Technical Paper ■ Author: Fritz Sorg, Rudolf Hanov, Heinz Raithel

Cast-resin transformers excel in their fire behavior

Power Transmission and Distribution

SIEMENS

Wherever distribution transformers are used in locations very close to people, GEAFOL cast-resin transformers are the low-risk answer. Cast-resin transformers lack the limitations of oil-insulated transformers but share their desirable properties, such as operational reliability and a long service life. Today more than 80,000 GEAFOL cast-resin transformers have already proven themselves in supplying electric power to subway tunnels, coal mines, airports, wind power systems and even on cruise ships and in nuclear power plants. In many cases, the key factor prompting decision-makers to choose the cast-resin version was its superior fire behavior. The results of fire behavior tests at well-known test laboratories prove that GEAFOL cast-resin transformers – especially in comparison to oil-insulated transformers – are the best choice when it comes to fire behavior.

Figure 1: GEAFOL cast-resin transformer in the test bay at the Siemens transformer plant in Kirchheim/Teck: If GEAFOL cast-resin transformers are involved by an external fire, they don't significantly affect the course of the fire thanks to their low fire load. Nor do their coils ignite from short-circuit arcs caused by intrinsic flaws. Moreover, no toxic components are produced, other than the type of flue gases common to fires.

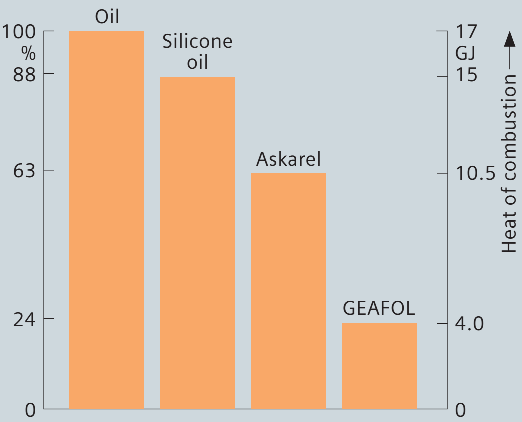

Figure 2: Combustion heat of the insulating materials of comparable 630-kVA transformers with different insulating materials: The combustion energy of a 630-kVA mineral oil transformer amounts to more than four times that of a GEAFOL cast-resin transformer.

Cast-resin transformers excel in their fire behavior

Fritz Sorg, Rudolf Hanov, Heinz Raithel*

The GEAFOL cast-resin transformers which Siemens Power Transmission and Distribution (PTD) produces at its transformer plants are fire-retardant and self-extinguishing (Figure 1).

If they are involved by an external fire, they do not significantly affect the course of the fire thanks to their low fire load. Nor do the coils of the GEAFOL cast-resin transformer ignite from short-circuit arcs caused by internal defects. Moreover, no toxic components are produced, other than the type of flue gases common to fires. Siemens advises its customers for safety reasons, especially with respect to fire behavior, to use GEAFOL cast-resin transformers in infrastructural projects such as department stores or office buildings. What's more, the operator benefits from other advantages, such as superior economy and excellent environmental compatibility.

Dry-type transformers must always be specified according to their tested and proven Environmental, Climatic and Fire Category. GEAFOL cast-resin transformers comply with Environmental Category E2, Climate Category C2 and Fire Category F1 – the highest categories defined in IEC 60076-11, which means that they deliver the highest level of operational safety.

If one compares the energy content liberated during complete combustion of all insulating materials in transformers filled with mineral oil, silicone oil, or ester liquid with that of cast-resin insulated distribution transformers, the comparison invariably favors the cast-resin transformer. For example, the combustion energy of a 630-kVA mineral oil transformer is more than four times that of a GEAFOL cast-resin transformer (Figure 2).

This comparison does not include characteristics such as flammability and combustion speed, but is shows that the fire load of cast-resin insulated transformers is substantially lower than that of liquid-filled transformers.

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The design of the windings and the cast-resin mixture determine the fire behavior

The fire behavior of the cast-resin transformers which Siemens manufactures, for example, in Kirchheim, Germany is dictated chiefly by the winding arrangement because this has a crucial influence on the properties of the cast resin mixes that can be used. One of the secrets of good or bad fire behavior of a cast-resin transformer is related to the mixing ratio of the insulation, which consists of an environmentally compatible and recyclable epoxy resin/quartz powder mixture in the GEAFOL transformer. The Kirchheim plant produces the insulating material for its cast-resin transformers from a mixture of two-thirds quartz powder and one-third epoxy resin to create transformers that are on the safe side with respect to their subsequent fire behavior.

This is confirmed by prestigious testing laboratories where Siemens has its cast-resin transformers tested for fire safety. As a case in point, in 2005 a 1500-kVA transformer was extensively and successfully tested in the testing laboratory of CESI (Centro Elettrotecnico Sperimentale Italiano) in Italy – including tests to validate Fire Category F1 according to IEC 600076 – 11 Section 28.3 (Figure 3).

