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Ceramic Heat Exchangers: Cost Estimates Using a Process-Cost Approach

Sujit Das
T. Randall Curlee
R. A. Whitaker

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CERAMIC HEAT EXCHANGERS: COST ESTIMATES USING A PROCESS-COST APPROACH

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ABSTRACT

This report documents the results of a study to estimate the cost of ceramic recuperators and examine the sensitivity of recuperator cost to changes in key technical and economic parameters. The focus of the work is on high-temperature recuperators of the fixed-head, tube-and-shell type in which the tubes and headers are replaced by silicon carbide. Both extrusion and slip-casting technologies are considered for the production of ceramic tubes. Slip casting is assumed to be the method used to produce the ceramic headers.

A process-cost approach, which explicitly represents the costs of each major step in a production process, is used to estimate the costs of the ceramic components of the recuperator. Previous correlation studies on the cost of metallic units are used to estimate the costs of the remaining metallic components.

The primary conclusion of the report is that ceramic heat exchangers are estimated to cost significantly more than comparably sized all-metallic heat exchangers. A 1,500 ft^2 ceramic recuperator, in which both the tubes and headers are replaced by silicon carbide, is estimated to cost about 68% more than a corresponding metallic unit. A recuperator in which only the tubes are replaced by ceramics is estimated to cost about 46% more than a comparable metallic unit.

Sensitivity analyses on the cost of ceramic tubes suggest several conclusions. First, tube cost is sensitive to production volumes at low levels -- i.e., less than 20,000 tubes per year -- but flattens out at higher production levels. Second, tube cost is quite sensitive to powder cost, given that materials contribute about 55% to 60% of the total cost of a tube in our base case. Third, the cost of capital can have a significant impact on tube cost, especially in the case of extrusion, which is more capital intensive than slip casting. Fourth, improvements in total yield can substantially reduce the cost of a tube. Tube cost is estimated to decrease by about 24% when total yield is increased from 65% to 85%. Finally, neither slip casting nor extrusion appears to be the clear winner in terms of producing ceramic tubes at the least cost.

CERAMIC HEAT EXCHANGERS: COST ESTIMATES USING A PROCESS-COST APPROACH

Sujit Das
T. Randall Curlee
Bob Whitaker

1. INTRODUCTION

The purpose of this report is to document the findings of a study to estimate the cost of ceramic heat exchangers and the sensitivity of heat exchanger cost to changes in key technical and economic parameters. The focus of the work is on high-temperature recuperators of the fixed-head, tube-and-shell type in which the tubes and the headers are replaced by silicon carbide. The remaining components of the heat exchanger are assumed to be manufactured from high-temperature metallics. Two methods for manufacturing ceramic tubes for heat exchangers are considered--slip casting and extrusion. Slip casting is assumed to be the method used to produce the ceramic headers.

A process-cost approach, which models explicitly the major steps in the production of ceramic tubes and headers, has been adopted to estimate the costs of the ceramic components. More specifically, rather generic slip-casting and extrusion process-cost models have been obtained from the Materials Systems Laboratory (MSL) at the Massachusetts Institute of Technology (MIT). These MIT models provide the foundation for our more detailed and focused models of silicon carbide tubes and headers. The MIT models have been extended and revised both in terms of their technical and economic content and in terms of their ease of use. The new models allow comparisons of the costs of the ceramic components using different processing technologies and allow sensitivity analyses on any

of the technical and economic parameters represented in the models. Results from previous correlation studies on the cost of metallic recuperators are used to estimate the costs of the non-ceramic components in our hypothetical fixed-head, tube-and-shell units.

In the following section, some general background information is given about ceramic heat exchangers. Section 3 discusses the general approach used in this study. A detailed discussion of the approach used to estimate the costs of the ceramic components and the enhancements made to the MIT models is given in Section 4. Section 5 presents a detailed discussion of the approach used to estimate the costs of non-ceramic components and the total cost of the recuperator. Results of our base-case study and sensitivity analyses are presented in Section 6. Conclusions are summarized in the final section.

2. SOME BACKGROUND

The main purpose of a heat exchanger is to capture heat that would otherwise be lost through waste gases or liquids and return that heat to some stage of the production process. Hayes and Richlen (1985) report that hot exhaust streams from some industrial operations can represent as much as 80% of the energy input to the process. In the typical application, the exhaust gases are used to heat the incoming combustion air. Total fuel requirements for the overall production process can subsequently be reduced.[1]

Two basic types of heat exchangers have been used historically--recuperators and regenerators. The basic difference between the two is that a recuperator is a continuous device that captures waste heat and continuously recycles the heat to the process. Regenerators use some form of thermal storage material and operate in a cyclic mode. Heat exchangers also vary in terms of the direction in which waste heat flows through the system in relation to the flow of the substance being heated. Countercurrent, co-current, and perpendicular flows are alternatives. Heat exchangers are also classified as gas-to-gas, gas-to-liquid, and liquid-to-liquid.

Within the recuperator category, several alternative configurations have been used -- e.g., shell-and-shell, plate-fin, and tube-and-shell. Richlen (1985) characterizes the shell-and-shell type as consisting of

---

[1]For additional background material on the different types of heat exchangers and how those exchangers are manufactured and used, see, for example, Richlen (1985) and Bliem et al. (1985).

"two concentric shells making up an inner passage through which the exhaust flows, and an annulus between the two shells through which the combustion air flows." (page 9). In the plate-fin type, the exhaust gases and the incoming air pass through alternate passages of the heat exchanger that are separated by flat plates covered with many fins. In the tube-and-shell configuration the exhaust gases flow over a collection of tubes through which the the incoming combustion air is flowing.[2] This work focuses only on gas-to-gas recuperators of the tube-and-shell type. See Fig. 2.1 for a simple graphical description of a tube-and-shell system.

Although heat exchangers have been used in various industrial processes for more than 60 years, technical problems have hindered their performance and further market acceptance -- especially with respect to high-temperature, highly-corrosive environments. Richlen (1985) suggests that when a heat exchanger is manufactured from carbon steel, the bulk material temperature should not exceed 425 degrees C. At temperatures in excess of 650 degrees C, corrosion resistance and strength become significant limitations for the higher-performance stainless steels. The typical approach to solving these problems is to simply mix the hot gases from the industrial process with ambient air to reduce the temperature of the mixture entering the heat exchanger to a level at which conventional metallics can be used. At lower temperatures, metallic heat exchangers offer reliability and ease of cleaning. Unfortunately, the dilution of

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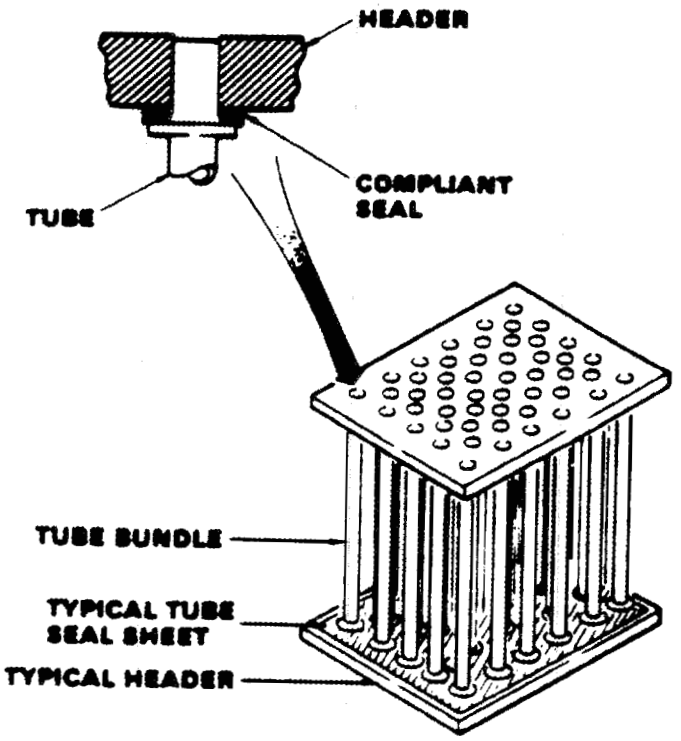
[2]For additional information on the types of heat exchangers and the potential roles ceramics may play in their manufacture, see Foster (1985).

A



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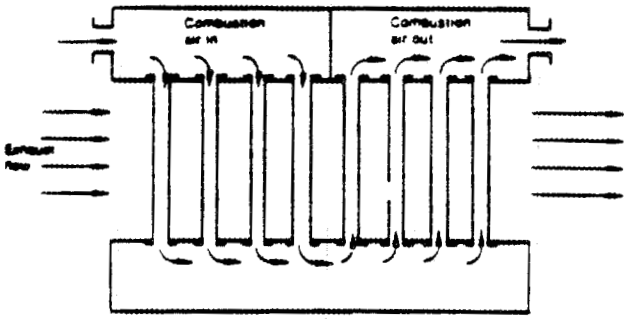

Fig. 2.1. A simple tube-and-shell recuperator
Source A: Strumpt, Kotchick, and Coombs (1985, p. 2-11)
Source B: Richlen (1985, p. 10)

the hot gases significantly degrades the heat quality and reduces the engineering efficiency of the heat transfer process.

To improve heat exchanger performance under high-temperature, highly-corrosive conditions, R&D has focused on replacing the heat-exchanger's most vulnerable components with either high-temperature metallics or ceramics. Some chrome-nickel alloys with very little iron have properties that can withstand high-temperature, highly corrosive environments, but are very expensive.

Ceramics are also typically more corrosion resistant and can withstand much higher temperatures than commonly used metallics. In addition, ceramics offer a potentially cheaper alternative to the expensive and import-vulnerable chrome-based alloys. Richlen (1985) reports that the ceramics currently being considered or used can tolerate bulk material temperatures in the range of 1300 degrees C. Unfortunately, ceramics pose their own set of problems. Severe leakage has sometimes been experienced because of thermal cycling. Further, ceramics are often difficult and costly to fabricate and repair.[3] The ceramic powder mentioned most often for heat exchanger applications is silicon carbide, which has relatively high resistance to thermal shock and oxidation and has very low volatility.[4]

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[3]Numerous papers have been published on various technical aspects of ceramic heat exchangers. Foster and Patton (1985) and Bliem et al. (1985) are good starting points for those interested in the technical problems and advantages associated with manufacturing and using ceramic heat exchangers of various configurations. Foster and Patton (1985) also give details of past and current commercial applications of ceramic heat exchangers in several manufacturing areas.

[4]For additional information on the good and bad points of silicon carbide and other ceramics that have been examined for use in high-temperature heat exchangers, see Federer and Tiegs (1985). That

Several attempts have been made at incorporating ceramics within different heat exchanger systems. While some of the new systems are only experimental, others are being used commercially. Companies involved in the design and building of ceramic recuperators of the tube-and-shell variety include C&H Combustion, AiResearch, Solar Turbines, and Hague International.[5]

The C&H Combustion system is the only operational tubular system to use all-ceramic internal parts. The tubes in the system are arranged in three zones, each using varying grades of silicon carbide tubes. Graham (1985) reports that C&H Combustion is designing commercial systems that can tolerate flue gases as high as 1,537 degrees C and can provide preheated air of up to 1,093 degrees C.[6]

The AiResearch system is referred to as a hybrid system because it consists of a ceramic recuperator and a metallic recuperator operating in series. The tubes in the ceramic recuperator are arranged in two bundles and are made of silicon carbide. The headers and walls are also manufactured from silicon carbide. Coombs, Kotchick, and Strumpf (1985) report that the system is designed to operate in industrial flue gas

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publication reports that silicon carbide is susceptible to both corrosion and strength degradation when exposed to certain harsh environments, such as those that may be posed by aluminum-remelt and steel-reheat furnaces.

[5]See Bliem, et al. (1985, page 14) for a listing of the different companies involved in the designing and building of ceramic heat exchangers of various types. In addition to tube-and-shell recuperators, ceramics have been used in other designs -- e.g., finned plate, shell-and-shell, helical, and heat wheel. Foster and Patton (1985) contains detailed discussions of the different types of ceramic heat exchangers and the applications in which those units have been used. See also U.S. Department of Energy (1984).

[6]See also Graham (1986) and Graham (not dated).

temperatures of up to 1,371 degrees C and can provide combustion air of up to 1,093 degrees C.[7]

The recuperator built by Solar Turbines is designed specifically for the highly corrosive gases from, for example, an aluminum reclamation furnace. It is also designed to operate at higher pressures than other tube-and-shell ceramic recuperators. The system utilizes silicon carbide tubes bonded to stainless steel sleeves, which are then joined to a metal header.[8] One of the problems that has often plagued the use of ceramics in heat exchangers is the joining of ceramics to ceramics and ceramics to metals.

The Hague International heat exchanger employs ceramics in the tubes and has been used commercially in the recuperation of aluminum melting furnaces. Ward (1985) reports that the system was designed to accommodate flue gas temperatures up to 1,371 degrees C and produce combustion air as high as 815 degrees C. The heat exchanger consists of 8 rows of 24 silicon carbide tubes held by two silicon carbide hex adapters. The entire assembly is held under spring tension, which facilitates maintenance and repair, but may also pose more leakage problems when compared to other designs.[9]

Several reports have concluded that the successful penetration of high-temperature heat exchangers into industries such as glass, cement, clay and pottery, and steel and other primary metals could have a

---

[7]See also Strumpf, Kotchick and Coombs (1985).

[8]See Bliem et al. (1985) and Ward, Russell, and Liang (1985) for details.

[9]See also Hague International (not dated).

significant impact on energy consumption in those markets. Fay and Kohnken (1983) estimate that about 50% of the energy lost through stack gases can potentially be recovered using ceramic heat exchangers. GTE Products and PAR Enterprises (1980) estimate that, in general, ceramic heat exchangers can be expected to provide fuel savings of between 20% and 50% in high-temperature applications. Ward (1985) reports that the Hague International unit mentioned above reduces overall fuel consumption an estimated 35% when operating near design efficiency. Other reports, such as Lownie and Holden (1983) and Holden et al. (1983) conclude that heat exchangers, in combination with other furnace technology improvements, can be expected to reduce furnace energy consumption by between 44% and 48%. Garrett AiResearch (1979) reports that metallic heat exchangers in aluminum furnaces can produce average fuel savings of about 32% when operated at about 815 degrees C. Chiogioji (1979) puts the estimated fuel savings for aluminum furnaces at between 20% and 25%. Lownie and Holden (1983) estimate that fuel savings between 17% and 37% can be expected in steel forging operations when metallic heat exchangers are used.

Figure 2.2 contains a graph from Coombs, Kotchick, and Strumpf (1985, page 49) that summarizes the theoretical fuel savings as a function of flue exhaust gas temperature and air preheat temperature. Note that the engineering efficiency of the heat exchanger increases sharply when exhaust and preheat temperatures are increased. The savings can approach 80% of the fuel consumption of an unrecuperated furnace operating at the same temperature level.

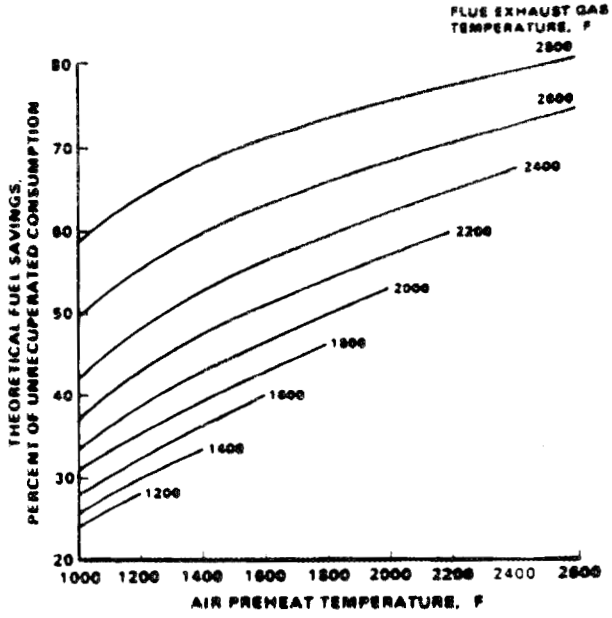

Fig. 2.2 Potential fuel savings from recuperation
Source: Coombs, Kotchick, and Strumpt (1985, p. 49)

Several attempts have also been made at estimating the aggregate energy conservation potential of high-temperature heat exchangers. Patton (1985) reports that the total amount of energy that could be recovered from high-temperature industrial waste streams in the United States is as high as one quad (10^{15} Btus). Richlen (1985) estimates that about 0.25 quads could be saved, assuming that high-temperature heat exchangers reduce fuel consumption by 30% in the high-temperature processes in which they are used. Curlee (1988) puts the estimate at about 0.28 quads for the same estimated 30% reduction in fuel consumption.

Some publications have examined the economic viability of ceramic heat exchangers. Bliem et al. (1985) and Foster and Patton (1985) contain several assessments of the expected costs and benefits of specific ceramic units. Hill (1980), Tennery (1981), and Coombs et al. (1985) contain additional economic assessments. In general, these assessments suggest that the expected payback period (a commonly used approach) for most heat-exchanger designs is no more than 1 to 2 years and in some cases is significantly less. For the most part, these reports do not, however, provide significant detail about the methodologies used. It is therefore difficult to assess their findings within a common framework or to make statements about the economic viability of ceramic heat exchangers in general. The remainder of this report focuses on one side of the overall economic viability question--i.e., the costs of ceramic tube-and-shell recuperators.

3. THE GENERAL APPROACH

3.1. SUPPLY VS. DEMAND SIDE ISSUES

The overall economic viability of ceramic heat exchangers will depend on two sets of issues. The first concerns how the use of ceramics in certain key components of the recuperator will affect the overall cost of the heat exchanger unit as compared to metallic units. These concerns may be termed supply-side issues. In the extreme, we may assume that the recuperator manufactured from ceramics has the same properties as those manufactured from conventional metallics and estimate economic viability solely on the basis of which unit is cheaper; or in other words we can compare "apples to apples."

However, from the previous section it is obvious that a ceramic heat exchanger is not the same as a conventional metallic heat exchanger; or in other words when examining ceramic vs. metallic recuperators we are really comparing "apples to oranges." Therefore, when examining overall economic viability we must not only estimate the different costs of the competing technologies, but must also estimate the values of the different units to potential demanders -- i.e., what can be termed demand-side issues. If a ceramic recuperator can operate at higher temperatures and in more corrosive environments, demanders will presumably be willing to pay a premium for that unit as compared to conventional metallic recuperators.

The balance of the marginal costs and the marginal benefits of the ceramic unit as compared to conventional metallic units will suggest the overall economic viability of ceramic recuperators. In other words,

viability will depend on how much more ceramic units cost when compared to metallic units, and whether that additional cost will be more than compensated by the additional benefits provided by the ceramic units. Viability cannot be defended solely by an assessment that concludes that the savings generated by a heat exchanger exceed the costs of that heat exchanger.

In this report we address only the supply-side issues. We examine only how much tube-and-shell recuperators may cost when ceramics are used to manufacture the tubes and headers. We also examine how those cost may vary when key economic and technical parameters are changed from our base-case scenario. As such, this work does not address the overall viability of ceramic heat exchangers. The demand-side questions and an assessment of overall economic viability await future work.

3.2. SCOPE OF WORK

A primary goal of this work is to be as generic as possible with respect to the design of the heat exchanger, specific applications, ceramics used, and so forth. It is not the intent of this work to assess the cost of any particular tube-and-shell recuperator, such as the specific designs mentioned in Section 2 of this report. The scope must be narrowed somewhat, however, to arrive at general but meaningful results.

