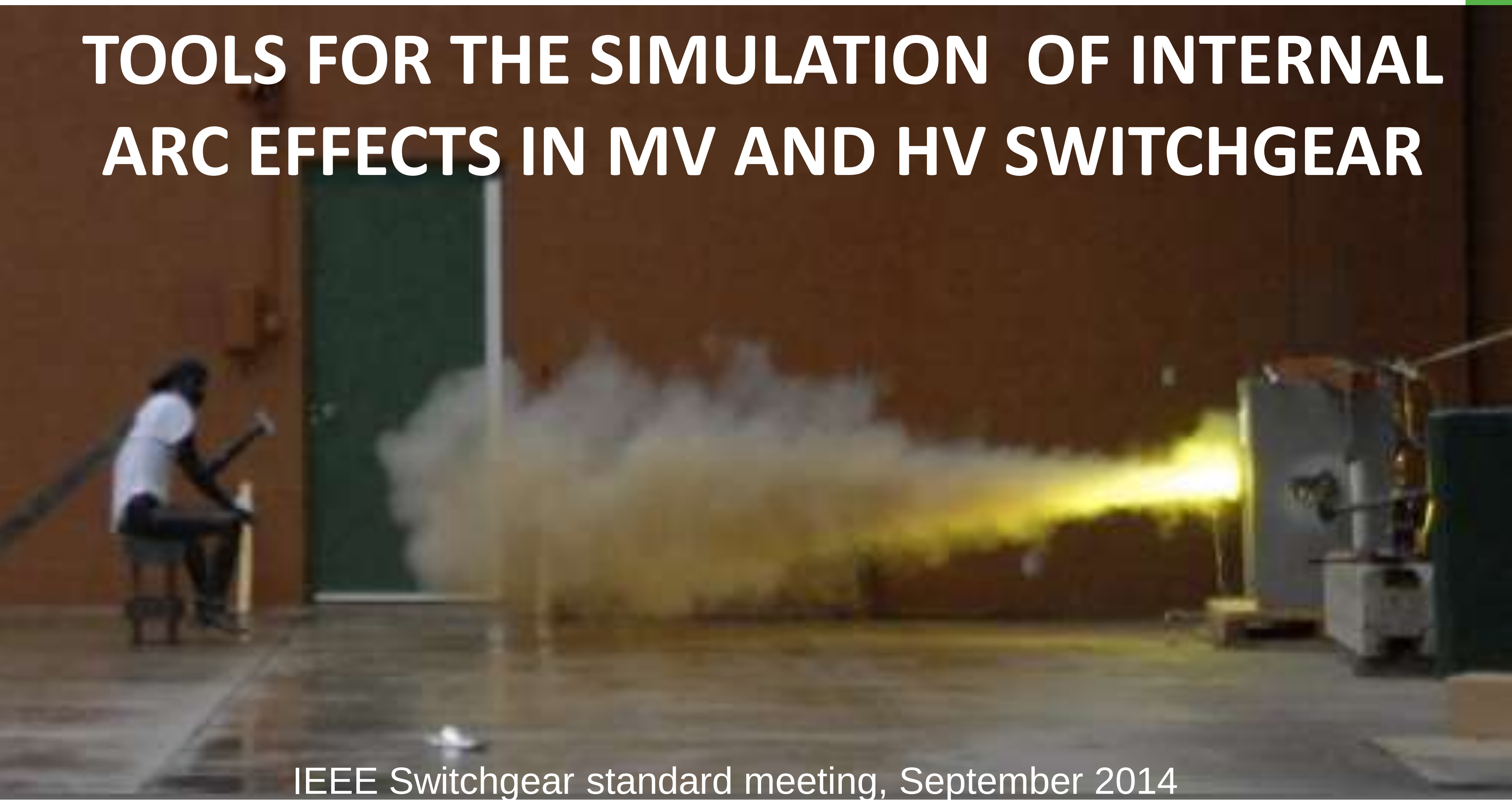
Engineered to order. Built to last.

TOOLS FOR THE SIMULATION OF INTERNAL ARC EFFECTS IN MV AND HV SWITCHGEAR



IEEE Switchgear standard meeting, September 2014

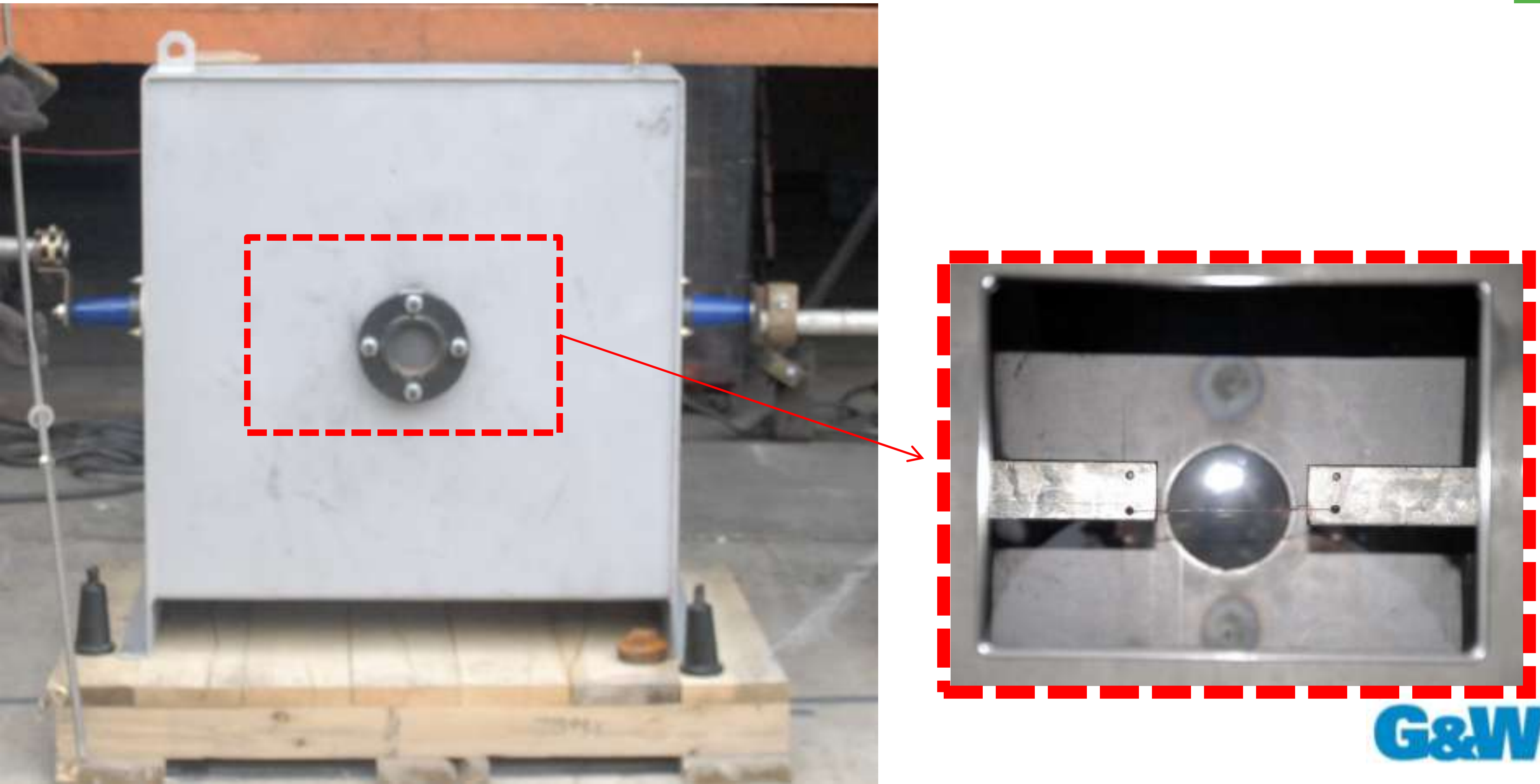
Nenad Uzelac, CIGRE A3.24 working group convener

Agenda

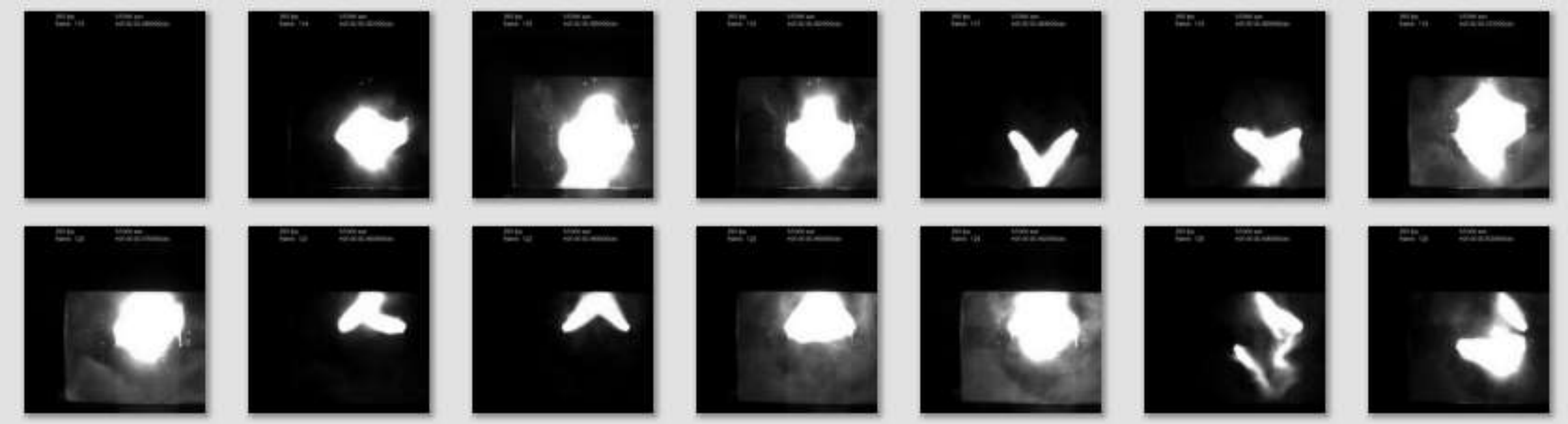
1. What is an Internal Arc?
2. CIGRE Working Group Intro
3. Effects of Internal Arc
4. Air vs SF_6 comparison
5. Design Reviews
6. Conclusion

