Robust fuse design

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Abstract

The paper describes an approach to fuse design which is based on optimisation methods, where the performance requirements are represented as constraints on the values which the design variables are allowed to take. A solution space for any given design concept can be developed, but to do this, the prototype testing needs to be conducted in an unconventional way. When a feasible solution space has been obtained, the design can be finalised in a way which is robust and less sensitive to dimensional tolerances and other variations.

Keywords: electric fuse, design, optimization.

1. Introduction

Electric fuses are designed to meet a given set of performance requirements (which can be regarded as constraints on the design), usually those specified in the appropriate international standard. These requirements include, for example, the need to comply with specified set of limits on: temperature rises on the tube or the ends; fusing or non-fusing times; power loss; let-through currents, I^2t, and peak arc voltage.

Some of these constraints require testing at a fixed multiple of the rated current of the fuse, while others (such as the breaking capacity tests) require testing at a fixed prospective (available) current.

Often it is desired to develop a set of fuses (which may be part of a homogeneous series), with different current ratings, but within a given body (case) size.

The traditional approach is to choose a **design concept** (based on experience) and then build a prototype fuse and test it in accordance with the standard, to see whether it meets the performance requirements. If the design fails to meet the requirements in some way, it is then modified, re-tested, and the development continues iteratively until a satisfactory design is obtained.

Unfortunately many of the performance requirements conflict with each other. For example a low watt loss requires a fuse with a relatively low resistance, while a low I^2t requires a relatively high resistance, and often the requirements are not met, in which case the design concept needs to be changed.

In this paper, an alternative approach is described. The tests are carried out in a different way, which enables the limits on the design variables to be determined, and the constraints to be drawn in a **solution space** [1]. Sometimes a *feasible* solution space does not exist, in which case the design concept can be abandoned at an early stage.

However if such a space does exist, all the ratings in the series can be designed quickly, and they can be located within the space to give **robust** designs which are less sensitive to dimensional tolerances and other variations, and which can also be optimized as desired.

2. Typical constraints

The general approach described here can be used for any type of fuse, but it is illustrated by referring to a typical set of performance requirements (constraints) for a low-voltage power fuse.

2.1 Thermal limits

The most common thermal design constraint is that the steady-state temperature rise must not exceed a specified limit when carrying a specified value of test current. The limiting value may be on the fuse tube (body) or end terminal, or both.

A closely related requirement is often that the power loss under these conditions must not exceed a certain limit.

2.2 Time-current requirements

There are two types of constraints on the time current characteristic. A **fusing** requirement means that the fuse must melt within a specified time when tested at a specified multiple of the fuse current rating. A **nonfusing** requirement means that the fuse must **not** melt within a specified time when tested at a specified multiple of the fuse current rating. Time-current **gates**, through which the time-current curve must pass, can be regarded as two constraints, one fusing and one non-fusing.

2.3 Breaking test requirements

Assuming that the design can successfully interrupt the specified prospective short-circuit test current, there may be limits on the allowable I^2t, peak current, and peak arc voltage values.

3. Feasible solution spaces

As an example, consider the design of a homogeneous series of power fuses which by definition uses the same notching pattern for the fuse elements. The case (body) size is the same for all ratings in the series, and the key variable is the thickness of the fuse element (T). The designs can be characterised by a pair of values (T, In), where In is the rated current of the fuse, *and is treated as an unknown quantity at this stage*.

The first step in the process is to choose two values of fuse element thickness T_X and T_Y, which are believed will cover the expected range of thicknesses needed. T_X and T_Y can be selected by experience, rules-of thumb, or modelling, and T_Y needs to be roughly 3-5 times larger than T_X.

Two sets of model fuses are then built, one set with thickness T_X and the other with thickness T_Y.

3.1 Thermal limits

To determine the feasible solution space for a temperature rise constraint, tests are carried out to determine the temperature rise as a function of test current for the model fuses. (Note that this is quite different from the conventional procedure, which is to assume that the rated current is known, which then requires one set of tests for each prototype rating).

Typical results are illustrated in Fig.1. By careful selection of the test currents, the points at which the curves cross the specified temperature limit line can be determined. This gives two currents I_X and I_Y.