In this test, a replica of a transformer leg was simultaneously exposed to:

- Flames from a trough filled with burning spirits
- Radiant heat from a vertical radiant heater wall (24 kW, 750 °C)

The following test criteria were used:

- The maximum temperature of emitted gases and its variation over time
- The generation of smoke development (the mean value of the degree of light transmission from the 20th to the 60th minute after the start of the test must not be less than 20 %).

The good results of the fire behavior tests were achieved without the addition of flame-retardant materials such as halogens. Nor had any additives such as alumina trihydrate been used that impair mechanical strength.

These tests had been preceded by earlier fire behavior tests for flue gases in the Allianz Technology Center and by tests of the pyrolysis products of molded cast-resin material used in GEAFOL transformers. The test results demonstrated that the transformers could not self-ignite due to short-circuit arcs associated with intrinsic flaws. If they become involved in an external fire, they do not significantly intensify the course of the fire thanks to their low fire load. The tests also demonstrated that any impairments or hazards due to heat and gases from the fire are largely the same as in ordinary fires.

These tests were designed to study the behavior of GEAFOL cast-resin transformers in critical operating conditions, for instance under the influence of highly energetic short-circuit arcs, or when the transformer becomes involved in external fires. Particular emphasis was placed on testing for environmental impact as well as for potential toxicity of the gases from the fire. Another priority was protection of bodies of water. A cast-resin insulated, dry-type transformer is fully compliant with the relevant standards, such as those of VDE 0101 concerning fire protection and protection of bodies of water. Such a transformer is therefore the product of choice for applications in which meeting these conditions is paramount.

The consequences of fire impact also had to be researched carefully and expertly in order to rule out absolutely any hazards such as those associated with PCB-filled transformers (PCB = polychlorinated biphenyls[1)]). The main criterion was the question of whether and under what conditions a cast-resin transformer can burn and what combustion products can occur. Combustion is an autonomous process once the source of ignition or fire has been removed, in other words, the process is determined by the energetic balance of the reaction heat and the heat dissipation. Heat input from the flame causes the plastic to be heated and decomposed. The gaseous decomposition products burn. It is the very nature of autothermal processes that without sufficient heat input from the combustion itself no sustainable combustion is possible. If cast-resin molded materials and windings embedded therein, or synthetic liquids and plastic insulating materials, are exposed to flames, the heat input can cause the temperature to reach the ignition level. In the presence of sufficient oxygen input, gaseous products then ignite.

Two conditions must therefore be met in order to maintain a stable, self-sustaining combustion: First, the temperature of the material must rise to the ignition point, which is above 450 °C in the GEAFOL cast-resin molded material. Second, the combustion must generate a sufficient quantity of heat to sustain itself.

Figure 3 a + b: Very good resistance to direct flame action was certified: 1,500-kVA GEAFOL cast-resin transformer under test at the CESI Test Institute in July 2005 before (above) and after (below) testing to verify compliance with IEC 600076 fire category F1.

1) Note: Production of PCB-filled transformers is banned today but there are still some in operation subject to strict regulations.

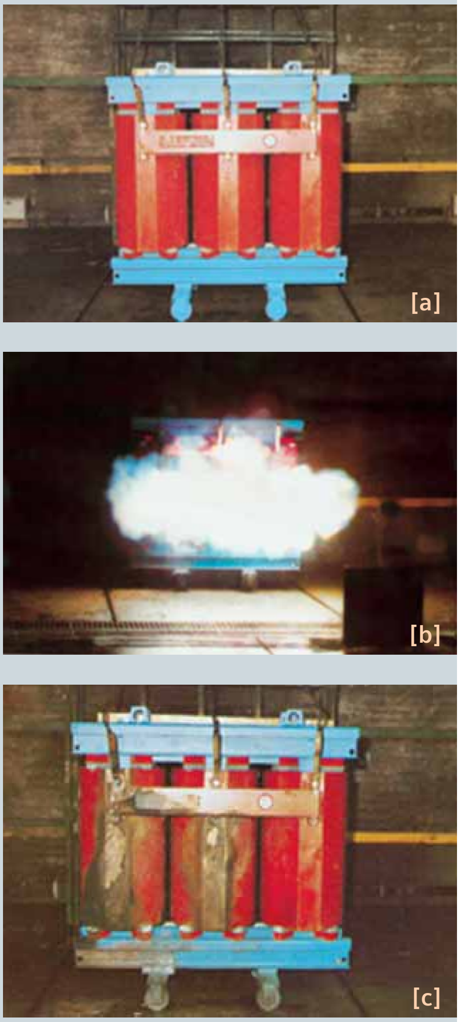

Figure 4: GEAFOL cast-resin transformer in the short circuit arc test:
a) Before the test
b) During the test
c) After the test

Realistic tests of the fire behavior of cast-resin transformers

The experimental tests of the fire behavior of cast-resin dry-type transformers were conducted under realistic conditions on complete transformers in two directions:

- The effect of high-power arcs on the interior and on the surface of the transformer
- The effect of adjacent fires on the transformer and an analysis of the gases from the fire

Standard versions of 800-kVA transformers were selected for these tests.

