Cost Effective and User Friendly Nitrogen Inerting Technology For Lead-Free Wave Soldering

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Abstract
It is well known that nitrogen (N_2) inerting in wave soldering can significantly reduce dross formation and improve solder wetting. For lead-free wave soldering, the benefits of N_2 inerting are even higher. However, there is still a lack of a mature N_2 inerting technology for wave soldering, which largely impedes its wide application. This paper presents a new generation N_2 inerting system for wave soldering to make the technology more cost effective and user friendly. Both lab-scale experiments and production trials were conducted, which demonstrates the following superior performances and benefits of applying the developed N_2 inerting technology: 1) low N_2 consumption for inerting, 2) low tendency of diffuser clogging, 3) low retrofitting cost, 4) an option for flux vapor collection, 5) reduced dross formation, 6) reduced machine down time for cleaning, 7) reduced flux usage, and 8) reduced soldering defects.

Introduction
Using gaseous N_2 to generate an inert atmosphere during wave soldering to minimize solder oxidation is well known, which not only saves solder material and lessens maintenance requirement but also improves solder wetting and ensures the quality of the formed solder joints. This N_2 inerting technology can be applied in an existing wave soldering machine by inserting in molten solder pot a protective housing with N_2 diffusers mounted inside (Figure 1). A N_2 gas blanket across the solder pot can be formed, thus reducing the tendency of solder oxidation.

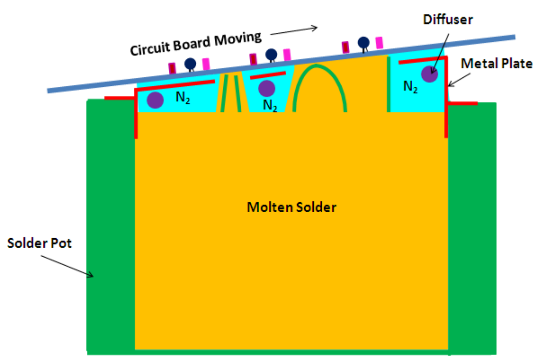

Figure 1: Protective housing over the solder pot, with diffusers inside

Along with a change from tin-lead to lead-free solders in the electronics industry, the value of N_2 inerting for wave soldering is further increased due to the following reasons. The process temperature by using a common lead-free solder is 30 to 40°C higher than that of the conventional tin-lead soldering. This significant increase in process temperature can largely promote dross formation. The cost of lead-free solder is normally around four times that of conventional tin-lead solder. Therefore, the economic loss associated with solder waste by dross formation is more significant in lead-free wave soldering. In addition, the wetting performance of a lead-free solder is intrinsically poor compared with that of the conventional tin-lead solder, and the quality of the formed solder joints is more sensitive to the state of oxidation on a lead-free solder surface.

However, there is still a lack of a mature N_2 inerting technology for wave soldering, which largely impedes its wide application. More specifically, a technology breakthrough is required to solve the following challenges: 1) N_2 consumption has to be minimized to improve the cost/benefit ratio of applying the technology, 2) O_2 concentration above the molten solder surface needs to be below an acceptable level to satisfy targeted low formation rates of solder dross and soldering defects, 3) the clogging of the porous diffusers either by solder splashing or flux contamination must be prevented to ensure a stable and long lasting performance, and 4) the retrofitting work has to be simple to reduce cost.

This paper presents a recent work related to developing a new generation N_2 inerting system for wave soldering to solve the above challenges and make the technology more cost-effective and user-friendly. Both lab-scale experiments and production trials were conducted, which demonstrated superior performance and benefits of applying the newly developed and patented technology.

Technology Development

a) Diffuser Selection

The diffuser used in the N_2 inerting system is normally made of a porous stainless steel tube. The porosity of the diffuser was optimized to generate a laminar flow of gaseous N_2 out of the diffuser. A laminar flow of N_2 is preferred for minimizing air intrusion from boundaries of the area to be inerted. More specifically, N_2 permeability through porous diffusers as a function of porosity was investigated. As listed in Table 1, the three diffusers being evaluated were named as grade A, B, and C, respectively. Among them, the grade A diffuser has the smallest porosity and the grade C diffuser has the largest porosity. A higher porosity is associated with a larger pore size.

