TOOLS FOR THE SIMULATION OF EFFECTS OF THE INTERNAL ARC IN TRANSMISSION AND DISTRIBUTION SWITCHGEAR

Circuit Breaker and Bay Development (CB²D)
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SIMULATION OF EFFECTS OF THE INTERNAL ARC

Study framework

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- Introduction
- Basic model
- Application limits of the basic model
- Application examples (Air, SF6)
- Sensibility study
- CFD software usage
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- Air and SF6 usage
- Effects on structures
- Burn-through
- Conclusion

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Introduction

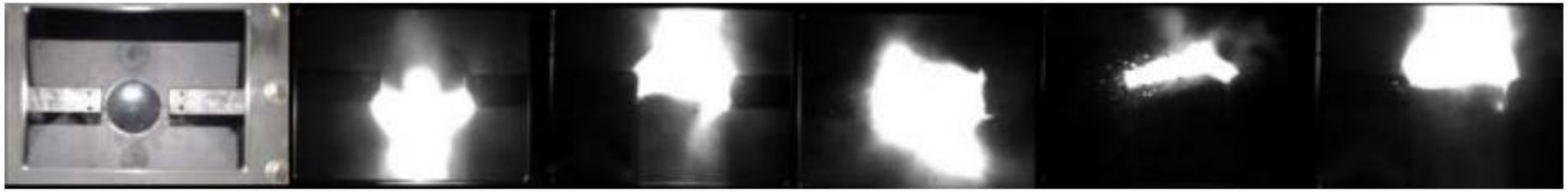


Figure 1-1: 13 kA electric arc moving between two conductors, at 5cm distance.

An internal arc fault = unintentional discharge of electrical energy within an enclosure.

The energy released from an electrical arc heats the SF6 gas or the air within the enclosure, resulting in a pressure rise

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Introduction

WG A3.24 : reviewing the existing literature (100+ white papers and applicable IEEE and IEC standards), and collecting the test data from numerous Internal Arc Tests.

Test data was collected for

- more than 70 different cases
- tank sizes ranging from small 5 l test tanks to large 1200 l GIS tanks
- fault currents ranging from 12 kA to 63 kA,
- with fault durations ranging from 10 ms to 1.2 s, both SF6 and air-insulated switchgear

Focus on 3 main effects of an internal arc:

- Pressure Rise
- Mechanical stress on enclosure and buildings
- Burn-through

Air can replace SF6 ?

SIMULATION OF EFFECTS OF THE INTERNAL ARC

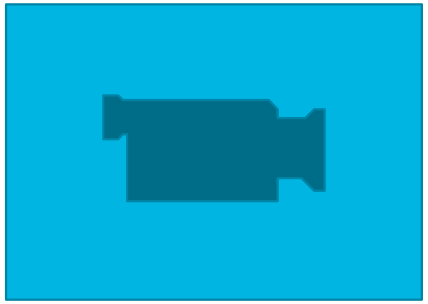
Introduction

Very rare event

Damage the electrical equipment and the switchgear buildings and endanger personnel.

Failures typically occur due to:

- external influences
- material or mechanical defects
- incorrect operation



SIMULATION OF EFFECTS OF THE INTERNAL ARC

Introduction

Physical impacts:

- **Pressure inside** a small closed enclosure (volume 200 liters) can accelerate to 12 bars in 4 cycles of power frequency during a 25 kA fault.

- **Arc temperature** can exceed 10,000 °C.

- **The arc energy** inside the arc compartment from a 25 kA fault for ¼ = 2 kg of dynamite.

- **Sound levels** can reach 160 dB (shotgun noise 150 – 160dB)

- **Debris** may travel at speeds up to 1000 km/h.

- **Resultant force** of the expelled gases : several tones on the walls

- **temperature of the hot gases** streaming out of an arcing compartment >1000 °C.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CALCULATION OF PRESSURE USING A BASIC MODEL

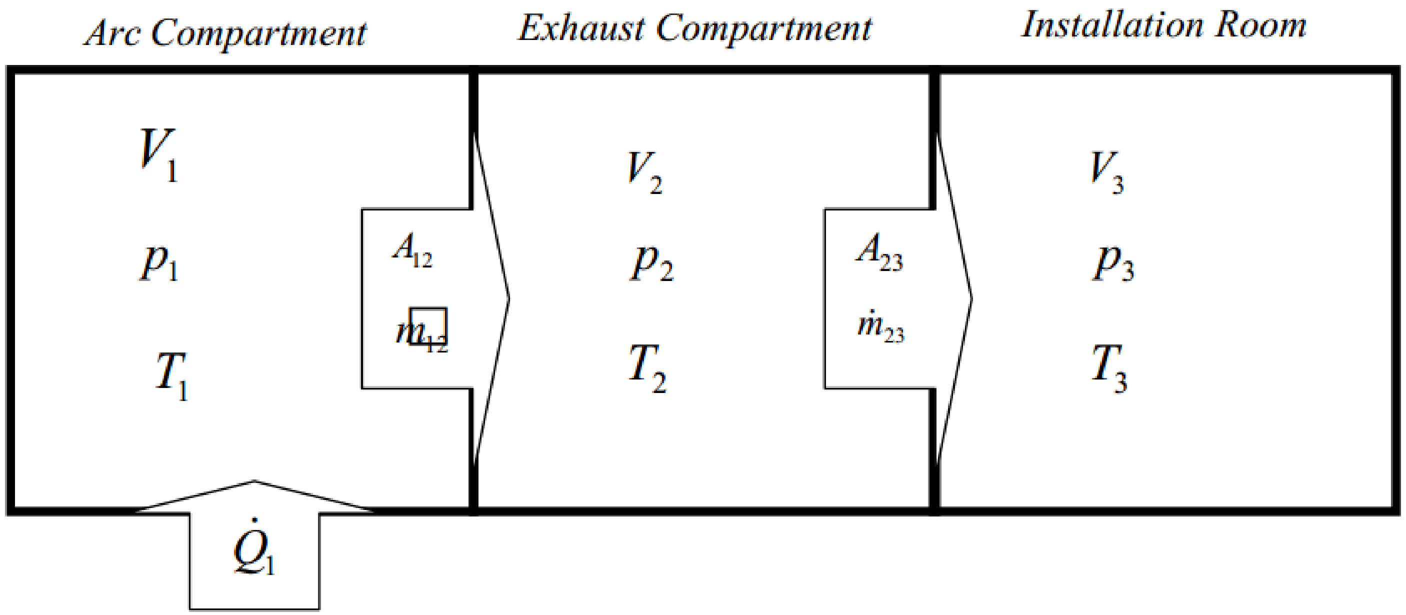


Figure 2-1: Principal arrangement and quantities used for pressure calculation.

Net volumes i.e. volume of compartment minus volume of built-in components.
The shape of the compartment is not considered.
The volume of the built-in components might reach 10 to 20 % of that of the arc compartment.

The energy supplied by the arc is taken as homogeneously distributed inside the arc compartment.
=>the model does not cover pressure waves, which might play a role in long, narrow compartments (channels)

Relief openings are represented by effective areas, i.e. the geometric cross-section of the opening diminished by the area of frames, slats, grills etc.

The discharge coefficient 0.7 for air [Dubbel1997] and 0.8 for SF6 [Anantavanich2008].

The opening of the relief device occurs instantaneously at the response pressure.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CALCULATION OF PRESSURE USING A BASIC MODEL

$$m_1 = \frac{p_1 V_1}{R_{s1} T_1}$$

$$m_2 = \frac{p_2 V_2}{R_{s2} T_2}$$

$$\rho_1 = \frac{m_1}{V_1}$$

$$\rho_2 = \frac{m_2}{V_2}$$

$$c_{v1} = \frac{R_{s1}}{\kappa_1 - 1}$$

$$c_{v2} = \frac{R_{s2}}{\kappa_2 - 1}$$

$$c_{p1} = \kappa_1 c_{v1}$$

$$c_{p2} = \kappa_2 c_{v2}$$

$$Q_1 = k_p W_{el}$$

The thermal transfer coefficient *kp describes the relationship between the thermal and electrical energy (cte)*

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CALCULATION OF PRESSURE USING A BASIC MODEL

Mass flow:

$$\Delta m_{12} = \alpha_{12} A_{12} \rho_{12} w_{12} \Delta t$$

α_{12} is the discharge coefficient, which considers the contraction of gas flow through an opening.

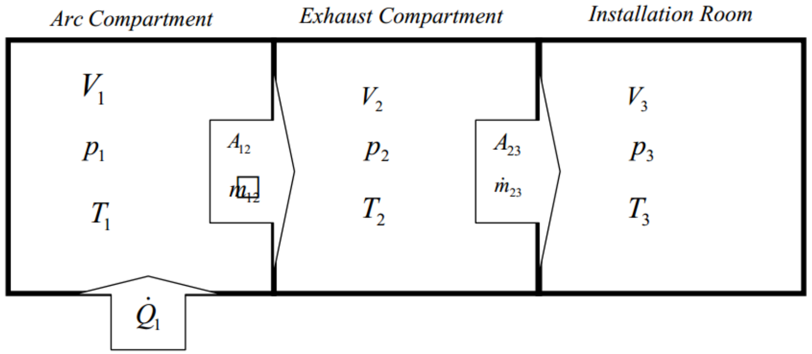


Figure 2-1: Principal arrangement and quantities used for pressure calculation.

$$\rho_{12} = \rho_1 \left(\frac{p_{12}}{p_1}\right)^{\frac{1}{\kappa_1}}$$

$$w_{12} = \sqrt{\frac{2\kappa_1}{\kappa_1 - 1}\frac{p_1}{\rho_1}\left(1 - \left(\frac{p_{12}}{p_1}\right)^{\frac{\kappa_1 - 1}{\kappa_1}}\right)}$$

If the ratio of pressure in $V1$ and $V2$ i.e. $p1/p2$ exceeds a value of 1.89 for air and 1.70 for SF6,
$p12$ is determined by the critical pressure $p1*$
for smaller ratios $p12$ is equal to the pressure in $V2$

$$p_1^* = p_1 \left(\frac{2}{\kappa_1 + 1}\right)^{\frac{\kappa_1}{\kappa_1 - 1}}$$

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CALCULATION OF PRESSURE USING A BASIC MODEL

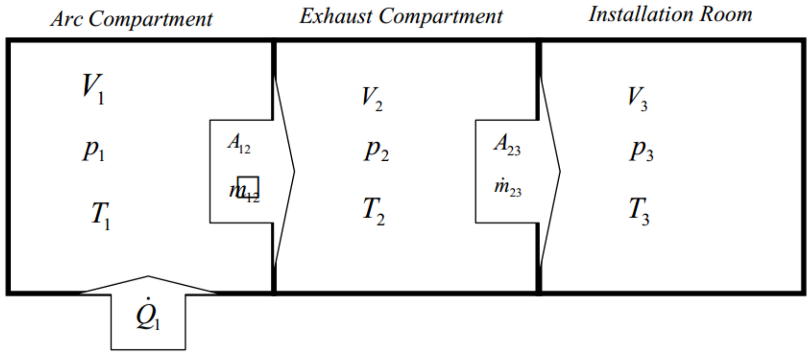


Figure 2-1: Principal arrangement and quantities used for pressure calculation.

The mass in volume V_1 is reduced after the time step Δt by the mass Δm_{12}

$$\Delta m_1 = -\Delta m_{12}$$

The mass from the exhaust compartment flowing into the installation room (V_3) is given by:

$$\Delta m_{23} = \alpha_{23} A_{23} \rho_{23} w_{23} \Delta t$$

Density and flow velocity are calculated using the equations provided above with all indices incremented by one. The change of mass in volume V_2 within Δt is the difference between the incoming mass Δm_{12} and the outgoing mass Δm_{23} during Δt.

$$\Delta m_2 = \Delta m_{12} - \Delta m_{23} \qquad (2\text{-}13)$$

CALCULATION OF PRESSURE USING A BASIC MODEL

Gas temperature:

The temperature change in the arc compartment with volume V_1 after the time step Δt is determined by the difference between the thermal energy input by the arc (ΔQ_1) and the energy loss due to gas flow out of the compartment (see ANNEX A.2.4 for details):

$$\Delta T_1 = \frac{\Delta Q_1 - \Delta m_{12}(c_{p1} - c_{v1})T_1}{m_1 c_{v1}} \qquad (2\text{-}14)$$

The corresponding temperature change in V_2 is:

$$\Delta T_2 = \frac{\Delta m_{12}(c_{p1}T_1 - c_{v2}T_2) - \Delta m_{23}(c_{p2} - c_{v2})T_2}{m_2 c_{v2}} \qquad (2\text{-}15)$$

The summation of all temperature changes ΔT_i provides the temperature at time t.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CALCULATION OF PRESSURE USING A BASIC MODEL

Gas pressure:

With given gas mass and temperature, the pressure in V_1 and V_2 at time t is given by the ideal gas law:

$$p_1 = \frac{(\kappa_1 - 1)}{V_1} m_1 c_{v1} T_1 \qquad p_2 = \frac{(\kappa_2 - 1)}{V_2} m_2 c_{v2} T_2$$

Temperature T_3 and pressure p_3 in the installation room are calculated correspondingly.

Gas data:

	Parameter	Air [Mende1975]	SF_6 [Solvay]	
c_v	specific heat capacity at constant volume	716	608	J kg^{-1}/K
c_p	specific heat capacity at constant pressure	1005	665	J kg^{-1}/K
ρ	gas density	1.205	6.07	kg/m^3
κ	heat capacity ratio (kappa)	1.403	1.0936	
M	molar mass	29	146	kg/kmole
R	universal (molar) gas constant	8314	8314	J K^{-1} $kmole^{-1}$
R_s	specific gas constant	287	56.9	J K^{-1} kg^{-1}

Table 2-1: Basic gas quantities at normal conditions (20 °C and 101.3 kPa).

The assumption of c_p being independent of temperature *acceptable up to temperatures where gases start to dissociate (approximately 2000 K for SF6 and 6000 K for air).*

This limits the applicability of the model.
Typically such high gas temperatures are reached in the arc compartment after opening of the relief device

kp factor:

Heat transfer coefficient kp : fraction of the electrical arc energy, participating to pressure rise in the arc compartment.

Theoretical approaches to calculate kp based on a detailed energy balance e.g. [Zhang2002] exist, however, this approach is not really feasible.