The low fire load of GEAFOL cast-resin transformers stems from the fact that over 90 percent of their weight is contributed by metallic materials such as electric sheet, aluminum and steel, and less than ten percent by insulating materials. Moreover, only about half of the mass of the insulating materials is combustible, while two-thirds of the cast-resin insulation consists of silicon dioxide (SiO_2) – in other words, of very fine quarz sand. The bottom line: Less than five percent of the total weight of a GEAFOL cast-resin transformer is contributed by combustible materials.

Fire behavior tests in the presence of arcs

Internal transformer defects in cast-resin transformers – such as shorts between turns, coil shorts, rarely flashovers (phase-phase or phase-ground) or disruptive discharges from the higher-voltage winding to the lower-voltage winding – can cause short-circuit arcs with temperatures of up to 10,000 °C that affect the insulating materials. The duration of such arcs is limited by fusegear that is located upstream to the transformer and typically has a break time of less than 0.3 seconds.

To evaluate the behavior of the cast-resin transformer in the presence of arcs, arc tests were conducted on an 800-kVA GEAFOL transformer at the high-power test station of Forschungsgemeinschaft für Hochspannungs- und Hochstromtechnik e.V., a testing laboratory in Mannheim, Germany. The test conditions were more demanding than conditions encountered in actual practice. Tests 1 and 2 posed the following conditions:

- Three-phase HV terminal short circuit, triggered by an igniter wire
- Short circuits of 0.5 second and 2 seconds duration
- Transformers at operating temperature (windings in the short circuit heated to nearly 100 °C)
- Short circuit power 150 MVA.

Figure 4 shows the transformer with the igniter wire poised directly beneath the delta connecting block, as well as the arc during the short circuit and the transformer after the two-second short circuit. Exposed to the heat of the short-circuit arc, some of the resin components of the cast-resin molded material were consumed by fire in a thin surface layer. What remained in place there was a quartz powder structure and traces of carbon black, with the quartz powder layers created by the fire providing a protective effect for the deeper resin layers. At the base points of the arc on the metallic terminals, the conductor material partially melted and vaporized. Once the arc collapsed, no residual burning of insulating materials was visible. This was also confirmed by films made with high-speed cameras. Despite the visible surface damage, the transformer remained functional.

Following the two arc test, the transformer was subjected to two additional tests: Holes were drilled into the HV windings of all three phases, then six-millimeter-thick nails were inserted and connected to igniter wire, with the object of creating direct short circuits at individual turns and windings. The result was the same: Although on phase U a portion of a HV coil was actually blown off by the extremely high forces of the short circuit, no ignition or subsequent burning of the cast-resin molded material or other insulation portions was induced, even by these rigorous measures.

Fire behavior tests with wood and propane fueled fire

As early as in 1983, fire behavior tests had been conducted with an 800-kVA GEAFOL cast-resin transformer in the fire test building at the Allianz Center of Technology in Ismaning, near Munich. To study the fire behavior, the test objects were exposed to two types of fire: external fires fueled by wood and external fires fueled by propane gas. These direct exposures to different external fires were designed to emulate the exposure of transformers to different patterns of flames. The wood-fueled fire – set up on the floor of the fire test building – exposed the test transformer on a relatively broad front, but its impact on the insulating materials of the windings was partially impeded by local shielding provided by the iron core and portions of the frame. On the other hand, the flames of the propane gas burner exposed the lower area of the windings directly and unimpeded.

The second test setup exposed the transformer to the most severe test. Though the overall extent and scope of the fire was greater with the wood fire than in the propane fire, the fire damage was clearly greater with the propane gas. The transformer was fitted at the core, LV- and HV-windings with a total of 16 high-temperature resistant nickel chrome-nickel thermocouples, in a symmetrical arrangement of eight thermocouples each for both tests. The firewood used for the external wood fire consisted of ten kilograms of untreated fir wood, stacked bonfire-fashion directly under the W transformer leg and ignited with the aid of excelsior. The calorific value of the applied amount of fir wood amounted to about 188 MJ and temperature of the flames ranged up to 1000 °C.

In the setup with the propane gas fire, eight propane gas burners with a broad flame pattern were arranged equidistantly around the base so as to evenly flame the underside of the HV winding of the U leg. The

