AN ABSTRACT OF THE THESIS OF

Jair A. Lizarazo-Adarme for the degree of Master of Business Administration in Business Administration presented on June 5, 2014.

Title: Development of a Pricing Methodology for the Manufacturing Production of a High Temperature Microchannel Recuperator.

Abstract approved: ____

John R. Becker-Blease

To improve energy efficiency of industrial processes, heat exchangers are used to transfer thermal energy between different process streams. The compact size and increased efficiency of microchannel based recuperators make them appealing in extreme environments where costly superalloys are mandatory. Due to the high manufacturing cost of microchannel heat exchanges they are only used in niche applications where other low cost alternatives are not available. This work combines a bottom-up manufacturing cost model and a developed pricing methodology to accomplish technology valuation of a novel 15 kW nickel superalloy heat exchanger hermetically sealed by laser welding. The integrated spreadsheet based bottom-up cost model and pricing tool, provides real-time feedback for the engineering design team to continuously monitor the effect on company's profit during the design process. Using Capital Assets Pricing Model (CAPM), Net Present Value (NPV) analysis and market pricing of potential product substitute it was determine that the capital investment of the designed dedicated manufacturing plant that produces 1,000 units per year will be recovered in 3 years with an Internal Rate of Return (IRR) of 36.51%.

Keywords: microchannel heat exchanger, high temperature, nickel superalloy, product pricing, cost model, product substitute, valuation methodology.

Development of a Pricing Methodology for the Manufacturing Production of a High Temperature Microchannel Recuperator

by
Jair A. Lizarazo-Adarme

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Business Administration

Presented June 5, 2014
Commencement June 2014

Master of Business Administration thesis of Jair A. Lizarazo-Adarme presented on June 5, 2014

APPROVED:

Major Professor, representing Business Administration

Dean of the College of Business

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Jair A. Lizarazo-Adarme, Author

ACKNOWLEDGEMENTS

First, I would like to express my sincere gratitude to my advisor, Dr. John R. Becker-Blease, for his constant support and for believing in me went I first presented to him this research project idea. This work would not have been completed without his excellent guidance, patience, and advice. While he motivated me to explore several valuation alternatives he kept me centered in the scope of this work. Secondly, I would like to express my gratitude to my spouse, Robert, my family, and my friends that in many ways supported me to achieve this academic goal.

I would also like to acknowledge the support of my peers at the Microproducts Breakthrough Institute (MBI). Their support was the most valuable resource to complete this project and to implement my new earned business skills. Their support added significant value to research and business activities during my tenure at the MBI. Their feedback guided me to understand the overlap point between management theory and human behavior in a business environment. Thank you again for your support and for thrusting my vision.

A special thank you to Sam Brannon, MBI colleague, for the long hours discussing heat exchanger technology and for his feedback that helped to determine the kind of calculations needed at an engineering level.

Last but not least, God who made this possible.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

DEVELOPMENT OF A PRICING METHODOLOGY FOR THE MANUFACTURING PRODUCTION OF A HIGH TEMPERATURE MICROCHANNEL RECUPERATOR

1 INTRODUCTION

Since the introduction of the first compact water-cooled integrated heat sink for silicon circuits (Tuckerman & Pease, 1981), microchannel based heat exchangers has evolve toward low fabrication cost (Denkenberger, 2010; Lu, 2013) and lower environmental impact (Gao, 2013). To move the technology forward into profitable business it is necessary to integrate existing manufacturing cost models with pricing methodology. The general goal of this research project is to combine a bottom-up manufacturing cost model and a developed pricing methodology to accomplish technology valuation of a novel 15 kW nickel superalloy heat exchanger hermetically sealed by laser welding.

1.1 Motivation

While heat exchangers operating principle remains the same across different industries, its configuration and allowed thermal stress varies by operating conditions such as temperature, pressure drop, and chemical nature of the operating fluids (Khan & Fartaj, 2011). However designing for mass manufacturing allows the development of market ready products and cost effective mass production.

In addition to cost driver of traditional microchannel devices for military application (Lajevardi, Leith, King, & Paul, 2011; Leith, King, & Paul, 2010), an alternative design with equivalent heat transfer performance (Brannon, 2013) shows potential for commercial application. However a valuation methodology that facilitates introduction of this technology to new markets is needed. This research project is motivated by the need of real-time feedback regarding cost and price implication of the technical decisions made during the design stage of microchannel heat exchangers.

1.2 Background

Compared to traditional shell and tube heat exchangers, microchannel heat exchangers provide a higher surface area per mass unit (Mohammed, Bhaskaran, Shuaib, & Saidur, 2011). This results in a lower demand for raw materials and allows the consideration of high temperature resistant nickel super alloy, which are considered cost-prohibited on shell and tube heat exchangers. Nickel super alloys allow operation of microchannel heat exchangers at temperatures over 800°C, with higher thermal gradients that increase operation thermal stress (Brannon, 2013).

To achieve the desired high surface area, microchannel devices are traditionally fabricated by stacking and bonding thin layers of material with chemically carved microchannel patterns on their surface (Paul & Paulraj, 2008). Since obtaining leak-free monolithic devices is a highly challenging effort due to micro size defects on the layer's surface, a bonding technique using laser welding has the potential to increase production yield while reducing fabrication cost (Brannon, 2013).

With shale gas extraction in the US, increasing industrial activities in developing countries, stronger environmental regulations and increase need of energy cost savings the heat exchangers market is forecasted to increase over 7.8% in the next 3 years (Acmite Market Intelligence, 2013, Alfa Naval, 2014, TechNavio, 2013). With a global demand on heat exchangers of USD $42.7

billion in 2012, the market by 2016 and 2020 is expected to approach USD $57.9 and USD $78.16 billion respectively (Acmite Market Intelligence, 2013).

While miniaturization has improve consumer electronics such cell phones, digital cameras and computers, miniaturization of industrial unit operations using microchannel technology is perceive to has a cost penalty over mature technology such tube-and-shell heat exchangers. The slow adoption of the microchannel technology is attribute to high ticket price of microchannel devices needed to retrofit existing facilities however competitive prices can facility the introduction to the market for either new installations or upgrades of existing once. Evaluation of several designs of high temperature heat exchangers (Sabharwall et al., 2011) shown that microchannel heat exchangers are capable of satisfying design requirements. The evaluation was carried out considering: thermal hydraulic performance, structural performance, material performance, technology readiness, system integration, inspection, maintenance, initial cost, and operability. The conclusion of the evaluation of heat temperature heat exchangers estimates that a 3,400 MWatt microchannel heat exchanger is 38% of the cost of a tube and shell heat exchanger. Since the same fabrication cost factor (total cost / material cost) of 6.5 for the tube and shell heat exchangers was assumed for the microchannel heat exchanger the only cost driver identify on cost estimation was the raw material cost.

1.3 Problem Statement

The lack of abundant financial information based on trustworthy cost models and pricing methodology have diminish the entrance to the market of microchannel based products that offer significant energy saving in a compact size. To support the development of business plans that facilitate mass production of microchannel devices is necessary to develop a pricing tool that provides reliable real-time feedback during the stage of microchannel heat exchangers. The needed computer subroutine should integrated pricing methodology with computer aid design software to facilitate design for manufacturing.

1.4 Research Objectives

The general objective of this research project is to develop a pricing methodology that allows valuation of microchannel based products with the following specific objectives:

(1) To provide real time feedback of product cost and price during the design stage.

(2) To develop a valuation methodology using suitable expected rate of return.

(3) To provide financial information that allows to identify strategies leading to development profitable business models.

Previous to the implementation of the pricing methodology, it was necessary in this research work to execute several upgrades in a preliminary cost model developed at the Microproducts Breakthrough Institute. These upgrades included integration of independent calculation modules, simplification of the user interface, and insertion of dynamic data exchange links with computer aid design software. In addition to provide visualization of 3D drawings simultaneously with manufacturing cost, these upgrades minimized manual data entry and allowed design engineers to identify in real-time changes leading to cost reduction during the manufacturing production of microchannel heat exchangers.

2 EXPERIMENTAL APPROACH

To provide a better understanding of the cost aspects of the microproducts technology and to facilitate identification of factors leading to create competitive advantage business strategies, this research project was carried out to enhance a developed manufacturing cost and to a develop a price valuation methodology for microchannel heat exchangers.

2.1 Product Costing

The total production cost of a given product is expressed as the sum of all cost contributions along their value chain, from raw materials to final consumers, and including primary activities and support activities. The support activities includes procurement, technological development, human resources management and firm infrastructure, while the primary activities are compose of inbound logistic, outbound logistic, marketing & sales, post sell service and direct operational cost.

Since all cost contribution to the value chain are high sensitive to the efficiency of the business model selected by the company the value contribution changes across industries. However because the cost of manufactured goods is highly sensitive to the complexity of the manufacturing steps, the total operation cost is expressed with respect to the operational cost.

$$TotalCost_j = OperationsCost_j \left(1 + \frac{Inbound\ Logistics_j}{OperationsCost_j} + \frac{Outbound\ Logistics_j}{OperationsCost_j} + \frac{Marketing\ \&\ Sales_j}{OperationsCost_j} + \frac{PostSellService_j}{OperationsCost_j} + \frac{\text{Support Activities}_j}{OperationsCost_j}\right)$$

Where TotalCost $_j$ is the total cost of product “j” and the OpCost $_j$ is the operations cost of product “j” that includes all direct production cost, it is also known as the Cost of Goods Sold (COGS). Expressing all cost contributions as cost ratios of the COGS the total manufacturing cost is given by $TotalCost_j = COGS_j\left(1 + \sum CostRatio_j\right)$. The cost ratios are obtained from company's financial statements.

