Title: Optimization of Heat Treatment Furnace Operation

Course:
Year: 1992
Author(s): D. Street, S. Blaine, J. Brunke and M. Ayabakan

Report No: P92019

Abstract: This project models and optimizes operation of a heat treatment furnace department of a foundry. Heat treatment furnace operation involves different operational temperatures, durations and atmospheres. It is inherently a batch process, but may be modeled as a linear program. The objective is to develop a tool to allow a weekly operational plan providing operators with a cost optimal strategy. Two methods were developed, one was formulated using pounds of furnace capacity and one using furnace time as variables. Both methods provided solutions, but the furnace hours best represented the nature of the problem. The program solutions provide a method to lower operational costs while providing insight to the characteristics of the process. The program may be rerun for any changes such as equipment failure or new parts to run, and a new department operation plan developed.

OPTIMIZATION OF
HEAT TREATMENT FURNACE OPERATION

Donna Street, Stevem Blaine
John Brunke, Murat Ayabakan

EMP-P9219

Optimization

of

Heat Treatment Furnace Operation

By

Donna Street

Steve Blaine

John Brunke

Murat Ayabakan

In partial fulfillment of the requirements

of EMGT 640

Portland State University

June 1992

Table of Contents

Heat Treatment Furnace Operation

Executive Summary

Donna Street, Steve Blaine, John Brunke, Murat Ayabakan

A tool was developed using linear programming techniques to improve operation in the Precision Castparts Heat Treatment Department.

The production schedule for a particular week was analyzed and the optimal strategy for running the department was found.

The program provides guidance to load furnaces in the most cost effective manner. Forecast of the weekly schedule for operations, labor (leave and overtime), and maintenance is enhanced. It also provides a tool for Engineering to study future equipment additions or modifications. Trade offs in operating cost can be predicted for changes in schedule and product mix. Impact of additional workload or downtime can be forecast.

Introduction

The heat treatment department at Precision Castparts Corporations Small Structures Plant (SSBO) processes thousands of stainless steel alloy parts each month. The parts made include artificial joints and turbine blades to mention a few. The properties of these materials are critical. To achieve these properties treatments are required at temperatures from 1100 to 2200 degrees Fahrenheit, for times from 1 to 20 hours, in either atmospheric air, argon, or vacuum.

The department has a number of furnaces available. Some are exclusively for vacuum processing and others are for either atmospheric air or argon processing. The cost of department operations varies with the type of processing required and which furnace is selected for each processing operation. The furnaces differ in capacity and efficiency. Meeting delivery schedule is the primary goal forcing parts to be moved through the department quickly. This often forces a furnace to be run with less than a full load. A methodology to assist operators in determining which furnace to run how much of each process has the potential to save the company money and improve department operations. This is the goal of this project.

Figure 1 shows the layout of the heat treat area. The department has seven different furnaces. Some of these furnaces are more costly to operate since they operate at higher temperatures and with argon or vacuum atmosphere. The furnaces have different capabilities, capacities, and efficiencies. The vacuum furnaces only had three processes scheduled and the problem became trivial. This report will therefore examine only the air/argon furnaces in detail. The vacuum furnace solution is included in Appendix III.

The Problem

The problem is to schedule the furnaces to reduce processing cost while meeting production schedule.

Furnaces C18 and C25 operate in air or argon and at temperatures from 1200 to 2100 degrees Fahrenheit. Furnaces C10 and C30 operate in vacuum over the same temperature range and can quench parts with argon.

In formulation of our problem the furnaces are identified as follows:

Furnace #1	C18	air or argon processing
Furnace #2	C25	air or argon processing
Furnace #3	C10	vacuum processing
Furnace #4	C30	vacuum processing

Appendix #1 shows the furnace capabilities, capacities, operational costs etc.

Methodology

Two different methodologies were employed for solving this problem. They were then compared. The problem formulations were all of a transportation type problem (1,2,3,4,5).

In the first method, the objective variables were pounds of material processed. The a_{ij} coefficients were in hours per pound and the C_{ij} coefficients were in dollars per pound.

In the second method the objective variables are in hours, the a_{ij} coefficients are in units of pounds per hour for the demand constraints, and the C_{ij} coefficients are in units of dollars per hour. This method is similar to that used by Chung (5, page 279) to create a transportation problem by using ratios of machine capacity.

Assumptions

Because of the batch nature of this process an initial difficulty was encountered.

The batch process lends itself to an integer solution. Reducing the number of batch runs will reduce cost. As an option we studied the calculation of a cost function of the pounds of material processed. This resulted in a non-linear problem. It was apparent that we would have to make certain assumptions to allow a linear program solution

Assumptions:

Method 1

The furnaces process material at a constant cost per pound regardless of percent capacity used. Therefore a half full batch costs the same per pound as a full batch to process. The time duration of each process was factored into the formulation.

Method 2

The assumption for this method is that batches are divisible at the same batch cost, but factors are included for partial batches in the derivation of the constraint coefficients.

Linear Program Conditions

It is important to verify that we have met the basic assumptions of linear programming:

1. Linearity and additivity. This assumption was key to simplify our program. For method 1, cost per pound is constant for each furnace and process. For method 2, cost per hour is constant. This is the key difference between the two methods.

2. Divisibility. The divisibility assumption applies because the problem was formulated in terms of pounds of material processed or hours of furnace operation, not batches. If this assumption could not be met the problem would have to be solved as an integer problem. If we had the tools to solve this type of problem in this manner we might be able to improve our solution.

3. Fitness or limited resources. There is finite number of furnaces and finite number of hours to process all the parts in the department, therefore this condition is met.

4. Deterministic. The variables do not change over the period of the study (one week).

Data Acquisition

Data for a typical production week was gathered. For furnaces 1 & 2, over 1200 parts were in the staging area waiting to be heat treated. There were 18 different heat treatment processes required for these parts. For furnaces 3 & 4, 135 parts required 3 different processes. Sample documentation showing process requirements and pounds per part are attached. See appendix II.

Parts mix varies from week to week. Studies could be run at the beginning of each week to give operators guidance to the most optimal method for the weeks operation.

Linear Program Formulation

Method 1

In order to avoid the integer/non-linear difficulties previously discussed, this problem was set up on a per pound basis.

The objective coefficients were computed for each of the 18 processes and for each furnace. Adjustments for different operating temperatures were then made to determine the furnace operating cost per hour ($/hr) for each process. These are sumarized in appendix I. The objective coefficients were then calculated in units of dollars per pound as follows:

$$C_{ij} = \frac{\text{Furnace operational cost per hour(\$/hr) x Cycle time(hrs)}}{\text{Furnace Capacity (lbs)}}$$

$$= \text{dollars per pound (\$/lb)}$$

These coefficients are only accurate for full furnace loads. Making the coefficients change with percent capacity results in a nonlinear problem. In this problem this assumption is justified as almost all furnace loads are near capacity due to the large number of parts in each process batch.

The constraints were then formulated for the time required to process parts in each of the furnaces. A limit of 5 days (3 shifts per days) was selected to process all the parts in order to meet delivery schedule. Each furnace has a capacity limit and the constraint was formulated with the coefficients in terms of pounds per hour. These were calculated for each furnace and each process as follows:

$$a_{ij} = \frac{\text{Cycle Time (hrs)}}{\text{Furnace Capacity (lbs)}} = \text{hrs/lb}$$

The variables (X_{ij}) are the pounds of each process to be processed in each furnace. The first subscript (1,2,3,4) is the furnace number. The second subscript (1 to 18 for argon/air, and 1 to 3 for vacuum) is the process number. For example; X_{214} is the pounds processed in furnace 2, of process 14.

The constraint equations are therefore:

1. The total hours available in furnace number 1

2. The total hours available in furnace number 2

3-21. The requirements to complete each required component.

All variables are non-negative.

It is a process scheduling problem. It is also similar to a transportation problem. We have a demand for parts and a supply of a resource (furnace time). In researching this problem we found similar problems in a number of sources. In a book by Chung(ref, page 279) there is a problem which has a number of machines which operate at different efficiencies are scheduled to process material in the most efficient manner. Machines are related in terms of their hourly production rates to make the problem a transportation problem. This is the same approach which we have taken.

Method 2

For this solution the problem was set up in a per hour basis.

The objective coefficients were computed for each furnace, at each process operation temperature. These are included in Appendix II.

C_{ij} = operational cost in dollars per hour (@ operational temperature). = \$/lb

These coefficients are valid for either full loads or partial loads unlike method 1. The objective function totals operational costs from both furnaces.

The constraints are 1) total available furnace hours (supply), and 2) to for each process to total demand for each process.

