Reflow Oven for a Pb-Free Soldering Process

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ABSTRACT From the standpoint of environmental protection, we cannot move forward without adopting Pb-free processes for the soldering of electronic components. Furukawa Electric, a leading manufacturer of reflow soldering systems, has now developed an oven designed for the Sn-Ag process, which at present seems to show the best chance of actual implementation. Compared to the Sn-Pb eutectic crystal solders used conventionally, the liquid phase temperature of Sn-Ag solder is about 30°C higher. The temperature for soldering must be at least 230°C. If the joints of the components having the highest thermal capacity are raised to this temperature, there is a major problem with the heat withstand properties of those with lower thermal capacity. The issue as far as the reflow oven is concerned is how small a temperature difference can be achieved between component joints. Other concerns addressed in the development work were bare-board temperature distribution, temperature profile reproducibility and obtaining wetting time, and satisfactory results were obtained. Results were especially good in terms of joint-to-joint temperature difference, which was reduced to about one-third of the former value.

1. INTRODUCTION

During the 20th century mankind has been polluting the environment at a fearsome rate. The pollution of rivers by industrial and household effluents; the depletion of the ozone layer by CFC gases that has received so much attention in the 90s; acid rain caused by gaseous emissions from factories and automobiles; and global warming. If immediate attention is not given to such environmental problems we will not be able to bequeath to our children and grandchildren a world where they can live in security.

Turning our attention to the field of electronics, we see that product life cycles have been dramatically shortened. Computers and cell phones are perfect examples of products that are soon replaced by models that have more functions at a lower price, and the ordinary consumer cannot wait to buy into the new convenience, carelessly discarding the outmoded item.

Sulfurous oxide gas and other components of factory and automobile exhaust gas combine with atmospheric moisture and fall to the ground as acid rain, causing trees to wither where they stand. Acid rain also attacks metals. The Pb used to solder electronic components is leached out by acid rain, becoming ground water that, when used for drinking purposes, builds up in the human body.

It was in the late 1990s that manufacturers began to feel a responsibility to reduce the harmful effects of Pb by developing Pb-free soldering processes. The first candidates were tin-silver (Sn-Ag) and tin-zinc (Sn-Zn) solder, but Sn-Zn soldered joints have no track record when it comes to reliability and zinc is a base metal exceedingly subject to oxidation, with the result that only a few manufacturers have had it under study.

The Pb-free oven developed in this work is specifically designed to use Sn-Ag solder.

2. DEVELOPMENTAL CONCEPT

The following are the main requirements for a reflow oven designed for Pb-free soldering.

(1) Uniform temperature distribution on bare boards: In measuring temperature profile, normal practice is to measure the temperatures of joints of components having large thermal capacity and small thermal capacity (ordinarily represented by substrate temperature), and estimates can then be made based on this data for components of intermediate size. If, however the bare board temperature distribution is large, the temperature may be too high or too low in unexpected locations making the oven difficult to use.

(2) Low value of ΔT: In reflowing using Sn-Pb eutectic crystal solder, soldering can be comfortably accomplished even when the upper temperature limit for the smallest components was about 240°C and joint temperatures for the largest components was 210°C (ΔT = 30°C). To implement Pb-free (Sn-Ag) soldering, however, the maximum temperature of the smallest components must be held to that same 240°C, while

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the temperature of the components having the largest thermal capacity must be raised to about 230°C, so that ΔT is only 10°C. Thus the problem is not the heating capacity of the oven itself, but how far the joint temperature of the largest components can be raised.

(3) Excellent reproducibility of temperature profile: While in Sn-Pb eutectic crystal soldering there was a margin of approximately 30°C with respect to the melting point, Sn-Ag soldering allows for only 10-15°C. What then becomes important is the reproducibility of the temperature profile. PCBs are not manufactured under individually set conditions. They are run in continuous batches, and with irregular insertion intervals. Under such conditions of production, the oven cannot be effectively used unless the temperature profile obtained is identical with that obtained under condition setting.