If financial statements are not available to calculate cost ratios, the total cost can be expressed as direct manufacturing cost and indirect manufacturing cost. The direct manufacturing cost are include in the COGS while the indirect cost includes investment related cost plus overhead. Investment related costs are a function of the fixed capital investment and are independent of the production rate of the plant, includes property taxes (2%), insurance (1%) and repairs (4%). The overhead charge is a function of the direct labor cost and is usually around 125% of the labor cost (Perry & Green, 1997, pp. 9–57). Then the total cost can be expressed as

$$TotalCost_j = 0.07 * CapitalBuilding\&Equipment + AnnualProd_j \\ * (1.25 * LaborCost + DirectCost)_i$$

Where direct cost includes maintenance, labor, consumables, utilities, raw materials. In other words COGS minus equipment and building depreciation.

Since determining operation parameters to manufacture microproducts devices goes beyond the scope of this work, the operational parameters for products developed at the Microproducts Breakthrough Institute (MBI) are used as the starting point for the cost model and pricing tool developed in this research project. As part of this research project a cost model developed at the MBI was upgrade to added integration with CAD software through addition of dynamic data links across several calculation modules and software packages. The interconnection of the several calculation modules allows real time estimation of manufacturing cost, providing to design engineers a comprehensive visualization of effects on heat transfer properties and manufacturing cost. The implementation of the pricing module provides real time feedback on IRR as raw material, device geometry, heat transfer constraints, and manufacturing parameter are define during the design stage.

To achieve a better understanding of manufacturing cost drivers, the manufacturing process was broke down into process steps until each step was associate with known manufacturing parameters. Then the cost were grouped into seven cost categories to establish the overall manufacturing cost. Typical cost elements includes raw materials (RM), capital facilities (CF), capital equipment (CE), labor cost (LC), process consumables (PC), process utilities (PU), and maintenance cost (MC). The impact of manufacturing variables (e.g. equipment throughput, loading rates, electricity cost, required labor, etc.) on each cost element is estimated through functional relationships (Leith et al., 2010) . The sum of the previous cost elements provides the Cost of Goods Sold (COGS). Overhead cost contributors such as sales and marketing, R&D, administration, management, profit and taxes are not considered in the estimation of the COGS.

The calculation of each cost category used on the bottom-up cost model is indicated below with all calculations giving for annual production volume at least indicated otherwise.

2.1.1 Raw materials (RM)

Raw material (RM) is the sum of all the starting material needed to fabricate one device, expressed in dollar per mass unit (USD/kg). While volume purchases would allow pricing negotiations leading to lower cost of raw materials an average bulk price was assumed in this cost model. Therefore the cost of raw material is consider constant for different production volumes. The total cost of raw material was calculated as:

$$RM_{device} = \sum_{material,i=1}^{n} Price_i * Density_i * DeviceVolume_i$$

$$\frac{USD}{device} = \sum_{i=1}^{n} \left(\frac{USD}{kg}\right)_i \left(\frac{kg}{m^3}\right)_i \left(\frac{m^3}{device}\right)_i$$

Where "*DeviceVolume*" corresponds to the volume of starting raw material needed (area * thickness) to create the desire microchannel network. The started raw material includes additional material needed for alignment and handling during each process steps. While recycle of some scrap material is possible, it was not consider during this cost calculation. Raw material per device includes all needed parts of the device such microchannel patterned layer, housing, alignment pins and interconnection pipes.

2.1.2 Capital Building (CB)

Capital Building (CB) is the fabrication cost of a new building in a green-field. Required foot print per equipment is calculated using equipment specifications plus components storage and assembling areas. Industrial standard fabrication cost per unit area are used for each type of space according to the utilities and services required in each process step. A facility depreciation of 25 year is consider during the calculations.

$$CB_{device} = \frac{1}{25 * AnnualProd} \sum_{ProcessStep,i=1}^{n} FabricationCost_i * RequiredArea_i$$

$$\frac{USD}{device} = \frac{1}{device} \sum_{i=1}^{n} \left(\frac{USD}{m^2}\right)_i (m^2)_i$$

Calculations includes equipment space, storage and assembling areas needed for operation of a continuous manufacturing line.

2.1.3 *Capital Equipment (CE)*

Capital equipment (CE) is the equipment needed in a dedicated manufacturing line to achieve the specified annual production volume. Process steps are determined by the design engineering team and varies according to the complexity of the microchannel layout within the device. Since the factor between equipment throughput and production rate can lead to fractional equipment count (raw equipment count) the equipment count is round-up to the next integer. This round-up of equipment count produces unwanted equipment idle time that increases equipment capital investment. Capital equipment utilization, calculated as the ratio between raw-equipment-count and roundup-equipment-count, lower than 100% indicates equipment excess capacity.

Equipment sharing is allow to decrease equipment’s idle time, however inadequate configuration of the production line may generate bottlenecks due to improper equipment scheduling. While the optimal configuration of the production line lies outside the scope of this work capital equipment utilization is reported to facilitate identification of cost saving strategies. A total production yield of 95% is assumed with equipment depreciation of 7 years and equipment installation cost as 6% of equipment cost.

$$CE_{device} = \frac{Yield}{7 * AnnualProd} \sum_{equip,i=1}^{n} (InstallationCost + EquipCost)_i (EquipCount)_i$$

$$\frac{USD}{device} = \frac{1}{device} \sum_{i=1}^{n} \left(\frac{USD}{Equip}\right)_i \left[\frac{device/_{hr}}{device/_{(hr * equip)}}\right]_i$$

The equipment count per process step (EquipCount $_i$) is calculate as the ratio between annual device production (device/hr) and the annual device production per equipment (device/(hr*equip)) roundup to the next integer.

2.1.4 *Labor Cost (LC)*

Labor cost (LC) is calculate using the equipment required full time equivalent (FTE) provided by equipment vendors and assumptions of best engineering practice. Labor on all equipment and assembly steps is performed by a Technician III with prevailing annual wage of $50,000 plus fringe benefits of 50%.

$$LC_{device} = \frac{LaborRate}{AnnualProd} \sum_{equip,i=1}^{n} (EquipFTE)_i \, (EquipCount)_i$$

$$\frac{USD}{device} = \frac{USD/(year * man)}{device/year} \sum_{i=1}^{n} \left(\frac{man}{equip}\right)_i (equip)_i$$

Tool labor includes load, operation and cleaning of tools and equipment. The equipment count is calculated as indicated previously using equipment sharing. Using a roundup equipment count avoids underestimation of required personnel which may not have the required training to freely move across different process steps during equipment idle time.

2.1.5 *Process Consumables (PC)*

The process consumable (PC) needed per process step is calculated from information provided on equipment's specifications and adjusted accordantly by the utilization time of each equipment per process step. Since process steps are determine based on the complexity of the desired microchannel network the rate of consumables per device adjusts automatically to reflect cost per device base in equipment utilization time per process step.

$$PC_{device} = \sum_{consm,i=1}^{m} \sum_{equip,j=1}^{n} \sum_{step,k=1}^{o} (ConsmPrice * EquipConsmRate)_{i,j,k}$$

$$\frac{USD}{device} = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k\ =1}^{o} \left(\frac{USD}{ConsmUnit} * \frac{ConsmUnit}{device} \right)_{i,j,k}$$

Bulk quotes were obtained for each consumable and considered constant for different production volumes.

2.1.6 *Process Utilities (PU)*

Process utilities (PU) is the sum of all utilities cost for each process step. It is calculated using equipment specifications and duration of each process step per equipment. Similar than process consumables, the process utilities cost per device adjusts automatically according to the complexity of the microchannel device. Material properties and equipment efficiency are taking into account to calculate required utility per device.

$$PU_{device} = \sum_{utility,i=1}^{m} \sum_{equip,j=1}^{n} \sum_{step,k=1}^{o} (UtilityPrice * EquipUtilityRate)_{i,j,k}$$

$$\frac{USD}{device} = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{o} \left(\frac{USD}{UtilityUnit} * \frac{UtilityUnit}{device} \right)_{i,j,k}$$

The price per unit of each utility is based on industrial local rates and waste water cost is estimated based on the water consumption rate.

2.1.7 *Maintenance Cost (MC):*

Maintenance cost (MC) as 4% the cost of capital equipment was assumed.

$$MC_{device} = \frac{4/100}{AnnualProd} \sum_{equip,i=1}^{n} (EquipCost)_i \, (EquipCount)_i$$

$$\frac{USD}{device} = \frac{1}{device} \sum_{i=1}^{n} \left(\frac{USD}{equip}\right)_i (equip)_i$$

The capital equipment used to calculate maintenance cost is the same equipment cost used to calculated capital cost as indicated above.

While the selected type of equipment can be used to produce devices of different dimension, materials and microchannel layout the results reported on this work correspond to a single product dedicated manufacturing facility. A trained reader can use the information presented here to estimate manufacturing cost of mixed production. Extra attention should be paid to idle labor and capital equipment utilization during cost estimation of mixed production to avoid inaccurate cost estimation.

2.2 Product Pricing

The methodology developed in this research work to estimate product pricing combined the previously outline bottom-up cost estimation with market expected rate of return, economic breakeven point and potential product substitutes. This section provides calculations details for each one of the tools used to obtained the needed information.

