ULTRA-LOW VOIDING HALOGEN-FREE NO-CLEAN LEAD-FREE SOLDER PASTE FOR LARGE PADS

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ABSTRACT
The electronic industry is evolving rapidly toward miniaturization, with major emphasis on thin product profiles. This is particularly true for portable devices, such as smart phones. To facilitate the implementation of thin profile, use of thin components such as LGA and QFN becomes mandatory. This means the solder paste will have great difficulty in venting the volatiles at reflow due to the low standoff. In the case of QFN, due to the incorporation of large thermal pads, therefore a significantly higher difficulty for the escape of flux volatiles at reflow, formation of large voids virtually becomes inevitable. Apparently the presence of large voids will greatly jeopardize the reliability of devices. While board design and process adjustment may alleviate the voiding challenge somewhat, an intrinsically voiding-free solder paste will be the most desirable solution. With the elucidation of voiding mechanisms and a deep understanding of the material factors contributing to the voiding, a new halogen-free, lead-free, and no-clean solder paste 44-29-3 was developed. The test results showed this paste was significantly lower in voiding than any other solder pastes tested in this study. It also exhibited nearly none solder beading, and a very acceptable performance on non-slump, wetting on OSP and ENIG under air, solder balling, and graping.

Key words: No-clean, flux, QFN, SAC305, halogen-free, Voiding, large thermal pad, low standoff, low solder beading

INTRODUCTION

The electronic industry is evolving rapidly toward miniaturization, with major emphasis on thin product profiles. To facilitate the implementation of thin profile, use of thin components such as LGA and QFN becomes mandatory. Quad Flat No Leads (QFN) , see Figure 1, has a number of benefits including (1) small size, such as a near die-sized footprint, thin profile, and light weight; (2) easy PCB trace routing due to the use of perimeter I/O pads; (3) reduced lead inductance; and (4) good thermal and electrical performance due to the adoption of exposed copper die-pad technology [1]. However, due to the large coverage area, large number of thermal via, and low standoff, voiding control at QFN assembly becomes a major challenge. The presence of voids will affect the mechanical properties of joints [2] and deteriorate the strength, ductility, creep and fatigue life [3, 4]. It can also produce spot overheating, hence reduce the reliability of joints.

The voiding behavior can be attributed to the materials, such as flux type, powder quality, surface finishes, etc. It can also be attributed to design, such as pad design, component design, solder mask design, and board design. In addition, process also has a strong impact on the voiding, and can be attributed to parameters such as the printing and reflow process, or human factors [5].

DESIGN OF FLUX

In this work, the primary goal is development of a solder paste without voiding at soldering.

Voiding is caused by the outgassing from interior of solder joint when the solder is at molten state. During reflow, the outgassing forms "bubbles" in the molten solder. Upon solidification, the bubbles are frozen as voids [6]. The bubbles intermittently form and then pop open when the bubbles either grow too large or migrate to the edge of joint. Hence it is the outgassing rate at temperature above the melting temperature of solder which dictates the voiding behavior, not the accumulated outgassing quantity.

The void content decreases with increasing flux activity and solderability [6]. Since higher flux activity supposedly will generate more fluxing reaction products therefore more outgassing, the lower void content associated with higher fluxing activity suggests a smaller amount of entrapped flux.

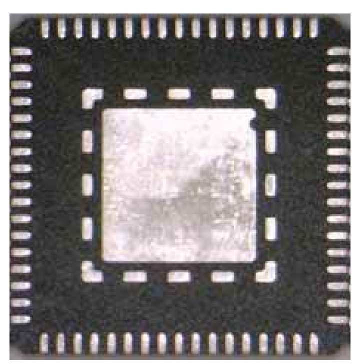

Figure 1. QFN component

When using a solder paste, the flux is in direct contact with the surface oxide of powders and surface-to-be-soldered. Hence at reflow any residual oxide is expected to be accompanied by some adhered flux. Considering that a higher activity flux usually removes the oxide more rapidly and completely, thereby leaving fewer spots for the flux to adhere to, a lower voiding caused by less flux entrapment becomes the logical outcome. The same explanation is applicable to the components or pad surface.