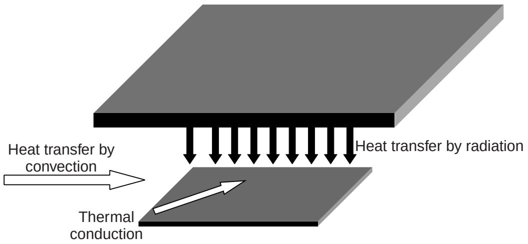
(4) Assured wetting time: Heat transfer involves considering both the thermal capacity of the object being heated and its thermal resistance. In ball grid arrays (BGAs) and other packaged components, the package and PCB are heated first, and only then is the joint heated by conduction, so that time is a crucial parameter in the temperature rise characteristics. For example, even if the package surface is exposed to a powerful flow of gas heated to 230°C, the joint inside will only get warm over a period of time. Thus it is more effective if the reflow zone can be kept at peak temperature while awaiting the rise in the temperature of the joints inside.

3. DETERMINING THE HEATING METHOD

3.1 Heat Transfer Mechanism

Figure 1 shows heat transfer when soldering PCBs in a reflow oven. Heat transfer takes place in three ways--radiation, convection and conduction. Of these, it is the rates of radiation and convection that can be controlled at the oven. Figure 3 shows the heat transfer rate due to far infrared heating, and, as can be seen, the infrared heat energy is significantly greater than that of the hot gas flow.

Salamander® ovens are designed for the reflow soldering of high-density PCBs of high thermal capacity, so that infrared serves as their primary heat source and hot gas as an auxiliary source. Nonetheless if only infrared is used for heating, there will be too large a difference between the temperature of components with low and high thermal capacity (ΔT_1 in Figure 2). Accordingly gas at a temperature intermediate between the two is applied, acting to cool the hotter component (the one with low thermal capacity) and further heating the component with high thermal capacity. This results in a reduction in the temperature difference to ΔT_2. This is the foundation of the theory of heating used in the Salamander series, and it will be obvious that to realize this effect the temperatures of the two heat sources must be independently controlled. Furthermore, to enhance the temperature equalizing effect of the hot gas, heat transfer coefficient α in the equation for convection heat transfer in Figure 1 should be on the high side. The value of α will change depending on the way in which the hot gas impinges on the object being heated and on the rate of gas flow. It is generally considered that a higher gas flow rate is desirable, but an excessively powerful gas stream can disturb the position of components on the PCB. Gas flow rate should normally be kept to no more than 4 or 5 m/s to avoid displacing surface-mounted components, and in the present work it was decided to consider the direction in which the gas impinged, without assuming any increase in gas flow rate. Figure 3 shows the relationship between gas flow direc-



Radiation
:$Q_R = F_{12} \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot \sigma (T_1^4 - T_2^4)$
Convection heat transfer
:$Q_C = \alpha (T_\infty - T_2)$
Thermal conduction
:$Q = -\lambda \cdot A \cdot \Delta T / \Delta X$

Shape factor F_{12}
(Heater for substrate)
Emissivity $\varepsilon_1 \cdot \varepsilon_2$
Stefan-Boltzmann coefficient
$\sigma = 5.68 \times 10^{-8} (W/m^2K^4)$
Heater temperature T_1
Substrate temperature T_2
Gas temperature T_∞

Figure 1 Heat transfer in a reflow oven

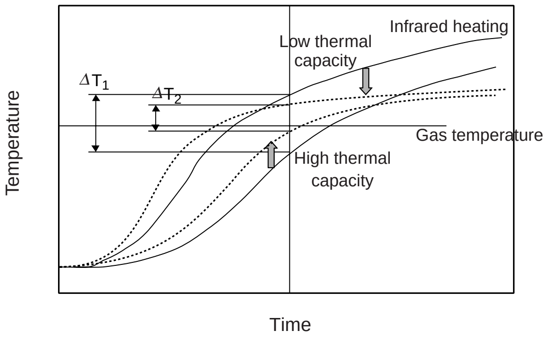
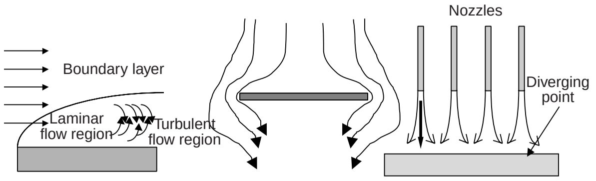


