

EFFECTS OF REDUCED PURITY NITROGEN IN THE INERT WAVE SOLDERING ENVIRONMENT

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Abstract

Soldering environments are inerted to improve the soldering process by mitigating the oxygen available near hot, molten solder. Nitrogen is used because it is the least expensive, most available inert gas. Traditionally, high purity nitrogen (5ppm) has been the inerting vehicle of choice for both equipment manufacturers and end users. The cost and availability of high purity nitrogen varies dramatically throughout the world, however. Some regions of the globe have proven that lower purity nitrogen atmospheres are very viable in the reflow process.

Research is now commencing on the application of lower purity nitrogen in the wave soldering environment. The successful application of lower purity nitrogen can reduce the total cost of ownership of an inerted wave process, and, therefore, make it more affordable and available to a broader base of electronics assemblers. The focus of this study is on the application of membrane-generated nitrogen, with typical residual oxygen levels (ROL's) of 1000 to 30,000 ppm. Preliminary studies indicate a high degree of compatibility with the wave soldering process, particularly in machines fitted with hot nitrogen knives.

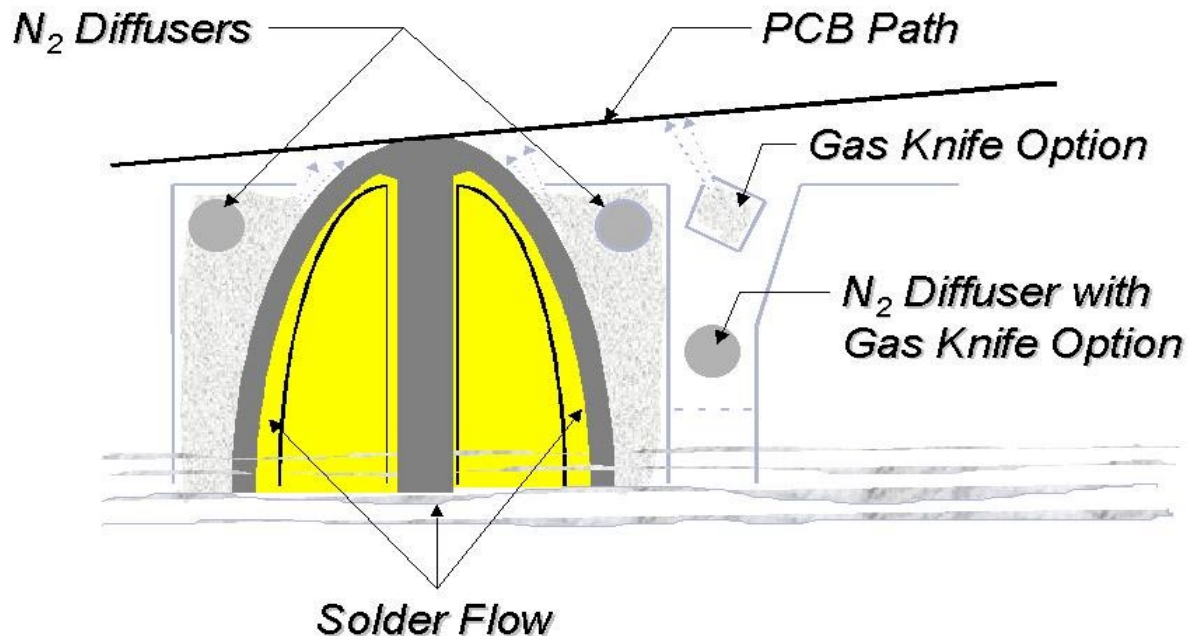
Introduction

The main benefits of inerting a wave soldering process stem from the reduction of dross production. Lowering macrodross production saves money and lessens maintenance requirements. Reducing microdross on the surface of flowing waves improves wetting to the solderable surfaces. Inerting at the site of soldering can be accomplished by diffusing the gas on each side of the flowing waves in an open system, or by installing a hood over the solder pot, which effectively closes off the soldering environment. Some wave solder machines inert the tunnel leading to the solder pot as well, to prevent oxidation from forming on the solderable surfaces during preheating.

The study being presented was performed on a 1998 Electrovert Econopak Plus wave soldering machine equipped with a CoN₂tour® inerting system. The CoN₂tour system is one that diffuses nitrogen along each side of the flowing waves in an open environment. Figure 1 illustrates a laminar wave in a CoN₂tour system with the optional hot gas knife debridging tool. Figure 2 is a photograph of the wave nozzle system. The wave used in this study did not have a hot knife.

