VARIABLE VOLTAGE RISE BEFORE THE BEGINNING OF THE ARCING PROCESS IN A LV FUSE LINK

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Abstract: The constrictions of the melting element are not cut in that moment the voltage rise across the constriction starts. They disrupt only when the voltage drop across the constriction has reached the value U_E. Breaking tests with LV fuse links and specially designed constrictions show a slow down of the voltage rise up to 0.4 ms for the constrictions to open and ignite the arcing process. This is important to know for a correct model of the arcing voltage.
Die Engstellen im Schmelzleiter werden nicht in dem Augenblick unterbrochen, in dem die Spannung über der Engstelle anzusteigen beginnt. Die Engstellen zerfallen erst, wenn die Spannung über der Engstelle auf den Wert U_E angestiegen ist. Schaltversuche mit NH-Sicherungseinsätzen und speziellen Engstellenformen zeigen eine Verzögerung des Spannungsanstiegs bis zu 0.4 ms, bevor die Engstelle zerfällt und den Lichtbogenvorgang einleitet. Dies muß beachtet werden, um ein genaues Modell für die Lichtbogenspannung anzugeben.

1 INTRODUCTION

The strangling of the constrictions in a melting element is a dynamical process that needs power and time. The current delivers the power. The time to strangle the constrictions depends on their shapes and on the melting current. Strangling starts only when the smallest cross section of the constriction has changed to liquid. In this moment the melting integral for adiabatic heating of silver and copper melting elements has grown up to about 85% of its final value. With smaller current densities and growing heat losses the melting moment is shifted to a higher percentage of the melting integral.
When a constriction in a melting element is cut by a current and arcing begins, then the arc voltage starts with the value $1*U_E$ per arc. The voltage U_E is made by an electrode effect. The deformation of the electric field next to the electrode needs energy, which is produced by the current in the strangled constriction. When the voltage drop along the strangled constriction exceeds the value U_E , the voltage drop needs more energy than an arc. The constriction will disrupt and lower the energy.
The calculation about the effect of the current forces to the shape of the constriction is difficult. T. Lipski described how to calculate the effect of the pinch forces on a strip fuse element by a short circuit current [1]. We look for a simple connection between the test conditions and the voltage rise.

2 FUSE LINKS AND TEST CONDITIONS

Many tests had been performed, in order to know the breaking behaviour of fuses at various working conditions. The voltage rise before the beginning of the arcing process has been analysed many years later. Breaking tests from over a period of ten years were evaluated. The tests were not prepared and not performed to deliver information for the voltage rise before arcing begins. For the breaking tests we used melting elements with specially formed constrictions in order to have a best heat conduction from the smallest cross section of the constriction to the unharmed area of the melting element (see figure 1). The melting elements were made of silver with three rows of constrictions in line, distance 9 mm. Width and thickness of the melting elements are listed in the table. In most cases an indicator wire has been installed parallel to the melting element. The melting integral of the indicator wire has been 5 A²s. The test voltage has been DC between 24 V and 484 V and AC 50 Hz between 245 V and 1117 V. The inner volumes of the fuse links were 18, 31, 56, 100 and 134 cm³. In many fuse links only one melting element was installed.

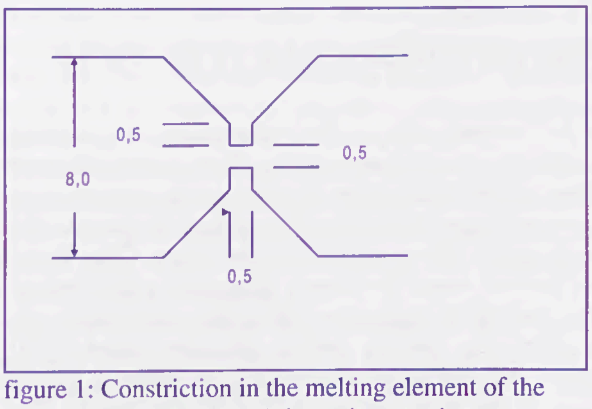

figure 1: Constriction in the melting element of the evaluated tests. Dimensions are in mm