In practice, kp determined by fitting the calculated pressure rise to the measured one before the operation of the pressure relief device.
kp-factors determined from tests under similar conditions.
If no experiments are available, kp -factors taken from publications should be used with caution.

Exothermic reactions: additional energy might heat up the gas resulting in a kp-factor possibly larger than 1. (1.6)

kp in air is lower than in SF6 [Dullni1994, Friberg1995].
for air at standard conditions with copper electrodes ranges from 0.40 to 0.65
for SF6 from 0.50 to 0.70.

CALCULATION OF PRESSURE USING A BASIC MODEL

kp improvement:

Gas temperatures above 10000 K never been measured in free burning arcs
other effects have to be considered, which keep the gas temperature lower.

Proposal: kp is density dependant

Tests with arc exhaust into a closed room [Dullni1994] have shown that the pressure rise in the exhaust compartment is not as high as anticipated when assuming a constant kp factor.

=> kp-factor diminishing with gas density

$$k_p(t) = k_{p0} c_0 \left(\frac{\rho(t)}{\rho_0}\right)^x \qquad \text{for} \qquad \rho(t) < \rho_c$$

$$k_p(t) = k_{p0} \qquad \text{for} \qquad \rho(t) > \rho_c$$

where $\rho(t)$ is the gas density at time t, $\rho 0$ is the normal gas density at ambient pressure and temperature, $kp0$ is the kp-factor before transition, $c0$ adapted pre-factor, and x is an exponent between 0.4 and 0.5

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CALCULATION OF PRESSURE USING A BASIC MODEL

Exothermic reaction energy :

The material of conductors and walls, where the arc has its roots, influences the value of the kp-factor.
Reactions with aluminium under exothermic energy release.

In this case, $kp > 1$ may give appropriate results [Zhang2002].

Another approach: to add the exothermic energy from evaporated metal to the arc energy avoiding an artificially augmented kp-factor.

From the reaction schemes, oxygen and SF6 release a very similar exothermic energy when reacting with aluminium [Bjørtuft2005].

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CALCULATION OF PRESSURE USING A BASIC MODEL

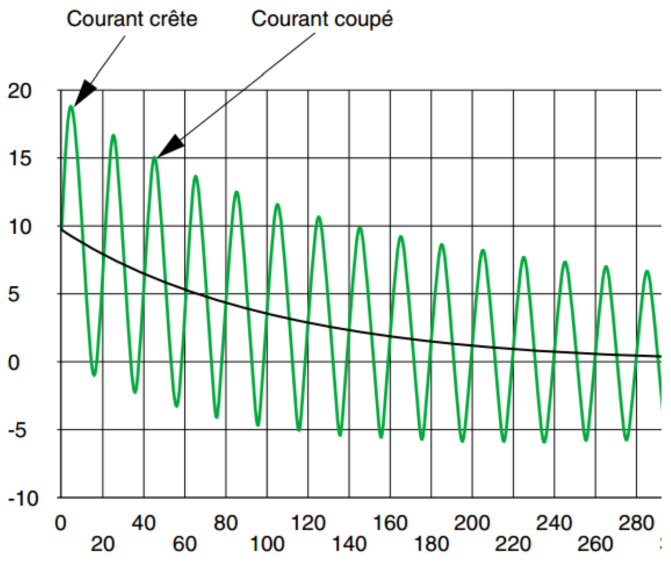
Arc current:

Temporal development of the single or three-phase fault current must be known.
Can be taken from test or from simulation.

Knowing the d.c. time constant of the circuit $\tau d.c.$ (0,045s), of the source circuit, the temporal development of the current $i(t)$ in a three-phase system can be calculated using e.g. the formula:

$$i_{phase} = \sqrt{2} I_{rms} \left[\sin(\omega t + \varphi - \theta_{phase}) - \sin(\varphi - \theta_{phase}) e^{-\frac{t}{\tau_{d.c.}}} \right]$$

inserting the angular frequency ω, the angle of fault initiation φ, and the shift between the phases, $\theta phase$.



SIMULATION OF EFFECTS OF THE INTERNAL ARC

CALCULATION OF PRESSURE USING A BASIC MODEL

Arc voltage:

In tests the arc energy is determined from measured line currents and phase-to-ground voltages:

$$\Delta W_{el} = (u_R i_R + u_S i_S + u_T i_T)\Delta t$$

If arc voltage data is missing, basic formulas, which have been extracted from three phase internal arc tests with MV metal enclosed switchgear separately for air and SF_6 and copper electrodes might be used [AiF2011]. These voltages have to be applied together with the energy equation *(2-19)* for arcs between phases.

$$\frac{U_{arc}}{d} = 30\,\frac{\mathrm{V}}{\mathrm{cm}} + \frac{1}{2} I_{rms}\,\frac{\mathrm{V}}{\mathrm{cm\ kA}} \leq 40\,\frac{\mathrm{V}}{\mathrm{cm}} \qquad (\mathrm{air}) \qquad (2\text{-}21)$$

$$\frac{U_{arc}}{d} = 40\,\frac{\mathrm{V}}{\mathrm{cm}} + \frac{1}{2} I_{rms}\,\frac{\mathrm{V}}{\mathrm{cm\ kA}} \leq 50\,\frac{\mathrm{V}}{\mathrm{cm}} \qquad (\mathrm{SF_6}) \qquad (2\text{-}22)$$

Here U_{arc} is the arc voltage between phases, d is the distance between pole centres, and I_{rms} is the effective short circuit current.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Application limits of the basic model

The model does not consider the evaporation of metal or insulation material

If considerable gas flow occurs in any compartment (e.g. in elongated rooms or channels) the approach with spatially averaged quantities is not applicable.

The model assumes a constant gas type in the exhaust compartment.
In case of SF6-insulated switchgear the gas in the exhaust compartment will be a mixture of SF6 and air.
Assumption of only air in the exhaust compartment is violated when the SF6 portion becomes remarkable (case for small exhaust volumes)

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Application examples

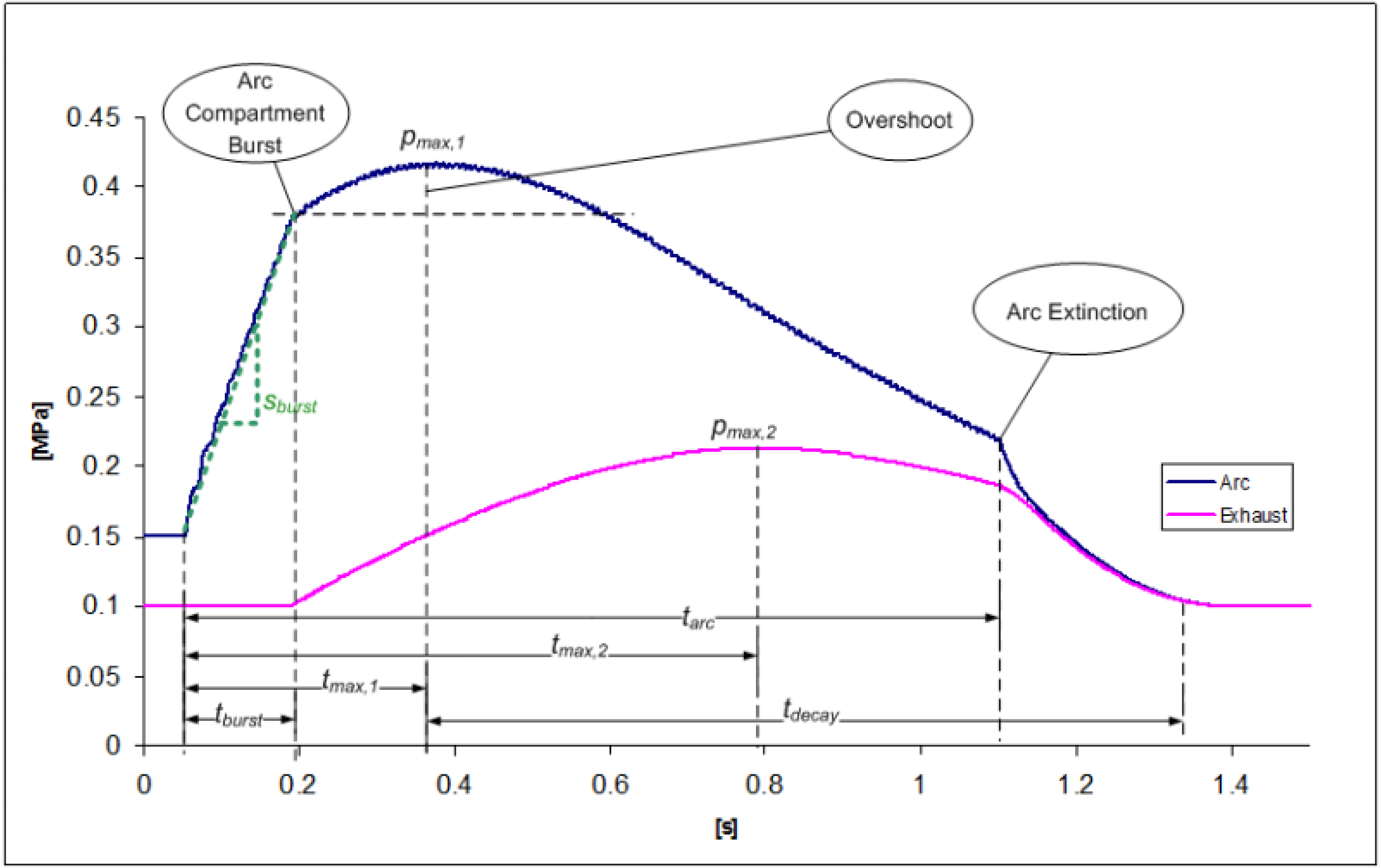
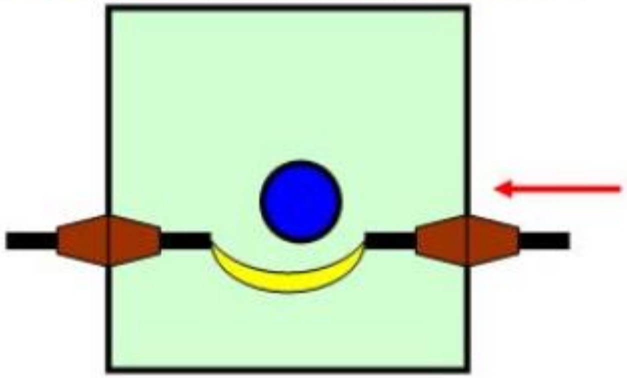


Figure 2-3: Characteristic values determined from calculated or measured pressure curve.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Application examples



Side view of container

- Welded cube-shaped steel container
- Single phase Cu terminals
- Linear electrode arrangement
- Arc ignited between two electrodes
- Circular relief device with bursting disc
- Exhaust into open air

Figure 2-4: Test cubicle used for cases A and E.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

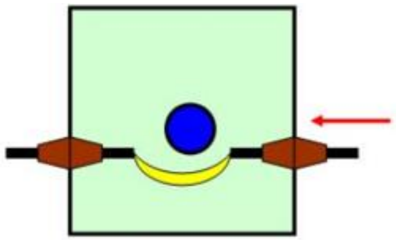
Air results

Case No.	A	B	C	D	
Volume of arc comp. (V_1)	0.509	0.509	0.648	0.27	m³
Volume of exhaust comp. (V_2)	>1000	1.275	>1000	0.58	m³
Volume of installation room (V_3)	n/a	>1000	n/a	>1000	m³
Initial filling pressure in V_1	150	160	100	120	kPa abs air
Initial filling pressure in V_2	100	100	100	100	kPa abs air
Area of the relief opening A_{12}	0.00456	0.00456	0.0763	0.049	m²
Discharge coefficient of A_{12}	0.7	1.0	0.7	1.0	
Response pressure of relief device	276	285	35,3	220	kPa rel
Area of the opening A_{23}	0	0.010	0	0.195	m²
Short-circuit current	14.5	14.5	14.5	38.8	kA rms
Number of phases	1	1	2	3	
Averaged phase-to-ground voltage	314	424	400	250	V
k_p-factor	0.4	0.55	0.7	0.6	

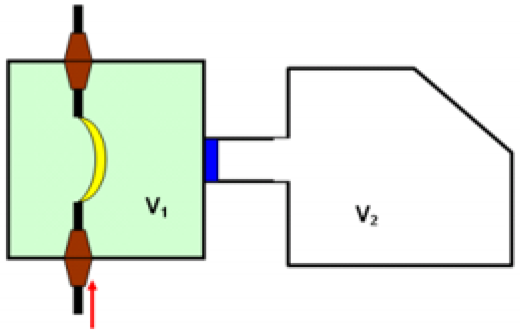
Table 2-3: Input parameters and initial values for MV switchgear cases with air insulation.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Air results



Side view of container



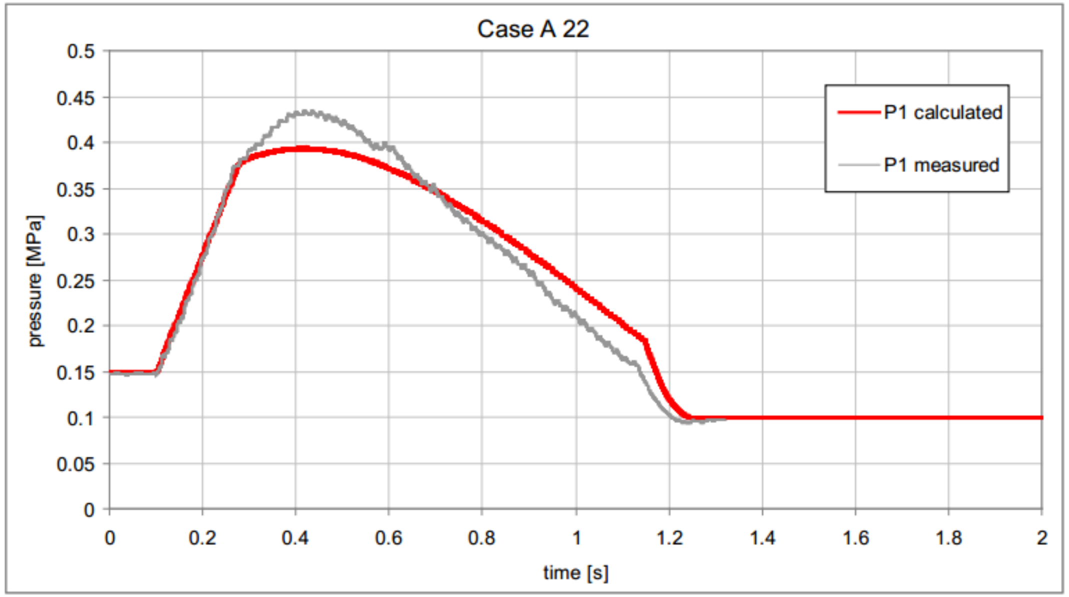


Figure 2-10: Case A – Measured and calculated pressure development in V_1 in air.

