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Article citation: Fjeld, E., & Hagen, S. T. (2015). Small scale arc fault testing of medium voltage metal enclosed switchgear. *IEEE Transactions on Power Delivery*(99). doi: http://dx.doi.org/10.1109/TPWRD.2015.2482002

Small-Scale Arc Fault Testing of Medium Voltage Metal Enclosed Switchgear

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***Abstract*—Internal arc fault tests are important for ensuring the safety of medium voltage metal enclosed switchgears. As these tests are conducted at full-scale, the costs of the test objects as well as the high power laboratory are significant. This paper presents an experimental study to clarify whether such tests can be simplified by downscaling. Tests with volume and energy downscaled to 1/3 and 1/10, respectively, were performed on a single-phase arrangement with air as the insulating gas. The test results showed that the internal pressure rise caused by the arc can be reproduced well using a smaller compartment and a lower current. The potential damage caused by the exhaust of the hot gas escaping through the pressure relief openings is more challenging to predict from small-scale tests.**

***Index Terms*—Arc energy, electrode erosion, internal arc, metal enclosed switchgear, pressure rise, single-phase, small-scale experiments, thermal hazard, thermal transfer coefficient.**

I. INTRODUCTION

To prove that a switchgear is safe in the event of an arc fault, manufacturers must test the product in a high power laboratory. Although it is generally assumed that arc faults in electrical equipment are rare, internal arc fault testing is a common testing procedure due to the severe consequences for personnel, the general public, equipment, and structures.

IEC Standard 62271-200 for metal-enclosed switchgear and control gear, up to and including 52 kV, specifies how to perform an internal arc fault test. During the test, the pressure withstand capability of the switchgear is tested as well as the discharge of hot gases to the environment, as improper gas discharge may endanger persons in the vicinity.

During a development project, internal arc tests require several weeks for each test loop. The tests are conducted at full-scale, and the costs of the test objects and of the high power laboratory are significant. It is easier to access laboratories able to perform small-scale tests. If small-scale experiments could be performed as an alternative and used to predict the results of the full-scale test, then it may be possible to reduce the number of test loops needed at full-scale, which will reduce development time and costs.

Only a few studies in the literature have examined small-scale internal arc fault testing. Granheim et al. [1] and Daalder et al. [2] performed full-scale experiments with a three-phase AC voltage source and model experiments with DC. In both studies, the pressure rise caused by the three-phase fault in a full-scale compartment was difficult to reproduce with a single-phase fault in a small-scale model. Zhang et al. [3] performed arc fault tests using varying sizes of the test vessel. Iwata et al. [4] performed tests with varying test current. They found that the volume and current considerably influenced the test result.

Based on this previous experience in scale-down [1]-[4], the present investigation seeks to evaluate scaled-down experiments that are performed by reducing the size of the test object and the arc energy. This could be equivalent to the scaling of the blast effect in explosions [5]. The main scaling rule is thus to maintain a constant energy per unit volume.

The investigation was conducted in two steps. First, initial experiments were performed in open air to investigate the scaling of the arc energy. Then, down-scaled experiments were performed with the arc burning in an enclosure. Both full-scale tests and small-scale tests were performed with a single-phase AC voltage source, and all tests were conducted at the NEFI High Power Laboratory in Norway. Portions of the results have previously been presented at conferences [6], [7].

II. BACKGROUND

The electric arc represents the energy source in the enclosed volume of the switchgear. During an internal arc fault test, the arc energy is a function of both the applied test current and the arc voltage, where the latter one depends on the experimental setup. For a single-phase arc, the electric energy input is given by

$$W_{arc}(t) = \int_0^t i(\tau) u_{arc}(\tau) \mathrm{d}\tau \qquad (1)$$

where t is the time after arc initiation, and i and u_{arc} are the momentary test current and arc voltage, respectively. The arc voltage depends mainly on the test current [8], the arc length [9], [10], and the cooling of the arc column.

Some of the arc energy will be absorbed by the surrounding gas, causing the pressure inside the switchgear to increase. The switchgear enclosures should be designed with sufficient mechanical strength to withstand the resulting pressure rise. By assuming an ideal gas and that the energy input causing

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Manuscript received 02-Oct-2014, revised 16-Jan-2015 and 06-May-2015, accepted 29-Aug-2015.