On machines equipped with hot gas knife debridging systems, the knife directs a thin stream of heated nitrogen at the bottom of the circuit board just after it exits the laminar wave. This stream is typically heated to 600 to 800° F and its velocity is controlled by regulating the pressure delivered to the knife. The pressure can range from 5 to 15 psi. At velocities strong enough to break solder bridges, however, the nitrogen stream entrains the ambient

Figure 1
Schematic Diagram of CoN₂ four Laminar Wave



atmosphere, which is not fully inerted. A previous study of the amount of oxygen entrained in the debridging stream indicated ROL's at the soldering environment can rise as high as 6% when the knife is active.¹ The average soldering environment achieved in these systems without hardware modifications has an ROL of 5%. In these systems, however, dross production was still decreased by as much as 50% over non-inerted systems, solder joints were bright and shiny, and no dross inclusion was found in cross sectional analysis of the joints. The study concluded that the knife was an excellent addition to the soldering system, and its benefits far outweighed the issues associated with air entrainment. Many inerted systems throughout the world have been using hot gas knives and soldering in 95% nitrogen with little adverse effects of the reduced purity environment.

Given that a 5 ppm ROL nitrogen feed results in a 50,000 ppm soldering environment which produces high quality solder joints with dramatic dross reductions, the question must be asked as to whether high-purity nitrogen is necessary in wave soldering operations. To find the answers to this question, the authors devised an experiment to evaluate the effects of reduced purity nitrogen in the inerted wave soldering process. An experiment was devised to encompass two types of board surface finish, two defect modes, and four levels of ROL's. Dross production and board quality were measured as output variables. A cost model has been formulated to factor in increased defects, increased dross production, and the lower costs of membrane-generated nitrogen.