Ceramics can be incorporated in several key parts -- e.g., tubes, tube sheets, tube-side headers, baffles, and the shell. In this study we focus only on the use of ceramics in the tubes and headers. We focus only on slip-casting and extrusion methods for manufacturing the ceramic

parts.[10] The actual cost of a unit will obviously depend on the specific technical design of the recuperator -- detailed factors that could not be taken into consideration in this study and at the same time remain as general as possible.

Subsequently, the cost estimates and the sensitivity analyses presented here should not be interpreted as exact estimates of the cost of a ceramic recuperator, but rather should be interpreted in a relative sense. For example, it is valid to compare the costs of recuperators given different powder costs or to compare a metallic recuperator of a given size to a ceramic recuperator of the same size. It is not particularly meaningful, however, to interpret point estimates as the costs of a particular ceramic recuperator.

3.3. PROCESS-COST MODELS

The first step in developing a process-cost model is to identify the process steps or unit operations. A flow sheet is then constructed to show the potential ordering of the process steps. The major inputs for each of the process steps are then identified -- e.g., energy, materials, labor, capital, and so forth. The quantities of each of the inputs required for a unit of output at each process step are then identified. Quantities of the different inputs are functions of various technical parameters -- e.g., product/design specifications, such as machining tolerances and part size and complexity; and processing parameters, such as heating temperatures, process yields, and inspection/quality controls. Inputs can also be made to vary nonlinearly with production size,

---

[10]Specifics of the models used are given below.

reflecting economies of scale. The per unit costs of the various inputs are then identified. The costs of the inputs can be constant on a per unit basis or can be made to vary with quantities purchased to reflect potential quantity discounts.

This information is in our case modeled using Lotus 123 software. This software package provides a blank worksheet similar to an accountant's spreadsheet. Any cell in the worksheet can contain numerical data or mathematical relationships that may depend upon information in other cells. Each process step is modeled separately; and for each process step, the cost of producing a given quantity of output at that step is estimated in spreadsheet fashion. Product design specifications, processing parameters, and input costs are all entered exogenously. The output of the first process step, in terms of total cost and the costs of individual inputs, becomes an input to the second production step and so forth. Thus at each production step we can estimate the total cost of the product at that step, the contribution of that production step to the total cost of the product at that point in production, and the contribution of each input to total cost and to the cost of a particular production step. Further, sensitivity analyses can be conducted by varying the costs of inputs, product/design specifications, and process parameters and observing the impacts on total costs and the costs at specific process steps.

3.4. THE MIT MODELS

The construction of a process-cost model that depicts a complicated series of process steps is a major undertaking. Therefore, in the interest of conserving resources, two rather generic process-cost models

were obtained from the Materials Systems Laboratory (MSL) at MIT. These models -- one for slip casting and one for extrusion -- serve as the starting points of our work to estimate the costs of ceramic tubes and headers.[11] The following gives a brief overview of the models.

Both models consider explicitly six process steps in the production of ceramic parts. The process steps and their order are illustrated in Fig. 3.1 and include materials preparation, extrusion/casting, drying, firing, machining, and quality control and storage. At each process step there are five major cost categories -- raw materials, energy, labor, capital, and overhead (i.e., taxes, insurance, and maintenance).

The costs of production at each process step are affected by various product/design specifications and processing parameters. These include, but are not limited to:

1. part size, volume, weight, and complexity
2. machining tolerances,
3. inspection variables,
4. processing additives,
5. cycle times,
6. drying parameters,

---

[11]The MSL at MIT maintains and is developing engineering-based models of the cost of producing numerous ceramic and non-ceramic components made by a variety of processes. In addition the generic slip-casting and extrusion models used in this work, MSL has detailed models for specific ceramic parts, such as cutting tool inserts and turbocharger rotors. Unfortunately, many of the models do not have published documentation, as is the case with the two models used in this work. For a more detailed description of the process-cost approach and in particular the types of models maintained at MIT, see, for example, Rothman (1985) and Poggiali (1985).

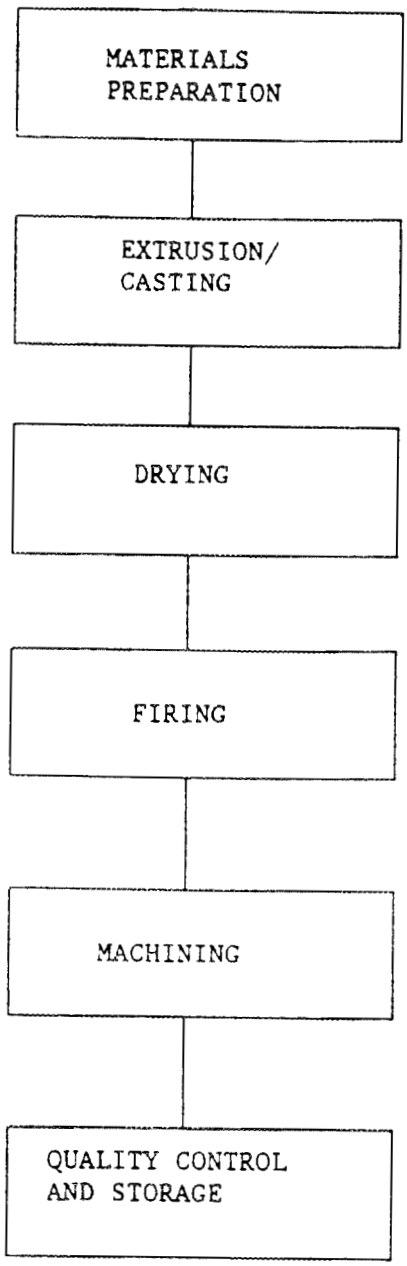

Fig. 3.1. Process steps in the MIT models

7. firing parameters, and

8. process yields.

Table 3.1 illustrates a representative process step from our extended process-cost models -- i.e., machining in the slip-casting model. For each process step, a similar representation is given and is divided into six sections -- i. e., equipment cost, process materials cost, energy cost, other cost, total cost of that process step, total cost of the product after the process step, and a distribution of the total cost after that step disaggregated by major input.

Table 3.2 gives an example of the inputs table used in the models. Note that factor prices are given for energy, materials, and other inputs. Sensitivity multipliers are also given in this table, which represent various product and process parameters. In some cases, for example energy, the user may choose among different energy types at different costs.

Table 3.3 presents an example of the summary table given at the end of the models. Note that this table gives a disaggregation of total cost by process step and input. Also given are the assumptions about key product and process parameters.

See Appendix A for complete printouts of the final process-cost models.

Table 3.1. A representative process step from the process-cost models: Machining in the slip-casting model

MACHINE SHOP

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Lathes	2	$51,006	$102,012
Special Chucks	2	$1,386	$2,772
Tooling Crane	1	$4,158	$4,158
Benches and Cabinet	1	$346	$346
Miscellaneous Tools	1	$2,772	$2,772
			=========
	Total ($/plant)		=>1.12E+05

====> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Fired Part	1.17		$129.39	$23.15
Coolant	0.01	$0.01	$0.00	$0.00
			==========	==========
Total =>			$129.39	$23.15

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	1.402	$0.0525	$0.07	$0.01
			==========	==========
		Total =>	$0.074	$0.01

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.263	$13.50	$3.55	$0.64
Capital Charges		12.0%	$0.93	$0.17
Taxes		1.2%	$0.06	$0.01
Insurance		1.0%	$0.05	$0.01
Maintenance		6.0%	$0.31	$0.06
			==========	==========
		Total =>	$4.91	$0.88

==========>COST OF MACHINING	=>	$4.98	$0.89
==========>COST AFTER MACHINING	=>	$134.37	$24.04

COST DISTRIBUTION

Materials	$80.72	60%
Energy	$9.94	7%
Labor	$15.70	12%
Capital Charges	$16.20	12%
Other	$11.81	9%

Slip Casting Model

Table 3.2. A representative inputs table from the process-cost models: Inputs to the slip-casting model

SLIP CASTING MODEL

FACTOR PRICES

		units	$/unit
==========> ENERGY			
	Electricity	Kwh*	$0.0525
	Natural Gas	Mbtu	$6.50
		units	$/unit
==========> MATERIALS			
	CHOOSE MATERIAL BY NUMBER ====>	2	$10.00
	1. SiC Standard Powder	lbs	$1.32
• Used Here Only*	2. SiC Submicron powder	lbs	$10.00
	3. Alumina Standard Powder	lbs	$0.86
	4.Alumina Submicron Powder	lbs	$11.00
	5. Silicon Nitride Powder	lbs	$20.00
	Water	gals	$0.01
	Binders	gals	$0.85
	Diamond Tool Inserts		$7.00
	Air	lbs	$0.0001
	Ware Support	lbs	$1.00
	Inert Gas Atmosphere	lbs	$0.16
	Slip Casting Molds	1	$20.00
	Vacuum Casting Molds	1	$10.00
			$20.00
	Ball Milling Material and Liners	lbs	$0.66
	For Hipping : Glass Encapsulation	lbs	$0.20
==========> OTHERS			
	Labor ($/man-hour)		$13.50
	Cost of Capital (% of initial investment)		12.0%
	Tax Burden (% of operating expenses)		1.2%
	Insurance (% of physical plant)		1.0%
	Maintenance (% of physical plant)		6.0%
	Years to Recover Investment		10
	Equipment Scaling Factor		0.3

INPUT FACTORS

Plant Capacity (pieces/yr)		25000
Max. Plant Capacity (pieces/yr)		250000
Working Days	days/yr	250
# of Shifts	#/day	3
Molding Stations	#	400
Time To Run Part	hrs	2500.0
Fraction of Total Time		41.67%

Table 3.2. (continued)

Green Density	gm/cc	2.08
Part Weight	lbs	5.59
Percent Water		40%
Percent Binder and Defflocculants		3%
Mold Life	pieces	50
Pressure Mold Life	pieces	10000
		50
Initial Particle Size	microns	1
Final Particle Size	microns	1
SiC Work Index		26.17
Alumina Work Index		17.19
VOLUMES		
Volume of Parts		25000
Choose Standard or Vacuum Casting (1,2) =>	1	120
		2
1. Standard Cycle Time	Minutes	120
2. Vacuum Cycle Time	Minutes	12
1. Standard Cycles/shift		2
2. Vacuum Cycles/shift		9
Mixing	lb/hr	746.4
Mixing Time	hrs	12
Lathe (hand operated)	parts/hr	12
Lathe CNC (complex geometry,)	parts/hr	25
Lathe CNC (simple geometry)	parts/hr	8
Inspection	parts/hr	20
Choose Geometry Factor (1=simple, 2=complex) =>		1

ASSUMED PROCESS YIELDS

Material Preparation	75%	96%
Slip Casting	78%	98%
Green Machining	80%	100%
Drying	80%	95%
Sintering	84%	98%
Grinding	86%	95%
Inspection	90%	90%
Total Yield		75%

Note: Ist column values indicate overall yields till that process step
IInd column values indicate yields at that individual step

INPUT FACTORS

DRYING PARAMETERS

Batch Weight	lbs	186
Weight of Ware Support	lbs	745
Specific Heat		0.25
Water Weight (%)		20%
Relative Humidity Entrance		70%

Slip Casting Model

Table 3.2. (continued)

Entrance Air Temperature	F	1022
Exit Air Temperature	F	77
Drying Heat Efficiency		60%
Lb Water/Lb Air Entrance		0.04
Lb Water/Lb Air Exit		0.01
Drying Time	hrs	24

FIRING PARAMETERS

Cycle Time	hrs	24
Firing Temperature	F	4172
Ambient Temperature	F	89.6
Firing Heat Efficiency (Tunnel)		60%
Firing Heat Efficiency (Periodic)		40%

CHOOSE FIRING METHOD ====>	2	2
1. Periodic		
2.Continuous		

VESSEL DIMENSIONS		
Diameter	cm	60
Height	cm	152
Volume	cu cm	429769.8
Packing Density		30%

OPTIONAL STEPS	
Green Machining (off=0,on=1)	0
Final Machining (off=0,on=1)	1

MACHINING COST AS A FUNCTION OF TOLERANCE

INPUT TOLERANCE HERE (#)=====>	3	80%

	in	mm	increase %
1.	0.02	0.508	20%
2.	0.01	0.254	40%
3.	0.005	0.127	80%
4.	0.002	0.051	140%
5.	0.001	0.025	200%
6.	0.0005	0.013	360%

Slip Casting Model

Table 3.3. A representative summary table from the process-cost models: Totals from the slip-casting model

TOTALS

==========> **PROCESS**

	$/piece	percent
Material Preparation	$76.07	55.94%
Isopressing	$1.04	0.76%
Green Machining	$0.00	0.00%
Drying	$9.62	7.07%
Firing	$42.66	31.37%
Finishing	$4.98	3.67%
Inspection	$1.62	1.19%
Total =>	$135.99	100.00%

==========> PROCESS COSTS

	$/piece	$/lb	Percent
Materials	$80.72	$14.44	59.4%
Energy	$9.94	$1.78	7.3%
Labor	$16.45	$2.94	12.1%
Capital Charges	$16.79	$3.00	12.3%
Other	$12.08	$2.16	8.9%
Total ========>	$135.99	$24.33	

==========> MATERIALS COST BREAKDOWN

	$/piece	$/lb	Percent
Ceramic Powder Cost	$74.64	$13.35	54.9%
Process Material Costs	$6.08	$1.09	4.5%

========> ASSUMPTIONS

POWDER COST ($/lb)	$10.00
PERCENT BINDER + WATER	43%
PLANT CAPACITY (pc/yr)	2.50E+04
BINDER BURNOUT TIME (hr)	24
FIRING TEMPERATURE (F)	4172
FIRING METHOD	2
TOTAL YIELD	75%

Slip Casting Model

4. ESTIMATING THE COST OF CERAMIC TUBES AND HEADERS

The current methods for manufacturing ceramic recuperator tubes include plastic extrusion, water-based extrusion, and slip casting. However, the most commonly used methods are water-based extrusion and slip casting. Plastic extrusion is more expensive and poses some technical problems for tubes with outside fins. (Tubes with fins are sometimes used rather than plain tubes to increase the heat transfer area.)[12]

In this work we consider only water-based extrusion and slip casting as alternative methods to produce ceramic tubes. Since ceramic headers cannot be extruded, only slip casting is considered for the manufacture of headers.

4.1. MIT Model Modifications

As discussed above, the MIT process-cost models of extrusion and slip casting serve as the starting points for estimating the costs of the ceramic components of the recuperator. These MIT models have been enhanced in three major ways. First, the process steps and input parameters have been modified and validated so that they conform to the actual practices the industry now uses in the manufacture of ceramic tubes for heat exchangers. Second, several functional relationships in the MIT models have been found to be incorrect, and those relationships have been corrected. Third, the models have been made more user friendly

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[12]Halstead (1985) provides a good comparison of the different manufacturing methods to produce ceramic tubes for recuperators.

by the writing of additional Lotus 123® macros. Some changes were made based on the current authors' review of the models. Other suggestions for general and specific modifications to the models resulted from consultations with industry representatives and private consultants.

Recall that the major sequential process steps for manufacturing a ceramic recuperator tube are materials preparation, extrusion/casting, drying, firing, machining, and quality control and storage. The major process steps in both the extrusion and slip-casting models are the same, with the exception that the extrusion process is replaced by a casting step in the slip-casting model. The process technology beyond the forming step is identical in both the extrusion and slip-casting models. Likewise, the costs of producing ceramic tubes in the process steps beyond forming are identical in the two models. The materials preparation step, which precedes the forming step, is more extensive in the extrusion model than in the slip-casting model. With regard to the two forming steps, extrusion is more capital intensive, while slip casting is more labor intensive.

Both models have been modified to represent the cost of manufacturing silicon carbide tubes with 2" outer diameters (OD), 1 5/8" inner diameters (ID), and 48" lengths. The starting material for tube manufacture is submicron silicon carbide powder. The input parameters are based on an assumed yearly production volume of 25,000 tubes, or 100 tubes per working day. See Appendix A for a complete listing of the inputs used in the slip-casting and extrusion models.

The cost of a ceramic header is calculated using the process cost model for slip casting. While company proprietary methods are currently

being used to manufacture headers, the slip-casting model is a close approximation of the actual methods used. Due to the lack of sufficient technical information, the slip-casting model for headers was developed by changing the following parameters in the slip-casting model for silicon carbide tubes.

First, an additional process step was added -- i,e., a green-machining step was added following the casting step. The base data for this additional step was obtained from the MIT slip-casting model. Therefore, the sequential process steps in the case of ceramic headers are materials preparation, casting, green machining, drying, firing, machining, quality control, and storage. Second, the pounds of powder material required per unit surface area of header was assumed to be 1.5 times that of a tube. Third, it was assumed that the final machining step is six times more labor intensive in the case of headers than in the case of ceramic tubes. Fourth, it was assumed that the overall yield in the case of headers is considerably lower than in the case of tubes. For the grinding and inspection process steps, yields for headers were assumed to be 90% of the corresponding yields for tubes. The overall yield in the case of headers is therefore 81% of the overall 75% yield for tube manufacture.

The estimated cost for a header is obtained by rerunning the slip-casting model given the above modifications. The modified model provides cost estimates in terms of a cost per tube ($/piece). That cost per tube is then divided by the outer surface area of a tube to give the estimated cost of a ceramic header per unit surface area ($/ft^2).

Recommendations about specific inputs to the process-cost models were provided by two independent sources: Mr. Irving Ruppel of Sohio Engineered Materials Company, Niagara Falls, New Jersey, and Dr. Dale Whitmer of Southern Illinois University, Carbondale, Illinois. There is a consensus among the authors and independent sources that the capital costs estimates are the least reliable of the various cost categories--especially if the time frame being modeled is several years into the future. Significant technological breakthroughs may occur. These gains may cause the current machinery being used by the ceramic tubes industry to become obsolete.

4.2. CORRECTIONS OF SPECIFIC FUNCTIONAL RELATIONSHIPS

An examination of the MIT models showed some functional relationships to be incorrect. In discussions with MIT staff, there was agreement that some parts of the models needed changes. The following specific modifications were made.

4.2.1. Energy Consumed in the Firing Step

In the firing step, the base case MIT models used the product of total energy (i.e., the energy required to remove binder and to heat the part and batch support) and total cycle time as the energy required during the soaking period. This soaking-period energy requirement is actually the energy required to compensate losses through furnace insulation due to transient conduction. The modified energy requirement equation for the soaking period is then:

energy = thermal conductivity of the insulation * surface of furnace * temperature gradient across furnace wall * soaking time.

In addition, the firing process in the MIT models includes the energy for the evaporation of water, the heating of the part and batch support, and soaking heat. It is very unlikely, however, that tubes will contain any water after the drying step. The energy required to evaporate water was therefore removed.

Further, the energy required to heat insulation was not considered in the MIT models. That energy requirement has been added to the models and is calculated as follows:

energy = internal surface area of furnace * thickness of insulation * density of insulation* heat capacity of insulation * (temp. difference/2 - ambient temperature).

The above formula is used to calculate the energy required to heat insulation in the case of drying, as well as for the drying step.

4.2.2. Firing Furnace

The MIT models depict a natural-gas-type kiln in the firing step. It is very unlikely, however, that the use of a gas-fired kiln would be acceptable for sintering silicon carbide, which requires a sintering temperature of 2,300 degrees C, good temperature control, and good atmospheric control. Propane burning in slight oxidizing conditions can get to 2,300 degrees C, but it involves a lot of heat losses in a natural-gas-type kiln and would not provide the proper atmospheric control. The electric kiln is generally recognized as the most efficient type of furnace for sintering silicon carbide parts. Therefore, in our firing step the natural-gas-type kiln given in the MIT models is replaced by an electric kiln. The model is altered to use electricity for firing rather than natural gas.

4.2.3. Batch Weight

It was found upon examination of the MIT models that batch weight (i.e., the total weight of parts being fired at one time) was fixed and not a function of production capacity (parts/year), number of operating days in a year, and part weight. Batch weight is now calculated using the following formula:

batch weight = production capacity * part weight/number of operating days/year * number of shifts/day.

