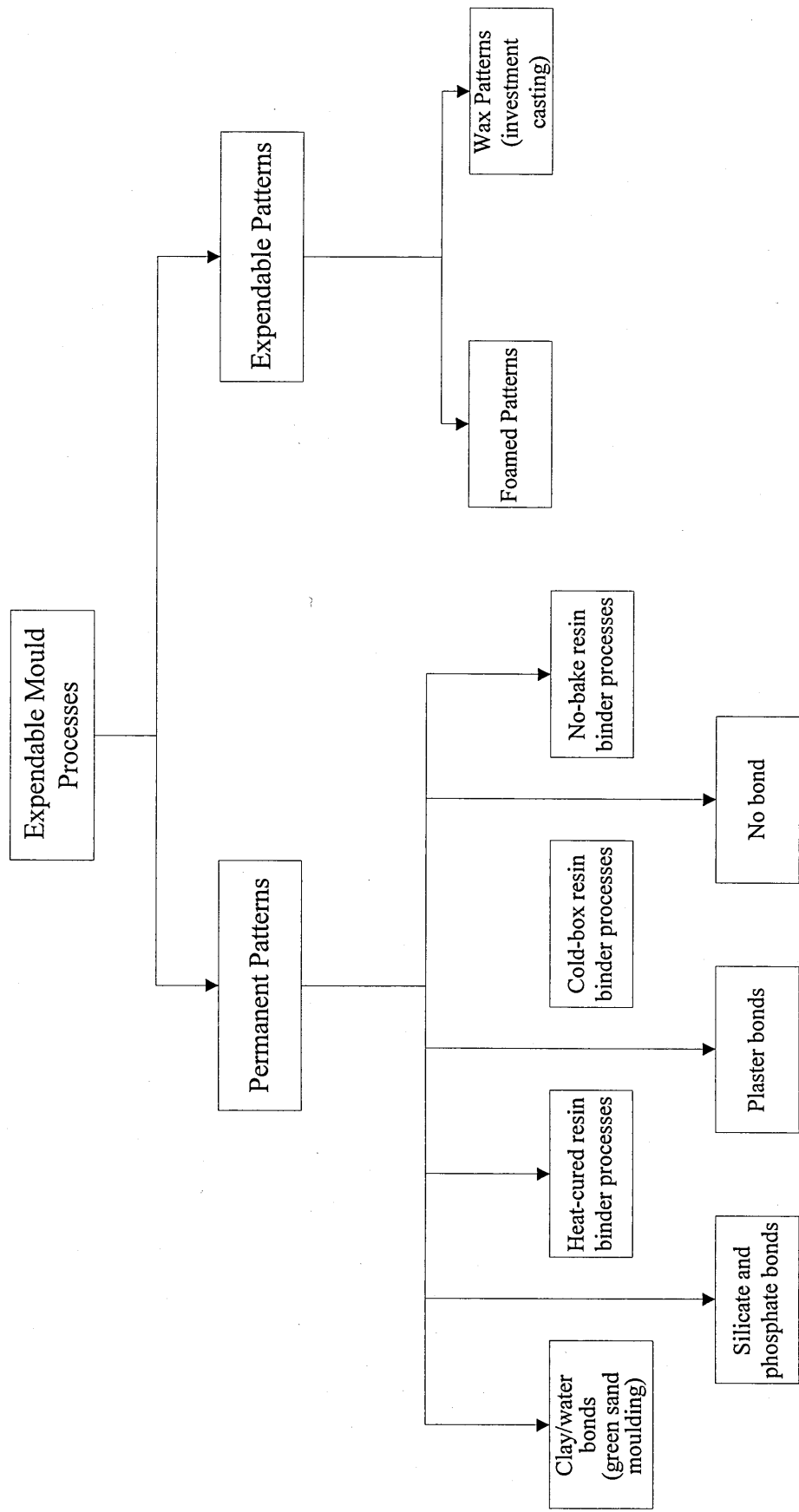


Figure 2 Permanent Mould Processes.

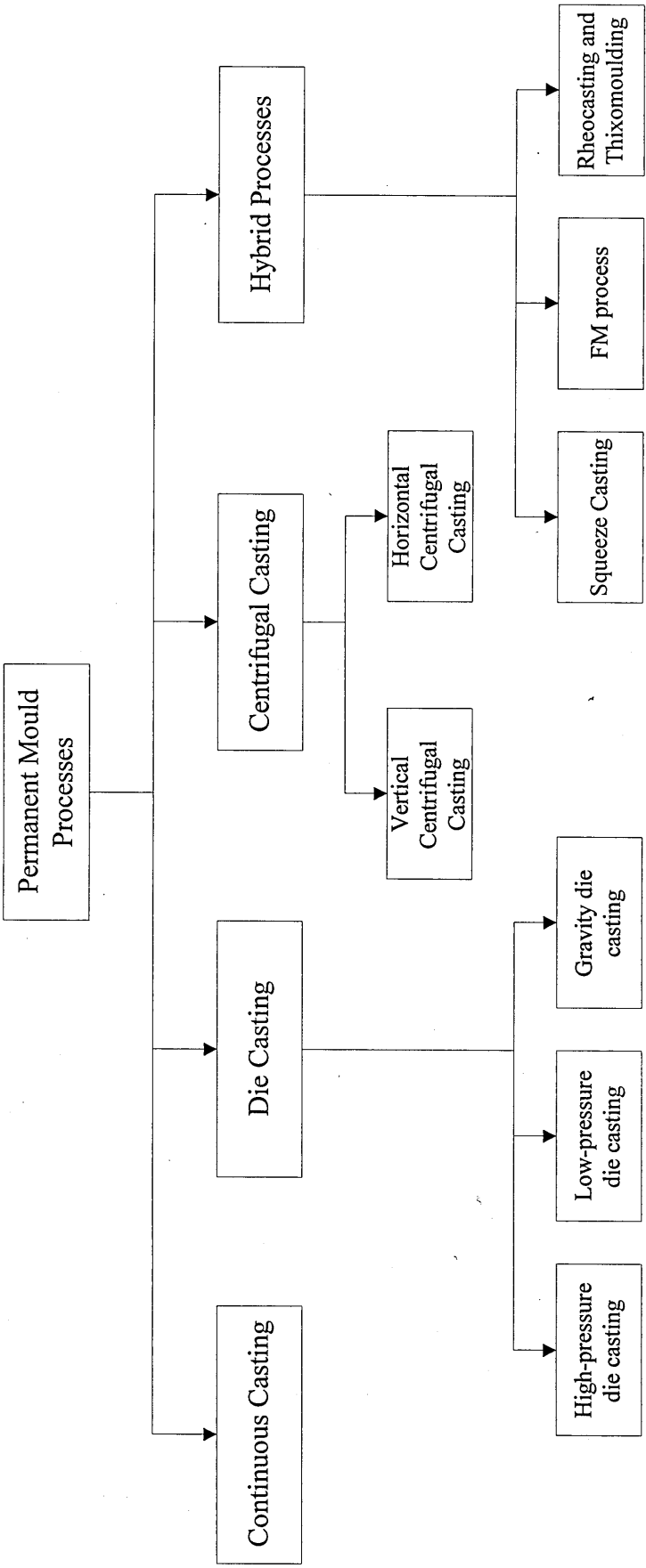
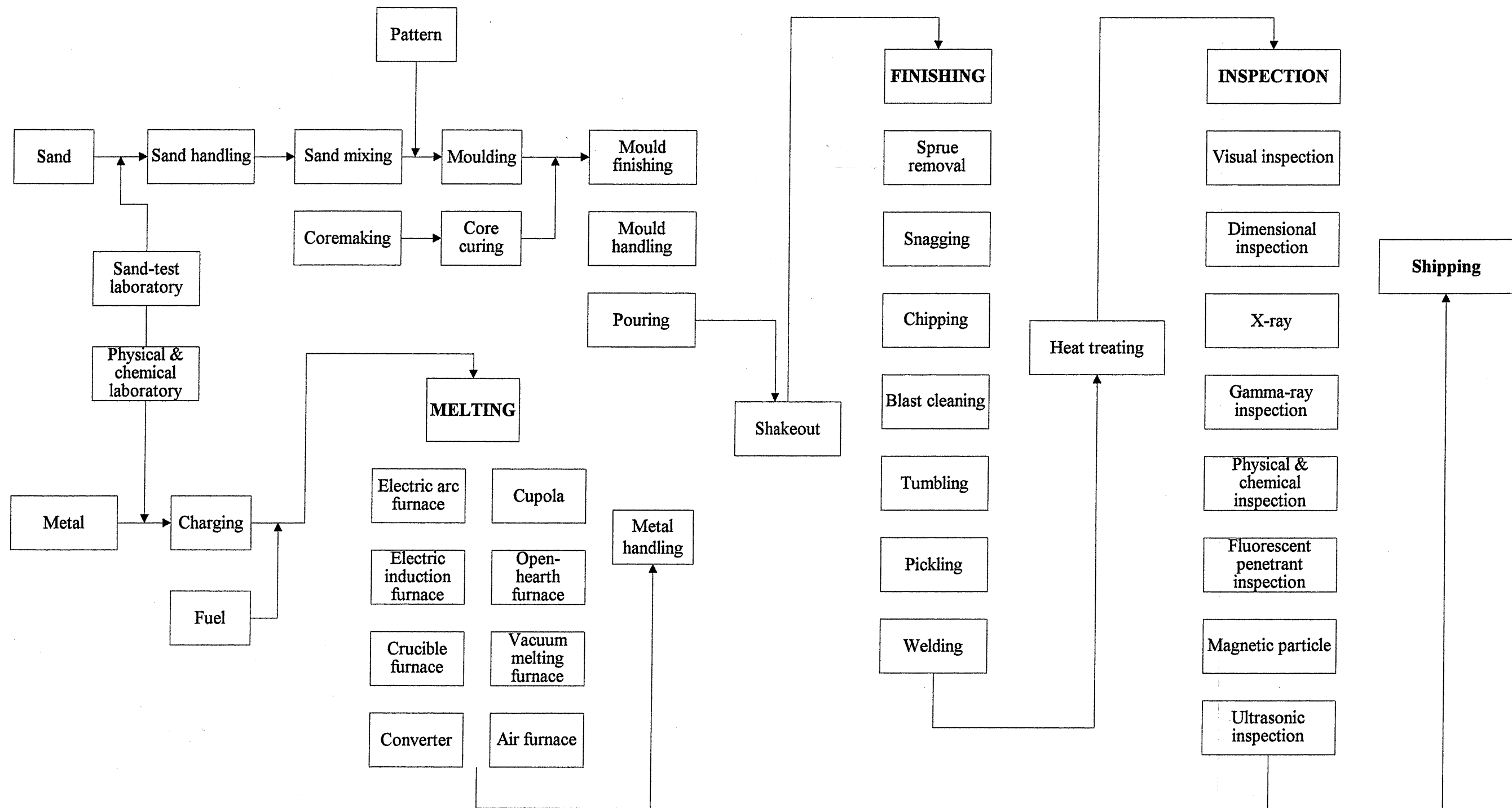


Figure 3 Flow chart of a typical foundry operation (ASM, 1988)



Expendable Mould Processes

Permanent Patterns

A flowchart of a typical foundry operation is shown in Figure 3. For most permanent pattern techniques, the following summary of the process applies:

1. Casting designed
2. Specification of metal or alloy to be cast
3. Patternmaking, core box construction
4. Mould and Core Preparation
5. Furnace Charge Preparation and Metal Melting
6. Pouring
7. Mould cooling
8. Shakeout, Cooling and Sand Handling
9. Quenching, Finishing, Cleaning and Coating
10. Dimensional verification, Non destructive testing (if required)

2.1.2 Pattern Making

A pattern is a form made of wood, metal, plastic, or composite materials around which a moulding material (usually sand) is formed to shape the casting cavity of a mould. Most patterns are removed from the completed mould halves and used repeatedly to make many duplicate moulds (US EPA, 1997 and Voigt, 1988). Figure 4 shows the schematic of a sand mould.

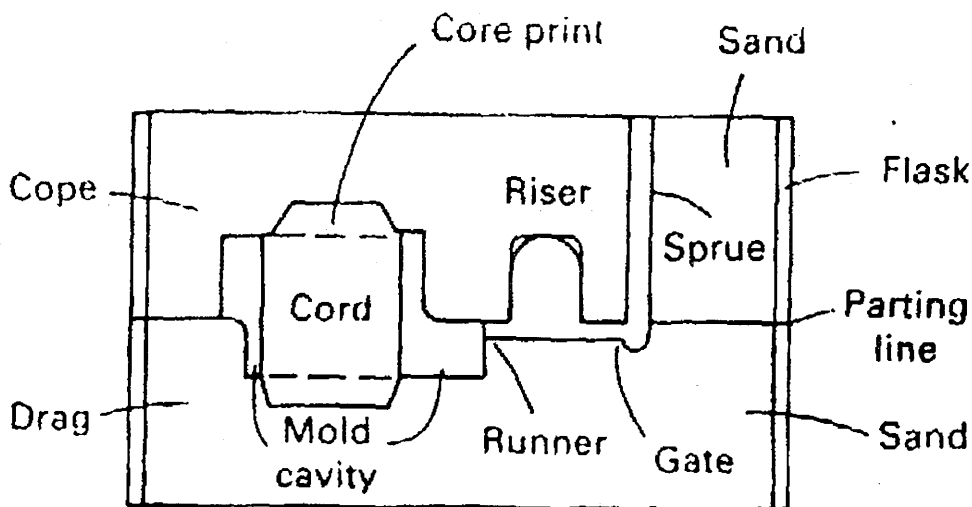


Figure 4 Schematic of a sand mould (Voigt, 1988).

The pattern equipment (tooling) needed to make a casting includes the pattern and may include one or more core boxes. Core boxes are used to make refractory inserts or cores that are placed within a mould cavity to form internal cavities or passageways within the casting. The selection of the type of pattern equipment used to make a casting depends on many factors, including the number of castings to be produced, the size and shape of the casting, the moulding or casting process to be used, and other special requirements such as the dimensional accuracy required.

The dimensional accuracy of a pattern determines the final dimensions of a casting. Patterns must be oversized to correct for the contraction of the metal upon cooling and any extra metal to be removed from the machined surfaces of a casting. A mould parting line must be selected, and draft or taper must be included on the vertical faces of the pattern to permit the removal of reusable patterns from the mould. Patterns include provisions for gating and risering, which facilitate the flow of metal into the mould cavity. For castings to be made with cores, the pattern and core boxes must include projections called core prints, which are used to support and locate cores in the mould cavity.

Pattern making, or foundry tooling, requires a high level of skill to achieve the close tolerances required of the patterns and coreboxes. This step is critical in the casting process since the castings produced can be no better than the patterns used to make them. Increasingly pattern shops are using computer-aided drafting (CAD), and computer-aided manufacturing (CAM).

2.1.3 Mould and Core Preparation

The typical inputs and outputs of the moulding and coremaking processes are shown in Figure 5 and Table 11.

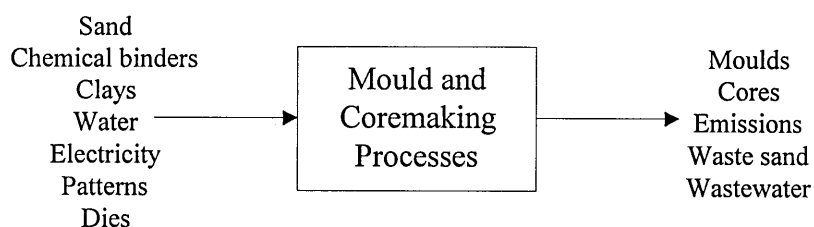


Figure 5 Typical inputs and outputs of the mouldmaking and coremaking process (Energetics, 1999).

Table 11 Key Energy and Environmental Facts: Mouldmaking and Coremaking.

Energy	Emissions	Effluents	By-products
Uses 7% to 20% (on the order of 1.2 to 3.5 GJ/tonne) of a foundry's total energy consumption, depending on the casting type and metal.	Particulate, VOCs, CO, hydrogen sulphide, SO ₂ , NO _x Benzene, phenols, and other HAPs if chemically bonded cores are used	Sludges from dust collection scrubbers	Waste sand

Energetics, 1999.

2.1.4 Green Sand Moulding



Figure 6 Pouring green sand moulds at Presto Castings.

Green sand moulding is the most common moulding process used in the United States (US EPA, 1997). The process utilises a mould made of compressed or compacted moist sand. The term “green” denotes the presence of moisture in the moulding sand, and indicates that the mould is not baked or dried (AFS, 1988).

A typical green sand mixture consists of sand, clay and water with minor additions of organic materials such as coal, cellulose, starches and glycol. The mixture is made up of about 85-95% silica sand, 4-10% bentonite clay, 2-10% carbonaceous materials, 2-5% water (US EPA, 1997).

The sand is muller which involves the application of compressing and shearing forces. The process entails forcefully compressing a liquid-solid mixture between opposing hard surfaces and smearing the compacted material apart, reassembling it and recompressing it. Over the mixing time all parts of the mixture should be subjected to the same energy input. The action of the muller spreads clay and additives over the surface of the sand grains and, when water is added, produces the clay-water bond that holds the sand grains together (Jorstad, 1993).

The mould is made by placing a flask around the pattern. Sand is placed on the pattern and then pressure applied to compact it firmly against the face of the pattern. After the mould has been compacted and the pattern removed, the mould is ready for finishing operations (Prucha, 1988). These operations usually consist of blowing out any loose sand, looking for any moulding defects and drilling the sprue cup (if applicable). Cores (if any) are placed in the drag, the cope can be accurately placed

on the drag and the mould sent to the pouring station. The mould is poured in a green (moist) state. Figure 6 shows small green sand moulds being poured.

When the casting has solidified the sand is removed from the casting during a process called shakeout. The sand is returned to storage bins for reconditioning for later use. The sand can be used many times with only small additions of new sand, clay and water.

2.1.5 Coremaking and dry sand moulding

Mouldmaking with dry sand is very similar to green sand except chemical binder systems are used instead of green sand binders.

Cores are primarily used to form internal passageways or cavities in castings. Cores can also be used to form sections of the mould for a cast shape that has external projections or negative draft, which prevents the pattern being withdrawn from the mould (Voigt, 1988). Cores are supported on core prints that are placed into the mould, this allows the molten metal to flow around all sides of the cores. An example of the variety of cores that can be made is shown in Figure 8.

There are three major categories for coremaking binders: no-bake processes, cold-box processes, heat-cured processes.

2.1.6 No-bake processes

A no-bake process is based on the ambient temperature cure if two or more binder components after they are combined on the sand. Curing of the binder system begins immediately after all components are combined. For a period of time after all initial mixing the sand mix is workable and flowable to allow the filling of the core/mould pattern. After an initial time period, the sand mix cures to the point where it can be removed from the box. Common no-bake processes are: furan, acid catalysed; phenolic urethane, phenolic, acid catalysed; alkaline phenolic, ester cured; alumina-phosphate, polyol isocyanate (Piwonka, 1988).

2.1.7 Cold-Box systems

The cold box process is a binder-sand mixture accelerated by a vapour or gas catalyst that is passed through the sand. Several different cold-box systems are used, employing different binders and gas or vapour catalysts. An example of the cold-box process is shown in Figure 7.

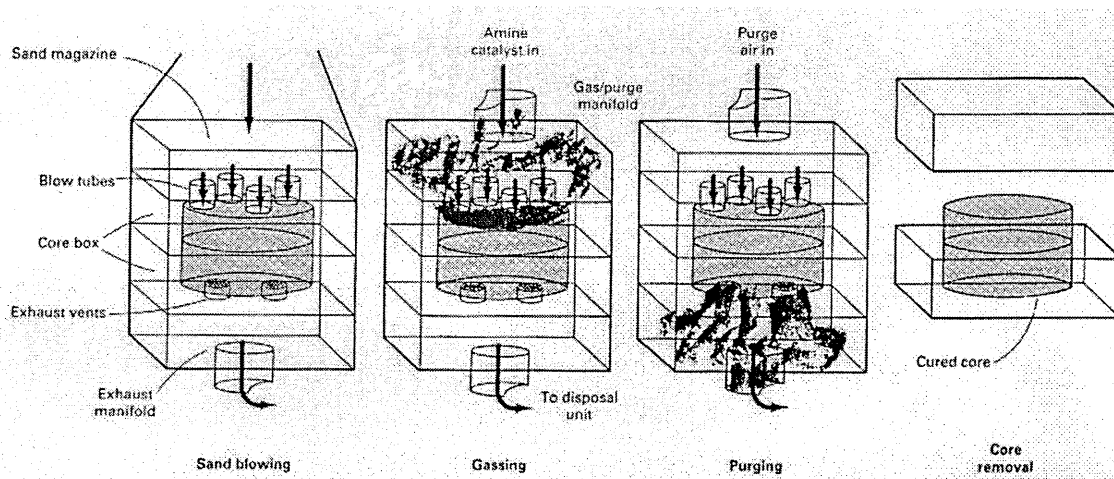


Figure 7 Cold box coremaking process (Piwonka, 1988).

The sand is coated with binder and is blown into the tooling cavity through entry ports (blow tubes or blow shoots) located in one half of the tooling. The resin is cured by a vaporised or gas catalyst which is introduced into the tooling cavity through 'cope vents' and through the sand entry ports. The vents are specifically placed, and the openings are sized to ensure that the catalyst gas develops a positive pressure in the tooling cavity. The open area of the exhaust vents is less than that of the gas inlet area. The pressurisation causes the gas/vapour to travel to all parts of the pattern cavity before it exits through the exhaust vents in the opposite site of the pattern or corebox. After the catalyst has been introduced into the cavity, a very dry "purge air" is introduced. This volume of air travels through the core and out through the exhaust vents, distributing the catalyst through the core and out of the exhaust vents. This ensures that the catalyst has been distributed to all cavities of the core box and also flushes residual gas from the core box. The dry purge air is often heated depending on the binder system. The core is now ready to be ejected from the core-box. Common cold box systems are as follows: phenolic urethane cured with an amine catalyst; sodium silicate with a carbon dioxide catalyst; furfuryl alcohol-base resins with a sulphur dioxide catalyst; acrylic/epoxy cured with sulphur dioxide; phenolic ester; phenolic resin with a carbon dioxide catalyst (Jorstad, 1993).

2.1.8 Heat cured systems

In the shell process, sand grains are coated with phenolic novolac resins and hexamethylenetetramine. The coated, dry sand is compressed and cured in a heated mould at 150-280°C for 10 to 30 seconds. Once the desired core thickness is cured the core is removed and the excess sand is removed.

In the hot box and warm box processes, the binder-sand mixture is wet. A liquid thermosetting binder and latent acid catalyst are mixed with dry sand and blown into a heated core box. Upon heating, the catalyst releases acid, which induces rapid cure within 10 to 30 seconds. Common hot box and warm-box processes are: phenolic hotbox, furan hotbox, urea formaldehyde hotbox and warmbox.

Core-oil binder is used in combination with a water-activated cereal to produce a coated sand mix that has green strength. Green strength permits the wet sand mix to be blown or hand rammed into a corebox at room temperature and to retain its shape when removed from the pattern. The uncured cores are placed on a flat board or dryer plate for oven drying.

Figure 8 Various cold-box and no-bake cores.

Coatings are frequently applied to cores to reduce casting defects at the mould metal interface, to improve casting surface finish, improve casting quality, reduce scrap and lower cleaning costs.

- ♦ Refractory minerals: coating once dried is 90-95% refractory. Refractory selection depends on metal cast, desired properties and cost.
- ♦ Carrier system: water or alcohol, transfers the refractory particles to the core or mould surface.
- ♦ Binder: bonds the refractory particles together and to the sand.
- ♦ Suspension agent: prevents hard settling of refractory during storage and use.

- ♦ Special additives: additives used to improve coating characteristics.

2.1.10 Sands

The refractory moulds used in casting consist of a particulate refractory material (sand) that is bonded together to hold its shape during pouring.

The following basic requirements apply to sands:

- ♦ dimensional and thermal stability at elevated temperatures
- ♦ suitable particle size and shape
- ♦ chemically unreactive with molten metals
- ♦ not readily wetted with molten metals
- ♦ freedom from volatiles that produce gas upon heating
- ♦ economical availability
- ♦ consistent cleanliness, composition, and pH
- ♦ Compatibility with binder systems

The most common sands used are various forms of silica sand (SiO_2). Other common sands used in sand casting are: Zircon sand (ZrSiO_4); Olivine minerals forsterite (MgSiO_4) and Fayalite (Fe_2SiO_4); Olivine; Chromite (FeCr_2O_4).

2.1.11 Shakeout, reclamation and reuse of spent sand

Mould and core sand removal from the casting can be accomplished by vibration, shotblast or thermal methods. Due to the high cost of foundry quality sand and increasing disposal costs sand is reclaimed and subsequently reused. Sand reclamation techniques are classified as either primary or secondary processes.

Primary reclamation, also known as attrition or particulation, involves breaking down the sand from moulds or cores to its original grain size. This includes screening the sand, removing tramp metal, and separating and removing fines and over-sized agglomerates. The sand is cooled (if necessary) before being sent for storage, returned to the sand system or blended with new sand. Primary reclamation does not completely remove the binder from the sand surface. The main primary techniques are: shot blast; rotating drum; vibration (ETSU, 1998b).

Secondary reclamation further processes the sand to remove residual binder. The sand is returned to a quality similar to, or even better than, that of new sand. The main secondary reclamation techniques are: high energy attrition, either pneumatic, mechanical or centrifugal; wet scrubbing; thermal treatment, usually a fluidised bed.

2.1.12 Expendable patterns

There are two basic categories in the expendable pattern processes, these are foamed patterns and wax patterns.

2.1.13 Lost foam casting

(also known as evaporative foam casting, expanded polystyrene moulding)

Figure 9 Typical inputs and outputs of the lost foam process (Energetics, 1999).

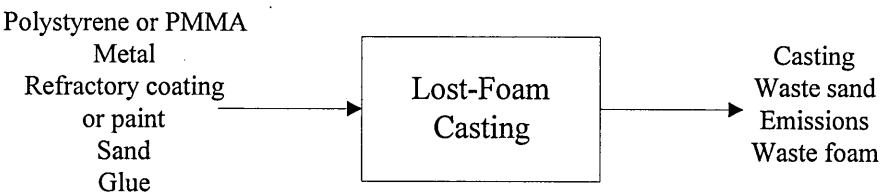


Table 12 Key Energy and Environmental Facts – Lost Foam Casting.

Energy	Emissions	Effluents	By-products
2.9 GJ/t of good casting shipped	Particulates, metallic oxide fumes, polystyrene vapours, HAPs	Effluents from dust collection scrubbers Wastewater from bead expansion	Waste sand Waste refractory material Waste foam

Energetics, 1999

Key process steps are as follows:

- ♦ **Production of foam pattern, usually made of polystyrene** (Figure 10). The foam beads are fed into the mould cavity. Steam is passed through the material in the cavity, this expands the beads and fuses them into a solid mass to form the foam pattern. The foam is cooled to prevent further expansion and then ejected from the mould either mechanically or pneumatically.
- ♦ **Assembly of pattern onto gating system** (Figure 11). Patterns usually consist of multiple pieces that are assembled and glued together.
- ♦ **Coating of pattern with refractory coating** (Figure 11). The coating provides a barrier between the smooth foam surface and the coarse sand surface, it is also permeable to allow the gas products from the vaporising foam to escape through the coating and into the mould.
- ♦ **Pattern placed in a sand flask** (Figure 13).
- ♦ **Sand is packed around the pattern.** Loose, dry, unbonded sand is introduced. into the flask. The flask is vibrated to compact the sand around the pattern.
- ♦ **Casting (pouring).** Castings are poured in a similar manner to other sand castings (Figure 14).
- ♦ **Sand removed.** After pouring the castings are allowed to cool. The flasks are moved into a dump-out area where sand and castings are separated (Figure 15).

- ♦ **Degating and finishing.** Castings are degated and cleaned using conventional methods.

Advantages of lost foam casting include:

- ♦ no mould parting line resulting in reduced casting cleaning
- ♦ no cores
- ♦ untreated, unbonded sand used
- ♦ ease of sand recycling
- ♦ good surface finish (due to refractory coating).

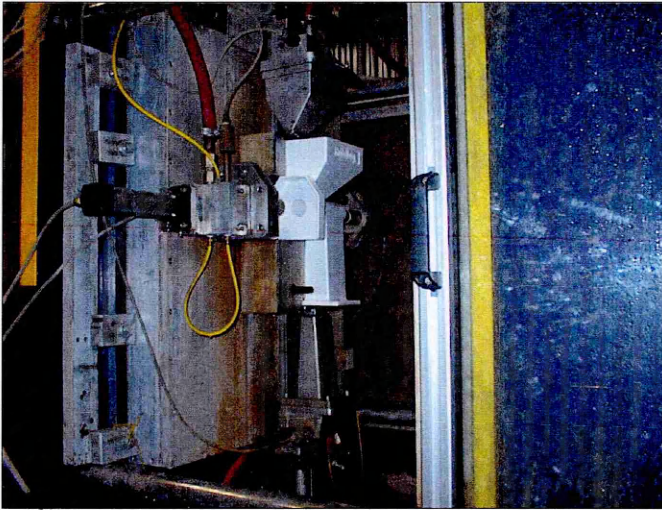


Figure 10 Manufacture of foam pattern (Inmetalna, 2000)

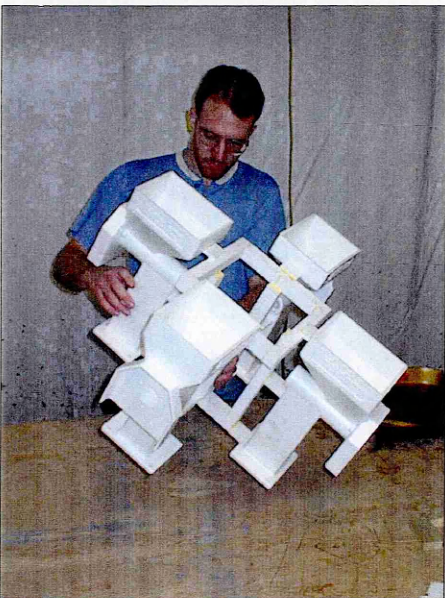


Figure 11, Figure 12 Assembly and coating of pattern (Inmetalna, 2000).



Figure 13 Placing pattern in the flask (Inmetalna, 2000).



Figure 14 Pouring metal into the mould (Inmetalna, 2000).



Figure 15 Removal of casting from moulding material (Inmetalna, 2000).

2.1.14 Investment Casting

The investment casting process produces castings with a higher degree of dimensional accuracy than any other casting process. The process can also produce castings with a high level of detail and complexity and excellent surface finish.

Figure 16 Typical inputs and outputs of the investment casting process (Energetics, 1999).

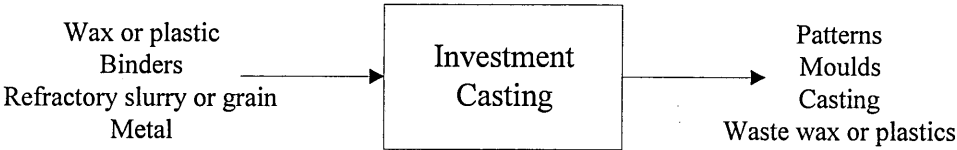


Table 13 Key Energy and Environmental Facts: Investment Casting.

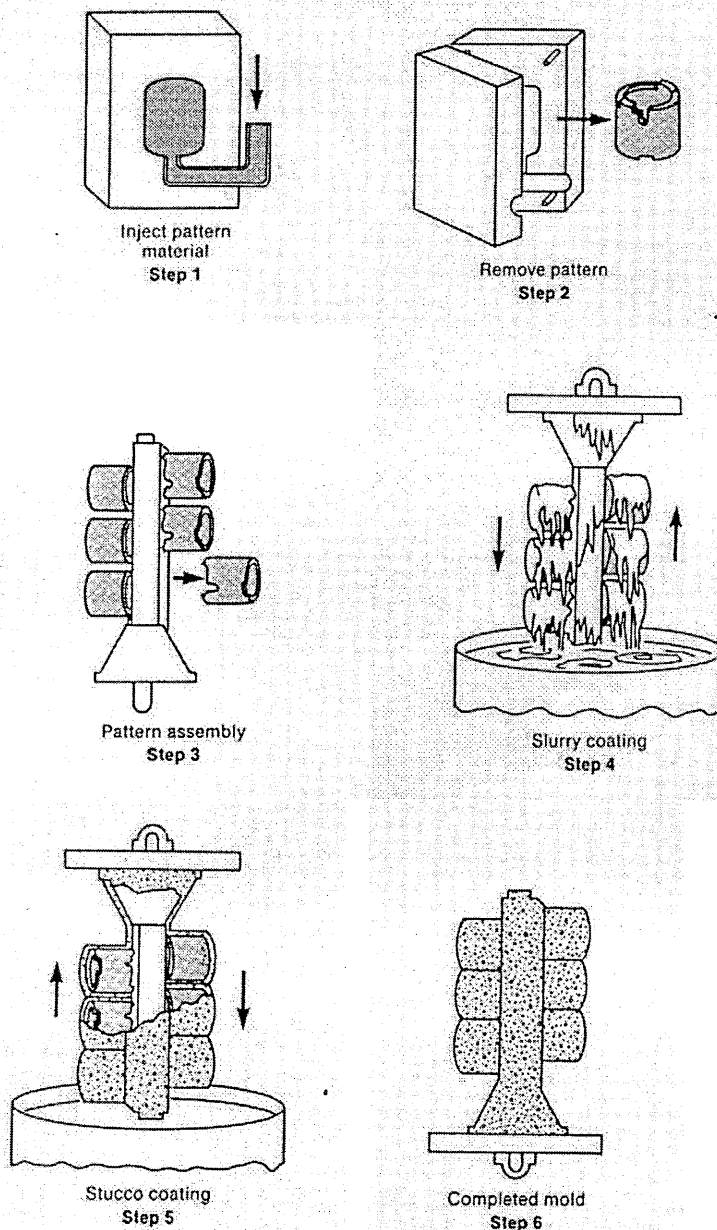
Energy	Emissions	Effluents	By-products
8.1 GJ/t of good casting shipped	Particulates, metallic oxide fumes	Wastewater with low pH and high in dissolved salts if soluble salt cores are used	Waste refractory, waxes, and plastics Typical Melt Losses: 1% to 5%

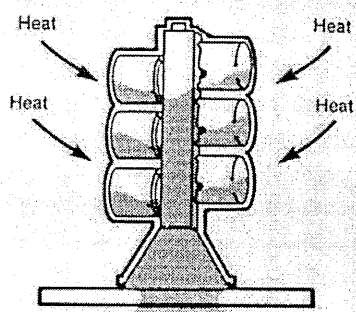
Energetics, 1999

The basic steps of the investment casting process are described below and shown in Figure 17 (Piwonka, 1988):

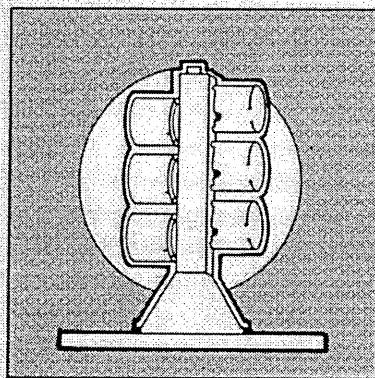
- ♦ **Production of heat-disposable patterns, usually made of wax or wax/resin mixtures.** Waxes are usually modified to improve their properties through the addition of resins, plastics, fillers, plasticisers, antioxidants and dyes. Patterns are made by injecting the pattern material at relatively low temperatures and pressures in split dies. If cores are required, they are inserted during the pattern making step. The cores are placed in the pattern die and the pattern wax or plastic is injected around the core. After the pattern is removed from the die, the cores are removed. Cores used in investment casting are typically collapsible metal assemblies or soluble salt materials which can be leached out with water or a dilute hydrochloric acid solution.
- ♦ **Assembly of the patterns onto a gating system.** Small and medium patterns are assembled into clusters. Replicas are attached to a gating system (sprue and runners) constructed of the same material to form a tree assembly.
- ♦ **Investing, or covering, the pattern assembly with ceramic to produce a monolithic mould.** A series of ceramic coatings are applied to the pattern clusters. Each coating consists of a fine ceramic layer with coarse particles embedded in its outer surface. The shells are then dried.
- ♦ **Melting out the pattern assembly to leave a precise mould cavity.** The mould is heated to liquify and remove the pattern.
- ♦ **Firing the ceramic mould to remove the last traces of the pattern material, to fire the ceramic and develop the high-temperature bond, and to preheat the mould ready for casting**

- ♦ **Casting (pouring).** The molten metal is poured into the central sprue and will travel through the individual sprues and runners filling the mould. The melting equipment used is generally induction furnaces but is somewhat dependent on the metal being melted. Most investment castings are gravity poured, however other casting methods include vacuum assist, pressurised casting, centrifugal casting and counter-gravity casting.
- ♦ **Shakeout, cut-off, and finishing.** Post-casting operations are similar to other casting methods.
- ♦ **Inspections and non-destructive testing.** Visual inspection to detect obvious scrap is often carried out. Depending on the end use of the casting other inspection techniques may be used.

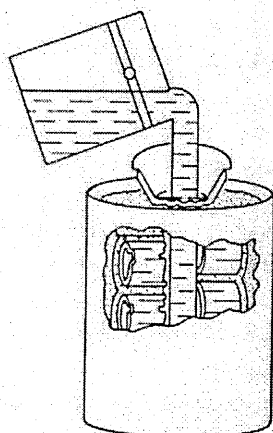




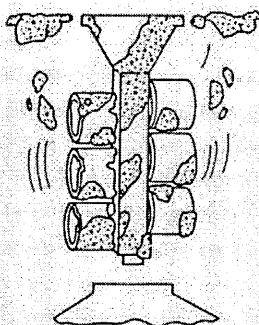
Dewax the shell mold
Step 7



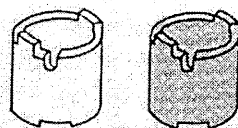
Fire the shell mold
Step 8



Pouring/casting
Step 9



Shakeout
Step 10



Casting Pattern
Finished product
Step 11

Figure 17 Investment casting process steps (Piwonka, 1988).

2.1.15 Permanent Mould Processes

2.1.16 Permanent Mould Casting

Permanent mould casting also referred to as gravity die casting, uses a metal mould consisting of two or more parts. The mould is used repeatedly for the production of many castings of the same form. Simple removable cores are usually made of metal, but more complex cores are made of sand or plaster. When sand or plaster cores are used, the process is called semi-permanent mould casting. Compared to sand casting, permanent mould casting permits the production of more uniform castings, with closer dimensional tolerances, superior surface finish, and improved mechanical properties. The improved properties are due to the fact that the mould is machined and has better cooling capabilities (Piwonka, 1988). Metals cast in permanent moulds include aluminium, magnesium, zinc, and copper alloys.

Mould separation can be manual, or semi-automatic and castings can be poured with the parting line vertically or horizontally however, castings are usually separated from the mould with a vertical parting line.

There are several different variations of gravity die casting these are (Piwonka, 1988):
Low pressure die casting: metal is forced into the mould cavity using low pressure applied to the molten metal;

Vacuum casting: a vacuum is created in the mould cavity which pulls the metal into the cavity;

Centrifugal casting: castings are poured using the force of a spinning mould to force the metal into the mould

Squeeze casting: metal is poured into the mould, the mould is then closed squeezing metal into the mould cavity.

The basic process for permanent mould casting is as follows (Jorstad, 1993):

1. A refractory wash or mould coating is brushed or sprayed onto those surfaces of the preheated mould that will be in direct contact with the molten metal alloy.
2. Cores, if applicable, are inserted, and the mould is closed either manually or mechanically.
3. The alloy, heated above its melting temperature, is poured into the mould through the gating system.
4. After the casting has been allowed to solidify, cores and other loose mould members are withdrawn, the mould is opened, and the casting is removed.
5. Steps 2-4 are repeated until repair of the refractory wall is required, at which time step 1 is repeated.
6. The usual foundry practice is followed for trimming gates and risers from the castings.

The basic difference between sand casting and permanent mould casting is the metal mould is used instead of sand. Permanent mould castings usually have better mechanical properties than sand castings because solidification is more rapid due to the metal mould.

2.1.17 Die Casting

Die casting is characterised by a source of hydraulic energy that imparts high velocity to molten metal to provide rapid filling of a metal die. The die absorbs the stresses of injection, dissipates the heat contained in the metal, and facilitates the removal of the shaped part in preparation for the next cycle. The hydraulic energy is provided by a system that permits control of actuator position, velocity, and acceleration to optimise flow and force functions on the metal as it fills the cavity and solidifies (Piwonka, 1988).

Figure 18 Typical inputs and outputs of the die casting process (Energetics, 1999).

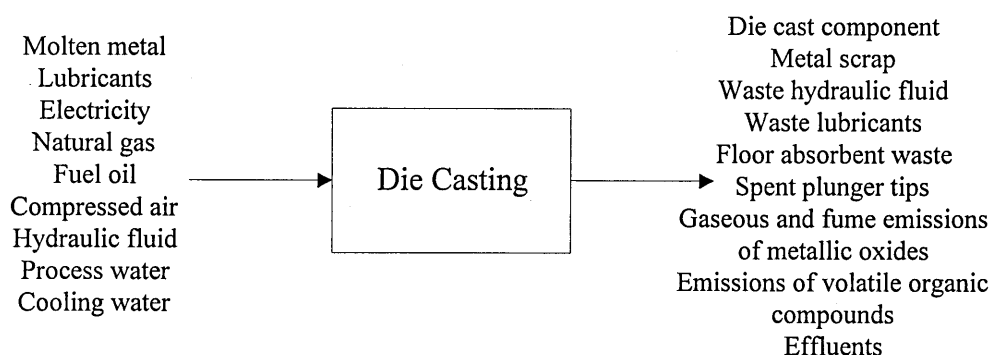


Table 14 Key Energy and Environmental Facts: Die Casting.

Energy	Emissions	Effluents	By-products
Hot Chamber (fuel-fired) 0.5 GJ/t plus 5.6 GJ/hr per tonne of metal	Gaseous and fume emissions of metallic oxides	Process wastewater, sometimes contaminated with oils and phenols	Scrap (typically 5% to 8%)
Cold Chamber (fuel-fired): 6.0 GJ/t plus 6.4 GJ/hr per tonne of metal	VOCs (if solvent-based lubricants are used)	Non-contact cooling water	Metallic fines
Die heating (Elec Resistance)			Spent lubricants, oils, and hydraulic fluid
Hot chamber: 4.4 GJ/tonne			Used floor absorbent
Cold chamber: 5.1 GJ/tonne			Used plunger tips

Energetics, 1999.

Four principal alloy families are commonly die cast: aluminium, zinc, magnesium and copper base alloys. There are two different methods of die casting: the hot chamber process and the cold chamber process.

The hot chamber process (NADCA and Piwonka, 1988) is the original die casting process. In the hot chamber machine, the injection mechanism is immersed in molten metal in a furnace attached to the machine. The hot chamber process minimises exposure of the molten alloy to turbulence, oxidising air, and heat loss during the transfer of hydraulic energy. As the plunger is raised, a port opens allowing molten metal to fill the cylinder. As the plunger moves downwards sealing the port, it forces molten metal through the gooseneck and nozzle into the die. After the metal has solidified the plunger is withdrawn, the die opens, and the resulting casting is ejected. Hot chamber machines are rapid in operation. Cycle times vary from less than one second for small components weighing only a few grams to thirty seconds for a casting of several kilograms. Metal is injected at pressures of 10.3 to over 31.0 MN/m². The prolonged intimate contact between molten metal and system components can cause erosion of system components particularly with aluminium alloys. For this reason hot chamber diecasting is used primarily for zinc and other low melting point alloys.

The cold chamber process (Piwonka, 1988) keeps the molten metal reservoir separate from the actuator for most of the process cycle. The metal is metered into the shot sleeve (or cold chamber) and is immediately injected into the die, exposing the actuator for only a few seconds. An example of a cold chamber plant is shown in Figure 19, the machine shown in the foreground is a 16 MN locking force machine.

For all diecasting methods the hydraulic piston rapidly accelerates the molten metal to the desired velocity for injection. The last phase of injection begins when the cavity is close to being filled. Intensification uses high pressure to increase the pressure on the metal to force the rapid freezing of the alloy into incipient shrinkage cavities. Die casting machines are sized by locking force holding the die closed. Machines range from 450 kN to 35MN locking force.

Heat from the molten metal in the die cavity must be removed to allow the casting to solidify. Heat flow from the casting depends on many factors including die geometry, lubrication. Internal water cooling lines in the die is the key method of controlling cooling, when internal cooling is not enough to cool the die, external die sprays are used.

After the casting has solidified and cooled it must be removed from the die. Slides and cores must be withdrawn first, followed by opening of the die by the ejector die motion. As the die opens the casting is ejected from the die by the ejector pin. This is done by stopping the ejector plate while the die continues to retract or by using an actuator driven by a rack and pinion. The casting is then taken from the pins manually, by dropping through the base of the machine under gravity, or by a robot or extractor.

When the casting has been removed from the die, external water sprays can be used to cool the die. Compressed air blow off is used to blow residual water and any other loose flash from the internal die surfaces. This is followed by a lubricant spray to provide an insulating release agent between metal and die. Lubricants are mostly carrier material which evaporates upon contact with the hot die surface, depositing a

thin uniform coating of die lubricant on the die face (Kaye, 1982). A lubricant is also applied to the shot cylinder. The compressed air then blows off any residual water from the die spray and the die is closed in preparation for the next cycle.

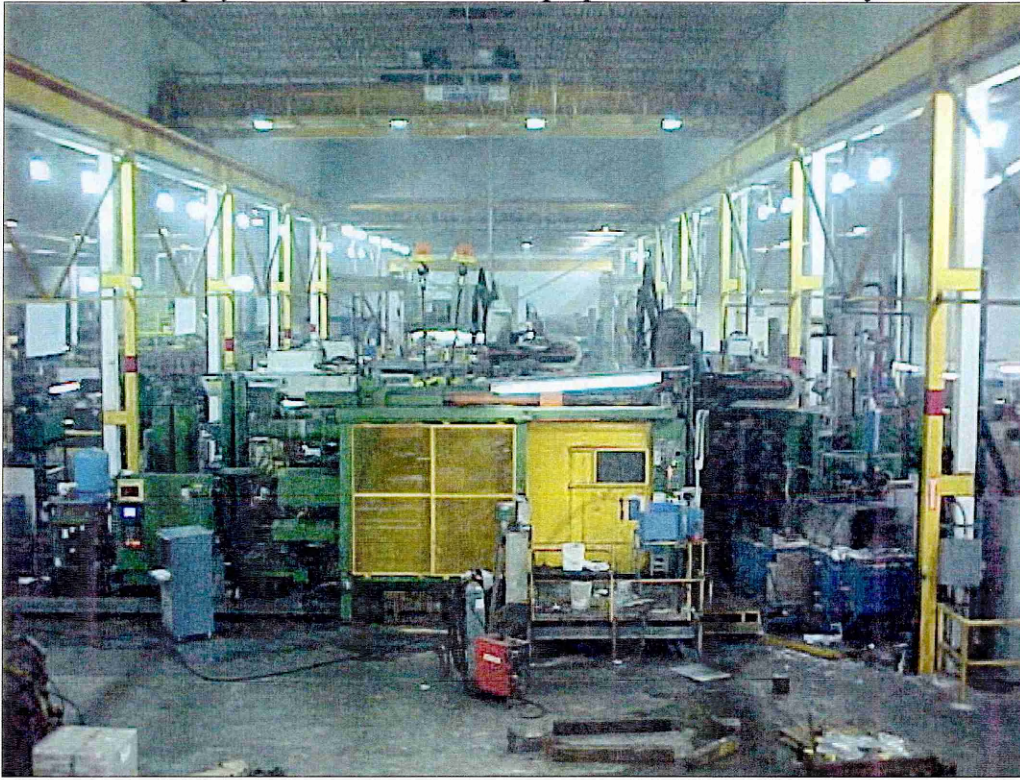


Figure 19 Cold-chamber diecasting plant.

Metal Melting

The melting operation is much more than transforming a solid into a liquid (Jorstad, 1993). This discussion covers primarily non-ferrous melting practices. In non-ferrous metal melting there are various auxiliary metal processing steps necessary other than melting and alloying. Generally the practices are fluxing, metal refining, deoxidation, degassing, and grain refining; molten metal pumping and filtration are also commonly practised in non-ferrous molten metal processing (Piwonka, 1988). The input output flow diagrams for different forms of melting both ferrous and non-ferrous metals follow.

2.1.18 Melting methods

Selection of melting methods and furnace type is dependent on the following factors: type of metal being melted, volume of metal being melted, number of different alloys in use, fuel type. The main type of furnaces used to melt ferrous metals are cupola and electric arc furnaces. The main types of furnaces used for non-ferrous metal melting are crucible furnaces, reverberatory furnaces and electric induction furnaces.

Figure 20 Typical inputs and outputs for cupola furnaces (Energetics, 1999).

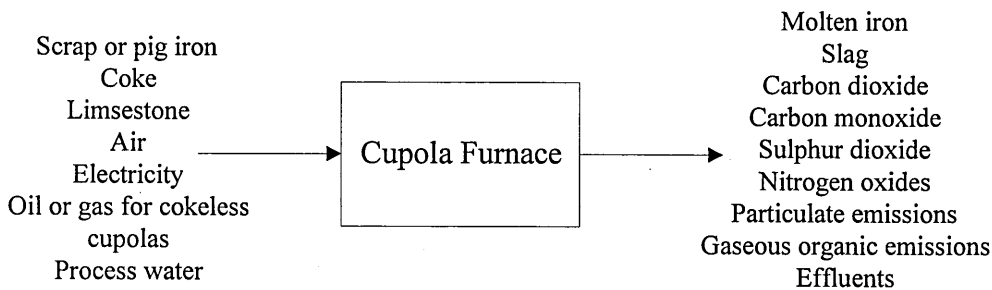


Table 15 Key Energy and Environmental Facts: Cupola Melting.

Energy	Emissions	Effluents	By-products
Coke: 6.7 Electricity: 1.3 Natural Gas: 1.9 Oxygen: 0.1 Total: 10.0 GJ/tonne of good castings shipped	CO ₂ , CO, SO ₂ , NO _x , Particulate, gaseous organic compounds. Largest source: incomplete combustion of carbon additives, dirt and scale on the scrap charge.	Largest Source: wet scrubber systems Typical scrubber water volume approx. 4200L/t of dust.	Slag Wet scrubber sludge Typical Melt Losses: 7-10%.

Energetics, 1999

Figure 21 Typical inputs and outputs of electric furnaces (Energetics, 1999).

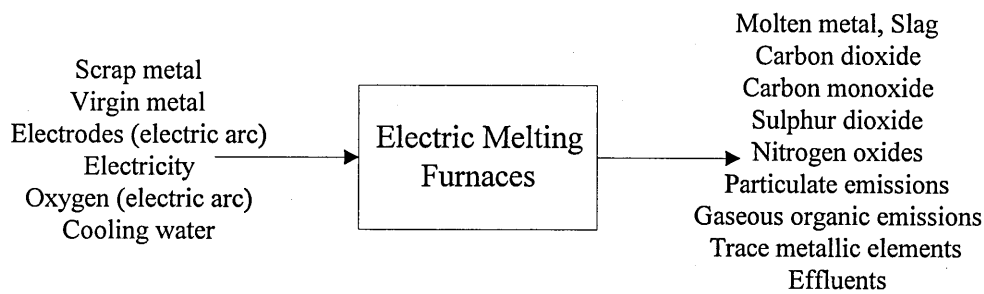


Table 16 Key Energy and Environmental Facts: Electric Melting Furnaces.

Energy	Emissions	Effluents	By-products
Energy Use by Furnace Type Induction: 5.0-5.6 GJ/t (modern furnaces) Electric Arc: 5.0-6.0 GJ/t Electric-Resistance-heated reverberatory: 6.0-9.2 GJ/t	Particulate (metallic and mineral oxides), CO, organic compounds, SO _x , NO _x .	Induction coil cooling water, scrubbing, quenching Constituents of concern: heavy metals, phenolic compounds	Slag Dust and sludge Melt Losses by Furnace Type Induction: 1-2% Electric Arc: 5% Electric Reverb.: up to 3%.

Energetics, 1999.

Figure 22 Typical inputs and outputs of fuel-fired melting furnaces (Energetics, 1999).

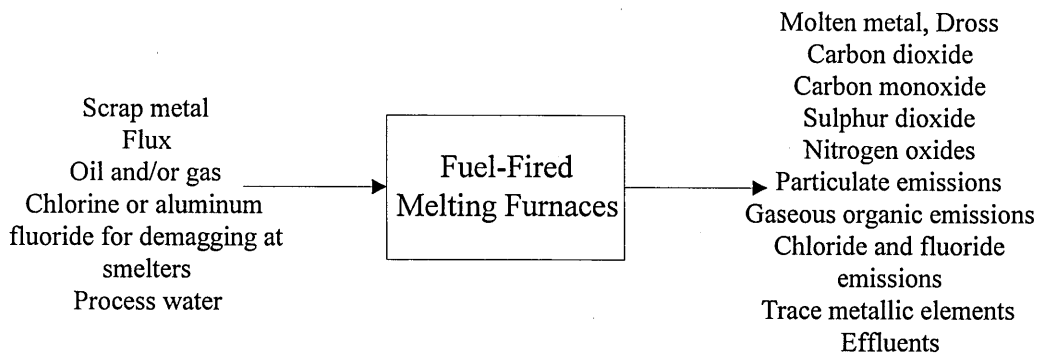


Table 17 Key Energy and Environmental Facts: Gas-Fired Melting Furnaces

Energy	Emissions	Effluents	By-products
Energy Use by Furnace Type Crucible: 2.1-7.9 GJ/t Reverb.: 2.9-5.8 GJ/t	Particulate (metallic and mineral oxides), CO, organic compounds, SO _x , NO _x , chloride and fluoride compounds	Demagging and wet-method residue processing if used.	Dross (Al melting furnaces) Dust Melt Losses by Furnace Type Crucible: 2-3% Reverb.: 2 to 12%

Energetics, 1999.

Crucible furnaces (Jorstad, 1993 and US EPA, 1997) are primarily used to melt smaller amounts of non-ferrous metals and a number of alloys. Crucible furnaces are indirectly fired and usually consist of a circular steel shell with a 8-13 cm layer of refractory into which a crucible is placed. Burners located inside the refractory lining apply heat that is transferred by conduction through the crucible into the metal to be melted. The crucible furnace is available in different configurations depending on whether the metal is poured or ladles. Fuel consumption in this type of furnace is relatively high: for aluminium 2.13 kWhr/kg metal melted.

Reverberatory (FM&T, 1999, Jorstad, 1993) furnaces are used to melt large amounts of aluminium to supply holding furnaces or to remelt scrap metal. Reverberatory furnaces range in capacity from about 910 kg to 91000 kg. These furnaces are generally used for producing large quantities of a single alloy at a uniform pouring temperature. The reverberatory furnace is constructed of refractory brick in a steel structure. The metal lies in a shallow open bath and is heated by flames and hot gases from the combustion of gas or oil. Most reverberatory furnaces use a nozzle-mix burner that throws a long flame, making use of “double-pass firing”. A luminous or semi-luminous flame, relatively high in the combustion chamber, that radiates heat to the refractory walls and roof. As the walls and roof become incandescent they radiate heat to the bath. On the return path to the flue, in the same wall as the burners, convective heat transfers from the gases. This radiation on the outgoing path and convection on the return path provide a double transfer of heat.

Metal may be charged in front or side door openings or through a door at the base of a flue stack. Metal is removed either through a pouring spout, by ladling or dipping from wells at one side if the furnace, or by pouring through transfer ladles through a tap hole below the surface of the melt.

There are two types of electric induction furnaces (Jorstad, 1993): coreless and channel. The channel-type is basically a transformer with the metal loop or channel forming the secondary of that transformer. This furnace is more efficient electrically (0.44kWhr/kg). The channel induction furnace is used in foundries to prepare both ingot and scrap. It often serves as a holding furnace for metal melted in other furnaces. The channel furnace cannot be turned off and must be started with molten metal.

The coreless induction furnace has a primary coil which generates an alternating magnetic field that induces eddy currents that heat the metal by resistance to the current flow. These furnaces operate at an electrical efficiency of 0.55-0.64 kWhr/kg of aluminium. The coreless furnace can be drained and restarted with solid metal.

2.1.19 Fluxing

Fluxing represents all additives to, and treatments of the molten metal with which chemical compounds or mixtures of such compounds are employed. The compounds are usually inorganic including metal salts that can be added in powder, granulated, or solid tablet form. Fluxes perform various functions including: degassing, cleaning, alloying, oxidation, deoxidation or refining. Fluxing includes the treatment of metals by inert or reactive gases to remove solid or gaseous impurities (Prucha, 1988).

Common fluxes fall into the following classes (Jorstad, 1993):

- ♦ covering fluxes: used to prevent gas pickup and to reduce dross formation by oxidation
- ♦ cleaning fluxes: used to remove solid nonmetallic inclusions
- ♦ degassing fluxes: added to the melt to remove entrapped gases
- ♦ drossing-off fluxes: used to recover metal from drosses.

2.1.20 Special Note on Magnesium

Magnesium and its alloys are exceptionally susceptible to oxidation, melt loss, and fires because of the extreme reactivity between magnesium and oxygen. Protection is always required when melting this alloy family.

Sulphur hexafluoride (SF₆) is commonly used in the fluxless melting process. SF₆ reacts with the molten metal to form a continuous layer of MgF₂ on the surface of the melt serving as a barrier to prevent oxygen from reaching the melt surface and to prevent burning. SF₆ is used in very low concentrations mixed with an inert cover gas. Typical mixes are 0.2-1.0% SF₆ in carbon dioxide, nitrogen or air.

SF₆ has an atmospheric lifetime of 3000 years and had 24,900 times the global warming potential of CO₂ (IMA, 1998). For this reason and supply reasons the prices of this gas has greatly increased. Alternative gases are being sought with SO₂ in low concentrations in an inert gas as a viable alternative.

Figure 23 Typical inputs and outputs of refining, pouring and cooling (Energetics, 1999).

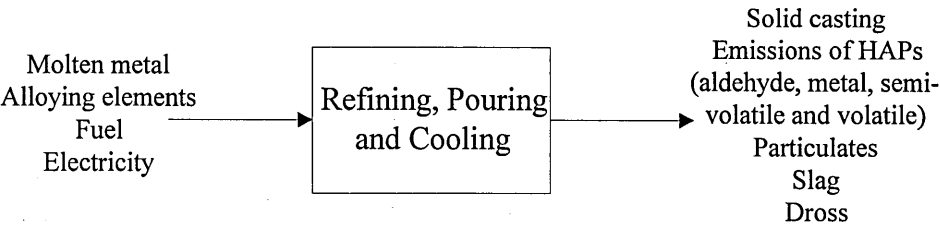


Table 18 Key Energy and Environmental Facts: Refining, Pouring, and Cooling (Energetics, 1999).

Energy	Emissions	Effluents	By-products
0.7 GJ/t of good castings shipped	Particulate metallic oxide fumes Organic compounds and hazardous air pollutants (including benzene and formaldehyde)	Minimal	Slag Dross Spent ladles and refractory materials Metal losses:~5%

Energetics, 1999.

2.2 Postcasting Operations

2.2.1 Finishing

A casting, regardless of the process used, is not a finished product when it is removed from the mould. Although the casting operation is complete, secondary processes must be carried out.

Postcasting (secondary) operations commonly performed on non-ferrous castings include trimming and cleanup, inspection and testing, finishing, machining, heat treating, impregnating and straightening. Not all of these secondary operations are performed on every casting; many castings are finished with only a trimming operation to remove gates and flash.

Figure 24 Typical inputs and outputs of cleaning and finishing (Energetics, 1999).

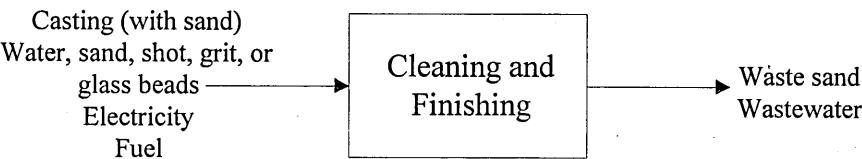


Table 19 Key Energy and Environmental Facts: Cleaning and Finishing.

Energy	Emissions	Effluents	By-products
1.2 GJ/t of good casting shipped	Dust, metallic particulates HAPs, VOCs, and organic compounds	Wastewater from finishing operations Wet scrubber wastewater	Spent foundry sand Dust Metal Typical Metal Losses: 0.5% to 1.0% as particulates; 10% to 20% from removal of gates, risers, fins, etc.

Energetics, 1999.

2.2.2 Cleaning and Trimming

After castings are removed from the mould, any core or mould refractory adhering to the casting must be removed. Gates, risers and flashing must be removed also.

Mould material (sand) is usually removed by wire brushing or surface blastcleaning. Air, water and mechanical blasting are the surface cleaning methods used.

Removal of core materials can require additional operations. Some binder systems used to make cores are relatively unaffected by thermal degradation at aluminium pouring temperatures.

Common methods include: mechanical vibration and impact; blast cleaning, baking the casting and core; ultrasonic shakeout.

2.2.3 Gating and Riser removal

The method selected to remove the risers and gating system depends on casting volume, weight and geometry.

- ♦ For high production die or permanent mould castings trim presses are used to remove parting line flash, gates and other excess material. This technique is only used for high production due to the cost of constructing special trim dies. Trim presses can be manually or robot operated.
- ♦ Band saws are used extensively for removing and trimming gates, risers and fins from castings other than die castings. Lubrication of the blade can be by a stick lubricant or oil spray.
- ♦ Abrasive cutoff is used to cut off castings too heavy or awkward to be lifted onto the table of a regular cutoff saw.
- ♦ Medium and high volume permanent mould and sand castings can be cut off with high speed rotary saws. The casting is held in place with hydraulic or pneumatic actuated fixtures.

After riser and gating removal blast cleaning can be used to clean the casting surface. Blast cleaning (Prucha, 1988) of castings is a process in which abrasive particles, usually steel shot or grit, are propelled at high velocity to impact the casting surface and thereby forcefully remove surface contaminants. The process can be used to provide a uniform cosmetic finish to the workpiece.

2.2.4 Finish Cleaning by Grinding and Filing

After riser and gating removal castings are usually given one or more finishing or cleaning operations. These operations are performed to smooth off the gate and riser areas, to remove any remaining excess metal, and to improve surface finish or appearance.

Abrasive wheels and belts are used for basic finishing of aluminium castings. Stubs, fins, parting lines, other surplus material and rough spots are removed by abrasive

wheels, belts or discs. This process is called snagging. Abrasive coated grinding belts are an efficient method for light snagging of castings, particularly die castings.

2.2.5 Heat Treatment

Heat treatment produces microstructural changes in the castings that can improve properties. Many aluminium castings meet requirements as-cast and are not heat treated, particularly die castings.

Heat treatment is used for the following

- ♦ homogenisation
- ♦ stress relief
- ♦ improved dimensional stability and machinability
- ♦ optimised strength, ductility, toughness and corrosion resistance.

2.2.6 Inspections of Castings

Castings are inspected to ensure that they conform to customer requirements. The earlier any defect is found the less cost the foundry will incur working on a defective casting.

Inspection of die castings usually consists only of chemical analysis, dimensional check, visual examination and leak tests.

The inspection of permanent mould sand and other castings can include the following.

1. Visual inspection of castings before trimming etc.
2. Rough dimensional check and visual examination after gates and riser removal.
3. Leak tests
4. Radiographic and penetrant inspections
5. Final inspection after castings are completely cleaned, heat treated, straightened, machined or welded.

2.2.7 Non-destructive testing

Inspection techniques may be classified into two broad groups; non-destructive methods and destructive methods. Destructive testing is carried out on small numbers of sample castings.

Non-destructive testing methods include visual and dimensional inspection, fluorescent powder and dye penetrant tests, radiographic (x-ray) inspection, leak tests, ultrasonic testing, and mechanical and physical property tests from separately cast samples.

Visual inspection is the examination of castings for surface defects, moulding errors and non filling. Casting defects such as sand holes, excessively rough surfaces, surface shrinkage, blowholes, misruns, cold shuts and surface dross usually can be detected visually. A visual inspection usually takes place after castings have had gating and risering removed.

Casting dimensions are checked with dial indicators, micrometers, vernier callipers and height gauges or a co-ordinate measuring machine (CMM). These checks can be aided by the use of gauges, jigs and fixtures.

Fluorescent powder, penetrant or dye penetrant inspection methods are very efficient at detecting surface defects that include cracks, flaws and discontinuities.

There are three common techniques used, these are:

- ♦ Fluorescent powder : Castings are immersed in a suspension of fluorescent powder in warmed penetrating oil. The suspension penetrates cracks and pores, and excess suspension is washed away in warm water. The casting is dusted, sprayed or chalked with a drying powder that draws the suspension from the cracks where it fluoresces and is visible under ultraviolet light.
- ♦ Dye penetrant: A coloured dye is used in suspension in the penetrating oil. After cleaning, the coloured dye is visible under normal light. Defects are not seen as readily as under ultraviolet light.
- ♦ Fluorescent penetrant: A fluorescent dye is used in suspension in penetrant oil. The excess suspension is washed away. A powder developer is applied and the casting is inspected under ultraviolet light.

Internal defects such as gas porosity, shrinkage, internal dross, and particles of foreign inclusions cannot be detected using surface inspection methods. Radiographic inspection is currently the best non-destructive method for determining the presence of internal defects. Skilled radiographers are used to interpret the film produced.

Filmless real-time radiographic inspection techniques allow x-ray images to be viewed on a video screen.

A casting that must be pressure-tight or leakproof often is tested by sealing openings in the casting and pressurising it with air, an inert gas or water.

If hydrostatic pressure is used, leaks are indicated by the seeping of water through the casting wall. If air or gas pressure is used, the pressurised casting is immersed in a tank of clear water, if bubbles appear, the casting is leaking.

Ultrasonic testing can be used to determine wall thickness as well as the position and size of defects. A beam of high-frequency acoustic energy is sent through the casting, until it hits an interface or defect. The interface or defect reflects portions of the energy, which are collected in a receiving unit and displayed on a screen.

2.2.8 Mechanical and Physical Property Tests

Common mechanical and physical property tests include:

- ♦ photographs, macrographs and micrographs;
- ♦ tensile tests to determine ultimate strength, yield strength and elongation, both separately cast and integral test bars from the casting are used;
- ♦ Bend, notch, impact and transverse tests to check ductility and shock resistance;
- ♦ hardness tests;
- ♦ fatigue and fracture toughness tests

Table 20 Summary of Environmental Effects from Metalcasting Processes (US EPA, 1997).

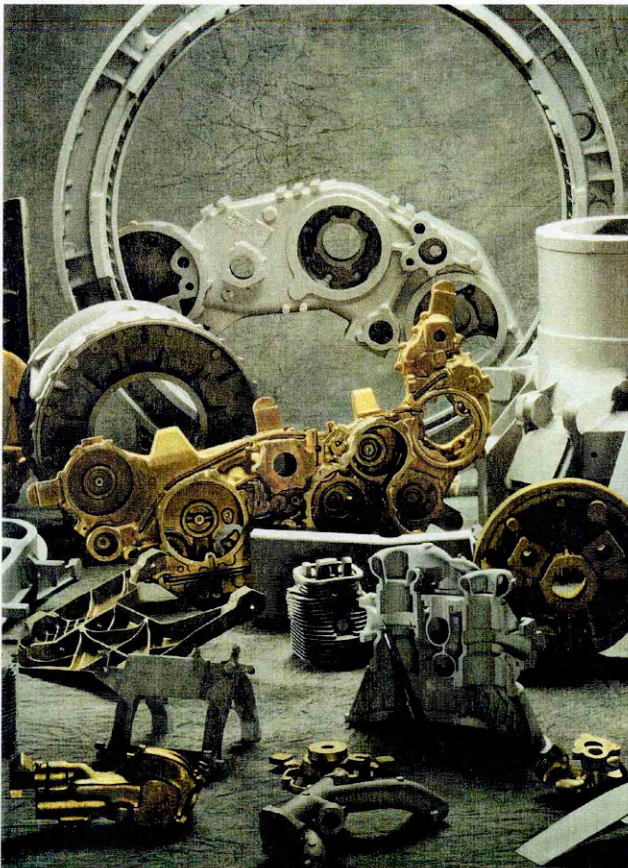
<i>Industrial Process</i>	<i>Material Inputs</i>	<i>Air Emissions</i>	<i>Wastewater</i>	<i>Residual Wastes</i>
Pattern Making	Wood, plastic, metal, wax, polystyrene	VOC's from glues, epoxies, and paints	Little or no wastewater generated	Scrap pattern materials
<i>Mould and Core Preparation and Pouring</i>				
Green Sand	Green sand and chemically bonded cores	Particulates, metal oxide fumes, carbon monoxide, organic compounds, hydrogen sulphide, sulphur dioxide, and nitrous oxide. Also emissions from chemically bonded cores	Wastewater containing metals, and organics from wet dust collection systems	Waste green and core sand
Chemical Binding Systems	Sand and chemical binders	Particulates, metallic oxide fumes, carbon monoxide, ammonia, hydrogen sulphide, sulphur dioxide, other HAPs	Scrubber wastewater with amines, high or low pH	Waste mould and core sand potentially containing metal and residual chemical binders
Permanent Mould	Steel Mould, sand, plaster, or salt cores	Particulates, metallic oxide fumes	Waste cooling water with elevated temperature, waste lubricants	Waste core sand or plaster
Investment/Lost Wax	Refractory slurry, and wax or plastic	Particulates, metallic oxide fumes	Waste cooling water with elevated temperature	Waste refractory material, waxes and plastics
Lost Foam	Refractory slurry, polystyrene	Particulates, metallic oxide fumes,	Little or no wastewater generated	Waste sand and refractory material

		polystyrene vapours and HAPs		potentially containing metals and styrene
Furnace Charge Preparation and Metal Melting				
Charging and Melting	Metal scrap, ingot and returned castings	Products of combustion, particulates, metallic oxide fumes		Spent refractory materials potentially containing metals and alloys
Fluxing and Dross Removal	Fluxing agents	Particulates and metal oxide fumes		Dross
Pouring	Ladles and other refractory materials	Particulates and metal oxide fumes		Spent ladles and refractory materials potentially containing metals
Quenching, Finishing, Cleaning and Coating	Unfinished castings, water, steel shot, solvents	Dust and metallic particulates	Waste cleaning and cooling water with elevated temperatures	Spent steel shot, metallic particulates, cutting wheels, metallic filings, dust from waste collection systems
Shakeout, Cooling and Sand Handling		Dust and metallic particulates; VOC and organic compounds from thermal sand treatment systems	Dust collector containing dust if wet collector used	Waste foundry sand and dust from collection systems, metal
Die Casting	Metal, fuel, lubricants, fluxing agents, hydraulic fluid	VOC's, water vapour from die and plunger tip lubricants	Waste cooling water with elevated temperature and wastewater contaminated with die lubricant	Waste hydraulic fluid, lubricants, floor absorbant, and plunger tips

2.3 Haley Industries Limited Casting Processes

The site under detailed examination is Haley Industries Ltd. Haley Industries Ltd. (HIL) is a manufacturer of precision light alloy castings primarily for the international aerospace industry. Customers include: Allied Signal Aerospace, Bell Helicopter Textron, Fiat Avio S.p.A, Rolls-Royce Allison, United Technologies Corporation. Typical products are: gearboxes, frames, tanks, covers, inlets (see Figure 24a).