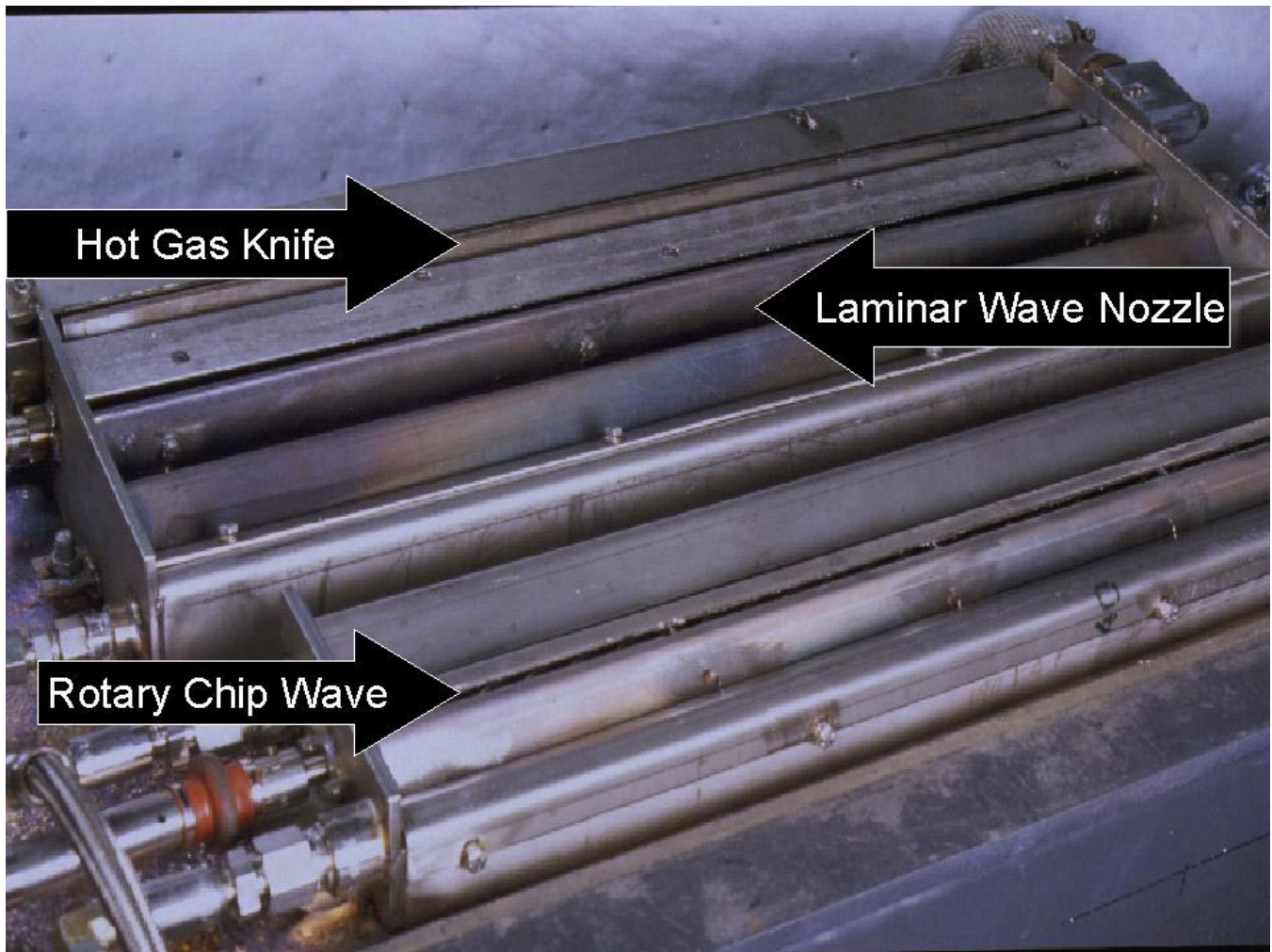


Figure 2
Photograph of CoN₂tour Plus Wave Nozzles

Experimental Setup

To simulate the lower purity membrane-generated nitrogen, cleaned, dried, compressed air was mixed into the house nitrogen line for the wave solder machine. A sample line was teed off the nitrogen input to the machine, so that the ROL's of the gas entering the machine could be continuously sampled throughout the execution of the tests.

Samples were also taken at the soldering environment between the chip and laminar waves. ROL's from the environment were within 0.04% (or 400 ppm) of the ROL's in the house line.

The process uses VOC-free flux that is applied by the Opti-Flux® reciprocating head ultrasonic fluxer. Heraeus SURF 11 was the flux used in these trials.

To measure the effects of higher ROL's on soldering performance, two test vehicles were chosen. Together, the two assemblies represent worst case soldering scenarios on the assembly line where the testing took place.

Board A was the highest volume board produced on the line. It is a high quality, FR-4 fabrication with a hot air solder leveled (HASL) surface finish. Although it has no bottomside surface mount components, it has many through hole pins oriented parallel to the wave with a high probability for bridging. It also has glossy solder mask with a high probability for solder balling.

Board B was a single-layer FR-3 fabrication with an organic solderability preservative (OSP) surface finish. The solder side of this assembly is moderately populated with 1206's, SOT-23's, and 16-pin SOIC's, in addition to through-hole components and test points that require good circumferential hole fill. The solder mask is a silk-screened semi-gloss finish. These assemblies historically showed marginal solderability unless soldered with one of the more active VOC-free fluxes on the market.

The tests were set up to create over 20,000 solder connections at each purity setting: 100%, 99%, 98%, and 97%. All other process parameters remained stable throughout the tests. To assure consistency beyond the normal production process window, an experienced process engineer ran the wave solder equipment and an experienced quality engineer inspected each board and logged the defects.

Results

Board A showed minor variations in solderability at the different defect levels. The typical mode of defects on these assemblies are solder bridges. Defect rates ranged from 74 defects per million (dpm) to 240 dpm, but showed no trends relating to nitrogen purity levels, nor any open joints that could be related to poor wetting. Statistical analysis of the data shows no difference in soldering defect rates with a 98.3% probability.² What was noted, however, was lower quality topside solder fillets on these assemblies. This issue was addressed after the final data collection run by increasing the flux deposition by approximately 15%. During the tests, 450 $\mu\text{g}/\text{in}^2$ of flux was applied to the boards; after the final tests, deposition was increased to 525 $\mu\text{g}/\text{in}^2$ and topside solder fillets appeared normal at the 97% purity setting. The increased deposition is well within acceptable control limits for this flux product. A slight decrease in solder balling on the glossy mask was noted as well, but not quantified, since even the micro-balling at full purity is well within the company's workmanship and quality standards.

Board B did not fare as well as Board A at higher ROL's. Defects doubled from 1040 dpm to 2079 dpm when purity stepped down to 99%, and nearly tripled to 2772 dpm when purity stepped down to 97%. This data led to two immediate conclusions:

- 1) Board B has a much tighter process window than originally thought, indicating serious solderability issues with this fabrication, and
- 2) This data is not representative of typical OSP behavior in the soldering process and should not be considered a definitive indicator for the purposes of this study.