2.2.1 *Capital Asset Pricing Model (CAPM)*

Capital Asset Pricing Model (CAPM) establish that in a competitive market the risk premium is directly proportional to the average market risk and is expressed in terms of return rates as:

$$(r_e - r_f) = \beta(r_m - r_f)$$

Where r_e is the expected return rate, r_f is the risk-free rate, r_m is the average market return rate and beta (β) is the average market risk factor. The free-risk investment is given by US Treasury bonds, however due economic policies its current rate is considerably low. The US Federal Reserve considers that near zero short-term interest rates promotes financing and spending that stimulates economic growth that helps to stabilize the US economy and financial system (US Federal Reserve, 2014). The return of 5 years Treasury bonds on March 2014 was 1.65% and 0.02% for 3 month bonds (US Department of the Treasury, 2014). The average market return of mutual funds on diversify emerging markets on March 20104 was 11.17% for 5 years maturity and 6.56% for 3 month maturity (Yahoo Finance, 2014a).

The market risk (or beta) can be calculated from data of an equivalent company. Velocys Inc. is the current processor manufacturer that uses microchannel technology. However since its product line includes process design and catalyst development (Velocys, 2014) its beta does not represent properly the heat exchanger manufacturing market. The three main companies within the industrial goods sector and diversify machinery industry are Danaher Corp, Xylem Inc., and SPX Corp. These companies have stock beta coefficients and Market Capitalization of 1.18, USD $54.86B; 1.25, USD $7.06B; and 1.81, USD $4.58B respectively (Yahoo Finance, 2014b). Using the Market Capitalization average weighted beta of 1.23 was obtained.

Then the expected rate of return or CAPM of a heat exchanger manufacturing company considering maturity of 5 years and 3 months is given by

$$CAPM_{5y} = r_e = 2.65 + (1.23)(11.17 - 2.65) = 13.130\%$$

$$CAPM_{3m} = r_e = 0.02 + (1.23)(6.56 - 0.02) = 8.064\%$$

The higher CAPM at higher maturity illustrates that investors will obtain higher rate of by doing long time investments. Because it is expected that investors willing to finance that microchannel technology are accustom to higher rates returns the 13.13% was used on this work. In addition, it is also expected that investors would consider that this new technology haves an intrinsic higher risk and decide that higher beta (β = 3.0) should apply.

$$CAPM_{5y} = r_e = 2.65 + (3.00)(11.17 - 2.65) = 28.210\%$$

This work provides results for two risk scenarios, β of 1.23 (CAMP = 13.13%) and 3.00 (CAMP = 28.21%)

2.2.2 Net Present Value (NPV)

The calculation of Net Present Value (NPV) of the project allows to determine the economic breakeven price at which the initial investment is recover at a given project duration and an expected rate of return (CAPM) associate with a beta risk factor (β). Since in this research project economics of scale also affects the economic breakeven price the results presented in this work include teen different production rates, four project duration, and two beta risk factors.

The initial cash flows of the project was calculated as the sum of capital equipment (CE), capital building (CB) and operation cost (variable cost plus overhead) needed to achieve production during the first year.

$$C_0 = CapitalBuilding\&Equipment + AnnualProduction * (TotalCost)_{device}$$

$$C_o = 1.07 * CapitalBuilding\&Equipment + AnnualProd_j$$
$$* (1.25 * LaborCost + DirectCost)_i$$

The cash flows for the following years is given by the profit at the beginning of the year, calculated as sales income at the beginning of the year (coming from previous year sales) minus operation cost for the current year (incurred at the beginning of the year).

$$C_n = AnnualProd * Profit = AnnualProd * (Price - TotalCost)_{device}$$

Then with NPV = 0, the equation is solve to obtain the economic breakeven price.

$$NPV = 0 = C_0 + \sum_{t=1}^{years} \frac{(C_n)_t}{(1 + r_e)^t}$$

For this work it was assumed that all factors in the NPV equation remain constant during the duration of the project. The changes in the factor on the NPV equation due to variation during the life of the project can be estimate with a market analysis that is outside the scope of this project.

This economic breakeven price does not offer any economic incentive to enter the market and investors would consider this technology only if higher retail price are possible. At this point a reference market price is necessary to establish the economic feasibility of a dedicated manufacturing plant for the production of microchannel heat exchanger.

2.2.3 *Market Floor Price*

The retail price of products is determine using demand curves generates from market studies. These market studies allow companies to estimate how much premium price consumers are willing to pay for additional benefits their products. In the case of commodities, new companies that want to enter the market have to compete with the prices of well-established companies. However in the case of new-to-the-world products, companies has flexibility establishing the profit level that they want to achieve with a particular product.

While heat exchanger is a well-established technology widely used in all goods industries, some particular operating conditions and design constraints make microchannel heat exchanger technology the best technological choice. In those cases, such as temperatures of 900°C, microchannel technology heat exchangers have few product competitors. Flat-plate heat exchanger is the closest device that offer some of the benefits of microchannel heat exchangers such high surface area per mass unit, compact size, and high energy efficiency. Currently do not exist any commercially off-the-shelf flat-plate heat exchanger made of nickel superalloy that can tolerate high operating temperatures and highly corrosive environments. Because of flat-plate heat exchanger for this operating conditions are custom make they should have a relative high price. Available of-the-shelf flat-plate heat exchanger are made of stainless steel than can operate up to 150°C.

To estimate the minimum market price of a microchannel heat exchanger an equivalent flat-plate heat exchanger was selected as the potential product substitute. One alternative to estimate the retail price of a nickel superalloy (Ni) heat exchanger is to assume that the price increment, with respected to stainless steel (SS) heat exchanger, is only due to additional raw material cost. In this approach all other cost categories involve during the fabrication of the nickel supperalloy heat exchanger are assume constant.

$$UnitPrice_{Ni} = UnitPrice_{SS} - RawMaterial_{SS} + RawMaterial_{Ni}$$

The raw material ($RawMaterial_i = Price_i * Density_i * DeviceVolume$) is calculated from market price of the raw material, material density, and device volume.

Since the strong nature of nickel supperalloys decreases equipment throughput and increases manufacturing cost along all cost categories, another technique to estimate price is to assume that the fabrication increases proportionally to the raw material cost. However since not fabrication cost are available, the price estimation assuming only raw material contribution correspond to the market floor price because all processing times and operating cost for nickel manufacturing of a device made of supperalloy are underestimated by assuming similar to those of stainless steel. This price estimation corresponds to an equivalent competitive technology and does not provide information of the premium price (market ceiling) that customer are willing to pay for a microchannel heat exchanger. Due to the process parameter at which heat exchanger are operated Life Cycle analysis and Total Cost of Ownership are necessary to estimate the ceiling price.

3 RESULTS AND DISCUSSION

Since microchannel technology provides energy and material cost saving benefits the development of manufacturing cost models and technology valuation (pricing methodology) are necessary steps to promote R&D that facilitate introduction of the new technology in the market place. Following a simple differentiation strategy has lead microchannel technology into slow growth and unwanted high manufacturing cost. To effectively decrease manufacturing cost it is necessary to implement continuous improvement costing strategies leading to design for manufacturing. As a result of this approach research at the Microproducts Breakthrough Institute (MBI) developed a new microchannel heat exchanger design based on laser-welding technology, named high temperature microchannel recuperator (half-array HTMR).

While the cost and pricing methodology outlined in Chapter 2 can be apply to any microchannel device, the results presented in this chapter correspond to manufacturing of half-array HTMR made of Haynes 213 with a heat duty capacity of 15 kilo-watts.

3.1 Product Costing

Results of the bottom-up cost model are used by design engineers to identify cost saving before the device is send out to the production line. Cost model results of the seven cost categories for the manufacturing of half-array HTMR as a function of annual device production are shown in Table 1. The constant cost of raw material and utilities is because average bulk prices were used in this model. While it is possible to negotiate volume discount for raw material and consumables, in was assumed for this model constant values for all production rates. The sum of all cost categories presented in Table 1 correspond to the cost of goods sold (COGS) use in accounting to prepared financial statements.

Table 1. Cost model results of the seven cost categories for the manufacturing of half-array HTMR as a function of annual device production.

Annual Production	Labor	Equip	Consum.	Raw Materials	Maint.	Facilities	Utilities	COGS (total)
50	$9,750	$6,937	$5,549	$1,527	$1,498	$103	$8.35	$25,372
100	$4,875	$3,469	$2,848	$1,527	$749	$52	$8.35	$13,527
200	$2,438	$1,734	$1,497	$1,527	$375	$26	$8.35	$7,604
500	$975	$694	$687	$1,527	$150	$10	$8.35	$4,051
1,000	$488	$347	$417	$1,527	$75	$5.15	$8.35	$2,866
2,000	$244	$173	$282	$1,527	$37	$2.58	$8.35	$2,274
5,000	$98	$69	$201	$1,527	$15	$1.03	$8.35	$1,919
10,000	$49	$35	$174	$1,527	$7.49	$0.52	$8.35	$1,800
20,000	$24	$17	$161	$1,527	$3.75	$0.26	$8.35	$1,741
50,000	$14	$11	$152	$1,527	$2.33	$0.17	$8.35	$1,715

Efforts to decrease COGS should focus on cost categories that are highly impacted by production volume. Table 1 shows that at increasing production volumes the cost driver changed from equipment and labor to consumables. Cost categories and capital equipment utilization for manufacturing of half-array HTMR as a function of annual device production are shown in Figure 1. Capital equipment utilization show in Figure 2 was calculated as

$$Capital\ Equip\ Utilization = \frac{\sum_{equip,i=1}^{n}(EquipCost * RawEquipCount)_i}{Total\ Equip\ Cost}$$

Where raw equipment count is the fraction count of equipment while total equipment cost is calculated rounding up to the next integer. Because of the differences in equipment throughputs is not expected that a dedicated production line operates at 100% capital equipment utilization.

