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WP3100: Technical Note 1 Part 1 (Version 1.0)

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1 Behaviour of fuses in parallel

The behaviour of fuses in parallel is depending on various factors. These factors and dependencies are being explained hereafter.

1.1 Discussion about fair current split in parallel

In an ideal environment the entity of the current I_N flows in equal parts through the fuses set in parallel. In reality every fuse is different. This means every fuse has a different internal resistance and voltage drop due to variation of the manufacturing process. Therefore almost identical fuses have to be selected for this application.

Principle of this application e.g. with 4 fuses in parallel

$$I_N = I_{F1} + I_{F2} + I_{F3} + I_{F4}$$

$$U_F = I_N \cdot 1/(1/r_{F1} + 1/r_{F2} + 1/r_{F3} + 1/r_{F4})$$

Equivalent AC circuit diagram for a circuit with 4 fuses in parallel:

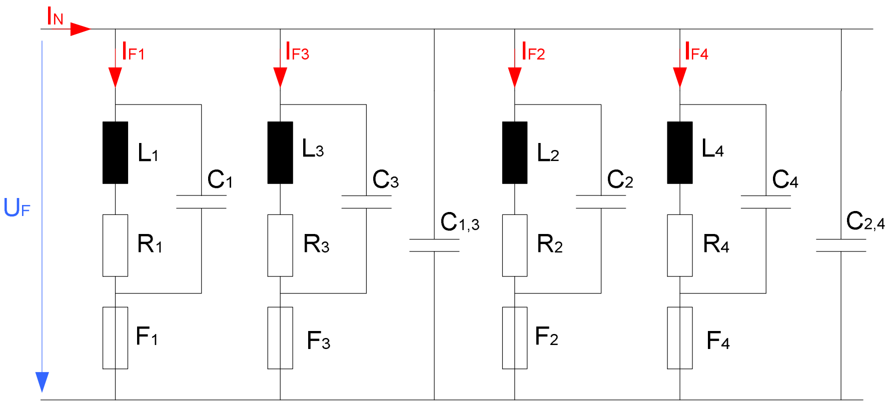

Figure 1: Schematic diagram for four fuses in parallel

The capacities of the circuit tracks on the print board are being shown schematically with $C_{1,3}$ and $C_{2,4}$. Further details of the print board layout are shown in chapter 3. As the layer thickness of the circuit tracks is very thin (35µm) and the distance between the various tracks in the millimetre range the capacities are very small.

$$C = C_{1,3} + C_{2,4} = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{(A_1 + A_2)}{d} \approx 0.2\,pF$$

$$C_{1,\min} = C_{2,\min} = C_{3,\min} = C_{4,\min} = 0.1\,fF$$

$$C_{1,\max} = C_{2,\max} = C_{3,\max} = C_{4,\max} = 120\,fF$$

Depending on the mounting orientation the value of C_n varies in between 0.1fF and 120fF. Reason for that is the position of the melting wire that is due to constructional reasons not in the centre of the housing.
The inductivities can be neglected as the dimensions of the MGA-S are very small.

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1.2 Discussion about thermal behaviour

The heat exchange happens only through the base material and the thermal radiation. Under the assumption that there are everywhere identical circumstances, no gas flows or otherwise the application is in vacuum the convection can be neglected.
In general heat has the main influence on the application so the aging is accelerated. That is the reason why the reliability of the parallel setting is becoming lower.