So in order to produce a low voiding flux, one can decrease the outgassing and increase flux activity. Regarding the outgassing, a higher boiling has been reported to exhibit a lower voiding, and has been explained by viscosity dictated flux-exclusion-rate model [7]. The fluxes drying out more readily will result in a flux remnant with a higher viscosity. It was explained that the higher viscosity remnant will have a greater difficulty to be excluded from the interior of the molten solder, therefore will have more chance to be entrapped in the molten solder and serve as an outgassing source, hence contribute more to the voiding. In other words, the solvent volatility affects voiding through the viscosity factor instead of direct solvent outgassing.

When designing the flux system for low voiding, the government regulation is another important constraint. The environmental consideration has driven the electronic industry away from the use of lead, and certain types of halogen compound at soldering. Disposal of hazardous waste cleaning water is another cost burden, and no-clean type of soldering process becomes a favorite choice of options. With all those factors being considered in the designing, a new halogen-free no clean lead-free solder paste, 44-29-3, has been developed, with emphasis on low voiding. The performance assessment, including the wetting, voiding, solder beading, slump and solder ball are presented and discussed below.

Table 1. Characteristics of solder pastes evaluated.

Flux	Characteristics	Metal load
A	Halogenated, no-clean	SAC305 T4 88.5%
B	Halogenated, no-clean	SAC305 T4 88.5%
C	Halogen-free, no-clean	SAC305 T4 88.75%
D	Halogenated, no-clean	SAC305 T4 88.5%
E	Halogen-free, no-clean	SAC305 T4 88.5%
44-29-3	Halogen-free, no-clean	SAC305 T4 88.5%

EXPERIMENTAL

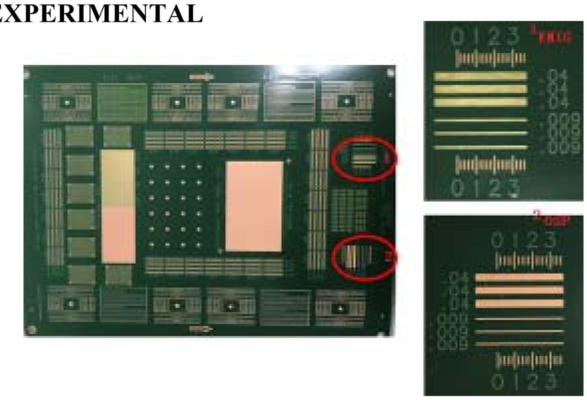

Figure 2. Test board used for wetting test

1. Materials

Six solder pastes were tested, including the newly developed halogen-free no-clean lead-free solder paste 44-29-3 and five conventional solder pastes as controls. The characteristics of those six solder pastes are shown in Table 1. All solder pastes employed 96.5Sn3.0Ag0.5Cu (SAC305), type 4 (20-37 microns) solder powder. Pastes A to E are commercially available materials.

2. Wetting Test

The test board is shown in Figure 2. The red circled areas 1, 2 are used for evaluating the wetting performance, with surface finish of area 1 being ENIG, and of area 2 being OSP. The stencil thickness is 0.12 mm (5 mil). Each paste was printed onto the test board and then sent through a BTU forced air convection reflow oven under air atmosphere with reflow profile shown in Figure 3. The reflowed coupon was then examined for wetting behavior.

3. Voiding and Graping Test

Figure 3. Reflow profile used for paste wetting test.

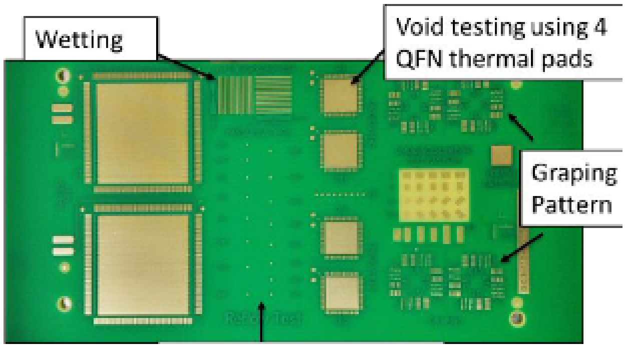

Figure 4. Picture of test board with QFN thermal pads.