The company's principal manufacturing facility is located near Haley, Ontario, 110 kilometres west of Ottawa. The company employs up to 420 people. Haley uses the chemically bonded sand moulding process to produce castings. Haley Industries Limited, formerly known as Light Alloys Limited, was constructed on this (Haley) site by the Canadian government in 1952 and currently occupies a 15,000 m² building.



The main processes carried out at the facility are:

- ♦ Mould and coremaking.
- ♦ Mould assembly.
- ♦ Metal melting and pouring.
- ♦ Shakeout and sand handling.
- ♦ Finishing and cleaning.
- ♦ Heat treat.
- ♦ Non destructive testing.

Figure 24a Typical castings made by Haley Industries Ltd.

A process flowchart of the main processes is shown in Figure 25. Figure 26 shows the overall plant layout.

Figure 25 Haley process flow chart.

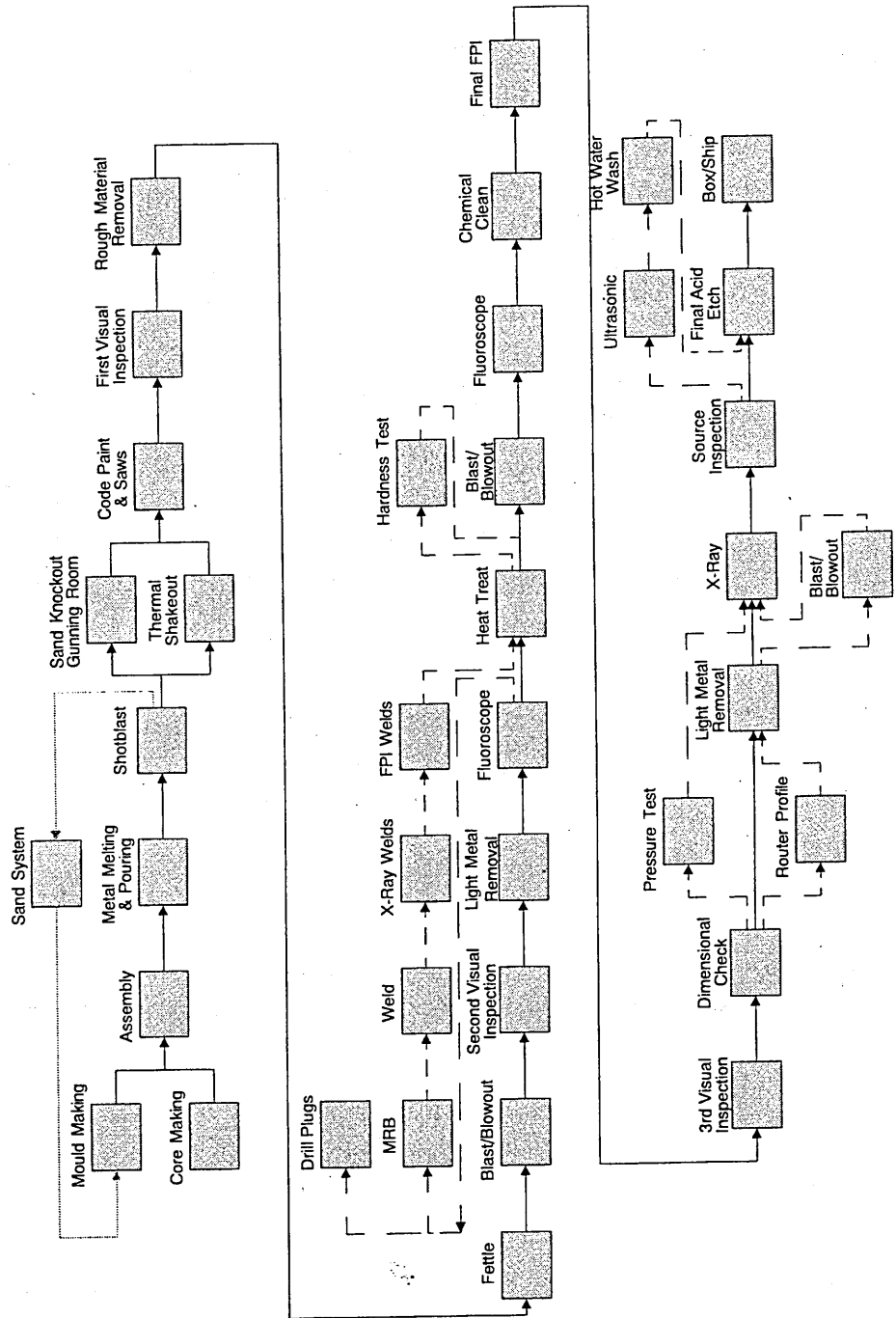
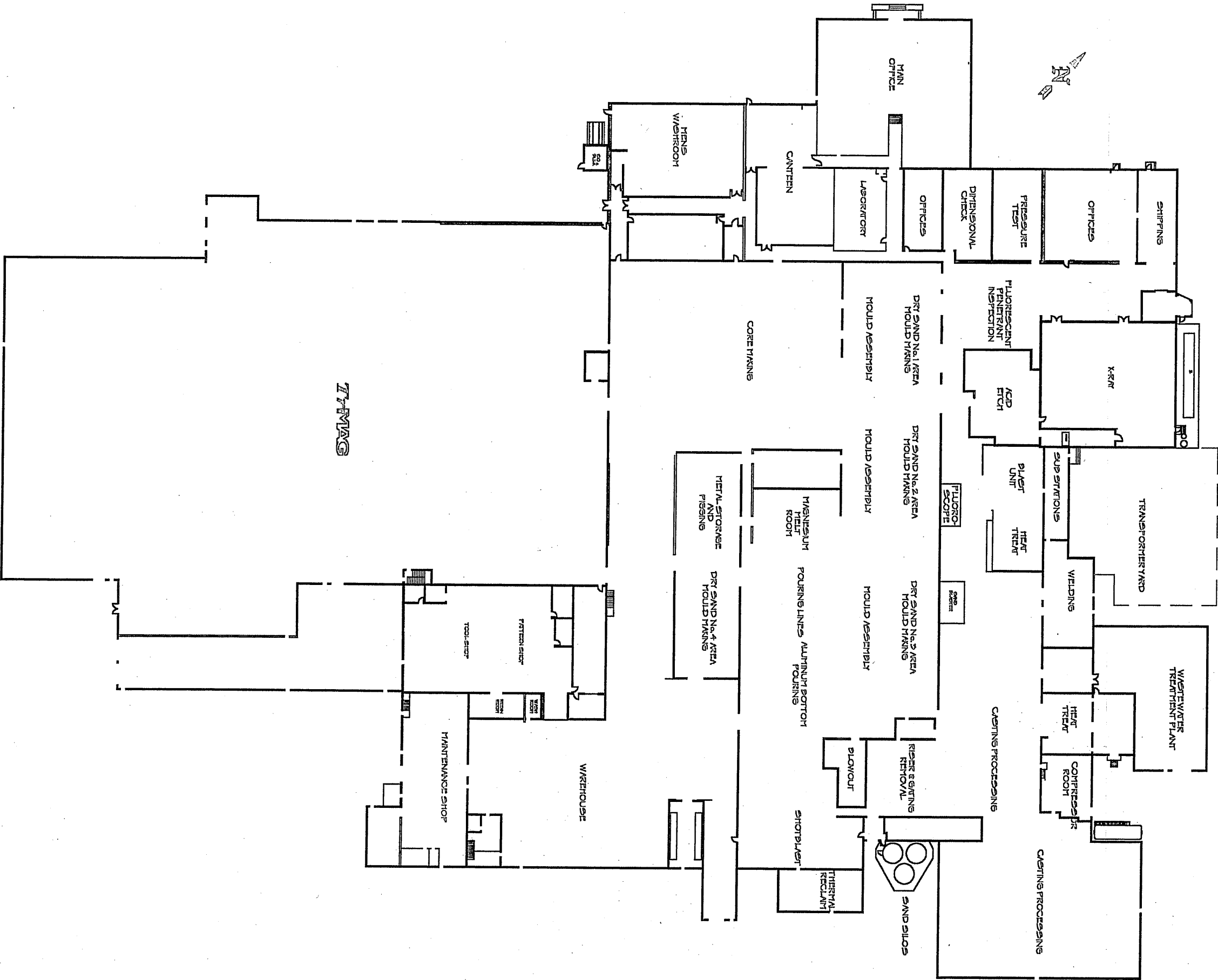


Figure 26 Haley Industries Limited plant layout.



2.3.1 Core Making

There are three chemical binder systems used in coremaking. These are (1) acrylic/epoxy, sulphur dioxide (SO_2), and (2) furan, SO_2 cold box binders, and a (3) urethane no-bake binder.

The steps involved in core making are:

- ♦ sand and binder mixing
- ♦ core box preparation
- ♦ core blowing, packing
- ♦ core gassing, setting
- ♦ core purging (cold box only)
- ♦ core ejection
- ♦ core finishing

Core sands, binders and additives are mixed in two different types of mixers, continuous and batch. Continuous mixers are used for silica sand in any of the binder systems. They produce large quantities of mixed sand. Batch mixers are used for speciality sands, such as glass bead and zircon sand. Batch mixers are only used for the cold-box binders. Pre-mixed sand is conveyed to the core machines as demanded by the core machine operators.

Core boxes are prepared for coremaking by applying core release, cleaning the vents and placing any loose pieces, locators, chills, wire etc. in the box as required. Large cores may have rods, wires or nails placed inside for structural support.

Cores are made on a variety of core machines depending on the geometry and size of the core. For all the cold-box cores the cycles are very similar, the sand is blown into the core box under pressure. Depending on the core size and geometry different blow pressures and times are used. The core is then gassed (cured) with sulphur dioxide, gas pressure and times are dependent on box geometry. The sulphur dioxide causes a chemical reaction in the binder that results in the sand curing in the core box. A purge cycle forces air and any remaining sulphur dioxide through the core and out to the scrubbers. The core box is opened and the core ejected either manually or automatically. The cores are then sent to core finishing. A cold-box core machine is shown in Figure 27.

Large brick cores are produced using a urethane no-bake binder system. Core box preparation involves placing locators, riser sleeves, chills, wire etc. into the box as required. A continuous mixer discharges mixed sand into the core box (Figure 28). Any hooks, rods or nails that are required are placed into the box. The core box is filled and packed. Once the box is full it is transferred to a holding line where the sand binder mix hardens. After approximately twenty minutes the core is ejected from the core box. The cores are sent to core finishing to file and drill the cores. The large casting area manufactures its own cores by hand packing with a urethane no-bake binder.

Once the core has been removed from the core box it must be finished. Fins, blow shoot, and vent marks are removed using files. The core may be patched using a patching sand, and vents are drilled as necessary. Core venting allows gases to escape during pouring.

When the cores have been finished they are collected together and taken to core storage. Vented pipe cores are checked to ensure the vent passage goes all the way through the core. Filtered smoke is passed through the core vent to verify that the passage is clear. Some cores are spray coated using an alcohol zircon based coating. Cores are collected from the different finishing stations into kits ready for assembly. Completed core kits are stored on buggies until needed in assembly.

Materials Used

- ♦ Granular media: silica sand, zircon sand, alumina silicate aggregate, glass bead.
- ♦ Binder systems: acrylic epoxy 2-part cold-box binder, furan 3-part binder cold box binder, sulphur dioxide, sodium silicate/sugar binder, urethane 3-part no-bake binder.
- ♦ Sand additives: sodium silicofluoride.
- ♦ Coating: alcohol-based zircon core spray, potassium borofluoride.
- ♦ Other materials: isopropyl alcohol, mudding compound (to smooth surface), incense, filters, insulating riser fabric, plastic tubing, release wax, lift hooks, tex vents, steel wire, rods, sleeves, locators, chills, nails, glass tubing.

Wastes produced

- ♦ Mixer calibration wastes, binder components.
- ♦ Mixed sand beyond its bench life.
- ♦ Broken cores.
- ♦ Sulphur dioxide/air, treated in the scrubbers to produce wastewater.
- ♦ Insulating riser fabric.
- ♦ Sand blend changeover wastes.
- ♦ Packaging materials.
- ♦ Waste isopropyl alcohol.



Figure 27 Cold box coremaking machines.

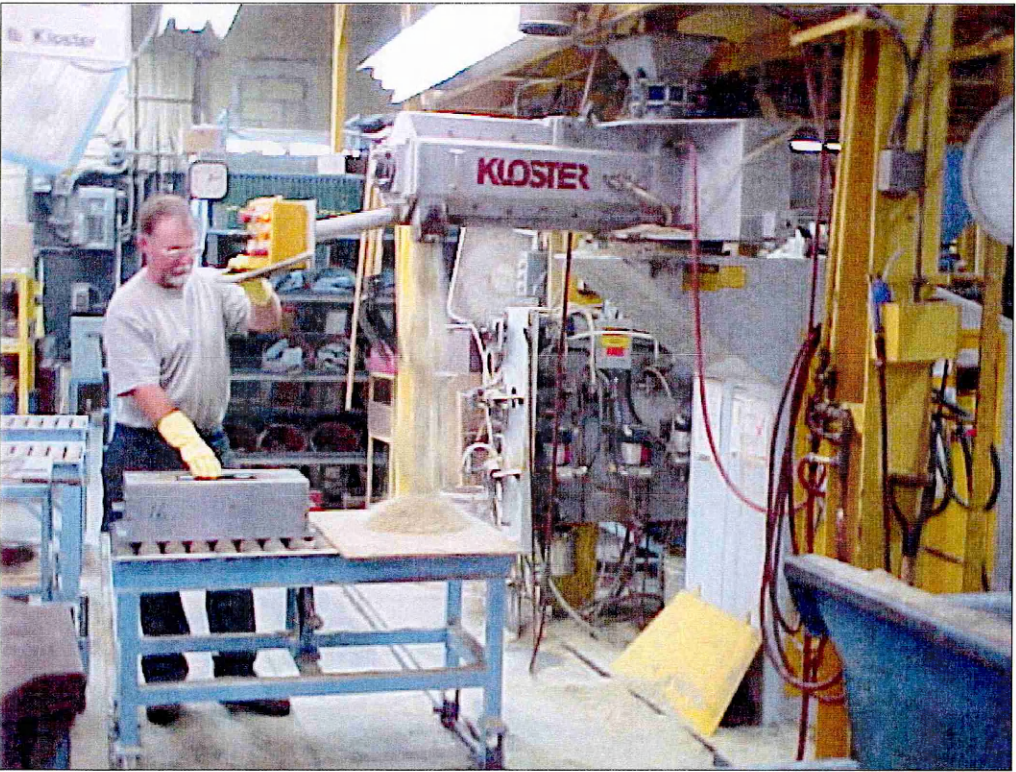


Figure 28 No-bake sand mixing and core making.

2.3.2 Mould Making and Assembly

Mouldmaking is divided into four self-contained areas, depending on the size of the mould being made. Three of the areas make moulds for both aluminium and magnesium castings. The fourth area makes aluminium castings only.

Pattern boxes are placed on a conveyer where they are prepared for mouldmaking (Figure 29). The loose pieces of the pattern box are assembled. Insulating riser sleeve fabric is cut and is placed over plastic cylinders on the cope. Metal frames are often placed in the box to give the mould structural strength. Chills, locators, filters, and any other materials are placed in the pattern box as required. The pattern box is sent by conveyer to the sand mixer where the box will be filled with sand.

The sand, binder and sodium silicofluoride (as required) is mixed in a continuous mixer. The sand used in the moulding areas is a blend of thermally reclaimed, mechanically reclaimed and new sand. The binder used is a phenolic urethane no-bake system. The sodium silicofluoride is used to prevent the magnesium from reacting with the sand.

The pattern box is filled and packed with the sand/binder mix (Figure 30). The top of the sand is flattened using a metal bar (strike-off). After approximately twenty minutes, the filled pattern box is conveyed to the rollover machine. The pattern box is clamped onto the rollover and turned upside down. The operator vibrates the box to draw the mould from the pattern box. The rollover turns the pattern box back to an upright position where the box is either returned to box preparation or to storage.

Some cores are pre-assembled before being delivered to the main assembly areas. Fixtures are used to verify the location of the cores being assembled. Materials and general procedures are the same as main assembly. The mould sections are delivered to assembly from mouldmaking. Filters are placed inside the mould to prevent oxides and other impurities from entering the casting cavity during pouring. Ceramic, steel, or cone filters are used depending on the metal being poured and the pouring method used.

Cores are inserted and glued into the mould (Figure 31, Figure 32). Gauges are used to check core positioning, and ball gauges are used to check the spacing between cores (Figure 31). An acetylene torch may be used to carbon blacken certain cores. This improves metal flow through the casting cavity. An oxygen-acetylene flame may be used to remove any moisture from the sand surfaces.

Once the cores, filters and any inserts are in place, the cope, and cheek (if there is one) are hoisted up, and rotated and lowered onto the drag. Steel sleeves are put through holes in the corners of the mould to align the different sections of the mould. Sand dowels are put into the steel sleeves to prevent metal from entering the sleeves, allowing the steel to be reused. Sand with a self-set binder is used to seal the parting line between the cope and the drag. The pouring box is pasted on to the top of the mould if it to be gravity poured. Paper is placed over the risers to prevent sand and dirt from entering the casting cavity before the pouring operation.

Materials used

- ♦ Blended sand.

- ♦ Binder: phenolic urethane 3-part no-bake binder, urethane no-bake binder.
- ♦ Additive: sodium silicofluoride.
- ♦ Metal filters: ceramic filters, steel filters.
- ♦ Other materials: core paste, patching sand, mudding compound, isopropyl alcohol, insulating riser fabric, acetylene, oxygen, plastic tubing, tex vents, steel wire, locators, screens, filters, chills, paper.

Wastes produced

- ♦ Mixer calibration wastes, binder components.
- ♦ Waste sand mixed with binder.
- ♦ Damaged moulds, broken cores.
- ♦ Insulating riser fabric.
- ♦ Packaging materials.
- ♦ Isopropyl alcohol.



Figure 29 Pattern box preparation.



Figure 30 Mould packing.

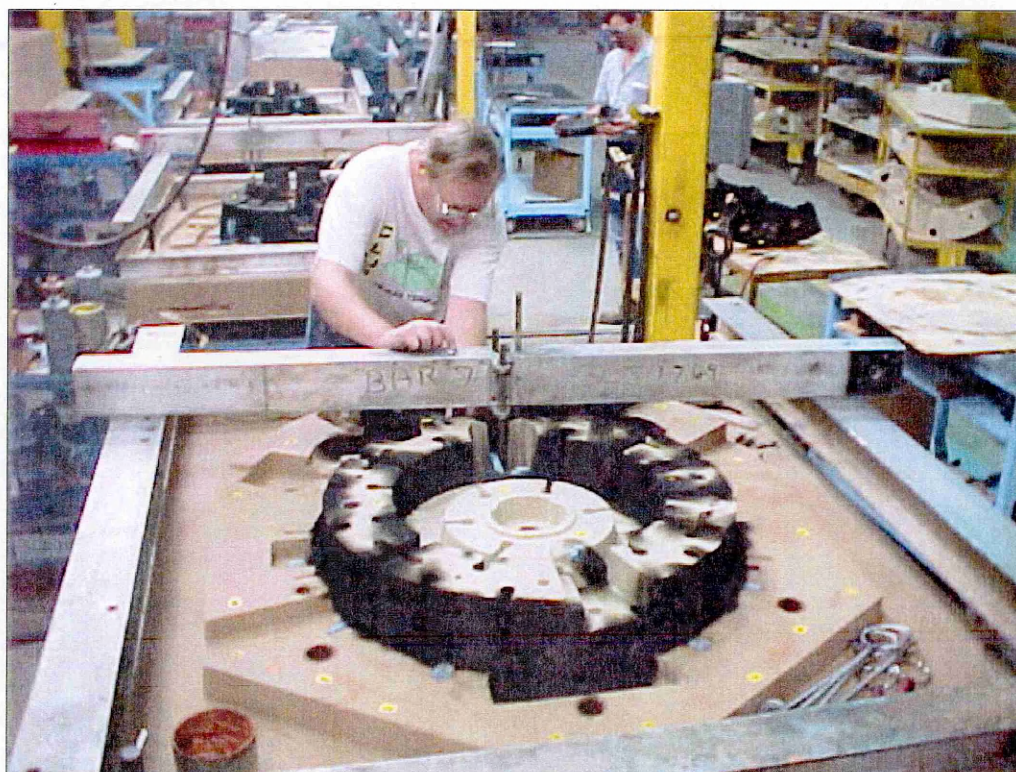


Figure 31 Mould assembly.



Figure 32 Close-up of mould assembly.

2.3.3 Furnace charge, metal melting and pouring

Magnesium melting and pouring

Each morning a list of moulds to be poured that day is prepared. From this information a list of the number of crucibles of each alloy is prepared. A computer calculates the charge composition of each crucible based on availability of scrap, new metal and cost. Each charge is made up of internal scrap and new metal. The initial charge is placed in a gas-fired crucible furnace and the charge is heated. The cover gas of SF₆ and CO₂ is turned on at the same time as the furnace to prevent the magnesium from oxidising. When the melt reaches a temperature of 740°C the melt is mixed. Fluxes and or degassing pills can then be used to remove impurities in the melt.

A small rapid sample is poured into a steel die, this sample is sent to the laboratory for metallurgical analysis using a spectrometer. Depending on the sample composition the additions required are calculated so that the melt meets internal alloy specifications. The additional metal is added and once it is melted the melt is mixed again. Three sets of samples are poured (1) disks for storage, (2) rapid samples, (3) fracture test bars. The rapid samples are analysed on the spectrometer and the fracture bar is examined for grain size. If the melt passes these tests the crucible is hoisted onto the pouring forklift truck (Figure 33, Figure 34). The forklift continues to supply the cover gases to the molten metal. Test bar moulds are the first moulds to be poured. Some of the test bars will be retained while others will be tensile tested.

The moulds are purged with the CO₂/SF₆ to eliminate oxygen from the moulds. When the metal has reached the pouring temperature pouring is started. Metal is poured into the mould until the risers begin to fill (Figure 35). Sulphur powder is sprinkled onto the moulds, forming a magnesium-sulphide skin on any exposed metal, thus inhibiting the magnesium from burning (Figure 36). Pouring is continued until there is only a small amount of metal remaining in the crucible. Excess metal in the crucible is pigged into ingots. The crucible is cleaned using flux. The poured moulds remain on the pouring lines until the metal is solidified, then the poured moulds are transported to the shotblast unit.

Aluminum Melting and Pouring

The required weights of alloys are prepared as in the magnesium melting area. The melt computer calculates the most economical additions to reach the desired melt composition, for this reason as much internal scrap is used as possible. The metal charge is put into the pre-heated electric furnace. When the metal reaches the required temperature the metal is transferred into heated pouring pots. The pot is stirred and other alloying components are added. The metal is allowed to sit before a rapid sample is poured and analysed using the spectrometer. Metal Stores prepares any additions that need to be made and takes them to the melt room. Nucleant pills are added to the melt to clean and grain refine the metal. Once the final additions are made the pot is degassed. Argon is used to remove dissolved hydrogen in the aluminium. Any other required additions are then made. The total charge is approximately 370 kg. A small sample of metal is subjected to a gas test. The test involves solidifying the sample under high pressure, if any surface bubbles appear the sample fails. If the melt passes the test the

metal is allowed to rest before a final sample is produced. The sample composition is checked on the spectrometer. If the melt passes, the crucible is either lowered into the bottom pour system or hoisted onto a forklift truck.

Bottom-pouring is completely automated. Moulds are moved into position above the crucible containing molten metal. The crucible is lifted until it is in contact with the cone filter under the mould. Pouring then begins and may take up to ten minutes per mould. Remaining metal in the crucible is either gravity poured or taken to the metal storage area to be pigged off into ingots.

Gravity pouring is similar to magnesium gravity pouring with some small differences. The pouring box is filled with metal before a sand plug is removed, allowing the metal to flow into the mould cavity (Figure 37). The pouring box is kept full during the pour in order to keep a steady pressure inside the mould. When the metal begins to fill the risers, the signal is given to stop pouring and the plug is placed in the pouring hole. Moulds are poured until 23-45 kg of metal remain in the crucible. The remaining metal is poured into ingots. The poured moulds remain on the pouring lines until they have solidified and are ready to be moved to the shotblast unit.

Materials used

- ♦ Metal: aluminium ingot, magnesium ingot, 356x, 357x alloy, aluminium beryllium master alloy, aluminium silicon master alloy, aluminium titanium master alloy, aluminium titanium boron master alloy, magnesium hardener, magnesium rare earth hardener.
- ♦ Fluxes: potassium aluminium fluoride; barium, fluoride flux; chloride flux; fluoride flux; alkali, alkaline earth chloride, fluoride, barium flux.
- ♦ Other additives: zirconium grain refiners, degasser pills, nucleant pills, SF₆, CO₂, sulphur powder, argon.

Internal scrap

- ♦ Magnesium alloys: EZ33, QE22, WE43, ZE41 alloys.
- ♦ Aluminum alloys: A356, A357, C355, 535.

Wastes produced

- ♦ Metal sludges, dross, filters filled with metal, gases from pigging, gases from mould decomposition.



Figure 33 Lifting a crucible of magnesium from the furnace.



Figure 34 Lowering crucible into pouring lift-truck.



Figure 35 Magnesium pouring.



Figure 36 Moulds after pouring.

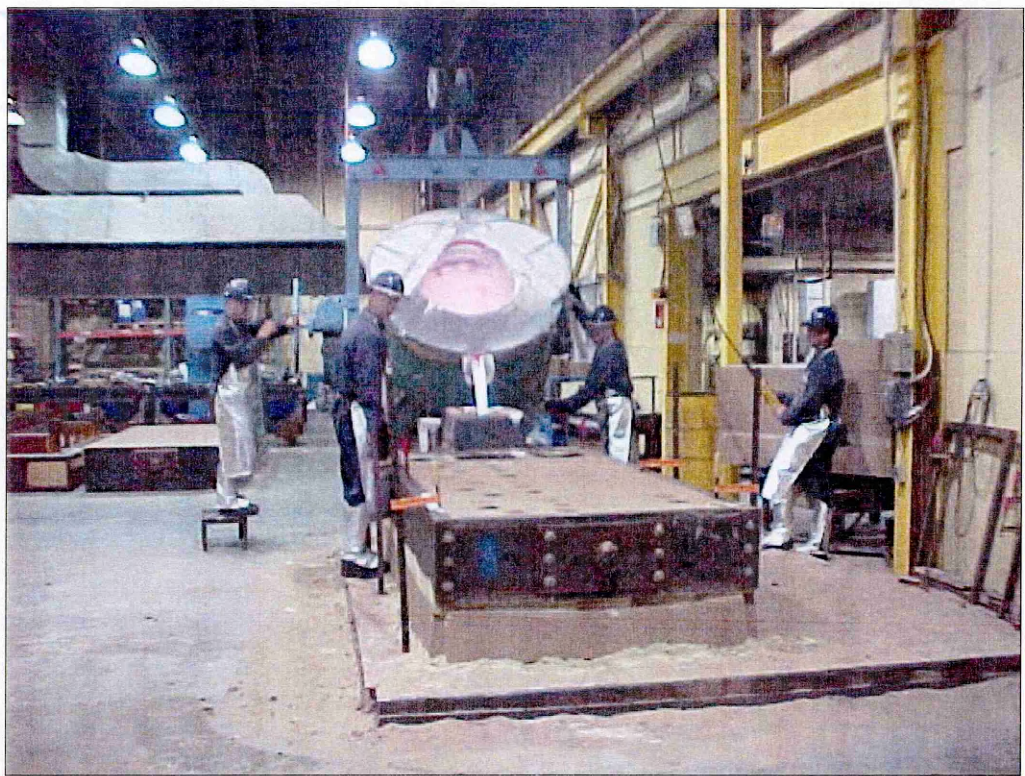


Figure 37 Aluminium large casting pouring.

2.3.4 Shakeout, cooling and sand handling

In order to remove the casting from the mould material, the poured mould is shotblasted. The poured moulds are placed on rotating tables attached to the doors of the shotblast unit (Figure 38). When the door holding the mould is closed the blasting is started. Steel shot is thrown at the mould until the sand has been broken into individual grains. The steel shot and sand are conveyed to the sand separators, these remove large pieces of flashing, sand plastics and separate the sand and steel shot. The sand is sent into the sand system (Figure 39, Figure 40). The steel shot is reused. The casting and frames, steel chills, wires, hooks and core inserts are left on the table. The casting moves to the next station. Chill and frames are reused.

Some poured moulds are not shotblasted or they require thermal shakeout to help remove core sand. The poured moulds are placed into large steel boxes and placed in the bakeout oven. As the temperature of the oven increases the binders in the sand change into gas causing the mould and cores to break down into individual sand grains. The sand is taken to the shotblast unit to be recycled. The castings are taken to blowout for removal of any remaining sand.

In the blowout area, any remaining sand room is manually removed (Figure 41). Pneumatic hammers, hammer, chisel and various other tools are used to remove any remaining sand. Blowers are used to blow the sand away leaving the casting clean. Chills are collected together for reuse. Sand is taken to the shotblast unit to be reused.

Materials used

- ♦ steel shot.

Wastes produced

- ♦ sand dust, spent steel shot, locators, metal flashing, plastic tubing, steel wire, screens, filters, nails.



Figure 38 Shot-blast unit for sand removal from casting.



Figure 39 Thermal reclaimer.

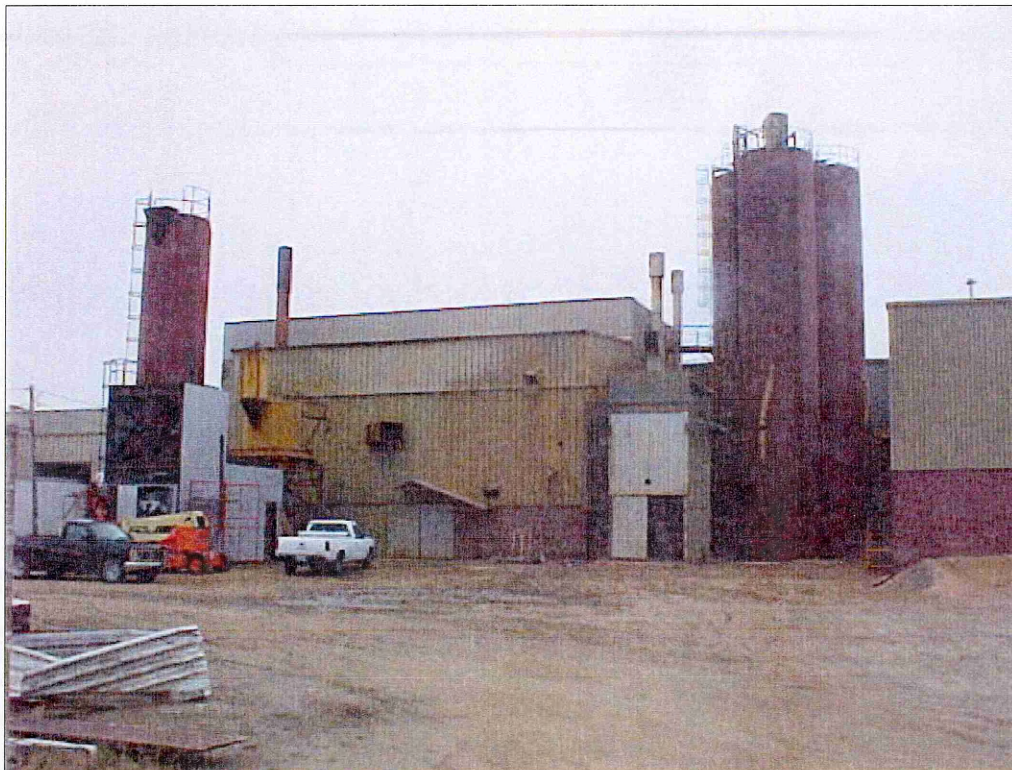


Figure 40 Dust storage, thermal reclaimer building and sand silos.

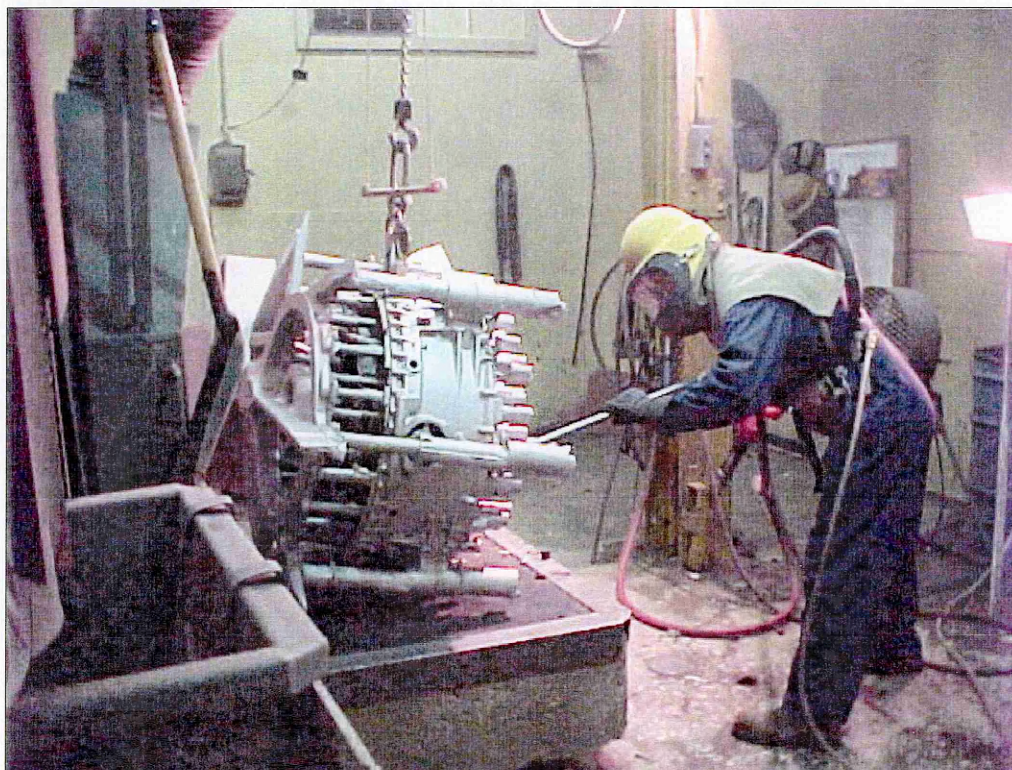


Figure 41 Manual sand removal (blow-out).

2.3.5 Finishing and cleaning

Finishing and cleaning processes remove excess metal from the casting processes range from rough material removal to precision metal removal and cosmetic processes. After sand removal has been completed the risers and gating are marked with paint using an internal alloy colour code. This facilitates internal recycling of scrap metal. The size of the casting determines the method used for riser removal. Large castings have risers removed using a large circular saw. The casting is clamped on a mechanical table which is rotated into position. A large circular saw mounted on a mechanical arm removes the risers in its path (Figure 42). The risers from the small and medium sized casting are removed using the band saws. The gating systems from all castings are removed at the band saws (Figure 43). Wax or spray lubricants are used to lubricate the saws when cutting aluminium castings. Once the risers and gating have been removed from the casting they are placed in barrels according to the alloy colour code and taken back to the melt room for re-melt.

After riser and gating removal the castings and test bars are stamped with a melt number and a record is entered into the computer system. The casting is inspected for surface defects and wall thickness. If a defect is found and is correctable the casting is marked for welding before being sent to finishing, otherwise the casting is scrapped. Test bars are sent for heat treatment.

A hand-held reciprocating saw is used to remove any gates, risers or excess metal that could not be removed with the band saws. Aluminium castings require a lubricating oil, whereas magnesium castings do not. After this operation the castings usually go to the router or the CNC machines.

A router consists of a spinning head on the end of a mechanical arm that machines the metal off in layers. The router is used for either rough material removal or for a precise surface depending on what stage of the process the casting is at. For a precision process the casting is mounted on a fixture that guides the router, allowing it to precisely remove a layer of metal.

The Computer Numerical Control (CNC) machine consists of a mechanical arm with a spinning head at the end. The spinning head is tipped with carbide inserts that are consumed in the process. Nozzles spray an oil/water mixture that serves to lubricate and cool the machine tool and the casting (Figure 44). The CNC can be used either for rough material removal or precise machining.

The chipping tool used is similar to a jack hammer but is approximately the same size as a drill. Because of its size, the chipper is generally capable of removing excess metal in hard-to-reach places (Figure 45). Once having been through this stage, the castings have the correct form but have a rough finish.

The sanders smooth the casting surfaces and remove any remaining flashing. The two types of sanders that are used are disk sanders and belt sanders. The belt sander is used for lighter castings because the operator must hold the casting. The heavier castings are placed on a table and sanded using a disk sander (Figure 46). After having been sanded, castings are sent to fettling to further improve their surface finish. Aluminium requires a

lubricating oil when using the disk sander and a wax lubricant when using the belt sander.

Fettling is used to clean up parts of the casting the sanders cannot reach. Angle and straight fettling guns are used to smooth the casting surfaces and to remove any remaining flashing, mismatches, joint lines and chill marks (Figure 47).

Ultrasonic inspection is used at various stages in the post-casting process. Ultrasonic inspection is used to check the wall thickness on passages of the casting. The ultrasonic machine is calibrated for the alloy to be inspected. The probe is cleaned and primed with the couplant gel. The probe is pressed against the casting wall and the wall thickness is read.

After previous finishing steps the castings do not have a uniform casting finish. Small and medium sized castings are blasted with steel grit. Alloys containing beryllium must be sand blasted. If the casting has a lot of internal shapes the shot blast unit does not adequately finish the casting, these castings must be finished in the sand blast unit.

The sand blast unit consists of a large chamber separated into two parts. In the first chamber the castings are sand blasted by an operator, the second operator cleans the sand out of any internal passages. Sand blasting is more labour intensive than the grit blast unit but the sand blaster can blast less accessible parts of the casting.

After blasting and blowout the castings are examined at second visual inspection. Here, the inspectors check for any surface defects such as over-fettling. Wall thickness is measured using a calliper and the casting is sometimes forwarded to ultrasonics. If a defect is found, the casting is marked and the defect is noted on the foundry traveller. If fettling is required, the casting undergoes second visual rework.

At the fluoroscope examination station the operator places the castings on a mechanical table in the x-ray room. A stationary x-ray machine takes a continuous picture of the casting. The operator views the image in separate room and controls the motion of the table. As the table moves, the operator can view the internal passages of the casting. If a defect is found the castings can be reworked or further examined with a boroscope. A boroscope uses fibre-optics to view internal components of the casting. Once an internal defect has been identified with the fluoroscope or the boroscope the operator attempts to correct the problem using custom fettling tools. Custom made flexible tools are attached to the fettling gun, making it possible to fettle inside a pipe or in other hard-to-reach areas of the casting.

Materials used

- ♦ latex paint, saw blades, petroleum wax, spray lubricant, coolant oil, hydraulic oil, carbide inserts, blasting sand, steel grit.

Wastes produced

- ♦ saw blades, spent machine coolant, metal fines and chips, spent blasting sand/dust, spent steel grit, wastewater from dust collectors.

2.3.6 Heat Treat

Castings made of WE43A and AZ91E alloys are heat treated directly prior to being welded (after x-ray). Otherwise, castings are heat treated after being welded. ZE41A and EZ33A alloys undergo a stabilising heat treatment. This heat treatment helps prevent any unwanted metallurgical changes in a casting during its operational life. Ageing is not required for these alloys. All other alloys undergo solution heat treatment. Before heat treatment, alloying elements are concentrated along grain boundaries. By heating the castings in an oven for a given time and temperature, the alloying elements go into solution (dissolve into the grains uniformly). This prepares the castings to be artificially aged. Some aluminium castings must go to straightening before being aged due to distortions associated with solution heat treatment. ZE41A and EZ33A are not artificially aged.

Aluminium castings often become warped during the solution heat treatment process. When this occurs, they are taken to the straightening department. The castings must then be straightened before they harden, or they will have to be solution heat treated again. The warped castings are mounted onto fixtures and are hammered or pressed back to within acceptable dimensions. After being straightened, castings are sent to the heat treat department and are artificially aged.

Castings of all alloys except ZE41A and EZ33A are sent to artificial ageing from either solution heat treatment or from straightening. After solution heat treatment, the alloying elements in a casting are uniformly distributed. Artificial ageing involves the heating of a casting in an oven for a given period of time at a given temperature. This allows the alloying elements to precipitate from solution into small grains within the base metal. These small grains render the casting much stronger.

The Brinell test is used to determine the casting hardness. Hardness is tested on some castings after heat treatment. From here, castings may go to chromium pickle, the walk-in sand blaster, blast/blowout, fluoroscope and eventually to acid etch.

Materials used

- ♦ carbon dioxide.
- ♦ water.

Wastes produced

- ♦ carbon dioxide.
- ♦ quench pit water.

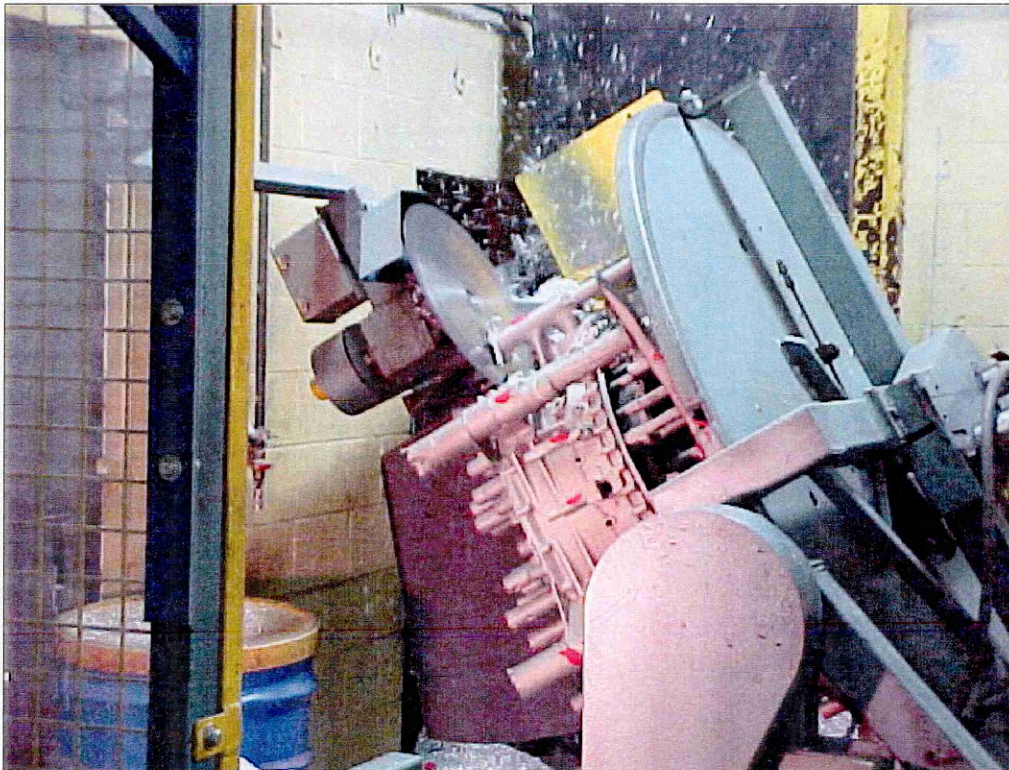


Figure 42 Riser cut-off saw.



Figure 43 Gating cut-off.



Figure 44 CNC milling.

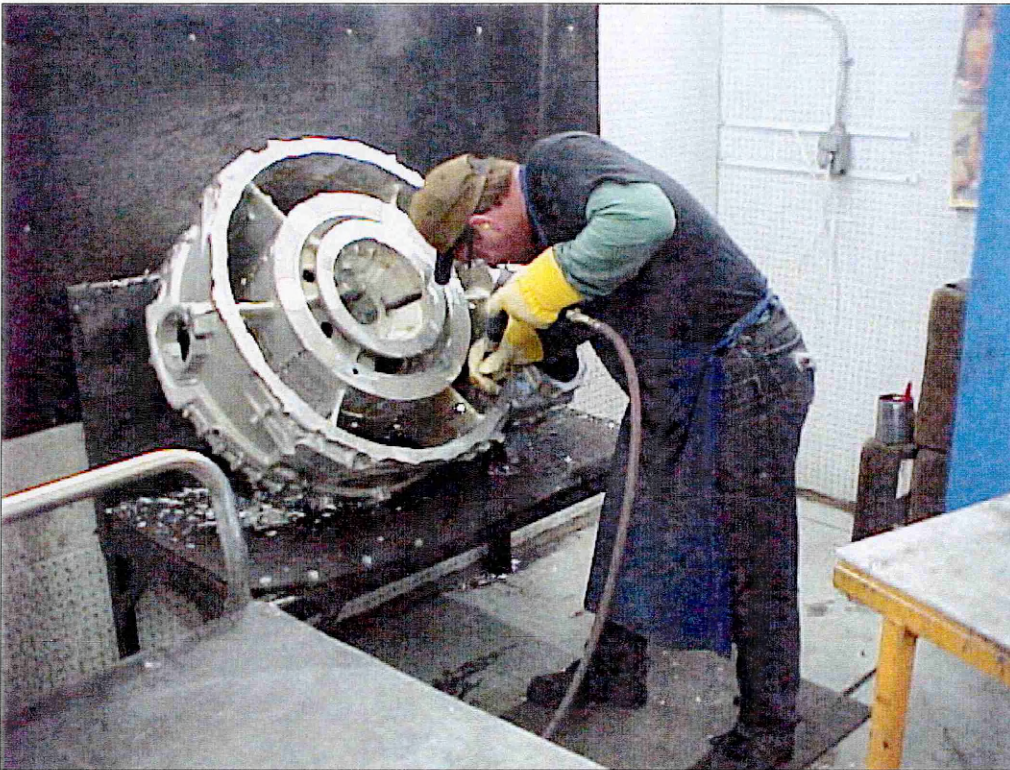


Figure 45 Casting clean-up (chipping).



Figure 46 Disk sanding a casting.



Figure 47 Casting clean-up (fettling).

2.3.7 Welding

Castings are welded for two reasons, (1) to fill plugs that contained sand (for ease of manufacturing), and (2) for defect welding. Castings to be repaired are checked in a the material review board where the attendant checks that the weld grid marking corresponds to the marks on the casting. If the weld is viable the paperwork is completed and the information is updated on the computer network. Castings to be plug welded are sent to be drilled which is done using a drill press. The hole depth is verified before the casting is sent to weld preparation.

Penetrant oil is brushed over the defect areas of defective castings. The casting is left to dry before the oil on the surface is removed and the defect is inspected under the ultraviolet light to indicate the exact defect location. If a defect is present some of the oil will remain in the defect after the main surface oil has been removed and will fluoresce under ultra violet light. The defect is dug out using a fettling gun. If the defect is too difficult to weld the casting is scrapped. Plug welding holes are also fettled. It is necessary to use tapping fluid on aluminium alloys, and this must be removed using a degreaser prior to welding.

The castings are preheated in an oven to prevent the casting from absorbing all the heat from the welding process and causing the weld to cool too quickly. A backing is applied to one side of the cavity. This backing holds the molten metal in the cavity while it cools. The cavity is welded on one side, then the backing is removed and the casting is allowed to cool. The weld is examined. If the weld is acceptable the casting is preheated again and the weld is completed on the other side of the cavity (Figure 48). To prevent the metal from oxidising, argon gas is used as a shield gas.

After welding, welds are subject to clean-up, wall thickness check, fluorescent penetrant inspection and x-ray examination. The wall thickness around the weld is checked using callipers or ultrasonic testing. If the weld thickness is greater than the surrounding wall it is fettled down to the wall thickness. The wall/weld thickness is re-checked and providing the wall thickness is adequate the casting goes to the weld fluorescent penetrant inspection.

At weld x-ray inspection station the welds are x-rayed in an x-ray booth. The film is processed and examined. If the weld is not acceptable the weld is either dug-out and re-welded, or the casting is scrapped. If all the welds are good the casting returns to the material review board to be logged out of the department, and follows the subsequent processing of the castings that did not have defects.

Materials used

- ♦ weld rods, argon gas, abrasive disks and rolls, tapping fluid, x-ray for inspection materials, water-based degreaser.
- ♦ see fluorescent penetrant inspection.

Wastes produced

- ♦ spent abrasives, spent degreaser.
- ♦ see x-ray.

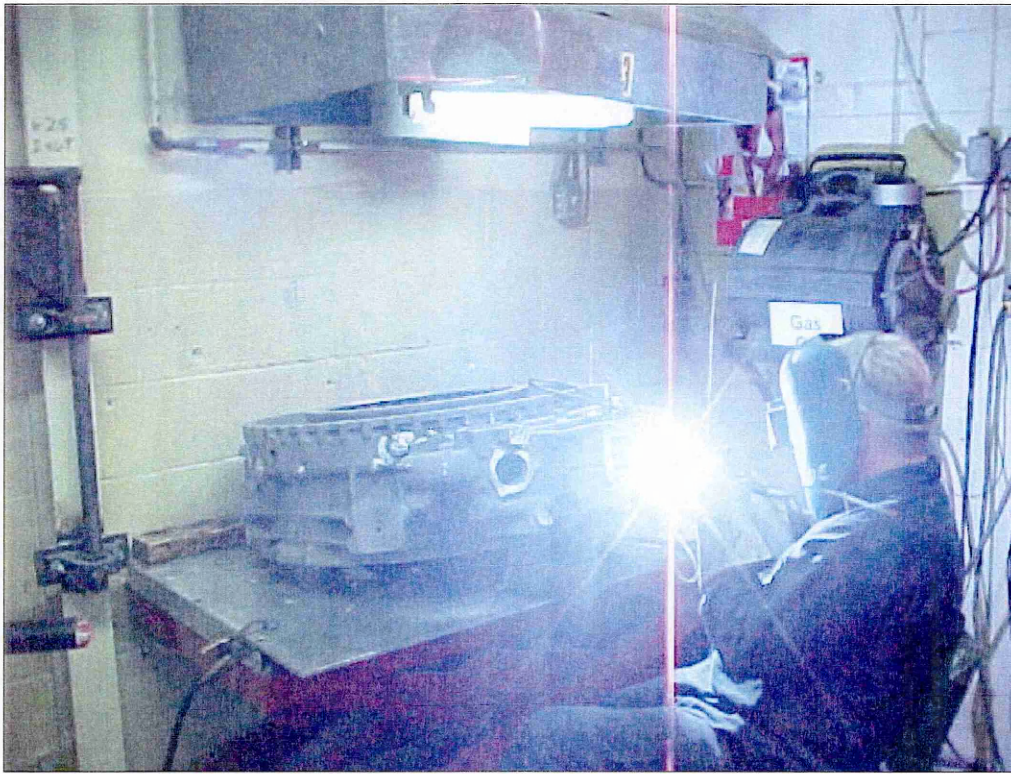


Figure 48 Welding a casting.

2.3.8 Non destructive testing

The quality of casting is determined by the dimensional and metallurgical quality. When castings are they must pass first article inspection. First article inspection demonstrates that the casting meets the customer's dimensional and metallurgical specifications. This is determined through dimensional layout of the casting, non-destructive testing and destructive testing. Once the casting is approved by the customer, the casting can enter full production. To verify that the casting continues to meet customer specifications non destructive dimensional and metallurgical tests are conducted on the part.

2.3.9 Acid Etch

The acid etch process removes a thin layer of metal, thus exposing a new surface of metal in preparation for fluorescent penetrant inspection (Figure 49). If sand blasting or shotblasting were used they could disguise defects. There are different acid etch procedures for aluminium and magnesium alloys.

Magnesium alloys

Castings are dipped in 5.5% sulphuric acid.

Rinsed in overflowing rinse.

Dipped in 15% hydrofluoric acid.

Rinsed in overflowing rinse.

Rinsed in hot water overflow rinse.

Aluminium alloys

Castings are dipped in 8% hydrofluoric acid and 53% nitric acid

Rinse in dragout rinse tank

Rinse in overflowing rinse water

Rinse in hot water overflowing rinse

After etching the castings are placed in a drying oven. Castings are then ready for dipping in fluorescent oil prior to inspection under ultraviolet light.

Materials used

- ♦ sulphuric acid.
- ♦ hydrofluoric acid.
- ♦ nitric acid
- ♦ water.

Wastes produced

- ♦ spent sulphuric, hydrofluoric, and nitric acids.
- ♦ acidic rinsewater.

2.3.10 Fluorescent penetrant inspection

After the castings have been acid etched the castings are dried, cleaned and any surface defects should be exposed. The castings are dipped in penetrant oil which penetrates any surface imperfections (Figure 50). The castings are dipped in rinsewater and then

thoroughly sprayed with water to remove any remaining oil. The castings are dried in an oven before being inspected. The inspection booths are dark, the casting is inspected under ultraviolet light. Surface imperfections retain the fluorescent dye, causing the imperfection to glow under the ultraviolet light.

Materials used

- ♦ penetrant oil, dry developer, non aqueous developer, penetrant solvent remover.
- ♦ water.

Wastes produced

- ♦ penetrant oil.
- ♦ rinsewater.

2.3.11 X-ray

Castings to be x-rayed are placed on rotating tables inside lead-lined booths. X-ray photographs are taken at particular viewing angles and planes specified by the customer. The x-ray film is developed in-house and then interpreted by industrial radiographers. Radiographers inspect the film for density changes in the casting that could indicate the presence of casting defects (Figure 51). If a defect is found, the casting may be reworked, welded or scrapped.

Materials used

- ♦ x-ray film, industrial x-ray fixer, industrial x-ray developer.
- ♦ water.

Wastes produced

- ♦ waste film, waste x-ray fixer (contains silver), waste x-ray developer.
- ♦ rinsewater.

2.3.12 Chromium Pickle

Some magnesium castings require chromium pickle for corrosion protection during shipping. The castings are dipped in a solution of nitric acid and sodium dichromate, followed by a dragout rinse and a hot water rinse. The castings are then dried in an oven and sent to the next processing step. This step is largely being replaced with oiling.

Materials used

- ♦ nitric acid, sodium dichromate, ammonium bifluoride.
- ♦ water.

Wastes produced

- ♦ dragout rinsewater high in chromium.

2.3.13 Third Visual Inspection

The third visual inspection check is used to check casting documentation and appropriate information is scribed onto the casting. Wall thickness is verified using callipers and an ultrasonic device. Welds are inspected and the casting is visually inspected for any surface defects. If any fettling is required, the casting is sent to the rework station. Otherwise, the casting is sent for a final x-ray or to dimensional check.

Materials used

- ♦ ultrasonic couplant

2.3.14 Dimensional Check

A dimensional check is used to verify that the castings are within specified dimensions. The castings are mounted onto fixtures and a series of flush pins are used to check the casting dimensions (Figure 52). Target guns are attached to the fixture in specific places and spot faces are drilled. Castings that do not meet dimensional criteria may be reworked to meet customer specifications.

Materials used

- ♦ tapping fluid

2.3.15 Rework

Rework receives castings that have not met specifications from the dimensional check station, the third visual inspection station, and from final inspection station. Castings are typically fettled to meet dimensional specifications.

Materials used

- ♦ tapping fluid, petroleum wax, abrasive disks and rolls.

Waste produced

- ♦ spent abrasive disks and rolls.

2.3.16 Pressure Test

Pressure testing verifies that castings are impermeable at certain pressures. The casting is mounted onto a fixture that has plugs to seal any pipes or cavities. Nitrogen gas is fed into the casting, and the casting and fixture are submerged in water. A pressure tight casting will not yield any gas bubbles, whereas bubbles will be seen coming from a leaky casting.

Materials used

- ♦ Nitrogen gas.
- ♦ Water.

Waste produced

- ♦ Waste nitrogen gas.
- ♦ Wastewater from tank cleaning.

2.3.17 Final Inspection

Final inspection ensures that all required functions of inspecting and testing have been completed. The casting is inspected for general appearance, surface finish, markings and wall thickness (Figure 53). Non compliant castings are reworked or welded. Castings that pass final inspection are released and prepared for shipping.

Materials used

- ♦ ultrasonic couplant.

Wastes produced

- ♦ very little waste produced.

2.3.18 Release and Quality Control Acceptance

Prior to shipping a release form must be prepared and any required documentation collected together, for example x-ray film pictures of the casting and test bars. A certificate of compliance is prepared, the castings are either packaged for shipping or must pass through quality control acceptance.

Depending on customer requirements, some castings must be reviewed and inspected by the quality control department. If the casting meets requirements it is prepared for shipping.

2.3.19 Shipping

Once a casting has been processed and inspected it is prepared for shipping. Magnesium castings are coated with protective oil to prevent corrosion. Castings are packaged in foam-filled cardboard boxes to protect the casting from mechanical damage. The boxes are sealed with tape and steel strapping.

Materials used

- ♦ anti-rust oil, wooden pallets, steel strapping, packaging foam, plastic.

Waste produced

- ♦ occasional oil waste when tank is cleaned



Figure 49 Acid etching castings before inspection.



Figure 50 Draining fluorescent penetrant oil from casting.



Figure 51 X-ray inspection of a casting.

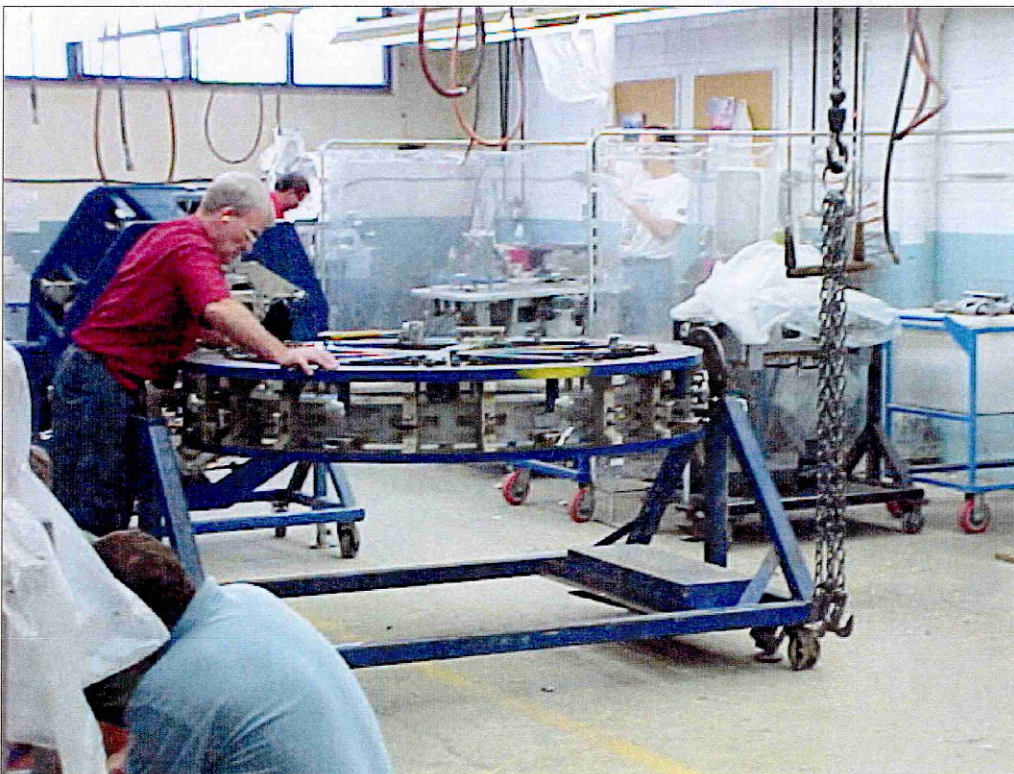


Figure 52 Dimensional inspection of castings.

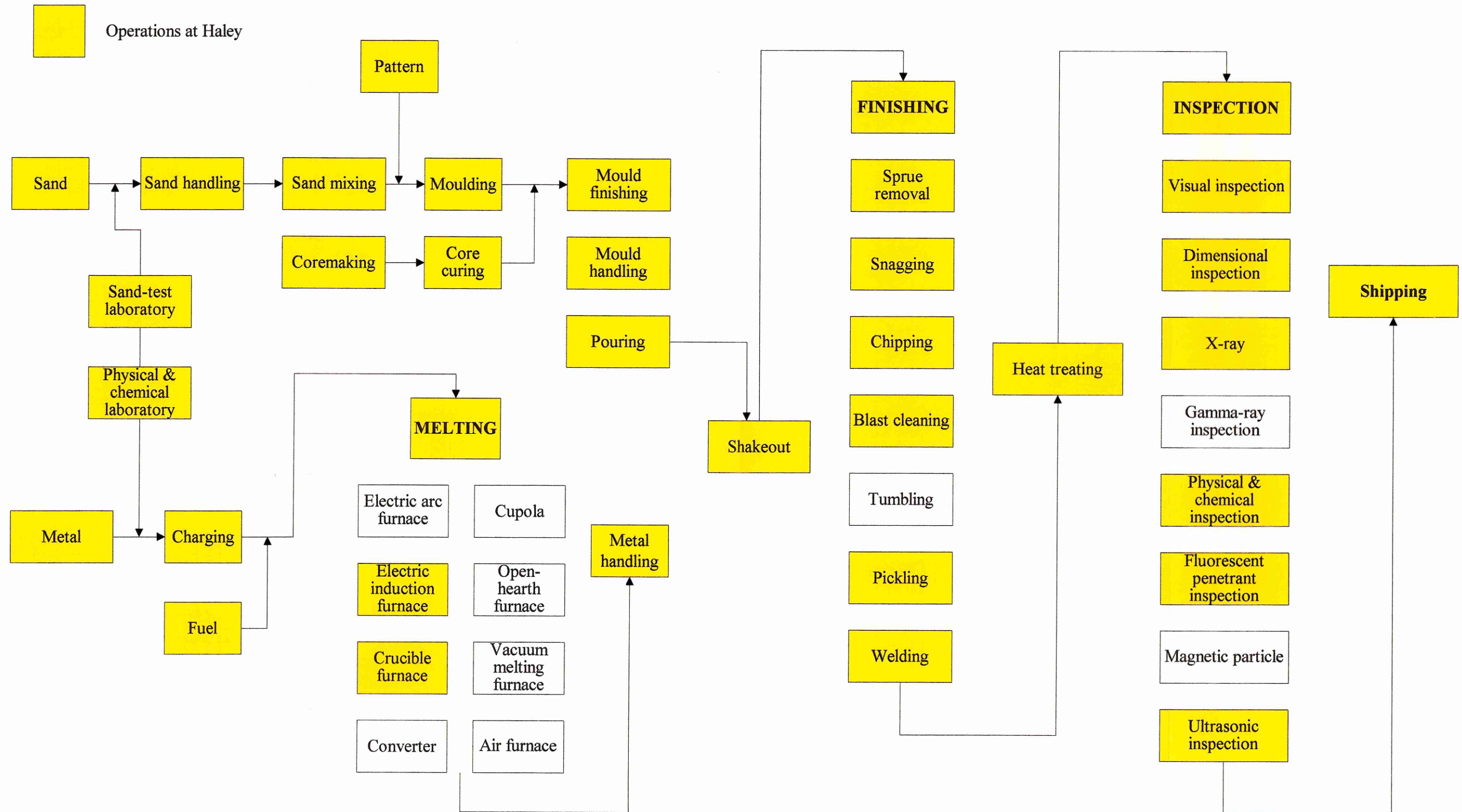


Figure 53 Final inspection prior to shipping.

2.4 Conclusions

- ♦ There is great diversity in metalcasting industry processes.
- ♦ When compared to common sand casting processes Haley Industries Limited is a good case study site, this is illustrated in Figure 54 which shows the flowchart of a typical foundry operation with the Haley processes highlighted.
- ♦ A summary of HIL processes and their environmental outputs is shown in Appendix A.

Figure 54 Modified Flow chart of a typical foundry operation to show operations at Haley Industries Limited.



3 DEVELOPMENT OF THE POLLUTION PREVENTION METHODOLOGY

3.1 Introduction

The purpose of this chapter is to develop an ordered methodology from available pollution prevention and cleaner production techniques that is suitable for the metalcasting industry.

Metalcasting plants are unique, from a clean manufacturing standpoint, because the product does not seriously impact the environment. When the castings have finished their useful life they are usually recycled through the system. The ancillary materials – the sand, fluxes and refractories make up most of the residuals from casting plants (Singh, 1996).

The Cast Metals Coalition (1998) has identified, in the Metalcasting Roadmap, the environmental challenges being faced by the industry.

“Improving environmental performance while keeping regulatory compliance costs at a minimum is one of the key challenges affecting the future competitiveness of metalcasters. How well the industry copes with increasingly stringent controls on emissions to the environment will have dramatic impacts on production costs as well as industry growth.”

For many years, environmental issues of manufacturing operations have been isolated and addressed with little or no interaction with other process objectives. This has resulted in the widespread adoption of pollution control strategies that focus primarily on end-of-pipe treatment, in which chemical, biological, and physical processes are applied to terminal streams to reduce toxicity or magnitude of environmentally undesirable compounds. This approach has enabled engineers to avoid in-plant changes and has, therefore, allowed the development of pollution control technologies as stand-alone devices that can be used to treat the symptoms without much regard to the root causes within the core processing operations. The result has been in the form of solutions that worked but nonetheless had poor economic indicators. This situation has led to the misconception that the solution to environmental problems of the process is an economic burden and that objectives of cost effectiveness and benign manufacturing cannot be reconciled (El-Halwagi, 1999).

According to Tordoff (1996) a good environmental program provides, at minimum, the following:

- 1) Compliance
 - a) Cost avoidance by eliminating fines and reducing legal fees
- 2) Profit improvement opportunities
 - a) Waste reduction and waste elimination
 - b) Productivity improvements
 - c) Lower capital expenditure for non-productive equipment
 - d) Reduction of workers compensation claims
- 3) Minimises bad press.

An approach that can achieve the above is pollution prevention or cleaner production.

A definition of pollution prevention as stated by Rossiter (1995) is "Pollution prevention seeks to eliminate pollution problems by not creating potential pollutants at all or, if their creation cannot be avoided, by not letting them reach the end of the pipe if this can reasonably be avoided."

An alternative definition by Sikdar (1999) is "Pollution prevention is a term that represents realisation of pollution reduction resulting from purposeful improvement in the designs of products and processes, rather than definite elimination of pollution."

Cleaner production aims to increase industrial production efficiency and at the same time reducing waste, wastewater and air emission generation (Oblina, 1999). This provides both environmental and economic benefits. Significant processing and economic benefits can accrue as a result of overall enhancement of process performance and a conservation of process resources. This enhancement translates into higher productivity, enhanced yield, de-bottlenecking of the process, higher recovery of valuable chemicals such as products, intermediates, unreacted raw materials, and reduced usage of material utilities for example water, solvents (El-Halwagi, 1999).

To achieve these benefits there are several key knowledge requirements (Higgins, 1995):

- ♦ a detailed knowledge of the industrial operation
- ♦ a working knowledge of applicable pollution prevention and other environmental regulations
- ♦ an understanding of potential pollution prevention alternatives
- ♦ an ability to make technical and economic appraisals of pollution prevention alternatives.

One of the key difficulties in the metalcasting industry is that the industry is made up of small businesses. Of the 3100 metalcasting establishments in the United States, 79% employ fewer than 100 people, only 4% having greater than 250 (CMC, 1998). The industry also has a very diversified product and process mix. Also, true yields in the foundry industry are estimated to be in the range of 50-60% and scrap levels average 7% for the industry (Clegg, 1998), this leads to relatively large amount of waste compared to shipped product. All these factors mean that the knowledge requirements listed above are unlikely to be readily available in this industry.

Due to the lack of pollution prevention expertise in the industry a prototype expert system was developed at the University of Alabama (Moynihan, 1998) to put expert knowledge into a software package so that it is easily available. The system was developed to provide a wide distribution of specialised expertise in a consistent manner. From the available information, the expert system relies on data from known metalcasting processes, also the system is primarily designed to address air pollution. The difficulty with this approach comes from the fact that the industry is highly diversified. An expert system can be used, however it cannot cover all industry sectors where there are different regulatory and production constraints on facilities. The other

difficulty with an expert system is that it needs to be continuously updated to keep up with continually emerging standards and technologies. A more flexible approach is desirable so that the optimum solution is determined at individual facilities.

Significant portions of the available technology were originally developed for pollution control, rather than prevention. This has been the case primarily due to the unavailability of appropriate methodologies, protocols, and reliable assessment tools to promote pollution prevention technologies. According to Eskamani (1999) in Pollution Prevention Assessment Tools for Manufacturers, this problem has only been recently addressed by the development of specific assessment tools that are either industry-sector or pollution-medium specific. However there are no published metalcasting specific methodologies.