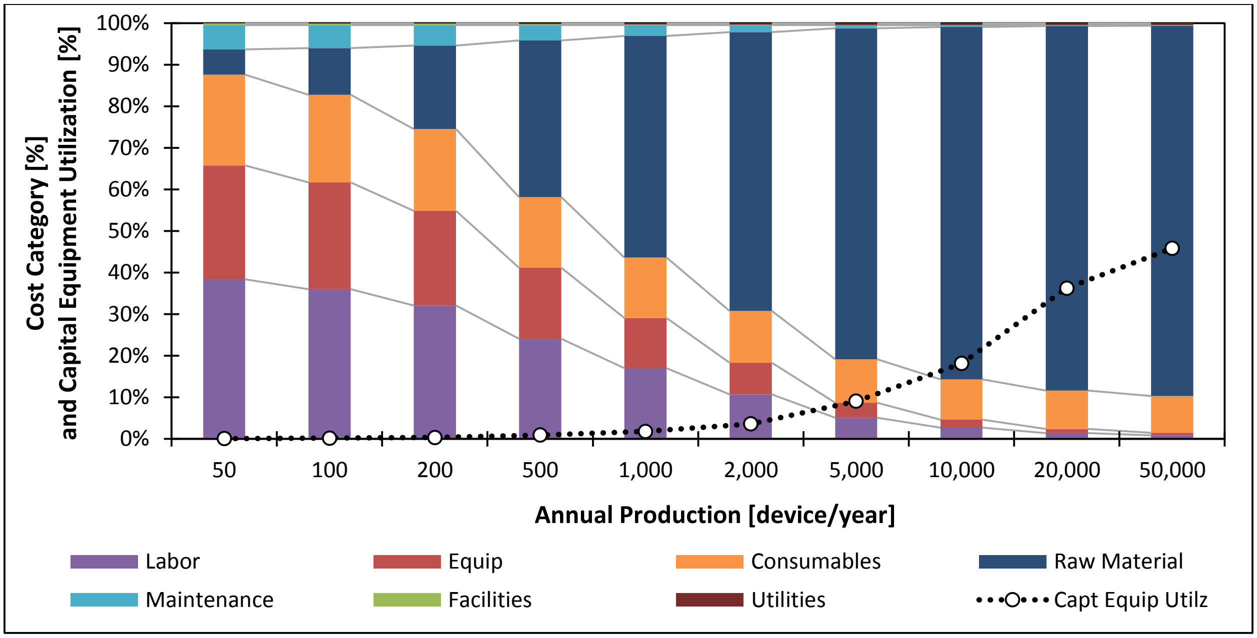

Figure 1. Cost categories and capital equipment utilization for manufacturing of half-array HTMR as a function of annual device production

Figure 1 illustrates that contribution of raw materials increases with increasing production rate. All other cost categories affected by economic scales decreases with increasing production. To this point the contribution effect of capital equipment utilization still unclear, while it is anticipated that low capital equipment utilization decreases profits, having plant capacity that allows potential future growth may have financial benefits.

To facilitate Pareto analysis of the cost categories that are function of production rate, raw material and utilities are removed from the analysis because both categories are independent of production rates. Remaining cost categories are normalized to illustrate the ratio change with respect to other cost categories. Normalized cost contributions of selected cost categories and capital equipment utilization for manufacturing of half-array HTMR as a function of annual device production are shown in Figure 2.

As discussed previously, Figure 2 illustrates the underutilization level of the plant and changes in cost drivers from equipment and labor to consumables at increasing production volume. Because the contribution of consumables increases as the production rate increase a strategies toward identification of operation parameters leading to decrease consumables should be consider.

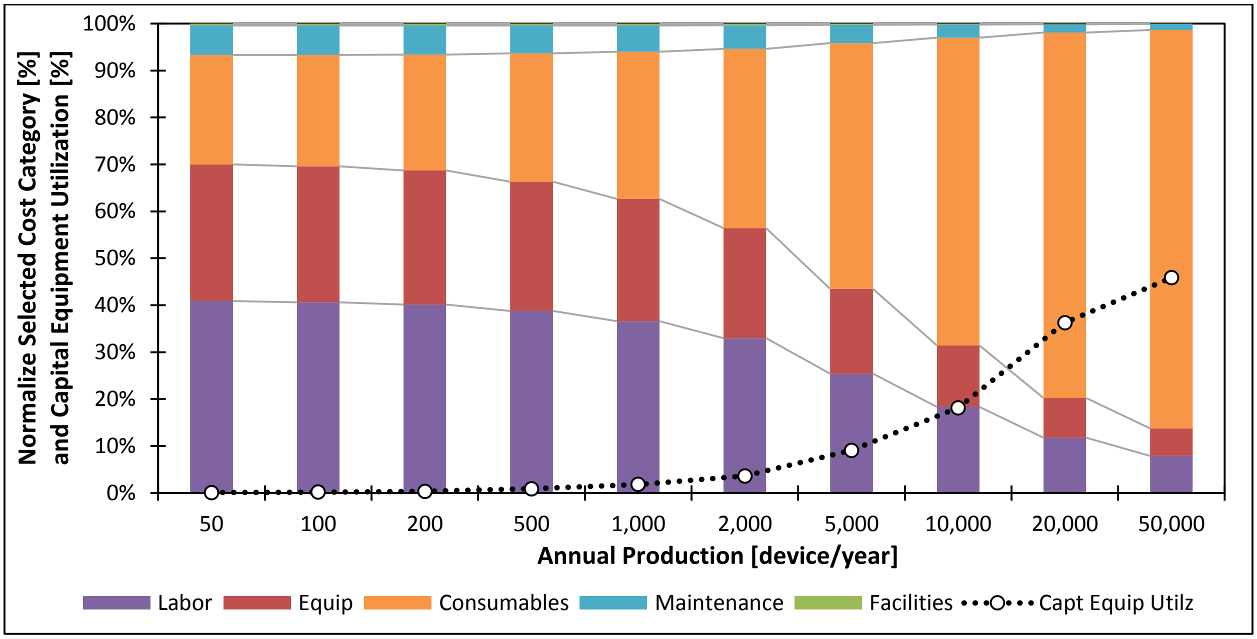

Figure 2. Normalized cost contributions of selected cost categories and capital equipment utilization for manufacturing of half-array HTMR as a function of annual device production.

One strategy to increase equipment utilization is to reduce plant capacity to operate a higher capital equipment utilization for any given production rate. The result of the bottom-up cost model shows that the plateau on capital equipment utilization for this single product dedicated manufacturing production line occurs at 75.35%. Differences in equipment throughput and equipment sharing restriction prevent the capital equipment utilization to reach 100%. Assuming that the process line can be optimize to achieve maximum plant capacity at an equipment utilization of 80% the manufacturing plant was scale-down using the exponential method (Perry & Green, 1997, pp. 9–67) also known as the rule of six-tents.

$$Cost_{new} = Cost_{old}\left(\frac{Equip\ Capacity_{new}}{Equip\ Capacity_{old}}\right)^{0.6}$$

$$= Cost_{old}\left(\frac{Equip\ Capacity_{new}/Capital\ Equipment\ Utilization_{new}}{Equip\ Capacity_{old}/Capital\ Equipment\ Utilization_{old}}\right)^{0.6}$$

Since in this case old and new equipment capacity are the same, the scale-down cost of the equipment is given by

$$Cost_{new} = Cost_{old}\left(\frac{Capital\ Equipment\ Utilization_{old}}{80\%}\right)^{0.6}$$

Capital cost, COGS, and capital equipment utilization of a manufacturing plant for half-array HTMR as function of annual production are shown on Table 2. The rule of six-tents described above affects equipment, facilities and maintenance cost categories while consumables, labor, utilities, and raw materials remain the same because are function of production volume. One can argue that labor utilization should also be scale-down along with the equipment, however this condition would require cross-trained employees that can move freely across equipment and process steps. Since this model was developed for high production rates, to simplify this model it was assume that a high production rates free movement of employees was unnecessary and restricted by specialized labor skills.

To scale-down the manufacturing plant it was assumed that equipment with lower throughput is commercially available and that the six-tenth rule is valid in these production range. These results illustrate that at the same capital equipment utilization, COGS and capital cost are not linearly correlated because of the exponential character of the six-tenth rule and the different depreciation rates of building and equipment.

Table 2. Capital cost, COGS, and capital equipment utilization of a manufacturing plant for half-array HTMR as function of annual production volume.

