A Review of Jetting Technologies for Fluid Dispensing -Identifying the Features that Influence Productivity

Garrett Wong
Nordson ASYMTEK
Carlsbad, CA, USA

Abstract
As consumer products continue to reduce in price, pressure is placed upon the manufacturing of sub-components for improving cost. Back in the mid-1990s, jet valves for fluid dispensing in electronics assembly entered the market, displacing older technology with significantly higher dispenser productivity resulting from high flow rates and reduced up/down motion requirements. As jet valve technology has evolved, valve actuation systems have continued to improve, pushing toward higher jet frequencies and smaller jetted dot volumes. In recent years, equipment suppliers have started promoting piezo-driven jet valves with significantly higher frequencies than traditional pneumatic-driven jets. However, in many cases, the implied promise of higher productivity and lower production costs per part resulting from higher frequency jetting never fully materialized.

In further studies, fluid flow rate and jet frequency are not always the largest levers to improve productivity in some applications. We will examine several fluid dispensing applications from PCB assembly to wafer-level packaging, and review the potential productivity enhancements from moving to higher frequency jetting. We will also review additional factors that may impact the realized production cost savings such as component part reliability considerations, process program layout, closed-loop process controls, and non-dispensing operations of the fluid dispenser.

High-frequency, piezo-driven jets can add value to a number of high-volume production applications. However, the frequency specification of a jet valve should not be the primary factor considered when selecting a dispensing process. Rather, a holistic view of the production costs and factors affecting productivity and cost-effectiveness should be used in making such decisions. In this paper, we seek to elevate the conversation above the noise of ever increasing jet frequency to see the bigger picture and identify what ultimately matters for reducing production costs per part.

Introduction
Fluid dispensing in the semiconductor assembly industry was revolutionized in the mid-1990s with the introduction of jet dispensing valves and jetting technology has become the industry standard method for non-contact dispensing of fluids in a wide range of applications. As jetting technology continues to improve and evolve, movement from pneumatic to piezoelectric-driven jet actuation has led to an increase in jetting frequency with new jets advertised run at up to 3,000Hz. Therefore the questions then arise as to when and why jet frequency matters.

On the surface, higher-frequency jetting should lead to improved application productivity and, therefore, improved cost of ownership for a dispensing system. However, jet frequency is only one piece of a larger puzzle when understanding cost of ownership. Additional factors beyond jet frequency and resulting line speed contribute to productivity improvement. Furthermore, cost of ownership should take into account replacement rates of consumable materials and any trade-offs between performance and longevity of the jet valve. There is always a trade-off to consider between performance and cost that may not always be at the forefront of a valve selection.

A Brief History of Jetting Technology in Fluid Dispensing for Electronics Assembly
In the mid-1990s, jet dispensing technology was introduced to the electronics assembly industry to dispense underfill and similar fluids. This non-contact method of dispensing multiple droplets of fluid to a target surface revolutionized the industry that had previously relied on contact dispensing methods, such as time-pressure, positive displacement and auger valve technologies. The advent of non-contact jet dispensing significantly improved dispensing productivity by eliminating z-axis moves, that are required with traditional needle dispensing, and allowing the dispense valve to "fly" over the target substrate at a constant height while ejecting dots of fluid.

The introduction of jetting technology into printed circuit board (PCB) assembly processes also allowed for further reduction of critical keep-out-zones (KOZs) around dies for underfill dispensing. With the fluid ejection orifice now above the top surface of the dies on the PCB, the nozzle position could be moved closer to the die edge than was previously possible with traditional needle dispensing. **(Figure 1)** By moving the position of the fluid relative to the die edge closer, the wet-out distance of the fluid was reduced and allowed components on the PCBs to be placed closer together, advancing the miniaturization trend.

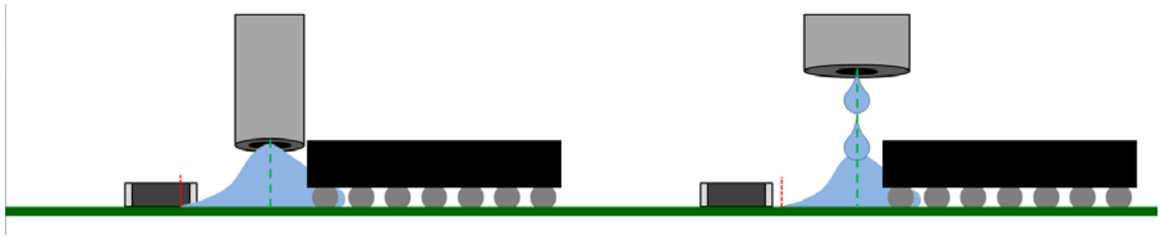

Figure 1 – KOZ: Needle Dispensing vs. Jet Dispensing

One of the advantages of jet dispensing is the ability to dispense individual, discrete dots of fluid. In this way, the dispensed fluid geometry and volume can be adjusted independent of the needle diameter, opening the door for more precise dispensed fluid controls. Adding or subtracting individual dots from a dispensed line or cavity allows for very tight control of dispensed fluid volume, producing improved cost-of-ownership and production yield. [1] The additional improvement to measure average dot mass further improved upon dispensed weight accuracy with closed-loop control over dot weights.

Early versions of jet valves utilized pneumatically actuated solenoids to create the driving force to expel the jet of fluid from the nozzle to the surface. As a result of the operational characteristics of these solenoids, jet valves were thus typically limited to operating frequencies between 100-400 Hz. In recent years, a variety of jet valve manufacturers have introduced piezoelectric-driven jet valves that overcome some of the initial issues with piezo-driven systems for consistency and accuracy. The primary advantage of piezoelectric drive systems is the ability to actuate at much higher frequencies than pneumatic drive systems, allowing for further refinement of jetting technology and extending capabilities.

Understanding Dispensing System Productivity (UPH)

When examining the dispensing process for electronics assembly, platform productivity is a core concern for high-volume manufacturing because it directly relates to the cost per part when depreciating the assembly equipment costs. Manufacturers always look for the next technology improvement to increase system UPH and thereby reduce their costs per part to align with industry and end customer demands for cheaper and cheaper goods. There are several factors that contribute to a complete picture of productivity. Some are directly related to the dispensing valve while others are more related to the dispensing platform. In understanding when and where improved jet frequency from a piezo-driven valve adds value to this process, it is important to start with understanding how much of the total cycle time for a part is from the jet dispensing versus other operations.

In this first case study, we will look at a mobile phone PCB. (**Figure 2**) On this PCB, the dispense pattern is an "L-pass" dispense for a single chip across multiple units with a change in direction for the dispense pattern due to the alternating board pattern layout.

