# Circuit protection solutions for space application

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## INTRODUCTION

The aim of this article is to outline the performance of the ESA ESCC qualified fuses from SCHURTER AG; how these innovative parts fit the needs for space and how the best fitting fuse can be chosen for customer specific application. Since the space industry is developing highly integrated applications with new functionality and higher power ratings, different circuit protection solutions are required to deal with these needs. Safe high current management, system availability, accurate protection functionality and safety requirements are only a few of many required properties.

## SCHURTER SPACE FUSES AT A GLANCE

With the established and ESA ESCC qualified space fuse called MGA-S (MGA Space) and the new qualified space fuse called HCSF (High Current Space Fuse), SCHURTER AG covers nominal current protection requirements for space application from 0.14 A up to 15 A or even more, if they are set in parallel. Both fuse types are sealed, based on solid state thin film technology and comply with the strict requirements of aerospace.

Table 1: Overview SCHURTER ESCC qualified fuses, as in [1], [2] and [3]

| **Product** | **MGA-S** | **HCSF** |
|---|---|---|
| ESCC Component No. | 400800101-400800112 | 400800224-400800236 |
| Fuse Acting | Very fast | Fast |
| Rated Current Range | 0.14 A – 3.5 A | 5 A – 15 A |
| Rated Voltage | 125 VDC | 125 VDC |
| Breaking Capacity | 300 A | 1000 A |
| Mounting + Size | SMD 1206 | SMD 3220 |
| Basic Failure Rate | < 1 FIT | < 1 FIT |

## TRENDS ON CIRCUIT PROTECTION

Since decades, telecommunication and navigation satellite applications drive the satellite market. In the last few years new requirements and topics like earth observation and global network communication are creating new markets in space application. These trends have an observable impact to the electronic requirements and of course on the circuit protection devices such as fuses. Table 2 gives a quick overview and shows the consequences on circuit protection requirements.

Table 2: Trends on circuit protection

| **Trend** | **Consequence on circuit protection requirements** |
|---|---|
| High electrical power | Circuit protection device deal with even higher currents and high voltages – higher rated current and rated voltage, high breaking capacity |
| High integrated electronic system | SMD, small in size, low power dissipation |
| New functionalities | Customer specific fuse characteristic, current pulse resistivity |
| Non-functional requirements | Availability, high reliability, space qualified (ESCC 4008), additional long term data requested |
| Decreasing development time | Accurate and easy applicable Spice Model of the fuses |

## INTERMEDIATE OR HIGH RATED CURRENT - FUSES IN PARALLEL APPLICATION

The use of fuses in parallel is an easy way to get higher rated currents above the level of the single fuse or if intermediate current ratings are required. In particular, the MGA (commercial fuse variant) and the MGA-S have been applied in sets of fuses for many times in high current applications. For having a reliable and well-fitting solution several important requirements have to be considered:

- Only fuses with identical rating can be matched.
- All parallel fuses should be out of the same manufacturing lot.
- The cold resistance and voltage drop differences of the parallel fuses must be within two percent.
- Fuses with a higher cold resistance value (still within specification) generate high power dissipation. Therefore, these fuses should not be used for parallel operations.
- Preferably the parallel fuse sets need to be defined and selected by the manufacturer.
- The manufacturer defines the optimal printed circuit board layout for the fuse set, design rules as in [7] and [8].