Figure 2 Temperature equalizing effect due to infrared and hot gas heating



	Parallel flow	Perpendicular flow	Nozzle flow (diverging point)
Heat transfer rate (W/m^2) T_2=200°C, T_∞=250°C	1560	2175	6500

Figure 3 Direction of hot gas flow and heat transfer rate (for circuit board)

tion and the rate of heat transfer. In conventional ovens a nozzle flow was applied at the center of the PCB with a parallel flow at the edges, but it can be seen from the figure that the use of a nozzle flow system, having a large number of nozzles results in an increase in the heat transfer rate.

3.2 Verifying Heating Structure

Photo 1 depicts the panel heater used in the present system showing the arrangement of nozzles. The heating structure was based on the use of such units. Figure 4 shows the improvements achieved in terms of heat transfer rate α. In comparisons using the same gas flow rate, the new system (with nozzles) showed an improvement of approximately 40%. This might at first sight be considered a disappointing increase, but in nozzle flow the heat transfer is extremely high at a point directly beneath the nozzles (the diverging point) and drops sharply toward the periphery so that on average this figure may be considered satisfactory. An evaluation of the heating characteristics of a QFP 144P mounted on a PCB was carried out, and the results are shown in Figure 5. For these experiments the heating conditions were set so that the joint temperature was at approximately 100°C for a specified period (70 s). Figure 5 shows the results for (left to right) infrared (IR) heating, hot-gas heating and a combination of the two, with data for a conventional heating system in the upper row and data for the unit developed in this work in the lower row. It is obvious that the new system results in improved hot-gas heating performance, with a marked reduction in the temperature difference at the joint between a PCB (represented by the temperature of the component having the smallest thermal capacity) and the component. The temperature difference between the two was further reduced when infrared heating was used in combination.

3.3 Effectiveness of Reflowing in Inert Atmosphere

Photo 2 shows the reflow condition of Sn-Pb eutectic crystal solder and Pb-free (Sn-Ag-Cu) solder, demonstrating that the Pb-free solder is far inferior in wettability (i.e., it has a higher surface tension when melted). It has been shown that wettability was slightly improved by reflowing