Table 1. Diffuser Specification

Diffuser Grade	ID	OD	Length	Porosity (sheet)	Porosity (tube)
A	0.25”	0.375”	18”	~ 17%	~ 24.5
B	0.25”	0.375”	18”	~ 26%	~ 28.7
C	0.25”	0.375”	18”	~ 36%	~ 36.7

The test was conducted by flowing N_2 into each seamless diffuser tube and measuring pressures at the upstream (P_{up}) and downstream (P_{down}) of each diffuser for a given N_2 flow rate. The pressure drop (ΔP) along the diffuser was then determined as follows:

$$\Delta P = P_{up} - P_{down}$$

The average pressure along the diffuser was also calculated as:

$$P_{ave} = (P_{up} + P_{down})/2$$

When $\Delta P/P_{ave}$ is much less than 1, the gas flow out of a porous tube can be considered as in a laminar flow pattern. In contrast, when $\Delta P/P_{ave}$ is close to 1, a turbulent gas flow is normally dominant. As indicated in Figure 2, the $\Delta P/P_{ave}$ value of the grade A diffuser is the smallest and is much below 1, within the N_2 flow rate of interest. While the grade A diffuser is the best option from a laminar flow standpoint, other factors such as gas momentum out of the diffuser and gas approachable distance for surface coverage may also need to be considered.

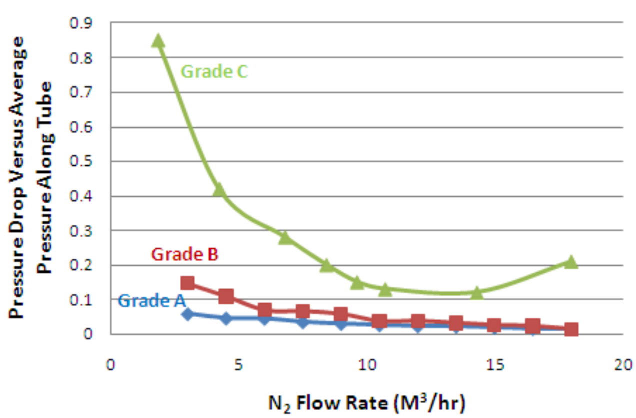

Figure 2: Permeability Test Result for Selecting Diffuser

b) <u>3D Computational Modeling</u>

3D computational modeling was used as a tool to evaluate and optimize various designs of the N_2 inerting system and to estimate N_2 inerting results under different process conditions. To pursue the modeling work, the permeability test described above was used again to obtain necessary parameters for modeling, such as the resistance of N_2 flow out of a porous diffuser. Figure 3 is a logarithmic plot of pressure drop across a diffuser wall versus N_2 flow rate per unit surface area of the diffuser. The flow resistance of a diffuser was estimated from the slope of the curve corresponding to the diffuser.

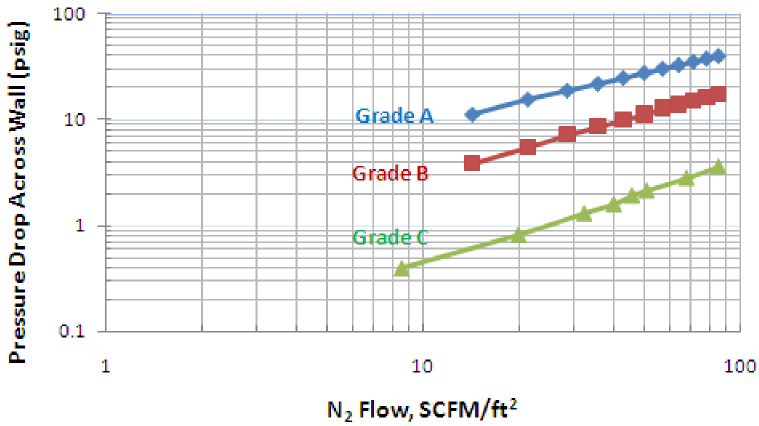

Figure 3: Permeability Test Result for Estimating Flow Resistance Figures 4 and 5 are two examples of the modeling results. One is O_2 distribution across a solder pot with dual waves and the other is a side view of N_2 flow field for a specific design under a given process condition.

