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Power Consumption and Closed-loop Nitrogen Control Considerations in Lead-free Reflow

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Abstract
When transitioning to lead-free reflow, consideration should be given to the additional costs of operation, above and beyond material costs.[1] Impacts to the overall reflow process should be carefully reviewed. Due to the higher operating temperatures required for lead-free processing, and the suggested use of nitrogen, equipment cost of ownership could dramatically increase.[2]

This paper evaluates power consumption rates for both lead-free and traditional leaded reflow processing along with reviewing a unique, closed-loop nitrogen control design that automatically varies the flow of nitrogen to maintain ppm levels and reduces nitrogen flow during idle states. Data obtained under loaded/unloaded conditions will be presented in relation to varying power consumption results. A cost of ownership model is also used to predict additional expenses over time, along with suggestions on equipment feature/option considerations for lead-free reflow processing.

Power Consumption Analysis
Reflow ovens present one of the greatest concerns regarding power consumption in an electronics-manufacturing environment. This is understandable due to the nature of the process of transferring heat to product then expending energy to remove heat for the cooling cycle. Efficient heat transfer techniques must be considered in reflow equipment design to deliver proper reflow profiles for leaded and lead-free processing, but it becomes more important in the consideration of power consumption.

In order to determine the power consumption characteristics during reflow processing, an OmniExcel 7 reflow system was utilized along with data gathering equipment. The OmniExcel system tested consisted of the following options along with the oven conditions in Table 1:
- OmniExcel 7
- Nitrogen system
- Rail heaters
- Pin chain conveyor with CBS (Center Board Support)
- Flux Extraction System

Other test and data gathering equipment consisted of the following:
- Fluke 43B Power Analyzer
- National Instruments Data Acquisition Equipment with LabView software
- Fluke i200s current probes
- Voltage probes utilizing a signal isolation module built around the ISO122 IC
- KIC and ECD profiling devices
- ELECTRVOERT standard profile board, 609 mm (24”) wide embedded with 5 TC’s to determine profile performance
- 16 gauge, 304 mm x 304 mm (12” x 12”) steel plates continuously loaded into oven, spaced 304 mm (12”) apart, to simulate production load

Table 1 – Reflow Oven Test Conditions

Standard Reflow Profile - refers to a recipe for processing average size PCB with Sn/Pb solder paste:									
Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Conveyor	Rail Heaters	
130	150	170	165	170	260	265	28"/min	Front	265 C.
130	150	170	165	170	260	265		Rear	265 C.
Load End Curtains: raised 10mm above pin chain.									
Lead Free Profile - refers to a recipe for processing average size PCB with Pb-Free solder paste, consisting of higher melting point alloy:									
Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Conveyor	Rail Heaters	
130	150	170	165	190	300	305	28"/min	Front	300 C.
130	150	170	165	190	300	305		Rear	300 C.
Load End Curtains: raised 10mm above pin chain.									

Several tests were run on the reflow system under the different operating conditions to determine power consumption of the system for comparison.

The first test consisted of starting the system from an ambient state to a leaded profile setting, allowing the system to stabilize at an idle state then loading the system with steel plates to apply load to the system. Table 2 represents the power consumption in Watts of power.

Table 2 – Power Consumption in Watts for Leaded Profile

Start Up	Average	33591
	Maximum	58425
Idle	Average	12281
	Maximum	13277
Load	Average	13883
	Maximum	15238

From the data collected above, we can determine that the maximum power consumption of the system is 58.4 kW at startup. Once the system stabilized at process ready and idle condition within 15 minutes, the average power consumption is 12.2 kW per hour. The system was then loaded with steel plates to simulate production. The steel plates used within the load testing are 50% of the maximum process width of the oven and represent a size and mass in excess of a majority of PCB's processed in the electronics industry. Once the system was loaded with steel plates, the average power consumption was 13.8 kW per hour. From this data we can determine that the difference between an oven idle state and loaded state is approximately 1.6 kW per hour.

Translating this power consumption into financial impact is a simple formula of:

Cost per kW * hours of production a day * days per week * weeks per year = total cost of power per year

In an example of a leaded process where the cost of a kW hour of power is $.07,[3] in a production environment of 5 days a week, 16 hours a day for 49 weeks per year,[4] translates into a total average annual cost of $3,809.62 under a loaded condition.

The reflow system tested above is designed with lower power consumption in mind. Compared to other legacy reflow products tested, there has been a tremendous improvement in the thermal efficiency and reduced power consumption. The previous reflow system tested averaged 21 kW per hour running a leaded reflow profile under idle conditions. Compared with the data above, power consumption was reduced from 21 kW per hour to 12.2 kW per hour with the new system design; this is a 41% reduction in power consumption for similar profile performance.