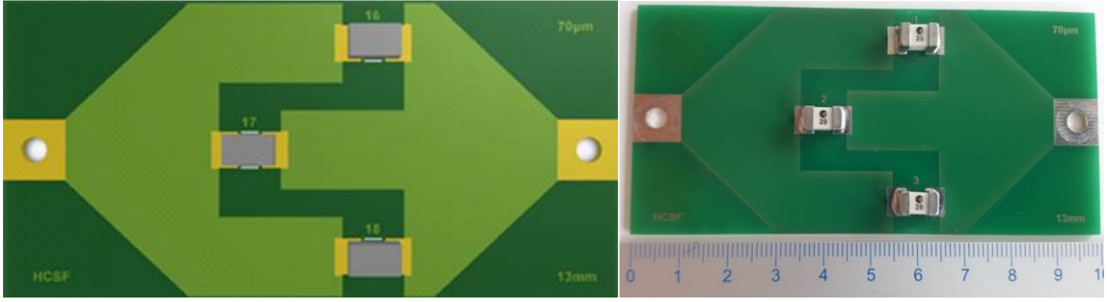

Fig. 1: PCB layout for 3 HCSF 10 A in parallel and characterisation test board, SCHURTER AG in March 2016

Some important facts:

- The resulting breaking capacity of a fuse set is defined by the breaking capacity of a single fuse – a conservative view if the interrupt event is usually absorbed by only one of the fuses.
- The reliability of the parallel fuse sets is approximately considered as a series connection. A failure of a single fuse can result in a failure of the entire fuse set.
- Fuses in parallel can increase the reliability of the protective system if the load current is much lower than the cumulated rated current of the fuse set.
- Fuses in parallel need much more PCB space than a single fuse because overlapped heat sources caused by the fuses power dissipation have to be prevented. Otherwise hotspots on the PCB could have a strong influence on the fuses or on the circuit boards life time.

Parallel sets of HCSF fuses enables high current ratings up to 60 A or even higher.

Table 3: High rated current fuse sets

| **Rated current** | **Rated voltage** | **Fuse set configuration** | **Total basic failure rate of the fuse set** |
|---|---|---|---|
| | | | |
| 20 A | 125 VDC | 2 x HCSF 10 A | < 2 FIT |
| 30 A | 125 VDC | 3 x HCSF 10 A or 2 x HCSF 15 A | < 3 FIT |
| 40 A | 125 VDC | 4 x HCSF 10 A | < 4 FIT |
| 50 A | 125 VDC | 5 x HCSF 10 A | < 5 FIT |
| 60 A | 125 VDC | 6 x HCSF 10 A or 4 x HCSF 15 A | < 6 FIT |

## ENHANCED AVAILABILITY – SAFE-LIFE APPLICATION

The space fuses from SCHURTER AG are used in spacecrafts such as telecom satellites to protect sub- systems from incorrect electrical functioning. Usually fuses are classified as critical components even if they are used in case of the safety requirements. The intention of redundancy is to increase the reliability and availability of the spacecraft during the entire mission time, see Fig. 2. A fuse must not fail during this useful operation life time (UOL) because of wear out. Therefore different kind of safe-life designs are applied.

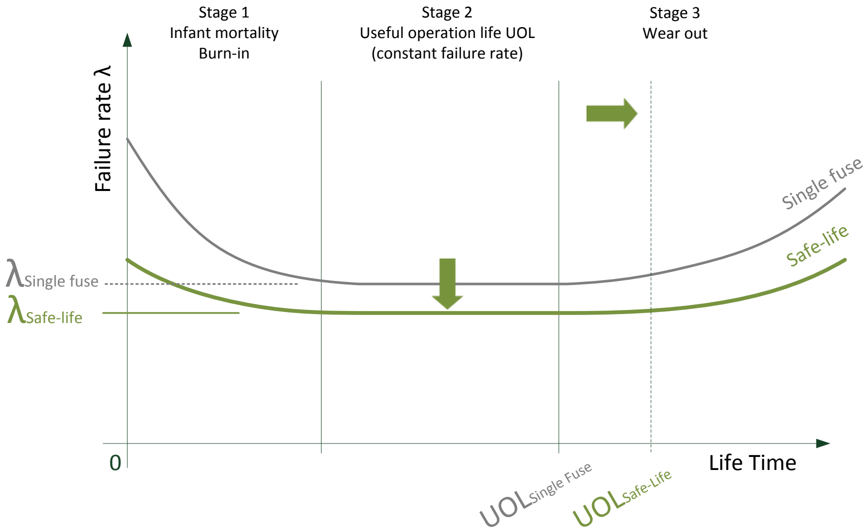

Fig. 2: Bathtub curve of a safe-life design

In many applications a back-up fuse – hot or warm redundancy – is integrated and takes over the protective function if the primary fuse fails. A major advantage of these variants are the interrupt free switchover if the primary fuse fail. In fact, if the system load does not shut down no significant voltage dip occurs.