These are the factors ordered according to their importance:

1. Conduction through the base material, mainly through the circuit track
2. Thermal radiation
3. (Convection)

Principle of the heat flow:

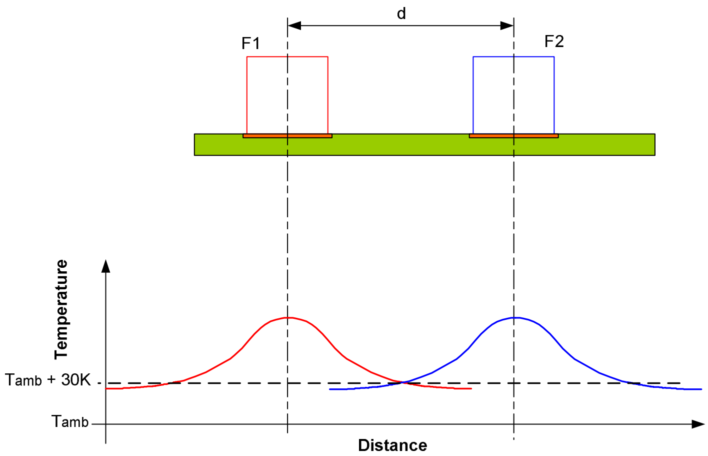
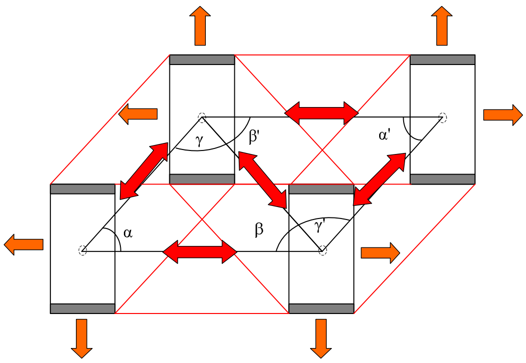


Figure 2: Heat flow between two fuses

Thermal radiation balance:



$$P = P_{F2} + P_{F3} + ... + P_{Fn}$$

$$P_{F1} = P_{F1} = ... = P_{Fn}$$

Figure 3: A fair configuration for four fuses

Thermal decoupling hinders any unwanted heating of the system. Schurter has elaborated and tested a fuse layout that allows minimal coupling in combination with space saving. This layout also helps to have an even thermal radiation exchange in between the fuses of the system. The middle thermal radiation at nominal rating and ambient temperature of 25°C of the MGA-S 3.5A is 6.7mW. In the case that two identical fuses are next to each other in the same alignment, the transmitting and absorbing performance is 1.5mW for each fuse. With three fuses in parallel the middle fuse absorbs 3mW whereas the outer two fuses just absorb half. Therefore this is a thermic imbalance and the application is not in balance.

Worked sample: Thermal radiation at nominal rating and ambient temperature of 25°C of the MGA-S 3.5A
Basic formula for the calculation of net power:

$$P = \varepsilon \cdot \sigma \cdot A \cdot (T_{Operation}^4 - T_{ambient}^4)$$

The MGA-S surface consists of two materials, with a relative partition of ceramics of 66% and tinned terminal contacts of 34%.

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Absolute value of the MGA-S surface AMGA-S			27mm2
Emission factor	Ceramic housing εk		0.85
	2 Tin terminals εsn		0.25
Stefan Boltzmann constant σ			5.678E-8 Wm-2K-4
Ambient air temperature Tamp		=	298.15K (25°C)
Max. Operation temperature on the fuse surface TOp		=	348.15K (75°C)

$$P_{MGA-S\max} = (0.66 \cdot \varepsilon_K + 0.34 \cdot \varepsilon_{Sn}) \cdot \left[A_{MGA-S} \cdot \sigma \cdot (T_{Op}^4 - T_{amp}^4)\right]$$

$$P_{MGA-S\max} = 6.7mW$$

1.3 Breaking capacity @ AC

The maximal short circuit current can be multiplied by the number of fuses in parallel. In case of two fuses in parallel the short circuit current doubles whereas with three fuses in parallel the value is threefold the value of a single fuse (50A @ 63VAC).

Quantity of MGA-S fuses in parallel	AC Voltage	Over Current in Ampere
2	63	**100**
3	63	**150**
4	63	**200**
5	63	**250**

Figure 4: AC Breaking capacity

The behaviour of the system with DC (discrete current) has to be tested first. Similar results are being expected.