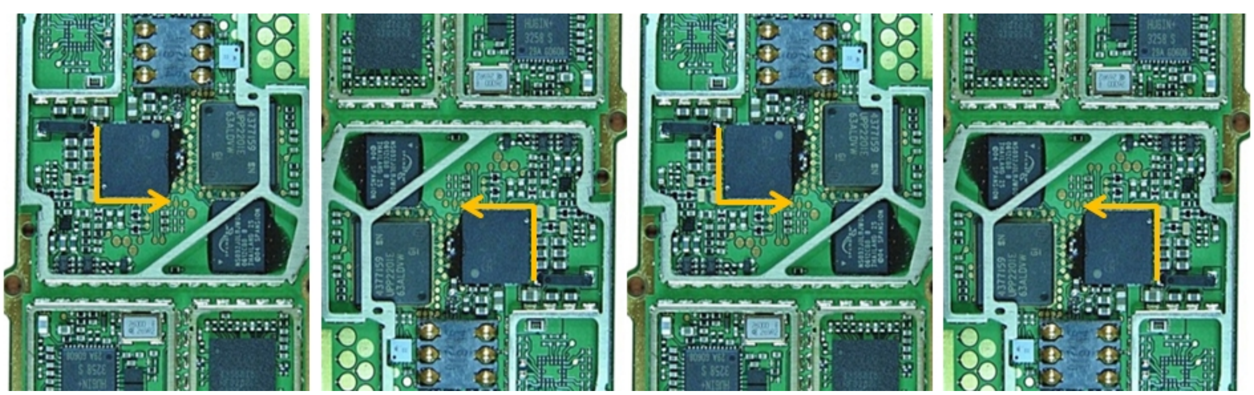

Figure 2 – "L-Pass" Dispensing on Mobile PCB

In this case, dispense time for all four units is a relatively small portion of the overall cycle time (16% at 200Hz) for the set of four parts. (**Table 1**) As a result, changing the jetting frequency from 200Hz to 300Hz reduces the dispense time by 50%, but has a much smaller impact on the overall cycle time for the part. While continued improvement through increased jet frequency is possible, at best, the total cycle time can only be reduced by a maximum of 16%. Other factors, such as improving non-dispense motion time, can have a much larger impact on improving the cycle time for these parts.

Table 1 – Cycle Time Break-Down for Mobile PCB Application

	200 Hz		300 Hz
Conveyance Time	2		2
Fiducial Time	3		3
Height Sense Time	3		3
Non-Dispense Motion Time	18		18
Dispense Time	5		2.5
Total time	**31**		**28.5**

By contrast, in a second test with underfill for a chip-on-strip application, more significant gains are achieved moving to higher jet frequencies. However, additional adjustments enabled by the higher jet frequency allow for even greater productivity improvements. In this example, the strip has 56 units and fluid is dispensed to each die in two passes to minimize the wet out distance from the die.

When dispensing multiple passes of underfill material, it is common to specify a minimum and maximum wait time between passes. The minimum wait time allows for sufficient time for underfill fluid to flow out beneath a die and ensures that fluid does not pile up and rollover the top of the die and keeps the wet out distance around the die to a minimum. The maximum wait time prevents the fluid at the die edge from reaching a "starved" condition wherein dispensing a second pass of fluid entraps air beneath the die and create voids that affect reliability of the device.

Running at 150Hz and using a traditional "stop and go" motion profile, it takes 284 seconds to dispense both passes to all 56 dies. (**Figure 3**) In this case, only half of the total strip can be dispensed at a time because of the maximum wait time allowed, requiring the dispense head to return to the starting position to start the second pass of dispensing before being able to dispense to additional units. The "stop and go" motion profile further affects the total cycle time by requiring short pauses during the dispense motion to allow for settling after the system accelerates and decelerates from a maximum velocity during the non-dispense moves before beginning a constant velocity move for dispensing the fluid along the edge of the die.

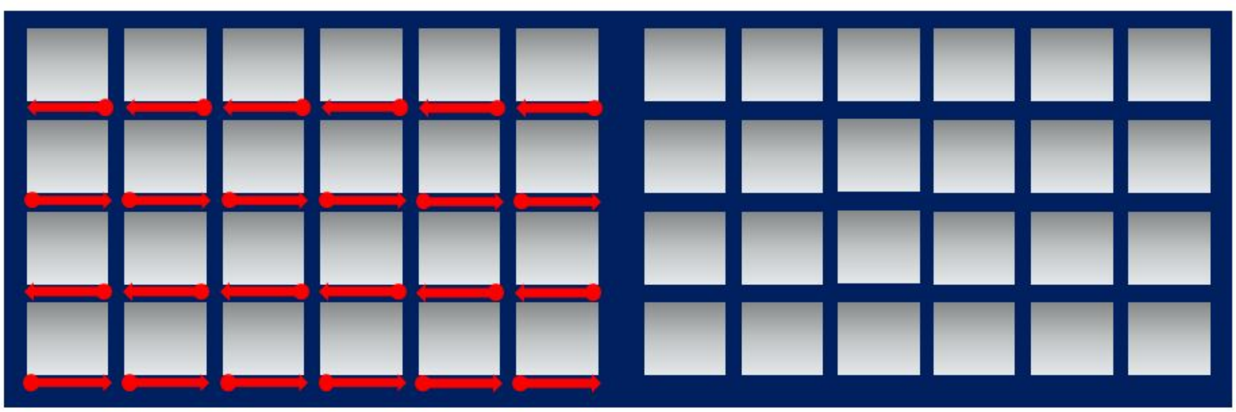

Figure 3 – Chip-on-Strip Underfill at 150Hz with Stop & Go Motion

By implementing a different motion profile called "continuous path motion," [2] the productivity is improved with the same 150Hz valve by 31%, reducing total cycle time from 284 seconds down to 197 seconds. (**Figure 4**) However, the dispense frequency of the valve at 150Hz still limits the maximum line speed while controlling the dispense weight per die. As such, it is still not possible to complete a first dispense pass to all of the dies before the maximum wait time requires returning to the first die to start a second pass.

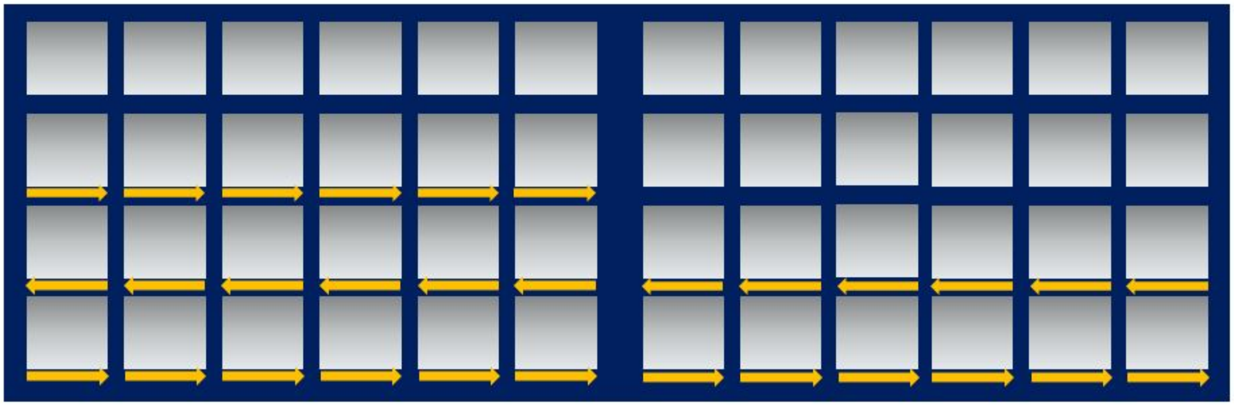

Figure 4 – Chip-on-Strip Underfill at 150Hz with Continuous Path Motion

Moving to a higher frequency jet valve at 300Hz and using the continuous path motion profile, it was then possible to complete dispensing of all 56 dies on the strip within the maximum wait time but also just above the minimum wait time. (**Figure 5**) The combination of the higher line speed achieved with the 300Hz jet and new motion profile allowed for further reducing the total cycle time down to 138 seconds, for a total cycle time reduction of 51% from the original 284 second cycle time.

