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Arrayed Microchannel Manufacturing Costs for an Auxiliary Power Unit Heat Exchanger

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Abstract

Chemical and energy conversion systems based on microchannel process technology demonstrate high performance in applications in which rates are controlled by diffusive heat and mass transfer flux. The accelerated heat and mass transfer intensifies the process leading to smaller unit operations used in a variety of mobile energy conversion systems including fuel reformers/converters, heat pumps and waste heat scavenging technologies. Fabrication of these microchannel unit operations has historically been performed using a stacked-shim approach in which individual metal sheets are first patterned with micro- and meso-scale flow channels and subsequently bonded in a stack to create a two-dimensional array of parallel microchannel flow paths. Recent work at the Microproducts Breakthrough Institute has focused on exploring the cost of goods sold and capital investment required for high volume manufacturing of MPT devices using process-based cost models developed in collaboration with industry partners. Here, a process-based cost model is presented showing the capital investment and cost-of-goods-sold as a function of annual production volume for a stainless steel heat exchanger designed, built and tested by Pacific Northwest National Laboratory, with potential applications in military markets. In this paper we present results and analysis of the cost modeling effort to date.

Keywords

Microchannel process technology, microchannel arrays, arrayed microchannel manufacturing, process-based cost model

1. Introduction

Chemical and energy conversion systems based on microchannel process technology (MPT) demonstrate high performance in applications in which rates are controlled by diffusive heat and mass transfer flux. MPT-based heat exchangers, absorbers/desorbers and chemical reactors all benefit from process intensification and have been used in a variety of mobile energy conversion systems including fuel reformers/converters, heat pumps and waste heat scavenging technologies. The service environments typical of MPTs often require the devices to be fabricated from metals such as aluminum, titanium, stainless steel or high temperature super alloys. Flow channels and associated critical dimensions in these devices can be as small as 50 um, but generally range from 100 to 1000 um in width and height with characteristic flow channel lengths normally in the mm to cm range. High surface area architectures (e.g. wicks or textured surfaces) are often included in the flow channels as well for enhanced mass transfer and/or catalytic functionality.

Fuel reforming systems that utilize MPT devices are being developed at the Microproducts Breakthrough Institute (MBI) for stationary and mobile fuel cell applications in which the efficiency, form factor or acoustic signature of generating electricity using an internal combustion engine is unfavorable (*e.g*. auxiliary power units for hotel loads in military vehicles or long-haul truck sleeper cabs). A typical system is illustrated in Figure 1 and is based on reforming of hydrocarbon fuels to generate hydrogen for fuel cell feed. This particular system design utilizes a number of MPT devices which are integrated with off-the-shelf components to form the fuel reformer (A). The preheater device is used to recover and transfer energy from hot combustion exhaust (1) to incoming air (2) prior to mixing with fuel to substantially increase system thermal efficiency. The 3.5 kW preheater (B) exhibits very low pressure drop on both the hot- and cold-side fluid paths and operates between 90 and 450^{o}C with an effectiveness close to 90%.

