APPENDICES

APPENDIX A

MASS FLOW RATE OF COOLING AIR ENERGY & EXERGY ANALYSES

A1. Mass Flow Rate of Cooling Air Energy Analyses

Table A1 (a)
Base case clinker cooler

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.3
	Cooling air	2.55	1.01	45.0	51.5	3.7
Output	Secondary air	0.45	1.14	850.0	423.2	30.2
	Tertiary air	0.42	1.13	650.0	296.6	21.1
	Cooled Clinker	1.00	0.92	115.0	82.8	5.9
	Exhaust gas	1.68	1.03	220.0	337.4	24.1
	Unaccountable losses				262.9	18.7

Table A1 (b)
5% increase in mass flow rate of cooling air

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.2
	Cooling air	2.68	1.01	45.0	54.1	3.8
Output	Secondary air	0.48	1.14	847.8	446.0	31.7
	Tertiary air	0.45	1.13	638.9	309.1	22.0
	Cooled Clinker	1.00	0.92	107.6	76.0	5.4
	Exhaust gas	1.76	1.03	209.6	334.1	23.8
	Unaccountable losses				240.5	17.1

Table A1 (c)
10% increase in mass flow rate of cooling air

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.0
	Cooling air	2.81	1.01	45.0	56.7	4.0
Output	Secondary air	0.50	1.14	845.5	468.6	33.3
	Tertiary air	0.47	1.13	627.8	320.9	22.8
	Cooled Clinker	1.00	0.92	100.3	69.2	4.9
	Exhaust gas	1.83	1.03	199.3	329.1	23.4
	Unaccountable losses				220.4	15.7

Table A1 (d)
15% increase in mass flow rate of cooling air

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	95.8
	Cooling air	2.93	1.01	45.0	59.2	4.2
Output	Secondary air	0.53	1.14	843.3	491.1	34.8
	Tertiary air	0.50	1.13	616.8	332.0	23.5
	Cooled Clinker	1.00	0.92	92.9	62.5	4.4
	Exhaust gas	1.91	1.03	188.9	322.4	22.9
	Unaccountable losses				202.7	14.4

Table A1 (e)
20% increase in mass flow rate of cooling air

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	95.6
	Cooling air	3.06	1.01	45.0	61.8	4.4
Output	Secondary air	0.55	1.14	841.0	513.5	36.3
	Tertiary air	0.52	1.13	605.7	342.5	24.2
	Cooled Clinker	1.00	0.92	85.5	55.7	3.9
	Exhaust gas	1.99	1.03	178.6	314.2	22.2
	Unaccountable losses				187.4	13.3

Table A1 (f)
Energy efficiencies

Cooling Air Flow Rate (kg/kg.ck)	Increment (%)	Energy Efficiency, $\eta_{cooler\ I}$ (%)	Recovery Efficiency, $\eta_{recovery,\ cooler}$ (%)
2.55	0	81.3	51.3
2.68	5	82.9	53.7
2.81	10	84.3	56.1
2.93	15	85.6	58.3
3.06	20	86.7	60.6

Table A1 (g)
Average improvement in energy efficiencies

	Energy	Energy Recovery
	1.6	2.4
	1.5	2.3
	1.3	2.3
	1.1	2.2
Average improvement in efficiency	**1.4**	**2.3**

Table A1 (h)
Energy recovery efficiency with exhaust heat recovery

Cooling Air Flow Rate (kg/kg.ck)	Recovery Efficiency, $\eta_{recovery,\ cooler}$ (%)
2.55	75.4
2.68	77.5
2.81	79.4
2.93	81.2
3.06	82.8

Table A1 (i)
Average energy saving

	Secondary Air	Tertiary Air
	22.6	12.4
	22.6	11.8
	22.5	11.2
	22.4	10.5
Average Energy Saving (kJ/kg)	**22.5**	**11.5**

A2. Mass Flow Rate of Cooling Air Exergy Analyses

Table A2 (a)
Base case clinker cooler

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.55	1.01	45.0	51.5	49.9	1.7	0.2
Output	Secondary air	0.45	1.14	850.0	423.2	202.8	220.4	26.6
	Tertiary air	0.42	1.13	650.0	296.6	159.9	136.7	16.5
	Cooled Clinker	1.00	0.92	115.0	82.8	72.4	10.4	1.3
	Exhaust gas	1.68	1.03	220.0	337.4	259.6	77.8	9.4
	Total Exergy losses						382.2	46.2

Table A2 (b)
5% increase in mass flow rate of cooling air

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.68	1.01	45.0	54.1	52.4	1.7	0.2
Output	Secondary air	0.48	1.14	847.8	446.1	214.0	232.1	28.0
	Tertiary air	0.45	1.13	638.9	309.1	167.8	141.3	17.1
	Cooled Clinker	1.00	0.92	107.6	76.0	67.1	8.9	1.1
	Exhaust gas	1.76	1.03	209.6	334.1	260.0	74.1	9.0
	Total Exergy losses						371.3	44.9