1) Internal Arc

An **arc fault** - a high power discharge of electricity between two or more conductors



INTERNAL ARC



EFFECT OF THE ARC

Internal Arc switchgear

Internal arc switchgear – swithcgear for which prescribed criteria, for protection of persons, are met in the event of internal arc as demonstrated by type tests

IEC 62271-200

Internal Arc Test

2)


CIGRE
SESSION
45
24th to 29th August
Du 24 au 29 août
2014
Paris - France / Palais des Congrès
Porte Maillot - 75017 Paris

CIGRE

- Founded in 1921
- Council on Large Electric Systems
- Promotes collaboration with experts from all around the world to improve electric power systems
- **Key role**: provides the pre-standardization input to IEC

CIGRE Study Committees

Technical committee chairman: Mark Waldron (UK)
Secretary: Yves Maugain (France)

A: Equipment

A1 Rotating electrical machines
E. Figueiredo (Brazil)

A2 Transformers
C. Rajotte (Canada)

A3 High voltage equipment
H. Ito (Japan)

Disseminate new technology and
Promote international standardization

B: Sub-system

B1 Insulated cables
P. Argaut (France)

B2 Overhead lines
K. Papailiou (Switzerland)

B3 Substations
T. Krieg (Australia)

B4 HVDC and Power electronics
B. Anderson (United Kingdom)

B5 Protection and Automation
I. Patriota de Siqueira (Brazil)

Perform studies on topical issues of electric power system and Facilitate the exchange of information

C: System

C1 System development & economics
P. Southwell (Australia)

C2 System operation & control
J. Vanzetta (Germany)

C3 System environmental performance
F. Parada (Portugal)

C4 System technical performance
P. Pourbeik (USA)

C5 Electricity markets & regulations
O. Fosso (Norway)

C6 Distribution systems & dispersed generation
N. Hatziagyriou (Greese)

D: Common technology

D 1 Materials and emerging test technique

D 2 Information systems and telecommunication

CIGRE Technical Committee Directions

Prepare the "strong and smart" power system of the future

This future power system will have to wheel over long distances bulk power from non carbon sources; it will interconnect the local grid, to compensate for the geographical/temporal variability or lack of flexibility of these sources. It will interface local energy networks (microgrids) which allow the optimized operation of dispersed generation, intelligent loads, storage.. This future Power system will rely massively on new techniques, UHV, DC and Power Electronics, ICT...

Make the best use of the existing equipment and system

Use better the full built-in capacity, operate the system nearer to its limits; operate the assets up to the end useful life, assess their condition, maintain, refurbish, extend their life, replace...

Answer the environment concerns

Develop environment friendly materials, less intrusive techniques (cables); use efficiently the assets; reduce carbon footprint of electricity...

Develop knowledge and information

Technical expertise, cooperation of worldwide experts and access to information are keys for the success of this evolution.

Study Committee A3 organisation

Chair
Hiroki Ito

Secretary
Edlehard Kynast

Special Reporters 2014
Anton Janssen
Antonio Carvalho

Session Secretary 2014
Andre Giboulet

23 Regular members

16 Observer members

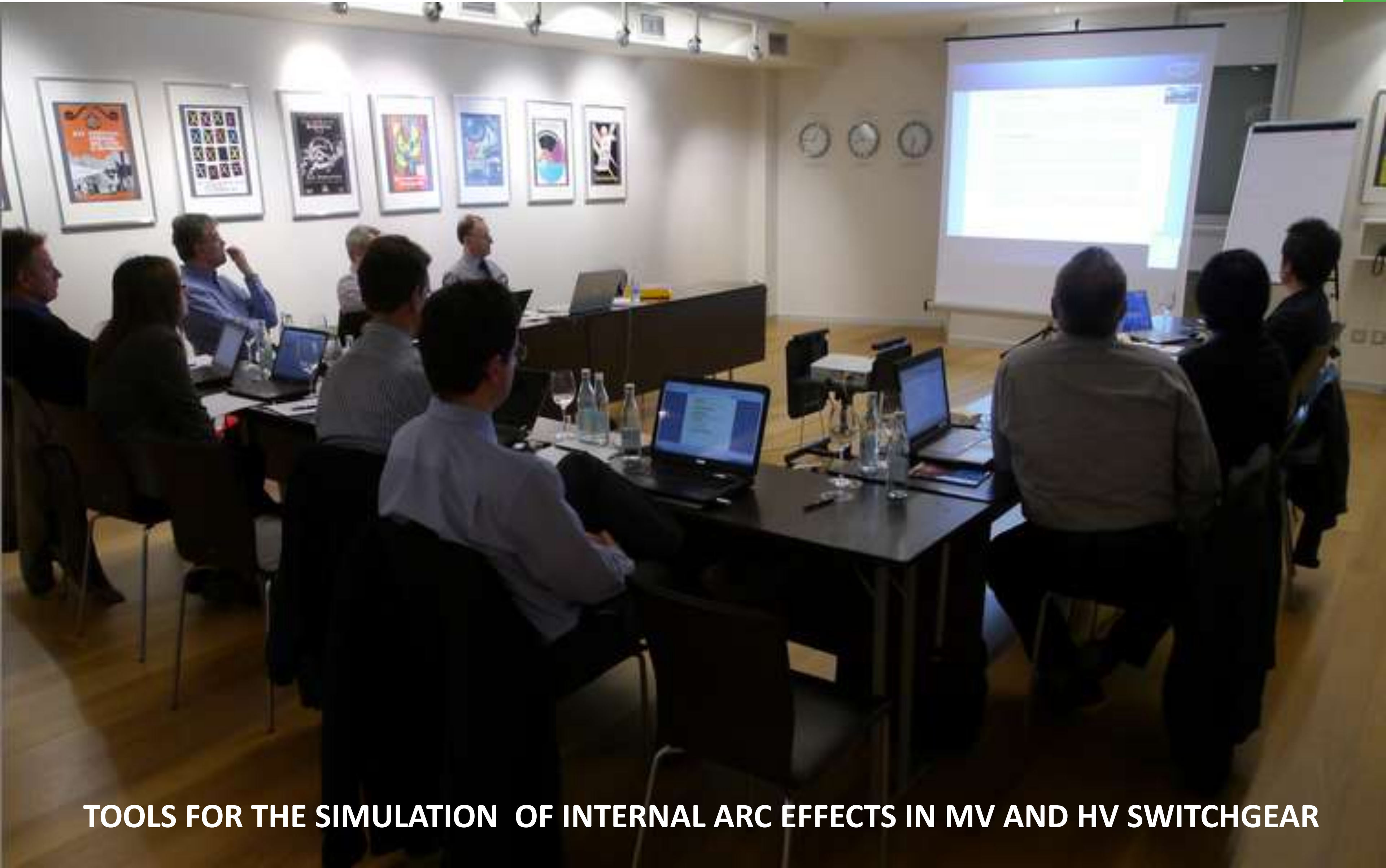
AG A3.01: Strategic Planning
- Hiroki Ito
- Edelhard Kynast
- Anton Janssen
- Ankur Masheshwari
- Paulo C. Fernandez
- Rene Smeets — CIRED liaison
- Mietek Glinkoski — IEEE liaison
- Denis Dufournet — IEC liaison
- Chistian Frank — DC equipment
- Slawomir Samek — SC B3 liaison

AG A3.02: Tutorial Planning
- Mietek Glinkoski
- Magne Runde
- Rene Smeets

AG A3.03: Greenbook
- Paulo C. Fernandez
- Lou van der Sluis — Document Advisers
- Harley Wilson — Document Advisers

Working Group		
WG A3.24	N. Uzelac (US)	Simulating internal arc and current withstand testing
WG A3.25	B. Richter (CH)	MO varistors and surge arresters for emerging system conditions
WG A3.26	A. Bosma (SE)	Capacitor bank switching and impact on equipment
WG A3.27	R. Smeets (NL)	Impact of application of vacuum switchgear at transmission voltages
WG A3.28	D. Dufournet (FR)	Switching phenomena for UHV & EHV equipment
WG A3.29	A. Maheshwari (AUS)	Deterioration & ageing of HV substation equipment
WG A3.30	A. Carvalho (BR)	Overstressing of HV substation equipment
WG A3.31	F. Rahmatian (CA)	Non conventional instrument transformers with digital outputs
WG A3.32/CIRED	N. Uzelac (US)	Non intrusive methods for condition assessment
WG A3.33	G. Li (CN)	Experience with equipment for series/shunt compensation
JWG A3/B4.34	C. Franck	Technical requirements and specifications of DC switchgear
WG A3.35	A. Mercier	Best practices for commissioning of controlled switching

CIGRE A3.24 working group



Background

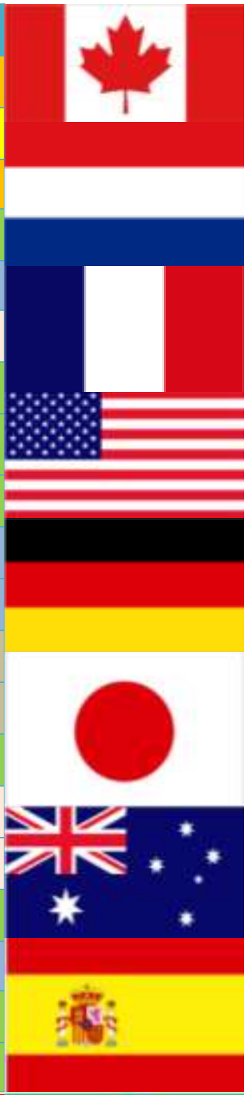
- Working group started in 2009
- 11 2-day working group meetings
- Last Working group meeting held in June 2013
- Deliverable: Technical Brochure 2014
- 20 members coming from 12 countries on four continents
- International experts in Internal Arc testing and computational modeling from HV and MV Switchgear manufacturers, users, labs and universities.

