Thermal Assessment of Glass-Metal Composition Plasma Display Panels Using Design of Experiments

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***Abstract*—A newly developed plasma display panel that utilizes a composition of glass, metal, and frit glass sealing material, in addition to functional thin and thick film glass-powder-based laminate composites was evaluated. This paper presents an approach for thermal design assessment of glass/metal plasma display panels under operational conditions. Quality function deployment and design of experiments were used to optimize design factors for thermal enhancement.**

***Index Terms*—Plasma display panel, reliability, thermal assessment.**

I. Introduction

PLASMA display panel (PDP) televisions are growing in popularity in various applications [1]. PDPs are just seven to ten centimeters thick, with over one hundred centimeters of diagonal display (Fig. 1); they dramatically advance current picture tube technology; can be viewed without distortion from a wide 160° angle; and provide extraordinary picture, color, brightness, and contrast.

PDPs are composed of a light-transmitting front panel, a cell structure forming barrier ribs, a structurally reinforced back panel, and hermetic seals (Fig. 2). The front panel has a dielectric layer (electric condenser), a parallel pair of electrodes, and an MgO layer for electrode protection and enhancement of secondary electron emitting capacity. In the back panel, there are data-addressing electrodes, a white dielectric layer for light reflection, barrier ribs, and phosphor layers. The combination of Ne and Xe is commonly used to discharge ultraviolet light and radiate it toward the back of the panel, which is coated with phosphor material [2]. Table I provides the design specifications for a conventional PDP.

PDPs have a unique light-producing mechanism. The electric field of the addressing electrode in the back panel triggers the gas to become a plasma state. Plasma display panels use gas plasma to produce light, with a technique very similar to that used for fluorescent tubes. This ready-to-discharge gas reacts with phosphors in the discharge region and creates red, green, and blue light in each sub-pixel. This is the only flat panel technology currently used to manufacture large-sized flat panel televisions [3], [4].

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One of the problems with plasma display panels is its relatively short life as a result of degraded strength. The heat dissipated due to low power efficiency leads not only to a decrease in the display quality but also to structural failure attributable to a critical thermal gradient. Thermally induced stress is the major failure mechanism of the early structural failure in PDPs. Table II introduces potential risk areas, causes, and failure mechanisms in PDPs.

Fig. 3 outlines our analysis process. The strength of the PDP panels was assessed by thermomechanical characterization via thermal shock testing [5], [6]. Temperature distributions and stress levels [7] were numerically calculated through thermal and structural analysis. Quality function deployment and design-of-experiments were performed to suggest the priority of design factors and optimized values for improvement. With today's ever-increasing complexity of electronic products, design of experiments has become an essential part of the modeling process for robust products. The time savings can be considerable when a careful experimental design takes only the most useful data [8].

II. Numerical Analysis

System-level analysis requires such information as system and parts dimensions, vent locations, fan characteristics, power consumption, and accessories like cables, connectors, and filters so that temperature profile, air velocity, and heat transfer information can be estimated.

Fig. 4 shows the components of a PDP module that were included in the numerical modeling. The investigation was based on a one hundred centimeter plasma display panel application. The glass front panel, metal back panel, barrier ribs, and seal were assessed for temperature distribution on the panel during operation. The thickness of the front plate, back plate, seals, and ribs are 2.8 mm, 0.5 mm, 0.15 mm, and 0.15 mm, respectively. Silicone pads, flexible PCBs, PCBs on the back panel (Fig. 5), and space (HS gap) were included as influencing factors in the analysis. Results obtained with a fully developed three-dimensional (3-D) model were compared with experimental results under operational conditions. In the simulation, the geometry of the ribs and electronic components was simplified without loss of their influences on the components of interest.

The dissipated power equals the difference between the total power input and the output as a light-emitting power. Power-added efficiency is the light-emitting power divided by the total input power. PDPs are currently capable of power-added efficiency values in the range of 2% to 5%. Peak dissipated power levels in a panel may not be more than 95% to

Fig. 1. PDP front and side view.

