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Cost Comparison Modeling Between Current Solder Sphere Attachment Technology and Solder Jetting Technology

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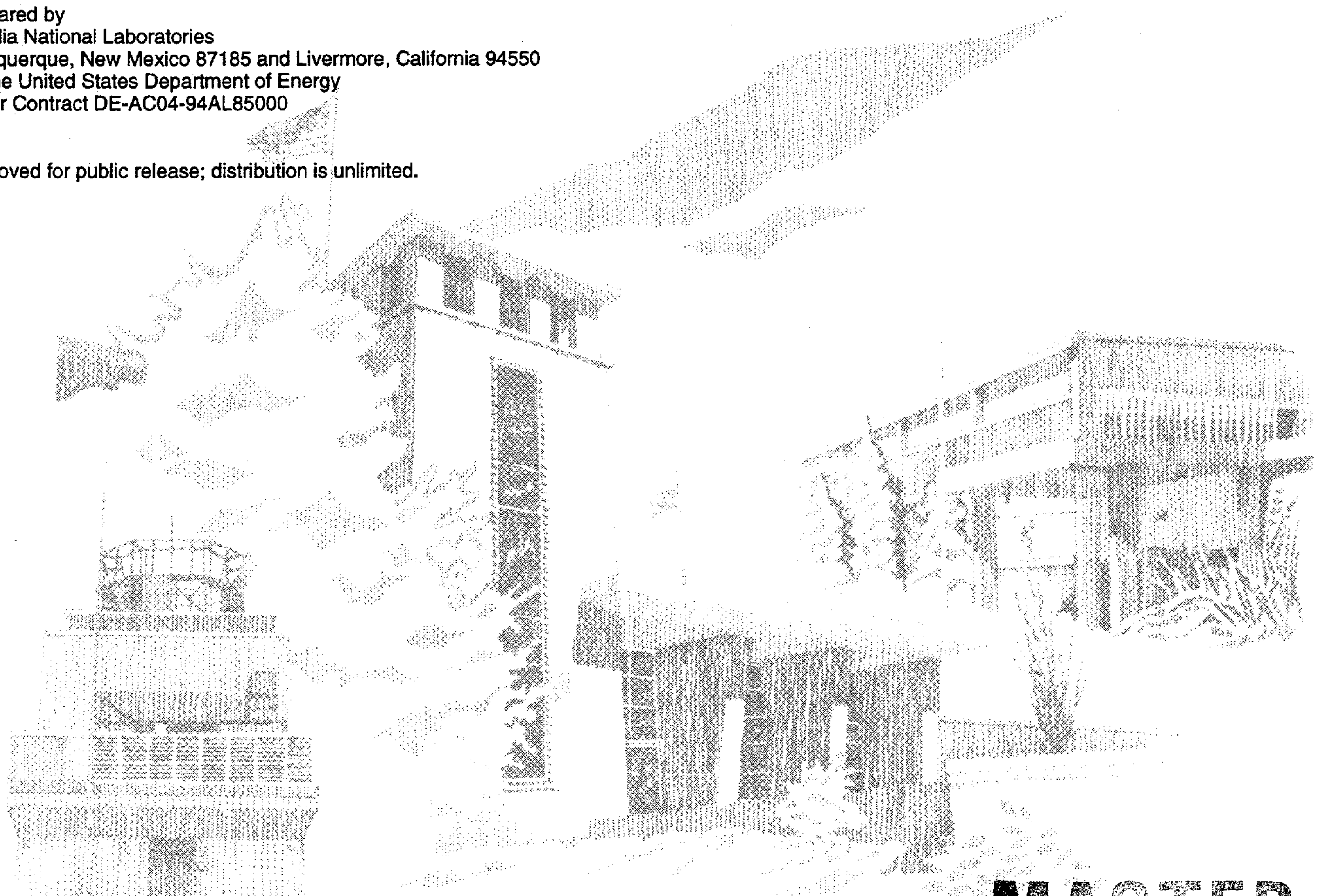

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COST COMPARISON MODELING BETWEEN CURRENT SOLDER SPHERE ATTACHMENT TECHNOLOGY AND SOLDER JETTING TECHNOLOGY

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Abstract

By predicting the total life-cycle cost of owning and operating production equipment, it becomes possible for processors to make accurate and intelligent decisions regarding major capitol equipment investments as well as determining the most cost effective manufacturing processes and environments. Cost of Ownership (COO) is a decision making technique based on inputting the total costs of acquiring, operating and maintaining production equipment. All quantitative economic and production data can be modeled and processed using COO software programs such as the Cost of Ownership Luminator program TWO COOL™. This report investigates the Cost of Ownership differences between the current state of the art solder ball attachment process and a prototype solder jetting process developed by Sandia National Laboratories. The prototype jetting process is a novel and unique approach to address the anticipated high rate BGA production requirements currently forecasted for the next decade. The jetting process, which is both economically and environmentally attractive, eliminates the solder sphere fabrication step, the solder flux application step as well as the furnace reflow and post cleaning operations.

Acknowledgment

Assistance and information provided by Sematech and Vanguard Automation Inc. was the cornerstone in developing the background data required to generate cost of ownership models for the solder sphere attachment process and the solder jetting process.

This author would also like to express his sincere thanks to both Susan Sackinger (department 1831) and Cathy Reber (department 1333). Their assistance in many of the details of the COO model and the base line input information were foundational in the creation of this report.

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COST COMPARISON MODELING BETWEEN CURRENT SOLDER SPHERE ATTACHMENT TECHNOLOGY AND SOLDER JETTING TECHNOLOGY