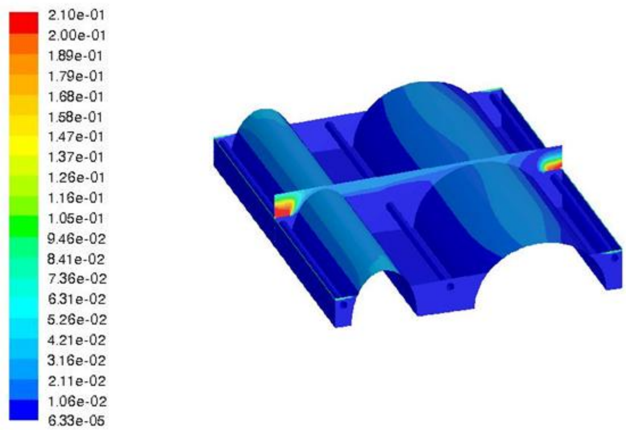

Figure 4: An Example of 3D Modeling Result on O_2 Distribution

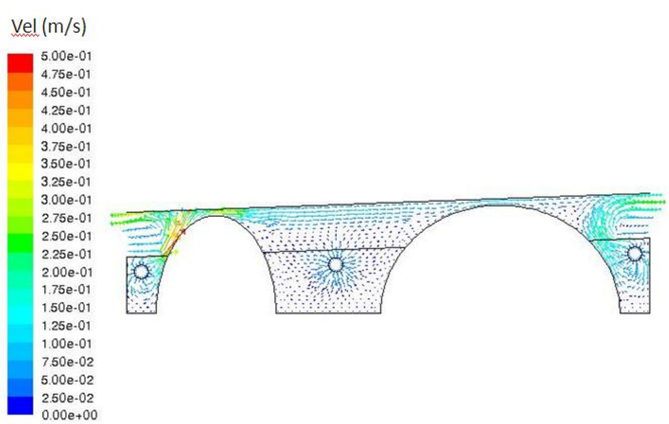

Figure 5: An Example of 3D Modeling Result on N_2 Flow Field

c) Anti-Clogging Diffuser

Clogging of porous diffuser in a N2 inerting system during wave soldering is a well-known issue. The clogging is normally caused by solder splashing or flux contamination. Clogging results in non-uniform N2 flow out of the diffuser and significantly reduces the efficiency of the inerting process. Cleaning a diffuser coated with flux residues is particularly difficult, and normally such a diffuser has to be replaced, which significantly increases cost.

More specifically, the flux contamination can come from either vapor phase or liquid phase. During a wave soldering process, a liquid flux is deposited on a circuit board to be soldered when the board enters the soldering machine. Part of the flux deposited on the board evaporates when the board enters the preheating zone. The remaining flux continues to evaporate when the board enters the solder pot region, especially when the board touches with a solder wave. The evaporated flux vapor can condense on solid surfaces at a temperature below the boiling point of the flux, which is around 150°C. Therefore, diffusers located near a solder wave can be easily clogged by flux vapor condensation. In addition, the residual flux left on the board can contaminate the molten solder when the board touches the solder wave. Those flux residues can thus be deposited on to a diffuser surface once the molten solder comes in contact with the diffuser. Therefore, to prevent diffuser clogging, it is necessary to eliminate both liquid phase contamination and vapor phase condensation.

As shown in Figure 1, normally there are three diffusers in the protective housing of a N2 inerting system for wave soldering with double waves. They are located at the front of the first wave, the back of the second wave, and in the middle between two waves. The middle diffuser is highly susceptible to clogging by both solder splashing and flux contamination due to the continual dynamic movements of solder waves and the tight space between the two waves. The front diffuser is located very close to the molten solder surface, and can be easily contaminated through direct contact with molten solder. The back diffuser, on the other hand, is positioned further from molten solder surface and its relatively colder temperature allows flux vapor to condense on the diffuser surface.

To protect the front and back diffusers from molten solder splashing and flux vapor condensation, one designed approach was to locate the front and back diffusers out of the solder pot (Figure 6). To maintain fluid communication, an open channel between each diffuser and the solder pot was included. The size of the channel was designed to be relatively narrow along the length of each diffuser. The purpose of this design is to create a uni-directional gas flow from each diffuser to the solder pot, thus eliminating or minimizing flux vapor condensation on the diffuser surfaces.