The tools and methods that will be studied in this chapter are:

- ♦ Pollution prevention strategies
- ♦ Evaluation criteria for methodologies
- ♦ Existing methodologies
- ♦ Preliminary assessment
- ♦ Process flowsheets
- ♦ Mass and energy balances
- ♦ Manufacturing process understanding
- ♦ Process integration, synthesis and design
- ♦ Pinch methods
- ♦ Exergy
- ♦ Energy and Resource Methodology
- ♦ Life-cycle analysis
- ♦ Total cost assessment
- ♦ Potential Failure Mode and Effects Analysis (FMEA)
- ♦ Decision Analysis/Identification of Constraints
- ♦ Modelling Methods/Approaches

3.2 Pollution Prevention Strategies

The hierarchy for waste reduction strategies within a process is:

1. Source reduction
2. Recycle/reuse
3. End-of-pipe treatment
4. Disposal (post process activities to handle the waste)

Some of the strategies that can be used to achieve source reduction are:

- ♦ Process efficiency improvements: reduce the amount of materials and energy used to perform required tasks. "Process optimisation always results not only in waste reduction but simultaneously in product quality improvement." (Leidel, 1996).
- ♦ Material input substitution or modification: replaces or reduces hazardous chemicals with less toxic alternatives. Material substitution is the exchange of one material for another, either a raw material, an ancillary material or indeed a product. The four prime movers for material substitution are: performance, cost, availability of resources and avoidance of pollution (Stewart, 1999).
- ♦ Process reformulation: can eliminate unnecessary manufacturing steps.
- ♦ Product redesign: modifies the product so that the process or materials used can be less wasteful.
- ♦ Operation and maintenance improvements: this approach is one of the most overlooked of all waste reduction areas because many wasteful operation practices have gone on so long that they have become standard operating procedures (Harceag, 1999).
- ♦ Inventory management and control: prevents product expiration and damage resulting in waste reduction.
- ♦ Recycling in-process substances: process wastes may be of sufficient quality to use as raw materials.
- ♦ Housekeeping: can reduce the potential for spills and release of chemicals.
- ♦ Training: promotion of awareness can help change operating standards.

It can be seen that the methods described above benefit not only the environment but save money and reduce wastefulness in the manufacturing process itself. Many of these approaches listed above are similar to total quality management (TQM) approaches. Total quality is based on the premise that to improve quality you need to change the processes that produce defects. Pollution may be considered to be a defect. Changing a process with a commitment to quality can prevent the 'defect' of pollution, avoiding 'rework' (control) after it is created (Ontario, 1993). As an example some of the benefits of Total Quality Management are: improved product quality, improved production flow, reduced operating costs, reduced operating losses, reduced liability exposure. Although many metalcasters may not be knowledgeable in pollution prevention methods many more will be familiar with the concept of total quality management.

Some of these methods for pollution prevention and process improvement have become subjects in their own right with extensive literature on carrying out such improvements. Material substitution is one of these fields. Systematic procedures have been developed for defining problems of pollution prevention by material substitution. The procedure

involves problem identification, material classification and search criteria specification (Gani, 1999).

3.3 Evaluation Criteria for Methodologies

From the preceding chapters it can be seen that the metalcasting industry has environmental issues in energy use, material consumption, water, waste and air. The methodology must use a multimedia approach, which deals with all air, water, and solid waste emissions and releases (Ontario Ministry, 1993). Therefore the methodology must consider all waste streams, identify their sources and quantify the true costs of pollution control, treatment, and waste disposal.

The metalcasting industry is very diverse both in terms of the processes used and the products supplied. For this reason the method must be suitable for both high production facilities and jobbing shops with a large product mix. The method must also be suitable for different casting methods.

The method must be flexible so that it can be used both by foundry person and environmental specialists. The small size of most facilities means that environmental work will be carried out either by a foundry person who is not an expert in environmental issues, or, by a contract environmental specialist who is not an expert in foundry processes or perhaps some combination of the two. However, pollution prevention relies on process knowledge and the ability to evaluate the environmental effects. The method must allow the foundry person and the environmental specialist to communicate effectively.

The data required by the methodology must be obtainable within the total resources available to the casting facility. The total resources will include already available data and data that needs to be collected by the foundry and its contracted consultants within available financial resources and acceptable time period.

There should be little duplication of effort so that the method can be carried out with minimal resources.

3.4 Existing Methodologies

There are many general methodologies to conduct a pollution prevention assessment. The techniques have many common elements.

In the Pollution Prevention Handbook, Higgins (1995) describes an approach for conducting a pollution prevention assessment. Higgins (1995) has chosen to make the approach generic to apply to as broad a spectrum of industries as possible. His approach is:

- 1) Data collection and audit preparation.
 - a) selection of team
 - b) review site information on processing operations and waste generation
 - c) gather data

- 2) Audit of waste.
 - a) conduct site investigation
 - b) construct process flow diagram
 - c) define process inputs and outputs
 - d) construct a material balance
- 3) Identification and ranking of pollution prevention alternatives.
- 4) Feasibility analysis
 - a) technical
 - b) economic
 - c) environmental
- 5) Assessment Report

This method is not very focused. The detailed analysis is conducted on the entire production process. This is a large task for complex manufacturing operations. A more focussed approach is needed so that only the priority areas are examined in detail. For efficiency detailed data collection should be conducted after a preliminary assessment.

The following list by Schramm (1997) conducts waste audits in four major steps:

1. Conduct a site investigation
2. Construct process flow diagrams
3. Define process inputs and outputs
4. Construct material balance

Again this method is not specific enough about how to do each step. There is also no evaluation of the results from the mass balance.

The Ontario Ministry of Environment (1993) has an overview of pollution prevention planning that is based upon the U.S. EPA method (1988) and the Ontario Waste Management Corporation method (1989). The full method is shown in Figure 63. This method is much more focussed than the previous methods. The method ranks the findings of the preliminary investigation and detailed assessments are carried out in that priority. The authors have assumed that the process is fully understood by either the people doing the audit or the people in the facility being investigated. The method includes a detailed investigation of the wastes being generated but not necessarily an in-depth study of the process itself. The evaluation step has not been specified.

Rossiter in "Apply process integration to waste minimisation" (1993) lists seven heuristic rules for pollution prevention. However, some of the rules are very specific to the process industries while some of the rules are too generic such as "eliminate waste materials at their source wherever possible."

Cohen (1992) and Allen have described a very general series of steps to identify and prioritise chemical wastes to be minimised. The steps are:

- ♦ establish emission rates,
- ♦ estimate the partitioning and fate of the emissions in the ambient environment,
- ♦ calculate human exposure to the emissions, and
- ♦ estimate a measure of risk associated with the exposures.

Although there are methods that have been specifically developed for waste minimisation in the process industries (Petek, 1996 and Schramm, 1997), there are no methods that have been developed specifically for the metalcasting industry.

3.5 Preliminary Assessment

The preliminary assessment should cover all material and energy use, and environmental discharges. However, the preliminary assessment only identifies areas for focus. Although some pollution prevention methods do have a preliminary assessment they tend not to list the steps required to do one. The Ontario (1993) Pollution Prevention Planning Guide has some questions to be answered at the site under investigation however some of the questions are too open-ended.

Integrated Environmental Management (O'Callaghan, 1996) uses four sets of 39 sequential steps, one each for Integrated Environmental Management, energy management, water management and waste management. The 39 steps give a comprehensive set of steps to follow to look for savings opportunities, materials and energy reduction. Methods for looking deeper into processes to make changes are not discussed. Each set of 39 steps considers each type of environmental release separately, although options are checked for conflicts. An overall view of a particular polluting substance or process has not been taken. However the method does highlight areas that are non-compliant with regulations, large waste generators, and energy users. For this reason this set of steps form a very comprehensive preliminary assessment.

Pistikopoulos (1994) et. al. have developed a methodology to evaluate the environmental impact of processes both in terms of raw material use, extraction and waste discharges. The main steps of the methodology are:

1. Definition of Process System Boundary
2. Environmental Impact Assessment
3. Incorporation of Environmental Impact Criteria in Process Synthesis and Design Optimisation.

They promulgate a global environmental impact vector (GEI)

$$GEI = \sum_{w=1}^W EI_w = [CTAM \cdot CTWM \cdot SMD \cdot GWI \cdot POI \cdot SODI]^T$$

where

EI is the environmental impact of each process.

$CTAM$ is the measure for air pollution, defined here as critical air mass. $CTAM$ is found by dividing the of mass of air emissions (kg pollutant/hr) by a regulatory limit value (kg pollutant/kg air) for a specific pollutant.

$CTWM$ is the measure for water pollution, defined here as the critical water mass. $CTWM$ is found by dividing the mass of water emissions (kg pollutant/hr) by a regulatory limit value (kg pollutant/kg air) for a specific pollutant.

SMD is the solid mass disposal in kg/h.

GWI is the global warming impact. *GWI* is found by multiplying the mass of pollutant emitted to the air (kg/h) by the global warming potential of each pollutant as compared to CO₂ (kg CO₂/kg pollutant).

POI is the photochemical oxidation impact. *POI* is calculated by ethylene discharged per hour.

SODI is the stratospheric ozone depletion impact. *SODI* is calculated by kg of CFC released per hour.

According to the authors (Pistikopoulos, 1994) the attractive features of this methodology are:

- ♦ the vector of waste emissions typically comprising a large number of wastes can effectively be transformed into an aggregated vector of low dimensionality
- ♦ the information provided is directly linked to impact on the environment rather than mass flowrates of waste effluents
- ♦ wastes associated with input to a process can be accounted for on a common basis.

In order to complete the Global Environmental Impact of a facility a high level of knowledge is required regarding emissions of specific pollutants, this can be very time-consuming and costly to determine.

The most important step of this method is the definition of the system boundaries. If the boundaries are set to include the entire life cycle of all materials and energy then a reasonable measure of pollution may be obtained. If the system boundaries are set at the facility itself the method does not evaluate the cost of purchasing materials and energy. The use of electricity could yield a lower environmental impact than the use of oil or gas depending on the system boundaries, because air emissions are not generated by the facility under investigation.

Another difficulty of this method is the limit value for each pollutant. Depending on the regulatory jurisdiction, pollutants that are regulated in one area may not be regulated in another region. If a material is purchased from the United States to be used in at a facility in Canada, whose limits are used to determine the environmental impact. In terms of metalcasting, this would require facilities not only to be familiar with their own regulatory standards, but the standards of other jurisdictions. For small companies with limited resources and environmental knowledge this is a large undertaking that does necessarily improve their own environmental situation.

The authors use process synthesis and design optimisation to minimise cost and/or pollution and meet the process goals. Although process optimisation is discussed later in this chapter, operating parameters for metalcasting are not as clearly defined as in the process industries. Without the optimisation this method does not give specific action items to work on to reduce material, energy costs and pollution prevention. However, it will display which media are of primary environmental concern. From this the contributing waste streams could be more closely examined. For metalcasting this method would be better suited for evaluating the environmental impact of alternate processes once the detailed assessment is completed.

The preliminary assessment is a very important step in a methodology. It must comprehensively evaluate regulatory compliance, material and energy use, and waste products and produce a definite list of action items. For metalcasting the Integrated Environmental Management steps (O'Callaghan, 1996) provide a clear list of items to be examined in more detail and can be easily understood by both environmental specialists and foundrymen alike.

3.6 Process Flowsheets

A process can be defined as one or more actions on inputs designed to produce an output with one or more specific characteristics. A process flowsheet is a graphical representation of process inputs and outputs, for this reason process flowsheets are a very useful engineering tool to facilitate the understanding of a process. A process flowsheet is a tool that allows the engineer to follow the production scheme, conduct the basic material and energy balances and simulate process performance (El-Halwagi, 1997). Process flowsheets illustrate how the raw materials are prepared, then converted through reaction into desired products, by-products, and wastes. Process flowsheets are necessary tools for several of the methodologies discussed in this chapter.

When examining the mass and energy inputs and output of a process the process can be displayed as in Figure 55.

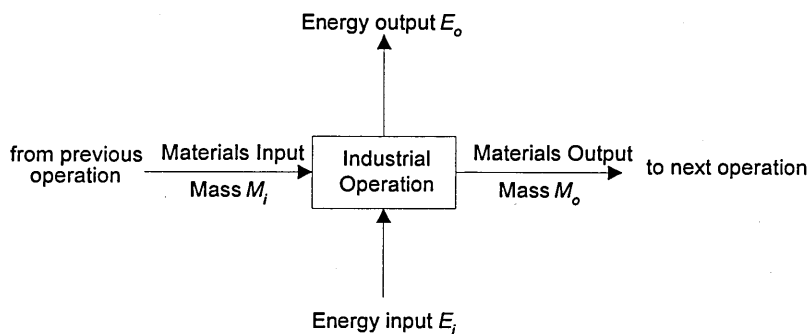
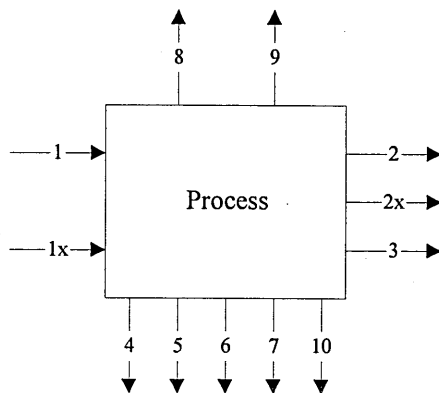


Figure 55 Graphical representation of an industrial process (Boustead, 1979).

According to Boustead (1979) all industrial processes, no matter how complex, can be subdivided into a sequence of operations linked by a flow of materials.

There are many different systems for drawing process flow diagrams, one of which is displayed below.



Where :

1	Raw input	5	To landfill
1x	Internal input	6	To ash pond
2	Product off-site	7	Hazardous waste off-site
2x	Internal product	8	Atmospheric point source emission
3	Recycled off-site	9	Atmospheric fugitive emission
4	Effluent to river	10	Nonhazardous waste off-site

Figure 56 A system for drawing process flowsheets (Freeman, 1997).

This system is fairly complex, in a manufacturing process with many steps and multiple inputs and rejects, this system may become difficult to read. One of the difficulties encountered when creating a flowsheet is to determine how many tasks and how much detail should be included.

A different type of flowsheet was presented by Friedler et al.(1994). The authors introduce a process graph (P-graph) to represent process structures in process synthesis. In a P-graph, an operating unit is represented by a horizontal bar, and a material by a circle. If a material is an input to an operating unit, the vertex representing this material is linked by an arc to the vertex representing the operating unit. If a material is an output from an operating unit, the vertex representing this operating unit is linked by an arc to the vertex representing the material. This type of flowsheet was developed to minimise the complexity involved in applying branch-and-bound algorithms by reducing the number of sub-problems generated and by reducing the sizes of the sub-problems. The authors then extended this method to help generate the optimal solutions for different classes of waste minimisation problems. This method requires a high level of knowledge about input and output products. It also relies on a knowledge of process synthesis techniques.

In order to improve a process it is important that the existing process is well understood and documented. The flowsheet(s) of the process should be an accurate reflection of how the process actually works. An accurate flowchart can be generated simply by spending time in the production facility and asking questions of operators and supervisors.

Flowcharts are excellent tools to be used in the metalcasting industry because many people are familiar with their use, and all the information required is available within the metalcasting facility.

3.7 Mass and Energy Balance

Material balances are the application of the conservation law for mass: "Matter is neither created nor destroyed." (except in nuclear processes). Raw materials are converted into products and waste while the energy systems drive the process. According to Rossiter (1995) both balances need to be considered in any review of waste minimisation. However if energy use is not significant in the process under review there is no need to complete an energy balance. In order to facilitate the completion of the balances a process flowchart is required.

The mass balance equation is:

$$M_i = M_o$$

Where:

M_i = raw materials input

M_o = output materials

The units to be used in these equations depend on the basis selected.

Similarly the energy balance is $E_i = E_o$

Where:

E_i = raw materials input

E_o = output materials

The units to be used in these equations depend on the basis selected.

The general procedure for conducting a material balance is:

1. Define system being analysed
2. Define system boundaries.
3. Select basis for calculations: total mass, mass of chemical compounds, mass of atomic species; total moles, moles of a chemical compound, moles of an atomic species.
4. List all known data, calculate compositions and flows from data as necessary.
5. Whenever possible seek out one component that can be used to relate or "tie" the inlet process streams to the outlet process stream. If there is a component that is localised in one stream and goes through the process unchanged, this component, which is called a tie substance, can be used to relate the total mass flows of the streams in which it appears.
6. List unknowns.
7. Write balances, count the number of independent balances that can be written. Check that unique solution is possible.
8. Solve the equations and check solution.

Although material and energy balances are very useful tools, they do have some limitations. One of the primary limitations is obtaining sufficient data to close the balance, a lack of historical data can lead to difficulties in characterising streams. Complex processes with numerous input and outputs can affect more than one environmental media resulting in a multimedia analysis. The exact composition of both incoming and outgoing streams can be unknown and can be difficult and/or costly to

analyse. Changes in plant operations can result in multiple material balance diagrams for different operating situations (Ontario, 1993).

There are also conflicting opinions on the need for closure of the balance. According to Higgins (1995) the goal in preparing a material balance is not to achieve complete closure but rather to highlight the principal sources of waste generation and to better understand the particular processes that contribute to them.

This is in contrast to Leidel (1996) who states that “We must establish a material balance and verify that the quantity of incoming materials is identical to the quantity of outgoing materials. As long as we can’t establish this balance we have confirmation that we really don’t know what happens in our foundry.”

According to Ontario Ministry of the Environment (1993) “the user should recognise that most balance diagrams will be incomplete, approximate or both.”. A potential reason for non-closure could be error associated with data. At some points in the production process it may be difficult or expensive to collect samples, data collected may be inaccurate or some form of emission may have been missed. Air emissions are particularly difficult to quantify. According to Martin et al. (1992) emissions reductions could be accomplished by: monitoring all emissions to ascertain the quantities and sources and comparing these against those for other sites or standards. Air emissions monitoring particularly can be very costly and time consuming. In order to evaluate whether the non-closure is related to lack of knowledge of the process or lack of data, the results should be checked to see if the data is ‘reasonable’. For example the data should be examined to verify that the data is in the correct order of magnitude and the result is physically possible.

Despite the limitations of material and energy balances they are a useful tool to organise data, identify gaps in both knowledge and data, and estimate missing information. When combined with the generation of a process flowchart, the user should have a clear picture of the material and energy inputs, outputs and interactions of the process being studied.

Mass and energy balances are very useful tools for the metalcasting industry because of their flexibility and ease of use. Mass balances can be used for analysing either a discrete process or an entire facility and can be used by anyone.

3.8 Manufacturing Process Understanding

In order to properly manage and control the wastes produced from industries, it is necessary to know the specific processes and waste characteristics (Soo, 1996). Both a qualitative and a quantitative understanding of the sources of pollutant is required (Castels, 1994). The close examination of the process makes it possible to identify the processes consuming resource and generating waste. Exact examination and evaluation of the industrial processes are required to manage and control the wastes produced from the processes effectively (Soo, 1996).

According to Schramm (1997) wastes generated from a process can be categorised into two groups according to their origins, whether brought from raw materials or produced during the operation.

The components of the former can be known from those raw materials used, while those of the latter can be estimated from the reactions occurred. Therefore, most of the characteristics of wastes can be estimated from adequate understanding of the process.

When examining production processes and materials of concern the following information is required:

- ♦ The cause pollution needs to be identified, including the release mechanism.
- ♦ The required function of the material or process.
- ♦ Process conditions needed to produce the product.
- ♦ Determine the effect of the presence of the undesirable compound to the environment.
- ♦ Determine whether the undesirable compound needs to be eliminated completely or reduced.
- ♦ Determine through literature what the best available practices are.

When making a process change difficulties can arise because a manufacturing process is a complex network of operations. Individual processes can be considered but the effect of any change on the entire system must be taken into account.

One technique that can help the understanding of different production measures on waste generation and emissions is the use of production-adjusted measurements (Malkin, 1997). Developing and Using Production-Adjusted Measurements of Pollution Prevention describes research that examined production related measures for the use of materials and the generation of waste products. The research developed a methodology for applying statistical and graphical tools to assess the accuracy of the factors (unit-of-product) used to adjust pollution prevention measures. Graphical analysis was used to qualitatively assess a unit-of-product, while regression analysis is used to quantitatively evaluate a unit-of-product. This method tests the correlation of key waste or chemical use streams with units-of-product. Comparison of chemical and waste use to production levels is essential to evaluate the effectiveness of process and environmental changes.

The authors stress the importance of accurate and meaningful measurement systems and their importance for the long-term success of pollution prevention in industrial settings. Varying production levels can affect waste or chemical usage. A method of evaluating chemical, waste use and comparing them to production levels is essential to evaluate the effectiveness of process and environmental changes. The paper defined the factor unit-of-product that is used to adjust gross quantities of waste or chemical usage.

The authors tested this methodology on five manufacturing facilities, the facilities were: metal finishing, paper recycling, semiconductor fabrication, electronics production and pharmaceutical production.

The five steps of unit-of-product analysis are:

Step 1: Process Description

- ♦ The purpose of this step is to map out the process under investigation
- ♦ Drawing the process flow diagram, tracing chemical inputs, outputs, and conversions.

Step 2: Identify and Collect Time Consistent Data

- ♦ It is necessary to have time consistent chemical and production data. For example daily production data must be compared to daily chemical usage.
- ♦ The authors recommend having at least 30 time periods. Depending on the length of time period this may not always be possible. The process must be consistent (no process changes) over the time period being considered.
- ♦ Waste data can be estimated from material balance calculations rather than measured directly.

Step 3: Graphical Analysis

Plots of production and chemical data allow one to see:

- ♦ Distribution of the data and trends in the data.
- ♦ Extreme data points or outliers
- ♦ Data entry errors.

Step 4 Regression Analysis

- ♦ Give a quantitative measure of whether its unit(s)-of-product are well correlated

Step 5 Repetition

- ♦ Periodical repetition of the analysis to check that the chemical and production data are still correlated.

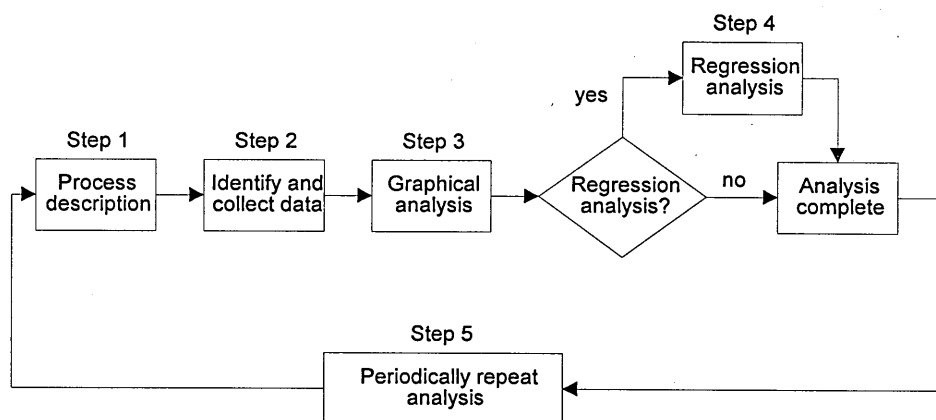


Figure 57 Flowchart of unit-of-product analysis (Malkin, 1997).

One difficulty with this method can be finding a unit-of-product that is well correlated to chemical use or waste generation. The waste or material usage per unit-of-product should be constant whatever the level of production. Ease of data collection and availability of existing measures can affect the unit-of-product selected. It should be noted that a complete lack of correlation between product levels and material used or waste generated can indicate that there are very wasteful practices being carried out.

The other main difficulty is to obtain enough data points. The authors suggest a minimum of 30 points without major process changes. Depending on the time span being used 30 time periods may not be available. Waste generation of individual process components may not be available, the authors note that in some production processes it may be possible to substitute chemical use data as a surrogate for chemical waste.

This method has excellent potential for the metalcasting industry as long as a meaningful unit-of-product is found for each material or waste being analysed.

3.9 Process Integration, Synthesis and Design

Process integration is a holistic approach to process design, retrofitting, and operation which emphasises the unity of the process (El-Halwagi, 1997). In changing the paradigm from end of pipe waste treatment to process synthesis-based pollution prevention, process developers/designers can in fact create more efficient processes, which generate smaller amounts of more benign wastes (Linninger, 1994).

There are three key components in any comprehensive process integration methodology: synthesis, analysis and optimisation.

Process synthesis is concerned with the activities in which the various process elements are integrated and the flowsheet of the system is generated so as to meet certain objectives. The synthesis and analysis activities are iteratively continued until the process objectives are realised.

Process analysis involves the decomposition of the whole into its constituent elements for individual study of performance. Each raw material needs to be studied to determine how it affects the amount of waste produced. The specification for each raw material entering the plant should be closely examined (Nelson, 1995). Once a process is synthesised, its detailed characteristics are predicted using analysis techniques. The techniques include mathematical models, empirical correlations, and computer-aided process simulation tools. In addition, process analysis may involve predicting and validating performance using experiments at the laboratory and pilot-plant scales, and even actual runs on existing facilities.

Process optimisation involves the selection of the “best” solution from among the set of candidate solutions. Once the objectives have been met optimisation must be performed. Optimisation helps select the ‘best’ solution from among the set of candidate solutions. The degree of applicability of a solution is quantified using an objective function which is to be minimised or maximised e.g. cost, waste etc. The search process is undertaken subject to the system model and restrictions which are termed constraints. The constraints are in the form of equality and inequality expressions. Equality constraints include material and energy balances, process modelling equations, and thermodynamic requirements. Inequality constraints can be environmental, technical or thermodynamic.

Two key branches of process integration are (El-Halwagi, 1997):

- ♦ Energy integration is a systematic methodology that provides a fundamental understanding of energy utilisation within the process and employs this

understanding in identifying performance targets and optimising heat recovery and energy-utility systems.

- ♦ Mass integration is a systematic methodology that provides a fundamental understanding of the global flow of mass within the process and employs this holistic understanding in identifying performance targets and optimising the generation and routing of species throughout the process (El-Halwagi, 1999).

Process integration techniques are inherently conservation-orientated because they enhance process efficiency by minimising the use and/or maximising the recovery of energy and materials. Rossiter (1995) states that any pollutant that reaches the end of the pipe represents a loss of raw materials. Process integration methodologies are classified under three main headings: pinch analysis; knowledge-based approaches; numerical optimisation approaches (Rossiter, 1995).

Pinch analysis is a systematic technique for analysing heat and/or mass flows through industrial processes. Pinch analysis is discussed in more detail later in this chapter.

Knowledge-based approaches can be used to describe all process synthesis and process integration methods that build upon an accumulated knowledge base of proven ideas. This includes methods in which specific pollution prevention ideas are transferred directly from one application to others: hierarchical design and review procedures, in which the logical sequence of flowsheet evolution provides a framework for identifying and evaluating waste minimisation options. In order for the metalcasting industry to use knowledge based approaches, specific ones would have to be developed for the industry.

Procedures for process synthesis and process integration can range from simple lists of heuristics (rules of thumb), through databases and hierarchical design procedures, to artificial intelligence programs. All these approaches build upon an accumulated knowledge base of proven ideas to develop good processes or process improvements with the minimum engineering effort.

There are a variety of numerical optimisation approaches, ranging from simulation using simplified mathematical models of the process to sophisticated mathematical programming methods. These are often combined with cost equations to quantify the impact of design decisions on process economics. Simple mathematical models have been used to develop cost versus emissions limit curves. More sophisticated techniques (linear and non-linear programming) have been used in many different applications including minimisation of waste, water and wastewater (Rossiter, 1995).

The result of process synthesis is a flowsheet that represents the configuration of various pieces of equipment and their interconnection.

The process integration approach links all the individual operations into an overall synthesis. If any unit operation is to be changed its effect on all other operations in the process has to be considered. Most of the literature dealing with process integration is concerned with the initial design of the process when modelling is particularly

appropriate, if this modelling can take into account possible future changes in unit operations then it has a long term viability for that industry,

The use of this approach has more limited applicability in an operating manufacturing unit. The integration approach can determine what needs to be changed for optimum performance but restraints within the manufacturing unit to continue profitable production will probably limit the options available. The complete redesign of a process can be very costly and cannot always be carried out on a working manufacturing facility. It would be applicable to a new metalcasting plant but it is not immediately applicable to most operating plant except for long term planning.

3.10 Pinch Methods

Pinch analysis is a technique, based on fundamental thermodynamics, for analysing heat and mass flows through industrial processes. The mass and energy flows in a process are closely linked, energy drives the processes that convert raw materials into products and wastes. According to Linnhoff (1995) both balances need to be considered in any review of waste minimisation. Pinch analysis is most commonly used for new process design, retrofit and expansion (Linnhoff, 1994).

The basic methodology for assessing minimal energy/mass needs consists of (Linnhoff, 1982):

- ♦ Construct heat and mass balance;
- ♦ Set targets for minimum practical energy/mass needs;
- ♦ Examine process changes that contribute to meeting the target;
- ♦ Obtain minimum energy, mass design that achieves process targets;
- ♦ Optimise by trading off energy/mass costs against capital costs.

The energy/mass targets are obtained using composite curves, an example of a composite curve is shown in Figure 58. For energy applications composite curves consist of temperature-enthalpy profiles of heat availability in the process (composite hot stream) and the heat demands of the process (composite cold stream). The minimum energy targets for the process are obtained by overlapping the hot and cold composite curves as shown in the diagram. The curves are separated by the minimum temperature difference $\Delta T_{\min}$ (pinch). The overlap shows the maximum process heat recovery possible and indicates the minimum hot utility requirement Q_{in} and the minimum cold utility requirement Q_{out} of the process for a chosen $\Delta T_{\min}$. Once the pinch has been identified the process can be considered to be two separate systems. The system above the pinch requires heat input, the system below the pinch rejects heat.

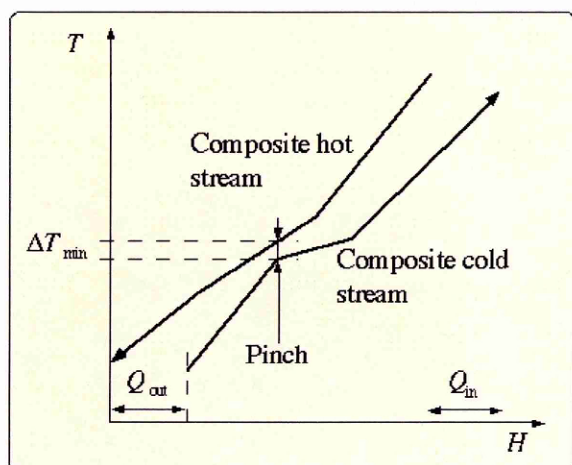


Figure 58 Composite curves and the pinch in a T-H diagram (Wall, 1996).

To achieve the minimum energy/mass targets for a process heat must not be transferred across the pinch, there must be no external cooling above the pinch and no external heating below the pinch. Violating these rules increases the energy/mass requirements (Linnhoff, 1998). For mass systems such as wastewater and freshwater flows, or pollutant emissions and recovery, contaminant concentration-mass curves are generated in a similar manner to the energy composite curves. To maximise the water reuse potential, the highest acceptable inlet concentration is needed. Specifying the maximum acceptable outlet concentration minimises the water flow rate. The plots produced are limiting water profiles; any water supply line below the curve satisfies the maximum acceptable outlet concentration (Linnhoff, 1995).

Further developments in pinch analysis are (Linnhoff, 1994):

1. Pressure Drop Optimisation, generally used for heat exchanger pressure drop, so that Heat Exchanger Networks optimised both thermally and for pressure drop.
2. Multiple-Base-Case Design, designs around a variety of operating conditions.
3. Distillation Column Profiles.
4. Low-Temperature Process Design, refrigerated systems.
5. Batch Process Integration.
6. Water Pinch, optimise water usage, particularly with respect to concentration of contaminants.
7. Total Site Integration.
8. Emissions Targeting, balances process emissions compared to fuel related emissions.

Although this technique has wide applicability to the process industries there are some difficulties in applying it to metalcasting. Pinch analysis frequently deals with a total site, where a combined heat and power system is present. Beyond metal melting and building heating metalcasting processes do not use heat systems. Therefore there is not a heat exchange network to optimise. There may be limited application for water pinch in the use of melting furnaces. Many metalcasting processes are reliant on certain properties of materials, for example sand grain shape, not just the chemical composition. Although the chemical constituent of a material may be unchanged through a process the physical form may no longer be usable. Pinch technology,

although frequently used in many industries to reduce emissions and optimise material use is limited in its applicability to the metalcasting industry, it can be used for specific applications but does not have broad applicability.

3.11 Exergy

Exergy analysis has been used for a number of years for calculation of useful energy wasted. The use of exergy principles enhance the understanding of thermal/chemical processes and allows sources of inefficiency to be quantified (Moran, 1994). Exergy is a property which measures the maximum capacity of a substance to cause change, a capacity which exists because the substance is not in equilibrium with the environment. Exergy is the work potential of a system or a particular form of energy in relation to the state of environment (Reddy, 1994 and Szargut, 1988). Alternately exergy or availability can be defined as potential for use, which, unlike energy and mass, exergy is not conserved (Moran, 1988). The state of the environment plays an important role in exergy analysis. Three types of exergy transfer are important in exergy analysis of a system i) exergy of work ii) exergy of heat and iii) exergy of a stream of matter.

The chief aim of exergy analysis is to detect and to evaluate quantitatively the causes of the thermodynamic imperfection of the process under consideration. Exergy analysis can indicate the possibilities of thermodynamic improvement of the process under consideration, however, an economic analysis is required to assess the viability of the possible improvement (Szargut, 1988).

The exergy of a stream of substance can be divided into four components: kinetic exergy B_k , potential exergy B_p , physical exergy B_{ph} , and chemical exergy B_{ch} (Szargut, 1988).

$$B = B_k + B_p + B_{ph} + B_{ch}$$

Exergy is measured in kJ, specific exergy (b) is measure in kJ/kg.

Where:

- ♦ Kinetic exergy is equal to the kinetic energy, when the velocity is considered relative to the surface of the earth.
- ♦ Potential exergy is equal to the potential energy, when it is evaluated with respect to the average level of the surface of the earth in the locality of the process under consideration.
- ♦ Physical exergy is the work obtainable by taking the substance through reversible physical processes from its initial state temperature T , pressure p , to the state determined by the temperature T_o and the pressure p_o of the environment.
- ♦ Chemical exergy is defined as the maximum additional useful work that could be produced by the interaction of the system with the reference environment after it has been brought to the thermo-mechanical dead (T_o, p_o) state (McGovern, 1990).

If the state parameters of the environment are constant then the exergy equation can be reduced to (Dunbar, 1992):

Exergy (B) = Physical (B_{ph}) + Chemical Exergy (B_{ch})

where

$$B_{ch} = U_o + p_o V_o - T_o S_o - \sum n_i \mu_i^e$$

and

$$B_{ph} = (U - U_o) + p_o (V - V_o) - T_o (S - S_o) + KE + PE$$

U = internal energy

V = volume

S = entropy

T = temperature

p = pressure

n_i = number of moles of substance i

KE = kinetic energy

PE = potential energy

μ_i = chemical potential of substance i

subscript

o = restricted dead state

The exergy equations :

1. pinpoint quantitatively the resource expenditures associated with irreversible conversions
2. give insight for discovering prospective means for achieving better utilisation of the resources and feedstocks.

The majority of processes are characterised by the production of waste products which are discharged to the environment. The state parameters and the composition of the waste products differ from those of the environment and, therefore, the waste products have a positive exergy, which is dissipated in the environment. Therefore the exergy of the waste products of the process represent its external exergy losses (Szargut, 1988).

In Exergy Analysis of Industrial Processes, van Gool (1992) states that although the usefulness of the exergy concept for the analysis of industrial processes is illustrated in literature in detail, the use of exergy analysis meets much resistance in industrial engineering departments. He states that the relations for highly irreversible processes can be obtained without lengthy and complex theories. However, his method is depended on the use of steady state processes. Complicated processes are aggregated into a limited number of irreversible unit operations connected by thermodynamically defined flows. Flows are described as originating from or going to reservoirs. These factors make it very difficult to analyse metalcasting type operations due to its batch nature. Depending on the time span taken metalcasting plants could be considered as flow systems.

The analysis of exergy losses are still complex particularly with respect to mixtures and blends. However, with further development and considerably more data this could be a viable methodology in the future.

There are many limitations to exergy analysis, some of which must be resolved before it can easily be used in the foundry industry. Some of the limitations of exergy analysis are:

- ♦ Data on chemical substances suitable for exergy analysis is not always readily available (McGovern, 1992). Most foundry processes involve chemical mixes, which makes the analysis complex. If chemical companies producing foundry chemicals provided the exergy values of their chemical mixes and blends, the use of exergy analysis would become viable. As more data bases of chemical exergy evolve the use of this method in the foundry industry will become possible.
- ♦ Improved methods are required for estimating the exergy of complex substances and mixtures (McGovern, 1992).
- ♦ Standard methods of specifying the state of the parameters of the common components of the environment.

3.12 Energy and Resource Methodology

The energy and resource methodology by Lee (1996) allows for the potential reuse value of resources to be determined as they pass through each stage of a technological process. In this methodology outputs from the system under investigation are regarded as potential input resources for the original system or other linked processes. The methodology does not assess whether the process is set up to use the minimum resources or whether the actual resources could be substituted for less harmful ingredients. It will assess the potential for reuse outputs. The energy and resources methodology combines features from life-cycle assessment, exergy analysis, and pinch analysis.

The methodology defines four new terms, these are:

- ♦ Standard Energy and Resource Minimisation (SERM) graphs which indicate where output resources which cross the system boundary are of high enough quality to have potential to be reused within the system.
- ♦ Operational Energy and Resource Minimisation (OERM) graphs analyse each operational step in a process and evaluates its efficiency in terms of the fuel and materials consumed and produced. This identifies which operational steps have the largest opportunities for improvement.
- ♦ Cumulative Energy and Resource Index (CERI) is a single value that incorporates all the flows crossing the system boundaries either to or from the environment. This index indicates the relative quality of the flows and hence indicates reuse potential.
- ♦ Optimum Resource Utilisation Profile (ORUP) is the solution which minimises the consumption of environmental resources and efficiently utilises the system resources.

The methodology consists of four stages:

1. Determination of system boundaries.
2. System inventory analysis to quantify all the inputs to, outputs from, and flows through the system.
3. Calculation of energy content of flows, exergy content of flows and exergetic potential.

4. Construction of Operational Energy and Resource Minimisation graph, Standard Energy and Resource Minimisation graph and the determination of the Cumulative Energy and Resource Index.

There are several limitations for the use of this methodology in metalcasting.

- ♦ The completion of the system inventory analysis relies on a detailed knowledge of the reactions occurring within the system boundary. This information is not always readily available.
- ♦ The lack of data regarding the exergy of proprietary and complex chemical blends.
- ♦ In the sand casting industry particularly the reuse potential of sand is not only dependent on the chemical composition of the sand but other measures such as grain size distribution, shape and the presence of impurities.
- ♦ The methodology relies on a flow system. Most metalcasting processes can be approximated to be flow systems, however, the resources consumed for each casting does not only depend on the casting size but the shape and configuration.

3.13 Life-Cycle Assessment

Life Cycle Assessment or Analysis (LCA) is a tool to evaluate the environmental effects of a product, process, or activity throughout its lifetime, from raw material acquisition to disposal. This includes identifying and quantifying energy and materials used and wastes released to the environment, assessing their environmental impact, and evaluating opportunities for assessment (Office of Enforcement, 1995).

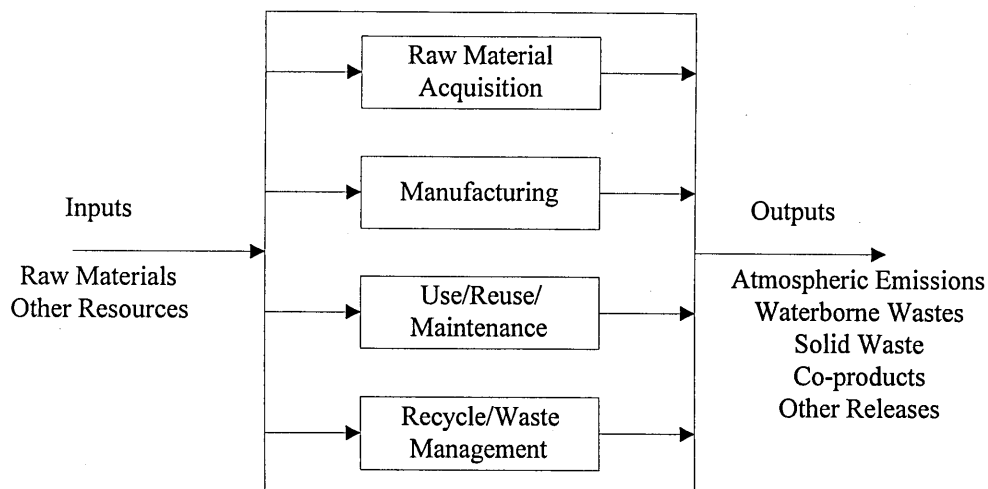


Figure 59 Life Cycle Stages (Office of Enforcement, 1995)

LCA studies are comparative and are used to aid in decision making, because they provide information on the environmental consequences associated with pollution prevention projects and competing alternatives (Boguski, 1996). LCA is of particular importance when analysing new products, materials or processes, because if they are wrongly assessed (or not assessed at all) the changes being made could lead to greater environmental impact than originally perceived (Lee, 1995). Cleaner production focuses

on reducing environmental impacts throughout the entire life-cycle of the product (Baas, 1995), thus making the cleaner production and LCA approach to environmental improvement highly compatible.

The life-cycle assessment is composed of four stages: goal definition and scoping, life cycle inventory, impact assessment, and improvement analysis.

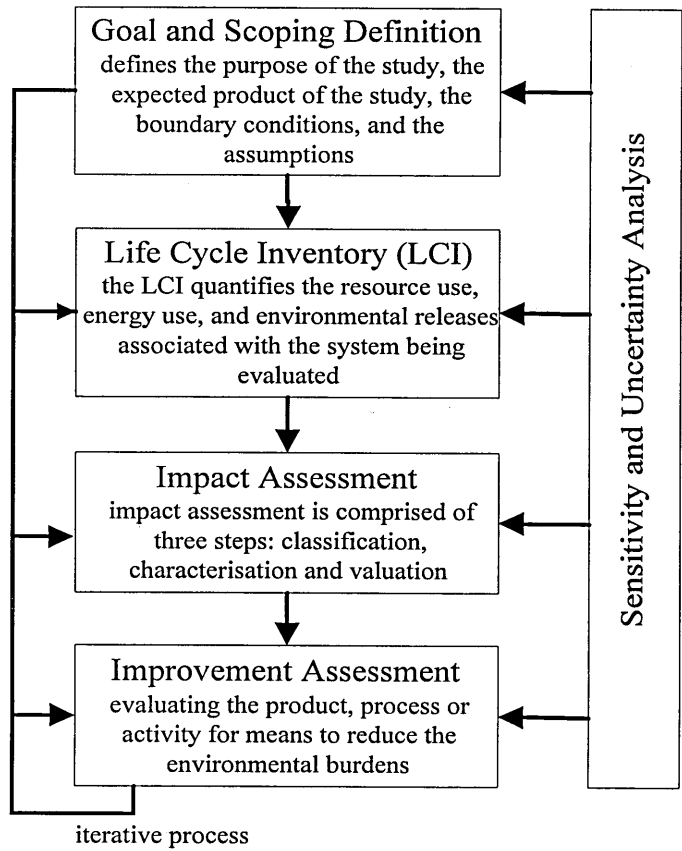


Figure 60 Technical Framework for LCA (Rhodes, 1997).

Goal and Scoping Definition: The definition of the scope of the LCA sets the borders of the assessment. The purpose and scope of the study are important when one is considering the exclusion of specific operations from the system. In a comparative study, it may be logical to exclude operations that are common to the products being studied (Boguski, 1996).

Life Cycle Inventory: The LCI quantifies the resource use, energy use, and environmental releases associated with the system being evaluated. The inventory centres on the material and energy balance for each operation within the system and for the life-cycle of the system itself. There are five basic steps in an LCI study (Boguski, 1996):

1. Define the scope and boundaries
2. Gather data

3. Create a computer model
4. Analyse and report the study results
5. Interpret the results and draw conclusions

Impact Assessment: The impact assessment is the most complex stage in the assessment because the effect of natural resource use and chemical releases need to be quantified. The typical measures used are impact on human health, ecological quality, and natural resource depletion (Boguski, 1996).

Improvement Assessment: The improvement assessment is a systematic evaluation of the needs and opportunities to reduce environmental burdens associated with energy and raw material use and waste emissions throughout the life cycle of a product, process, or activity. This analysis may include both quantitative and qualitative measures of improvements (AIChE, 1999).

Conducting a full LCA is resource intensive and time-consuming. There are three levels of LCA, these are conceptual, simplified and detailed. The conceptual LCA is used to make an assessment of environmental aspects based on a limited and usually qualitative inventory. The results of a conceptual LCA can be presented using qualitative statements or simple scoring systems, indicating which components or materials have the largest environmental impact, and why. Limitations in the inventory can occur in the form of omission of one or more phases in the life-cycle. The simplified LCA aims to provide essentially the same results as a detailed LCA, but with a significant reduction in expenses and time used. The simplified LCA covers the whole life cycle but uses generic data and has a simplified assessment.

Another way to reduce the work involved in assessing a process or product change may be to conduct an energy and material analysis. An energy and material analysis is similar to the inventory phase in a LCA since it quantifies all materials and energy that enter or exit the system under study. Energy and material analysis focuses on one specific phase or production process, it does not explicitly evaluate environmental impact.

The US EPA (Office of Compliance, 1995) has realised that in many cases decision makers may not have the time or resources to examine each life cycle stage or to collect all pertinent data. To simplify the analysis the boundaries of the assessment can be set to material entering the facility and exit from the facility. Their simplified methodology consists of:

1. Identifying the process steps to be reviewed
2. Identifying the raw materials used
3. Indicate energy involved with operating the process activity
4. Indicate the quantity of water consumed in each of the process steps being evaluated
5. Indicate any other inputs
6. For each process step, indicate the products that result
7. Indicate the air releases associated with each process step
8. Indicate the wastewater discharges and liquid hazardous wastes associated with each process step.
9. Identify the solid waste generated from each step

Although a full LCA considers the whole material and energy supply chains. The analysis can be limited to optimisation within the boundaries of a manufacturing process, in this case the broader material and energy supply chain is not of concern (Clift, 1999). However, where process changes are contemplated which entail a change in material inputs - feedstock or reagents - or in energy consumption, then LCA needs to be used to elucidate the full environmental implications of the changes, and to avoid the risk of apparently preventing pollution, but actually transferring it to some other point in the material or energy supply chain.

Due to the time and resources required for detailed LCA, it would not be feasible for the metalcasting industry unless the information is generated by industry associations or chemical suppliers. The most useful analysis would probably be an energy and material analysis, conceptual or a simplified LCA. The most useful system boundaries for the industry would likely be: materials entering the facility, through processing, to final disposal of by-products and wastes. The impact analysis step would probably have to be qualitative only, due to the lack of consistent methods for impact analysis and the lack of data available.

3.14 Total Cost Assessment

A key feature of cleaner production is the fact that cost assessment is an integral part of the approach. Detailed cost assessments (that take into account costs of raw materials and energy, and other production costs, as well as waste, wastewater and/or air emission management costs) and identification of potential savings are the basis of a concept for industrial production improvement (Oblina, 1995).

Total Cost Assessment (TCA) has been defined as a long term comprehensive financial analysis of the full range of costs and savings of an investment that are or would be experienced directly by the organisation making or contemplating the investment (Office of Compliance, 1995).

The American Institute of Chemical Engineers (1999) defines TCA as the identification, compilation, and use of environmental and human health costs information associated with a business decision. Their methodology is designed to provide insight into all environmental and health costs associated with the development of new products, processes, and manufacturing sites.

TCA is a highly relevant methodology to evaluate the feasibility of pollution prevention options.

The American Institute of Chemical Engineers methodology consists of six steps:

1. Goal Definition and Scoping: identifies and defines the project and purposes of the assessment.
2. Streamline the Analysis: refines above steps by connecting the objectives to sustainability metric and impact categories.
3. Identify Potential Risks: Evaluates the relative importance of the impact categories and the feasibility of expressing costs for each category of an alternative or project.

4. Conduct Financial Inventory: defines costs as follows:
 - Type 1: Direct costs for the manufacturing site.
 - Type 2: Potentially hidden corporate and manufacturing site overhead costs.
 - Type 3: Future and contingent liability costs.
 - Type 4: Internal intangible costs such as consumer acceptance, worker morale etc.
 - Type 5: External costs such as costs borne by society, including deterioration of the environment through pollutant dispersions.
5. Conduct Impact Assessment: Review costs to determine the largest contributors for each category and to assess how that information may be best incorporated into the overall decision process.
6. Document Results: Document the assumptions and the results for each scenario and costs decision.

From the above steps it can be seen that there are many parallels to Life-Cycle Assessment. TCA evaluates environmental projects in terms of costs rather than pollutants, however to some extent cost reflects environmental impact.

Kennedy (1997) lists three levels of detail that can be applied to a TCA, these are: shortcut, balanced and advanced.

The shortcut TCA minimises the amount of data gathering and calculation required. The shortcut TCA is used for annual budgeting, businesses with simple manufacturing operations, generating first cut numbers for discussion.

The balanced approach uses more cost categories than shortcut approach and is a compromise between speed and accuracy. This method is probably the most appropriate for most metalcasting operations, since cost may not be the only factor in decision making. The balance approach does not include as many costs metrics as the detailed assessment.

The detailed assessment is a rigorous analysis of a project. Though it is much more resource intensive. A more detailed analysis can show more subtle benefits or negatives to a project. A more detailed analysis does however give better reliability of the numbers.

Table 21 Cost Categories for the Three Approaches to TCA (Kennedy, 1997)

Approach	Shortcut	Balanced	Advanced
Capital Costs	Equipment purchase	all the previous plus	all the previous plus
		Disposal of old system	Working capital
		Initial permits	Delivery and freight charge
		Building modifications	Training
Operating Costs	Chemicals Materials Waste Disposal	Process modifications	Start-up chemicals
		Research & design	Salvage value
		all the previous plus	all the previous plus
		Ancillary chemicals	Waste storage
		Storage	Recycling revenues
		Waste testing	Semiannual planning
		Waste-treatment chemicals	5 year permit renewals
		Safety training	Self-audit
		Personal protective equipment	Outside certifications
		Insurance	Quality control reject costs
		Chemical taxes and fees	Impacts on other processes
		Annual permits	
		Paperwork time	
		Production costs	
		Maintenance labour	
		Maintenance materials	
		Water/sewer use	
		Electricity	
		Gas/oil/steam	

Total costs assessment when combined with an energy and material analysis or life cycle assessment can be a powerful decision making tool. Life-cycle assessment can provide ecological information and total cost assessment can provide economic information.

3.15 Potential Failure Mode and Effects Analysis (FMEA)

FMEA is a form of risk analysis. A FMEA will help identify potential process (or environmental) failure modes so that corrective actions can be initiated to eliminate them or reduce their potential for occurrence (Chrysler, 1995).

The steps for conducting an FMEA are (Chrysler, 1995 and Blanchard, 1990):

1. Development of process flowsheet.
2. Identify each significant system component that is likely to fail.
3. Description of the failure modes.
4. Identify potential causes of failure.
5. Determine the possible effects of failure.
6. Assess the probability of occurrence.
7. Assess the criticality of failure.

8. Possible corrective action or preventive measures.

Many foundries will be familiar with this activity as it is required under the automotive quality standard QS-9000 for automotive suppliers. A FMEA should be performed before the final design of a process or piece of equipment so that a process failure mode is not unknowingly designed into the process.

3.16 Decision Making

Decision analysis is concerned with making decisions with uncertain outcomes and difficult trade-offs. It provides a formal methodology for systematic examination of a complex and opaque decision situation, formulation of alternative courses of action, treatment of information and uncertainty, preferences, and evaluation of supposedly the 'best' alternative or course of action (Huang, 1995). There are three features to any decision: the decision to be made, the chance and unknown events which can affect the results, and the result itself. Decision analysis constructs models using logical or mathematical representations of the relationships between these three features. The models allow the decision maker to estimate the possible implications of each course of action. Most decision analysis problems consist of one or more of the following features: uncertainty, multiple objectives, multiple options or sequentiality (Spradlin, 1997). Figure 61 shows the steps involved in the decision making process.

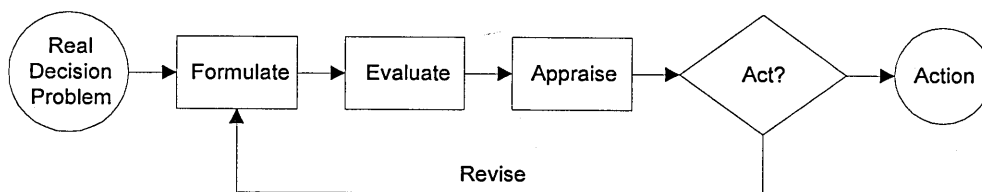


Figure 61 Schematic of the decision analysis process (Huang, 1995).

In Decision Analysis in Energy and Environmental Modelling (Huang, 1995) different decision making techniques are identified and references are made to case studies where the techniques are used in energy and environmental studies.

Classification of decision making techniques (Huang, 1995):

- ♦ Decision making under uncertainty is a class of techniques for decision making where the outcomes are uncertain and evaluation of trade-offs are difficult. Some of the techniques used to make decisions under uncertainty are: decision tree, influence diagram, multiple attribute utility theory.

- ♦ Multiple criteria decision making refers to decision making in the presence of multiple objectives. Multiple criteria problems are classified into two sub classes: multiple objective decision making and multiple attribute decision making.
- ♦ Decision support systems are any interactive, flexible and adaptable computer based system, specifically developed for supporting the solution of a particular management problem aimed at improved decision making. Decision support systems support the solution of complex problems that would otherwise be difficult to handle.

The energy and environmental applications discussed in the paper are large projects such as site selection of power plants, energy planning and policy analysis, environmental control and management. These projects are long time frame and capital intensive with a great deal of uncertainty. Metalcasting facilities generally do not have the resources to generate complex models.

A simpler and visual approach to making decisions is mind-mapping. Mind mapping (Buzan, 1993) is a technique used for stimulating creative thinking. Mindmaps provide a visual map of all the factors and their links on one page. Mindmaps enable the whole knowledge 'picture' to be kept in view at all times, thus giving you a more balanced and comprehensive understanding of the subject in its entirety. Buzan (1993) states that "In general decision-making the Mind Map helps to balance competing factors."

Decision analysis can require complex models and mathematics to evaluate uncertainty and risk. These methods are normally beyond the resources of metalcasters. Simple, visual approaches to decision making more easily applicable and can still lead to some valuable insights.

3.17 Modelling and Simulation Methods/Approaches

A model is a simplified description of a system to assist calculations or predictions. A model may be used as a representation of a system to be brought into being, or to analyse a system already in being (Blanchard, 1990). Experimental investigation utilising a model yields a design or operational decisions in less time and at less cost than direct manipulation of the system itself. This is particularly true when it is not possible to manipulate reality because the system is not in existence, or when manipulation is costly or disruptive as with complex industrial systems (Blanchard, 1990). Models can be physical, analogue, schematic or mathematical. Several of the methods described in this chapter are in effect creating a model of the system under investigation.

In the manufacturing industries simulation is used to determine production schedules, inventory levels, and maintenance procedures; to do capacity planning, resource requirements planning, and process planning; and more (Chase, 1995). Simulation is particularly appropriate to situations in which the size or complexity of the problem makes the use of optimising techniques difficult or impossible (Chase, 1995). The difficulty associated with simulation is that a simulation model must be built for each problem situation. There are many simulation packages available.

The case study site (Haley Industries Ltd.) purchased a simulation software package, however there were many difficulties encountered resulting in the investment being abandoned. Some of the difficulties encountered were: considerable computer programming was required, required data was not available, long term detailed data collection on individual processes was required to create meaningful simulations.

Process simulation tools, although useful, need considerable amounts of data to be meaningful. Frequently highly detailed process analysis is not available. Mathematical models that can predict plant performance are seldom going to be available to the foundryman.

3.18 Evaluation of Reviewed Techniques

The techniques evaluated have been grouped into accepted or rejected methods. The main reason for acceptance or rejection has also been described below. A more detailed explanation of the pros and cons of each method is shown in Table 22.

3.18.1 Accepted

- ♦ Preliminary assessment: comprehensive analysis of all environmental issues.
- ♦ Process flowsheet: excellent visual tool to facilitate understanding of the process under investigation.
- ♦ Mass and energy balance: facilitates quantitative understanding of the process under investigation.
- ♦ Manufacturing process understanding: facilitates understanding of the process under investigation and can help in search for best practices.
- ♦ Life-cycle assessment: good comparison of environmental releases of different options.
- ♦ Total costs assessment: good financial comparison of different options.
- ♦ Failure mode and effects analysis: assesses potential failures of a system.

3.18.2 Rejected

- ♦ Process integration: method is beyond the resources of most metalcasting facilities.
- ♦ Pinch methods: this method relies on a flow system and only evaluates recycling potential of process energy and materials.
- ♦ Exergy: poor availability of data.
- ♦ Energy and resources methodology: examines reuse potential only of materials.
- ♦ Modelling: method is beyond the resources of most metalcasting facilities.
- ♦ Decision analysis: for detailed risk evaluation there is a lack of data and resources to adequately assess the consequences of making a decision.

Based on the summary table the methods selected for use are:

- ♦ preliminary assessment;
- ♦ process flowsheet;
- ♦ mass and energy balance;
- ♦ manufacturing process understanding;
- ♦ life-cycle assessment;
- ♦ total cost assessment;
- ♦ failure mode and effects analysis.

Table 22 Summary of pros and cons of evaluated methods.

Method Name	Purpose	Pros	Cons	Pollution prevention strategy	Multimedia	Diverse processes	Variable level of complexity	Data availability	To be included in methodology
Preliminary assessment	To assess the materials, energy and environmental discharges at a facility and to identify and prioritise areas that need improvement.	GEI vector: ▪ Compares the environmental impact of all media in a non dimensional number. 39 steps: ▪ Comprehensive analysis covers all environmental issues.	GEI vector: ▪ Does not examine energy use. ▪ Does not take into account cost factors. 39 steps: ▪ Large focus on energy, particularly heating and ventilation.	Can be used to achieve any pollution prevention strategy.	✓	✓	✓	✓ x	✓
Process flowsheet	A graphical representation of process inputs and outputs to facilitate the understanding of a process.	▪ Can be used on any process. ▪ Simple to use. ▪ Can be used for both general and in-depth analysis.	▪ Must be used in conjunction with other methods to quantify inputs and outputs.	Can be used to achieve any pollution prevention strategy.	✓	✓	✓	✓	✓
Mass and energy balance	To generate a quantitative model of mass and energy inputs and outputs to and from the process under investigation.	▪ Can be used on any process. ▪ Covers all environmental releases.	▪ Not always possible to achieve closure.	Can be used to achieve any pollution prevention strategy.	✓	✓	✓	✓ x	✓
Manufacturing process understanding	To gain an understanding of the factors and constraints involved with the process under investigation.	▪ Process needs to be understood to assess wastefulness. ▪ Essential to understand process before making changes.	▪ No cons for metalcasting.	Can be used to achieve any pollution prevention strategy.	✓	✓	✓	✓	✓
Process integration	To design, retrofit or operate a process so that the process meets certain objectives.	▪ Process integration approach very useful.	▪ Process analysis techniques generally not within foundry resources.	Can be used to achieve any pollution prevention strategy.	✓	✓ x	x	✓ x	x
Pinch methods	To analyse the heat and mass flows through an industrial process.	▪ Useful for some furnace applications.	▪ Limited applicability.	Recycling in-process substances.	x	x	x	✓	x
Exergy	To enhance the understanding of thermal and chemical processes and identify sources of inefficiency.	▪ Comprehensive analysis covers all environmental media. ▪ Excellent potential once databases established.	▪ Lack of data for foundry chemicals. ▪ Does not take into account qualitative measures. ▪ Difficult to assess reactions and products.	Can be used to achieve any pollution prevention strategy.	✓	✓	✓	x	x
Energy and Resources Methodology	To examine the reuse potential of wastes generated from a process.	▪ No pros for metalcasting.	▪ Lack of exergy values for foundry mixtures ▪ Does not account for qualitative material factors. ▪ Lack of data on chemical reactions in metalcasting processes. ▪ Does not examine source reduction.	Recycling in-process substances.	x	✓	x	x	x

Method Name	Purpose	Pros	Cons	Pollution prevention strategy	Multimedia	Diverse processes	Variable level of complexity	Data availability	To be included in methodology
Life-cycle assessment	To evaluate the environmental effects of a product, process or activity throughout its lifetime.	<ul style="list-style-type: none"> Flexible with respect to degree of complexity. Aid in evaluation of alternate solutions. 	<ul style="list-style-type: none"> Availability of data over entire life cycle. Difficulty with assessing environmental impacts. 	Can be used to achieve any pollution prevention strategy.	✓	✓	✓	✓ x	✓
Total cost assessment	To evaluate the environmental costs of a product, process or activity throughout its lifetime.	<ul style="list-style-type: none"> Flexible with respect to degree of complexity. Aid in evaluation of alternate solutions. 	<ul style="list-style-type: none"> Availability of cost data over entire life cycle. Difficulty in enumerating all future costs. 	Can be used to achieve any pollution prevention strategy.	✓	✓	✓	✓ x	✓
Failure mode and effects analysis	To assess the potential failure modes of a process, and the consequences of those failures.	<ul style="list-style-type: none"> Familiar to many foundries. Useful too for examining release mechanisms. 	<ul style="list-style-type: none"> Designed for process not environmental analysis. 	Can be used to achieve any pollution prevention strategy.	✓	✓	✓	✓	✓
Decision analysis	To evaluate the risks, uncertainties and potential consequences involved with making a decision	<ul style="list-style-type: none"> Visual approaches such as mind maps and decision trees can be useful to display options. 	<ul style="list-style-type: none"> Some methods too complex for metalcasters. Risks and uncertainties can be difficult to quantify. 	Can be used to achieve any pollution prevention strategy.	n/a	✓	✓	✓ x	x
Modelling	To create a model of a system so that the behaviour of the system can be analysed under different situations.	<ul style="list-style-type: none"> Useful approach as part of other methods. 	<ul style="list-style-type: none"> Some methods beyond resources of most metalcasters. 	Can be used to achieve any pollution prevention strategy.	✓	✓	✓	x	✓ x

- ✓ applicable
 x not applicability
 ✓ x limited applicability

3.19 Development of the Methodology

Pollution prevention projects can be broken down into six technical elements:

1. Preliminary assessment.
2. Detailed assessment.
3. Generation of options.
4. Evaluation of options.
5. Implementation.
6. Maintenance.

The methodologies selected from the literature review can be classified as either assessment methods or evaluation methods. The methods are classified as follows:

3.19.1 Assessment of processes

- ♦ preliminary assessment
- ♦ process flowsheet
- ♦ mass and energy balance
- ♦ manufacturing process investigation

3.19.2 Evaluation of generated options

- ♦ life cycle assessment
- ♦ total cost assessment
- ♦ failure mode and effects analysis.

From these elements and selected methods the methodology for pollution prevention in metalcasting can be developed. The flowcharts in Figure 62 and Figure 63 show complete waste minimisation and pollution prevention methodologies incorporating all six elements. The basis of both these methodologies was the waste minimisation procedure developed by the United States Environmental Protection Agency (Ontario, 1993 and Petek, 1996). The Ontario Pollution Prevention Planning method is aimed at providing information regarding the development and implementation of a pollution prevention programme for industrial, commercial or institutional businesses (Ontario, 1993). The integral approach methodology for waste minimisation in the process industries was developed to obtain optimal waste minimisation options for those industries (Petek, 1996).

Both these methods have an additional element, this step is a management step. The first two steps in both the Ontario (1993) and the Petek (1996) method are related to setting company policy, organising the assessment team and overall goal setting for the programme. These elements are very important in order to start a programme. However, it has been assumed that management commitment to environmental compliance and improvement exists within the metalcasting organisation undertaking the assessment.

The methodology at this point is:

1. Preliminary assessment.
2. Detailed assessment.

- 2.1. Process flowsheet.
- 2.2. Mass and energy balance.
- 2.3. Manufacturing process understanding.
3. Generation of options.
4. Evaluation of options.
 - 4.1. Life cycle assessment.
 - 4.2. Total cost assessment.
 - 4.3. Failure mode and effects and effects analysis.
5. Implementation.
6. Maintenance.

There are several steps that need to be added to complete this methodology.

3.19.3 Preliminary assessment

The preliminary assessment step selected in the initial review was the 39 steps of Integrated Environmental Management (O'Callaghan, 1996). This method provides a comprehensive study of all environmental releases. For the purpose of this investigation the 39 steps of environmental management should be omitted as these pertain to the creation of an environmental management system.

The preliminary assessment will result in the identification of the areas that require detailed assessment and improvement. These activities must be prioritised and then objectives set.

3.19.4 Detailed assessment

At this point the detailed assessment contains three steps: process flowsheet, mass and energy balance and manufacturing process understanding. The order of these steps is very important. The process flowsheet must be completed to obtain an accurate picture of material and waste flows. The mass balance equations can then be derived from the process flowsheet. Understanding the manufacturing process is very important to ensure that any less visible outputs and reactions occurring within the system are understood. For this reason this step belongs after the process flowsheet is developed but before the mass and energy balance.

Data collection is frequently placed at the beginning of a methodology. This can result in large amounts of data being collected. It then becomes quite an onerous task to analyse all this data. In order to collect only the data required, a good understanding of the process is required. With detailed process knowledge the critical process measures should be identified and the relevant data collected.

The first detailed assessment step in which quantitative data is required is the mass and energy balance. For this reason data collection must be conducted before the mass and energy balances. In order to facilitate data collection and completion of both the flowsheet and mass balance steps, a step has been added to identify the critical process factors and key production measures.

3.19.5 Generation of options

The generation of different pollution prevention options is an activity that requires a multidisciplinary approach. The potential changes to be examined are:

- ♦ Process efficiency improvements.
- ♦ Material input substitution or modification.
- ♦ Process reformulation.
- ♦ Product redesign.
- ♦ Operation and maintenance improvements.
- ♦ Inventory management and control.
- ♦ Recycling in-process substances.
- ♦ Housekeeping.
- ♦ Training.

3.19.6 Evaluation of options

There are four elements of evaluating pollution prevention options, these are: technical evaluation, environmental evaluation, economic evaluation, and risk analysis. From the literature review the evaluation techniques selected were: life cycle assessment, total cost assessment, failure mode and effects analysis. The environmental evaluation step is life cycle assessment. The economic evaluation step is total cost assessment. The failure mode and effects analysis can be used in either the technical evaluation or the risk analysis. The evaluation steps are carried out in parallel, however should the options fail the environmental or technical assessment they must be modified or rejected. The completed evaluation step should yield either a single solution or a small number of solutions to be optimised before selecting the final solution. The optimisation step may produce a hybrid of several options.

The reporting and evaluation step is very important. The selected option needs to be justified so that the people responsible for allocating funding can follow the pros and cons of the different options and the reasons why the selected option was chosen.

3.19.7 Implementation

The implementation of a pollution prevention project contains the steps as shown in Figure 62. Through project experience two other elements must be added to the implementation. Generally, the detailed design does not occur until funding has been approved, so this step must be added.

During and after a project is installed, the new system must be optimised, for example: machine settings are tested and adjusted, process control points are set and optimised. This step is carried out by making sample runs of product and verifying the effect the changes have made.

3.19.8 Maintenance

After a new or modified process is installed it must be maintained and continuously improved. Process limits need to be set, and gradually as the process capability is learned the limits must be adjusted.

Once the adjusted process has reached steady state it should be evaluated to ensure that it met the original pollution prevention objectives. If the project meets the objectives then the next priority project is started, otherwise the project must be further optimised and implemented.

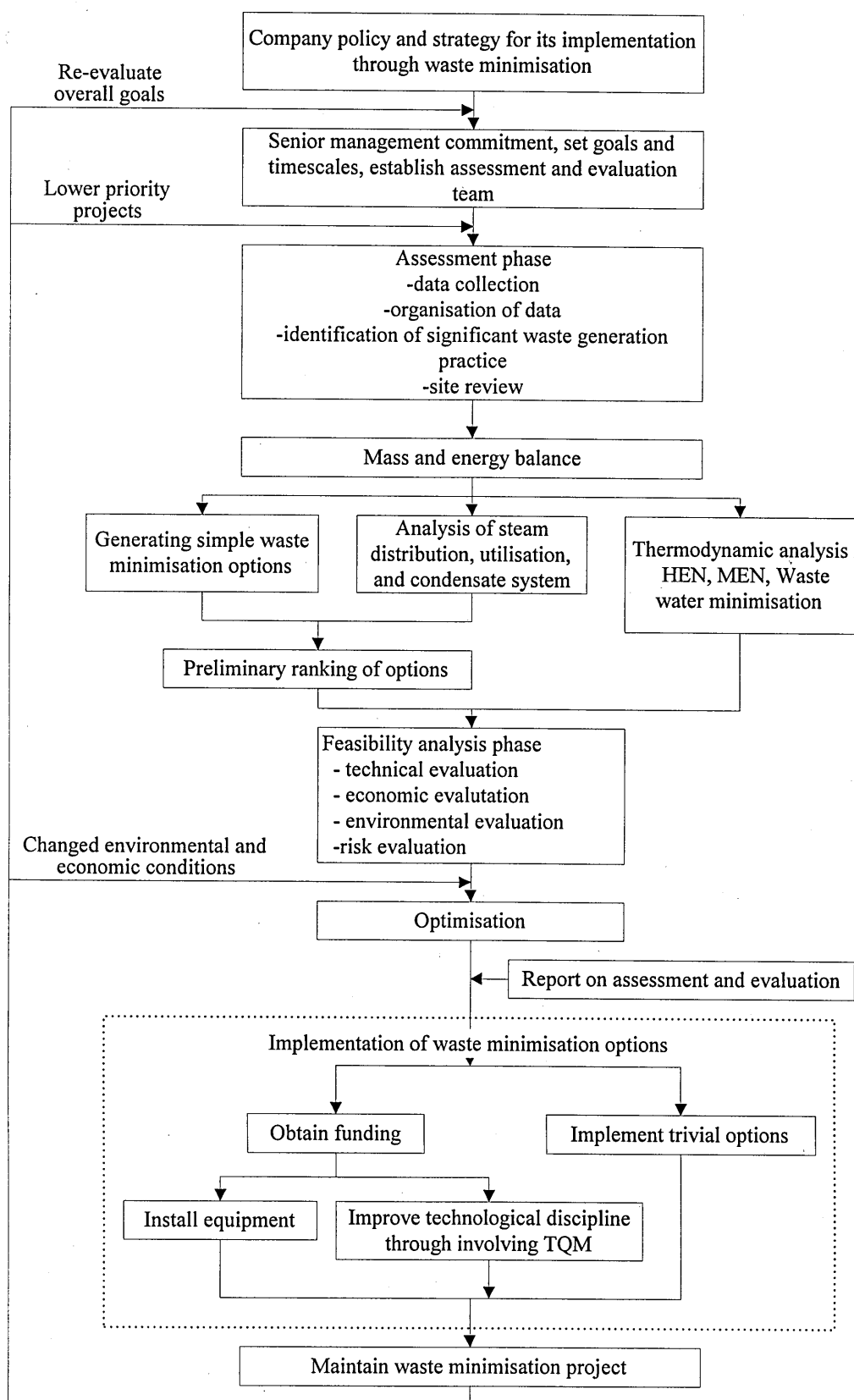


Figure 62 Methodology for waste minimisation in process industries (Petek, 1996).