Table A2 (c)
10% increase in mass flow rate of cooling air

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.81	1.01	45.0	56.7	54.8	1.8	0.2
Output	Secondary air	0.50	1.14	845.5	468.6	225.1	243.5	29.4
	Tertiary air	0.47	1.13	627.8	320.9	175.5	145.4	17.6
	Cooled Clinker	1.00	0.92	100.3	69.2	61.7	7.5	0.9
	Exhaust gas	1.83	1.03	199.3	329.1	259.1	70.0	8.5
	Total Exergy losses						361.4	43.7

Table A2 (d)
15% increase in mass flow rate of cooling air

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.93	1.01	45.0	59.2	57.3	1.9	0.2
Output	Secondary air	0.53	1.14	843.3	491.2	236.3	255.0	30.8
	Tertiary air	0.50	1.13	616.8	332.1	182.9	149.2	18.0
	Cooled Clinker	1.00	0.92	92.9	62.5	56.3	6.2	0.7
	Exhaust gas	1.91	1.03	188.9	322.5	257.0	65.5	7.9
	Total Exergy losses						352.1	42.5

Table A2 (e)
20% increase in mass flow rate of cooling air

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	3.06	1.01	45.0	61.8	59.8	2.0	0.2
Output	Secondary air	0.55	1.14	841.0	513.5	247.3	266.2	32.2
	Tertiary air	0.52	1.13	605.7	342.5	190.1	152.5	18.4
	Cooled Clinker	1.00	0.92	85.5	55.7	50.7	5.0	0.6
	Exhaust gas	1.99	1.03	178.6	314.2	253.4	60.8	7.3
	Total Exergy losses						343.5	41.5

Table A2 (f)
Exergy efficiencies

Cooling Air Flow Rate (kg/kg.ck)	Increment (%)	Exergy Efficiency, $\eta_{cooler\ II}$ (%)	Exergy Recovery Efficiency, $\eta_{recovery\ II,\ cooler}$ (%)
2.55	0	53.8	43.2
2.68	5	55.1	45.1
2.81	10	56.3	47.0
2.93	15	57.5	48.8
3.06	20	58.5	50.6

Table A2 (g)
Average improvement in exergy efficiencies

	Exergy	Exergy Recovery
	1.3	2.0
	1.2	1.9
	1.1	1.8
	1.0	1.8
Average improvement in efficiency	**1.2**	**1.9**

Table A2 (h)
Exergy recovery efficiency with exhaust heat recovery

Cooling Air Flow Rate (kg/kg.ck)	Exergy Recovery Efficiency, $\eta_{recovery\ II,\ cooler}$ (%)
2.55	52.6
2.68	54.1
2.81	55.4
2.93	56.7
3.06	57.9

APPENDIX B

COOLING AIR TEMPERATURE ENERGY & EXERGY ANALYSES

B1. Cooling Air Temperature Energy Analyses

Table B1 (a)
Base case clinker cooler

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.3
	Cooling air	2.55	1.01	45.0	51.5	3.7
Output	Secondary air	0.45	1.14	850.0	423.2	30.2
	Tertiary air	0.42	1.13	650.0	296.6	21.1
	Cooled Clinker	1.00	0.92	115.0	82.8	6.3
	Exhaust gas	1.68	1.03	220.0	337.4	9.4
	Unaccountable losses				262.9	18.7

Table B1 (b)
5% decrease in cooling air temperature

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	99.3
	Cooling air	2.55	1	29.0	10.2	0.7
Output	Secondary air	0.45	1.14	824.4	410.1	30.1
	Tertiary air	0.42	1.13	629.0	286.6	21.0
	Cooled Clinker	1.00	0.92	106.2	74.7	5.8
	Exhaust gas	1.68	1.03	208.8	318.0	9.4
	Unaccountable losses				272.3	20.0

Table B1 (c)
5% increase in cooling air temperature

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	93.5
	Cooling air	2.55	1.02	61.0	93.6	6.5
Output	Secondary air	0.45	1.14	876.3	436.7	30.2
	Tertiary air	0.42	1.13	671.6	306.9	21.2
	Cooled Clinker	1.00	0.92	124.1	91.2	6.7
	Exhaust gas	1.68	1.03	231.5	357.4	9.4
	Unaccountable losses				253.0	17.5

Table B1 (d)
Energy efficiencies

Cooling Air Temperature (˚C)	Change (%)	Energy Efficiency, $\eta_{coolerI}$ (%)	Recovery Energy Efficiency, $\eta_{recovery,\ cooler}$ (%)
45.0	0	81.3	51.3
29.1	-5	80.0	51.2
60.9	5	82.5	51.5