Introduction

Cost of Ownership (COO) is a decision making technique based on inputting the total costs of acquiring, operating and maintaining a piece of production equipment. All quantitative economic and production data can be modeled and processed using COO software programs such as the Cost of Ownership Luminator program TWO COOL™ which uses definitions and standards developed by Sematech. [1] By predicting the total life-cycle cost of owning and operating production equipment, it becomes possible for processors to make accurate and intelligent decisions regarding major capital equipment investments as well as determining the most cost effective manufacturing environments. The building blocks of COO modeling are extremely basic and can be applied to any manufacturing process. A COO metric can be expressed quantitatively as the sum of the fixed cost (Fc) plus the operating costs (Oc) plus the yield costs (Yc) divided by the throughput (T) multiplied by the composite yield (Y) multiplied by the utilization (U) or:

$$COO = \frac{(Fc + Oc + Yc)}{(TYU)}$$

The fixed costs (Fc) are normally defined as those expenditures associated with the purchase cost of a piece of equipment. They are typically the function of the purchase price, installation costs and the facilities overhead (normally the operation and depreciation of the process area or the space rate). The operating cost (Oc) or the production cost is the expense of operating the equipment in a production environment and the COO model breaks this down into five major areas: consumables, waste disposal, materials, maintenance, and personnel. Consumables would be considered utilities and supplies that would be consumed in the production process. Yield Costs (Yc) are those costs directly attributable to the performance characteristics of the manufacturing equipment. The yield cost is typically defined as the number of parts lost due to breakage times the value of the part at that point, plus the number of parts rejected by inspection due to process defects times the value of the part at the inspection point. Throughput (T) for this model was evaluated as the direct process time. The upstream time required to move material to the processing location was not factored into this model. The composite yield (Y) is the percentage of good units produced by the process and is expressed as a fraction while the Utilization (U) is the percentage of time the equipment is in operation (also expressed as a fraction) and is determined on a per week or per year basis. The COO metric is in dollars per unit and is defined as the cost per good unit equivalent. This metric is a stand alone metric and can be used in straight head to head comparisons when evaluating changes to process steps or when comparing existing processes to potentially new processes. The COO metric normally determines the cost per good unit equivalent over the lifetime of the equipment.[2]

Overview of Solder Sphere Attachment Process

As I/O requirements for discrete devices have increased, the strategies for packaging have moved from Dual In-line Packages (DIPs), to Peripheral Leaded Devices (PLDs), to Pin Grid Arrays (PGAs) and to Ball Grid Arrays (BGAs). Both PGAs (for through hole) and BGAs (for surface mount) provide high I/O to surface area ratios while also maintaining higher pitch spacing reducing potential problems with signal cross talk or solder bridging.

Currently Vanguard Automation, Motorola, Universal, Ultraclean International and Shibuya (Japan) are the major companies who have or are developing high speed solder ball placement systems. The total number of these high speed systems which will be in use in a production environment in the next year is estimated to be 60 systems with this number possibly increasing by five fold in the following five years. Any projections beyond this are valueless because of the rapidly changing technology.

The solder sphere attachment process evaluated in this paper is based on the VAI 5200 automatic solder ball placement system manufactured by Vanguard Automation. The VAI 5200 system is fully automated and operator handling is confined to BGA part transfer to and from the stockroom. The solder sphere attachment process involves the dispensing of a solder flux on the BGA package pads, the placement of solder spheres on the pads and furnace reflow of the solder. An in depth explanation of all of the process steps and a detailed description of the VAI 5200 system can be found on pages 5 and 6.

The VAI 5200 system is considered by the Sematech Package to Board Project Technical Advisory Board (PTAB) to be at the forefront of BGA ball placement technology. Based on this assessment, the development of a cost analysis model of the VAI 5200 system was recommended by the PT advisory board.

Although BGA packaging is still in its infancy, seventeen Vanguard VAI 5020 systems (nonautomated version of the VAI 5200), and one VAI 5200 system have been sold, with orders for 20 VAI 5200 systems already received. Vanguard indicated that of the seventeen VAI 5020 systems sold, the following Sematech member companies have purchased at least one VAI 5020 system: Hewlett-Packard, National Semiconductor, Rockwell International, Intel, Texas Instruments, and Motorola.

Overview of Solder Jetting Process

The solder jetting process could potentially be the next evolutionary step in the progression of solder attachment to BGA packages. The jetting process is a significant advance over the existing solder sphere attachment process since it eliminates the solder sphere fabrication step, the solder flux application step as well as the furnace reflow and post cleaning operations. The jetting process discussed in this paper would employ a modified version of the VAI 5200 system. Modifications to the existing VAI 5200 system would include removal of the fluxing equipment, replacement of the solder sphere gravity placement mechanism with a solder jetting head, the addition of a nitrogen blanket (to maintain an inert environment) and the addition of an internal preheat cell. The costs of the jetting system discussed in this report are estimated baseline engineering and manufacturing costs for a prototype system and should not be considered as the commercial cost.

Overview of Fluxless Soldering using Plasma Assisted Dry Soldering (PADS)

A novel upstream addition to the **solder jetting** process would be the use of an automated plasma etching system which would preclean the component surfaces and lower the surface activation energy by removing surface oxides and contaminants. This upstream step would allow direct solder jetting without the use of soldering fluxes and would also eliminate the need for a post cleaning system. Design and cost information on a high volume automatic PADS system was obtained from Integrated Electronic Innovations (IEI) and was used in developing the COO Solder Jetting model and is shown in tables 9 and 10.

The use of the PADS system could be beneficial in reducing soldering defects with the **solder ball** placement system but it could not be used as a replacement for the solder fluxing operation, since the flux is also used as an adhesive to hold the solder balls in place until solder reflow has occurred. Because there would be no significant cost savings with the use of a PADS system and the solder ball placement system, no COO model for this hardware configuration was generated.

Overview of Fluxless Soldering using an Organic Inhibitor

A current trend in the soldering industry has been the development of organic inhibitors to reduce or eliminate the presence of surface contaminants and surface oxides on solderable surfaces. Organic inhibitors such as EG Imidazol can be used on components which already have solder protective coatings or with components which have bare metal substrates such as copper. They are an extremely attractive option and like the PADS system they eliminate the need for prefluxing or post cleaning when they are coupled with the use of inert atmospheres during the soldering process. A cost model for the **solder jetting** process with the use of organic inhibitors was developed and is shown in tables 11 and 12.

The use of an organic inhibitor could be beneficial in reducing soldering defects with the **solder ball** placement system but it could not be used as a replacement for the solder fluxing operation, since the flux is also used as an adhesive to hold the solder balls in place until solder reflow has occurred. Because there would be no significant cost savings with the use of an organic inhibitor and the solder ball placement system, no COO model for this process change was generated.

Project Objectives

Baseline Input Information

The Cost of Ownership model requires baseline information such as factory floor space for either clean room or non-clean room conditions, personnel data burden rates, system utilization rates, building and equipment depreciation schedules, estimated monthly through put, number of hours per shift, number of shifts per week, etc. To insure that a true cost comparison was performed between the current solder ball attachment process and the proposed solder jetting process all of the input information for baseline values were set equal to each other for the COO model. This baseline information was obtained from the Sematech Cost Resource Model supplied by Cathy Reber, Department 1333 Sandia National Labs and is shown in table I. Utility costs associated with electric power consumption based on local industrial rates are also shown in table I. Please note that these utility costs just like floor space costs and burden rates, etc. will change depending on the geographic location of the manufacturing facility.