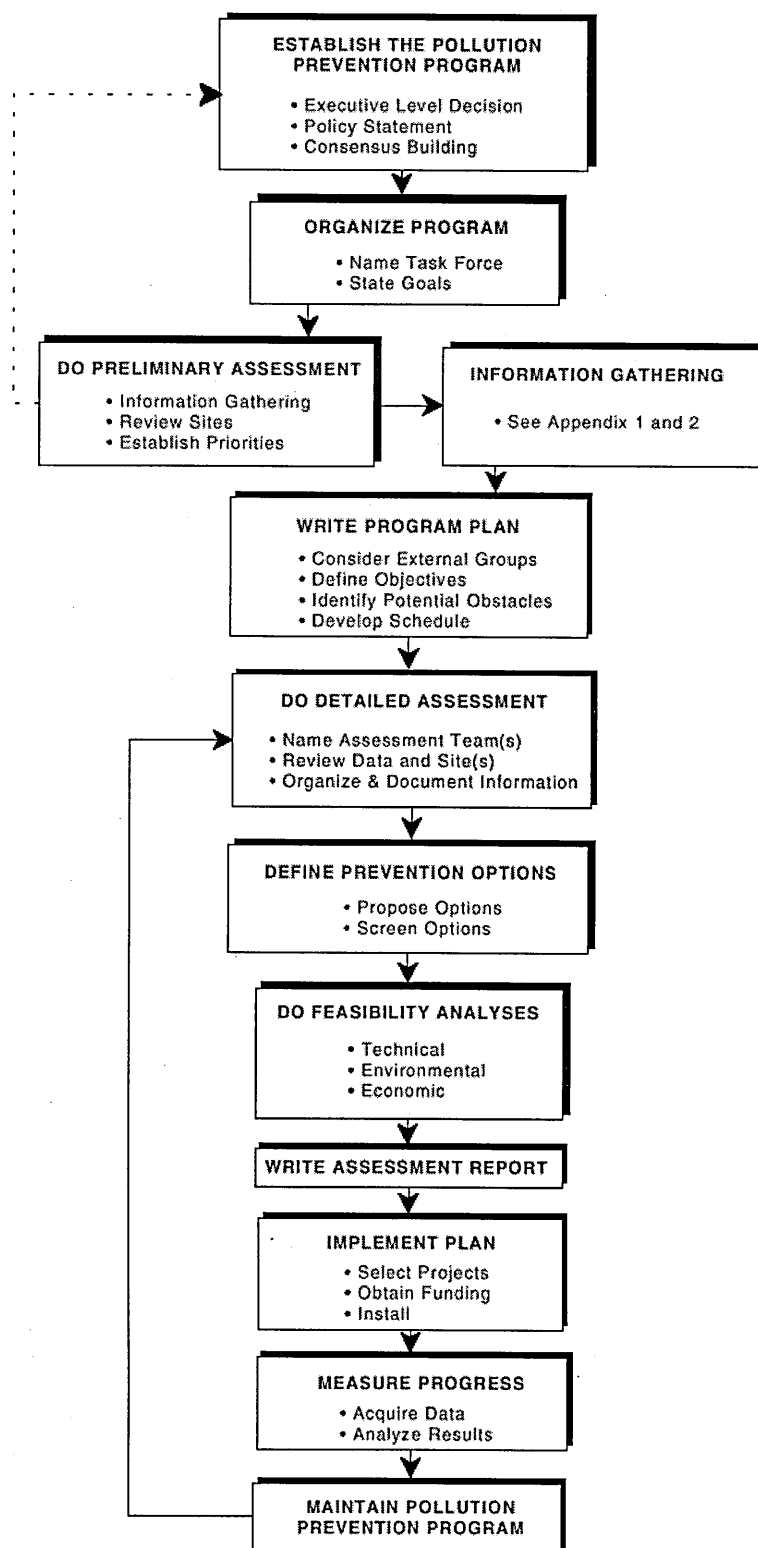


Figure 63 Pollution prevention planning overview (Ontario, 1993).

3.20 Pollution Prevention Methodology for the Metalcasting Industry.

The developed methodology is detailed below.

3.20.1 Preliminary assessment

The preliminary assessment should examine regulatory compliance and any other industry standards. The preliminary assessment should also contain a comprehensive assessment of energy and materials usage and waste generation. A method that can achieve this is the 39 steps for waste, water and energy usage. The preliminary assessment will help to establish priorities for the detailed assessments.

3.20.2 Define objectives

The objectives and scope of the investigation need to be clearly set. Without clearly stated objectives it will be difficult to assess the potential solutions. System boundaries are required for many of the methodologies that follow and therefore should be clearly stated.

3.20.3 Develop process flowsheet

A process flowsheet should detail the manufacturing steps, the inputs and outputs of each processing step. Depending on the complexity of the process the use of multiple flowsheets may make material transformations clearer.

3.20.4 Identify critical process factors and key production measures

Before data is collected, an understanding of the process under investigation should be gained. This investigation should include a review of the production methods, the controls in place and the process data collected. A review of process related literature should advance knowledge on the foundry process under review, and should detail best available techniques and technologies. Production measures related to the process under investigation should be evaluated to find out how production measures affect the use of materials and energy, and waste generation.

One of the difficulties for small and medium-sized companies is access to information databases, many of the specialised search engines are costly to access. There are some good resources for metalcasting information, that provide technical papers and guidelines for low cost. Some of the resources are the American Foundrymen Society Library, North American Die Casting Association, the Casting Development Centre (UK), the US Environmental Protection Agency and the US Department of Energy.

3.20.5 Identify data requirements, collect data

Through careful analysis of the process the time and data required for the investigation can be reduced. Through identification of the significant process factors, it may be discovered that the required data is not being collected, this can then be set up.

The data collection step may require taking samples for laboratory analysis, or installation of meters on equipment.

3.20.6 Completion of mass and energy balance

The completion of the mass and energy balance should illustrate the specific parts of the production processes generating wastes and emissions and should quantify these. If data is found to be missing it can either be estimated or collected at this point. If it is not possible to collect the data, estimates can be made, sensitivity analysis can be carried out to evaluate the effect of estimation error.

3.20.7 Identify alternate practices

Review waste generating process for source reduction potential through: process efficiency improvements, material input substitution or modification, process reformulation, product redesign, operation and maintenance improvements, inventory management and control, in-process recycling, employee training. Sources for finding alternate manufacturing practices are: industry literature and conference proceedings, supplier information, other manufacturing sectors.

3.20.8 Preliminary ranking of options

The preliminary ranking of options is designed to reduce the number of options undergoing a full feasibility study. Criteria for evaluating the options must be generated. These criteria selected will depend on the constraints on the facility. The same criteria can be used for both the preliminary ranking and detailed feasibility study, however in the former the evaluation will be purely qualitative. Some potential evaluation criteria are:

- ♦ Regulatory compliance and permitting.
- ♦ Waste quantity and toxicity.
- ♦ Waste management costs.
- ♦ Impact on worker health and safety
- ♦ Speed and ease of implementation.
- ♦ Demonstrated effectiveness in other facilities and industries
- ♦ Potential for negatively impacting product quality.
- ♦ Production compatibility and impact on facility layout.

Suggested improvements can be classified into the following categories to assist in their evaluation: inventory management and improved operations; equipment modifications; product process modifications; recycling and reuse (Ontario, 1993).

3.20.9 Feasibility analysis

The feasibility analysis is to assess remaining potential improvements in detail.

The analysis should consist of technical, environmental and a cost assessment. The detail of the analysis will depend upon the magnitude and risk of the changes being suggested. Fast payback, low risk changes may not require extensive examination whereas long payback or higher risk changes may need extensive examination before they can be implemented.

Where multiple simultaneous improvements are being considered to prevent pollution there are three different feasibility scenarios: the solutions can be mutually

incompatible, directly additive or partially additive, the potential emissions reduction methods must be considered together to determine feasibility (Rossiter, 1995).

Technical evaluation

The technical evaluation is needed to ensure that the pollution prevention solution fits with overall production requirements.

Some of the technical evaluation criteria include:

- ♦ Effect on product quality;
- ♦ Installation time and production downtime;
- ♦ Worker health and safety
- ♦ Facility space and layout;
- ♦ Compatibility with existing production procedures and rates;
- ♦ Labour, expertise and skill level required for operation and maintenance;
- ♦ Utility capacities;
- ♦ Reliability;
- ♦ Commercial availability;
- ♦ Proven performance in a similar application;
- ♦ Permitting requirements and schedule;
- ♦ Regulatory constraints.

When evaluating changes that have the potential to affect product quality test casting should be made. At the case study facility (Haley Industries Ltd.), typically a small casting run or test plate run is made to assess the quality of the castings.

In order to evaluate potential failure modes of the modified process a Potential Failure Mode and Effects Analysis can be carried out. The process should be checked for both product quality and environmental failure modes.

3.20.10 Environmental analysis

Environmental analysis involves the comparison of the different options in terms of their environmental impact. A life-cycle inventory or a material and energy analysis of both the original process and the proposed options should be compiled. For a facility with very few resources, this analysis can be qualitative. It is important that the proposed change does result in a net reduction in the environmental outputs. Generally this evaluation will inventory all materials, energy and wastes associated with the process. It should evaluate waste reduction, ensure that no other environmental problems will be created, verify permitting requirements and schedule, and any regulatory constraints.

3.20.11 Economic analysis

The final report should include ranked implementation options with cost benefit analysis. Total Cost Assessment provides a comprehensive financial cost benefit analysis for environmental projects. Where costs are not available a qualitative assessment can be done.

3.20.12 Optimisation

Based on the results of the technical, environmental and economic studies more optimal solution may be discovered or need to be found. The optimisation phase should be used to refine the options being studied.

3.20.13 Reporting and evaluation

The reporting step summarises the finding from the investigation and explains the ranking of pollution prevention options

3.20.14 Implementation

Implement trivial options

Some of the options may require only procedural or administrative changes. These options require no capital investment and should be implemented immediately. In most processes there will be small operational changes that can be made with a minimum of effort and money.

Obtain funding

Detailed design

Install projects

Optimise

Once the project has been installed, further refinement will be necessary.

3.20.15 Maintain process control

Ongoing process records should be kept to ensure that the project has achieved its goals and so that the process can be continually refined. Techniques such as monitoring, analysis, auditing and continuous improvement should be applied.

3.20.16 Compare results to initial objectives

It is important to ensure that the initial objectives were fulfilled. If the objectives have not been met then further generation of options and detailed assessment are required.

3.20.17 Continuous improvement of implemented processes

The improvement of the implemented processes never stops. Continual refinement of the process must continue. Pollution prevention is on-going. Once all the major issues identified by the methodology have been addressed another preliminary assessment should be conducted. Continual regulatory change, production process evolution, product changes mean that the priority environmental issues will change over time. From the process data being collected on a regular basis, continual tightening of the process is possible.

The improvement of the implemented processes never stops. Continual refinement of the process must continue.

3.20.18 Start on next process as identified in the preliminary assessment

With the completion of each detailed assessment and implementation of improvements to address an environmental issue the entire process begins again. A detailed assessment is carried out on the next highest priority environmental issue that was identified in the preliminary assessment.

3.21 Conclusions

This chapter has reviewed many commonly used pollution prevention techniques. Although there are pollution prevention methodologies in existence there are none specifically developed for the metalcasting industry.

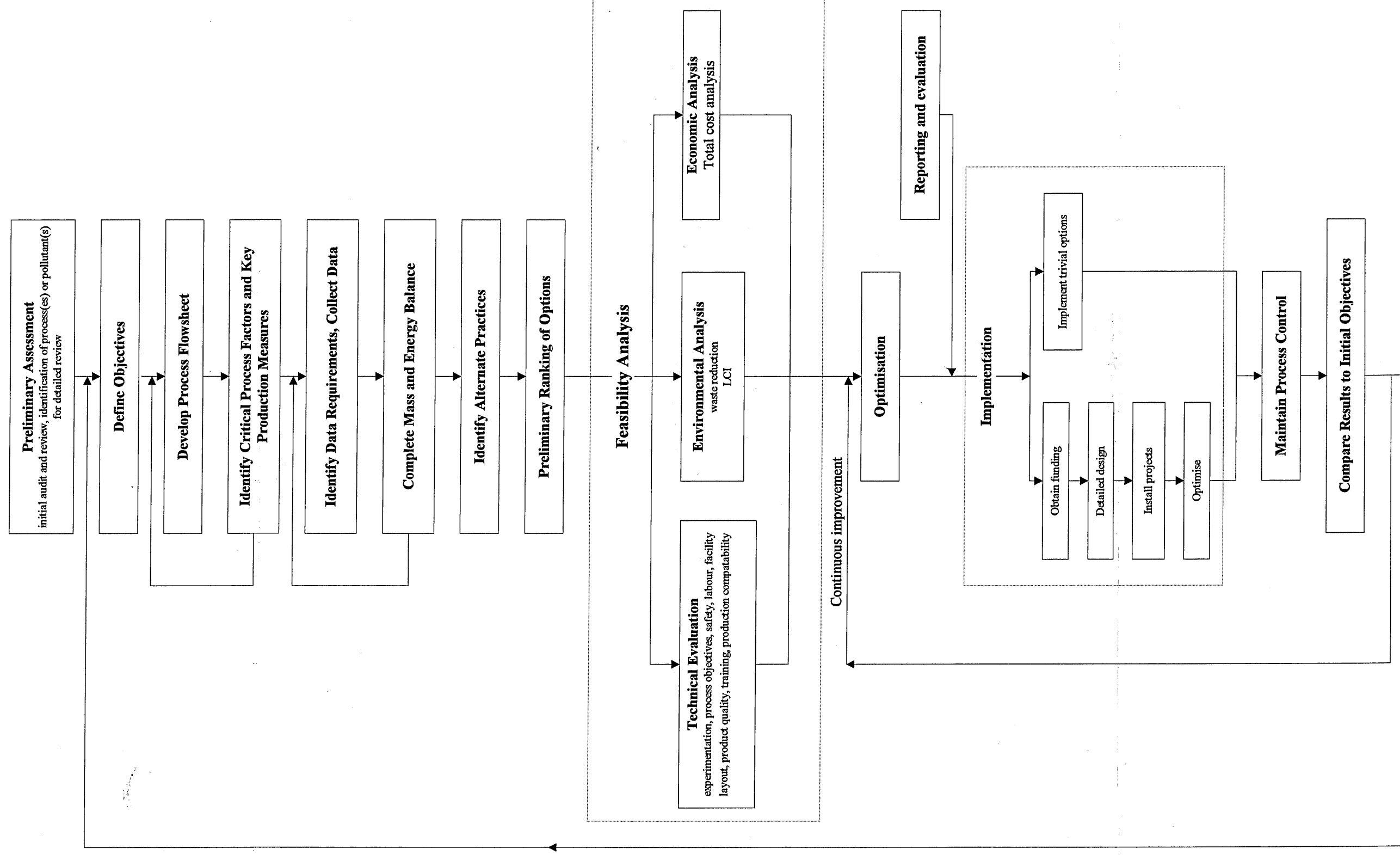
Some of the difficulties encountered by the metalcasting industry in complying with environmental regulations are: high process diversity, cost, and availability of personnel. Commonly used techniques were reviewed with these difficulties in mind. The methodology takes into account these issues by using well established methods, using process knowledge and collecting information efficiently.

Some of the differences between this methodology and methods developed for other process sectors are:

1. The development of the process flowsheet is specified.
2. The identification of significant process factors is not contained in other methodologies. It is often assumed that the critical process factors are well known and understood, however this is often not the case.
3. Data collection is frequently placed at the beginning of the detailed assessment. This can lead to inefficient data collection and a waste of time and money. This method requires significant background work on understanding the process and available measures so that the data collection step can be as efficient as possible.
4. The techniques for feasibility analysis have been specified. So that established and consistent methods of environmental and costs analysis are used.
5. The implementation step has been expanded from other methodologies.
6. Multiple feedback loops have been used to show the iterative nature of the detailed assessment.

This method has been developed for the metalcasting industry and results of the test on a case study site will be described in following chapter.

Pollution Prevention Methodology for the Metalcasting Industry



4 AUDIT OF A WORKING METALCASTING FACILITY

4.1 Introduction

The purpose of this chapter is to investigate the environmental issues at a working metalcasting facility. The site under detailed examination is Haley Industries Ltd (HIL). Haley Industries Ltd. is a manufacturer of light alloy castings primarily for the international aerospace industry. A site plan is shown in Figure 64.

4.2 Site Environmental Issues

- ♦ Air emissions are not well quantified, therefore it is not possible to assess compliance.
- ♦ Landfill management and monitoring: The landfill is a non-hazardous landfill, however, hazardous waste and recyclable materials are being disposed of on the site. The landfill is being used up too quickly, there are many opportunities to redirect much of this waste.
- ♦ Wastewater treatment not compliant with regulations.
- ♦ Heating and ventilation not well managed, frequent employee complaints in the winter.

Strengths

- ♦ Profitable company.
- ♦ Well established in its industry.

Weaknesses

- ♦ Reactive approach to environmental issues.
- ♦ Lack of education in environmental issues.
- ♦ Lack of monitoring and targeting.
- ♦ Lack of sufficient personnel devoted to improving environmental performance.

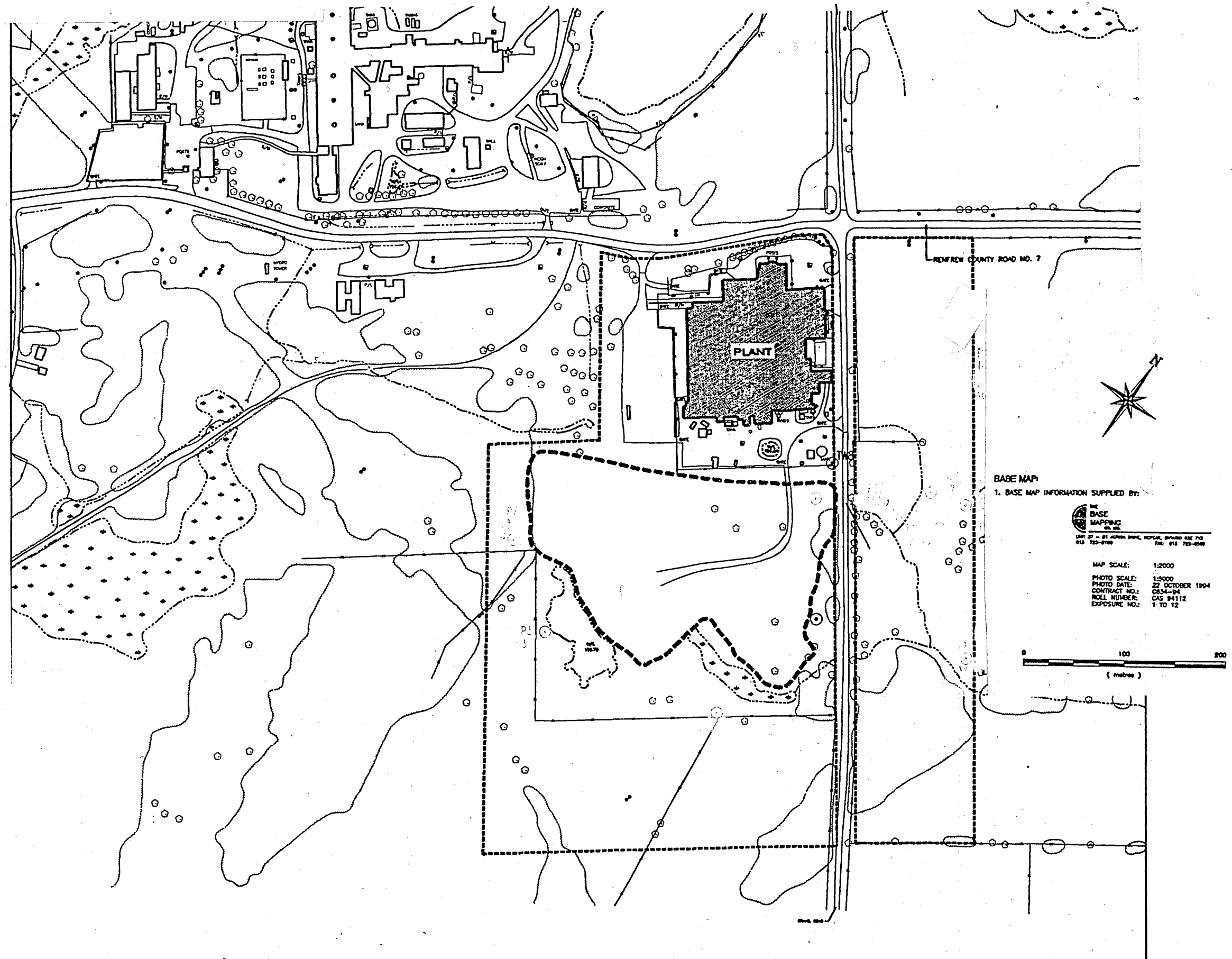
Opportunities

- ♦ Great potential for materials savings and hence waste and cost reduction.
- ♦ Potential for energy savings.

Threats

- ♦ Poor environmental compliance record.

Figure 64 Haley Industries Limited site plan.



4.2.2 Environmental Regulation

Environmental protection in Canada is the responsibility of all three levels of government: federal, provincial, municipal. This method of protection allows issues of both national and local importance to be addressed (Phyper, 1994).

Federal responsibilities for environmental legislation include: environmental management at federal facilities (such as airports and international harbours); transportation (other than on roads within the provinces); discharges that may be deleterious to fish; the import and export of goods and wastes; and issues deemed to be in the national interest such as the proper management of special materials (such as polychlorinated biphenyls). The Canadian Environmental Protection Act (CEPA) covers the registration of new chemicals and will be used to set regulations to control chemicals on the Priority Substance List. The revised CEPA also requires pollution prevention measures to be taken when dealing materials on the toxic substance list.

Provincial jurisdiction includes emissions to air, discharges to water, waste management, and intra-provincial road transportation . Federal regulations can be used by provincial agencies if province-specific regulations have not been passed, but Ontario has issued regulations for many environmental situations.

Municipal governments can impose environmental requirements on activities within their jurisdictions or on those who use their facilities. Many municipalities in Ontario have established noise and sewer-use by-laws.

The liabilities and penalties for non-compliance have greatly increased. Legislation places responsibility not only on corporations and organisations, but also their officers and managers. Both federal and provincial legislation makes the officers of a company who participate, authorise, or acquiesce to an offence, guilty of the offence and liable for punishment.

The following is a list of regulations that affect Haley Industries Ltd.

4.2.3 Federal

- ♦ Canadian Environmental Protection Act 1999
Sets out the duties and powers of Environment Canada and the responsibility people with respect to materials and toxic substances.
- ♦ Environmental Code of Practice for aboveground storage tanks and systems containing petroleum products.
- ♦ Guidelines for Canadian Drinking Water Quality
- ♦ Transportation of Dangerous Goods Act
Pertains to marine, air, rail, and inter-provincial and international road transportation.

4.2.4 Provincial (Ontario)

- ♦ **Environmental Protection Act**
The act is directed toward the protection and conservation of the natural environment. General prohibition on causing any “adverse” effects to the natural environment. Sets out permitting requirements for all media except water.
- ♦ **Waste Audits and Waste Reductions Workplans**
Sets out the requirements for large industrial, commercial and institutional (IC&I) sector establishments to develop waste audits and workplans.
- ♦ **Industrial, Commercial and Institutional Source Separation Programs**
Requires large IC&I establishments to implement source-separation and recycling programs.
- ♦ **General Waste Management Regulation**
A general waste regulation governing the designation and exemption of wastes, sites, and systems. Also sets out standards and requirements for the management of municipal, industrial and hazardous wastes.
- ♦ **Ambient Air Quality Criteria Regulation**
Sets desirable air quality criteria for specific contaminants
- ♦ **General Air Pollution Regulation**
Defines air pollution index, opacity requirements, fuel burning requirements, sets maximum half-hour impingement concentrations for 87 substances.
- ♦ **Spills Regulation**
Clarifies the duties and rights with respect to spills contained in the Environmental Protection Act.
- ♦ **Effluent Monitoring and Effluent Limits- Metal Casting Sector**
Applies to 6 plants and establishes daily and monthly loading limits for 13 parameters at two plants. Plants are Haley Industries Ltd. and Ford Windsor Casting Plant.
- ♦ **Ontario Water Resources Act**
General prohibition against the discharge of any material into water. Sets out permitting requirements for water discharges.

In general, for metal casting, the regulations of most concern are provincial. For metal casting facilities in cities, sewer-use by-laws are of concern and set some discharge limits. In Ontario plants that discharge directly to a body of water are governed by the MISA (Municipal and Industrial Strategy for Abatement) program see Reg. 562/94.

4.2.5 Costs and Penalties for Non-Compliance

Penalties for non-compliance with the Environmental Protection Act:

- ♦ Control Orders
- ♦ Stop Orders
- ♦ Remedial Orders
- ♦ General Offences
- ♦ A person found guilty of an offence under the EPA can be convicted for each day or part day on which the offence occurs or continues, a fine not more than \$10,000 on a first conviction and not more than \$25,000 on each subsequent conviction.
- ♦ A corporation found guilty of an offence under the EPA can be convicted for each day or part day on which the offence occurs or continues, a fine not more than \$50,000 on a first conviction and not more than \$100,000 on each subsequent conviction.

4.2.6 Compliance audit 1998.

Many of these issues have been outstanding for many years.

Waste Disposal

- ♦ Hazardous sand waste being disposed as non-hazardous waste.
- ♦ Source separation program for recyclable materials does not meet regulation.

Landfill

- ♦ Certificate of Approval not yet received for landfill (was received in June 1998).
- ♦ Recyclable waste being disposed of on landfill.

Water

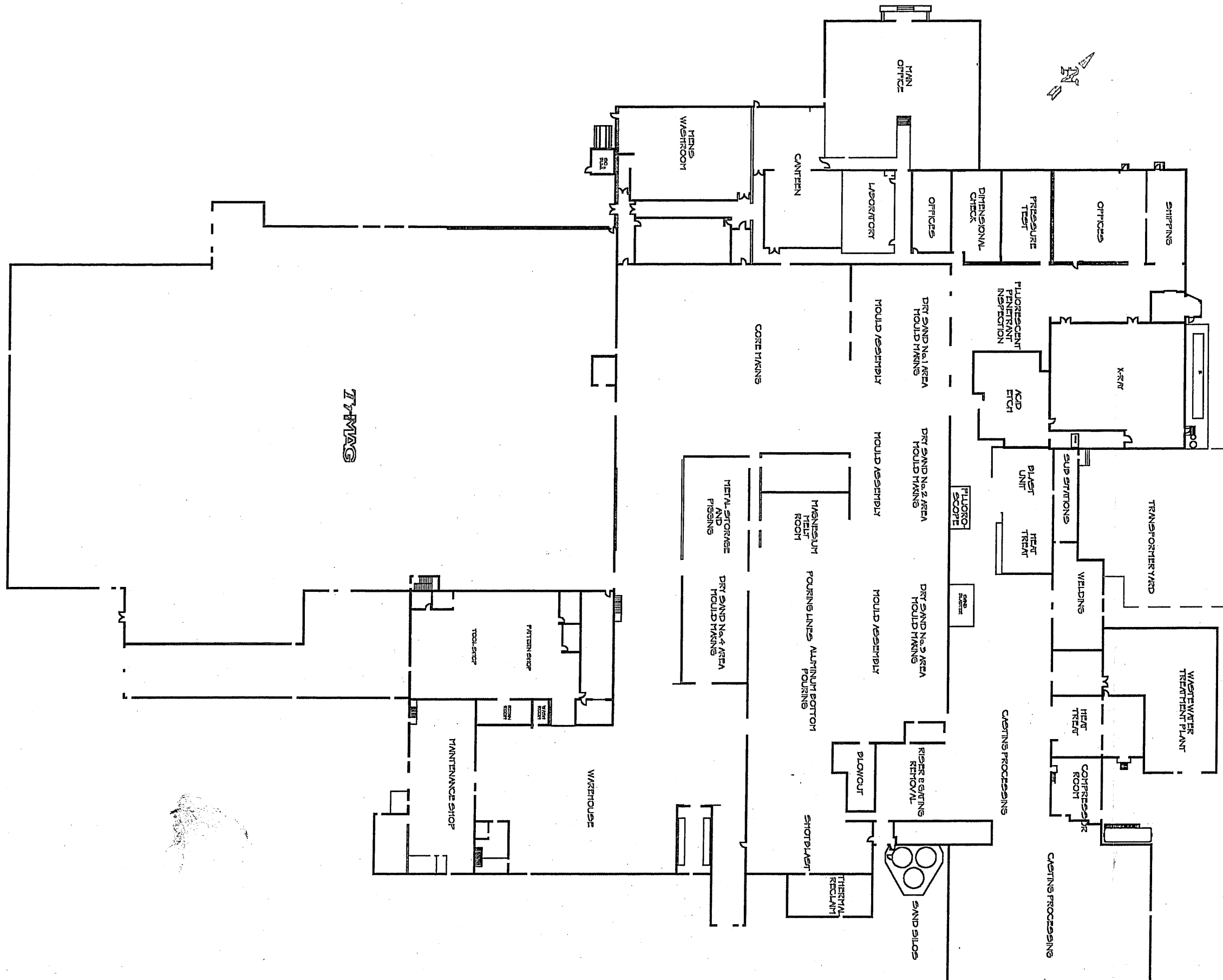
- ♦ Effluent quality does not meet MISA regulation.

Air Emissions

Certificates of Approval required for the following processes:

- ♦ Sand binder changeover in 1995 from furan based system to phenolic urethane system;
- ♦ Magnesium meltroom furnace conversion from oil to natural gas 1996/7;
- ♦ Wastewater additional ventilation 1998;
- ♦ Magnesium burning on the landfill;
- ♦ Make-up air and space heating units;
- ♦ Site air emissions inventory required.

Figure 65 Site Layout Diagram



4.3 Energy and air emissions

4.3.1 Site and scope of audit

The two main energy sources used on the site are natural gas and electricity. Electricity and natural gas bills are for both Haley Industries Ltd. and TriMAG. TriMAG is a magnesium die-casting facility that started up in 1996 and entered full production in May 1997. Further die casting cells were installed in late 1997 and in 1998. There is very little data on TriMAG’s energy consumption for the period under examination. Although the energy bills are combined Haley Industries is by far the largest energy user. This audit only covers the activities of Haley.

4.3.2 Overall energy use

Electricity supply

Electrical power is fed from Ontario Hydro to a single 7MVA transformer which steps the voltage down to 2300V. It then distributes to three substations containing transformers that step the voltage further to 600V. Power factor is not displayed on the electricity bill, however a recent audit estimated it to be approximately 90%.

Electricity tariffs

The basis for charging for electricity is:

Usage	first 12500 kWh	\$0.0865 per kWh
	next 1,130,000 kWh	\$0.0608 per kWh
	then	\$0.0358 per kWh
Demand	50kW	no charge
	then	\$6.450 per kW
Step down allowance		credit

Natural gas supply

The basis for charging natural gas is less clearly defined and fluctuates depending on the market value of natural gas and administration charges.

Climate data

Climate data is from the Petawawa, Ontario weather station located approximately 50km west of Haley.

The electricity, natural gas and climate data are shown in Table 23 and Table 24.

Table 23 Electricity, natural gas and climate data for 1997.

Date	Natural gas		Use (kWh)	Electricity		Weather data	
	use (m ³)	Cost (\$)		Demand (kW)	Costs (\$)	Temp. (°C)	Precip. (mm)
Jan-97	380,715	\$53,403.31	1,279,786	3225	\$90,558.02	-13.3	84.0
Feb-97	312,036	\$43,864.35	1,206,941	2938	\$86,499.47	-9.9	85.0
Mar-97	314,664	\$47,139.96	1,270,205	3080	\$89,469.66	-5.7	42.4
Apr-97	212,753	\$27,075.34	1,333,902	2933	\$91,644.01	4.2	37.0
May-97	97,522	\$12,695.19	1,385,592	2927	\$93,444.80	9.2	82.4
Jun-97	35,118	\$4,869.08	1,379,126	3204	\$93,969.64	19.1	19.8
Jul-97	28,869	\$4,054.31	1,265,246	3354	\$90,703.12	20.3	74.3
Aug-97	10,661	\$1,634.91	1,397,966	3104	\$94,122.55	17.6	122.6
Sep-97	54,383	\$7,311.72	1,437,989	3390	\$97,012.65	13.6	95.2
Oct-97	141,475	\$20,472.85	1,523,424	3169	\$98,900.99	6.6	62.5
Nov-97	201,504	\$24,861.49	1,567,000	3358	\$101,418.66	-1.2	73.4
Dec-97	302,473	\$45,849.32	1,521,276	3431	\$100,177.71	-7.5	35.0

A Oct-Nov 1997 study of TriMAG's substation showed that the average demand (kW) over the study period was 677 kW with a maximum of 887.5 kW. TriMAG operates continuously 24 hours a day 7 days per week for 50 weeks a year. This gives a total annual energy consumption of 5,686800 kWh, this represents 34% of the total electricity consumption site wide and 26% of the maximum demand.

Table 24 Electricity, natural gas and climate data for 1998.

Date	Natural gas		Cost (\$)	Use (kWh)	Electricity Demand (kW)	Costs (\$)	Weather data	
	use (m ³)						Temp. (°C)	Precip. (mm)
Jan-98	371,133		\$55,999.77	1,570,529	3425	\$102,068.95	-9	101.7
Feb-98	292,525		\$46,480.23	1,527,442	3497	\$100,734.26	-4.4	18.6
Mar-98	318,645		\$48,154.18	1,677,142	3244	\$104,739.93	-1.4	123.1
Apr-98	201,216			1,560,977	3300	\$100,908.79	7.2	63.2
May-98	117,930			1,529,144	3284	\$100,416.41	16.7	29.2
Jun-98	139,138			1,440,713	3475	\$98,243.78	18.7	153.6
Jul-98	121,748			1,217,840	2860	\$87,066.92	19.9	60.7
Aug-98	87,667			1,352,464	3049	\$92,869.26	19.4	86.6
Sep-98	129,668			1,551,024	3470	\$102,166.91	14.7	127.8
Oct-98	161,960			1,617,645	3378	\$104,073.54	8	41.2
Nov-98	219,990			1,666,628	3479	\$106,352.33	1.9	58.6
Dec-98	284,732			1,643,065	3474	\$105,482.78	-4.5	49.9

The natural gas billing changed during this period for this reason costs have not been included.

4.3.3 Thermal and energy use changes

There have been many changes to both facilities that have altered energy use patterns. Where possible, natural gas fired furnaces and space heaters have been installed to reduce energy costs.

Changes in 1997:

- ♦ Large casting area bake-out oven installation was completed. The furnace is natural gas fired.
- ♦ The magnesium meltroom furnace conversion from oil to natural gas was completed.
- ♦ TriMAG installed a large die-casting machine and associated furnaces, the die-casting machine is powered by electricity, the furnaces are both electric and natural gas fired.
- ♦ A new addition was built on to the building for TriMAG, this resulted in additional space heating and make-up air which are both natural gas fired.
- ♦ A small addition was made to the wastewater treatment plant, this added an air blower and two space heaters.

Changes in 1998:

- ♦ The electricity powered thermal sand reclaimer was shutdown.
- ♦ TriMAG installed two die cast machines and associated equipment. The furnaces for these machines are natural gas fired.

Changes since 1998:

- ♦ A natural gas-fired thermal sand reclaimer installed.
- ♦ A compressed air storage system was installed to reduce line pressure.
- ♦ A building addition for casting processing was built, this added additional lighting, heating and ventilation.
- ♦ TriMAG installed a 1800 kg/hr aluminium reverberatory furnace.

Total energy use.

Figure 66 shows the total energy use at both Haley and TriMAG. The total energy use is highly cyclical due to the high winter heating demands. The increase base energy use from 1997 to 1998 was due to increased production levels at both Haley and TriMAG.

Energy use per kg of casting and mean monthly temperatures

Figure 67 shows a strong correlation between energy consumption normalise with metal poured when compared to outside air temperature. This is largely due to the natural gas consume to heat the building.

Electricity delivered 1997-98 and Electricity demand 1997-98.

Figure 68 shows fairly steady electricity consumption with an increasing trend. The increase in electricity consumption was due to increasing production levels in both the Haley and TriMAG facilities. Each facility has a two week plant shutdown that occurs either in July or August, this is reflected in the energy consumption for those months.

Figure 69 shows a gradual increase in the maximum electricity demand. This can be attributed to TriMAG bringing additional equipment on line.

Electricity use and mean monthly temperatures.

Figure 70 shows the electricity use per kg of metal poured vs. the outside air temperature. The plot shows very high scatter with no correlation between energy use and outside air temperature. This chart confirms that electricity is not used for heating purposes.

Electricity use and poured metal

Figure 71 shows that there is very little correlation between production level and electricity use. This indicates wasteful practices in building services such as lighting, compressors, fans.

Natural gas delivered 1997-98

Figure 72 shows the consumption of natural gas from 1997-98. The natural gas use show a high seasonal variability. In 1997 very little natural gas was used for production equipment, this is shown by the low consumption in June, July and August. However, both facilities added natural gas-fired in 1997 and 1998, this is reflected in the increased usage in June, July and August 1998.

Natural gas and mean monthly temperatures.

Figure 73 shows the natural gas use versus the mean monthly temperatures. There is a very strong relationship between mean monthly temperature and natural gas consumption. This is because natural gas is used primarily for space heating. The amount of scatter increases at 17°C, in general, space heating is no longer used at that temperature but production use continues. The scatter above 17°C can also be attributed to the increasing gas use for production purposes as evident in Figure 72. From the natural gas curve the equation for use compared to temperature was:

Heat supplied = $-98484 \times \text{temperature} + 3\text{E}+06$.

Total Energy Delivered in Common Units (kWh)

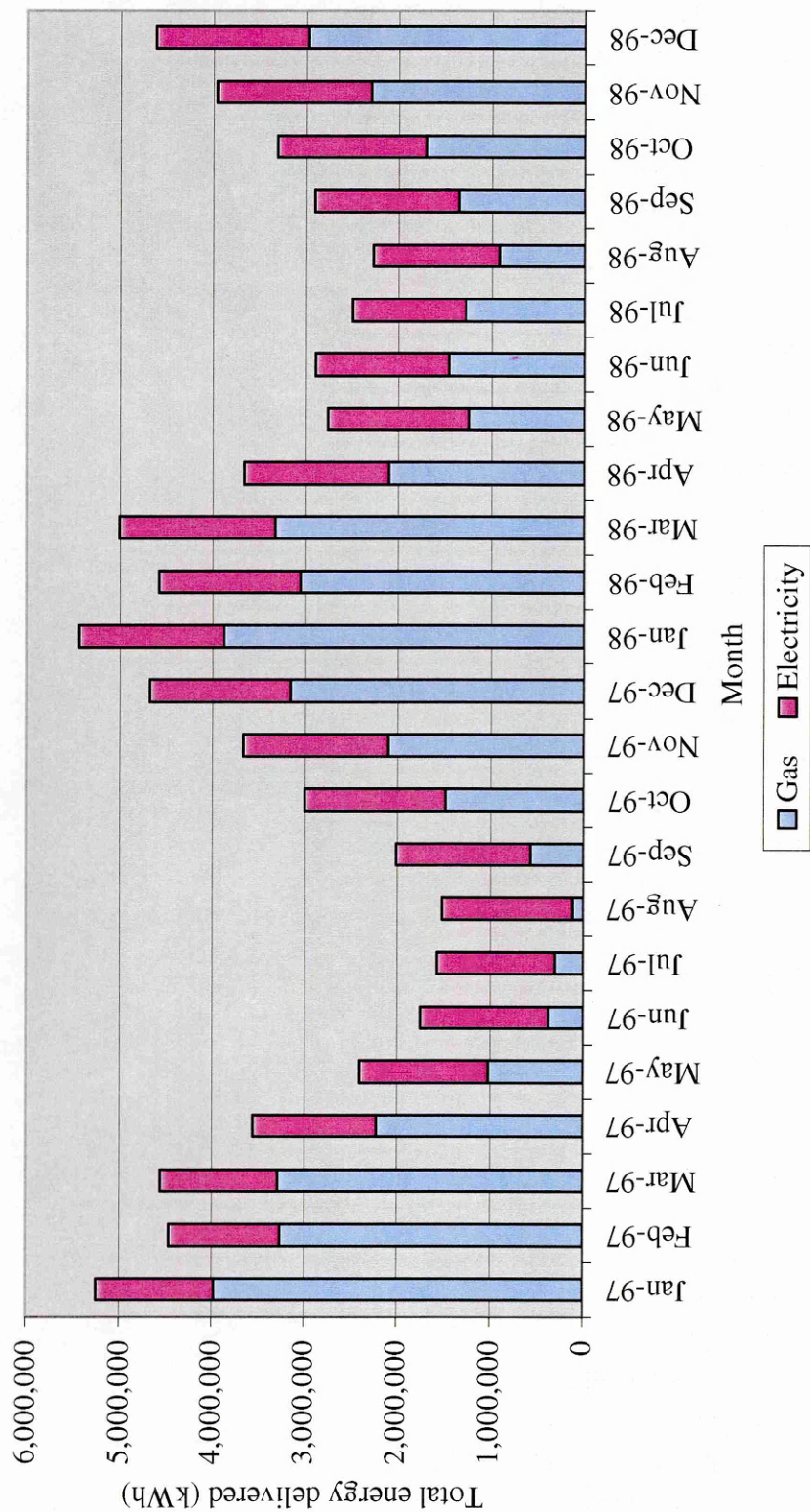
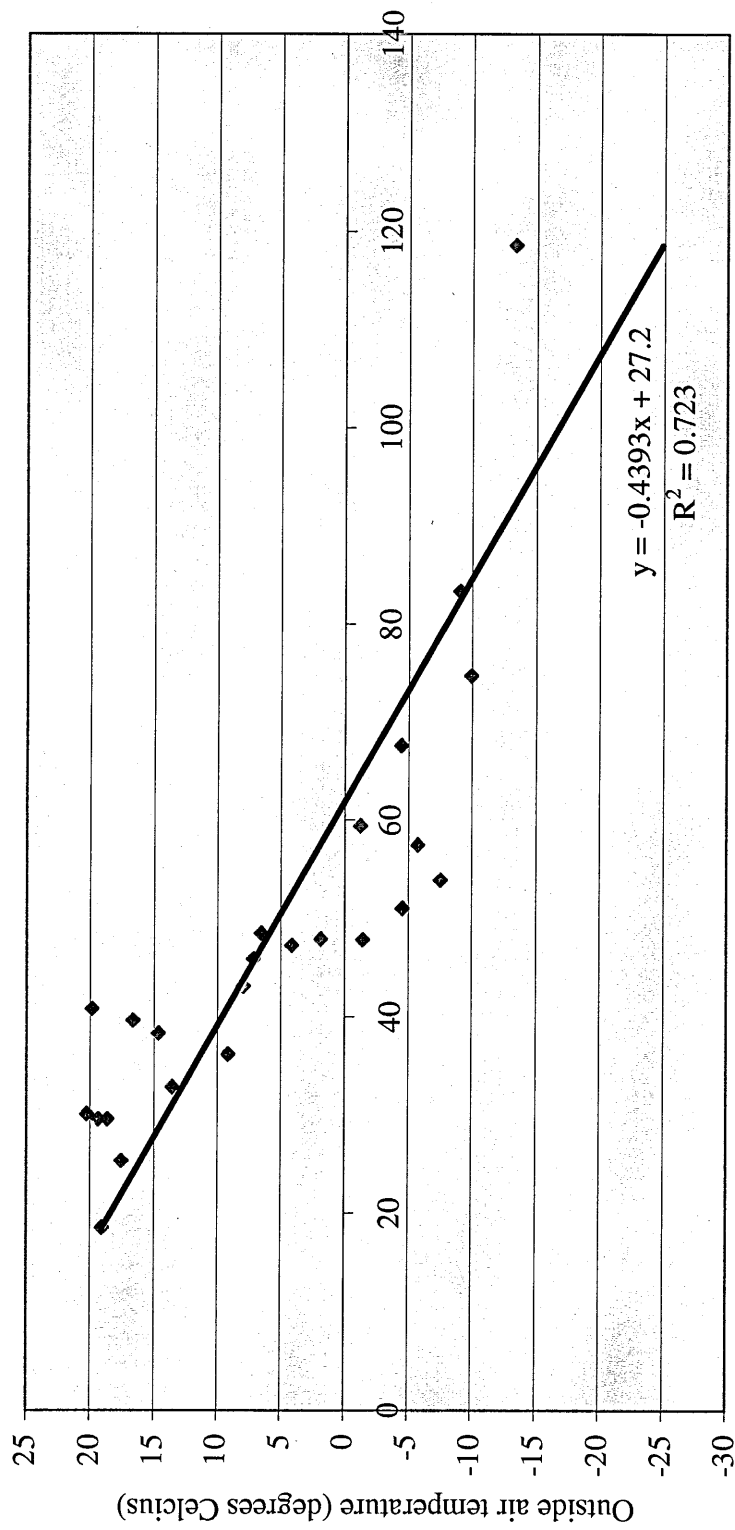


Figure 66 Total energy delivered, 1997-98

Energy per kg of Casting vs. Outside Air Temperature.



Energy (kWh) per kg casting poured.

Figure 67 Energy used per kg of casting poured vs. outside air temperature.

Electricity Delivered (kWh), 1997-98

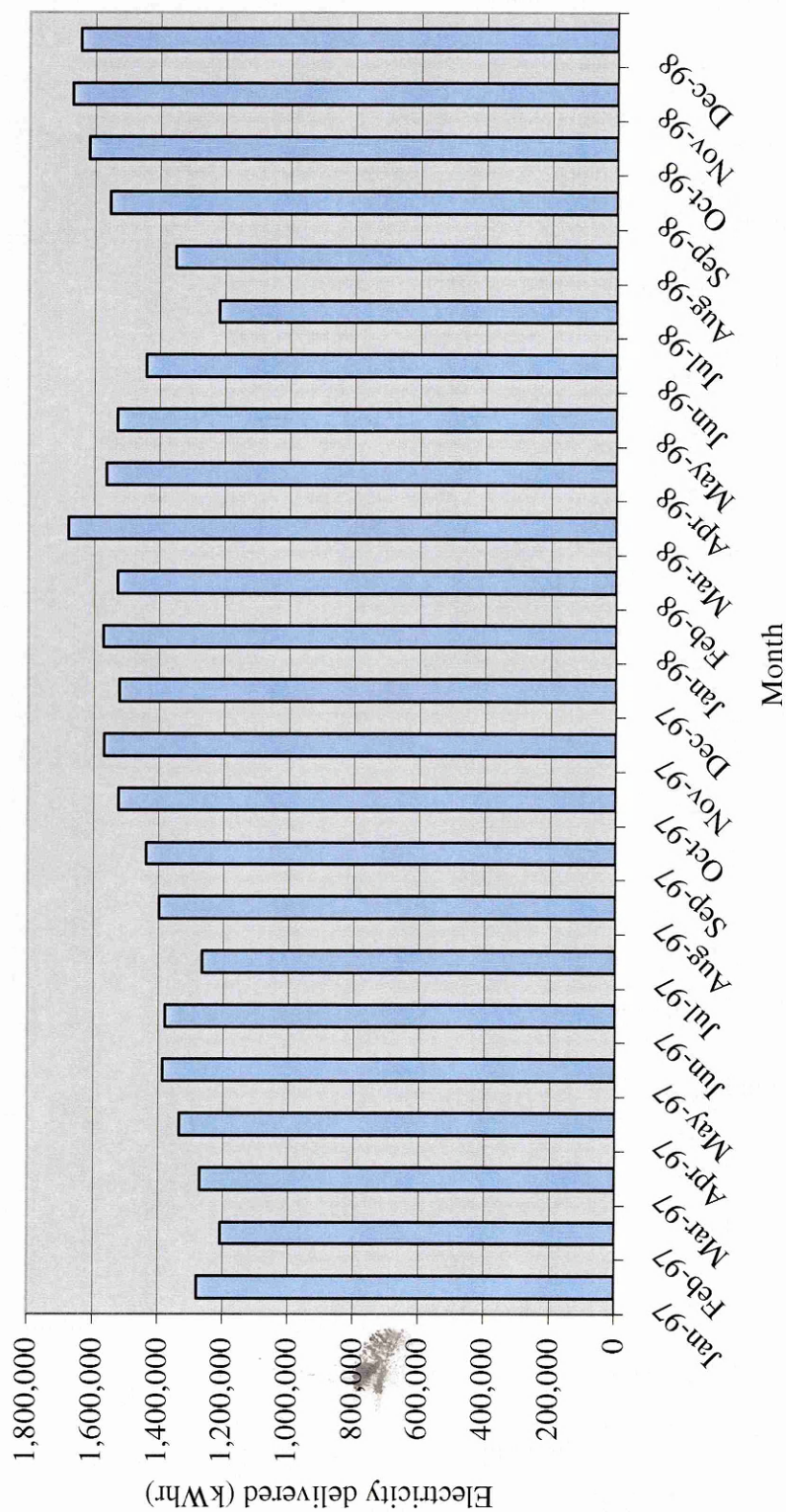


Figure 68 Electricity delivered, 1997-98.

Electricity Maximum Demand (kW), 1997-98

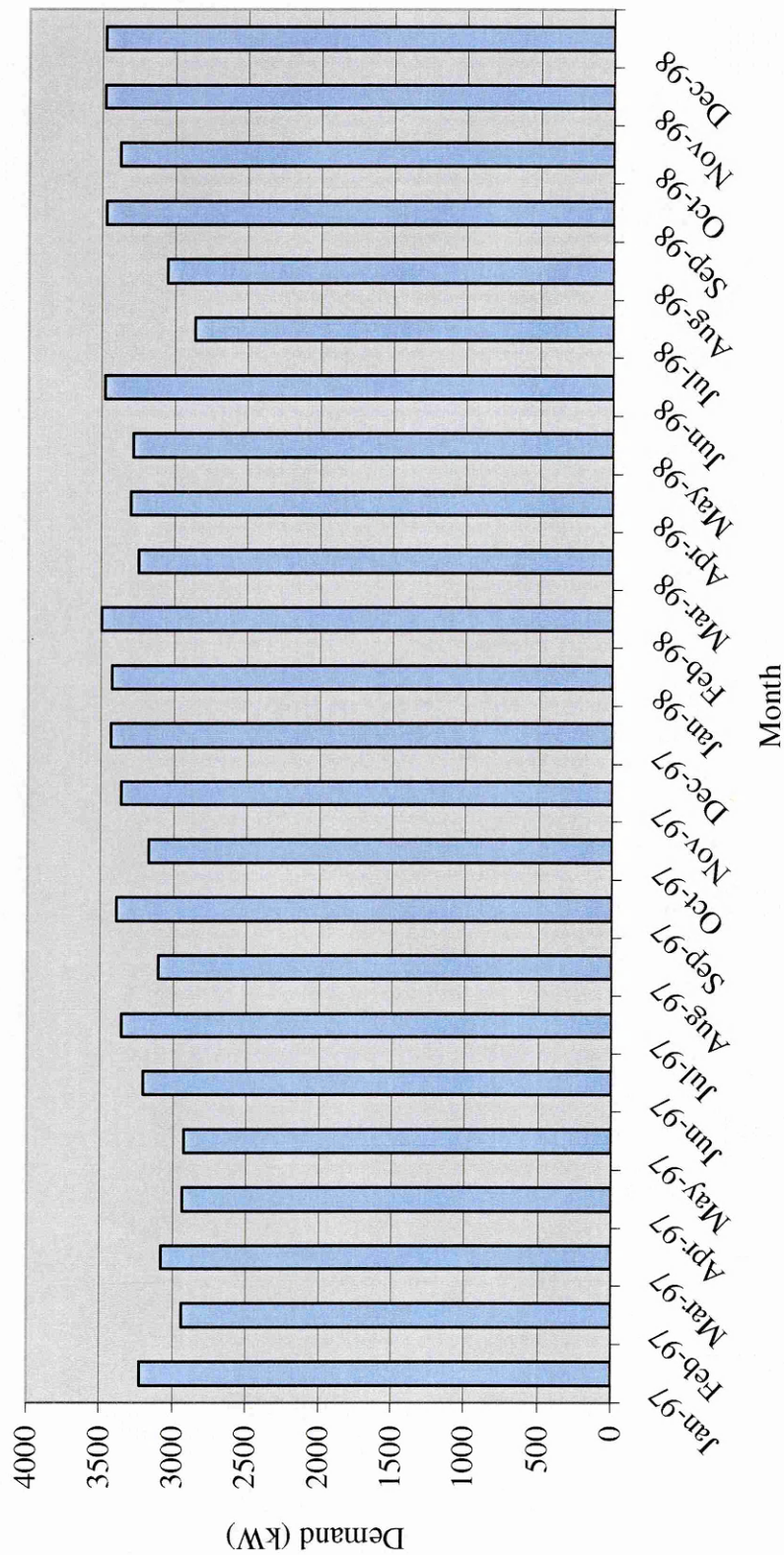


Figure 69 Electricity maximum demand, 1997-98.

Electricity Used per kg of Casting vs. Outside Air Temperature.

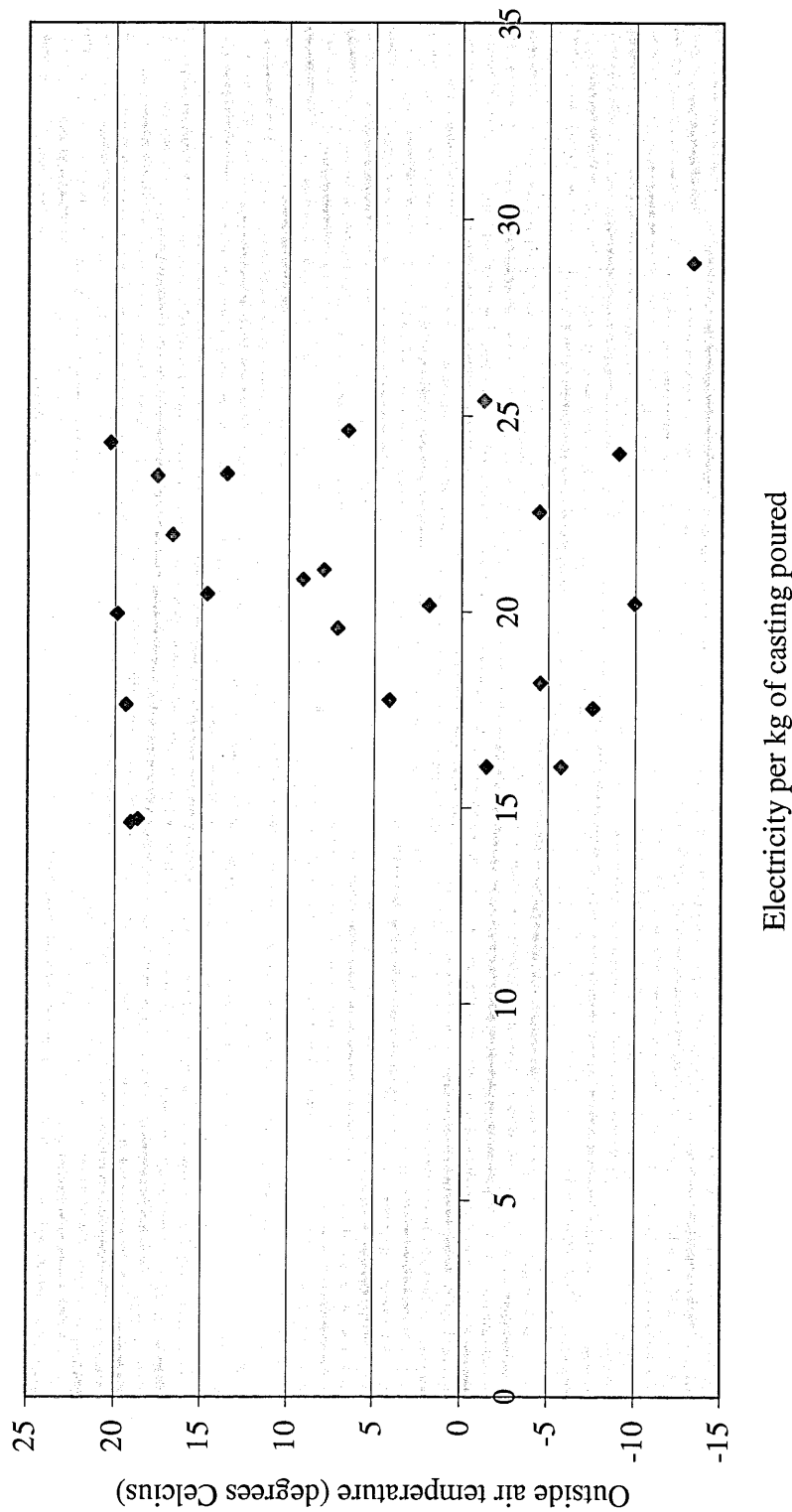


Figure 70 Electricity used per kg of casting poured vs. outside air temperature.

Electricity Use vs. Poured Metal

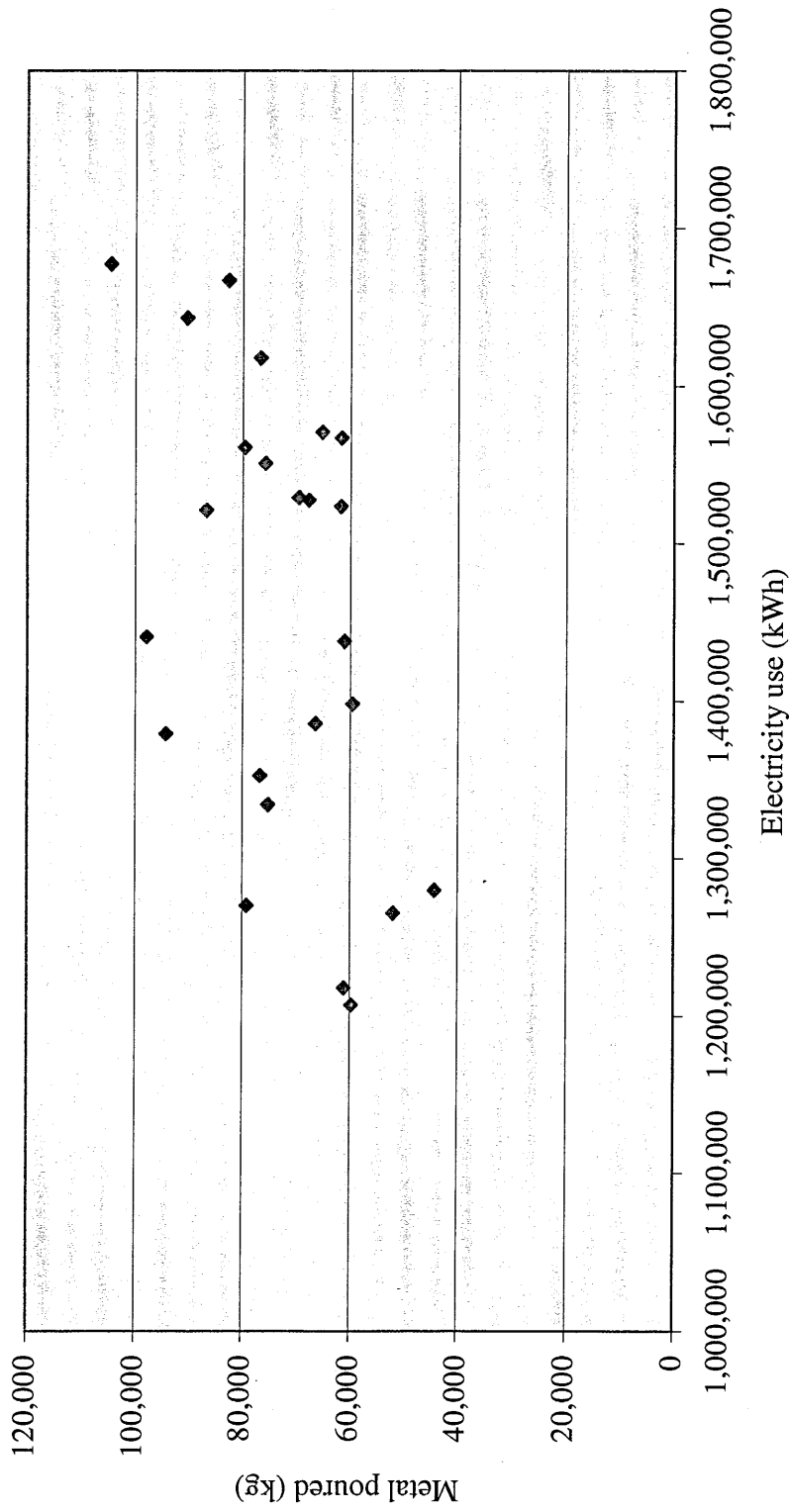


Figure 71 Electricity Use vs. Poured Metal.

Natural Gas Use, 1997-98

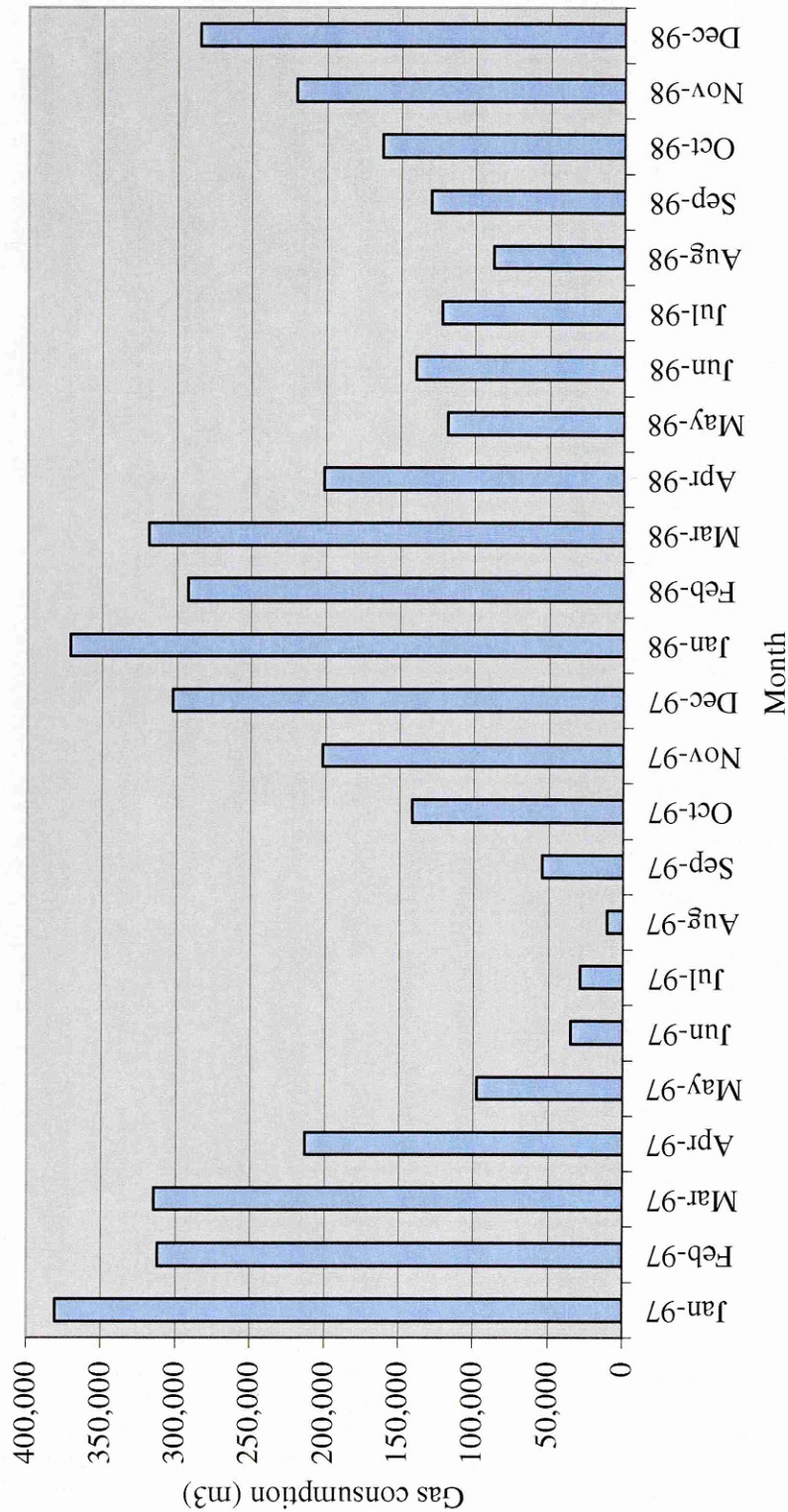


Figure 72 Natural gas usage, 1997-98.

Natural Gas Usage vs. Mean Monthly Temperatures

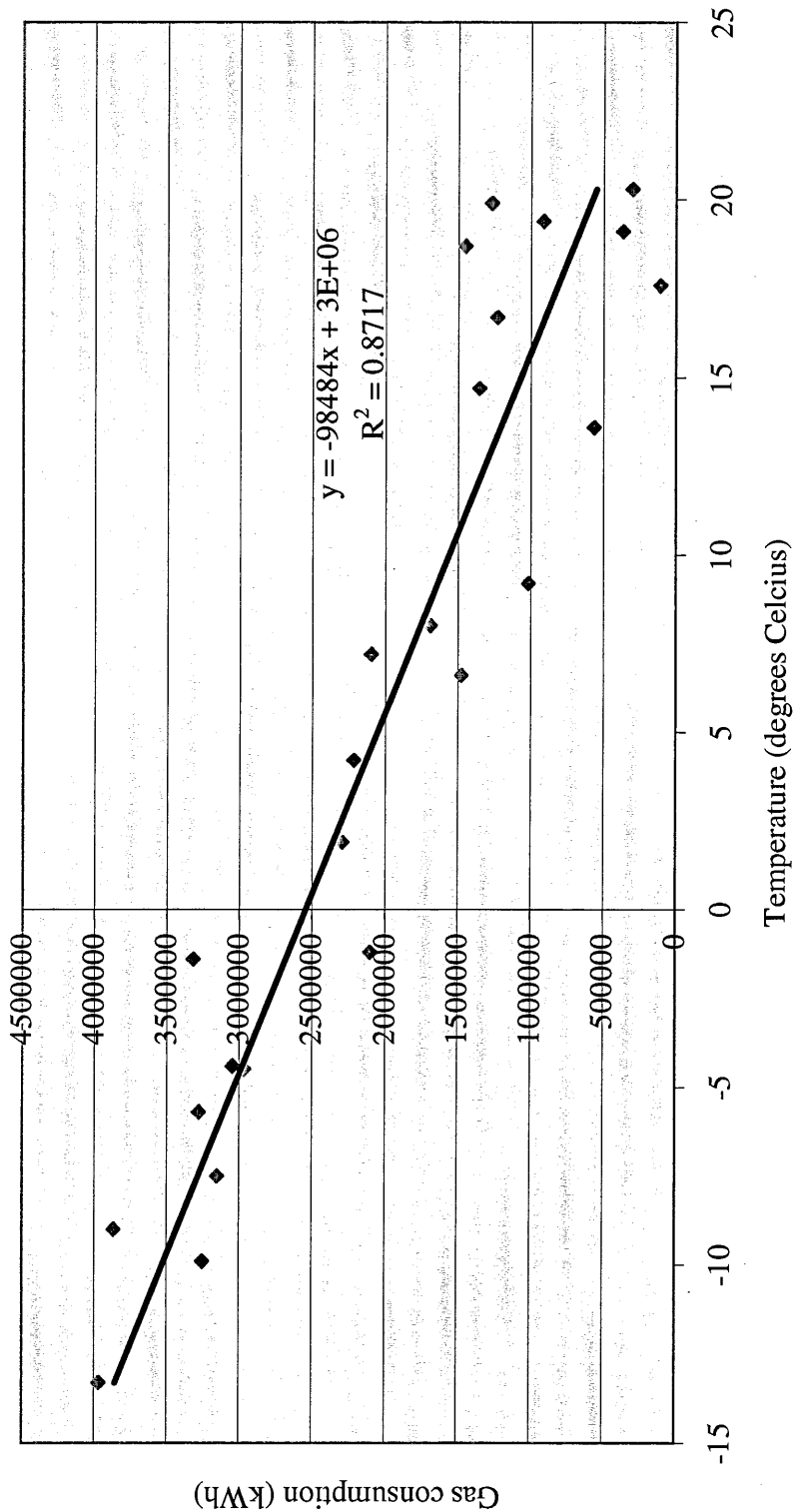


Figure 73 Natural gas usage vs. mean monthly temperatures.

4.3.4 Building Services: Heating Ventilation and Air Conditioning

Figure 74 is a facility layout showing ventilation fans at the site.

Building Heating

The building is heated using gas-fired make up air units and space heaters. In general electricity is not used for heating. A few offices have small space heaters to supplement gas heating. Due to the infrequent use of electricity for heating no data is available with respect to quantity.

Boiler Use

Hot water is used for very few processes and process water is typically heated at the location of use. Due to the spread of the facility hot water for hand-washing is provided by local hot water heaters. The boilers used in the facility are small and are used for hot water supply to the scrubbers.

Building Inside Temperatures

There are two temperature monitoring locations in the facility, these are the core room and the melt room. Monitoring since the year under investigation revealed that the average temperature in the core room winter/spring is 20°C. In September a minimum of temperature of 13.7°C and maximum of 28°C were measured in the core room, this can be attributed to large swings in the outside air temperature. The melt room had an average temperature of 24°C. Summertime temperatures vary, the plant offices are air conditioned, the manufacturing areas are not air conditioned, some employees have circulation fans at their work stations.

The base temperature where neither heating or air conditioning is used is not easily calculated. The temperature depends on the area of the plant and the other heat sources. From the natural gas curve it has been estimated to be 17°C. According to Environment Canada a base temperature of 18°C is used. Environment Canada's base temperature will be used in all calculations.

Building Ventilation

Ventilation is typically achieved by roof fans and wall fans. The facility has a very large make-up air deficit. A ventilation audit was carried out in 1997. The results are as follows:

1997 Ventilation Audit Summary

17 air-make up units 313500 CFM or 8877 m³/min.