4.2.4. Capital Costs

The capital cost parameters have been changed in all the process steps in both the extrusion and slip-casting models to reflect current industry costs and the specific ceramic parts being produced. These estimates are based on a maximum yearly production volume of 250,000 pieces or a daily production volume of 1,000 pieces. Given this maximum production volume the capital cost for the various process steps are as follows: materials preparation -- $154,000; casting -- $34,568; extrusion -- $900,000; indirect heated dryer -- $348,000; sintering (periodic) -- $2,000,000; sintering (tunnel) -- $3,000,000; machine shop -- $224,000; and quality control and storage -- $150,000. The capital costs are assumed to be the same for both models, with the exception of the forming step (i.e., extrusion or casting). Note that the capital costs for any level of production lower than the maximum level are calculated by what is commonly referred to as the "6/10 rule". The capital costs of our base-case production capacity of 25,000 parts per year is calculated according to this commonly used methodology. See, for

example, Rothman (1985) for a detailed discussion of this capital cost methodology.

4.3. OPERATING ENHANCEMENTS

The MIT models have been enhanced in two major ways to improve the models' ease of use. The first enhancement allows the user much easier access to the internal workings of the model. As stated earlier, the model has been developed on spreadsheets using Lotus 123®. These spreadsheets contain numerous formulas, constants, and descriptive labels. To help understand the inner workings of the model, an application program has been written to process a spreadsheet in the following manner:

(1) to compile a listing of all cell addresses that are referenced by formulas (these addresses are identified and are given descriptive names for clarity);

(2) to provide a cross-listing of every formula location that references a particular address;

(3) to list each formula with the supplied descriptive names inserted beside each address; and

(4) to list all constants and their present values.

The print-outs and listings produced by the program have two main benefits. First, spreadsheet cell locations can quickly be referenced to determine their contents and meaning. Second, modifications to any cell can be made very easily and the effects of the modifications can be traced throughout the model beforehand. Without these enhancements, following the workings of the model is like walking through a maze.

The second enhancement allows the model to be run using menus, which makes the model much more user friendly. The new macros allow the individual not familiar with Lotus to run the model independently. In particular, the macros allow the user to view any section of the model including all input parameters and process steps. Selected parameters may be temporarily changed in order to make a run and review the results. Another option enhances sensitivity analyses by allowing the user to select an input parameter and then view the results of the particular analysis graphically. See Appendix B for a detailed description of the Lotus 123® macros.

5. ESTIMATING THE TOTAL COST OF A CERAMIC RECUPERATOR

Estimating the total cost of a ceramic tube-and-shell recuperator is a four step procedure. First, the cost of a metallic tube-and-shell recuperator is estimated by employing previous correlation studies that relate total cost to heat-transfer area. Second, the cost of metallic tubes and headers is estimated and subtracted from the estimated total cost of the metallic system. Third, the cost of ceramic tubes and headers is estimated using the process-cost models for slip casting and extrusion discussed above. Finally, the estimated cost of ceramic tubes and headers is added to the estimated cost of the remaining metallic components estimated in the second step to provide an estimate of the total cost of a recuperator in which the tubes and headers are made from silicon carbide. In the case of extrusion, only the tubes are made from silicon carbide.

5.1. THE COST OF METALLIC RECUPERATORS

The material of construction for metallic heat exchangers considered here is a nickel superalloy called Inconel 600, which has good creep resistance, corrosion resistance, and high-temperature strength properties. Inconel 600 has been judged to be compatible with silicon carbide tubes and headers in the hostile environments in which our hypothetical recuperator might be used. The size of the heat exchanger tubes is assumed in all cases to be 2" OD x 1 5/8" ID x 48" L. An increase in the size of a recuperator, reflected in its surface area, is

modeled as an increase in the number of tubes used rather than an increase in tube size.

Corripio, Chrien, and Evans (1982) have correlated the cost of metallic tube-and-shell heat exchangers with heat transfer area. This procedure contrasts with cost estimation procedures that take into account shell diameter, number and length of the tubes, types of heads, and other construction details. For example, Purohit (1983) has developed cost equations for shell-and-tube heat exchangers that consider various configurations as classified by the Tubular Exchanger Manufacturers Association (TEMA). However, the accuracy of Corripio's, Chrien's, and Evans' (1982) simplified correlations of cost vs. heat-transfer area is sufficient for preliminary cost estimates. This method is also consistent with our goal of being as generic as possible in our cost estimation. The correlation study yielded cost estimates of plus or minus 30% compared to the actual estimates. The cost equation given in Corripio, Chrien, and Evans (1982) for metallic, fixed-head, tube-and-shell heat exchangers is as follows:

$$\text{Cost (\$)} = \exp[8.551 - 0.30863(\ln A) + 0.06811(\ln A)^2]* \exp[-1.1156 + 0.0906(\ln A)]* [1.2040 + 0.50764(\ln A)]$$

where A = heat transfer area in ft^2.

The above cost equation is applicable only for metallic (Inconel 600) heat exchangers with a design pressure up to 100-psig and a heat-transfer surface area of between 150 and 12,000 ft^2. The cost is given in 1979 dollars. The cost is converted to 1987 dollars by multiplying the ratio of the 1987 and 1979 Chemical Engineering Fabricated Equipment Indices (CE) (i.e., CE 1987/CE 1979) by the cost given in 1979 dollars.

The estimated cost of a heat exchanger includes only manufacturing cost. No installation costs are included.

5.2. THE COST OF METALLIC TUBES AND HEADERS

The contribution of metallic tubes to the total cost of metallic heat exchangers is calculated as the product of total heat-transfer surface area and the cost of a tube per unit heat-transfer surface ($/ft^2). The current cost of a Inconel 600 tube (2" OD x 1 5/8" ID x 48" L) is $84/piece for 1,000 pieces (source: Inco Alloys International, Atlanta Sales Office). The unit tube cost is therefore $40/ft^2.

While the above metallic tube cost is a good base-case estimate, actual tube cost will vary depending on tube size, among other factors. For the same heat transfer area, smaller size tubes are cheaper, but maintenance costs are higher than for larger size tubes. Further, Hall, Matley, and McNaughton (1982) report that a fixed tubesheet heat exchanger of size 600 ft^2 costs 30% higher when 8 ft tubes are used as compared to 16 ft tube lengths. It is not known what tube size, if any, was assumed in the correlation study reported in Corripio, Chrien, and Evans (1982).

The contribution the metallic headers make to the total cost of metallic heat exchangers is estimated from information given in Purohit (1983). That publication reports that the cost of headers in percentage terms remains fairly constant for changes in shell diameter. In the case of base carbon-steel heat exchangers, headers contribute about 6% of total costs. When Inconel 600 is used, the headers contribute approximately 11% of total cost.

The "other" category of costs includes all component costs other than tubes and headers and is obtained by subtracting the estimated costs of tubes and headers from the estimated total cost of the metallic heat exchanger.

5.3. THE TOTAL COST OF A CERAMIC HEAT EXCHANGER

It is assumed that the design of our ceramic recuperator is similar to a metallic tube-and-shell recuperator. The only difference is that the metallic tubes and in some cases headers are replaced by silicon carbide. The costs of the ceramic tubes and headers are based on the assumed heat-transfer area of the recuperator. Although the thermal conductivity of silicon carbide (i.e., 25 W/m K at 649 degrees C) is greater than that of Inconel 600 (i.e., 17 W/m K at 649 degrees C), the overall heat transfer coefficient of the two is about the same. Penty and Bjerklie (1980) have found that the contribution of thermal conductivity is less than 10% of the overall heat transfer coefficient for the convective heat transfer coefficient on the tube side and shell side in a low pressure heat exchanger. Therefore, for the same amount of heat transferred, the heat-transfer area is assumed to be the same for both metallic and ceramic heat exchangers.

The cost of ceramic tubes for a given recuperator is calculated as the product of the cost of tubes per unit surface area ($/ft^2) and the heat-transfer surface area. As mentioned above, two ceramic tube manufacturing technologies are being considered -- slip casting and extrusion. The unit costs for tubes obtained from the process-cost models divided by the outer surface area gives the cost of tubes per unit surface area.

Data on the cost of ceramic headers is difficult to obtain. Most of the current literature expresses the cost of headers in $/cubic inch. For example, Standard Oil Engineered Materials Company, Refractories Division at Keasbey, New Jersey quotes a price of $0.60 to $2.00 per cubic inch, depending on the header's shape. However, there exists no direct relationship between the volume of the header and the heat transfer surface area of a heat exchanger. Therefore we cannot use this volume/surface area relationship. To maintain the consistency in our cost calculations, the cost of a ceramic header for a particular size recuperator is calculated based on the recuperator's header surface area. The header surface area of a metallic heat exchanger, which is assumed to be the same surface area as for a ceramic heat exchanger, is calculated by dividing the estimated cost of the metallic header (estimated as described in Section 5.2) by the unit cost of metal ($/ft^2) (also given in Section 5.2). The product of header surface area so obtained and the cost of the header per unit surface area ($/ft^2) gives the cost of a ceramic header for a particular-sized recuperator. (Section 4.1 gives details about the method used to determine the cost of a ceramic header of a particular size.)

The total estimated cost of a ceramic recuperator of a particular size is given by adding the total cost of ceramic tubes, the cost of the ceramic headers, and the cost of the remaining metallic components (or the "other" costs) of the recuperator.

6. MODEL RESULTS

This section presents results from the methodology and models described in the preceding sections. We first focus on the estimated per unit cost of ceramic tubes and headers. Our focus then turns to the estimated total cost of ceramic recuperators. In both cases -- i.e., tubes and total recuperator costs -- the analyses can be divided into two main parts -- (1) the selection of a set of base-case parameter values and the estimation of costs based on those base-case values, and (2) an assessment of the sensitivity of the base-case costs to changes in key economic and technical parameters.

6.1. THE ESTIMATED COST OF CERAMIC TUBES AND HEADERS

6.1.1. The Base-Case Assumptions

Table 6.1 gives the major assumptions for our base-case scenario. For a complete listing of all the assumptions used in the process cost models, see Appendix A.

6.1.2. Cost Distribution for the Two Tube Manufacturing Technologies

Figure 6.1 gives the estimated base-case costs for the manufacture of silicon carbide ceramic tubes using both extrusion and slip-casting methods. Also given is the distribution of those costs by the major cost components.

Note that for our base-case inputs, extrusion is estimated to be slightly more expensive than slip casting -- i.e., $139.47 per tube for extrusion and $135.99 for slip casting. There is currently quite a lot of debate about the cost of these two competing technologies, and our

Table 6.1. Major assumptions in the base-case scenario

Tube size:	2" OD x 1 5/8" ID x 48" L
Tube weight:	5.59 lbs.
Powder:	submicron silicon carbide
Production volume:	25,000 tubes/year
Operating time:	250 days/year
Number of shifts:	1/day
Powder cost:	$10/lb.
Sintering Temperature:	2,300 degree C
Total yield: extrusion:	77%; slip casting: 75%
Labor cost:	$13.50/hour
Cost of capital:	12%

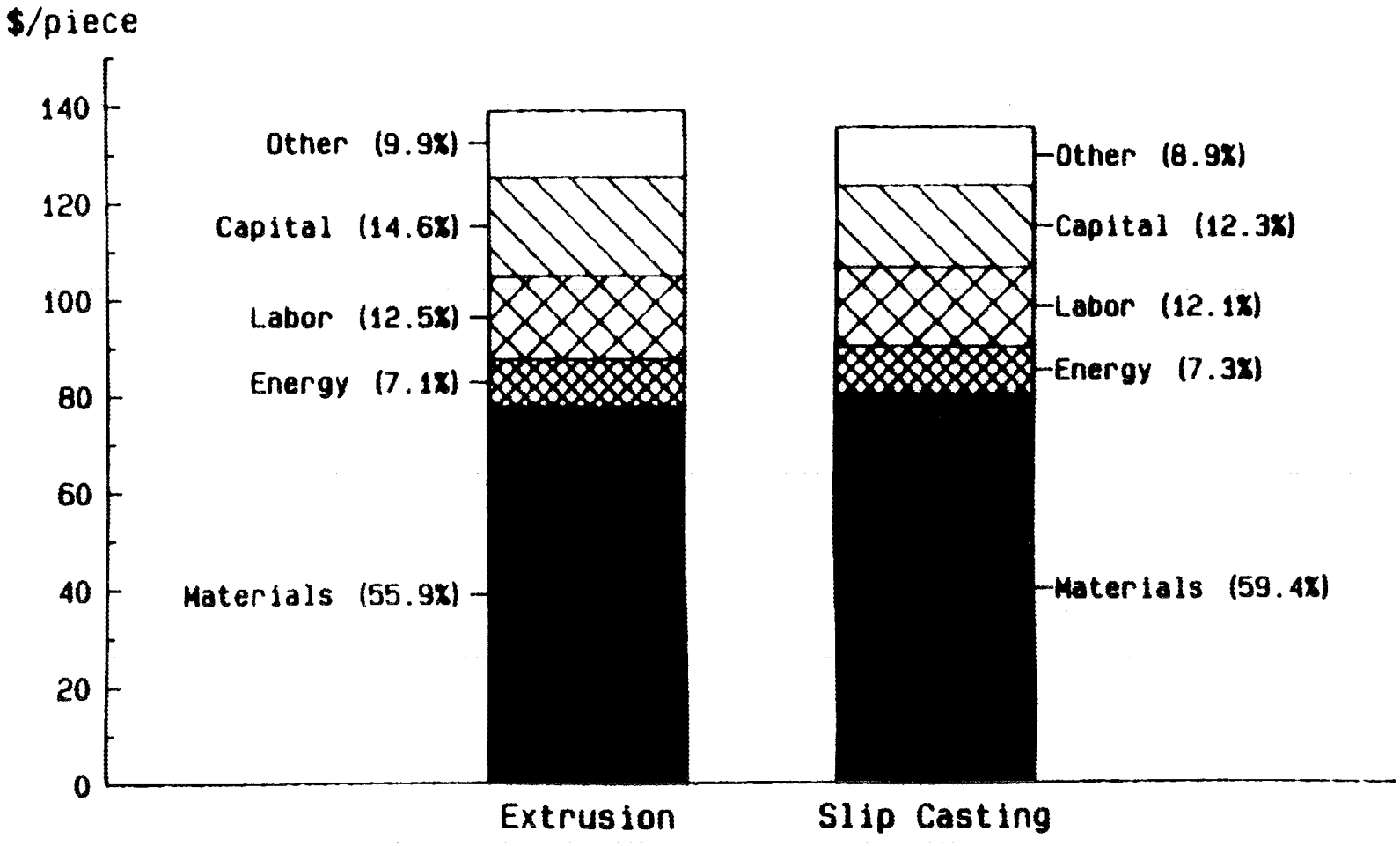

Fig. 6.1. The estimated base-case cost of manufacturing silicon carbide tubes by extrusion and slip casting

Extrusion : $ 139.47/piece
Slip Casting : $ 135.99/piece

estimated costs conclude that there is no clear winner. Since we have assumed that the costs of the competing technologies are identical beyond the forming step, the slight cost difference can be explained by extrusion's more expensive capital cost at the extrusion step and the higher cost of materials preparation. Although slip casting is assumed to be more labor intensive than extrusion and the yield for slip casting is lower at the casting and inspection steps, extrusion, given these base-case assumptions, remains slightly more expensive.

As far as the cost disaggregation is concerned, the cost of materials is by far the largest cost component for both technologies--i.e., 56% in the case of extrusion and about 59% in the case of slip casting. The costs of capital, labor, other inputs, and energy follow in terms of their overall contributions to the cost of manufacturing ceramic tubes. Capital costs are slightly higher for extrusion because, as discussed above, the extrusion step is very capital intensive. Slip casting is more materials intensive because of lower assumed yields with that process. Although slip casting is more labor intensive at the slip-casting step, extrusion is more labor intensive at the materials preparation step. Labor thus contributes about the same percentage (i.e., 12%) to total cost in both extrusion and slip casting. Energy's contribution to total tube cost is also about the same (i.e., 7%) for both slip casting and extrusion.

In the following subsections we consider the sensitivity of the estimated base-case costs to changes in key economic and technical parameters. All parameters remain at their base-case levels, with the

exception of the single parameter on which sensitivity analysis is being conducted.

6.1.3. Production Volume vs. Tube Cost

The sensitivity of tube cost to changes in production volume is summarized in Fig. 6.2. At low levels of production volume the cost is obviously very sensitive to changes in output. The cost per tube decreases drastically -- i.e., about $550/tube -- when yearly production volume is increased from 1,000 tubes to about 20,000 tubes in the cases of both production technologies. Cost per tube flattens out at volumes above about 20,000 tubes/year, and at about 80,000 tubes/year, tube manufacturing cost remains essentially constant at about $97/tube. There are no significant differences between the costs of the two technologies across the entire range of production volume being considered.

The cost variations resulting from changes in production volume can be explained by the more complete utilization of capital equipment in larger scale operations. Because capital equipment is not infinitely divisible, it is likely that the marginal piece of equipment required for that production volume capacity will not be utilized fully. At lower production capacity levels, this unused capacity can be a large part of total capacity. Capital cost can, subsequently, be increased sharply. As production volume increases, this problem becomes less severe. While the marginal piece of equipment may not be fully utilized at larger production volumes, the percent of the total equipment capacity that is utilized becomes larger.[13]

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[13]Note that while this is an intuitive explanation of the relationship between production volume and per-unit cost, the process-cost models actually incorporate these cost changes within the commonly-used "6/10 rule". See Rothman (1985) for an explanation of this rule.