Upstream Consumables Pricing Requirements

Pricing for all of the consumable materials was obtained from as many vendors as possible, however in some cases only one vendor could be located. The part type and production rate requirements were based on information obtained from the Prismark report on BGA Substrate Technology and Cost Analysis prepared by Prismark for Sematech[3]. The Prismark report referenced projected monthly production rates of approximately 100,000 parts. The Prismark report also indicated that the current technology was continuing to move towards strip formatted parts with a trend towards high end 440 I/O devices and up. Pricing requirements for monthly utilization of solder balls were based on a single metal alloy system (60/40 solder). The monthly consumable quantity of solder balls (required for quote purposes) was also based on Prismark report information. Pricing requirements for the equivalent amount of bar solder needed for the solder jetting process were based on the individual solder ball volume multiplied by the estimated total number of solder balls required per month. Ten percent overages were incorporated for the solder balls and twenty percent overages were used for the bar solder. Estimates on monthly solder flux and flux thinner utilization were obtained from Vanguard Automation. Estimates on detergent and soponifier consumption for the Detrix Inline 20 cleaning system was obtained from Honeywell DASD (who currently use a Detrix system). Estimates on the consumable rate of Sulfur Hexafloride for the PADS system was obtained from IEI. A comparison of the various recurring costs for the solder ball attachment process for nominal and maximum utilization is shown in table II. A comparison of the various recurring costs for the solder jetting process for nominal utilization and maximum utilization is shown in table VI.

Estimates on standard plastic overmolded strip formatted package costs were obtained from Amkor Anam.[4] Because Amkor Anam is not involved with die fabrication, engineering cost estimates were used to determine an average cost for the complete part upstream cost (incoming unit) prior to the solder sphere attachment process. For modeling purposes, a 100% increase was used to determine the part end cost (completed unit). The part incoming costs and completed costs were required as an input step to the TWO COOL program but did not affect the cost of ownership values for the solder ball/solder jetting process.

Solder Sphere Attachment System Description

The solder sphere attachment system which was evaluated for this paper uses the VAI 5200 automated BGA placement work station manufactured by Vanguard Automation. The VAI 5200 system has a floor foot print of approximately 36 ft^2 and requires 220VAC 3 phase with a normal current requirement of 10 amps. The VAI 5200 system also incorporates an in-line conveyor with the backend magazine to provide direct interfacing with the reflow operation. The VAI 5200 system is fully automated and has an average cycle time of approximately 20 seconds with a minimum cycle time of 10 seconds. The VAI 5200 system has interchangeable tooling for various strip formats. Based on a 10 second cycle time and four parts per strip, a maximum output of 1440 parts per hour can be achieved (at a maximum strip length of 200mm). The system also has high speed placement verification with automatic off load for audit/reject purposes (Note: The average output of 720 parts per hour was used because this number more closely matched actual through put rates for high I/O large format body size parts). Although Vanguard indicated that the system up time was 96%, Amkor Anam[4] (who use four different Vanguard systems and recently purchased a

VAI 5200), indicated that general engineering testing, operator training and maintenance requirements resulted in a normal system uptime of approximately 80%. This lower value was used in the COO models.

In addition to the VAI 5200 system, an in-line continuous feed Hollis reflow furnace with an approximate foot print of 38 ft^2 requiring 220VAC 3 phase and 35 amps and a Detrix Inline-20 cleaning system with an approximate foot print of 80 ft^2 requiring 220VAC and 40 amps were also evaluated for the COO model.

Normal production procedures require strip formatted parts to be first magazine loaded into the VAI 5200 work station. Additional magazines can be loaded into the machine at regular intervals while the machine is operating. Solder flux is then selectively applied to the component pads via the use of a stencil process. This is followed by the solder ball placement process which uses a proprietary gravity feed that allows for all of the solder balls to be placed simultaneously. To transport parts through the various operations, the VAI 5200 work station uses a walking beam combined with precision lift and positioning devices. Following inspection, the part strips are automatically conveyed to a continuous in-line reflow furnace. Start to finish furnace reflow time is ten minutes with capabilities to maintain a continuous feed rate of ten seconds between parts. After reflow, the parts are cleaned and returned to stock. A basic step diagram of the solder sphere attachment process is shown in figure 1.

Figure 1
Step Diagram of Solder Sphere Attachment Process

1. Singulated or strip formatted parts are removed from stock and sent to the solder ball attachment line.
2. Parts are magazine loaded into the VAI 5200 system.
3. Parts are fluxed using a stencil application process.
4. AUER boat is automatically attached to the strip or singulated parts and solder balls are placed on the parts using a proprietary gravity feed process.
5. The parts are automatically inspected for proper ball placement and magazine off loaded and conveyor fed to the reflow furnace.
6. Solder balls are reflowed.
7. Parts are conveyor fed to in line cleaning station. AUER boats are removed and returned to VAI 5200 and parts are returned to stock.

Solder Sphere Attachment System Non-recurring Pricing Requirements

Pricing for the complete VAI 5200 solder sphere placement system was based on a quote received by Vanguard Automation Inc.[5] The pricing included the complete workcell cost plus the cost of AUER boats, tooling, screens and plates for different part types and an in-line conveyor. Costs for an in-line continuos reflow Hollis furnace were also obtained. Pricing for a Detrix Inline 20 cleaning system was obtained and is included in the final COO model. Complete non-recurring costs for the solder sphere attachment system are provided in table III.

Plasma Assisted Dry Soldering (PADS) System Description

Information on the Phase IV PADS system currently at the prototype stage of development was obtained from Mike Pennington of IEI. The Phase IV system has an eight cubic foot plasma chamber. The PADS system uses a Sulfur Hexafloride/Argon plasma gas mixture with an estimated consumable gas rate of approximately 50sccm. The Phase IV system has a foot print of 65 ft^2 and requires 220VAC 3 phase and 30 amps. The Phase IV will be fully automated and will use a Simplematic Cassette front and backend magazine loading system. Although the Phase IV is still currently at the prototype level of production development, the magazine feed rate appears to be compatible with the VAI 5200 system.