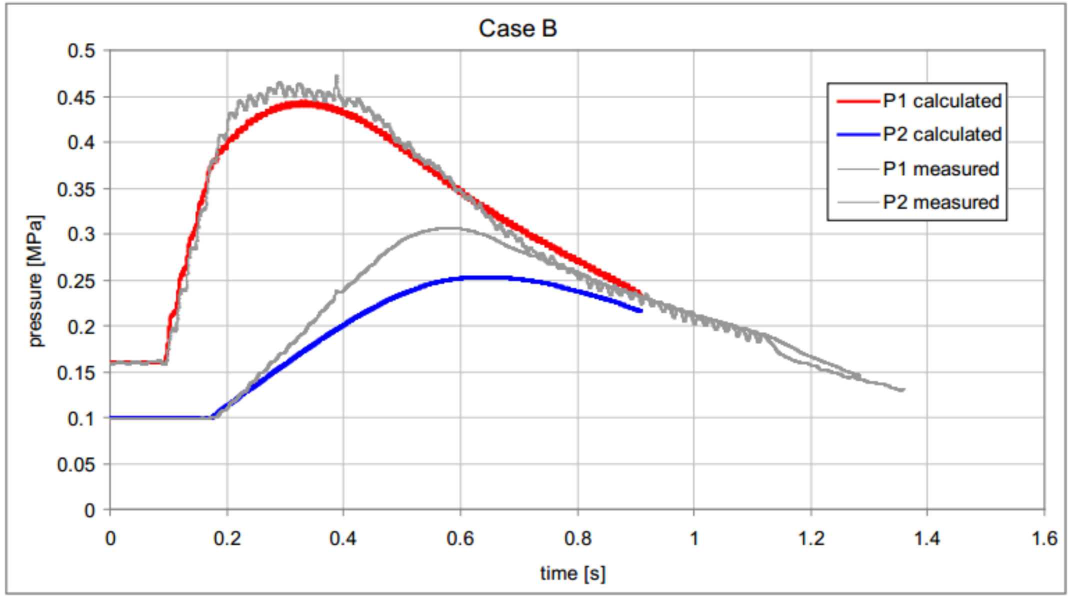
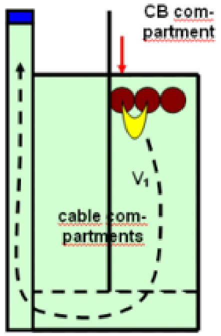


Figure 2-11: Case B – Calculated pressure developments in V_1 and V_2 in air and comparison with test.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Air results



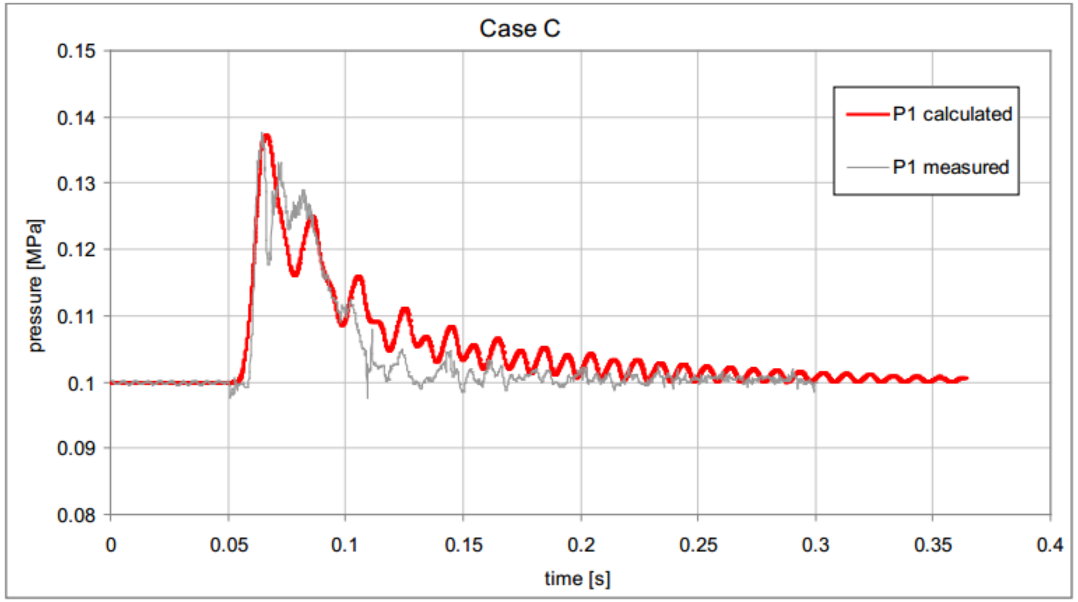
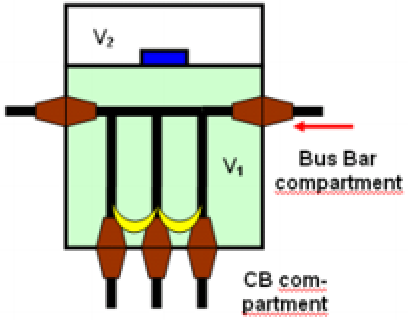


Figure 2-12: Case C – Calculated pressure development in V_1 in air and comparison with test.



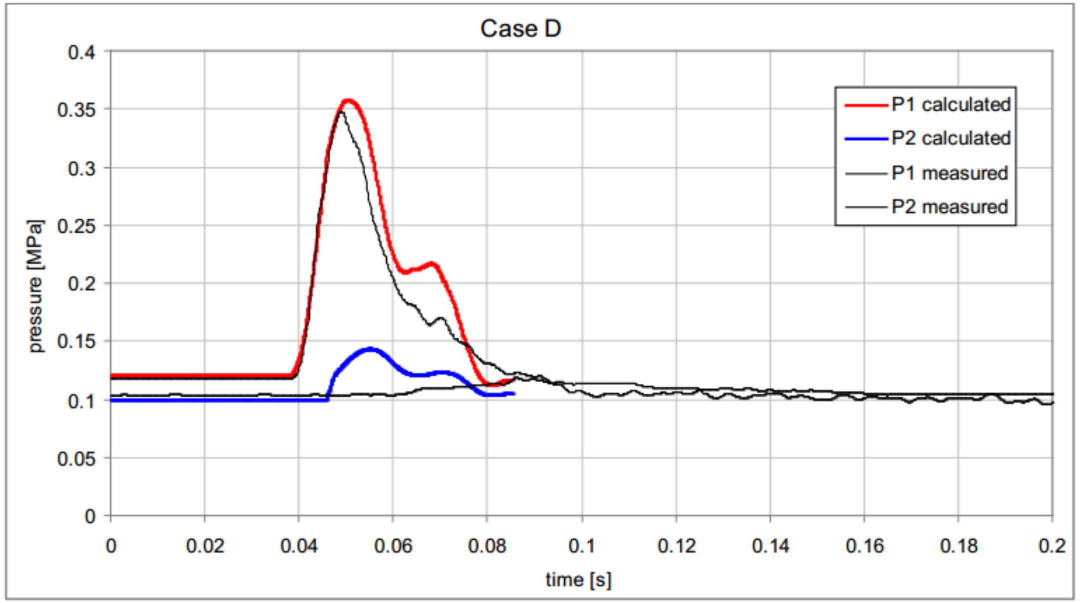


Figure 2-13: Case D – Calculated pressure developments in V_1 and V_2 with air as filling gas and comparison with test.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Air results

Calculation with the basic model and measured results show **good agreement**.

Peak pressure and drop of pressure in the arc compartment show **good coincidence**.
The kp-factor is taken between 0.4 and 0.7 (accordance with published data).

Exhaust compartment: less satisfying agreement with the test results.
This could be a matter of the position of the pressure sensor during the particular test when the exhaust compartment is much longer than wide (like a channel).

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Conclusion

good agreement between test and simulation as long as the input arc energy is known.
Pressure peaks and decay can be simulated within a deviation of 10 %.

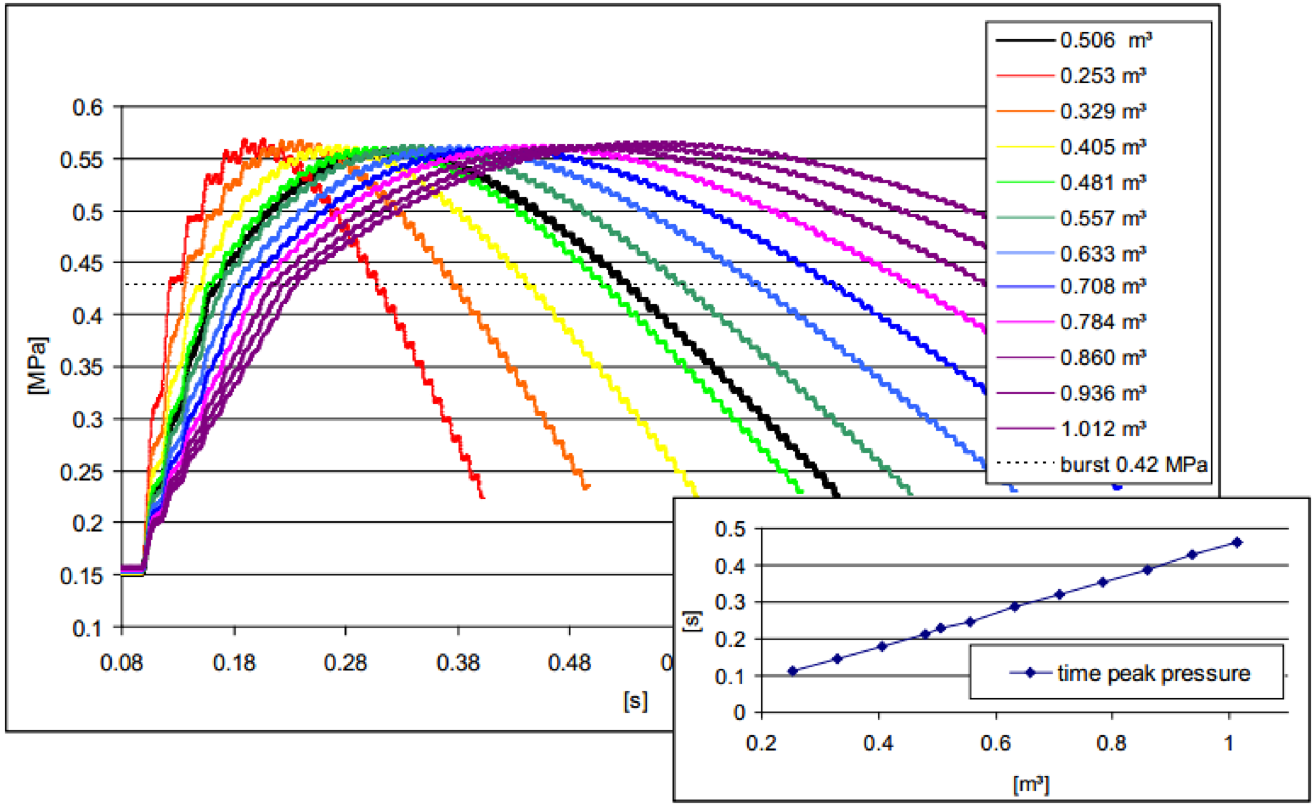
The comparison also indicates that for most arrangements common input parameters can be used such as a kp-factor of 0.5 for air and 0.7 for SF6, a relief area discharge coefficient of 0.7

Enhanced models with adapted input parameters, temperature- dependent gas properties or separate gas equations for different gas species – also including evaporation of electrode material – are appropriate to improve the agreement between simulation and test results

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Sensibility

Sensitivity to arc compartment volume



igure 3-5: Pressure development over time with varying volume of arc compartment [m³] (simulation for air).