An additional test was conducted with the reflow system with only the profile change to reflect a lead-free process. The system was started from an ambient state to a lead-free profile setting, allowing the system to stabilize at an idle state then loading the system with steel plates to apply load to the system. Table 3 represents the power consumption in Watts of power.

Table 3 - Power Consumption in Watts for Lead-free Profile

Start Up	Average	**35524**
	Maximum	**58179**
Idle	Average	**13453**
	Maximum	**14255**
Load	Average	**15996**
	Maximum	**17038**

From the data collected above we can determine that the maximum power consumption of the system is 58.1 kW at startup. Once the system stabilized at process ready and idle condition within 15 minutes, the average power consumption is 13.4 kW per hour. The system was then loaded with steel plates to simulate production. The steel plates used within the load testing are 50% of the maximum process width of the oven and represent a size, and mass in excess of a majority of PCB's processed in the electronics industry. Once the system was loaded with steel plates, the average power consumption was 15.9 kW per hour. From this data we can determine that the difference between an oven idle state and loaded state is approximately 2.5 kW per hour for a lead-free process.

In an example of a lead-free process where the cost of a kW hour of power is $.07,[3] in a production environment of 5 days a week, 16 hours a day for 49 weeks per year,[4] translates into a total average annual cost of $4,389.22 under a loaded condition.

In comparing the leaded and lead-free process we can determine the impact of power consumption of the different processes. This data is represented in Table 4:

Table 4 – Power Consumption Comparison Between Leaded and Lead-free Process

		Leaded	Lead-free	Difference
Start Up	Average	**33591**	**35524**	**1932**
	Maximum	**58425**	**58179**	**-246**
Idle	Average	**12281**	**13453**	**1172**
	Maximum	**13277**	**14255**	**978**
Load	Average	**13883**	**15996**	**2112**
	Maximum	**15238**	**17038**	**1800**

From the test results and comparison of data, we can determine that moving to a lead-free process under similar production loading it would consume approximately 2.1 kW per hour more energy over a leaded process.

There is a financial impact of power consumption when moving from a leaded to a lead-free process. In a production environment with cost of a kW hour of power is $.07,[3] in a production environment of 5 days a week, 16 hours a day for 49 weeks per year.[4] This translates into a total average additional annual cost of $579.53 under a loaded condition for a lead-free process. This figure may not seem like a tremendous amount, and one should consider that any machine design that can minimize power consumption would have a significant savings of the life of the reflow system.

Closed-loop Nitrogen Control

The benefits of nitrogen in a reflow environment have been widely debated over the years. With the introduction of lead-free pastes, this is again becoming a factor.[2]

Nitrogen serves a purposes in a reflow environment. The use of nitrogen protects board surfaces through multiple reflow passes, prevents oxidation of pads and leads and allows better wetting of material. This is most evident in the lead-free process. Higher temperatures will act as a catalyst for the process of oxidation, due to the higher temperatures in the lead-free process, nitrogen will act as an insurance to protect against oxidation. Although not required for lead-free processing, nitrogen will allow wider process windows. There are downsides to the use of nitrogen, which includes initial cost of equipment, the cost of nitrogen and the extra maintenance required on the reflow machines due to the flux volatiles trapped in the machine.

Reflow ovens are typically inerted by injecting sufficient quantities of nitrogen into the tunnel to create a positive pressure sufficient to prevent air infiltration at the tunnel apertures. Nitrogen reduction techniques include minimizing the size of the apertures and employing long isolation zones. Open-loop systems must utilize a sufficient amount of gas to handle the largest boards and highest throughput, regardless of the actual operating conditions. In order to satisfy the worst-case condition, the greatest amount of gas must be consumed at all times. Some reflow systems offer receipe control of nitrogen injection where some products may not need an inert environment. In this case, the system will automatically turn on or off the nitrogen flow as configured in the recipe.

In order to reduce the consumption of nitrogen within the reflow process of products that do require specific oxygen ppm levels, new design approaches need to be considered. An innovative, closed-loop nitrogen flow control was developed to ensure consisent oxygen ppm levels while minimizing the nitrogen consumed.

Closed-loop control relies on dynamic sampling of the atmosphere by appropriating only the amount of nitrogen required to sustain the required oxygen ppm level. With closed-loop control, the gas supply is split into two streams. The first stream is used to supply a constant flow of gas required to inert the oven under the best conditions (smallest boards and lowest throughput). A variable flow valve controlled by a closed-loop PID controller regulates the second stream. The flow in this stream varies in response to the current ppm count as measured by an oxygen analyzer. This is demonstrated in Figure 1.