Solder Jetting System Description

Several strategies for high production rate solder jetting were evaluated. Modifications to existing solder ball placement systems verses the development of completely new solder jetting systems were investigated. Several companies were contacted regarding existing platforms but based primarily on input received from the Sematech PTAB committee, the VAI 5200 system was selected. The Sematech advisory board indicated that the number and types of modifications required to convert the VAI 5200 ball placement system over to a ball jetting system were significantly less when compared to other similar systems. In addition to the low number of required modifications, the VAI 5200 system is fully automated and is capable of very high through put rates. Except for the removal of the flux application cell and the solder ball placement cell, all other existing design features of the VAI 5200 system would still be utilized. Only three significant new design features would be required to modify the VAI 5200 system. These would include the addition of a solder jetting work cell, modifications to the cover hoods to provide a nitrogen blanket for the jetting cell and the addition of an internal preheat cell.

The system floor footprint for the VAI 5200 as well as the feed rate, throughput rate and off load rates would remain the same. Following the automatic inspection point, the parts would be removed from the backend magazine and returned to stock. The need for a reflow furnace is completely eliminated since the molten solder would be jetted directly onto the parts and the need for a post cleaning station would also be eliminated since a PADS system would be used and the flux application step would no longer be required. A flow diagram of the solder jetting process is shown in figure 2.

Solder Jetting Cell Description

The solder jetting cell would be composed of four separate solder jetting heads. Each head would contain an interchangeable isotropic graphite jetting grid (which would be preselected based on the part being jetted), a 304 stainless housing for the grids and a piezo electric actuator for each Jetter. The four jetting heads would share a common solder reservoir and the four piezo electric actuators would be connected in parallel to a single power supply. The existing VAI 5200 software program which controls the rate of solder ball placement would be modified and used to drive the rate at which the piezo electric actuators would be pulsed. The solidification hold time would be for a minimum of 20 seconds but would be matched to the preheat time to insure continuos product flow. The jetting cell would be equipped with a nitrogen blanket and atmospheric control curtains at the exit and entrance points. Cost estimates for the solder jetting cell are shown in table IV. The envisioned manufacturing approach for the jetting cell is that the cell components could either be assembled by the supplier (in this case, Vanguard) at the time the solder jetting system was being built or that the completed cell and the required power supply would be separately purchased items. The estimated assembly costs to install the jetting cell in the jetting system are shown in item 2 of table VI. The costs of the jetting cell discussed in this report are estimated baseline engineering and manufacturing costs for a prototype system and should not be considered as the commercial cost. The cost of the jetting cell power supply is the actual purchase price.

Figure 2
Step Diagram of Solder Jetting Process

1. Singulated or strip formatted parts are removed from stock and sent to the solder jetting line.
2. Parts are magazine loaded into the PADS system.
3. Plasma Etching process strips oxides and other contaminants from part surfaces.
4. Parts are magazine loaded into Solder Jetter.
5. Parts are preheated and solder is jetted onto the part pads.
6. The parts are automatically inspected for proper jetting placement and magazine off loaded.
7. Parts are returned to stock.

Preheat Cell Description

The preheater cell would employ a topside IR preheater composed of a bank of adjustable quartz lamps capable of obtaining a part pad temperature of 110°C +/-20°C. Preheat time would be determined by thermal shock considerations but on average would be for a minimum of 20 seconds to a maximum of 40 seconds. The COO program was run at the 20 second rate primarily because this rate was the same as the average rate of the existing VAI 5200 solder ball placement system.

Solder Jetting System Pricing Requirements

All costs associated with the modifications to the VAI 5200 system were based on engineering estimates. The base cost for the VAI 5200 system was used but a reduction of $70,000 was made (based on a Sandia engineering estimate) since the flux application cell and the solder ball gravity placement cell would not be used. The costs associated with the manufacturing of the jetting head are shown in table IV. The costs associated with all of the modifications to the VAI 5200 system are shown in table V. The cost on line 5 of table V would be for a prototype system while the cost on line 6 would be for a tenth unit. The only changes in the price of the tenth unit and the prototype unit was that both the software and hardware engineering support was reduced by half. Using the prototype cost as a base line value, a 100th system learning curve value using a .631 factor of improvement was used.[6] The estimated cost for a 100th system is shown on line 7 of table V. The costs of the jetting system discussed in this report are estimated baseline engineering and manufacturing costs for a prototype system and should not be considered as the commercial cost.

Cost of Ownership Model

The TWO COOL™ version 2.1.2 cost of ownership program was used for the COO model for the solder sphere attachment process and the solder jetting process. Information from tables I through VI was inputted into the program. As previously stated in the introduction, the program provides a good unit equivalent cost as well as an average monthly cost. Because actual production scrap rates were unknown, the equipment was automatically assumed to be 100% efficient. Because of this programmed-in assumption, the good unit equivalent cost without scrap was the same as the good unit equivalent cost with scrap.

Six different COO models were generated with the TURBO COOL option of TWO COOL. A base line production rate for the solder ball placement system and the solder jetting system (with and with out the PADS module) which closely matched the projected monthly production rate of 100,000 parts was first run. In all three cases, (ball placement, Jetter w/ & w/o PADS) a cost of ownership number was generated. In all three cases, the utilization time was found to be 23%. All three runs were identified as "Nominal."

The TURBO COOL program was then rerun but at the maximum utilization and maximum capacity (100%). This second set of runs produced new cost of ownership numbers which were significantly lower (Note: lower is better for cost of ownership). These second three runs were identified as "Maximum." However the new monthly production output of 419,908 was over four times higher than the projected requirements of 100,000.

The two solder jetting runs that did not contain the PADS system were generated with the assumption that an organic inhibitor was used on the parts prior to shipment and the need for the PADS system would be eliminated. These two runs are shown separately in tables XI and XII.

The six TURBO COOL program runs are shown in tables VII - XII. The significance in the differences of the throughput quantity as well as the utilization values will be reviewed in the results and discussion section.

Results and Discussion

Under all six COO modeling conditions a good unit equivalent savings of between 41% to 68% was achieved with the solder jetting process (average savings: 54%). The savings were primarily realized because of the elimination of the solder sphere fabrication step although additional savings were also realized as a result of the elimination of the solder flux, flux thinner and detergents and soponofiers and the reduction of electric power consumption.