Motivation of Work

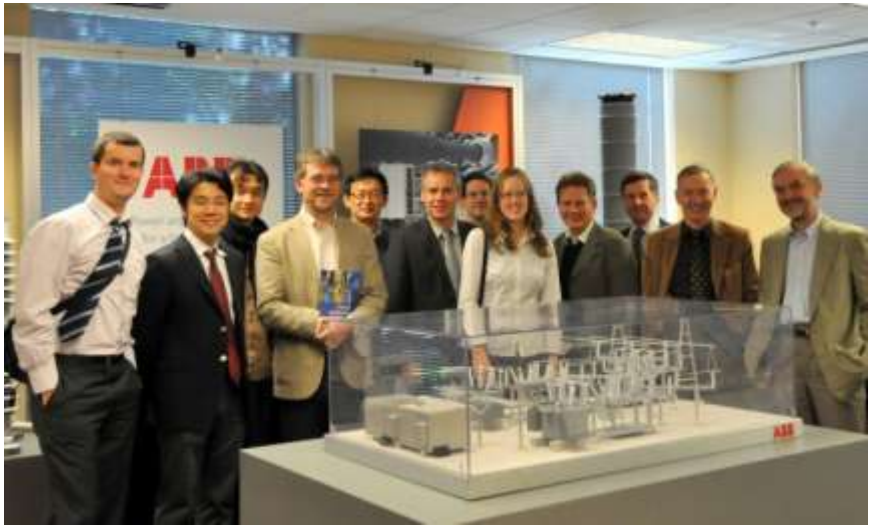
- To provide methods for pressure rise calculations, allow benchmarking
- To verify design modifications by simulations
- To provide guidance to perform reviews of the simulations provided by the manufacturer
- To reduce internal arc tests for environmental reasons by improving the hit rate of the design
- To replace SF_6 in GIS for testing by air with proper consideration of the differences

Working group members

Name	Country	Company	Interest
Lopez-Roldan	Australia	Powerlink	Utility
Feitoza Costa	Brazil	Cognitor	Consulting
Pater	Canada	Hydro-Québec	Utility
Douchin	France	Schneider	Manuf. MV Switchgear
Vinson	France	Alstom	Manuf. HV Switchgear
Pietsch	Germany	RWTH Aachen	University
Dullni	Germany	ABB	Manuf. MV Switchgear
Singh	Germany	Schneider	Manuf. MV Switchgear
Reiher	Germany	Siemens	Manuf. MV Switchgear
Yoshida	Japan	Mitsubishi Electric	Manuf. HV Switchgear
Uchii	Japan	Toshiba	Manuf. HV Switchgear
Kim	Korea	KERI	Test Laboratory
Smeets	Netherlands	KEMA	Test Laboratory
Schoonenberg	Netherlands	Eaton	Manuf. MV Switchgear
Van der Sluis	Netherlands	TU Delft	University
Fjeld	Norway	Telemark University	University
del Rio	Spain	Ormazabal	Manuf. MV Switchgear
Kriegel	Switzerland	ABB	Manuf. HV Switchgear
Glinkowski (Secretary)	USA	ABB	Manuf. MV Switchgear
Uzelac (Convenor)	USA	G&W	Manuf. MV Switchgear



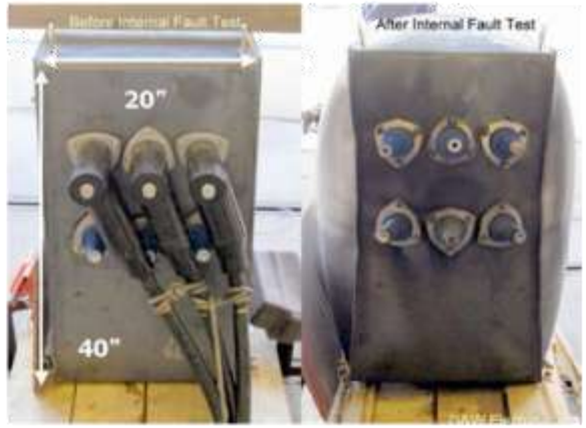
Working group

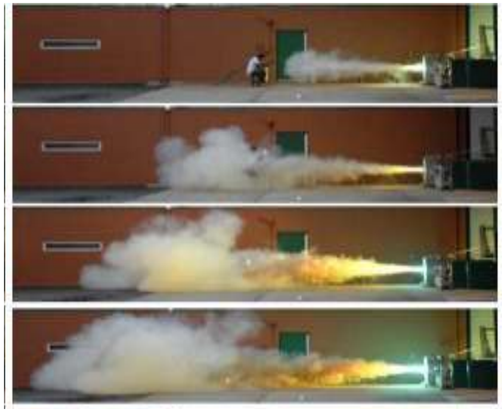


Work methodology

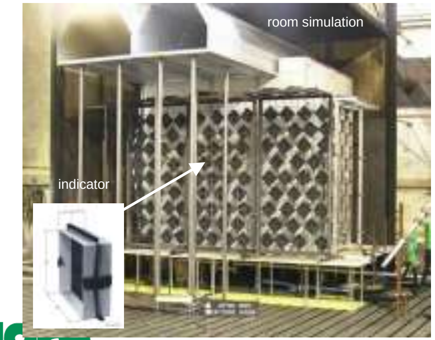
- Research:
  - Reviewed 100+ white papers and standards
  - Collected test data from 80 internal fault tests
  - Performed testing on SF6 vs Air
- Development:
  - Developed mathematical models
  - Developed testing guidance
- Validation:
  - Validated software simulations with test data

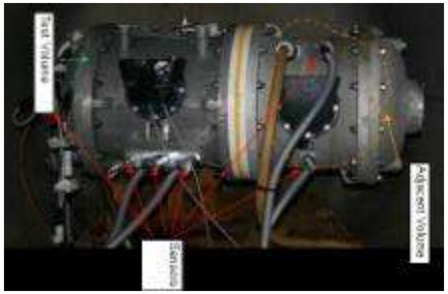
Analyzed 80+ cases





- AIR, SF6, N2
- 5 ltr – 1200 ltr
- 12kA – 63kA
- 10ms – 1.2s

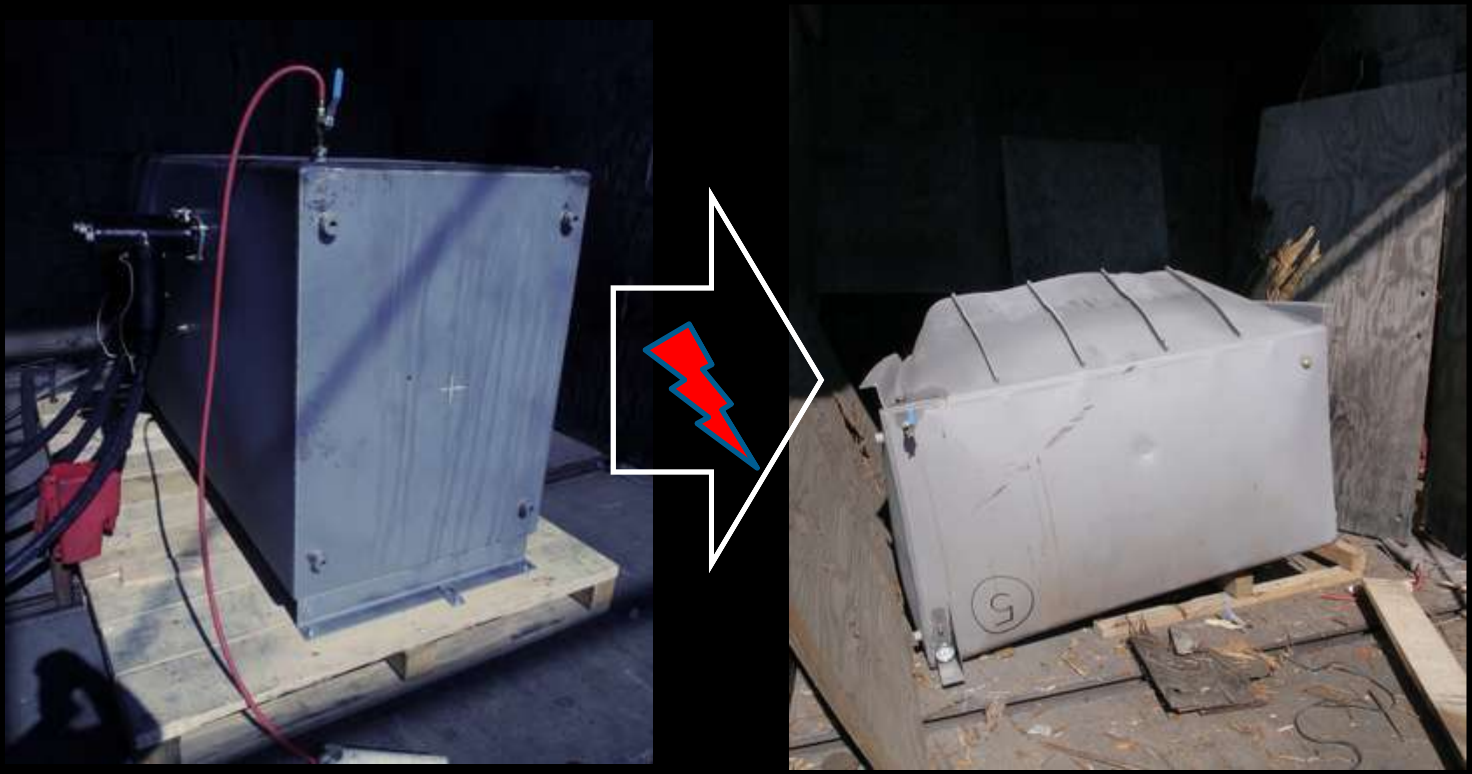




Internal Arc

- Energy of 25kA, 0.25s = Energy of 2kg TNT
- Temperature > 1000°C
- Pressure rise ~ 10bars (25kA,4 cycles,200l)
- Force on walls ~ several tons