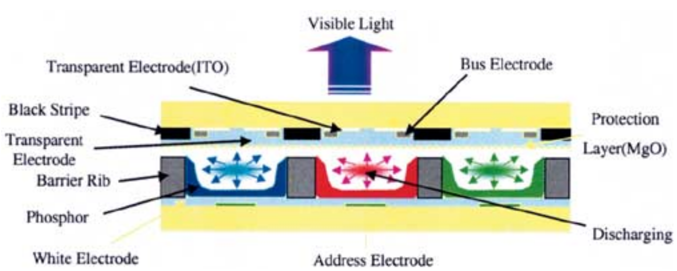


Fig. 2. Cross section of plasma display panel.

TABLE I
CONVENTIONAL PDP DESIGN SPECIFICATION

Items			Dimension	Roles
Front Panel	Glass	Thickness	2.8mm	Light transmission
	Dielectric	Thickness	25μm	Capacitor or a electric condenser
	Indium Tin Oxide	Thickness	1000-1500Å	Sustain electrode
		Width/ Pitch	0.23mm/1.29mm	
	Cr/Cu/Cr	Thickness	0.1/2.0/0.2μm	Bus electrode
		Width	0.23mm	
	MgO	Thickness	8000Å	Electrode protection Secondary electron emitting capacity
Back Panel	Electrode	Thickness	15μm	Data-addressing
		Width/ Pitch	0.2mm	
	Dielectric	Thickness	18μm	Light reflection Electric condenser
	Barrier Rib	Thickness	100-130μm	Discharge area formation
		Width/Pitch	50/430μm	Structural strength
	Phosphor	Thickness	25μm	Red, green, and blue color light formation
	Glass	Thickness	2.8mm	Back panel substrate
Seal		Height	130μm	Discharge gas leakage protection
		Width	4mm	

98% because some of the dissipated power will diffuse through the matching circuitry on the panel.

The dissipative power consumption in white pixel mode was estimated from the relationship between total power consumption and temperature distribution, measured to be about 75% to 85% of total power. Fig. 6 shows the simulation result with 80% power consumed for heat dissipation. Three-pixel modes-full white, white and black, and black-gave different temperature profiles because the light color combination and light intensity level are created by controlling the discharging power of each

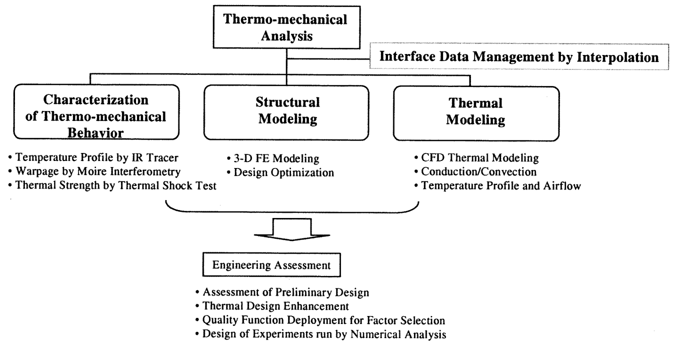


Fig. 3. Outline of analysis process.

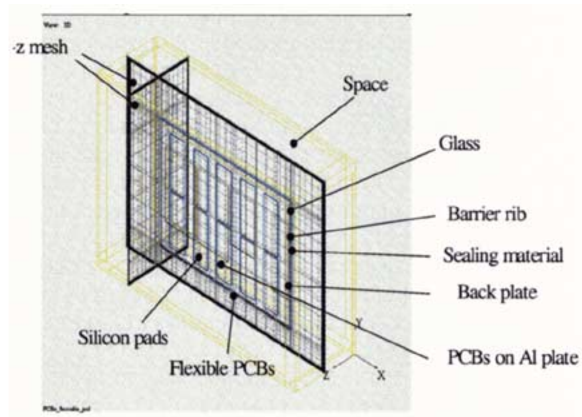


Fig. 4. Components of the simulation model.

Fig. 5. PCBs on back of PDP.

sub-pixel. White pixel mode is created by the combination of three sub-pixels applied with equally distributed and highly intensified power. The pixel has three sub-pixels covered with red, green, and blue florescence.

III. MEASUREMENT FOR VERIFICATION

The temperature profile of the front panel was calibrated with thermocouple and then measured using infrared thermography, while one of the back panels was measured by thermocouples during white pixel mode operation. The ambient temperature was 22.7 °C. The address voltage and sustain voltage applied to the vertical and horizontal electrodes were 65 V and 190 V, respectively. The sustain current was 1.24 A.