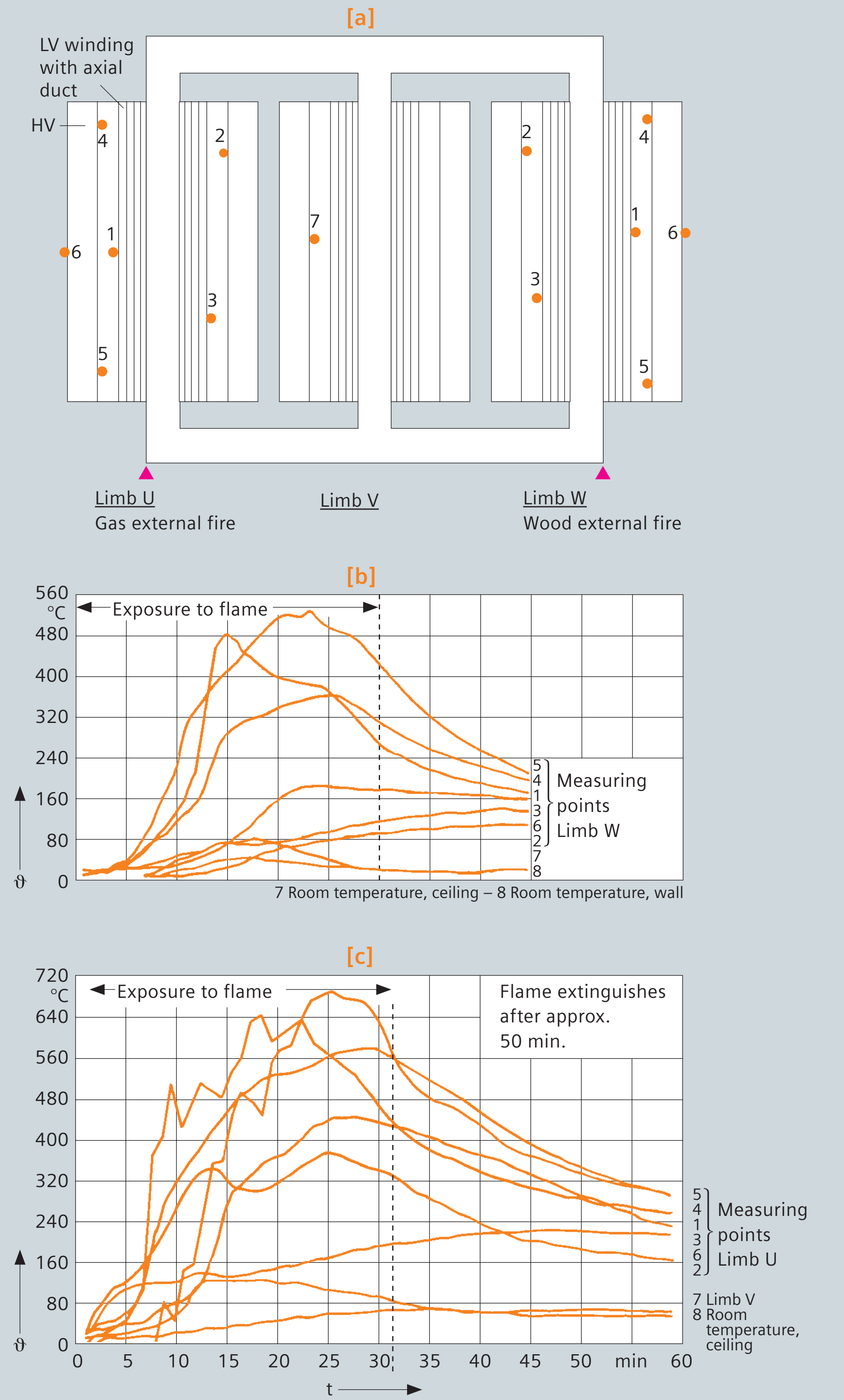

Figure 5: Temperature-time relation at the test transformer during the course of the fire:
a) Location of the thermocouples at the transformer
b) Test 1 with external wood fire
c) Test 2 with external propane gas fire

distance of the burner from the lower edge of the coil was about 60 millimeters, the flame orientation about 45°, and the flame temperature ranged up to 1200 °C. The external flame was maintained for 30 minutes. The measured gas consumption during that time amounted 2,400 grams. At a specific calorific value of 46,340 kJ/kg this corresponds to a total calorific value of about 111 MJ. The variation of the temperature over time at the windings of the transformer reflects the course of the fire with the wood setup and the propane gas setup, respectively (Figure 5).

Under the prolonged effect of the high temperatures of the external fire, the insulating materials of the LV and HV windings ignited, and due to the draft effect of the axial channel in the LV winding and of the leakage channel, more intense combustion with a visible flame occurred above the transformer (Figure 6). Noteworthy was the fact that the outer surface of the HV winding was set afire only in the immediate area of the external fire, and that the fire spread only minimally to the adjacent transformer leg.

Figure 6: Combustion sequence during exposure to flames of the external wood fire:
The outer surface of the HV winding was ignited only in the immediate area of exposure to the external fire, and hardly any fire spread to the adjacent leg.

Figure 7 shows the fire behavior of the transformer in a temporal sequence during the test with the external propane gas fire. The fire and the visible flame were more intense than in the wood fire. Nevertheless, the flame action diminished immediately after the propane gas burner was shut off, and self-extinguished completely in about 20 minutes.

Burning portions of the insulation self-extinguished after removal of the external energy input. The hard-paper component of the support blocks continued to burn with small flames. Surfaces exposed directly to the flames were severely affected, while adjacent portions of the insulating material remained largely undamaged. Even in the leakage channel, the fire did not spread horizontally – despite the extremely abundant input of oxygen (Figure 9).