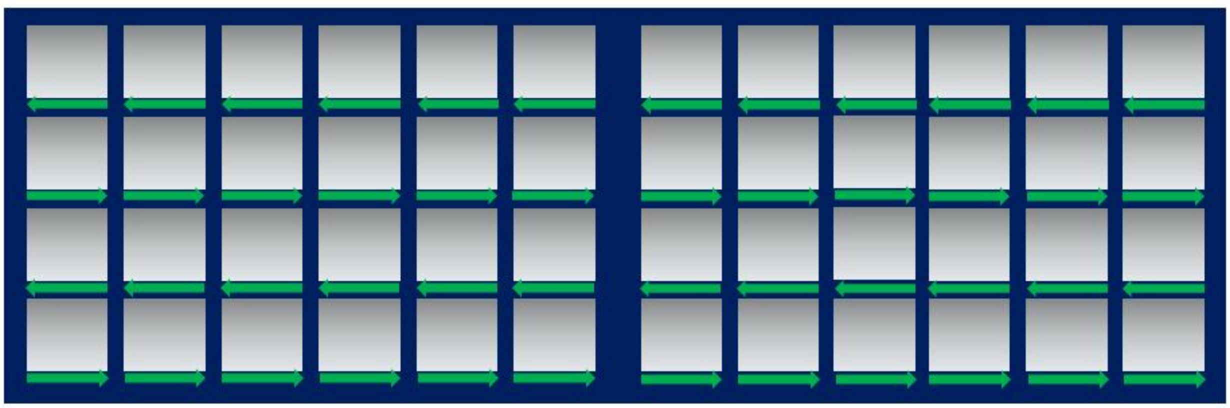

Figure 5 – Chip-on-Strip Underfill at 300Hz with Continuous Path Motion

As a comparative reference, running at 300Hz with the stop and go motion profile and the original dispense pattern (**Figure 3**) resulted in a total cycle time of 277 seconds. As such, it becomes obvious that changes to a dispense pattern must be made in tandem with changes to the dispense frequency in order to realize the full benefits of the improved capabilities of the new jetting system.

Additional Considerations for High Density Packages

In a final case study of productivity improvement with higher frequency jetting, we examine a wafer-level package underfill application. In this example, underfill is dispensed onto a 300mm wafer with > 250 devices per wafer. With wafer-level packages and similar high density dispensing applications, it is generally better to use continuous path motion because of the small distances between dispense locations and, therefore, relatively small amount of non-dispense motion time. Running at higher dispense frequencies for a given dot size and target dispense volume of fluid, which translates to a higher line speed and reduces the cycle time to complete a dispense pass. **Figure 6** shows an example wafer pattern and measured productivity when increasing the dispense frequency to 166Hz, 300Hz, and 600Hz. When increasing frequency, there is a significant improvement in the productivity (wafers per hour) with the high density of devices on the wafer making better use of high line speeds enabled by jetting at high frequency. It is important to note that the productivity gains made by going to higher frequencies begin to diminish as the frequency continues to increase.

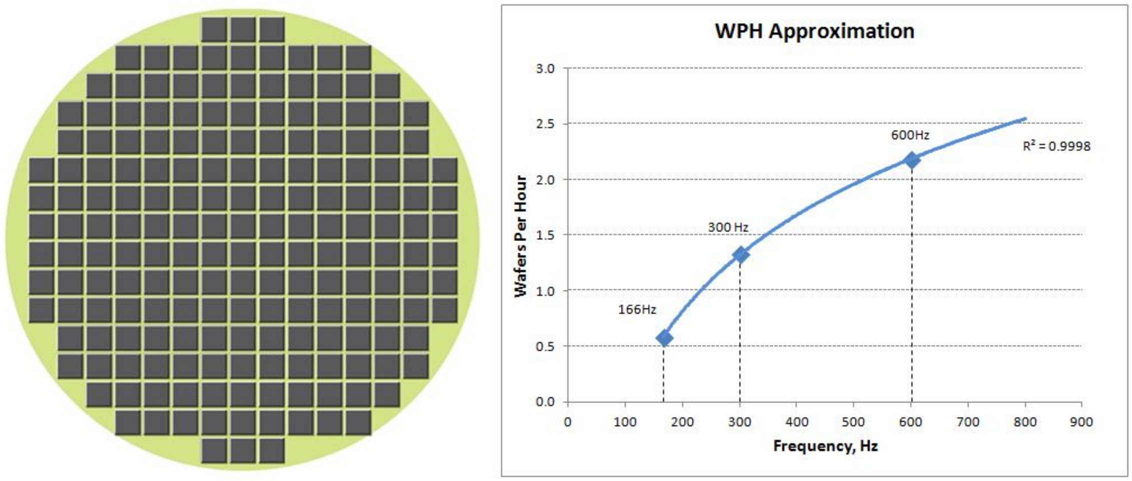

Figure 6 – Example 300mm Wafer & Productivity Projection Chart

Higher density substrates like wafer-level packages or high density chip-on-strip applications are more likely to become impacted by minimum and maximum wait times between passes. A minimum wait time is generally set to allow sufficient time for the dispensed fluid to flow out beneath a die to avoid dispensing excessive fluid in a second pass that may then end up rolling up over the top of the die. Maximum wait times are also set to ensure that when dispensing a second pass of fluid air is not entrapped beneath the die causing voids and device reliability failures. (**Figure 7**) Such wait times can present an additional upper limit for productivity enhancement with higher frequency jetting.

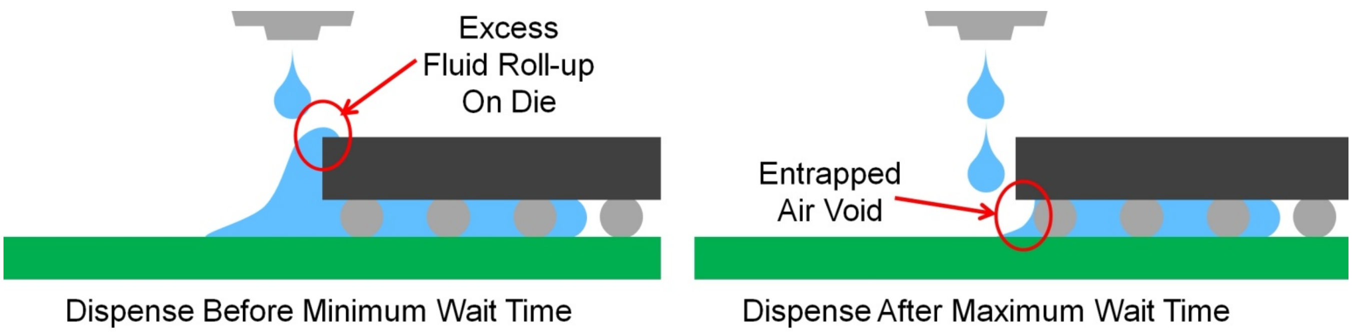

Figure 7 – Examples of Minimum and Maximum Wait Time Impacts

With the earlier chip-on-strip case, running at a higher frequency than 300Hz, such as 500Hz, would result in completing the first pass more quickly, but the minimum wait time between passes would result in the dispenser sitting idle until the minimum wait time is completed and the second pass can be completed. As such, the only additional productivity improvement from the higher frequency would be from completing the second pass more quickly. However, if the substrate requires heating in order to maintain fluid viscosity for the desired flow out characteristics of the dispensed fluid, the part must either move to a post-dispense heating station to complete the full flow-out of the fluid (adding cost to the dispensing platform for the post-dispense station) or the dispenser sits idle while the flow out time completes before conveying the part out and conveying in a fresh part.