Annual Production	Capital Cost	Capital Cost* (scale-down)	COGS	COGS* (scale-down)	(COGS*) / COGS	Capital Equipment Utilization
50	$2,556,818	$43,683	$25,372	$16,985	66.94%	0.09%
100	$2,556,818	$66,211	$13,527	$9,373	69.29%	0.18%
200	$2,556,818	$100,357	$7,604	$5,557	73.07%	0.36%
500	$2,556,818	$173,904	$4,051	$3,257	80.41%	0.91%
1,000	$2,556,818	$263,590	$2,866	$2,485	86.70%	1.81%
2,000	$2,556,818	$399,527	$2,274	$2,095	92.14%	3.63%
5,000	$2,556,818	$692,325	$1,919	$1,858	96.80%	9.07%
10,000	$2,556,818	$1,049,369	$1,800	$1,776	98.64%	18.13%
20,000	$2,556,818	$1,590,546	$1,741	$1,734	99.57%	36.27%
50,000	$3,885,902	$2,782,142	$1,715	$1,711	99.80%	45.84%

It is expected that lower capital cost increases the internal rate of return (IRR) and allows lower economic breakeven prices. Due to the increase in capital equipment utilization by downsizing the manufacturing plant the COGS at 1,000 units per year is 86.7% of the COGS of an underutilize plant, representing cost reduction of 13.3%. However doubling the production rate to 2,000 units per years offer cost reduction of 7.86%. Investors and process engineers should consider the financial value of having excess capacity that facilitate future company growth.

3.2 Product Pricing

The price of a half-array HTMR was determine using three different tools: (1) Capital Assets Pricing Model (CAPM) to estimate expected rate of return at two beta risk factors; (2) Net Present Value (NPV) to calculate the economic breakeven price given expected rate of return, duration of the project and annual production rate; and (3) estimation of the retail price of a potential product substitute to establish the reference point with the current market.

Economic breakeven price for fabrication of half-array HTMR as a function of annual production rate, risk factor (β), and project duration for original and scale-down manufacturing plant size are shown in Table 3. While all these prices generates positive cash flows necessary to maintain in operation and recover the initial investment they do not provide any economic benefit to justify the investment in the technology.

As expected, these results indicate that for both risk factors and both size of the manufacturing plant the economic breakeven price decreases with increasing production rate and duration of the project. The results also shows that the economic breakeven price increases with increasing beta risk factor and decreases if capital equipment utilization increases. The trend at all conditions was as expected and none unusual behavior was observed in the results of the economic breakeven price calculation.

To be able to calculate the additional financial benefit that should came along with the investment in high-tech it is necessary to establish a reference point within the market. Without a market baseline is impossible to estimate cash flows that determine the profitability of a manufacturing plant. Currently it is not an available off-the-shelf heat exchanger that can withstand the operating conditions for which the nickel superalloy microchannel heat exchanger was designed for. The closest equivalent equipment is a flat-plate heat exchanger of 17.6 kwatts in stainless steel 316 (Bell & Gossett, Model BPNR415-28 LCA) quoted online for USD $2,575.00 with the industrial vendor Grainger. While this flat plate heat exchanger has similar duty than the half-array HTMR it can operates unto 150°C. Other technical specifications are 24.38 pounds, 0.566 sq. ft. surface area per plate, 0.0273 gallons per channel, 435 psig design pressure, 28 plates.

Table 3. Economic breakeven price for fabrication of half-array HTMR as a function of annual production rate, risk factor (β), and project duration for original and scale-down manufacturing plant size.

	Original Manufacturing Plant Size							
	β = 1.23				β = 3.00			
Annual Rate	**3 years**	**5 years**	**10 years**	**20 years**	**3 years**	**5 years**	**10 years**	**20 years**
50	$70,277	$58,409	$49,888	$46,327	$79,855	$67,901	$60,329	$58,312
100	$36,337	$30,285	$25,941	$24,125	$41,220	$35,125	$31,264	$30,236
200	$19,366	$16,224	$13,967	$13,024	$21,902	$18,737	$16,732	$16,198
500	$9,184	$7,786	$6,783	$6,364	$10,312	$8,904	$8,013	$7,775
1,000	$5,790	$4,974	$4,388	$4,143	$6,448	$5,627	$5,106	$4,967
2,000	$4,093	$3,568	$3,191	$3,033	$4,517	$3,988	$3,653	$3,564
5,000	$3,075	$2,724	$2,473	$2,367	$3,358	$3,005	$2,781	$2,721
10,000	$2,735	$2,443	$2,233	$2,145	$2,971	$2,677	$2,490	$2,441
20,000	$2,566	$2,302	$2,113	$2,034	$2,778	$2,513	$2,345	$2,300
50,000	$2,493	$2,242	$2,062	$1,986	$2,696	$2,443	$2,283	$2,240
	Scale-down Manufacturing Plant Size							
	β = 1.23				β = 3.00			
Annual Rate	**3 years**	**5 years**	**10 years**	**20 years**	**3 years**	**5 years**	**10 years**	**20 years**
50	$41,842	$37,666	$34,668	$33,415	$45,193	$40,987	$38,321	$37,609
100	$22,248	$20,009	$18,401	$17,729	$24,046	$21,790	$20,360	$19,978
200	$12,420	$11,157	$10,250	$9,871	$13,434	$12,162	$11,355	$11,140
500	$6,490	$5,822	$5,342	$5,141	$7,027	$6,353	$5,927	$5,813
1,000	$4,495	$4,030	$3,696	$3,556	$4,868	$4,399	$4,103	$4,023
2,000	$3,484	$3,124	$2,866	$2,758	$3,773	$3,411	$3,181	$3,119
5,000	$2,865	$2,571	$2,361	$2,273	$3,101	$2,805	$2,617	$2,567
10,000	$2,651	$2,382	$2,188	$2,107	$2,867	$2,596	$2,424	$2,378
20,000	$2,539	$2,283	$2,099	$2,022	$2,744	$2,487	$2,323	$2,280
50,000	$2,481	$2,233	$2,055	$1,981	$2,680	$2,431	$2,272	$2,230

Assuming that this corrugated flat plate heat exchanger can be fabricated with nickel superalloy it would be the product substitute for the half-array HTMR. One option to estimate the price of the product substitute is to assume that by changing the material from stainless steel to nickel superalloy all other cost categories would maintain the same. In this case the retail price would increase from USD \$2,575.00 to USD \$6,827.93.

$$UnitPrice_{Ni} = UnitPrice_{SS} - RawMaterial_{SS} + RawMaterial_{Ni}$$
$$= \$2{,}575.00 - \$308.80 + \$4{,}561.73 = \$6{,}827.93$$

A second option to estimate the price of the product substitute is to use the cost-to-material ratio (cost/material cost). This technique is preferred because it assumes that fabrication time and operation cost is proportional to material cost. Additional resources needed to handle high-priced materials are propagated proportionally through the calculations. However in this case production costs, profit margin, distribution cost, and overhead costs are unknown. The estimate price using a price-to-material ratio, rather than a cost-to-material ratio, produces an overestimated retail price that is 5.6 times higher than the retail price assuming similar processing times and operation cost.

$$UnitPrice_{Ni} = UnitPrice_{SS} * \left(\frac{RawMaterial_{Ni}}{RawMaterial_{SS}}\right) = \$2{,}575.00 * \left(\frac{\$4{,}561.73}{\$308.80}\right) = \$38{,}093.04$$

The reason for the higher estimated price using a price-to-material ratio is because every item on the value chain is change proportional to material cost, which is not the real case. Therefore in this work it is assumed that the market floor price (USD \$6,827.93) is obtained by considering similar processing times and operation cost for those of stainless steel.

The results in Table 3 shows that all conditions at production rate equal or higher than 1,000 units per year the economic breakeven price is lower than the market floor price. Economic breakeven price and equipment capital utilization for manufacturing of half-array HTMR as a function of annual device production, excess plant capacity and beta risk factor for a 3 years project duration are shown in Figure 3.

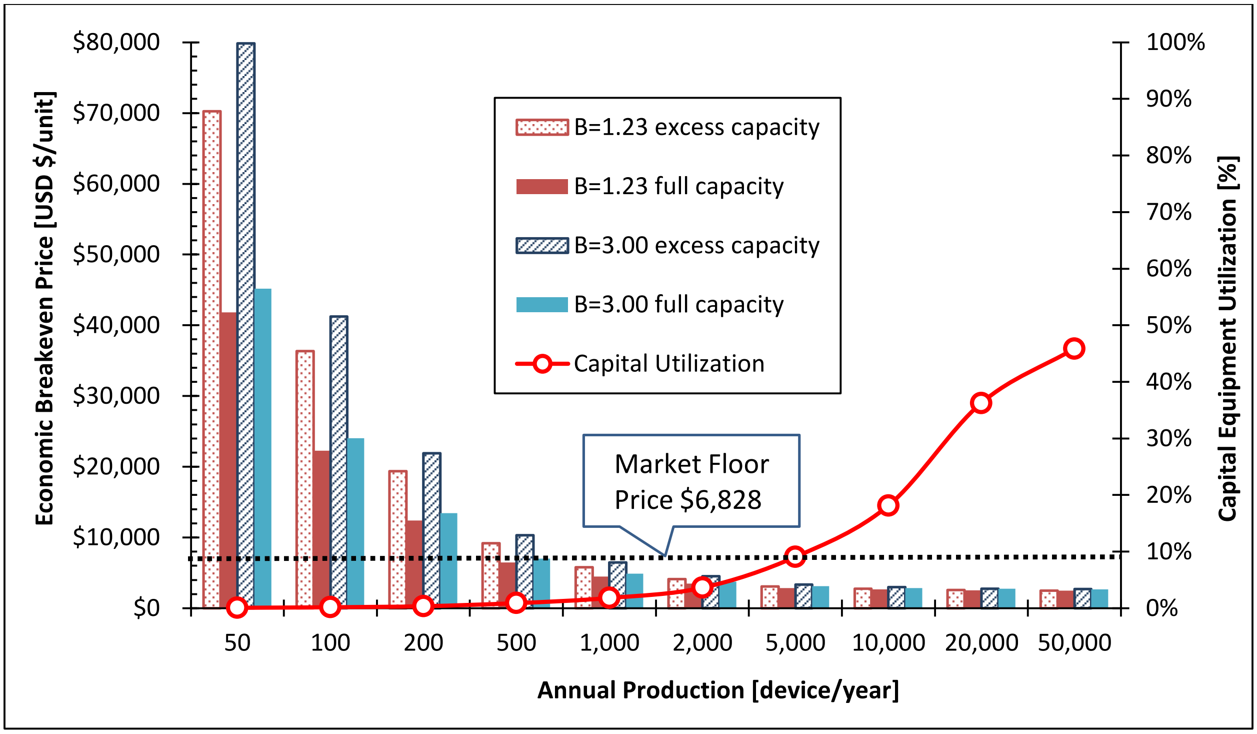

Figure 3. Economic breakeven price and equipment capital utilization for manufacturing of half-array HTMR as a function of annual device production, excess plant capacity and beta risk factor for a 3 years project duration