The coefficients of the demand constraints were derived as follows:

1. The total pounds of each process was divided by the furnace capacity, then rounded up to make whole "batches".

2. The "batches" was multiplied by the hours per batch.

3. The total pounds to be processed was divided by total hours (2).

The units of the "batches" (lb/lb) is dimensionless. Then multiplied by hours (units hours). Total pounds divided by this number then yields pound per hour.

d = Integer(lbs matl to be processed/furnace capacity)

$$a_{ij} = \frac{\text{total lbs to be processed in this process}}{d * \text{hours/ batch}}$$

The variables (X_{ij}) are the hours of furnace time for each process, for each furnace. The first subscript (1,2,3,4) is the furnace number. The second subscript (1 to 18 for argon/air, and 1 to 3 for vacuum) is the process number. For example; X_{214} is the hours in furnace 2, of process 14.

The constraint equations are therefore:

1. The total hours available in furnace number 1

2. The total hours available in furnace number 2

3-21. The requirements to complete each required component.

All variables are non-negative.

Note: these are the same as in method 1.

LINDO

The linear programs were solved using LINDO (6). The solution for the method 1 problem was obtained in 6 iterations for the air/argon problem and in 6 iterations for the vacuum processed parts (see Appendix III). The method 2 solution was run for the air/argon processes only and gave a solution in 7 steps.

A warning message was given by LINDO for the method 1 air/argon processed parts. The two first constraint equations were multiplied on both sides by 10 to better scale the problem.

The Solution By Method 1

LINDO gave a solution to the problem as follows:

Furnace # 1

Process	Pounds
5	1943
6	459
7	462
8	3460
9	525
18	639

Furnace #2

1	14707
2	1318
3	10964
4	669
8	823
10	2333
11	2618
12	1314

Process	Pounds
13	2770
14	1046
15	2142
16	578
17	2003

The objective function value is $3015.35.

Looking at the results we see that only process 8 is split between the two furnaces. As expected furnace #2 is preferred as it has the lower cost per pound. The capacity of furnace #2 is entirely used up, and furnace #1 has over 37 hours available. This indicates what reserve capacity this department has.

Solution by Method 2

LINDO produced the following solution for the problem when the problem was constructed on an hours basis and the total weekly available furnace hours was held to 130 each:

Furnace #1

Process	Hours
4	5
5	55.2
6	21
7	3.8
10	12.3
16	5.1
17	3.86
18	4.0

Furnace #2

Process	Hours
1	40
2	3.5
3	35.2
8	12
11	8.8
12	3.5
13	7.6
14	4.3
15	10
17	5

The value of the objective function is $3595.08.

Sensitivity Analysis

METHOD 1

SHADOW PRICES. Furnace one has a surplus of 37.9 (379.4 in equation due to scaling) hours which can be used for processing. The shadow price for this constraint is therefore zero. Any additional processing should be done in Furnace one until the surplus is exhausted.

The shadow price for an additional hour of furnace two is $9.40. This tells us that for each additional hour of use of furnace two should cost us less than $9.40 to operate the furnace or adding the additional resources is not profitable.

The shadow prices of the remaining constraints (weight constraints for processes 1-18) are the cost per pound to process an aditional pound of material. For example, the shadow price for process 6 from the LINDO run is $0.315/lb.

RANGE ON THE OBJECTIVE FUNCTION COEFFICIENTS. The objective function ranges show how the price per pound can decrease or increase by the indicated amount without changing the solution. For instance, the cost per pound of furnace one, process 5 can increase $0.054 before requiring a new solution to the problem. It can also decrease to zero.

RANGE ON RIGHTHAND SIDE COEFFICIENTS. For constraints one and two (time constraints on furnaces one and two respectively), the right hand side ranges show how much additional time could be made available for a particular furnace before the optimal solution would change. For furnace one, the amount of available time could increase to infinity (due to the fact that there is slack) and the available time could decrease 37.94 hours and the given solution would still remain optimal.

For furnace two, the amount of available time could increase 9.206 hours and decrease 2.189 hours and the given solution would remain optimal.

The right hand side ranges for the remaining constraints (weight constraints on processes 1 through 18) tell us the range of weights for which the given solution remains optimal. For example for process 15, the amount of material could range from 0 to 2799.474 lbs and the solution remains unchanged. Note that all processes except 1, 3, and 8 can decrease to zero and the solution does not change.

SENSITIVITY ANALYSIS FOR METHOD 2

The sensitivity analysis is very similar to that for method one. The slack in furnace 1 is 10.78 hours and the shadow price for furnace 2 is $5.00 per hour. The objective coefficient ranges give an indication of the impact of a cost increase (perhaps due to labor or energy) and its affects on the solution. The right hand side coefficients show how either available furnace hours or pounds of each process can be varied without changing the solution. This is discussed above in the method 1 analysis.

Discussion

These results are for a "snapshot" of a particular week of data and can deviate significantly in other weeks. The value of this program is the insight that it gives in understanding the availability of resources and the impacts of various process\parts mixes on that.

Without this information operators might load parts into any available furnace. The solution specifies which process goes in which furnace. Without this planning tool parts might be loaded in a less cost effective manner or in a manner which won't meet production schedule.

Sensitivity analysis showed slack in furnace one for both methods. This would assist the shift supervisor in scheduling labor, knowing how much labor/furnace surplus is available for the week.

Scheduling maintenance on equipment could also be done using the slack. This would maintain optimal schedule and not require overtime for maintainance. If maintenance requirements exceed slack time a new solution could be run and new schedule created.

Both methods produced a solution with similar objective function values. The assumptions did drive processes into different furnaces. As method 1 assumed a continuous process it deviated more from the batch nature of the solution. It did not yield correct furnace hour impacts however. If the batch nature of the processes is reintoduced into the solution we find that the actual number of hour required on furnace one is 108 (vs 82) and 142 hours (vs 120). This is a significant deviation.

Method two tends to retain the batch nature in the solution and actually schedules total furnace resource time within a much closer margin. When time resources are reduced, more of the processes are forced into both furnaces, but with 130 hours per week available for each furnace(note method two showed that 120 hours per furnace per week was infeasible), only one process was forced into both furnaces. It did not correctly divide time resources between the furnaces, but it did schedule more time than needed so the work can be completed.

In terms of cost per pound, furnace 2 is much more efficient than furnace 1, so method 1 drove all the material towards that furnace. Without resource constraint all material goes to that furnace. Method 2 recognized that the smaller furnace 1 was more economical for batches within its capacity.

The more accurate method is method 2, however the most accurate would be to develop an integer solution which would fully recognize the batch characteristics of this process. Method two however provide a good solution of the problem.

Conclusions

A linear program can be developed to solve a batch type problem. Selection of the formulation can greatly affect the solution. Solutions found gave a reasonable plan for department operations. The process can be understood using this tool and decisions on department operational procedures, resource requirements, etc. can be better made.

References

(1) Shapiro, Roy D. "Optimization Models for Planning and Allocation: Text and Cases in Mathematical Programming", John Wiley and Sons, New York, 1984.

(2) Lee, Sang M. ,et al, "Management Science", Wm Brown, Dubuque, Iowa, 1985.

(3) Deckro, Richard, Course notes, EMGT 640. Portland State University 1992.

(4) Chung, A.M., "Linear Programming", C.E. Merrill, Columbus Ohio, 1963.

(5) Winston, W.L., "Introduction to Mathematical Programming, Applications and Algorithms", PWS-Kent, Boston, 1991.

(6) Scharage, Linus, "LINDO, Users Manual", The Scientific Press, San Francisco, 1991.