50 continuous exhaust units draw 331992 CFM or 9401 m³/min.

22 intermittent exhaust units draw 8000 CFM or 226.5 m³/min.

Since the ventilation audit was carried out the air deficit has increased due to the addition of additional fans.

Several studies have been made to reduce the need for make-up air. The following recommendations were made in two 1989 studies (AISCO, 1989) these issues have not been addressed.

- ♦ Balance the ventilation within individual process areas to reduce air and contaminant migration within the plant based on continuous exhaust requirements.
- ♦ Balance intermittent exhaust systems individually and interlock their operation with appropriate supply air systems where possible.
- ♦ Use low-volume, high-velocity hoods to remove contaminated air directly from production areas as a replacement for the existing high volume remote roof exhaust systems.
- ♦ Filter exhaust air and pass through heat exchangers to pre-heat incoming make-up air.
- ♦ Install a central control facility for the mechanical ventilation systems.

During this audit it was noted that the ducting of the make-up air and space heaters should be examined in more detail. Due to the location of some of the exhaust fans and make-up air units, it is probable that fresh air is not being used optimally before being vented.

4.3.5 Energy Output Analysis

Sundry gains and direct rejects of energy

The total volume of the Haley building is: 3801905 ft³ or 107658 m³.

The total heated volume of the Haley building is: 3202775 ft³ or 90692 m³.

The total surface area of the Haley building is: 215262 ft² or 19998 m².

The total Haley floor area is: 160257 ft² or 14888 m².

Inside air temperature (T_i) is approx. 20°C.

Outside temperature (T_o) was approx. 4.4°C in 1997.

Base temperature (T_b) is 18°C.

Natural gas usage for process: 24880 m³/month.

Natural gas use for heat: 1793575 m³ 1997.

Assume hours of continuous ventilation are 16 hours per day, 5 days per week, 50 weeks per year or 4000 hours.

Annual internal sundry gains = $(UA + nV/3) \times (T_i - T_b) \times (\text{hours per year})/1000$

Annual heating energy = $(UA + nV/3) \times (T_b - T_o) \times (\text{hours per year})/1000$

where:

U (Wm⁻²K⁻¹) is the effective overall U-value for the buildings at the site,

A (m²) is the exposed surface area of all the buildings at the site,

n (hr⁻¹) is the effective overall number of fresh air ventilation airchanges that the buildings experience

V (m³) is the total enclosed volume of the site buildings.

These equations reduce to:

Sundry gains/heating energy = $(T_i - T_b)/(T_b - T_o) = (20-18)/(18-4.4) = 0.147$ (1997).

Total heat delivered annually is 1793575 m³ natural gas or 18707984 kWh/yr.

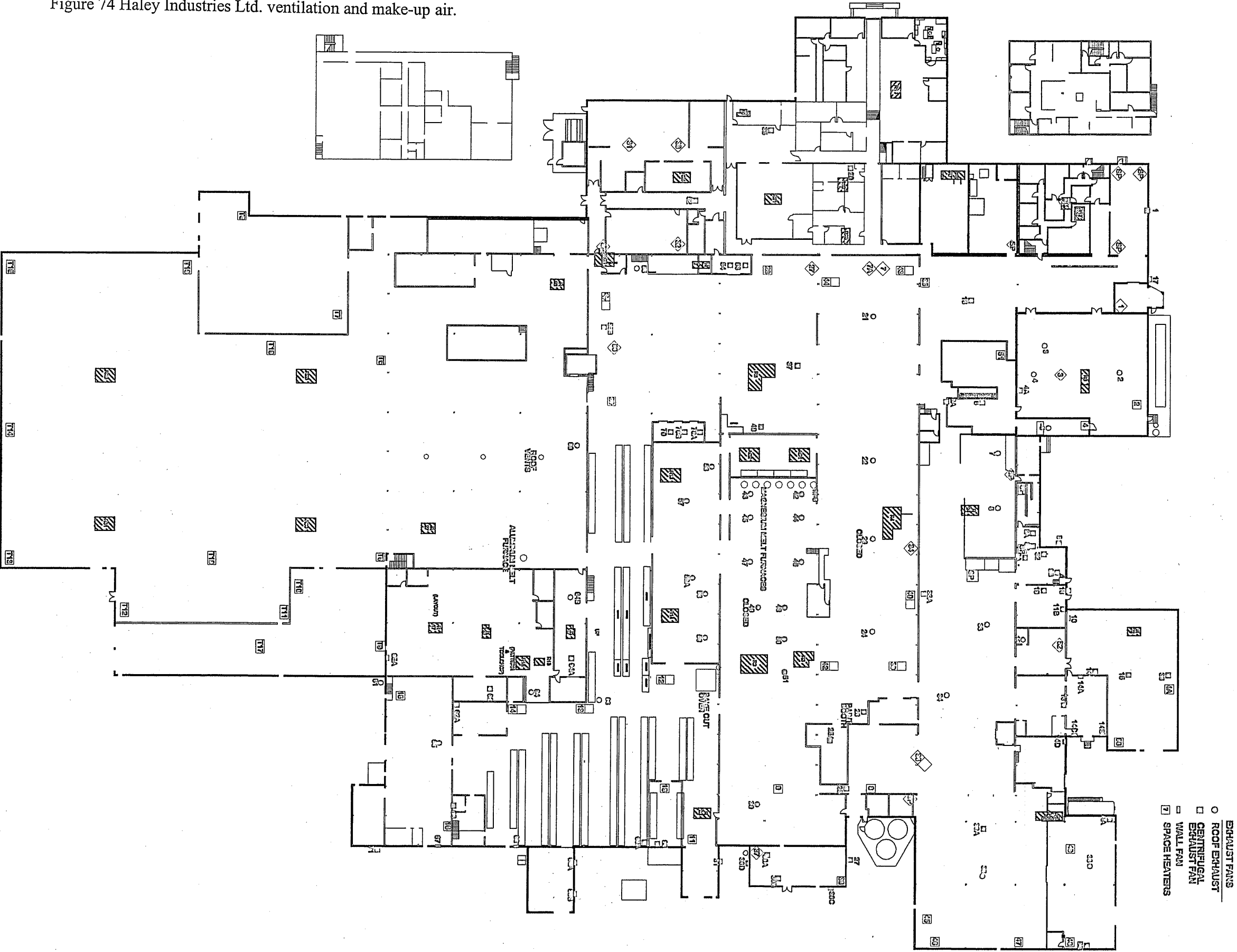
This means that the sundry gains are: 2750074 kWh/yr.

From a 1997 ventilation audit the daytime output of the fans is 9401 m³/min.

This gives an air change rate of 5.2 air changes per hour.

It can be deduced that the U-value of the building is 7.9.

Figure 74 Haley Industries Ltd. ventilation and make-up air.



4.3.6 Energy outputs

Outputs = Fuel energy losses from combustion, conversion and distribution
+ electrical energy directly rejected during utilisation
+ fabric transmission losses
+ ventilation heat losses

Flue losses = 0.14 x Gas energy to processes = 1569719
Electrical energy directly rejected = compressor energy and thermal reclaimer energy =
3729428 kWh + 360kW x 3456hrs = 3729428
Fabric transmission losses = 9858214
Ventilation heat losses = 11644289
= 26801650 kWhr

4.3.7 Energy Balance Sheet

<i>Inputs</i>	kWh
Gas (Haley only ~90%)	19 640 274
Electricity (Haley only)	12 592 024
Fuel Oil	22 200 estimate
Totals	32 254 498
<i>Outputs</i>	
Flue gas losses	1 569 719
Electrical devices (compressors, thermal reclaimer)	3 729 428
Fabric transmission losses	9 858 214
Ventilation losses	11 644 289
Totals	26 801 650
Residual	17%

- ♦ There are many reasons for such a large discrepancy between the inputs and output. There are many sections of the building that have false ceilings, the volume above the false ceiling is unheated, therefore the fabric transmission losses would be significantly reduced. These spaces act as an intermediate between the heated areas and the outside.
- ♦ The number of working hours was difficult to assess as it varies in different sections of the facility.
- ♦ The building has many different sections, the oldest being constructed in 1951, the newest being 1998. The old building was essentially un-insulated, however at some time some insulation was added. This means that the u-value is probably less than assumed.
- ♦ The temperature of the facility varies greatly, the melting area being the warmest and the warehouse being one of the coolest.

The lack of balance shows the difficulty of collecting data in a facility that has had many additions and changes over many years. The lack of accurate drawings and information on energy use has a large impact on the accuracy of any investigation into energy savings.

4.3.8 Energy Throughput Analysis

This briefly examines the significant pieces of equipment in the facility.

Lighting audit

A 1996 lighting audit found the following:

	4' x 2 tubes	4' x 4 tubes	8' x 2 tubes	100W	400W
No. Fixtures	420	411	794	10	187
No. lamps	840	1644	1588	10	187
Energy Use per lamp	40W new tubes 34W	40W new tubes 34W	110W new tubes 95W	100W	400W
Total Energy Demand	28.6 - 33.6 kW	55.9 - 65.8 kW	150.9 – 174.7 kW	1 kW	74.8 kW
Operating hours	min: 10 hrs, 5 days/wk max: 16 hrs, 5 days/wk	min: 10 hrs, 5 days/wk max: 16 hrs, 5 days/wk	min: 10 hrs, 5 days/wk max: 16 hrs, 5 days/wk	on at all times	on at all times
Annual Energy Use	kWh	kWh	kWh	kWh	kWh
Minimum	74360	143000	392340	8760	655248
Maximum	139776	273728	726752	8760	655248
Comments	Usage dependent on shifts. Some lighting is on motion sensors.	Usage dependent on shifts. Some lighting is on motion sensors.	Usage dependent on shifts. Used for workstation lighting, turned off on the off-shift.		

From this audit the following can be calculated:

Annual minimum consumption: 1273708 kWh. or 7.7%

Annual maximum consumption: 1804264 kWh. or 10.9%

Therefore energy consumption: from lighting is 7.7-10.9% of the total electricity consumption.

Heat Treat

The heat treat department operates 24 hours per day 7 days per week. The heat treat furnaces are all electric, forced air circulation furnaces. Heat treat cycles used are depending on the specifications of the customer.

Table 25 Heat Treat Furnaces

Furnace #	Electricity Consumption	Function and Temperatures
Heat Treat Furnace #1	75kW, 3 phase, 550V	Artificial ageing both Al and Mg alloys. Maximum temperature: 227°C.
Heat Treat Furnace #3	110kW, 3 phase, 550V	Stabilising Mg, ageing Al and Mg alloys. Maximum temperature: 330°C.
Heat Treat Furnace #4	100kW, 3 phase, 550V	Solution heat treat of AZ Mg alloys, stabilising Mg, ageing Al and Mg alloys. Maximum temperature: 413°C.
Heat Treat Furnace #6	300kW, 3 phase, 575V	Solution heat treat and artificial ageing of Al and Mg alloys. Maximum temperature: 544°C.
Heat Treat Furnace #7	200kW, 3 phase, 575V	Solution heat treat and ageing Al and Mg alloys. Maximum temperature: 544°C.
Heat Treat Furnace #8	104kW, 3 phase, 575V	Stabilising Mg, ageing Al and Mg alloys. Maximum temperature: 330°C.

AZ alloys are magnesium alloys containing aluminium, zinc alloys.

4.3.9 Compressor Use

Compressed air is a heavily used energy source in the facility.

The compressors were monitored for a period of two weeks in May 1997 by Ontario Hydro to assess energy consumption. Results were as follows:

Table 26 Compressor Energy Consumption 1997

Equipment Name	Max. kW	Avg. kW	Est. Annual Energy Use kWh	Annual Demand Cost	Usage Cost
#2: 125 Hp	107	91.2	766080	\$8,288	\$46,577.7
#3: 125 Hp	95.0	69.7	585480	\$7,353	\$35,597.2
#4: 150 Hp	119.19	45.27	380520	\$9,288	\$23,135.6
#1: 200 Hp	164.9	92.7	778680	\$12,771	\$47,343.7
Total	486	299	2,510,760	\$37,700	\$152,654.2
Total Annual Compressor Cost					\$190,354

Demand cost: \$6.45/kW

Use cost: \$0.0608/kWh

Use based on 50 weeks per year, 7 days per week

The estimated total energy consumption of the compressors is 15% of overall electricity consumption. The maximum demand of the compressors is approximately 15% of total maximum demand.

It has been observed that compressed air practices could be significantly improved. the following wasteful practices have been observed:

- ♦ Employees use compressed air hoses for floor sweeping instead of brooms.
- ♦ After shift hours and during breaks compressed air leaks can be heard in many areas of the facility.

Aluminium melting

Aluminium melting is carried out using electric furnaces. There are a total of four electric units used for melting aluminium with a total demand of approximately 400kW.

Other equipment

Other significant energy consuming equipment is as follows:

- ♦ Thermal reclaimer: 360kW unit, removed in 1998.
- ♦ Shotblast unit: 2 machines each with 3 x 30 hp electric motors.
- ♦ Abrasive blast unit: 2 x 30 hp electric motors.
- ♦ Ventilation fans and make-up air unit fans: total power unknown.
- ♦ Bake-out oven: natural gas, use patterns unknown.
- ♦ Magnesium crucible furnaces, 7 x 400 lb furnaces gas-fired.

Process air emissions

Most significant process emissions are generated from materials used in the manufacturing process. The main air emissions sources are listed below.

- ♦ Magnesium shavings from casting finishing are burnt on the landfill site, this produces a large plume of white smoke.
- ♦ The binder system in use on the large aluminium castings produces a white smoky discharge when the sand is removed from the casting. This smoke has a distinctive odour.
- ♦ The bake-out oven is used to facilitate sand removal on some castings. The emissions from this source consist of natural gas combustion products and combusted products of the organic sand binder systems.
- ♦ The mould pouring operation releases organic products from the breakdown of the sand binder system.
- ♦ Gas-fired melting furnaces release combustion products as well as flux products and metal fumes. Sulphur hexafluoride and carbon dioxide are used to protect the magnesium melt from burning, excess gas is released. Sulphur hexafluoride is a very potent greenhouse gas with approximately 24,000 times the greenhouse warming potential of carbon dioxide.
- ♦ Thermal reclaimer, the reclaimer in place at the time of the audit was electric fired, the organic products from the sand were not being properly combusted. The reclaimer installed in 1999 is gas-fired it is believed that complete combustion of the organic components of the binder system is being achieved.
- ♦ Wastewater treatment has two exhaust fans that ventilate the acid treatment tanks.
- ♦ Casting welding releases metal fumes and argon to the atmosphere.

- ♦ The acid etch area has large fans over the acid baths, these fans emit hydrofluoric, nitric and sulphuric acid fumes to atmosphere.

4.3.10 Options for energy savings

General

- ♦ Energy use of the major electricity consuming processes are not currently monitored, therefore potential for saving electricity is difficult to quantify. An energy monitoring station should be installed to monitor the electricity use.

Compressed air

- ♦ Employees should be educated in the costs of compressed air use. Wasteful practices such as floor sweeping should be stopped.
- ♦ Shut off valves should be installed on branch lines, this would allow the lines to be closed during the off-shift, this would minimise the impact of compressed air leaks.
- ♦ A program for repairing air leaks should be instituted.

Heating and ventilation

- ♦ An investigation into the state of building insulation should be carried out. From this a priority list of areas to insulate should be produced.
- ♦ Balance the ventilation within individual process areas to reduce air and contaminant migration within the plant based on continuous exhaust requirements.
- ♦ Low-volume, high-velocity hoods should be installed to remove contaminated air directly from production areas as a replacement for the existing high volume remote roof exhaust systems.
- ♦ Investigate the ducting of make-up air and the location of exhaust fans to ensure that the make-up air is being fully utilised.
- ♦ Educate employees on the use of intermittent fans to ensure that they are only used when necessary.
- ♦ Investigate the feasibility of preheating incoming make-up air by passing exhaust air through heat exchangers. The processes of particular interest are: heat treat, thermal reclamation, compressors, melting.

4.3.11 Conclusions

This site has the potential to reduce its energy consumption. However, in order to quantify the potential savings, better quality data must be obtained. This can be achieved by installing an energy monitoring system to monitor individual substations or key energy consuming equipment. Although there is much room for improvement, particularly with respect to heating and ventilation, the technology and methods to achieve this energy conservation are well documented.

4.4 Materials and Waste Audit

4.4.1 Site and Scope of Audit

Haley Industries Ltd. has its own landfill site that has been in operation since 1952. Waste costs for Haley Industries are extremely low, since most waste is disposed of on-site. The year under review was July 96-June 97.

4.4.2 Material Input Analysis

The purchased items for the three main areas of the production facility are listed in
The foundry area uses large quantities of sand and its associated binders and additives in its processes. The foundry area has only one wastewater stream that comes from the sulphur dioxide scrubbers.

Most of the materials used in melting and pouring are either shipped as product, or recycled either internally or externally. The largest cost item used in melting and pouring that does not end up in the product is sulphur hexafluoride. Sulphur hexafluoride is a potent greenhouse gas with approximately 24000 times the greenhouse warming potential of carbon dioxide.

Processing uses relatively little materials compared to the other areas. This is because processing's main function is cleaning and inspection of castings.

Table 27, Table 28, and Table 29. The products used in these areas largely end up in the waste stream. Some items have been omitted due to low quantities or products that are shipped as product.

The foundry area uses large quantities of sand and its associated binders and additives in its processes. The foundry area has only one wastewater stream that comes from the sulphur dioxide scrubbers.

Most of the materials used in melting and pouring are either shipped as product, or recycled either internally or externally. The largest cost item used in melting and pouring that does not end up in the product is sulphur hexafluoride. Sulphur hexafluoride is a potent greenhouse gas with approximately 24000 times the greenhouse warming potential of carbon dioxide.

Processing uses relatively little materials compared to the other areas. This is because processing's main function is cleaning and inspection of castings.

Table 27 Foundry materials, 1996-97.

Foundry				
Material	Use	Quantity	Cost	Fate
Silica 56 sand	mouldmaking	2482 tonnes	\$155,000	Landfill
Silica 71 sand	coremaking	177 tonnes	\$23,000	Landfill
Zircon sand	coremaking	80 tonnes	\$42,000	Landfill
Glass Bead	coremaking	4898 kg		Landfill
Silica 32 sand	coremaking	low		Landfill
Sodium silicofluoride	mould, core making	139 tonnes	\$97,000	Landfill, air
Steel shot	shotblast unit	50068 kg	\$28,000	Landfill
Phenolic Urethane No-bake Part I	mouldmaking	50.5 tonnes	\$120,000	Landfill, air
Phenolic Urethane No-bake Part II	mouldmaking	45 tonnes	\$142,000	Landfill, air
Phenolic Urethane No-bake Catalyst	mouldmaking	2494 kg	\$15,000	Landfill, air
Acrylic/Epoxy Cold Box Part I	coremaking	2494 kg	\$13,700	Landfill, air
Acrylic/Epoxy Cold Box Part II	coremaking	1814 kg	\$12,000	Landfill, air
Furan cold-box Part I	coremaking	4481 kg	\$14,000	Landfill, air
Furan cold-box Part II	coremaking	2177 kg	\$11,000	Landfill, air
Furan cold-box Part III	coremaking	524 kg	\$2,200	Landfill, air
Isopropyl Alcohol	mouldmaking	6510 l	\$4,700	Recycled off-site
Zip Stik 5510	mouldmaking	4807 kg	\$29,000	Landfill, air
Zip Slip 125H	mouldmaking	100 l	\$1,600	Landfill, air
Sulphur dioxide	coremaking	20952 kg	\$22,500	SO2 scrubbers
Sodium hydroxide	SO2 scrubbers	37680 l	\$25,500	Wastewater

Table 28 Melting and pouring materials 1996-97.

Melting and Pouring					
Material	Use	Quantity	Cost	Fate	
Magnesium alloys shipped		79773 kg			Customer
Aluminum alloys shipped		75084 kg			Customer
Zirmax hardener	meltroom	23129 kg	Shipped in castings, some to scrap		
Beryllium	meltroom	635 kg	Shipped in castings, scrap metal		
Master Alloys, additives, fluxes	meltroom	Low	Shipped in castings, scrap metal		
Carbon Dioxide	heat treat, meltroom	419740 kg	\$47,000	Air	
Sulphur flour	melting and pouring	907 kg	\$600	Air/landfill	
Sulphur hexafluoride	melting and pouring	6385 kg	\$307,000	Air	

Table 29 Casting processing and auxiliary materials 1996-97.

Processing and auxiliary				
Material	Use	Quantity	Cost	Fate
Blast Grain 54 grit	finishing	8617 kg	\$10,000	Landfill
Coarse Abrasive	finishing	65306 kg	\$11,000	Landfill
Steel grit	finishing	18503 kg	\$11,000	Landfill
Limosol degreaser	finishing	615 l	\$2,300	Landfill
Nitric Acid	acid etch	6354 kg	\$3,800	Wastewater
Sodium dichromate dihydrate	acid etch	1250 kg	\$2,400	Wastewater
Sulphuric Acid (93%)	acid etch	4647 l	\$1,800	Wastewater
Hydrofluoric acid (70%)	acid etch	4160 l	\$12,000	Wastewater
Ardrox P-134D	F.P.I.	2460 l	\$20,000	Wastewater
Ardrox PR50	F.P.I.	216 cans	\$1,800	Landfill
Ardrox developers	F.P.I.	Very Low		Landfill
AGFA G355 Fixer	x-ray	11275 l	\$16,000	Off-site silver recovery, disposal
AGFA G135 Developer	x-ray	6150 l	\$21,000	Wastewater
X-Ray film*		3265 kg approx.		
Argon	1380m ³ (gas) + 2240 l (liquid)		\$15,000	Air
Activated Carbon	wastewater	5669 kg	\$12,500	Landfill
Lime (Calcium hydroxide)	wastewater	24943 kg	\$5,000	Landfill
Sodium metabisulphite	wastewater	2000 kg	\$2,000	

All dollar figures are Canadian dollars.

* this amount of film represents waste film only, generally film is archived and/or sent to customers.

4.4.3 Material Output Analysis

Waste Disposal Costs

Company	Type of Waste	Total Cost (1996-97)
Haley Industries landfill site	Sand, general waste	not available
Anachemia Ltd.	Hazardous organic wastes	\$11965 (1997)
Stablex Inc.	Hazardous inorganic wastes	\$7375
Beauman	Recyclables (paper, glass, cans)	\$520
Fluorescent Lamp Recyclers	Fluorescent lights and ballasts	approx. \$500

Company	Type of Waste	Total Revenue (1996-97)
Central Machinery & Metals	Waste metal/dross	approx. \$35000
Environmental Control Systems	X-Ray Fixer	\$20,000 approx. (Mar-Dec 1997)
Environmental Control Systems	X-Ray Film	\$7000 approx. (Mar-Dec 1997)
	Scrap Iron/Steel	Unknown

Basis of charging for waste disposal

Type of Waste	Cost per unit	Total Cost (1996-97)
Sand, general waste	No cost, costs related to maintenance and environment only.	Not available
Hazardous organic wastes	Charges dependent on type of waste.	
Isopropyl alcohol	\$125 per 210L drum	\$3500
Waste oil	\$150 per 210L drum	\$1950
Contaminated oil	\$175 per 210L drum	\$2370
Waste resin	\$225 per 210L drum, \$75 - \$95 per 20L pail	\$2465
Misc. organic wastes	various	\$1680
Hazardous inorganic wastes	Charges dependent on type of waste. Transport charge \$1075	
Pot Shed sludge	\$150 per 210L drum	\$900
Chromate sludge	\$450 per cubic metre	\$5400
Fluorescent lights and ballasts	10 cents per foot of bulb, transportation charge	approx. \$500
Recyclables		
Tin/Aluminum	45 bins @ \$6.50 per bin	\$293
Glass	13 bins @ \$6.50 per bin	\$85
Paper	14 bins @ \$6.50 per bin	\$91
Cardboard	no charge	no charge

- ♦ In 1996 a clean-up of stores and the warehouse resulted in abnormally high oily waste disposal

The following is a summary of waste generation and the route of the waste.

Generating Area	Waste List	Disposal Route
General Plant	Cleaning supplies steel wool, paper towels, kimwipes, absorbent, dustbane.	Landfill
	Corrugated Cardboard	Recycle
	Glass bottles	Recycle/Landfill, if separated from regular waste they are recycled.
	Safety supplies gloves, earplugs, dust masks, face shields, respirator filters, aprons.	Landfill
	Batteries	Landfill
Foundry	Sand	Reclaim, landfill approx. 75% reclaim.
	Foundry process waste sleeves, plastic inserts, venturi tubes, vents.	Landfill
	Plastics jugs, bottles, chemical pails.	Landfill
	Shotblast (Wheelabrator) flashing, steel shot fines.	Landfill
	Shotblast (Wheelabrator) dust collector sludge/fines	Landfill
	Waste sand chemicals	Sent for treatment/disposal
Meltroom	Scrap metal	Reused or sold for recycle
	Aluminum, Magnesium Dross	Sold for recycle
Finishing Department	Abrasive wastes sand, sanding discs, sanding drums.	Landfill
	Blast cabinet fines aluminum oxide	Landfill
	Metal cuttings	Combusted on landfill
	Metal dust collector sludges	Landfill
	Plastics, misc.	Landfill
	Steel grit fines	Landfill
X-Ray Department	X-Ray lead packs	Landfill
	X-Ray film	Sold for silver recovery
Maintenance and Pattern Shop	Wood waste old pattern boxes, sawdust	Landfill

Stores, shipping	Empty chemical drums	Crushed and sold for scrap
	Waste pallets	Sent off-site for re-use
	Cardboard	Recycle
	Plastic packing	Landfill
Electrical maintenance	Fluorescent light bulbs	Sent for recycle
	Wires, components etc.	Landfill
Building projects	Construction waste	Landfill
Offices	Plain paper	Recycle/Landfill
	Newsprint, envelopes, magazines	Landfill
Cafeteria	Aluminum cans	Recycle
	Plastic, glass drink bottles	Recycle
	Domestic garbage	Landfill
Wastewater Treatment	Sewage Treatment Sludge	Off-site disposal
	Metal hydroxide sludges	Landfill
	Spent activated carbon	Landfill
	Chromium sludge	Hazardous (secure) landfill site

Alternative routes

The company generally has very low annual solid waste costs. The remote location of the company makes it difficult in many cases to use alternate methods of waste disposal, however there are opportunities for waste reduction.

Estimate quantities of waste

Type of waste	Quantity	Disposal Route
General garbage	unknown	Haley landfill site
Sand (various types)	2750 tonnes	Haley landfill site
Blasting media	145 tonnes	Haley landfill site
Activated carbon	6 tonnes	Haley landfill site
Metal hydroxide sludges	approx. 50 tonnes	Haley landfill site
Chromium sludge	12 m ³	Hazardous waste site
Waste oil	6 m ³	

* Wastewater has not been included in this section.

The number of personnel on-site is approximately 450 people, this includes contractors.

Most of the waste generated at Haley Industries is process waste. Therefore this does not correspond to the number of people in the plant.

Comparison with similar sites

There is currently little data to compare Haley to. However, the ferrous casting industry produces an average of 0.611 tonnes of solid waste per ton of casting (Kaempf, 1995). Haley produces approximately 17.2 tonnes of solid waste per ton of finished casting. **Non-ferrous castings are approximately 3 times less dense than ferrous castings but manufacturing materials are very similar.

In casting magnesium and alloys, for each ton of production from 50 up to 100-130 kg of wastes is formed, containing as much as 40-50% metallic magnesium (Kulinskii, 1995).

Solid waste classification

Material	Use	Quantity
Lakeshore 56 sand	mouldmaking	2476 tonnes
Barnes silica 71	coremaking	177 tonnes
Zircon sand	coremaking	80 tonnes
Sodium silicofluoride	mouldmaking, coremaking	60 tonnes
BTA Glass Bead	coremaking	4.9 tonnes
Blast Grain 54 grit	finishing	8.6 tonnes
Coarse Abrasive	finishing	65 tonnes
Steel grit (5330)	finishing	50.0 tonnes
GL 40	finishing	18.5 tonnes
Activated Carbon	wastewater treatment	5.6 tonnes
Magnesium/aluminum fines		
Total Solid Waste		approx. 2946 tonnes

95 % of the solid waste stream that is landfilled is sand related. From the above table it can be seen that the fourth largest waste is sodium silicofluoride. Sodium silicofluoride leaves the plant either as an air emission or on the sand waste. The leachate toxicity value for fluoride is 240 mg/L.

Test date, media	Average	High	Low
April 97, dust (15 samples)	2050 mg/l	3590 mg/l	114 mg/l
May 97, dust (3 samples)	1875	2460 mg/l	1576 mg/l

From this data it can be seen that the high fluoride levels render this waste as hazardous.

- The magnesium and aluminium fines are combusted on the landfill to stabilise them.
- Food waste is shipped to the local municipality landfill site.
- Fine paper was recycled, since the year under investigation this has ceased.
- Cardboard is recycled.
- Glass and cans are recycled.
- There is currently no plastic recycling

Liquid wastes

Beyond the wastes treated in wastewater there are several liquid wastes that must be disposed of off-site. These are chemical binder residuals, isopropyl alcohol, machine coolant, compressor oil.

Gaseous and vaporous wastes

There are no CFC's used in the facility. Isopropyl alcohol is released to the air from the spray booths. The primary air emission of concern is sulphur hexafluoride (SF₆) represents 97% of HIL's greenhouse emissions. According to industry data (IMA, 1998) Haley uses approximately ten times the recommended amount of SF₆ gas. Due to its high costs and potency as a greenhouse gas the reduction potential should be investigated. Other air emissions have been listed in the energy section.

Hazardous wastes

The largest hazardous waste stream comes from the sand system. Waste dust contains sodium silicofluoride which makes the dust leachate toxic.

Other hazardous wastes include chromium sludge and waste binder chemicals.

Waste storage areas

There are several waste storage areas:

Skips for aluminium dross, magnesium dross, scrap steel and cardboard. These products are all sold for recycling.

Low volatility chemical stores: waste resin drums are stored here.

Garage at back of plant: contains chromium sludge, waste isopropyl alcohol and any waste oil.

Applicable regulation

The applicable regulations have been listed at the beginning of the chapter. There are several areas where the regulations are not being complied with.

- ♦ The sand dust is classified as a hazardous waste and should either be treated before disposal or shipped off-site.
- ♦ The magnesium fines are classified as hazardous waste, they are being burnt on the landfill without an air emissions permit.

Clean-up costs

The treatment costs for becoming compliant with the regulations has not been quantified. There is little need for clean-up on the site, waste is stored in designated areas or finally disposed on the landfill site.

Waste reduction opportunities

A thorough examination of the sand system is required to identify ways of reducing sand-related waste.

Waste reclamation

An opportunity exists for thermal reclamation of the waste sand, this would enable more sand to be re-used rather than landfilling. A project is currently underway to replace the existing reclamation system. Costing is not currently available.

Waste recycling

The main opportunities for recycling are: plastics containers, paper and wooden pallets.

Collection and sorting waste

Waste from the production areas is collected by mechanic helpers who deposit waste on the garbage truck and remove for final disposal. There continues to be a problem with people putting recyclables in the waste bins. The mechanic helpers remove as much cardboard as possible but this is a time consuming process and is not always possible.

Scrap metal is kept separate there are bins for magnesium, aluminium and steel. There is a good separation program for metals.

In 1996 a fine paper recycling program was established. There has been a significant increase in the amount of paper captured and recycled however there is still room for improvement. The newsprint is not currently separated for recycling. It is becoming increasingly difficult to find room for all these separate containers. The plant is very spread out with three different sets of offices and a cafeteria. Note: In 1998 the paper ceased to be recycled and is now landfilled.

4.4.4 Waste disposal alternatives

Waste reuse: The main area for waste reuse option for waste is sand. It has to be thermally reclaimed before Haley can increase its re-use. Waste chemical drums are either returned to the supplier or crushed and sold for scrap steel. At this time there are no significant reuse possibilities for other wastes.

Waste incineration: There is no possibility for incinerating waste on-site, most of the waste is not incinerable. The company that disposes the organic hazardous wastes refines and recycles wastes where possible. Magnesium fines are currently burnt on the landfill, however, Haley does not have the permits and controls in place to do this.

Heat uses: Haley has several gas furnaces from which the waste heat could be used, see energy audit.

Combined heat and power: A combined heat and power plant would not be viable here. HIL does not use only a small amount of process heat. The only use for heat in the plant would be preheat air for some furnaces, this would not justify a CHP unit.

Refuse-derived fuel production: The primary wastes generated in terms of quantity are sand, steel shot and blast grit non of which is combustible.

Composting: Process wastes are not compostible, cafeteria wastes could be composted but are mainly fatty wastes .

Pyrolysis, gasification: Chemical decomposition via heat would evolve organic combustible wastes from our waste sand. This is effectively what thermal reclamation of sand achieves. The current reclamation unit run on electricity which is expensive to run. The purchase of a new thermal reclamation could allow exhaust air to preheat combustion air and save energy costs as well as reuse more sand (a gas-fired reclaiming was installed in 1999).

Hydrolysis/fermentation: Most of the process wastes are inorganic, therefore there are no possibilities for hydrolysis.

4.4.5 Summary

- ♦ The site generates large quantities of waste but has low waste disposal costs. The reason for this is that Haley has its own landfill site. This also leads to careless waste practices as these practices do not affect short term costs.
- ♦ 95% of the wastes are related to the sand system. This waste is not being disposed of appropriately. This system requires further investigation.
- ♦ Sulphur hexafluoride is costly and is being consumed in quantities far above industry recommendations.
- ♦ The stabilisation of magnesium fines on the landfill does not have a permit, either a permit needs to be obtained or alternate disposal practices sought.

4.4.6 Conclusions

This facility generates a large quantity of solid waste when compared to the weight of castings produced.

The initial compliance audit identified several waste related activities that were non compliant with regulations. These were:

- ♦ Hazardous sand waste being disposed as non-hazardous waste.
- ♦ Source separation program for recyclable materials does not meet regulation.
- ♦ Recyclable waste being disposed of on landfill.

The reduction of waste at this site is a complex issue that requires a thorough examination.. Although there are opportunities for increased waste recycling the amount of waste involved is small and should be easily addressed. The reduction of sand waste involves an examination of the manufacturing process.

The sand related waste is the largest waste stream and also a hazardous waste, the toxicity and quantity of this waste needs to be addressed.

4.5 Water Analysis

4.5.1 Water Input Analysis

There are two sources of water used on this site: process water and well (potable) water.

The process water comes from a nearby lake and is purchased from Timminco Metals. Water from this source is untreated and is used in the manufacturing processes and in the toilets and urinals. The potable water comes from an onsite well for which there are no charges. The water is softened in some areas of the plant. There is no metering on this well. Well water is used in human contact applications such as drinking water, cafeteria washing water, showers and sinks and x-ray. The well water has a metallic taste and has resulted in an increase in bottled water consumption.

The water bills for process water are shown below. Billing is done on a bi-monthly basis, this makes it difficult to compare process water consumption, climate data or production data. However, in general production levels increased for both Haley and TriMAG over the period under examination. The water quantities listed below also include TriMAG process water. In 1999 TriMAG began full flow monitoring of their daily water consumption. Based on shipped quantities of water and cooling water make-up TriMAG consumes approximately 30 – 40 m³/day.

Date	Process Water Consumption	Cost
Nov - Dec 1996	8609 m ³	\$5761
Jan - mid March 1997	10280 m ³	\$6052
mid March - April 1997	8141 m ³	\$5679
May - June 1997	6310 m ³	\$5360
July - August 1997	8960 m ³	\$5822
September - October 1997	7700 m ³	\$5603
November - December 1997	6630 m ³	\$5415
January - February 1998	6790 m ³	\$5444
March - April 1998	8011 m ³	\$5656
May - June 1998	8520 m ³	\$5745
July - August 1998	8570 m ³	\$5755
September - October 1998	6270 m ³	\$5353
November - December 1998	9800 m ³	\$5968

Monthly fixed charges are \$2233, \$900 of which is payment in arrears.

The highest charge for water consumption over a two month period is \$1786, the lowest charge is \$1087. With a 1997 total including current monthly charge of \$23,131.

Timminco have set a maximum daily consumption of approximately 220m³/day and a maximum flowrate of 2.5 L/sec.

Process water is used in the following: SO₂ scrubbers, dust collectors, non-contact cooling water, heat treat, acid etch and fluorescent penetrant inspection.

Potable water is used for hand washing, emergency showers, water fountains, x-ray processors, cafeteria.

During and since the year under examination there has been reductions in water consumption, these are:

- ♦ Magnesium crucible cleaning converted from wet to dry process, this saved 3000 l/week.
- ♦ The two main x-ray processors were replaced in 1997 saving approximately 70000 l/week of water.
- ♦ The wet dust collectors on the sand system were replaced with a dry dust collector. This saved 21000 l/week.
- ♦ Scrubber effluent recycling system was installed, water savings not known.
- ♦ Water fountains that ran continuously were replace or eliminated. Estimated water savings 70000 l/week.
- ♦ Compressor after-cooler was turned off, it is only required during hot humid weather, this reduced water consumption by approximately 115000 l/week.
- ♦ The heat treat department mainly uses quench temperatures of 90°C, 82°C, however, approximately twice a month a temperature of 25°C is required. Previously cooling had been achieved by turning on water and overflowing the tank. This consumed large quantities of water (60m³). An air-based heat exchanger was installed to cool the water with outside air. This can achieve temperature reduction faster with only a minimal discharge of water.

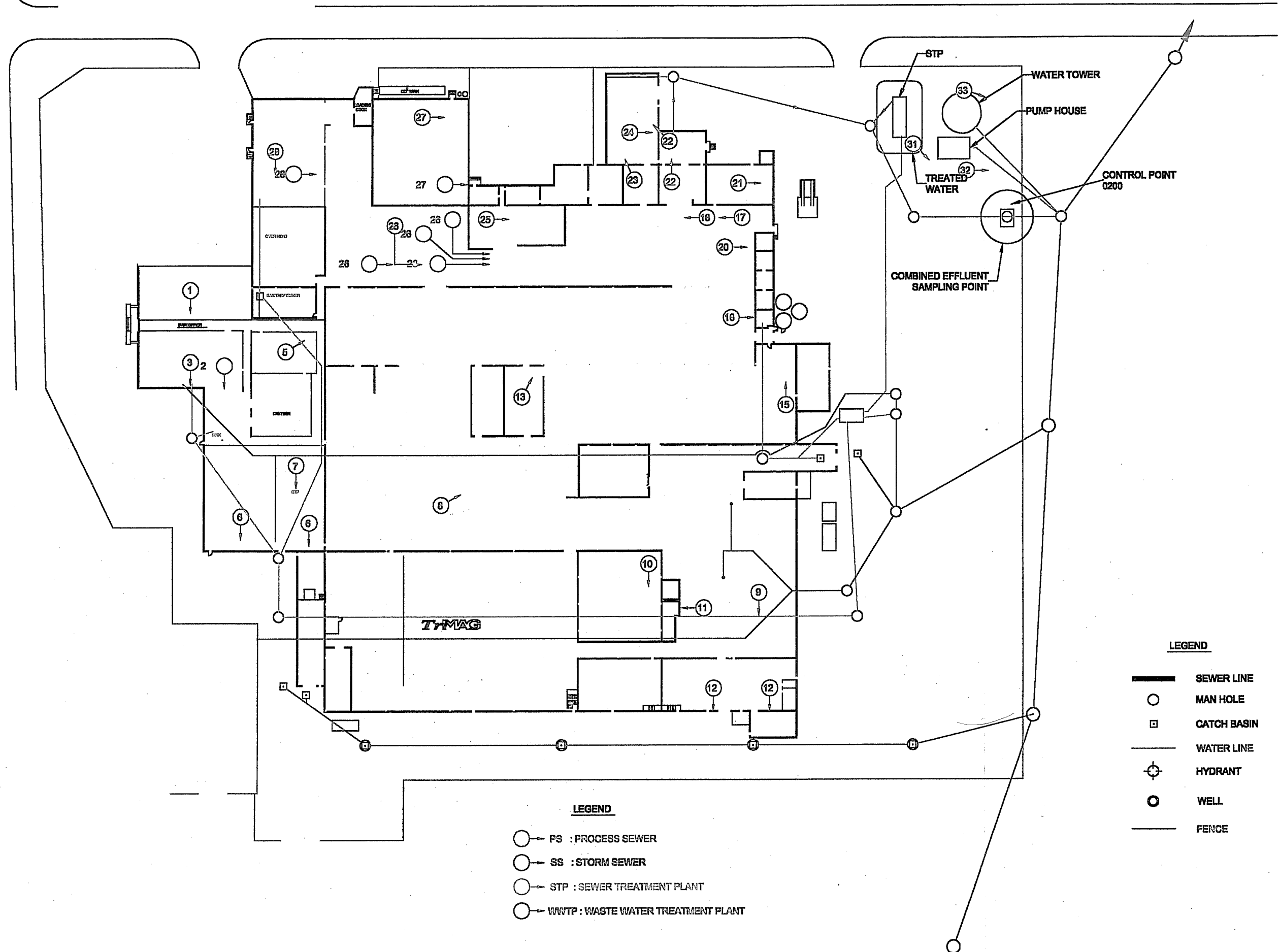
There are no diagrams of the water handling and distribution system available.

With the exception of compressor cooling water and heat treat there are no processes that are temperature dependent.

Due to limited water supply HIL has committed to water conservation within the facility. There have been attempts to use well water only, however the water is too hard for some of the manufacturing processes and leaves a film on the castings.

Alternate water supplies have been investigated. The options are: using on-site groundwater wells, creating a pipeline to the Ottawa River, trucking water from a neighbouring town. The groundwater wells drilled to date have not yielded acceptable water flow or quality for the production processes. A pipeline from the Ottawa River would yield excellent water quality, however the cost of this option is prohibitive. Trucking water 30km each trip would require two full time drivers to meet water quantity demands, this cost alone makes this option undesirable.

Figure 75 Drain locations



4.5.2 Water Output Analysis

Due to the rural location of the facility there are no sewers. Haley treats and directly discharges wastewater to a creek. A diagram of effluent lines is shown in Figure 75.

Effluent treatment costs have two components, fixed costs and production related costs. Fixed costs include sampling and testing, the frequency of these tests are governed by regulation. Production related costs include chemicals and sludge disposal they are related to the quantity of water treated.

The cost effluent treatment is the cost of operating both a process and sanitary wastewater treatment system.

Approximate total cost for 1997: \$72,800

Approximate total cost for 1998: \$140,000

These costs do not include manpower.

The significant increase in costs were due to a wastewater treatment plant upgrade, that resulted in the addition of several new treatment processes and additional monitoring.

The changes made were:

- ♦ Magnesium melting crucible cleaning was changed from a wet process to a dry process in 1997.
- ♦ The two main x-ray processors were replaced in 1997, resulting in large water reductions. Rinse water recirculators were added to the new processors resulting in further reductions.
- ♦ X-ray fixer effluent began to be disposed off-site in 1997, generating a revenue.
- ♦ The wet dust collectors on the sand system were replaced with a single dry dust collector in early 1998.
- ♦ Scrubber effluent recycle system was installed reducing the quantity and the pH of effluent.
- ♦ Water fountains that ran continuously were replaced or eliminated in 1998.
- ♦ New wastewater treatments were introduced for dye penetrant rinse water.

Average monthly effluent flows are shown below.

Date	Flow (m ³)	Date	Flow (m ³)
Jan-97	108	Jan-98	54
Feb-97	108	Feb-98	43
Mar-97	137	Mar-98	87
Apr-97	153	Apr-98	81
May-97	98	May-98	82
Jun-97	95	Jun-98	89
Jul-97	135	Jul-98	93
Aug-97	160	Aug-98	100 est.
Sep-97	156	Sep-98	100 est.
Oct-97	129	Oct-98	100 est.
Nov-97	101	Nov-98	100 est.
Dec-97	138	Dec-98	100 est.

The quantity of sewage per person was estimated to be 91 l/person/day. There were approximately 400 people on site in 1998.

Construct output analysis: see mass balance in Appendix B.

Effluent quantities and qualities: see spreadsheet in Appendix B.

The general description of regulations that affect wastewater was described earlier in this chapter. The required monitoring and effluent standards for the facility are listed below. Reference Ontario Regulation 5 /95.

Parameter	Monitoring Frequency	Daily Effluent Limit (kg/day)	Monthly Average Limit (kg/day)
Ammonia	Weekly		7.22
TSS	Daily	17.8	3.60
BOD	Weekly	8.85	3.60
Phosphorus	Weekly		0.309
Cyanide	Weekly		0.393
Aluminum	Weekly		0.360
Copper	Weekly		0.144
Chromium	Weekly		0.144
Silver	Weekly		0.106
Zinc	Weekly		0.144
Phenolics	Daily		0.00703
pH	Daily	>6.0, <9.5	
Toxicity	Monthly		

After the process water upgrade was commissioned in early 1998, it was found that the sanitary sewage plant could not treat the increasing sanitary system loads. In order to meet the regulatory requirements this needs to be replaced, the estimated cost is \$500,000.

Losses and leaks: There are hot water heat treat quench tank loses approximately 800L/day, this could be from leakage or evaporation.

4.5.3 Water Throughput Analysis

A summary of the effluent generating process, waste characteristics and treatment follows.

Scrubber Effluent

- ♦ Generated by: Sulphur dioxide off gases from core curing are scrubbed with a sodium hydroxide scrubber system to prevent release of SO₂ to the atmosphere.
- ♦ Characteristics: high sulphite, phenolics, can be high pH, suspended solids.
- ♦ Treatment steps: pH adjustment, precipitation of suspended solids, oxidation using hydrogen peroxide, passed through carbon to remove trace organics, equalisation with other treated effluents.

Spent Acid Overflow, Acid Rinses and Metal Dust Collectors

- ♦ Generated by: Surface treatments for castings include sulphuric, hydrofluoric and nitric acid etching. Spent sulphuric acid and rinse water is sent to wastewater. The metal dust collectors collect metallic dusts from casting processing.
- ♦ Characteristics: very low pH and dissolved metals from etching processes, suspended solids from dust collectors.
- ♦ Treatment steps: pH adjustment, hydroxide precipitation of metals, equalisation with other treated effluents.

Chromating Waste and Sludge

- ♦ Generated by: Some magnesium castings are chromated to provide surface protection to the piece during shipping.
- ♦ Characteristic: very low pH, hexavalent chromium, dissolved metals.
- ♦ Treatment steps: chromium reduction, pH adjustment, hydroxide precipitation of metals, equalisation with other treated effluents.

Dye Penetrant Waste

- ♦ Generated by: In order to inspect for surface flaws the castings are dipped in a solution of light oils which contain fluorescent dye. The castings are then rinsed off to remove excess oil and inspected under black light. The rinse water is the effluent.
- ♦ Characteristic: high BOD, toxicity.
- ♦ Treatment steps: blended with bentonite clay and polymers to absorb the oils and form a sludge, the sludge and clean water are passed through a band filter. Carbon columns are used to remove trace organics.

Sanitary Sewage and X-Ray Processing

- ♦ Major parameters in sanitary waste are BOD, TSS and ammonia which are currently treated in an activated sludge unit, with a rated capacity of 40m³/d and 9 kg/d BOD.
- ♦ Quality control procedures at Haley use x-ray inspection of castings which generates x-ray fixer, rinses and developer.
- ♦ The x-ray fixer is treated off-site.
- ♦ The developer and rinsewater are treated in the sanitary sewage plant.

Sludge Treatment System

- ♦ The sludge treatment system receives sludges from the scrubber, acid rinse/metal dust collector treatment and clarifier underflow. The sludges are combined in a holding tank and pumped to a plate and frame filter press. The filter cake is sent to Haley's landfill.

Equalisation and polishing

- ♦ The treated process wastewaters are combined and fed through clarification and final pH adjustment.

4.5.4 Water conservation and money saving opportunities:

Table 30 Potable water conservation opportunities.

Use	Potential for reduction
Cafeteria	Water is used for dishwashing and cooking. Low potential for reduction.
Water Fountains	Generally, the water fountains are being replaced with bottled water. The potable water is safe to drink, however, it has a metallic taste. The use of bottled water has significantly reduced excess use of potable water.
Sinks, showers	Several faucets in both the men's and women's washrooms drip constantly, these should be replaced.
X-ray	Considerable water reduction has already been achieved in x-ray. There is one high water use processor remaining, however, replacement cost is high. Long term HIL would like to use digital x-ray.

Table 31 Process water conservation opportunities.

Use	Potential for reduction
Toilets/Urinals	Low water use toilets have been used with limited success in TriMAG. The timing for the automatic urinals has been adjusted to reduce water use. Low potential for reduction.
SO ₂ scrubber water use	Generally, the water fountains are being replaced with bottled water. The potable water is safe to drink, however, it has a metallic taste. The use of bottled water has significantly reduced excess use of potable water.
Acid etch water use	Several faucets in both the men's and women's washrooms drip constantly, these should be replaced.
Metal dust collectors	Considerable water reduction has already been achieved in x-ray. There is one high water use processor remaining, however, replacement cost is high. Long term HIL would like to use digital x-ray.
Dye Penetrant	This process is the largest water consumer in the facility. There is little opportunity for water reduction. There is potential for effluent recycle is possible.
Heat treat	Significant reductions have already been achieved here. Low potential for reduction.
Compressor cooling water	Cooling water is only used on an as required basis depending on weather conditions. This waste has potential for reuse.

Due to the low cost of water at this site, reduction of sanitary water quantities yields only the benefit of reducing hydraulic load on the sanitary treatment system.

4.5.5 Summary

The quantity of water used at Haley/TriMAG is relatively small. Due to the location of the facility water availability is a constraint on manufacturing processes, therefore many efforts have already been made to reduce water consumption. The replacement of the sewage treatment plant is required in order to meet effluent requirements. To reduce water consumption further, some of the treated effluent streams could be reused within the process. This would have to be closely monitored to ensure that product quality is not affected and that effluent toxicity requirements can be met without the clean water streams in the effluent.

4.6 Summary of Audit Findings

There are a large number of environmental issues that need addressing at this site. From the summary items in the energy, waste and water items the following items have been ranked in terms of severity. The ranking criteria were compliance, toxicity and cost.

- 1) The sand/dust waste is the largest waste stream at the facility, it is also classified as hazardous waste due to high fluoride leachate toxicity. The sand waste is not currently being disposed of in a manner compliant with environmental regulations.
- 2) The sanitary sewage treatment plant is emitting an effluent that is not compliant with environmental regulations. The sewage treatment plant needs replacing to accommodate the number of employees at both Haley Industries and TriMAG.
- 3) The potential for reducing or eliminating the use of sulphur hexafluoride (SF₆) gas through material substitution or gas controls needs to be investigated. The use of SF₆ is both costly and emits large quantities of greenhouse emissions.
- 4) Develop alternate disposal methods for magnesium chips.
- 5) A review of site wide air emissions is required in order to identify and address non-compliant emissions.
- 6) The largest energy use in the facility is heating energy. Alternate strategies for heating and ventilation need to be investigated.

This audit identified many areas that need further attention. The first priority for this site must be to attain environmental compliance.

5 APPLICATION OF THE POLLUTION PREVENTION METHODOLOGY TO HALEY INDUSTRIES LIMITED.

5.1 Preliminary Assessment

The top five environmental issues identified in the preliminary assessment were:

- 1) The sand/dust waste is the largest waste stream at the facility, it is also classified as hazardous waste due to high fluoride leachate toxicity. The sand waste is not currently being disposed of in a manner compliant with environmental regulations.
- 2) The sanitary sewage treatment plant is emitting an effluent that is not compliant with environmental regulations. The sewage treatment plant needs replacing to accommodate the number of employees at both Haley Industries and TriMAG.
- 3) The potential for reducing or eliminating the use of sulphur hexafluoride (SF₆) gas needs to be investigated. The use of SF₆ is both costly and emits large quantities of greenhouse emissions.
- 4) Develop alternate disposal methods for magnesium chips.
- 5) A review of site wide air emissions is required in order to identify and address non-compliant emissions.
- 6) The largest energy use in the facility is heating energy. Alternate strategies for heating and ventilation need to be investigated.

Since the preliminary assessment was conducted concerns arose over the air emissions from the thermal reclaimer stack.

A 1999 phytotoxicology investigation (Gizyn, 2000) of a nearby magnesium mining and production facility examined and sampled the foliage from 22 points around the mine's property. Several points were at the boundary of the Haley Industries property. One particular point downwind of Haley Industries showed elevated levels of fluoride and boron on the elm tree foliage, see Table 32.

Table 32 Pollutant concentration on American elm foliage adjacent to Haley Industries production plant (Gizyn, 2000).

Parameter	Rural Limit (µg/g)	Measured Value (µg/g)	Notes
Fluoride	15	1000	Foliar injury on elm trees ascribed to fluoride.
Boron	75	240	
Chromium	8	1.2	
Iron	500	350	

Prior to the release of the phytotoxicology report, Haley Industries was given indications of the findings with respect to fluoride. The most likely source of fluoride was the thermal reclaimer so air emissions testing of the stack was commissioned.

The average emission rates of total particulate, hydrogen fluoride (HF) and total fluoride (as HF) is summarised in Table 33. The sand processing rate during the emissions testing was 1.5 tonnes per hour.

Table 33 Emission Rate Summary (CTI, 2000).

Contaminant	Average Emission Rate (mg/s)
Total Particulate	6.71
Hydrogen Fluoride	373
Total Fluoride (as HF)	374

Table 34 Physical Exhaust Gas Parameter Summary (CTI, 2000).

Gas Parameter	Units	Test HF1	Test HF2	Test HF3	Average
Volumetric flow rate	am ³ /sec	4.62	4.38	4.37	4.46
Volumetric flow rate	DSm ³ /sec	4.12	3.89	3.84	3.95
Velocity	m/s	16.5	15.6	15.6	15.9
Temperature	°C	52.8	53.9	56.7	54.5
Moisture Content	%	2.48	2.63	2.85	2.65

DS represents Dry, Standard conditions (25°C, 1 atm)

Ontario Regulation dispersion modeling was conducted to determine the maximum point of impingement (POI) concentration for each contaminant. The point of impingement is the nearest, off-property point where the air pollution is of interest. The results are shown in Table 35.

Table 35 Point of Impingement Summary (CTI, 2000).

Contaminant	Emission Rate g/s	POI Concentration (µg/m ³)	MOE POI Criteria (µg/ m ³)	%POI Criteria
Total Particulate	0.00671	1.24	100	1
Fluorides (as HF)- gaseous – growing season	0.3725	68.70	4.3	1598
Fluorides (as HF)- total–growing season	0.3737	68.92	8.6	801
Fluorides (as HF)- total–non-growing season	0.3737	68.92	17.2	401

In order to meet the POI concentration limit of $4.1 \mu\text{g}/\text{m}^3$ a minimum stack height of 50m would be required.

5.1.1 Identification of problem to be studied

The process chemical responsible for both solid waste leachate toxicity and the thermal reclaimer air emissions non-compliance is sodium silicofluoride. Due to the environmental impact associated with the use of sodium silicofluoride, environmental and process alternatives will be sought using the pollution prevention methodology.

5.2 Objectives

- ♦ **To meet required air emissions standards for fluoride.**
Ontario Regulation 346 requires a maximum point of impingement concentration of gaseous HF of $4.3 \mu\text{g}/\text{m}^3$ for the growing season.
- ♦ **To render the solid waste stream from the sand system to be non-hazardous.**
Ontario Regulation 347 requires that the fluoride leachate concentration must be less than 240 mg/L. A proposed regulation change would reduce this to 150 mg/L.
- ♦ **To assess the waste and material reduction potential in the sand system.**
In 1998 approximately 4290 tonnes of sand/dust was landfilled. This waste was mostly hazardous waste due to the use of sodium silicofluoride.

5.3 Process Flowsheets

The flowsheets needed to describe the sand processes are:

- ♦ Sand system, silos to shotblast.
- ♦ Sand system, shotblast to silos.
- ♦ Sand binder practices.
- ♦ Sodium silicofluoride practices.

These flowsheets are shown in Appendix C.

5.3.1 Sand system flowchart, silos to shotblast

This flowchart shows the sand originating from the storage silos, passing through production and ending at the shotblast unit where the sand is removed from the casting.

Sand is stored in three silos: thermally reclaimed, reclaimed, and new sand. The sand to be used in the moulding areas is a blend of sand from all three silos. The sand is blended and then transported to mixer hoppers using low velocity air transport. The sand is stored in hoppers above each sand mixer until required. Each sand hopper is vented so that dust can be removed.

The mixers blend the sand, inhibitor and binder. Sand calibration waste from the mixers can contain sodium silicofluoride, for this reason it is put into sand bins to be reused after processing. The mixed sand is packed into the pattern box. The sand is

levelled using a strike-off bar. The strike-off waste is put into sand bins for reuse. During mould packing and strike-off some sand may be spilled onto the floor. If the spilled sand is contaminated it is put into waste bins and sent to landfill.

New sand only is used for coremaking. Sand is transported from the new sand silo to the mixer hoppers using a high velocity air transport. The operation of the hoppers and mixers are similar to the moulding areas.

Cores made at Mixer 5 are hand packed and struck-off using the same method as in the moulding areas. Strike-off wastes are put in sand bins for reuse. If the floor area is clean around the mixer, floor sweepings are also put in sand bins for reuse.

Mixer 6 and the batch mixer alternate between two different binder systems, any uncured sand waste from the blend changeovers is sent to the landfill site. Strike-off wastes and floor sweepings from these mixers are also sent to the landfill.

Broken cores from the coremaking areas are put into sand bins for processing and reuse.

The moulds and cores are assembled together. Occasionally moulds or cores break and have to be scrapped. These are processed through the shotblast unit so that the sand can be reused.

After the castings are poured the sand is removed from the casting and the sand is processed through the sand system.

5.3.2 Sand system flowchart, shotblast to silos

This flowchart shows the processing of the sand from the shotblast unit to the sand silos.

The poured mould and casting are placed inside the shotblast unit. The unit propels steel shot at the mould. The sand and steel shot mix is transported by elevator to the separator. The separator consists of a rotating screen and two air curtains. The separator separates the sand, steel shot and contaminants.

The mix of steel shot and sand passes through a rotating screen which removes large pieces of flashing and other tramp material. The sand and steel shot mix is spread into a thin stream. The air curtain consists of suction onto the stream of abrasive. The steel shot falls through the air stream without being disturbed by it due to the weight of the shot. The steel shot is then processed for reuse in the shotblast unit.

The sand is sucked backwards where it falls into a pipe which goes to the sand storage tank. Dust is pulled through a dust outlet by the dust collector. Dust is then sent to a dust storage tank for disposal. The sand in the storage tank is conveyed using an elevator to another air curtain. After the air curtain, sand passes through a magnetic separator. The magnetic separator removes small pieces of steel shot from the sand before the sand goes to storage in the reclaimed sand silo. The silo has a vent to allow any fines to escape from the silo.

Some of the sand from the (mechanically) reclaimed sand silo is thermally reclaimed. The sand to be thermally reclaimed is further screened to remove sand lumps and metal flashing and passed through a magnetic separator. During reclamation weak sand grains tend to break down into smaller grains. When sand is cooled the fines are removed by a dust collector and the sand is transported to the thermally reclaimed sand silo.

5.3.3 Sand binder flowchart

Chemical binder components are stored in drums in the chemical storage area. Each mixer has a set of day tanks. When the mixer demands chemical the binders are pumped from their day tanks into the mixer. Sand, binder and inhibitor is mixed in the mixer. The mixers use the following

Mixer 1: 0.95% based on sand	Mixer 4: 0.90% based on sand
Mixer 2: 0.90% based on sand	Mixer 5: 1.2% based on sand
Mixer 3: 0.75% based on sand	Mixer 6: 0.9% based on sand
	Batch mixer: approx. 1.0% but is dependent on type of sand.

All percentages are % weight of binder based on weight of sand.

Calibration wastes from mixers 1-5 are either put into plastic pails for off-site disposal or are left to solidify and are disposed of on the landfill site. Calibration wastes from mixer 6 and the batch mixer are either put back into the day tanks or are put into pails for off-site disposal.

Mixers 1-5 use no-bake sand, after an initial work-time the binder begins to cure. Once the binders have hardened the mould is stripped from the pattern box. The mould continues to cure after it has been stripped. During this cure some solvent emissions are released.

Mixer 6 and the batch mixer use cold-box binders. After mixing the binders do not cure until catalysed with sulphur dioxide. The sulphur dioxide is not consumed in the reaction so it is vented to wet scrubbers.

Some cores are sprayed. The spray is prepared by adding potassium borofluoride and checking its viscosity and density. Adjustments are made by adding isopropyl alcohol.

Mould assembly uses a variety of alcohol based materials, as they are used the solvent evaporates.

During the pouring operation the chemical binders decompose due to the heat. Further decomposition occurs during the shotblast process.

5.3.4 Sodium silicofluoride flowchart

Sodium silicofluoride (Na_2SiF_6) is packaged in 22.5 kg bags on pallets. These bags are emptied into the sodium silicofluoride transporter which moves the chemical to the hoppers in the individual areas.

The sodium silicofluoride is fed from the hoppers to the sand mixer by the chemical feeders. The inhibitor is added to the sand in the following quantities:

Mixer 1: 1.16% based on sand

Mixer 4: aluminium casting only

Mixer 2: 1.17% based on sand

Mixer 5: 1.3% based on sand

Mixer 3: 0.47% based on sand

Mixer 6: 1.2% based on sand

All percentages are % weight of inhibitor based on weight of sand.

The chemical feeders are calibrated at regular intervals. Due to the hazardous nature of sodium silicofluoride waste from the chemical calibration is put back into the hoppers for use.

Patching sand and core spray have potassium borofluoride added as an inhibitor. All chills and some cores are sprayed with an alcohol based zircon refractory core spray. Potassium borofluoride is added to this coating at 4% by weight. Patching sand is used to clean up small surface defects on cores. Potassium borofluoride is added to the patching sand at 1-2% by sand weight.

When the molten metal is poured, the inhibitors are heated and turn into a gas that protects the surface of the molten magnesium from oxidation. It is probable that hydrogen fluoride air emissions are released during pouring. Sodium silicofluoride starts to decompose at 500°C , it is unlikely that all the hydrogen fluoride is consumed by the molten magnesium, especially since magnesium begins to freeze at 645°C . Some emissions may continue to be released during shotblasting depending on the temperature of the casting and the heat retained in the sand.

Sand processing removes sand fines generated by the thermal and mechanical stresses exerted on the sand. The sand fines are removed by the dust collector, these fines contain high levels of fluoride (20-50 mg/kg).

Thermal reclamation heats the sand to remove residual binder, however the temperatures required to completely combust the organics in the binder cause hydrogen fluoride to be released from the remaining sodium silicofluoride. Thermal reclamation can also cause sand grains to break down which produces a dust waste stream high in fluoride.

5.4 Critical Process Factors and Key Production Measures

To consistently produce castings of good quality, foundries must control two major variables of the casting process: melting practices and mould conditions.(Jorstad, 1993). The case study foundry in this project uses chemically bonded sand as the moulding media. This text describes some of the variables related to sand processes.

In sand casting the moulding material is also the largest producer of waste. Knowledge of foundry processes and their emissions will allow foundries to make the best decisions, regarding compliance (Laitar, 1996).

This section examines the basic processes in use at the case study site (Haley Industries Ltd.) and the best practices for those processes from industry literature.

5.4.1 Metal, sand and binder systems in use at Haley Industries Ltd.

Table 36 Main alloys poured at Haley Industries Ltd.

Magnesium Alloys	Major Elements	Aluminium Alloys	Major Elements
AZ91C-T6	Al 9.0, Zn 0.6, Mn 0.2	C355-T6	Si 5.0 Cu 1.2, Mg 0.5
AZ91E-T6	Al 9.0, Zn 0.6, Mn 0.2 0.005 Fe Max.	A356-T6	Si 7, Mg 0.5
AZ92A-T6	Al 9.0, Zn 1.8, Mn 0.2	A357-T6	Si 7, Mg 0.5
EZ33A-T5	RE 3.0, Zn 2.5, Zr 0.6	D357	Si 7, Mg 0.58
QE22A-T6	Ag 2.5, Re 2.0, Zr 0.6	535	
EQ21A-T6	Ag 1.5, RE 2.1, Cu 0.08, Zr 0.7		
WE43A-T6	Y 4.0, Nd 2.3, Zr 0.7		
ZE41A-T5	Zn 4.2, RE 1.3, Zr 0.7		

All alloys names are ASTM designations.
RE is rare earths.

The sand/binder processes used at HIL are:

- ♦ phenolic urethane no-bake, used for moulds only, makes up 76% of binders in use
- ♦ urethane no-bake binder for very large moulds and some large cores, makes up 10% of binder in use;
- ♦ furan cold-box, sulphur dioxide catalysed, 10% of total binder used
- ♦ acrylic-epoxy cold-box, sulphur dioxide catalysed, 4% of total binder used.

Most of the sand used at HIL is silica sand. Speciality sands such as zircon sand, glass bead and ceramic are in limited use, however, these sands make up only 1% of sand purchases and will not be discussed separately.

5.4.2 Critical process variables

In order to minimise the material consumed and the waste produced in the sand moulding process the following must be achieved:

- ♦ minimise scrap castings
- ♦ minimise core and mould scrap
- ♦ minimise sand usage/ maximise reuse
- ♦ minimise binders and additives, in general chemical binders cannot be reused or recycled.

This can be achieved by good sand and binder process control. The degree of control exercised in moulding and coremaking has a significant effect on the quality attained and on scrap and reject levels (ETSU, 1996). Chemical binder addition to sand is typically 1-3% by weight, but for one tonne of mixed sand, binders account for 30-60% of the raw material cost (ETSU, 1998). Foundry sand comprises of 97-99% of the chemical binder mix. For this reason foundry sand has a dramatic influence on the properties of the 1 or 2% of the binder that its mixed with (Carey, 1996).

Good sand and binder process control can :

- ♦ Reduce the number of scrap moulds/cores and reject castings.
- ♦ Reduce the sand purchase and disposal costs due to greater use of reclaimed sand.
- ♦ Reduce air emissions such as volatile organic compounds and odorous emissions.
- ♦ Reduce special wastes such as containers and out of date binder.

Sand control involves control of the entire system, as with any system, the function of each component in the system is dependent upon the function of the other components. Some of the operations that make up the system are: sand mixing, moulding, pouring, shakeout, cooling, sand handling equipment (belt conveyers, hoppers, bins), dust collection equipment, screens, magnetic separators, and practice on the moulding floor. Sand tests can be used to monitor progress towards system control. The level of control that a given system can achieve, however, is very dependent upon the basic engineering of the sand system, and the casting process (Pedicini, 1989).

Sand system control involves three steps:

- 1) identification of the variables in the process that affect the consistency and uniformity of the sand;
- 2) achieving control over the variables that can be controlled; and
- 3) optimising conditions.

There is no ideal sand formulation that will produce satisfactory results in every system.

5.4.3 Chemical binders.

The components of the Phenolic urethane no-bake system are:

- Part I: phenolic polyol dissolved in organic solvent
- Part II: polymeric MDI-type isocyanate dissolved in solvent
- Part III: amine-type catalyst

The components of the Polyether-polyol-urethane no-bake binder are:

- Part I: polyol resin
- Part II: coreactant MDI-type isocyanate.
- Part III: amine-type catalyst.

The key variables in phenolic and polyether-polyol urethane moulding and coremaking are (Otte, 1997):

- ♦ Raw Materials
 - Sand
 - Binder
 - Part I: phenolic resin
 - Part II: polyisocyanate resin catalyst
 - Additives
- ♦ Temperature
 - Sand (controls chemical reaction rates and solvent evaporation)
 - Binder (controls viscosity and pumping characteristics)
- ♦ Mixing efficiency (how well the binder is distributed on the sand)
 - Mixer operation
 - Mixer maintenance and cleaning
- ♦ Compaction
 - Vibration and hand packing for no bake, blowing for cold-box
- ♦ Mould Wash
- ♦ Both the polyether-polyol-urethane binder and the phenolic urethane binder are very moisture sensitive, the sand and binder must be protected from moisture (Samuel, 1988 and Weddington, 1991).

5.4.4 Sand and binder mixing

There are two types of mixers used with chemical binders, these are batch mixers and continuous mixers.

Batch mixers are generally used when small volumes of mixed sand with a relatively long bench life are employed (cold-box and warm or hot box binders).

Continuous mixers are ideal for all types of cold-setting systems. Continuous mixers tend to be high throughput which means that good operational controls are essential to minimise waste and ensure a consistent quality of mixed sand (ETSU, 1998a).

A continuous mixer consists of a trough or tube containing a mixing screw. Dry sand is metered into the trough at one end through an adjustable sand gate. Liquid catalyst and binder are pumped from storage tanks or drums by metering pumps and introduced through nozzles into the mixing trough (Brown, 1994).

The critical control variables for chemical binder mixers are (Otte, 1988):

- ♦ Sand temperature: Controls the speed of the chemical reaction that sets the sand.
- ♦ Sand feed rate: Establishes the amount of binder needed to get desired strength.
- ♦ Binder & catalyst temperature: Affects the viscosity and pumping efficiency of the binder components.
- ♦ Binder flow rate: In conjunction with the sand flow rate, determine the amount of binder on the sand and the strength of the finished core or mould. Too much binder can lead to wasteful excess and, in extreme cases, gas porosity in the castings.
- ♦ Catalyst flow rate: Determines the rate of reaction of most chemical sand binders.
- ♦ Mechanical function (vibration, motor resistance to load, motor speed etc.): Affects distribution of binder on the sand grains and output of the mixer.
- ♦ Sand size distribution: Affects the amount of binder needed to coat the sand grains.

Recommendations for Sand Selection when using Urethane binders (Ashland, 1994):

- ♦ Shape: A round grain shape provides the best physical properties for a given binder level.
- ♦ Fineness: AFS 50-80 suggested.
- ♦ pH and ADV: Sands that are strongly basic or acidic in nature may be detrimental to the curing reaction and therefore the physical properties of the cured sand.
- ♦ Moisture: Sands with moisture levels above 0.25% exhibit slower cure rates, lower ultimate core strength and poor flowability.
- ♦ Combustibles: The loss-on-ignition of the sand should be maintained below 2.0% maximum on reclaimed sand.
- ♦ Temperature: Along with catalyst level, sand temperature also controls the rate of cure. To maintain rapid cure rates at minimal catalyst levels, a sand temperature between 27-32°C should be selected.
- ♦ Segregation: Periodic changes in the sieve distribution of the sand as a result of separation of the grain sizes during handling and storage can affect the tensile strength, flowability and casting quality at a given binder level.
- ♦ Binder temperature: Part I and Part II binders should be kept at 21-27°C in cold weather.
- ♦ Isocyanate portion highly water reactive. The binders must be protected from moisture.