Power of Internal Arc



3) Effects of Internal Arc fault:

1.	Pressure rise inside switch	
2.	Arc Burn-through	
3.	Mechanical Stress on switch enclosure	
4.	Mechanical stress on the installation room	

1. Pressure rise effect

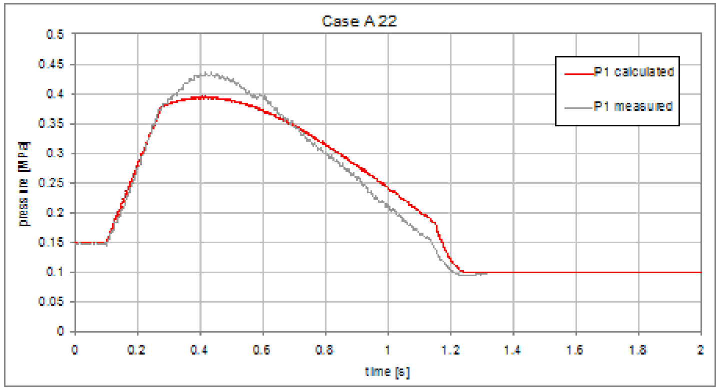
Before Internal Arc Test

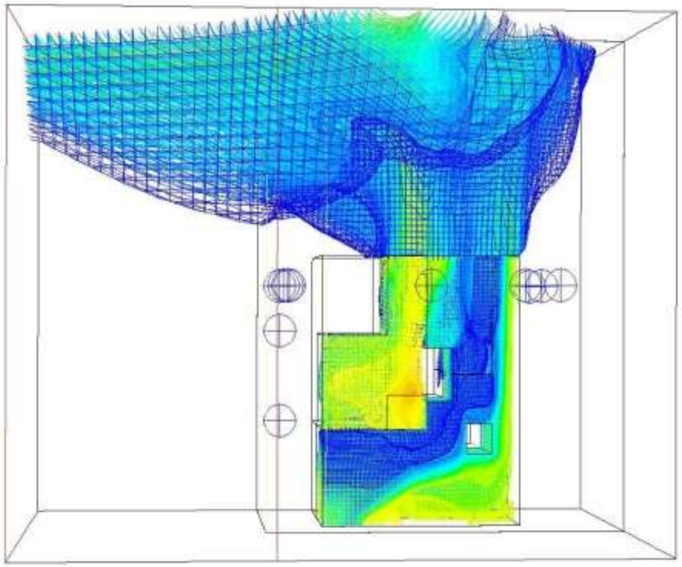
After Internal Arc Test

Pressure rise calculations:

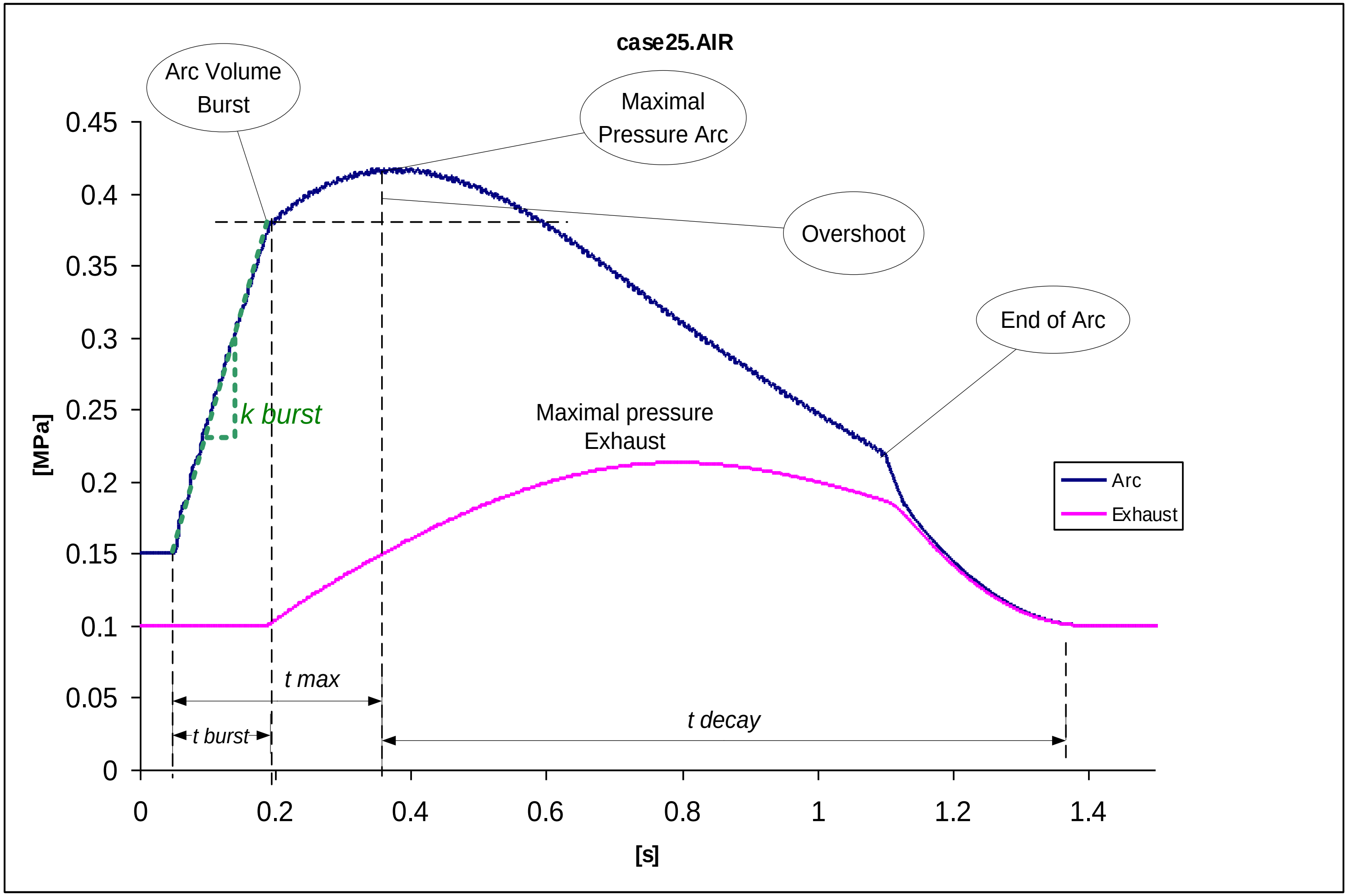
Methods for pressure rise calculations

- **Simplified Analytical Model:**
  based on ideal gas equations, to calculate uniform pressure rise inside switchgear
- **Enhanced Analytical Model**
  Simplified + additional approximations
- **CFD Model:**
  calculate pressure distribution and gas flow in odd shapes geometry and very large rooms .



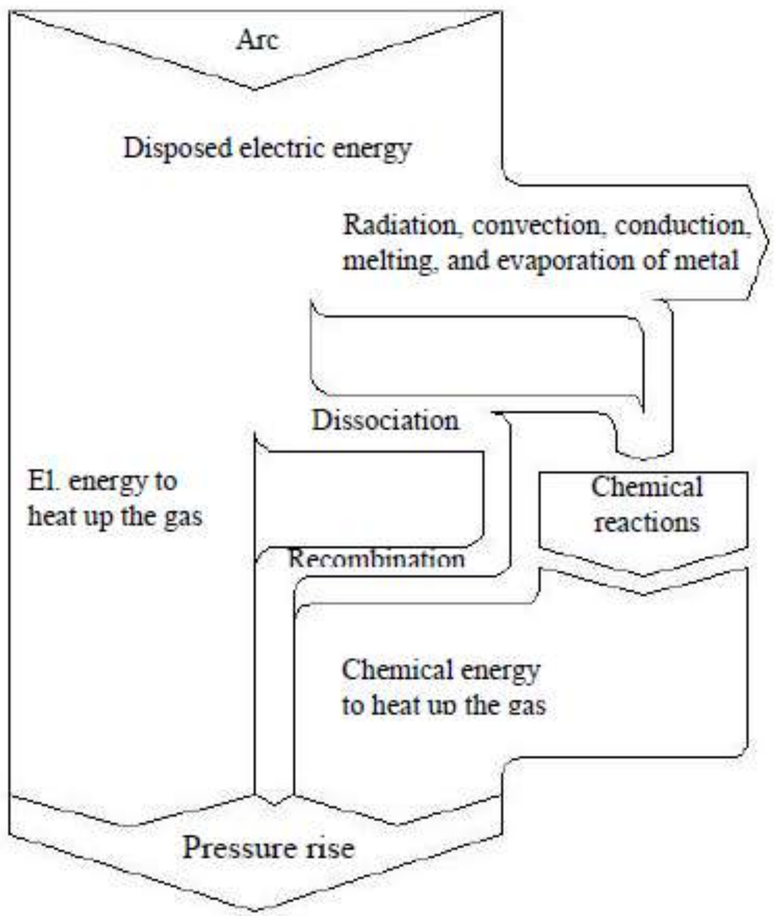


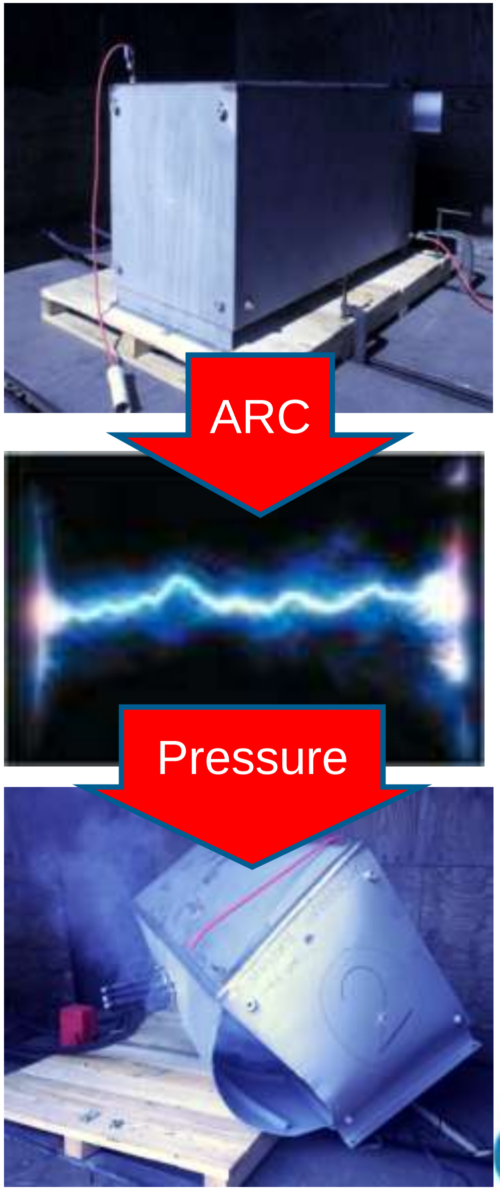
Pressure Rise curve



Characteristic values determined from calculated or measured pressure course.