### Hot redundancy

This variant is the most simplified option because only two similar fuses are set in parallel. Each fuse is designed to carry the load current. But at nominal operating condition each fuse carries only half of it.

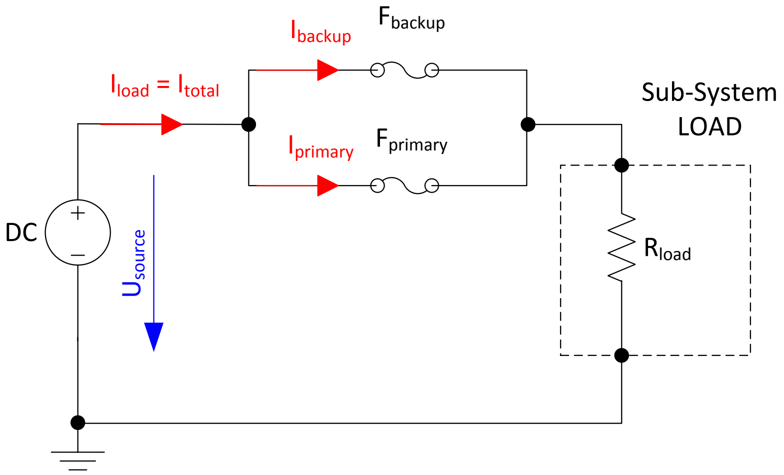

Figure 3: Simplified schematic hot redundancy

Facts and key figures:

- Hot redundancy is suitable for MGA-S and HCSF fuses.
- It works internally like a balancing system. Both fuses will be maintained from each other.
- Low power loss – total power loss is half of a single fuse's power loss
- The typical overload interrupt time of the system will be significant dissimilar compared to a single fuse. In particular, at low overcurrent conditions it works like a single fuse with the double current rating.
- The system's new typical $I^2t$ is approx. four times higher compare to a single fuse.

- Based on the basic FIT of SCHURTER space fuses and the formula (1) below the expected basic failure rate of the hot redundancy is < 0.5 FIT.

$$\lambda_{hot\ redundancy} = \frac{1}{\frac{1}{\lambda_{primary\ fuse}} + \frac{1}{\lambda_{back-up\ fuse}}} \tag{1}$$

**Warm redundancy**
This variant generally applies a current limiting resistor ($R_{back\text{-}up}$) in series to the back-up fuse. As a result, the overload operating characteristic is very similar to the one that a single fuse has because the primary fuse deals with the load current as long as this fuse is in good condition.

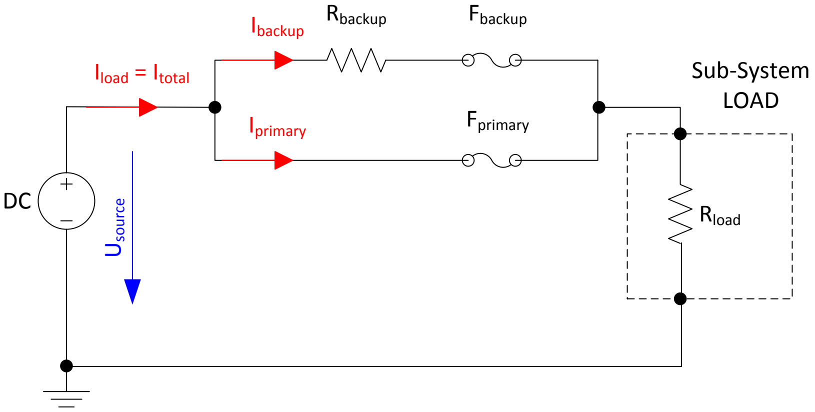

Figure 4: Simplified schematic warm redundancy

The function of a warm redundancy can be described as simple state machine as shown in Fig. 5. State A is to keep holding as long as no significant degradation, aging effects or even a failure occurs. At the time when the primary fuse fails the back-up fuse take over without interruption (State B).