Photo 1 Panel heater used in the present system showing arrangement of nozzles

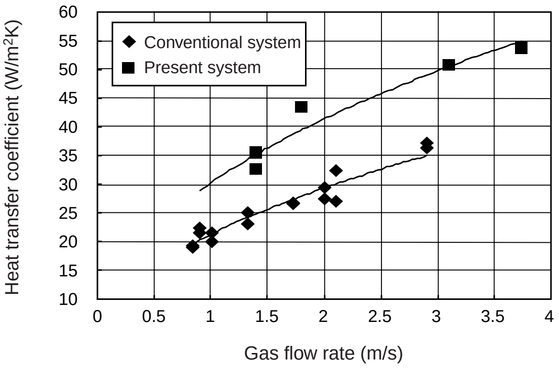


Figure 4 Thermal coefficients of conventional and present heating systems

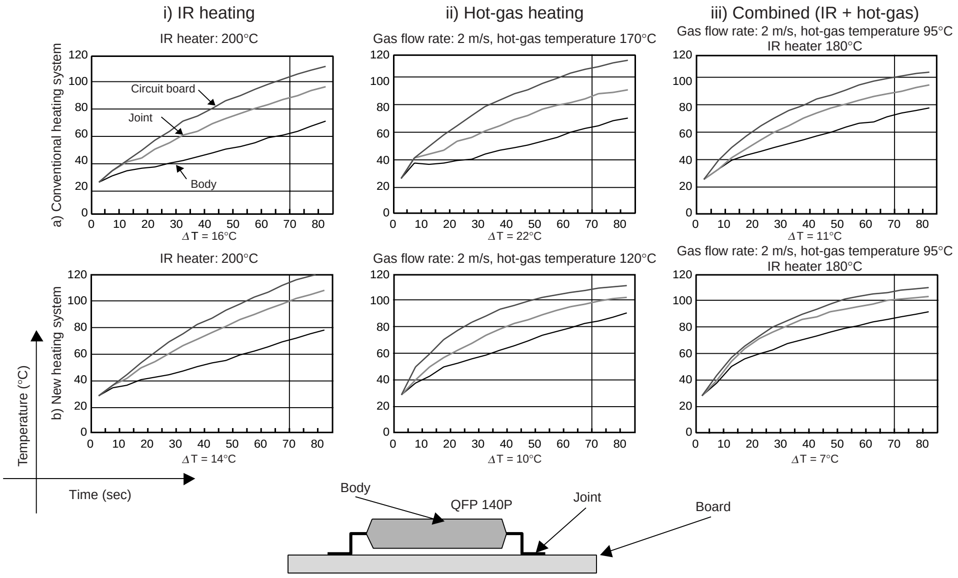


Figure 5 Temperature difference (ΔT) between joint and substrate for conventional and present heating systems

in a nitrogen atmosphere. Many manufacturers are introducing equipment to automate external appearance inspections. Since this equipment inspects the shape of fillets at the ends of the leads (joints) of the electronic components, it is expected that if wettability is so poor that the fillets are malformed, more components will be rejected. This data suggests the possibility that by reflowing in a nitrogen atmosphere, the frequency of wrong decisions by the inspection equipment can be reduced. Also, when reflowing the second surface of a two-sided reflowed PCB, oxidation during the first pass can be inhibited, improving soldering quality.

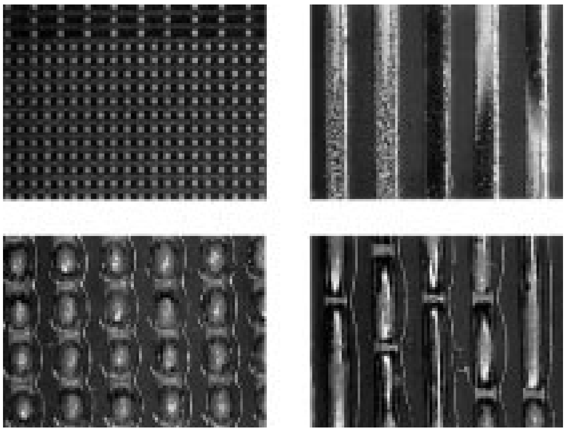


Photo 2 Wettability of Pb-free (Sn-Ag-Cu) solder

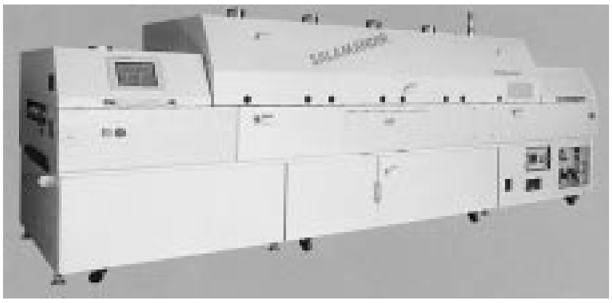


Photo 3 Appearance of the Salamander XN III-525 PZ system

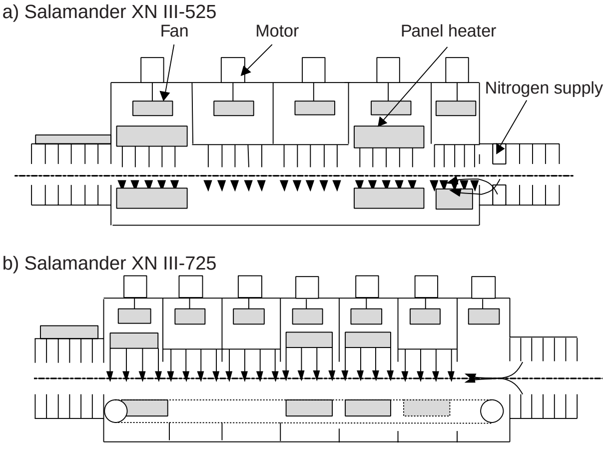


Figure 6 Comparison of heating zone configurations of the Salamander XN III-525 and XN III-725