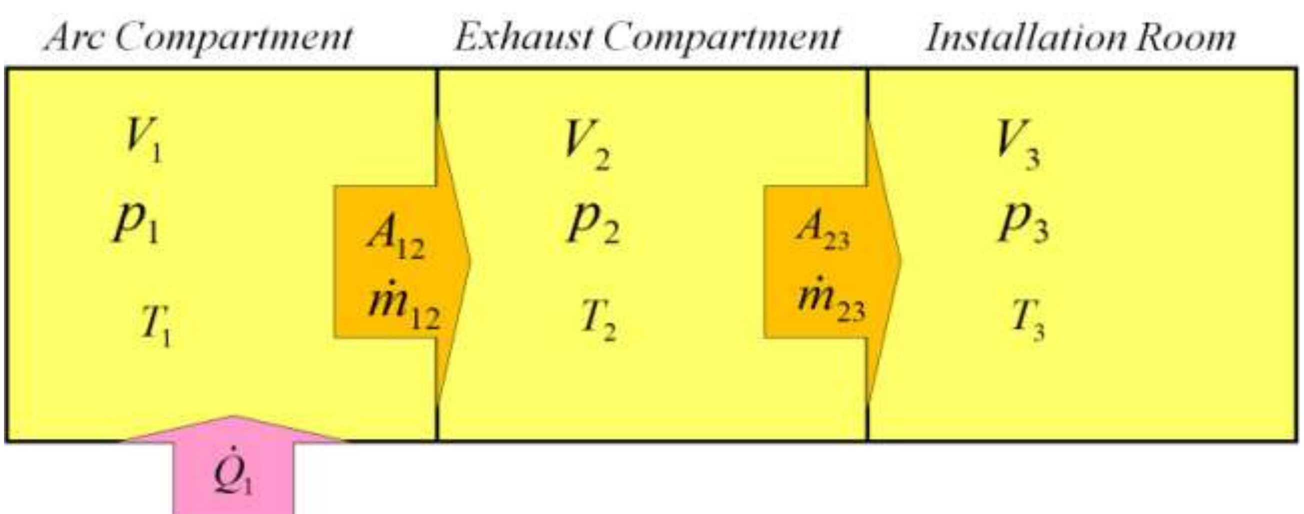
Internal Arc Energy balance in gas





T.R. Bjortuft et al., "Internal arc fault testing of gas insulated metal enclosed MV switchgear" CIRED, June 2005

A) Simplified analytical model



Simplified analytical model

- Outlined in detail in Technical Brochure.
- Used to quickly calculate uniform ΔP using ideal gas equation in V1, V2 and V3
- Some limitations exist.
  - Both analytical models don't calculate spatial differences in pressure inside the volumes
  - Applicable for simple geometries where uniform pressure can be assumed
  - Applicable for smaller volumes (approx <50 m^3) where pressure waves are negligible.

Energy conservation equations during arcing in closed tank

$$\Delta P = \frac{R}{M}\rho\Delta T$$

R gas constant

M weight of gas molecule

ρ gas density

P pressure increase

T temperature increase of SF6

$$\Delta T = \frac{Q'}{c_v \rho V}$$

$Q' = K_p * W_{el}$ thermal energy absorbed by the gas

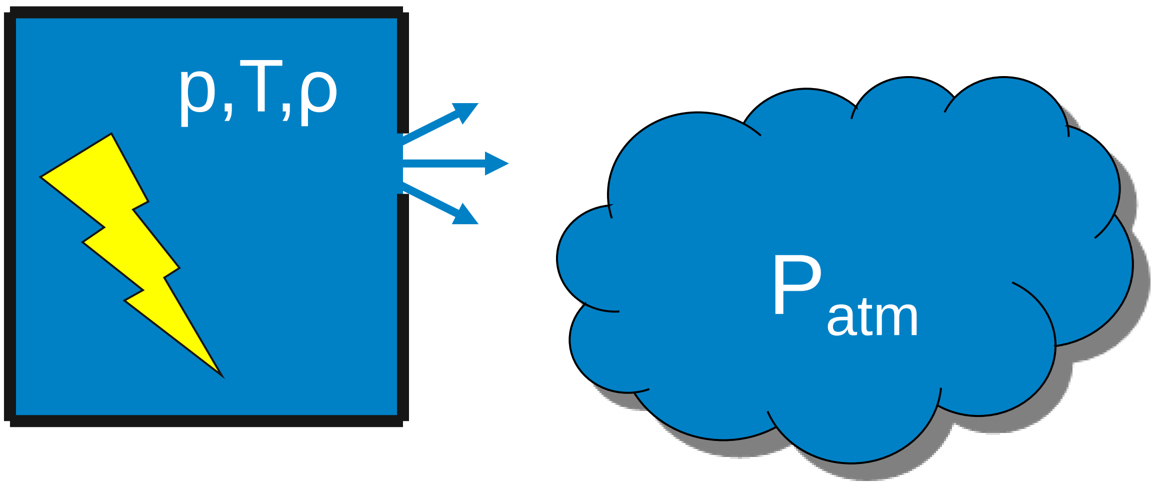
W_{el} Electric energy of the arc

K_p coefficient accounting for the energetic absorption of gas

c_v specific heat

V volume of enclosure

Net Energy conservation equation during arcing in open tank

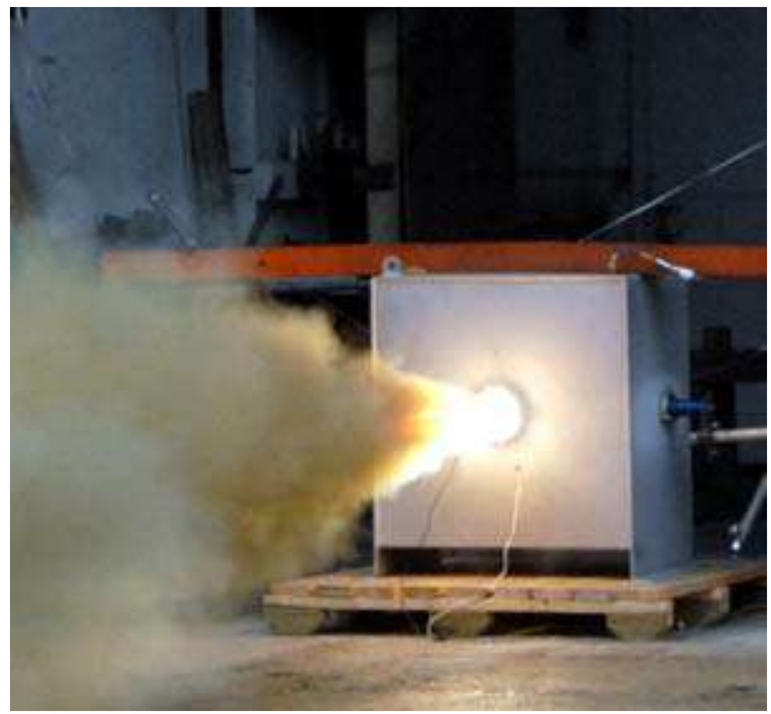


$$W = mC_v(T, p)\Delta T + \frac{\Delta m u^2}{2} + p_{atm}\Delta V$$

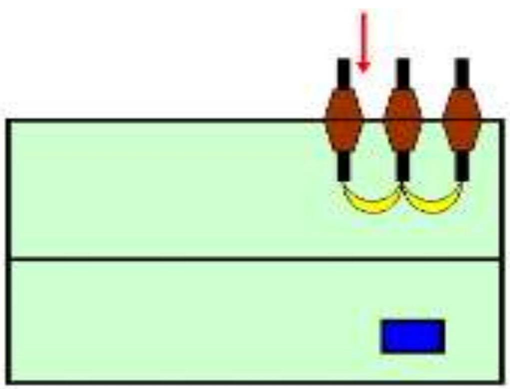
Net change of heat = Increase of internal energy of the gas inside the tank +
Change of kinetic energy of the gas at the exit +
Work performed by the gas at the exit

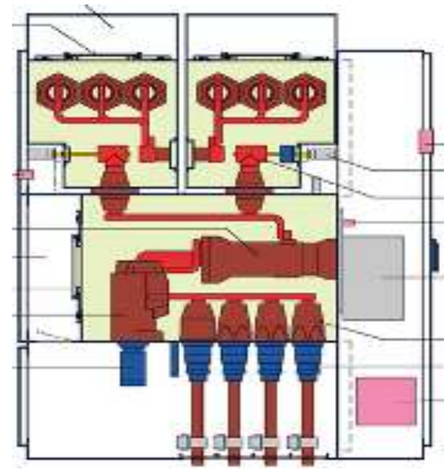
Rupture Disc

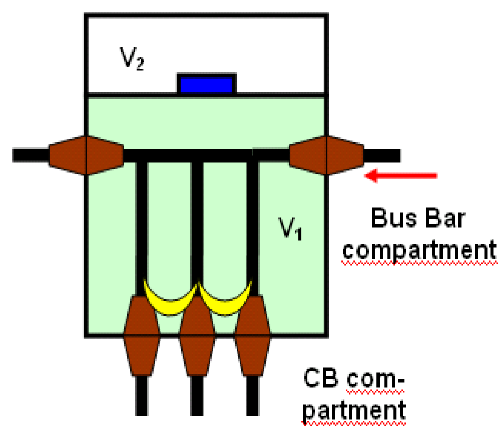
In order to minimise the risk of bursting, enclosures may be equipped with a bursting disc that activates once a certain pressure is reached.