We performed also tests with two melting elements inside the fuse links and tests with copper melting elements, marked by "K" in the file name in the table.
We evaluated some breaking tests, performed with fuse links with copper melting elements and another shape of constrictions, formed by round holes of 3.0 mm dia-

meter and 3.5 mm distance in a row of parallel constrictions. The distance of the rows has been 8.0 mm. There were 6 rows per strip. Test conditions and test results are listed in the table and marked by "C-4".

The tested fuse links mostly were taken out of the production lot. The position of the melting element inside the fuse link and its correctness has not been inspected before the test. The melting elements were embedded in quartz sand.

3 THE VOLTAGE RISE TIME

When the constrictions in a melting element are strangled by the current forces, the resistance of the constrictions rises and the voltage drop along the constriction rises too. When the test current density decreases, the voltage drop increases slowlier up to the value U_E = 55V. We assume the melting integral and the melting current to have almost the same values before the constriction is strangled and the voltage drop along the constriction rises faster and after the constriction is disrupted. When we determine how the maximum voltage rise time de-pends on the current density in the melting moment, we get a distribution according to diagram 1. The discrimi-nation is acceptable for current densities above 7000 A/mm². For small current densities below 7000 A/mm² the values are closer and closer.

We define the i²t-ratio as the value of the actual melting integral divided by the melting integral for adiabatic heating. When we plot the maximum voltage rise time versus the i²t-ratio, we get diagram 2. The discrimination is acceptable for an i²t-ratio above 3. For a small i²t-ratio below 3 the values are closer and closer.

We need both the diagrams 1 and 2. Sometimes only diagram 1 delivers the correct value for the voltage rise time. The value can be calculated before the beginning of the voltage rise and before the arcing process begins.

4 THE VOLTAGE RISE TIME AT DC AND AC

An AC current heats up the constrictions in a melting element by current pulses after short pauses. Current values smaller than a limiting value lead to heat losses in the current pause that exceed the heating up effect of the current pulse. The constrictions cool down. Only in the time interval when the current pulse above the limiting value reaches its maximum value, the constrictions are disrupted. For melting current densities below 8000 A/mm², the constrictions according to figure 1 do not disrupt in the first half wave of a 50 Hz current. The melting integral then is more than four times the value for adiabatic heating. For melting current densities above 8000 A/mm² the voltage rise time is below 400 µs.

A DC short circuit current does not have a current pause before the melting moment. For time constants of 15 ms a melting current density of 8000 A/mm² results in about 15 ms melting time. Small differences in the cross section of the constrictions or in the density of the quartz sand can easily lead to a better cooling and to a remarkable difference in the melting moment and therefore in the voltage rise time. In DC-tests the values for the time to reach $3 * U_E$ spread about a greater region than in AC tests. The test results for DC-tests therefore are loaded with a bigger error. The evaluation of breaking tests with identical test conditions delivers different values of the voltage rise time. We may use the average value for the diagrams or plot every evaluated value in order to know the error range.

At DC there have been tests performed with melting current densities below 7000 A/mm² and i²t-ratio up to 9.

5 INFLUENCES TO THE RISE TIME

If only the current does the strangling, the i²t-ratio and the melting current density define the voltage rise time. There are effects that shorten the time. The constriction is elongated by the heat, but the big rest of the melting element remains nearly at its initial temperature. The sand is only compressed by vibration, not solid. For melting times more than 5 ms the quartz sand next to the hot constriction is heated up some degrees centigrade. For melting times of more than 50 ms the sand is heated up above 300 °C. The temperature rise of the sand can make the sand grains move and can create mechanical forces to the constrictions of the melting element. The liquid constriction can be cut. The rise time then is shorter than in the case of undisturbed strangling.