The plotted results illustrated the production rate at which the economic breakeven price crosses the market floor price. Only conditions on which the economic breakeven point is below the market floor price provides potential economic benefits. This also indicates that a production rate of 1,000 units per year and 1.81% capital equipment utilization manufacturing of half-array

HTMR has the potential to generate profits. For low production rates increasing the beta risk factor from 1.23 to 3.00 increases the breakeven price in a smaller proportion that it does to increase the plant excess capacity. However compare to low production rates, this difference is smaller at high production rates because the original manufacturing facility was designed to operate a higher capital equipment utilization rate as is illustrated in Figure 3.

Table 4 shows the Internal Rate of Return (IRR) for fabrication of half-array HTMR as a function of annual production rate, selling price, and project duration for original and scale down manufacturing plant size (Market floor price USD $6,827.93.) The table illustrates that each combination of production rate and project duration generates different internal rates of return (IRR) according to the retail selling price per unit. The increasing trend of the IRR is due to (1) increasing production rates because total manufacturing cost is favored by economics of scale; (2) increasing project duration because the initial investment is recover at lower rate per year; and (3) increasing price because profit per device increases. In addition, these results indicates that at increasing project duration and production rate the IRR becomes less sensitive to capital utilization. However since the capital utilization increased as the production rate increases additional studies leading to identify the value of excess plant capacity should be perform to facilitate production growth.

Investors should consider projects conditions for which the IRR is higher than the expected rate of return because it produce a financial benefits. Only one of the results presented in Table 4 has IRR lower than 3.13% ($\beta = 1.23$) and five conditions are lower than 28.21% ($\beta = 3.00$). All these unwelcome IRR occurred at production rates lower than 1,000 units per year. Since production rate equal or higher than 1,000 units per years produce economic benefits the following section focus in identify the root of economic differences between production rates of 1,000 and 50,000 units per years at project duration of 3 years.

Table 4. Internal Rate of Return (IRR) for fabrication of half-array HTMR as a function of annual production rate, selling price, and project duration for original and scale down manufacturing plant size (Market floor price USD $6,827.93.)

	Original Manufacturing Plant Size							
	Price = 1 x (floor price)				Price = 2 x (floor price)			
Annual Rate	**3 years**	**5 years**	**10 years**	**20 years**	**3 years**	**5 years**	**10 years**	**20 years**
50	-	-	-	-	-	-	-	-
100	-	-	-	-	-	-	-	-
200	-	-	-	-	-	-	11.23%	16.31%
500	-	-	13.73%	18.32%	68.96%	82.73%	86.83%	87.00%
1,000	36.51%	52.98%	59.60%	60.15%	167.45%	175.57%	176.68%	176.68%
2,000	100.77%	112.31%	114.92%	114.98%	291.10%	295.74%	296.05%	296.05%
5,000	183.09%	190.61%	191.53%	191.53%	460.11%	462.67%	462.75%	462.75%
10,000	230.80%	236.81%	237.35%	237.36%	560.58%	562.49%	562.53%	562.53%
20,000	262.23%	267.46%	267.86%	267.86%	627.33%	628.93%	628.96%	628.96%
50,000	277.34%	282.25%	282.60%	282.60%	659.38%	660.87%	660.89%	660.89%
	Scale-down Manufacturing Plant Size							
	Price = 1 x (floor price)				Price = 2 x (floor price)			
Annual Rate	**3 years**	**5 years**	**10 years**	**20 years**	**3 years**	**5 years**	**10 years**	**20 years**
50	-	-	-	-	-	-	-	-
100	-	-	-	-	-	-	-	-
200	-	-	-	-	31.29%	48.23%	55.38%	56.06%
500	22.68%	40.41%	48.53%	49.46%	183.28%	190.79%	191.71%	191.71%
1,000	97.78%	109.51%	112.23%	112.29%	312.18%	316.45%	316.70%	316.70%
2,000	162.19%	170.54%	171.71%	171.72%	432.84%	435.62%	435.72%	435.72%
5,000	223.60%	229.81%	230.40%	230.40%	552.23%	554.18%	554.23%	554.23%
10,000	252.44%	257.90%	258.34%	258.34%	609.55%	611.22%	611.26%	611.26%
20,000	270.33%	275.39%	275.76%	275.76%	645.63%	647.16%	647.19%	647.19%
50,000	281.34%	286.17%	286.51%	286.51%	668.41%	669.87%	669.89%	669.89%

Cash flows (in millions) and IRR for a three years project of an original size and a scale-down manufacturing plant for production of half-array HTMR at 1,000 and 50,000 units per year (Market floor price USD $6,827.93) are show in Table 5. Selected results of Table 3 and Table 4 are summarized in Table 5 to facilitate analysis of IRR and capital equipment utilization.

Table 5. Cash flows (in millions) and IRR for a three years project of an original size and a scale-down manufacturing plant for production of half-array HTMR at 1,000 and 50,000 units per year (Market floor price USD $6,827.93.)

Capital Equipment Utilization & (units/year)	Price Base	$/unit	Cash Flow Year 0	Cash Flow Years 1 to 3	IRR
Original size 1.8% Utilz. (1,000)	β = 1.23	$5,790	($5.86)	$2.49	13.13%
	β = 3.00	$6,448	($5.86)	$3.15	28.21%
	1.0 x Floor Price	$6,828	($5.86)	$3.53	36.51%
	1.5 x Floor Price	$10,242	($5.86)	$6.94	104.59%
	2.0 x Floor Price	$13,656	($5.86)	$10.35	167.45%
Scale down 80.0% Utilz. (1,000)	β = 1.23	$4,495	($3.34)	$1.42	13.13%
	β = 3.00	$4,870	($3.34)	$1.79	28.21%
	1.0 x Floor Price	$6,828	($3.34)	$3.75	97.78%
	1.5 x Floor Price	$10,242	($3.34)	$7.17	207.09%
	2.0 x Floor Price	$13,656	($3.34)	$10.58	312.18%
Original size 45.8% Utiliz. (50,000)	β = 1.23	$2,493	($90.25)	$38.31	13.13%
	β = 3.00	$2,696	($90.25)	$48.45	28.21%
	1.0 x Floor Price	$6,828	($90.25)	$255.04	277.34%
	1.5 x Floor Price	$10,242	($90.25)	$425.73	469.19%
	2.0 x Floor Price	$13,656	($90.25)	$596.43	659.38%
Scale-down 80.0% Utilz. (50,000)	β = 1.23	$2,481	($89.05)	$37.80	13.13%
	β = 3.00	$2,681	($89.05)	$47.80	28.21%
	1.0 x Floor Price	$6,828	($89.05)	$255.13	281.34%
	1.5 x Floor Price	$10,242	($89.05)	$425.83	475.69%
	2.0 x Floor Price	$13,656	($89.05)	$596.53	668.41%

Table 5 shows that for each plant size at constant production volume the initial capital investment remained constant while the IRR and cash flow of following years increases proportional to the selling price due to higher profits. The IRR increases with increasing production volume because economics of scale as indicated by the two production rates with similar capital equipment utilization; however because of the different capital equipment utilization of the original manufacturing plant the IRR is penalize by the excess capacity decreasing its IRR. However the low excess capacity does not move the investment in the technology into a no-go category, other hand it indicates a profit potential business with an installed growth capacity.

In addition, this shows that improving plant utilization at low production rates increases business profitability. While the six-tenth rule allowed to adjust the plant capacity to be able to compare manufacturing lines with similar capital equipment utilization the scale-down technique should be incorporate into the bottom-up cost model at the process step level to prevent bottleneck in the production line and improve equipment count and building size.

Relationship between sell price and IRR for manufacturing of half-array HTMR for production rates of 1,000 and 50,000 units per year are shown in Figure 4. Since there are not current off-the-shelf product substitutes for the half-array HTMR the region with economic interest is located above the market floor price. The data from Table 5 plotted in Figure 4 illustrates the linear relationship between sell price and IRR discussed previously while the shaded region corresponds to the region of excess capacity which is a contributing factor of lower IRR. Dotted lines represent the condition with excess capacity and the solid lines the 80.0% capacity utilization.

Since variable production cost remain constant for a given production rate, changes on curve’s slope are due to the effect of plant size (excess capacity) in fixed production cost and initial capital investment. This effect on IRR due to excess capacity is reduce by the effect of economics of scale at higher production rates.