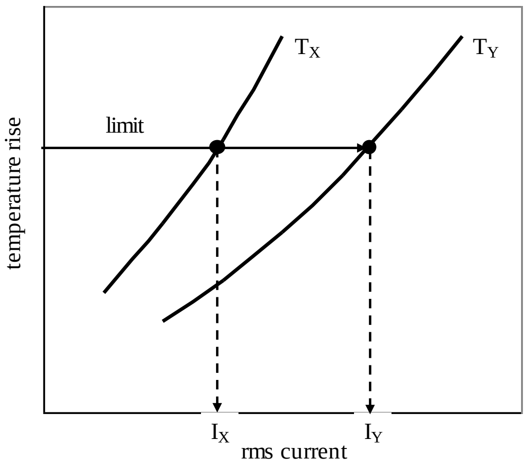

Fig. 1: Temperature rise versus test current for two different fuse element thicknesses.

In general the thermal constraint is that the temperature limit must not be exceeded when tested at k_1In. (k_1 is usually 1.0, but not always - see section 4).

At the limiting points $I_X = k_1In_X$ and $I_Y = k_1In_Y$, where In_X and In_Y are the maximum possible current ratings for fuses with element thicknesses T_X and T_Y. This gives $In_X = I_X / k_1$ and $In_Y = I_Y / k_1$. A pair of points (T_X, In_X) and (T_Y, In_Y) are then plotted in the (T, In) plane in Fig.2.

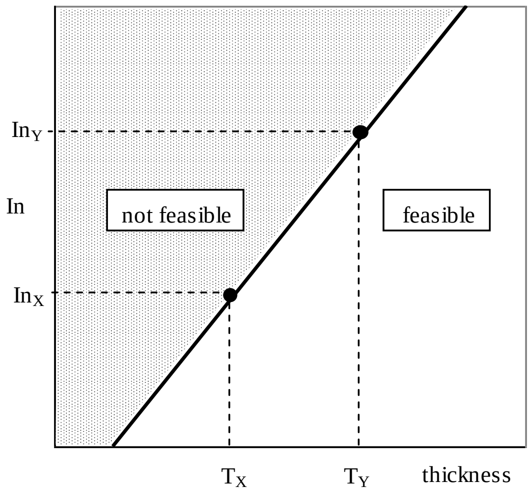

Fig. 2: Maximum possible current rating, based on a temperature-rise test limit.

Drawing a straight line through the two points divides the plane in Fig.2 into two regions. The upper (shaded) region represents designs which are not feasible - for any given rating the element thickness is too low, and the temperature rise limit would be exceeded. The lower (unshaded) region represents feasible designs. If the temperature-rise limit were the only constraint on the design, an arbitrarily large thickness could be used, which would ensure cool running.

Power-loss limits can be dealt in a similar way. However, as they are usually specified for each individual rating in a series, this results in a number of straight-lines sections in the (T, In) plane, rather than a single line.

Note that for Fig.2 and all subsequent diagrams, logarithmic scales are used on both axes. Since the range of thicknesses and the other variables in the region of the constraints is less than one decade, the test curves can be represented quite accurately by a power law, which results in a straight line when these points are transferred to the (T, In) plane.

3.2 Time-current requirements

For time-current constraints, tests are conducted to give time-current test points for times in the vicinity of the specified prearcing time t*. This is regardless of whether it is a fusing or a nonfusing requirement.

Typical results are shown in Fig.3. From these tests the rms currents which cause operation in the time t* can be determined, I_X for a thickness T_X and I_Y for a thickness T_Y.

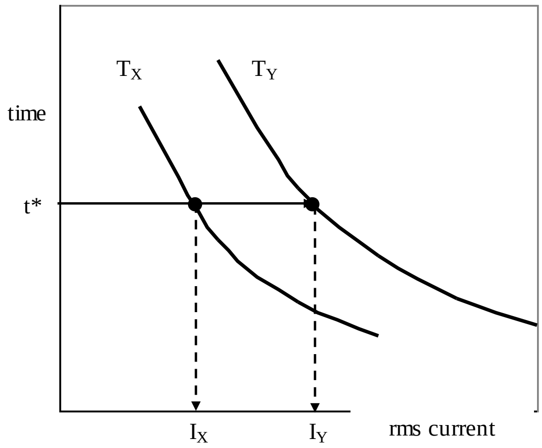

Fig. 3: Time-current test data in the vicinity of a specified fusing (or nonfusing) time for two different element thicknesses.