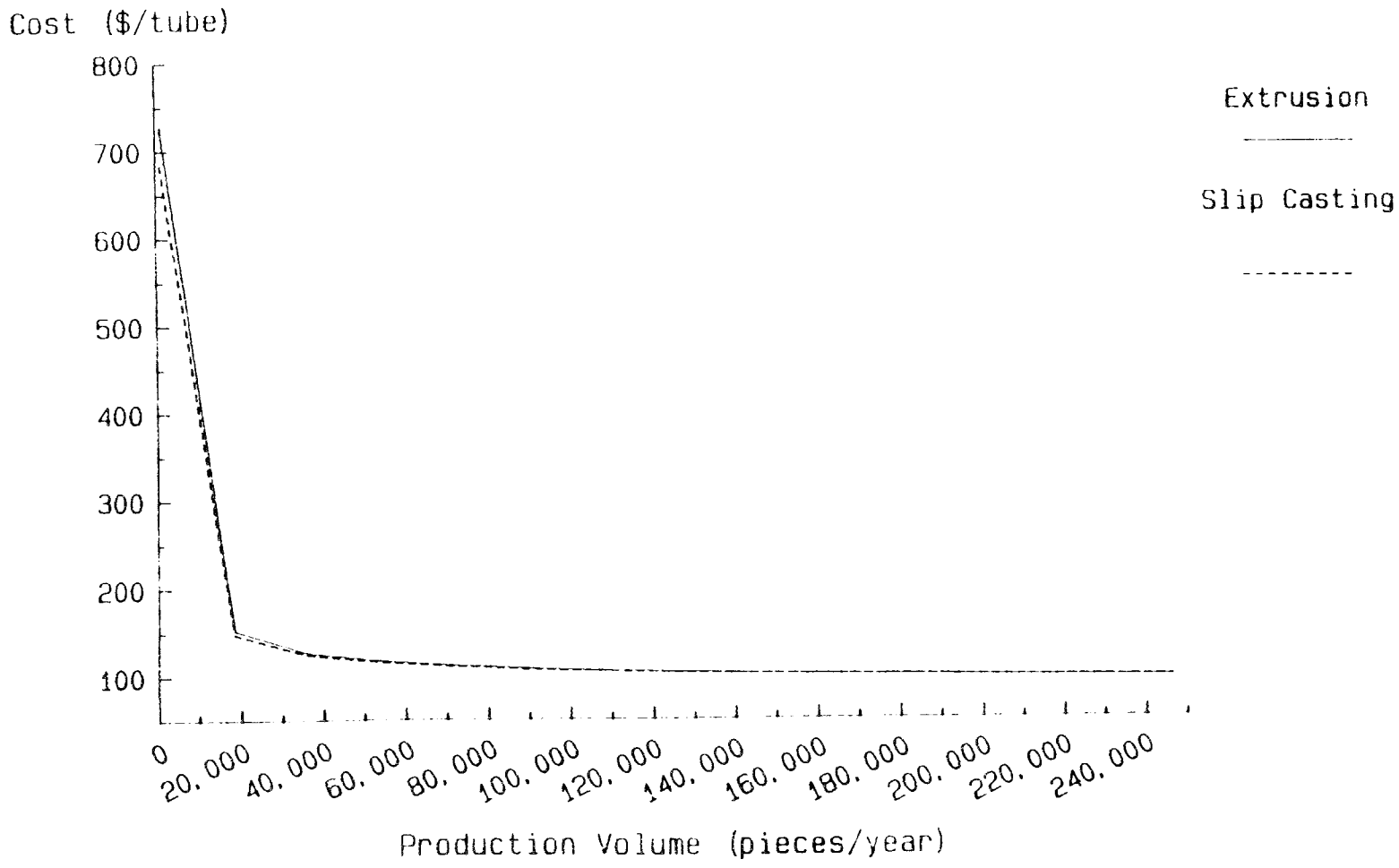

Fig. 6.2. The sensitivity of tube cost to changes in production volume

6.1.4. Powder Cost vs. Tube Cost

Figure 6.3 shows the estimated relationship between the cost of powder and the total cost of manufacturing a ceramic tube. The cost of tubes is estimated to increase linearly by $7.23 and $7.46 for each $/lb increase in powder cost. The increase in cost for the slip-casting technology is slightly higher than for extrusion because yield is assumed to be slightly lower in the case of slip casting. Note that at lower powder costs, slip casting is estimated to be slightly less costly than extrusion, while at higher powder costs the opposite is true. At lower powder costs, slip casting is less costly because of that technology's lower capital equipment cost. But as powder costs go up, the lower yielding slip casting technology contributes to higher materials costs, which eventually -- at about $24/lb. -- exceeds the cost advantage that slip casting has in terms of lower capital equipment cost.

6.1.5. Capital Cost vs. Tube Cost

As stated earlier, there is significant uncertainty about how the cost of capital equipment may change during the next 10 to 20 years, or the time frame when ceramic heat exchangers may be used extensively. Economies of scale and other technical factors may play an important role. It is therefore important to examine the sensitivity of tube cost to capital cost changes.

Figure 6.4 illustrates the estimated relationship between tube cost and percentage changes in the cost of capital at the various process steps. Rather than examining the sensitivity of tube cost to the cost of capital at any particular step, Fig. 6.4 examines how total tube cost changes when capital cost at each process step changes by some given

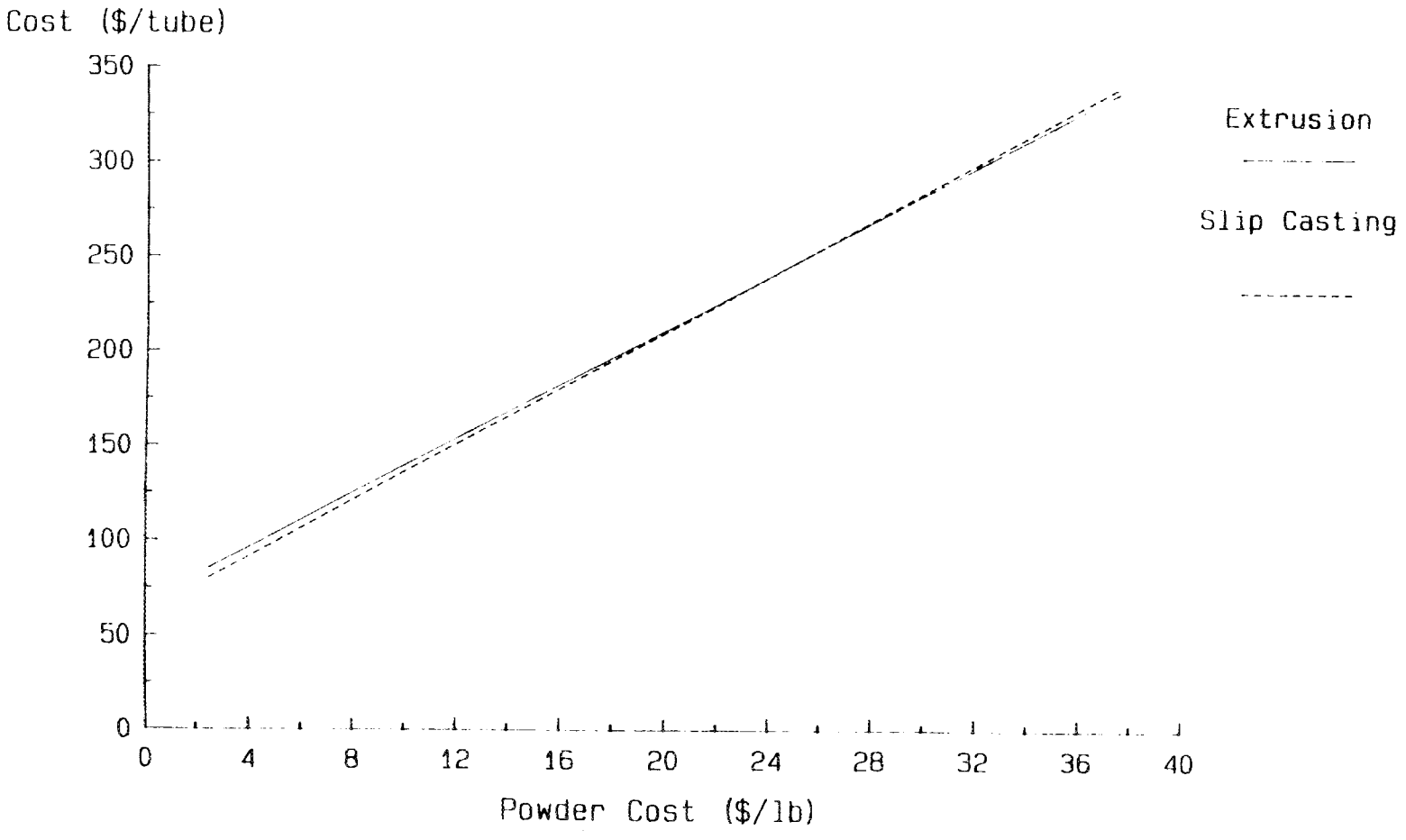

Fig. 6.3. The sensitivity of tube cost to changes in powder cost

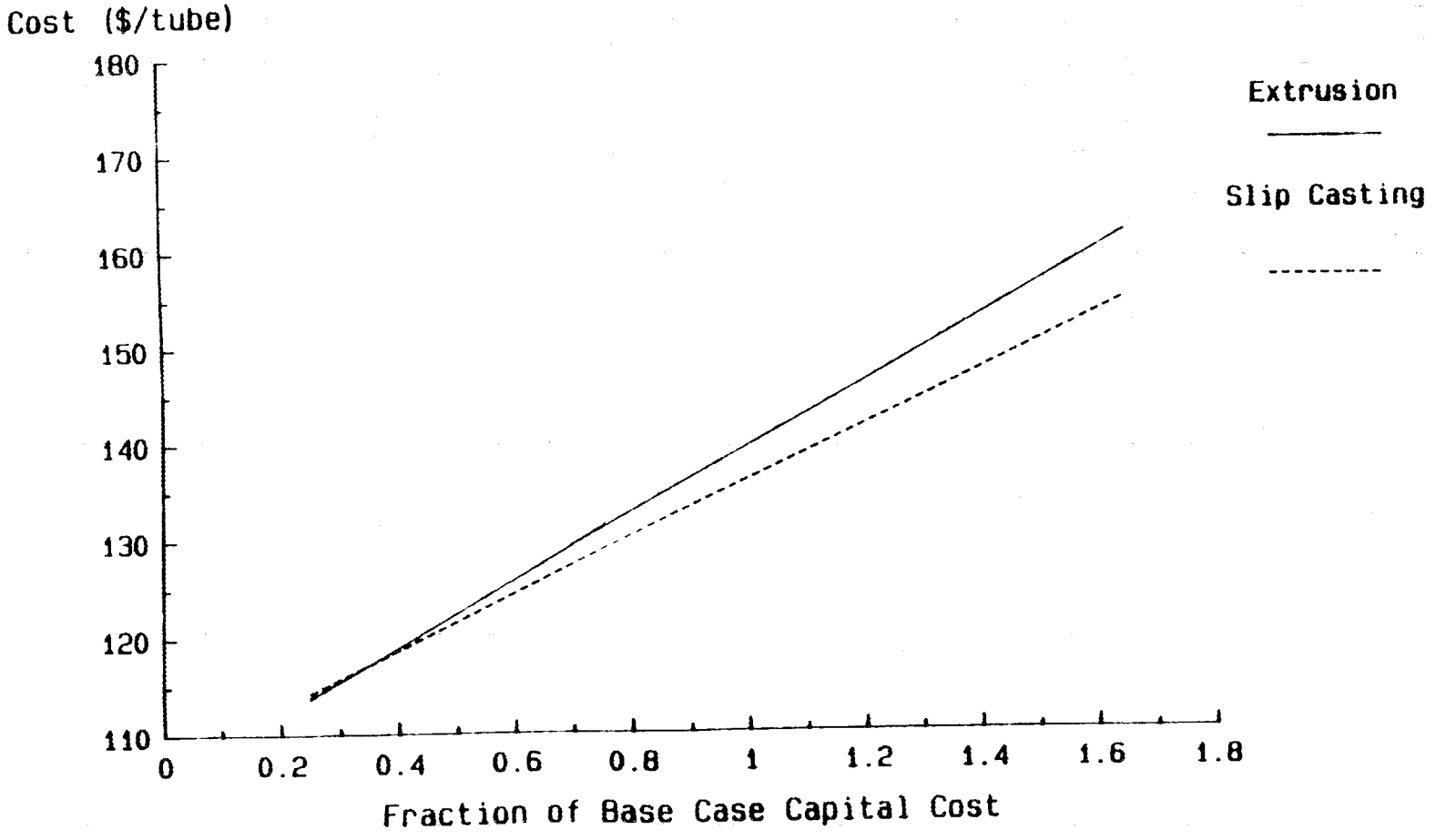

Fig. 6.4. The sensitivity of tube cost to changes in capital cost

percentage from the base-case capital costs. A value of 1 corresponds to the capital cost estimate used in the base case. A value of, for example, 0.8 indicates that all capital costs at all production steps equal 80% of the base case values. A value of 1.3 indicates that capital costs have been increased to 130% of the base case values and so forth.

Tube cost is estimated to increase linearly with increases in capital charges in the cases of both technologies. Recall from our base-case results shown in Fig. 6.1 that capital costs are estimated to contribute 14.6% of the total cost for extrusion compared to 12.3% for slip casting. As a result, tube cost, when extrusion is used, is more sensitive to changes in capital cost than is slip casting.

6.1.6. Total Yield vs. Tube Cost

Yield refers to the percentage of output at any process step that is acceptable for the next process step, or, in the case of the final process step, the percentage of output that passes final inspection. In our process-cost models, total yield is defined as the product of the individual process yields. Given this definition, and given that numerous process steps are involved, there are an infinite number of combinations of individual process-step yields that can result in any given total yield. To avoid this problem, we examine variations in total yield by varying the yield at the final process step -- i.e., inspection. The yields at all other process steps remain fixed.

Figure 6.5 illustrates the estimated relationship between total yield and tube cost. The cost of tubes decreases close to linearly with an increase in total process yield. For example, when inspection yield increases from 76% to 100% (i.e., total yield increases from 65% to 85%)

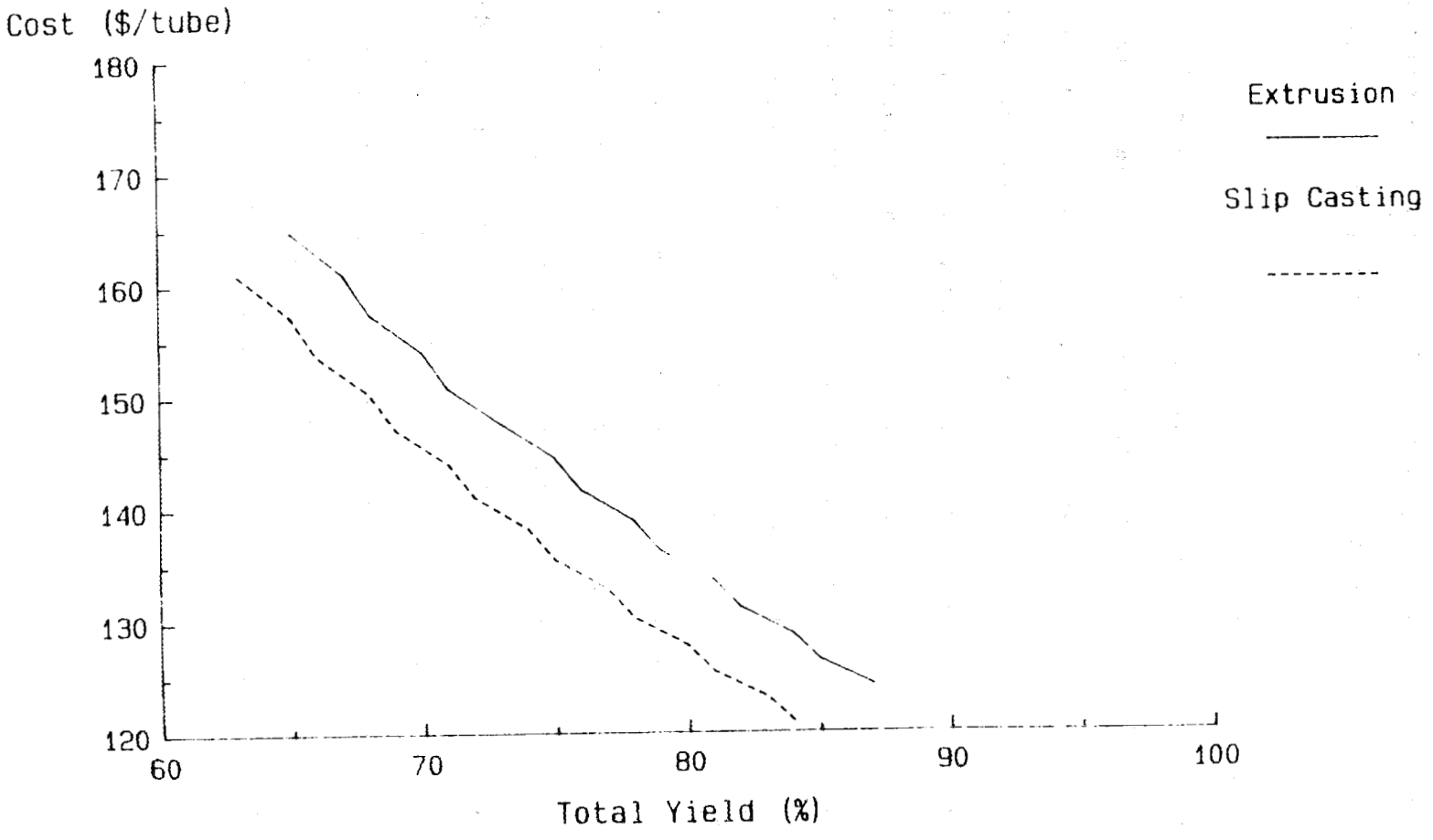

Fig. 6.5. The sensitivity of tube cost to changes in total yield

the cost of a tube decreases by about $40 for both slip casting and extrusion. The difference in tube cost between the two technologies is not sensitive to total yield.

6.1.7. Labor Cost vs. Tube Cost

Figure 6.6 illustrates the estimated relationship between labor cost and tube cost. The cost per tube is shown to increase linearly with increases in labor cost. For each $1 per hour increase in labor cost, tube cost is estimated to increase $1.29 and $1.22 for extrusion and slip casting, respectively. The increase in cost is greater in the case of extrusion because the materials preparation step is more labor intensive for the extrusion technology. The difference in tube cost between the two technologies is not particularly sensitive to changes in labor costs.

6.1.8. The Estimated Cost of Ceramic Headers

Recall from Section 4.1 that ceramic headers are depicted as a type of specialized tube. Further recall that ceramic headers can be produced only by the slip-casting method. Headers cannot be extruded.

Given our base-case assumptions, the cost of a ceramic header is estimated to be $119.12/ft^2. Since headers are assumed to be a specialized type of tube, the general conclusions drawn from the previous sensitivity analyses on the cost of tubes also applies to headers. See Section 4.1 for complete details about the methodology used to estimate the cost of headers.

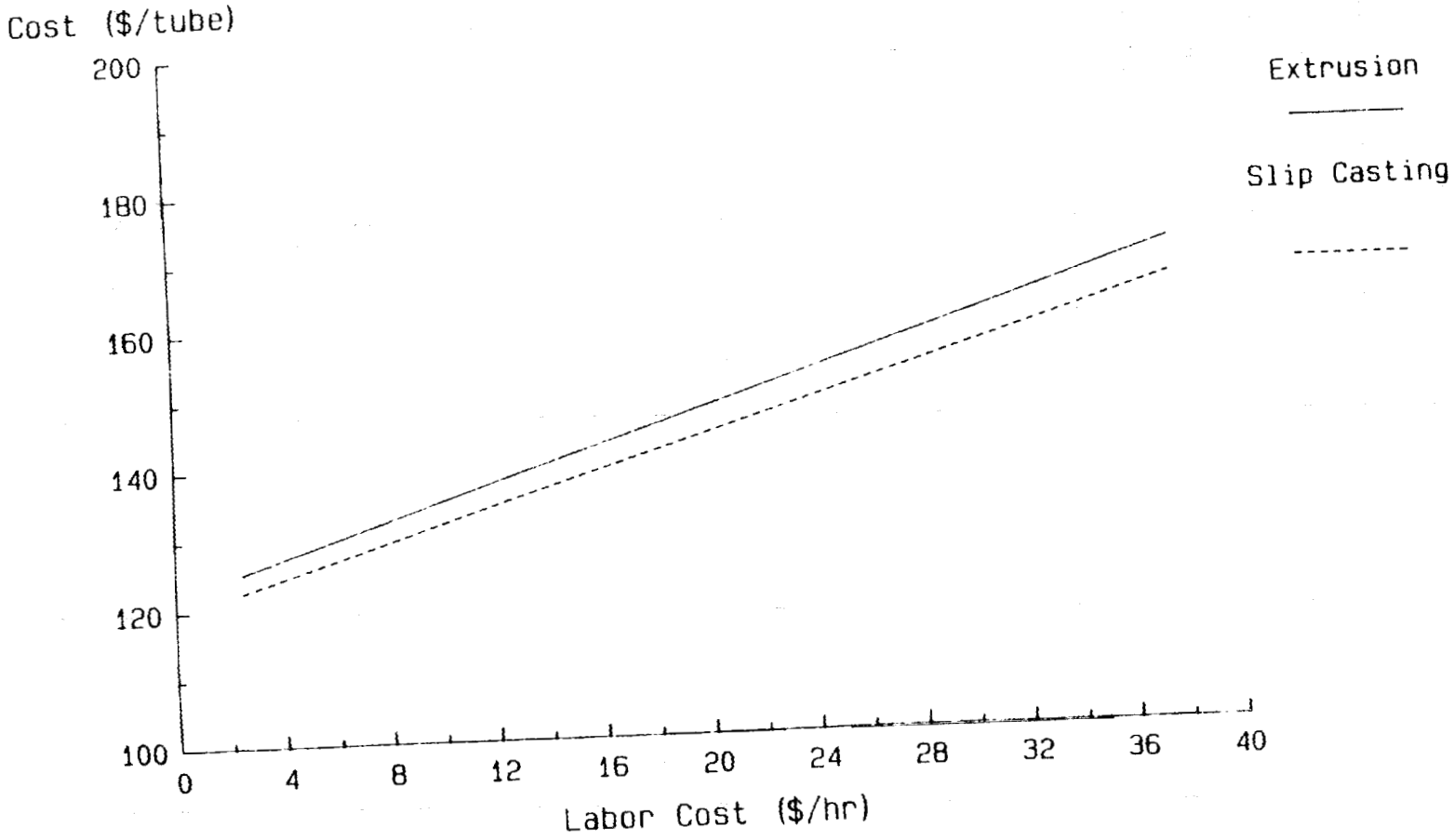

Fig. 6.6. The sensitivity of tube cost to changes in labor cost

6.2. THE ESTIMATED COST OF CERAMIC RECUPERATORS

Recall that we consider only tube-and-shell recuperators in which the tubes and in some cases headers are replaced by silicon carbide. In the case of slip casting, we consider recuperators in which the tubes alone are replaced, as well as units in which both the tubes and headers are replaced. In the case of extrusion, we consider only recuperators in which the tubes are replaced by ceramics, since extrusion cannot be used to manufacture headers.