Table B1 (e)
Average improvement in energy efficiencies

	Energy	Energy Recovery
	1.3	0.1
	1.2	0.1
Average improvement in efficiency	**1.2**	**0.1**

Table B1 (f)
Energy recovery efficiency with exhaust heat recovery

Cooling Air Temperature (˚C)	Recovery Efficiency, $\eta_{recovery,\ cooler}$ (%)
45.0	75.4
29.1	74.5
60.9	76.2

Table B1 (g)
Average energy saving

	Secondary Air	Tertiary Air
	13.1	10.0
	13.5	10.3
Average Energy Saving (kJ/kg)	**13.3**	**10.1**

B2. Cooling Air Temperature Exergy Analyses

Table B2 (a)
Base case clinker cooler

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.80
	Cooling air	2.55	1.01	45.0	51.5	49.9	1.7	0.20
Output	Secondary air	0.45	1.14	850.0	423.2	202.8	220.4	26.63
	Tertiary air	0.42	1.13	650.0	296.6	159.9	136.7	16.52
	Cooled Clinker	1.00	0.92	115.0	82.8	72.4	10.4	1.28
	Exhaust gas	1.68	1.03	220.0	337.4	259.6	77.8	9.38
	Total Exergy Destroyed				262.9		382.2	46.18

Table B2 (b)
7.4% increase in exergy destruction with every 5% decrease in cooling air temperature

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.99
	Cooling air	2.55	1	29.1	10.5	10.4	0.1	0.01
Output	Secondary air	0.45	1.14	819.7	410.1	198.6	211.5	25.60
	Tertiary air	0.42	1.13	625.1	286.6	156.0	130.6	15.81
	Cooled Clinker	1.00	0.92	104.5	74.7	64.8	9.8	1.20
	Exhaust gas	1.68	1.03	206.7	318.0	245.5	72.5	9.38
	Total Exergy Destroyed						401.7	48.62

Table B2 (a)
7.4% decrease in exergy destruction with every 5% increase in cooling air temperature

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.34
	Cooling air	2.55	1.02	60.9	93.6	88.2	5.5	0.66
Output	Secondary air	0.45	1.14	880.3	436.7	206.9	229.8	27.64
	Tertiary air	0.42	1.13	674.9	306.9	163.7	143.2	17.22
	Cooled Clinker	1.00	0.92	125.5	91.2	79.7	11.5	1.40
	Exhaust gas	1.68	1.03	233.3	357.4	273.3	84.1	9.38
	Total Exergy Destroyed						362.9	43.64

Table B2 (d)
Exergy efficiencies

Cooling Air Temperature (˚C)	Change (%)	Exergy Efficiency, $\eta_{coolerII}$ (%)	Recovery Exergy Efficiency, $\eta_{recovery\ II,\ cooler}$ (%)
45.0	0	53.8	43.2
29.1	-5	51.4	41.4
60.9	5	56.4	44.9

Table B2 (e)
Average improvement in exergy efficiencies

	Exergy	Exergy Recovery
	2.4	1.7
	2.5	1.7
Average improvement in efficiency	**2.5**	**1.7**

Table B2 (f)
Exergy recovery efficiency with exhaust heat recovery

Cooling Air Flow Rate (kg/kg.ck)	Exergy Recovery Efficiency, $\eta_{recovery\ II,\ cooler}$ (%)
45.0	52.6
29.1	50.2
60.9	55.0

APPENDIX C

MASS FLOW RATE OF CLINKER ENERGY & EXERGY ANALYSES

C1. Mass Flow Rate of Clinker Energy Analyses

Table C1 (a)
Base case clinker cooler

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.3
	Cooling air	2.55	1.01	45.0	51.5	3.7
Output	Secondary air	0.45	1.14	850.0	423.2	30.3
	Tertiary air	0.42	1.13	650.0	296.6	20.9
	Cooled Clinker	1.00	0.92	115.0	82.8	5.9
	Exhaust gas	1.68	1.03	220.0	337.4	24.0
	Unaccountable losses				262.9	18.9

Table C1 (b)
5% decrease in mass flow rate of clinker

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.2
	Cooling air	2.68	1.01	45.0	54.1	3.8
Output	Secondary air	0.48	1.14	850.0	447.2	31.8
	Tertiary air	0.45	1.13	650.0	314.6	22.4
	Cooled Clinker	1.00	0.92	100.6	69.6	5.0
	Exhaust gas	1.76	1.03	220.0	352.8	25.1
	Unaccountable losses				221.4	15.7