1.4 Reliability of fuses in parallel

Regarding the reliability the system works as a series connection as the failure of a single fuse makes the entire system fail. The parallel setting is only working if all fuses are in function. Not until five MGA-S 3.5A fuses in parallel the total failure of the system can be prevented for a short period. Please refer to the chart in chapter 1.5. of time.

Reliability principle:

Figure 5: Series connection

1.4.1 Behaviour of fuses in parallel at constant failure rate

We are looking at a system where the failure rate is considered as constant. The picture shows n fuses in parallel. Moreover the system is considered not to have any dependencies in between the fuses what is in reality never the case.

1.4.2 Assumption for calculation

Consideration of the **useful operation life time UOL** at constant failure rate λ: 1FIT = 1 failure per 10^9 hours. Λ is heavily depending on environmental conditions (temperature, cosmic radiation in space, vacuum, etc.).

According to the Poisson process the reliability of n fuses in parallel shows that after the operation time t no fuse fails and therefore the system remains intact:

$$R_n(t) = (e^{-\lambda * t})^n$$

The Reliability of one up to 5 fuses in parallel versus time in years as follows:

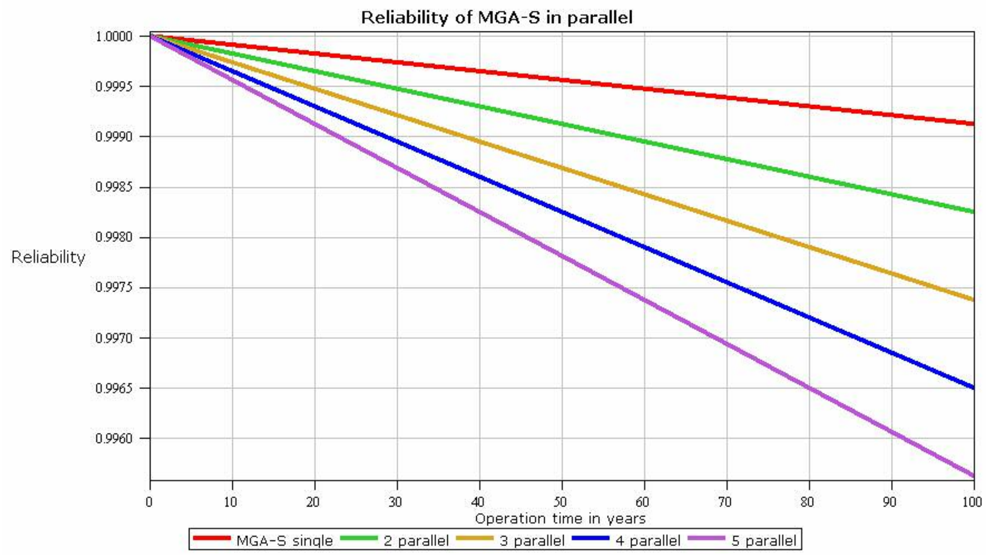

Figure 6: Reliability of the MGA-S at 1 FIT

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1.4.2.1 Failure rate λ

The failure rate is considered as probability measure for the failure of the parallel circuit. The total failure rate is depending on the number of fuses and is calculated as follows:

$$\lambda_n = \sum_{i=1}^{n} \lambda_i$$

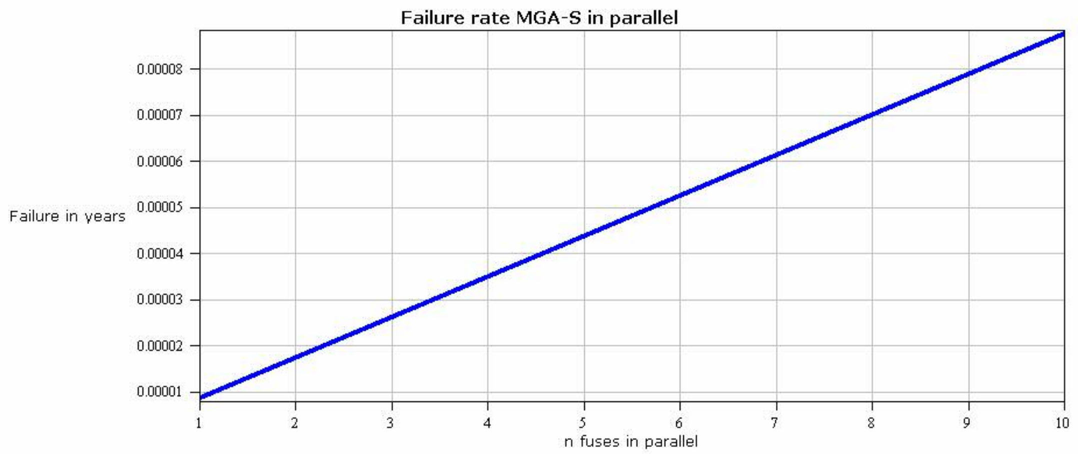

Figure 7: Failure rate at 1 FIT

1.4.2.2 MTTF (mean time to failure)

The average lifetime of the system is depending on the number of fuses and is calculated as follows:

$$MTTF = g(n) = \frac{1}{\sum_{i=1}^{n} \lambda_n}$$

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The average lifetime in connection of one up to ten fuses in parallel is as follows:

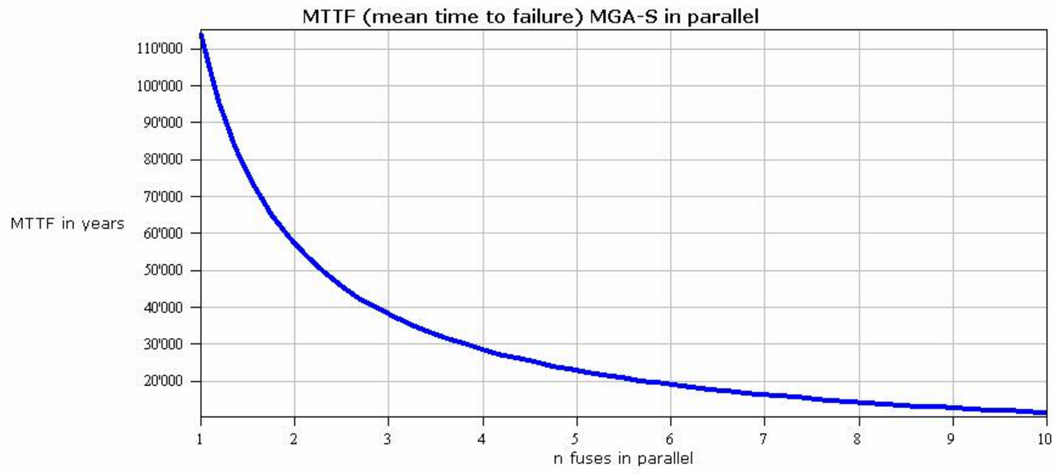

Figure 8: MTTF at 1 FIT

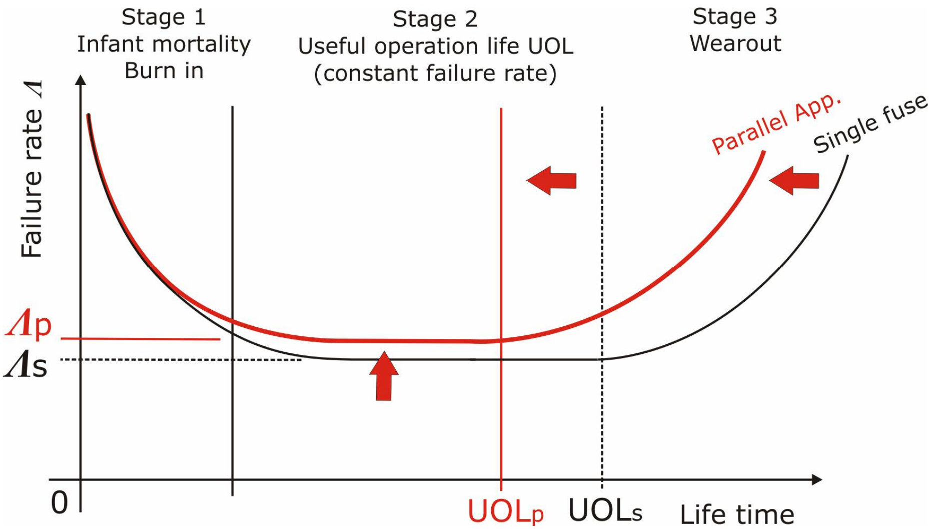

Figure 9: Failure rate at useful operation life UOL

1.4.3 Conclusion

1. The reliability of the parallel setting is becoming lower with the number of fuses.
2. The most impact on the reliability of the parallel setting has the fuse with the lowest reliability.

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1.5 Overcurrent split at variable fuses in parallel application

In case of a failure of one of the fuses in a parallel setting the corresponding current of that fuse is being distributed to the remaining fuses in the system. Should the rated current already be 3.5A this failure of a single fuse leads to an overload of the entire system. Consequently all the remaining fuses are being overloaded. The effects on the life-span of this new system are depending on the current, the aging of the components and the number of fuses in parallel. In the worst case a chain reaction is possible in correlation of the increasing current distribution.

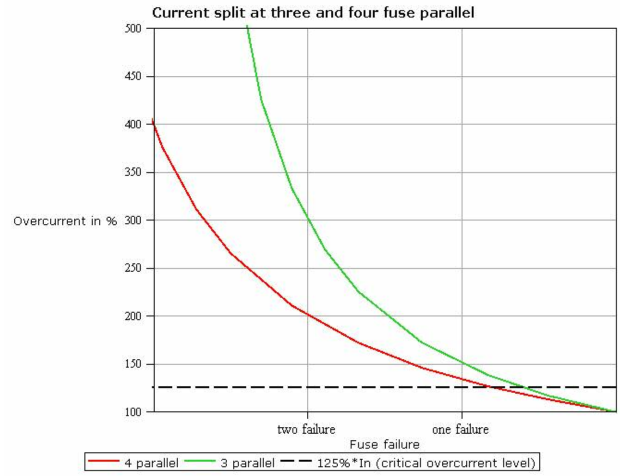

Figure 10: Current split 3 and 4 fuses in parallel

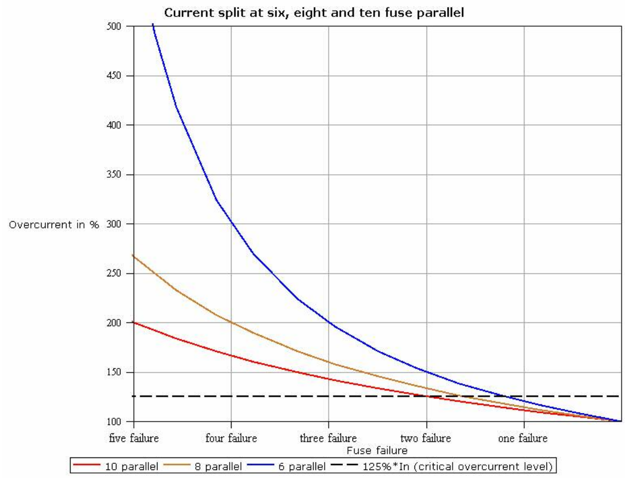

Figure 11: Current split 6, 8 and 10 fuses in parallel

1.6 Advantage and risk analysis

1.6.1 Advantage with MGA-S fuses in parallel

- The MGA-S is a well known fuse for space application.
- There are low engineering costs in order to protect systems with currents over 3.5A
- The costs of the additional equipment maybe lower than a new development of a fuse.
- The AC breaking capacity is depending on the number of fuses in parallel.
- (Failure at >= 5 fuses in parallel may not lead to the failure of the entire system as the remaining current can be absorbed by the other fuses).