At the limiting points, $I_X = k_2 In_X$ and $I_Y = k_2 In_Y$, where k_2 is the specified multiple of the rated current.

For a **fusing** constraint,

$$In > I_X / k_2 \text{ for } T=T_X \quad \text{and} \quad In > I_Y / k_2 \text{ for } T=T_Y$$

This generates the two points shown in Fig.4. A straight line through these points divides the plane into two regions. The upper (unshaded) region is feasible. In this region, for a given rated current, the fuse element thickness is less than the limiting value, and the fuse will operate within the specified time, which is the requirement.

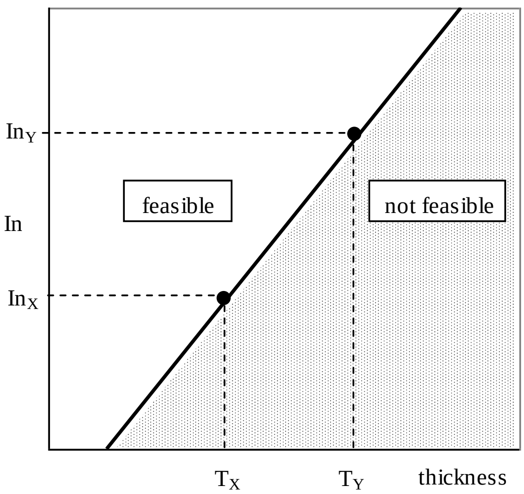

Fig. 4: Minimum current rating to meet a specified fusing requirement.

For a **nonfusing** constraint, the reverse is true.

$$In < I_X / k_2 \text{ for } T=T_X \quad \text{and} \quad In < I_Y / k_2 \text{ for } T=T_Y$$

The result is shown in Fig.5. The upper (shaded) region is not feasible. In this region, for a given rated current, the fuse element thickness is less than the limiting value, and the fuse will operate within the specified time, which violates the requirement.

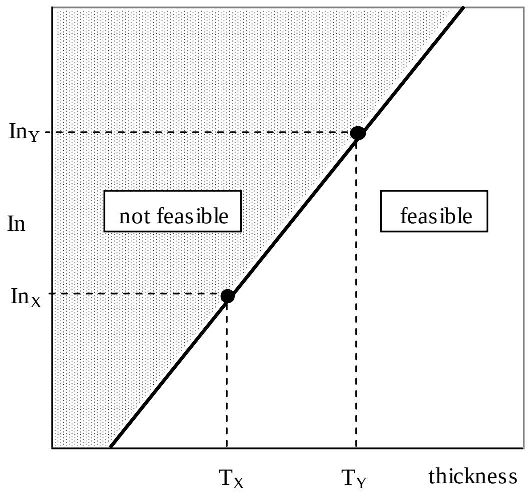

Fig. 5: Maximum current rating to meet a specified nonfusing requirement.

3.3 Breaking test requirements

Assuming that the design is capable of successfully interrupting the specified prospective short-circuit test current, then tests on model fuses will give I^2t or peak current increasing as a function of element thickness, as shown in Fig.6.

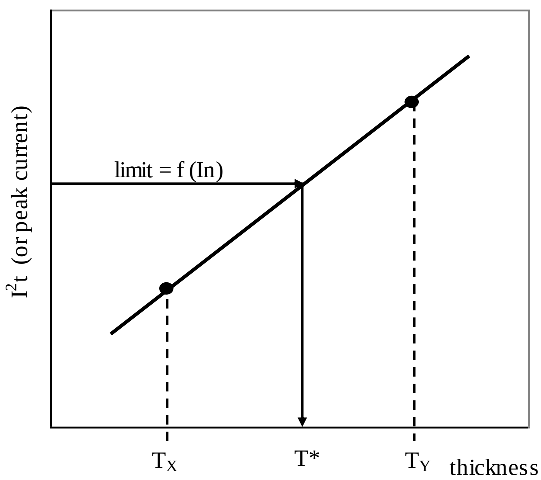

Fig. 6: I^2t or i_{peak} test data for two different fuse element thicknesses at a specified prospective current.