Table C1 (c)
10% decrease in mass flow rate of clinker

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.0
	Cooling air	2.81	1.01	45.0	56.7	4.0
Output	Secondary air	0.50	1.14	850.0	471.2	33.5
	Tertiary air	0.47	1.13	650.0	332.6	23.6
	Cooled Clinker	1.00	0.91	86.3	55.8	4.0
	Exhaust gas	1.83	1.03	220.0	368.2	26.1
	Unaccountable losses				180.4	12.8

Table C1 (d)
15% decrease in mass flow rate of clinker

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	95.8
	Cooling air	2.93	1.01	45.0	59.2	4.2
Output	Secondary air	0.53	1.14	850.0	495.2	35.1
	Tertiary air	0.50	1.13	650.0	350.7	24.9
	Cooled Clinker	1.00	0.91	71.9	42.7	3.0
	Exhaust gas	1.91	1.03	220.0	383.5	27.2
	Unaccountable losses				138.7	9.8

Table C1 (e)
20% decrease in mass flow rate of clinker

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	95.6
	Cooling air	3.06	1.01	45.0	61.8	4.4
Output	Secondary air	0.55	1.14	850.0	519.2	36.7
	Tertiary air	0.52	1.13	650.0	368.7	26.1
	Cooled Clinker	1.00	0.9	57.6	29.3	2.1
	Exhaust gas	1.99	1.03	220.0	398.9	28.2
	Unaccountable losses				97.3	6.9

Table C1 (f)
Energy efficiencies

Clinker Flow Rate (kg/kg.ck)	Decrement (%)	Energy Efficiency, $\eta_{cooler\ I}$ (%)	Recovery Efficiency, $\eta_{recovery,\ cooler}$ (%)
1.00	0	81.3	51.3
0.95	5	84.3	54.2
0.90	10	87.2	57.1
0.85	15	90.2	60.0
0.80	20	93.1	62.8

Table C1 (g)
Average improvement in energy efficiencies

	Energy	Energy Recovery
	3.0	2.9
	2.9	2.9
	3.0	2.9
	2.9	2.9
Average improvement in efficiency	**3.0**	**2.9**

Table C1 (h)
Energy recovery efficiencies with exhaust heat recovery

Clinker Flow Rate (kg/kg.ck)	Energy Recovery Efficiency, $\eta_{recovery,\ cooler}$ (%)
1	75.4
0.95	79.3
0.90	83.2
0.85	87.1
0.8	91.0

Table C1 (i)
Average energy saving

	Secondary Air	Tertiary Air
	24.0	18.0
	24.0	18.0
	24.0	18.0
	24.0	18.0
Average Energy Saving (kJ/kg)	**24.0**	**18.0**

C2. Mass Flow Rate of Clinker Exergy Analyses

Table C2 (a)
Base case clinker cooler

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.55	1.01	45.0	51.5	49.9	1.7	0.2
Output	Secondary air	0.45	1.14	850.0	423.2	202.8	220.4	26.6
	Tertiary air	0.42	1.13	650.0	296.6	159.9	136.7	16.5
	Cooled Clinker	1.00	0.92	115.0	82.8	72.4	10.4	1.3
	Exhaust gas	1.68	1.03	220.0	337.4	259.6	77.8	9.4
	Total Exergy losses						382.2	46.2

Table C2 (b)
5% decrease in mass flow rate of clinker

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.68	1.01	45.0	54.1	52.3	1.7	0.2
Output	Secondary air	0.47	1.14	850.0	447.3	211.8	235.5	28.4
	Tertiary air	0.44	1.13	650.0	314.7	167.5	147.2	17.8
	Cooled Clinker	1.00	0.92	100.6	69.6	62.0	7.6	0.9
	Exhaust gas	1.77	1.03	220.0	352.9	273.5	79.4	9.6
	Total Exergy losses						358.1	43.3

Table C2 (c)
10% decrease in mass flow rate of clinker

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.81	1.01	45.0	56.7	54.8	1.8	0.2
Output	Secondary air	0.50	1.14	850.0	471.2	223.1	248.1	30.0
	Tertiary air	0.46	1.13	650.0	332.6	175.9	156.8	18.9
	Cooled Clinker	1.00	0.91	86.3	55.8	50.7	5.1	0.6
	Exhaust gas	1.85	1.03	220.0	368.2	285.6	82.6	10.0
	Total Exergy losses						335.3	40.5

Table C2 (d)
15% decrease in mass flow rate of clinker

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.93	1.01	45.0	59.2	57.3	1.9	0.2
Output	Secondary air	0.52	1.14	850.0	495.3	233.2	262.0	31.7
	Tertiary air	0.48	1.13	650.0	350.7	183.9	166.8	20.2
	Cooled Clinker	1.00	0.91	71.9	42.7	39.7	3.0	0.4
	Exhaust gas	1.93	1.03	220.0	383.6	298.5	85.1	10.3
	Total Exergy losses						310.9	37.6