To address the issues concluded from the first run of Board B, a separate investigation was launched into the solderability issues. It was determined that the boards were not coated with Entek 106A as originally thought, but a substitute OSP. Furthermore, they had exceeded their six-month shelf life.

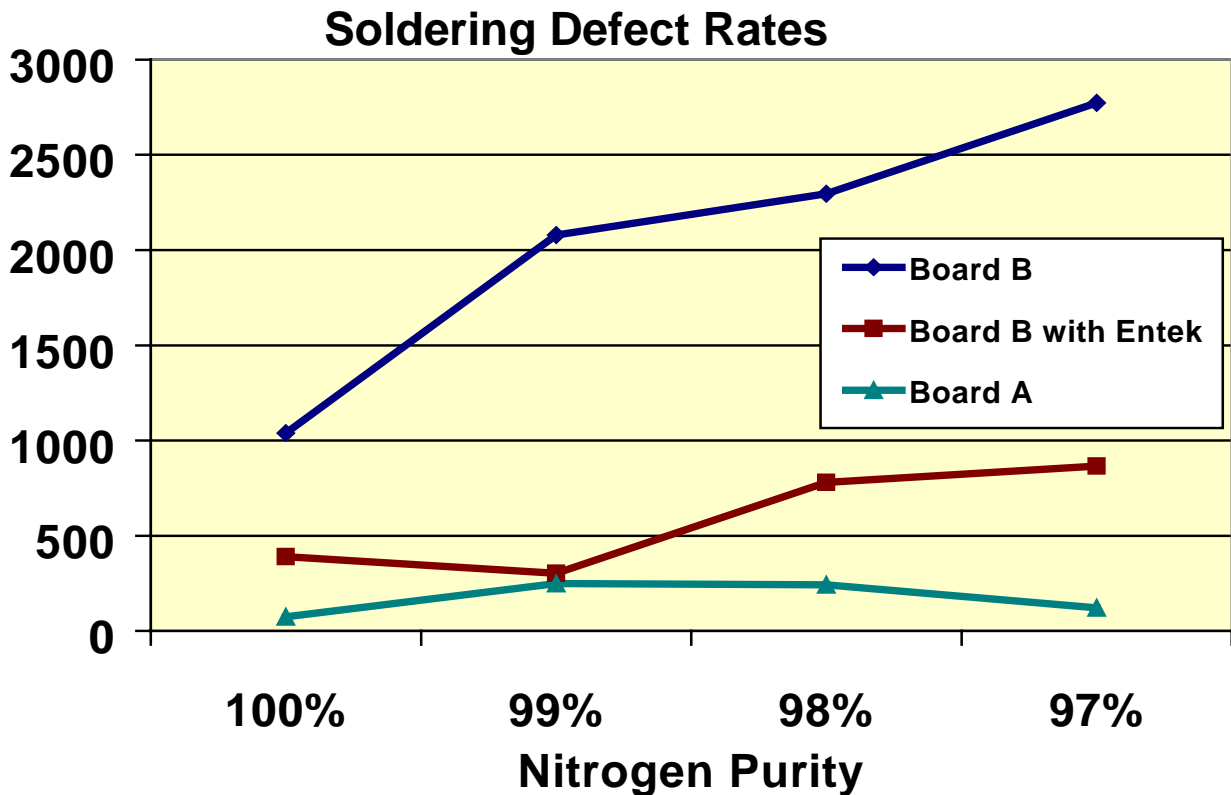
To generate meaningful data for this study, 200 boards were stripped of the lower quality OSP, microetched, and recoated with Entek 106A.³ Upon return to the Cherry Hill, NJ manufacturing facility, the boards were subjected to a reflow thermal excursion, allowed to sit

overnight, subjected to an adhesive cure thermal excursion, allowed to sit over two nights, and finally wave soldered three days after the first reflow excursion. The normal production process for these assemblies does not include a solder reflow step, but it was included to simulate the most common production process found in modern assembly operations.

The recoated boards showed a dramatic decrease in solderability issues from their original counterparts. The total number of defects are graphically depicted in figure 3. The typical defect mode for these boards are insufficient or open solder joints. The defect rate for open solder joints remained at approximately 400 dpm at all nitrogen purity levels. The incidence of solder bridging on this assembly increased at the lower purity levels, however.