5.4.5 Pouring emissions

A large contributor to foundry air emissions is the use of chemically bonded moulds and cores. The main processes of concern are: core and mouldmaking, pouring and cooling. The emissions generated during mould and coremaking are generally specific to the binder system in use. The pouring and cooling emissions are less dependent on the binder, because all organic binders generate similar thermal decomposition products (Laitar, 1996). Typical decomposition products include: acrolein, aromatic isocyanates, aromatic hydrocarbons, benzene, cresols, formaldehyde, hexane, methanol, xylenes, methylene chloride, naphthalene, phenol,

styrene, toluene, polycyclic organic matter, carbon dioxide, hydroxyethyl acrylate (Rusin, 1991).

The phenolic urethane binder has a high potential for VOC emissions due to the organic content which is currently 100% of the make-up of both part I and II (Baker, 1997).

5.4.6 Sand processing, reuse and recycling

After casting, the mould material (sand) must be removed from the casting. This can be accomplished by vibration, shotblast or thermal methods. Foundry mould and core sand reclamation, after use, is necessary due to the high cost of foundry quality sand and increasing disposal costs. Figure 76 shows a flowchart of potential reclamation operations.

The American Foundrymen's Society Sand Reclamation and Re-Use Committee has defined reclamation as: The physical, chemical, or thermal treatment of a refractory aggregate to allow its re-use without significantly lowering its original useful properties as required for the application involved.

The requirements of any reclamation system are as follows:

- ♦ Lump and tramp material must be removed.
- ♦ Magnetic and non-magnetic metal must be removed.
- ♦ Inert and organic material must be reduced to an acceptable level. This level depends on the sand used, the binder system used, the metal poured, and the sand to metal ratio.
- ♦ The grain distribution of the reclaimed sand must be similar to the new sand specification used.
- ♦ Fines must be removed to a uniform level. Fines are high in both organic and inorganic impurities.
- ♦ The binder coating on the sand grain must be removed in a uniform manner. For a new coating of binder to be of maximum efficiency the sand grain surfaces must be uniform.
- ♦ The reclaimed sand should produce good quality castings, with good shake-out characteristics.

Sand reclamation techniques are classified as either primary or secondary processes (Prucha, 1988 and ETSU, 1998b).

Primary reclamation

Primary reclamation, also known as attrition or particulation, involves breaking down the sand from moulds or cores to its original grain size. This includes screening the sand, removing tramp metal, and separating and removing fines and over-sized agglomerates. The sand is cooled (if necessary) before being sent for storage, returned to the sand system or blended with new sand. Removal of fines is especially critical. Fines carry contaminants, increase the amount of binder needed and decrease the permeability. And as grain size decreases, LOI increases. Levels of LOI above 3.5% are generally not considered acceptable for moulds (Modern Casting, 1988).

Primary reclamation does not completely remove the binder from the sand surface. The main primary techniques are: shot blast; rotating drum; vibration.

Shotblasting (ETSU, 1995) involves loading the mould and casting directly into the shot blast machine. The action of the shot blast results in complete disintegration of the mould and also cleans the surface of the casting. The sand and shot are subsequently separated.

To control the build-up of binder, foundries can take several steps. These include:

- ♦ using a practical minimum binder addition to the sand on each recycle;
- ♦ ensuring efficient mixing of the sand and binder;
- ♦ using as low a sand to metal ratio as possible and delaying knockout for as long as possible to enable heat from the casting to penetrate and destroy more binder in the moulds and cores;
- ♦ ensuring that the reclamation unit is operating to provide maximum abrasion of resin from the sand grains and removing all released fines;
- ♦ ensuring an adequate addition of new sand at each cycle.

Secondary reclamation

Secondary reclamation further processes the sand to remove residual binder. The sand is returned to a quality similar to, or even better than, that of new sand. The main secondary reclamation techniques are: high energy attrition, either pneumatic, mechanical or centrifugal; wet scrubbing; thermal treatment, usually a fluidised bed (Stancliffe, 1997).

Mechanical reclamation of nobake sands usually involves both crushing the agglomerates and removal of fines. Mechanical attrition reclamation is by far the cheapest and most common method and depending on the chemical binder system in use 60-90% sand reuse is commonly achieved. Thermal reclamation ensures total sand re-use is possible with the exception of natural losses (Stancliffe, 1997).

Most current thermal reclamation plants are based on fluidised bed systems (ETSU, 1995). Particulated sand and contaminated dust is fed to the plant and forms a bed which is then fluidised and heated. The temperature to which the bed is heated depends on the method used for controlling volatile organic compounds i.e. after burning or in-chamber decomposition. The hot, treated sand is discharged to a cooler where the temperature is reduced to an acceptable level. Emissions from the plant are ducted to a bag filter.

Sand reclaiming can change the sand in many ways and will (Ruttermann, 1985):

1. Increase the spread of the grain distribution.
2. Increase the grain fineness number.
3. Increase percentage retained in the 140 screen and finer.
4. Increase the percentage retained on the 40 screen and coarser.
5. Add a loss-on-ignition (L.O.I.) percentage to the sand.
6. Add unwanted contamination constituents to the sand.

Mechanical attrition does not remove all the residual binder from the sand, so that continued re-use of reclaimed sand results in residual binder levels increasing until a steady state is reached which is determined by (Brown, 1994):

- ♦ the amount of burn-out which occurs during casting and cooling
- ♦ the effectiveness of the reclamation equipment
- ♦ the percentage of new sand added
- ♦ the type of binder used

The equilibrium of residue left on the sand is approximately expressed as:

$$P = \frac{TB}{1 - TR}$$

where

P is the maximum percentage of resin that builds up on the sand (LOI of reclaimed sand)

B is the binder addition percentage

T is the fraction of binder remaining after reclamation

R is the fraction of sand reused.

5.4.7 Sand and waste yields

Silica sand is weak. It has high thermal expansion characteristics, which can result in poor dimensional quality of castings. Phase changes that occur in the silica structure during heating and cooling cause thermal breakdown of the sand. When silica sand is subject to mechanical stress during mulling or mechanical reclamation the sand disintegrates into finer particles, called fines. These factors force foundries to dump large quantities of sand/fines to landfill (Ramrattan, 1996). Fines content should be less than 1% (Scott, 1997) and the surface area of the sand should not vary more than 5%, less is better.

The yield of a sand system is a function of sand grain durability and is unique for a given reclamation process application. Yield can only be defined within the context of quality and performance criteria for a specific sand (usable aggregate into v. usable aggregate out of the reclamation process) (AFS, 1989).

The addition of new sand requires the dumping of an equal amount of used sand to maintain the sand balance. The amount of sand to be recycled at a foundry will depend on such factors as core loads, sand to metal ratio, nature and percentage of binder, nature and percentage of catalyst, sand grain configuration and screen distribution as well as the time between metal pouring and shakeout (Modern

Casting, 1988). Typical natural losses from a foundry would be estimated at around 3-5% extreme cases may be a few percent more (Stancliffe, 1997).

Economically , the foundries desire to reduce the total sand cost which includes the purchase cost, freight cost, and disposal costs (Simpson, 1989).

The disposal of waste foundry sand can cause leachate products such as phenol leachate, acidic substances, heavy metals etc (Rusin, 1991).

Cost savings associated with identifying and reducing sand loss may be recognised in a variety of ways. Less sand waste generated means: decreased waste management costs, raw material savings (Singh, 1996).

Silica sand losses can be as much as 15% of input tonnage, attributed to the following causes (Leidel, 1988): thermal breakdown; spilled sand, contaminated with other refuse; sand adhering to castings; sand losses, due to attrition during reclamation.

Sand Properties

The important sand properties for new sand, reclaimed sand and storage and distribution are listed below.

Important New Sand Properties

- ♦ screen distribution
- ♦ grain shape
- ♦ surface area of grains
- ♦ smoothness of grain surface
- ♦ sand density, grain and bulk
- ♦ contaminants
- ♦ sand surface chemistry
- ♦ Loss-on-ignition (LOI)
- ♦ pH
- ♦ moisture
- ♦ sand durability
 - ♦ thermal shock
 - ♦ crushing or splitting
 - ♦ surface durability

Important Mechanically and Thermally Reclaimed Sand Properties

- ♦ screen distribution
- ♦ grain shape
- ♦ smoothness of grain surface
- ♦ surface area of grains
- ♦ sand density, grain and bulk
- ♦ sand surface chemistry
- ♦ LOI
- ♦ pH
- ♦ moisture
- ♦ contaminants

- ♦ base sand
- ♦ residual additives
- ♦ residual binder
- ♦ steel shot etc.

Important Factors for Sand Storage and Distribution

- ♦ temperature control
- ♦ sand blend
- ♦ sand segregation
- ♦ transport method
- ♦ moisture content

5.4.8 Cost Factors

Sand use can be a major cost for foundries. The cost factors for an existing sand practice are (FM&T, 1987):

- ♦ New sand costs (including transportation and unloading costs at the plant).
- ♦ Processing costs associated with new sand prior to use if applicable.
- ♦ On-site storage expenses for new sand.
- ♦ Material handling expenses incurred in moving new sand to point of use.
- ♦ Cost of binders and other additives used with new sand.
- ♦ Disposal costs for all dust collected during material handling and core and moulding processes where new sand is involved.
- ♦ Material handling costs incurred in reusing sand if applicable.
- ♦ Cost of handling and conveying refuse sand to storage.
- ♦ Refuse sand storage expenses.
- ♦ Refuse sand disposal costs, including handling, transportation, and dump site fees or cost of maintaining on-site pit, etc.

5.4.9 Inhibitors for magnesium alloys

Molten magnesium alloys have a great affinity for free or combined oxygen. This affinity can result in the partial or complete oxidation of the magnesium alloy if the same foundry sand was used as in other metals. The defect caused by this oxidation is called burning. Inhibitors are added to the foundry sand to prevent this reaction (AFS, 1965). The casting shown in Figure 77 was made using a mould without inhibitors and demonstrates burning defects.

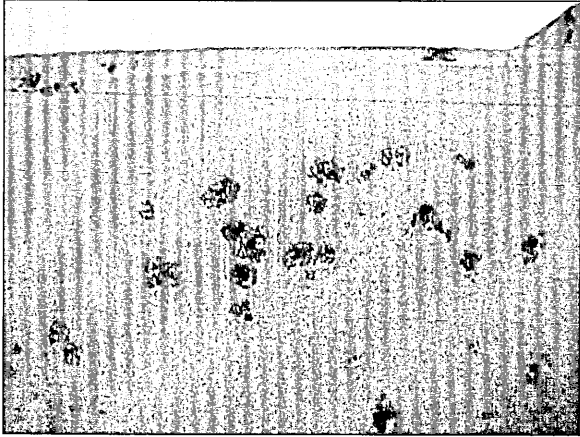


Figure 77 Burning on magnesium casting made without an inhibitor.

The mechanisms by which moulding sand inhibitors function has been ascribed to three principle reactions:

1. Formation of a protective film on the surface of the molten magnesium alloys as it enters and takes form in the sand mould.
2. Formation of a protective atmosphere in the mould cavity.
3. Formation of a protective coating around the sand grains forming the mould.

The first reaction is the most important of the three reactions. Protective atmospheres are beneficial, but are unable to confer adequate protection when heavy sections are involved. The main compounds in use are fluoride, sulphur or boron compounds including: sulphur powder, boric acid, potassium fluoroborate. The compound used by Haley Industries Limited is sodium silicofluoride also know as sodium fluorosilicate (Na_2SiF_6).

The presence of inorganic impurities in the sand mix can present problems during reclamation because inorganic impurities cannot be completely removed by thermal reclamation. The most common alternative is potassium borofluoride, however, according to Weddington and Mobley (1991) the presence of foreign agents, such as sodium or potassium compounds, on foundry sand may alter their mechanical properties when bonded with resins or clay-water binder systems. Also, depending on the inorganic contaminant this build-up can result in sand leachate toxicity (Leidel, 1996).

5.4.10 Haley Industries Ltd. sand system

This section contains a comparison of the HIL sand system to best practices.

Chemical binders

The HIL chemical binder practices were compared to chemical binder best practices (ETSU, 1998a).

A summary of the findings is as follows:

- ♦ Good quality sand is used with less than 0.1% moisture and no oil contamination.
- ♦ Fines content in the blended sand for October-December 1999 was 0.59%. This is acceptable.

- ♦ The sand used is a round grain silica sand. Contamination in the reclaimed sand is from the use of sodium silicofluoride, this gives the blended sand an average pH of 4.3.
- ♦ Sand and binder chemicals are well protected from moisture.
- ♦ Desiccant cartridges are fitted to the resin storage air vents.
- ♦ Blended sand is normally consistent as long as the relative quantities of new, mechanically reclaimed and thermally reclaimed sand are used.
- ♦ Sand temperature is not well controlled or monitored.
- ♦ Binder chemical addition rates from October-December 1999 was 0.9% based on sand weight. This is very good as typical binder additions are 1.0-2.0%.
- ♦ Binder chemicals are heated to maintain consistent temperatures.
- ♦ Mixer operators are well trained on chemical binder calibration.
- ♦ There are no records on the quantity of mixed sand wasted.
- ♦ The advantages of bulk purchasing of binder chemicals should be investigated.

In general HIL maintains good chemical binder practices. Potential areas for improvement are: sand temperature monitoring and controls, record keeping to monitor mixed sand wasted.

Sand processing and recycling

The HIL sand system consists of a shotblast primary reclamation unit, and a thermal reclaimer for secondary reclamation. This combination of reclamation equipment should be capable of maintaining good quality sand.

Sand and waste yields

The sand yield for the sand system between October and December 1999 was 21.5%. This means that 21.5% of sand used is landfilled. For October to December 1999 this resulted in 644 tonnes of sand and dust being landfilled. This waste rate is very poor and warrants further investigation. The use of inhibitors means that this waste was also leachate toxic.

Sand properties

Sand tests are conducted daily on the sand system. The sand is tested for: LOI, ADV at pH 4, ADV at pH 7, pH, sand sieve analysis.

According to Scott (1997) sand surface area measurements are more important than the sieve analysis. Surface area calculation is not conducted at HIL.

Inhibitor use

The use of inhibitor not only causes environmental issues but causes some operation and maintenance problems. The main issues are listed below.

- ♦ Most foundries thermally reclaim sand at approximately 800°C. HIL cannot reclaims its sand above approximately 500°C, above this temperature the inhibitor causes the sand to form lumps and a crystalline build-up to form along the walls of the reclaimer.
- ♦ Sodium silicofluoride is a hazardous chemical, occupational safety precautions must be taken by those who handle the chemical.

- ♦ Sodium silicofluoride is hygroscopic, this can cause difficulties during summer operation. The chemical tends to clump which can prevent it from being evenly mixed into the sand.
- ♦ Sodium silicofluoride is acidic. The phenolic urethane binder cures at a neutral to alkaline pH this means that additional catalyst must be used to cure the binder.

5.5 Data Requirements

A list of purchased materials for the foundry and their quantities is required.

5.5.1 Sand data

Existing data

Blended sand	Tested daily for LOI, ADV, pH, sieve.
Thermally reclaimed	Tested 2-3 times per week for LOI, ADV, pH, sieve.
Mechanically reclaimed (primary only)	Tested 2-3 times per week for LOI, ADV, pH, sieve.

Sand meters that measure the quantity of sand processed is read weekly on each mixer.

Data required

Daily reading of sand meters so that relative quantities of sand and inhibitor are known.

5.5.2 Fluoride data

Existing

There was no data being collected on the use of sodium silicofluoride. Calibration data from the chemical feeders are available. The operators at Mixers 5 and 6 cannot turn off the inhibitor, therefore the quantity added can be calculated using the sand flow rate and the calibration data. The operators at Mixers 1,2,3 have the capability to add inhibitor as they require. For this reason a counter for the inhibitor is required on these mixers.

Data required

- ♦ Quantity of inhibitor used at mixers 1, 2,3.
- ♦ Daily inhibitor usage at each mixer so that inhibitor inputs to the sand system can be calculated.
- ♦ Concentration of fluoride in mechanically reclaimed sand, thermally reclaimed sand, dust from main dust collector, dust from thermal reclaimer.

5.5.3 Binder data

Binder practices are generally good when compared to typical addition rates. For this reason chemical binders will not be investigated further.

5.5.4 Data collection

- ♦ Sand meters were already present on all sand mixers. In order to collect data on the inhibitor use, meters were installed on mixers 1-3.
- ♦ Sand and inhibitor meters were read daily for 3 months.
- ♦ Sand and dust samples were collected and sent to an external laboratory for analysis. Parameters measured were fluoride, sodium and fluoride leachate. The sodium readings were used solely as a quality control check.
- ♦ The thermal reclaimer records for dust production were not available for October or November.

The laboratory results obtained for the dust samples are shown below:

Dust from storage tank	Fluoride concentration (mg/kg)	Fluoride leachate concentration (mg/L)
Sample 1	29400	2590
Sample 2	25200	2730
Sample 3	55400	3080
Sample 4	44600	2570
Sample 5	23900	1670
Sample 6	46200	3290

Thermal reclaimer dust	Fluoride concentration (mg/kg)	Fluoride leachate concentration (mg/L)
Sample 1	42500	3030
Sample 2	43000	3350

According to the operators that empty the dust storage tank there is a large variation in the quality of the dust. Some dust loads appear to be largely sand sized grains, others are very fine dust. This difference in visual appearance can indicate the different quality of the dust and thus the fluoride levels.

The collected data is shown in Appendix D.

5.6 Mass and Energy Balances

For the process under examination an energy balance will not be conducted. The energy audit in the preliminary assessment did not identify any significant concerns with this process.

5.6.1 Assumptions

The sand system can be considered to be operating at steady state. The loss-on-ignition removes all sand binder and the fluoride component of the sodium silicofluoride from the sand being tested.

5.6.2 Equations

- 1) Conservation of mass: $M_i = M_o$

- 2) Total sand use = Total sand used at all mixers
- 3) Sand losses = New sand inputs
- 4) Fluoride losses = Fluoride inputs
- 5) Fluoride losses = Dust lost from sand system + Dust lost from thermal reclaimer + Air emissions from thermal reclaimer

6) Residual binder (Brown, 1994),
$$P = \frac{TB}{1 - TR}$$

where:

P = Maximum percentage of binder build-up (LOI of sand).

B = Binder addition as a percentage.

T = Fraction of binder remaining after reclamation (LOI of reclaimed sand).

R = Fraction of sand re-used.

7) Residual fluoride,
$$F = \frac{(F_{thermal})(B)}{1 - (F_{thermal})(R_{thermal})} + \frac{(F_{mechanical})(B)}{1 - (F_{mechanical})(R_{mechanical})}$$

where

F = Maximum percentage of fluoride build-up.

B = Fluoride addition as a percentage.

$F_{thermal}$ = Percentage of fluoride remaining on thermally reclaimed sand.

$F_{mechanical}$ = Percentage of fluoride remaining on mechanically reclaimed sand.

$R_{thermal}$ = Fraction of thermally reclaimed sand used.

$R_{mechanical}$ = Fraction of mechanically reclaimed sand used.

The mass balance spreadsheets are in Appendix E.

5.6.3 Conclusions

In order to meet air emission limits the Point of Impingement concentration of hydrogen fluoride must be reduced from 68.7 $\mu\text{g}/\text{m}^3$ to 4.3 $\mu\text{g}/\text{m}^3$. At a thermal reclaimer processing rate of 1.5 tonnes/hr, a maximum input of 0.038% sodium silicofluoride can be added at the mixers to achieve compliance. If the thermal reclaimer processes sand at its maximum rate of 3.0 tonnes/hr a maximum of 0.019% sodium silicofluoride can be added at the mixers.

The current maximum fluoride leachate toxicity was measured to be 3350 mg/L. The current regulatory limit is 240 mg/L but will be changing to 150 mg/L in 2001. If linear relationships are assumed between fluoride in and the leachate toxicity of the waste, a maximum input of 0.027% sodium silicofluoride would be required to meet the new leachate toxicity limit.

5.7 Alternate Practices

1. Use alternate inhibitor.
2. Treatment of hazardous solid waste and air emissions.
3. Recycle waste dust and treat air emissions.
4. Eliminate the use of sodium silicofluoride in aluminium moulds and cores.
5. Optimise and reduce the sodium silicofluoride additions in magnesium castings and eliminate its use in aluminium castings.

6. Coat magnesium moulds and cores with alcohol based coating containing inhibitor.
7. Coat magnesium moulds and cores with water based coating containing inhibitor.

5.8 Preliminary Ranking of Options

Without conducting a detailed feasibility study the ease of implementation is as follows:

1. Eliminate the use of sodium silicofluoride in aluminium moulds and cores by turning off the inhibitor feed.
2. Optimise and reduce the sodium silicofluoride additions in magnesium castings and eliminate its use in aluminium castings.
3. Use alternate inhibitor.
4. Treatment of hazardous solid waste and air emissions.
5. Recycle waste dust and treat air emissions.
6. Coat magnesium moulds and cores with alcohol based coating containing inhibitor.
7. Coat magnesium moulds and cores with water based coating containing inhibitor.

5.9 Feasibility Analysis

For the technical evaluation one particular casting has been selected as the indicator casting as to the suitability of the process. The casting selected is a helicopter main transmission for the Sikorsky Blackhawk helicopter. The casting has a pour weight of 170 kg and a finished weight of 57 kg, the casting also has heavy wall sections.

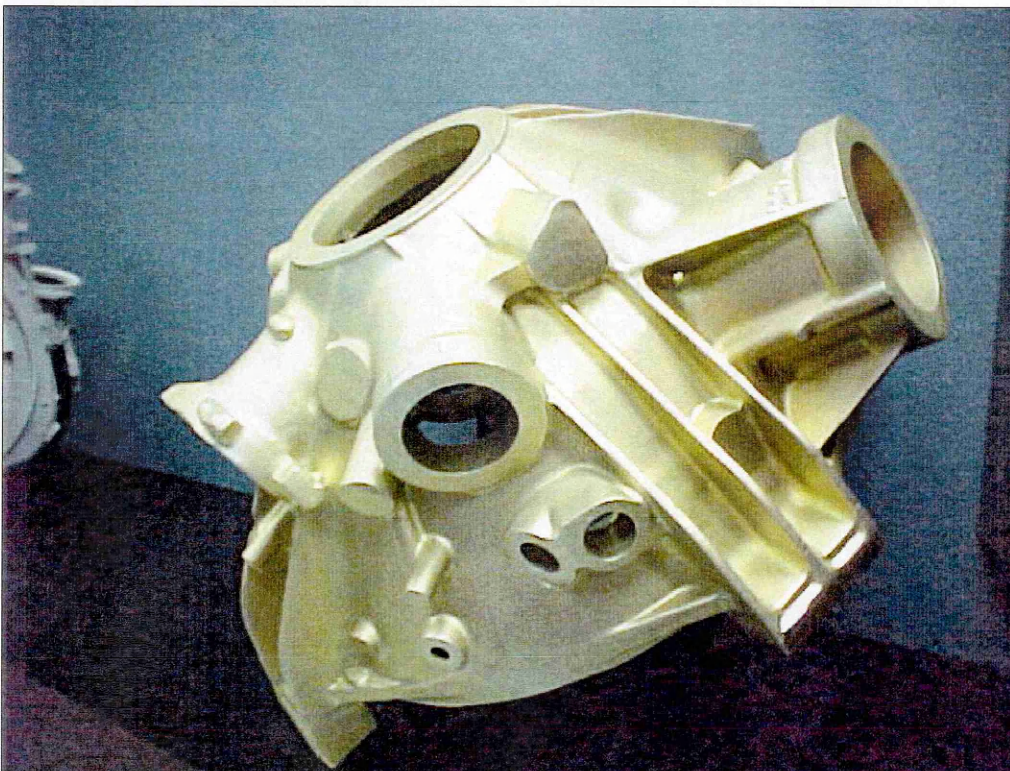


Figure 78 Helicopter main transmission casting.

5.9.1 Option 1: Use of alternate inhibitors.

Pollution prevention strategy: material input substitution or modification.

Technical evaluation

Commonly used inhibitors and the mechanism by which they protect are shown in the list below (AFS, 1965).

Protective surface film

- ♦ Sulphur, S
- ♦ Ammonium borofluoride, NH_4BF_4
- ♦ Ammonium fluosilicate, $(\text{NH}_4)_2\text{SiF}_6$
- ♦ Ammonium acid fluoride, $\text{NH}_4\text{F} \cdot \text{HF}$
- ♦ Potassium fluoborate, KBF_4
- ♦ Sodium fluoborate, NaBF_4
- ♦ Aluminium fluoride, AlF_3

Protective atmosphere

- ♦ Sulphur, S
- ♦ Sulphur dioxide, SO_2
- ♦ Boron trifluoride, BF_3
- ♦ Diethylene glycol
- ♦ Sulphur hexafluoride, SF_6

Sand grain coating

- ♦ Boric acid, H_3BO_3
- ♦ Carbon, C
- ♦ Diethylene glycol

According to (AFS, 1965) protective atmospheres or sand grain coating will not protect heavy casting sections. Another difficulty with the use of protective atmospheres is that sand moulds are porous, allowing gas to escape. This means that gas must continuously be added, which wastes the gas, or moulds must be poured in enclosed chambers. Inhibitors that coat the sand grain will prevent a reaction with thin wall castings under favourable conditions only, this means that boric acid, carbon and diethylene glycol may work in conjunction with other inhibitors but not on their own.

HIL metallurgists have continuously been looking for alternative inhibitors. Some of the chemicals that have been evaluated are:

- ♦ Sodium silicofluoride (Na_2SiF_6)
- ♦ Potassium fluoroborate (KBF_4)
- ♦ Polytetrafluoroethylene (Teflon)
- ♦ Trichlorotrifluoroethane
- ♦ Potassium aluminium fluoride ($\text{KAlF}_4 + \text{K}_3\text{AlF}_6$)

To date all alternatives to sodium silicofluoride have been rejected due to working temperature, cost, environmental or occupational health and safety reasons.

A summary of the technical evaluation criteria and the changes that the proposed option would have on production are listed below.

Technical criteria	Comments
Effect on product quality	There is very little data or literature available on the differences between the different inhibitors. Little change in product quality is expected.
Installation time and production downtime	Installation time would be short. To convert to an alternate inhibitor, existing chemical feeders could be used as long as the alternate inhibitor was added in similar quantities.
Worker health and safety	The main alternative to Na_2SiF_6 is KBF_4 . The main decomposition product of KBF_4 is boron trifluoride (BF_3). Boron trifluoride is highly toxic. Most of the boron and fluoride compounds listed as alternative inhibitors produce hazardous decomposition products. Several of the inhibitors themselves are listed as poisonous chemicals. Most of the alternatives have similar hazards to Na_2SiF_6 .
Facility space and layout	No change.
Compatibility with existing production	Existing production practices would not be affected.
Labour, expertise and skill level required for operation and maintenance	The same type of production equipment and calibration practices would be used as the current practice. Therefore no change is expected.
Utility capacities	No change.
Reliability	Same as current practices. No change.
Commercial availability	Practice currently employed in many foundries.
Proven performance in a similar application	Well proven at both Haley and many other facilities.

Environmental evaluation

Inputs	
Chemical use	Although other chemical compounds would be used, the quantities would be similar.
Energy: electricity, natural gas, compressed air	No change to current practices.
Water use	No change to current practices.
Outputs	
Waste heat	No change to current practices.
Solid wastes	The main compounds that can be used for inhibitors are boron and fluoride compounds. Similar waste problems to current practice anticipated. Waste quantity would not change.
Wastewater	No wastewater is generated through inhibitor use.
Air emissions	The thermal decomposition of alternate inhibitors

	would release sulphur, boron or fluoride emissions. The quantity would not change from current practices.
--	--

Regulatory concerns	Comments
Permitting requirements	Certificate of Approval would be needed for air emissions.
Regulatory constraints	Air emissions and solid waste limits are in effect for fluoride, boron and sulphur.
Can options meet objectives	The known alternate inhibitors function using the same mechanism as Na ₂ SiF ₆ and contain boron, fluoride or sulphur. It is unlikely that inhibitor substitution is an environmentally viable option.

Cost assessment

Costs assessment will not be carried out as this option cannot meet environmental criteria.

Conclusion

It is unlikely that this option can meet environmental objectives.

5.9.2 Option 2: Treatment of solid waste and air emissions.

Pollution prevention strategy: this option uses end-of-pipe treatment followed by disposal.

Technical evaluation

The equipment that would be required to treat the air emissions would be a dry scrubber. This consists of a gas cooling system, a reagent injection system and a fabric filter system. In order to remove hydrogen fluoride, lime would be the reagent used.

The solid waste stream could either be disposed off-site or could be stabilised and disposed of on-site.

A summary of the technical evaluation criteria and the changes that the proposed option would have on production are listed below.

Technical criteria	Comments
Effect on product quality	Existing practices would continue, therefore there would be no change to product quality.
Installation time and production downtime	Since both the solid waste treatment and the air emissions treatment are end-of-pipe solutions equipment could be installed without interrupting production. Production would have to be shut down for final ducting/piping connection only.
Worker health and safety	There would be no change from existing practices, however existing inhibitor is hazardous.
Facility space and layout	Controls could be installed at the back of the facility, thus not taking up any production space.
Compatibility with existing production	Existing production practices would not be affected.
Labour, expertise and skill level required for operation and maintenance	Frequent waste testing and potentially air monitoring would be required. This would require environmental expertise. Maintenance would have to be trained on maintaining new equipment. If the waste stabilisation were done on-site additional labour would be required.
Utility capacities	Electricity required for waste processing.
Reliability	Equipment failure or human error would result in non-compliance.
Commercial availability	Dry scrubbers are employed by many other industries. Waste stabilisation or shipment is a common practice.
Proven performance in a similar application	End-of-pipe environmental controls are well proven at many facilities.

Environmental evaluation

Inputs	
Chemical use	Inhibitor purchased quantities would not change. Stabilisation chemicals would have to be purchased for both the dry dust collector and waste stabilisation.
Energy: electricity, natural gas, compressed air	Increased energy use to drive fans on dry dust collector. Increased electricity and natural gas used to stabilise solid waste.
Water use	If waste stabilisation used some water would be used in this process.
Outputs	
Waste heat	No change to current practices.
Solid wastes	The solid waste quantity would increase if stabilisation were used due to chemical additions. Solid waste toxicity would be reduced.
Wastewater	Both solid waste and air emissions treatments would be dry processes.
Air emissions	Air emission toxicity would be reduced due to collection and treatment.

Regulatory concerns	Comments
Permitting requirements	Certificate of Approval would be needed for air emissions. If solid waste treated on site a Certificate of Approval would be required.
Regulatory constraints	Air emissions limits must be complied with.
Can options meet objectives	Yes

Cost assessment

The typical costs for baghouses are (US EPA, 2000a and 2000b):

Capital cost: \$107,000-1,190,000.

Operation and maintenance costs: \$66,000-\$387,000.

Off site solid waste disposal has been priced at \$250.00 per tonne with a transport cost of \$1200 load (25 tonne max.). Based on 1999 sand purchases of 3508 tonnes this would costs \$1,045,000.

On-site stabilisation costs are unknown, however material would have to be purchased to stabilise the fluorides; equipment would have to be purchased to mix the dust and chemicals; and additional labour would be required.

Conclusion

Although this option can meet current environmental standards it is very costly and does not eliminate the pollution at source. Regulatory changes could make this process non-compliant. Any failure of the control equipment would result in a spill to the environment.

5.9.3 Option 3: Recycle waste dust and treat air emissions.

Pollution prevention strategy: this option uses recycling of in-process substances for solid waste, air emissions control uses end-of-pipe treatment followed by disposal.

Technical evaluation

A summary of the technical evaluation criteria and the changes that the proposed option would have on production are listed below.

Technical criteria	Comments
Effect on product quality	Waste Na_2SiF_6 in sand dust may not be in available form for use. The use of large quantities of dust will reduce permeability of mould increasing potential of gas related defects.
Installation time and production downtime	Installation time and production downtime: A new sand/dust transport and storage system would have to be installed.
Worker health and safety	Increased dust in sand mix, potential for increased respirable dust.
Facility space and layout	No change.
Compatibility with existing production	Existing production practices would not be affected.
Labour, expertise and skill level required for operation and maintenance	Some environmental expertise and frequent waste testing would be required to ensure environmental compliance. Continual adjustments would have to be made depending on the dust quality.
Utility capacities	Increase in compressed air usage to transport dust.
Reliability	Equipment failure would result in non-compliance. Any changes in sand blend would affect dust quality. Process would be vulnerable to upsets thus affecting product quality.
Commercial availability	Sand and dust transportation in common use in most foundries.
Proven performance in a similar application	Similar applications not known.

This option would be unlikely to provide castings with adequate protection. This option also presumes that all fluoride is recycled and can be used indefinitely.

Environmental evaluation

Inputs	
Chemical use	Inhibitor purchased quantities would be minimal. Stabilisation chemicals for air emissions would be required.
Energy: electricity, natural gas, compressed air	Increased energy use to drive fans on dry dust collector. Increased compressed air use to transport dust.

Water use	None.
Outputs	
Waste heat	No change to current practices.
Solid wastes	Very small generation.
Wastewater	Both solid waste and air emissions treatments would be dry processes.
Air emissions	Air emission toxicity would be reduced due to collection and treatment.

Regulatory concerns	Comments
Permitting requirements	Certificate of Approval would be needed for air emissions. If solid waste treated on site a Certificate of Approval would be required.
Regulatory constraints	Air emissions limits must be complied with.
Can options meet objectives	No

Cost assessment

Costs assessment will not be carried out as option cannot meet environmental criteria.

Conclusion

This option would be unlikely to be technically or environmentally feasible.

5.9.4 Option 4: Eliminate the use of Na₂ SiF₆ in aluminium moulds and cores.

Pollution prevention strategy: operation and maintenance improvements. This would be carried out by the operators turning off the inhibitor feed to the sand mixer.

Technical evaluation

A summary of the technical evaluation criteria and the changes that the proposed option would have on production are listed below.

Technical criteria	Comments
Effect on product quality	No change. Some risk associated with operator error.
Installation time and production downtime	No additional equipment or installation required.
Worker health and safety	Reduced employee exposure to fluoride chemicals.
Facility space and layout	No change.
Compatibility with existing production	Existing production practices would not be affected.
Labour, expertise and skill level required for operation and maintenance	Operators must be trained to ensure that inhibitor is used in magnesium castings. No change in maintenance practices.
Utility capacities	No change.
Reliability	Production operators must be relied upon to reduce usage.
Commercial availability	Mixer controls already present.
Proven performance in a similar application	Process optimisation well established.

Ratio of Aluminium and Magnesium Poured by Volume.

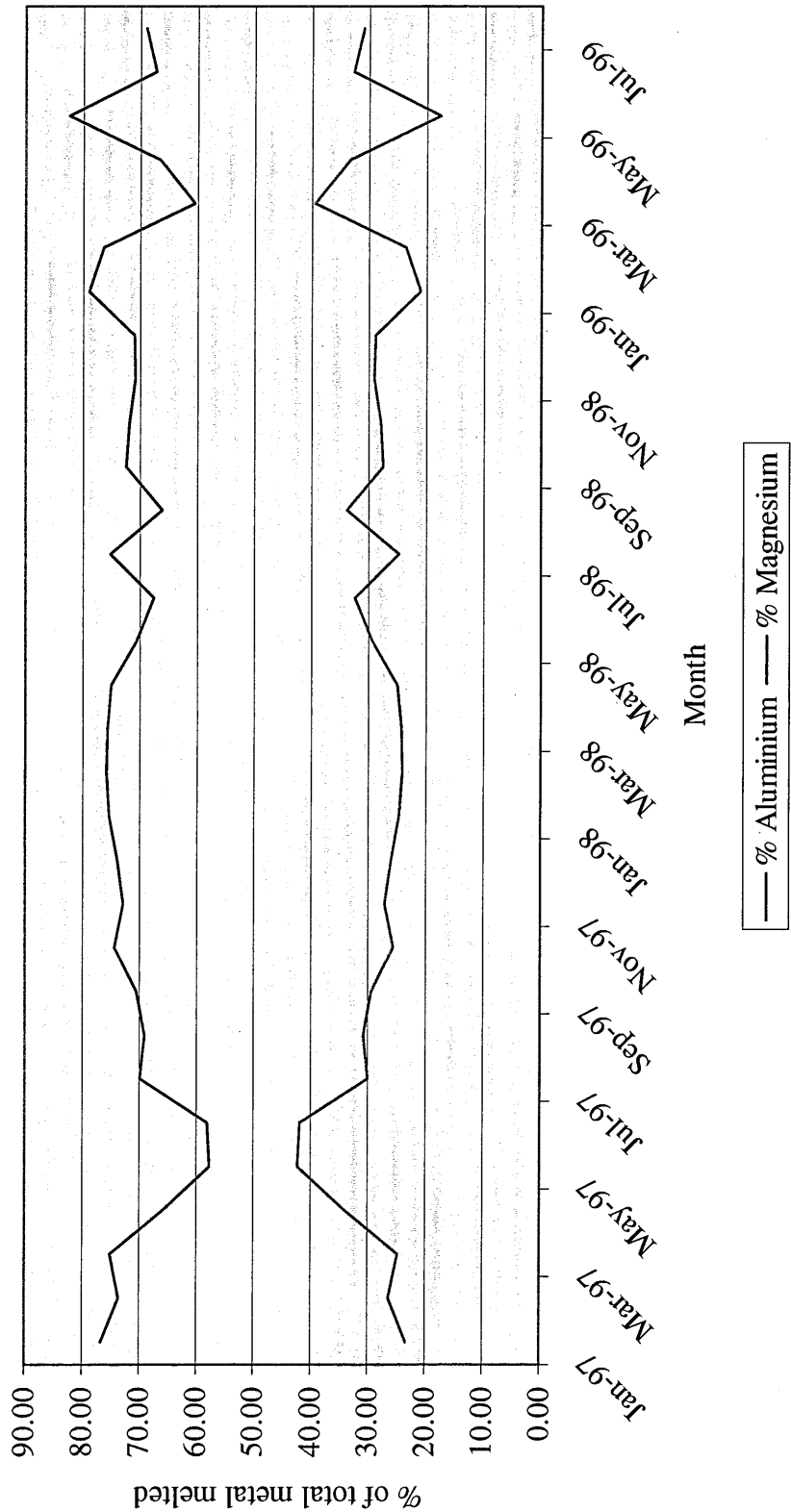


Figure 79 Graph to show relative quantities of aluminium and magnesium poured.

Environmental evaluation

A chart showing the volume of magnesium and aluminium castings poured is shown in Figure 79. From this chart it can be seen that aluminium castings represent approximately 30% of castings made. The associated inhibitor reduction would be insufficient to achieve environmental compliance.

Inputs	
Chemical use	Inhibitor purchased quantities would be reduced.
Energy: electricity, natural gas, compressed air	No change.
Water use	None used.
Outputs	
Waste heat	No change to current practices.
Solid wastes	No change to existing volume.
Wastewater	None produced.
Air emissions	Air emission toxicity would be reduced.

Regulatory concerns	Comments
Permitting requirements	None.
Regulatory constraints	Air emissions and solid waste limits are in effect for fluoride.
Can options meet objectives	No.

Cost assessment

Costs assessment will not be carried out as this option cannot meet environmental criteria.

Conclusion

According to the mass balance this option will not achieve compliance.

5.9.5 Option 5: Reduce the percentage of Na₂ SiF₆ used in magnesium castings and eliminate its use in aluminium castings.

Pollution prevention strategy: process efficiency improvements as well as operation and maintenance improvements.

Technical evaluation

A summary of the technical evaluation criteria and the changes that the proposed option would have on production are listed below.

Technical criteria	Comments
Effect on product quality	Product quality would have to be closely examined during humid ambient conditions.
Installation time and production downtime	No additional equipment or installation required.
Worker health and safety	Reduced employee exposure to fluoride chemicals.
Facility space and layout	No change.
Compatibility with existing production	Existing practices would remain unchanged.
Labour, expertise and skill level required for operation and maintenance	Operators must be trained to ensure that inhibitor is used in magnesium castings. No change in maintenance practices.
Utility capacities	No change.
Reliability	Production operators must be relied upon to reduce usage.
Commercial availability	Mixer controls already present.
Proven performance in a similar application	Process optimisation well established

The technical evaluation of this option involved experimentation to assess the minimum possible inhibitor addition that could guarantee good quality castings. The experimental procedure and results are detailed in Appendix F. The minimum inhibitor addition to ensure a good test casting was approximately 0.4% with a residual in the sand of 0.1-0.2%. This minimum was set for a small but thick wall casting. For large castings more a higher percentage of inhibitor would have to be added to ensure zero defects related to burning.

Environmental evaluation

Inputs	
Chemical use	Inhibitor purchased quantities would be reduced.
Energy: electricity, natural gas, compressed air	No change in energy consumption.
Water use	No water used in this process.

Outputs	
Waste heat	No change to current practices.
Solid wastes	Solid waste quantity would not be reduced. Solid waste toxicity would be reduced.
Wastewater	No wastewater generated.
Air emissions	Air emission toxicity would be reduced.

The inhibitor addition to achieve a good casting is too high to achieve compliance.

Regulatory concerns	Comments
Permitting requirements	Certificate of Approval would be needed for air emissions.
Regulatory constraints	Air emissions and solid waste limits are in effect for fluoride. Solid wastes would have to be monitored to ensure that compliance is maintained.
Can options meet objectives	No.

Cost assessment

Costs assessment will not be carried out as this option cannot meet environmental criteria.

Conclusion

It is unlikely that this option can meet environmental objectives.

5.9.6 Option 6: Use inhibitor in alcohol based mould and core coating.

Pollution prevention strategy: process efficiency improvements, material input substitution/modification, process redesign.

Technical evaluation

The evaluation of this option required significant casting trials. These are detailed in Appendix G.

A summary of the technical evaluation criteria and the changes that the proposed option would have on production are listed below.

Technical criteria	Comments
Effect on product quality	If coatings process is well controlled product quality can be improved.
Installation time and production downtime	Significant installation time required for conveyers, coating equipment and ventilation controls.
Worker health and safety	Negligible employee exposure to fluoride chemicals. Employee exposure to isopropyl alcohol fumes.
Facility space and layout	Major layout change required to accommodate central coating station and ventilation, treatment of off-gases.
Compatibility with existing production	Major change in production practices.
Labour, expertise and skill level required for operation and maintenance	Operators must be trained to coat moulds correctly. Maintenance must be trained to maintain coating equipment.
Utility capacities	Increase ventilation required.
Reliability	With proper equipment and operation, highly reliable process.
Commercial availability	Coating use well established in sand casting industry.
Proven performance in a similar application	Coating use well established in sand casting industry.

Environmental evaluation

Inputs	
Chemical use	Inhibitor purchase would be very low. Isopropyl alcohol purchase would increase, as would coating purchase.
Energy: electricity, natural gas, compressed air	Increased energy use for building heating to make up for air losses through additional ventilation.
Water use	No water used in this process.

Outputs	
Waste heat	Increase ventilation.
Solid wastes	No change to solid waste quantity. Solid waste would be non toxic.
Wastewater	No wastewater produced.
Air emissions	Fluoride in air emission would be virtually eliminated.

Regulatory concerns	Comments
Permitting requirements	Certificate of Approval would be needed for air emissions. Additional approvals would be required for alcohol air pollution controls.
Regulatory constraints	Air emissions and solid waste limits are in effect for fluoride, boron and sulphur.
Can options meet objectives	Yes.

Cost assessment

No cost information is currently available for this option.

Conclusion

This option can meet all the fluoride regulatory requirements. However, there is concern that long term, alcohol based coatings will not be available due to air emissions concerns.

5.9.7 Option 7: Use inhibitor in water based mould and core coating.

Pollution prevention strategy: process efficiency improvements, material input substitution/modification, process redesign.

Technical evaluation

The evaluation of this option required significant casting trials. These are detailed in Appendix H.

Foundry coatings are suspensions of a high temperature mineral or refractory in a liquid carrier (in this case water). After being applied to the core or mould surface the liquid is removed by evaporation and a layer of refractory (and inhibitor) is left on the sand surface. This layer can prevent or minimise the penetration of molten metal into the sand, can reduce burn-on and the erosion of sand, and generally improve surface finish (Vingas, 1986).

A summary of the technical evaluation criteria and the changes that the proposed option would have on production are listed below.

Technical criteria	Comments
Effect on product quality	If coatings process is well controlled product quality can be improved.
Installation time and production downtime	Significant installation time required for ovens, conveyers and coating equipment.
Worker health and safety	Negligible employee exposure to fluoride chemicals.
Facility space and layout	Major layout change required to accommodate central coating station and drying ovens.
Compatibility with existing production	Major change in production practices.
Labour, expertise and skill level required for operation and maintenance	Operators must be trained to coat moulds correctly, assemblers must be trained to inspect coating. Maintenance of coating and drying equipment is critical for water based applications.
Utility capacities	Utilities required for drying ovens.
Reliability	With proper equipment and operation, highly reliable process.
Commercial availability	Coating use well established in sand casting industry.
Proven performance in a similar application	Coating use well established in sand casting industry.

Environmental evaluation

Inputs	
Chemical use	Inhibitor use would be significantly reduced. Coatings would have to be purchased.
Energy: electricity, natural gas, compressed air	Increased energy use for drying ovens. Potential for heat recovery.
Water use	Coating are premixed, very little water used.

Outputs	
Waste heat	Waste heat would be rejected from the drying ovens.
Solid wastes	The solid waste quantity would not change, however fluoride would be virtually eliminated.
Wastewater	No wastewater generated.
Air emissions	Fluoride air emissions would be virtually eliminated.

Regulatory concerns	Comments
Permitting requirements	Certificate of Approval would be needed for air emissions.
Regulatory constraints	Air emissions and solid waste limits are in effect for fluoride, boron and sulphur.
Can options meet objectives	Yes.

Based on the casting trials and production data (1999) it was estimated that the average coating use would be 54 l/day. Assuming a density of 1.9 kg/l and 250 production days per year a total of 13500 l/yr of coating would be used. The large casting trials used 4% inhibitor. This would mean that approximately 1030 kg of inhibitor would be used per year, representing a 99.1% decrease. This decrease would bring both the solid waste and the air emissions well below regulatory limits.

Cost assessment

Although detailed costs are not well established at this time, the following estimates can be made.

Capital costs (purchase and installation)	\$ (Canadian)
Purchase of coating equipment (based on quote), 4 units	\$13,800
Conveyer relocation (estimates)	\$100,000
Drying ovens (estimated maximum)	\$400,000
Operating costs	
Estimated 2 additional people per shift (2 shifts)	\$200,000
Calibration of equipment	similar to existing process
Savings on finishing costs (approx. 4 people). Most foundries use coating to reduced casting finishing costs.	-\$200,000
Coating purchase cost (estimated based on current coating costs)	\$40,000
Inhibitor costs	\$700

Conclusion

This option is the only option that eliminates the fluoride toxicity of both the air and the solid waste without adding any other environmental issues.

5.10 Optimisation

Only three of the evaluated options are capable of achieving environmental compliance with respect to fluoride. The options are:

Option 2: Treatment of hazardous solid waste and air emissions.

Option 6: Coating magnesium mould and cores with an alcohol based coating containing inhibitor.

Option 7: Coating magnesium mould and cores with a water based coating containing inhibitor.

Table 37 shows a comparison of these three options.

Table 37 Comparison of three options that meet environmental criteria.

	Option 2 Treatment of hazardous solid waste and air emissions.	Option 6 Coating magnesium mould and cores with an alcohol based coating containing inhibitor.	Option 7 Coating magnesium mould and cores with a water based coating containing inhibitor.
Production risk	No change	Potential for alcohol to damage sand binder. Any residual alcohol could result in casting defects. Improper control of coating could cause casting defects.	Improper control of coating could cause casting defects.
Environmental risk	Equipment failure or poor maintenance practices would mean potential non conformances.	Failure of ventilation air emissions control equipment could result in non conformances.	No environmental failure modes.
Warehousing	No change	Reduced warehouse space needed for coating.	Reduced warehouse space needed for coating.
Energy costs	Energy used to run control equipment.	Increased ventilation and drying equipment required. Increase in energy use.	Drying equipment required. Increase in energy use.
Material purchases	No change	Alcohol based coating estimated to cost \$80,000 per year.	Water-based coating estimated to cost \$40,000 per year.
Occupation health and safety	Employee exposure to hazardous chemicals in manufacturing area is unchanged. Increased maintenance exposure.	Employee exposure to fluoride chemicals reduced significantly. Potential to increase exposure to alcohol fumes.	Employee exposure to fluoride chemical reduced significantly. No other hazards introduced.
Labour	Increased labour to treat and handle sludges and by-products from control equipment.	Increased labour to coat cores and moulds. Potential to reduce casting processing labour.	Increased labour to coat cores and moulds. Potential to reduce casting processing labour.
Calibration	Calibration of 6 mixers, 3 days per week.	Calibration of 2 coating tanks daily.	Calibration of 2 coating tanks daily.

5.11 Reporting and Evaluation

The option selected at this point is Option 7, as it is the only option that ensures compliance without introducing other environmental issues to the site. Further optimisation is needed before this becomes a production process.

Option 2 has very high operation costs associated with it. This option leaves Haley vulnerable to non-compliances in the event of control equipment failure. Any future regulatory changes that required a pollution prevention approach could not be complied with using this option.

Option 6 requires a significant change to the manufacturing process. This change would increase labour costs in the foundry but decrease material costs. Increased health and safety risk associated with the use of isopropyl alcohol would also result. The metalcasting industry as a whole is generally changing coatings from alcohol base to water base due to volatile organic compound concerns. If this option was implemented the fluoride problems would be dealt with.

Option 7 requires a very significant change to the manufacturing process. The change would increase labour costs in the foundry, but material costs would be lowered considerably. Other sodium silicofluoride related problems such as thermal reclaimer clumping, sodium feeder plugging and operator exposure would be eliminated. Coatings are most often used for improving casting surface finish. Improving the surface finish would decrease casting clean-up costs thus minimising the increase in labour. A plant layout change would have to be made to accommodate drying ovens. However, environmentally this option is by far the best as it eliminates the fluoride problems at source without introducing new environmental issues.

Table 38 shows a comparison of all options identified.

Table 38 Summary of Technical and Environmental Feasibility Criteria

Technical Evaluation Criteria	Option 1 Use of alternate inhibitors.	Option 2 Treatment of solid waste and air emissions.	Option 3 Recycle waste dust and treat air emissions.	Option 4 Eliminate the use of Na₂ SiF₆ in aluminium moulds and cores.	Option 5 Reduce the percentage of Na₂ SiF₆ used in magnesium castings and eliminate its use in aluminium castings.	Option 6 Use inhibitor in alcohol based mould and core coating.	Option 7 Use inhibitor in water based mould and core coating.
Effect on product quality.	Little change in product quality.	No change.	Waste Na ₂ SiF ₆ in sand dust may not be in available form for use. The use of large quantities of dust will reduce permeability of mould increasing potential of gas related defects.	No change. Some risk associated with operator error.	Product quality would have to be closely examined during humid ambient conditions.	If coatings process is well controlled product quality can be improved.	If coatings process is well controlled product quality can be improved.
Installation time and production downtime.	Installation time would be short. To convert to an alternate inhibitor, existing chemical feeders could be used as long as the inhibitor was added in similar quantities.	Installation time would be short, as both air emissions and waste treatment are end-of pipe solutions the production downtime would be minimal.	A new sand/dust transport and storage system would have to be installed.	No additional equipment or installation required.	No additional equipment or installation required.	Significant installation time required for conveyers, coating equipment and ventilation controls.	Significant installation time required for ovens, conveyers and coating equipment.
Worker health and safety.	Most inhibitors produce hazardous decomposition products.	No change	Increased dust in sand mix, potential for increased respirable dust.	Reduced employee exposure to fluoride chemicals.	Reduced employee exposure to fluoride chemicals.	Negligible employee exposure to fluoride chemicals. Employee exposure to isopropyl alcohol fumes.	Negligible employee exposure to fluoride chemicals.
Facility space and layout.	No change.	Controls can be placed at the back of the facility, thus not taking up any production space.	No change.	No change.	No change.	Major layout change required to accommodate central coating station and ventilation, treatment of off-gases.	Major layout change required to accommodate central coating station and drying ovens.
Compatibility with existing production.	Existing production practices would not be affected.	Existing production practices would not be affected.	Existing practices would remain unchanged.	Existing practices would remain unchanged.	Existing practices would remain unchanged.	Major change in production practices.	Major change in production practices.
Labour, expertise and skill level required for operation and maintenance.	No change.	Some environmental expertise and frequent waste testing would be required to ensure environmental compliance.	Some environmental expertise and frequent waste testing would be required to ensure environmental compliance.	Operators must be trained to ensure that inhibitor is used in magnesium castings. No change in maintenance practices.	Operators must be trained to ensure that inhibitor is used in magnesium castings. No change in maintenance practices.	Operators must be trained to coat moulds correctly. Maintenance must be trained to maintain coating equipment.	Operators must be trained to coat moulds correctly, assemblers must be trained to inspect coating. Maintenance of coating

							and drying equipment is critical for water based applications.
Utility capacities.	No change.	Electricity required for waste processing.	Increase in compressed air usage to transport dust.	No change.	No change.	Increase ventilation required.	Utilities required for drying ovens.
Reliability.	Same as current practices.	Equipment failure would result in non-compliance.	Any changes in sand blend would affect dust quality. Process would be vulnerable to upsets thus affecting product quality.	Production operators must be relied upon to reduce usage.	Production operators must be relied upon to reduce usage.	With proper equipment and operation, highly reliable process.	With proper equipment and operation, highly reliable process.
Commercial availability.	Practice currently employed in many foundries.	Solid waste stabilisation chemicals available. Air emissions controls commercially available.	Sand and dust transportation in common use in most foundries.	Mixer controls already present.	Mixer controls already present.	Coating use well established in sand casting industry.	Coating use well established in sand casting industry.
Proven performance in a similar application.	Well proven at both Haley and many other facilities.	End-of-pipe environmental controls are well proven at many facilities.	Similar applications not known.	Process optimisation well established.	Process optimization well established	Coating use well established in sand casting industry.	Coating use well established in sand casting industry.
Permitting requirements.	Certificate of Approval needed for air emissions.	Certificates of Approval required for both air emissions controls and waste treatment.	Certificate of Approval needed for air emissions.	None.	None.	Certificate of Approval required for VOC controls and ventilation.	Certificate of Approval required for drying ovens.
Regulatory constraints.	Air emissions and solid waste limits for fluoride, boron and sulphur.	Air emissions and solid waste limits for fluoride.	Air emissions and solid waste limits for fluoride.	Air emissions and solid waste limits for fluoride.	Air emissions and solid waste limits for fluoride.	Air emissions limits for VOC's	None.
Can option meet objectives?	No	Yes	No	No	No	Yes	Yes

5.12 Implementation

This project has not yet been implemented. Casting trials are ongoing to test different coating application methods and different types of coatings.

5.13 Process Control

Although the project has not yet been implemented, process control measures have been investigated. There are three measures for coatings: baume, density and viscosity. Haley has purchased equipment to evaluate the suitability of the measures to its requirements.

5.14 Compare results to initial objectives

It has been estimated that the final change over for this project will be September 2001. Based on current projections this project will achieve all targets, however these will be evaluated after the project is implemented.

5.15 Discussion and Conclusions

In general the pollution prevention methodology was very effective at assessing this case study. Figure 80 shows the developed methodology with the steps carried out in the case study highlighted. Some difficulty was encountered carrying out the following steps: data collection, technical, environmental and economic evaluation.

The difficulties encountered when collecting data centered around data availability and cost of collecting data that was not readily available. At the beginning of this case study there was no accurate data on the use of sodium silicofluoride beyond mixer calibration data and purchased quantities. The available data did not give information on usage patterns. A considerable number of sand samples were submitted for laboratory analysis, individually the sample analysis costs are low but with the number of samples required to get significant data the costs increase quickly. The technical evaluation of several options involved process experimentation. Difficulty was encountered in getting production time allotted to test samples. Some of the data required for the life cycle inventory and the cost assessment was not available at all. For this reason a qualitative analysis was carried out.

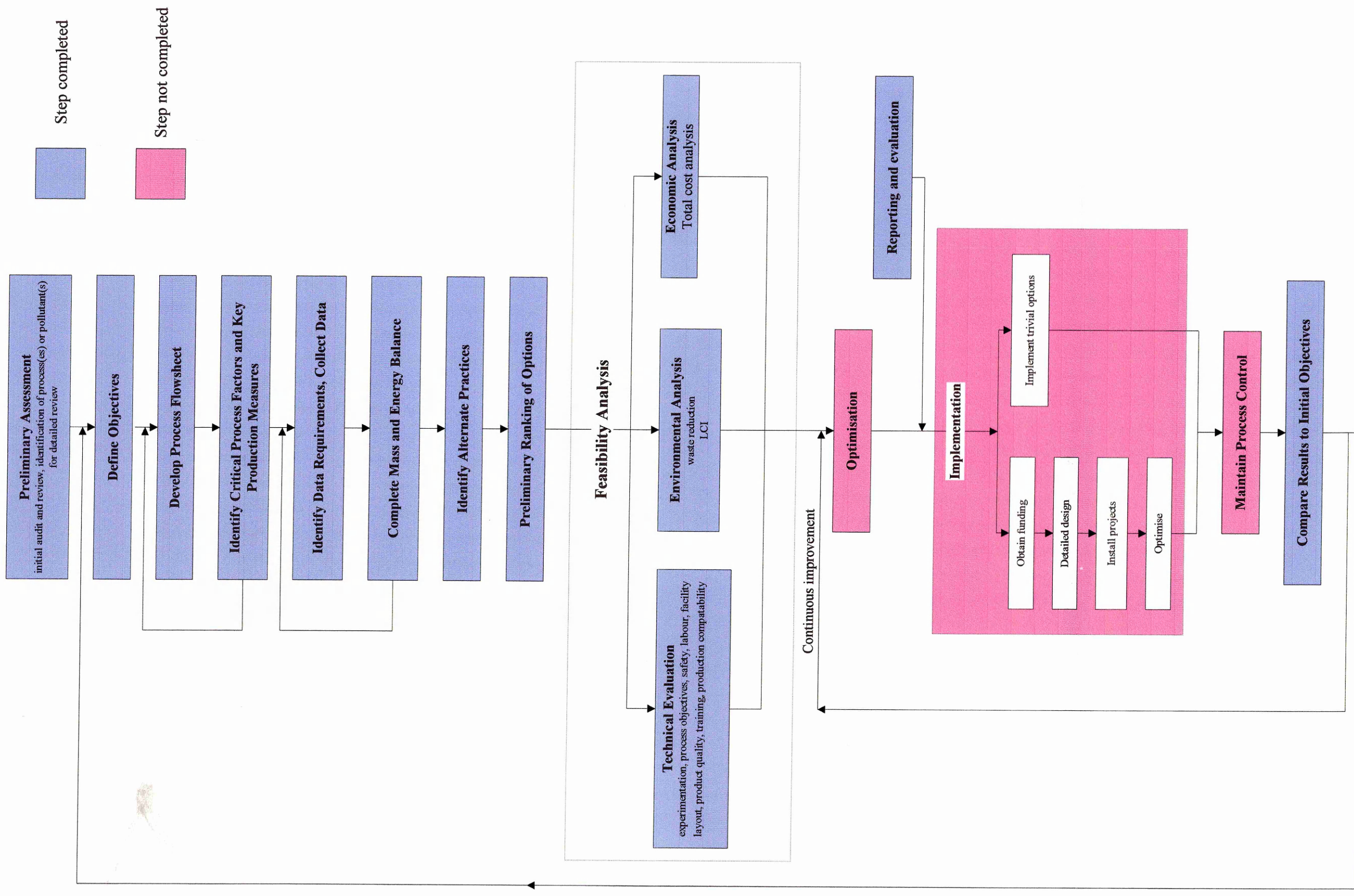
The latter stages of the developed methodology were not adequately tested by this case study. Due to the amount of development required on the coating process, the implementation of this project will continue well beyond the completion of this thesis. However, by following the methodology, new options for eliminating fluoride emissions and waste were generated.

The change from adding inhibitor to the bulk of the sand to adding the inhibitor in a coating will result in a considerable reduction in inhibitor usage. This new process is

a significant change in the way cores and moulds are made at HIL. Improper mould and core coatings can result in significant scrap castings, however good coating practices can improve casting quality. There is much work to be done at HIL to ensure that the new process is thoroughly tested and that the new process layout is well thought out.

Operating costs will probably increase, however, it should be noted that the current method of handling the waste is not in compliance and that the selected option is significantly less costly than environmental controls.

Pollution Prevention Methodology for the Metalcasting Industry



6 DISCUSSION

The initial investigation in this project was to determine the characteristics of the metalcasting industry particularly with respect to environmental issues and the manufacturing processes used. The initial investigation into the metalcasting industry showed that the main characteristics of the industry were: metalcasting is dominated by small business; the industry producing diverse products and using many different processes (almost all metals and alloys can be cast); the industry having a high product scrap rate (>10%); metalcasting is energy intensive and produces a number significant air, land and water emissions; the industry is vulnerable to increasing environmental costs; there is a lack of pollution prevention expertise in the industry. From this information it was determined that a methodology needed to be developed that could be used by the metalcasting industry to implement pollution prevention solutions to environmental problems. The methodology had to provide environmental solutions at a cost that allowed companies to continue profitable operations, with continued improvements in quality on a long-term basis.

The methods used to reduce pollution to a minimum in other industries were identified. The methods being: preliminary assessment; process flowsheets; mass and energy balance; manufacturing process understanding; process integration, synthesis and design; pinch methods; exergy; energy and resource methodology; life cycle assessment; total cost assessment; potential failure mode and effects analysis; decision making; modelling and simulation approaches.

The criteria selected to evaluate the applicability of these methods to the metalcasting industry were:

- ♦ the methodology must consider all waste streams, sources and costs
- ♦ the method had to be suitable for both high production and jobbing shops
- ♦ the method had to be usable by both foundry personnel and environmental specialists
- ♦ the data required by the method had to be obtainable within available personnel and financial resources.

The evaluation of the methods resulted in the following selections: preliminary assessment, process flowsheets, mass and energy balance, manufacturing process understanding, life cycle assessment, total cost assessment, potential failure mode and effects analysis. The methods were combined into an ordered methodology that was presented as a flowchart. The main steps in the developed methodology are:

- ♦ Preliminary assessment
- ♦ Definition of objectives
- ♦ Development of process flowsheet
- ♦ Identification of critical process factors and key production measures
- ♦ Identification of data requirements and data collection
- ♦ Completion of mass and energy balances
- ♦ Identification of alternate practices
- ♦ Preliminary ranking of options
- ♦ Feasibility analysis: technical, environmental, cost

- ♦ Optimisation
- ♦ Implementation
- ♦ Comparison with the initial objectives.

There were several differences between the developed methodology and existing methodologies for other industry sectors. The differences between existing methodologies and the one developed in this thesis are:

- ♦ the development of the process flowsheet is specified
- ♦ the identification of significant process factors is not contained in other methodologies
- ♦ the data collection step is placed after the process flowsheet and the identification of significant process factors
- ♦ the techniques for feasibility analysis have been specified
- ♦ the implementation step has been specified
- ♦ multiple feedback loops have been used to show the iterative nature of the detailed assessment.

In order to test the developed methodology, the environmental issues at a working metalcasting facility were investigated by applying the methodology to Haley Industries Ltd.

The main issues that emerged from this application and needed to be addressed at the facility were:

1. The sand waste was the largest waste stream and was classified as hazardous waste due to high levels of fluoride. The fluoride (inhibitor) was added to the sand to eliminate burning defects in magnesium castings.
2. The sanitary sewage treatment facility was not achieving allowable discharge limits.
3. Large use of sulphur hexafluoride in the melting and pouring area had high cost and released significant quantities of greenhouse gases.
4. Source reduction and separation of waste was required to meet environmental regulations and to reduce landfillable quantities
5. There was very little data on air emissions. A detailed review of the facility air emissions was required.
6. High heating and ventilation costs needed further investigation.

The issue selected for further in-depth investigation was the reduction of toxicity of the sand waste. The objectives set for the detailed assessment were:

1. To render the sand system waste to be non-hazardous
2. To meet required air emissions standards for fluoride
3. To assess the waste and material reduction potential in the sand system.

Sodium silicofluoride is added to sand moulds and cores to prevent casting defects in magnesium castings. The sodium silicofluoride was creating large quantities of hazardous solid waste and air emissions from the sand system. The application of the methodology identified seven alternate processes. The analysis of these alternate identified only three of these processes that could meet environmental objectives. The selected option involves adding inhibitor chemical to a surface coating on the

sand, thus reducing emissions by 99%. The benefits from selecting this option over traditional emissions controls are: reduced material purchase costs, reduced environmental compliance costs, reduced environmental and occupational risks, potential to improve product though improved surface finish.

The methodology was successful at analysing the problem and identifying potential solutions. An evaluation of each step of the methodology follows:

- ♦ The objectives of the project were defined based on regulatory criteria. These criteria provided goals that had to be met. This step is necessary in any project and no problems were encountered in this step.
- ♦ Development of the process flowsheet: four flowsheets were developed in order to show the complete process. The process flowsheets formed a vital part of the analysis because once completed it produced an easy to use representation of the process. During the development of these flowsheets it was found that many foundry personnel and staff did not have a good understanding of the process.
- ♦ Identification of critical process factors and key production measure: This step involved literature searches into available data. There was very little background data available on this case study. The study of literature revealed best practices for many processes and revealed solutions used by other foundries on similar problems. This stage helped to gain a good understanding of the process and what affects changes can have, it also helped to identify potential alternate practices.
- ♦ The identification of data attempted to streamline the data that needed to be collected. This step was quite successful and allowed the user to only collect and analyse meaningful data. Although data collection was time consuming for this project there was very little extraneous data collected.
- ♦ The mass balance helped when analysing the feasibility of several options. It helped provide a benchmark of the current situation against what had to be achieved.
- ♦ The identification of alternate practices is a well established step used in many other methodologies. Some of the generated options were identified through the identification of critical process factors.
- ♦ The preliminary ranking of option was carried out based on the ease of implementation. Most of the most favourable options were rejected during the feasibility study. This step was not particularly useful for this project, however, it may be more valid in projects with options that stand out as being able to improve environmental performance at a low cost. This step needs further evaluation.
- ♦ The technical evaluation varied greatly in the time taken and work required to achieve a meaningful result. When the option being considered was a commonly used technology the technical feasibility did not require much investigation. Options that were generated that were innovative or unique to the facility under investigation needed considerable testing. This step is absolutely essential to any pollution prevention methodology. The difficulty encountered here was the question of "What is required to assess the feasibility of this process?" Although this can be unique to each project, there should be guidelines for carrying out this step. These might include experimental guidelines for the industry or simply a list of factors to be examined.

- ♦ The environmental analysis was supposed to have involved a life cycle inventory. This proved very difficult to do. The data required was not available. The mass balance proved to be very useful as it showed what the targets were to achieve compliance for that process. Further investigation is required into this step.
- ♦ The economic analysis encountered similar difficulties to the environmental analysis. Additional difficulties were found with billing and production dates. Financial data frequently used different time periods, production months were not consistent with calendar months. Economic analysis is frequently the most important step of a project as it can determine whether a project is financially viable.
- ♦ The optimisation and implementation steps were not tested.

Overall the methodology was effective, however further development and testing required.

The case study relates quite well to the industry as a whole. The use of inhibitor in sand castings is not a common practice, however the use of additives to prevent casting defects is a common practice. Sand casting represents approximately 60% of the total tonnage of castings shipped. Thus the fact that Haley Industries Ltd. is a sand casting facility using commonly used binder systems means that the benefits of the methodology should be similar to other sand casting facilities.

The methodology developed in this thesis comes at a time when more stringent regulations restricting pollutant emissions are being passed by regulatory authorities and current regulations are being more strictly enforced. Some regulatory authorities are developing regulations that require the pollution prevention approach to reduce or eliminate the use of some chemicals and pollutants.

The developed methodology addresses many of the issues identified in the problem statement. The methodology involves steps to identify, quantify and evaluate environmental issues and solutions for the best environmental and economic solution.

Pollution prevention solutions are not always easy to implement, as shown in the case study. The purchase, maintenance and treatment of by-products from end-of-pipe controls is expensive. Controls are often simple to install with only a minimum disruption to production processes. Pollution prevention solutions to environmental issues have both environmental and economic benefits, these benefits are not always easily visible or quantifiable. In order to gain the maximum benefits from a pollution prevention assessment one must attempt to look and quantify the environmental and economic benefits, the developed methodology has achieved this.

7 CONCLUSIONS

The developed pollution prevention methodology for the metalcasting industry provides a systematic method to analyse environmental issues at metalcasting facilities and to develop solutions that are both environmentally and cost effective.

The benefits that can be gained from the application of this methodology are:

- ♦ Reduced waste, storage, handling, treatment and disposal costs.
- ♦ Reduced raw material and feedstock purchasing costs.
- ♦ Reduced operating costs through better management and production efficiencies.
- ♦ Reduced usage of energy, water and other resources.
- ♦ Lower capital expenditure for non-productive equipment.
- ♦ Reduced environmental compliance costs.
- ♦ Enhanced casting yield, reduced casting defects.
- ♦ Decreased regulatory reporting requirements .
- ♦ Lowered housekeeping costs.

During the course of this thesis the following was accomplished:

- ♦ The environmental issues in the metalcasting industry were investigated.
- ♦ The manufacturing processes used in the metalcasting industry were investigated.
- ♦ The methodologies used to reduce pollution to a minimum in other industries were investigated.
- ♦ An ordered methodology to complete pollution prevention assessments at metalcasting facilities was developed.
- ♦ The methodology was tested at a working metalcasting facility (Haley Industries Ltd.).
- ♦ An innovative solution was found to a complex environmental problem by improving the manufacturing process.

7.1 Recommendations for further work

- ♦ Develop a standard simple method for conducting a life cycle inventory.
- ♦ Test the methodology out on other types of casting facilities.
- ♦ Test methodology for ease of use by foundry process people.
- ♦ Develop recommendations for the type of data that should be routinely collected at metalcasting facilities.
- ♦ Develop a guideline for conducting technical feasibility analysis at casting facilities.
- ♦ Develop a cost model to provide reliable information for cost benefit analysis.