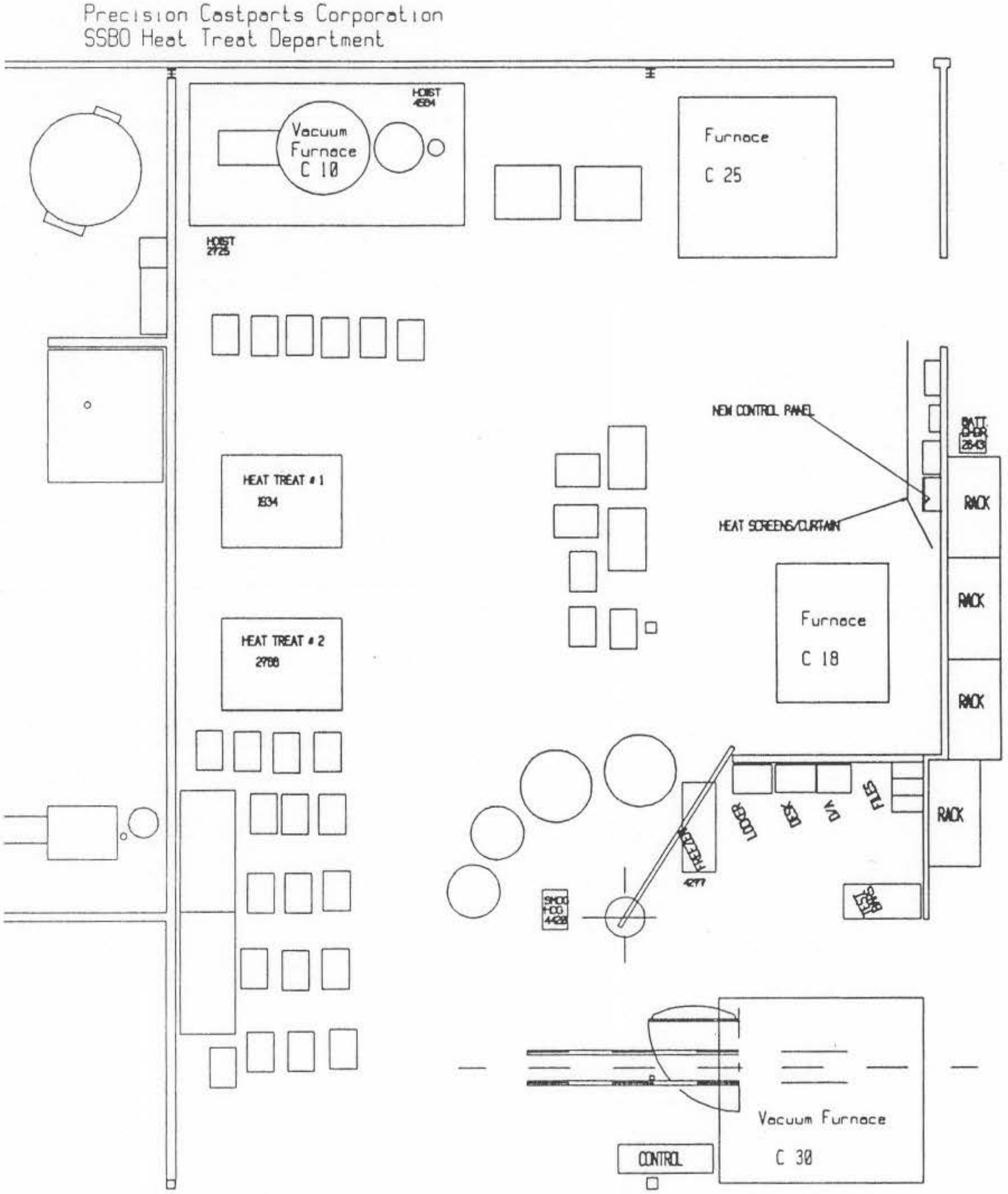

Figure 1 Heat Treatment Department Layout

	Solutions for the Air/Argon Furnaces			
Process	M1 F1	M1 F2	M2 F1	M2 F2
	lbs	lbs	hrs	hrs
1	0	14707	0	40
2	0	1318	0	3.5
3	0	10964	0	35.2
4	0	669	4.79	0
5	1943	0	55.2	0
6	459	0	20.96	0
7	462	0	3.8	0
8	3460	823	0	12
9	525	0	4	0
10	0	2333	12.2	0
11	0	2618	0	8.8
12	0	1314	0	3.5
13	0	2770	0	7.6
14	0	1046	0	4.3
15	0	2142	0	10
16	0	578	5.1	0
17	0	2003	3.86	5.03
18	639	0	4	0
	7488	43285	113.91	129.93

Figure 2 Comparision of Method 1 and Method 2 Results

Appendix I

Heat Treatment Furnace

Operational and Cost Data

EMGT 540 - Heat Treat Project Data - Furnace Cost Summary - 1700 (f)

Furnace	Furnace Name	$/hr Labor	$/hr Supplies	$/hr Argon	$/hr Repairs	$/hr Electric	$/hr Gas	$/hr Total	Pounds Capacity
----	----	----	----	----	----	----	----	----	-----
1	C18	2	1	4	1	0	6	14	800
2	C25	2	2	5	1	0	7	17	1500
3	C10	1	1	0	4	3	0	9	900
4	C30	2	1	1	4	4	0	12	1000

27-May-92

EMGT 540 - Heat Treat Project Data

Process #	REF #	TEMP (deg F)	CYCLE TIME (HRS)	ATMOSPHE	PART #	# OF PIECES	POUNDS/PIECE	POUNDS	Furn 1 $/hr	Furn 2 $/hr	Furn 1 $/pound	Furn 2 $/pound	Furn 1 hr/pound	Furn 2 hr/pound
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1	1050	1750	4	argon	3154	1	93	93	14	17	0.07	0.045	0.005	0.00266
					3396	29	25	725						
					4493	12	30	360						
					5420	119	70	8,330						
					5882	18	150	2,700						
					6331	1	94	94						
					6511	1	140	140						
					7241	3	165	495						
					7266	1	38	38						
					7674	18	55	990						
					7856	2	195	390						
					8071	4	88	352						
							TOTAL POUNDS	14,707						
2	1051	1900	3.5	argon	3025	2	33	66	15	18	0.066	0.042	0.00438	0.00233
					7438	2	44	88						
					7439	22	17	374						
					10309	6	45	270						
					10339	4	130	520						
							TOTAL POUNDS	1,318						
3	1052	2000	4.4	argon	3154	1	93	93	16	19	0.088	0.056	0.0055	0.00293
					3396	28	25	700						
					3797	2	63	126						
					5420	117	70	8,190						
					5640	8	50	400						
					5682	4	150	600						
					7241	3	165	495						
					7680	3	120	360						
							TOTAL POUNDS	10,964						

EMGT 540 - Heat Treat Project Data

Process #	REF #	TEMP (deg F)	CYCLE TIME (HRS)	ATMOSPHE	PART #	# OF PIECES	POUNDS/PIECE	POUNDS	Furn 1 $/hr	Furn 2 $/hr	Furn 1 $/pound	Furn 2 $/pound	Furn 1 hr/pound	Furn 2 hr/pound
4	1053	2100	5	argon	4730	2	120	240	17	20	0.106	0.066	0.00625	0.00333
					5126	2	120	240						
					5730	3	13	39						
					10036	10	15	150						
							TOTAL POUNDS	669						
5	1162	1400	18.4	air	10435	29	67	1,943	8	10	0.184	0.123	0.023	0.01226
							TOTAL POUNDS	1,943						
6	1205	1325	21	argon	5655	17	27	459	12	15	0.315	0.21	0.02625	0.014
							TOTAL POUNDS	459						
7	1208	1400	3.8	argon	4973	2	71	142	12	15	0.057	0.038	0.00475	0.00253
					5662	4	80	320						
							TOTAL POUNDS	462						
8	1225	1750	4	argon	3293	252	17	4,284	14	17	0.07	0.045	0.005	0.00266
							TOTAL POUNDS	4,284						
9	1227	1750	4	argon	7084	5	105	525	14	17	0.07	0.045	0.005	0.00266
							TOTAL POUNDS	525						
10	1250	1900	4.1	argon	746	109	11	1,199	15	18	0.077	0.049	0.00512	0.00273
					4730	1	120	120						
					5802	4	120	480						
					5126	2	120	240						
					5730	3	13	39						
					4730	1	120	120						
					10265	1	135	135						
							TOTAL POUNDS	2,333						

27-May-92

EMGT 540 - Heat Treat Project Data

Process #	REF #	TEMP (deg F)	CYCLE TIME (HRS)	ATMOSPHE	PART #	# OF PIECES	POUNDS/PIECE	POUNDS	Furn 1 $/hr	Furn 2 $/hr	Furn 1 $/pound	Furn 2 $/pound	Furn 1 hr/pound	Furn 2 hr/pound
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
11	1251	1900	4.4	argon	8126	22	119	2,618	15	18	0.083	0.053	0.0055	0.00293
							TOTAL POUNDS	2,618						
12	1264	1900	3.5	argon	746	109	11	1,199	15	18	0.066	0.042	0.00437	0.00233
					10506	1	115	115						
							TOTAL POUNDS	1,314						
13	1268	1925	3.8	argon	7680	4	120	480	15	18	0.071	0.046	0.00475	0.00253
					7461	19	110	2,090						
					7855	1	200	200						
							TOTAL POUNDS	2,770						
14	1280	2000	4.3	argon	90201	1	18	18	16	19	0.066	0.055	0.00537	0.00286
					7240	2	140	280						
					7084	6	105	630						
					7088	1	118	118						
							TOTAL POUNDS	1,046						
15	1282	2000	5	argon	3293	126	17	2,142	16	19	0.1	0.063	0.00625	0.00333
							TOTAL POUNDS	2,142						
16	1294	2100	5.1	argon	7457	1	131	131	17	20	0.108	0.068	0.00637	0.0034
					10339	2	130	260						
					7439	11	17	187						
							TOTAL POUNDS	578						