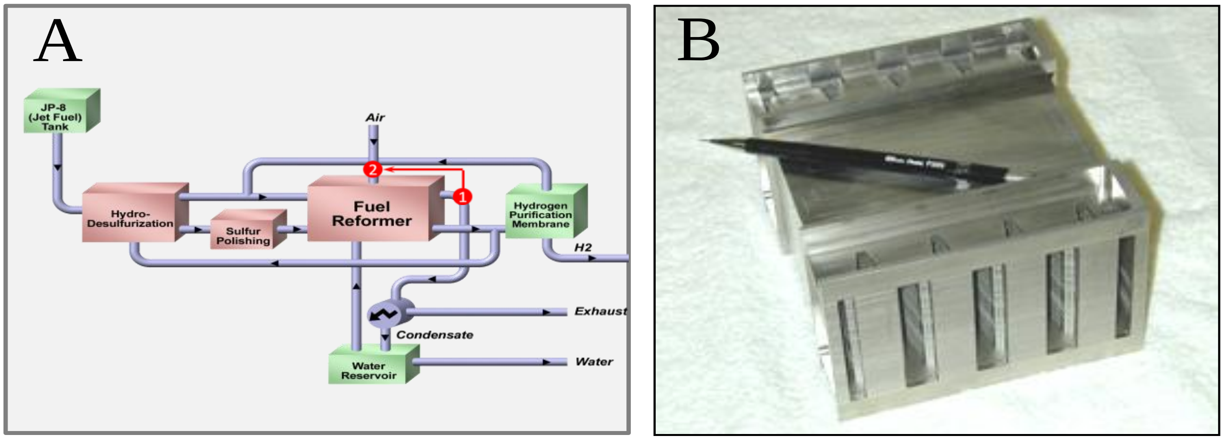

Figure 1: Fuel reforming system utilizing MPT devices (A). The 7 kW system requires one 3.5 kW air preheater (B) with external dimensions of approximately 15 cm (W) x 15 cm (L) x 15 cm (H).

MPT enabled APUs have been used to successfully convert a range of complex liquid fuels (*e.g*. diesel, JP8, biodiesel, etc.) to electricity using a number of commercially available fuel cell stacks. Both mobile and stationary systems have been demonstrated and all are characterized by rapid cold-start capability, a short warm transient response profile and quiet operation. MPT-enabled APU systems are performance- and cost-competitive with existing technologies in a number of military and commercial markets. To move from technology demonstration to market entry and commercialization, however, requires a better understanding of the manufacturing processes and associated cost structures necessary to fabricate components in production volumes. Recent work at the MBI has focused on developing volume-sensitive cost estimation models for predicting the manufacturing costs of MPT devices fabricated using a range of processing technologies. The process-based cost models are used to develop an understanding of the economic trade-offs between candidate processes and are utilized in a design for manufacturing approach to MPT device development. In prior work we have presented results and analysis of cost modeling efforts to estimate the high volume manufacturing cost of an MPT device used in heat-activated cooling systems. In that prior study, we illustrated that there exists a significant difference in fabrication costs when using contract manufacturing (for demonstration and prototyping purposes) as compared to using a dedicated process line. The estimated unit cost and required capital equipment investment for manufacturing the MPT devices was used to illustrate differences between equipment choices and to provide a framework for evaluating a make vs. buy decision. In the current paper, we apply the same process-based cost model methodology to further explore the cost of manufacturing an MPT device. The current study focuses on illustrating manufacturing cost sensitivity such that primary cost drivers are identified and prioritized.

2. Manufacturing Approach

The first step in the modeling methodology is to define the fabrication process and develop the functions and equations that relate manufacturing parameters to the individual cost elements. A typical microlamination [1] process flow sheet for manufacturing of MPT devices is illustrated in Figure 2[2]. The architecture of the absorber device is based on a stacked-shim fabrication process in which shims are first patterned (with flow channels and/or fluidic vias) and then bonded in a monolithic stack. Two specially machined end-plates are joined to either end of the device to allow addition of interconnects for fluidic communication to and from the device. The service environment of the MPT device has a great influence on the choice of shim and end-plate materials and, in turn, the material choice has a significant impact on available fabrication processes and processing conditions. In the present study, the service environment of the air preheater requires sufficient mechanical strength at modest temperatures in a mildly corrosive hot gas stream. To meet the material performance requirements of the prototype system, austenitic 316L stainless steel is used for both shim and end-plate architectures.