Line Speed & Dispense Accuracy

It is worth mentioning at this point the effects of line speed on dispense position accuracy. With the increasing line speed resulting from higher dispense frequency, inertia and stiffness of a dispense platform begin to affect dispense position accuracy. Turning corners at high speed for performing an “L-pass” dispense pattern (Figure 2) or between rows in a continuous path dispensed (Figure 5) can result in a large radius at the corner or a “ringing” effect after turning the corner.[3] These effects may result in fluid being dispensed in undesirable locations. In maximizing the benefits of a high frequency jetting valve, it is important to consider the valve delivery system capabilities in addition to the performance of the jet valve itself as a sub-system of a total system solution for a fluid dispensing process.

Dot Size & Flow Rate

An additional benefit of high frequency piezo-driven valve systems is the ability to maintain high fluid flow rates when moving to smaller dot sizes. A given application normally specifies a target dispense volume required and a desired minimum productivity. These two pieces of information define the required dispense flow rate. Dispense flow rate (Q) is a function of dot volume (V) and frequency of dispensing dots (*f*) per the following formula:

$$Q = f \times V$$

Where:
Q = volumetric dispense flow rate (L / s)
f = dispense frequency (Hz, dots / s)
V = fluid volume per dot (L / dot)

If dot volume is kept constant and a higher jet frequency is used, the effective flow rate increases and cycle time decreases for dispensing the target dispense volume. Conversely, if the dot volume is reduced, a higher frequency is required to maintain the equivalent target dispense flow rate.

At first glance, decreasing the dot volume may not make much sense. However, in volume-sensitive applications, such as LED silicone-phosphor encapsulation where changes in the dispensed volume have a significant impact on LED color quality, moving to smaller dot volumes while maintaining an equivalent (or higher) flow rate allows for tighter control and increased resolution of the dispensed volume. Gaining full benefit of this capability requires tying the dot size control and higher frequency jetting to closed-loop process controls that can automatically add or subtract dots to a dispense pattern to maintain a target dispense volume. [1]

For example, if a current LED dispensing process uses a 200Hz jet frequency with a 100 microliter dot size and 10 dots of fluid per cavity for a total of 1 milliliter per cavity in 0.1 seconds, the flow rate is 10 milliliters per second. In this example, adding or subtracting a single dot of fluid represents a 10% change in the total dispense volume. With a higher frequency jet that is able to dispense the same fluid with at 600Hz, it would then be conceivable to reduce the dot size to 33 microliters per dot and maintain the same 0.1 seconds dispense time per cavity using 30 dots, instead of 10. In this case, the volumetric control by adding or subtracting a single dot of fluid improves from ±10% to ±3%.

Dot Size & In-Air Stream Width

A second benefit of moving to a smaller dot size is a reduced in-air stream width of the fluid. A smaller in-air stream width can then allow for jetting dots closer to a die edge and reducing the wet-out distance from the die or jetting between higher density components. (**Figure 8**) As the dispense gap between components reduces (X) for a given dispense platform accuracy (±35µm for industry-leading automated fluid dispensers today), the in-air stream width must likewise reduce in order to avoid dispensing fluid on top of the dies. Jet hardware design, interaction with fluid properties, and actuation of the jet can all affect the resulting in-air stream width, but in general, reducing dot volume leads to a reduced in-air stream width. However, as noted above, moving to a smaller dot size requires more dots to achieve a target dispense volume and again establishes a trade-off between productivity and quality or yield.

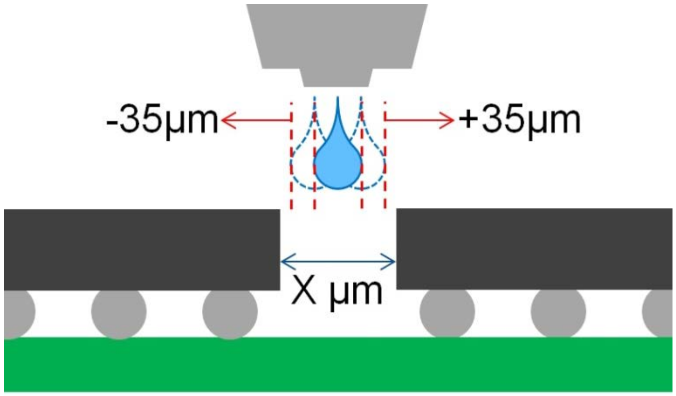

Figure 8 – Example of Dispensing Into a Narrow Dispense Gap

In the wafer-level packaging example from Figure 6 above, tests were performed with two different dot weights to examine the effect of reducing dot weight on productivity and part yield. (**Table 2**) As a result of the narrow gap between dies, variations in the dispensed dot size and position would periodically result in fluid landing on top of a neighboring die, resulting in yield loss.

Table 2 – Trade-off Between Dot Size, Productivity, and Device Yield

Dot Size (µg)	Dispense Frequency (Hz)	Productivity (UPH)	Yield Loss Per Hour (%)	Dots Per Hour (DPH)
15	300	312	2.10%	624,000
15	800	572	2.10%	1,144,000
9	800	390	0.20%	1,300,000

By reducing dot size, the reduced in-air stream width of the fluid provided much greater tolerance for variations in the dot placement to avoid contaminating the neighboring dies. As such, the yield loss dropped dramatically. However, with the reduced dot volume, more dots were required to meet the target dispense weight per die, and therefore, running at the same jet frequency (800Hz), the productivity reduced. In this case, the customer had to determine the acceptable balance between productivity and yield loss of the parts. In this case, the question then starts moving toward "what is my true cost-of-production for these parts?"

Is High-Frequency Jetting Always the Most Cost-Effective Solution?

With the above demonstrated advantages of moving to high-frequency jetting, it is natural to conclude that piezo-driven jet valves running at high frequency should be the right choice for most dispense applications to improve productivity and production yield levels. However, piezo-driven valve systems may not always be the most cost-effective solution for high-volume, long-term production environments.

Valve-to-Valve Consistency

Historically, piezo-driven jet valves have had a number of issues with valve-to-valve consistency and the ability to jet a wide range of fluids. Although this has improved significantly over the past decade, it is still common to have performance differences between individual valves due to even minor differences in piezo-electric crystal response and assembly process tolerances. As a result, integrated calibration controls within the jetting system (jet valve with firing controller) to normalize performance of the jet valve become necessary in order to replicate a dispensing process across multiple dispensing systems in high-volume production environments. Lacking such controls, a large-scale production may see variation in dispense weight or fluid ejection velocity as much as ±20% when using identical parameter settings. Such changes could spell the difference between good, clean fluid break-off from the nozzle and satellite generation or fluid accumulation that result in yield losses and, in turn, affect production costs.