							POUNDS/PIECE	POUNDS	Furn 1 $/hr	Furn 2 $/hr	Furn 1 $/pound	Furn 2 $/pound	Furn 1 hr/pound	Furn 2 hr/pound
	1432	1975	3.8	argon	10435	24	67	1,608	16	19	0.076	0.048	0.00475	0.00253
					10436	5	79	395						
							TOTAL POUNDS	2,003						
18	1433	1750	4	air	10407	11	42	462	10	12	0.05	0.032	0.005	0.00266
					10353	1	177	177						
							TOTAL POUNDS	639						

EMGT 540 - Heat Treat Project Data

Process #	REF #	TEMP (deg F)	CYCLE TIME (HRS)	ATMOSPHE	PART #	# OF PIECES	POUNDS/PIECE	POUNDS	Furn 3 $/hr	Furn 4 $/hr	Furn 3 $/pound	Furn 4 $/pound	Furn 3 hr/pound	Furn 4 hr/pound
1	1422	1750	9	vacuum	3688	9	47	423	9	12	0.09	0.108	0.01	0.009
					7443	8	45	360						
					4535	20	42	840						
							TOTAL POUNDS	1,623						
2	1436	1400	10.6	vacuum	10506	2	115	230	7	10	0.082	0.106	0.0117	0.0106
					7461	21	110	2,310						
					90201	1	18	18						
							TOTAL POUNDS	2,558						
3	1437	1925	9.8	vacuum	6964	6	290	1,740	10	13	0.109	0.127	0.011	0.0098
					7461	41	110	4,510						
					10084	9	205	1,845						
					10306	14	200	2,800						
					8071	4	88	352						
							TOTAL POUNDS	11,247						

27-May-92

LABOR BREAKDOWN

Furnace #1 & #2

Time To Load/Unload & Do Paperwork = 1 Hour
Avg Time/Furnace Cycle = 4.47
Labor Hrs/Furn Hr = 0.22

Furnace #8

Unload/Load = 0.5
Time/Furn Cycle = 4.3
Labor Hrs/Furn Hr = 0.12

Furn	Labor Hrs/Furn Hr	Ratio
#1	0.220	0.69
#2	0.220	0.69
#8	0.116	0.36
#10	0.185	0.58
#18	0.266	0.83
#25	0.319	1.00
New	0.313	1.00

Furnace #10

Unload/Load = 1.5
Avg Time/Furn Cycle = 8.1
Labor Hrs/Furn Hr = 0.185

Furnace #18

Unload/Load = 1.25
Avg Time/Furn Cycle = 4.7
Labor Hrs/Furn Hr = 0.266

Furnace #25

Unload/Load = 1.5
Time/Furn Cycle = 4.7
Labor Hrs/Furn Hr = 0.319

New Furnace #C30

Unload/Load = 1.5
Time/Furn Cycle = 4.8
Labor Hrs/Furn Hr = 0.313

FURNACE COST DATA
pg 1 of 5

EXPECTED MAINTENANCE COSTS

FURN #	COST	RATIO
#1	$ 4,000	0.33
#2	4,000	0.33
#8	1,000	0.08
#10	50,000	4.17
#18	12,000	1.00
#25	12,000	1.00
NEW	24,000	2.00

FURNACE COST DATA
pg 2 OF 5

ELECTRICAL CONSUMPTION CALC.

Furnace #1 & #2   Heater Capacity = 120KW   Motors = 4 HP
or 3KW/Hour

	Time/Cycle	KW
To Temp Furnace at 70% or 84 + 3 KW/H	1.53	133.1
At Temp Furnace at 25% or 30 + 3 KW/H	2.94	97.0
Avg KW/Hour = 51.5	4.47	230.1

Furnace #18 Blowers = 4HP or 3KW/Hour
" #25 " = 5HP or 3.7KW/Hour

Furnace #10

To Temp   25v x 3400 amps x 1.73 = 147.1KW/Hour
At Temp (Avg)   15v x 1700 amps x 1.73 = 44.1KW/Hour

Pumps Operate Through Cycle (21HP) or 15.7KW/Hour

		Time/Cycle	KW
Pump Down	15.7 KW/Hour	1.8	28.3
Heat Up	147.1 + 15.7	1.8*	293.0
At Temp	44.1 + 15.7	2.8**	167.0
Cool Down	15.7	2.2	34.5
Avg = 60.8 KW/Hour		8.6	523.0

* Furn reaches temp in avg. of 1.8 hours load takes longer
** Includes some load heat up time

Electrical Consumption

Furnace #1	51.5 KW/Hour	13.91
#2	51.5 KW/Hour	13.91
#10	60.8 KW/Hour	16.40
#18	3.0 KW/Hour	0.81
#25	3.7 KW/Hour	1.00
EST. NEW	75.0 KW/Hour	20.20

FURNACE COST DATA
pg 3 of 5

ESTIMATED SUPPLY COST/YR

FURN #	FIXTURES BASKETS	TC	ARGON*	TOTAL	RATIO TO #25
#1	2,500	11,000		13,500	0.23
#2	2,500	11,000		13,500	0.23
#8	-----	1,000		1,000	0.017
#10	7,000	11,000		18,000	0.31
#18	31,200	11,000		42,200	0.73
#25	46,800	11,000		57,800	1.00
NEW #C30	7,000	11,000		18,000	0.31

*See Derivation Below Will Be Separate

ARGON USE/CYCLE

#10 Backfill to -5 in Hg then maintain level while cooling. Before unloading, equalize to atmosphere pressure with Argon. This procedure uses argon equivalent to the chamber volume, or 57.75 ft^3. On an operating basis this is 7.1 ft^3/furn hour (57.75/8.1)

#18 Purge for one hour at 150 scfh, run in furnace for an average of 4.7 hours at 120 scfh, and cool for an avg. of 0.5 hours at 120 scfh. Total Argon used/cycle is 774 scf. On a furnace hour basis this is 774/4.7 or 165 ft^3/furn hour.

#25 Purge for two hours at 150 scfh, run for 4.7 hours at 120 scfh, and cool for an avg. of 0.5 hours at 120 scfh. Total Argon used/cycle is 924 scf. or 197 ft^3/ furn hour.

NEW Estimated use is 100 ft^3/cycle or 21.3 ft^3/furn hour.

FURN #	FT^3/FURN HOUR	RATIO TO #25
#10	7.1	0.04
#18	165.0	0.84
#25	197.0	1.00
NEW	21.3	0.11

GAS CONSUMPTION

Only furnaces #18 & #25 use gas. BTU rating of #18 is 1,800,000 BTU/HR & #25 is 2,000,000/HR

1,800,000/2,000,000 = 0.90

FURNACE	RATIO TO #25
#18	0.90
#25	1.00

RENT

Rent is for fork trucks. Fork trucks are not used for the vacuum furnaces or freezer. Fork truck rent should be divided equally between remaining furnaces (furnace hours will determine apportionment).

SALARY & FRINGE

Divided equally between all furnaces (furnace hours will determine apportionment).