The soldermask on Board B was not fully cured. During the wave soldering process, microdross from the waves' surfaces clung to the soldermask. At higher ROL's, more microdross formed and sometimes caused electrical shorts on the boards when it clung near interconnects. On boards with better mask cure, microdross clinging was not an issue at any setting. This phenomenon was readily apparent on the circuit cards that had been stripped and recoated. Higher defect levels were empirically correlated to poorer mask cure. Boards that had more visible microdross on the mask had more solder defects. Defect levels of a particular panel could be predicted by quickly glancing at the amount of microdross on the mask – clean mask had very few defects, contaminated mask had lots of shorts. This information leads to the conclusion that board fabrication quality has a much larger factor in assembly quality than the inert environmental purity.

Figure 3



Dross Generation

Dross generation is difficult to gage in a general manner. Many factors influence the amount of dross produced from a wave soldering process: wave height, the number of boards crossing the wave, the type of flux used, the solder temperature, the turbulence of the waves, the front/back flow ratio, and the original solder quality. Additionally, other factors influence the methods by which dross generation is measured: the nominal amount of dross that builds over the exposed surface of the solder pot, mechanical separation techniques, chemical separation techniques, or no separation whatsoever, where dross can contain as much as 90% usable metal.

For the purpose of gathering dross generation information, all influences on production should remain as stable as possible. For the purpose of interpreting dross generation information, prudence and common sense should be employed. The dross generated from a specific machine in a specific environment is not necessarily indicative of another machine's performance in a different atmosphere.

To provide dross generation information, the Econopak was dedrossed, both waves were run continuously for four hours, and the machine was dedrossed again. A chemical oxide separation agent was used to try to more accurately gage the dross produced; typical dross on this system contains 90% usable metal and only 10% oxides. During each test, approximately 50 boards crossed the waves. Due to the nature of the production boards that were run during the tests, the waves were run at heights that were higher than normal. The rotary chip wave was run at a main pump speed of 400 RPM with a rotary speed of 225 RPM; the laminar wave was run at 275 RPM. These pump speeds represent wave heights of .375 inches. The typical process on this machine runs wave heights of .270 to .300 inches.

The amount dross generated at 100%, 98.5%, 97%, were 3.85 lb/hr, 4.95 lb/hr, and 6.15 lb/hr, respectively. The results are shown in figure 4 and indicate a definite increase in dross production with an increase in ROL's.

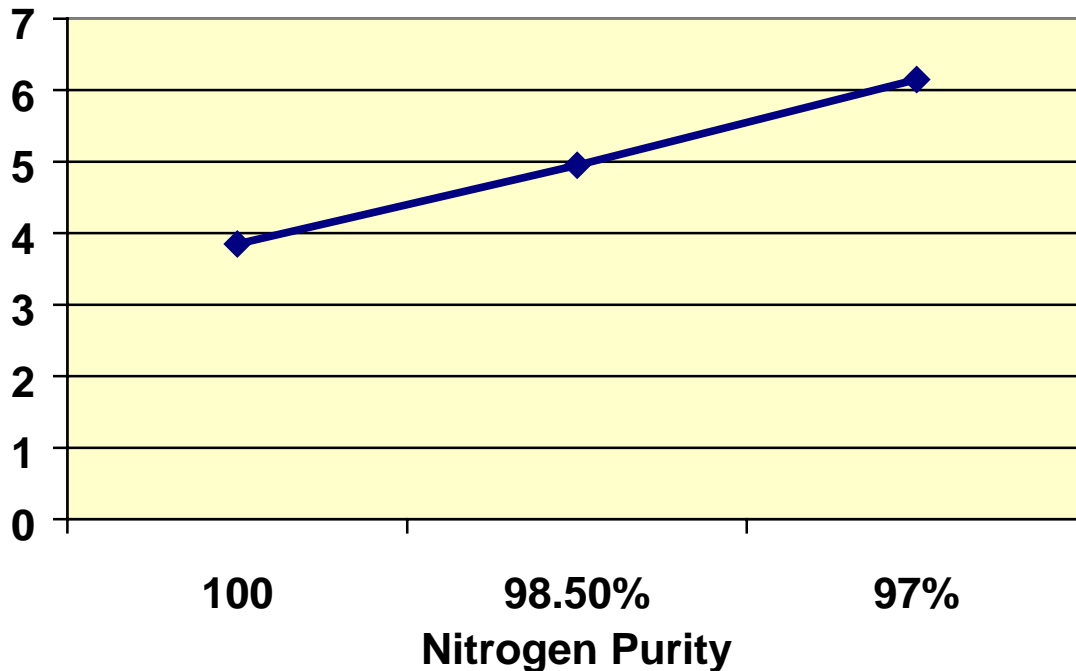
These results are not indicative of typical dross production on an Econopak machine; special tests were set up during regular production to try to normalize the data. The machine usually operates in the "Intermittent Wave" mode, where the wave pumps turn on when a board approaches and turn off when the board exits the wave area. The intermittent mode greatly reduces dross, particularly on assembly lines with low throughput. The amount of dross skimmed from the pot after the four-hour, continuous-run tests was about equal to what is typically produced after 32 hours of regular production. Therefore, one cannot interpret the data to state that dross production increases either by 50% or by two pounds per hour. The only inference that can be drawn from this information is that dross formation increases as inert gas purity decreases.