1.6.2 Risks with fuses in parallel

- The reliability across the operating life time of the system (parallel setting) is decreasing as the failure rate of the parallel setting is depending on the number of fuses.
- Because of thermo coupling of the fuses, there must be kept a minimum distance between the fuses.
- The breaking characteristic of the fuses in parallel is not linear transformable to the single MGA-S fuse. The parallel application has a shorter breaking time at high over current.
- Fuses in parallel need more PCB space
- Selection process: The manufacturing yield is decreasing with the number of fuses as the cold resistance and voltage drop values should not exceed 2% tolerance.

2 Requirements for fuses in parallel

The following requirements for fuses in parallel are necessary:

- Only MGA-S fuses with identical rating can be used.
- All parallel fuses should be out of the same manufacturing batch.
- The cold resistance and voltage drop difference of the parallel fuses must be within two percent.
- Fuses with a higher cold resistance value (still within specification) have high power dissipation. Therefore these fuses should not be used for parallel settings.
- The parallel fuse sets need to be defined and selected by the manufacturer.
- The manufacturer defines the optimal fuse layout (Setting of fuses).
- (Optional) With consideration of the mounting orientation of the fuses the robustness of the system in case of a short circuit can be improved and stabilised.

3 Design for 2, 3, 4 and 5 MGA-S in parallel

The fuse layout is very important. With loads exceeding 70% of the rated current and the wrong fuse layout the power dissipation cannot be absorbed. This will lead to a high local temperature load of the base material and can damaging the PCB. Due to the low melting point of the solder this may lead to the destruction of the circuit tracks. This circuit tracks layout for more than two fuses can be a very demanding task for an engineer as the correct dimension of the in- and outgoing current feed is essential. Therefore the optimal fuse setting layout must be designed by the manufacturer. This should be a part of the ESCC- qualification as the layout is an integral part of the product. The setting of two up to five fuses in parallel are listed below, all based on extensive tests.