The non-recurring costs associated with the elimination of the reflow furnace and the in line cleaning system were found not to be a significant cost reduction factor by themselves because the added cost of the PADS Phase IV system as well as the 27% increase in the cost of the proposed jetting system off set these costs. The 35% reduction (53 ft^2) in overall floor space requirements was significant only in the fact that the space could be used for other types of equipment. The actual savings for a non-clean room environment based on a straight 25 year depreciation was $53.00 per year and was considered insignificant.

One of the most significant results of this investigation was that the VAI 5200 system for either the solder ball attachment process or the proposed solder jetting process would easily be able to achieve the monthly production rates of 100,000 parts per month which is currently forecasted in the Prismark report.[3] The 100,000 parts per month value is the baseline production rate that packaging leaders in the BGA industry are currently running at. The COO model found that at a modest weekly utilization of 23%, this production rate could easily be achieved. A maximum through put for the two systems was also generated primarily to determine the estimated maximum production rate a single system could achieve. If production rates move beyond 400K/month, additional systems could be purchased.

The change over from DIP and QFP package configurations to BGA packages has been occurring at a slower rate than anticipated primarily because of the lack of an effective BGA to PWB rework method. Although the BGA to PWB reflow process has an extremely high yield rate, there currently is no effective in situ rework process available. As a result, BGA parts are often being removed and replaced rather than being reworked. Currently, this rework issue has dampened the anticipated increased BGA production rates as well as the transition to higher complexity BGA parts and higher dollar value BGA parts.

Conclusions

The good unit equivalent cost for the solder ball process for a production capacity of approximately 100,000 parts per month with no scrap loss was found to be : $0.373. See table VII.

The good unit equivalent cost for the solder ball process for a maximum production capacity of 419,908 parts per month with no scrap loss was found to be : $0.247. See table VIII.

The good unit equivalent cost for the solder jetting process with the PADS system for a production capacity of approximately 100,000 parts per month with no scrap loss was found to be: $0.220. See table IX.

The good unit equivalent cost for the solder jetting process with the PADS system for a production capacity of 419,908 parts per month with no scrap loss was found to be: $0.087. See table X.

The good unit equivalent cost for the solder jetting process using an organic inhibitor for a production capacity of approximately 100,000 parts per month with no scrap loss was found to be: $0.175. See table XI.

The good unit equivalent cost for the solder jetting process using an organic inhibitor for a production capacity of approximately 419,908 parts per month with no scrap loss was found to be: $0.077. See table XII.

The proposed solder jetting process in conjunction with the PADS system or with the use of an organic inhibitor is a novel and unique approach to address the anticipated high rate BGA production requirements currently forecasted for the next decade and has numerous advantages over the current solder ball attachment process. The elimination of fabricated solder balls, solder flux, flux thinners, as well as the need for post cleaning with its requirements for water consumption, cleaning detergents and soponifiers are environmentally attractive while at the same time being cost effective. In comparing solder ball attachment verses direct solder jetting, although many cost factors were reduced or eliminated by using a solder jetting approach, the most critical element between the two systems was found to be the recurring cost of solder balls. The COO model was able to clearly demonstrate that by essentially removing this major recurring cost, a dramatic cost savings could quickly be achieved.

Because there currently is no actual sales price for the solder jetting system, a return on investment (ROI) for the jetting system could not be calculated. However using the estimated manufacturing and engineering costs as a baseline value, a series of possible commercial costs was generated and an estimated return on investment (ROI) for each value was calculated. Four different ROI curves were generated. These included High and Low rate production with the PADS system and without the PADS system. These values are shown in figures 3 and 4. The ROI calculations were based on the Prismark monthly production rates of 100,000 parts as well as the maximum capacity production rate of 419,908 parts. These ROI values were reduced by a factor of 30 months or more when the PADS system was removed and an organic inhibitor was used. For the maximum utilization values without the PADS system, the ROI values are slightly higher primarily because the ratio of the consumable (recurring) costs to the fixed (nonrecurring) costs increased. It needs to be noted however, that the good unit equivalent cost for this approach (solder jetting w/ organic inhibitor @ maximum throughput) was the lowest at $0.077 as compared to $0.247 for the equivalent solder ball attachment process.

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2. Process Equipment Cost Modeling Using Cost of Ownership Software to Measure and Enhance Productivity. Paper by David W. Jimenez of Wright, Williams and Kelly.

3. Ball Grid Array Substrate Technology and Cost Analysis. Prepared by Prismark LLC for Dr. Didier Kane of Sematech. Report No. 1023. December 1995.

4. Information on customer use of the Vanguard VAI 5200 System and BGA Packaging was obtained from Richard Cooly, Production Manager for Amkor/Anom PBGA Facility Chandler AZ. Received March 15, 1996.

5. Vanguard 5020 BGA Machine. Vanguard Proposal Number B960222A01. Received February 22, 1996.

6. Learning Curve Values were based on data obtained for the Learning Curve Handbook published by the American Graduate University & Procurement Associates Inc. Covina Ca.

7. Phone conversation with Vanguard Automation marketing on July 31, 1996.

Baseline Input Information
Table I

Available Hours per week:	40 & 168
Shift Teams:	1 & 4
Weeks per Year:	50 & 52
Depreciation Method:	Straight 5
Personnel Data	
• Operator (burden rate):	40K/yr.
• Technician (burden rate):	80K/yr.
• Engineer (burden rate):	120K/yr.
Parts per month:	100,013 & 419,908
Building Depreciation:	Straight 25
Non-clean room factor:	$25/sq. ft.
Electric Power - Kilowatt-hour	$0.06
Supplier Service Coverage:	Not factored
ES & H Permits:	Not factored
Fully Loaded Utilization:	Base Line
Down Time (all reasons):	20%

Total Estimated Recurring Costs (Consumable) for Solder Ball Attachment
Table II

Solder Spheres (12.7M/wk) Nominal	@ $0.25/K	$3,175.00/wk
Solder Spheres (53.3M/wk) Maximum	@ $0.25/K	$13,335.00/wk
Solder Flux (12 Gallons/wk) Nominal	$336.00/wk	
Solder Flux (51 Gallons/wk) Maximum	$1411.20/wk	
Flux Thinner (8 Gallons/wk) Nom.	$220.00/wk	
Flux Thinner (34 Gallons/wk) Max.	$924.00/wk	
Water Soponofiers & Detergents Nom.	$25.00/wk	
Water Soponofiers & Detergents Max.	$105.00/wk	
Power Consumption (Kilowatt-hours) N	$36.00/wk	
Power Consumption (Kilowatt-hours) M	$150.00/wk	
Recurring Cost Solder Ball (Nom.)	$197,118/year	
Recurring Cost Solder Ball (Max.)	$828,135/year	