For a each rating the I^2t or peak current limit is given, and so the maximum permissible element thickness T* can be found. This corresponds to a single point in the (T, In) plane.

Fig.7 shows two such points plotted for two adjacent current ratings in the homogeneous series. It is convenient to join these with a straight line and shade the region to the right hand side as not feasible.

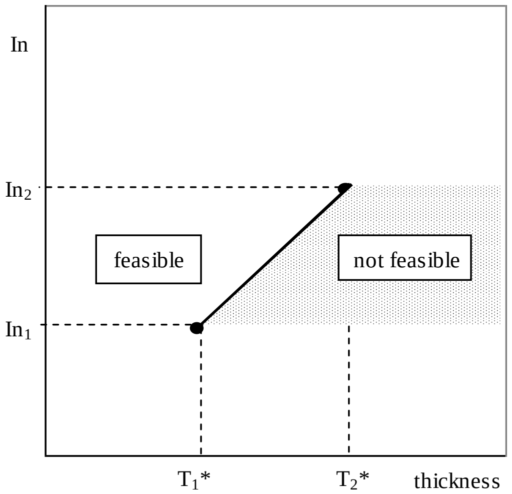

Fig. 7: Minimum possible current rating, based on I^2t or i_{peak} requirements.

For a homogeneous series with a table of I^2t or peak current limits for each rating, Fig.7 can be developed into a series of points joined by straight lines.

A similar procedure can be used for peak arc voltage limits if these are specified.

3.4 Physical limits

In addition to the thermal and electrical constraints there are physical limits to the value of element thickness which can be used. These limits are determined by the manufacturing processes used in the fuse construction, and are very simply added to the (T, In) plane as shown in Fig.8.

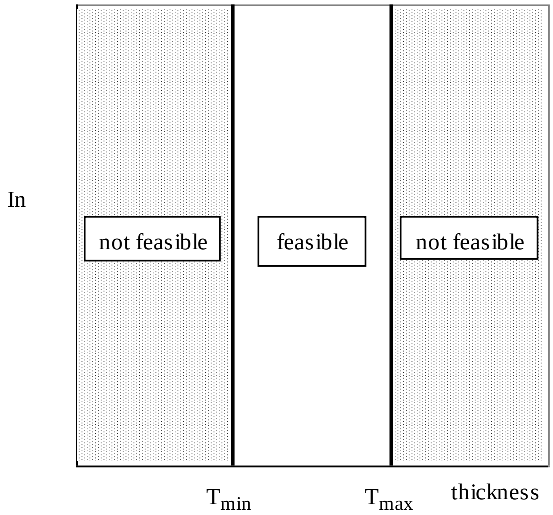

Fig. 8: Feasible fuse element thicknesses.

4. Typical example

When all the performance requirements are plotted on the (T, In) plane a complete picture of the design concept emerges.

As an example consider the performance requirements for a 600V class J fast-acting power fuse in the 200A case size. This size includes current ratings of 110A, 125A, 150A, 175A and 200A. The performance requirements are:

Thermal requirements

(a) Tube rise must not exceed 85 degC at 1.1 In
(b) Blade rise must not exceed 60 degC at 1.1 In

(i.e. $k_1 = 1.1$)

Fusing requirements

(a) fuse must operate within 2 hours at 1.35 In
(b) fuse must operate within 480s at 2 In

(As this is a "fast-acting" fuse there are no nonfusing requirements).

I^2t and peak current limits

At the 100kA and 50kA test levels, the I^2t, peak current and peak arc voltage must not exceed the values specified in Tables 1 and 2.

Table 1: Performance requirements at 100kA

In (A)	I^2t (kA^2s)	ipeak (kA)	Varc (kV)
110	100	14.5	3
125	150	15.5	3
150	175	17	3
175	225	18.5	3
200	300	20	3

Table 2: Performance requirements at 50kA

In (A)	I^2t (kA^2s)	ipeak (kA)	Varc (kV)
110	200	16	3
125	200	16	3
150	200	16	3
175	200	16	3
200	200	16	3

At the 50kA level the limits are the same for all current ratings.

Based on test data derived from tests conducted using the methods described in section 3, the (T, In) plane is shown in Fig.9, with all the above constraints applied. A final feasible solution space is seen to exist, the rest of the plane being shaded because one or more of the constraints are violated. (The peak arc voltage requirement was easily met, and is not shown).