cc: Art Greenwood
George Harriman
Bob McClelland
Bob McGinley
Terry Spaulding

MM/tlg
Clack/x505

FURNACE COST DATA
pg 5 of 5

Appendix II

Sample Week

Heat Treatment Department

Production Schedule

```
SFSOB1.         JOB DBERNT29          P R E C I S I O N  C A   P A R T S  C O R P .          04/22/92    11:07      :    8
                                                     MSGNUM DISPATCH LIST
                                                   HI TMP HEAT TREAT

PLANT: SSBO
DEPARTMENT: 107

 DUE OUT                     MSGNUM EXPEDITE      JOB         PART         PART        NBR     DAYS      JOB     JOB STD    SETUP
  OPER    PART  JOB          /CYCLE PRIORITY    STATUS        DESC          ENG        PCS    IN W/C  DUE DATE     HRS       HRS     CURR/WC
05/14/92

   14017 10436 0006-02    1162    20-SMP   21-SCHED    STRUT END    CURT RUND        4      1    05/15/92       1.3               HTHTP
                                                                                 --------                     -------   -------
                                                             TOTALS FOR DATE         4                           1.3       0.0
05/21/92

   14017 10435 0388-03    1162             21-SCHED    STRUT END    CURT RUND        8      1    05/26/92       2.7               HTHTP
                                                                                 --------                     -------   -------
                                                             TOTALS FOR DATE         8                           2.7       0.0
03/19/92

   14013 05655 0087-07    1205             25-R        BRACKET      C. MCCLUNG       4      1    04/10/92       0.1               HTHTP
                                                                                 --------                     -------   -------
                                                             TOTALS FOR DATE         4                           0.1       0.0
04/22/92

   14013 05655 0087-02    1205             24-F        BRACKET      C. MCCLUNG      13      1    05/14/92       0.4               HTHTP
                                                                                 --------                     -------   -------
                                                             TOTALS FOR DATE        13                           0.4       0.0
04/15/92

   14013 04973 0004-02    1208    20-SMP   24-F        IMPELLER     T. MCGINNI       2      2    04/24/92       5.3               HTHTP
                                                                                 --------                     -------   -------
                                                             TOTALS FOR DATE         2                           5.3       0.0
05/12/92

   14011 05662 0231-01    1222             21-SCHED    HUB          M. MCCARTH       2      1    05/15/92       1.0               HTHTP
         05662 0231-03    1222             21-SCHED    HUB          M. MCCARTH       1      1    05/15/92       0.5               HTHTP
         05662 0232-03    1222             21-SCHED    HUB          M. MCCARTH       1      1    05/18/92       0.5               HTHTP
                                                                                 --------                     -------   -------
                                                             TOTALS FOR DATE         4                           2.0       0.0
04/16/92

   14011 03293 0035-01    1225             21-SCHED    LUG          K. KRUEGER     126      1    05/07/92       0.0               HTHTP
                                                                                 --------                     -------   -------
                                                             TOTALS FOR DATE       126                           0.0       0.0
```