In Figure 9 is it is clearly evident that the aluminum of the LV winding of the U leg has been heated to a level exceeding the melting temperature. In addition, the overall view of the HV windings shows that the fires at the outer legs did not spread to the center leg in substantial degree (Figure 8).

Figure 8: Condition of the test object after the fire behavior test: The overall view of the HV windings also shows that the fires at the outer legs did not spread to the center leg in substantial degree.

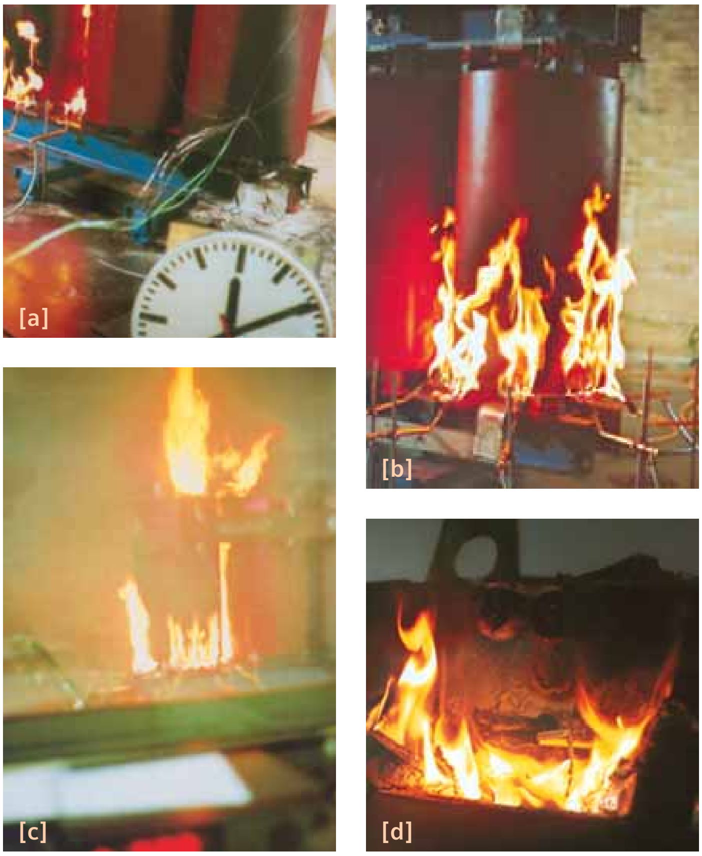

Figure 7:
Combustion sequence during exposure by the external propane gas fire.
a) After six minutes
b) After eight minutes
c) After 20 minutes
d) After 33 minutes

Figure 9: LV windings after the fire behavior test: Surfaces exposed directly to the flames were severely affected, while adjacent portions of the insulating material remained largely undamaged. Even in the leakage channel the fire was did not spread horizontally – despite the extremely abundant input of oxygen.

Flue gas:
sample collection and analysis results

The fire room where the tests were conducted has a floor space of four by four meters and a height of 4.1 meters. It was ventilated by fresh air blown through one firewall, with the flue gas exhausted through opposite firewall. This is where the 3-cm-thick pipe for the collection of the flue gas samples was located. The pipe ran up vertically the entire height of that wall and was equipped at 50-cm intervals with apertures about 10 square centimeters in size to admit the flue gas. Located in these apertures were storage filters. The flue gases were extracted by a membrane pump, and pumped at a rate of 30 liters per minute directly to the gas chromatography mass spectrometer. The line was about 25 meters long. During the measurement, the line and the membrane pump were heated to 200 °C. Ten microliters of flue gas were collected at 20-second intervals through a split system and a gas metering device for online measurement. A capillary gas chromatograph installed here was used only as an interface for the mass spectrometer, not for the preliminary separation of the combustion gases. At approximately one-second intervals, mass spectra in the range from m/e = 12 to m/e = 650 were obtained and stored (m/e: mass-charge ratio).

Concurrently with the online registration of the mass spectra, gas samples were withdrawn for the quantitative analysis of the flue gas components (gas collecting tubes). Table 1 summarizes the mass-spectrometric results of the combustion gas analyses and shows the qualitative composition of the combustion gases from the online analysis as a relative function of the maximum peak CO_2 intensity = 100 %.

m/e	Molecular or fragment ion		Isotope ratio		Maximal peak intensity²⁾ %	
					Wood fire	Gas fire
22	CO_2^{2+}	Carbon dioxide, double charged			0.27	0.34
25	C_2H^+	Fragment ion of azetylene			0.025	0.03
26	$C_2H_2^+$	Azetylene			0.18	0.17
44	CO_2^+	Carbon dioxide	$^{12}C_{100}$	$^{16}O_{100}$	100	100
45	$^{13}CO_2^+$	Carbon dioxide isotope	$^{13}C_{1.12}$		1.81	2.17
46	$C_2H_5O^+$	Fragment of Ethanol				
	$^{12}C^{16}O^{18}O$	Carbon dioxide isotope		$^{18}O_{0.204}$	0.65	0.75
	$C_2H_6O^+$	Ethanol				
50	$C_4H_2^+$	Aromatic fragment			0.02	0.02
78	$C_6H_6^+$	Benzene			0.06	0.06
91	$C_7H_7^+$	Toluene fragment			0.05	0.04
92[1)]	$C_7H_8^+$	Toluene			0.03	0.02