The presentation of Fig.9 gives a complete picture of how the design concept meets the various performance requirements, on a single sheet of paper.

For the 110A, 125A and 150A ratings, the feasible solution space is bounded by the constraints imposed by the tube temperature rise limit and the requirement for operation within 2h at 1.35 In. The first of these requires a relatively low element resistance, while the second requires a relatively high resistance. However, for this design concept, a band exists where both conditions can be met, and a convenient available thickness can be selected near the middle of this band, which will give a robust design, so that dimensional tolerances do not cause the design to fail to comply with the requirements.

For the 175A and 200A ratings, the peak current limit becomes more important than the 1.35 In fusing requirement, and for the 200A rating the width of the range of feasible thicknesses becomes rather small. For the 200A fuse, the design is less robust, and Fig.9 shows exactly why this is so.

If the width of the feasible band is reasonably large, it is possible to choose a thickness which will optimize the design, according to some desired criterion. For example if it is desired to have a low watt loss, the actual design point can be chosen to be near to the right-hand side of the feasible solution space. If it is desired to lower the peak current and I^2t, a point nearer to the left-hand side can be chosen.

5. Conclusion

The method described differs from conventional design methods in that the current rating of prototype fuse designs is treated as an unknown quantity until the very end of the procedure. This requires a different approach to testing, but with careful planning the number of test samples needed can be minimised.

The reward is that when the design of a homogeneous series is completed, the resulting plot, equivalent to Fig.9, gives much more valuable information than a set of tables of test results.

In the example given, element thickness was chosen as the key variable, as it usually is. However the method can be applied equally well if other variables are chosen.

6. References

[1] Diwekar, U.: “Introduction to Applied Optimization”. 2nd edition, Springer, 2008.

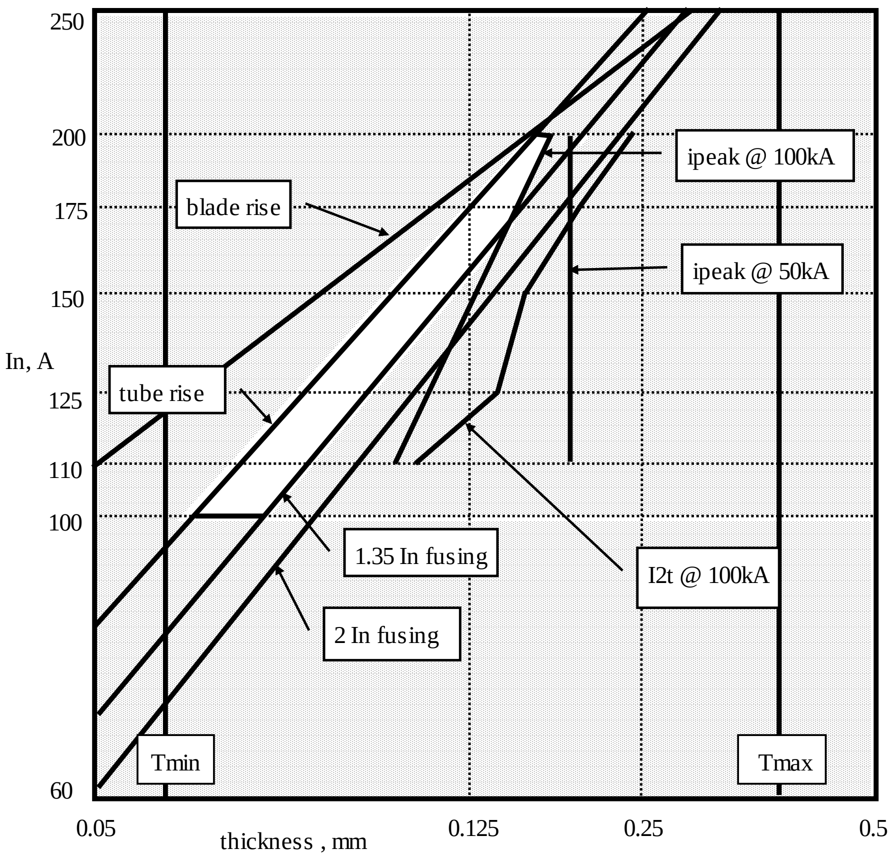

Fig. 9: Example showing all constraints and feasible solution space for a fast-acting class J fuse.