The more the current density decreases, the more constrictions are cut mechanically. When the number of the constrictions rises, the probability that a liquid constriction is cut mechanically, rises too.

The moving hot sand grains can cut a liquid constriction, but later on it can also put together the ends of the interrupted constriction. This reduces the current density again and enlarges the voltage rise time.

With the current density below 7000 A/mm², the heat losses by conduction along the melting element create different maximum temperatures in the constrictions. Not all constrictions will disrupt simultaneously but only row by row. The voltage cannot rise at once up to $3 * U_E$.

If we have current densities below 5000 A/mm², the constrictions next to the ends of the melting element are cooled effectively by the contacts. Their temperature rise slowlier then that of the middle constriction, which is strangled most and delivers the maximum rise time of the voltage drop value $1 * U_E$. When the middle constriction is disrupted and the arc burns, the outer constrictions are heated up faster and strangled faster. The voltage rises faster. This leads to a smaller rise time between $1 * U_E$ and $3 * U_E$. The measured voltage is a mixture of arc voltage and voltage drop along the constrictions.

Parallel constrictions in a row disrupt simultaneously, when there is only the effect of the current. If there is additionally the mechanical effect, then the liquid constrictions can be cut and the voltage rises faster. Is the liquid constriction interrupted before the beginning of the voltage rise, then I assume this to be a mechanically performed disruption.

When all constrictions have the same cross section, then all cross sections have the same current density too. In order to have the rise time to reach the voltage value $3*U_E$ only influenced by the current heat, we need identical constrictions and a simultaneous voltage rise along the constrictions.

6 ONE STRIP MELTING ELEMENTS

We assume to have one strip melting elements with only one constriction per row. The melting element is disrupted, when one constriction is interrupted. It is also possible to have the liquid constriction mechanically cut. When the cross sections of the constrictions differ something, the current density differs too. The strangling does not occur simultaneously. If the cross section differs more than 7.5%, the melting integral differs more than 15%. The smaller cross section is almost strangled, before the greater cross section becomes liquid. The voltage rise up to the value $3*U_E$ occurs in steps of $1*U_E$.
One strip melting elements with two and more parallel constrictions in one row mostly deliver the maximum rise time.

7 MELTING ELEMENT OF PARALLEL STRIPS

The melting integral is delivered by all parallel strips of the melting element. The rise time becomes maximum, when all constrictions are strangled only by current forces. When the smallest cross section of a strip becomes liquid and is cut mechanically, then this strip does not carry any current any longer. The cross section of the melting element is reduced. The current density in the remaining cross section increases. The voltage along the the remaining strips rises faster and the voltage rise time is reduced. In diagram 1 the rise time is shifted towards a higher current density. The rise time values then harmonize with the values in diagram 1.
When one row of constrictions of the strip is cut mechanically, we cannot read the voltage rise time in diagram 2.