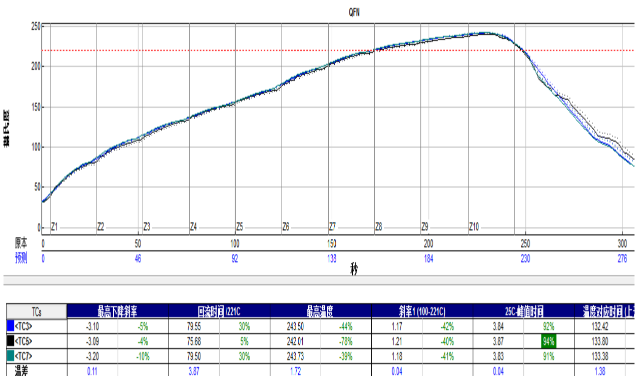

Figure 5. Reflow profile used for QFN voiding and graping test.

The test board with QFN thermal pads [8] and immersion Sn surface finish shown in Figure 4 was used for voiding and graping test. The test procedure is described below:

1) Place the test board onto printer.
2) Print the paste onto the test board using DEK printer, using stencil with a thickness 5 mil (125µ).
3) Place 4 dummy QFN components per board onto the paste
4) Send the populated board through BTU oven with profile shown in Figure 5 and air reflow atmosphere
5) Examine the voiding with X-ray inspection equipment
6) Examine the graping and slump with optical microscope. The details of the pad pattern used for graping test is shown in Figure 6.

4. Solder Ball Test

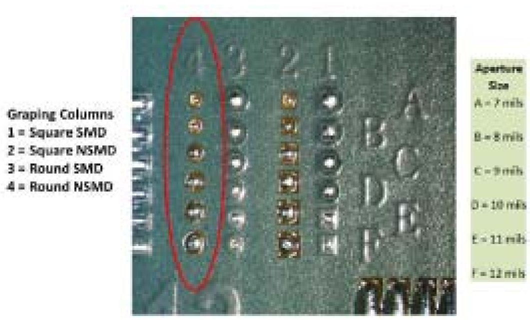

Figure 6. Details of graping pattern after reflow

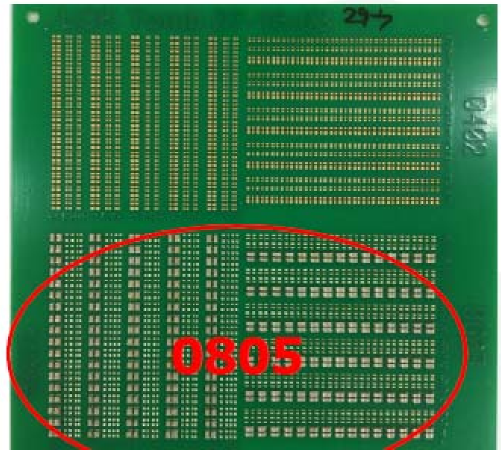

Figure 7. The test board used for solder beading test.

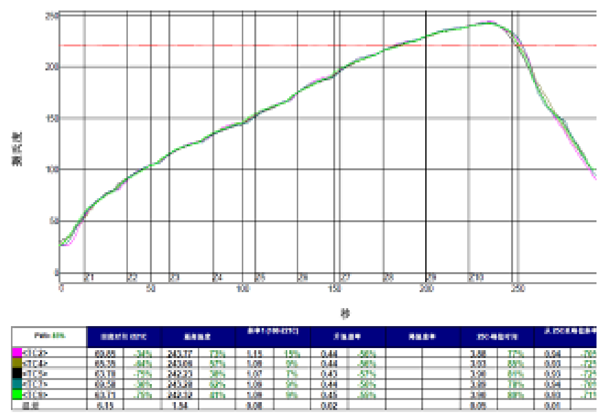

Figure 8. Reflow profile used for solder beading test.

Use a three-hole stencil, with hole diameter of 6.35 mm (0.25 inch), and thickness of 0.125 mm (5 mil). Print each paste onto a ceramic coupon, then sent through BTU reflow oven with reflow profile shown in Figure 3 under air atmosphere, inspect the coupon and count the solder balls.

5. Solder Beading Test

1) Print solder paste using 5mil (125µ) thick stencil
2) Place 0805 chip capacitor by pick & place equipment (360 capacitors assembled for each test board, see Figure 7)
3) Reflow test board in BTU oven using reflow profile as below (see Figure 8)
4) Evaluate the solder beading performance under optical microscope.

6. Hot Slump Test

1). Print test coupons using the 4 mil (100µ) IPC slump stencil. Design is shown in Figure 9 (left).
2). Select the valid prints and place the test coupons in an oven set at 180°C for 10min.