Table C2 (e)
20% decrease in mass flow rate of clinker

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (KJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	3.06	1.01	45.0	61.8	59.8	2.0	0.2
Output	Secondary air	0.54	1.14	850.0	519.2	243.4	275.8	33.3
	Tertiary air	0.50	1.13	650.0	368.7	191.9	176.8	21.4
	Cooled Clinker	1.00	0.90	57.6	29.3	27.8	1.5	0.2
	Exhaust gas	2.02	1.03	220.0	398.9	311.5	87.4	10.6
	Total Exergy losses						286.5	34.6

Table C2 (f)
Exergy efficiencies

Clinker Flow Rate (kg/kg.ck)	Decrement (%)	Exergy Efficiency, $\eta_{cooler\ II}$ (%)	Exergy Recovery Efficiency, $\eta_{recovery\ II,\ cooler}$ (%)
1.00	0.0	53.8	43.2
0.95	5.0	56.7	46.2
0.90	10.0	59.5	48.9
0.85	15.0	62.4	51.8
0.80	20.0	65.4	54.7

Table C2 (g)
Average improvement in exergy efficiencies

	Exergy	Exergy Recovery
	2.91	3.08
	2.76	2.68
	2.95	2.90
	2.95	2.86
Average improvement in efficiency	**2.89**	**2.88**

Table C2 (h)
Exergy recovery efficiency with exhaust heat recovery

Cooling Air Flow Rate (kg/kg.ck)	Exergy Recovery Efficiency, $\eta_{\text{recovery II, cooler}}$ (%)
1.00	52.56
0.95	55.82
0.90	58.89
0.85	62.08
0.80	65.21

APPENDIX D

GRATE SPEED ENERGY & EXERGY ANALYSES

D1. Grate Speed Energy Analyses

Table D1 (a)
Base case clinker cooler

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.3
	Cooling air	2.55	1.01	45.0	51.5	3.7
Output	Secondary air	0.45	1.14	850.0	423.2	30.2
	Tertiary air	0.42	1.13	650.0	296.6	21.1
	Cooled Clinker	1.00	0.92	115.0	82.8	5.9
	Exhaust gas	1.68	1.03	220.0	337.4	24.1
	Unaccountable losses				262.9	18.7

Table D1 (b)
9.1% increment in grate speed

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.3
	Cooling air	2.55	1.01	45.0	51.5	3.7
Output	Secondary air	0.45	1.14	872.5	434.8	31.0
	Tertiary air	0.42	1.13	677.7	309.8	22.1
	Cooled Clinker	1.00	0.92	115.0	82.8	5.9
	Exhaust gas	1.68	1.03	242.7	376.7	26.8
	Unaccountable losses				199.0	14.2

Table D1 (c)
18.2% increment in grate speed

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.3
	Cooling air	2.55	1.01	45.0	51.5	3.7
Output	Secondary air	0.45	1.14	883.7	440.5	31.4
	Tertiary air	0.42	1.13	696.2	318.6	22.7
	Cooled Clinker	1.00	0.92	115.0	82.8	5.9
	Exhaust gas	1.68	1.03	254.0	396.3	28.2
	Unaccountable losses				164.9	11.8

Table D1 (d)
27.3% increment in grate speed

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.3
	Cooling air	2.55	1.01	45.0	51.5	3.7
Output	Secondary air	0.45	1.14	883.7	440.5	31.4
	Tertiary air	0.42	1.13	686.9	314.1	22.4
	Cooled Clinker	1.00	0.92	115.0	82.8	5.9
	Exhaust gas	1.68	1.03	231.3	357.0	25.4
	Unaccountable losses				208.6	14.9

Table D1 (e)
36.4% increment in grate speed

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Q (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.3
	Cooling air	2.55	1.01	45.0	51.5	3.7
Output	Secondary air	0.45	1.14	861.2	429.0	30.6
	Tertiary air	0.42	1.13	650.0	296.6	21.1
	Cooled Clinker	1.00	0.92	115.0	82.8	5.9
	Exhaust gas	1.68	1.03	186.0	278.6	19.9
	Unaccountable losses				316.0	22.5

Table D1 (f)
Energy efficiencies

Grate Speed (m/s)	Increment (%)	Energy Efficiency, $\eta_{\text{cooler I}}$ (%)	Recovery Efficiency, $\eta_{\text{recovery, cooler}}$ (%)
0.11	0	81.3	51.3
0.12	9.1	85.8	53.1
0.13	18.2	88.2	54.1
0.14	27.3	85.1	53.8
0.15	36.4	77.5	51.7

Table D1 (g)
Average improvement in energy efficiencies

	Energy	Energy Recovery
	4.6	1.8
	2.4	1.0
Average improvement in efficiency	**3.5**	**1.4**