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overpressure (W_{in}) is uniformly distributed in the enclosed volume, the pressure rise can be estimated from the following:

$$\Delta p(t) = \frac{\kappa - 1}{V} W_{in}(t) = \frac{k_p(\kappa - 1)}{V} W_{arc}(t) \qquad (2)$$

where κ is the adiabatic index, with a value of 1.4 used for air. k_p is a thermal transfer coefficient introduced in the literature (e.g., [11]) to describe the part of the arc energy that is transferred to the gas:

$$k_p = \frac{W_{in}}{W_{arc}} \qquad (3)$$

Usually the k_p factor is found by measuring the pressure rise in the arc compartment and adjusting k_p based on the best fit with (2). It should be noted that (2) calculates the pressure rise due to an increase in the mean gas temperature. This is only valid below the dissociation temperature of the gas, i.e., about 6000 K for air [12], which is lower than the temperature of the arc plasma.

It is possible that metal vapor from the electrode erosion may react chemically with components of the insulating gas, depending on the electrode material. Limiting the electrodes to Cu and Al and the surrounding gas to air (i.e., oxygen), the following oxidation processes may occur [13]:

$$Cu + \tfrac{1}{2} O_2 = CuO + 157 \text{ kJ/(mol Cu)} \qquad (4)$$
$$Cu + \tfrac{1}{4} O_2 = \tfrac{1}{2} Cu_2O + 84.5 \text{ kJ/(mol Cu)} \qquad (5)$$
$$Al + \tfrac{3}{4} O_2 = \tfrac{1}{2} Al_2O_3 + 838 \text{ kJ/(mol Al)} \qquad (6)$$

The energy shown on the right hand sides of (4) through (6) is the molar enthalpy of formation used to calculate the chemical energy released during exothermic reactions. This energy is calculated from the solid material and includes the energy required to increase the temperature of the material as well as the melting and vaporization energies.

III. INVESTIGATIONS OF THE ARC ENERGY IN OPEN AIR

The main objective of this work was to investigate whether small-scale arc fault testing can be made possible by reducing the size of the test object and the arc energy. The arc energy can be scaled by reducing the test current or the electrode gap. Initial experiments were performed to examine how variations in the test current and the electrode gap influence the arc energy.

During an internal arc fault test, an arc was ignited inside the switchgear compartment. However, the initial experiments were performed in open air in order to save time and costs, as only the electrodes had to be changed before a new test.

Fig. 1 shows the simple single-phase arrangement built for the initial experiments. The basis was two horizontally opposed rod-shaped electrodes with 20 mm diameter. The electrodes were separated with a gap, g, which could be varied from 17 to 200 mm. Each electrode was attached to a Cu bar by two metal clamps. Some 36 kV support insulators separated the Cu bars from the nonmagnetic aluminum U-profile that was used to secure the arrangement to the concrete surface.

The current was fed to the Cu bar on one side, and the other Cu bar was connected to the ground potential. The arc was ignited between the electrodes by a thin copper wire with a diameter of 0.5 mm.

The magnitude of the circuit voltage was chosen to ensure the arc reignited after each current zero (power factor less than 0.17 ind.). The arc duration was 1 s, which is typical for internal arc fault testing of medium voltage (MV) switchgears in Europe.

The arc voltage and current were measured and recorded by the metering system of the laboratory. The arc energy was calculated using (1), and the accumulated arc energies during the 1 second arc ($W_{tot} = W_{arc}(t = 1\text{s})$) are presented in Figs. 2 and 3.

Fig. 2 shows that the increase in arc energy is more than proportional with the test current. This is a result of the fact that the electrode erosion increases with test current, as reported in [6]. Then, the arc length and hence the arc energy will increase. Al electrodes appear to have a steeper increase in arc energy with current than Cu electrodes, because the Al electrode gap increases more when the current is increased [6]. The equations given in Fig. 2 are achieved by quadratic regression based on the very few test cases, and are only valid within the limits of the given experimental setup.

Fig. 3 shows that the increase in arc energy is almost linear with the initial electrode gap. The equations given in the figure are achieved by linear regression. The equations are based on few test cases and are only valid for the given experimental setup. E.g. if the gap size is further reduced from 17 mm, the arc energy will eventually deviate from the linear line and eventually reach zero.