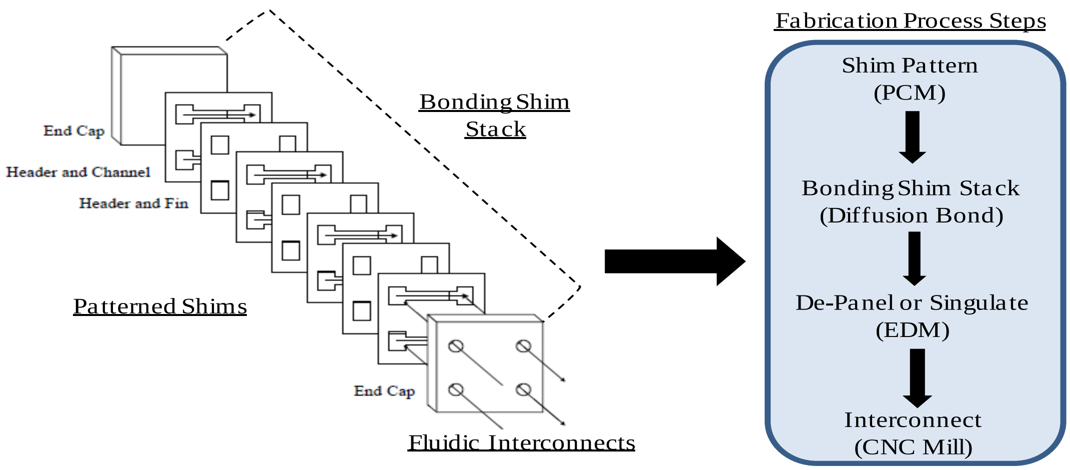

Figure 2: Typical construction scheme and fabrication process steps for stainless steel MPT device.

A number of fabrication processes have been used at MBI to build demonstration devices. The most-widely used process steps, however, appear in Figure 2 and are especially well-suited for fabricating metallic-based MPT devices at low (prototype) volumes. In the present study, this "default" manufacturing process flow is considered in which photochemical machining (PCM) is used to pattern shims, diffusion bonding for joining of the shim stack, electro-discharge machining (EDM) for final device perimeter shaping and CNC milling to define fluidic interconnects.

At demonstration and prototyping fabrication volumes, the cost associated with shim patterning and shim stack bonding has been a significant fraction of the total fab cost for MPT devices made at MBI. Typically, however, these fabrication processes have been performed by third party contract manufacturers and the cost of device fab is very likely not representative of that which could be achieved using a dedicated production line as is assumed with the cost model. Using the default process flow illustrated in Figure 2, the process-based cost model is used to predict manufacturing costs of the air preheater over a range of production volumes representative of the anticipated market.

3. Process-Based Cost Modeling

Process-based cost models have been used to estimate manufacturing costs for a range of materials and products including diamond films, carbon nanotubes, steel powder and injection molded plastics[3-6]. Using this approach, the total manufacturing cost is broken down into a number of cost elements associated with each step in the production process. Each cost element is estimated separately and then all are summed to establish an overall manufacturing cost. Typical cost elements include capital equipment, labor, direct materials, indirect materials, energy/utilities, facilities and maintenance. Variation in each cost element is estimated through creation of functional relationships that quantify the impact of manufacturing variables (e.g. production volume, equipment through-put, labor and loading rates, electricity cost, etc.) on each cost element. The output from the process-based model is an estimate of cost of goods sold (COGS); typical overhead cost contributors such as sales and marketing, R&D, administration, management, profit and taxes are not considered. Application of the process-based cost modeling methodology to manufacturing of a device such as the air preheater shown in Figure 1 can be used to illustrate the relative contribution of design, materials and fabrication process choice on final device cost. Identification of these cost drivers is a critical enabler in effectively prioritizing the fabrication processes that give the highest probability for commercial success. Cost model sensitivity analyses can be used to determine areas of technical and/or financial risk and are a useful tool in developing more sophisticated economic assessments; for example supporting a "make vs. buy" decision in manufacturing production. The process-based cost model is used here to identify primary cost drivers in the manufacture of the air preheater device across a range of production volumes and to determine a range of COGS in an effort to determine the feasibility for military markets.

4. Cost Model Approach

Two cost models were used in the analysis of the COGS of the air preheater. The models were developed for manufacturing process flow with two manufacturing processes, photochemical machining (PCM), and diffusion bonding. The basis for these models is bottom up costing. Bottom up costing requires discrete analysis of all the required costs for a particular process. This analysis includes raw material, labor cost, tool capital cost, facilities, machine maintenance, utilities and supplies. The COGS per device is calculated by finding the total cost of each process as well as the raw material required to fabricate the device. Because of the nature of the micro channel device, which is scaling up in the manufacturing phase, by finding the manufacturing cost for a single shim, we would be able to estimate the cost per device and the total manufacturing cost. Therefore, for all the cost elements, the model is designed to calculate the cost per shim. The cost model is developed within Excel spreadsheets in order to simplify the design and verification of the models.

The material used for this investigation was assumed to be 316 stainless steel. A volume price for the material was determined through interaction with a vendor. For PCM, it was assumed that the etch depth was 250µm into a 24"x24" panel that was 500µm thick. The size of the air preheater was assumed to be 6"x6" allowing for 16 devices per panel stack. The blind cut area for the lamina designs was assumed to be 60 sq. cm. The cycle time for making panels was based on the etching rate of 316 stainless steel using ferric chloride. Cycle times for other lithography steps (e.g. photoresist application, cleaning, inspection) was based on input from a PCM equipment vendor.