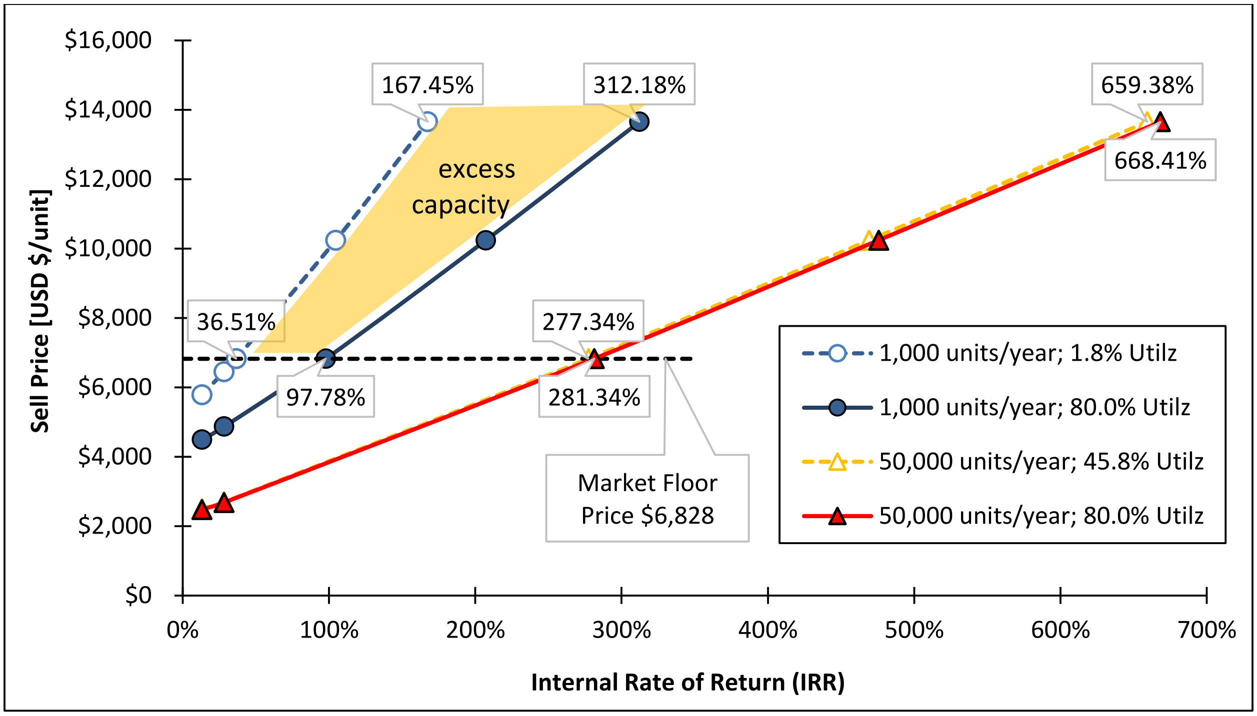

Figure 4. Relationship between sell price and IRR for manufacturing of half-array HTMR for production rates of 1,000 and 50,000 units per year.

Relationship between IRR and production rate for manufacturing of half-array HTMR for production rates of 1,000 and 50,000 units per year is shown in Figure 5. In an effort to linearize the relationship between IRR and production rate results were plotted in a semi-log chart. As in Figure 4, the shaded region corresponds to the region of excess capacity which is a contributing factor of lower IRR. Dotted lines represent the condition with excess capacity and the solid lines the 80.0% capacity utilization. Figure 5, illustrates the asymptotic character of the IRR with higher production rates independent of the capacity utilization of the manufacturing plant. The not linear nature of the relationship between IRR and production rate is attributed to economics of scale and it is assumed that the market has the capacity to absorb the increasing production.

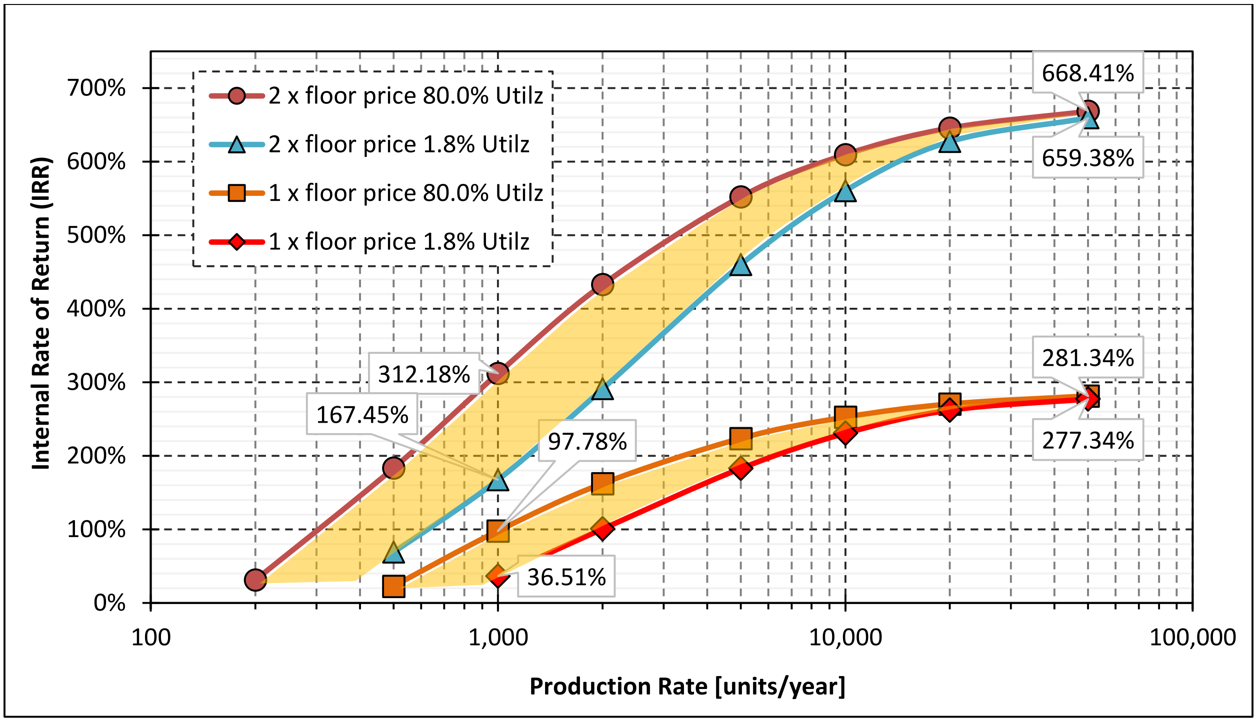

Figure 5. Relationship between IRR and production rate for manufacturing of half-array HTMR for production rates of 1,000 and 50,000 units per year.

In addition, these results illustrates that for half-array HTMR, product price is the leading factor of IRR. Since price strategy is the main contributor to IRR, a market study leading to determining a demand curve necessary to value the technology during development of business plans or licensing negotiations.

3.3 Business Strategy and Porter Competitive Forces

The low adoption of microchannel heat exchanger in the industrial sector suggest that the several advantages of the technology compare with traditional shell and tube heat exchangers are not enough to promote significant interest in the technology. The low adoption of the technology has been attributed (Leith et al., 2010) to the high manufacturing cost. As a competitive scope business strategy, microchannel technology can provide cost effective alternatives to traditional units operations with higher total cost of ownership cost. The several cases in which microchannel technology can be apply to decrease power requirement while achieving optimal driving forces, suggest that a manufacturing facility for development and fabrication of microchannel technology should select an integrated cost leadership differentiation business strategy.

To successfully implement an integrated cost leadership business strategy the business entity should be able to:

1. **Adapt quickly to environmental changes.** The emerging market created by the shell gas exploration and reduction on fossil fuel dependency are among the two environmental changes that will favor the commercialization of microproduct technology.
2. **Learn new skill and technology more quickly.** Among the new skills that the company needs to learn is laser-welding and 3D printing technology in particular metal laser sintering. The advances on metal laser sintering technology allows fast fabrication of metal prototypes with equivalent network of microchannel of those of a device made by traditional bonding of patterned layers. While 3D printing would not the primary mass production technique, it would facilitate the development and testing of new microchannel devices. In the case of laser-welding the company should develop required operation knowledge to increase manufacturing yields to tolerable rates for several types of material and thicknesses.
3. **Effectively leverage its core competencies while competing against its rivals.** Leverage in area of product testing and extreme operation conditions is necessary to test proof-of-

concept and validate equipment designs with robust testing protocols using appropriate design of experiment (DOE) techniques within the right statistical framework.

The integrated cost model and pricing methodology outlined in this work provides real-time manufacturing feedback by integrating manufacturing production methodologies and process engineering. This developed bottom-up estimation tool, facilitates design-for-manufacturing at the same time that allows identification of new R&D areas.

Within the framework of Porter Five Competitive Forces, a business entity that manufacture microchannel heat exchangers would face the following competitive forces:

1. **Threat of new entrants.** Will be minimum if existing technologies barriers regarding know-how still in place. For example the technology of the half-array HTMR is protected by a U.S. Patent and the know-how has been restricted to researchers at the Microproducts Breakthrough Institute. In addition the high cost of a dedicated manufacturing line that required high capital investment can potentially be substitute at low production rates by laser-sintering technology.
2. **Threat of substitute products or services.** Since flat-plate heat exchangers have a similar operation advantages than those of microchannel technology, improvements on the flat-plate heat exchanger technology can considerably reduce the total cost of ownership while compare to microchannel based products. A medium threat of product substitute should be consider.
3. **Bargaining power of customers (buyers).** Will be high if substitute products enter the market, otherwise will be low. In the case of the half-array HTMR this threat is low

because currently manufacturing companies do not seems to show interest in developing low cost heat exchanger for high temperature applications. Power plants, solar thermal energy and fuel cell application will be among the industry sectors with this operating conditions. However the price of microchannel device should be low enough to allow competition with traditional commodities.