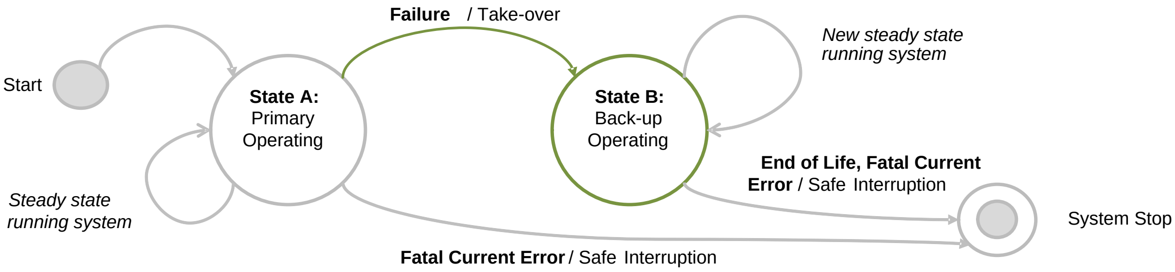

Fig. 5: State machine safe-life

The design limits of this variant is caused by the ohmic loss of the series resistor at back-up operation (State B). The figure below shows the power loss of the resistor depends on load current and their MGA-S related resistance. The resistance value is holding continually ten times bigger than the warm resistance of the best suitable MGA-S rated current type.

Fig. 6: Back-up operating series resistor based ohmic loss

Table 4: Statistic linear regression model

| **Parameter / Result** | **Value** |
|---|---|
| Number of observations | 7 |
| Error degrees of freedom | 5 |
| $R^2$ | 0.94 |
| Root mean square error | 0.0515 |
| F-statistic vs. constant model | 77.7 |
| p-value | 0.000312 |

High ohmic loss of the series resistor, if the back-up fuse takes the protective function over from interrupted or failed primary fuse, is a disadvantage of this variant. It is well-known that in typical space applications the power loss has to be as low as possible. Unwanted occurring heat energy of about 1 W or even more is usually not permitted on electronic circuit boards. Therefore, this solution is only suitable for small load currents less than approx. 1 Ampere – see Fig. 6. The systems new pre-arcing time characteristic compare to the characteristic of the similar single fuse is shown in the Fig. 7 and Fig. 8 below.