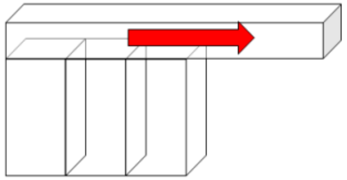
The peak pressure does not depend on the arc compartment volume as long as the process can be considered as a slow process and the exhaust compartment is relatively large.

time to reach the peak pressure t_{max} is proportional to the volume

SIMULATION OF EFFECTS OF THE INTERNAL ARC

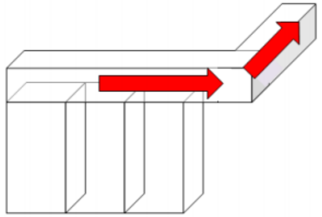
CFD software usage

Motivations



CFD allows :

- Space-dependency of an arc model (energy input, vaporization..) and results
- Dynamic processes like reflection, diffraction and interference of gas flows (wave theory)
- Compressible gas flow



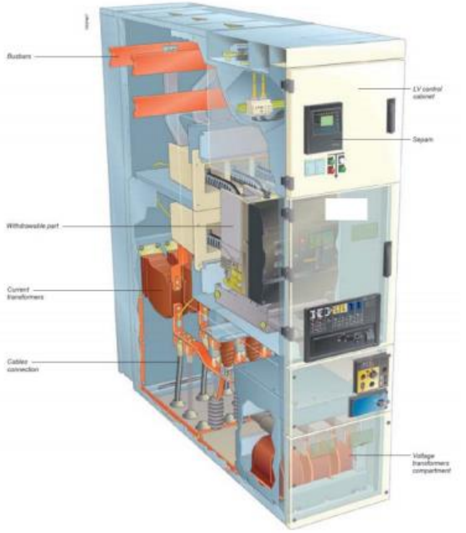
CFD is typically used in:

- Assessing the actual geometry of the switchgear and installation room (simulating actual electrical installations when they differ from the manufacturer's requirements or from the test conditions)
- Analysing the influence of the location of pressure relief openings in rooms.
- Analysing the influence of specific flap design, the influence of grids and absorbers.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CFD software usage

(a)



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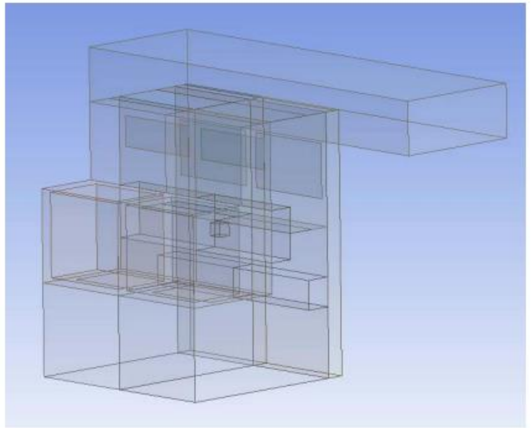

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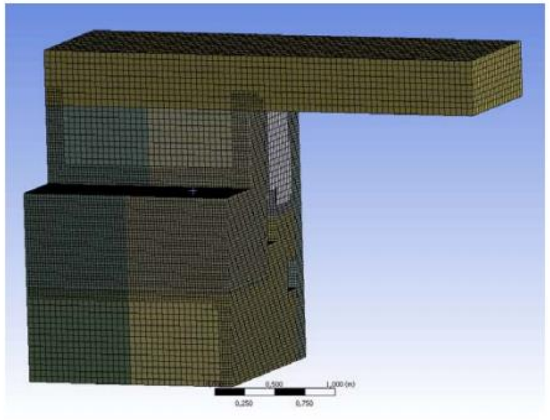
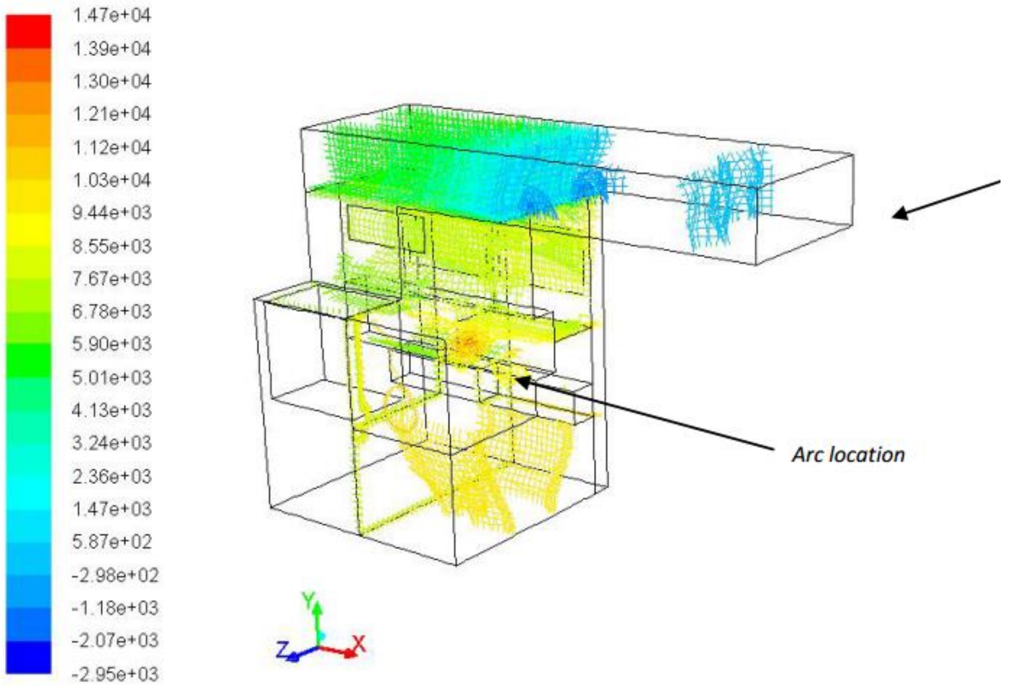


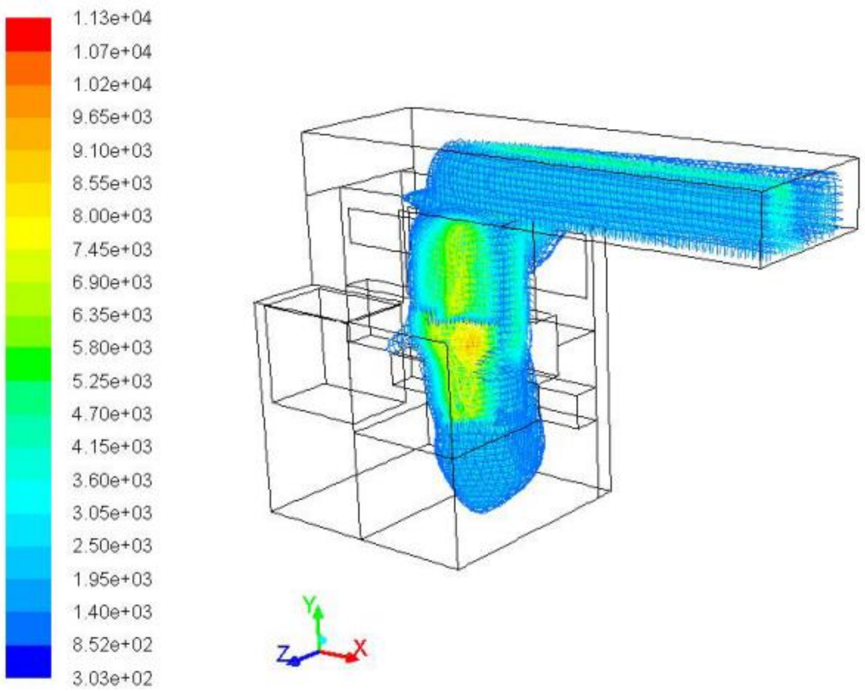
(d)

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CFD software usage

The most complete approaches, where the arc would be modeled using physical equations describing the arc roots, the arc plasma column, the effect of electro-magnetic fields on the motion of the arc, the transfer of energy from the arc plasma to the surrounding gas etc. have never been applied to internal arc to our knowledge.





Pressure and Temperature 55ms after ignition (50kA)

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CFD software usage: Conclusion

The main advantages:

- time and spatial resolution of the results
- pressure waves are included
- the actual geometry of the switchgear and installation room is considered
- the influence of the location of pressure relief openings can be analysed.

The accuracy depends on:

- quality of the models used to describe the internal arc physics,
- appropriate meshing of the flow domain.

Use of CFD for internal arc simulation is complex.
CFD methodology has to be calibrated with actual test results, on a sufficient sample of cases.
Engineering skills of the user.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Internal Arc Testing

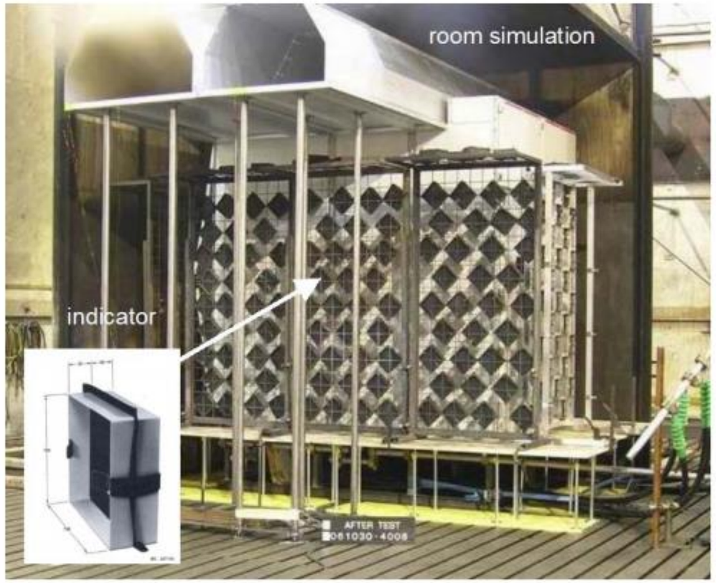
For > 52kV:

To prove internal arc withstand ability of the enclosure against bursting and burn-through . The IEC 62271-203 standard allows this ability **to be demonstrated by test or by calculations based on test results performed on a similar arrangement or by a combination of both**.

Normal insulating gas, usually SF6, at rated filling density.

The switchgear is considered adequate if no external effect occurs and no personnel damage

Usage of a pressure-resistant container of adequate size (release of (contaminated) SF6 into the environment may not be acceptable)



For <52kV:

In contrast to internal arcing in GIS > 52 kV, the standards IEC 62271-200, IEC 62271-201, and IEEE C37.20.7, allow **no possibility of verifying internal arc withstand ability by calculation**, even when based on the testing of equivalent designs.

Internal arc testing of metal-enclosed medium voltage switchgear is very common (proximity of medium voltage installations to the public)

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Internal Arc Testing

Standardisation status

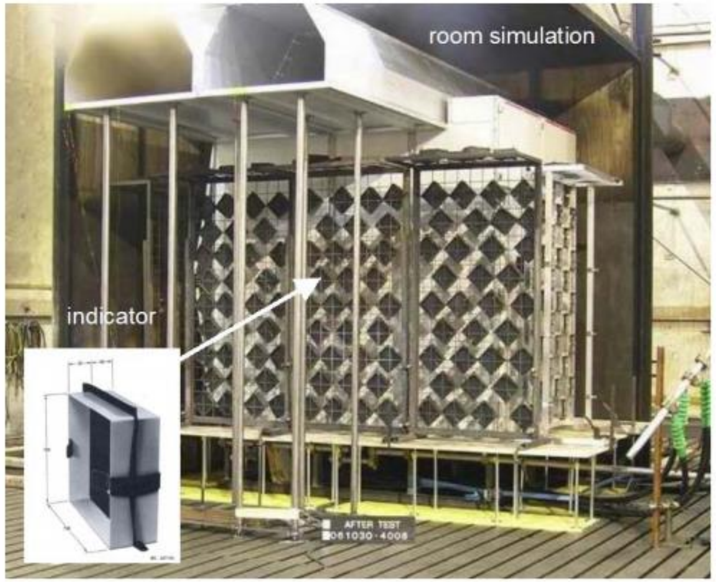
With the release of IEC 62271-200 in 2003 **an Internal Arc Classification** (IAC) was defined, taking into account various levels of accessibility of the switchgear:

- Type A: Accessible by authorised personnel only;
- Type B: Accessible by general public;
- Type C: Not accessible, i.e. out of reach (pole-mounted switchgear);

Test of the thermal effects of the hot gases : special black cotton cloth indicators of size 15x15 cm are used in a steel frame to avoid mutual ignition.

Criterion to pass internal arc tests : absence of ignition of any indicators by hot gases. Ignition by glowing particles, however, is allowed.

High-speed video is normally used in order to make a distinction between the causes of ignition. However, in many cases, the real reason of ignition (hot gases or particles) cannot be identified.



SIMULATION OF EFFECTS OF THE INTERNAL ARC

Air and SF6

Standard IEC 62271-200 (ed.2.0,2011) (clause 6.106.3): "For environmental reasons, it is recommended to replace SF6 with air at the rated filling pressure (± 10 %)"
including the note: “note2 Test results with air instead of SF6 are considered to be representative”.

Environmental reasons: solid (metal-sulphides and -fluorides) as well as gaseous SF6 decomposition products (SF4, H2S, SO2, HF, CF4, S2F10, S2OF10) are mostly very poisonous, especially in the presence of humidity.

In addition, test laboratories wish to minimise their emission of clean SF6, a greenhouse gas, and certainly of polluted SF6.

Technically, it is not clear yet, that testing in air presents similar conditions as testing in SF6.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Air and SF6

RESULTS FROM THE LITERATURE

0.3 m3 SF6 compartment [Daalder1989]. Three-phase current (15 - 20 kA) was supplied from a 7.2 kV circuit to arcs between Cu electrodes with 100 mm distance.

- Significantly higher arc voltage in SF6 (720 V) than in air (480 V);
- Rise and fall (after pressure relief) of pressure in the arcing volume are faster in air than in SF6
- differences exist in exhaust characteristics in SF6 (slower cooling)

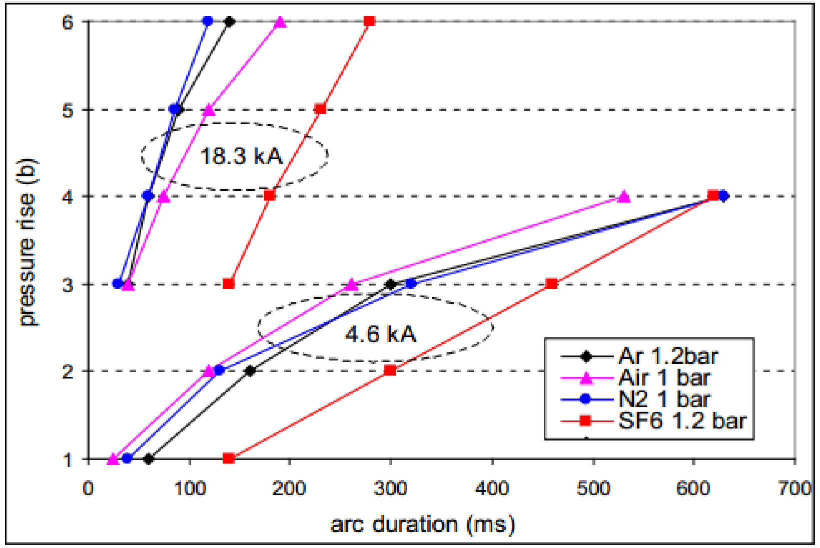


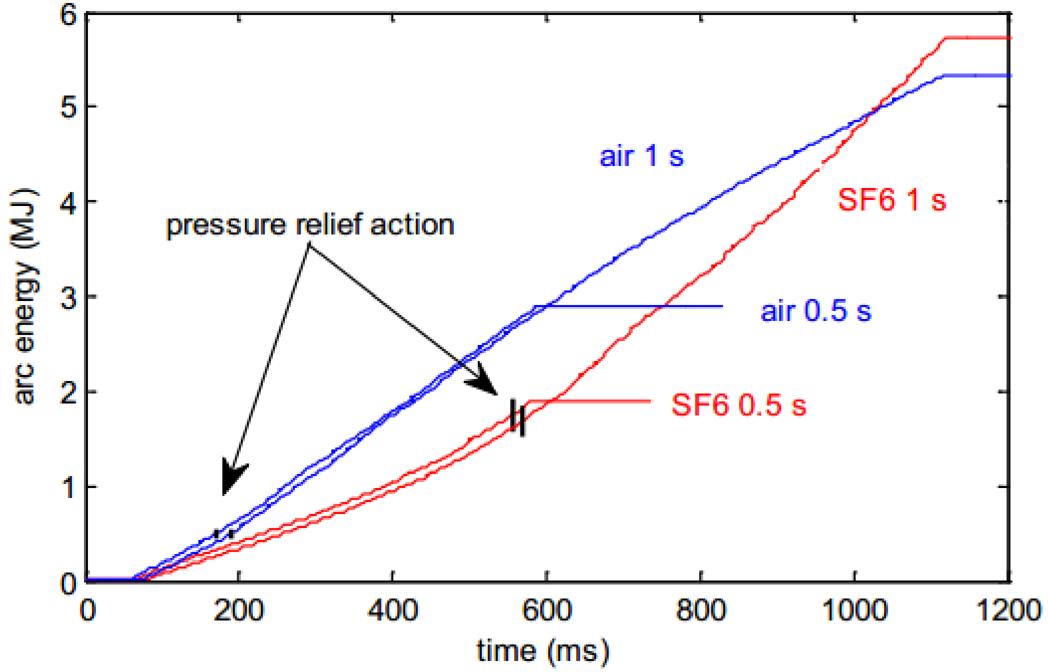
Figure 5-5: Pressure rise from a three-phase fault internal arc in various gases (argon, air, nitrogen and SF_6 with initial pressure 1 or 1.2 bar, see legend) in a cubicle model of 0.24 m^3 (18.3 and 4.6 kA).