8 TEST VOLTAGE BELOW $N*U_E$

Six breaking tests N00R1D until N00R6D were performed at 24 V DC with fuse links with two parallel melting elements inside. In all tests the melting integral is the value of both strips in parallel. The maximum arc voltage values differ very much.
When the test voltage u_T is small, the inductivity L of the test circuit must deliver the necessary voltage for the voltage rise. The current must decrease fast, to reach the voltage $u = -L*di/dt = N*U_E$. Tests have shown, when sufficient energy is stored in the inductivity, the voltage rises as fast as at high test voltages. When the current density additionally is below 8000 A/mm², the constrictions are strangled very slowly and the current changes slowly too. A small test current i_T means a long melting time. The melting current i_M is almost equal to the test current. The time constant $\tau = L/R$ of the test circuit and the test current $i_T = u_T / R$ deliver $L = \tau * R = \tau * u_T / i_T$. When the current changes, the inductivity L delivers the voltage $-L*di/dt = \tau * u_T / i_T * (di/dt) = N * U_E$. The numerical values for the tests were N=3, τ = 15 ms and $i_T \approx i_M$. We get for the necessary current change per ms the value $-di/dt$ [A/ms] $\approx 3*55*i_M / 15*24 \approx 0.5*i_M$.
For voltage rise times of > 1 ms and small inductivities, the inductivity cannot deliver the voltage necessary for the voltage drop along the strangled constriction in order to reach the value $N*U_E$. In the tests N00R2D and N00R3D the voltage drop reached more than $1*U_E$ but less than $3*U_E$. When we insert the voltage rise time up to $2*U_E$ in both the diagrams 1 and 2, the values harmonize with the other evaluated voltage rise time values.
When the constrictions disrupt and arcing begins, the arc voltage can rise up to about $3*U_E$. The shape of the arc voltage curves (not given here) show, that both strips did the arcing process.
In test N00R1D we found a very short rise time of about 80 µs. One strip has been cut mechanically when the constrictions have changed to liquid. The voltage rise is controlled by only one strip. The encreased current density leads to a voltage rise time according to diagram 1. The value 80 µs does not harmonize with the values in diagram 2. In the following arcing process the arc voltage reaches to about 250 V. The arc voltage curve of test N00R1D shows, that only one strip controlled the arcing process.
In the tests N00R5D and N00R6D the voltage rise time of about 100 µs is very short and the melting time of 30 ms is very long. I assume the liquid constriction in one strip to be cut by moving sand grains. Therefore only one strip controlled the voltage rise. The melting current divided by half of the initial cross section delivered the current density 13400 A/mm². The rise time values 110 µs and 95 µs correspond to the current density for one strip only. The values are plotted in diagram 1. Both test results are not implied in diagram 2. The oscillograms indicate that only one strip led the arc current.
Test N00R4D shows a fast voltage rise along the melting element up to the value $2*U_E$. The rise time 95 µs indicates, that only one strip controls the voltage rise. The second strip is cut. The voltage rise time harmonizes with the values in diagram 1.
After 240 µs the voltage drop decreases to 60 V within the next 300 µs. This means that again both strips carry the current. In this moment the current density in both strips is 5200 A/mm². The voltage drop rises up to $3*U_E$ within the next 300 µs. We may read the current density 5200 A/mm² and the voltage rise time 300 µs + 300 µs = 600 µs. Both the values harmonize with diagram 1. We may also read the i^2t-ratio 9.4 and the whole voltage rise time of 840 µs. These values harmonize with the values in diagram 2. Both the evaluations are not quite correct, but they indicate how the diagrams may be completed.

9 INFLUENCE OF SHAPE AND MATERIAL

Referred to the i^2t-ratio the voltage rise time becomes independent on the material and on the shape of the constrictions (see diagram 2). When all strips of the melting element contribute to the voltage rise, diagram 2 delivers the maximum rise time at the selected test conditions.

The shape of the constrictions, the material and the test conditions deliver the actual melting integral value of the melting element, the melting moment and the melting current. There exist methods to calculate the values at the melting moment for different shapes of constrictions, materials and test conditions, e.g. the program STROMex. The melting current and the cross section of the constriction deliver the melting current density. With the maximum voltage rise time of diagram 2 and the melting current density we can draw diagram 1. For each shape of constrictions and each material there exist the diagrams 1 and 2.

Constrictions as defined in figure 1 show an effective heat loss from the constriction to the melting element. The rise time of the voltage drop along the constriction depends on the rise time of the temperature of the constriction. Within the possible accuracy of the evaluation copper melting elements resulted in the same maximum voltage rise time (see diagrams 1 and 2).

The results refer to the investigated constrictions as shown in figure 1. They can be transferred to constrictions with another shape. The voltage rise time normally is smaller for another shape of the constrictions.

Breaking tests with copper melting elements and another shape of constrictions C-4 have been evaluated in the same way. The heatflow from the smallest cross section of the constriction to the unharmed melting element was less. Diagram 2 demonstrates, that the maximum voltage rise time harmonizes with the values for other shape of the constrictions. The rise time of C-4 melting elements did not change much with the melting current density.