6.2.1. Surface Area vs. Recuperator Cost

Recall that the cost of all types of recuperators considered in this analysis is based on surface area. The costs of the tubes and headers are taken from the base-case scenarios discussed above. Given our base-case assumptions, the estimated cost of a ceramic tube is \$139.47 (\$64.91/ft^2) for slip casting and \$135.99 (\$66.56/ft^2) for extrusion. The cost of a header, given our base-case assumptions, is \$119.12/ft^2.

Figure 6.7 illustrates the estimated relationship between surface area and the total cost of a fixed head, tube-and-shell recuperator. Our estimates suggest that the relationship between surface area and total cost is linear. Hall, Matley, and McNaughton (1982) have found similar results with respect to fixed-head and U-tube types of tube-and-shell heat exchangers.

For each square foot increase in recuperator size the total cost of the recuperator is estimated to increase as follows: (1) metallic: \$49.71; (2) ceramic (ceramic header: slip casting): \$85.42; (3) ceramic (metallic header: slip casting): \$74.61; and (4) ceramic (metallic

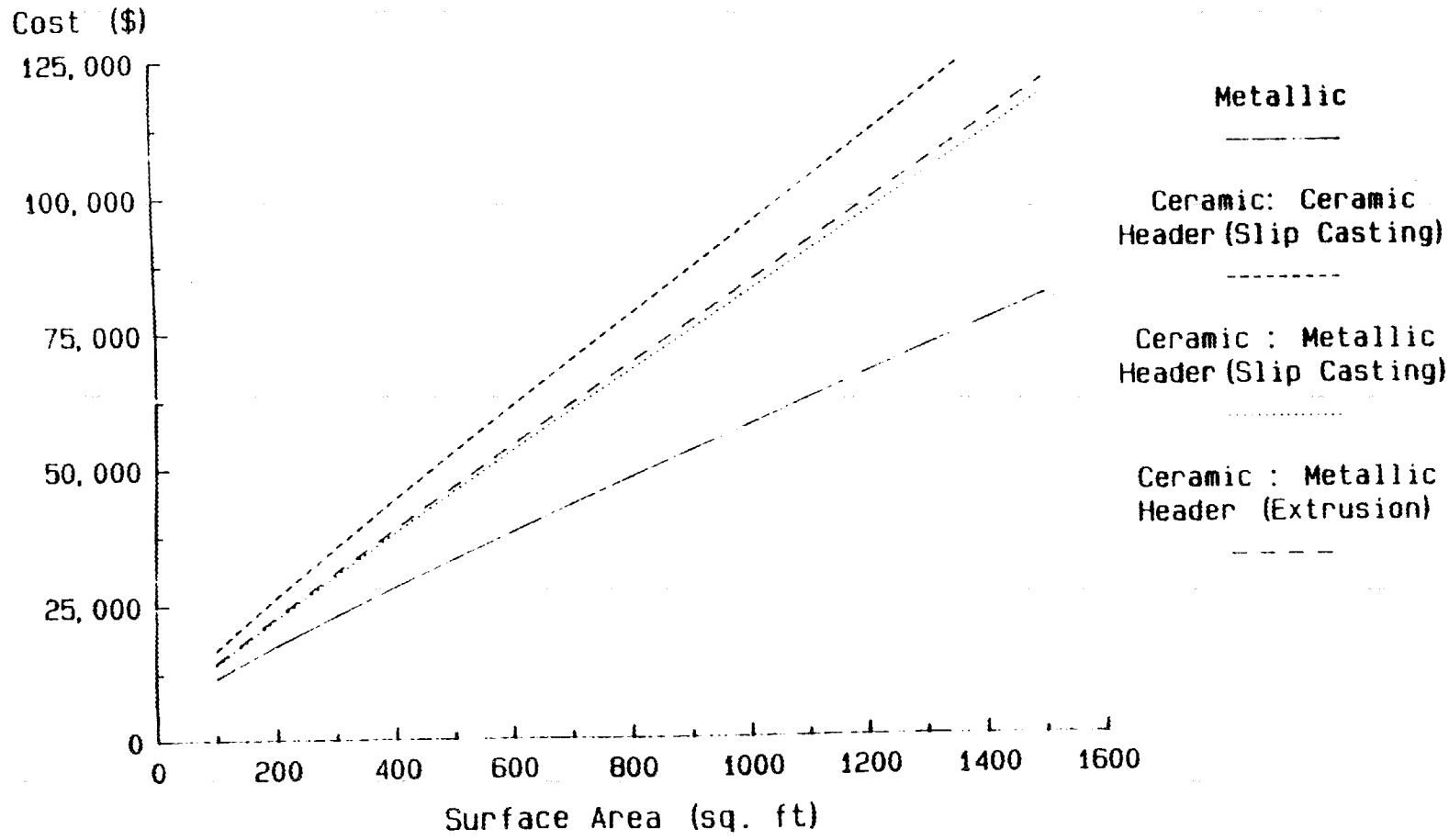

Fig. 6.7. The sensitivity of fixed head, tube-and-shell recuperator cost to changes in surface area

header: extrusion): $76.27. The cost curve is most sensitive to surface area when both tubes and headers are replaced by ceramics. The cost of a tube is about the same for both slip casting and extrusion in our base case. Therefore the estimated cost of a recuperator when only ceramic tubes are used is about the same when either slip casting or extrusion is used.

As is obvious from the figure, the replacement of metallic components with ceramic ones adds significantly to the total cost of the recuperator. When only the tubes are replaced, the cost of a heat exchanger goes up an estimated 21% for a 100 ft^2 unit and an estimated 46% for a 1,500 ft^2 unit. The addition of ceramic headers adds an additional 22% to the total cost of both sized heat exchangers. For example, the estimated cost of a 1,500 ft^2 metallic heat exchanger is $81,328, while the same sized unit with both ceramic tubes and headers is estimated to cost $136,380.

6.2.2. Surface Area vs. Contribution of Components to Total Cost

Figure 6.8 illustrates the estimated relationship between surface area and the contributions that specific system components make to the total cost of the heat exchanger. More specifically, six curves are given -- three for all metallic heat exchangers and three for ceramic heat exchangers in which both the tubes and headers are replaced by ceramics. The costs of both the all-metallic and ceramic units are disaggregated into tube cost, header cost, and other cost.

For both metallic and ceramic units, we find that as surface area increases, the percentage of total cost contributed by tubes increases at a decreasing rate. The percentage of total cost contributed by the other

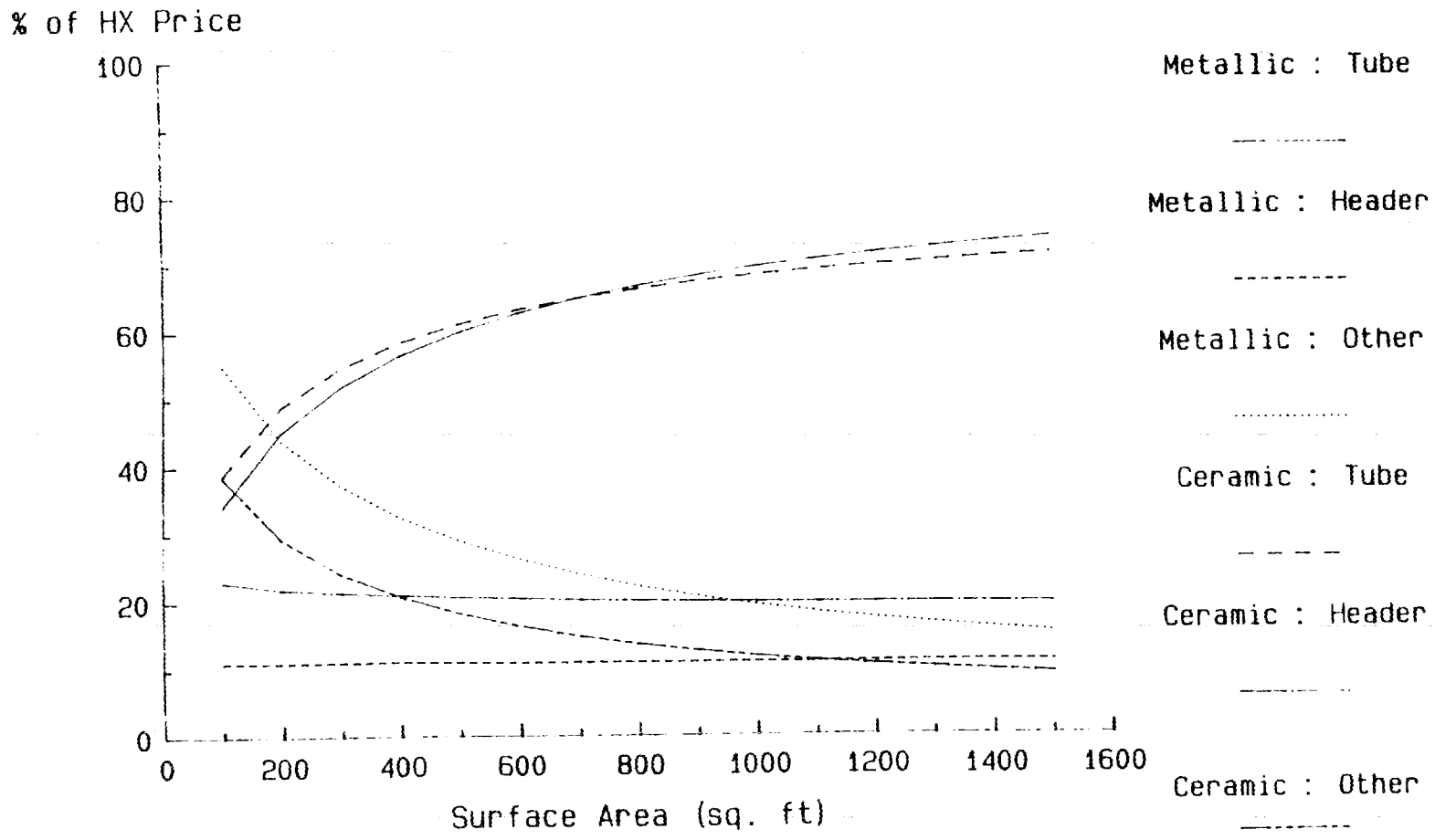

Fig. 6.8. The estimated relationship between surface area of the contribution of components to total cost

cost category is estimated to decrease at a decreasing rate when surface area is increased. In the case of a metallic heat exchanger, the share of total cost contributed by tubes increases from, for example, 34% to 74% when surface area is increased from 100 ft^2 to 1,500 ft^2. The other cost category is estimated to decrease from 55% to 15% for the same change in the metallic unit's surface area. The corresponding figures for a ceramic heat exchanger are 39% to 71% for tube cost and 38% to 9% for the other cost category. Headers are estimated to contribute a relatively constant percentage to total heat exchanger cost -- i.e., about 11% for metallic units and about 21% for ceramic units.

6.2.3. Surface Area vs. Recuperator Cost (Additional Runs)

Figure 6.9 gives some additional runs illustrating the estimated relationship between surface area and total recuperator cost. In this figure we consider only ceramic recuperators in which only the tubes have been replaced by ceramics.

From Figs. 6.7 and 6.9 we know that the estimated cost of a heat exchanger is about the same when either slip casting or extrusion is used. The difference between tube cost for the two technologies is only \$1.66 per ft^2. Figure 6.9 also shows how estimated costs increase when tube production volume is small -- i.e., 2,500 tubes/year compared to the base case of 25,000 tubes/year. More specifically, the cost of a heat exchanger is estimated to increase by 149% when production volume is decreased from the base case of 25,000 to 2,500 tubes per year. The base-case cost of a 1,500 ft^2 unit is \$121,175, while the cost of the same size units is estimated at \$301,813 when tube production is only 2,500 tubes/year. For each square foot increase in recuperator surface

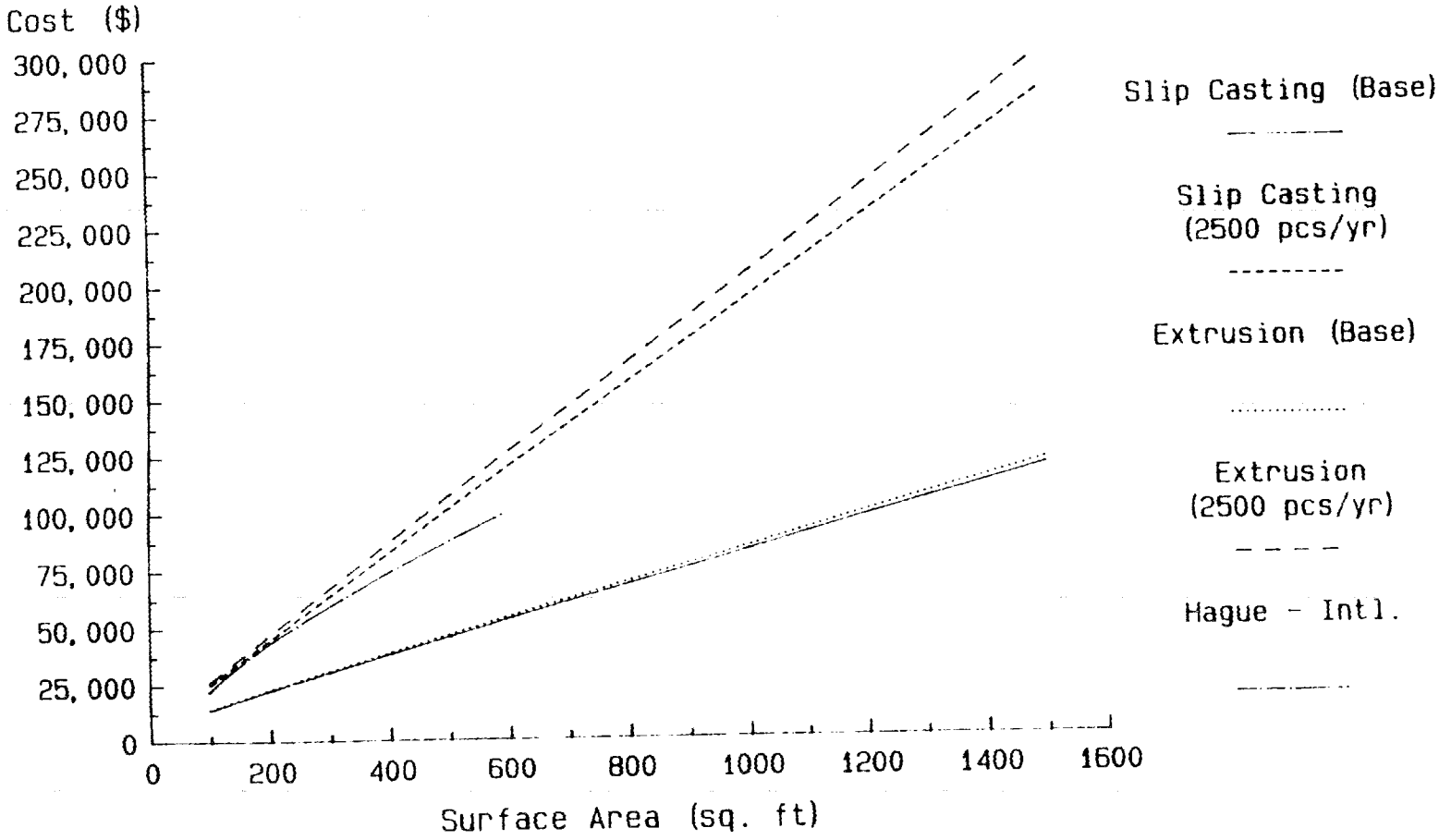

Fig. 6.9. The sensitivity of recuperator cost to changes in tube cost

area the total cost of the recuperator is estimated to increase as follows: (1) extrusion (base case):$76.27; (2) extrusion (2,500 tubes/year): $196.70; (3) slip casting (base case): $74.61; and (4) slip casting (2,500 tubes/year): $185.75.

As mentioned in Section 2 of this report, there are several companies that have manufactured various types of ceramic heat exchangers. Among these companies is Hague International, which currently manufactures a commercial, fixed-head, shell-and-tube type heat exchanger that contains tubes manufactured from silicon carbide. These units are two pass recuperators, where the combustion air is preheated in two passes -- the first pass being from the cold header through two rows of ceramic tubes, and the second pass being from the turnaround header through three rows of ceramic tubes to the hot or discharge header. Of the various ceramic heat exchangers currently being produced, the Hague International system is the closest to the hypothetical heat exchangers represented in this work. Figure 6.9 gives data obtained from Hague International on the cost of their heat exchangers. The current cost, for example, of a 590 ft^2 heat exchanger is $98,521. Note that the Hague International price quotes match our cost estimates closely when yearly production is only 2,500 tubes/year. The Hague International price quotes are somewhat higher than our base-case estimates.

6.2.4. Tube Cost vs. Recuperator Cost

It is possible that tube cost will decrease as the tube manufacturing technologies mature. A reduction in tube cost may result from improved process yields, reductions in powder and capital costs, and so forth. As was reported in Fig. 6.8, tube cost is estimated to

contribute in the range of 39% to 71% of the total cost of a ceramic heat exchanger. Figure 6.10 shows the estimated variation in the cost of a heat exchanger when tube cost is changed. Four different sized heat exchangers are considered -- i.e. surface areas of 250 ft^2, 500 ft^2, 1,000 ft^2, and 1,500 ft^2. The tube manufacturing technology assumed in this figure is slip casting, and both the heat exchanger's tubes and headers are assumed to be made of silicon carbide. The cost of the largest sized unit is estimated to be most sensitive to changes in tube cost.