4. THE SALAMANDER XN III SERIES

Salamander XN III is a line of nitrogen gas reflow ovens that have been commercially introduced, incorporating the new heating system described above for Pb-free soldering. Photo 3 shows the appearance of the Salamander XN III-525 PZ system, and Figure 6 shows a comparison of the heating zone structures of the Salamander XN III-525 and XN III-725. Both infrared and hot-gas heating are used in the zone in which rapid heating of the PCB occurs, with hot-gas heating used in the zone in which the temperature is maintained constant. Of the heating zones of the 525, zone 5 measures 450 mm in length and the other zones 600 mm, while in the 725, all zones are 450 mm. The 725 was developed to provide a more flexible temperature profile, the larger number of zones making it possible to achieve a greater variety of temperature profiles.

4.1 Features

The Salamander XN III series has the following features:

(1) The nozzle-flow hot-gas heating system reduces temperature differences between components: Figure 7 shows the temperature difference between PCB and component (a 45x45 mm BGA) for the XN III and the previous model. It can be seen that the difference has been reduced to one-third.

(2) Thermal energy is controlled independently for infrared and hot gas: The same level of temperature profile reproducibility was obtained for the Salamander XN III as for the XN, probably due to the accuracy with which the infrared and hot-gas heat sources are controlled. Figure 8 compares the change in temperature when processing PCBs individually and continuously, and demonstrates the outstanding stability of the oven when insertion conditions are changed. And optimum conditions can be set according to the thermal characteristics of the PCB and the mounted components simply by changing the distribution of heating energy.

(3) Small differences in temperature profile for the same settings in any given oven type: This is a major advantage to users who operate volume-production lines. Once conditions are determined for one oven, the others can be run under the same conditions,

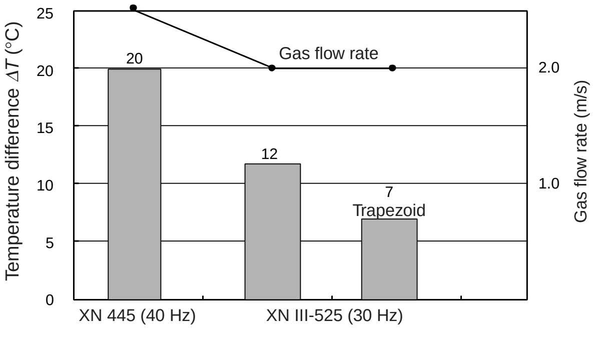


Figure 7 Temperature difference ΔT between center of 45x45 mm BGA (at 235°C) and PCB

greatly reducing the time required for set-up. This is the result of the accuracy of infrared and hot-gas control.

(4) Excellent bare-board temperature distribution: Figure 9 shows the temperature distribution on a bare PCB. Because of the uniformity of gas flow from the nozzles, disparity of temperature stays within a range of 5°C.

(5) Trapezoidal temperature profiles can be achieved: In packaged components such as BGAs, where the joints are inside the package, heat energy cannot be conveyed to the joint directly by radiation or convection. Thus in reflow soldering of such components the package or substrate is first heated and heating proceeds by conduction. The package, however has its own thermal capacity and heat resistance so that the heat applied is not transferred to the joints immediately but rises gradually over time. Figure 10 shows a comparison between the ordinary triangular (peaked) temperature profile and the trapezoidal profile. It can be seen that at the flat portion of the trapezoidal profile the temperature at the center of the BGA gradually approaches that of the substrate, and it will be realized that the longer this flat portion is the less will be the temperature difference between the two. Thus with the trapezoidal temperature profile it is possible to bring components having high thermal capacity to their maximum temperature while limiting the temperature rise of components of low thermal capacity (i.e., reduce ΔT), and to obtain the hold time at 220°C or above that is essential for Pb-free soldering.