The final device required 150 shims/device. To bond these laminae together, it was assumed that a bond area of 400 cm^2 per shim was needed at a bonding temperature of 980˚C with a heating rate of 5˚C/min and a cooling rate of 0.23˚C/min. The work envelop of the vacuum hot press was determined to be 1016mm. These assumptions allowed us to contact a furnace vendor for budgetary quotation. Further, it was assumed that the diffusion bonding hold time was 120 min with a furnace load time of 30 min.

A large number of parameters were identified that directly or indirectly influence the COGS. These parameters were categorized as raw material, device geometry, process based parameters, and operations parameters. Additional details are provided in Leith et al. 2010[7]. Single variable sensitivity analyses were conducted to isolate key parameters for consideration.

5. Results and Discussion

5.1 COGS

A key assumption for the model is that the entire market demand is satisfied by the production volume of a single factory. Figure 3 shows the key cost drivers for COGS as a function of market size i.e. production volume. Application of the cost model to different annual market sizes shows the total COGS significantly decreasing from more than 5,000 USD for a demand of 200 devices/year to less than 500 USD for 10,000-20,000 devices/year. The results suggest that an increase in production of 100x will lead to more than 10 times reduction in cost. Compared with contract manufacturing services used to prototype the air preheater device, this is a cost reduction of well over 30X. As suggested in the graph, this is largely due to an improvement in the utilization of labor and capital. Expendable supplies (e.g. photoresist) and raw material are the major cost drivers above 10,000 units per year.

This curve suggests that for the particular product and production line specified (e.g. 24" work envelope), production volumes beyond 10,000 units per year would yield minimal reductions in COGS. Thus, the type of product and production line investigated here would need market sizes on the order of 10,000 units per year in order to be viable. While this is not as large as originally expected and while a COGS of 500 USD per year is easily within the range of military markets, the size of military markets are not expected to be this large. It is expected that military markets would be an order of magnitude smaller which drives the COGS over 1,000 USD per unit. These numbers are at least with the realm of possibility for military markets. A more detailed analysis is provided below.

For a market size of 200 devices/year the dominant cost drivers are labor and tools (in this context, the "tool" parameter represents the depreciated expense of the necessary capital equipment investment). Since the cycle time of most of the tools used in the patterning and bonding processes are quite low, in high production volume the model increases the number of tools in a few process steps to meet the market demand. As the increase of tool cost is not proportional to the escalation of production volume, there is a considerable decline in tool and labor cost per device at high manufacturing volumes and as a result the total cost of the device is substantially reduced.

The use profile and, ultimately, cost of utilities, maintenance, and supplies (e.g. indirect materials) are based on raw tool count and also contribute to device cost reduction as production volume is increased. Conversely, the cost of raw material per device is constant for all market sizes and in the model simulation is not dependent on the production volume.