6.2.5. Header Cost vs. Recuperator Cost

As discussed in Section 4.1, the cost of headers is expressed in terms of dollars per ft^2. Figure 6.11 illustrates the estimated relationship between total heat exchanger cost and the cost of the headers. Four sizes of heat exchangers are considered -- i.e., 250 ft^2, 500 ft^2, 1,000 ft^2, and 1,500 ft^2. The tube manufacturing technology assumed in this figure is slip casting and the ceramic heat exchanger's tubes and headers are both made from silicon carbide. As expected, the cost of a heat exchanger is less sensitive to header cost variations when compared to variations in tube cost. Recall that the header contributes only about 21% to total recuperator cost, whereas tubes contribute in the range of 35% to 75%. For each one dollar per ft^2 increase in header cost, the total costs of different sized units is estimated to increase as follows: (1) 250 ft^2: \$56; (2) 500 ft^2: \$92; (3) 1,000 ft^2: \$158; and (4) 1,500 ft^2: \$224. To illustrate, a reduction in header cost from \$385 per ft^2 to \$24 per ft^2 results in the estimated cost of a 1,000 ft^2 unit changing from \$132,638 to \$79,831 -- a reduction of about 40%.

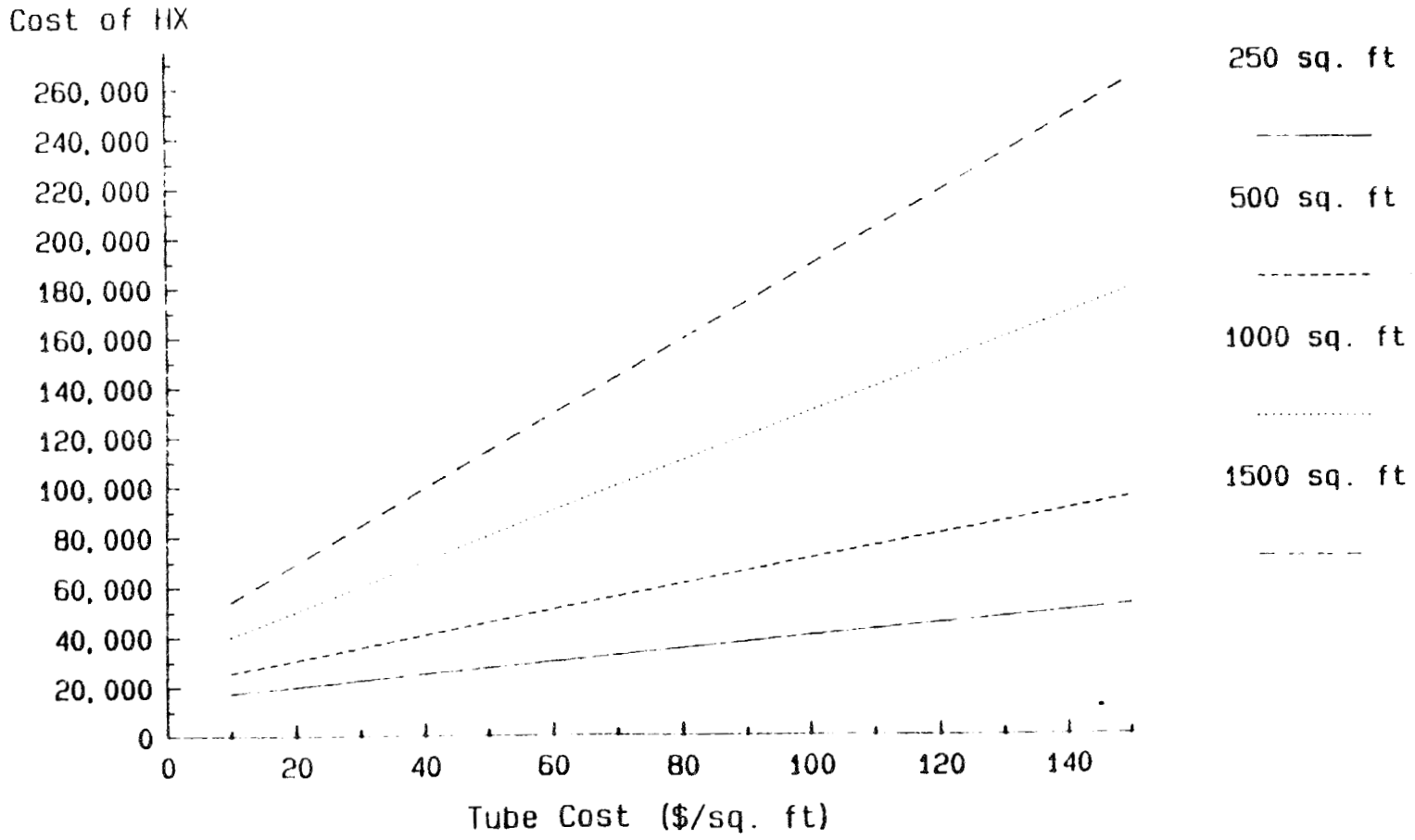

Fig. 6.10. The sensitivity of recuperator cost to changes in tube cost

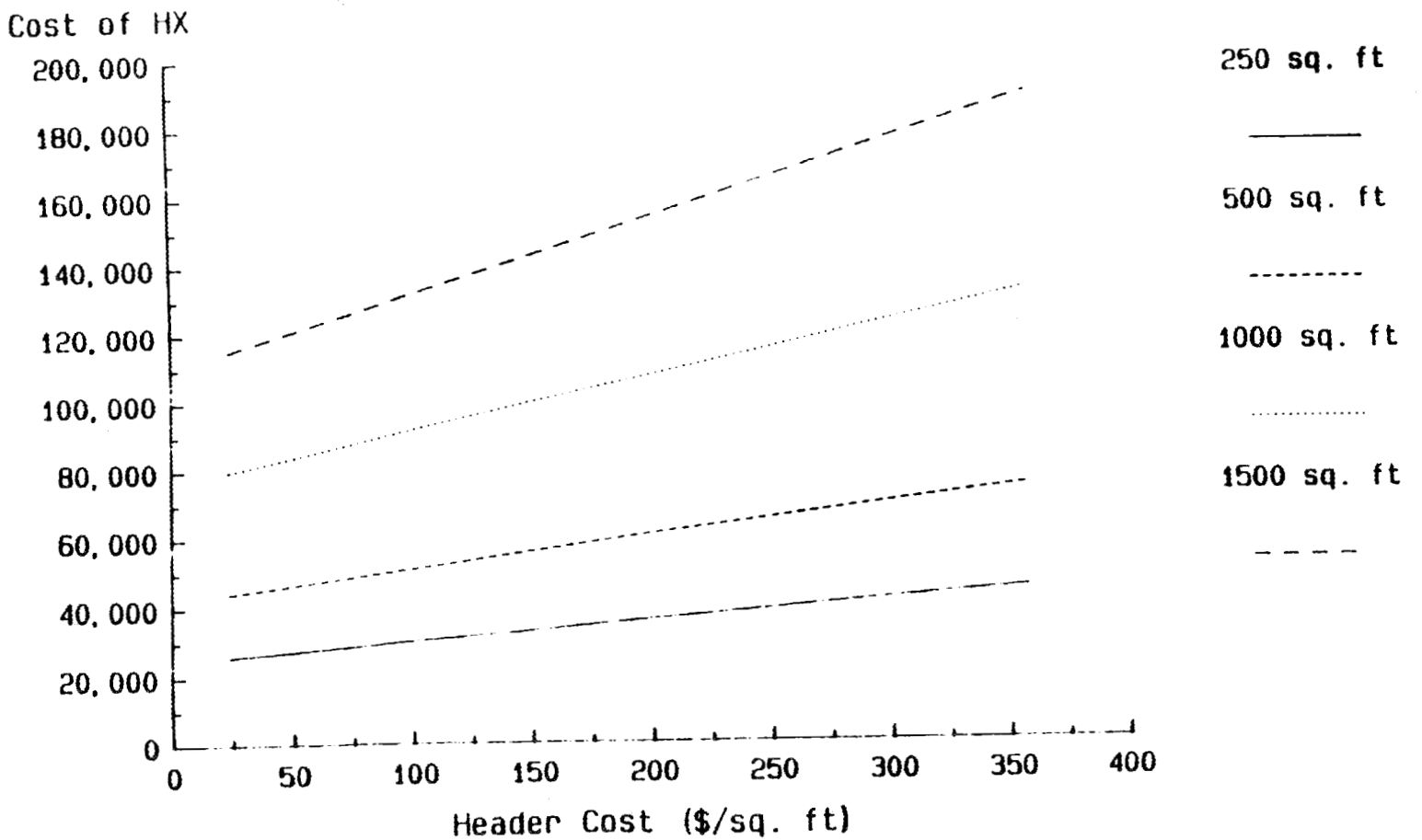

Fig. 6.11. The sensitivity of recuperator cost to changes in header cost

7. CONCLUSIONS

7.1. TUBE COST

The current major manufacturers of silicon carbide tube are Norton Company, Worcester, Massachusetts; Coors Porcelain Company, Golden, Colorado; and Standard Oil Company, Niagara Falls, New York. The first two companies mainly use slip-casting technology, while the third uses extrusion. For the type and size of tube considered in this assessment, the above companies give price quotes of between $250 and $350 per tube based on an order of 100 tubes. For quantities of 1,000 the price quote is about 10% less.

Our models predict a cost of about $700 per tube for a quantity of 1,000 tubes per year. However, this cost is artificially high for this production volume because we have assumed that total capital investment is dedicated only to the manufacture of tubes. This is obviously not the case with the above manufacturers. A more reasonable estimate of $/tube for comparison purposes is the estimated cost for 20,000 tubes per year or more -- i.e., the production levels at which the cost per tube flattens out. Our models estimate a cost of about $150/tube at a production volume of 20,000/year. With respect to which production technology -- i.e., slip casting or extrusion -- is the least costly, our analysis does not suggest a clear winner. Although extrusion requires more materials preparation and is more capital intensive at the extrusion step, extrusion's yield is higher than slip casting. Our sensitivity analyses suggest several conclusions. First, tube cost is sensitive to production volumes at low levels -- i.e., less than 20,000 tubes per year

-- but flattens out at higher production levels. Second, tube cost is quite sensitive to powder cost, given that materials contribute about 55% to 60% of the total cost of a tube. The cost of a tube is estimated to vary from $85 to $340 per tube when the cost of powder varies from $2.50/lb. to $37.50/lb., respectively. Third, the cost of capital can have a significant impact on tube cost, especially in the case of extrusion, which is more capital intensive than slip casting. Fourth, improvements in total yield can substantially reduce the cost of a tube. Tube cost is estimated to decrease by $40/tube when total yield is increased from 65% to 85%. Finally, while tube cost is sensitive to changes in labor cost, the sensitivity is not as great as with other economic parameters or technical factors.

7.2. TOTAL RECUPERATOR COST

The primary conclusion of this report is that the cost of a ceramic heat exchanger is estimated to be significantly higher than a comparably sized all-metallic heat exchanger. For example, it is estimated that a 1,500 ft^2 ceramic recuperator, in which both the tubes and headers are replaced by silicon carbide, will cost about $55,000 more than a comparably sized all-metallic recuperator. In percentage terms, the ceramic unit is estimated to cost about 68% more than the corresponding metallic unit. If we keep the size of the recuperator constant, do not replace the metallic headers, and replace only the tubes with silicon carbide, the estimated cost of the ceramic unit is an estimated $37,356 higher than the metallic unit -- about a 46% cost increase when compared to the metallic unit.

There is, unfortunately, very little real-world data against which these estimates can be compared. Of the current ceramic recuperators being manufactured, the Hague International design is the closest to the hypothetical recuperators depicted in this work. When compared to data obtained from Hague International on the costs of their units, the estimates from our models are not unreasonable. In fact, when the yearly production volume for ceramic tubes is decreased from our base case of 25,000 tubes/year to 2,500 tubes/year, the cost estimates from our model are quite similar to the Hague International price quotes.

7.3. FINAL CONCLUSIONS

Given that ceramic recuperators are estimated to cost more than all-metallic recuperators, the economic viability of ceramic recuperators will turn on the marginal benefits of the ceramic units as compared to the less expensive all-metallic units. An assessment of those potential benefits and thus an assessment of the overall economic viability of ceramic recuperators awaits future work. For now, the conclusions presented here suggest what those marginal benefits must be in the minimum for ceramic recuperators to be an attractive alternative to metallic units. In addition, the sensitivity analyses from this study suggest how specific improvements in key technical and economic parameters might lessen the costs of ceramic heat exchangers and thus make those heat exchangers more economically viable.

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APPENDIX A

MODEL PRINTOUTS FROM THE SLIP-CASTING AND EXTRUSION PROCESS-COST MODELS

SLIP CASTING MODEL

FACTOR PRICES

	units	$/unit
==========> ENERGY		
Electricity	Kwh*	$0.0525
Natural Gas	Mbtu	$6.50

	units	$/unit
==========> MATERIALS		
CHOOSE MATERIAL BY NUMBER ====>	2	$10.00
1. SiC Standard Powder	lbs	$1.32
* Used Here Only* 2. SiC Submicron powder	lbs	$10.00
3. Alumina Standard Powder	lbs	$0.86
4.Alumina Submicron Powder	lbs	$11.00
5. Silicon Nitride Powder	lbs	$20.00
Water	gals	$0.01
Binders	gals	$0.85
Diamond Tool Inserts		$7.00
Air	lbs	$0.0001
Ware Support	lbs	$1.00
Inert Gas Atmosphere	lbs	$0.16
Slip Casting Molds	1	$20.00
Vacuum Casting Molds	1	$10.00
		$20.00
Ball Milling Material and Liners	lbs	$0.66
For Hipping : Glass Encapsulation	lbs	$0.20
==========> OTHERS		
Labor ($/man-hour)		$13.50
Cost of Capital (% of initial investment)		12.0%
Tax Burden (% of operating expenses)		1.2%
Insurance (% of physical plant)		1.0%
Maintenance (% of physical plant)		6.0%
Years to Recover Investment		10
Equipment Scaling Factor		0.3

INPUT FACTORS

Plant Capacity (pieces/yr)		25000
Max. Plant Capacity (pieces/yr)		250000
Working Days	days/yr	250
# of Shifts	#/day	3
Molding Stations	#	400
Time To Run Part	hrs	2500.0
Fraction of Total Time		41.67%

Green Density	gm/cc	2.08
Part Weight	lbs	5.59
Percent Water		40%
Percent Binder and Deffloculants		3%
Mold Life	pieces	50
Pressure Mold Life	pieces	10000
		50
Initial Particle Size	microns	1
Final Particle Size	microns	1
SiC Work Index		26.17
Alumina Work Index		17.19
VOLUMES		

==========

Volume of Parts		25000
Choose Standard or Vacuum Casting (1,2) =>	1	120
		2
1. Standard Cycle Time	Minutes	120
2. Vacuum Cycle Time	Minutes	12
1. Standard Cycles/shift		2
2. Vacuum Cycles/shift		9
Mixing	lb/hr	746.4
Mixing Time	hrs	12
Lathe (hand operated)	parts/hr	12
Lathe CNC (complex geometry,)	parts/hr	25
Lathe CNC (simple geometry)	parts/hr	8
Inspection	parts/hr	20
Choose Geometry Factor (1=simple, 2=complex) =>		1

ASSUMED PROCESS YIELDS

Material Preparation	75%	96%
Slip Casting	78%	98%
Green Machining	80%	100%
Drying	80%	95%
Sintering	84%	98%
Grinding	86%	95%
Inspection	90%	90%
Total Yield		75%

Note: Ist column values indicate overall yields till that process step
IInd column values indicate yields at that individual step

INPUT FACTORS

==========

DRYING PARAMETERS

Batch Weight	lbs	186
Weight of Ware Support	lbs	745
Specific Heat		0.25
Water Weight (%)		20%
Relative Humidity Entrance		70%

Slip Casting Model

MATERIAL PREPARATION

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Mixers lbs/hr	12	$5,012	$60,142
Pumping Equipment lbs/hr	2	$4,511	$9,021
Ball Mills	4	$501	$2,005
Materials Handling Equipment	1	$6,014	$6,014
		Total ($/plant) =>	$77,183

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Powder	7.46	$10.00	$74.64	$13.35
Water	2.986	$0.01	$0.030	$0.01
Binder	0.224	$0.85	$0.190	$0.03
Milling Media	0.000	$0.66	$0.000	$0.00
Mill Liner	0.000	$0.66	$0.000	$0.00
	Total =>		$74.86	$13.39

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for blending(kwh)	0.007	$0.0525	$0.000	$0.000
Electricity for milling(kwh)	0.000	$0.0525	$0.000	$0.000
		Total =>	$0.000	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.010	$13.50	$0.14	$0.02
Capital Charges		12.0%	$0.73	$0.13
Taxes		1.2%	$0.05	$0.01
Insurance		1.0%	$0.04	$0.01
Maintenance		6.0%	$0.25	$0.04
		Total =>	$1.20	$0.22

==========>COST OF MATERIALS PREPARATION	=>	$76.07	$13.61

COST DISTRIBUTION

	Materials	$74.86	98%
	Energy	$0.00	0%
	Labor	$0.14	0%
Slip Casting Model	Charges	$0.73	1%
	Other	$0.34	0%

MATERIAL PREPARATION

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Mixers lbs/hr	12	$5,012	$60,142
Pumping Equipment lbs/hr	2	$4,511	$9,021
Ball Mills	4	$501	$2,005
Materials Handling Equipment	1	$6,014	$6,014
		Total ($/plant) =>	$77,183

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Powder	7.46	$10.00	$74.64	$13.35
Water	2.986	$0.01	$0.030	$0.01
Binder	0.224	$0.85	$0.190	$0.03
Milling Media	0.000	$0.66	$0.000	$0.00
Mill Liner	0.000	$0.66	$0.000	$0.00
	Total =>		$74.86	$13.39

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for blending(kwh)	0.007	$0.0525	$0.000	$0.000
Electricity for milling(kwh)	0.000	$0.0525	$0.000	$0.000
		Total =>	$0.000	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.010	$13.50	$0.14	$0.02
Capital Charges		12.0%	$0.73	$0.13
Taxes		1.2%	$0.05	$0.01
Insurance		1.0%	$0.04	$0.01
Maintenance		6.0%	$0.25	$0.04
		Total =>	$1.20	$0.22

==========>COST OF MATERIALS PREPARATION => $76.07 $13.61

COST DISTRIBUTION

	Materials	$74.86	98%
	Energy	$0.00	0%
	Labor	$0.14	0%
Slip Casting Model	Charges	$0.73	1%
	Other	$0.34	0%

CASTING

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Benches and Jigs	1	$1,253	$1,253
Pumping Equipment lbs/hr	5	$4,511	$22,553
Materials Handling Equipment	1	$7,518	$7,518
		Total ($/plant) =>	$31,324

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Prepared Slurry	1.28		$76.07	$13.61
Mold	0.026	$20.00	$0.51	$0.09
Total =>			$76.58	$13.70

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for pumping(kwh)	0.011	$0.0525	$0.001	$0.000
		Total =>	$0.001	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.008	$13.50	$0.11	$0.02
Capital Charges		12.0%	$0.28	$0.05
Taxes		1.2%	$0.02	$0.00
Insurance		1.0%	$0.02	$0.00
Maintenance		6.0%	$0.10	$0.02
		Total =>	$0.52	$0.09

==========>COST OF CASTING	=>	$1.04	$0.19
==========>COST AFTER CASTING	=>	$77.11	$13.79

COST DISTRIBUTION

	Materials	$75.38	98%
	Energy	$0.00	0%
	Labor	$0.24	0%
Slip Casting Model	Charges	$1.01	1%
	Other	$0.47	1%

GREEN MACHINING

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Lathe (hand operated)	1	$15,036	$0
CNC Lathe (programed)	2	$25,059	$0
Materials Handling Equipment	1	$7,518	$0
		Total ($/plant) =>	$0

Note: A value of "zero" for ($/plant) indicates process not being used.