We get the minimum rise time for wire melting elements. Even then the rise time is above zero but below 100 µs.

10 CONCLUSIONS

The rise time has not been found to depend on any inner volume of the fuse link. It is a prearcing effect and not an effect of the arcing process.

The voltage rise time is independent of the test voltage.

For test voltages much less than $N*U_E$ the voltage drop along N constrictions does not rise up to $N*U_E$.

When there is only the effect of the current, we assume the voltage along the constriction rises linearly up to the value $N*U_E$, before the constriction is disrupted. The voltage rise time is controlled by the i^2t-ratio according to diagram 2. All parallel strips in a fuse link deliver the voltage rise time.

When one row of constrictions of a strip of a multi strip melting element is interrupted mechanically as soon as it has become liquid, the melting current in the remaining strips rises. The current density can be calculated. Diagram 1 delivers the voltage rise time versus the melting current density. Diagram 2 cannot be used.

When one strip failes as soon as the constriction in a row becomes liquid, the rise time must be read in diagram 1. The value can be calculated before the beginning of the voltage rise and before the arcing process begins.

The influence of the test conditions to the rise time can be calculated. Different voltage rise time by a different shape of the constrictions is due to the different heat conduction along the constriction. For i^2t-ratio < 6 the maximum voltage rise time can be found in diagram 2 or approximately by the formula $t = 290 * \ln(i^2t\text{-ratio})$.

At small melting current densities some constrictions very often are interrupted by moving hot sand grains. The current density in the remaining strips rises. The voltage rise time is reduced and can be found in diagram 1. We must therefore calculate all possibilities one by one. Only one possibility will occur in one breaking test. Small test current densities mean currents that leave the range of short circuit currents and enter the range of overcurrents.

When the test voltage is very small, the voltage drop along the melting element cannot reach the value $N*U_E$.

The arcing process can be calculated more accurate.

A strip that is cut mechanically before the arcing process starts, maybe takes part in the following arcing process, when the arc voltage exceeds the dielectric strength of the interrupted strip.

1 REFERENCES

[1] T.Lipski: Application of the arc-pinch-forces-interaction theory to the calculation of striation modulus of the strip h.b.c fuses ; ICEFA 1984, Trondheim, N