(6) Flux-collecting system: Figure 11 shows the flux-collecting system and the energy-saving structure. Flux from the fumes in the recirculated air in the oven is deposited at points where the temperature is low (below the solidifying point). This can contaminate equipment and cause malfunctions, requiring regular cleaning. In the present system fumes are first led to a bypass duct, the walls of which are chilled. When the amount of solidified flux increases, it passes through the walls and collects in a vessel. This system greatly reduces the frequency of flux cleaning.

(7) Energy-efficiency: This system has lower power consumption (Figure 11). As described above, Salamander systems control infrared rays and hot gas independently, so thermal interference cannot be avoided. One disadvantage of conventional ovens, in which heat is actively radiated from the walls of the oven making it impossible to control gas temperature, has been avoided. It has been found, however, that

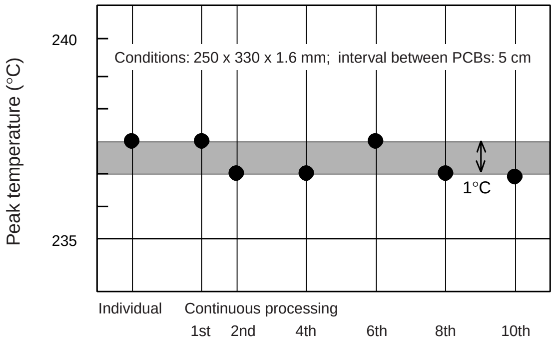


Figure 8 Stability of temperature profile during continuous processing of circuit boards

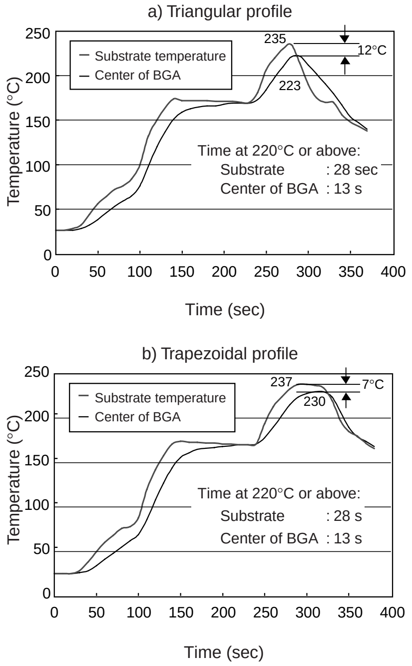


Figure 10 Comparison between triangular (peaked) and trapezoidal temperature profiles

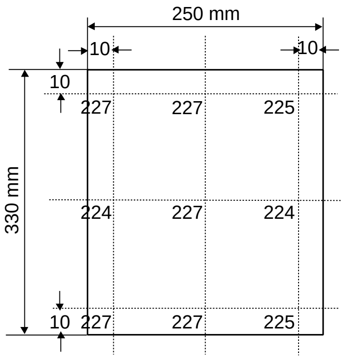
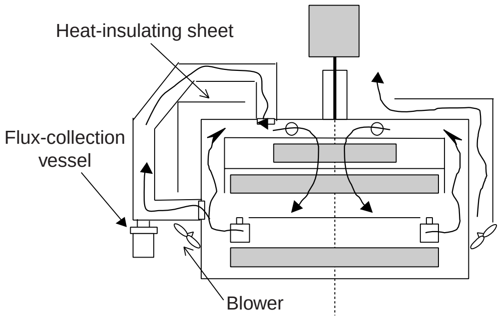


Figure 9 Temperature distribution on bare PCB



- Energy is saved by normally retaining heat in the oven by means of a heat-insulating plate.
- Heat is dissipated by the blower when it is difficult to control hot gas temperature.