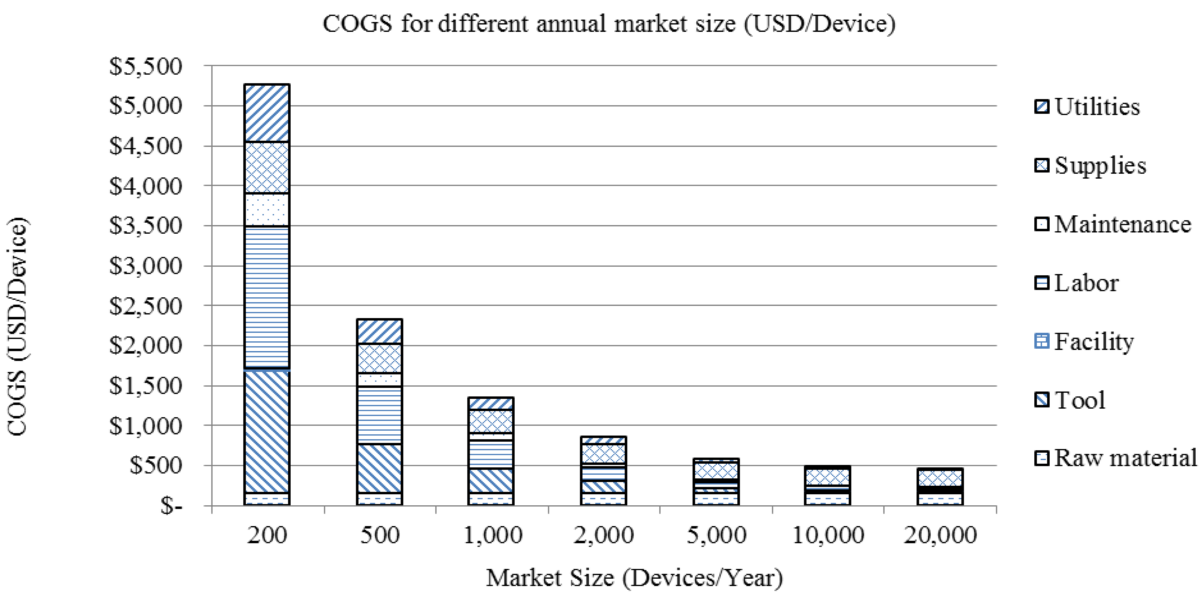

Figure 3: Estimated air preheater COGS (USD/Device) as a function of annual market size, fixed and variable costs

In a manufacturing environment, the cost of raw materials will, in practice, generally decreases as volumes increase as a result of high-volume price discounts from sheet metal suppliers. In the current model analysis, however, the price per unit mass of stainless steel sheet stock remains fairly constant over the device production range investigated.

The breakout of costs per process step as a function of market sizes is demonstrated in Figure 4. PCM seems to be the higher cost regardless of production volume. This is in large part because the number of patterning events per device is 150 compared with the single bonding event. This suggests significant opportunities for cost reduction during patterning i.e. small improvements can add up. At higher production volumes, raw material involves a considerable percentage of COGS (roughly 33%) which is typical of the high volume production of mechanical goods.

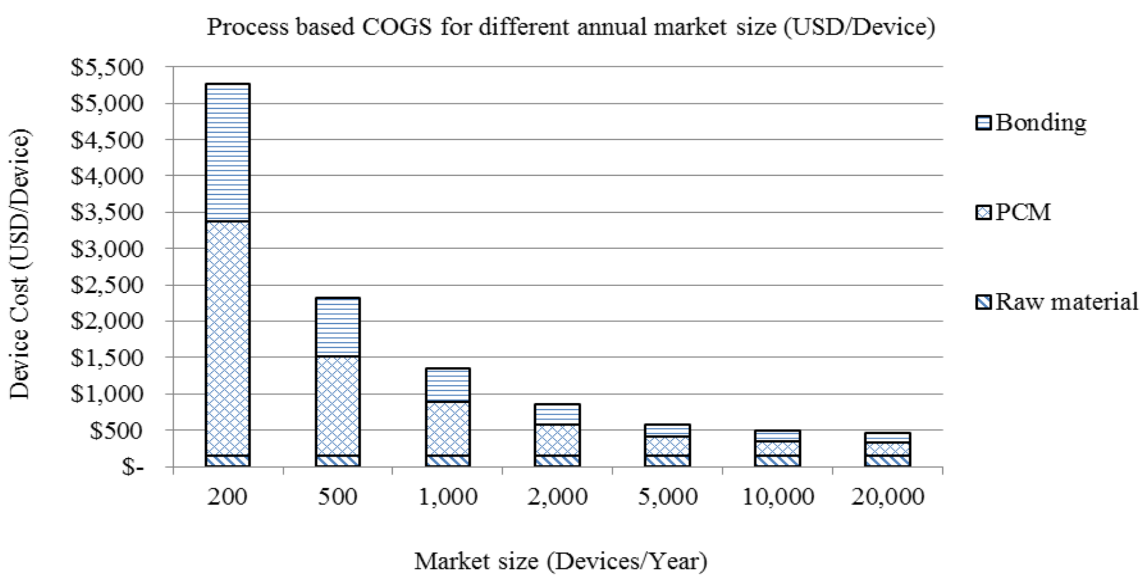

Figure 4: Contribution to COGS (USD/Device) of manufacturing process steps and raw materials for projected air preheater production volumes.