Table D1 (h)
Energy recovery efficiency with exhaust heat recovery

Grate Speed (m/s)	Recovery Efficiency, $\eta_{recovery, cooler}$ (%)
0.11	75.4
0.12	79.9
0.13	82.3
0.14	79.2
0.15	71.6

Table D1 (i)
Average energy saving

	Secondary air	Tertiary air
	11.5	13.1
	5.7	8.8
Average energy saving	**8.6**	**11.0**

D2. Grate Speed Exergy Analyses

Table D2 (a)
Base case clinker cooler

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (kJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.55	1.01	45.0	51.5	49.9	1.7	0.2
Output	Secondary air	0.45	1.14	850.0	423.2	202.8	220.4	26.6
	Tertiary air	0.42	1.13	650.0	296.6	159.9	136.7	16.5
	Cooled Clinker	1.00	0.92	115.0	82.8	72.4	10.4	1.3
	Exhaust gas	1.68	1.03	220.0	337.4	259.6	77.8	9.4
	Total Exergy losses						382.2	46.2

Table D2 (b)
9.1% increment in grate speed

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (kJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.55	1.01	45.0	51.5	49.9	1.7	0.2
Output	Secondary air	0.45	1.14	872.5	434.8	205.8	228.9	27.7
	Tertiary air	0.42	1.13	677.7	309.8	164.1	145.7	17.6
	Cooled Clinker	1.00	0.92	115.0	82.8	72.4	10.4	1.3
	Exhaust gas	1.68	1.03	242.7	376.7	282.8	93.9	11.3
	Total Exergy losses						348.7	42.1

Table D2 (c)
18.2% increment in grate speed

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (kJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.55	1.01	45.0	51.5	49.9	1.7	0.2
Output	Secondary air	0.45	1.14	883.7	440.5	207.3	233.2	28.2
	Tertiary air	0.42	1.13	696.2	318.6	166.8	151.8	18.3
	Cooled Clinker	1.00	0.92	115.0	82.8	72.4	10.4	1.3
	Exhaust gas	1.68	1.03	254.0	396.3	294.0	102.3	12.4
	Total Exergy losses						330.0	39.9

Table D2 (d)
27.3% increment in grate speed

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (kJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.55	1.01	45.0	51.5	49.9	1.7	0.2
Output	Secondary air	0.45	1.14	883.7	440.5	207.3	233.2	28.2
	Tertiary air	0.42	1.13	686.9	314.1	165.4	148.7	18.0
	Cooled Clinker	1.00	0.92	115.0	82.8	72.4	10.4	1.3
	Exhaust gas	1.68	1.03	231.3	357.0	271.3	85.7	10.4
	Total Exergy losses						349.6	42.2

Table D2 (e)
36.4% increment in grate speed

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Sensible Energy, Q (kJ/kg.ck)	Useless Energy (kJ/kg.ck)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	525.5	826.0	99.8
	Cooling air	2.55	1.01	45.0	51.5	49.9	1.7	0.2
Output	Secondary air	0.45	1.14	861.2	429.0	204.3	224.6	27.1
	Tertiary air	0.42	1.13	650.0	296.6	159.9	136.7	16.5
	Cooled Clinker	1.00	0.92	115.0	82.8	72.4	10.4	1.3
	Exhaust gas	1.68	1.03	186.0	278.6	222.7	55.9	6.7
	Total Exergy losses						400.0	48.3

Table D2 (f)
Exergy efficiencies

Grate Speed (m/s)	Increment (%)	Exergy Efficiency, $\eta_{cooler\ II}$ (%)	Exergy Recovery Efficiency, $\eta_{recovery\ II,\ cooler}$ (%)
0.11	0	53.8	43.2
0.12	9.1	57.9	45.3
0.13	18.2	60.1	46.5
0.14	27.3	57.8	46.1
0.15	36.4	51.7	43.7

Table D2 (g)
Average improvement in efficiencies

	Exergy	Exergy Recovery
	4.1	2.1
	2.3	1.2
Average improvement in efficiency	**3.2**	**1.7**

Table D2 (h)
Exergy recovery efficiency with exhaust heat recovery

Grate Speed (m/s)	Exergy Recovery Efficiency, $\eta_{\text{recovery II, cooler}}$ (%)
0.11	52.6
0.12	56.6
0.13	58.9
0.14	56.5
0.15	50.4

APPENDIX E

HEAT RECOVERY OF EXHAUST AIR ENERGY & EXERGY ANALYSES

Table E1
Varying mass flow rate of cooling air

Cooling Air Flow Rate (kg/kg.ck)	Increment (%)	Recovery Efficiency, $\eta_{recovery,\ cooler}$ (%)	Recovery Exergy Efficiency, $\eta_{recovery\ II,\ cooler}$ (%)
2.55	0	75.4	52.6
2.68	5	77.5	54.1
2.81	10	79.4	55.4
2.93	15	81.2	56.7
3.06	20	82.8	57.9