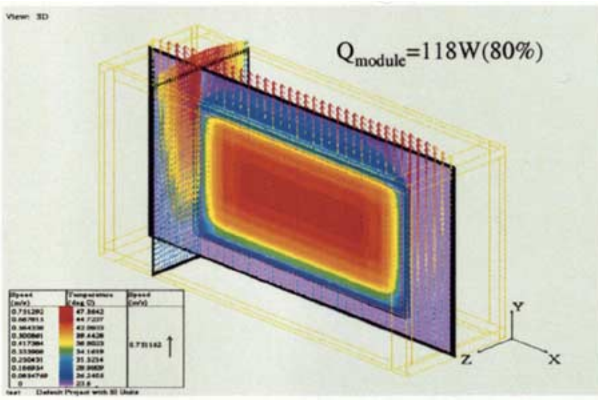


Fig. 6. Simulation result of 80% power consumption.

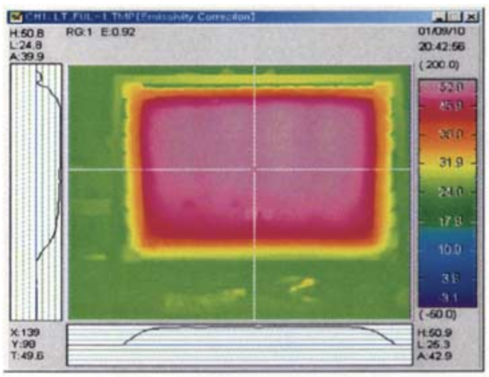


Fig. 7. Thermal image of front panel (IR measurement).

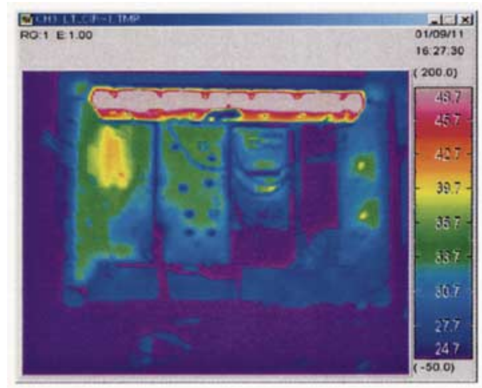


Fig. 8. Temperature map of backside of PDP (IR measurement).

TABLE II
POTENTIAL RISK AREAS, CAUSES, AND FAILURE MECHANISMS

Potential risk areas	Causes	Failure mechanisms
Manufacture and assembly	Firing process	Large thermal stress
	Residual stress	Reduced strength
	Contact	Scratches
	Contamination	Display quality reduction
	Warpage	Misfit, misalignment
Structure	Thin and large area plate	Deformation, handling
		Flexural strength reduction
	Laminated and sealed [3]	Stress concentration and leakage
Material	Glass	Crack, fracture
	Low thermal conductivity	Large thermal gradient
	CTE mismatch	Thermal stress, deformation
	Static corrosion [4]	Reduced strength
	Outgassing	Display quality reduction
Efficiency	Low light- emitting efficiency	Large thermal gradient, cost up

The thermal images of the front panel and a backside view of the printed circuit board are shown in Figs. 7–9 show the location of temperature-measured points for comparison with simulation. The estimation shows approximately a 10% or less difference from the experimental values. Table III shows the temperatures and differences in percentages of fourteen points on the front panel and the back panel in white pixel mode, while Table IV shows the white/black pixel mode. Figs. 10 and 11 show the estimated temperatures and differences in percentages for 15 points on the front and back panels in white/black pixel mode. Fig. 12 gives the temperature profile measured in white/black pixel mode.