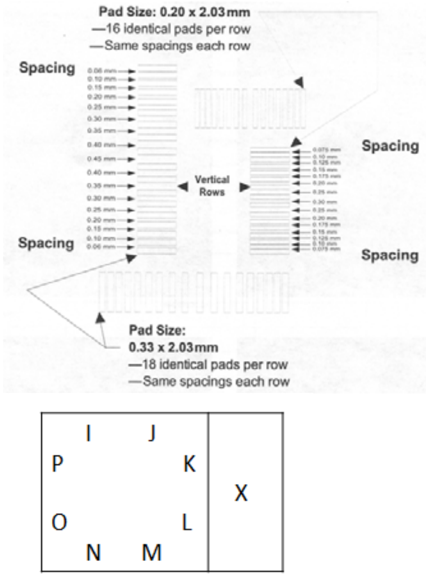

Figure 9. Slump test stencil thickness 0.1mm (left) the slump data chart (right)

I :number of bridges on the left side of the top horizontal row

J :number of bridges on the right side of the top horizontal row

k :number of bridges on the top of the right side vertical column

L :number of bridges on the bottom of the right side vertical column

M :number of bridges on the right side of the bottom horizontal row

N: number of bridges on the left side of the bottom horizontal row

O: number of bridges on the bottom of the left side vertical column

P: number of bridges on the top of the left side vertical column

X: total number of bridges

3). Using the optical microscope to determine the amount of bridging among the 8 sections of solder deposits.
4). Organize the data in the Figure 9 (right)

RESULTS

1. **Wetting**

On OSP, the wetting behavior of those pastes can be differentiated. Figure 10 (left) shows the solder spread appearance on OSP. The pastes B, C, D, E and 44-29-3 showed good wetting, all pastes can spread to the ruler mark of zero, except A showed dewetting on wide rulers. The wetting length data when compared against the ruler is

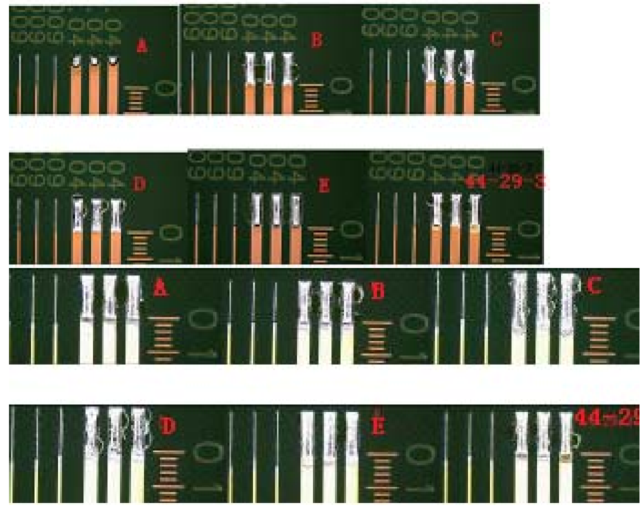

Figure 10. Wetting of solder pastes under air on OSP (left) and ENIG (right)

shown in Table 2. On ENIG, all the six pastes wetted well, with paste C a little better and covered up to 0.4 mark. Paste 44-29-3 is similar to paste A, B, and E, and slightly less than paste D. Thus the wetting of paste 44-29-3 on OSP and ENIG is very competitive among commercially pastes.

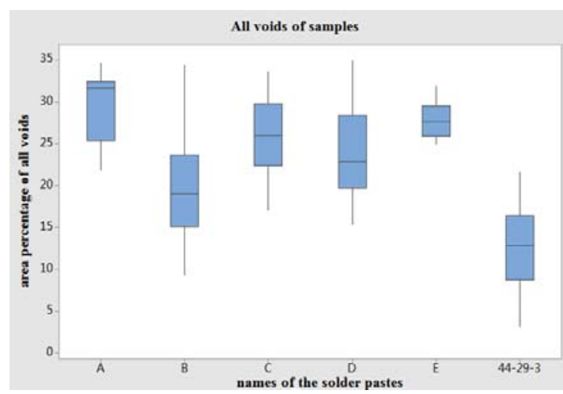

Figure 11. The chart of all voiding performance of the samples (area %)

2. **Voiding**

The voiding performance of each paste is shown in Table 3. The halogen-free paste 44-29-3 exhibits the lowest Total Voids, almost half of the void content of the second lowest voiding paste B, which is halogenated.