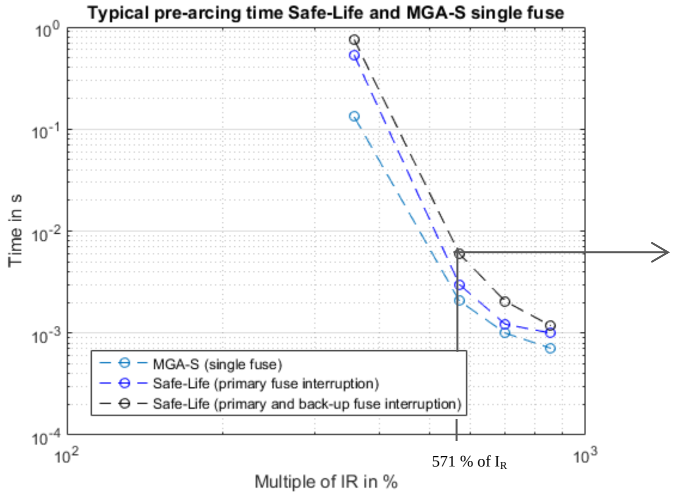

Fig. 7: Typical pre-arcing time

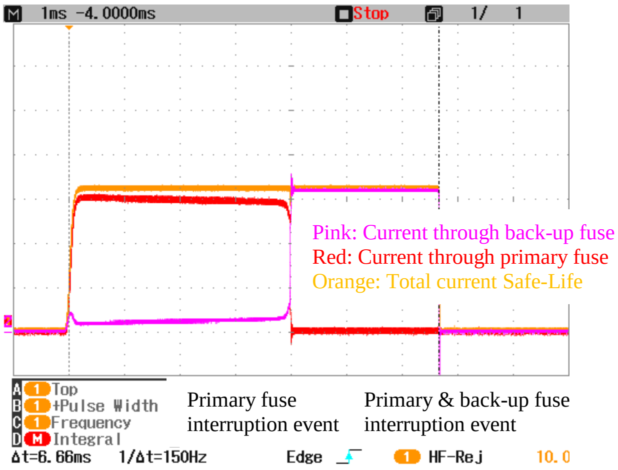

Fig. 8: Interruption events at 571 % of $I_R$

Guidelines:

- It is suitable for MGA-S small rated current variants only.
- The current ratio $I_{backup}/I_{primary}$ should be less than 10 %. Based on this definition the back-up resistance value has to be about 10 times larger or even more compared to the warm resistance of the fuses.
- The back-up fuse covers the same current rating or even more.

Facts and key figures:

- The system is working time lagged compare to the single fuse
- The system's new typical $I^2t$ is more than double of a single fuse – higher current pulse resistivity expected
- It is sensitive to ambient temperature changes. The current ratio is depending on the ambient temperature – approx. linear dependency in the operating range – 55 °C to 85 °C.
- The effect of a changing current ratio is strongly affected by the back-up resistance value – non-linear dependency.

- The influence of the ambient temperature to the current ratio increases reversely proportional to the back-up resistance value. As an effect, at higher temperature the safe-life system is discharging the primary fuse current load. It works like a balancing system.
- The expected basic failure rate of the warm redundancy is

$$\lambda_{warm\ redundancy} = \frac{1}{\frac{1}{\lambda_{primary\ fuse}} + \frac{1}{\lambda_{back-up\ fuse} + \lambda_{back-up\_resistor}}} \qquad (2)$$

## FUSE SELECTION FOR APPLICATION SPECIFIC CIRCUIT PROTECTION

The criteria on fuses for effective circuit protection varies depending on the application requirements like protection functionality level. In particular for space application, the remarkable environment conditions, the high reliability and availability of safety requirements of the system need additional dimensioning actions to get the best fitting fuse. High current pulses or repeating pulses affect the expected life time of a fuse. Depending on several parameters like duty cycle, operating temperature, current peak, melting energy $I^2t$ etc. Large number of pulses might therefore affect the life-time of the fuse. However since many factors are involved, customer requests for extended data and technical support to select the right fuse for their specific application. The most important design parameters for fuses and their related data are listed below:

Table 5: Design parameter

| **Application Requirements / Parameter** | **Relation** | **Fuse performance data** | **SCHURTER Fuses for Space** | |
|---|---|---|---|---|
| | | | **MGA-S** | **HCSF** |
| Safety requirements (electrical protection reaction sensitivity – fail safe) | ←→ | Fuse tripping characteristic - quick acting F, very fast acting FF | FF | F |
| Safety requirements (reliability, availability) | ←→ | Design / technology – e.g solid state, qualification and reliability data, safe-life concept | Solid state<br>ESCC QPL<br>Rel. data available | Solid state<br>ESCC QPL<br>Rel. data available |
| Environment requirements (space, ground, etc.) | ←→ | Qualification and approval as in [1], ESCC-Q-ST-30-11C as in [4] | ESCC 4008001 | ESCC 4008002 |
| Supplied voltage | ←→ | Rated voltage | 125 VDC | 125 VDC |
| Average load current | ←→ | Rated current | 0.14 – 3.5 A | 5 – 15 A |
| Short inrush current | ←→ | Breaking capacity (e.g. HCSF safe-operating area) | Max 300 A | Min 1000 A<br>See Safe-Operating Area data in E-HB, as in [7] |
| Current pulse profile (duty cycle, peak current, amount of pulses during mission time) | ←→ | $I^2t$, current pulse derating factor | See MGA-S Data Sheet as in [5] and SCHURTER guide to fuse selection | See HCSF Data Sheet, as in [6]and E-HB, as in [7] |
| Ambient temperature | ←→ | Temperature derating | See MGA-S Data Sheet | See HCSF Data Sheet or E-HB |
| Size and mounting | ←→ | E.g. SMD | SMD 1206 | SMD 3220 |