Some test setups with Cu electrodes were repeated 5-7 times to investigate the reproducibility of the arc energy. This is reported in [14]. These tests were assumed to be identical, independent, and Gaussian distributed. The number of identical tests is insufficient for a reliable statistical analysis, but the results indicated good reproducibility with a standard deviation less than 2% [14]. The deviation in arc energy was found to decrease somewhat with increasing test current.

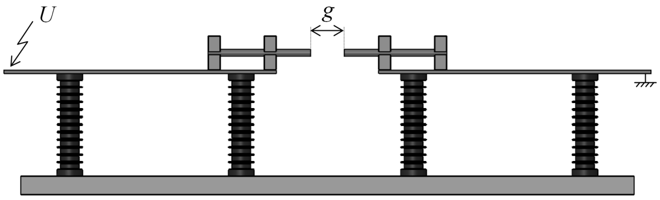

Fig. 1. Schematic of the test arrangement in open air. The arc burns between electrodes separated by a gap g.

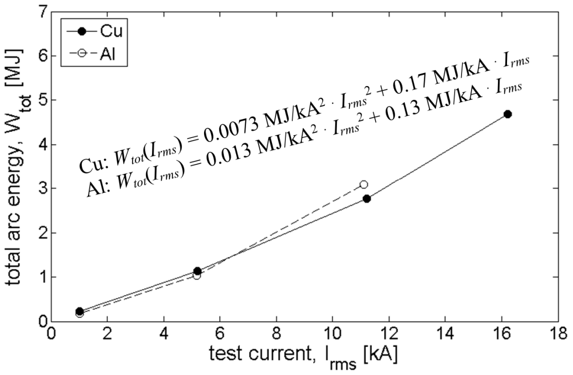

Fig. 2. Total arc energy, W_{tot}, as a function of test current, I_{rms}, for Cu and Al electrodes with 20 mm diameter and a gap of 100 mm. The equations are achieved by quadratic regression and are only valid for the given experimental conditions.

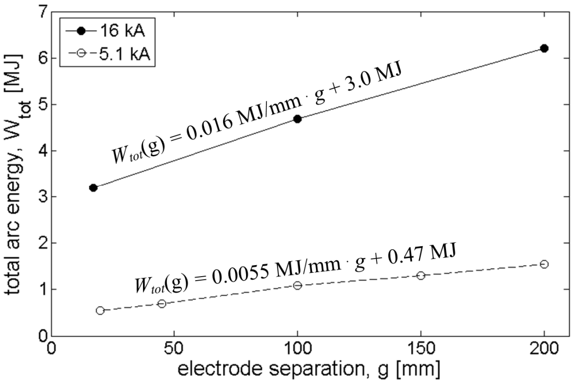

Fig. 3. Total arc energy, W_{tot}, as a function of initial electrode gap, g, for two different test currents. Cu electrodes with a diameter of 20 mm. The equations are achieved by linear regression and are only valid for the given experimental conditions.

IV. PRESSURE BUILDUP DUE TO ARC IN ENCLOSURE

Down-scaled tests were performed with arcs in enclosures. The purpose was to determine if small-scale tests can be used to reproduce the pressure rise caused by the full-scale arc fault. The small scale was achieved by reducing the size of the test object and the arc energy to provide a constant specific energy input.

Hot gases released to the outside of the enclosure during pressure release may endanger nearby personnel. Temperature measurements were obtained as part of an initial investigation to predict this thermal effect at a small scale.

A. Experimental

A simplified full-scale prototype was constructed as a cubic container with volume V_P = 0.343 m^3, corresponding to a typical SF$_6$-insulated medium voltage switchgear. The cubicle was made of 4 mm thick welded steel plates to avoid the risk of rupture due to pressure rise. The cubic container will herein be denoted as the “arc compartment.” Air at atmospheric pressure was used as the insulating gas inside the arc compartment, as IEC Standard 62271-200 permits replacing SF$_6$ with air during testing.