Total Estimated Non-recurring Costs
for Current BGA Solder Sphere Attachment Process
Table III

VAI 5200 BGA Workcell:	$410,000
(Based on a standard system)	
Tooling, Screens & Plates:	$5,000
AUER Boats (40 boats):	$800
Conveyor:	$3,000
Hollis Reflow Furnace:	$79,750
Post Cleaning Station:	$230,500
Total NR Cost:	$729,050

Recurring Costs (Consumables)
Solder Jetting Process
Table IV

Bar Solder (150 lb./wk~20% overage) N	$427.00/wk
Bar Solder (630 lbs/wk~20% overage) M	$1793.40/wk
Sulfur Hexafloride (.5 lbs/wk) Nominal	$8.00/wk
Sulfur Hexafloride (2.1 lbs/wk) Max.	$33.60/wk
Power Consumption (Kilowatt-hours) N	$17.00/wk
Power Consumption (Kilowatt-hours) M	$71.00/wk
Recurring Cost Solder Jet (Nom.)	$23,420/year
Recurring Cost Solder Jet (Max.)	$98,712/year

Estimated Component Cost of Four Head
Solder Jetting Prototype
Table V

Isotropic Graphic 440 Grids (POCO):	$6,640
(6 grids @ $1,660ea.)	
304 Stainless Housing:	$8,500
(4 chambers plus solder reservoir)	
4 Piezo Electric Actuators:	$11,200
(@ $2,800 ea.)	
Power Supply:	$7,500
Total Jetting Head Cost:	$33,480

The Total Estimated Non-recurring Manufacturing Costs for a Prototype Unit, a 10th Unit and a 100th Unit
Table VI

1. VAI 5200 BGA System:	$345,000
(without solder ball placement head and flux application cell)	
2. Modifications to Workcell	
• Nitrogen Blanket:	$2,000
• Modified Cover Hoods:	$5,000
• Solder Jetting Head:	$33,480
• Housing (and assembly) for Jetting Heads:	$6,000
• Preheat Station:	$4,000
• Design Change for Preheat:	$24,000
• Analog/Digital Sensors:	$6,000
• Software Modifications:	$60,000
• Engineering Development:	$120,000
3. Tooling & Plates:	$3,000
4. Part Carrier Fixtures (40 carriers):	$1,800
5. Prototype Manufacturing Cost:	$613,280
6. Tenth Unit Manufacturing Cost:	$523,280
7. 100th Unit Manufacturing Cost:	$514,280
8. Phase IV PADS System	$262,000
Total Non-recurring Manufacturing Cost (10th unit only):	$785,280

Table VII

Cost of Ownership for DA 1 Model
Process: Solder Ball Attachment for VAI 5200
Nominal Production Rate

Management Report	Costs	Definitions
Cost Per System	$729,050	Original Purchase Price
Number of Systems Required	1	Maximum Units Needed
Total Depreciable Costs	$729,050	Sum of all Capitalized Costs
Available Hours Per Week	40 hours	Hours Per Week
Weeks Per Year	52 weeks	Weeks Per Year
Required Number of Parts Per Week	23,080	Parts Per Week
Equipment Utilization Capability	80.00%	% of Hours/week system is aval.
Production Utilization Capability	80.00%	% of Hours/week System is aval.
Equipment Yield	100.00%	Equipment Yield
Good Unit Equivalents Out Per Week	23,080.0	Volume Reqmt* Equip. Yield
Good Unit Equivalent Cost W/o Scrap	$0.373	Total Costs/Year/(GUE/Yr.)
Cost Per Productive Minute	$1.067	Lifetime Costs/Total Lifetime
Average Monthly Cost W/o Scrap	$35,835.00	Average Mo. Cost/Life of Equip
LIFE OF EQUIPMENT	5 years	Straight 5
Equipment Costs	$729,050	Sum of all Equipment Costs
Cost Per Good Unit Equivalent	$0.126	Sum of Eqp. Costs/Yr/(GUE/yr.)
Recurring Costs	$1,421,034	Sum of all Recurring Costs
Cost Per Good Unit Equivalent	$0.246	Sum of recur. Costs/Yr/(GUE/yr.)
TOTAL COSTS	$2,150,084	Total Costs
Total Cost Per Good Unit Equivalent (Cost of Ownership)	$0.373	Total Costs/Yr/(GUE/Yr)

Table VIII

Cost of Ownership for DA 1 Model
Process: Solder Ball Attachment for VAI 5200
Maximum Production Rate

Management Report	Costs	Definitions
Cost Per System	$729,050	Original Purchase Price
Number of Systems Required	1	Maximum Units Needed
Total Depreciable Costs	$729,050	Sum of all Capitalized Costs
Available Hours Per Week	168 hours	Hours Per Week
Weeks Per Year	52 weeks	Weeks Per Year
Required Number of Parts Per Week	96,768	Parts Per Week
Equipment Utilization Capability	80.00%	% of Hours/week system is aval.
Production Utilization Capability	80.00%	% of Hours/week System is aval.
Equipment Yield	100.00%	Equipment Yield
Good Unit Equivalents Out Per Week	96.768.0	Volume Reqmt* Equip. Yield
Good Unit Equivalent Cost W/o Scrap	$0.300	Total Costs/Year/(GUE/Yr)
Cost Per Productive Minute	$2.961	Lifetime Costs/Total Lifetime
Average Monthly Cost W/o Scrap	$99,474.00	Average Mo. Cost/Life of Equip
LIFE OF EQUIPMENT	5 years	Straight 5
Equipment Costs	$729,050	Sum of all Equipment Costs
Cost Per Good Unit Equivalent	$0.030	Sum of Eqp. Costs/Yr/(GUE/yr.)
Recurring Costs	$5,239,398	Sum of all Recurring Costs
Cost Per Good Unit Equivalent	$0.217	Sum of recur. Costs/Yr/(GUE/yr.)
TOTAL COSTS	$5,968,448	Total Costs
Total Cost Per Good Unit Equivalent (Cost of Ownership)	$0.247	Total Costs/Yr/(GUE/Yr)