SCHEDULE DATA
EXAMPLE 1 OF 1

```
INFOPAC PAGE:     2
BMS08025          JOB #BMS0023      P R E C I S I O N   C A S T P A R T S   C O R P .      04/16/92   20:34   PAGE   1
                                         PART MASTER SUMMARY WITH ASSIGNMENTS
PLANT CODE : 001                                    ACTIVE PARTS
 PART   DESC      BU CT DS HD PROD        PART        PLANNER   CUSTOMER    PCS/  PCS/ YIELD  DIP  SHELL ALLOY POUR  SHIP FIXED XRY
                        CD CD  ENG         ENG                              MOLD  LOT    %    CODE  WT          WT    WT   LT   SM

P00?70  VANE      00  1 [illegible]       C. [illegible] [illegible] [redacted]  [illegible]
[illegible] ARM   01  [illegible]         C. [illegible] [illegible] [redacted]  [illegible]
P00731  SHAFT     04  [illegible]         C. [illegible] [illegible] [redacted]  [illegible]         14   [illegible]
[illegible] SUPPORT 04 [illegible]        C. [illegible] [illegible] [redacted]  [illegible]
[illegible] SUPPORT 04 [illegible]        C. [illegible] [illegible] [redacted]  [illegible]
[illegible] STOP  [illegible]             C. [illegible] [illegible] [redacted]  [illegible]
[illegible] RETAINER [illegible]          C. [illegible] [illegible] [redacted]  [illegible]
[illegible] BRACKET 00 [illegible] ZUERN/KRUE K. [illegible] [illegible] [redacted]  4  120  [illegible]  7  4100A  [illegible]
P00997  BRACKET   00  [illegible] ZUERN/KRUE K. KRUEGER SBURNSID [redacted]  4  120  [illegible]  7  4100A  [illegible]
P01014  LINK      00  [illegible]         [illegible]  BKURAN [redacted]  30  600  [illegible]
P01071  HOUSING   00  [illegible]         C. [illegible] [illegible] [redacted]  [illegible]
[illegible] BODY  [illegible]             C. [illegible] [illegible] [redacted]  [illegible]         10   [illegible]
P01170  BODY      04  [illegible]         C. [illegible] [illegible] [redacted]  [illegible]
P01223  HOUSING   01  [illegible]         C. [illegible] [illegible] [redacted]  [illegible]         10   [illegible]  14.[illegible]
[illegible] BODY  01  [illegible]         C. [illegible] [illegible] [redacted]  12  [illegible]
P01267  SEAT      00  [illegible]         C. [illegible] [illegible] [redacted]  16  160  [illegible]  13  [illegible]
[illegible] COVER [illegible]             C. [illegible] [illegible] [redacted]  [illegible]
[illegible] CRANK [illegible]             C. [illegible] [illegible] [redacted]  14  [illegible]
[illegible] NOZZLE [illegible]            C. [illegible] [illegible] [redacted]  [illegible]
[illegible] PART  04  [illegible]         C. [illegible] [illegible] [redacted]  [illegible]
[illegible] DETENT 04 [illegible]         C. [illegible] [illegible] [redacted]  [illegible]  17  [illegible]  1.00  [illegible]  X
[illegible] LOCK  00  [illegible]         C. [illegible] [illegible] [redacted]  32  160  [illegible]  13  [illegible]
[illegible] LINK  [illegible]             C. [illegible] [illegible] [redacted]  [illegible]
P01370  BODY      01  [illegible]         C. [illegible] [illegible] [redacted]  [illegible]
[illegible] STEM  04  [illegible] MEDICAL R. [illegible] [illegible] [redacted]  10  [illegible]
[illegible] STEM  04  [illegible] MEDICAL R. [illegible] [illegible] [redacted]  10  100  [illegible]
P01470  HINGE     04  [illegible]         C. [illegible] [illegible] [redacted]  [illegible]  0.73  [illegible]
P01471  HINGE     [illegible]             C. [illegible] [illegible] [redacted]  [illegible]  0.73  [illegible]
[illegible]
[illegible]
[illegible]
[illegible] HINGE 00  [illegible]         C. [illegible] [illegible] [redacted]  [illegible]  104  [illegible]  1.00  47
P01513  HANDLE    01  [illegible]         C. [illegible] [illegible] [redacted]  14  [illegible]  0.47  [illegible]
[illegible] BAR   [illegible]             C. [illegible] [illegible] [redacted]  [illegible]
[illegible] BAR   [illegible]             C. [illegible] [illegible] [redacted]  [illegible]
[illegible] SEGMENT [illegible]           C. [illegible] [illegible] [redacted]  [illegible]
[illegible] SEGMENT [illegible]           C. [illegible] [illegible] [redacted]  [illegible]
P01523  BODY      01  [illegible]         C. [illegible] [illegible] [redacted]  [illegible]  11  [illegible]  X
P01543  PLATE     01  [illegible] D R MCNEILL/MC C. [illegible] [illegible] [redacted]  [illegible]  15  [illegible]  X
P01557  STEM      04  [illegible] MEDICAL R. [illegible] BKURAN [redacted]  [illegible]
[illegible] STEM  [illegible] MEDICAL     R. [illegible] [illegible] [redacted]  [illegible]
[illegible] STEM  [illegible] MEDICAL     R. [illegible] [illegible] [redacted]  [illegible]
P01570  CARRIER   00  [illegible] MCNEILL/MC C. MCCLUNG [illegible] [redacted]  [illegible]  10  [illegible]  X
P01583  STEM      04  [illegible] MEDICAL R. EGBERT  BKURAN [redacted]  10  100  91.00 1711  [illegible]  1012X  [illegible]  0.50  [illegible]
P01584  STEM      04  [illegible] MEDICAL R. EGBERT  BKURAN [redacted]   6   60  93.00 1711   6  1012X  [illegible]
P01585  STEM      04  [illegible] MEDICAL R. EGBERT  BKURAN [redacted]   6   60  90.00 1711   6  1012X  [illegible]
[illegible] STEM  [illegible] MEDICAL     R. [illegible] [illegible] [redacted]  [illegible]
P01592  ADAPTER   00  3 P R IMPELLER P  T. MCGINNI  MMCNEILL [redacted]   1   12  90.00 1812  13  [illegible]  [illegible]  17.31  [illegible]
P01596  NOZZLE    01  3 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   1   16  94.10 1823  30  6015J  40  24.50  44   X
```

```
INFOPAC PAGE:     3
BMS08025          JOB #BMS0023      P R E C I S I O N   C A S T P A R T S   C O R P .      04/16/92   20:34   PAGE   2
                                         PART MASTER SUMMARY WITH ASSIGNMENTS
PLANT CODE : 001                                    ACTIVE PARTS
 PART   DESC      BU CT DS HD PROD        PART        PLANNER   CUSTOMER    PCS/  PCS/ YIELD  DIP  SHELL ALLOY POUR  SHIP FIXED XRY
                        CD CD  ENG         ENG                              MOLD  LOT    %    CODE  WT          WT    WT   LT   SM

P01597  NOZZLE    01  3 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   1   16  90.00 1823  15  6015J  40  24.75  44   X
P01640  SUPPORT   04  2 P R MCNEILL/MC  C. MCCLUNG  BKURAN   [redacted]   4   80  90.00 1812  15  5010J  28   2.75  70
P01686  PART      04  1 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   4   80  96.20 1812   8  5010B  20   1.97  32
P01707  IMPELLER  01  3 I R IMPELLER P  T. MCGINNI  MMCNEILL [redacted]   1    4  95.00 1812  28  5010G 100  43.00  45
P01722  IMPELLER  01  3 D R IMPELLER P  T. MCGINNI  MMCNEILL [redacted]   1    9  90.00 1812   9  4100F  30  12.00  52
P01753  EDUCTOR   01  1 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]  10  100  93.40 1812   9  5010B  35   1.30  44
P01760  END BELL  00  1 P R GEBO/MCCAR  M. MCCARTH  MMCNEILL [redacted]  16  176  90.00 1812  12  5010B  12   0.19  42   X
P01761  END BELL  00  1 P R GEBO/MCCAR  M. MCCARTH  MMCNEILL [redacted]  40  800  90.00 1812  18  5010B  25   0.14  49   X
P01762  GIMBAL    00  1 P R GEBO/MCCAR  M. MCCARTH  MMCNEILL [redacted]  10  250  96.00 1812  10  5010B  18   0.28  46   X
P01767  NOZZLE    01  3 P R ZUERN/KRUE  C. MCCLUNG  MMCNEILL [redacted]   1   16  90.00 1823  14  6015J  32   7.00  45   X
P01791  STEM      04  1 P R MEDICAL     R. EGBERT   BKURAN   [redacted]  10  100  90.00 1711   6  1012X  16   0.50  33
P01792  STEM      04  1 P R MEDICAL     R. EGBERT   BKURAN   [redacted]   6   60  92.00 1711   7  1012X  13   1.00  28
P01793  STEM      04  1 P R MEDICAL     R. EGBERT   BKURAN   [redacted]   6   60  85.00 1711   6  1012X  11   0.50  32
P01794  STEM      04  1 P R MEDICAL     R. EGBERT   BKURAN   [redacted]   6   60  85.00 1711   6  1012C  14   0.50  29
P01802  BODY      01  2 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   4   88  97.80 1823  13  5010B  30   3.50  45   X
P01803  BODY      01  2 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   4   88  97.80 1823  13  5010B  29   3.25  44   X
P01836  MOUNT     00  2 P R GEBO/MCCAR  M. MCCARTH  MMCNEILL [redacted]   4   80  93.30 1812  13  5010B  27   1.50  42   X
P01849  PULLY     04  1 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]  16  160  91.40 1812  16  5010B  30   1.25  33   X
P01879  VALVE     01  3 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   1   20  97.80 1812   4  3470A  19   4.63  34   X
P01917  HOUSING   01  3 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   1   10  93.70 1812  10  5010B  30   8.00  40   X
P01925  PAD       00  1 P R ZUERN/KRUE  K. KRUEGER  SBURNSID [redacted]   4   40  89.00 1819   5  6020A  20   1.19  31
P01930  NOZZLE    00  3 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   1   20  93.80 1823  14  6015J  36  15.50  49   X
P01932  HOUSING   00  3 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   1   20  94.40 1823  18  3470A  28   9.75  44   X
P01940  IMPELLER  00  2 P R IMPELLER P  T. MCGINNI  MMCNEILL [redacted]   1   12  93.10 1812   4  5010B  12   6.00  38
P01941  IMPELLER  01  2 D R IMPELLER P  T. MCGINNI  MMCNEILL [redacted]   1   20  94.60 1812   9  5010B  15   8.00  44
P01943  BODY      01  2 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   4  100  96.30 1812   8  3470A  24   2.38  41   X
P01958  JACK PAD  00  1 P E MCNEILL/MC  C. MCCLUNG  BKURAN   [redacted]  24  240  95.00 1812  15  5010B  31   0.06  46
P01961  NOZZLE    01  3 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   1   18  95.00 1812  10  3470A  25  10.00  36   X
P01977  SEAL      00  3 P R ZUERN/KRUE  K. KRUEGER  SBURNSID [redacted]   1    8  92.70 1823  22  2622A  57  12.25  51
P01979  BODY      01  2 I R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   4   28  94.10 1812  12  3470A  48   3.06  37   X
P02031  LINK      00  1 P R ZUERN/KRUE  K. KRUEGER  SBURNSID [redacted]  44  440  92.00 1819  13  6030A  18   0.13  55
P02032  LINK      00  1 P R ZUERN/KRUE  K. KRUEGER  SBURNSID [redacted]  44  440  90.00 1819  13  6030A  18   0.13  60
P02033  HINGE     00  1 P R ZUERN/KRUE  K. KRUEGER  SBURNSID [redacted]  24  480  88.20 1819  12  6030A  20   0.50  64
P02065  NOZZLE    00  3 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   1   16  90.00 1823  16  1050A  50  28.00  38   X
P02066  HOUSING   00  3 P R ZUERN/KRUE  K. KRUEGER  SBURNSID [redacted]   1    1  93.80 1812  44  5010G 115  16.50  49
P02067  BRACKET   00  2 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   2   40  97.30 1812   7  5010B  35   4.40  46
P02074  IMPELLER  00  3 D R IMPELLER P  T. MCGINNI  MMCNEILL [redacted]   1    2  95.00 1812  30  4400E 150  70.00  40
P02079  GUIDE     00  1 P R MCNEILL/MC  C. MCCLUNG  BKURAN   [redacted]   4   80  91.00 1812   3  5010B  15   1.20  41   X
P02103  FITTING   00  3 P R MCNEILL/MC  C. MCCLUNG  BKURAN   [redacted]   2   20  87.60 1823  25  5010B  58   5.00  51   X
P02132  VALVE     04  2 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   4   40  93.00 1812  10  3470A  24   1.56  38   X
P02169  IMPELLER  01  3 P R IMPELLER D  T. MCGINNI  MMCNEILL [redacted]   1    4  95.00 1812  35  5010G 100  61.00  45
P02187  PLATE     00  1 P E MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   4   88  89.00 1812  13  5010B  22   1.50  41   X
P02193  SUPPORT   00  2 P R ZUERN/KRUE  K. KRUEGER  SBURNSID [redacted]   4   80  85.30 1812  17  3100A  35   1.50  47
P02202  BODY      01  1 P E MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]  15  150  89.00 1812  19  3100B  38   1.42  40   X
P02229  SHAFT     04  2 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   4   80  93.40 1812  24  5010B  70   6.50  42   X
P02249  SEAL      00  3 P R ZUERN/KRUE  K. KRUEGER  SBURNSID [redacted]   1   15  97.00 1812  13  5010G  38   7.63  40
P02251  SEAL      00  3 P R ZUERN/KRUE  K. KRUEGER  SBURNSID [redacted]   1    6  95.00 1812  11  5010G  32   5.00  42
P02274  HOOK      00  1 P R MCNEILL/MC  C. MCCLUNG  MMCNEILL [redacted]   8   80  75.00 1812  14  5010A  25   0.28  60   X
P02365  SEAL      00  3 P R ZUERN/KRUE  K. KRUEGER  SBURNSID [redacted]   1   20  96.50 1812  16  2622A  35   6.50  41
```

FORM F108OX

PART WEIGHT DATA
EXAMPLE 1 OF 1

```
Page    1    HEAT TREAT REFERENCE LIST BY REFERENCE NUMBER    27 FEB 92  07:49
       oF                   QCH-                         QCH-                         QCH-
REF#   TEMP HRSATTEMP ATMOS MED1 COOLRT1 TOTEMP1 ATTEMP1 MED2 COOLRT2 TOTEMP2 ATTEMP2 MED3 COOLRT3 TOTEMP3 ATTEMP3 DEWPT

1000     -1      0.50 AIR   AIR      0         0    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1001    900      1.50 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1002    925      1.50 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1003   1000      1.50 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1004   1050      1.50 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1005   1100      1.50 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1006   1125      1.50 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1007   1150      1.50 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1008   1150      4.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1009   1150     16.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1010   1200      2.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1011   1325      8.00 AIR   FUR      0      1150    8.00 AIR      0       120    0.00          0       0      0.00     0
                             COMMENTS
1050   1750      1.00 ARG   FCR      0       120    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1051   1900      0.50 ARG   FCR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1052   2000      1.00 ARG   FCR      0       120    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1053   2100      1.50 ARG   FCR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1080   1350      2.00 VAC   APV      0       120    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1100    450      1.50 AIR   OIL      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1101    500      1.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1102    625      3.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1103    900      1.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1104    900      2.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1105    900      3.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1106    925      1.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1107    925      2.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
1108    925      4.00 AIR   AIR      0        70    0.00          0         0    0.00          0       0      0.00     0
                             COMMENTS
```