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Air and SF6

The arc energy is calculated as ∫iauadt, with ia, ua the momentary arc current and voltage.
Results for arc durations of 0.5 and 1 s show clear differences between SF6 and air
Energy of SF6 arcs is (initially) smaller than of arcs in air. This is a direct consequence of the initially lower arc voltage of the SF6 arc;

Figure 5-6: Photographic impressions of the release of hot gases as a result of arcing in SF_6 (left column) and air (right column). Arc duration was 1 s, pictures are taken with an interval of 0.2 s.

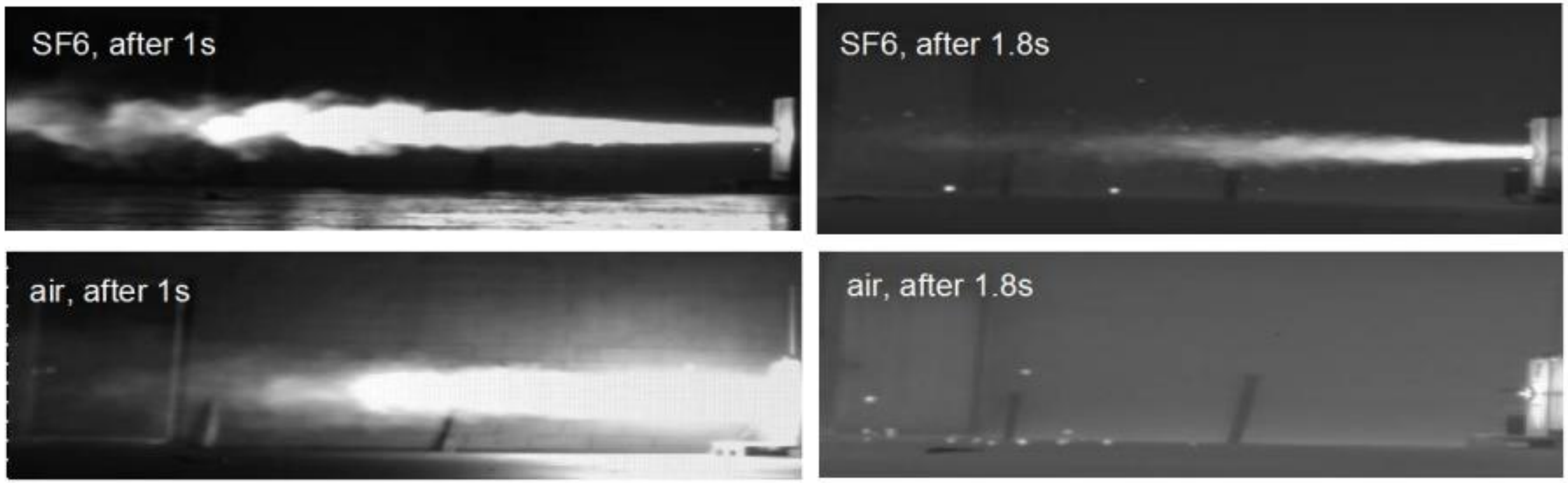


SIMULATION OF EFFECTS OF THE INTERNAL ARC

Air and SF6

Cooling of exhaust gas after arcing (IR analysis)

- the exhausted air is hotter than the exhausted SF6
- the cooling down after arcing in SF6 is much slower than in air
- the exhausted air has a wider jet stream than the exhausted SF6.



SIMULATION OF EFFECTS OF THE INTERNAL ARC

Air and SF6: Conclusion

Arc compartment: The mechanical stress with air is higher than with SF6

Intermediate compartment: When exhaust gas from the arcing compartment is released into adjacent compartment(s) the mechanical stress of it is larger in tests with SF6 than with air.

For worst-case situations (e.g. long arc duration) the arc energy in SF6 can be higher than in air.

The gas stream duration is longer with SF6 and it cools down slower than with air.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

EFFECT OF INTERNAL ARC ON STRUCTURES

There are three major effects which affect the switchgear and adjacent personnel.

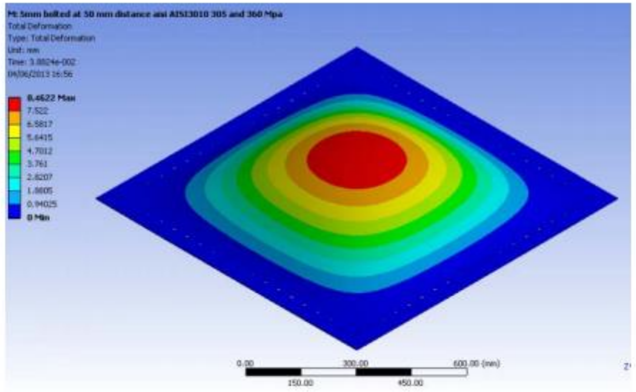
1. Mechanical stress on the switchgear due to the overpressure
2. Mechanical stress on the building walls due to the overpressure
3. Burn-through

Mechanical stress on switchgear due to the overpressure

major safety issue for personnel inside the installation room

A basic assumption is made that the load acting on the plates is static, which means it is applied slowly so that dynamic effects can be neglected, but it has provided a guideline for the strength of plates.

Figure 6-2: Test object after arc resistance test.



SIMULATION OF EFFECTS OF THE INTERNAL ARC

EFFECT OF INTERNAL ARC ON STRUCTURES

ELASTO-PLASTIC REGIME

The dynamics equation for a nonlinear single degree of freedom system becomes incremental at a given time t_i

$$m\Delta\ddot{y}_i + c_i\Delta\dot{y}_i + k_i\Delta y_i = \Delta F_i \qquad (6\text{-}5)$$

where y is displacement , $\dot{y}$ is velocity and $\ddot{y}$ is acceleration for F, which is the applied force, Δ represents the change in value during an infinitesimal time increment at the ith time step, m is the mass , c is damping, and k is stiffness.

the applicability of above equation becomes difficult for complex structures and high plastic deformations => FEA required

Figure 6-6: Deformation of structure after an internal arc test in the SF_6-filled switch.

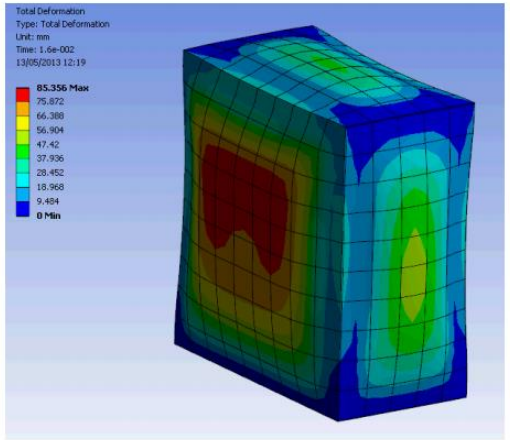


Figure 6-9: Total deformation of structure (simulation) after internal arc test in air.

Good match with tests

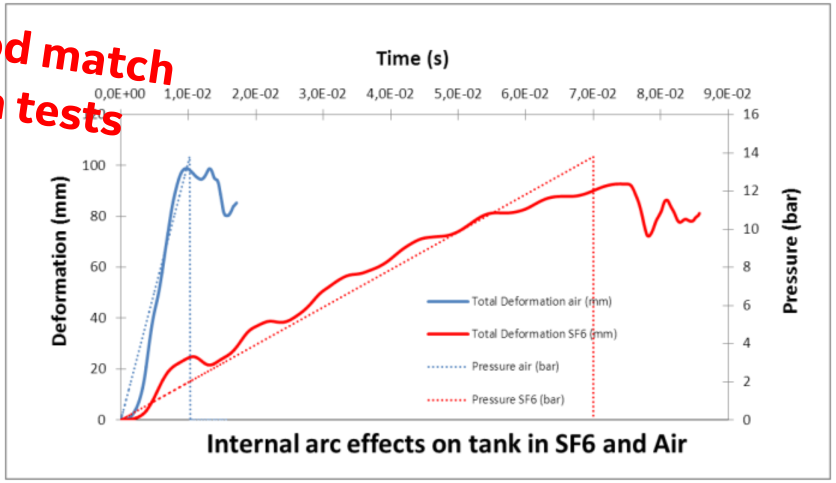


Figure 6-11: Deformation time-history (simulation) Dynamic effects for test in SF_6 and air.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

EFFECT OF INTERNAL ARC ON STRUCTURES

Pressure on building walls: comparison with test results (GIS case)

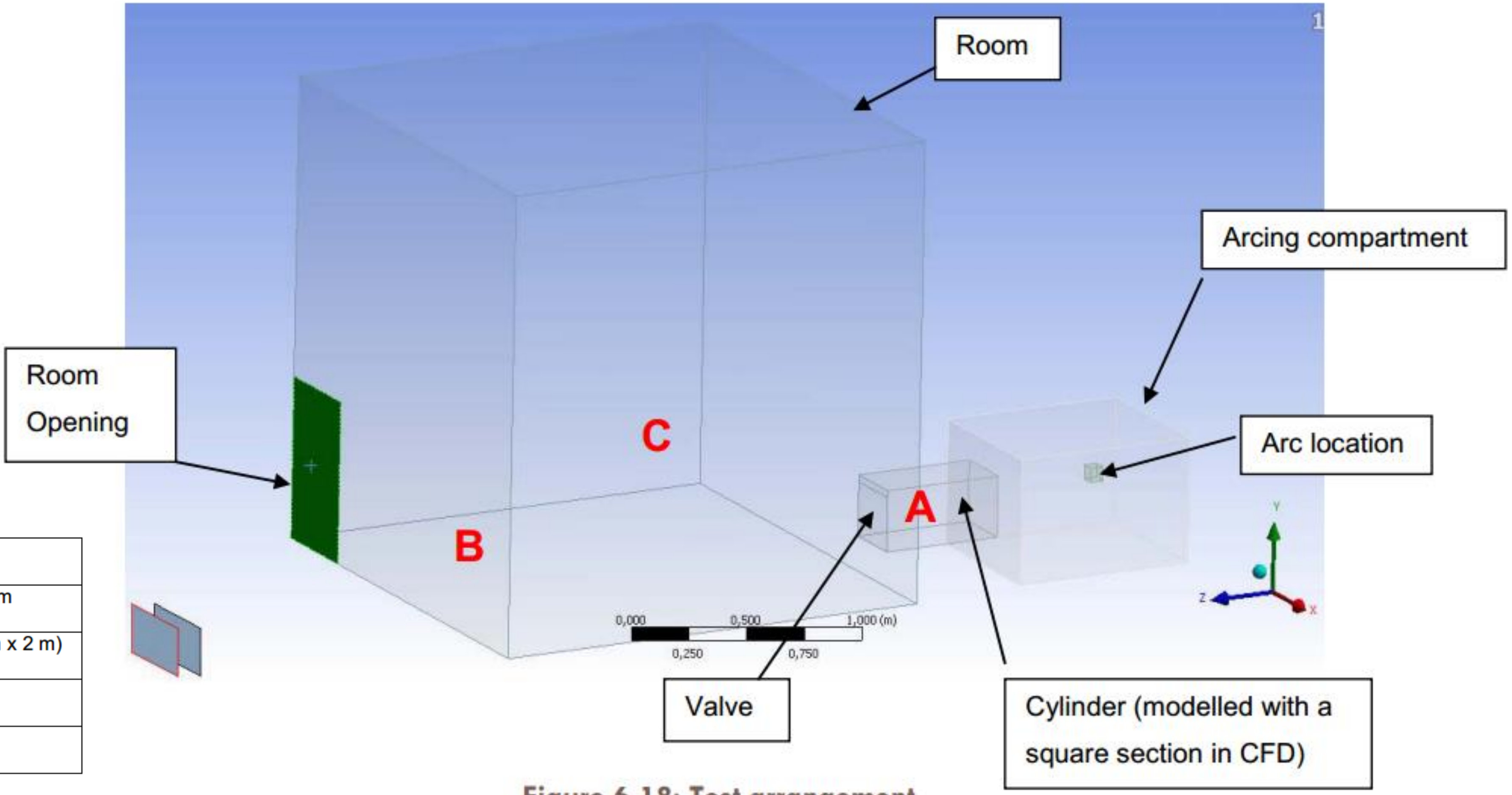


Figure 6-18: Test arrangement.