Table IX

Cost of Ownership for DA 1 Model
Process: PADS/Solder Jetting for Modified VAI 5200
Nominal Production Rate

Management Report	Costs	Definitions
Manufacturing Cost Per System	$785,280	Est. Manufacturing Cost
Number of Systems Required	1	Maximum Units Needed
Total Depreciable Costs	$785,280	Sum of all Capitalized Costs
Available Hours Per Week	40 hours	Hours Per Week
Weeks Per Year	52 weeks	Weeks Per Year
Required Number of Parts Per Week	23,080	Parts Per Week
Equipment Utilization Capability	80.00%	% of Hours/week system is aval.
Production Utilization Capability	80.00%	% of Hours/week System is aval.
Equipment Yield	100.00%	Equipment Yield
Good Unit Equivalents Out Per Week	23,080.0	Volume Reqmt* Equip. Yield
Good Unit Equivalent Cost W/o Scrap	$0.220	Total Costs/Year/(GUE/Yr)
Cost Per Productive Minute	$0.630	Lifetime Costs/Total Lifetime
Average Monthly Cost W/o Scrap	$21,182.00	Average Mo. Cost/Life of Equip
LIFE OF EQUIPMENT	5 years	Straight 5
Equipment Manufacturing Costs	$785,280	Est. Sum of all Manuf. Costs
Cost Per Good Unit Equivalent	$0.136	Est. Sum of Manful. Costs/Yr/(GUE/yr.)
Recurring Costs	$485,646	Sum of all Recurring Costs
Cost Per Good Unit Equivalent	$0.084	Sum of recur. Costs/Yr/(GUE/yr.)
TOTAL COSTS	$1,270,926	Total Costs
Total Cost Per Good Unit Equivalent (Cost of Ownership)	$0.220	Total Costs/Yr/(GUE/Yr)

Table X

Cost of Ownership for DA 1 Model
Process: PADS/Solder Jetting for Modified VAI 5200
Maximum Production Rate

Management Report	Costs	Definitions
Manufacturing Cost Per System	$785,280	Est. Manufacturing Cost
Number of Systems Required	1	Maximum Units Needed
Total Depreciable Costs	$785,280	Sum of all Capitalized Costs
Available Hours Per Week	168 hours	Hours Per Week
Weeks Per Year	52 weeks	Weeks Per Year
Required Number of Parts Per Week	96,768	Parts Per Week
Equipment Utilization Capability	80.00%	% of Hours/week system is aval.
Production Utilization Capability	80.00%	% of Hours/week System is aval.
Equipment Yield	100.00%	Equipment Yield
Good Unit Equivalents Out Per Week	96,768.0	Volume Reqmt* Equip. Yield
Good Unit Equivalent Cost W/o Scrap	$0.087	Total Costs/Year/(GUE/Yr)
Cost Per Productive Minute	$1.040	Lifetime Costs/Total Lifetime
Average Monthly Cost W/o Scrap	$34,934	Average Mo. Cost/Life of Equip
LIFE OF EQUIPMENT	5 years	Straight 5
Equipment Manufacturing Costs	$785,280	Est. Sum of all Manful. Costs
Cost Per Good Unit Equivalent	$0.032	Est. Sum of Manful. Costs/Yr/(GUE/yr.)
Recurring Costs	$1,310,772	Sum of all Recurring Costs
Cost Per Good Unit Equivalent	$0.054	Sum of recur. Costs/Yr/(GUE/yr.)
TOTAL COSTS	$2,096,052	Total Costs
Total Cost Per Good Unit Equivalent (Cost of Ownership)	$0.087	Total Costs/Yr/(GUE/Yr)

Table XI

Cost of Ownership for DA 1 Model
Process: Organic Inhibitor/Solder Jetting for Modified VAI 5200
Nominal Production Rate

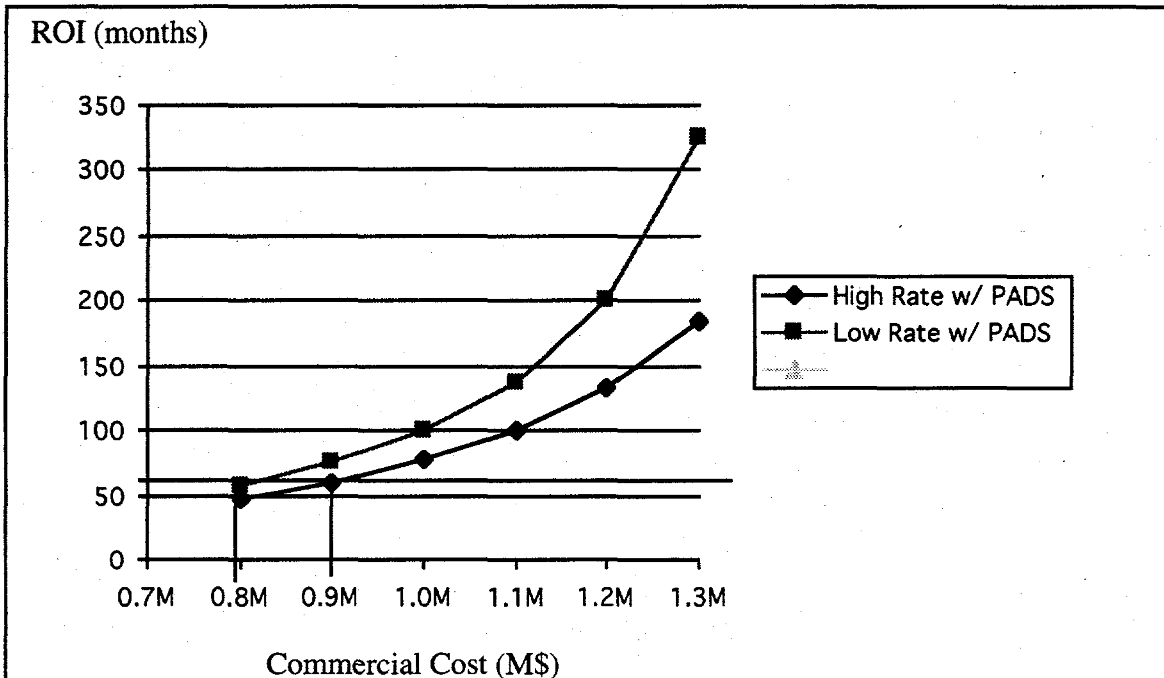
Management Report	Costs	Definitions
Manufacturing Cost Per System	$523,280	Est. Manufacturing Cost
Number of Systems Required	1	Maximum Units Needed
Total Depreciable Costs	$523,280	Sum of all Capitalized Costs
Available Hours Per Week	40 hours	Hours Per Week
Weeks Per Year	52 weeks	Weeks Per Year
Required Number of Parts Per Week	23,080	Parts Per Week
Equipment Utilization Capability	80.00%	% of Hours/week system is aval.
Production Utilization Capability	80.00%	% of Hours/week System is aval.
Equipment Yield	100.00%	Equipment Yield
Good Unit Equivalents Out Per Week	23,080.0	Volume Reqmt* Equip. Yield
Good Unit Equivalent Cost W/o Scrap	$0.175	Total Costs/Year/(GUE/Yr)
Cost Per Productive Minute	$0.502	Lifetime Costs/Total Lifetime
Average Monthly Cost W/o Scrap	$16,857.00	Average Mo. Cost/Life of Equip
LIFE OF EQUIPMENT	5 years	Straight 5
Equipment Manufacturing Costs	$523,280	Est. Sum of all Manful. Costs
Cost Per Good Unit Equivalent	$0.091	Est. Sum of Manful. Costs/Yr/(GUE/yr.)
Recurring Costs	$488,137	Sum of all Recurring Costs
Cost Per Good Unit Equivalent	$0.085	Sum of recur. Costs/Yr/(GUE/yr.)
TOTAL COSTS	$1,011,417	Total Costs
Total Cost Per Good Unit Equivalent (Cost of Ownership)	$0.175	Total Costs/Yr/(GUE/Yr)