PROCESS DATA
EXAMPLE 1 OF 1

Appendix III

Vacuum Furnace Solution

```
MIN     0.01 X31 + 0.008 X32 + 0.012 X33 + 0.012 X41 + 0.01 X42
   + 0.014 X43
SUBJECT TO
      2)  0.01 X31 + 0.0117 X32 + 0.011 X33 <=   120
      3)  0.009 X41 + 0.0106 X42 + 0.0098 X43 <=   120
      4)  X31 + X41 =   1623
      5)  X32 + X42 =   2558
      6)  X33 + X43 =   11247
END

LP OPTIMUM FOUND AT STEP      6

     OBJECTIVE FUNCTION VALUE

      1)      180.40070

VARIABLE        VALUE          REDUCED COST
     X31      1623.000000          .000000
     X32          .000000         .000127
     X33      9433.637000          .000000
     X41          .000000         .000182
     X42      2558.000000          .000000
     X43      1813.364000          .000000


     ROW   SLACK OR SURPLUS     DUAL PRICES
      2)          .000000         .181818
      3)        75.114230          .000000
      4)          .000000        -.011818
      5)          .000000        -.010000
      6)          .000000        -.014000

NO. ITERATIONS=       6
```

```
RANGES IN WHICH THE BASIS IS UNCHANGED:

                    OBJ COEFFICIENT RANGES
VARIABLE      CURRENT      ALLOWABLE       ALLOWABLE
               COEF        INCREASE        DECREASE
  X31        .010000       .000182        INFINITY
  X32        .008000      INFINITY         .000127
  X33        .012000       .000120         .000200
  X41        .012000      INFINITY         .000182
  X42        .010000       .000127        INFINITY
  X43        .014000       .000200         .000120

                    RIGHTHAND SIDE RANGES
   ROW        CURRENT      ALLOWABLE       ALLOWABLE
               RHS         INCREASE        DECREASE
    2       120.000000     19.947000       84.311890
    3       120.000000     INFINITY        75.114230
    4      1623.000000   8431.190000     1623.000000
    5      2558.000000   7086.249000     2558.000000
    6     11247.000000   7664.718000     1813.364000
```

Appendix IV

LINDO Solution Method 1

```
MIN     0.07 X11 + 0.066 X12 + 0.088 X13 + 0.106 X14 + 0.184 X15
     + 0.315 X16 + 0.057 X17 + 0.07 X18 + 0.07 X19 + 0.077 X110
     + 0.08299999 X111 + 0.066 X112 + 0.071 X113 + 0.086 X114 + 0.1 X115
     + 0.108 X116 + 0.07599999 X117 + 0.05 X118 + 0.045 X21 + 0.042 X22
     + 0.056 X23 + 0.066 X24 + 0.123 X25 + 0.21 X26 + 0.038 X27 + 0.045 X28
     + 0.045 X29 + 0.049 X210 + 0.053 X211 + 0.042 X212 + 0.046 X213
     + 0.055 X214 + 0.063 X215 + 0.068 X216 + 0.048 X217 + 0.032 X218
SUBJECT TO
      2)  0.05 X11 + 0.0438 X12 + 0.055 X13 + 0.0625 X14 + 0.23 X15
     + 0.2625 X16 + 0.0475 X17 + 0.05 X18 + 0.05 X19 + 0.0512 X110
     + 0.055 X111 + 0.0437 X112 + 0.0475 X113 + 0.0537 X114 + 0.0625 X115
     + 0.06369999 X116 + 0.0475 X117 + 0.05 X118 <=  1200
      3)  0.0266 X21 + 0.0233 X22 + 0.0293 X23 + 0.0333 X24 + 0.1226 X25
     + 0.14 X26 + 0.0253 X27 + 0.0266 X28 + 0.0266 X29 + 0.0273 X210
     + 0.0293 X211 + 0.0233 X212 + 0.0253 X213 + 0.0286 X214 + 0.0333 X215
     + 0.034 X216 + 0.0253 X217 + 0.0266 X218 <=  1200
      4)  X11 + X21 =   14707
      5)  X12 + X22 =   1318
      6)  X13 + X23 =   10964
      7)  X14 + X24 =   669
      8)  X15 + X25 =   1943
      9)  X16 + X26 =   459
     10)  X17 + X27 =   462
     11)  X18 + X28 =   4284
     12)  X19 + X29 =   525
     13)  X110 + X210 =   2333
     14)  X111 + X211 =   2618
     15)  X112 + X212 =   1314
     16)  X113 + X213 =   2770
     17)  X114 + X214 =   1046
     18)  X115 + X215 =   2142
     19)  X116 + X216 =   578
     20)  X117 + X217 =   2003
     21)  X118 + X218 =   639
END

LP OPTIMUM FOUND AT STEP      6
```

```
        OBJECTIVE FUNCTION VALUE

        1)     3015.3460

  VARIABLE        VALUE          REDUCED COST
      X11          .000000         .000000
      X12          .000000         .002102
      X13          .000000         .004462
      X14          .000000         .008703
      X15      1943.000000          .000000
      X16       459.000000          .000000
      X17       462.000000          .000000
      X18      3460.921000          .000000
      X19       525.000000          .000000
      X110         .000000         .002342
      X111         .000000         .002462
      X112         .000000         .002102
      X113         .000000         .001222
      X114         .000000         .004120
      X115         .000000         .005703
      X116         .000000         .008045
      X117         .000000         .004222
      X118      639.000000          .000000
      X21     14707.000000          .000000
      X22      1318.000000          .000000
      X23     10964.000000          .000000
      X24       669.000000          .000000
      X25          .000000         .054226
      X26          .000000         .026579
      X27          .000000         .004778
      X28       823.078900          .000000
      X29          .000000         .000000
      X210     2333.000000          .000000
      X211     2618.000000          .000000
      X212     1314.000000          .000000
      X213     2770.000000          .000000
      X214     1046.000000          .000000
      X215     2142.000000          .000000
      X216      578.000000          .000000
      X217     2003.000000          .000000
      X218         .000000         .007000
```

```
 ROW   SLACK OR SURPLUS     DUAL PRICES
  2)    379.431400         .000000
  3)       .000000         .939850
  4)       .000000        -.070000
  5)       .000000        -.063898
  6)       .000000        -.083538
  7)       .000000        -.097297
  8)       .000000        -.184000
  9)       .000000        -.315000
 10)       .000000        -.057000
 11)       .000000        -.070000
 12)       .000000        -.070000
 13)       .000000        -.074658
 14)       .000000        -.080538
 15)       .000000        -.063898
 16)       .000000        -.069778
 17)       .000000        -.081880
 18)       .000000        -.094297
 19)       .000000        -.099955
 20)       .000000        -.071778
 21)       .000000        -.050000

NO. ITERATIONS=       6
```

```
RANGES IN WHICH THE BASIS IS UNCHANGED:

                    OBJ COEFFICIENT RANGES
VARIABLE      CURRENT     ALLOWABLE     ALLOWABLE
              COEF        INCREASE      DECREASE
  X11       .070000     INFINITY       .000000
  X12       .066000     INFINITY       .002102
  X13       .088000     INFINITY       .004462
  X14       .106000     INFINITY       .008703
  X15       .184000     .054226       INFINITY
  X16       .315000     .026579       INFINITY
  X17       .057000     .004778       INFINITY
  X18       .070000     .000000       .000000
  X19       .070000     .000000       INFINITY
  X110      .077000     INFINITY       .002342
  X111      .083000     INFINITY       .002462
  X112      .066000     INFINITY       .002102
  X113      .071000     INFINITY       .001222
  X114      .086000     INFINITY       .004120
  X115      .100000     INFINITY       .005703
  X116      .108000     INFINITY       .008045
  X117      .076000     INFINITY       .004222
  X118      .050000     .007000       INFINITY
  X21       .045000     .000000       INFINITY
  X22       .042000     .002102       INFINITY
  X23       .056000     .004462       INFINITY
  X24       .066000     .008703       INFINITY
  X25       .123000     INFINITY       .054226
  X26       .210000     INFINITY       .026579
  X27       .038000     INFINITY       .004778
  X28       .045000     .000000       .000000
  X29       .045000     INFINITY       .000000
  X210      .049000     .002342       INFINITY
  X211      .053000     .002462       INFINITY
  X212      .042000     .002102       INFINITY
  X213      .046000     .001222       INFINITY
  X214      .055000     .004120       INFINITY
  X215      .063000     .005703       INFINITY
  X216      .068000     .008045       INFINITY
  X217      .048000     .004222       INFINITY
  X218      .032000     INFINITY       .007000
```

```
              RIGHTHAND SIDE RANGES
ROW      CURRENT      ALLOWABLE      ALLOWABLE
           RHS        INCREASE       DECREASE
  2    1200.000000     INFINITY     379.431400
  3    1200.000000    92.060500     21.893900
  4   14707.000000   823.078900   3460.921000
  5    1318.000000   939.652300   1318.000000
  6   10964.000000   747.231900   3141.996000
  7     669.000000   657.474400    669.000000
  8    1943.000000  1649.702000   1943.000000
  9     459.000000  1445.453000    459.000000
 10     462.000000  7988.030000    462.000000
 11    4284.000000  7588.628000   3460.921000
 12     525.000000  7588.628000    525.000000
 13    2333.000000   801.974200   2333.000000
 14    2618.000000   747.231900   2618.000000
 15    1314.000000   939.652300   1314.000000
 16    2770.000000   865.371500   2770.000000
 17    1046.000000   765.520900   1046.000000
 18    2142.000000   657.474400   2142.000000
 19     578.000000   643.938100    578.000000
 20    2003.000000   865.371500   2003.000000
 21     639.000000  7588.628000    639.000000
```