4. **Bargaining power of suppliers.** According to the London Metal Exchange, in the last five years price oscillation of nickel has been small. In addition due to increasing applications at high temperature new supper alloys formulation have been developed and introduce in the market place. However because it is only one supplier of nickel supperalloys a monopoly pricing strategy gives to the supplier a higher bargain power that will be difficult to overturn during volume price negotiations.
5. **Intensity of competitive rivalry.** At this point is minimum because few research centers (competitors) are working on developing bottom-up cost models that demonstrates the cost effective proposition of microchannel technology.

Potential application on which half-array HTMR can take significant market share includes solar thermal energy, solid oxide fuel cells, compact nuclear reactors, hydrocarbon cracking processes, high temperature reactors systems for production of ammonia, synthesis gas, ethylene glycol, among others.

4 CONCLUSIONS

The general objective of this research project is to develop a pricing methodology that allows valuation of microchannel based products with the following specific objectives:

(4) To provide real time feedback of product cost and price during the design stage.

(5) To develop a valuation methodology using suitable expected rate of return.

(1) To provide financial information that allows to identify strategies leading to development profitable business models.

The pricing methodology developed and implemented in this research work, to estimate product pricing combines a bottom-up cost estimation model with market expected rate of return, economic breakeven point and minimum retail price of potential product substitutes. Extrapolation of obtained result should consider the following assumption and limitations.

1. Cost, price, and production rates were considering constant during the duration of the project to calculate economic breakeven price and IRR.
2. Raw materials and process consumables are not taking benefits of volume negotiations leading to cost reductions. Bottom-up calculation of disposition cost of scrap metal and solid waste as well as recycling benefits are not included in the model.
3. While capital equipment utilization was used to scale-down the manufacturing plant, it was assumed that because of specialized labor requirements the equipment FTE remains the same after scale-down. While it may be possible to cross training employees to freely move them across equipment and process steps a methodology to down-scale labor would

be necessary. The bottom-up cost model was developed for high production rates in which free movement of employees is unnecessary and restricted by specialized labor skills.

4. Down-sizing of manufacturing plant was carried out to compare IRR at similar capital equipment utilization. Matching production rates with plant capacity is not always the best financial decision because it future expansion may impose additional capital investment that significantly decreases the IRR.

5. While the selected type of equipment can be used to produce devices of different dimensions, materials, and microchannel layout the results reported on this work correspond to a single product dedicated manufacturing facility. A trained reader using this information to estimate manufacturing cost of mixed production, should paid extra attention to idle labor and capital equipment utilization.

6. The result presented of this research project are based on minimum retail price (market floor price) and do not include premium retail price (market ceiling price) that customers are willing to pay for the half-array HTMR. Additional studies that include Life Cycle Analysis and Total Cost of Ownership are necessary to estimate the demand curves or retail ceiling prices.

The conclusions achieve during this research project are:

1. If cost of raw material is not considered, increasing production rate of half-array HTMR in a dedicated manufacturing plant changes cost driver categories labor and equipment to consumables. At higher production rates cost of raw materials is the driving cost.

2. Economic breakeven price of half-array HTMR decreases with increasing production rate, increasing duration of the project, increasing capital equipment utilization, and increasing beta risk factor.
3. Compare to a possible product substitute, retail price of half-array HTMR present economic benefits at production rates equal or higher than 1,000 units per year, beta risk factor equal or lower than 3.00, project duration equal or higher than 3 years and capital equipment utilization equal or higher than 1.81%.
4. At internal rate of return (IRR) of 36.51% is obtained by selling half-array HTMR at estimated minimum retail price for production rate of 1,000 units per years, 3 years project duration, and capital equipment utilization of 1.81%. Increasing any of these three parameters increases IRR.
5. Internal rate or return (IRR) for production of half-array HTMR has an asymptotic character with increasing production rate. Contribution due to increasing capital equipment utilization diminished with increasing production rate.
6. A business entity dedicated to the manufacturing and development of microchannel heat exchangers should implement an integrated cost leadership business strategy that adapt quickly to environmental changes, learn quickly new skills & technology, and effective leverage its core competencies.
7. On the framework of Porter Five competitive forces, a business entity dedicated to the manufacturing and development of microchannel heat exchangers has (1) low threat of new

entrants, (2) medium threat of product substitute, (3) low power bargain of customers, (4) high power bargain of suppliers and (5) minimum competitive rivalry.

The recommended future work leading to enhance the development of microchannel based products are:

1. Add volume pricing structure to raw material and consumables to favor accurate estimation at different production rates.
2. Develop market studies leading to generate demand curves that allow to estimate actual retail prices. Market study should include market segmentation due to different operating temperatures.
3. Enhance the capability of the pricing tool with demand curves that allow estimation of potential maximum IRR leading to development of accurate business plans and technology licensing negotiations.
4. Segregated COGS categories using accounting principles to provide all necessary elements needed to elaborate several kind of financial statements.
5. Maintain simplified data entry structure by including structured data bases that import several parameter linked to a singular user define parameter.
6. Maintain equipment cost updated by obtaining new vendor quotes or by standard methodology such as the Chemical Engineering Plant Cost Index (CEPCI).

5 REFERENCES

Acmite Market Intelligence. (2013). *Market Report: Global Heat Exchanger Market* (Market Report No. E1020). Retrieved from http://www.acmite.com/market-reports/environmentals/global-heat-exchanger-market-report.html

Alfa Naval. (2014). *Alfa Naval Annual Report 2013*. Retrieved from http://www.alfalaval.com/about-us/investors/Reports/annual-reports/Documents/Annual_report_2013.pdf

Brannon, S. (2013, June). *Development of an Economical High Temperature Microchannel Recuperator for Solid Oxide Fuel Cells*. Oregon State University, Corvallis, OR.

Denkenberger, D. C. (2010). *Low-cost high-effectiveness microchannel heat exchanger: Fabrication, modeling, and validation*. University of Colorado at Boulder.

Gao, Q. (2013, December). *An economic and environmental assessment model for microchannel device manufacturing*. Oregon State University, Corvallis, OR. Retrieved from http://hdl.handle.net/1957/44921

Khan, M. G., & Fartaj, A. (2011). A review on microchannel heat exchangers and potential applications. *International Journal of Energy Research*, *35*(7), 553–582.

Lajevardi, B., Leith, S. D., King, D. A., & Paul, B. K. (2011). Arrayed microchannel manufacturing costs for an auxiliary power unit heat exchanger. In *Proceedings of the 2011 Industrial Engineering Research Conference* (pp. 21–25).

Leith, S. D., King, D. A., & Paul, B. K. (2010). Toward Low-Cost Fabrication of Microchannel Process Technologies–Cost Modeling for Manufacturing Development. *Proc. 2010 AIChE Annual Meet., Salt Lake City, UT*.

Lu, B. (2013). *Metal-Based Microchannel Heat Exchangers: Manufacturing and Heat Transfer Testing*.

Mohammed, H., Bhaskaran, G., Shuaib, N., & Saidur, R. (2011). Heat transfer and fluid flow characteristics in microchannels heat exchanger using nanofluids: a review. *Renewable and Sustainable Energy Reviews*, *15*(3), 1502–1512.

Paul, B. K., & Paulraj, P. (2008, November). Microchannel structures having bonded layers including height control features.

Perry, R. H., & Green, D. W. (Eds.). (1997). Manufacturing Cost Estimation. In *Perry's Chemical Engineering Handbook* (Seventh., Vols. 1-30, Vol. 9). McGraw-Hill.

Sabharwall, P., Kim, E. S., Siahpush, A., Anderson, N., Glazoff, M., Phoenix, B., … Patterson, M. (2011). *Feasibility study of secondary heat exchanger concepts for the advanced high temperature reactor* (No. INL/EXT-11-23076). Idaho National Laboratory (INL).

TechNavio. (2013). *Global Heat Exchanger Market 2014-2018* (No. IRTNTR3098). Retrieved from http://www.technavio.com/report/global-heat-exchanger-market-2014-2018

Tuckerman, D. B., & Pease, R. F. W. (1981). High-performance heat sinking for VLSI. *Electron Device Letters, IEEE*, *2*(5), 126–129. doi:10.1109/EDL.1981.25367

US Department of the Treasury. (2014). *Daily Treasury Bill Rates Data*. Retrieved from http://www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/TextView.aspx?data=billrates

US Federal Reserve. (2014, March 10). Why are interest rates being kept at a low level? *Current FAQs*. Retrieved from http://www.federalreserve.gov/faqs/money_12849.htm

Velocys. (2014, March). Overview. *Our Products*. Retrieved from http://www.velocys.com/our_products_overview.php

Yahoo Finance. (2014a). *Mutual Funds*. Retrieved from http://finance.yahoo.com/market-overview/

Yahoo Finance. (2014b, March). Xylem Inc (XYL). *Company*. Retrieved from http://finance.yahoo.com/q?s=xyl