Table XII

Cost of Ownership for DA 1 Model
Process: Organic Inhibitor/Solder Jetting for Modified VAI 5200
Maximum Production Rate

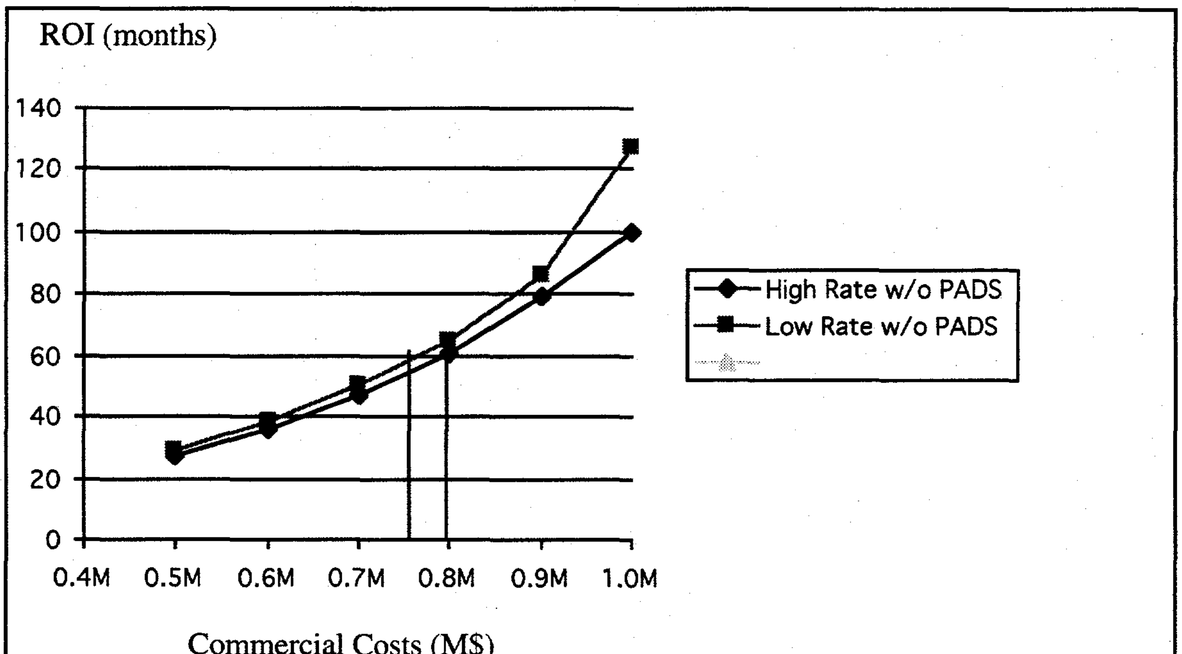
Management Report	Costs	Definitions
Manufacturing Cost Per System	$523,280	Est. Manufacturing Cost
Number of Systems Required	1	Maximum Units Needed
Total Depreciable Costs	$523,280	Sum of all Capitalized Costs
Available Hours Per Week	168 hours	Hours Per Week
Weeks Per Year	52 weeks	Weeks Per Year
Required Number of Parts Per Week	96,768	Parts Per Week
Equipment Utilization Capability	80.00%	% of Hours/week system is aval.
Production Utilization Capability	80.00%	% of Hours/week System is aval.
Equipment Yield	100.00%	Equipment Yield
Good Unit Equivalents Out Per Week	96,768.0	Volume Reqmt* Equip. Yield
Good Unit Equivalent Cost W/o Scrap	$0.077	Total Costs/Year/(GUE/Yr)
Cost Per Productive Minute	$0.918	Lifetime Costs/Total Lifetime
Average Monthly Cost W/o Scrap	$30,847.00	Average Mo. Cost/Life of Equip
LIFE OF EQUIPMENT	5 years	Straight 5
Equipment Manufacturing Costs	$523,280	Est. Sum of all Manful. Costs
Cost Per Good Unit Equivalent	$0.022	Est. Sum of Manful. Costs/Yr/(GUE/yr.)
Recurring Costs	$1,327,519	Sum of all Recurring Costs
Cost Per Good Unit Equivalent	$0.055	Sum of recur. Costs/Yr/(GUE/yr.)
TOTAL COSTS	$1,850,799	Total Costs
Total Cost Per Good Unit Equivalent (Cost of Ownership)	$0.077	Total Costs/Yr/(GUE/Yr)

Figure 3
ROI(months) verses Commercial Cost
for Jetting System with PADS



(Two vertical lines on the graph represent costs for a 60 month ROI)

Figure 4
ROI(months) verses Commercial Cost
for Jetting System without PADS



(Two vertical lines on the graph represent costs for a 60 month ROI)

Internal Sandia Distrubution:

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