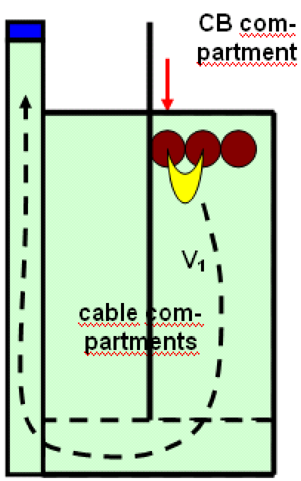


a) Simplify geometry









b) Calculate pressure rise for each case

Simplified model equations

$$Q_1 = k_p \cdot W_{el}$$

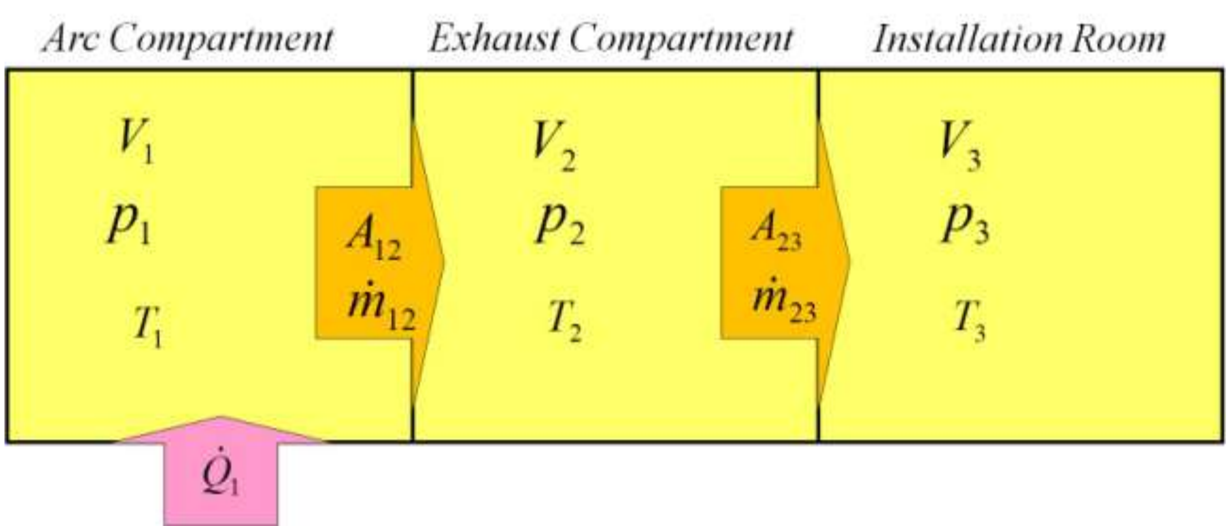
$$\Delta m_2 = \Delta m_{12} - \Delta m_{23}$$

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

$$\Delta T_1 = \frac{\Delta Q_1 - \Delta m_{12}\left(c_{p1} - c_{v1}\right)T_1}{m_1 c_{v1}}$$

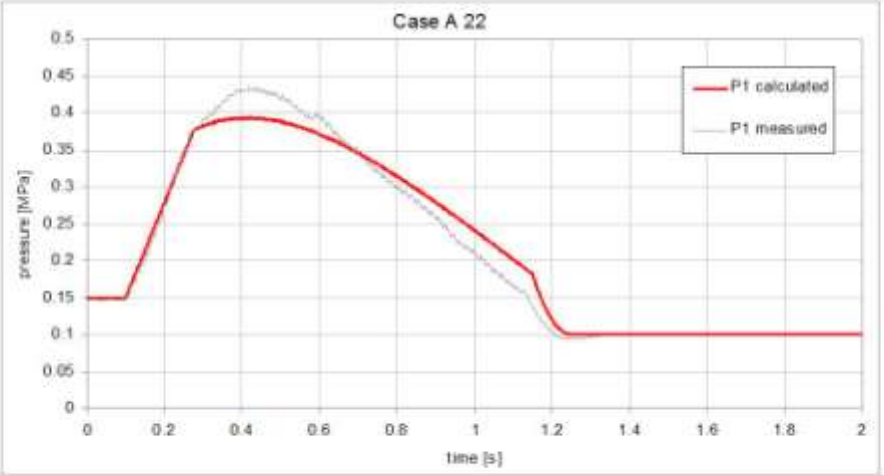
$$p_1 = \frac{\left(\kappa_1 - 1\right)}{V_1} \cdot m_1 \cdot c_{v1} \cdot T_1$$

For better calculation prediction, Kp-factor and arc voltages need to be taken from the similar test

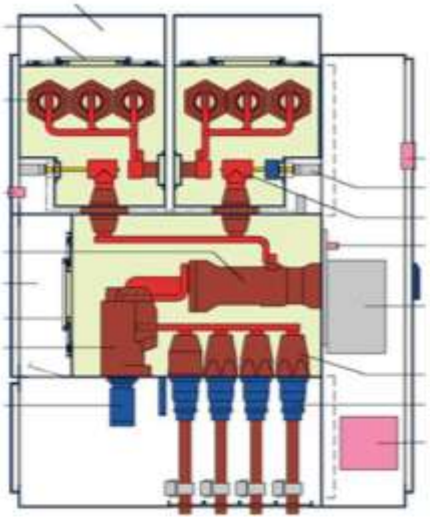


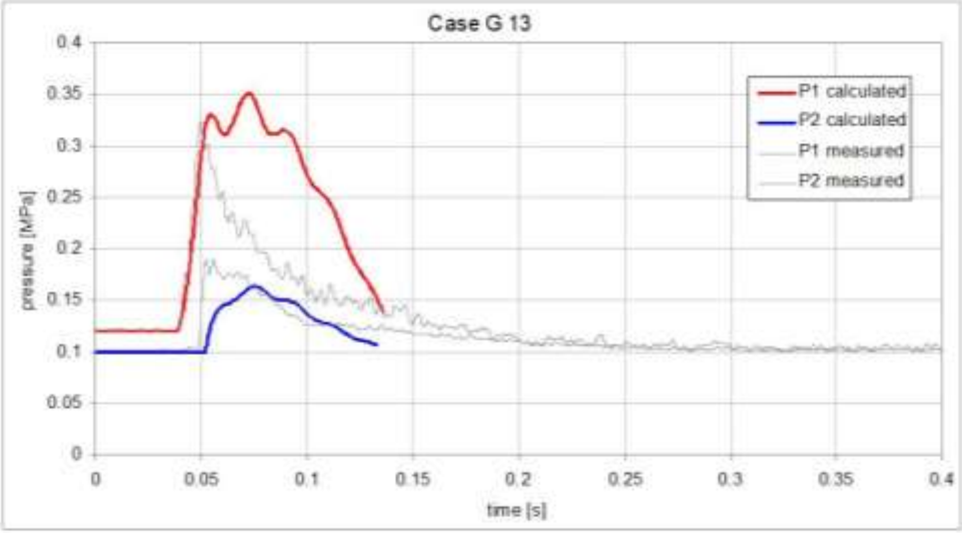
c) Comparison with test results

Calculation results of pressure rise in arcing compartment within 10% from measured.