REFERENCES

- AISCO Inc. Burlington, Ontario, *Investigation of Plant Ventilation Systems*: Report for Haley Industries Limited. March 1989, not published.
- American Foundrymen's Society (1988). *Casting Buyer's Guide*, 1st edition.
- American Foundrymen's Society (1995). *Foundry Industry Research Plan – 1995*.
- American Foundrymen's Society (1998). *1999 Metalcasting Forecast and Trends*.
- American Foundrymen's Society. (1965). Sand Practices for Magnesium Alloys. *AFS Recommended Practices for Sand Casting Aluminum and Magnesium Alloys*.
- American Institute of Chemical Engineers (AIChE). (1999), *Total Cost Assessment methodology and internal managerial decision making tool*. American Institute of Chemical Engineers.
- Archer, Hugh V., Wolff, Margeret L. et al. (1994). Foundry calculates the value of pollution prevention. *Water Environment and Technology*, June 1994, 59-61.
- Ashland Chemical (1994). *Pep Set® No-Bake Binders*, Technical Bulletin, Foundry Products Division, Ohio.
- ASM International (1988). *Metals Handbook*, Ninth Edition, Volume 15 Casting.
- Baker, Derek (1997). *Metal Casting and Surface Finishing*, Jan/Feb 1997.
- Bates, C. (1997). Personal communication. In: *Energy and Environmental Profile of the U.S. Metalcasting Industry*. September 1999. Available from www.oit.doe.gov/metalcast
- Blanchard, B. S. and Fabrycky, W.S. (1990). *Systems Engineering and Analysis*. 2nd edition, Prentice Hall, ISBN 0-13-880758-2.
- Boguski, Terrie., Hunt, Robert et. al. (1996). LCA methodology. In: *Environmental Life-Cycle Assessment*. edited by Mary Ann Curran, McGraw-Hill.
- Boustead, I. and Hancock G.F. (1979). *Handbook of Industrial Energy Analysis*. Ellis Horwood Limited.
- Brown, John R. ed. *Foseco Foundryman's Handbook*, 10th edition, Butterworth-Heinemann, 1994.
- Bundy Environmental Technology (2000). *Dry Scrubber Systems*. www.bundyenvironmental.com.

Buzan, Tony and Buzan Barry. (1993) *The Mind Map Book: Radiant thinking*. London: BBC books.

Cast Metals Coalition (CMC). (1995). *Beyond 2000: A vision for the American metalcasting industry*. Available from American Foundrymen's Society, Des Plaines, Illinois or www.oit.doe.gov/metalcast/mcvision

Cast Metals Coalition (CMC). (1998). *Metalcasting Industry Technology Roadmap*. Available from American Foundrymen's Society, Des Plaines, Illinois.

Castels, F. et. al. (1994). Life Cycle Inventory Analysis of Energy Loads in Chemical Processes. In: *Pollution Prevention via Process and Product Modifications*. edited by M.M. El-Halwagi and D.P. Petrides, AIChE Symposium Series Vol. 90.

Chase, Richard and Aquilano, Nicholas. (1995). *Production and Operations Management: Manufacturing and Services*. 7th edition, Irwin. ISBN 0-256-16546-7.

Chrysler Corporation, Ford Motor Company, General Motors Corporation. (1995). *Potential Failure Mode and Effects Analysis (FMEA) Reference Manual*. Automotive Industry Action Group.

Church & Trought Inc.(CTI). (2000). *Thermal Sand Regenerator Stack Sampling Program*. Prepared for Haley Industries Ltd. (unpublished).

Clegg, A.J. (1998). *Sustainable development: The implications and opportunities for the foundry industry*, Foundryman, 91(2), February 1998.

Clift, R., Azapagic, A. (1999). The Application of Life-Cycle Assessment to Process Selection, Design and Operation. In: *Tools and Methods for Pollution Prevention*. edited by Subhas Sikdar and Urmila Diwekar. The Netherlands: Kluwer Academic Publishers, 69-84.

Cohen, T. and Allen, D. (1992). An integrated approach to process waste minimisation research. *Journal of Hazardous Materials*, 29, 237-253.

Dorfmueller Anton. (1992). World Foundry Congress Focuses on Environmental Control, Reuse, *Modern Casting*, December 1992.

Dunbar, W.R and Lior N. and Gaggioli R.A. (1992). The Component Equations of Energy and Exergy. *Journal of Energy Resources Technology*, Vol. 114, March 1992, 75-83.

El-Halwagi, M. (1999). Sustainable Pollution Prevention Through Mass Integration. In: *Tools and Methods for Pollution Prevention*. edited by Subhas Sikdar and Urmila Diwekar. The Netherlands: Kluwer Academic Publishers, 233-275.

El-Halwagi, Mahmoud M. (1997). *Pollution Prevention through Process Integration*. Academic Press.

Energetics (1999). *Energy and Environmental Profile of the U.S. Metalcasting Industry*. September 1999. Available from www.oit.doe.gov/metalcast/

Envirowise (2000). *Environmental Legislation Affecting the Foundry Industry*. Update October 2000. Reference note 089. Available from www.envirowise.gov.uk.

Eskamani, G. (1999). Pollution Prevention Assessment Tools for Manufacturers. In: *Tools and Methods for Pollution Prevention*. edited by Subhas Sikdar and Urmila Diwekar. The Netherlands: Kluwer Academic Publishers, 343-365.

ETSU. (1995). *EG 4 Chemically Bonded Sand: Use and Reclamation*, Environmental Technology Best Practice programme, available through ETSU, Oxford.

ETSU. (1995). *Foundry Energy Consumption*. Environmental Technology Best Practice Programme, available through ETSU, Oxford.

ETSU. (1996). *GG142 Improving Metal Utilisation in Aluminium Foundries*. Environmental Technology Best Practice Programme, available through ETSU, Oxford.

ETSU. (1998a). *GG104 Cost Effective Management of Chemical Binders in Foundries*. Environmental Technology Best Practice Programme, available through ETSU, Oxford.

ETSU. (1998b). *GG119 Optimising Sand Use in Foundries*. Environmental Technology Best Practice Programme, available through ETSU, Oxford.

Foundry Management and Technology (1999). *Databook 1999*, Penton publications.

Foundry Management and Technology. (1987). *Sand/Binders/Sand Preparation*. *Foundry Management and Technology*, Penton Publications, 12/87, D3-D10.

Freeman, Harry M. (1997). *Industrial Pollution Prevention Handbook*. McGraw-Hill, Inc.

Friedler, F. Varga, J.B. et al. (1994). Algorithmic Approach to the Integration of Total Flowsheet Synthesis and Waste Minimisation. In: *Pollution Prevention via Process and Product Modifications*. edited by M.M. El-Halwagi and D.P. Petrides, AIChE Symposium Series Vol. 90.

Gani, R. Harper, P.M. (1999). Computer aided product design and pollution prevention through substitution. In: *Tools and Methods for Pollution Prevention*. edited by Subhas Sikdar and Urmila Diwekar. The Netherlands: Kluwer Academic Publishers, 299-315.

Ghosh A.K. and Dutta S.P. (1993). Sustainable Manufacturing for the Foundry Industry. *American Foundrymen's Society Transactions*, Paper 930114, 71-75.

Gizyn, William (2000). *Phytotoxicology 1999 Investigation: Timminco Metals – Ross*. Report No. SDB-028-3511-2000. Ontario Ministry of the Environment. (unpublished).

Goodway, Martha. (1988). History of Casting. In: *Metals Handbook*, Volume 15, Casting, 9th edition, ASM International, 15-23

Harceag V, Winckelbauer G. (1999). Pollution prevention: an opportunity for the Romanian iron and steel industry. In: *Tools and Methods for Pollution Prevention*. edited by Subhas Sikdar and Urmila Diwekar. The Netherlands: Kluwer Academic Publishers, 39-49.

Henley, Ernest and Rosen, Edward (1969). *Material and Energy Balance Computations*. New York, Wiley.

Higgins, Thomas E. (1995). *Pollution Prevention Handbook*. CRC Press Inc.

Himmelblau David M.(1995). *Basic Principles and Calculations in Chemical Engineering*, Sixth Edition, Prentice Hall.

Huang, J.P. and Poh, K.L. and Ang, B.W. (1995). Decision analysis in energy and environmental modeling. *Energy*, 20(9), 843-855.

In Metal North America (2000). www.inmetalna.ca, Winnipeg, Manitoba.

International Magnesium Association. (1998). *Recommended Practices for the Conservation of Sulphur Hexafluoride in Magnesium Melting Operations*. Technical Committee Report, International Magnesium Association.

J.L. Richards & Associates Ltd.(1989). Haley Industries Ltd. Energy Audit, Haley Station, Ontario, 1989. (unpublished).

Jorstad John L. and Rasmussen Wayne M. (1993). *Aluminum Casting Technology*. 2nd Editions. Edited by Donna L. Zalensas, American Foundrymen's Society, Des Plaines, Illinois. ISBN 0-87433-157-9.

Kaempf Douglas E. , Kwan Quon Y. (1995). Environmental Compliance in Metalcasting, *Foundry Management & Technology*, October 1995.

Kaye, Alan and Street, Arthur. (1982). *Die Casting Metallurgy*, Butterworth Scientific, London.

Kennedy, Mitchell, (1998). Total Cost Assessment for Environmental Engineers and Managers, John Wiley and Sons.

Kotzin, Ezra. (1981). *Metalcasting and moulding processes*. American Foundrymen's Society Publication, Illinois.

Kulinskii, A.I., Zuev, N.M. (1995). Processing of Foundry Wastes from Magnesium Production, *Russian Journal of Non-Ferrous Metals*, Vol 36 No. 4, p28-34.

Laitar R.A., Geoffrey M.M. (1996). New Foundry Binder Technologies: A Review of Environmental and Productivity Improvements, *American Foundrymen's Society Transactions*, Paper 96-117, p929-936.

Lee, J.J. (1996). *Development and analysis of an environmental resource management tool*. PhD thesis, Cranfield University, UK.

Lee, J.J., O'Callaghan P. and Allen D. (1995). Critical review of life cycle analysis and assessment techniques and their application to commercial activities. *Resources, Conservation and Recycling*, 13, 37-56.

Leidel D.S. (1995). Pollution Prevention and Foundries. In: *Industrial Pollution Prevention Handbook*. edited by Harry M. Freeman, McGraw-Hill Inc. p667-684.

Leidel D.S. (1996). Pollution Prevention – The Options. In: *American Foundrymen's Society Transactions 1996*. Paper 96-101.

Leidel, D.S. (1988). Myths, misconceptions and mistakes in sand reclamation. *American Foundrymen's Society Transactions*, Vol. 96., p21-26.

Linnhoff B., Townsend D.W. et al. (1982). *User Guide on Process Integration for the Efficient Use of Energy*. IChemE, Rugby, UK.

Linnhoff March, (1998). *Introduction to Pinch Technology*.
www.linnhoffmarch.com.

Linnhoff, B. (1993). Pinch Analysis – A State of the Art Overview. *Chemical Engineering Research and Design Transactions*, 71(5), September 1993.

Linnhoff, Bodo (1994). Use Pinch Analysis to Knock Down Capital Costs and Emissions, *Chemical Engineering Progress*, August 1994.

Linnhoff, Bodo (1995). Pinch Analysis in Pollution Prevention, In: *Waste minimization through process design*, editor Alan Rossiter, McGraw-Hill.

Linninger, Andreas A. et. al. (1994). Synthesis and Assessment of Batch Processes for Pollution Prevention. In: *Pollution Prevention via Process and Product Modifications*. edited by M.M. El-Halwagi and D.P. Petrides, AIChE Symposium Series Vol. 90.

Malkin, M. and Baskir, J. and Greiner, T.J. (1997). *Developing and Using Production-Adjusted Measurements of Pollution Prevention*. National Risk Management Research Laboratory, Office of Research and Development, U.S. EPA.

Martin, P.K., O'Callaghan P.W. and Probert, S.D. (1992). Environmental auditing: estimating and reducing corporate greenhouse-gas emissions using monitoring and targeting software systems. *Applied Energy*, 269-288.

McDermott Ryan P. (1999). Rethinking Environmental Controls, *Foundry Management and Technology*, p24-32, 52, April 1999.

McGovern, J.A. (1990). Exergy analysis – a different perspective on energy Part 2: rational efficiency and some examples of exergy analysis. In: *Proceedings of the Institution of Mechanical Engineers, Journal of Power and Energy*, Vol. 204, 263-268.

McGovern, J.A. (1990). Exergy analysis – a different perspective on energy Part 1: the concept of exergy. In: *Proceedings of the Institution of Mechanical Engineers, Journal of Power and Energy*, Vol. 204, 253-262.

Modern Casting (1988). Is the profit line the bottom line in sand reclamation?, Haley Industries: Thermal Reclamation Meets Premium Casting Needs. *Modern Casting*, Volume 78, No. 5, May 1988.

Modern Casting, (1998) 32nd Census of World Casting Production, AFS, 1998.

Moran M.J. and Sciubba E. (1994). Exergy Analysis: Principles and Practice. *Journal of Engineering for Gas Turbines and Power*, April 1994, Vol. 116, 285-290.

Moran, Michael J. and Shapiro, Howard N. (1988). *Fundamentals of Engineering Thermodynamics*, John Wiley and Sons.

Moynihan G.P., Undemane A.N., Jefcoat I.A. (1998). Development of a Prototype Expert System for Pollution Prevention and Control in the Foundry. In: *American Foundrymen's Society Transactions 1998*, Paper 98-14, 119-123.

Nelson, Kenneth E. (1995) Process modifications that save energy, improve yields, and reduce waste. In: *Waste minimization through process design*. edited by Alan Rossiter, McGraw-Hill Inc.

Noel, Maurice (1991) Foundry Sand Binders: Incidence on Working Environment, *Foundry Binders and the Environment*, 58th World Foundry Conference, Poland, September 1991. Available from the American Foundrymen's Society, Des Plaines, Illinois.

North American Die Casting Association (NADCA) (2000) www.diecasting.org

O'Callaghan, Paul W. (1996). *Integrated Environmental Management Handbook*. Chichester: John Wiley & Sons.

Oblina, R. (1999). Promoting cleaner production as a tool for improvement of industrial production efficiency and environmental protection. In: *Tools and Methods*

for *Pollution Prevention*, edited by Subhas Sikdar and Urmila Diwekar. The Netherlands: Kluwer Academic Publishers, 19-38.

Oblina, R. and Flowers, C. (1995). Development of Computer Supported Information System Shell for Measuring Pollution Prevention Progress, EPA/600/R-95/130.

Office of Enforcement and Compliance Assurance, (1995). Federal Facility Pollution Prevention Project Analysis: A primer for applying life cycle and total cost assessment concepts. US Environmental Protection Agency.

Ontario Ministry of the Environment. (1993). *Pollution Prevention Planning Guidance Document and Workbook*, Queens Printers for Ontario, ISBN 0-7778-3963-6.

Ontario Waste Management Corporation. (1989). *Hazardous Waste Audit and Reduction Manual*. Second edition. ISBN 0-7729-5851-3.

Otte J.A. and Scott Jr. W.D. (1997). Process Control for a Phenolic Urethane No-bake Foundry. American Foundrymen's Society Transactions, Paper 97-151, p153-160.

Otte, A.J., Smith R.L., Scott W.D. (1988). Process-control instrumentation for a foundry sand and binder mixer. In: Ensuring quality castings worldwide conference, BCIRA, University of Warwick, March 29-31 1988, Paper 21.

Pedicini, L.J. and Mizzi-Krysiak M.B. (1989). Sand Testing and Sand System Design. American Foundrymen's Society Transactions, Paper 89-63, p373-388.

Petek J. and Glavic P. (1996). An integral approach to waste minimization in the process industries. *Resources, Conservation and Recycling*, 17 (1996), 169-188.

Phyper John-David, Ibbotson B, (1994). The Handbook of Environmental Compliance in Ontario, 2nd edition, McGraw-Hill Ryerson Limited.

Pistikopoulos E.N. and Stefanis, S.K. et al. (1994). A Methodology for Minimum Environmental Impact Analysis. In: *Pollution Prevention via Process and Product Modifications*. edited by M.M. El-Halwagi and D.P. Petrides, AIChE Symposium Series Vol. 90.

Piwonka, Thomas S. Molding and Casting Processes. In: *Metals Handbook*, Volume 15, Casting, 9th edition, 1988, ASM International, 203-338.

Prucha, Thomas. Foundry Equipment and Processing. In: *Metals Handbook*, Volume 15, Casting, 9th edition, 1988, ASM International, 341-573.

Ramrattan S.N. and Guichelaar P.J. et al. (1996). Study of Foundry Granular Media and its Attrition. American Foundrymen's Society Transactions, Paper 96-113, p877-886.

Reddy, K.A. (1994). Application of exergy analysis to industrial processes-a case study. *Indian Chemical Engineer*, Section B, 36(1-2), 46-52.

Reuland W., Wabiszewski, E. et al. (1997). Beneficial Reuse of Foundry By-Products; marketing and customer education is the key to making it happen. In: Proceedings of the 9th AFS Environment, Health and Safety Conference. American Foundrymen's Society.

Rhodes S. and Brown L. (1997). *A technical framework for life cycle impact assessment*, Resource Canada Workshop, November 1997.

Roberge, H. and Sikora, R. and Baetz, B.W. (1994). Use of optimization modelling to evaluate industrial waste reduction options. *Waste Management*, 14(7), 649-654.

Roberge, H.D. and Baetz, B.W. (1994). Optimization modeling for industrial waste reduction planning. *Waste Management*, 14(1), 15-48.

Rooy, Elwin L. Nonferrous Casting Alloys. In: *Metals Handbook*, Volume 15, Casting, 9th edition, 1988, ASM International, 743-854.

Rossiter, A.P., Kumana, J.D. (1995). *Pollution prevention and process integration*. In: *Waste minimization through process design*. edited by Alan P. Rossiter, 43-52.

Rossiter, A.P., Spriggs, H.D. and Klee, R. H. (1993). Apply process integration to waste minimization. *Chemical Engineering Progress*, January, 30-36.

Rusin, Karen (1991). History and Present State of Foundry Binder Systems: The environmental point of view, *Foundry Binders and the Environment*, 58th World Foundry Conference, Poland, September 1991. Available from the American Foundrymen's Society, Des Plaines, Illinois.

Rutterman, J. (1985) Sand and its effective use in no-bake systems. *Casting engineering and foundry world*, Winter 1985.

Samuel D.G. and Roshan H.M. (1988) Studies on Tensile Strength of Phenolic Urethane No-Bake Sand Compacts as Influenced by Material Variables, American Foundrymen's Society Transactions, Vol. 96, p1-21.

Schramm W. (1997). New findings on the generation of waste and emissions, and a modified cleaner production assessment approach - illustrated by leather production. *Journal of Cleaner Production*, 5(4), 291-300.

Scott, William D. and Otte J.A. Jr. (1997). Process control tips for a phenolic urethane no-bake foundry. *Modern casting*, Oct 1997.

Shen, Thomas T. (1995). *Industrial Pollution Prevention*. Berlin Springer-Verlag.

Sikdar, Subhas K., Drahos J, Drioli E. (1999). Tools for Pollution Prevention. In: *Tools and Methods for Pollution Prevention*, edited by Subhas Sikdar and Urmila Diwekar. The Netherlands: Kluwer Academic Publishers, 2-3.

Singh, S., Ramrattan S.N. et. al. (1996). *Simulation of a Foundry Sand System*. American Foundrymen's Society Transactions, Paper 96-114.

Soo Yang, B. (1996) Industrial processes and waste characterization. *Resources, Conservation and Recycling*, 16, 93-112.

Southam Information Products. *ECOLOG CD Pollution legislation system*, Don Mills, Ontario.

Spradlin, Tom. (1997). *A lexicon of decision making*. Decision analysis society of INFORMS, <http://faculty.fuqua.duke.edu/daweb/>

Stancliffe, M R. (1997). On the re-bond – how to get the best from your chemically bonded reclaimed sand. *Foundryman*, July 1997, p261-269.

Stewart, J.R. and Swindall, W.J. (1999). Material Substitution. In: *Tools and Methods for Pollution Prevention*. edited by Subhas Sikdar and Urmila Diwekar. The Netherlands: Kluwer Academic Publishers, 333-341.

Szargut J, Morris D, Steward F. (1988). *Exergy analysis of thermal, chemical and metallurgical processes*. Hemisphere Publishing Corporation.

Szargut, J. (1980). International Progress in Second Law Analysis. *Energy*, 5(8/9), 709-718.

Tordoff, B. (1996) The Benefits of Good Environmental Performance. In: *8th American Foundrymen's Society Environmental Health and Safety Conference*, 51-76.

U.S. Department of Energy (US DOE). (1997). Department of Energy Metal Casting Competitiveness Research Act of 1990, Annual Report Fiscal Year of 1997.

United States Environmental Protection Agency. (1992). *Facility Pollution Prevention Planning Guide*. EPA/600/R-92/088.

United States Department of Energy (DOE). (1997). *Beyond 2000: A Vision for the American Metal Casting Industry*. Available from <http://www.oit.doe.gov/IOF/metalcast/mcvision.html>.

US Environmental Protection Agency (2000a). *Air Pollution Technology Fact Sheet: Fabric Filter – Reverse Air Cleaned Type*. Available from www.epa.gov

US Environmental Protection Agency (2000b). *Air Pollution Technology Fact Sheet: Fabric Filter – Mechanical Shaker Air Cleaned Type*. Available from www.epa.gov

US Environmental Protection Agency. (1997). *Office of Compliance Sector Notebook Project: Profile of the Metal Casting Industry*, available from www.epa.gov

US EPA (1990). *1990 Pollution Prevention Act*, available from www.epa.gov

van Gool, Willem. (1992). Exergy Analysis of Industrial Processes. *Energy*, 17(8), 791-803.

Vingas G.J. (1986). Mould and Core Coatings: Past Present and Future. *American Foundrymen's Society Transactions*, Paper 86-81.

Voigt, Robert. Patterns and Patternmaking. In: *Metals Handbook*, Volume 15, Casting, 9th edition, 1988, ASM International, 189-199.

Wall Goran and Gong Mei. (1996). Exergy Analysis versus Pinch Technology. In: *Efficiency, Costs, Optimization, Simulation and Environmental Aspects of Energy Systems*. edited by P. Alvfors et. al., Stockholm, ISBN 91-7170-664-X.

Weddington V.L. and Mobley C.E., (1991) Influence of Sand Surface Chemistry on Bonding. *American Foundrymen's Society Transactions*, Paper 91-131.

Zalensas, Donna L. ed. (1993). *Aluminum Casting Technology*. 2nd edition, American Foundrymen's Society, Des Plaines, Illinois.

APPENDIX A SUMMARY OF ENVIRONMENTAL EFFECTS

	Resource Utilisation				Input Materials			Output Materials				Wastewater		Air Emissions		Waste Management							Costs				
	Electricity	Natural Gas	Propane Usage	Compressed Air	Water	Raw materials	Ancillary materials	Supplier packaging	Consumables	Product loss	By-products	Rejects	Supplier packaging	Customer packaging	Start-up, shutdown wastes	General waste	Requires on-site treatment prior to discharge	Utilizes non-contact cooling water	Process causes fugitive emissions	Process causes stack emissions	Process creates solid wastestreams	Process creates hazardous wastes		Process creates non-hazardous industrial wastes	Waste streams are disposed on-site	Waste streams are disposed off-site	Waste streams are internally recyclable
Manufacturing Process																											Direct costs associated with this impact
Foundry Preparation																											
Chill/core spray preparation			x				x		x												x						
Pattern cleaning			x				x		x																		
Corebox cleaning							x		x																		
Corebox preparation			x				x	x	x												x						
Chill spray			x				x	x	x																		
Coremaking																											
Batch mixer sand preparation	x																										
Cold-box coremaking			x				x	x	x												x						
Core finishing			x				x	x	x												x						
SO2 gas scrubbing	x						x														x						x
Zircon calcining	x						x	x																			
Core stores/spraying			x				x	x	x																		
Cold box continuous mixer	x						x	x	x																		x
No-bake continuous mixer	x						x	x	x																		x
Core making, hand pack			x				x	x	x																		x
Mouldmaking/Assembly																											
Pre-assembly			x				x		x																		
Pattern box preparation																											
Mouldmaking			x				x	x	x																		
Assembly			x																								
#1, #2, #3 no-bake continuous mixer																											
#4 no bake continuous mixer	x						x	x	x																		x
	x						x	x	x																		x

	Resource Utilisation				Input Materials			Output Materials					Wastewater		Air Emissions		Waste Management							Costs				
	Electricity	Natural Gas	Propane Usage	Compressed Air	Water	Raw materials	Auxiliary materials	Supplier packaging	Consumables	Product loss	By-products	Rejects	Supplier packaging	Customer packaging	Start-up, shutdown wastes	General waste	Requires on-site treatment prior to discharge	Utilizes non-contact cooling water	Process causes fugitive emissions	Process causes stack emissions	Process creates solid wastestreams	Process creates hazardous wastes	Process creates non-hazardous industrial wastes		Waste streams are disposed on-site	Waste streams are disposed off-site	Waste streams are internally recyclable	Waste streams are externally recyclable
Manufacturing Process																												
Melting/Pouring																												
Mould purging																												
Magnesium melting																												
Magnesium pouring																												
Aluminum melting																												
Aluminum pouring																												
Sand																												
Sand removal/preparation																												
Thermal sand removal																												
Shotblast sand removal																												
Gunning room																												
Sand System																												
Mechanical reclamation																												
Thermal reclamation																												
Dust collection																												
Casting Processing																												
Riser/gating removal																												
Router																												
CNC																												
Chipping																												
Sanding																												
Fettling																												
Sand blast																												
Shot blast																												
Drilling																												
Welding preparation																												
Welding																												
Weld clean up weld inspection																												
Heat treat																												

	Resource Utilisation				Input Materials			Output Materials							Wastewater		Air	Waste Management							Costs			
	Electricity	Natural Gas	Propane Usage	Compressed Air	Water	Raw materials	Ancillary materials	Supplier packaging	Consumables	Product loss	By-products	Rejects	Supplier packaging	Customer packaging	Start-up, shutdown wastes	General waste	Requires on-site treatment prior to discharge	Utilizes non-contact cooling water	Process causes fugitive emissions	Process causes stack emissions	Process creates solid wastestreams	Process creates hazardous wastes	Process creates non-hazardous industrial wastes	Waste streams are disposed on-site	Waste streams are disposed off-site	Waste streams are internally recyclable	Waste streams are externally recyclable	Direct costs associated with this impact
Manufacturing Process																												
Straightening																												
Chromium pickle																												
Inspection and Non-destructive Testing																												
First visual inspection																												
Ultrasonics																												
Second visual																												
Fluoroscope																												
Rework																												
Boroscope																												
Acid etch	x																											
F.p.i.	x																											
X-ray																												
Dimensional check																												
Layout																												
Pressure test																												
Shipping																												
Large Casting Area																												
Coremaking/Mouldmaking	x																											
Assembly																												
Melting/Pouring	x																											
Sand Removal																												
Material Removal	x																											
Casting handling	x																											
Facilities																												
Warehouse																												
Material receiving																												
Maintenance																												
Wastewater	x																											
Heating																												
Lighting	x																											
Compressors	x																											

	Resource Utilisation				Input Materials				Output Materials				Wastewater		Air	Waste Management						Costs							
	Electricity	Natural Gas	Propane Usage	Compressed Air	Water	Raw materials	Ancillary materials	Supplier packaging	Consumables	Product loss	By-products	Rejects	Supplier packaging	Customer packaging	Start-up, shutdown wastes	General waste	Requires on-site treatment prior to discharge	Utilizes non-contact cooling water	Process causes fugitive emissions	Process causes stack emissions	Process creates solid wastestreams		Process creates hazardous wastes	Process creates non-hazardous industrial wastes	Waste streams are disposed on-site	Waste streams are disposed off-site	Waste streams are internally recyclable	Waste streams are externally recyclable	
Manufacturing Process																													Direct costs associated with this impact
Exhaust fans	x																			x									
Air-makeup	x	x																		x									

**APPENDIX B WATER MASS BALANCE AND EFFLUENT
RESULTS**

Haley Wastewater Mass Balance - Predicted post-treatment values based on pilot testing

	Scrubbers		Compressors		Dust Collectors		Acid Etch		Chromating		Photographic + Sanitary		Dye Penetrant		Total	
	L/d		L/d		L/d		L/d		L/d		L/d		L/d		L/d	
Flow	3790	4.5%	26,800	31.9%	1,890	2.2%	9,500	11.3%	1,890	2.2%	20,132	24.0%	20,000	23.8%	84,002	100%
	kg/d		kg/d		kg/d		kg/d		kg/d		kg/d		kg/d		kg/d	
Ammonia	0.0015		0.0029		0.0040		0.0000		0.0115		0.0351		0.0054		0.0603	MISA
TSS	1.4288		0.0000		0.3600		0.4275		0.0000		0.6049		0.0000		2.8213	7.22 1% Ammonia
BOD ₅	0.5268		0.0000		0.0312		0.0000		0.0000		1.3335		0.0000		1.8915	3.6 78% TSS
TP	0.0004		0.0003		0.0002		0.0001		0.0000		0.0759		0.0004		0.0773	3.6 53% BOD ₅
Cyanide	0.0000		0.0000		0.0000		0.0000		0.0000		0.0000		0.0000		0.0000	25% TP
Al	0.0064		0.0670		0.0384		0.0133		0.0000		0.0036		0.0139		0.1426	0% Cyanide
Cr	0.0002		0.0008		0.0030		0.0191		0.0010		0.0000		0.0000		0.0242	40% Al
Cu	0.0025		0.0048		0.0014		0.0040		0.0000		0.0033		0.0000		0.0159	17% Cr
Ag	0.0000		0.0000		0.0000		0.0000		0.0000		0.0258		0.0000		0.0258	11% Cu
Zn	0.0016		0.0431		0.0109		0.0311		0.0000		0.0023		0.0000		0.0891	24% Ag
Phenol	0.0002		0.0000		0.0007		0.0008		0.0000		0.0000		0.0000		0.0017	62% Zn
															0.0007	24% Phenol

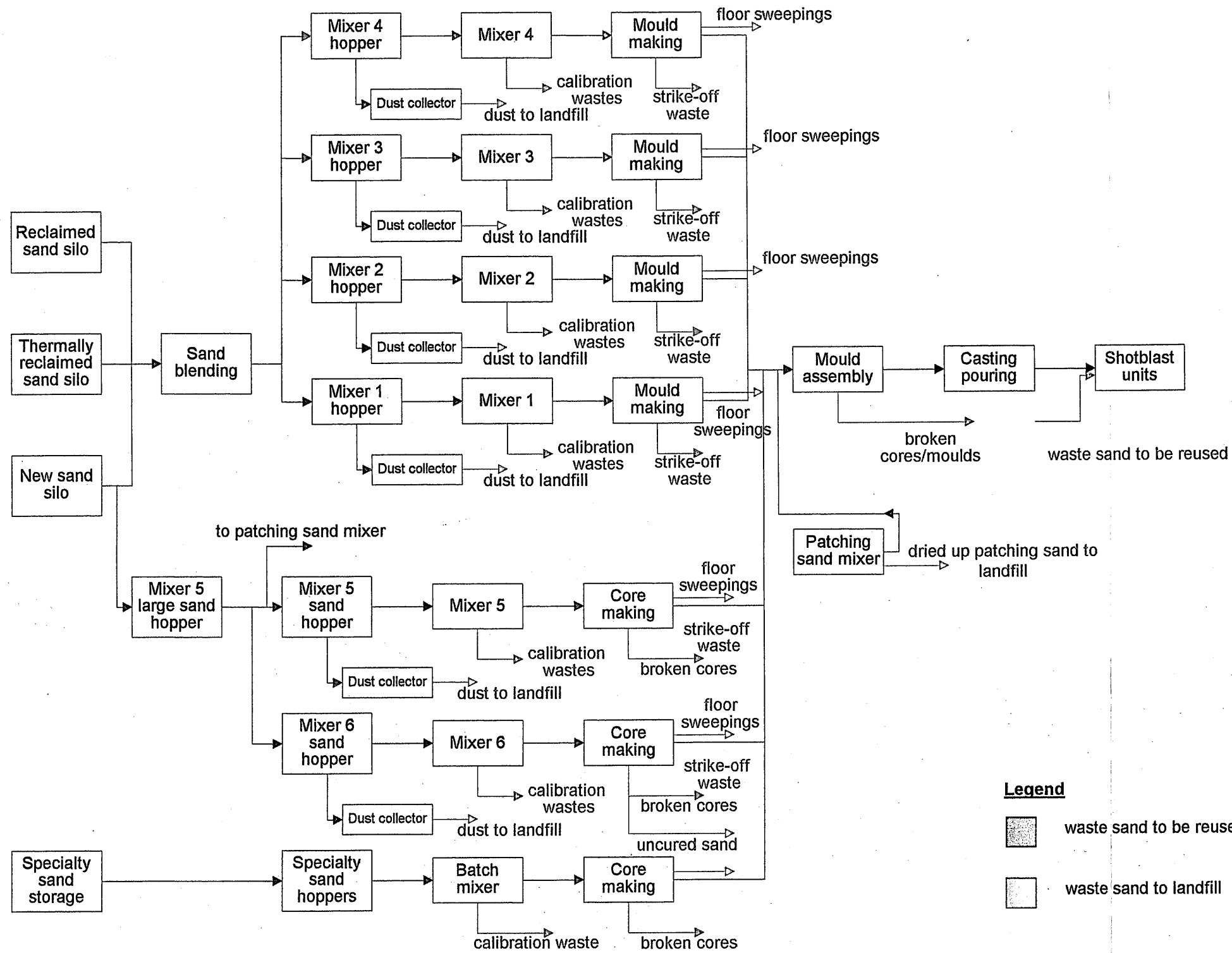
	Wheelabrators		TriMAG		Total	
	L/d		L/d		L/d	
Flow	7192	7.0%	11300	11.0%	102,494	100%
	kg/d		kg/d		kg/d	
Ammonia	0.0347	29.4%	0.0228	19.4%	0.118	MISA
TSS	0.1079	1.2%	6.3167	68.3%	9.246	7.22 2% Ammonia
BOD ₅	6.4728	59.7%	2.4860	22.9%	10.850	3.6 257% TSS
TP	0.0000	0.0%	0.0000	0.0%	0.077	3.6 301% BOD ₅
Cyanide	0.0000	0.0%	0.0000	0.0%	0.000	0.309 25% TP
Al	0.0255	15.2%	0.0000	0.0%	0.168	0% Cyanide
Cr	0.0000	0.0%	0.0000	0.0%	0.024	47% Al
Cu	0.0004	2.4%	0.0000	0.0%	0.016	17% Cr
Ag	0.0000	0.0%	0.0000	0.0%	0.026	11% Cu
Zn	0.0005	0.6%	0.0000	0.0%	0.090	24% Ag
Phenol	0.0025	59.7%	0.0000	0.0%	0.004	62% Zn
					0.007	60% Phenol

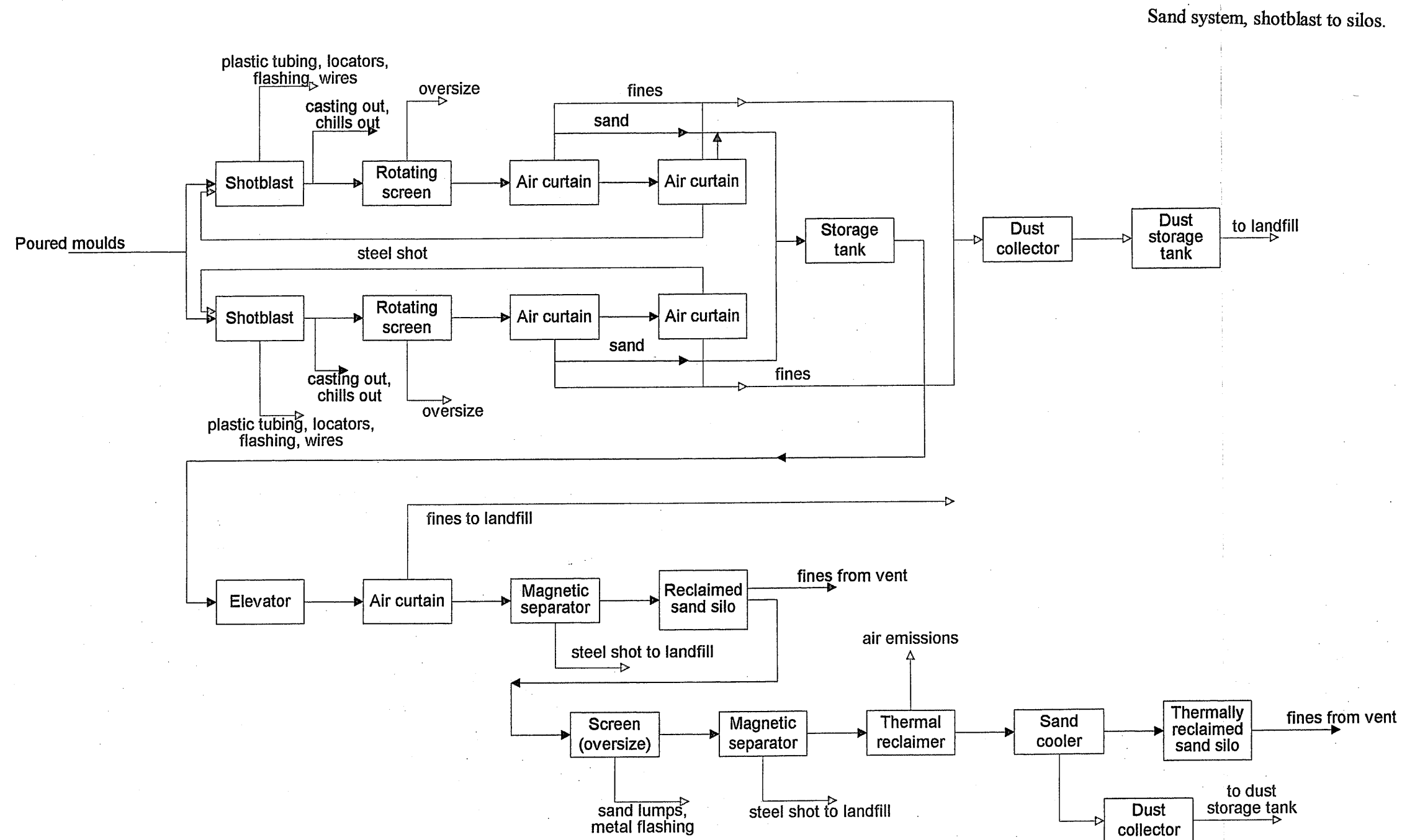
SAMPLING RESULTS AT CONTROL POINT 0200													
DATE	FLOW m3	PHEN mg/L	TSS mg/L	BOD mg/L	CN mg/L	NH3 mg/L	P mg/L	AL mg/L	CR mg/L	CU mg/L	AG mg/L	ZN mg/L	pH
01/01/1998	plant shutdown												8.3
01/02/1998	plant shutdown												8.26
01/03/1998	plant shutdown												8.29
01/04/1998	plant shutdown												8.46
01/05/1998	plant shutdown												8.21
01/06/1998	80	0.39	0.0312	8	0.6								7.9
01/07/1998	60	0.149	0.0089	42	2.5								8.53
01/08/1998	70	0.142	0.0099	29	2.0								8.25
01/09/1998	50	0.317	0.0159	561	28.1								7.54
01/10/1998	70	0.019	0.0013	326	22.8								8.73
01/11/1998	30	0.022	0.0007	19	0.6								9.2
01/12/1998	30	0.087	0.0026	78	2.3								8.24
01/13/1998	50	0.125	0.0063	64	3.2								7.17
01/14/1998	80	0.067	0.0054	605	48.4								8.83
01/15/1998	60	0.067	0.0040	155	9.3								7.26
01/16/1998	70	0.077	0.0054	544	38.1								6.96
01/17/1998	60	0.015	0.0009	334	20.0								7.9
01/18/1998	40	0.022	0.0009	63	2.5								8.91
01/19/1998	60	0.069	0.0041	286	17.2								7.03
01/20/1998	30	0.028	0.0008	68	2.0								7.26
01/21/1998	30	0.024	0.0007	12	0.4								6.86
01/22/1998	90	0.025	0.0023	723	65.1								6.84
01/23/1998	80	0.049	0.0039	246	19.7								7.44
01/24/1998	no samples			246	0.0								8.36
01/25/1998	no samples			246	0.0								8.41
01/26/1998	20	0.055	0.0011	2264	45.3								7.08
01/27/1998	30	0.089	0.0027	1149	34.5								6.85
01/28/1998	50	0.156	0.0078	1905	95.3								6.82
01/29/1998	70	0.051	0.0036	177	12.4								7.15
01/30/1998	60	0.458	0.0275	1984	119.0								7.45
01/31/1998	80	0.149	0.0119	2465	197.2								8.51
	54	0.1061	0.0064	608	32.9								8.03
DATE	FLOW	PHEN	TSS	BOD	CN	NH3	P	AL	CR	CU	AG	ZN	pH
02/01/1998	60	0.209	0.01254	1669	100.14								8.63
02/02/1998	40	0.013	0.00052	122	4.88								6.88
02/03/1998	80	0.012	0.00096	92	7.36								7.7
02/04/1998	70	0.033	0.00231	1970	137.9								7.14
02/05/1998	50	0.019	0.00095	362	18.1								6.97
02/06/1998	50	0.013	0.00065	686	34.3								8.24
02/07/1998	40	0.015	0.0006	152	6.08								7.69
02/08/1998	20	0.004	0.00008	108	2.16								7.67
02/09/1998	70	0.008	0.00056	126	8.82								7.7
02/10/1998	70	0.015	0.00105	953	66.71								7.74
02/11/1998	50	0.02	0.001	254	12.7								7.83
02/12/1998	30	0.039	0.00117	315	9.45								7.88
02/13/1998	65	0.009	0.000585	1524	99.06								8.53
02/14/1998	35	0.009	0.000315	1509	52.815								8.4
02/15/1998	35	0.01	0.00035	2542	88.97								7.87
02/16/1998	100	0.028	0.0028	853	85.3								7.93
02/17/1998	90	0.008	0.00072	217	19.53								7.89
02/18/1998	40	0.017	0.00068	2066	82.64								7.93
02/19/1998	10	0.014	0.00014	973	9.73								7.9
02/20/1998	40	0.01	0.0004	1037	41.48								7.81
02/21/1998	30	0.004	0.00012	181	5.43								
02/22/1998	20	0.008	0.00016	882	17.64								

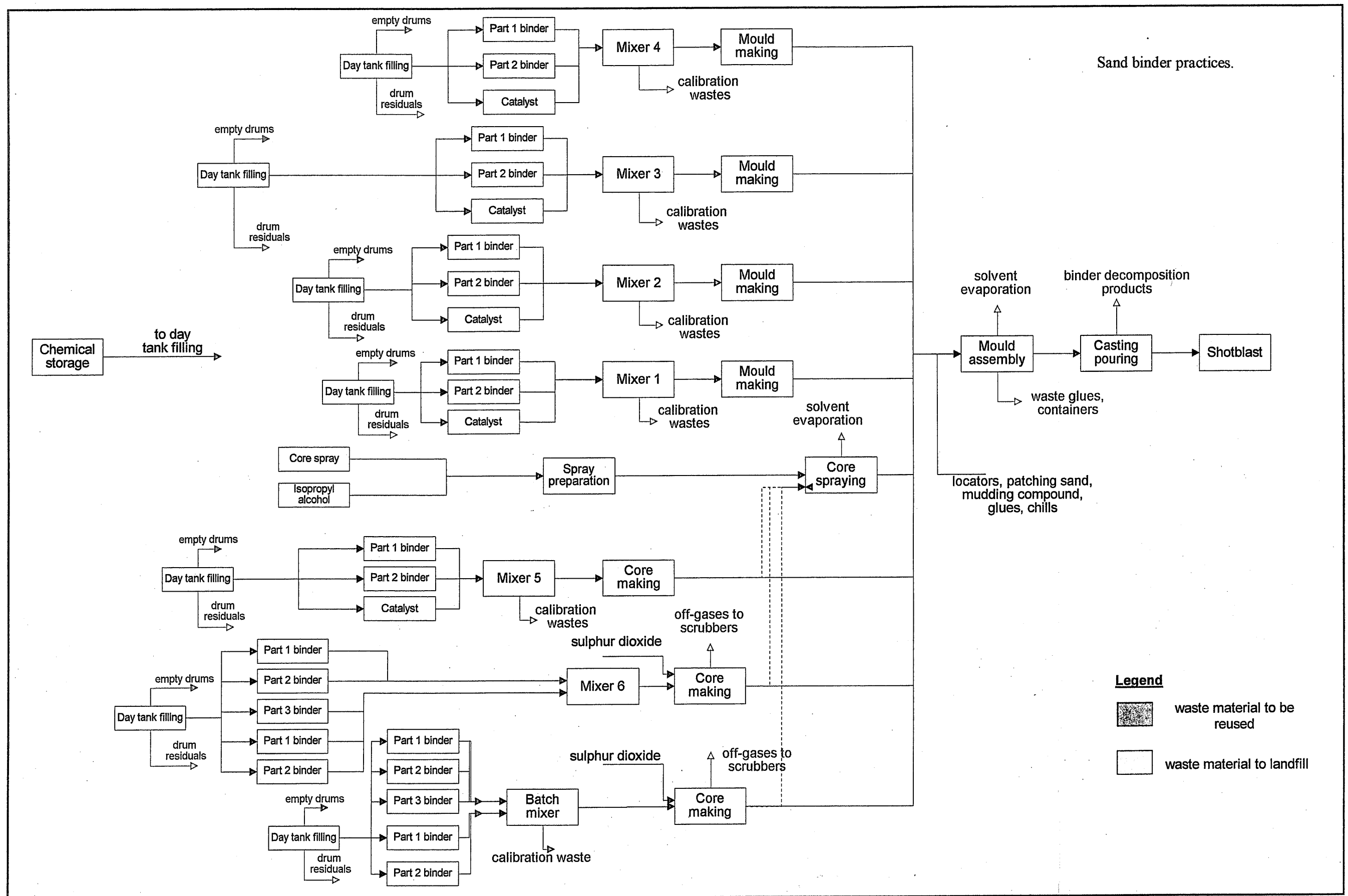
02/23/1998	30	0.024	0.00072	152	4.56																			8.42	
02/24/1998	50	0.011	0.00055	130	6.5																			8.02	
02/25/1998	40	0	0	237	9.48	19	0.76	0	0.8	0.032	0.84	0.0336	0.44	0.0176	0.79	0.0316	0.27	0.0108	0.02	0.0008	0.32	0.0128	7.92		
02/26/1998	30	0.025	0.00075	591	17.73																		8.48		
02/27/1998	20	0.03	0.0006	673	13.46																		7.97		
02/28/1998	40	0.02	0.0008	530	21.2																		8.51		
43.03571	0.222393	0.001146	746.6429	35.14732	384.25	20.7	0.00325	0.0002	2.01	0.117	7.965	0.432	2.84	0.198	0.34	0.015	1.20	0.066	0.04	0.002	0.81	0.041	7.376		
DATE	FLOW	PHEN	TSS	BOD	CN	NH3	P	AL	CR	CU	AG	ZN	pH												
	m3	mg/L	kg/d	mg/L	mg/L	kg/d	mg/L	kg/d	mg/L	mg/L	kg/d	mg/L	kg/d												
03/01/1998	75	0.001	0.000075	5	0.375								8.45												
03/02/1998	75	0.026	0.00195	462	34.65								8.25												
03/03/1998	75	0.023	0.001725	85	6.375								8.25												
03/04/1998	75	0.019	0.001425	44	3.3	13	0.98	0.006	0.00045	0.49	0.037	1.01	0.076	0.10	0.008	0.07	0.005	0.07	0.005	0.01	0.001	0.33	0.025	8.46	
03/05/1998	78	0.011	0.000858	unreasonable									7.64												
03/06/1998	96	0.023	0.002208	34	3.264								8.75												
03/07/1998	82	0.022	0.001804	7	0.574								9.18												
03/08/1998	80	0.007	0.00056	6	0.48								9.25												
03/09/1998	75	0.01	0.00075	38	2.85								8.82												
03/10/1998	95	0.033	0.003135	14	1.33								8.79												
03/11/1998	95	0.037	0.003515	8	0.76	4	0.38	0	1.03	0.098	1.38	0.131	0.131	0.20	0.019	0.03	0.003	0.03	0.003	0.032	0.003	0.54	0.051	8.77	
03/12/1998	100	0.031	0.0031	6	0.6								8.64												
03/13/1998	95	0.021	0.00195	0	0								8.9												
03/14/1998	76	0.012	0.000912	14	1.064								9.05												
03/15/1998	82	0.012	0.000984	0	0								8.4												
03/16/1998	95			0									8.44												
03/17/1998	93	0.047	0.004371	5	0.465								8.31												
03/18/1998	102	0.028	0.002856	7	0.714	7	0.71	0	0.65	0.086	0.97	0.099	0.25	0.026	0	0.000	0.04	0.000	0	0.000	0.49	0.050	8.26		
03/19/1998	94	0.025	0.00235	0	0								8.36												
03/20/1998	83	0.016	0.001328	0	0								8.83												
03/21/1998	71	0.015	0.001085	0	0								8.9												
03/21/1998	70	no sample	0	0									8.31												
03/22/1998	93	0.02	0.00186	6	0.558								8.26												
03/23/1998	86	0.026	0.002236	5	0.43								8.09												
03/24/1998	92	0.027	0.002484	0	0	6	0.55	0.009	0.000828	1.70	0.156	1.33	0.122	0.10	0.009	0	0.000	0.04	0.000	0	0.000	0.24	0.000	8.2	
03/26/1998	97	0.034	0.003298	0	0								8.58												
03/27/1998	100	0.022	0.0022	26	2.6								8.88												
03/28/1998	86	0.02	0.00172	22	1.892								8.57												
03/29/1998	86	0.006	0.000516	7	0.602								8.61												
03/30/1998	93	0.024	0.002232	36	3.348								8.54												
03/31/1998	96	0.011	0.001056	43	4.128								0.019												
	86.8	0.020	0.0019	28.4	2.35	5.8	0.48	0.0038	0.00032	0.805	0.073	0.93	0.082	0.10	0.009	0.025	0.002	0.035	0.002	0.0105	0.001	0.2775	0.019	8.54	
Note	Measured flow rates in January and February do not appear to be accurate this is due to flow rates considerably less than flume minimum capacity.																								
Acute lethality		Jan-98	Feb-98	Mar-98																					
RBT	Pass	Pass	Pass	Pass																					
DM	Pass	Pass	Pass	Pass																					

APPENDIX C PROCESS FLOWSHEETS

Sand system, silos to shotblast.







Legend



waste material to landfill

APPENDIX D FOUNDRY CHEMICALS

Name	Main ingredients	Quantity Purchased			Disposal Route		
		1997	1998	1999			
Mouldmaking/coremaking media							
		Approx. cost			Approx. cost		
Silica sand, mouldmaking	95% SiO ₂	2616 tonne	\$175,203	4289 tonne	\$287,287	3467 tonne	
					\$233,836	Landfill as waste sand, dust	
Silica sand, coremaking	100% SiO ₂	176871 kg	\$21,530	163265 kg	\$19,875	9524 kg	
					\$1,159	Landfill as waste sand, dust	
Zircon sand		37007 kg	\$15,160	31565 kg	\$12,930	32109 kg	
					\$13,150	Landfill as waste sand, dust	
Glass bead		4535 kg	\$3,300	7256 kg	\$5,280	8254 kg	
					\$6,005	Landfill as waste sand, dust	
Sand Additives							
Sodium silicofluoride	Na ₂ SiF ₆	123606 kg	\$86,525	119070 kg	\$83,350	109998 kg	
					\$77,000	Landfill on waste sand, dust	
						Air emissions as dust and volatiles	
Sand Binders							
Phenolic Urethane Part I Pepset 1670/1675	10-40% Naphtha Petroleum 1-10% Phenol	50420 kg	\$127,680	44793 kg	\$113,430	46712 kg	
						\$110,905	
Phenolic Urethane Part II Pepset 2670/2675	50-100% higher oligomers of MDI 30-60% Naphtha Petroleum 1-10% Petroleum distillates	38786 kg	\$126,420	33149 kg	\$108,045	36508 kg	
						\$111,130	
Phenolic Urethane Catalyst Pepset Catalyst 3501	60-100% Naphtha Petroleum 10-30% 4-Phenylpropyl pyridine	2030 kg	\$14,925	1679 kg	\$12,210	2268 kg	
						\$13,565	
No-bake Part I Pepset I 7130	43-58% Trimethylol propane, poly po adduct 43-58% triethylene glycol	trial use only		4826 kg	\$30,655	10118 kg	
						\$63,370	
No-bake Part II Pepset II 7200	100% higher oligomers of MDI	trial use only		5084 kg	\$22,935	11475 kg	
						\$52,035	
No-bake Catalyst Pepset Catalyst 7305	80-95% dipropylene glycol 10-15% Tris 2-dimethylamino propylamine	trial use only		615 kg	\$7,605	645 kg	
						\$7,035	
Acrylic/Epoxy cold box Part I Isoset 4304	40-70% epoxy resin 15-40% cumene hydroperoxide 1-5% cumene 1-5% 2-phenyl-2-propanol	2041 kg	\$10,670	2268 kg	\$11,855	2721 kg	
						\$18,280	
Acrylic/Epoxy cold box Part II Isoset 4305	30-60% epoxy resin 30-60%trimethylolpropane tri acrylate	1814 kg	\$12,175	2268 kg	\$15,215	2270 kg	
						\$15,230	
						Landfill on waste sand, dust	
						Air emissions	

Name	Main ingredients	Quantity Purchased				Disposal Route
		1997	1998	1999		
Furan cold box Part I Instadraw 1400	40-50% Methyl ethyl ketone peroxide 40-45% Dimethyl phthalate <3% Hydrogene peroxide 9-12% Diisobutyl phthalate	3085 kg	\$15,590	2268 kg	\$15,215	\$10,320 Landfill on waste sand, dust Air emissions
Furan cold box Part II Instadraw 1700	60-100% Methanol <0.2% Ethylene Diamine 1-10% N-beta-(amino ethyl)-gamma-aminopropyltrimethoxy silane	492 kg	\$2,060	476 kg	\$1,995	\$1,465 Landfill on waste sand, dust Air emissions
Furan cold box Part III Instadraw 3114	1-10% Methanol 1-3% formaldehyde <1.0% phenol 30-60% furfuryl alcohol 100% SO2	5660 kg	\$17,510	6603 kg	\$20,430	\$12,405 Landfill on waste sand, dust Air emissions
Sulphur dioxide, cold box catalyst		21 tonne	\$25,560	25.5 tonne	\$31,115	Wastewater, air emissions
Core/chill coating						
Ceramol 567	10-30% Isopropanol 40-70% Zircon 10-30% n-heptane note: 1997 contained trichloroethane	2550 kg		3110 kg		5985 kg Air emissions, landfill
Isomol 578	10-30% isopropanol 60-99% zircon 1-5% n-heptane	1558 kg		2727 kg		0 kg Air emissions, landfill
Patching sand binder Carsil 320	60-99% sodium silicate <10% sugar	1845 kg		1230 kg		1260 kg Air emissions, landfill
Mudding compound	isopropyl alcohol					Air emissions, landfill
Riser sleeves Kalmin 5251 sleeves 1x6 1.5x10 2x10 3x10 4x12 6x2.5	10-30% alumino silicate fibre 10-30% mineral wool fibre minor cellulose fibre 1-5% potassium borofluoride	# sleeves 74256 74200 82224 9282 2300 336		# sleeves 74256 87800 93744 10530 1850 0		landfill as dust and general waste
Isopropyl alcohol		5972 kg	\$4,800		\$4,350	5972 kg air emissions, remainder recycled
Zipstick					7000L est.	
Zipslip	silicone				140 L	
Caustic soda	50% NaOH					Wastewater
Locators	Plastic					49040 kg Air emissions, landfill

Name	Main ingredients	Quantity Purchased			Disposal Route	
		1997	1998	1999		
Potassium borofluoride	100% KBF4	none purchased			100 kg est.	see sodium silicofluoride

Total Packaging		# containers		
		1997	1998	1999
Pallets		411	395	279
Drums		492	513	548
Boxes		1899	1528	1500 est.
Bags		15100	14170	7035
Pails		248	198	unknown
Plastic bottles		3924	unknown	unknown

Materials not included: plastic locators, glass tubing, steel wire, chills, nails, lift hooks, steel sleeves, tex vents, incense, plastic tubing, acetylene, oxygen, screens, ceramic filters, steel filters, paper, steel wool.

Sand Mixer Readings

Sand flow Na₂SiF₆ flow
kg/hr

Mixer 1	19184	223.2
Mixer 2	11102	129.6
Mixer 3	9796	46.0
Mixer 4	23673	none
Mixer 5	8163	107.4
Mixer 6	8163	97.9

Date	Mixer 1			Mixer 2			Mixer 3			Mixer 4			Mixer 5			Mixer 6			
	Sand hours	Sand kg	Na ₂ SiF ₆ hours	Sand hours	Sand kg	Na ₂ SiF ₆ hours	Sand hours	Sand kg	Na ₂ SiF ₆ hours	Sand hours	Sand kg	Na ₂ SiF ₆ hours	Sand hours	Sand kg	Na ₂ SiF ₆ hours	Sand hours	Sand kg		
Material <td>Units<td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></td>	Units <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td>																		
4-Oct-99	1.1	21102.4	0.00	1.2	13322.4	0.00	0.6	5877.6	0.00	0.3	7101.9	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	
5-Oct-99	0.9	17265.6	0.00	1.1	12212.2	0.00	0.7	6857.2	0.00	0.3	7101.9	0.4	3265.2	0.4	42.97	0.3	2448.9	0.3	
6-Oct-99	1.3	24939.2	0.00	1.4	15542.8	0.00	0.9	8816.4	0.00	0.4	9469.2	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
7-Oct-99	0.9	17265.6	0.00	1.3	14432.6	0.00	0.9	8816.4	0.00	0.4	9469.2	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	
8-Oct-99	1.0	19184.0	0.00	1.8	19983.6	0.00	0.9	8816.4	0.00	0.4	9469.2	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	
12-Oct-99	0.7	13428.8	0.3	0.9	9991.8	0.5	0.8	7836.8	0.3	0.3	36.80	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	
13-Oct-99	1.2	23020.8	0.7	1.5624 meter error	14250.0	1	0.8	7836.8	0.8	0.8	36.80	0.2	4734.6	0.4	42.97	0.3	2448.9	0.3	
14-Oct-99	0.7	13428.8	0.3	0.6696 meter error	14250.0	0.9	0.9	6857.2	0.7	0.7	6857.2	0.2	4734.6	0.4	42.97	0.4	3265.2	0.4	
15-Oct-99	1.1	21102.4	0.7	1.5624 meter error	14250.0	0.9	1.1	9796.0	0.9	1.1	9796.0	0.2	4734.6	0.4	42.97	0.4	3265.2	0.4	
18-Oct-99	0.9	17265.6	0.6	1.3392	17763.2	0.9	1.2	11755.2	1.1	0.3	50.60	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	
19-Oct-99	0.7	13428.8	0.4	0.8928	1.2	13322.4	0.5	0.9	8816.4	0.9	0.4	41.40	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4
20-Oct-99	0.9	17265.6	0.4	0.8928	2	22204.0	1.1	1.4256	0.8	0.9	9796.0	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	
21-Oct-99	0.6	11510.4	0.4	0.8928	1.6	17763.2	0.8	1.4256	0.8	0.3	36.80	0.4	3265.2	0.4	42.97	0.3	2448.9	0.3	
22-Oct-99	0.9	17265.6	0.6	133.92	0.2	2220.4	0.1	103.68	0.9	0.5	9796.0	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	
25-Oct-99	1.2	23020.8	0.7	1.5624	1.2	13322.4	0.5	64.80	1.3	1.3	12734.8	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
26-Oct-99	0.9	17265.6	0.6	133.92	1.1	12212.2	0.5	64.80	1.3	1.3	12734.8	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
27-Oct-99	1.0	19184.0	0.7	1.5624	1	11102.0	0.7	90.72	1.2	1.2	11755.2	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
28-Oct-99	0.6	11510.4	0.4	0.8928	1.8	19983.6	1.1	142.56	0.6	0.3	73.60	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
29-Oct-99	0.6	11510.4	0.4	0.8928	1	11102.0	0.6	77.76	1.3	1.3	12734.8	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
1-Nov-99	0.6	11510.4	0.4	0.8928	1.2	13322.4	0.6	77.76	1.3	1.3	12734.8	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
2-Nov-99	0.7	13428.8	0.3	0.6696	1.4	15542.8	0.7	90.72	0.9	0.8	8816.4	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	
3-Nov-99	0.6	11510.4	0.4	0.8928	0.9	9991.8	0.5	38.88	0.9	0.4	41.40	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
4-Nov-99	0.6	11510.4	0.4	0.8928	0.8	8881.6	0.3	38.88	1.2	1.2	11755.2	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
5-Nov-99	0.8	15347.2	0.5	111.60	0.7	7771.4	0.4	51.84	1.2	1.2	11755.2	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
8-Nov-99	1.2	23020.8	0.7	1.5624	1.7	18873.4	0.8	103.68	1.2	1.2	11755.2	0.4	3265.2	0.4	42.97	0.6	4897.8	0.6	
9-Nov-99	1.0	19184.0	0.5	111.60	1.5	16653.0	0.7	90.72	1.2	1.2	11755.2	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
10-Nov-99	1.6	30694.4	0.7	1.5624	1.6	17763.2	0.7	90.72	1.7	1.7	16653.2	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
12-Nov-99	1.0	19184.0	0.6	133.92	1.4	15542.8	0.4	51.84	1.2	1.2	11755.2	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
15-Nov-99	1.1	21102.4	0.7	1.5624	1.3	14432.6	0.8	103.68	1.2	1.2	11755.2	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
16-Nov-99	1.1	21102.4	0.4	0.8928	1.2	13322.4	0.5	64.80	0.7	0.6	6857.2	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	
17-Nov-99	0.9	17265.6	0.6	133.92	1.3	14432.6	0.4	51.84	1.1	0.9	27.60	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
18-Nov-99	1.1	21102.4	0.6	133.92	1.6	17763.2	0.8	103.68	1.1	0.9	41.40	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
19-Nov-99	1.8	34531.2	0.9	200.88	2.2	24424.4	1	129.60	1.2	1.2	50.60	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
22-Nov-99	1.0	19184.0	0.6	133.92	1.7	18873.4	0.8	129.60	1.1	1.1	50.60	0.4	3265.2	0.4	42.97	0.5	4081.5	0.5	
23-Nov-99	1.1	21102.4	0.5	111.60	1.2	13322.4	0.6	77.76	1.1	1.1	50.60	0.5	11836.5	0.4	42.97	0.5	4081.5	0.5	
24-Nov-99	1.2	23020.8	0.6	133.92	1.6	17763.2	0.9	116.64	0.9	0.8	36.80	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	
25-Nov-99	1.1	21102.4	0.6	133.92	1.6	17763.2	0.9	116.64	0.8	0.7	36.80	0.2	4734.6	0.4	42.97	0.4	3265.2	0.4	
26-Nov-99	1.2	23020.8	0.5	111.60	1.3	14432.6	0.7	90.72	0.8	0.7	32.20	0.5	11836.5	0.5	53.71	0.3	2448.9	0.3	
29-Nov-99	1.4	26857.6	0.8	178.56	0.9	9991.8	0.7	90.72	0.9	0.4	41.40	0.2	4734.6	0.5	53.71	0.5	4081.5	0.5	
30-Nov-99	0.8	13428.8	0.3	66.96	1.1	12212.2	0.8	103.68	0.9	0.2	41.40	0.2	4734.6	0.3	32.23	0.5	4081.5	0.5	
1-Dec-99	0.8	15347.2	0.4	89.28	1.1	12212.2	0.8	103.68	0.7	0.2	32.20	0.2	4734.6	0.3	32.23	0.5	4081.5	0.5	
2-Dec-99	1.1	21102.4	0.6	133.92	1.4	15542.8	0.4	51.84	0.8	0.4	36.80	0.4	9469.2	0.3	32.23	0.4	3265.2	0.4	
3-Dec-99	0.8	15347.2	0.5	111.60	1.3	14432.6	0.7	90.72	0.6	0.2	27.60	0.2	4734.6	0.3	42.97	0.3	2448.9	0.3	
4-Dec-99	0.3	5755.2	0.3	66.96	0.4	4440.8	0.3	38.88	0.5	0.1	23.00	0.1	2367.3	0.3	32.23	0.3	2448.9	0.3	
6-Dec-99	0.8	15347.2	0.5	111.60	1.1	12212.2	0.5	64.80	0.2	0.2	9.20	0.2	4734.6	0	0.00	0.2	1632.6	0.2	
											36.80	0.3	7101.9	0.3	32.23	0.5	4081.5	0.5	

7-Dec-99	2.5	47960.0	0.0	1.4	312.48	0.00	2.5	27755.0	1.6	207.36	2.1	20571.6	0.0	2.4	110.40	0.00	0.9	21305.7	0.5	4081.5	0.0	0.00	0.8	6530.4	0	0.00	
8-Dec-99	1.0	19184.0	0.6	133.92	0.0	0.00	1	11102.0	0.4	51.84	0.8	7836.8	0.7	0.7	32.20	0.3	0.3	0.3	7101.9	0.3	2448.9	0.5	53.71	0.8	78.34	0.4	39.17
9-Dec-99	1.2	23020.8	0.7	156.24	0.0	0.00	1.4	15542.8	0.9	116.64	1.1	10775.6	1	1	46.00	0.3	0.3	0.3	7101.9	0.5	4081.5	0.5	53.71	0.4	3265.2	0.4	39.17
10-Dec-99	1.3	24893.2	0.7	156.24	0.0	0.00	1.3	14432.6	0.8	103.68	1.3	12734.8	1.1	1.1	50.60	0.4	0.4	0.4	9469.2	0.3	2448.9	0.3	32.23	0.5	4081.5	0.5	48.96
13-Dec-99	0.9	17265.6	0.7	156.24	0.0	0.00	1.1	12212.2	0.7	90.72	0.7	6857.2	0.7	0.7	32.20	0.1	0.1	0.1	2367.3	0.2	1632.6	0.2	21.48	0.5	4081.5	0.5	48.96
14-Dec-99	1.1	21102.4	0.6	133.92	0.0	0.00	0.9	9991.8	0.7	90.72	1.3	12734.8	1.2	1.2	55.20	0.7	0.7	0.7	16571.1	0.4	3265.2	0.4	42.97	0.4	3265.2	0.4	39.17
15-Dec-99	1.1	21102.4	0.6	133.92	0.0	0.00	1.1	12212.2	0.6	77.76	1.3	12734.8	1.2	1.2	55.20	0.7	0.7	0.7	16571.1	0.4	3265.2	0.4	42.97	0.3	2448.9	0.3	29.38
16-Dec-99	0.8	15347.2	0.6	133.92	0.0	0.00	1.1	12212.2	0.6	77.76	1.1	9796.0	1	1	46.00	0.2	0.2	0.2	2367.3	0.3	2448.9	0.3	32.23	0.3	2448.9	0.3	29.38
17-Dec-99	1.1	21102.4	0.7	156.24	0.0	0.00	1.3	14432.6	0.8	103.68	1.1	10775.6	1	1	46.00	0.2	0.2	0.2	2367.3	0.3	2448.9	0.3	32.23	0.4	3265.2	0.4	39.17
20-Dec-99	1.0	19184.0	0.6	133.92	0.0	0.00	1.3	14432.6	0.9	116.64	1	9796.0	0.9	0.9	41.40	0.3	0.3	0.3	7101.9	0.3	2448.9	0.3	32.23	0.4	3265.2	0.4	39.17
21-Dec-99	1.1	21102.4	0.8	178.56	0.0	0.00	1	11102.0	0.5	64.80	1	9796.0	0.9	0.9	41.40	0.2	0.2	0.2	4734.6	0.3	2448.9	0.3	32.23	0.3	2448.9	0.3	29.38
22-Dec-99	0.8	15347.2	0.3	66.96	0.0	0.00	0.8	8881.6	0.6	77.76	1.1	10775.6	0.9	0.9	41.40	0	0	0	0	0.4	3265.2	0.4	42.97	0.3	2448.9	0.3	29.38

APPENDIX E SAND MASS BALANCE

Sand and additive use, October-December 1999.