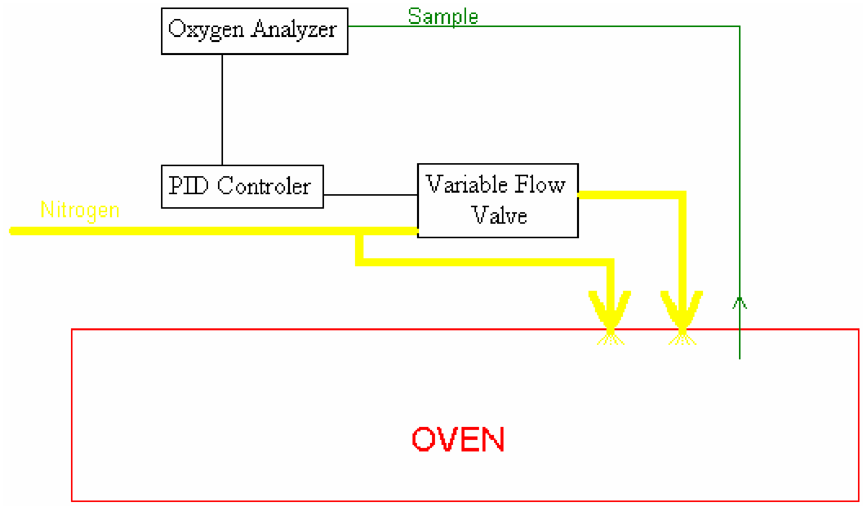

Figure 1 – Example of Closed-loop Nitrogen Flow

Closed-loop oxygen ppm control is not widely used due to the difficulties associated in stabilizing reflow ovens. These difficulties arise from the slow response and non-linear conditions associated with maintaining an inert atmosphere. The slow response results from the inherent sluggishness of oxygen analyzers coupled with injecting a relatively small amount of makeup gas into a large chamber. Non-linearity is a function of the need to pressurize the oven above a threshold limit below which the atmosphere will collapse in an exponential fashion.

Under production loading conditions, the system will continually montitor the oxygen ppm level within the reflow system and automatically control the flow of nitrogen into the system. The source gas, which is typically cryogenic nitrogen of 2-5 oxygen ppm purity, is ideal for controlling an atmosphere purity of lower than 50 oxygen ppm and may be suitable up to 850 oxygen ppm. Above these amounts, control becomes unstable due to the small amount of makeup gas and the slow response time described above. Therefore, systems requiring lower purity should utilize a pre-mixed source gas of lower purity generated by the Oxygen Mixer Valve. The ppm level will be maintained within 15% above the desired set point that is saved within each individual recipe for specific products. Under this design concept different oxygen ppm levels can be maintained for different products. Additional difficulties arise with lower purity atmospheres that are far above the base purity of the gas.

Providing lower levels of overall nitrogen consumption can also be accomplished through innovative software control. One method of reducing nitrogen usage is to turn off the nitrogen flow when long periods of machine inactivity occur. This could occur during production break, product changeovers or unscheduled downtime of other systems. In Figure 2, a software screen shows a feature of Standby Time in the reflow system control software.

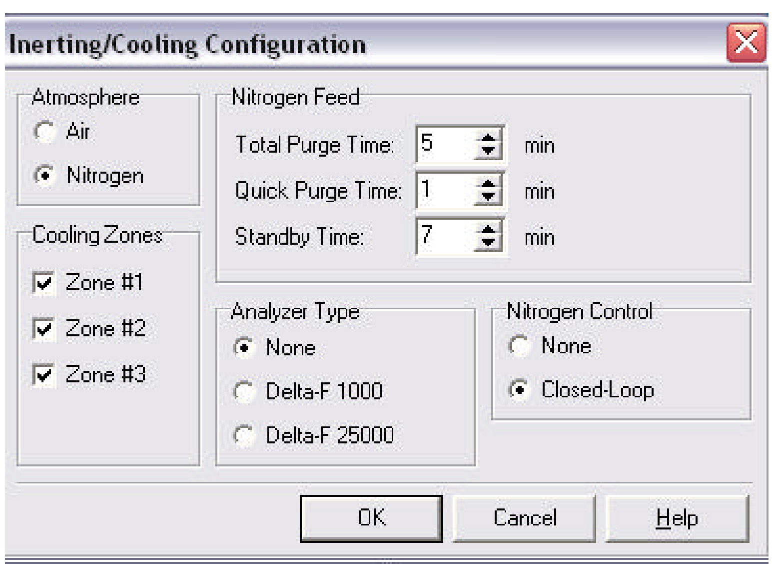

Figure 2 – Nitrogen Flow Control Screen

By setting this feature to a time limit as designated by an Engineer, the system will turn off the nitrogen flow to the machine when is senses that no product has been processed for that period of time. When the reflow system senses a product through a SMEMA connection, the machine will go into nitrogen purge time as designated in the software. Once the purge is complete the reflow system will send a SMEMA signal to release product into the reflow system.