SCHURTER AG offers customers a wide range of well-grounded technical data to the MGA-S and HCSF. Experienced specialists from SCHURTER AG gladly supports in any cases to design-in the best fitting protection device for customer specific applications.

## RELIABILITY MONITORING REPORT MGA-S BURN-IN SCREENING 2008- 2015

As already stated the SCHURTER MGA-S and HCSF are high reliable and robust fuses which have a basic failure rate clearly under 1 FIT. Over the last decades SCHURTER AG produced overall several millions of the standard fuse MGA and of the ESCC qualified variants MGA-S and HCSF with satisfied customers. The ESCC qualified parts undergo several screening tests during production control according to ESCC 4008. The burn-in test is one of this required screening procedure. SCHURTER AG continuously monitors and analyses this data to keep up the product quality level and get the latest reliability data. Since the very beginning of the MGA-S production no single part failed in these internal test procedures, in particular caused by electrical failure.

Table 6: Reliability data of the MGA-S based on burn-in measurement

| **Production time frame** | **2008 - 2015** |
|---|---|
| | |
| Total screened parts/ device quantity n | 173’250 |
| Accelerated device hours (cumulated) | 115’333’913 |
| Failed parts | 0 |

The acceleration factor is determined by the Arrhenius Equation (3).

$$Acceleration\ factor = e^{\frac{E_A}{k_B}\times\left(\frac{1}{T_{operation}}-\frac{1}{T_{stress}}\right)} \tag{3}$$

The accelerated device hours result from the multiplication of the total screened parts quantity, the screening test duration and the calculated acceleration factor, as in (4).

$$Acceleration\ device\ hours = n \times t_{burn-in} \times acceleration\ factor \tag{4}$$

Table 7: Burn-in test conditions, calculation data and physical constants

| | |
|---|---|
| Activation Energy $E_A$ | < 0.7 eV, for more details please contact SCHURTER AG |
| Boltzmann Constant $k_B$ | |
| Operation Temperature $T_{operation}$ | 55 °C |
| Stress Temperature $T_{stress}$ | 80 °C |
| Screening test duration $t_{burn-in}$ | 168 h |
| Supply current | Continually rated current at stress temperature |

Early failures significantly affect the time dependent on the failure rate of the parts. Caused by weak parts these failures occur at the beginning of the life time – stage 1 see Fig 9. In particular, the burn-in test is an effective and well established method to select this weak fuses in the stage 1.