IV. QUALITY FUNCTION DEPLOYMENT (QFD)

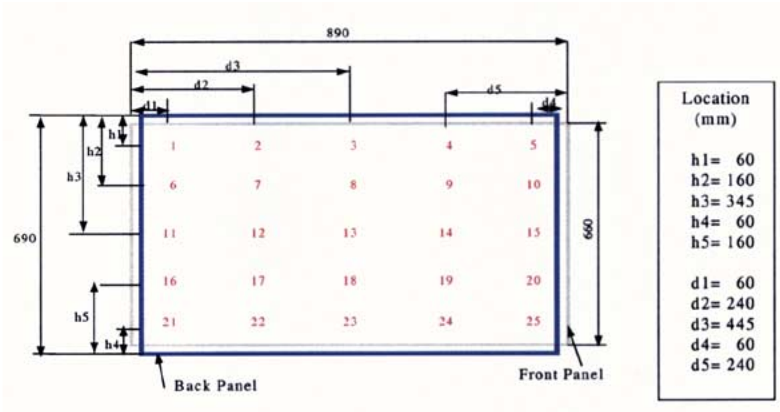
The basic principle for QFD applications is to develop a unique QFD system using a realistic approach appropriate to the characteristics of the design. In this study, manufacturing engineers, quality and reliability engineers, and design engineers discussed and completed a quality matrix (Table V) for PDP design improvement, based on their engineering expertise and existing physical and numerical models. In the quality matrix, the technical requirements of the PDP module were listed in the far left column. Each related component or part is marked down and shown with values added. Three levels of value are selected: 1, 3, and 9. On the top row, components and their detailed specifications are listed. The column on the right shows the priority order for technical requirements. Factors critical to quality are listed on the bottom row, with values expressing their priority in design. The heatspreader and holder have the highest points, which mean they are most crucial for quality concerns.

V. DESIGN OF EXPERIMENTS

A design of experiment (DOE) was set up to investigate the effect of thermal characteristics, that is, temperature distribution following design changes in the PDP panel. Designed experiments are by far superior to the traditional one-factor-at-a-time method because they take into account interactions among variables, are efficient, and can eliminate all causes of variation except the one of interest [9].

The focus was on two-level factorial design, in which each input variable was varied at high (+) and low (−) levels. Table VI shows the DOE matrix for a two-level design on five factors affecting PDP reliability in thermal management. The five factors interact to produce an unexpected breakthrough in product quality.

In this study of the new PDP structure, the goal was to reduce thermal gradients and maximum temperatures on panels, which cause overstress and out of plane deformation of parts. If the stress level can be "stabilized," then part dimensions for thermal management can be adjusted so the parts can be easily manufactured and assembled. The heatspreader, holding mechanism, thermal adhesive, cabinet, and printed circuit board connections were selected as critical factors to investigate. Noise factors were defined as environmental conditions, such as ambient temperature and pressure or the process and/or operating history



Points	Front Panel	Back Panel
1	42.9	46.3
2	47.3	48.8
3	46.2	50.2
4	46.3	50
5	43.9	45.9
6	48.4	49.7
7	50	52.3
8	50.5	53.1
9	50.7	53.4
10	49.6	49.1
11	47.3	47.4
12	49.5	52.2
13	49.6	52.2
14	50.3	52.4
15	49.3	45
16	44.5	44.2
17	46.8	48
18	47.7	47.8
19	47.7	49.4
20	47	44.5
21	40.4	37.3
22	42	38.7
23	41.5	39.2
24	41.4	39.4
25	41.2	37.9

Fig. 9. Location of temperature measurement points and measured data.

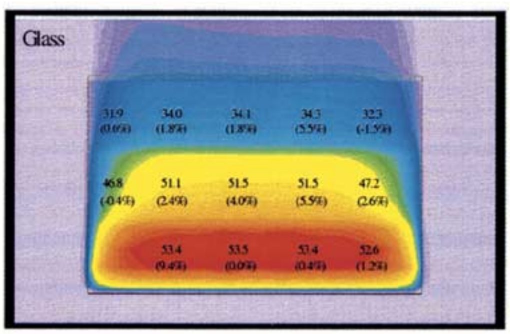


Fig. 10. Simulated temperatures on front panel at white/black pixel.

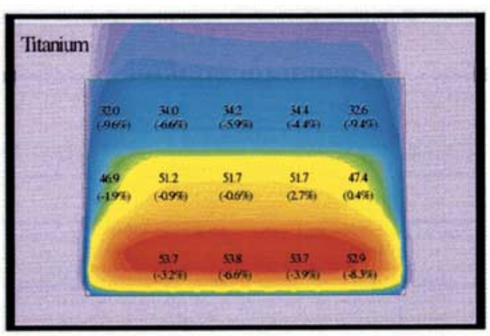


Fig. 11. Simulated temperatures on back panel at white/black pixel.