The majority of the dross was generated by the rotary chip wave. The rotary chip wave is the most active turbulent wave available. It's performance is unmatched on assemblies that are densely populated with small chip components or have poorly designed pads, but it's high degree of activity may not be necessary in all applications. A less active model may be a better choice in a lower purity soldering environment. A higher flow rate of nitrogen at the chip wave diffusers may also help to mitigate dross production. Solder recovery systems are also available to recover usable solder from the dross that is skimmed, so the higher dross production from the rotary wave should not be a large factor in the decision to inert.

Ultimately, the amount of dross generated in a particular application is highly dependent on the application itself. The most accurate data should be available from the soldering

equipment manufacturers. Most manufacturers have laboratory and demonstration machines available to model particular production conditions and generate data for specific analysis.

Figure 4
Dross Production



Cost model

Nitrogen Costs

To model the economic feasibility of membrane-generated nitrogen, three cost drivers must be quantified: the costs of nitrogen, the costs of defects, and the cost of dross.

The cost of nitrogen can only be provided by nitrogen providers. Markets vary regionally, and generation costs vary with desired purity levels, flow rates, and electricity costs. Many providers are hesitant to quote non-application specific rates for non-commercial purposes, such as technical publications. The best approach to finding the actual cost of nitrogen in a particular geographic area is to contact local providers.

In addition to the cost of liquid nitrogen, the expense of storing the nitrogen should also be considered. The cost of a liquid nitrogen storage facility can vary greatly depending on tank size, site location and local building codes. Typically, the nitrogen consumer pays for the tank pad, and the provider installs the tank and leases it to the consumer. The pad for a 6,000 or 9,000 gallon tank can range from \$20,000 to \$60,000. The best approach to estimating an actual cost is to get the pad specifications from the gas provider and consult a local engineering firm.

The cost of membrane-generated nitrogen often includes an air compressor to feed the generator and a liquid nitrogen backup tank to provide a continuous gas feed during routine maintenance or power shortages. In the application of membrane-generated nitrogen for inerting a wave soldering machine, a backup liquid system may not be necessary if the generator and the machine are considered a single unit from a maintenance and calibration perspective. Additionally, an air compressor should not be required if the assembly facility can provide high enough pressure and flow from its house line. Eliminating the need for costly feed and backup systems can make membrane-generated nitrogen affordable not only because of the low installation cost, but also because of the low carrying costs.

Dross Costs

The cost of dross is simple to identify. It is the price paid per pound for bar solder minus the price received for dross reclaim. Solder reclaim providers typically separate the usable metal from the dross, pay a discounted market value for the tin and lead, and often charge a refining fee. A statement from the reclaim providers should indicate the total number of pounds received, the amount of usable metal, and the amount of money paid to the dross producer. The total price paid for the dross shipment divided by the number of pounds of dross shipped will indicate the price received per pound for dross. When subtracted from the price paid for bar solder, the cost of dross results. For example, if bar solder costs \$2.50 per pound and dross is recovered at \$1.00 per pound, the cost of dross is calculated at \$1.50 per pound.

Defect Costs

The cost of a defect varies among manufacturers and product lines, but a model can be developed that captures the majority of cost drivers. The model employed by Siemens Information and Communication Networks, Inc, was developed as a cooperative effort by the engineering, production control, cost accounting and quality assurance departments. It includes labor, lost production time, scrap and extraordinary rework, but excludes overhead and consumables. The argument can be made to exclude overhead burdens because overhead allocation is already absorbed as part of regular production. Consumable expense, or the cost of touch-up flux and wire solder, is negligible in the final cost of fixing the defect.