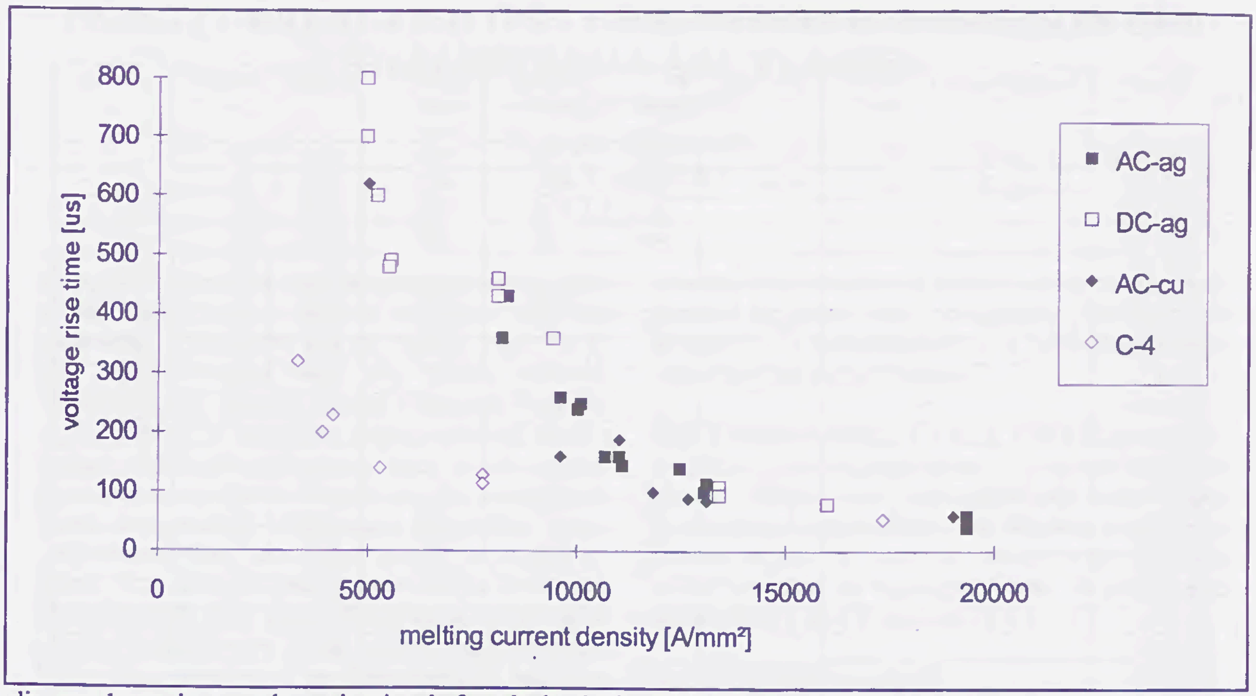

diagram 1: maximum voltage rise time before the beginning of the arc versus melting current density

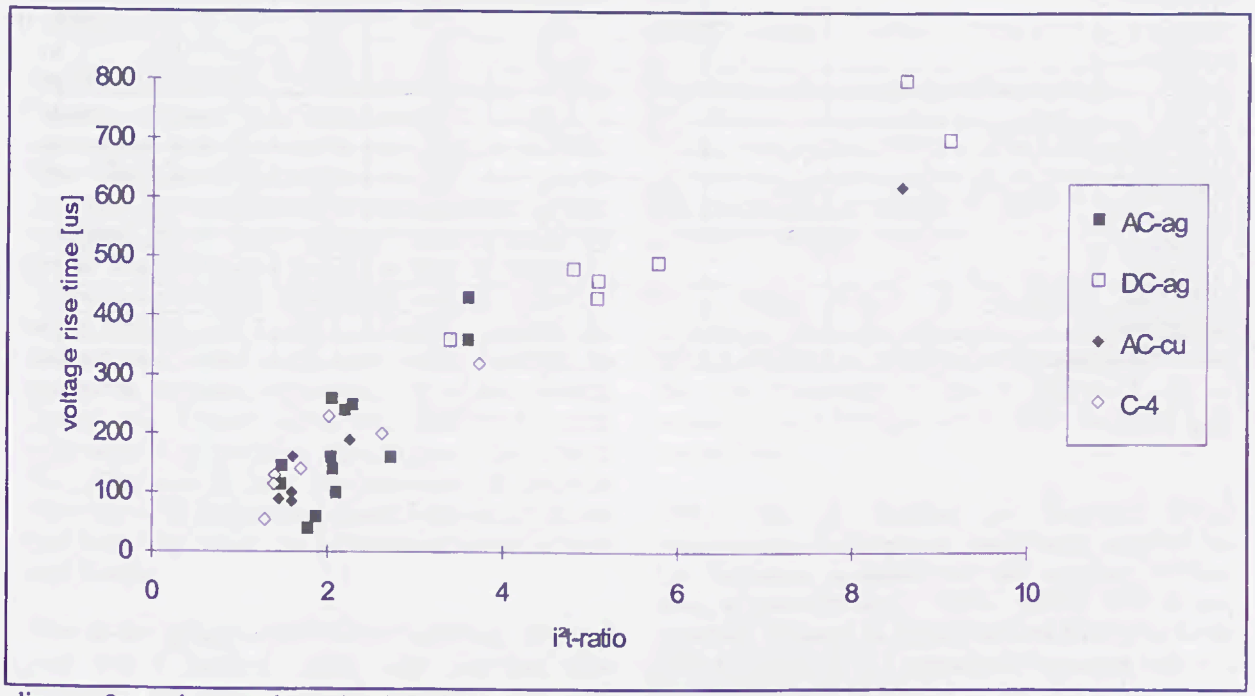

diagram 2: maximum voltage rise time before the beginning of the arc versus i²t-ratio