Two small-scale arc compartment models were built with scaling factors of approximately 1/3 and 1/10, as illustrated in Fig. 4. The volumes of the model compartments are given by

$$V_{M1} = 0.118\ \text{m}^3 \approx 1/3\ V_P \tag{7}$$
$$V_{M2} = 0.0359\ \text{m}^3 \approx 1/10\ V_P \tag{8}$$

where V_{M1} is the volume of small-scale model 1 (M1), and V_{M2} is the volume of small-scale model 2 (M2).

The test objects were equipped with pressure relief discs with a relative burst pressure p_{burst} = 1.6 bar. The opening area of the discs was 110 mm in diameter. Due to practical limitations, the three different arc compartments were equipped with the same pressure relief discs. Each of the two model compartments was equipped with one disc. The prototype compartment was equipped with two discs to be sure the pressure relief was effective enough to prevent rupture of the arc compartment. The pressure relief openings are indicated in Fig. 5. The incorrect scaling of the opening areas will not affect the pressure build-up or the k_p-calculations. However, the pressure decrease is not expected to be the same for all scales.

A linear, single-phase electrode arrangement, as used in the initial experiments, was placed into the compartment by means of 36 kV insulated bushings (Fig. 5). An arc was ignited in the electrode gap using an ignition wire. The electrodes were rod-shaped with a diameter of 20 mm, and they were made of either Cu or Al.

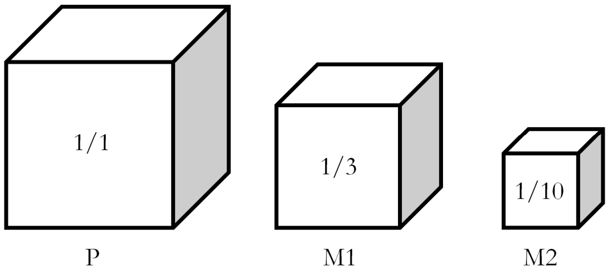

Fig. 4. Arc compartment with three different volumes. Prototype (P) has a volume corresponding to a typical medium voltage switchgear.

TABLE I
CONDITIONS FOR TESTS PERFORMED IN AN ARC COMPARTMENT

Test no.	Arc comp.	V [m^3]	Electr. mat.	g [mm]	I_{rms} [kA]
1	P	0.343	Cu	100	15.3
2	P	0.343	Al	100	15.5
3	M1	0.118	Cu	100	6.75
4	M1	0.118	Al	100	7.16
5	M1	0.118	Cu	20	10.1
6	M2	0.0359	Cu	100	2.03
7	M2	0.0359	Cu	20	4.01

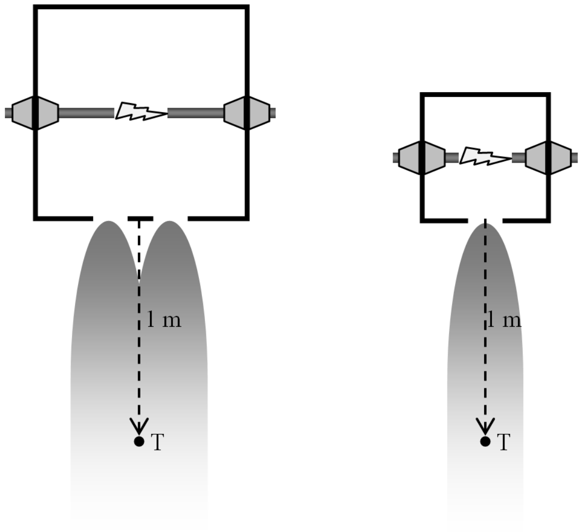

Fig. 5. Cross-section of the arc compartment and gas exhaust. A temperature sensor was located 1 meter from the pressure relief opening(s). The left figure represents the full-scale prototype (P) with two pressure relief discs, and the right figure represents the small-scale model compartments (M1 and M2) with only one relief disc.