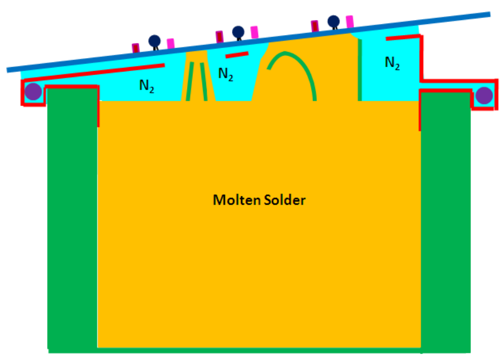

Figure 6: Locating the Front and Back Diffusers out of a Solder Pot

An alternative design involves installing shielding plates around both diffusers located right above the molten solder surface. Each shielding plate is bottom-sealed and gas flow is maintained through an open channel at the top (Figure 7). As above, the partial enclosing of the diffuser and uni-directional flow can eliminate or minimize liquid phase contamination and vapor phase condensation.

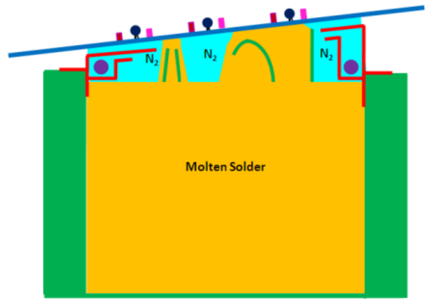

Figure 7: Installing a Bottom-Sealed Plate around the Front and back Diffusers

Prevention of the middle diffuser clogging is a complex challenge, as clogging can result from solder splashing, flux vapor condensation, or direct contact with the molten solder. To solve the first two problems, an approach was designed to increase the temperature of the middle diffuser. More specifically, a metal fin was attached to the middle diffuser and the fin was inserted into the molten solder (Figure 8). By maintaining the diffuser temperature above the melting point of the solder, solidification of solder splashing and condensation of flux vapor on the diffuser surface was eliminated.. The design also allowed the splashed solder to automatically drip down due to its high surface tension and non-wetting on the diffuser surface.

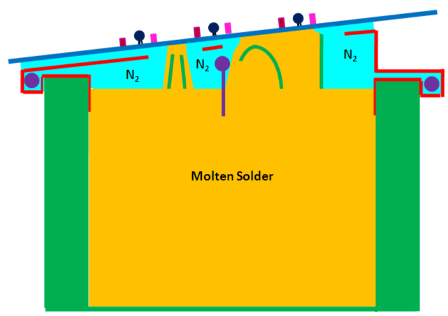

Figure 8: Adding a Metal Fin on the Middle Diffuser

As mentioned previously, flux residues can get into molten solder, thus deposited on a diffuser surface when the diffuser contacts with the molten solder. We are looking at several options to reduce or eliminate this issue.

d) <u>An Optional Ventilation Hood</u>

A wave soldering machine normally contains a gas exhaust outlet located above the solder pot to collect flux vapor. When a N_2 inerting system is installed in the solder pot, the N_2 flow pattern from the diffusers can be altered by the suction from the exhaust system, thus reducing the inerting efficiency. To minimize this problem, the gas exhaust system is partially closed in a lot of wave soldering applications. However, this method doesn't completely eliminate the interference of gas exhaust with the N_2 flow pattern and can reduce the efficiency of the flux vapor removal.

To address the problem, a special ventilation hood was designed as an optional addition to the N_2 inerting system. As shown in Figure 9, the hood contains double metal layers and the ventilation is applied between the two layers by connecting to the gas exhaust outlet of the machine. The ventilation hood's unique design acts as a boundary gas trap around the solder pot. When a circuit board passes underneath the ventilation hood, the generated flux vapor can be collected at the boundary slot; while at the same time, entry of surrounding air into the solder pot area can be minimized as a result of evacuation through the boundary trap (Figure 9).