Jet Valve Consumables Costs

A second, more significant consideration is the cost of the jet valve consumables. Jet valve consumable hardware (such as nozzles, seats, drive pin/poppet, etc.) has long been manufactured with various types of steel or tungsten carbide. These materials are generally selected for chemical stability when interacting with a wide variety of dispensed fluids as well as good performance in standing up to wear/abrasion from different fillers in the fluids like silica, acrylic, or phosphor. However, over millions of jet cycles and large volumes of fluid running through these materials, the fillers and the repeated impact between a poppet and nozzle seat cause wear and the parts must be replaced. As jetting frequency increases, the time to reach a set number of jet cycles reduces and therefore consumable replacement costs increase over a given time period. For example, if we look at the example processes from Table 2 and assume a given consumable part wears out after 60 million jet cycles at a cost of $300 per part and the production line runs for 135 hours per week for 4.5 weeks per month, we find the monthly consumable costs in **Table 3**.

Table 3 – Monthly Consumable Costs for Different Production Scenarios

Dot Size (µg)	Dispense Frequency (Hz)	Units per Month	Dots Per Hour (DPH)	# of Consumables Used per Month	Consumables Cost per Month ($)	Consumables Cost per Unit ($)
15	300	189,540	624,000	6.3	$1,895	$0.01
15	800	347,490	1,144,000	11.6	$3,475	$0.01
9	800	236,925	1,300,000	13.2	$3,949	$0.02

On a per month basis, the consumables cost rises when moving from a 300Hz process to an 800Hz process, but the cost per part remains the same as the number of dots (jet cycles) per unit remains constant. However, when moving to the smaller dot size, the number of dots required per unit increases and, therefore, the cost per part increases, as well as the monthly cost of the consumable parts. Again, there is a notable trade-off that the manufacturer must balance between this cost per part from the consumables contribution and the production line yield.

A second consideration for jet valve consumables is the frequency at which the valve is serviced for cleaning and maintenance. Valve consumables are typically serviced or exchanged at various times: at the end of a syringe of fluid or at the end of life of the consumable itself. This may happen per-shift, per-day (when running multiple shifts), or for a longer rate that is typically dictated by the pot life of the fluid (if in excess of 24 hours). When exchanging these valve consumables, it is desirable to only have to remove from the dispensing platform those individual parts requiring service such that down time of the dispensing platform is minimized and actual time producing parts is maximized. Performing such consumable exchanges may run as long as 15 minutes. If this is performed once per 8-hour shift, it equates to 0.75 hours of the production day. Many of today's latest jet valves, and piezo jets in particular, have considerably improved this practice by offering exchangeable cartridge-type consumables that significantly reduce the service time and allow the actuator body of the jet to remain on the dispensing platform while only swapping out the wetted parts. In this way, consumable exchanges and valve servicing can be reduced from 15 minutes per shift to 1 or 2 minutes per shift.

Production Line Efficiency & Yield Losses

Costs of moving to a higher jet frequency should also be examined in terms of the efficiency of a larger production line. If the dispensing equipment is the bottle neck in the production line, then increasing capacity at the jet dispenser by using increased jet frequency improves the overall production line efficiency. A well-balanced production line will have each piece of process equipment running at more or less the same productivity (UPH) level and, therefore, no individual piece of equipment in the production line sits idle waiting for either an upstream or downstream process step to complete. With a given production line potentially costing around $5 million, the slowest piece of the production line is the one that paces the entire line and by which the entire investment ought to be weighed. In this case, individual part yield losses from one process step in the production line may have a lower overall cost-per-part impact for the entire production line if such yield losses are accepted with a higher total throughput for the entire production line.

Piezo Jet Actuator Longevity

A final consideration when considering the costs of moving to a higher frequency, piezo-driven jetting system is the longevity of the piezo stack itself. Early versions of piezo-driven jet valves began appearing shortly after the release of the first mass-production pneumatic jet in the mid-1990s. One of the issues with these early piezo-driven jets was the durability and longevity of the piezoelectric drive system. In many of these early units, the piezo stack and drive mechanism wore out and exceeded operating tolerances, resulting in poor fluid dispensing after only a few hundred million jet cycles. Recalibration of the piezo valve or replacing the piezo stack altogether is costly, often requiring sending the valve back to the manufacturer and running anywhere from $2,000 to the full cost of the jet valve. By contrast, pneumatic solenoids in pneumatic jet valves typically had to be replaced due to wear after 1 to 2 billion jet cycles at a typical cost of < $600. Such pneumatic solenoid replacements can be performed at a customer site, eliminating transportation delays and equipment down time. As a result, cost and performance differences allowed the pneumatic valves to become the dominant jetting technology.

As mentioned earlier, there have been significant advances in the designs of piezo jet valves over the past decade that now call for reconsideration of piezo valves as an alternative to pneumatic jet valves in different applications. A number of valve manufacturers currently advertise an expected life of their piezo jet valve drive systems up to ~1 billion jet cycles. When running at higher frequencies and higher DPH, it then takes less time to reach 1 billion jet cycles and thus more frequent jet actuator repair cycles.

Table 4 – Annual Repair Rate of Jet Actuator for Various Examples

Dispense Pattern	Actuator Type	Dispense Frequency (Hz)	Dots Per Hour (DPH)	# of Hours to Reach 1 Billion Cycles	# of Actuator Repairs per Year (@ 7,000 hours per year)
Chip-on-Strip	Pneumatic	150	240,975	4,150	1.69
Chip-on-Strip	Pneumatic	300	481,320	2,078	3.37
Wafer	Pneumatic	300	624,000	1,603	4.37
Wafer	Piezo	800	1,144,000	874	8.01
Wafer	Piezo	800	1,300,000	769	9.1

In **Table 4** above, we show estimated repair rates for the jet valve actuators given the different dispense applications and assuming that both pneumatic solenoids and piezo jet actuators only last to 1 billion jet cycles. With lower cost and potentially longer-lasting pneumatic solenoids, it is readily apparent that the jet actuator repair costs for the pneumatic valves are much lower on a per year basis. However, productivity for the pneumatic valves running at the lower frequency is also lower. It is quite shocking to note, however, the high number of actuator repairs required for the wafer applications running with piezo jet valves. In these cases with extremely high DPH duty cycles, it becomes readily apparent that, when the jet actuator has a 1-billion jet cycle life, the annual cost for these repairs significantly increases. In order for these processes to have a more reasonable cost for jet valve servicing, the piezo jet life must double or quadruple to 2-4 billion jet cycles before requiring servicing.

Conclusions

In conclusion, the arrival of modern piezo jet valves with longer-lasting piezo stacks, improved valve-to-valve consistency, and higher continuous operation frequency, have introduced a new, more modern age in jet valve technology for the mass-market. These latest-generation valves often present significant opportunities for improving productivity for various applications, as well as the potential for improved process controls and production yield levels. However, these improvements may come at a cost and manufacturers who are evaluating the use of piezo-driven jet valves should analyze the larger picture for cost-per-part than just UPH when selecting an appropriate jetting technology for their production model.

Acknowledgements

The author wishes to thank the Applications team from the company, and, in particular, Sonia Aldridge, Hanzhuang (Hannah) Liang, and Floriana (Ria) Suriawidjaja, for their assistance in running the various application tests noted in this paper. He also wishes to acknowledge Dan Ashley, Brian Chung, Greg Hartmeier, Al Lewis, Chris Marion, Akira Morita, and Roberta Foster-Smith for their suggestions and input on content for this paper and assistance with editing.