The first step is determining the number of defects generated in a given period of time. A representative week, month, or quarter can be used. The longer time periods are more likely to smooth out quality spikes caused by noise or external factors. Extrapolate the number of total defects to an annual basis, N_{defects} . The second step is determining how many of these defects get captured at a visual inspection stage, or get passed along to be discovered later at an electrical test. Call the number of defects repaired at visual inspection N_v and the number captured at electrical test N_t . Determine the time required to touch up the defect at each station, including data entry and retest, and call each time T_v and T_t .

Find the labor and fringe benefit rate at each area. Multiply the annual labor hours spent on rework by the labor rates, yielding the cost of repairing all the defects, C_v , and C_t . The total cost of repairing defects is the sum of C_v and C_t .

The total cost of defects repaired for the period, $C_{\text{repairs}} = C_v + C_t$. The cost of defects which were not successfully repaired must now be calculated. These calculations are often based more on estimated information than hard production data. Estimate the number of poor rework occurrences that will require specialized or extraordinary repair, such as lifted pads, broken traces, or damaged solder mask, N_e . Estimate the time required for this type of repairs, T_e . Multiply time spent on extraordinary repairs by the labor/benefit rate to gauge the cost of

extraordinary repair, C_e . Next, estimate the number of populated PWA's that are scrapped due to poor rework – multiple lifted pads, damaged barrels, burned or delaminated substrate, etc. Multiply the number of damaged boards per year by the average cost of a PWA to arrive at the cost of scrap, C_s .

The total cost of *poor* rework can now be calculated by adding the cost of extraordinary rework to the cost of scrap due to rework, $C_{\text{damage}} = C_e + C_s$. This figure is an extremely important factor in the defect cost calculation, as it can add tremendous cost that is not typically visible when figuring costs based on time studies alone. The estimates can sometimes be difficult to arrive at, but even conservative estimates contribute significantly to the calculated cost of the defects.

Finally, to arrive at the cost of an individual defect, add the cost of repairs and the cost of damage, and divide the sum by the number of defects logged annually, N_{defects} .

As an example, assume an assembler uses the following *conservative* numbers:

Table 1
Defect Cost Worksheet

Number of wave solder joints produced monthly	30 million
Monthly defects produced at rate of 100 dpm	3000 joints
N_{defects} , Number of defects annually	36,000
Percent caught at visual inspection	90%
N_v , Number of defects caught at visual inspection	32,400
Time to repair each defect and enter data	30 seconds, 0.5 min.
T_v , Time to repair at visual inspection	270 hours
Labor & benefit rate = \$12.00/hour	
C_v , Annual cost to repair at visual inspection	\$3,240
N_t , Number of defects passed to electrical test	3,600
Time to repair defect, enter data, and retest board	300 seconds, 5.0 min
T_t , time to repair and retest	300 hours
Labor & benefit rate = \$18.00/hour	
C_t , Annual cost to repair & retest	\$5,400
C_{repairs}	\$8,640
Number of extraordinary repairs per day	1
N_e , Number of extraordinary repairs per year	300
Time required for each extraordinary repair	30 min, 0.5 hour
T_e , Time spent on extraordinary repair each year	150 hours
Labor & benefits rate = \$12.00/hr	
C_e , Annual cost of extraordinary repair (300 days/year)	\$1,800
Number of boards scrapped monthly due to poor rework	2
Average cost of a fully populated board	\$300
C_s , Annual cost of scrap	\$7,200
C_{damage}	\$9,000

Using the equation:

$$C_{\text{per defect}} = (C_{\text{repairs}} + C_{\text{damage}}) / N_{\text{defects}}$$

the cost of a defect can be calculated as:

$$\begin{aligned} &(\$8,640 + \$9,000) / 36,000 \\ &= \$0.49 \\ &= \mathbf{49 \text{ cents per defect!}} \end{aligned}$$

This example uses conservative numbers, but illustrates the cost of a single wave solder defect, and helps to emphasize the individual cost drivers for any given facility. Including overhead rates in the repair and test areas can easily double the cost of a defect.

The Cost Tradeoff

Membrane-generated nitrogen offers a much lower initial capital expenditure than liquid nitrogen, but, depending on usage, can actually have a higher unit cost. When the cost of tank rental and delivery charges for liquid nitrogen are factored in, however, the prices can become very competitive, even at the low flow rates used to support one or two production wave solder machines. The cost of membrane-generated nitrogen typically decreases with increasing flow rates, so the higher rates required by debridging knives or multiple machines increases the economy of site-generated nitrogen.