Determine Kp - factor



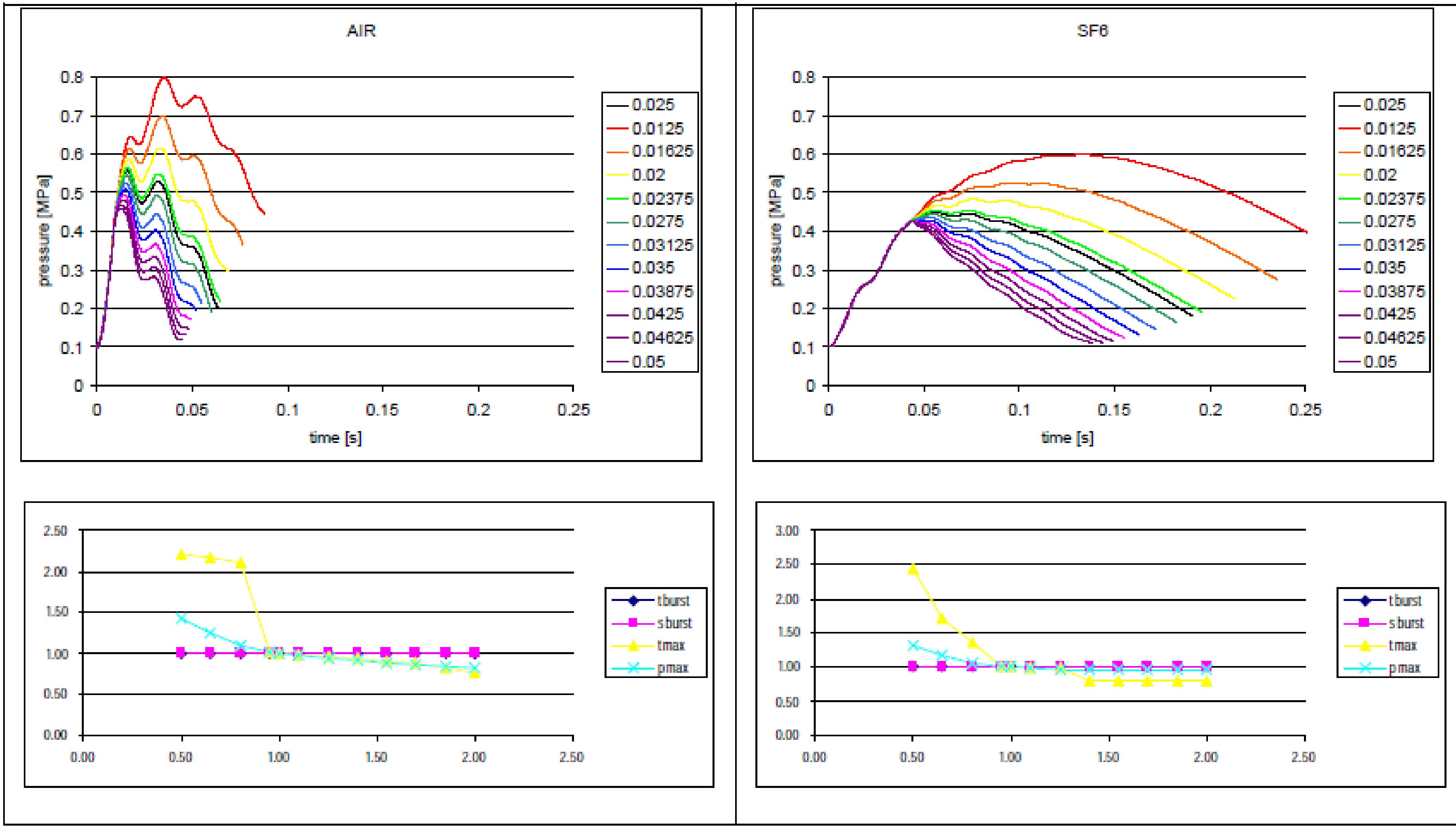


d) Use software tools to predict results

Must test similar object to determine Kp-factor

1. Different switch / compartment size
2. Different fault currents
3. Different rupture disc openings
4. Different gas

Example: Influence of rupture disc area



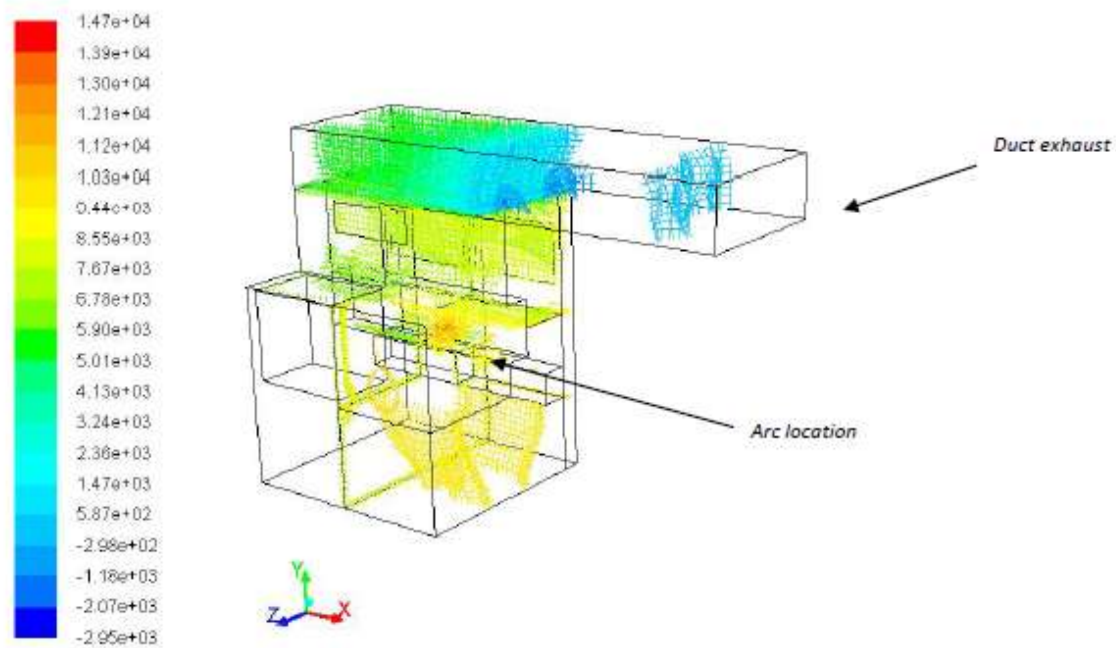
B) Enhanced Analytical Model

- Used to calculate uniform ΔP inside volumes, with some added approximations to improve the simplified model.

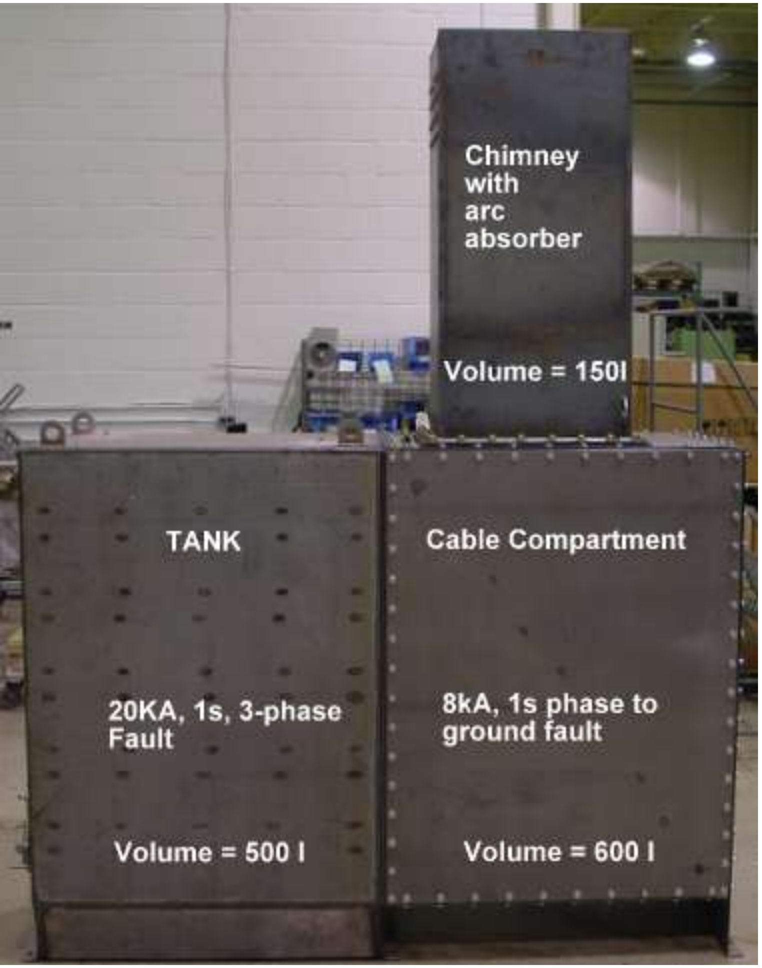
  – density dependent kp-factor
  – exothermic reaction energy
  – pressure dependent arc voltage
  – mixing of gas in compartments
  – metal evaporation and ablation of insulators
  – arc absorbers in the exhaust flow
  – speed of relief opening device
  – temperature dependent gas data

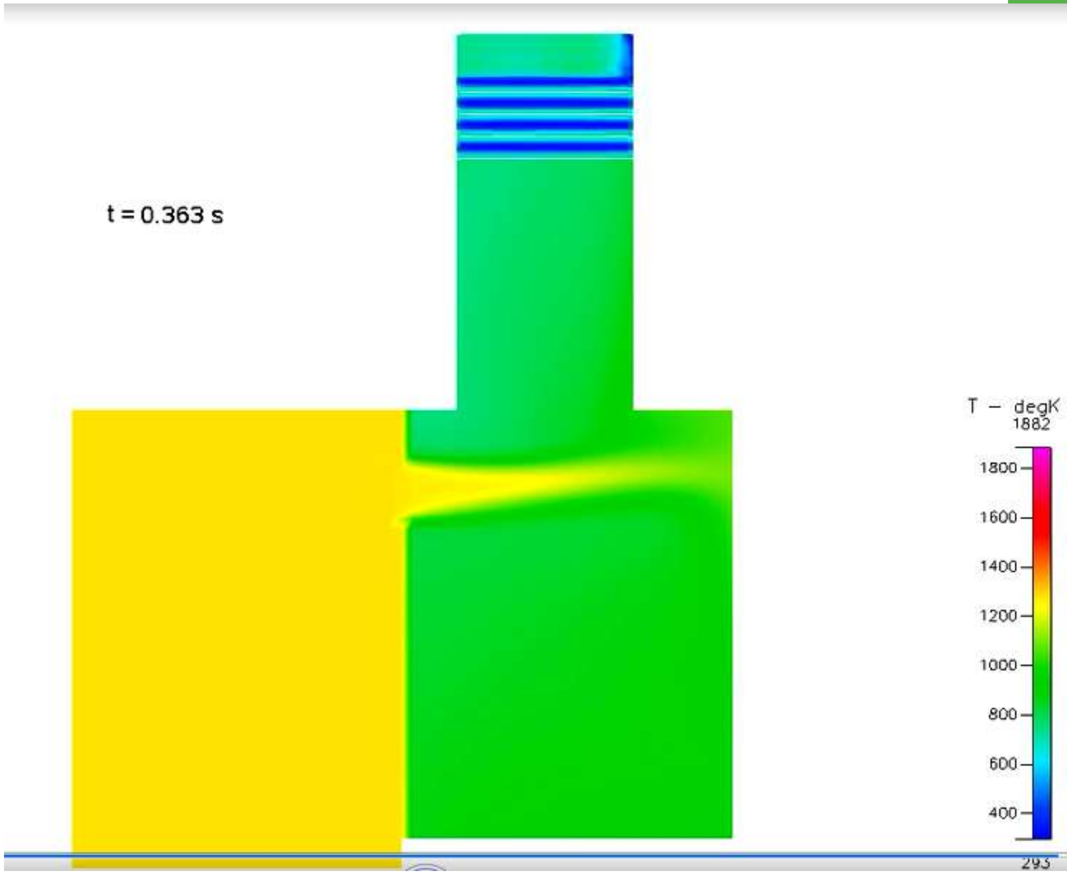
C) CFD Model

- Used with complex geometry
- Spatial resolution of the results
- Pressure waves are included
- Can model arc absorbers