[10]–[12]. Characteristics considered were maximum temperature and temperature gradients on the glass panel (Fig. 13).

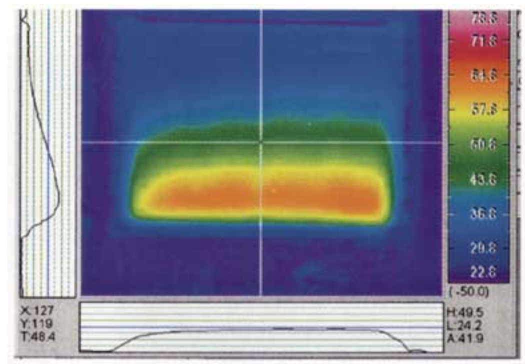


Fig. 12. Measured temperature distribution at white/black pixel.

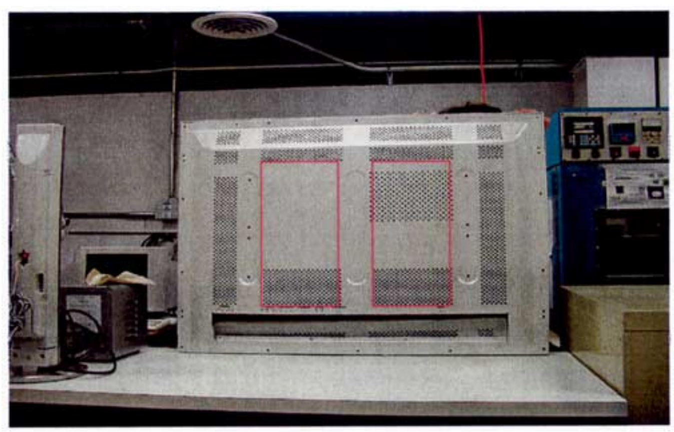


Fig. 13. Vent location (dots-before, red line–after).

VI. Conclusion

The experiments used a two-level factorial design with sixteen runs. Table VII shows sixteen trial results of thermal analysis; the maximum temperature on the panel was chosen as the response characteristic. The main effects plotted in Fig. 14 show that the maximum temperature of the panel is influenced mostly by heatspreader shape and the air gap between the spreader and other barriers, but very little by the materials of the heatspreader, and not at all by the size of the flexible PCB (FPCB). The interaction plot in Fig. 15 shows that there is an interactive relation between heatspreader shape and gap. Moreover, the effect of shape depends on gap size.

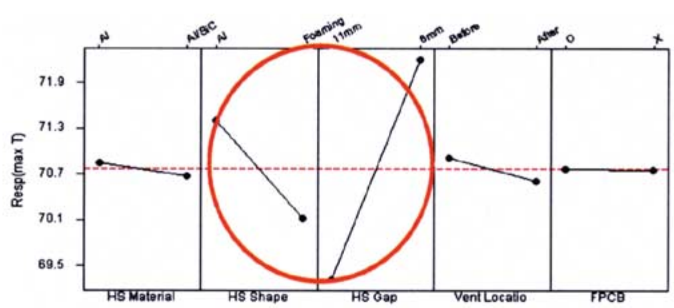


Fig. 14. Main effect plot for response (max. temperature °C).

TABLE III
SIMULATION TEMPERATURES AND RELATIVE ERRORS BETWEEN MEASURED AND SIMULATED ON WHITE PIXEL MODE

Front Panel	43.2	46.5	46.7	46.8	43.6	46.7	49.4	49.8	49.9	47.3	36.8	37.1	37.1	36.5
Error(%)	0.50%	1.30%	2.40%	4.50%	4.10%	0.40%	4.00%	3.10%	1.20%	2.30%	6.70%	3.10%	5.60%	8.80%
Back Panel	43.4	46.7	46.8	47	43.8	46.8	49.6	49.9	50.1	47.5	40.9	41.2	41.3	40.5
Error(%)	6.90%	1.90%	1.50%	0.90%	0%	1.90%	0.40%	1.20%	0.80%	3.90%	3.80%	2.70%	9.80%	4.10%