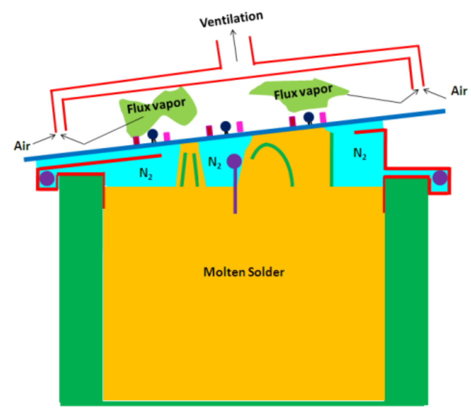

Figure 9: Adding a Ventilation Hood for Collecting Flux Vapor and Preventing Air Intrusion

Lab-Scale Evaluations

a) <u>Analysis of O_2 Concentrations</u>

A Novastar dual wave soldering machine was used for lab-scale experimental studies. The width of the solder wave was ten inches. The protective housing with three diffusers, as shown in Figure 8, was installed in the solder pot. The solder pot was maintained at 260°C. A quartz plate to simulate a circuit board was loaded on the moving chain and statically located on the top of the solder pot. The ventilation hood containing double metal layers was also installed on the moving track above the solder pot (Figure 9). The ventilation was maintained at 250 CFM. To evaluate O_2 concentrations, eight gas sampling tubes were mounted around the solder pot (Figure 10). The O_2 concentration at each sampling tube was measured by using an O_2 analyzer. As shown in Figure 11, the O_2 level for all eight positions around the solder pot is below 400 ppm at a total N_2 flow rate of 12 Nm^3/ hr or less. As indicated in Figure 11, the values of N_2 flow rates from the three diffusers are expressed in the form of "front/middle/back" in the unit of Nm^3/hr.

Figure 10: Eight Sampling Tubes Around Solder Pot

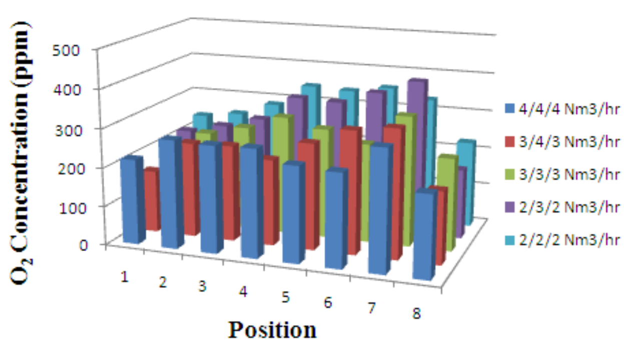

Figure 11: O_2 Distribution around Solder Pot

b) Middle Diffuser

To prove the concept of using a hot middle diffuser to prevent solder contamination, a diffuser attached with a metal fin was prepared (Figure 12). Figure 13 demonstrates that when the middle diffuser with a N_2 flow rate of 4 Nm^3/hr is in an operating position in the solder pot with two waves activated at 260°C, the diffuser surface can be maintained solder-free. Any solder splash on the diffuser would automatically drip down due to the conductive heating of the metal fin which makes the middle diffuser's temperature above the solder's melting point.

Figure 12. A Metal Fin Mounted on the Middle Diffuser

Figure 13: Solder-Free Middle Diffuser

c) Dross Formation

Dross formation rate under N_2 inerting condition was investigated and compared with that in air. The surface area inside the solder pot for dross formation study was 10" X 11.5". For dross formation under N_2 inerting, the protective housing with three diffusers as shown in Figure 8 was installed in the solder pot. The solder pot was maintained at 260°C with two waves activated. A quartz plate to simulate a circuit board was loaded on the moving chain and statically located on the top of the solder pot. N_2 flow rate from each of the three diffusers was controlled to be 4 Nm^3/hr. For dross formation in air, the protective housing with the three diffusers was removed and other conditions were maintained to be the same. As shown in Figure 14, dross formation rate was largely minimized when N_2 inerting was applied. More specifically, the dross formation rate was only 3 to 6 wt% of that in air. For this experiment, the O_2 level in the N_2 supply source was around 5 ppm.