To maintain constant energy per unit volume during scaling, the arc energy should be scaled by the same factor as the volume [5]. The energy during a certain time period depends on the test current and the arc voltage or the electrode gap. According to the scaling factors for the volume given in (7) and (8), the electrode gap for M2 should have been set to 100 mm $/\sqrt[3]{10} =$ 46 mm. However, as the arc is burning, the electrode gap increases due to erosion, and the relative increase depends on the applied current [6]. Based on the few tests available from the experiment in open air, it is not possible to predict the initial gap and test current that will give the proper scaling of the mean gap *and* the arc energy. Instead it was decided to scale the arc energy by changing only one parameter (test current or electrode gap) at a time. Fig. 3 shows that it is not practical to reduce the arc energy by 1/10 or even 1/3 by only reducing the electrode gap and keeping the test current constant. Two different electrode gaps were thus chosen: 20 and 100 mm. The test current was reduced to give the desired scaling of the arc energy, based on the results from the initial experiments. An estimate of the current needed was made based on Figs. 2 and 3, and a value achieved by the laboratory within ± 0.5 kA was considered acceptable. Table I summarizes the different test conditions.

The pressure inside the arc compartment was measured with a piezoresistive pressure sensor from GE Druck, type UNIK 5000, model PTX 5072-TB-A1-CA-H0-PN. The sensor was placed in the ceiling of the arc compartment.

To assess the thermal effect of hot gases released to the outside of the enclosure during the internal arc fault testing, special black cotton cloth indicators were used to simulate clothing or skin. According to IEC Standard 62271-200, one pass-fail criterion of internal arc tests is the absence of ignition of such cotton indicators positioned in the gas exhaust. Smeets et al. [15] reported this to be the most critical pass/fail criterion. The flammability of these cotton indicators is to a certain degree subject to statistical randomness [16]. Thus, as an alternative to testing whether flammability can be predicted from small-scale tests, temperature measurements were performed with a thermocouple placed 1 meter from the pressure relief opening (see Fig. 5). The distance to the temperature sensor could not be scaled according to the rules of geometrical similarity, as the opening area of the pressure relief discs was not scaled (same discs used for all models). The distance was thus kept constant, and the measurements should be regarded as a first step to assess the possibility of scaling the thermal effects of an arc fault.

B. *Results*

The results of the tests performed in arc compartments are summarized in Table II. W_{open} is the accumulated arc energy up to the time when the pressure relief discs open. Since the k_p factor is determined from the pressure rise until pressure relief, W_{open} is used when determining the scaling factor of the arc energy. The scaling factor is given by the fraction $W_{open,M}/W_{open,P}$, where $W_{open,M}$ and $W_{open,P}$ are the arc energies up to pressure relief for the small-scale model test under consideration and for the corresponding prototype test, respectively. As seen from Table II, the arc energy for model M1 had a scaling factor in the range 0.31–0.37, and model M2 had a factor in the range 0.10–0.12. The pressure relief discs opened after about 50 ms, which means that the arc energy will depend on the asymmetrical part of the current, i.e. where on the voltage cycle the current starts to flow. In addition, it is not possible to predict the exact value of the arc energy because of the random nature of the arc itself. The scaling factors of the arc energy are thus within typical limits for these kinds of experiments.

The measured pressure development inside the arc compartment is plotted in Figs. 6–8. Fig. 6 shows the result for Cu electrodes with a 100 mm gap for both prototype and small-scale models, while Fig. 7 provides the result for Cu when the electrode gap in the models was reduced to 20 mm. For model M2 in Fig. 7 (test 7), there was a malfunction of the pressure relief disc, and it did not open until the relative pressure reached 3.4 bar. The mass flow out of the pressure relief opening is higher at 3.4 bar than at 1.6 bar. It means that the pressure decrease in the beginning will be faster for test 7. The higher peak pressure means that the temperature of the enclosed gas is higher in this test compared to the other tests.

The results of the two tests with Al electrodes are displayed in Fig. 8. Only one of the two pressure relief discs opened in the prototype test with the Al electrodes, which accounts for the slower decrease in pressure.

Given the speed of sound and the size of the test

TABLE II
RESULTS FOR TESTS PERFORMED IN ARC COMPARTMENT

Test no.	Arc comp.	W_{tot} [kJ]	W_{open} [kJ]	$\frac{W_{open,M}}{W_{open,P}}$	k_p [-]
1	P	4530	284	1.0	0.46
2	P	5113	296	1.0	0.44
3	M1	1564	98.9	0.35	0.47
4	M1	1690	90.8	0.31	0.50
5	M1	1561	105	0.37	0.41
6	M2	424.5	28.6	0.10	0.50
7	M2	480.4	34.9	0.12	0.40

compartments, pressure equalization within the arc compartment occurs within about 1 ms. Thus, one can assume that the pressure in the arc compartment is practically uniform regarding the structural response, long before the pressure relief discs open. Measurements from the pressure sensor together with (2) were used to determine the k_p factor. The k_p factor providing the best fit to the measured values was found to be between 0.40 and 0.50 for all tests. The results are listed in Table II. The higher peak pressure in test no. 7 (Fig. 7) did not affect the calculation of the k_p-factor, as only values up to 1.6 bar was used for this.