Table 1: Mass spectroscopy of the combustion products of a cast-resin transformer
1) For m/e larger than 92, no data that meet the specified premises
2) CO_2 peak set = 100 %

The course of the fire can be tracked by the intensity of the molecular ions of carbon dioxide CO_2^+ (mass-charge ratio m/e = 44; Figures 10 and 11). Carbon dioxide is therefore used as the target gas for the evaluation of the course of the fire.

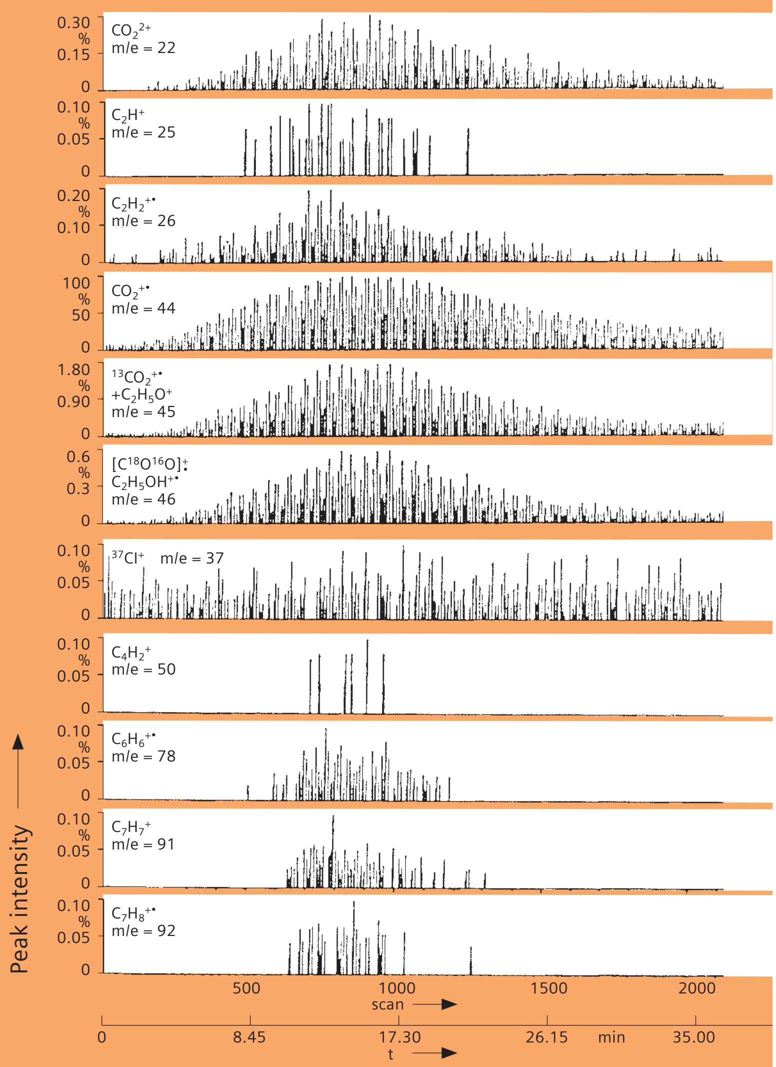

Figure 10: Mass chromatogram during exposure to the external wood fire (Scan 1 TO 2278. During this test 2,278 gas samples were obtained)