table 1: fuse links, test conditions and test results listed

file-name	melting element	cross sect. mm²	test voltage V	test current A	melting current/A	current den-sity A/mm²	i²t-ratio	rise time µs	remarks
N00R785D	1 x 8 x.150	0,075	484 =	2000	700	9427	3.4	360	
N1R16D	1 x 16 x .20	0,20	400 =	1450	1110	5470	5.78	490	$2*U_E$
N1R17D	"	"	"	"	1100	5420	4.80	480	$2*U_E$
N1R33D	"	"	"	1000	990	4950	8.6	800	$1*U_E$
N1R34D	"	"	"	"	"	"	9.1	700	$1*U_E$
K1R35D	"	"	"	"	1000	5000	8.56	620	Cu; $2*U_E$
N00R1D1	2 x 8 x .10	0,1	24 =	1200	810	16000	2.77	80	1B
N00R2D2	"	"	"	"	"	8100	5.08	430	$2*U_E$
N00R3D1	"	"	"	"	"	"	5.09	460	$2*U_E$
N00R4D1	"	"	"	680	520	5200		600	1B + 1B
N00R5D1	"	"	"	"	670	13400		110	1B
N00R6D1	"	"	"	"	"	"		95	1B
N00R415	2 x 8 x .13	0.13	550 AC	1950	1440	11077	1.48	145	
N0R306	1 x 16 x .150	0,15	"	1830	1870	12467	2.06	140	
N0R308	"	"	"	1000	1600	10667	2.04	160	
N1R885	"	"	"	5700	2900	19333	1.78	40	
N1R886	"	"	"		"	"	1.87	60	
N1R889	1 x 16 x .15	"	"	600	1230	8200	3.6	360	
N1R890	"	"	"	"	1250	8333	3.6	430	
N1R013	"	0,21	660 AC	3700	2750	13095	1.47	115	
N0R645	1 x 16 x.10	0,1	550 AC	650	1010	10100	2.29	250	
N2R651	"	"	"	650	960	9600	2.05	260	
N2R652	"	"	"	"	1010	10100	2.20	240	
N3R419	1 x 16 x .20	0,2	380 AC	3000	2610	13050	2.10	100	
N3R425	"	"	"	1300	2200	11000	2.72	160	
K2R27-1	1 x 24 x .217	0.326	660 AC	2400	3590	11012	2.26	190	Cu; 2.HW
K2R30	"	"	"	4400	4130	12700	1.44	90	Cu
K2R25	1 x 24 x .120	0.18	"	2400	2360	13111	1.59	85	Cu
K2R14	"	"	"	1600	2130	11830	1.59	100	Cu
K2R02-25	6 x 8 x .148	0.444	"	2640	4260	9595	1.6	160	Cu
K2R02-26	"	"	"	"	"	19000		60	Cu; 3B/6
K1M14D	1 x 14 x .150	0.30	500 =	1500	1250	4167	2.01	230	C-4
K1M15D	"	"	400 =	1450	1170	3900	2.62	200	C-4; $4*U_E$
K1M39D	"	"	"	1000	990	3310	3.73	320	C-4; $2*U_E$
K1M13D	2 x 10.5 x .15	0.49	550 =	4600	2590	5290	1.69	140	C-4
K2M304	1 x 21 x .15	"	550 AC	1830	3800	7750	1.40	130	C-4
K2M305	"	"	"	"	3790	7740	1.39	115	C-4
K1M410	2 x 10.5 x .143	0,43	1117 AC	25000	7450	17326	1.28	55	C-4