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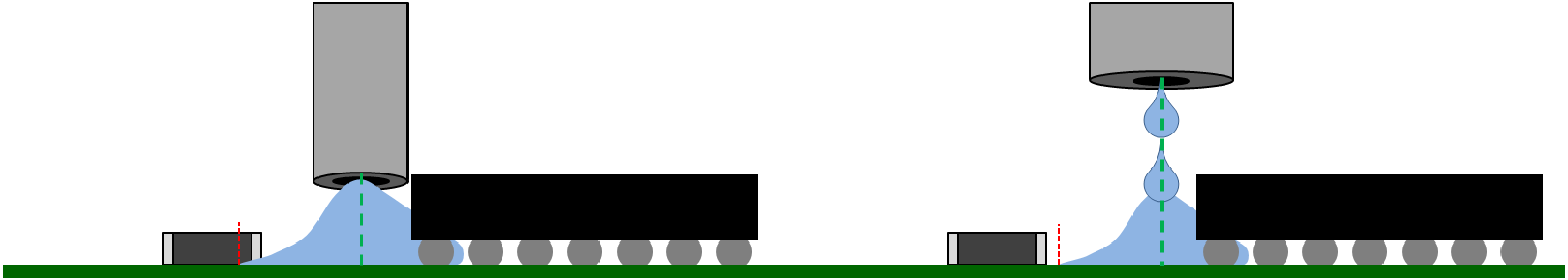
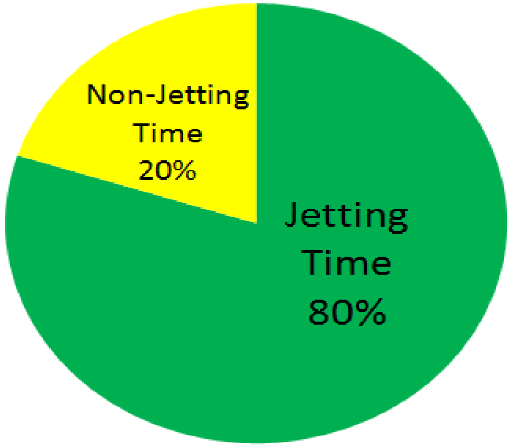
Jetting versus Needle Dispensing



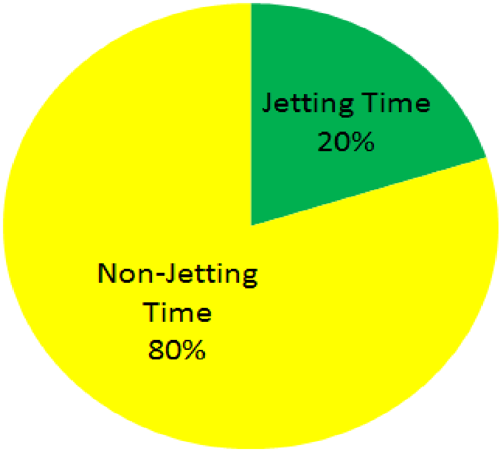
- Benefits of Jetting:
  - Non-contact dispensing at constant z-height
  - Finer resolution dispense volume control
  - Smaller Keep-Out Zone (KOZ) or wet-out distance
  - Higher productivity

Impact of Frequency on UPH

Frequency has <u>HIGH</u> impact on UPH

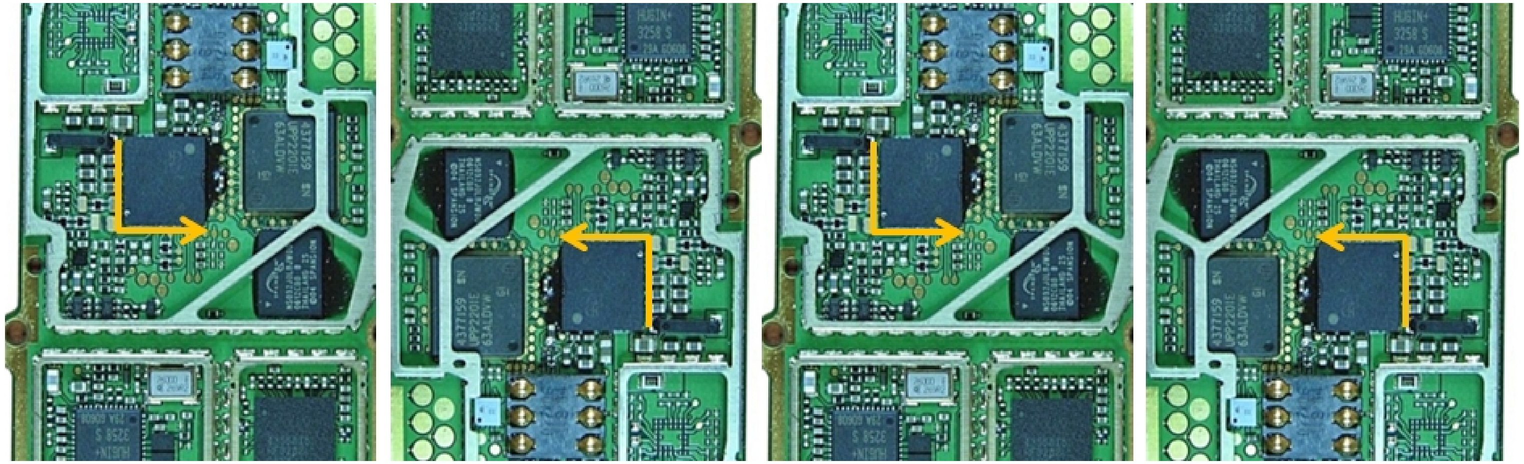


Frequency has <u>LOW</u> impact on UPH



- Units Per Hour (UPH) can be broken down into individual cycle time per part
- Total cycle time includes additional factors: conveyance time, height sensing, fiducial finding, motion time, etc.
- “Dispense-heavy” applications will see a larger benefit of high frequency jetting
- Other factors, like fluid flow out time, may limit possible UPH gains

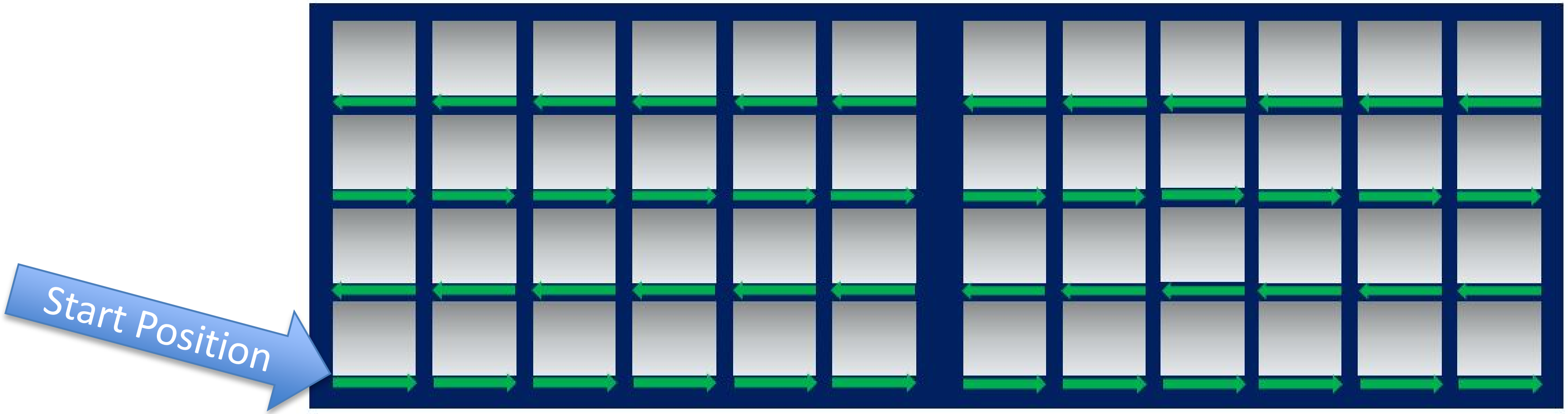
Example 1 – Mobile PCBA



	200 Hz		300 Hz
Conveyance Time	2		2
Fiducial Time	3		3
Height Sense Time	3		3
Non-Dispense Motion Time	18		18
Dispense Time	5		2.5
Total time	31		28.5