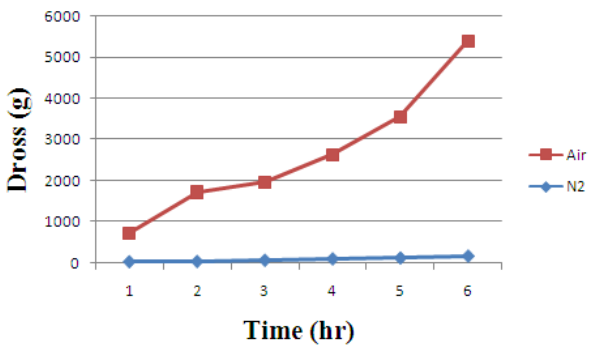

Figure 14: Dross Formation in N_2 and in Air

d) Ventilation Hood for Collecting Flux Vapor

To evaluate the efficiency of the double-layered ventilation hood (Figure 9) in collecting flux vapor, a hot flux reservoir was installed in the solder pot to continually generate flux vapor. The flux reservoir is made of a stainless steel tube with capped ends and connected to a flux supply source. The tube reservoir was horizontally positioned with an open slot on the top surface and a metal fin at bottom along the length of the tube. The metal fin on the reservoir was inserted in the molten solder, so that liquid flux could continually boil off and form vapor. A quartz plate to simulate a circuit board was loaded on the moving chain and located above the solder pot. As shown in Figure 15, the flux reservoir was able to generate a significant amount of flux vapor above the solder pot. After the top cover was installed in position with a ventilation flow of 250 CFM, efficient removal of the generated vapor was demonstrated (Figure 16).

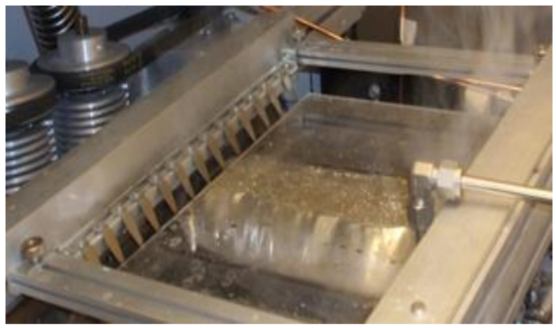

Figure 15: Flux Vapor Generated from a Hot Flux Reservoir

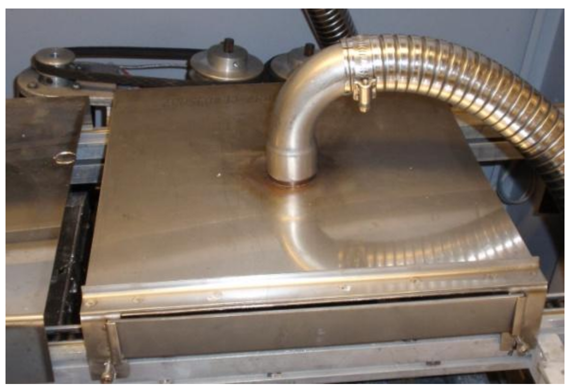

Figure 16: Collecting Flux Vapor using the Top Cover

Production Trials

To further verify the developed N_2 inerting technology, a series of production trials were conducted through a cooperative effort with Advantech Co., Ltd. (Taipei, Taiwan). During the production trials, a modified version of the nitrogen interting system was used due to machine and process constraints. The modifications include:

a) A top cover with flexible curtains on both sides of the protective housing (Figure 17) was installed above the molten solder pot (Figure 18) to further assist N_2 inerting.
b) The center diffuser was located in the top cover.

Figure 17: Protective Housing Inserted in a Solder Pot with Two Waves

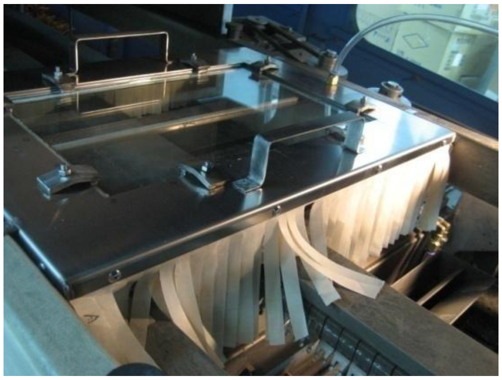

Figure 18: Top Cover with Flexible Curtains on both Sides

The nitrogen was supplied via a PSA unit that was located at the production site of Advantech. The O_2 level from the PSA unit was around 44 ppm. Nitrogen flow rate for each of the three diffusers was 4 Nm^3/hr. To investigate oxygen levels in the N_2 inerting area, a portable O_2 analyzer with an integral pump unit was used. The average O_2 level around the solder pot ranges from 2000 to 3000 ppm. The following results were obtained after a month-long trial program with the N_2 inerting system..

a) Dross Reduction

Table 2 outlines the dross reduction results with the nitrogen inerting system. Application of N_2 inerting reduced dross formation from 6.4 kg per day to 2.9 kg per day.The 53% reduction rate surpassed the 50% target set by Advantech for the reduction of dross.