TABLE IV
SIMULATION TEMPERATURES AND RELATIVE ERRORS BETWEEN MEASURED AND SIMULATED ON WHITE/BLACK PIXEL MODE

Front Panel	31.9	34	34.1	34.3	32.3	46.8	51.1	51.5	51.5	47.2	53.4	53.5	53.4	52.6
Error(%)	0.60%	1.80%	1.80%	5.50%	1.50%	0.40%	2.40%	4.00%	5.50%	2.60%	9.40%	0.00%	0.40%	1.20%
Back Panel	32	34	34.2	34.4	32.6	46.9	51.2	51.7	51.7	47.4	53.7	53.8	53.7	53.9
Error(%)	9.60%	6.60%	5.90%	4.40%	9%	1.90%	0.90%	0.60%	2.70%	0.40%	3.20%	6.60%	3.90%	8.30%

TABLE V
HOUSE OF QUALITY IN DESIGN QFD

Values added (⑨③①)	Components and details	Heat spreader •dimension • material • surface treatment • titanium thickness • shape • numbers	Holder1 • dimension • material • location • connection	Holder2 • shape	Holder3	Screw • dimension • type	Interface material • type • dimension	Cabinet • vent location • vent size • hole ratio • material • dimension	accessories • heat pipe • fan	Sealing • Material • numbers	Priority Level in Technology
Technical requirement											Order (Value)
Low temperature gradient	1	⑨					③	①	⑨		4 (11)
Low temperature	2	⑨					③	①	⑨		3 (12)
Panel strength	3	③	⑨			③		③			2 (13)
Product Slimness	4	③	⑨								10 (5)
Weight	5	⑨	①	①				③	①		2 (13)
Size	6	⑨	①	①				③	⑨		6 (9)
Material cost	7	⑨	③				③				1 (14)
PCB connection	8	③	①					⑨			13 (2)
Reworkable	9	⑨	⑨				⑨	①	①		8 (7)
Assembly simplification	10	⑨	⑨				③	③	③		9 (6)
Manuf. simplification	11	③	①					③	①		5 (10)
Panel fixture	12		⑨			③	⑨	③			11 (4)
Panel stress	13	⑨	③			③	⑨	①	⑨	①	4 (11)
Environmental friendly	14						⑨	③			14 (1)
Warpage	15	③	⑨			③	③		③		7 (8)
Noise	16							③	⑨		12 (3)
CTQ Priority (Order)		861 (1)	496 (2)			108 (6)	360 (4)	233 (5)	486 (3)	11 (7)	

TABLE VI
FACTORS FOR A DOE ON PDP DESIGN (CTQ: MAX. TEMPERATURE OR Δ T)

Design Factor	Low Level	High Level
Heatspreader Material	Al	Al/SiC
Heatspreader Shape	Original (Al)	Forming
Heatspreader Gap (mm)	6	11
Vent Location	Before (Figure13)	After (red line)
FPCB Size	Before (o)	After (x)

The larger gap size shows better thermal management, no matter what material is used for the heatspreader and where the vent is located, but the available information about the best gap size is not sufficient for this analysis. There is no interaction between heatspreader material and shape, heatspreader material and size, heatspreader material and vent location, heatspreader material and FPCB size, or vent location and FPCB size.

From the normal probability plot (Fig. 16) of the main and interaction effects, the heatspreader gap and shape and their interaction demonstrate the major influence on the analysis response. The abnormality level correlates to the influencing level. The x-axis in the Pareto chart (Fig. 17) is the analysis result of effect, which shows the average results of eight factors at one level subtracted from the ones at the other level. The larger the value, the greater is the influence on the response characteristics. The

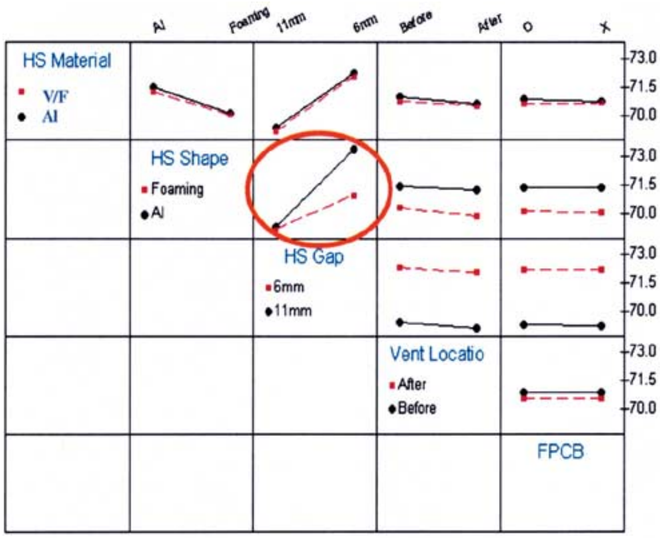


Fig. 15. Interaction plot for response (max. temperature °C).