Fig. 9 displays pictures of the jets escaping through the pressure relief openings. This is believed to be the plasma from within the compartment. The length of the jets decreases with scaling because the pressure inside the small-scale arc compartments will drop faster and because there is less plasma. The measured temperature in the gas exhaust is given in Fig. 10. It should be noted that the results might only be of qualitative nature because of the boundary conditions.

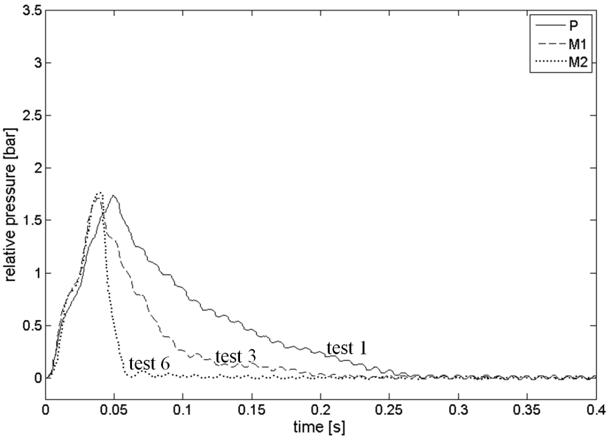

Fig. 6. Measured pressure inside the arc compartment as a function of time. Cu electrodes with 100 mm gap.

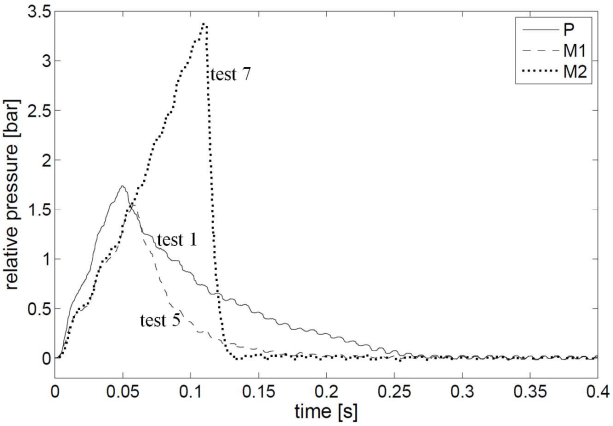

Fig. 7. Measured pressure inside the arc compartment as a function of time. Cu electrodes. Prototype (P) with 100 mm electrode gap. Small-scale models M1 and M2 with 20 mm gap.

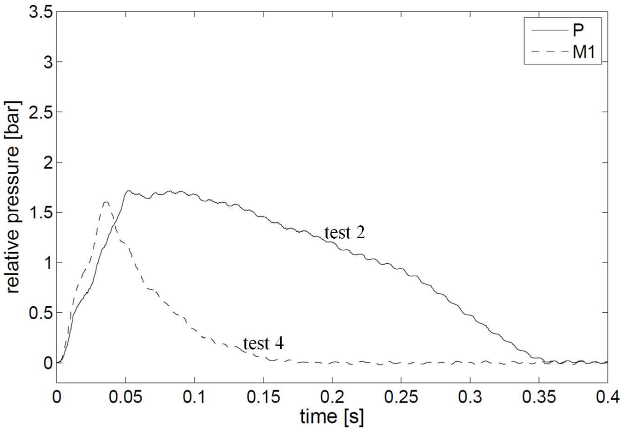

Fig. 8. Measured pressure inside the arc compartment as a function of time. Al electrodes with 100 mm gap.