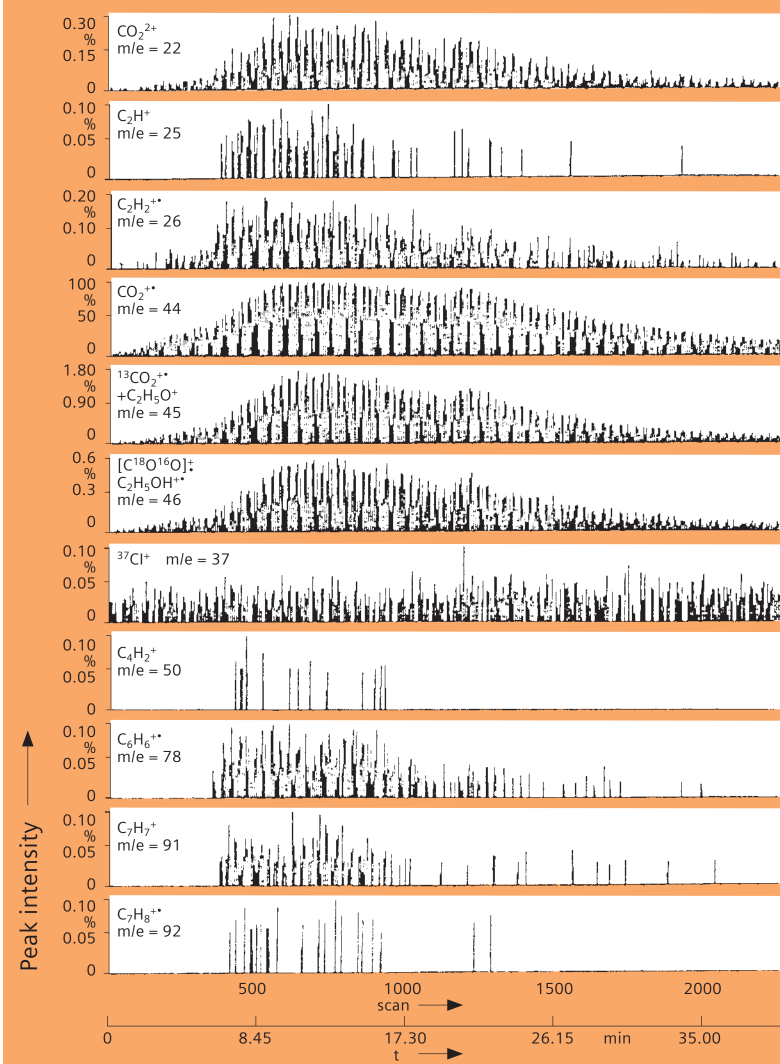

Figure 11: Mass chromatogram during exposure to the external propane gas fire (Scan 1 TO 3534. During this test 3,534 gas samples were obtained)

An exposure of the transformer to external flames can only generate the kind of molecular ions and fragment ions that exhibit behavior analogous to that of CO_2 in the mass chromatogram, in other words, ions whose concentration increases after ignition of the combustion. On the other hand, the $^{37}CL^+$ ion for example appears even in the initial mass spectra: Its concentration is independent of the course of the fire. That leads to the conclusion that chlorine ions do not originate from combustion gas components but from chlorine-containing contaminants in the air.

Table 2 shows the results of the quantitative analysis of the gas samples from the gas collecting tubes. As expected, during the exposure to the external propane flames an increased proportion of carbon dioxide was observed, and otherwise only small amounts of azetylene, besides the components of the air. The combustion gases during the exposure to the external wood fire, on the other hand, also contained ethylene, benzene, toluene and ethyl benzene. However, at least benzene and toluene could not be caused by the wood fire alone, since both these components were also shown to be present in the online tests of the combustion gases during exposure to the external propane flames. The carbon monoxide content was determined through gas chromatography. The highest carbon monoxide content found in the tested gas sample from a gas collecting tube was 0.044 milliliter per 100 milliliters.

Component	Gas collecting tube no.							
	Wood fire				Propane gas fire			
	1	3	6	8	9	11	14	16
Water	0.17	–	–	–	–	–	0.13	–
Azetylene	–	0.003	0.002	0.002	0.003	0.005	0.004	–
Nitrogen	82.6	78.9	78.9	75.0	79.4	79.6	79.3	79.7
Carbon monoxide	0.003	0.01	0.012	0.08	–	0.012	0.013	0.003
Ethylene	0.005	–	0.005	–	–	–	–	–
Oxygen	15.4	18.8	18.9	23.4	19.4	18.1	17.9	19.2
Argon	1.29	0.95	0.99	1.19	0.92	0.90	0.92	0.92
Propene	0.001	–	–	–	–	–	–	–
Carbon dioxide	0.56	1.40	1.29	0.43	0.29	1.36	1.67	0.15
Butene	0.0002	–	–	–	–	–	–	–
Benzene	0.002	0.001	0.003	–	–	–	–	–
Toluene	0.001	0.001	0.002	–	–	–	–	–
Ethylbenzene1)	0.0009	–	–	–	–	–	–	–

Table 2: Concentration of combustion gas components in the gas collecting tubes (evacuated glass vessels), stated in ml per 100 ml
1) No larger molecules than ethyl benzene were detected.

Combustion products "under the looking glass"

The measurements showed that the GEAFOL cast-resin molded material contains very small quantities of chorine-containing compounds as impurities that result from the production of the epoxy resin by the conversion of bisphenol A with epichlorohydrin.

To make absolutely certain that the combustion products do not contain the toxic substances 2,3,7,8-Tetrachlorodibenzodioxin (TCDD) and 2,3,7,8-Tetrachlorodibenzofuran (TCDF) which can occur during pyrolysis of askarel, the resin molding compound was burnt in the Bayer-ICI-Shell apparatus (pyrolysis temperature 600 °C) and the combustion products examined for presence of these two substances.

This was done by capturing the combustion products in a filter and in methanol as an absorption solution. The extract from the filter was combined with the absorption solution, known quantities of 2,3,7,8-TCDD and 2,3,7,8-TCDF were added to part of this solution which was examined like the second half of the test solution using gas chromatography. The chromatograms are shown in Figure 12. They show that 2,3,7,8-TCDD and 2,3,7,8-TCDF are not contained in the combustion products. The detection limit is 0.05 µg/g.