Appendix V

LINDO Solution Method 2

```
MIN     14 X11 + 17 X21 + 15 X12 + 18 X22 + 16 X13 + 19 X23 + 17 X14
     + 20 X24 + 8 X15 + 10 X25 + 12 X16 + 15 X26 + 12 X17 + 15 X27 + 14 X18
     + 17 X28 + 14 X19 + 17 X29 + 15 X110 + 18 X210 + 15 X111 + 18 X211
     + 15 X112 + 18 X212 + 15 X113 + 18 X213 + 16 X114 + 19 X214 + 16 X115
     + 19 X215 + 17 X116 + 20 X216 + 16 X117 + 19 X217 + 10 X118 + 12 X218
SUBJECT TO
       2)  X11 + X12 + X13 + 2 X14 + X15 + X16 + X17 + X18 + X19 + X110
     + X111 + X112 + X113 + X114 + X115 + X116 + X117 + X118 <=  130
       3)  X21 + X22 + X23 + X24 + X25 + X26 + X27 + X28 + X29 + X210
     + X211 + X212 + X213 + X214 + X215 + X216 + X217 + X218 <=  130
       4)  193 X11 + 367 X21 =   14707
       5)  188.3 X12 + 376.6 X22 =   1318
       6)  178 X13 + 311.5 X23 =   10964
       7)  133.8 X14 + 133.8 X24 =   669
       8)  35.2 X15 + 52.8 X25 =   1943
       9)  21.9 X16 + 21.9 X26 =   459
      10)  121.57 X17 + 121.57 X27 =   462
      11)  178.5 X18 + 357 X28 =   4284
      12)  131.25 X19 + 131.25 X29 =   525
      13)  189.67 X110 + 284.51 X210 =   2333
      14)  148.75 X111 + 297.5 X211 =   2618
      15)  187.7 X112 + 375.4 X212 =   1314
      16)  182.2 X113 + 364.5 X213 =   2770
      17)  121.6 X114 + 243.3 X214 =   1046
      18)  142.6 X115 + 214.2 X215 =   2142
      19)  113.3 X116 + 113.3 X216 =   578
      20)  175.7 X117 + 263.5 X217 =   2003
      21)  159.75 X118 + 159.75 X218 =   639
END

LP OPTIMUM FOUND AT STEP      9
```

```
OBJECTIVE FUNCTION VALUE

1)    3595.0820

VARIABLE        VALUE           REDUCED COST
   X11          .000000         2.432912
   X21        40.073570          .000000
   X12          .000000         3.502276
   X22         3.499734          .000000
   X13          .000000         2.288316
   X23        35.197430          .000000
   X14         5.000000          .000000
   X24          .000000         7.995447
   X15        55.198860          .000000
   X25          .000000         2.995448
   X16        20.958900          .000000
   X26          .000000         7.995447
   X17         3.800280          .000000
   X27          .000000         7.995447
   X18          .000000         3.002276
   X28        12.000000          .000000
   X19         4.000000          .000000
   X29          .000000         7.995447
  X110        12.300310          .000000
  X210          .000000          .495052
  X111          .000000         3.502276
  X211         8.800000          .000000
  X112          .000000         3.502276
  X212         3.500267          .000000
  X113          .000000         3.505430
  X213         7.599451          .000000
  X114          .000000         4.007208
  X214         4.299219          .000000
  X115          .000000          .025439
  X215        10.000000          .000000
  X116         5.101501          .000000
  X216          .000000         7.995447
  X117         3.856054          .000000
  X217         5.030327          .000000
  X118         4.000000          .000000
  X218          .000000         6.995447
```

```
ROW   SLACK OR SURPLUS   DUAL PRICES
 2)    10.784090        .000000
 3)     .000000        4.995447
 4)     .000000        -.059933
 5)     .000000        -.061061
 6)     .000000        -.077032
 7)     .000000        -.127055
 8)     .000000        -.227273
 9)     .000000        -.547945
10)     .000000        -.098709
11)     .000000        -.061612
12)     .000000        -.106667
13)     .000000        -.079085
14)     .000000        -.077296
15)     .000000        -.061256
16)     .000000        -.063088
17)     .000000        -.098625
18)     .000000        -.112024
19)     .000000        -.150044
20)     .000000        -.091064
21)     .000000        -.062598

NO. ITERATIONS=     9
```

```
RANGES IN WHICH THE BASIS IS UNCHANGED:

                    OBJ COEFFICIENT RANGE
VARIABLE       CURRENT      ALLOWABLE      ALLOWABLE
               COEF         INCREASE       DECREASE
   X11      14.000000      INFINITY        2.432912
   X21      17.000000      4.626315       INFINITY
   X12      15.000000      INFINITY        3.502276
   X22      18.000000      7.004553       INFINITY
   X13      16.000000      INFINITY        2.288316
   X23      19.000000      4.004552       INFINITY
   X14      17.000000      7.995447       INFINITY
   X24      20.000000      INFINITY        7.995447
   X15       8.000000      1.996966       INFINITY
   X25      10.000000      INFINITY        2.995448
   X16      12.000000      7.995447       INFINITY
   X26      15.000000      INFINITY        7.995447
   X17      12.000000      7.995447       INFINITY
   X27      15.000000      INFINITY        7.995447
   X18      14.000000      INFINITY        3.002276
   X28      17.000000      6.004553       INFINITY
   X19      14.000000      7.995447       INFINITY
   X29      17.000000      INFINITY        7.995447
   X110     15.000000       .330029       INFINITY
   X210     18.000000      INFINITY         .495052
   X111     15.000000      INFINITY        3.502276
   X211     18.000000      7.004553       INFINITY
   X112     15.000000      INFINITY        3.502276
   X212     18.000000      7.004553       INFINITY
   X113     15.000000      INFINITY        3.505430
   X213     18.000000      7.012784       INFINITY
   X114     16.000000      INFINITY        4.007208
   X214     19.000000      8.017712       INFINITY
   X115     16.000000      INFINITY         .025439
   X215     19.000000       .038212       INFINITY
   X116     17.000000      7.995447       INFINITY
   X216     20.000000      INFINITY        7.995447
   X117     16.000000       .025480        .330098
   X217     19.000000       .495052        .038212
   X118     10.000000      6.995447       INFINITY
   X218     12.000000      INFINITY        6.995447
```

```
                    RIGHTHAND SIDE RANGES

    ROW      CURRENT      ALLOWABLE       ALLOWABLE
               RHS         INCREASE        DECREASE
     2      130.000000     INFINITY       10.784090
     3      130.000000     2.571191       5.030327
     4    14707.000000   1846.130000     943.627000
     5     1318.000000   1894.421000     968.310400
     6    10964.000000   1566.947000     800.925900
     7      669.000000    721.455500     669.000000
     8     1943.000000    379.599900    1943.000000
     9      459.000000    236.171500     459.000000
    10      462.000000   1311.022000     462.000000
    11     4284.000000   1795.827000     917.915000
    12      525.000000   1415.412000     525.000000
    13     2333.000000   2045.418000    2333.000000
    14     2618.000000   1496.522000     764.929200
    15     1314.000000   1888.385000     965.225000
    16     2770.000000   1833.554000     937.199000
    17     1046.000000   1223.879000     625.570700
    18     2142.000000   1077.496000     550.749000
    19      578.000000   1221.837000     578.000000
    20     2003.000000   1894.764000     677.508700
    21      639.000000   1722.758000     639.000000
```