3.1 Fuse- Layout for two, three, four and five fuses in parallel

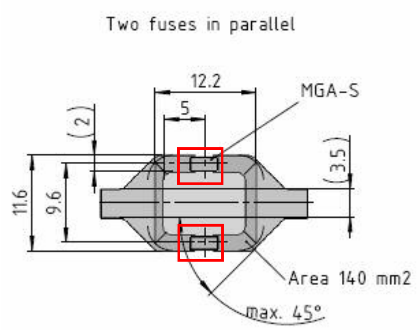

Figure 12: Two fuses in parallel

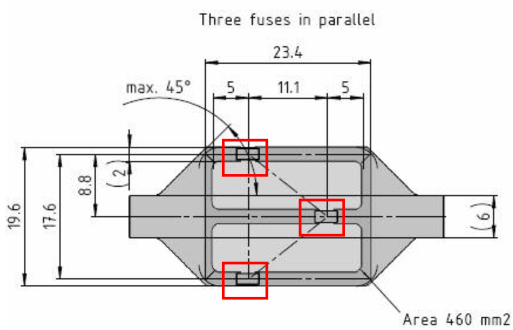

Figure 13: Three fuses in parallel

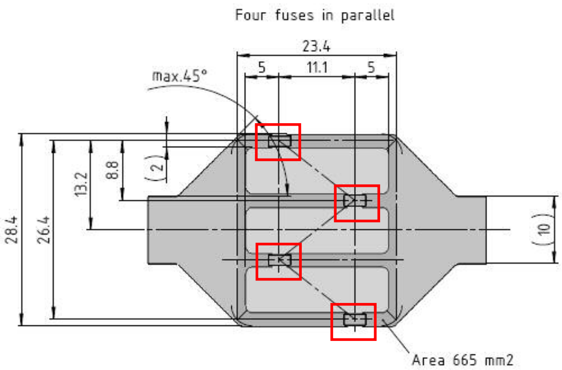

Figure 14: Four fuses in parallel

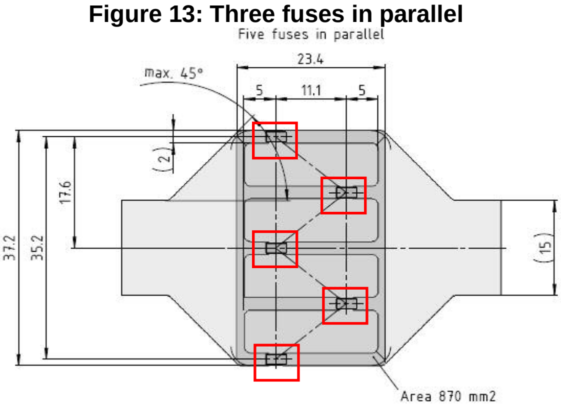

Figure 15: Five fuses in parallel

Fuse layout for circuit track with 35um copper-clad according to Schurter drawing no. 0906.2168.

4 Package for fuses in parallel

Each fuse set is proposed as a package with a unique part number. In the blister tape each package is put next to each other with at least one open position in order to separate more than one package. The corresponding fuse layout belongs to the package and is attached to the basic documents.

Rated current in A	Quantity of fuses in parallel	Rated voltage VAC/VDC	ESCC Component Number	Schurter Part Number
7	2	32 / 125	to be defined	to be defined
10.5	3	32 / 125	to be defined	to be defined
14	4	32 / 125	to be defined	to be defined
17.5	5	32 / 125	to be defined	to be defined

5 Fuse selection method

We prefer to match the fuse package by using the regression line, which helps to define similar fuses in a package for two, three, four and five fuses in parallel. Each batch has to generate a new regression line.