5.2 Capital Cost

Figure 5 below shows an analysis of capital equipment investment necessary to enable various annual market sizes. This figure suggests that a capital equipment investment of under 3 million USD would be necessary to enable a cost of 500 USD per device. Depending on market conditions, this is not an insurmountable figure for investment. A significant change in capital equipment investment is needed beyond 10,000 units per year. The capital facility cost is a function of the number of capital tools needed and, therefore, space requirements would follow the trend in Figure 5.

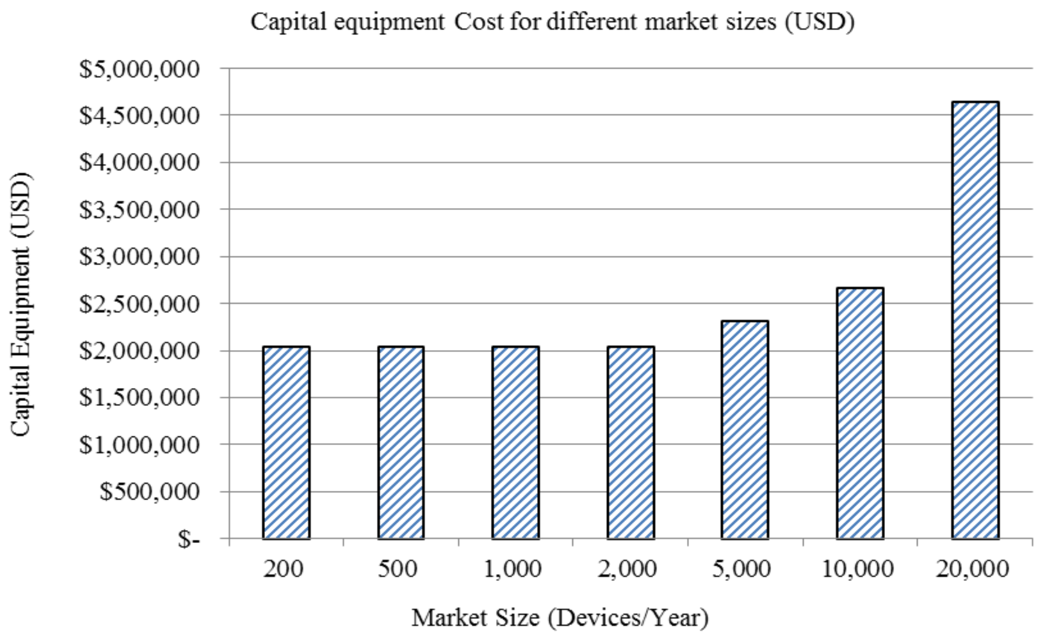

Figure 5**:** Estimated capital equipment investment (USD) as a function of manufacturing volume.

5.3 Sensitivity Analysis

A sensitivity analysis was performed on all model parameters by changing values ±50% to determine the percentage of change in total COGS for market sizes of 2,000 and 20,000 devices per year. Parameters were prioritized based on the degree of impact to COGS and the top 11 parameters are shown in Figure 6.

Figure 6 shows the tornado diagram for the low (2,000) and high (20,000) volume production conditions. In both cases the yield of tools are in the top six parameters. Not surprisingly, the bonding yield has the largest impact. Estimates for bonding yield were around 70% based on expert testimony from over a decade of diffusion bonding these types of devices. Further, the bonding step is the last step in microlamination. Consequently, all raw materials and value-added processing up to that step is wasted by poor yields at bonding. Even though patterning yields were expected to be much higher and patterning steps are toward the front of the process, patterning yields were also found to significantly affect COGS. This is largely due to the loss of raw material which, based on Figure 4, is at least 33% of COGS at high volumes and just over 10% at 2,000 devices per year.

The geometry parameters such as shims per panel, shims per device, and shim thickness are in the top six parameters for both analyses suggesting that they greatly impact the cost of goods sold in both low and high volume production. These parameters are all tied directly to the amount of raw material needed per device. More raw material per device results in higher material cost and higher total cost per device. Assuming that panel size stays constant, shims per panel speaks to shrinking the xy dimensions of the device by increasing the functionality per unit surface area. Therefore, anything that can be done in design to shrink dimensions likely would have a significant impact. As is widely known in the MPT literature, shrinking the etch depth dimension can have a squared effect on shrinking xy dimensions. This suggests that pushing microchannel heights lower can have significant repercussions on the overall cost of the device by reducing the thickness and xy dimensions of laminae leading to less raw material.