To balance the cost tradeoffs, the consumer must evaluate the expense of a tank pad installation and the unit cost of gas against the expense of higher dross production and potentially higher defects.

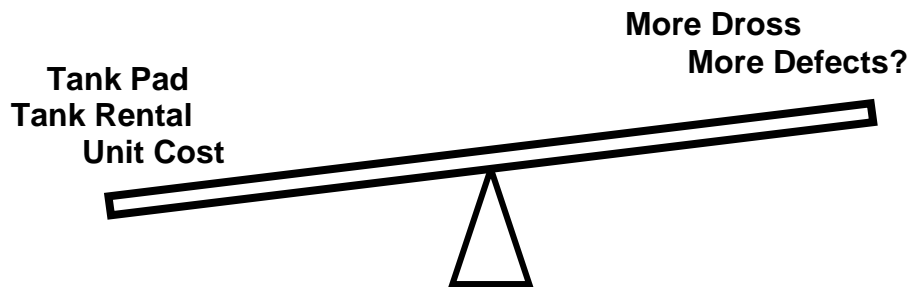


Figure 5
Balancing the Costs of Nitrogen Inerting

On PWB's of moderate quality, no insurmountable solderability issues were noted at ROL's of up to 3%. Assuming that an assembler has reasonable supplier quality, higher defects should not be an issue. The balance is now reduced to dross production versus the costs of the storage facility and any unit cost differential. Installation costs in excess of \$30,000 and rental costs of up to \$7,000 or more annually can tip the scales in favor of slightly higher dross production, particularly if the dross is separated and reused at the consumer's site.

Assemblers with existing nitrogen storage facilities may not fully realize a sizable cost reduction from the use of membrane-generated nitrogen. Assemblers currently running wave solder machines in air who are considering the move to inert wave soldering may find a considerable benefit of using membrane-generated gas, particularly when justifying the expense of new soldering and inerting systems. At Siemens' Cherry Hill, NJ facility, the move to inert soldering two years ago cut dross production to half its previous levels in air atmospheres. If lower purity nitrogen were employed, dross production levels may have been cut by 40% instead of 50%. The dross reduction would still be a considerable improvement in efficiency, while affording a much more favorable atmosphere for solder wetting with a very little operational cost differential.

Summary and Conclusions

Nitrogen inerting opens the process window in wave soldering. The degree of inerting dictates the openness of the window. Inerting with a higher purity nitrogen opens the window a little more; inerting with a lower purity opens it a little less. Nitrogen inerting lowers dross production, helping assemblers realize a considerable operational cost savings. Lower purity nitrogen also lowers dross production, but not as much as full purity. Membrane-generated nitrogen can save capital expense when installing an inert wave soldering system.

Solderability differences between 97% purity and 100% purity nitrogen are marginal in wave soldering. In situations where significantly higher defects are produced at 97% purity, the process owner might be better advised to allocate resources to resolving material quality issues rather than increasing the purity of the soldering environment. A root cause solution is always preferable to a "Band-Aid."

Very little information has been published on the application of membrane-generated nitrogen in the wave soldering environment. More data on dross generation and solderability needs to be generated and published. Consumers should urge equipment developers and nitrogen suppliers to continue research in this area and provide the necessary information. The lower total cost of ownership of a site-generation system makes inert wave soldering available to a much broader base of assemblers.

Board quality was the leading cause of defects in this experiment. The OSP coating was the primary factor. After the OSP was replaced with Entek 106A, solder mask quality was determined to be the second largest cause of defects. Higher quality boards showed no solderability differential in the higher ROL environments.

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Schematic drawing and photograph of CoN₂tour Plus wave nozzles courtesy of Speedline Thermal Systems. CoN₂tour Plus ® is a registered trademark of Speedline Thermal Systems Inc., Grand Prairie, Texas.

Boards were stripped, microetched, and recoated with Entek 106A courtesy of Enthone-OMI. Entek ® is a registered trademark of Enthone-OMI, New Haven, Connecticut.

Opti-Flux ® is a registered trademark of Ultrasonic Systems, Inc, Amesbury, Massachusetts.

References

¹ Optimizing the Inert Soldering Environment With the Use of Hot Nitrogen Knives, Chrys Shea and Gary Shipe, Nepcon West '98.

² Juran's Quality Control Handbook, Fourth Edition. Chapter 23, Basic Statistical Methods, Test 7, The proportions of two populations are equal, p. 23.69.

³ Coutesy of Enthone-OMI