Arcing compartment	0.3 m^3
Cylinder volume and length	0.039 m^3, 0.54 m
Room volume	8 m^3 (2 m x 2 m x 2 m)
Room opening	0.3 m^2
Valve area	0.049 m^2

SIMULATION OF EFFECTS OF THE INTERNAL ARC

EFFECT OF INTERNAL ARC ON STRUCTURES

The arc current was 20 kA.

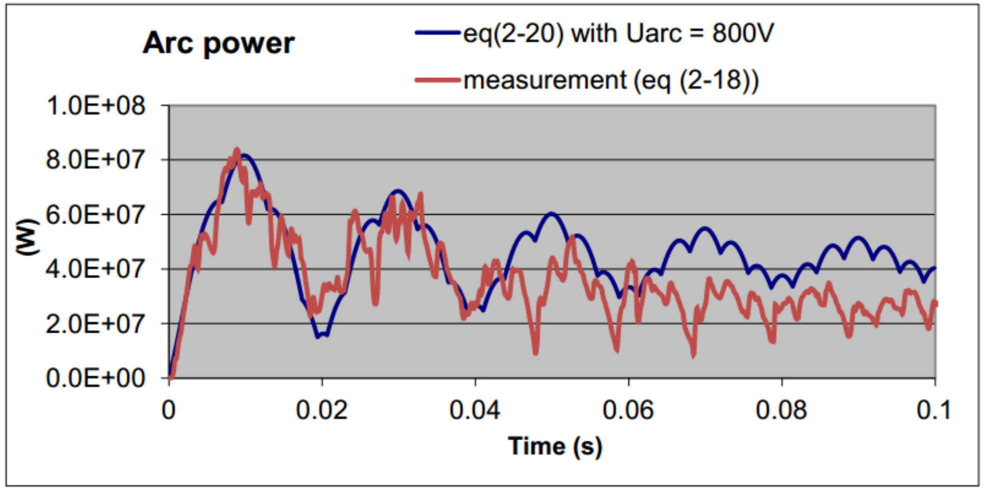
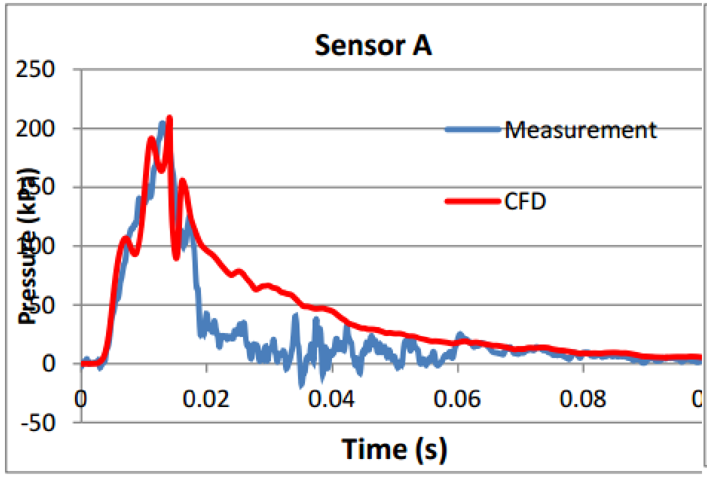
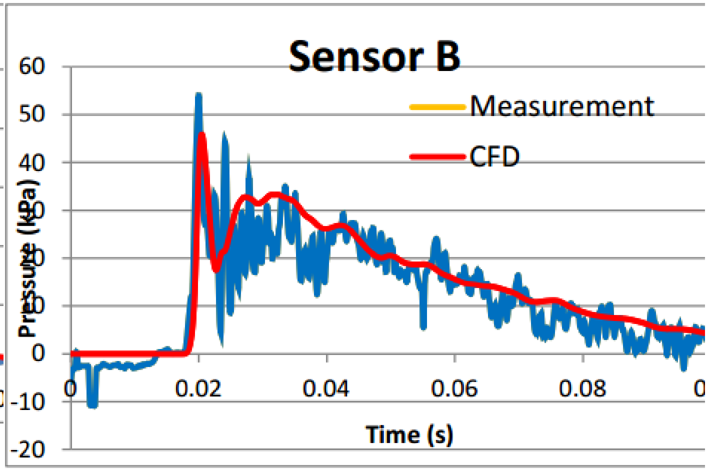
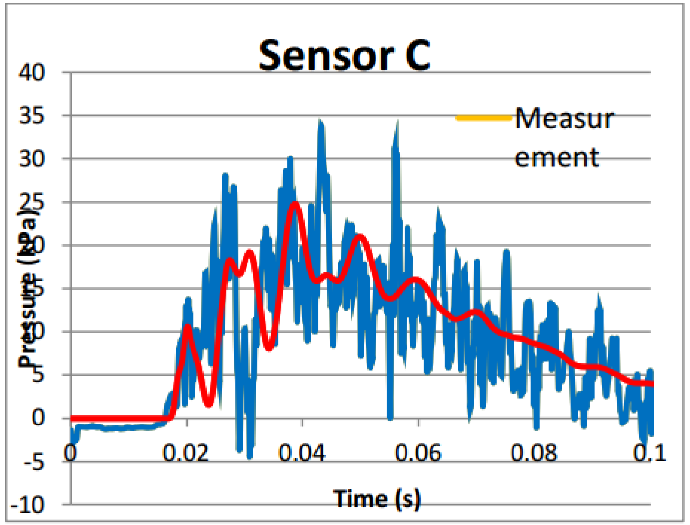


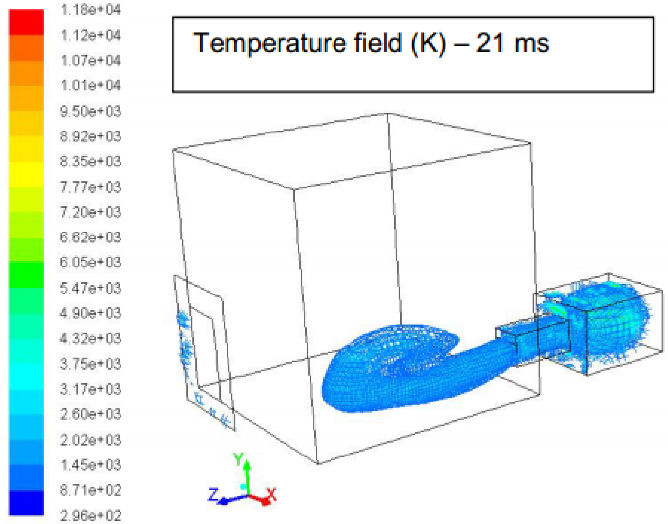
Figure 6-19: Arc power, measurement versus formula.

From the pressure sensor A curve, it can be deduced that the valve opens at 203 kPa.



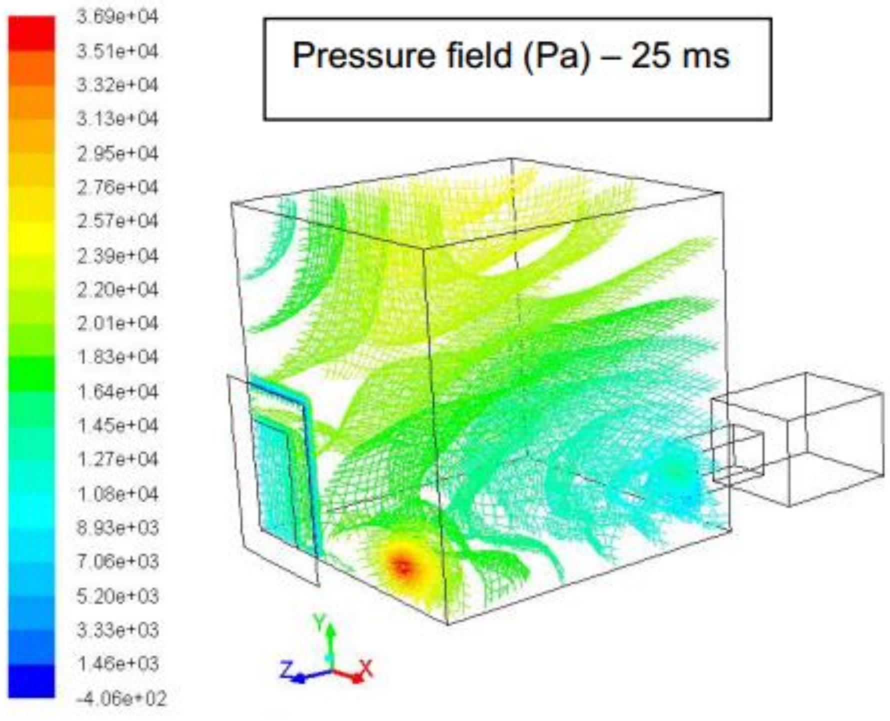


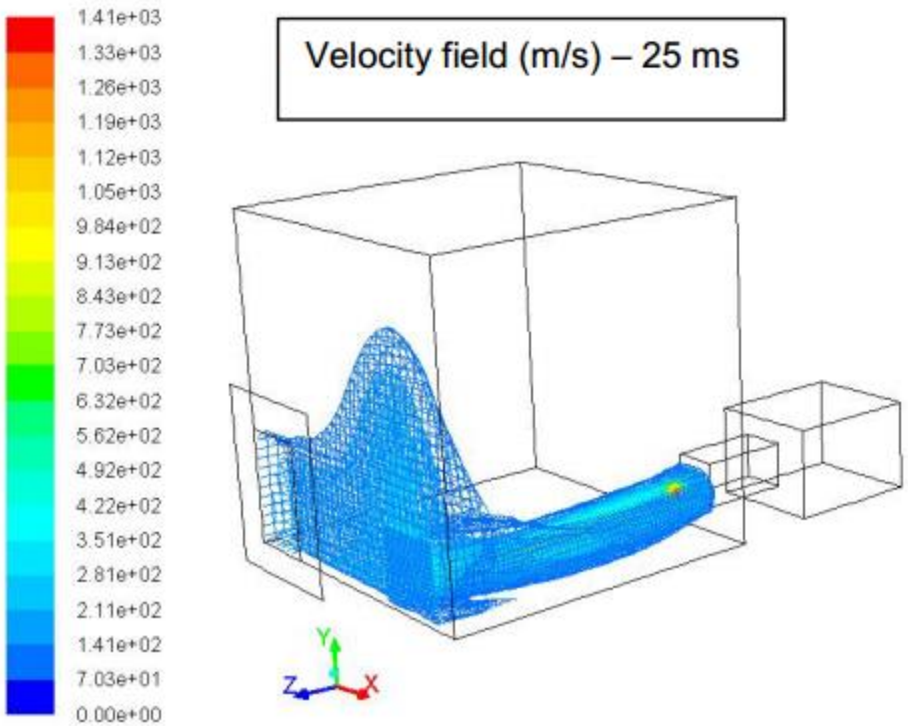




SIMULATION OF EFFECTS OF THE INTERNAL ARC

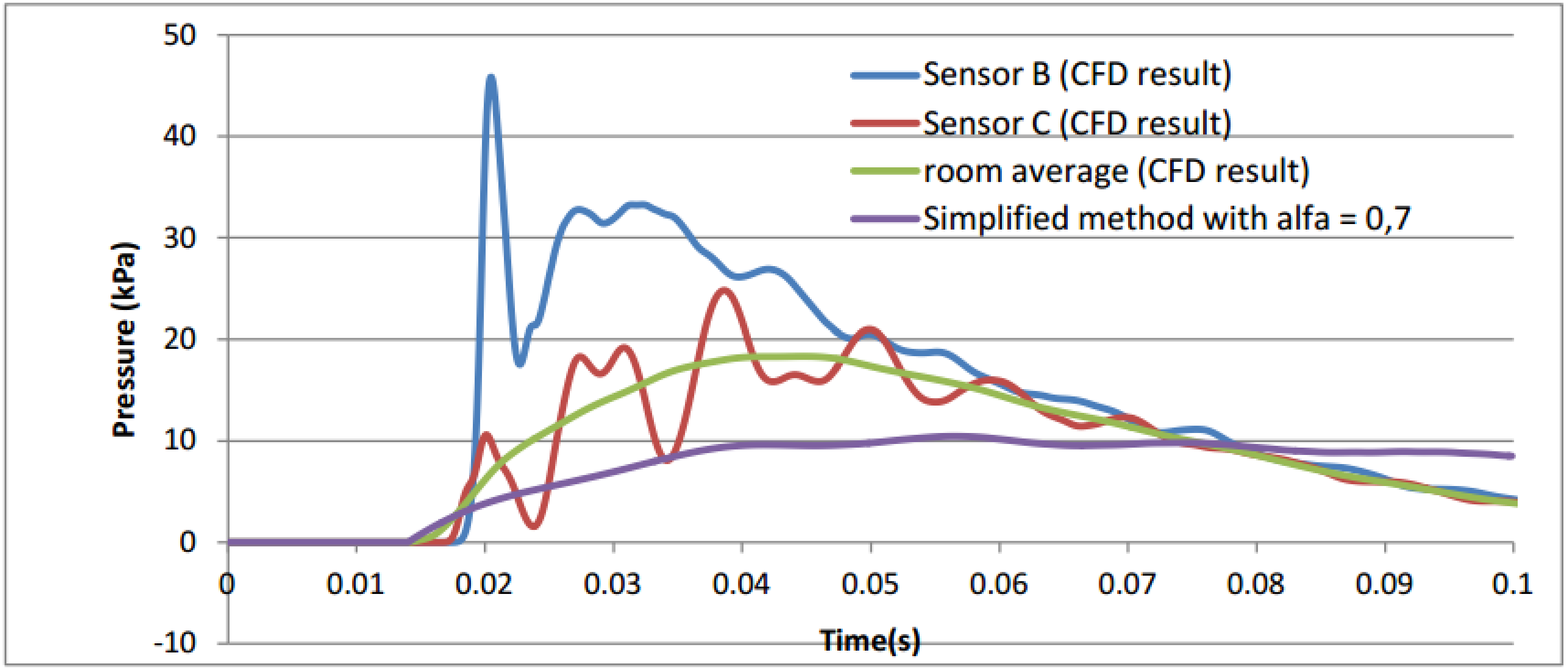
EFFECT OF INTERNAL ARC ON STRUCTURES





SIMULATION OF EFFECTS OF THE INTERNAL ARC

EFFECT OF INTERNAL ARC ON STRUCTURES



The basic method underestimates the pressure peak: it is 10 kPa, 45 % below the reference value (18.3 kPa). In order to get a correct result, the kp-factor should be tuned from 0.22 to 0.34.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CONCLUSIONS FOR THIS GIS CASE

For the different methods, one can conclude that:

- CFD: the pressure development within the switchgear room is properly modelled
- Basic and enhanced method: before 45 ms, the uniform pressure calculated is not relevant, and local pressure peaks (sensor B) are not calculated. After 45 ms, the simplified method underestimates the space averaged pressure, whereas the enhanced method gives a correct peak value.