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Cast Part	1.26		$77.11	$13.79
Tool Inserts (300 parts/tool)	0.004	$7.00	$0.00	$0.00
Total =>			$77.11	$13.79

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for machine(kwh)	0.527	$0.0525	$0.000	$0.000
		Total =>	$0.000	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.283	$13.50	$0.00	$0.00
Capital Charges		12.0%	$0.00	$0.00
Taxes		1.2%	$0.00	$0.00
Insurance		1.0%	$0.00	$0.00
Maintenance		6.0%	$0.00	$0.00
		Total =>	$0.00	$0.00

==========>COST OF GREEN MACHINING	=>	$0.00	$0.00
==========>COST AFTER GREEN MACHINING	=>	$77.11	$13.79

COST DISTRIBUTION

	Materials	$75.38	98%
	Energy	$0.00	0%
	Labor	$0.24	0%
Slip Casting Model	Charges	$1.01	1%
	Other	$0.47	1%

INDIRECT HEATED DRYER 2 only with firing option 2

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Drier and System	4	$37,589	$150,356
Materials Handling Equipment	4	$6,014	$24,057
		Total ($/plant) =>	$174,413

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Part After Green Machining	1.26		$77.11	$13.79
Air	35.1	$0.000	$0.004	$0.00
Ware Support (1 year life)	0.0016	$1.00	$0.002	$0.00
Total =>			$77.11	$13.79

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Energy to Heat Insulation (Btu)	1414	$0.00001	$0.0092	$0.002
To Evaporate Water (Btu)	21528	$0.00001	$0.1399	$0.025
To Heat Part (Btu)	1659	$0.00001	$0.0108	$0.002
To Heat Batch Support (Btu)	6636	$0.00001	$0.0431	$0.008
To Heat Incoming Air (Btu)	199	$0.00001	$0.0013	$0.000
To Heat Water in Incoming Air (Btu)	10618	$0.00001	$0.0690	$0.012
Soaking Heat (Btu)	72093	$0.00001	$0.4686	$0.084
Total Using Assumed Drying Efficiency		=>	$1.2366	$0.221

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.452	$13.50	$6.11	$1.09
Capital Charges		12.0%	$1.55	$0.28
Taxes		1.2%	$0.11	$0.02
Insurance		1.0%	$0.09	$0.02
Maintenance		6.0%	$0.53	$0.09
		Total =>	$8.38	$1.50

==========>COST OF DRYING	=>	$9.62	$1.72
==========>COST AFTER DRYING	=>	$86.72	$15.51

COST DISTRIBUTION

	Materials	$75.38	87%
	Energy	$1.24	1%
	Labor	$6.35	7%
Slip Casting Model	Charges	$2.57	3%
	Other	$1.19	1%

```
+-------------------------------------------------------------------+
 DIRECT HEATED DRYER   1          with firing option 1
+-------------------------------------------------------------------+

==========> EQUIPMENT                  UNITS   $/UNIT   $/plant
                                     ---------------------------
                   Drier and System        4  $37,589       $0
      Materials Handling Equipment         4   $6,014       $0
                                                       =========
                                     Total ($/plant) =>      $0

Note : A value of "zero" for ($/plant) indicates process not being used.

==========> PROCESS MATERIALS          UNITS   $/UNIT   $/piece   $/lb
                                     ------------------------------------
         Part After Green Machining     1.26             $0.00    $0.00
                               Air      35.1  $0.0001   $0.000   $0.000
                                                      ==================
                                     Total  =>          $0.00    $0.00

==========> ENERGY                     UNITS   $/UNIT   $/piece   $/lb
                                     ------------------------------------
    Energy to Heat Insulation (Btu)     1414 $0.00001   $0.000   $0.000
           To Evaporate Water (Btu)    21528 $0.00001   $0.000   $0.000
                  To Heat Part (Btu)    1659 $0.00001   $0.000   $0.000
        To Heat Batch Support (Btu)     6636 $0.00001   $0.000   $0.000
                  Soaking Heat (Btu)   72093 $0.00001   $0.000   $0.000
                                                      ==================
Total Using Assumed Drying Efficiency                =>  $0.0000   $0.000

==========> OTHERS                                     $/piece   $/lb
                                                     -------------------
           Direct Labor (man-hours)    0.452   $13.50    $0.00    $0.00
                     Capital Charges               12.0%   $0.00    $0.00
                               Taxes                1.2%   $0.00    $0.00
                           Insurance                1.0%   $0.00    $0.00
                         Maintenance                6.0%   $0.00    $0.00
                                                      ==================
                                               Total =>    $0.00    $0.00

==========>COST OF DRYING                            =>    $0.00    $0.00

==========>COST AFTER DRYING                         =>    $0.00    $0.00

                   COST DISTRIBUTION

                              Materials                    $0.00        0%
                                 Energy                    $0.00        0%
                                  Labor                    $0.00        0%
 Slip Casting Model             Charges                    $0.00        0%
                                  Other                    $0.00        0%
```

FIRING - TUNNEL KILN 2 with firing option 2

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Tunnel Kiln with Cars	3	$451,069	1.35E+06
Materials Handling Equipment	3	$50,119	1.50E+05
Total ($/plant) =>			1.50E+06

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Part After Drying	1.19		$86.72	$15.51
Air	33.36	$0.0001	$0.003	$0.00
Inert Gas Atmosphere	33.36	$0.16	$5.337	$0.95
Total =>			$92.06	$16.47

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Energy to Heat Insulation (Kwh)	2	$0.05250	$0.1020	$0.018
To Heat Part (Kwh)	2	$0.05250	$0.105	$0.019
To Heat Batch Support (Kwh)	8	$0.05250	$0.419	$0.075
Soaking Heat (Kwh)	87	$0.05250	$4.551	$0.814
Total Using Assumed Firing Efficiency =>			$8.6281	$1.543

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.430	$13.50	$5.80	$1.04
Capital Charges		12.0%	$12.70	$2.27
Taxes		1.2%	$0.86	$0.15
Insurance		1.0%	$0.72	$0.13
Maintenance		12.0%	$8.61	$1.54
		Total =>	$28.70	$5.13

==========>COST OF FIRING =>		$42.66	$7.63
==========>COST AFTER FIRING =>		$129.39	$23.15

COST DISTRIBUTION

	Materials	$80.72	62%
	Energy	$9.87	8%
	Labor	$12.15	9%
Slip Casting Model	Charges	$15.27	12%
	Other	$11.38	9%

FIRING - PERIODIC 1

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Periodic Kiln	10	$87,708	$0
Materials Handling Equipment	10	$12,530	$0
		Total ($/plant) =>	$0

Note: A value of "zero" for ($/plant) indicates process not being used.

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Part After Drying	1.19		$0.00	$0.00
Air	33.36	$0.0001	$0.000	$0.00
Inert Gas Atmosphere	33.36	$0.16	$0.000	$0.00
	Total =>		$0.00	$0.00

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Energy to Heat Insulation (Kwh)	2	$0.05250	$0.0000	$0.000
To Heat Part (Kwh)	2	$0.05250	$0.0000	$0.000
To Heat Batch Support (Kwh)	8	$0.05250	$0.0000	$0.000
Soaking Heat (Kwh)	87	$0.05250	$0.0000	$0.000
Total Using Assumed Firing Efficiency		=>	$0.000	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.430	$13.50	$0.00	$0.00
Capital Charges		12.0%	$0.00	$0.00
Taxes		1.2%	$0.00	$0.00
Insurance		1.0%	$0.00	$0.00
Maintenance		6.0%	$0.00	$0.00
		Total =>	$0.00	$0.00

==========>COST OF FIRING	=>	$0.00	$0.00
==========>COST AFTER FIRING	=>	$0.00	$0.00

COST DISTRIBUTION

	Materials	$0.00	0%
	Energy	$0.00	0%
	Labor	$0.00	0%
Slip Casting Model	Charges	$0.00	0%
	Other	$0.00	0%

MACHINE SHOP

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Lathes	2	$51,006	$102,012
Special Chucks	2	$1,386	$2,772
Tooling Crane	1	$4,158	$4,158
Benches and Cabinet	1	$346	$346
Miscellaneous Tools	1	$2,772	$2,772
		Total ($/plant) =>	1.12E+05

====> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Fired Part	1.17		$129.39	$23.15
Coolant	0.01	$0.01	$0.00	$0.00
Total =>			$129.39	$23.15

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	1.402	$0.0525	$0.07	$0.01
		Total =>	$0.074	$0.01

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.263	$13.50	$3.55	$0.64
Capital Charges		12.0%	$0.93	$0.17
Taxes		1.2%	$0.06	$0.01
Insurance		1.0%	$0.05	$0.01
Maintenance		6.0%	$0.31	$0.06
		Total =>	$4.91	$0.88

==========>COST OF MACHINING	=>	$4.98	$0.89
==========>COST AFTER MACHINING	=>	$134.37	$24.04

COST DISTRIBUTION

	Materials	$80.72	60%
	Energy	$9.94	7%
	Labor	$15.70	12%
Slip Casting Model	Charges	$16.20	12%
	Other	$11.81	9%

QUALITY CONTROL AND STORAGE

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Ultrasonic Testers			
Special Tables, Jigs, and Other Miscellaneous Equipment	5	$12,530	6.26E+04
Storage Racks(30discs/rack)	5	$2,506	$12,530
		Total ($/plant) =>	7.52E+04

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Machined Parts	1.11		$134.37	$24.04
Total =>			$134.37	$24.04

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	0.052	$0.0525	$0.003	$0.000
		Total =>	$0.003	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.056	$13.50	$0.75	$0.13
Capital Charges		12.0%	$0.59	$0.11
Taxes		1.2%	$0.04	$0.01
Insurance		1.0%	$0.03	$0.01
Maintenance		6.0%	$0.20	$0.04
		Total =>	$1.62	$0.29

==========>COST OF QUALITY CONTROL	=>	$1.62	$0.29
==========>COST AFTER QUALITY CONTROL	=>	$135.99	$24.33

COST DISTRIBUTION

	Materials	$80.72	59%
	Energy	$9.94	7%
	Labor	$16.45	12%
Slip Casting Model	Charges	$16.79	12%
	Other	$12.08	9%

TOTALS

==========> PROCESS

	$/piece	percent
Material Preparation	$76.07	55.94%
Isopressing	$1.04	0.76%
Green Machining	$0.00	0.00%
Drying	$9.62	7.07%
Firing	$42.66	31.37%
Finishing	$4.98	3.67%
Inspection	$1.62	1.19%
Total =>	$135.99	100.00%

==========> PROCESS COSTS

	$/piece	$/lb	Percent
Materials	$80.72	$14.44	59.4%
Energy	$9.94	$1.78	7.3%
Labor	$16.45	$2.94	12.1%
Capital Charges	$16.79	$3.00	12.3%
Other	$12.08	$2.16	8.9%
Total ========>	$135.99	$24.33	

==========> MATERIALS COST BREAKDOWN

	$/piece	$/lb	Percent
Ceramic Powder Cost	$74.64	$13.35	54.9%
Process Material Costs	$6.08	$1.09	4.5%

========> ASSUMPTIONS

POWDER COST ($/lb)	$10.00
PERCENT BINDER + WATER	43%
PLANT CAPACITY (pc/yr)	2.50E+04
BINDER BURNOUT TIME (hr)	24
FIRING TEMPERATURE (F)	4172
FIRING METHOD	2
TOTAL YIELD	75%

Slip Casting Model

```
+-------------------------------------------------------------+
Cost of A Heat Exchanger
+-------------------------------------------------------------+

CHOOSE SHELL-AND-TUBE HEAT EXCHANGER TYPE====>                1
      1. FIXED-HEAD TYPE
CE Fabricated Equipment Cost Index (Ist Qtr '79)          252.5
CE Fabricated Equipment Cost Index (Jun '87)              317.8
Cost of Metallic (Inconel 600) Tube ($/sq.ft)            $40.00
Cost of Silicon Carbide Tube ($/sq.ft)                   $64.90
Percent Metallic Header Cost                                 11%
Surface Area of Heat Exchanger (sq. ft)                     200


Cost of Metallic Heat Exchanger (Inconel 600)           $17,704
Cost of Tube                                             $8,000
Cost of Header                                           $1,947
Cost of Other                                            $7,757

Cost of Ceramic Heat Exchanger                          $26,537
Cost of Tube                                            $12,981
Cost of Header            Ceramic: on=1            1    $5,800
Cost of Other                                            $7,757
```

Slip Casting Model

EXTRUSION MODEL

FACTOR PRICES

==========> ENERGY	units	$/unit
Electricity	Kwh*	$0.0525
Natural Gas	Mbtu	$6.50

==========> MATERIALS	units	$/unit
CHOOSE MATERIAL NUMBER ====>	2	$10.00
1. SiC Standard Powder	lbs	$1.32
* Only Used * 2. SiC Submicron powder	lbs	$10.00
3. Alumina Standard Powder	lbs	$0.28
4.Alumina Submicron Powder	lbs	$11.00
Water	gals	$0.01
Binders	gals	$0.85
Diamond Tool Inserts		$7.00
Extrusion Die (8" dia)		$500.00
Extrusion Die (6" dia)		$450.00
Extrusion Die (2" dia)		$250.00
Air	lbs	$0.0001
Ware Support	lbs	$1.00
Inert Gas Atmosphere	lbs	$0.16

==========> OTHERS	
Labor ($/man-hour)	$13.50
Cost of Capital (% of initial investment)	12.0%
Tax Burden (% of operating expenses)	1.2%
Insurance (% of physical plant)	1.0%
Maintenance (% of physical plant)	6.0%
Years to Recover Investment	10
Equipment Scaling Factor	0.3

INPUT FACTORS

Plant Capacity (pcs/yr)		25000	
Max. Plant Capacity (pcs/yr)		250000	
Working Time	days/yr	250	
Shifts	#/day	3	
Time For Run	hrs,yrs	2500.00	0.07
Fraction of Total Time	extrude	41.67%	
	fire	558.63%	
Part Weight	lbs	5.59	
Part Outer Diameter	inches	2	
Part Inner Diameter	inches	1.625	
Part Length	inches	48	
Part Volume	cu in	51.25	

Percent Water		18%
Percent Binder		3%
Part Green Density	gm/cc	1.96
Green Density as a % of Final Density	%	0.65
Final Density	gm/cc	3.02
Die Life	inches	100000

VOLUMES

Volume of Parts		25000
Mixing	lb/hr	72
Extruder	in/min	8
Green Machining Rate	parts/hr	45
Lathe CNC (tooled, tolerance .04in)	parts/hr	8
Inspection	parts/hr	20

ASSUMED PROCESS YIELDS

Material Usage	77%	96%
Extrusion	80%	98%
Green Machining	82%	100%
Drying	82%	98%
Sintering	84%	98%
Grinding	86%	95%
Inspection	90%	90%
Total Yield		77%

Note: Ist column values indicate overall yields till that process step.
IInd column values indicate yields at the individual process step.

OPTIONAL STAGES (off=0/on=1)

Green Machining	0	0
Final Finishing	1	1

INPUT FACTORS

DRYING PARAMETERS

Batch Weight	lbs	186
Weight of Ware Support	lbs	745
Specific Heat		0.25
Water Weight (%)		20%
Relative Humidity Entrance		70%
Entrance Air Temperature	F	1022
Exit Air Temperature	F	77
Drying Heat Efficiency		60%
Lb Water/Lb Air Entrance		0.04
Lb Water/Lb Air Exit		0.01
Drying Time	hrs	24

Extrusion Model

FIRING PARAMETERS

Cycle Time	hrs	24
Firing Temperature	F	4172
Ambient Temperature	F	89.6
Firing Heat Efficiency (Tunnel)		60%
Firing Heat Efficiency (Periodic)		40%
CHOOSE FIRING METHOD ====>	1	1

1. Continuous
2. Periodic

MACHINING COST AS A FUNCTION OF TOLERANCE

INPUT TOLERANCE HERE (#)=====>	3	80%

	in	mm	increase %
1.	0.02	0.508	20%
2.	0.01	0.254	40%
3.	0.005	0.127	80%
4.	0.002	0.051	140%
5.	0.001	0.025	200%
6.	0.0005	0.013	360%

MATERIAL PREPARATION

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Mixers lbs/hr	12	$5,012	$60,142
Pumping Equipment lbs/hr	2	$4,511	$9,021
Other	2	$251	$501
Materials Handling Equipment	1	$7,518	$7,518
	Total ($/plant) =>		$77,183

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Powder	7.23	$10.00	$72.31	$12.94
Water	1.302	$0.01	$0.013	$0.00
Binder	0.217	$0.85	$0.184	$0.03
	Total =>		$72.51	$12.98

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for blending(kwh)	0.186	$0.0525	$0.010	$0.002
		Total =>	$0.010	$0.002

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.100	$13.50	$1.35	$0.24
Capital Charges		12.0%	$0.71	$0.13
Taxes		1.2%	$0.05	$0.01
Insurance		1.0%	$0.04	$0.01
Maintenance		6.0%	$0.24	$0.04
		Total =>	$2.38	$0.43

==========>COST OF MATERIALS PREPARATION	=>	$74.90	$13.41

COST DISTRIBUTION

Materials	$72.51	97%
Energy	$0.01	0%
Labor	$1.35	2%
Capital Charges	$0.71	1%
Other	$0.33	0%

EXTRUDING

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Extruder - 120 ton	6	$60,142	$360,855
Pumping Equipment lbs/hr	15	$4,511	$67,660
Materials Handling Equipment	3	$7,518	$22,553
		Total ($/plant) =>	$451,069

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Prepared Powder	1.24		$74.90	$13.41
Extrusion Die Function of Diameter	0.00060	$250	$0.149	$0.03
Total =>			$75.05	$13.44

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for Extruding(kwh)	0.028	$0.0525	$0.001	$0.000
		Total =>	$0.001	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.003	$13.50	$0.03	$0.01
Capital Charges		12.0%	$3.97	$0.71
Taxes		1.2%	$0.27	$0.05
Insurance		1.0%	$0.22	$0.04
Maintenance		6.0%	$1.35	$0.24
		Total =>	$5.84	$1.05

==========>COST OF EXTRUDING	=>	$5.99	$1.07
==========>COST AFTER EXTRUDING	=>	$80.90	$14.48

COST DISTRIBUTION

Materials	$72.66	90%
Energy	$0.01	0%
Labor	$1.38	2%
Capital Charges	$4.68	6%
Other	$2.17	3%

Extrusion Model

GREEN MACHINING

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Lathe (hand operated)	2	$15,036	$0
CNC Lathe (programed)	1	$25,059	$0
Materials Handling Equipment	1	$7,518	$0
		Total ($/plant) =>	$0

* Note: A value of "zero" for ($/plant) indicates process not being used

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Extruded Part	1.22		$0.00	$0.00
Tool Inserts (300 parts/tool)	0.004	$7.00	$0.00	$0.00
Total =>			$0.00	$0.00

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for machine(kwh)	0.227	$0.0525	$0.000	$0.000
		Total =>	$0.000	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.049	$13.50	$0.00	$0.00
Capital Charges		12.0%	$0.00	$0.00
Taxes		1.2%	$0.00	$0.00
Insurance		1.0%	$0.00	$0.00
Maintenance		6.0%	$0.00	$0.00
		Total =>	$0.00	$0.00

==========>COST OF GREEN MACHINING	=>	$0.00	$0.00
==========>COST AFTER GREEN MACHINING	=>	$0.00	$0.00

COST DISTRIBUTION

Materials	$0.00	0%
Energy	$0.00	0%
Labor	$0.00	0%
Capital Charges	$0.00	0%
Other	$0.00	0%

INDIRECT HEATED DRYER — only with option 1

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Drier and System	4	$37,589	$150,356
Materials Handling Equipment	4	$6,014	$24,057
		Total ($/plant) =>	$174,413

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Machined Part	1.22		$80.90	$14.48
Air	34.02	$0.0001	$0.0034	$0.001
Ware Support (1 year life)	0.0203	$1.00	$0.020	$0.00
	Total =>		$80.92	$14.49

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
To Heat Insulation (Btu)	1370	$0.00001	$0.0089	$0.002
To Evaporate Water (Btu)	20855	$0.00001	$0.1356	$0.024
To Heat Part (Btu)	1607	$0.00001	$0.0104	$0.002
To Heat Batch Support (Btu)	6429	$0.00001	$0.0418	$0.007
To Heat Incoming Air (Btu)	193	$0.00001	$0.0013	$0.000
To Heat Water in Incoming Air (Btu)	10286	$0.00001	$0.0669	$0.012
Soaking Heat (Btu)	69855	$0.00001	$0.4541	$0.081
Total Using Assumed Drying Efficiency		=>	$1.1981	$0.214

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.438	$13.50	$5.92	$1.06
Capital Charges		12.0%	$1.50	$0.27
Taxes		1.2%	$0.10	$0.02
Insurance		1.0%	$0.08	$0.02
Maintenance		6.0%	$0.51	$0.09
		Total =>	$8.12	$1.45

==========>COST OF DRYING	=>	$9.34	$1.67
==========>COST AFTER DRYING	=>	$90.24	$16.15

COST DISTRIBUTION

	Materials	$72.68	81%
	Energy	$1.21	1%
	Labor	$7.30	8%
Extrusion Model	Capital Charges	$6.18	7%
	Other	$2.86	3%

DIRECT HEATED DRYER — only for firing option 2

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Drier and System	1	$22,553	$0
Materials Handling Equipment	1	$6,014	$0
Total ($/plant) =>			$0

* Note: A value of "zero" for ($/plant) indicates process not being use

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
SiC After Green Machining	1.22		$0.00	$0.00
Air	34	$0.0001	$0.000	$0.00
Total =>			$0.00	$0.00

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
To Heat Insulation (Btu)	1370	$0.00001	$0.0000	$0.000
To Evaporate Water (Btu)	20855	$0.00001	$0.0000	$0.000
To Heat Part (Btu)	1607	$0.00001	$0.0000	$0.000
To Heat Batch Support (Btu)	6429	$0.00001	$0.0000	$0.000
Soaking Heat (Btu)	69855	$0.00001	$0.0000	$0.000
Total Using Assumed Drying Efficiency =>			$0.0000	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.438	$13.50	$0.00	$0.00
Capital Charges		12.0%	$0.00	$0.00
Taxes		1.2%	$0.00	$0.00
Insurance		1.0%	$0.00	$0.00
Maintenance		6.0%	$0.00	$0.00
Total =>			$0.00	$0.00

==========>COST OF DRYING =>	$0.00	$0.00
==========>COST AFTER DRYING =>	$0.00	$0.00

COST DISTRIBUTION

Materials	$0.00	0%
Energy	$0.00	0%
Labor	$0.00	0%
Capital Charges	$0.00	0%
Other	$0.00	0%

FIRING - TUNNEL KILN firing option 1

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Tunnel Kiln with Cars	3	$451,069	1.35E+06
Materials Handling Equipment	3	$50,119	1.50E+05
		Total ($/plant) =>	1.50E+06

d.