TABLE VII
SIXTEEN TRIAL RESULT OF THERMAL ANALYSIS ON PDP PANEL

HS Material	HS Shape	HS Gap	Vent Location	FPCB	Resp(max) C)
Al	Forming	6mm	After	O(present)	70.9 °C
Al/SiC	Al	11mm	After	X(enhanced)	69.2 °C
Al/SiC	Forming	11mm	After	O(present)	69 °C
Al/SiC	Al	6mm	Before	X(enhanced)	73.4 °C
Al	Forming	11mm	Before	O(present)	69.6 °C
Al	Al	11mm	After	O(present)	69.4 °C
Al/SiC	Forming	6mm	Before	O(present)	71. 1 °C
Al	Forming	6mm	Before	X(enhanced)	71.2 °C
Al/SiC	Forming	6mm	After	X(enhanced)	70.8 °C
Al/SiC	Al	11mm	Before	O(present)	69.3 °C
Al	Forming	11mm	After	X(enhanced)	69 °C
Al/SiC	Forming	11mm	Before	X(enhanced)	69.4 °C
Al	Al	6mm	After	X(enhanced)	73.4 °C
Al	Al	6mm	Before	O(present)	73.7 °C
Al	Al	11mm	Before	X(enhanced)	69.6 °C
Al/SiC	Al	6mm	After	O(present)	73.2 °C

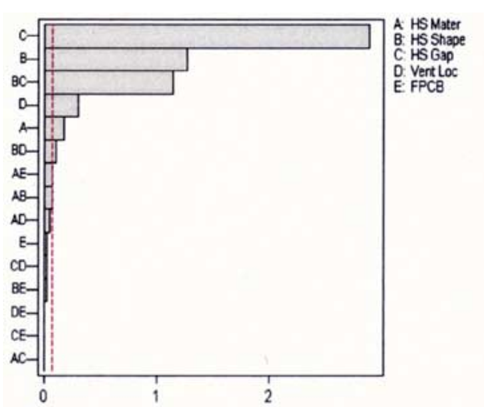


Fig. 16. Normal probability plot of the effects (Response is max temperature).

conditions of optimum level from the cube plot (Fig. 18) are an Al/SiC heatspreader, a 11 mm gap, and a vertical fin heat sink. The maximum response temperature is 69 °C.

In order to determine the optimized gap size for best thermal performance, sensitivity analysis was performed. Up to 20 mm, the maximum temperature of the panel decreases dramatically.

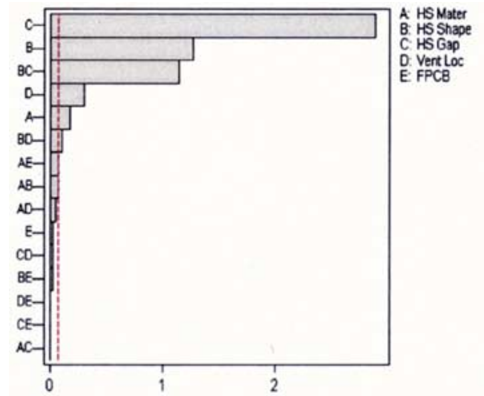


Fig. 17. Pareto chart of the effects (Response is max temperature).