Comments on the results

The tests with short-circuit arcs induced by an external source of ignition on the outer surface of the GEAFOL transformers as well as within demonstrated that the cast-resin transformer cannot be caused to ignite even by extreme exposure to highly energetic arcs. However, an external fire that spreads to the transformer can ignite the insulating materials. But when the ignition source is removed, the resulting flames self-extinguish without significant horizontal propagation of the combustion. It can be concluded that the cast-resin, dry-type transformer cannot self-ignite due to highly energetic arcs, and that the course of the fire, when the transformer becomes involved in an external fire, does not intensify significantly, i.e. no more than due to the low fire load. In the combustion gases formed by the burning of this transformer only benzene, toluene and methylbenzene were demonstrated besides carbon monoxide – but no typical, specific components that could be attributed to the cast-resin mixture.

The toluene and methylbenzene contents amounted to ten percent of the then applicable maximum workplace concentration (MAK value) – in the safe range if one considers that in this case the MAK values are being compared to short-time effects during the course of the fire. Even four times the technical guideline concentration (TRK value) of benzene is not hazardous in this context. During the new tests in 2005, the measured emission values were far below the then permissible workplace limits (which replaced MAK in that year).

The only relevant toxic component generated by the burning of the cast-resin transformer appears to be carbon monoxide. But carbon monoxide is a gas that is commonplace in fires. A laboratory test demonstrated, on the other hand, that the two highly toxic substances, namely 2,3,7,8-Tetrachlorodibenzodioxin and 2,3,7,8-Tetrachlorodibenzofuran, are not formed in the combustion of a cast-resin transformer.

The results of these extensive tests, then, support the conclusion that the operation of GEAFOL cast-resin transformers in electrical systems does not create any risks of significantly intensifying a fire or risks of toxicity that exceed the normal risk in residential or industrial fires.

What's more, the excellent fire behavior of GEAFOL cast-resin transformers is not only validated by tests: GEAFOL transformers, which Siemens manufactures in the range from 50 kVA to 40 MVA, have proven by the thousands, in many years of worldwide use, that they work safely, economically and reliably, even under difficult conditions.

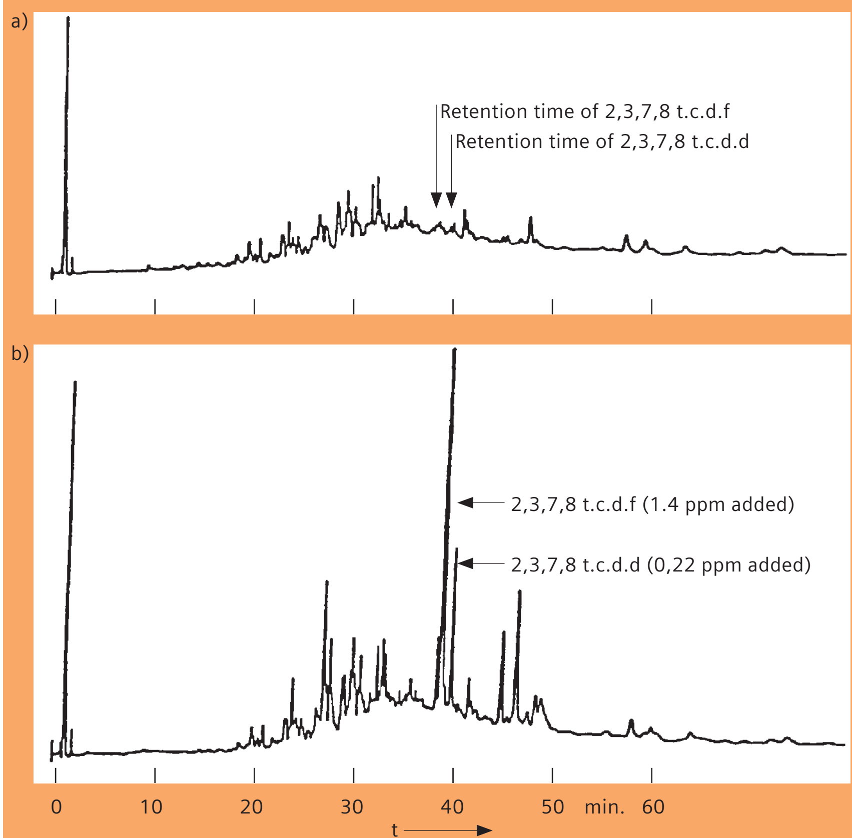

Figure 12: Gas chromatograms of the products of combustion from the resin moulding compound (Bayer-ICI-Shell apparatus; pyrolysis temperature 600 °C
a) from cast resin (aliquot par after sample evaluation)
b) from cast resin (aliquot par after sample evaluation, with addition of 1.4 ppm of 2,3,7,8 tetrachlorodibenzofuran and 0.22 ppm of 2,3,7,8 tetrachlorodibenzodioxin before sample evaluation).

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