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
SiC After Drying	1.19		$90.24	$16.15
Air	33	$0.0001	$0.0033	$0.001
Inert Gas Atmosphere	33	$0.16	$5.33	$0.95
	Total =>		$95.57	$17.11

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
To Heat Insulation (Kwh)	2	$0.05250	$0.0854	$0.015
To Heat Part (Kwh)	2	$0.05250	$0.1047	$0.019
To Heat Batch Support (Kwh)	8	$0.05250	$0.4187	$0.075
Soaking Heat (Kwh)	87	$0.05250	$4.5492	$0.814
Total Using Assumed Firing Efficiency		=>	$8.5965	$1.539

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.430	$13.50	$5.80	$1.04
Capital Charges		12.0%	$12.70	$2.27
Taxes		1.2%	$0.86	$0.15
Insurance		1.0%	$0.72	$0.13
Maintenance		12.0%	$8.61	$1.54
		Total =>	$28.70	$5.14

==========>COST OF FIRING	=>	$42.63	$7.63
==========>COST AFTER FIRING	=>	$132.87	$24.27

COST DISTRIBUTION

Materials	$78.02	59%
Energy	$9.81	7%
Labor	$13.10	10%
Capital Charges	$18.88	14%
Other	$13.06	10%

Extrusion Model

FIRING - PERIODIC firing option 2

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Periodic Kiln	10	$87,708	$0
Materials Handling Equipment	10	$12,530	$0
Total ($/plant) =>			$0

* Note: A value of "zero" for ($/plant) indicates process not being use

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
SiC After Drying	1.19		$0.00	$0.00
Air	33	$0.0001	$0.0000	$0.000
Inert Gas Atmosphere	33	$0.16	$0.00	$0.00
Total =>			$0.00	$0.00

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
To Heat Insulation (Kwh)	2	$0.00001	$0.0000	$0.000
To Heat Part (Kwh)	2	$0.00001	$0.0000	$0.000
To Heat Batch Support (Kwh)	8	$0.00001	$0.0000	$0.000
Soaking Heat (Kwh)	73	$0.00001	$0.0000	$0.000
Total Using Assumed Firing Efficiency =>			$0.000	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.430	$13.50	$0.00	$0.00
Capital Charges		12.0%	$0.00	$0.00
Taxes		1.2%	$0.00	$0.00
Insurance		1.0%	$0.00	$0.00
Maintenance		6.0%	$0.00	$0.00
Total =>			$0.00	$0.00

==========>COST OF FIRING =>	$0.00	$0.00
==========>COST AFTER FIRING =>	$0.00	$0.00

COST DISTRIBUTION

Materials	$0.00	0%
Energy	$0.00	0%
Labor	$0.00	0%
Capital Charges	$0.00	0%
Other	$0.00	0%

MACHINE SHOP

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Lathes and accessories	1	$112,266	1.12E+05
Total ($/plant) =>			1.12E+05

d.

====> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Fired Part	1.17		$132.87	$23.78
Coolant	0.01	$0.01	$0.0001	$0.00
Total =>			$132.87	$23.78

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	1.402	$0.0525	$0.074	$0.013
Total =>			$0.074	$0.013

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.263	$13.50	$3.55	$0.64
Capital Charges		12.0%	$0.93	$0.17
Taxes		1.2%	$0.06	$0.01
Insurance		1.0%	$0.05	$0.01
Maintenance		6.0%	$0.32	$0.06
Total =>			$4.91	$0.88

==========>COST OF MACHINING	=>	$4.99	$0.89
==========>COST AFTER MACHINING	=>	$137.85	$24.68

COST DISTRIBUTION

Materials	$78.02	57%
Energy	$9.88	7%
Labor	$16.66	12%
Capital Charges	$19.81	14%
Other	$13.49	10%

QUALITY CONTROL AND STORAGE

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Ultrasonic Testers			
Special Tables, Jigs, and Other Miscellaneous Equipment	1	$70,166	7.02E+04
Storage Racks(30discs/rack)	10	$501	$5,012
		Total ($/plant) =>	7.52E+04

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Machined Parts	1.11		$137.85	$24.68
Total =>			$137.85	$24.68

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	0.026	$0.0525	$0.001	$0.000
		Total =>	$0.001	$0.000

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.056	$13.50	$0.75	$0.13
Capital Charges		12.0%	$0.59	$0.11
Taxes		1.2%	$0.04	$0.01
Insurance		1.0%	$0.03	$0.01
Maintenance		6.0%	$0.20	$0.04
		Total =>	$1.62	$0.29

==========>COST OF QUALITY CONTROL	=>	$1.62	$0.29
==========>COST AFTER QUALITY CONTROL	=>	$139.47	$24.97

COST DISTRIBUTION

Materials	$78.02	56%
Energy	$9.88	7%
Labor	$17.41	12%
Capital Charges	$20.40	15%
Other	$13.76	10%

TOTALS

==========> PROCESS STEPS	$/lb	percent
Material Preparation	$13.41	53.71%
Extruding	$1.07	4.30%
Green Machining	$0.00	0.00%
Drying	$1.67	6.70%
Firing	$7.63	30.57%
Finishing	$0.89	3.58%
Inspection	$0.29	1.16%
Total =>	$24.97	100.00%

==========> PROCESS COSTS	$/piece	$/lb	Percent
Materials	$78.02	$13.97	55.9%
Energy	$9.88	$1.77	7.1%
Labor	$17.41	$3.12	12.5%
Capital Charges	$20.40	$3.65	14.6%
Other	$13.76	$2.46	9.9%
Total ========>	$139.47	$24.97	

==========> MATERIAL COST BREAKDOWN	$/piece	$/lb	% of tota
Ceramic Powder Costs	$72.31	$12.94	51.8%
Process Material Costs	$5.71	$1.02	4.1%

ASSUMPTIONS

MATERIAL COST ($/LB)	$10.00
PART WEIGHT (LBS)	5.59
PART DIAMETER (IN)	2.00
FIRING TEMPERATURE (F)	4172
PLANT CAPACITY (PCS/YR)	25000
% TIME OCCUPIED	41.67%
TOTAL YIELD (%)	77%

+----------+
Cost of A Heat Exchanger
+----------+

CHOOSE SHELL-AND-TUBE HEAT EXCHANGER TYPE====>	1
1. FIXED-HEAD TYPE	
CE Fabricated Equipment Cost Index (Ist Qtr '79)	252.5
CE Fabricated Equipment Cost Index (Jun '87)	317.8
Cost of Metallic (Inconel 600) Tube ($/sq.ft)	$40.00
Cost of Silicon Carbide Tube ($/sq.ft)	$66.56
Percent Metallic Header Cost	11%
Surface Area of Heat Exchanger (sq. ft)	200
Cost of Metallic Heat Exchanger (Inconel 600)	$17,704
Cost of Tube	$8,000
Cost of Header	$1,947
Cost of Other	$7,757
Cost of Ceramic Heat Exchanger	$23,017
Cost of Tube	$13,313
Cost of Header + Other	$9,704

Extrusion Model

APPENDIX B

DETAILED DESCRIPTION OF NEW PROCESS-COST MODEL MACRO

The macro included in the MIT models was written to provide easy access to the worksheet. One goal was to allow the user to be able to move about freely within the model and view the various input parameters and process steps. Another goal was to permit experimentation with the input parameters and view the results, but not disrupt the model's original status.

This guide is furnished to assist you in using the macro. It is assumed that the user has some basic knowledge of Lotus and its worksheet commands.

Invoking the Macro

The macro begins automatically when the worksheet is loaded. If you quit the macro and later wish to return, type <Alt>-M and the macro will execute again.

Figure 1 is an example of the introduction screen that appears when the model is retrieved.

Input_Parameters Process_Steps Make_a_Run Quit
Factor Prices, Input Factor, Yields, etc.

SLIP CASTING MODEL

Energy and Economic Analysis Section
Oak Ridge National Laboratory
Oak Ridge, Tennessee

December 1987

A Modified Version of Production Cost Model
Developed By
Materials Systems Laboratory, MIT

Figure 1. Introduction Screen

Menu Selections

Figure 2 below shows the full extent of the macro's menu selections. The macro was written to simulate Lotus-123 command menus, i.e. execution is temporarily halted to let the user select a menu item by highlighting the choice and pressing <ENTER> or by typing the first character of the item. The only difference between the Lotus menus and the macro menu is the use of the <Esc> key: pressing <Esc> will not back up a level in the macro menu as it will for the Lotus menus.

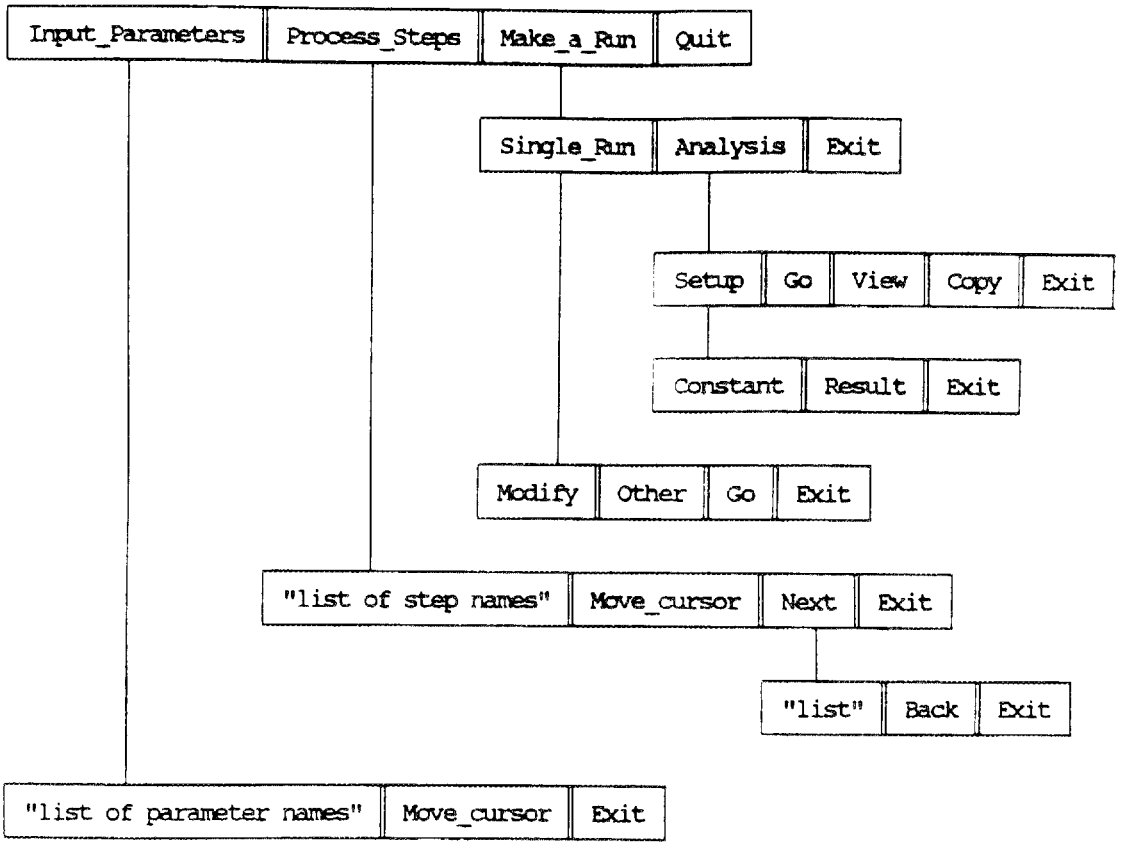

Figure 2. Macro Menus

Input_Parameters : to view the input parameters of the model. This option allows you to move around the worksheet to the areas containing input formulas and constants. Input parameter names specific to the model you are currently using will appear in the macro menu for your selection.

"list of names" : to move the worksheet window to different groups of input parameters. Input parameters are grouped and named into several categories. There will be three or four input parameter group names in the menu list depending on the model. Choosing one takes you to that area of the worksheet.

Move_cursor : frees the cell pointer. You may now move the cell pointer to any location in the worksheet by using any of the cursor control keys. Press <Enter> to return to the macro.

Exit : to return to the **Main Menu**.

Process_Steps : to view the process steps of the model. This option allows you to move around the worksheet to the areas containing the process analysis results. Process step names specific to the model you are using will appear in two macro menus for your selection.

"list of step names" : to move the worksheet window. This is a partial list of process step names. Choosing one takes you to that area of the worksheet.

Move_cursor : frees the cell pointer for user cursor control. Press <Enter> to return to macro control.

Next : to change menus and display a different process step list.

"list" : to move the worksheet window. This is the remaining list of process names.

Back : to return to **Process_Steps** menu.

Exit : to return to **Main Menu**.

Exit : to return to **Main Menu**.

Make_a_Run : to modify and recalculate the worksheet and view the results. Two options are available. One, the Single_Run option allows you to change any input parameter and see the impact of your changes on the model. Two, the Analysis option focuses on one input parameter and several cell formulas of your choice. The value of the input parameter is permitted to vary from a given starting by an increment value; the cell formulas are displayed on the screen and may be viewed graphically.

Single_Run : to modify input parameters and view results. This option is for modifying several input parameters at one time. All input factors are saved to preserve the current status of the model; so, alterations may be made freely without having to remember the original values. If your wish is to make permanent changes, leave the macro to make the transformation.

Modify Other Go Exit
Edit Basic Parameters

Basic Parameters

POWDER COST ($/lb)	$10.00
PLANT CAPACITY (pc/yr)	2.50E+05
BINDER BURNOUT TIME (hr)	24
FIRING TEMPERATURE (F)	4172
FIRING METHOD	2
TOTAL YIELD	75%

Figure 3. Example of a Single_Run Menu.

Modify : to modify basic parameters. A list of the model's basic parameters appears on the screen when the Single_Run option is selected (see Figure 3). **Modify** frees the cell pointer to float over the basic parameter values. You may enter a new value for any of the parameters by typing the new number and pressing <Enter>. Pressing <Enter> without entering a new value returns you to the **Single_Run** menu.

Other : to modify any input parameters in the worksheet. This option works the same as **Modify**. Highlighted values will be cells that contain constants - formulas are protected from modification.

Go : to recalculate the worksheet. All formulas that reference the basic and/or input parameters that were altered through the Modify and Other options will change. However, after recalculation, the original values (saved when **Single_Run** began) are reinserted into their original worksheet locations. So, while all formula results, i.e. Totals, Analysis, Process Steps, etc. show the results of user modification, those modifications have been reset to original status. You may wish to browse through the worksheet using the **Process_Steps** menu.

Exit : to return to **Make_a_Run** menu.

Analysis : to perform the sensitivity analysis (i.e. to focus on one input parameter and view its affect on several cell formulas). You may choose an input parameter, give it an initial value, and watch the result of up to six formulas as the input parameter is incremented (by an amount you set) and the formulas are recalculated.

Setup : to enter the constant and result cell addresses to be targeted for analysis.

```
Constant  Result  Exit
Change Constant List

            Constant                    Result
            List                        List
            ---------                   ---------
      @ -> C17                          F24
  Start ->        10                    AB19
    Inc ->       2.5                    Q37
                                        Q38
```

Figure 4. Setup Screen

Constant : to set the constant for analysis. First, you are prompted to enter the address of a cell that will be altered. (Note: be sure that this is a legal cell address.) Next, you enter the starting value; this is the initial value the constant has during the first iteration. Last, the increment value is set; this value will be added to the starting value after each

iteration. In the worksheet, the cell pointer will stop at the '@ ->','Start ->', and 'Inc ->' locations (see Figure 4). To enter or change the current entry, type the address or value and press <Enter>. To leave the entry unaltered, just press <Enter> and the cell pointer will skip this location.

Result : to enter a new result list. The current address list is erased. You may enter a maximum of six addresses. The cell pointer is positioned below the 'Result List' title (see Figure 4). Type the address you wish to view and press <Enter>; the cell pointer will move down on location. If less than six results is desired, then press <Enter> without entering an address to return to the **Setup** menu.

Exit : to return to the **Analysis** menu.

Go : to make fifteen iteration runs. The current value at the address specified in the constant list is saved for later replacement. Next, the following occurs:

1 : your starting value is inserted into the constant's cell address.
2 : the worksheet is recalculated.
3 : the values for each address listed in the result list is copied into a window for viewing and graphing.
4 : the increment value is added to the current value at the constant's cell address - step 2 & 3 are repeated.
5 : step 4 is repeated until there are 15 new constant values and results.

Once the iterations have been completed, the original value of the constant is restored.

View : to see a graph of the results.

Copy : to save the results. The result matrix is copied to an area below address FT36. The use may copy several Analysis runs for later printing. The user is responsible for maintaining this area, i.e. deleting old results.

Exit : to return to then **Make_a_Run** menu.

Exit : to return to the **Main Menu**.

Quit : Macro control is stopped and you are returned to Lotus.

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