Table 2. Spread length (marker scale reading) of paste on different surface finishes

	A	B	C	D	E	44-29-3
OSP	<0	0	0	0	0	0
ENIG	0	0	0.4	0.1	0	0

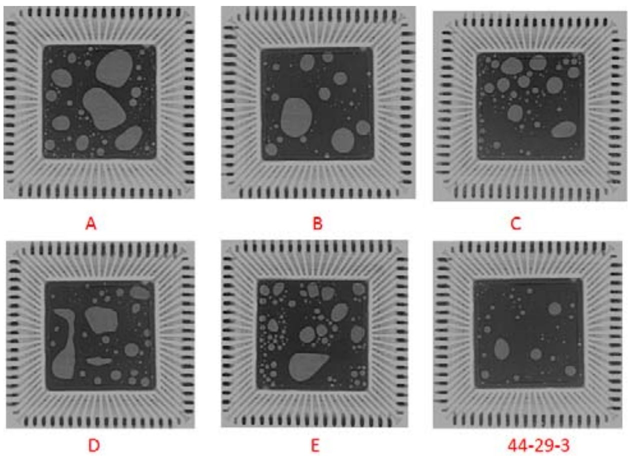

Figure 12. Example of voids for each paste measured by X-ray machine

Table 3. Voiding performance (area %) of various solder pastes

No.	Largest void (%)	SD	Total voids (%)	SD
A	9	2	30	4
B	7	2	20	6
C	6	1	25	3
D	11	2	24	6
E	7	1	28	2
44-29-3	7	2	12.7	5

Note: the largest void is the largest void among all the test coupons, and the data all voids is the average of all test coupons

All other pastes are quite higher in voiding. The same conclusion can be seen from Figure 11 directly. Paste 44-29-3 is also near the lowest on the "Largest void" ranking. Figure 12 shows the X-ray image of the QFN joint of solder pastes. Paste 44-29-3 exhibits an outstandingly low voiding behavior among all pastes tested.

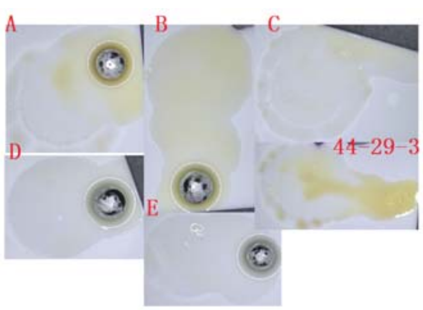

Figure 13. Picture of solder balls around the paste deposits on ceramic coupon

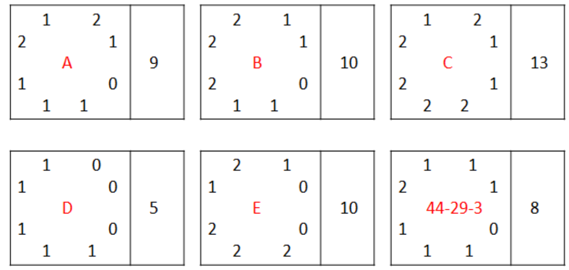

Figure 14. The chart of the slump performance

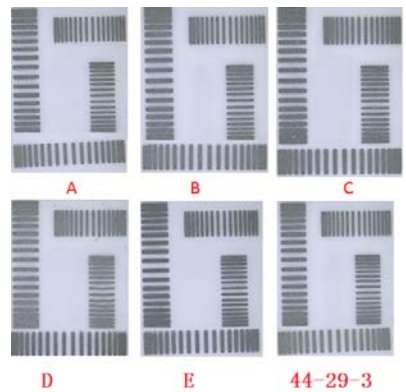

Figure 15. The picture of the hot slump samples after 10 minutes at 180°C.

3. Solder Ball

Table 4 shows the total number of solder balls within the flux residue of the 3 solder deposits for each solder paste. Paste B and E are the lowest in solder balling, followed by 44-29-3 and D, with A and E being the highest in solder ball counts. The appearance of the solder deposits after reflow is shown in Figure 13. Picture size varied with the residue area size. All solder pastes met the solder balling requirement of J-STD-005.