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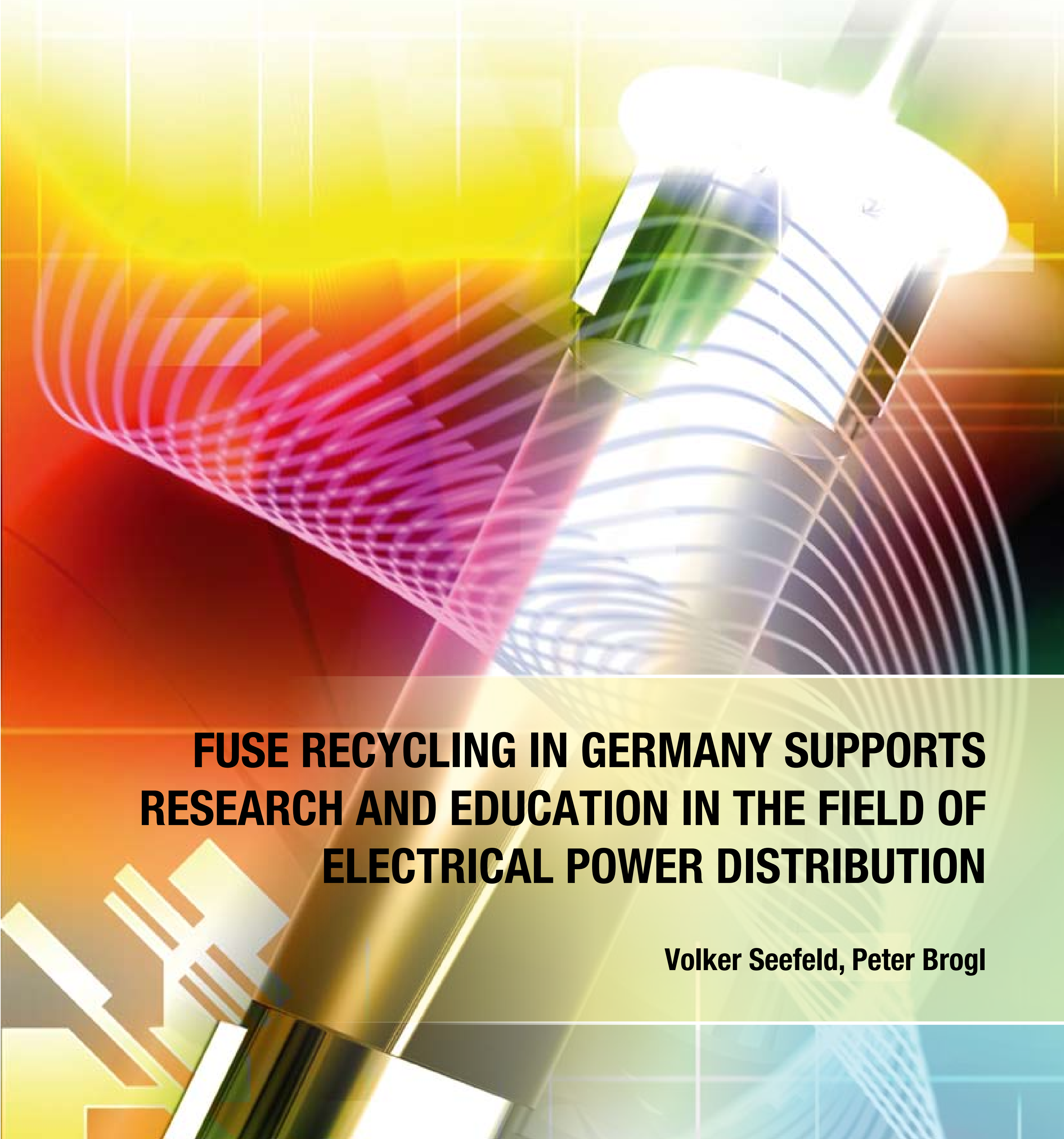

FUSE RECYCLING IN GERMANY SUPPORTS RESEARCH AND EDUCATION IN THE FIELD OF ELECTRICAL POWER DISTRIBUTION

Volker Seefeld, Peter Brogl