In addition:

- For all methods, results are very senitive to the bursting pressure of the tank valve.
- For basic and enhanced methods, results are very sensitive to kp and discharge coefficients values.
- No general rules for use of the simplified method for GIS rooms

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Burn-through

This effect is caused by the arc which can **burn on a surface of the metallic enclosure** : This melts and then punctures the wall.

The arc will produce a pressure buildup within the faulty volume and an erosion process will take place at the arc root location.

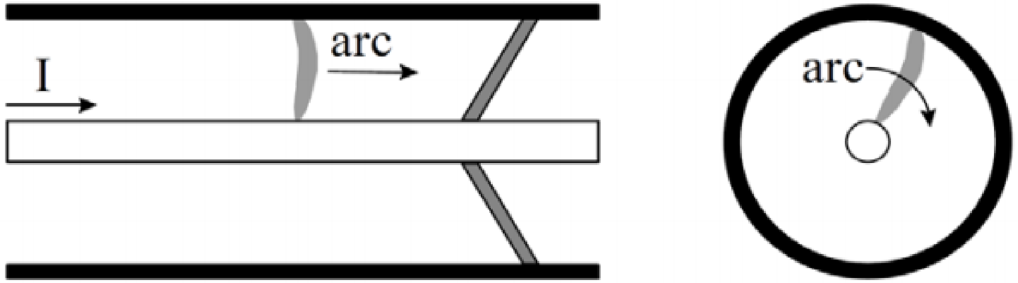
The effects cannot be fully predicted by simple thermal conduction models since **too many parameters play an important role**.

Difficult to predict the movement of the arc and to determine the energy input at the arc root.

The time to burn-through depends mainly on the current density, the thickness of the enclosure wall, the type of material and the duration of the fault

Burn-through might happen faster with SF6 then with air under the same conditions

Figure 6-36: Typical views of a HV GIS enclosure in the case of burn-through.



SIMULATION OF EFFECTS OF THE INTERNAL ARC

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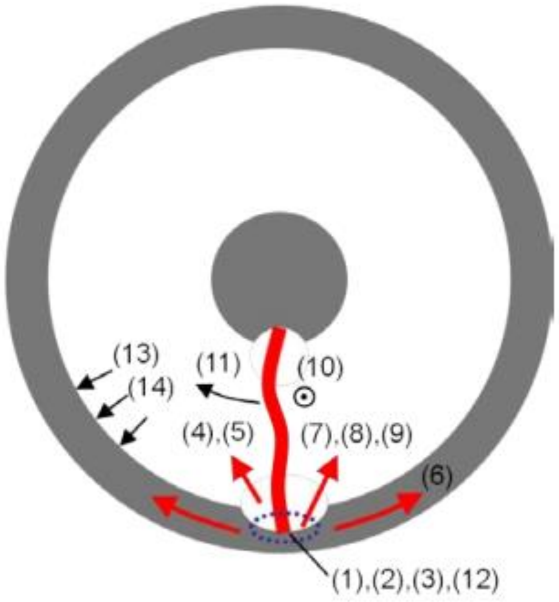


	Influencing factors
Input power	(1) Electrode fall voltage
	(2) Heat of chemical reaction (exothermic energy)
	(3) Radius of arc root (concentration of input power)
Power loss	(4) Heat transfer from arc to gas (conduction)**
	(5) Heat transfer from arc to gas (convection)**
	(6) Heat transfer within metal wall(s)
	(7) Heat transfer from enclosure to gas (conduction)**
	(8) Heat transfer from enclosure to gas (convection)**
	(9) Heat consumption by metal evaporation
Arc motion	(10) Axial velocity - Contribution "ta" *
	(11) Azimuthal velocity
Other	(12) Drag forces at arc foot
	(13) Pressure exerted on the tank wall after disk opening
	(14) Pressure exerted on the tank wall *** (peak pressure)

SIMULATION OF EFFECTS OF THE INTERNAL ARC

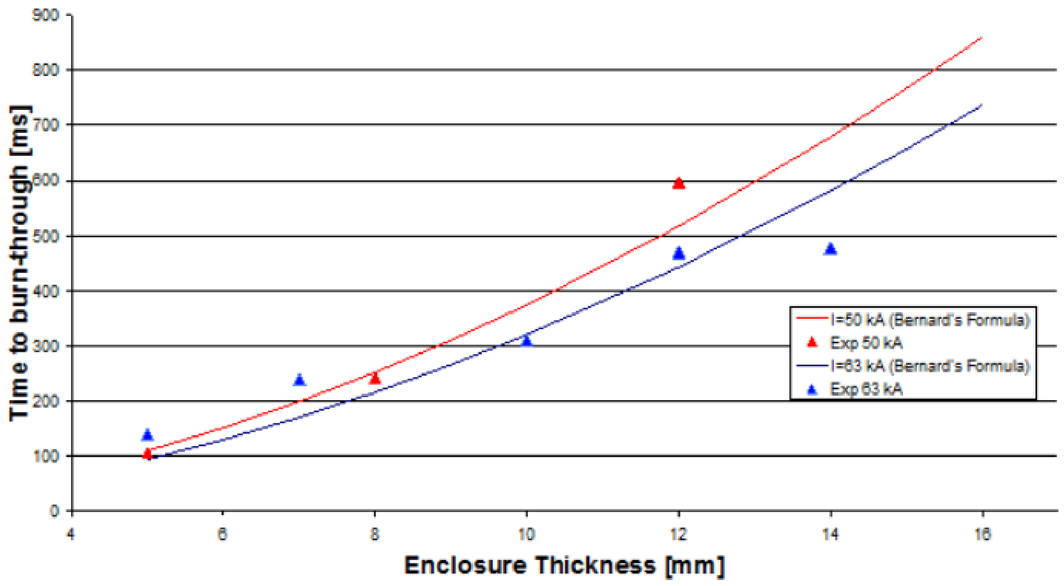
Burn-through : Conclusion

The generic formula for burn-through time can be written as: $t_b = k \frac{h^\alpha}{I^\beta}$

Authors/Reference	Material	Arc condition	k	α	β
[Babusci1998]	Aluminum	Moving, coaxial arrangement	173	2	1
[Bernard1982]	Aluminum	Moving, coaxial arrangement	87.4	1.77	0.67
Diessner [Chu1980]	Aluminum	Moving, coaxial arrangement	150	2	1
[Trinh1989]	Aluminum	Moving, coaxial arrangement	179	1	0.73
[Petterson1977]	Aluminum	Stagnant, Rod to plane	540	1	1
[Babusci1998]	Steel	Moving, coaxial arrangement	750	2	1

where tb is time to enclosure burn-through, h is enclosure thickness (mm), I is arc current (kA), α is a constant characteristic of the enclosure, and β is a constant characteristic of the arc current.

It will be considerably larger for steel than aluminum.



SIMULATION OF EFFECTS OF THE INTERNAL ARC

GENERAL CONCLUSION

The motivation for this work was multifaceted:

a. **To provide methods for pressure rise calculations** and allow benchmarking with performed tests
b. **To provide methods for calculation of other effects** of the internal arc
c. **To verify design modifications by simulations** and reduce the number of internal arc tests for environmental reasons
d. **To replace SF6 with air** during internal arc testing

The authors agree that simulations cannot replace type tests, but they could be used for interpolation between the known tests and make good predictions.

The working group reviewed existing software tools for calculating the effects of an internal arc fault, focusing on **3 main effects of an internal arc**:

- Pressure rise
- Mechanical stress on enclosure and buildings
- Burn-through

SIMULATION OF EFFECTS OF THE INTERNAL ARC

GENERAL CONCLUSION

Providing methods for pressure calculation

* **Basic** : more than 80 cases (in the brochure)

Agreement between calculations and measurements of the pressure rise within +/- 20 %
for the arc compartment after adjusting the kp factor and coefficient α.
(the coefficient kp of 0.5 for air and 0.7 for SF6, the discharge coefficients α between 0.7 and 1.0.)

The pressure rise inside the compartments can be successfully predicted as long as the input arc energy is well known => arc voltage should taken (not calculated) from the previous internal arc test on the similar switchgear design.

The basic model also helps to understand which parameters are contributing more to pressure rise then others. For example, arc voltage has much more influence on maximum pressure then level of asymmetry of the fault current.

Pressure rise calculations are less accurate for the exhaust compartment.

For large installation rooms and arc/exhaust compartments with complex geometry where pressure isn't uniform, CFD calculation should be used

SIMULATION OF EFFECTS OF THE INTERNAL ARC

GENERAL CONCLUSION

Providing methods for calculating other effects of the internal arc.

- Mechanical Stress on switchgear due to overpressure
- Mechanical stress on building walls due to overpressure
- Burn-through

Mechanical deformation (von Mises stresses) of the switchgear enclosure can be reasonably accurately calculated with FEA software

With CFD calculations the localised time-dependent pressure is obtained, which can be used to determine the size and placement of pressure relief openings in the building.

The burn-through time can be evaluated using different empirical formulas ;the test results agree with calculations.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

GENERAL CONCLUSION

Replacing SF6 with air during internal arc testing

Authors agreed that replacement of SF6 with air during internal arc testing provides mixed results.
There is no “silver bullet” recommendation: each case must be evaluated separately. Some observations are listed below:

Arc compartment: Pressure development and resulting mechanical stresses in air are in most cases higher than in SF6. Burn-through might happen faster with SF6 then with air under the same conditions.

Exhaust compartment: Pressure development and the resulting mechanical stresses in SF6 are in most cases higher than in air.

indicators: indicator ignition might be comparable for both cases.
Ignition of the indicators would be hardest to predict even with CFD software.

More work has to be done to investigate the correlation between the flammability of the cotton samples, incident heat energy densities, and arc flash protection requirements.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Annex

EQUATIONS FOR PRESSURE RISE CALCULATION

PRESSURE SENSORS: TYPES AND ACCURACIES

COTTON INDICATORS: ENERGY ABSORPTION AND FLAMMABILITY

ROOM PRESSURE CALCULATION USING CFD EXAMPLES

EFFECTS OF NEUTRAL EARTHING ON THE INTERNAL ARC

FIGURES FROM SENSIBILITY ANALYSIS

EFFECT ON REPLACING SF6 WITH AIR ON BURN-THROUGH

GE

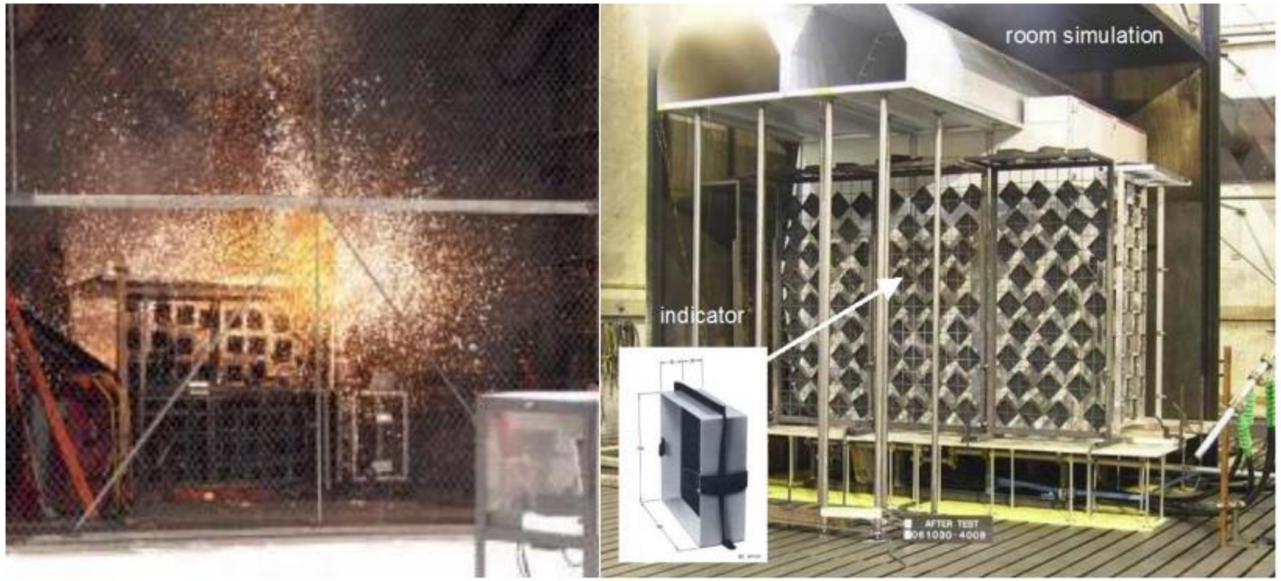
SIMULATION OF EFFECTS OF THE INTERNAL ARC

Introduction

The main goal: to reduce the number of tests and - for environmental reasons - to eliminate testing where SF6 is released to the environment.

The international standard for MV metal-enclosed switchgear, IEC 62271-200, permits SF6 to be replaced by air

The standard for HV Gas-Insulated switchgear, IEC 62271-203, allows the extension of test results by calculation methods



SIMULATION OF EFFECTS OF THE INTERNAL ARC

CALCULATION OF PRESSURE USING A BASIC MODEL

	Approach /model	Appropriate Application	Limitations
1)	**Basic** (low complexity)	To quickly calculate uniform pressure rise inside an arc compartment and the exhaust volume in typical MV switchgear and HV GIS applications.	• Doesn't consider spatial non-uniformity of gas parameters (pressure, temperature, density) in each volume part. • Not applicable if the relief opening area is too large in relation to the compartment volume. • Calculations are not reliable, when gas temperature exceeds approx. 2000 K for SF_6 and 6000 K for air. • Doesn't consider gas mixtures in the exhaust compartment.
2)	**Enhanced** (medium complexity)	To calculate uniform pressure rise as under 1) adding further approximations to better match test results and calculation.	• Doesn't consider spatial non-uniformity of gas parameters (pressure, temperature, density) in each volume part. • Limitations and applications depend on the implemented approximations.
3)	**CFD** (High complexity)	For calculating spatial pressure distribution and gas flow in odd shapes geometry and large rooms.	• High effort for the modeling and meshing of the rooms and switchgear • Requires large computing power and time.