4. Hot slump

Figure 14 shows the slump performance of the studied pastes. Paste D is the best in slump resistance, only 5 bridges in total happened. Paste 44-29-3 is the second best one, with a total number of bridges 8, slightly more than D. Paste C is the poorest one on slump resistance, exhibited 13 bridges. The pictures of the actual samples after 180°C for 10 minutes are shown in Figure 15. Except for sample C, all pastes performed acceptably for hot slump resistance.

5. Graping

Graping is determined by counting the total number of solder dorms showing graping in four sets of the graping patterns. Each graping pattern has 96 solder deposits which results in a total of 384 possible graping solder dorms when 4 sets are used. The results are shown in Table 5. Figure 16 displays the propensity of graping for each solder paste by showing the solder dorms at the same location for each paste. The graping

Table 4. Solder balls of various solder pastes on Ceramic Coupon with 3 deposits

	A	B	C	D	E	44-29-3
Number	>20	<10	>20	10~20	<10	10~20

Table 5. Graping occurrence rate (%) of the solder pastes with 384 solder dorms examined for each paste.

	A	B	C	D	E	44-29-3
Graping (%)	35	22	9.4	44.5	18.7	27

Table 6. Solder beading performance of various solder pastes.

	A	B	C	D	E	44-29-3
Number	108	37	108	4	57	6
Percent	30%	10%	30%	1.1%	16%	1.7%

Note: Stencil thickness is 5mil, with 360 chip capacitor 0805 tested for each paste

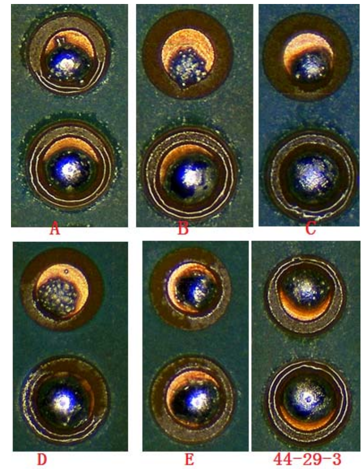

Figure 16. The picture of graping performance of all pastes.

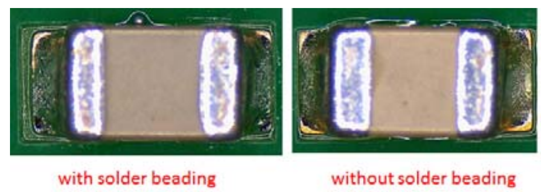

Figure 17. Example of chips with (left) and without (right) solder beads

resistance of paste 44-29-3 is ranked in the middle among all pastes tested.

6. Solder Beading

Among the paste A, B, C, D, and E which have been used widely in industry, D is the best paste in solder beading performance, with only 1.1% solder beading observed. Under the same test condition, 44-29-3 has almost the same performance as D, with less than 2% solder beading rate, as shown in Table 6. Figure 17 shows example of picture with or without solder beads by the side of chip.

SUMMARY

The results of all solder pastes on all tests are shown in Table 7. The acceptable performance is highlighted in green, while that unacceptable is in red. Solder paste 44-29-3 is the best in low-voiding performance, and is the only one met all the requirements among all pastes tested.

CONCLUSION

The miniaturization trend is driving industry to adopting low standoff components, including components with large pads. This resulted in large voids, and consequently jeopardized the reliability of devices. While board design and process adjustment may alleviate the voiding challenge somewhat, an intrinsically voiding-free solder paste will be the most desirable solution. With the elucidation of voiding mechanisms and a deep understanding of the material factors contributing to the voiding, a new halogen-free, lead-free, and no-clean solder paste 44-29-3 was developed. The test results showed this paste was significantly lower in voiding than any other solder pastes tested in this study. It also exhibited nearly none solder beading, and very acceptable performance on non-slump, wetting on OSP and ENIG under air, solder balling, and graping.

Table 7. Summary of solder paste performance

Paste	Halogen	Wetting (air)		Solder beading	Voiding	Slump	Solder ball	Graping
		OSP	ENIG					
A	Y	Poor	OK	30%	30	9	>20	35%
B	Y	OK	OK	10%	20	10	<10	22%
C	N	OK	OK	30%	25	13	>20	9.4%
D	Y	OK	OK	1.1%	24	5	10~20	44.5%
E	N	OK	OK	16%	28	10	<10	18.7%
44-29-3	N	OK	OK	1.7%	12.7	8	10~20	27%

Legend: good; unacceptable

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