Conclusion

There has been a tremendous amount of discussion and focus on the transition to lead-free production in the future and what the impact will be. While initial capital equipment costs are a consideration, overall cost of ownership in power consumption and nitrogen consumption in reflow equipment should be considered and analyzed. This data can help determine financial impact to an organization that may not always be considered.

References

1. Chin, Spencer. "European lead-free law could cost U.S. companies a bundle". www.ebnews.com, May 4, 2001: last accessed December 2, 2003.
2. Dong, Ross, and Schwarz. "N2 Inerting for Reflow of Lead-free Solders". Advanced Packaging, Novevember 2003, pgs. 29-31.
3. Energy Information Administration website (www.eia.doe.gov) , last accessed December 2, 2003.
4. Example from interview with EMS provider of automotive electronic assemblies, July 2003.

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Technical Focus

- Determine power consumption effects on reflow systems between leaded and lead free production
  - Controlled tests to determine power consumption
  - Translate into actual costs
- Review of closed loop nitrogen control in reflow
  - Analysis of closed loop nitrogen control design

Power Consumption Testing Tools

- OmniExcel 7 reflow system
  - Nitrogen system
  - Pin chain conveyor with rail heaters
  - Center board support
  - Flux Extraction System
- Fluke 43B Power Analyzer
- National Instruments Data Acquisition Equipment with LabView Software
- Fluke i200 current probes
- Voltage Probes
- KIC and ECD profiling devices
- 24” wide profile board
- 12” x 12” 16 gauge steel plates

Machine Test Conditions

Standard Reflow Profile - refers to a recipe for processing average size PCB with Sn/Pb solder paste:

Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Conveyor	Rail Heaters	
130	150	170	165	170	260	265	28"/min	Front	265 C.
130	150	170	165	170	260	265		Rear	265 C.
Load End Curtains: raised 10mm above pin chain.									

Lead Free Profile - refers to a recipe for processing average size PCB with Pb-Free solder paste, consisting of higher melting point alloy:

Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Conveyor	Rail Heaters	
130	150	170	165	190	300	305	28"/min	Front	300 C.
130	150	170	165	190	300	305		Rear	300 C.
Load End Curtains: raised 10mm above pin chain.									

- Baseline tests conducted on lead profile
  - Unloaded and loaded conditions
- Tests conducted with lead free profiles
  - Unloaded and loaded conditions
- Loaded conditions
  - 12” x 12” 16 gauge steel plates, spaced 12” apart

Power Consumption Results

		Leaded	Lead-free	Difference
Start Up	Average	**33591**	**35524**	**1932**
	Maximum	**58425**	**58179**	**-246**
Idle	Average	**12281**	**13453**	**1172**
	Maximum	**13277**	**14255**	**978**
Load	Average	**13883**	**15996**	**2112**
	Maximum	**15238**	**17038**	**1800**

- 2.1 kW hour additional for lead free processing

Power Cost Example

- Cost per kW * hours of production a day * days per week * weeks per year = total cost of power per year
- Production 5 days per week, 16 hour days, 49 weeks per year
- kW hour of power is $.07
  - Loaded Lead profile = $3,809.62 per year
  - Loaded Lead Free profile = $4,389.22 per year
  - Lead free process is an additional $576.53 per year