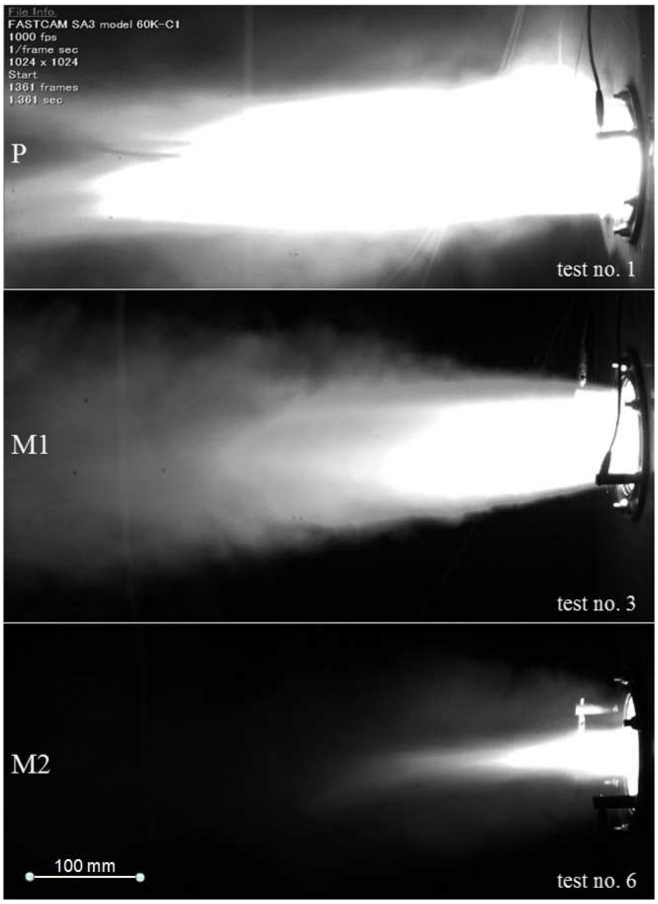

Fig. 9. The maximum extension of the glowing jets escaping from the pressure relief opening when using Cu electrodes. The length of the jets decreases as the scaling goes down.

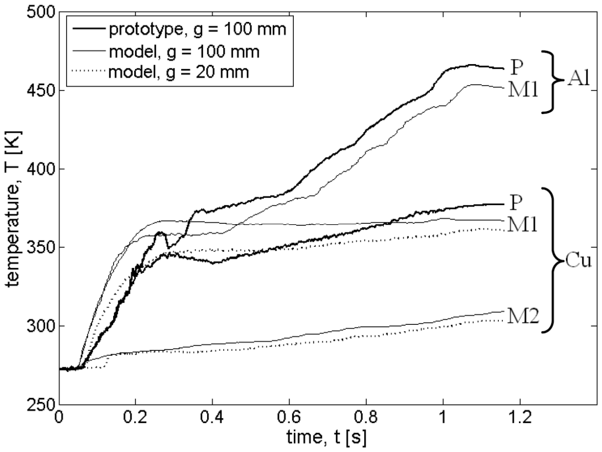

Fig. 10. Measured temperature in gas exhaust 1 meter away from the pressure relief opening(s). The temperature decreases with scaling. The temperatures when using Al electrodes was measured to be higher than those using Cu electrodes.

V. DISCUSSION

The arc energy for an arc burning in a compartment will not be exactly the same as that when the arc is burning in open air [14]. W_{open} was found to be somewhat higher compared to the energy at the same time (0.05 s) for the arc burning in open air. The increase is due to the increased pressure and agrees with observations made in [10]. However, the uncertainty when scaling the arc energy based on measurements in open air is small.

The experiments in the arc compartment were designed to investigate whether the scaling method of the arc energy (by reducing the test current and/or the electrode gap) has any influence on the pressure rise. From Figs. 6 and 7, it can be seen that the pressure rise was closer to that for the prototype in the small-scale tests performed by reducing the test current and keeping the electrode gap constant at 100 mm. Table II also shows a better match in the k_p factor for these tests compared to the tests where the electrode gap was reduced to 20 mm. This is because a higher fraction of arc energy is taken by the arc roots and is transferred to the electrodes for the shorter gaps.