5.1 Regression line

$$f_{reg}(x) = a \cdot \left(x - \overline{x}\right) + \overline{y}$$

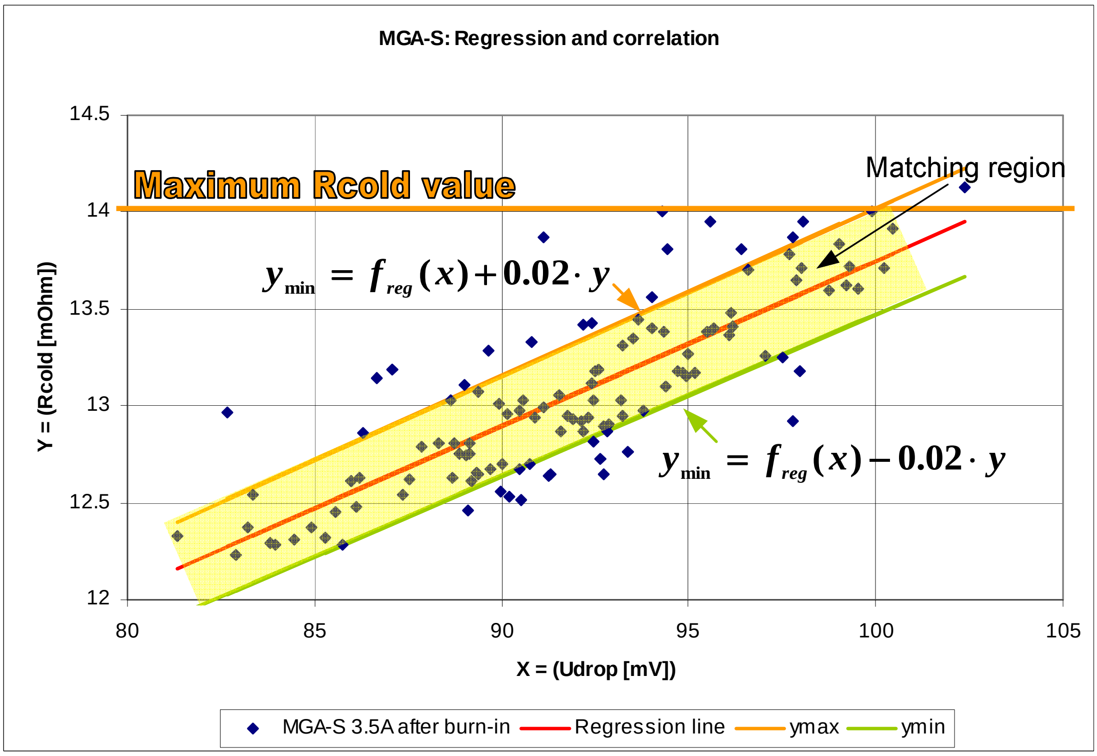

Figure 16: Selection method

65% to 75% of the fuses are located in the matching region.

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The following table represents the yield for the parallel selection by different quantities of fuses:

Quantity of fuses in a package	Max. Yield in % of the matching region
2	95
3	63
4	44
5	27

6 Tool and process list

6.1 Tool list

- Board for fuse set: After the selection of fuse sets they should be put in special loading devices in order to separate them clearly from each other.
- Power supply for over current tests: Manufacturing is not equipped to perform a complete electrical testing of these sets. New power supplies / current sources for currents exceeding 100A are necessary.
- Test boards: Test boards for all fuse sets for electrical testing.
- Cold resistance and voltage drop measurements can be performed with the existing equipment.
- (Optional) Should the orientation of the fuse element into the fuses be taken in account further equipments are necessary (Analyser for frequency spectrum and X-Ray).

6.2 Process list

All additional procedures take place right after the electrical-burn-in (Chart F3).

- New tape and reel process
- Quality documents showing the single values of the fuse sets.
- Fuse- Layout document
- (Optional) With the orientation of the fuse: The position of the melting wire in the housing needs to be clear before the fuse is being labelled. This will enable the customer to verify the correct mounting orientation.

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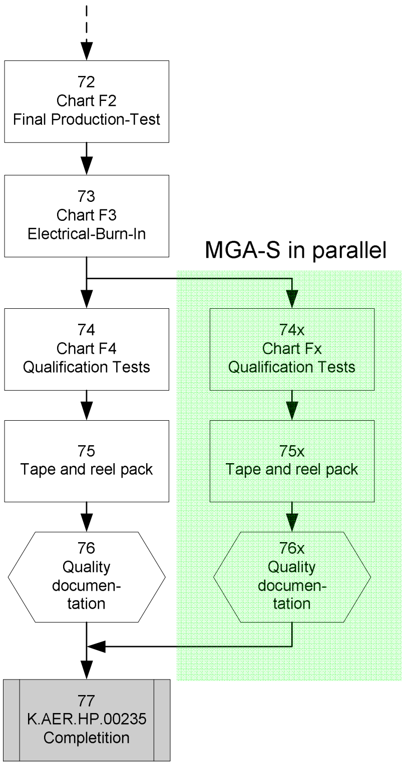

Figure 17: New process for MGA-S parallel

7 Summary

Setting fuses in parallel requires additional selection and testing for the manufacturing process. Only fuses with identical rating and type can be used. The cold resistance and voltage drop values of these fuses have to be within 2%. As an option the mounting orientation of the fuse may be taken in account.

For the selection and testing various methods as capacity testing or x-ray of the fuses are possible, all with various costs. With the electrical and burn in test the early failures are being detected and thus the failure rating minimised. Any further tests of the parallel set up are not necessary.

The reliability of the parallel fuse sets is considered as a series connection. The more fuses are used in parallel the lower the average live span expectancy. A failure of a single fuse can result in a failure of the entire parallel fuse package.

Chapter 3 shows the optimised layouts for two up to five fuses in parallel. This set up reduces the thermo couplings to a minimum. This parallel setting requires additional testing and selection procedures that make the final fuse packages more expensive. Furthermore the yield per batch is lower as for single fuses.