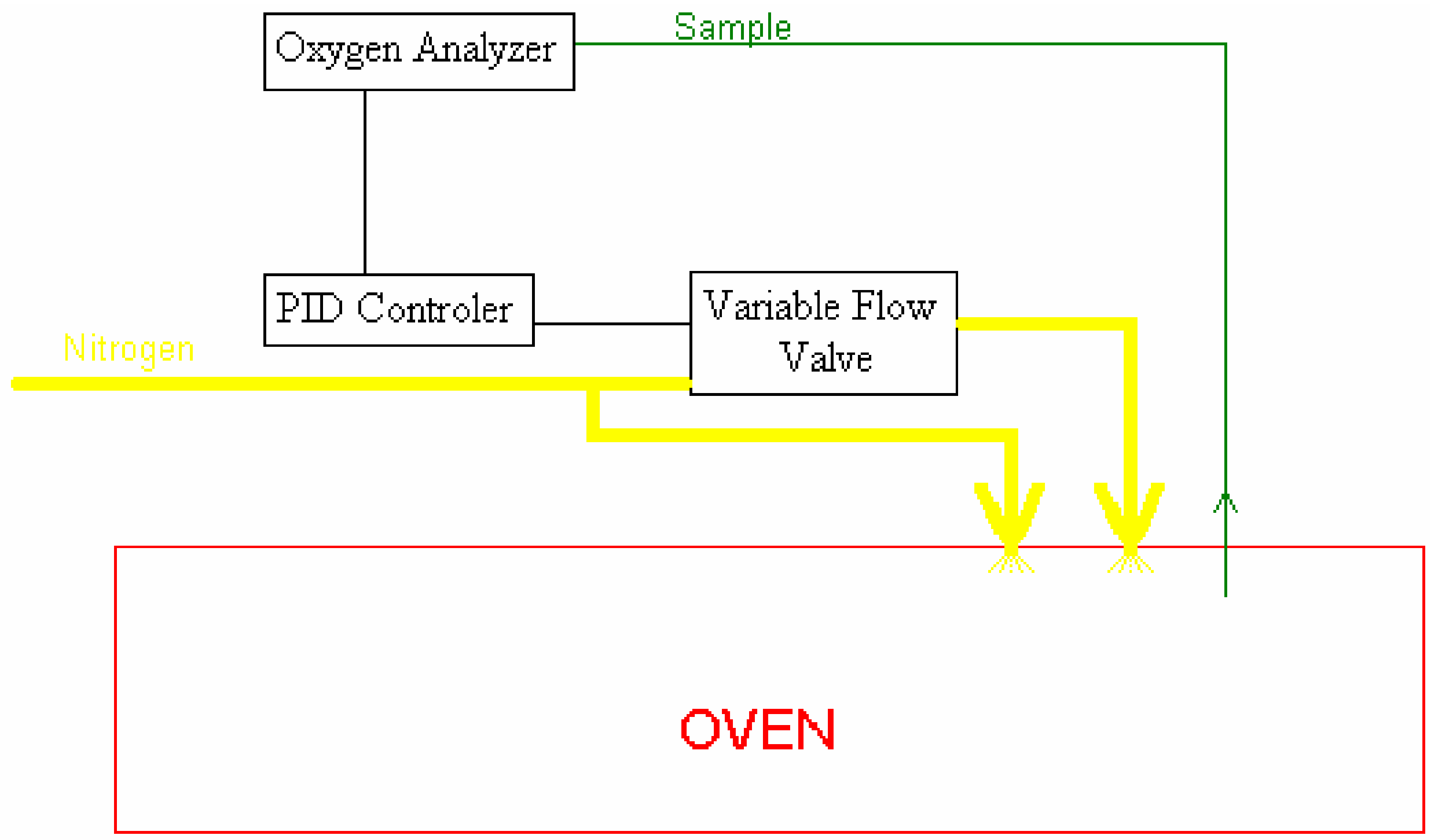
Nitrogen Control Systems

- Open loop manual flow valves
  - Manually adjust flow of N2 into reflow system for desired O2 ppm level under loaded conditions
  - Set up for worst case conditions
    - Widest boards and highest throughput requirements
- Closed loop nitrogen control
  - Manually adjust flow of N2 into reflow system for desired O2 ppm level under static conditions
  - Additional flow only needed for loaded conditions

Closed Loop Nitrogen Control

- Two stream nitrogen flow
  - Continuous flow to maintain O_2 ppm level at static condition
  - PID controlled variable nitrogen flow for reflow zone
- Set up under best considerations
  - Smallest boards and lowest throughput
- Maintain desired O_2 ppm levels for each product by recipe

Closed Loop Nitrogen Control



Closed Loop Nitrogen Control Benefits

- Under un-loaded conditions
  - Minimized flow of nitrogen to sustain O2 ppm levels
  - Minimize nitrogen consumption for line change over
- Loaded Conditions
  - Nitrogen flow will automatically adjust for visibilities in production loading
  - Controlled O2 ppm levels by recipe

Conclusion

- Lead free processing will add additional power costs
  - Varies by reflow system and production loading
- Closed loop nitrogen control
  - Suggested where O_2 levels must be maintained
  - Strategy for additional savings on consumption of nitrogen