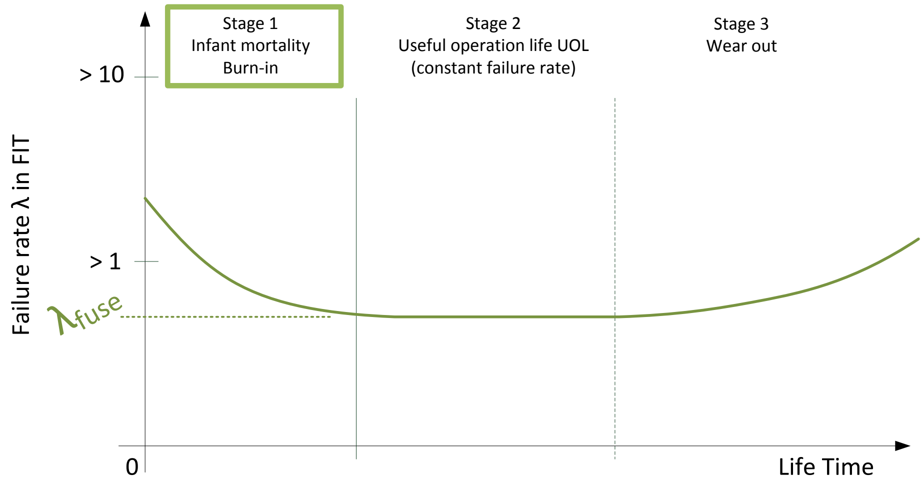

Fig 9: Bathtub curve of a fuse

As stated above, no weak fuses have ever been observed since the very beginning of the MGA-S production in 2008. The figure below represents the determined upper bound average failure rate in time, based on MGA-S burn-in production data from the period between 2008 till 2015.

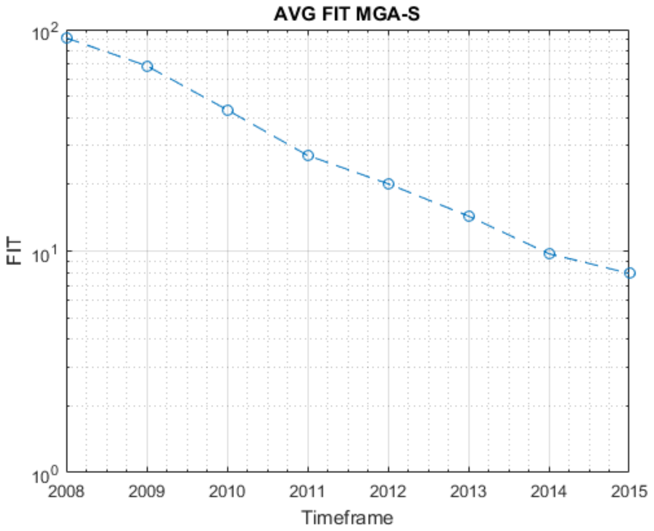

Fig 10: Upper average failure rate based on burn-in data of MGA-S production period 2008 - 2015

Depending on the year's production quantity the calculated upper average failure rate according to (5) is decreasing strongly. The latest reliability analysis data shows an average failure rate of the MGA-S which includes potential early failures in stage 1 of about 8 FIT. This statistical calculation respects the chi-square distribution and includes the 60 % confidence level for zero failure criteria.

$$Average\ failure\ rate = \frac{\chi^2/2}{acceleration\ factor \times n \times t_{burn-in}} \tag{5}$$

## CONCLUSION

The space fuses MGA-S and HCSF from SCHURTER AG covers wide range of the requirements for safe and reliable circuit protection in space and aerospace applications. Every year actualized reliability data of the MGA-S in particular based on the screening tests or even life tests like the every two years repeating operating life test according to ESCC 4008 Chart F4 are available and confirm the high quality and stability of these fuses. Set of similar fuses in parallel are a proven option if intermediate or in particular higher currents are requested for. Safe-life concept supports to extend the availability and reliability of the circuit protection device. Therefore SCHURTER AG is able to provide extended data of the MGA-S and HCSF and kindly help in any technical cases to finally have the best fitting solution for customers application.

## REFERENCES

[1] ESCC Generic Specification No. 4008, *FUSES*, ESCC Secretariat, Issue 4, July 2015
[2] ESCC Detail Specification No. 4008/001, *FUSES, 0.14 TO 3.5 AMPS BASED ON TYPE MGA-S*, ESCC Secretariat, Issue 5, September 2015
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[8] Technical Note, *MGA-S 3.5 A IN PARALLEL OPERATION*, SCHURTER AG, 0106.0264, December 2014.