Simulations of pressure rise using (2) showed that 40%–50% of the arc energy was transferred to the gas in both the full-scale prototype and small-scale model tests up to pressure peak (Table II). It is important to note that the conditions of (2) are far from the real situation, and changes in this factor do not necessarily reflect the real physics. First, the heating of the volume is not uniform, and the temperature will thus not be uniform during the 50 ms it takes to reach the peak pressure. Second, the temperature of the core of the arc is higher than the dissociation temperature, and here the pressure might increase without an increase in temperature. Despite these simplifications, the k_p factor was found to be almost unchanged during scaling. That might indicate that the arc volume (where dissociation occurs) is relatively small compared to the volume around the arc for all scales.

The reported experiments in the arc compartment represent single tests. A k_p factor of 0.46 is reported for the prototype test with Cu electrodes in Table II. However, data from five tests reported in [17] with the same experimental test conditions up to pressure relief gave a mean k_p value of 0.43. These results indicate that the variation in the k_p factor between identical tests may be of the same order as the difference in k_p factor between some of the different tests reported in this paper.

From Fig. 10, it appears that the temperature measured in the gas exhaust with the small-scale model M1 almost reaches the same temperatures as the prototype, while model M2 has a much lower temperature. This is believed to be due to the fact that the length of the plasma jet decreases as the scaling goes down, as seen in Fig. 9. This is because the pressure relief opening area was not scaled (same pressure relief discs used for all models). If the opening area was scaled correctly, the same temperatures might expect to be measured if the distance to the sensor was reduced according to the scaling (i.e. 69 cm for M1 and 46 cm for M2). However, effects other than the air entrainment will affect the temperature in the jet, as recombination of dissociated gases and chemical reactions between air and vaporized electrode material. The scaling of the amount of dissociated gases and vaporized electrode material is not known and are not necessarily according to the scaling factor. Further investigations are thus needed to conclude on this. Cotton indicators are used instead of temperature measurements in real arc fault tests. Then it is not enough that the small scale models are able to predict the temperature of the gas exhaust, and future measurements of the heat radiation are required.

The higher temperature measured in the case of Al electrodes is believed to be due to greater release of energy from the chemical reactions occurring in the diffuse boundary between the plasma jet and the surrounding air. From (4) through (6) it can be seen that the exothermic energy release from the oxidation of Al is more than 10 times greater per mole of fuel than the energy release with Cu. The possibilities of such reactions are assumed to be possible based on the measured electrode erosion [6].

Like any experimental investigation, there are practical limitations. Internal arc tests are time and cost consuming, which limits the number of test cases. The arc energy depends on many factors of the experimental design, and not all could be changed in a systematic way during the investigation. To be able to predict the arc energy in a reasonable way, some dimensions were not scaled according to the geometrical similarity, e.g. the electrode diameter and the electrode gap. In addition, the same pressure relief discs were used for all tests. It is important to bear in mind that the measured arc energies and temperatures reported are limited to the given experimental setup, and cannot be transferred to another setup. E.g. the k_p-factor might change if the freedom of motion of the arc is increased [14].

Despite these simplifications, the results show that it is possible to use small scale test models in a laboratory with limited short-circuit performance in an early stage of a development project to determine the pressure rise the enclosure must be designed to withstand. In this manner, small scale tests can be used to reduce development time and costs. So far, however, it seems like full scale high power laboratory facilitates are needed to assess the thermal part of an arc fault test. Future investigations are needed to conclude on this.

VI. CONCLUSIONS

The pressure rise measured in the model compartments was found to reproduce the pressure rise in the prototype with good accuracy. According to the simplified model where ideal gas and uniform heating of the gas volume is assumed, it was found that between 40%–50% of the arc energy was transferred to the gas (giving the pressure rise) in both the full-scale prototype and small-scale model tests. The experiments have thus shown that it is reasonable to assume an almost unchanged k_p-factor for all relevant conditions.

The ignition of cotton indicators is a complex process dependent on many factors that are not easy to control during scaling. It is believed to be challenging to predict the ignition from small-scale tests.

The results show that accurate downscaling is not simple and needs a lot of effort. Based on this, it is disputable whether downscaling is useful. Pressure calculations with a constant k_p-factor can be used with reliable precision to determine the pressure stress the enclosure should be designed to withstand.

ACKNOWLEDGMENT

The authors would like to thank ABB Power Systems Division in Skien, Norway, and the staff at NEFI High Power Laboratory for valuable help during the experiments.

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