Table E2
Varying temperature of cooling air

Cooling Air Temp. (˚C)	Decrement (%)	Recovery Efficiency, $\eta_{recovery,\ cooler}$ (%)	Recovery Exergy Efficiency, $\eta_{recovery\ II,\ cooler}$ (%)
45.0	0	75.4	52.6
29.1	-5	74.5	50.2
60.9	5	76.2	55.0

Table E3
Varying mass flow rate of clinker

Clinker Flow Rate (kg/kg.ck)	Decrement (%)	Recovery Efficiency, $\eta_{recovery,\ cooler}$ (%)	Recovery Exergy Efficiency, $\eta_{recovery\ II,\ cooler}$ (%)
1	0	75.4	52.6
0.95	5	79.3	55.8
0.90	10	83.2	58.9
0.85	15	87.1	62.1
0.8	20	91.0	65.2

Table E4
Varying grate speed

Grate Speed (m/s)	Increment (%)	Recovery Efficiency, $\eta_{recovery,\ cooler}$ (%)	Recovery Exergy Efficiency, $\eta_{recovery\ II,\ cooler}$ (%)
0.11	0	75.4	52.6
0.12	9.1	79.9	56.6
0.13	18.2	82.3	58.9
0.14	27.3	79.2	56.5
0.15	36.4	71.6	50.4

APPENDIX F

ENERGY & COST SAVING ANALYSES

Table F1
Energy saving

Operating Parameters	Average Improvement in Energy Recovery Efficiency (%)	Energy Saved (kJ/kg.ck)			Contribution (%)
		Rotary Kiln	Pre-Calciner	TOTAL	
Mass Flow Rate of Cooling Air	2.32	22.54	11.48	34.01	30.86
Cooling Air Temperature	0.14	13.31	10.12	23.43	21.26
Mass Flow Rate of Clinker	2.88	23.98	18.01	41.99	38.10
Grate Speed	0.77 (up to 18.2% optimization)	4.75	6.02	10.77	9.78
TOTAL		**64.58**	**45.63**	**110.21**	**100.00**

Table F2
Cost saving

Operating Parameters	Average Improvement in Energy Recovery Efficiency (%)	Cost Saving (USD/tonne.ck)			Contribution (%)
		Rotary Kiln	Pre-Calciner	TOTAL	
Mass Flow Rate of Cooling Air	2.32	0.105	0.054	0.159	30.86
Cooling Air Temperature	0.14	0.062	0.047	0.109	21.26
Mass Flow Rate of Clinker	2.88	0.112	0.084	0.196	38.10
Grate Speed	0.77 (up to 18.2% optimization)	0.022	0.028	0.050	9.78
TOTAL		**0.301**	**0.213**	**0.514**	**100.00**

NOTES:

Ave. fuel price = 4.664 USD/GJ

Plant produces 3000tpd clinker

Table F3
Exhaust air recovery

Contributors	Energy Saved (kJ/kg.ck)	Cost Saving (USD/tonne.ck)	Contribution (%)
Operational Parameters	110.2	0.51	24.62
Exhaust Heat Recovery	337.4	1.24	75.38
TOTAL	447.6	1.75	100.00

APPENDIX G

INCREMENTAL OPERATIONS COST ANALYSES

Table G1
Cooling air mass flow rate upgrades

Material	Original Mass Flow Rate (kg/kg clinker)	Mass Flow Rate (kg/kg clinker) after 5% Increment	Additional Air Mass Flow Rate (kg/kg ck)	Additional Air Volume Flow Rate (m^3/h)	Fan Motor Power (kW)	Energy Requirement per day (kWh)	Additional Cost Requirement per day (USD)
Cooling air	2.55	2.68	0.13	21563	27.6	442	35
Secondary air	0.45	0.48	0.02	11912	15.2	244	19
Tertiary air	0.42	0.45	0.02	9781	12.5	200	16
Exhaust air	1.68	1.76	0.08	20000	25.6	410	33
TOTAL					81	1296	103

Density of Air at 45C = 1.109kg/m3
Density of Air at 850C = 0.3149kg/m3
Density of Air at 650C = 0.3835kg/m3
Density of Air at 220C = 0.7174kg/m3
Assuming cement plant produces 187.5 tonnes of clinker per hour, 52.1 kg.ck/s
Average fan motor power consumption per unit volume air flow rate is 0.002674kW/cmh