Labor cost showed up in the top six parameters in both analyses. Labor is a significant factor at lower production volumes but becomes marked less important at higher production volumes. As suggested above, this is mainly due to better labor utilization at higher production volumes. These top six parameters were considered for Monte Carlo simulation.

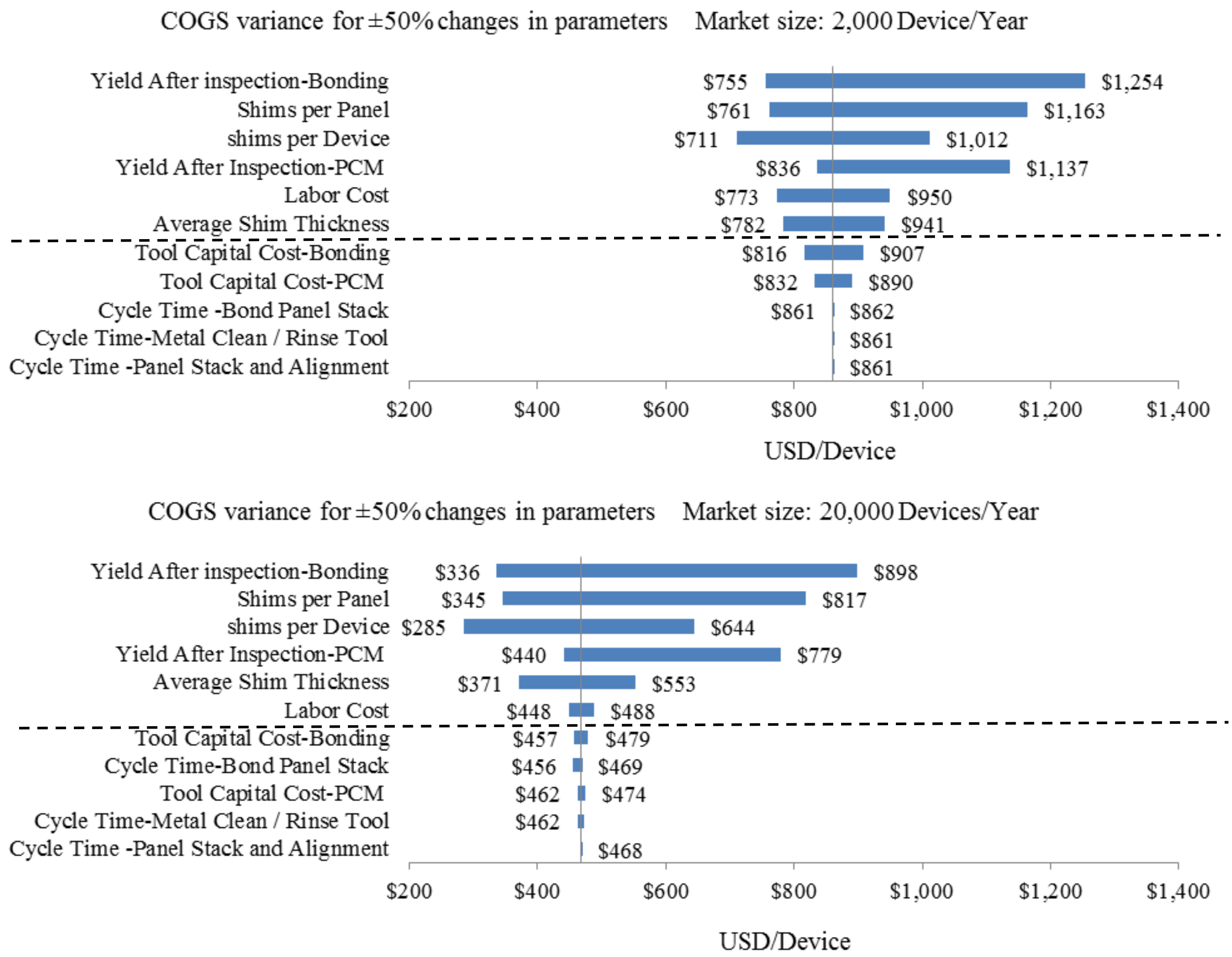

Figure 6: Contribution to COGS of different manufacturing cost parameters for annual production volumes of 2,000 and 20,000 units.