Table 1-1: Model selection table.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CALCULATION OF PRESSURE USING A BASIC MODEL

Electric	**Geometric**	**Media**	**Mechanical characteristics**
Fault current (rms,peak) Rated voltage Circuit (3Ø/1Ø) Arc voltage Arc duration Type of fault	Volume of arcing and exhaust compartments if applicable Relief opening area Exhaust compartment openings Phase to phase distance Phase to ground distance Inner diameter of GIS enclosure	Type of gas (Air, SF_6, Mixture) Filling pressure c_V, c_p k_p -factor Ambient temperature Material of conductor	Operating pressure of the relief device Bursting pressure of the arcing enclosure Material of enclosure Wall thickness of the enclosure Manufacturing type of the enclosure (casting, plate welding, etc.)

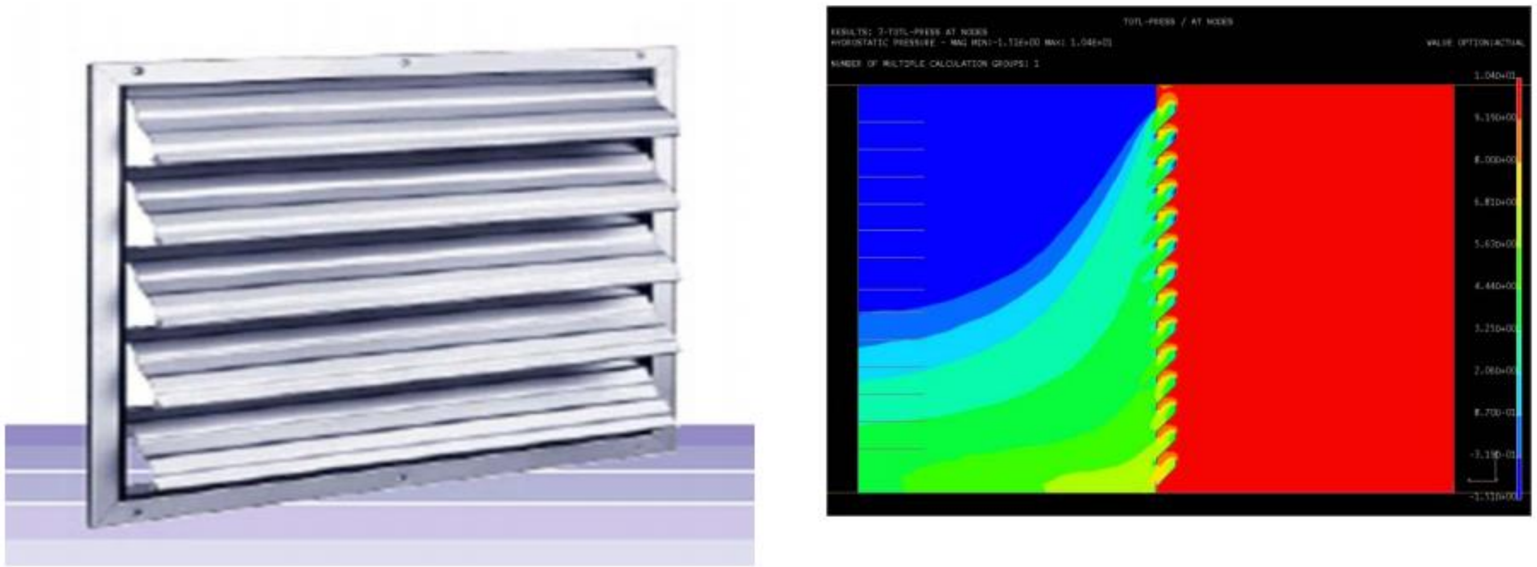
Table 7-1: Design input for internal arc withstand simulation review.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

CFD software usage

When pressure relief is made using a grid, a labyrinth or all types of porous media [Besnard2008], the pressure drop across this device must be modeled. Formula *(4-1)* can be implemented in CFD:

$$\Delta p = -\left(\frac{\mu}{K} v + C_2 \frac{1}{2} \rho v^2\right) \Delta d \qquad (4\text{-}1)$$



(a) (b)

Figure 4-4: An Example of a pressure relief opening with a labyrinth. (a) Outline of pressure relief opening. (b) Pressure distribution.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

Internal Arc Testing

Internal arc: **mechanical and thermal stressing of the equipment**.

Materials involved may produce hot decomposition products, in the form of gases or vapours, which may be discharged to the outside of the enclosure, and **endanger personnel or the general public**.

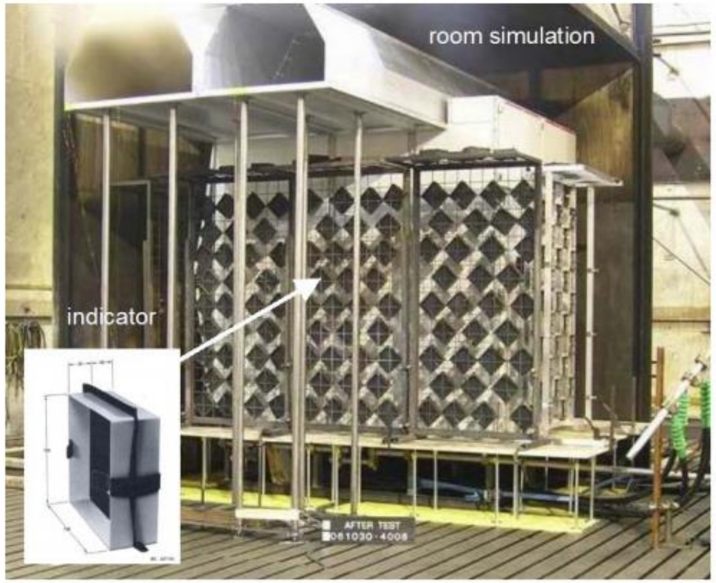


Figure 5-1: Indicator racks located at the front and side of an MV panel for internal arc testing.

SIMULATION OF EFFECTS OF THE INTERNAL ARC

EFFECT OF INTERNAL ARC ON STRUCTURES

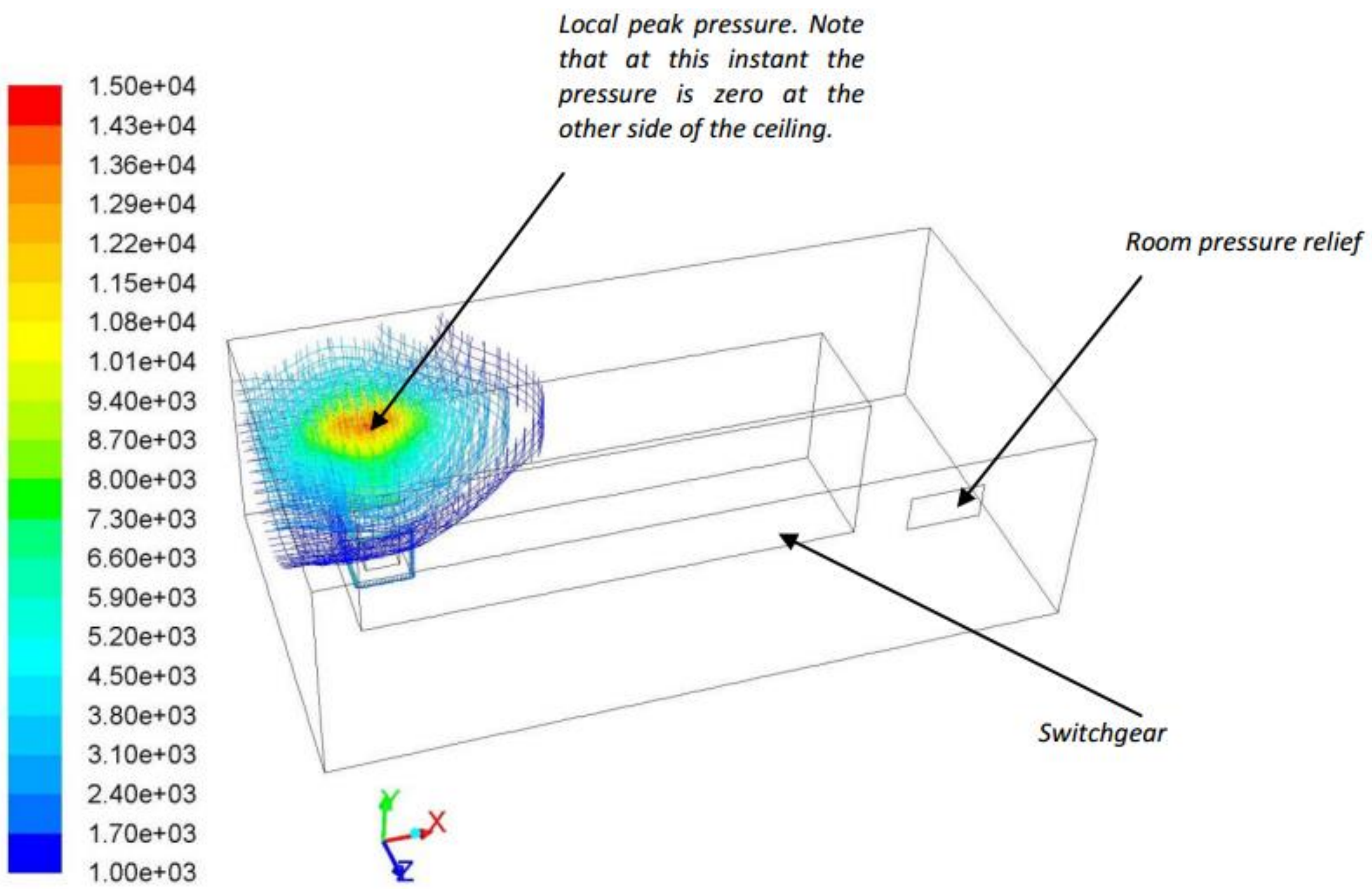


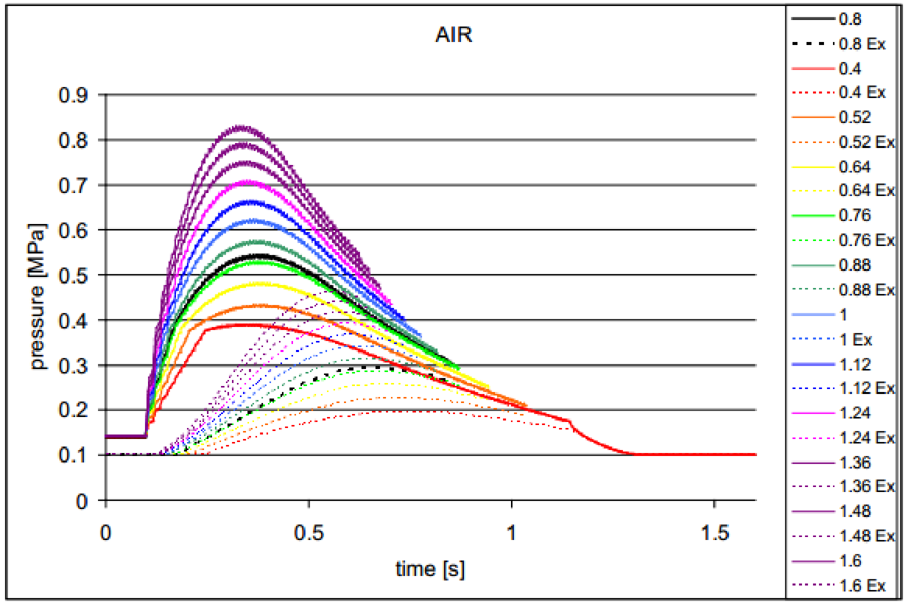
Figure 6-12: Example of pressure field within a switchgear room. Beginning of the event (11 ms after fault initiation).

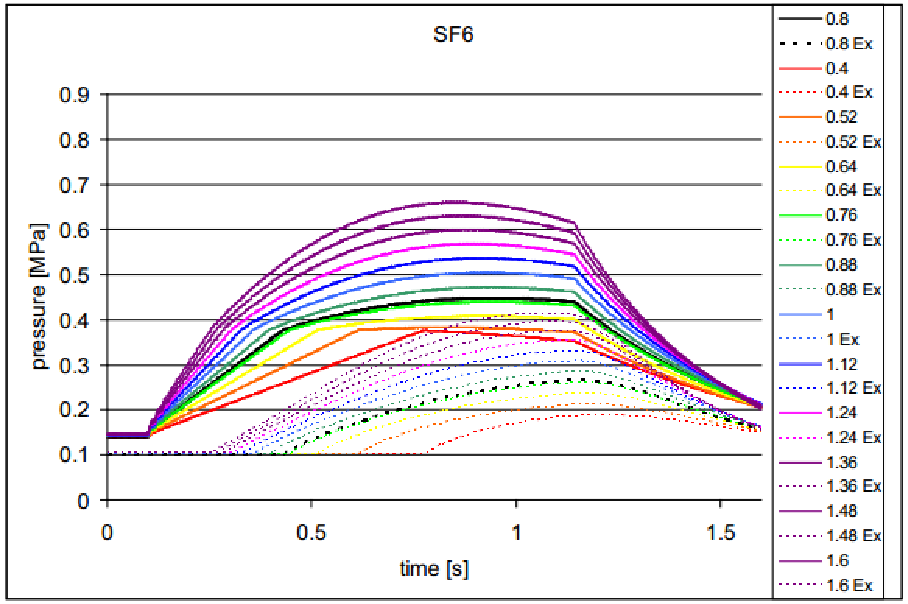
SIMULATION OF EFFECTS OF THE INTERNAL ARC

Sensibility

Sensitivity to power input

The power provided to the system has a great influence on the pressure curve for both the arc and the exhaust compartments. The parameters $Irms$, $Uarc$, kp are equivalent





** accelerates the process before bursting of the pressure relief device*
** increases the maximum pressure in arc compartment if overshoot is present. The peak pressure growth is generally higher for air than for SF6.*
- *increases the maximum pressure in the exhaust compartment*