- L-pass dispensing
- Alternating dispense orientation
- Dispense time is only 16% of total cycle time

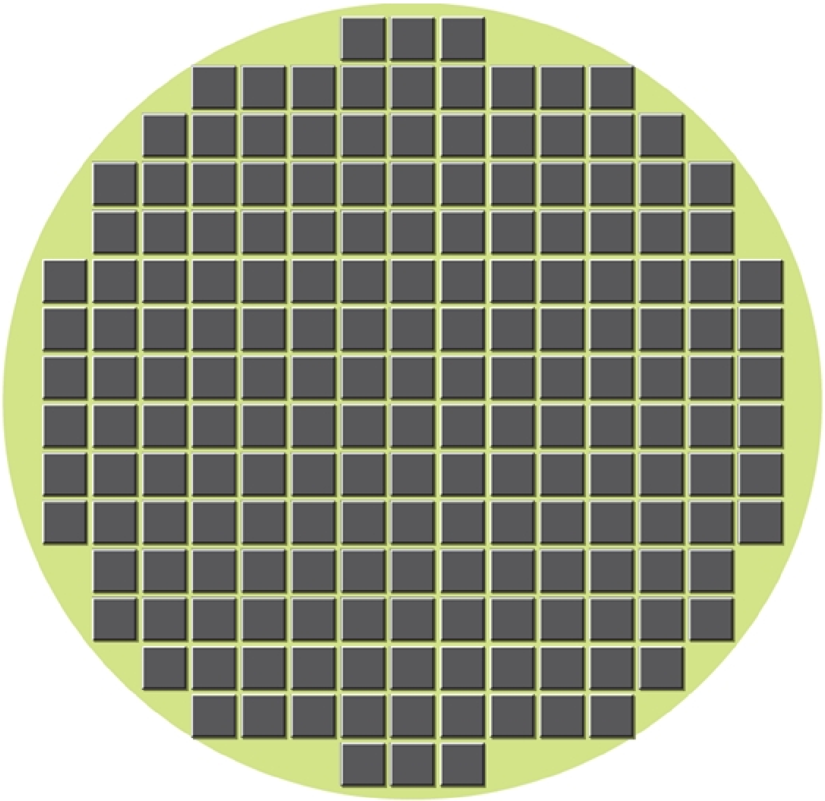
Example 2 – Chip-on-Strip Underfill

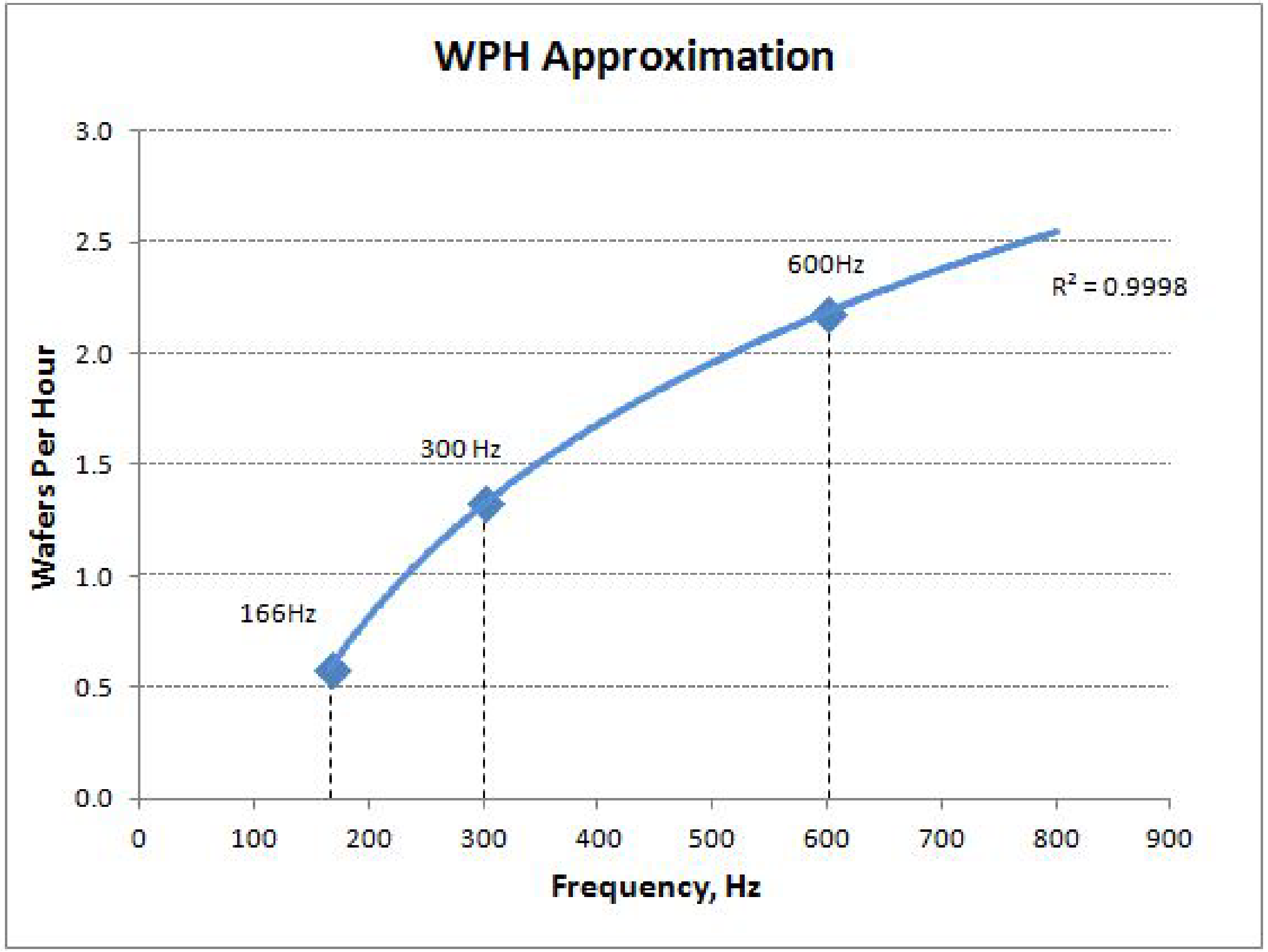


- Multi-pass dispensing
- Minimum & maximum wait times between passes
- Stop-and-go versus continuous path motion
- Higher percentage of dispense time in total cycle time