5.4 Monte Carlo Simulation

To increase the level of confidence with regard to COGS, Monte Carlo simulations were performed by applying probability distributions to the top six parameters and calculating the COGS under 1,000 simulations using random number generators. Discrete uniform distributions were applied to shims per panel and shims per device. Normal distributions were used for both yields. Triangular distributions were used for shim thickness and labor costs. All distributions were based on expert testimony from over a decade of prototyping these types of devices. Distributions for design parameters (shims per panel, shim per device, shim thickness) expressed uncertainty over the requirements of the final design. Distributions for manufacturing parameters (labor cost and yield) expressed uncertainty over labor content and process capability.

The results of running the Monte Carlo simulation at 20,000 units/year are shown in Figure 7. The mean, median, and standard deviation of the distribution is $520, $473, and $211, respectively. The mean of $520 is close to the COGS shown in the original model in Figures 3 and 4. The final distribution is non-symmetric and skewed toward lower cost. Approximately 90% of the curve is below about $800.

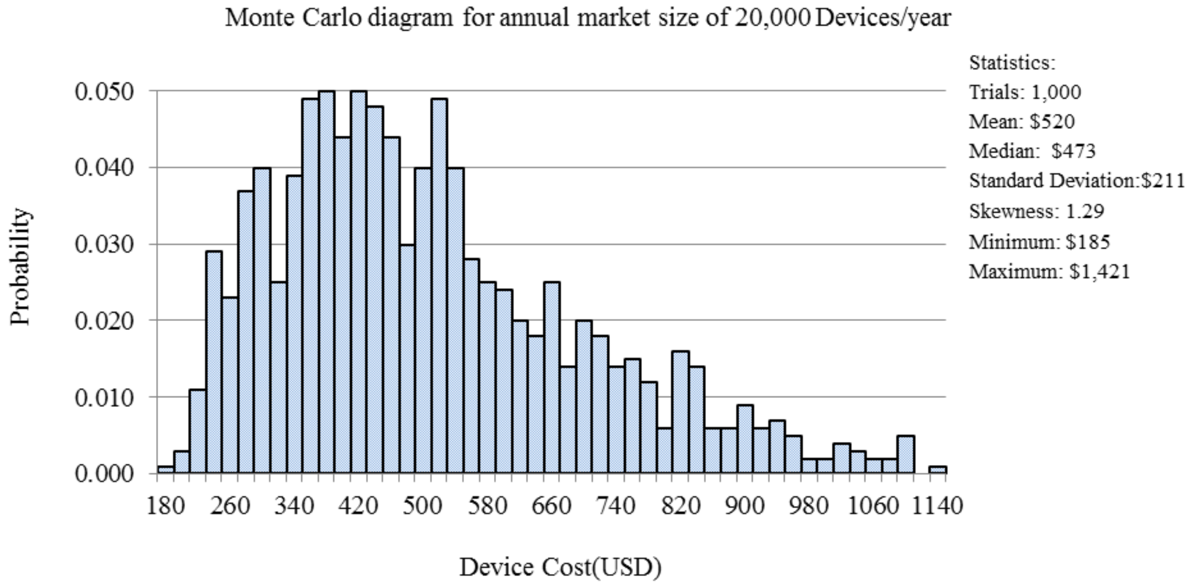

Figure 7**:** Monte Carlo simulation results for 20,000 units per year showing the probability of realizing a given manufacturing cost for production of the air preheater.

6. Summary

An arrayed microchannel manufacturing cost model was exercised to determine the likely cost-of-goods-sold (COGS) achieved and capital investment needed to produce an air preheater for an auxiliary power unit as a function of market demand. Using expected values, the total COGS was expected to be less than 500 USD per unit for a production volume of 10,000 units/year. Compared with contract manufacturing services used to prototype the air preheater device in the past, this is a cost reduction of well over 30X. The capital equipment investment needed to enable a production volume of 10,000 units per year was 2.5 million USD. Production volumes beyond 10,000 units per year are expected to yield minimal reductions in COGS. Monte Carlo simulation shows that at 20,000 units per year, the expected value of COGS would be $520 with a 90% confidence that it would be under $800.

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