Table G2
Clinker mass flow rate upgrades

Fans	Cooling Air Mass Flow Rate (kg/kg clinker)	Cooling Air Volume Flow Rate (m^3/h)	Power (kW)	Energy Requirement per day (kWh)	Additional Energy Requirement per day (kWh)	Additional Cost Requirement per day (USD)
Cooling Air Fans	2.55	431270	552.0	8832	464	37
Secondary Air Fans	0.45	268028	343.1	5489	288	23
Tertiary Air Fans	0.42	205411	262.9	4207	221	18
Exhaust Air Fans	1.68	439226	562.2	8995	472	38
Grate	-	-	200.4	3206	168	13
Conveyors	-	-	400.8	6413	337	27
TOTAL			1920.6	37143	1950	155

Density of Air at 45C = 1.109kg/m3
Density of Air at 850C = 0.3149kg/m3
Density of Air at 650C = 0.3835kg/m3
Density of Air at 220C = 0.7174kg/m3
Assuming cement plant produces 187.5 tonnes of clinker per hour, 52.1 kg.ck/s

Table G3
Fan power consumption

	Fan air flow (cmh)	Fan Power (kW)	Static Pressure (mbar)	Motor (kW)
	15931	39.4	89	55
	15808	36.9	84	59
	28628	57.3	72	107
	30794	55.7	65	143
	28860	59.4	74	138
	28744	60.8	76	134
	27535	48.3	63	120
	29916	43.9	54	113
	59377	47.9	29	140
	66586	61.1	33	198
	57488	44.8	28	58
	54619	36.5	24	123
	43738	57.2	47	145
	48847	38	28	130
TOTAL	536871	687.2	766	1663
Average	38348	49.1	55	119

Average fan kW per unit cmh:	0.00128001
Average cmh per unit fan kW:	781.2441793
Efficiency:	46.06%

APPENDIX H

ECONOMIC ANALYSES

Table H1
Monthly cash flow

	Mass Flow Rate of Cooling Air	Cooling Air Temperature	Mass Flow Rate of Clinker	Grate Speed
Increment in Energy Consumption	1296 kWh per day	NA	1950 kWh per day	160kWh per day
	USD 103.00 per day		USD 155.00 per day	USD 12.75 per day
	USD2,575.00 per month		USD 3,875.00 per month	USD 318.80 per month
Energy Saving	USD 11,925.00 per month	USD 8,175.00 per month	USD 14,700.00 per month	USD 3,750.00 per month

Table H2
Economic appraisal

Method of Appraisal / **Operational Parameters**	**Payback Period (months)**	**Present Value (USD)**
Mass Flow Rate of Cooling Air	54.8	7742
Temperature of Cooling Air	2.4	437860
Mass Flow Rate of Clinker	11.1	483141
Grate Speed	17.4	132775

Table H3
Investment costs

	Mass Flow Rate of Cooling Air	Temperature of Cooling Air	Mass Flow Rate of Clinker	Grate Speed
Investment Cost (USD)	512,400.00	20,000.00	120,000.00	59,800.00

Table H4
Energy cost

Energy Cost	
Electrical	USD 79.70/MWh
Fuel	USD 4.644/GJ

Table H5
Cost of conserved energy

	Mass Flow Rate of Cooling Air	Temperature of Cooling Air	Mass Flow Rate of Clinker	Grate Speed
Cost of Conserved Energy (USD)	0.99	0.04	0.41	0.37
Incremental Cost per year (USD)	30,900.00	-	46,500.00	3,825.60
Annual Energy Savings (USD)	142,149.00	97,928.00	175,501.00	45,014.00

Table H6
Cost estimation

Mass Flow Rate of Cooling Air			
VSD for fan motors	**USD512,400.00**	USD200/fan motor HP	1911kW
Installation			2562HP
Temperature of Cooling Air			
Insulation	**USD20,000.00**	41.1kJ/kg.ck	
Piping			
Installation			
Mass Flow Rate of Clinker			
Feed Rate Reprogramming	**USD120,000.00**	USD200/motor HP	444kW
VSD for conveyor motors			597HP
Grate Speed			
VSD for grate motor	**USD59,800.00**	USD200/motor HP	299HP
Installation			

APPENDIX I

EMISSION REDUCTION ANALYSIS

Table I1
Average emission rate

Emission	Average Emission (kg/tonne clinker)
NOx	3.2
CO	2.5
PM (Dust)	0.21
CO2	368

Energy Use
3600000kJ/tonne clinker

Table I2
Average emission reduction

Operating Parameters	Energy Recovery (kJ/tonne clinker)	Average Emission Reduction (kg/tonne clinker)			
		NO_x	CO	PM (Dust)	CO_2
Mass Flow Rate of Cooling Air	34013	0.030	0.024	0.002	3.477
Cooling Air Temperature	23427	0.021	0.016	0.001	2.395
Mass Flow Rate of Clinker	41992	0.037	0.029	0.002	4.293
Grate Speed	19607	0.017	0.014	0.001	2.004