Table 2: Production Result on Dross Reduction

Month	Workin g Days	Solder Add/month (kg)	Solder Add/ day (kg)	Dross/month (kg)	Dross/day Average (kg)	Reduction Rate
Jan 2010	20	242	12.1	116	6.4	
Feb 2010	16	203	12.7	110	6.4	
Mar 2010	27	299	11.1	168	6.4	
Aug 16 to Sept 11	22	180	8.2	64.5	2.9	(6.4-2.9)/6.4 =53%

b) Equipment Maintenance

Prior to the use of nitrogen, Advantech would spend a total of 40 minutes per day for cleaning the dross in the solder pot. During the nitrogen trial period, the maintenance on the solder pot was reduced to 15 minutes per day, resulting in a 60% reduction in machine downtime.

c) Flux Reduction

Table 3 presents the benefit of applying N_2 inerting on flux reduction. A 10% reduction of flux per day was achieved when nitrogen inerting was introduced to the production system.

Table 3: Production Result on Flux Reduction

Month	Working Days	Consumption (gallons)	Average/day	Reduction Rate
Jan 2010	20	20	1	
Feb 2010	16	20	1	
Mar 2010	27	25	1	
Aug 16 to Sept 11	22	20	0.9	(1-0.9)/1 = 10%

d) Defect Reduction

During the nitrogen trial period, Advantech experienced a 25% reduction in solder bridging. This equates to a 10% reduction in rework hours for Advantech. In the area of improved plated-through hole fill, there was no major difference observed in the nitrogen trial versus their standard production process in air.

e) Summary of Benefits

Table 4 summarizes the benefits of applying nitrogen inerting system in Advantech's wave soldering process. As indicated, the total saving per month is 45,800 NTD.

Table 4: Summary of the Benefits with Applying N_2 Inerting

Item	Reduction Rate	Savings/day (NTD)	Cost of Inerting System (NTD)	Savings/Month (NTD)
Dross	53%	2100 (A)		46,200 (B)
Cleaning hours	60%	375 (C)		8250
Flux	10%	50		1100
PTH Fill Improvement	0%	0%		0
Bridging	25%			
Sub Total				55,500
Monthly Costs			9750	
Total Savings/Month				45,800

Notes:
*A – Solder bar @ 1000 NTD, recycling: 400 NTD, savings = (6.4-2.9)*600 = 2100 NTD/day*
*B – Nitrogen trial was for 22 days. Monthly savings 2100*22 = 46,200 NTD/month*
*C – Man-hr cost saving = (40-15) minutes*15 NTD/min = 375 NTD/day*

Conclusions

A range of new design concepts have been incorporated into the nitrogen inerting system for wave soldering applications to demonstrate significant reduction in dross formation, solder defects and machine maintenance. A fundamental study involving CFD modeling of the flow fields inside the solder pot and permeability tests were undertaken to optimize the diffuser selection and positioning. Other design improvements including the front/back diffuser covers, middle diffuser fin and double-layered top cover have been demonstrated to minimize solder and flux clogging, resulting in reduced machine downtime. Through the initial beta site implementation at Advantech, the benefits of the system were re-affirmed on scale-up to a production environment. To minimize customization and accommodate a wide variety of production-scale wave soldering machines, several standard design options are currently being evaluated. These include further design optimization of the middle diffuser for reduced clogging and more efficient inerting as well as design flexibilities to address size/shape variations.

The new design for nitrogen inerting of wave solder systems has demonstrated that it is robust and flexible, which allows for simple modifications to accommodate equipment variations. Through improvements in productivity, quality and reduced maintenance, the new system should be able to reduce overall cost of ownership for the electronics printed circuit board assembly industry.

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