October

Sand Blend	%
New Sand	11.90%
Mech. Sand	36.90%
Therm. Sand	51.30%

Units:	Inhibitor					Binder	
	Total sand kg	New sand kg	Mech. Sand kg	Therm. Sand kg	Na ₂ SiF ₆ kg	Part 1 kg	Part 2 kg
Mixer 1	329965	39266	121757	169272	2176.2	1633.3	1336.4
Mixer 2	269231	32038	99346	138115	1776.4	1332.7	1090.4
Mixer 3	177308	21100	65427	90959	793.5	731.4	598.4
Mixer 4	146773	17466	54159	75294	0	594.4	726.5
Mixer 5	58774	58774	0	0	773.4	282.1	423.2
Mixer 6	60406	60406	0	0	724.61	271.8	271.8

Total sand	1042456 kg	
Total new sand	229050 kg	Percentage new sand 21.97
Total Binder (All parts)	9292.4 kg	Percentage binder 0.89
Total inhibitor	6244.1 kg	Percentage inhibitor 0.60

November

Sand Blend	%
New Sand	10.3
Mech. Sand	37.6
Therm. Sand	52.0

Units:	Inhibitor					Binder	
	Total sand kg	New sand kg	Mech. Sand kg	Therm. Sand kg	Na ₂ SiF ₆ kg	Part 1 kg	Part 2 kg
Mixer 1	418211	43076	157247	217470	2589.1	2070.1	1693.8
Mixer 2	313076	32247	117717	162800	1853.3	1549.7	1268.0
Mixer 3	22369	2304	8411	11632	910.8	92.3	75.5
Mixer 4	158609	16337	59637	82477	0	642.4	785.1
Mixer 5	68569	68569	0	0	902.33	329.1	493.7
Mixer 6	77549	77549	0	0	930.24	349.0	349.0

Total sand	1058383	kg					
Total new sand	240081	kg				22.68	
Total inhibitor	7185.8	kg				0.68	
Total Binder (All parts)	9697.7	kg				0.92	
						Percentage new sand	
						Percentage inhibitor	
						Percentage binder	

December

Sand Blend	%
New Sand	10.3
Mech. Sand	37.5
Therm. Sand	52.2

Units:	Inhibitor					Binder	
	Total sand kg	New sand kg	Mech. Sand kg	Therm. Sand kg	Na2SiF6 kg	Part 1 kg	Part 2 kg
Mixer 1	318454	32801	119420	166233	2232	1576.3	1289.7
Mixer 2	210938	21727	79102	110110	1451.5	1044.1	854.3
Mixer 3	157716	16245	59143	82328	662.4	650.6	532.3
Mixer 4	111263	11460	41724	58079	0	450.6	550.8
Mixer 5	41631	41631	0	0	547.8	199.8	299.7
Mixer 6	51427	51427	0	0	616.9	231.4	231.4

Total sand	891429 kg	
Total new sand	175290 kg	19.66
Total inhibitor	5510.6 kg	0.62
Total Binder (All parts)	7911.1 kg	0.89
		Percentage new sand
		Percentage inhibitor
		Percentage binder

Sand mass balance

Sand data	Unit	October	November	December
Total sand use	kg	1042456	1058383	891429
Total new sand	kg	229050	240081	175290
Total inhibitor	kg	6244.1	7185.8	5510.6

Inhibitor data	Unit	Na	Si	F
Calculated composition	% mass	24.4	14.9	60.6
Measure composition	% mass	25.5	18.6	56.0

Thermal reclaimer data	Unit	
Sand processing rate (1999-2000)	kg/hr	1500
Maximum sand processing rate	kg/hr	3000
Estimated dust losses (Dec 1999)	%	11.8

Thermal Reclaimer Emissions	Unit	
Current POI concentration	ug/m3	68.7
Required POI concentration	ug/m3	4.3
Total Fluoride air emission rate	mg/sec	374.0
Fluoride emission rate at maximum sand processing rate	mg/sec	748.0
Current HF emission rate	mg/sec	373.0
Required HF emission rate	mg/sec	23.3

Leachate toxicity of dust	Unit	
Current observations (average)	mg/L	2789.0
Current observations (maximum)	mg/L	3350.0
Current limit	mg/L	240.0
Proposed limit	mg/L	150.0

Dust losses from thermal reclaimer	Units	October	November	December
Total thermally reclaimed sand	kg	473640	474379	416750
Thermal reclaimer losses	kg	55890	55977	49177
Total mechanical sand into reclaimer	kg	529530	530356	465927
Total sand processing time	hr	353.0	353.6	310.6

Fluoride balance (current)	Units	October	November	December
Total Fluoride in	kg	3497	4024	3086
Total Fluoride as air emissions	kg	475	476	418
Total Fluoride on sand waste	kg	3021	3548	2668
Total quantity of waste sand	kg	229050	240081	175290
Average concentration of F on waste sand/dust	mg/kg	13191	14778	15219

Concentration of F on sand waste to meet air emissions at current sand processing rate	mg/kg	826	925	953
Max. F into system to meet air emissions at current reclamation rate	kg	218.8	251.8	193.1
Concentration of F at mixer	mg/kg	209.9	237.9	216.6
Concentration Na₂SiF₆ at mixer	mg/kg	374.8	424.8	386.8
Max. addition % based on sand	%	0.0375	0.0425	0.0387

Concentration of F on sand waste to meet air emissions at max. sand processing rate	mg/kg	412	461	475
Max. F into system to meet air emissions at maximum reclamation rate	kg	109.4	125.9	96.5
Concentration of F at mixer	mg/kg	104.9	118.9	108.3
Concentration Na₂SiF₆ at mixer	mg/kg	187.4	212.4	193.4
Max. addition % based on sand	%	0.0187	0.0212	0.0193

Max. F into system to meet leachate of 240 mg/L	kg	250.5	288.3	221.1
Max. F into system to meet leachate of 150 mg/L	kg	156.6	180.2	138.2
Concentration of F at mixer	mg/kg	150.2	170.2	155.0
Concentration Na₂SiF₆ at mixer	mg/kg	268.2	304.0	276.8
Max. addition % based on sand	%	0.0268	0.0304	0.0277

Residual fluoride on sand

Thermally reclaimed sand	Fluoride concentration
Sample 1	458 mg/kg
Sample 2	486 mg/kg
Sample 3	442 mg/kg
Sample 4	534 mg/kg
F _{thermal}	480 mg/kg

Blended sand	Fluoride concentration
Sample 1	730 mg/kg
Sample 2	694 mg/kg
F _{blend}	712 mg/kg

Unreclaimed sand (mechanical)	Fluoride concentration
Sample 1	1800 mg/kg
Sample 2	1210 mg/kg
Sample 3	1610 mg/kg
F _{mechanical}	1540 mg/kg

		October	November	December
Residual fluoride (calculated)		0.071%	0.081%	0.074%
Residual fluoride (calculated)	mg/kg	714	810	739
Residual fluoride (measured)	mg/kg	712	712	712

APPENDIX F REDUCED INHIBITOR CASTING TRIALS

F.1 Reduced percentage trials

The use of sodium silicofluoride was introduced in 1981. Previous to 1981 sulphur was used as an inhibitor, sulphur caused negative effects on the health and safety of the workers because when in contact with the metal it produces sulphur dioxide. The common alternative at the time was potassium fluoroborate which was significantly more expensive, also potassium fluoroborate has a higher activation temperature. Initial testing was conducted using 0.75% and 1.0% based on sand. No documentation was found to support the current quantities of 0.6-1.2% based on sand weight.

Several sets of test trials were conducted to look at the effects of reducing the quantity being added to the moulds. The original test casting was a step plate approximately 2 cm x 10 cm x 20 cm. Two plates were poured every day for 13 working days, one plate per day had 0.6% inhibitor added the other plate had no additions, however there was a residual left in the recycled sand. No evidence of burning was found in any of the test plates. Upon investigation it was found that burning normally occurs in heavy cast sections, to reproduce this the test plate was increased to 9 cm thick. The result of no inhibitor additions in these plates can be seen in the following photographs.

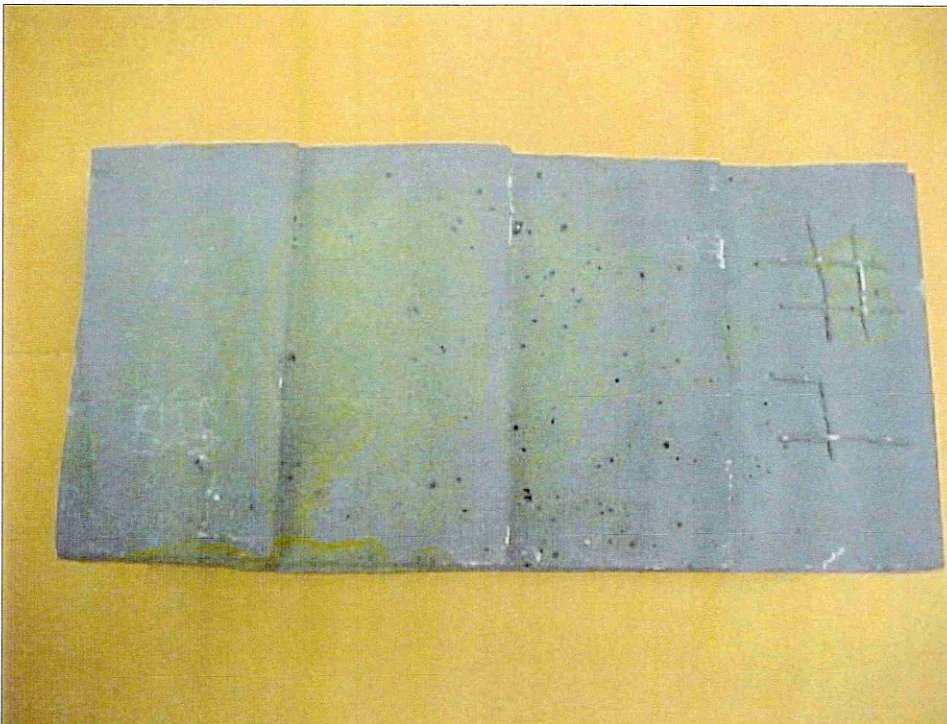


Figure 1 Top view of casting with burning defect.

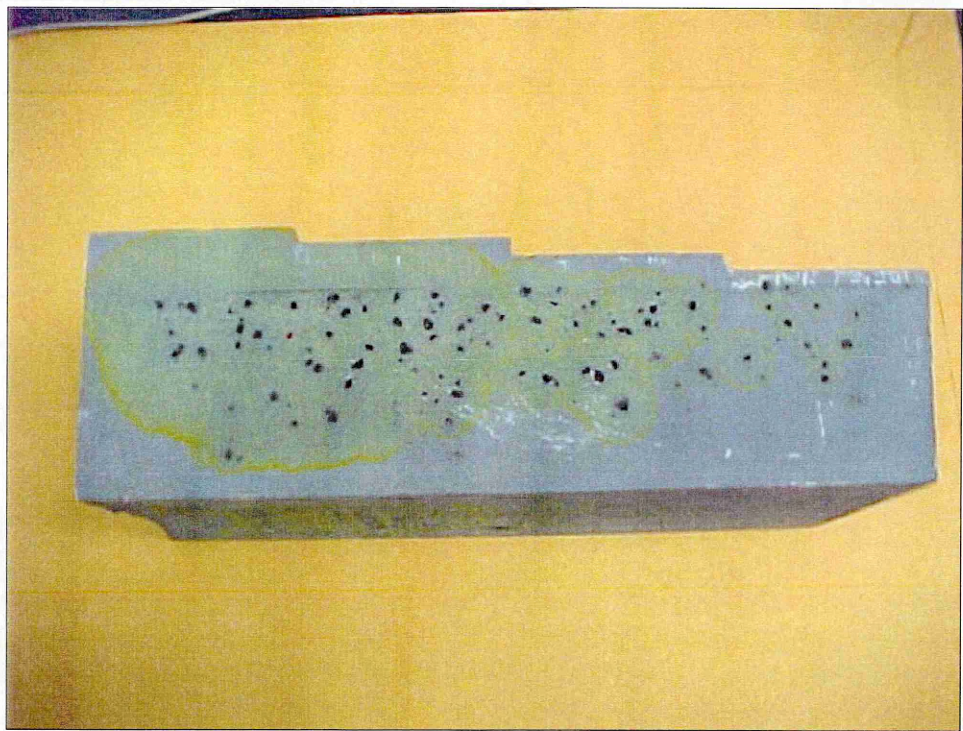


Figure 2 Side view of casting with burning defect.



Figure 3 Close-up of burning.

The following table shows the results from the larger test plates.

% inhibitor added	# test plates	Results
0% (residual approx. 0.2%)	2	severe burning of castings
0.27%	3	moderate burning of all castings
0.30%	3	1 plate no burning, 2 plates light burning
0.40%	3	2 plates no burning, 1 plate 1 burning mark on in-gate
0.56%	1	no burning

From these trials it was evident that the quantity if inhibitor could not be reduced enough to render the dust non-hazardous as long as inhibitor was being added to the bulk of the sand.

APPENDIX G ALCOHOL BASED COATING TRIALS

G.1 Alcohol Based Coating Trials

The experiments completed on alcohol based coatings were:

- ♦ Test plates with different inhibitor levels.
- ♦ Test plates with stock coating (2% KBF_4) as inhibitor.
- ♦ Cover castings five castings were made in total.

G.2 Coated test plates

It was suggested by foundry personnel that the quantity of inhibitor used in the stock mix would not prevent burning. Three sets of five test plates were made each with different quantities of inhibitor. The experimental method is described below.



Figure 1, 2 Test plate pattern, cope side (left) and drag side (right).

1. The pattern box was prepared as normal: inserting fabric riser sleeves, plastic locators and ensuring the pattern box is clean.
2. The sodium feeder on the mixer was turned off and the mixer was started.
3. Sand was packed into the two mould halves.
4. The mould halves were left to sit until cured.



Figure 3, 4 Mould packing and curing.

5. The mould halves were rolled over and removed from the pattern boxes.
6. The moulds were cleaned up, removing loose sand and excess sand metal's flow path.
7. The moulds were taken to the chill spray booth and sprayed.

8. After spraying the moulds were assembled as normal.

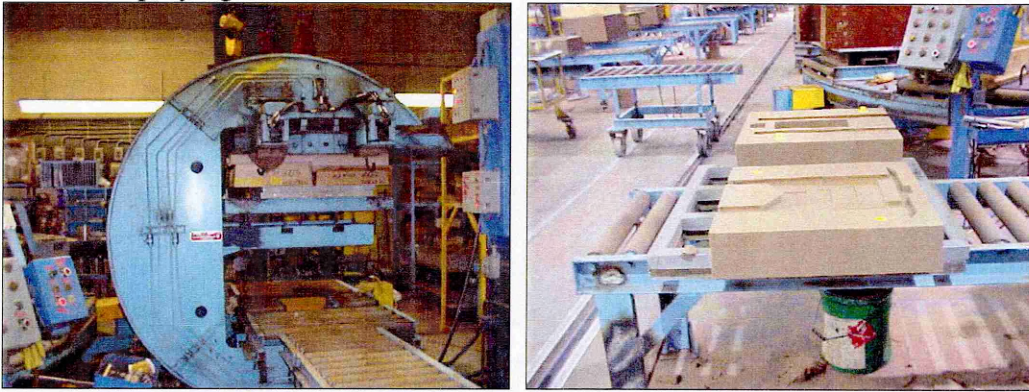


Figure 5, 6 Removing mould from pattern box.

9. Completed moulds were placed on the pouring lines.

10. The moulds were purged as normal using a mix of carbon dioxide and sulphur hexafluoride.

11. Normal pouring practices were used, magnesium alloy ZE41A was used in all trials.

12. After casting were solidified the casting was removed from the mould using a hammer to split the mould.

13. The gates and risers were removed from the casting.

14. The casting was blasted to clean up the surface and remove any dirt adhering to the surface.

15. The castings were acid etched to produce a clean surface ready for inspection.



Figure 7, 8 Mould assembly.

16. The inspection technique used to detect this type of defect is fluorescent penetrant inspection. The casting is dipped in fluorescent oil that penetrates any surface defects. The casting is rinsed to remove the penetrant oil, the casting is dried and then inspected under black light. The black light shows up the oil left in any surface defects.



Figure 9, 10 Moulds before and after pouring.



Figure 11, 12 Breaking casting away from the mould.



Figure 13 Test plates before clean up.

G.3 Results

Inhibitor use	# test plates	Observations
2% KBF_4 + 2% Na_2SiF_6	5	no burning
4% KBF_4	5	no burning
2% KBF_4	5	no burning

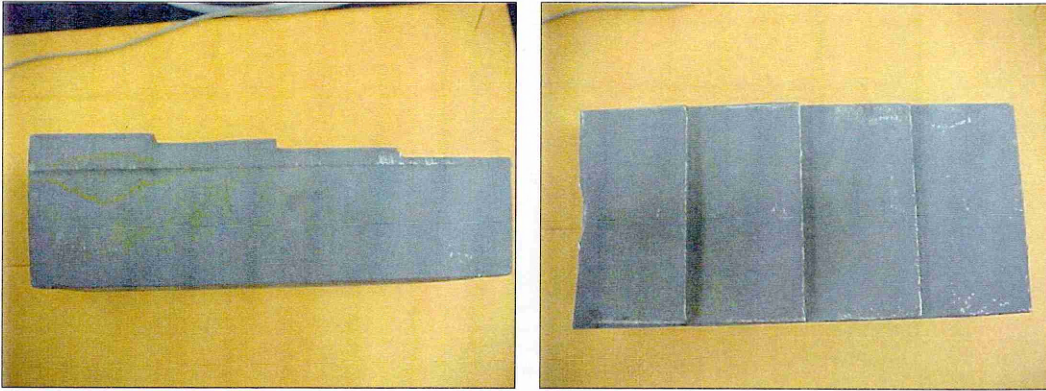


Figure 14, 15 Test plates after inspection.

G.4 Conclusions

- ♦ There was no evidence of burning in any of the castings made with sprayed moulds.
- ♦ Any further testing should use the stock core spray to eliminate the need for multiple recipes.
- ♦ Surface coating sand moulds is a viable alternative to adding inhibitors to the bulk of the sand.

G.5 Coated castings

Two small production casting were selected to test the use of mould coatings. The parts selected were two small cover castings the 3105658 and 3108205. Three castings were made of the 3105658 and two of the 3108205. Only a small number of castings were made so that there was minimal interruption to production. The casting described in detail below is the 3105658.

G.5. Core making

All the cores were made as normal.

G.5. Mouldmaking and assembly

1. Moulds were made without inhibitor.
2. Moulds were processed as normal.
3. Moulds were cleaned up prior to coating.
4. Moulds were assembled as normal.



Figure 16, 17 Mouldmaking.

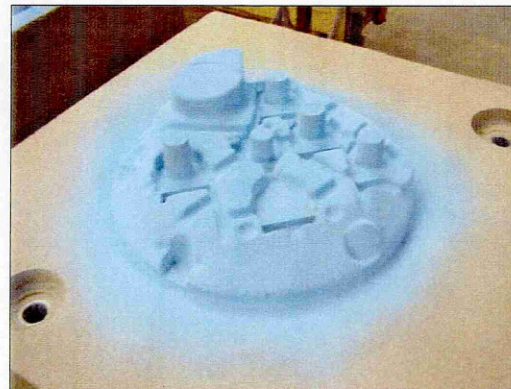


Figure 18, 19 Mould coating.



Figure 20, 21 Mould and cores awaiting assembly.

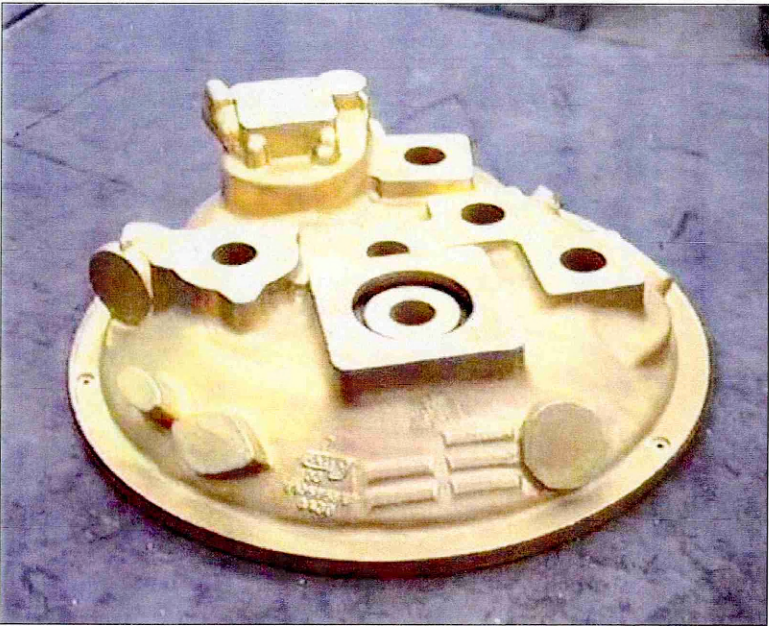


Figure 22 Finished 3105658.

G.5. Clean up and inspection

The castings were cleaned up and inspected at fluorescent penetrant inspection. No defects related to the coatings were found.

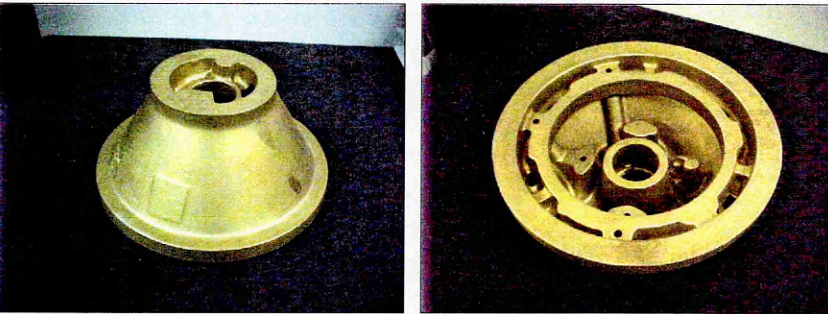


Figure 23 Finished 3108205.

APPENDIX H WATER BASED CASTING TRIALS

Water Based Coating Trials

Due to concerns over volatile organic emissions using alcohol based coatings the casting industry is generally moving towards using water based coatings.

Evaluation of Different Coatings

Six different coatings were obtained from a coating supplier to evaluate different types of coatings. The coatings evaluated were :

- ♦ Rheotec 204: water based carrier with talc and graphite refractory.
- ♦ Rheotec 463 A: water based carrier with alumino silicate and coke coating.
- ♦ Holcote 578: water based carrier with zircon refractory.
- ♦ Isomol 578: alcohol based carrier with zircon refractory.
- ♦ Dycote 34ESS: water based carrier with graphite and sand particles.
- ♦ Dycote 11: water based carrier with graphite refractory.

The trials completed were:

1. Evaluation of coating and sand binder compatibility.
2. Evaluation of brushing application on surface finish and casting dimensions (not discussed here).
3. Evaluation of the effect of the sprayed coating on casting surface finish.
4. Evaluate ability of coatings mixed with inhibitor (Na_2SiF_6) to protect the magnesium.

Procedure:

1. Binder compatibility

This test was done using Rheotec 204, Rheotec 463A, Holcote 578 and Isomol 578 as well as Dycote 34ESS.

- ♦ The five coatings were applied by both brushing and dipping on sand mixed with every binder system.
- ♦ The coatings were observed to determine if they were compatible with the binder systems.

2. How brushing affects the surface finish and dimensions.

- ♦ Fifteen test plates were made.
- ♦ The first four coatings were applied by brushing to three moulds each.
- ♦ Three moulds were left bare to give a good basis for comparison.
- ♦ They were poured in aluminium to observe surface finish.
- ♦ The castings were taken out by hand to preserve the finish obtained while pouring.
- ♦ The dimensions were taken to determine the thickness of the coatings.

3. How spraying affects the surface finish.

- ♦ Twelve test plates were made.

- ♦ The Rheotec 204, 463 A and Dycote 11 coatings were sprayed on 4 test plates each. The Baume's of the four coatings were adjusted to the right value (suggested by the coating supplier).
- ♦ Two of those four were sprayed with a medium thickness and two were sprayed with a heavy thickness.
- ♦ Each of the coatings was mixed with sodium silicofluoride with a 2% by weight ratio.
- ♦ The mixtures were applied to one mould each.
- ♦ The moulds were poured in aluminium.
- ♦ The castings were taken out by hand to preserve the finish obtained while pouring.
- ♦ The castings were observed at fluorescent penetrant inspection to find any surface defects .

4. How coatings mixed with sodium silicofluoride protect the magnesium

- ♦ Six test plates were made with blended sand containing no added sodium.
- ♦ Four test plates were made with blended sand containing no added sodium.
- ♦ Two moulds were sprayed with Dycote 11 mixed with 2% by weight sodium silicofluoride.
- ♦ Two moulds were sprayed with 4% by weight sodium silicofluoride.
- ♦ Two moulds were sprayed with Dycote 11 containing no sodium silicofluoride.
- ♦ Four moulds were not coated bare.
- ♦ The moulds were poured in magnesium.
- ♦ The casting were taken out by hand to preserve the finish obtained during the pouring.

Results

1. Binder compatibility.

Coating	Solvent	Compatible with binder systems	Comment
Rheotec 204	Water	yes	Easy to apply, uniform.
Rheotec 463A	Water	yes	Harder to apply, thicker.
Holcote 578	Water	yes	Very thin, hard to brush.
Isomol	Alcohol	yes ¹	Brush marks very visible Health and safety issues.
Dycote 34 ESS	Water	yes	Contains very coarse sand grains, very hard to apply uniformly.

¹Recent tests show that alcohol may be harmful to the Pepset binder systems.

2. How brushing affects the surface finish and dimensions.

The average thickness of the coatings

Rheotec 204	0.005
Rheotec 463 A	0.0055
Holcote 578	0.0065
Isomol 578	0.006

The surface finish is impossible to evaluate due to the presence of many brush marks.

3. How spraying affects the surface finish.

		Baume	Coating Thickness	FPI results
Rheotec 204	OX 1	32.0	Light	Gas
	OX 3		Light	Some shrinking, light gas.
	OX 2		Heavy	Gas, shrinking in areas.
	OX 4		Heavy	Gas.
	OX 14 + 2% Na ₂ SiF ₆	35.0	Light	Light gas
Rheotec 463A	OX 5	40.0	Light	Some gas
	OX 6		Light	Light gas
	OX 7		Heavy	Light gas
	OX 8		Heavy	Gas
	OX 15 +2% Na ₂ SiF ₆	40.0	Light	Light gas
Dycote 11	OX 9	29.0	Light	OK
	OX 10		Light	OK
	OX 11		Heavy	OK
	OX 12		Heavy	OK
	OX 13	30.0	Light	OK

The surface finish was evaluated by a visual inspector and was found to be between 120 and 200 for all the test plates. On average, castings made in aluminium usually have a surface finish between 120 and 300 rms.

4. How the coatings mixed with Sodium Silicofluoride protect the magnesium.

Test plate	% by weight SSF	Defects observed
OX 1	2%	Shrink, No burning
OX 2	2%	Shrink, No burning
OX 3	4%	Shrink, No burning
OX 4	4%	Shrink, No burning
OX 5	0%	Shrink, No burning
OX 6	0%	Shrink, No burning
NS 1	No coating	No burning
NS 2	No coating	No burning
NS 3	No coating	No burning
NS 4	No coating	No burning

Discussion

The first trial showed that visually the coatings were compatible with every binder system. It also gave a view of how those coatings would affect the surface finish and the dimensions. The coatings tested all seemed to produce a positive effect except for the Dycote 344 ESS. This coating contains sand with very coarse grains, which creates a very rough surface. This coating was immediately rejected since surface finish is essential.

The other four coatings seemed to be acceptable so were further tested. The coatings were applied to moulds to be poured in aluminium. Aluminium was chosen because it penetrates into the sand more than magnesium. The coatings were applied by brushing. This was found to be a very long process, combined with a drying period for the water-based coatings. Application of the coating by brushing left very visible brush marks on the castings that would make the surface finish unacceptable. The alcohol based coating, Isomol 578, was found to be very difficult to handle due to the health and safety issues it created. For all these reasons, it was rejected. The Holcote 578 was also rejected because the principal refractory in it is zircon which makes it very expensive. The two Rheotec coatings seem to yield good results and so were considered as possible replacement. The dimensions obtained and the brush marks indicated the need for a new application method. It was then decided to do some testing by spraying the coatings. The Dycote 11 coating was also added to the testing.

The results obtained with spraying were conclusive; the Dycote 11 was the only spray that did not create gas defects. When the coating was mixed with sodium silicofluoride no defects were observed. The surface finishes obtained were equivalent if not better than what can usually be obtained. The spraying also proved to be a very efficient application method.

Consequently, the next test was done with Dycote 11. The outcome was not as conclusive however, none of the test plates burned. It was thought that the coating might be an inhibitor in itself so four test plates were left bare. These did not burn

either. Further testing will be done to determine if the moulds were actually made without sodium. According to the geometry of the casting, it seems unlikely that it would not burn when no sodium is present. It should however be noted that the sand used is blended sand that has been reclaimed and contains a residual amount of chemical.

Conclusion

The outcome of the experiment is promising but more research needs to be done to determine the amount of sodium needed and the effect of the coating on the castings themselves. Further testing must involve production castings to ensure that coating is an acceptable option.

Part Number: 145D6311-02

OX: 33, Melt Number: 41-55792

Core making

Cores made with the addition of sodium silicofluoride: 2, 3, 5, 6, 11, 12, 14, 15, 30, 31.

Cores made without sodium silicofluoride: 4, 7, 8, 9, 10, 13, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29.

Mould making

- ♦ The 6311 has a cope, cheek and drag. These were all made with without the addition of sodium silicofluoride. The residual in the sand was estimated to be 0.1-0.2%. Several cheeks were scrapped during mould making, however this is normal.
- ♦ Some difficulty could arise when coating the cheek because both sides need coating.
- ♦ The moulds have to be cleaned up before coating was applied.
- ♦ Dycote 11 was applied to the mould and core sections.
- ♦ The coating was dried using a heat gun.
- ♦ Moulds and cores were assembled as normal.

Clean up and inspection

- ♦ Castings were cleaned up before inspection.
- ♦ Castings were inspected at fluorescent penetrant inspection and x-ray. No defect were found at fluorescent penetrant inspection. Hot tears were noted on view E2 and E4 at x-ray. Hot tears are a common defect for this casting.
- ♦ This casting did not require defect welding and was shipped as normal.

Part Number: 70351-38111-002

OX: 887, Melt Number: 41-56014

Core making

Cores made as normal: 2, 3, 5, 6, 11, 12, 14, 15, 30, 31.

Cores made without sodium silicofluoride: 4, 7, 8, 9, 10, 13, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29.

Mould making

Both the cope and the drag were made without sodium additions to the sand. Due to the use of blended sand there was some residual sodium silicofluoride. This is estimated to be 0.08% fluoride, or 0.14% sodium silicofluoride.

Coating

- ♦ Dycote 11, a graphite-water spray was used with 4% inhibitor added by weight.
- ♦ The cope and drag had to be cleaned up before coating.
- ♦ The coating was dried using a hand-held heat gun.

Assembly

The assembly took approximately 5 hours to complete. The normal assembly time was 3 hours. Some of the reasons were:

- ♦ After the cope and drag were cleaned up by the assembler, coating needed to be reapplied to some areas, this meant that the coating had to be dried, using only a hand-held heat gun which was time-consuming.
- ♦ Some areas of coating were missed, the assembler identified these areas, the coating was subsequently applied and dried.
- ♦ No other exceptions were noted.

Pouring

The pour proceeded as normal.

Shakeout

The casting was shaken-out two hours exactly after pouring. The casting was still hot and considerable smoke was being emitted, especially when core 4 was shaken out.

Inspection

Burning was evident at the location of both Core 19's. This is one of the hottest sections of the casting.

There were some issues with wall thickness but these are not isolated to this casting.

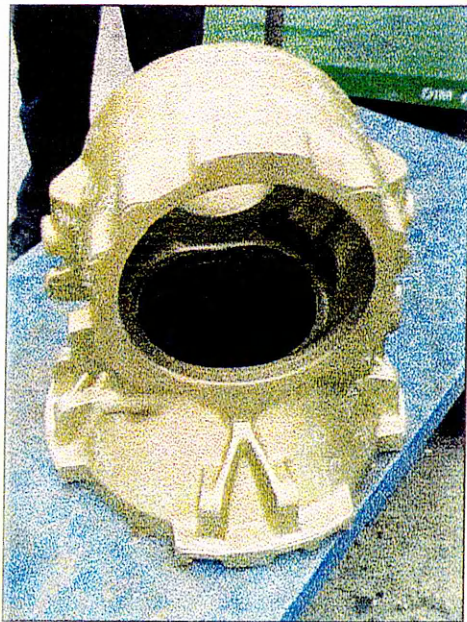
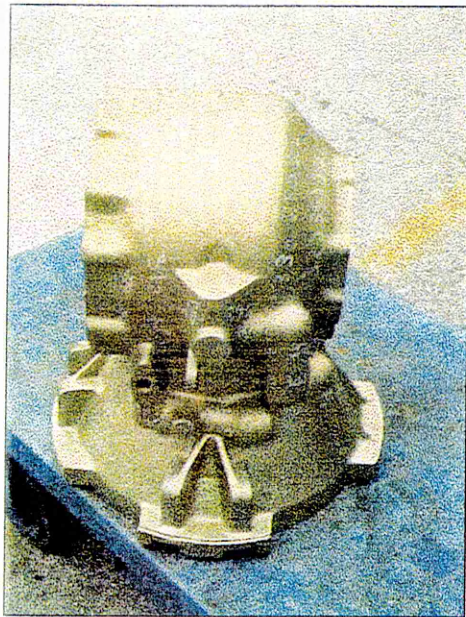


Figure 1 145D-6311

Discussion

There are two potential reasons for the burning at core 19:

1. Core 19 was improperly coated. Core 19 is made of a binder that turns black upon curing. The coating was also black, this made it difficult to inspect the level of coating.
2. A thicker coating or more inhibitor is required for such a large casting.

The existing manufacturing operation will have to be modified to ensure proper casting clean-up prior to coating. The current operation involves the assemblers cleaning up the mould during assembly. Mould clean-up will have to be done prior to core coating.

Conclusions

- ♦ Overall this trial can be considered a success. However, there is considerable work to be done to make coatings a viable manufacturing process.
- ♦ A more representative test plate mould needs to be created to better simulate a real casting.
- ♦ Application and drying methods need to be improved.
- ♦ The colour of three-part sand is very dark, this made it difficult to see if it was properly coated.

Conclusions from test castings

The trials done to date prove that the coating is a viable alternative to adding inhibitor to the bulk of the sand.

Several actions are required before this process is production ready.

- ♦ Coating method needs to be selected: all the trials carried out to date used spray coatings, however, flow-coating and dipping need to be evaluated.
- ♦ The interaction between mould purging and inhibitor needs to be examined.
- ♦ There are three common methods of drying water-based coating, these are: forced air convection, infra-red, microwave. These three methods need to be investigated to evaluate the relative advantages and disadvantages of each method.

This page left intentionally blank.



Figure 2 Filling pattern box with sand.

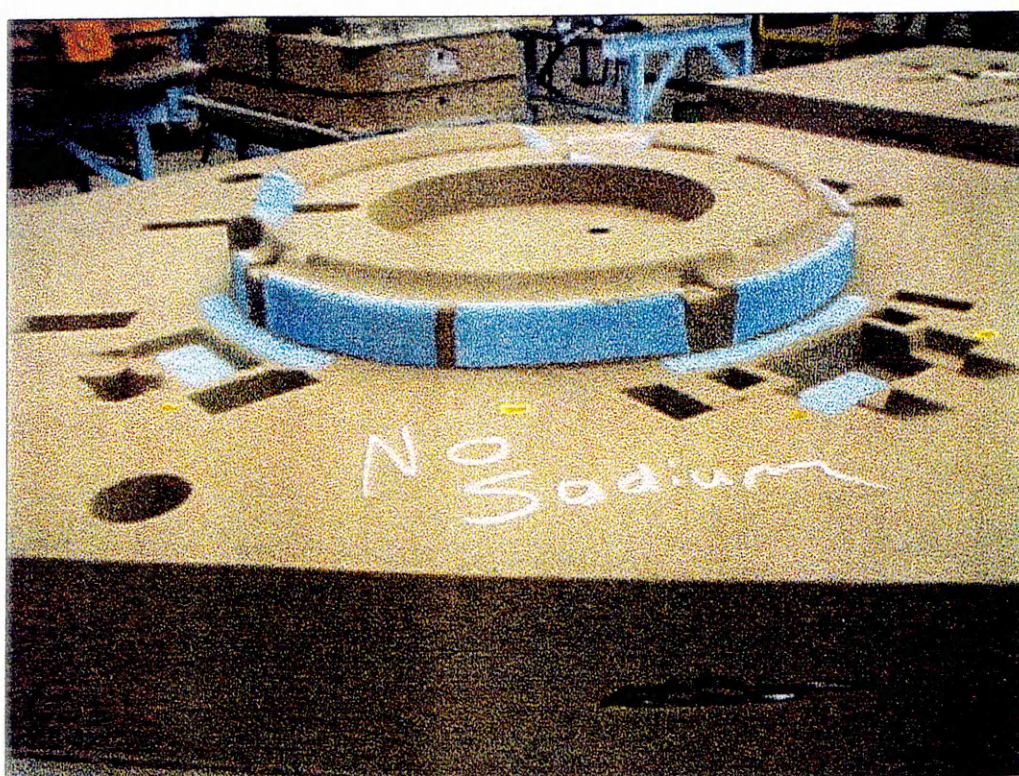


Figure 3 70351-38111 drag prior to coating.

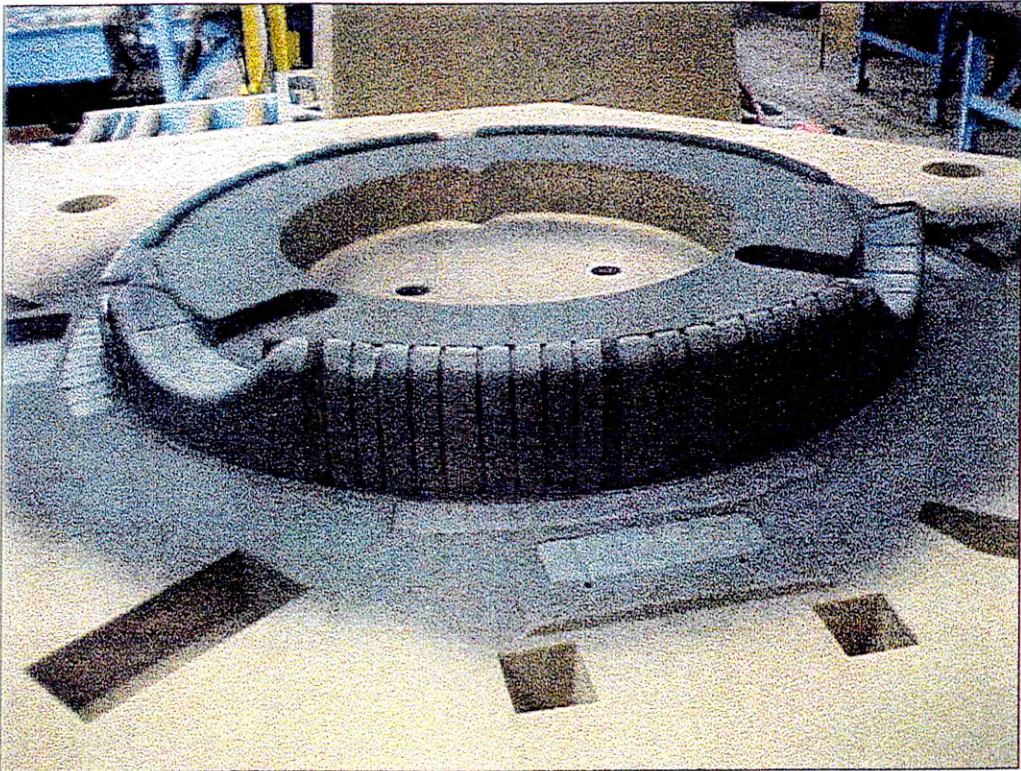


Figure 4 Partially coated 70351-38111 drag.

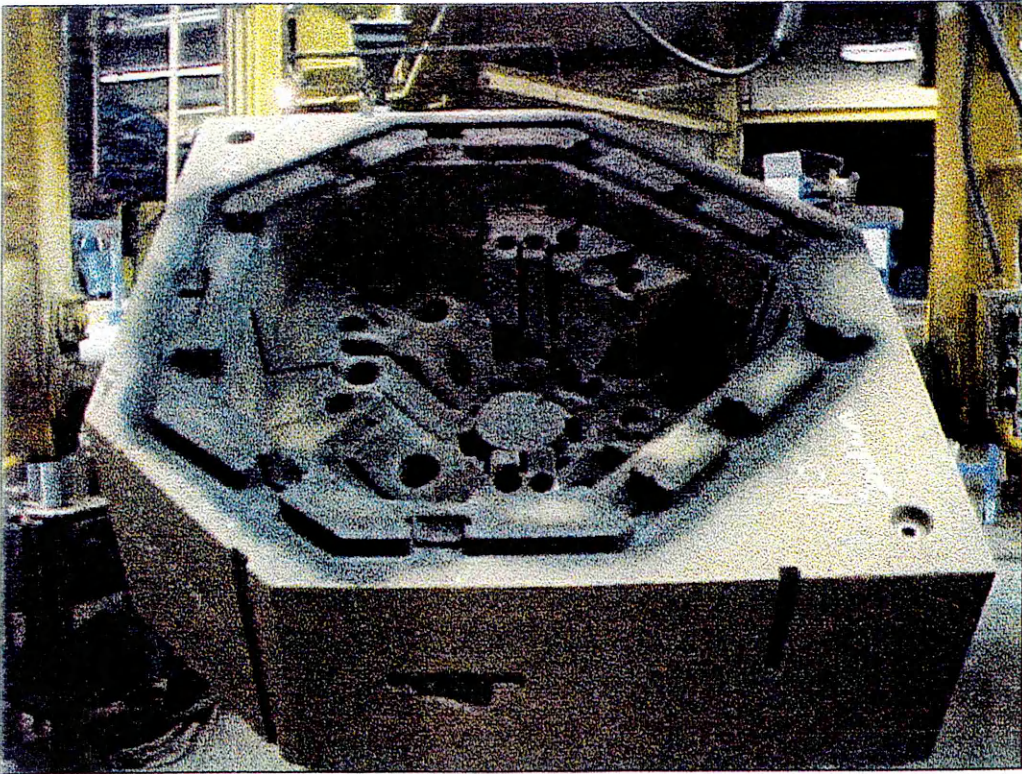


Figure 5 Coated 70351-38111 cope.



Figure 6 70351-38111 cope during assembly.

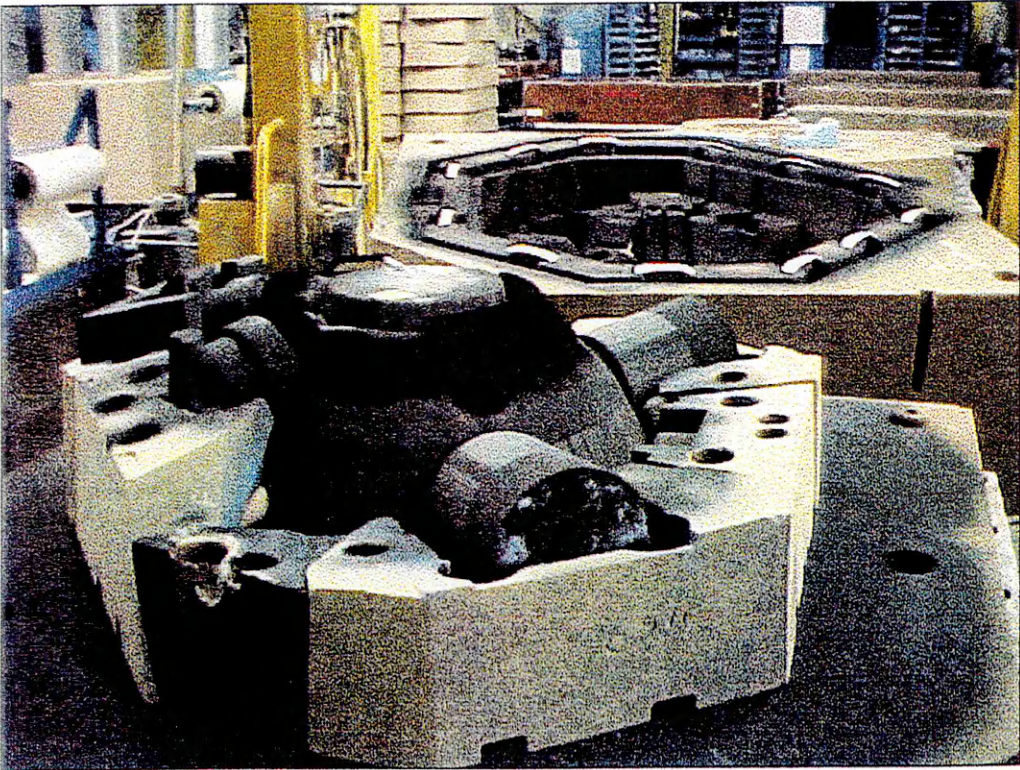


Figure 7 Completed 70351-38111 cope and drag.

This page left intentionally blank.

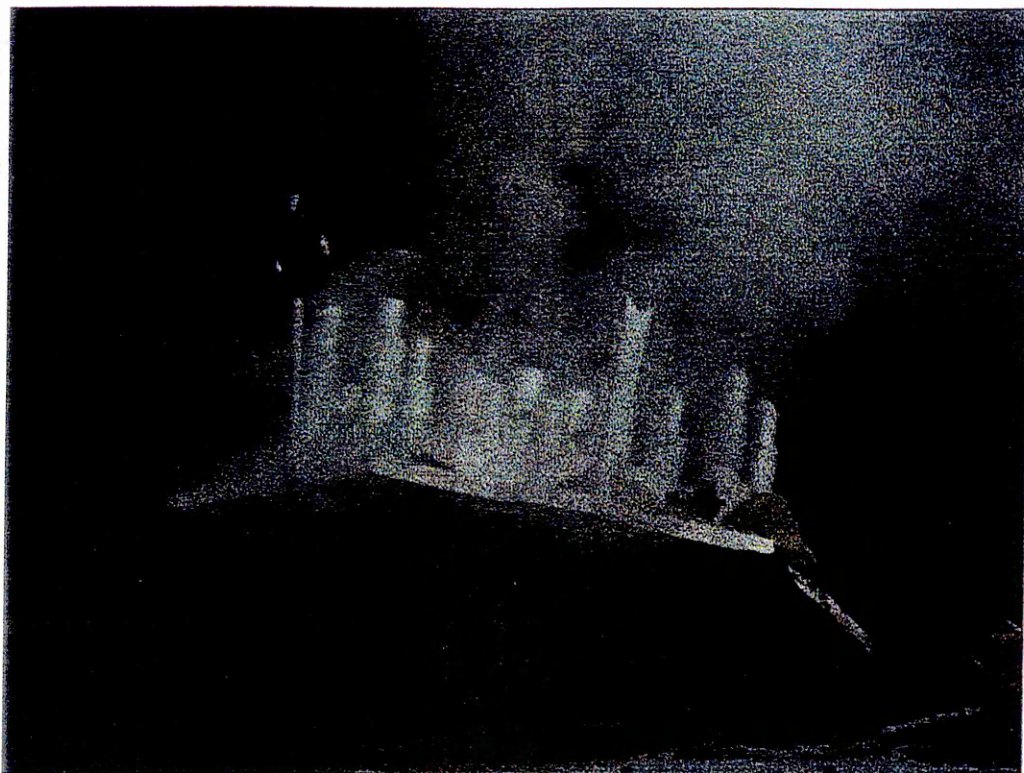


Figure 10 70351-38111, two hours after pouring, during initial shotblast.

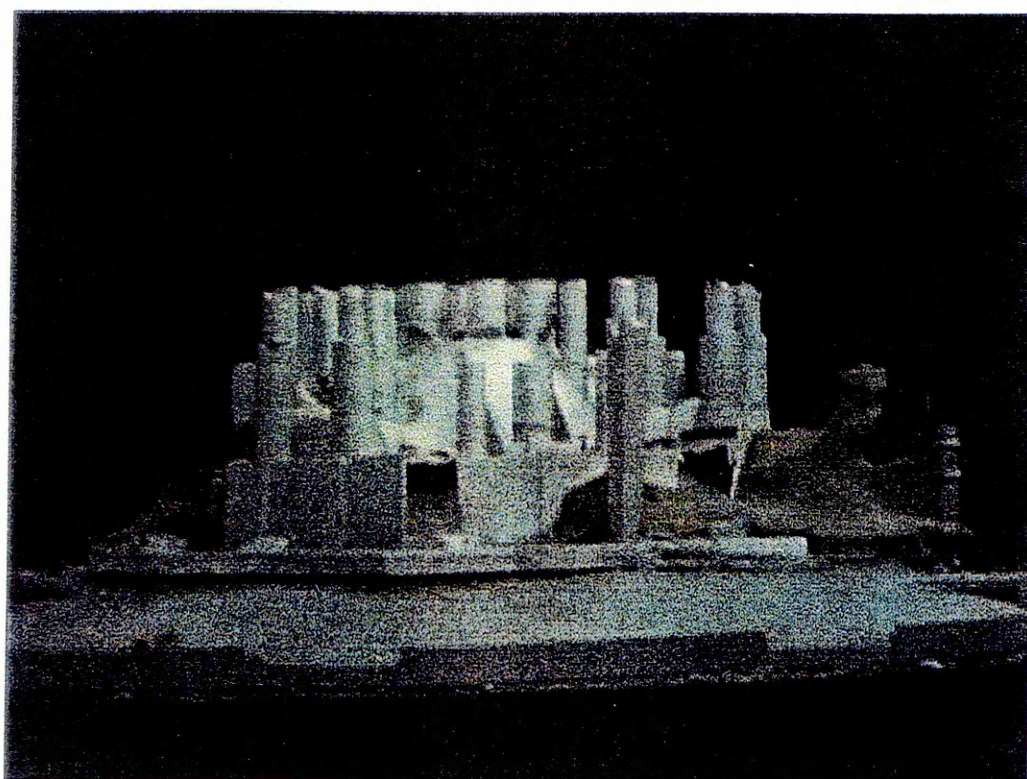


Figure 11 70351-38111 during shotblast.

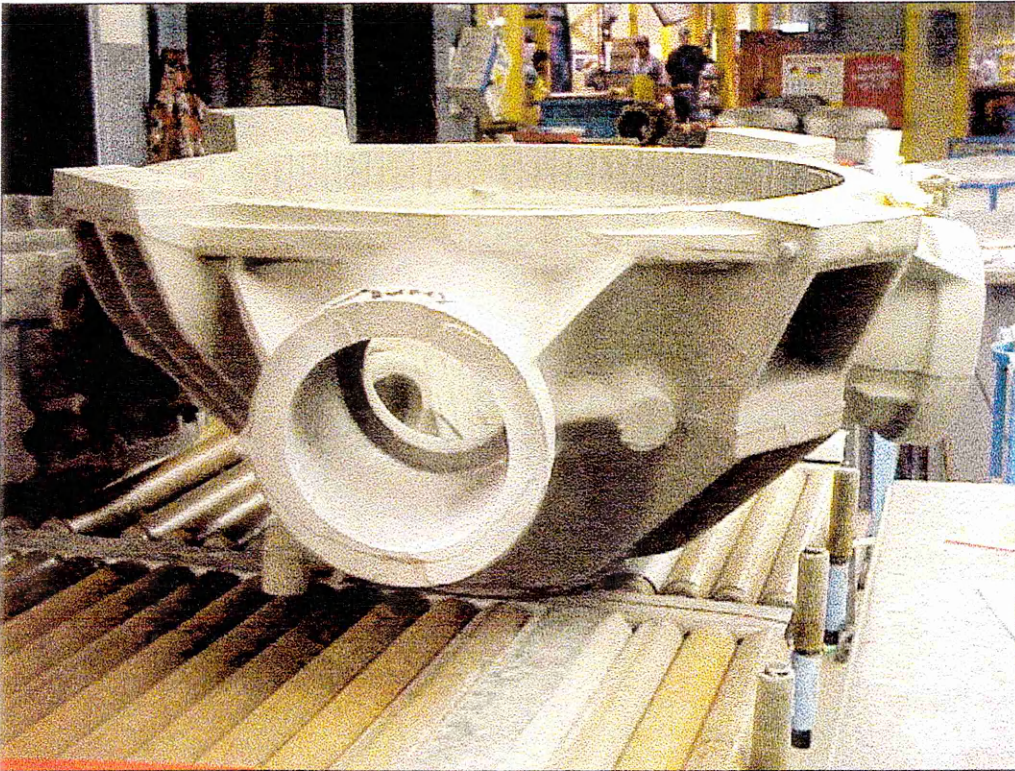


Figure 12 70351-38111 after fluorescent penetrant inspection.

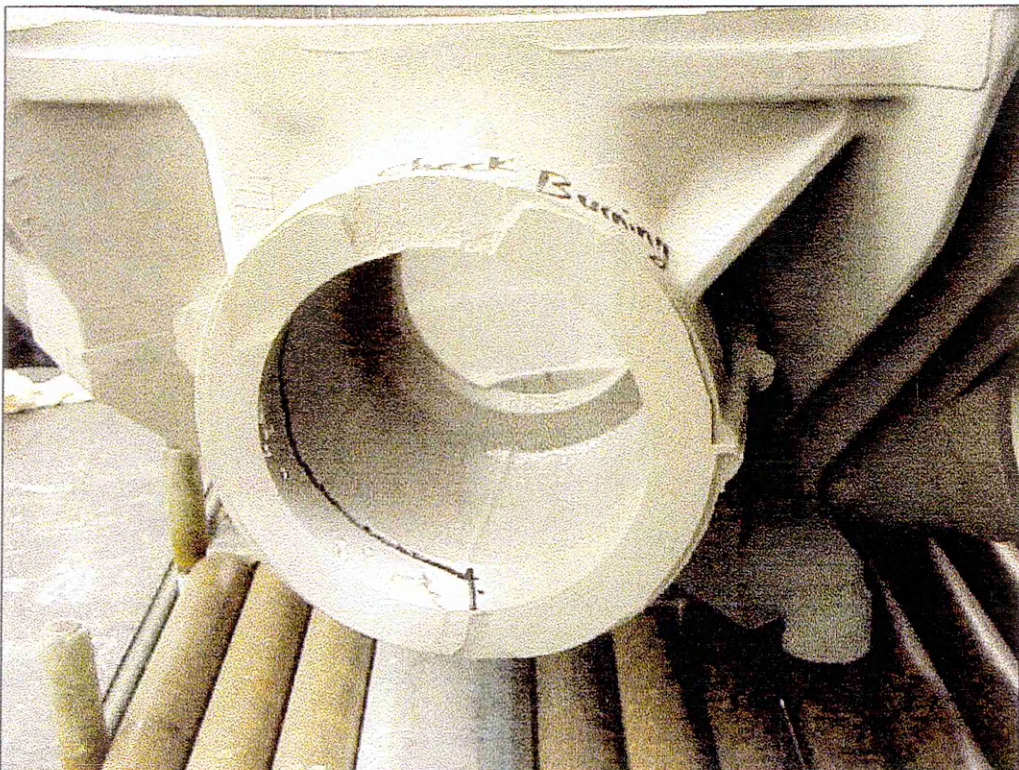


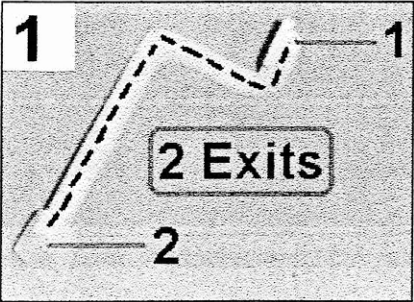
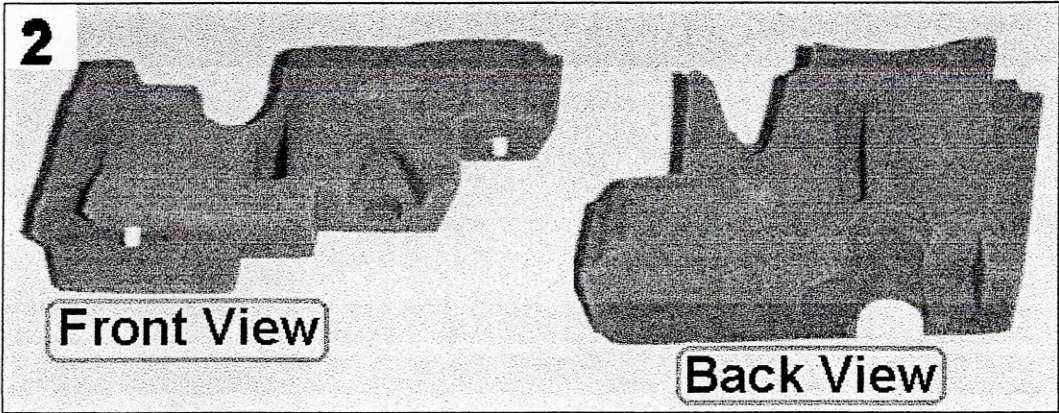
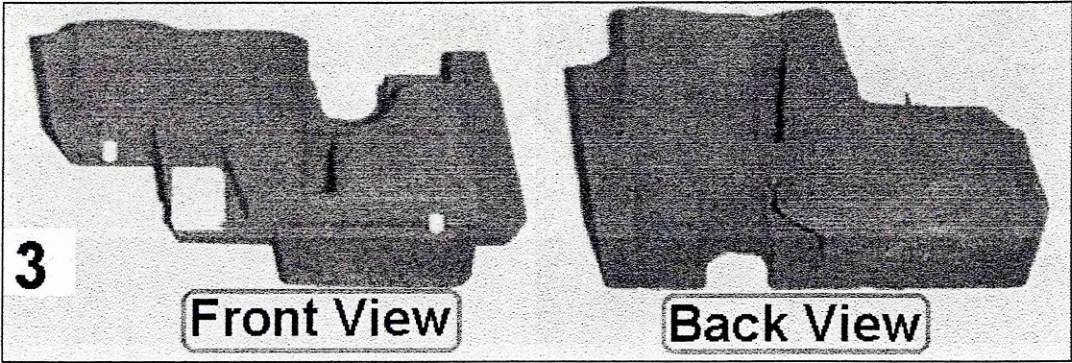
Figure 13 Location of core 19 where some burning occurred.

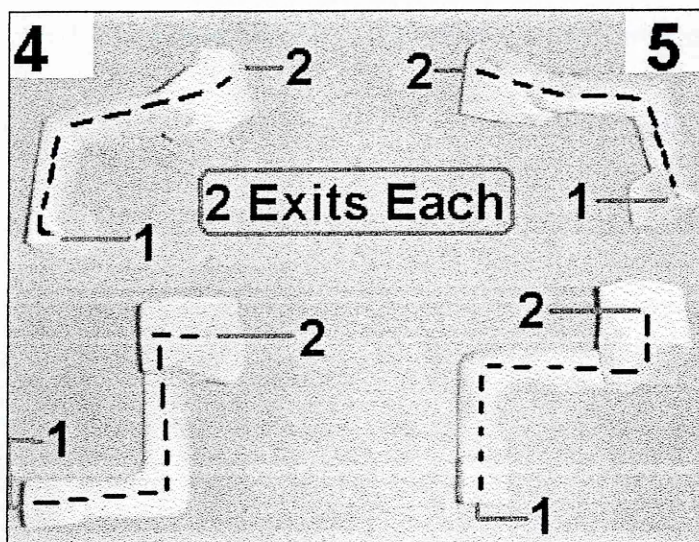
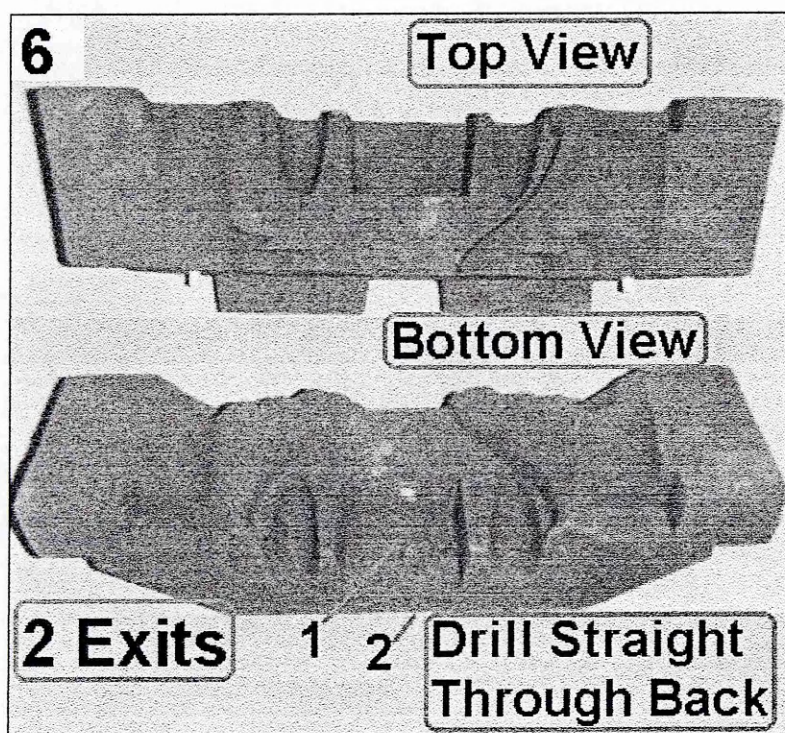


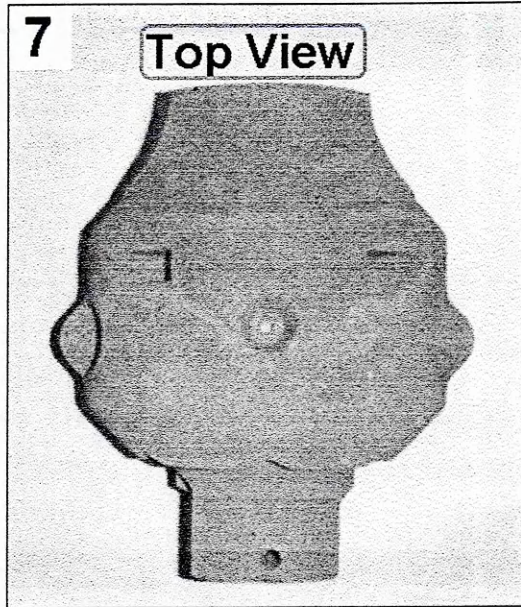
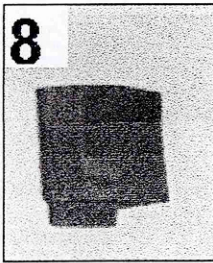
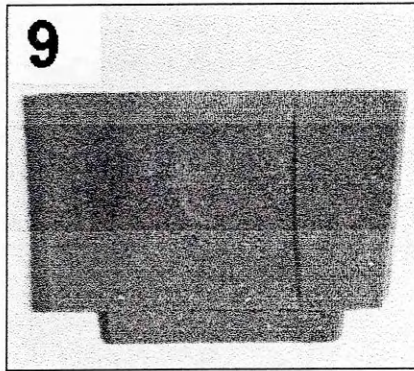
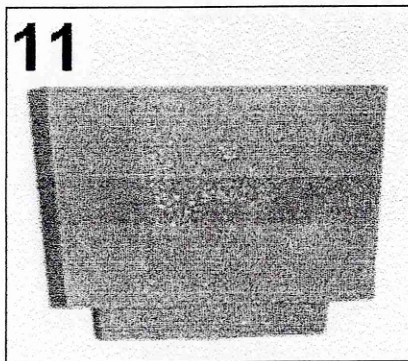
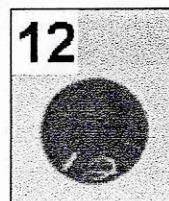
Figure 14 Close-up of burning on 70351-38111.

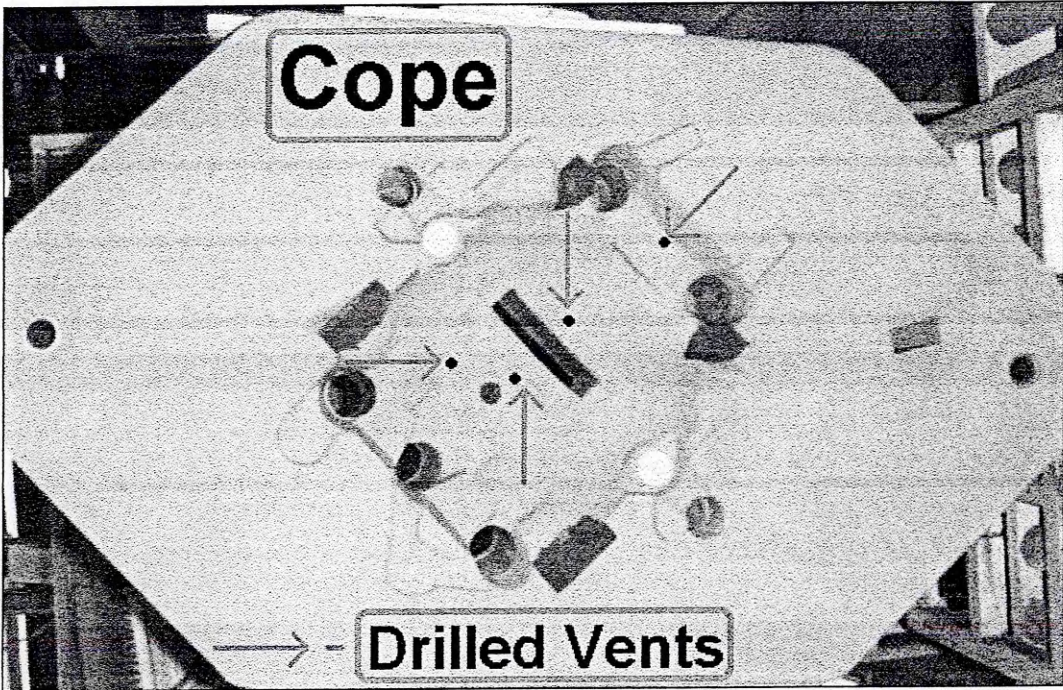
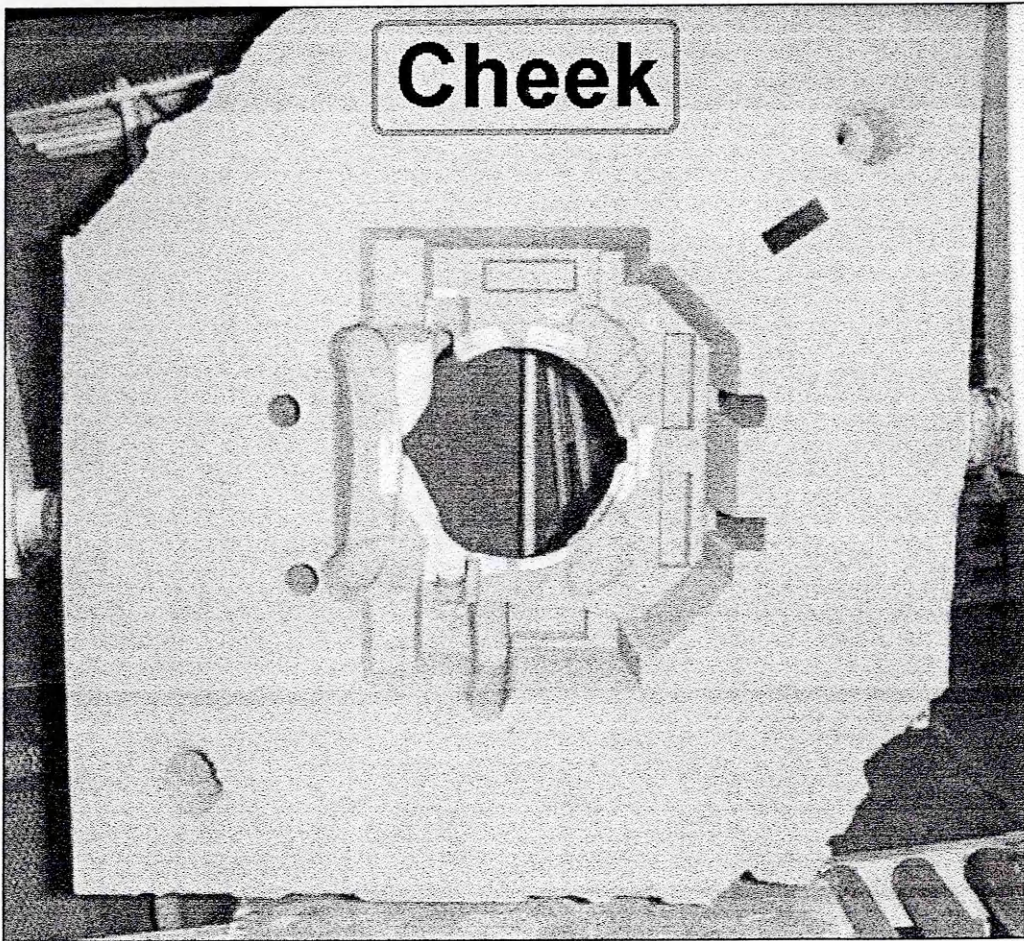
MOULD SECTIONS AND CORES OF THE TEST CASTINGS

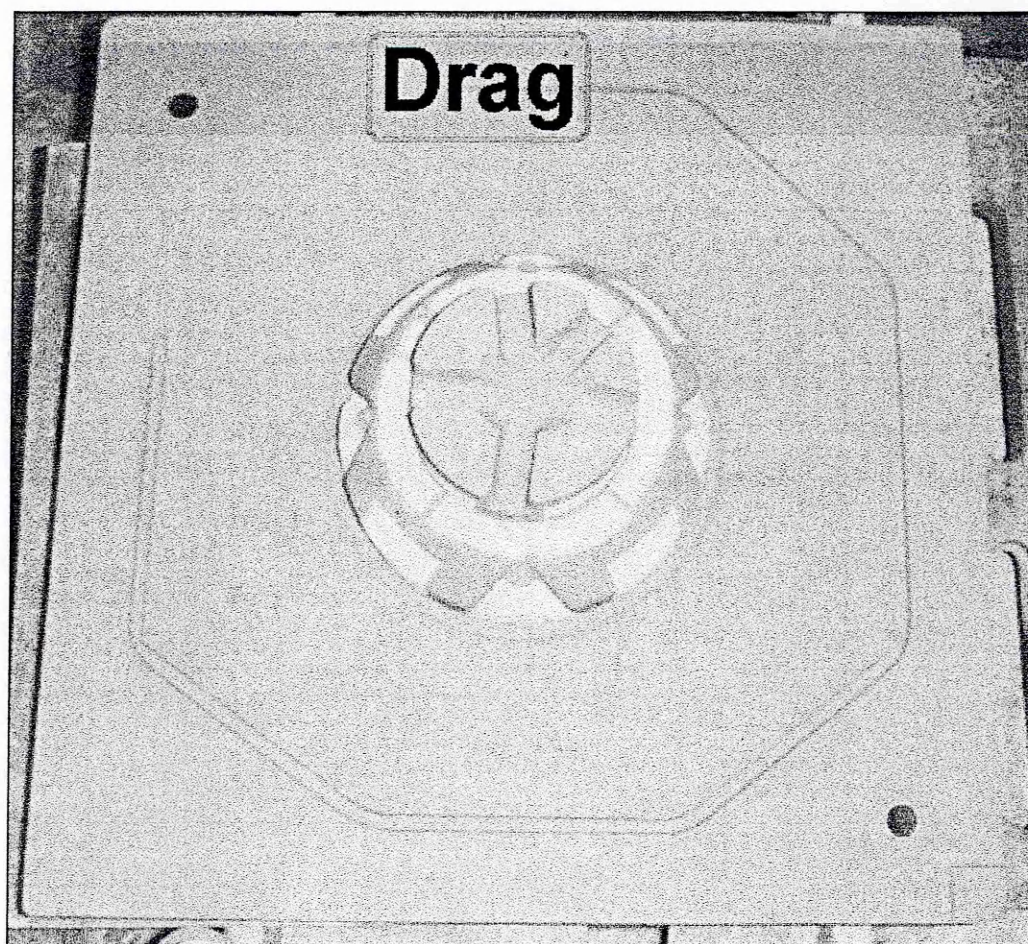
Cores and mould sections of the 145D-6311 (pictures not to scale).











Cores and mould sections of the 70351-38111(pictures not to scale).