Figure 11 Flux collecting system and energy-efficient structure

Table 1 Specifications of typical systems

	XN III-525PZ	XN III-725PC
Dimensions (LxHxH) (mm)	4750x1200x1500	5150x1200x1500
Weight (kg)	1200	1400
PCB dimensions	250x330 mm	
Permissible component height	Top 13 mm/bottom 13 mm (specifiable)	
No. of zones	5	7
Control method	PLC+touch panel	PLC+computer
Storage capacity for production conditions	50 patterns	Up to hard disk capacity
Communication circuit	RS-232C	Ethernet
Nitrogen supply capacity & oxygen concentration	300 ppm @ 200 l/min	
Power requirement	40 kVA	47 kVA

depending on the temperature settings, there is a region in which interference presents no problem even without radiation. In the present system, therefore, the outer walls of the oven are covered in heat-insulating sheets and radiation is suppressed in the region where thermal interference is not a problem, so that when control of gas temperature becomes impossible air is conveyed to the oven walls and insulating sheets promoting heat dissipation and limiting energy waste.

(8) Low nitrogen consumption: In Salamander systems the oxygen concentration in the oven is controlled by the nitrogen gas flow rate. Thus when the oven is used at a high concentration of oxygen the supply of nitrogen can be curtailed, reducing running costs. If the supply were curtailed too much, however, the static pressure in the oven would drop to the point where oxygen concentration would be subject to the effects of external disturbance. The new ovens are equipped with a nitrogen flow rate optimizer that provides sufficient nitrogen to keep oxygen concentration at the limit of stability, assuring optimum nitrogen gas flows at all processing conditions.

4.2 Specifications

Table 1 shows the specifications of the Salamander XN III-525PZ and XN III-725PC systems, which are typical of the series. The 725PC has in its control system a personal computer running Windows NT, for easy adaptation to a network environment.

4.3 Model C Control System

Figure 12 is a schematic diagram of the Model C control system, in which process condition management, data entry, current status display, etc., are effected by personal computer. The monitor is a TFT color liquid crystal panel (touch panel included) for visual display of system status. Data for system operation is fed to a programmable logic controller (PLC), which provides continuous control of the system. The computer used is normally an MSDOS machine, backed up by a notebook computer in case of malfunction. Network connection is easy so that software upgrades can be downloaded. Work is currently going forward on providing an on-line diagnostic capability.

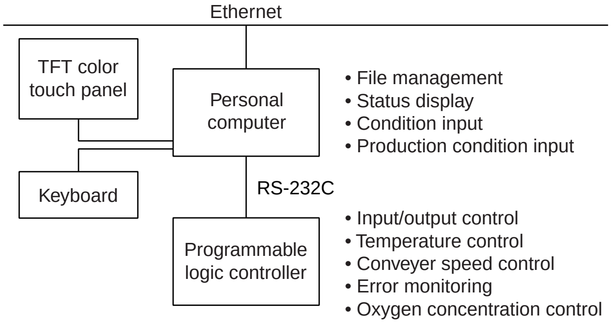


Figure 12 Schematic of Model C reflow oven system

5. CONCLUSION

It is expected that the use of Pb-free solder in the mounting of electronic components will expand greatly from this year on, but there are a number of problems that remain unsolved in terms of solder cream and the heat withstand properties of the components. For example a trapezoidal temperature profile is extremely effective in limiting the maximum temperature of components, but the time above a given temperature is extended raising the danger of changes in the capacitance of electrolytic capacitors. Process optimization cannot be achieved solely by the efforts of equipment manufacturers; electronic component makers, materials manufacturers and assemblers must also be intimately involved. Furukawa Electric, as a leading equipment manufacturer, is a participant in the NEDO Pb-free solder project, and is supplying and acquiring information for practical implementation of Pb-free soldering. We intend that in future we will serve not only as an equipment manufacturer but will also cooperate with users with respect to the process as a whole. In closing we would like to express our appreciation to the staff of the Planning Dept., Hiratsuka Works for cooperating so effectively in this development work.

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