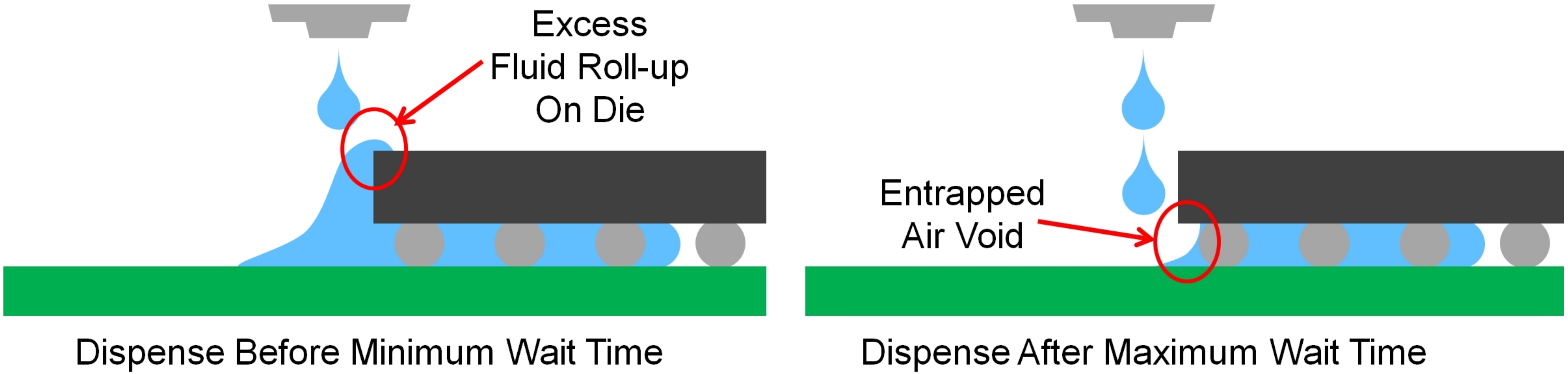
- 150Hz (zoned) => 284s/strip
- 150Hz (continuous) => 197s/strip
- 300Hz (continuous) => 138s/strip

Example 3 – Wafer Level Packaging





Minimum & Maximum Wait Times



- Minimum wait times avoid fluid over the top of the die
- Maximum wait times avoid creating voids under the die caused by entrapping air during “starved” conditions

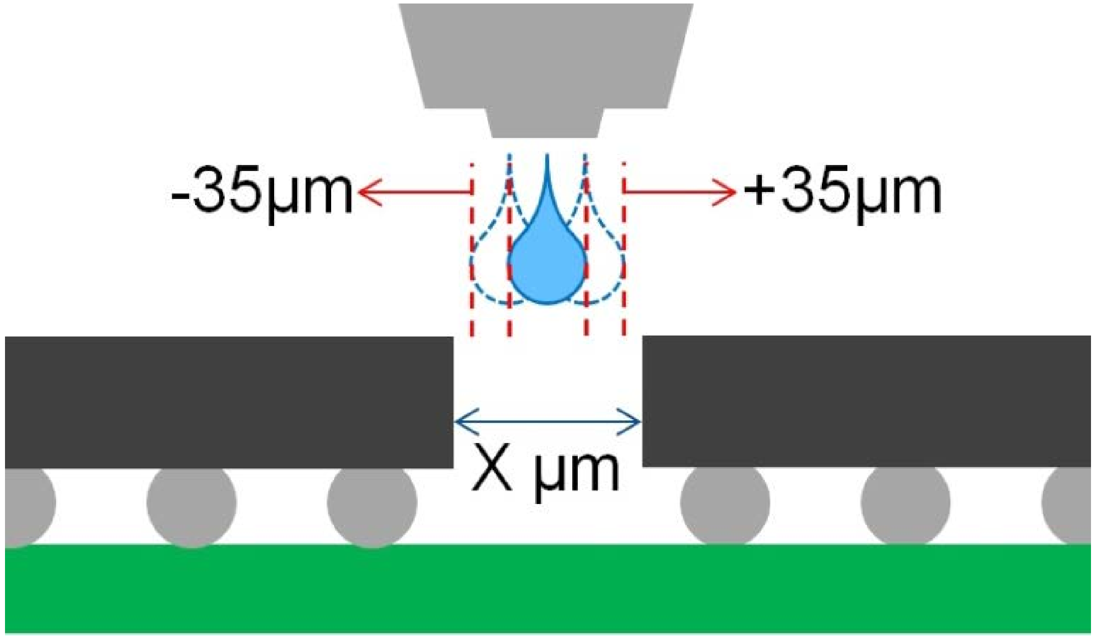
Trade-off: Dot Size and Flow Rate

$$Q = f \times V$$

- Q = volumetric dispense flow rate (L / s)
- f = dispense frequency (Hz, dots / s)
- V = fluid volume per dot (L / dot)

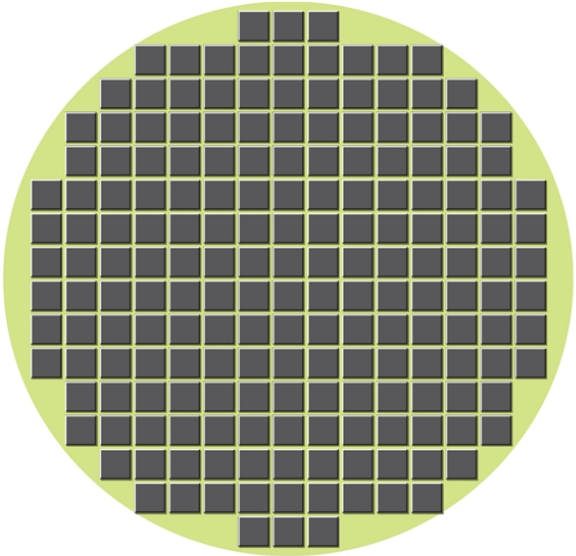
- Smaller dots require higher frequency to maintain flow rate
- Smaller dots give better resolution for volume/mass control

Trade-off Dot Size and Stream Width



- Stream width decreases with dot volume/weight
- Additional controls in hardware and valve actuation can also affect stream width

Trade-off: Dot Size, UPH, and Yield



Dot Size (µg)	Dispense Frequency (Hz)	Productivity (UPH)	Yield Loss Per Hour (%)	Dots Per Hour (DPH)
15	300	312	2.10%	624,000
15	800	572	2.10%	1,144,000
9	800	390	0.20%	1,300,000

- Higher frequency with same dot size improved UPH
- Smaller dots improved yield but decreased UPH
- Proper balance must be chosen

Trade-off: UPH & Cost-of-Ownership

- Cost-of-Ownership:
  - Consumables
  - Valve Maintenance
  - Production Line Efficiency
  - Operator Intervention

Dot Size (µg)	Dispense Frequency (Hz)	Units per Month	Dots Per Hour (DPH)	# of Consumables Used per Month	Consumables Cost per Month ($)	Consumables Cost per Unit ($)
15	300	189,540	624,000	6.3	$1,895	$0.01
15	800	347,490	1,144,000	11.6	$3,475	$0.01
9	800	236,925	1,300,000	13.2	$3,949	$0.02

Dispense Pattern	Actuator Type	Dispense Frequency (Hz)	Dots Per Hour (DPH)	# of Hours to Reach 1 Billion Cycles	# of Actuator Repairs per Year (@ 7,000 hours per year)
Chip-on-Strip	Pneumatic	150	240,975	4,150	1.69
Chip-on-Strip	Pneumatic	300	481,320	2,078	3.37
Wafer	Pneumatic	300	624,000	1,603	4.37
Wafer	Piezo	800	1,144,000	874	8.01
Wafer	Piezo	800	1,300,000	769	9.1

The End

Thank you