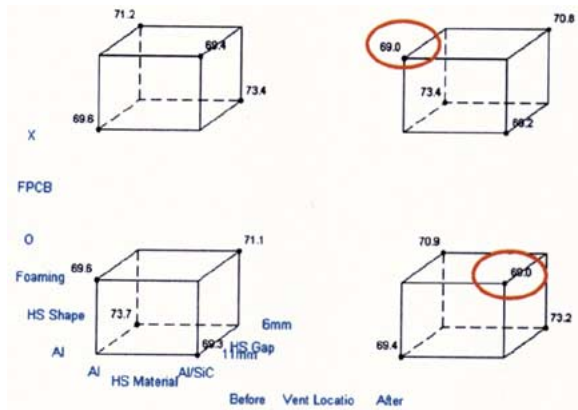


Fig. 18. Cube plot for response (max temperature).

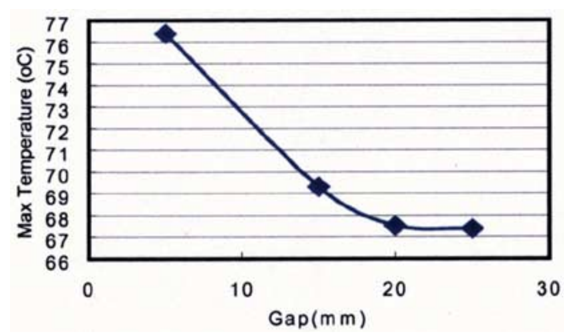


Fig. 19. Maximum temperatures versus gap.

Increasing the air gap beyond 20 mm, there is only a minimal reduction in the panel temperature (Fig. 19).

From this study, the most influential factors of the PDP thermal design were found to be the heatspreader and the gap between the heatspreader and other barriers. To ensure actual improvements in product quality and process efficiency, the simulation results need to be validated with real experiments. Nevertheless, the findings of this study help reduce the number of experiments and save product design time.

With the model developed in this study, the temperature distribution resulting from any kind of graphic mode combination during operation can be estimated, including the critical temperature gradient condition through design. Therefore, long before the final product appears, the weak, temperature-sensitive point of a panel can be recognized at the system level, and thermal elements such as heat spreaders, vents, fans, thermal barriers, and accessories can be introduced through sensitivity analysis and design of experiments for optimal thermal management.

REFERENCES

[1] CFO News. (2001) Competitive technologies to reap benefits of growing flat panel TV market. Tech. Rep., Corp. Financials Online, Inc.. [Online]. Available: http://www.cfonews.com/ctt/c030 399z.htm

[2] UDW. (2000) The plasma tutorial. Tech. Rep., Univ. Durban-Westville, Durban, South Africa. [Online]. Available: http://plasma.udw.ac.za/plasma/tut/tut.html

[3] Hermetic. (2000) Engineering data: Glass-to-metal seals—Their nature. Tech. Rep., Hermetic Industries. [Online]. Available: http://www.hermetic-ind.com/techdata.html

[4] S. T. Gulati, "Invited Address. "Stress corrosion in silicate glasses and its impact on CRT panel design," in *SID Dig.*, 1993, pp. 39–42.

[5] M. Lee and J. Lee, "Thermomechanical analysis for plasma display panel," in *Proc. IMAPS, Eur. Microelectron. Packag. Interconn. Symp.*, 2000, pp. 484–489.

[6] M. Lee and M. Pecht, "Thermal characteristics of glass-metal composition plasma display panels," *IEEE Trans. Adv. Packag.*, vol. 25, pp. 488–494, Nov. 2002.

[7] ——, "Thermomechanical analysis of glass/metal composition plasma display panels," *IEEE Trans. Comp. Packag. Technol.*, submitted for publication.

[8] K. Hofmeister and W. Slabey, *A Tutorial on the Principles of Quality Function Deployment: Excerpts from the Implementation Manual for the Three Day QFD Workshop*. Allen Park, MI: Amer. Supplier Insti., 1987.

[9] M. J. Anderson and S. L. Kraber. (2002) Keys to successful designed experiments. Tech. Rep., Stat-Ease, Inc., Minneapolis, MN. [Online]. Available: http://www.statease.com/pubs/doe-keys.pdf

[10] S. Timoshenko and D. H. Young, *Strength of Materials*, 4th ed. Princeton, NJ: Van Nostrand Reinhold, 1962, pp. 113–119.

[11] R. M. Christensen, *Mechanics of Composite Materials*. Melbourne, FL: Krieger, 1991.

[12] Flotherm, *Flotherm Manuals Version 3.1*. Southborough, MA: Flomerics, 2002.

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