CFD model example:

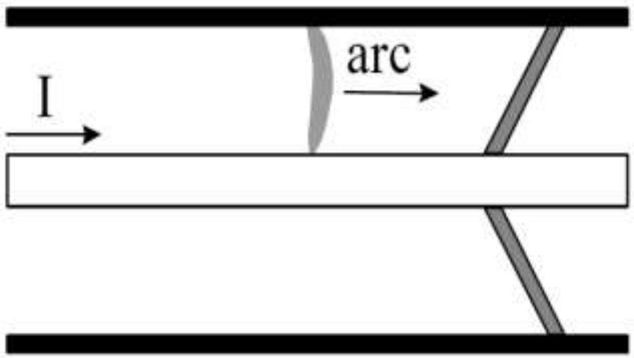


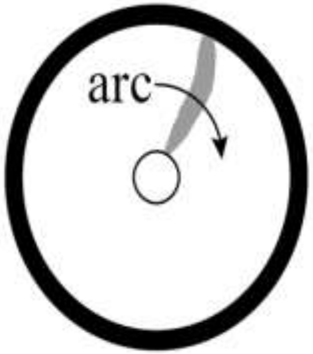


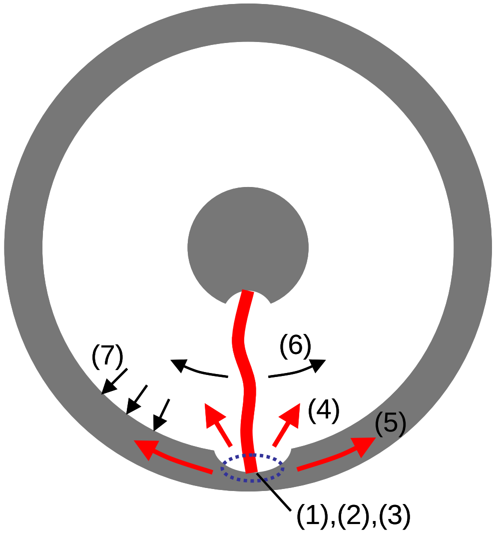
Pressure Rise Summary

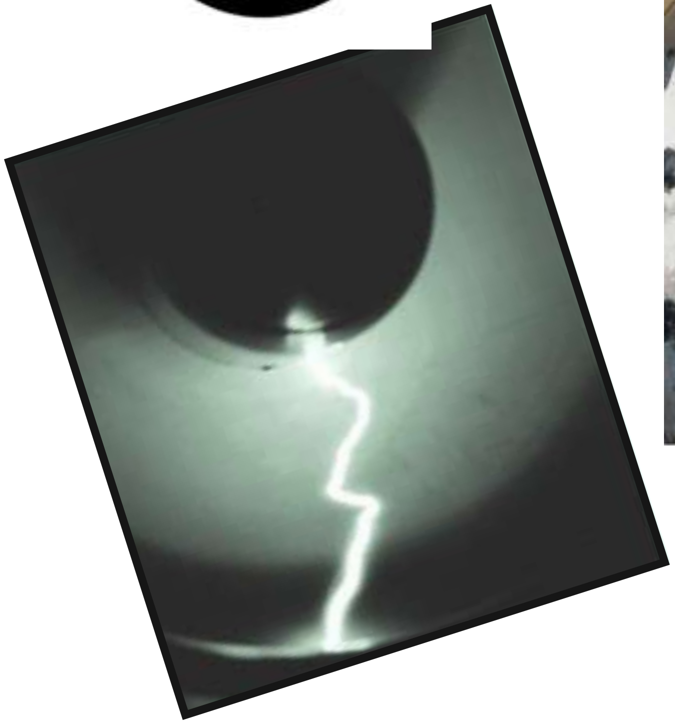
- Proposed 3 models for calculating the pressure rise.
- Pressure rise depends on:
  - Larger the arc voltage or arc current, the larger the maximum pressure
  - Larger the volume, the longer the time it takes for the pressure to increase & decrease
  - Larger the diameter of pressure relief valve, the smaller the maximum pressure

2. Arc Burn-through: GIS Single-phase Busbar

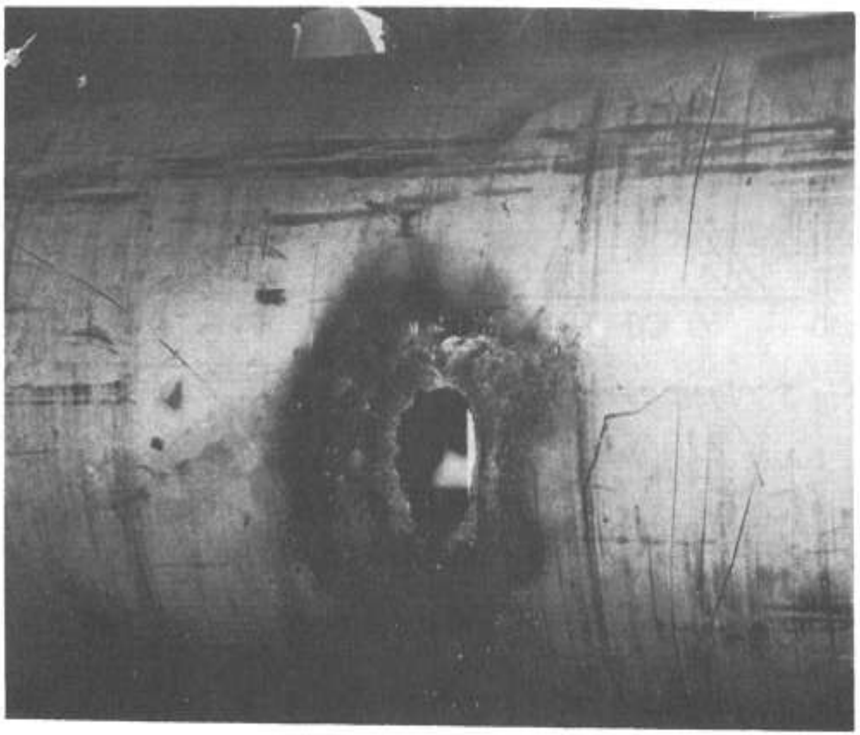




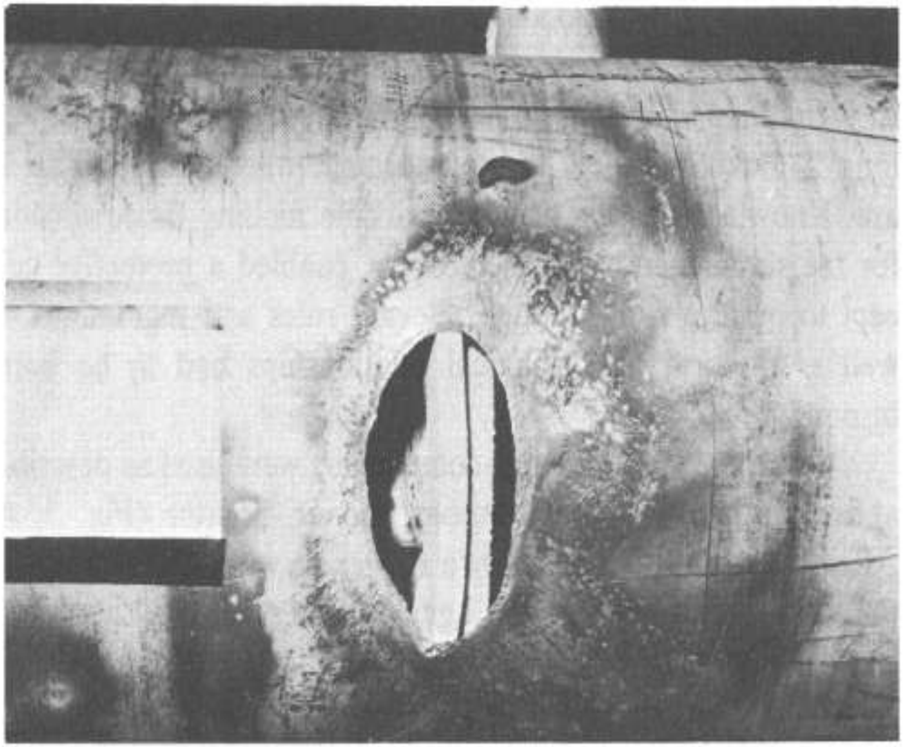




Example of Single-Phase Busbar after internal arcing



a) $i = 10.8\ kA, t = 390\ ms$



b) $i = 40.6\ kA, t = 190\ ms$

H. Strasser, K.D. Schmidt, and P. Hogg, "Effects of arcs in enclosures filled with SF6 and steps taken to restrict them in SF6 switchgear," IEEE, November 1973

Evaluation of the burn-through time

- The time to burn-through (t) can be estimated as

$$t = k\frac{h^2}{I}$$

k depends on the material
h is the enclosure thickness
I is the arc current

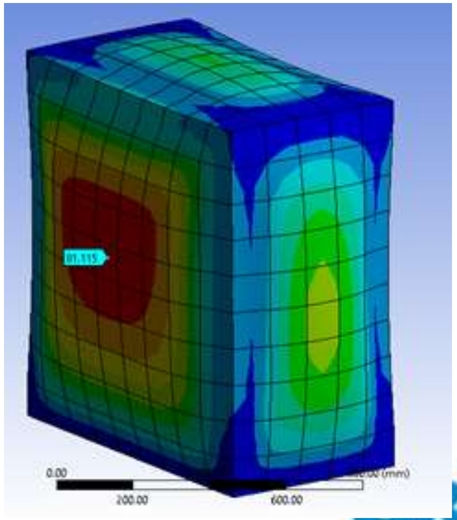
- The time to burn-through increases with the increase of the enclosure thickness and the decrease of the arc current .
- It will be 4 times larger for steel than aluminum.

Burn through summary

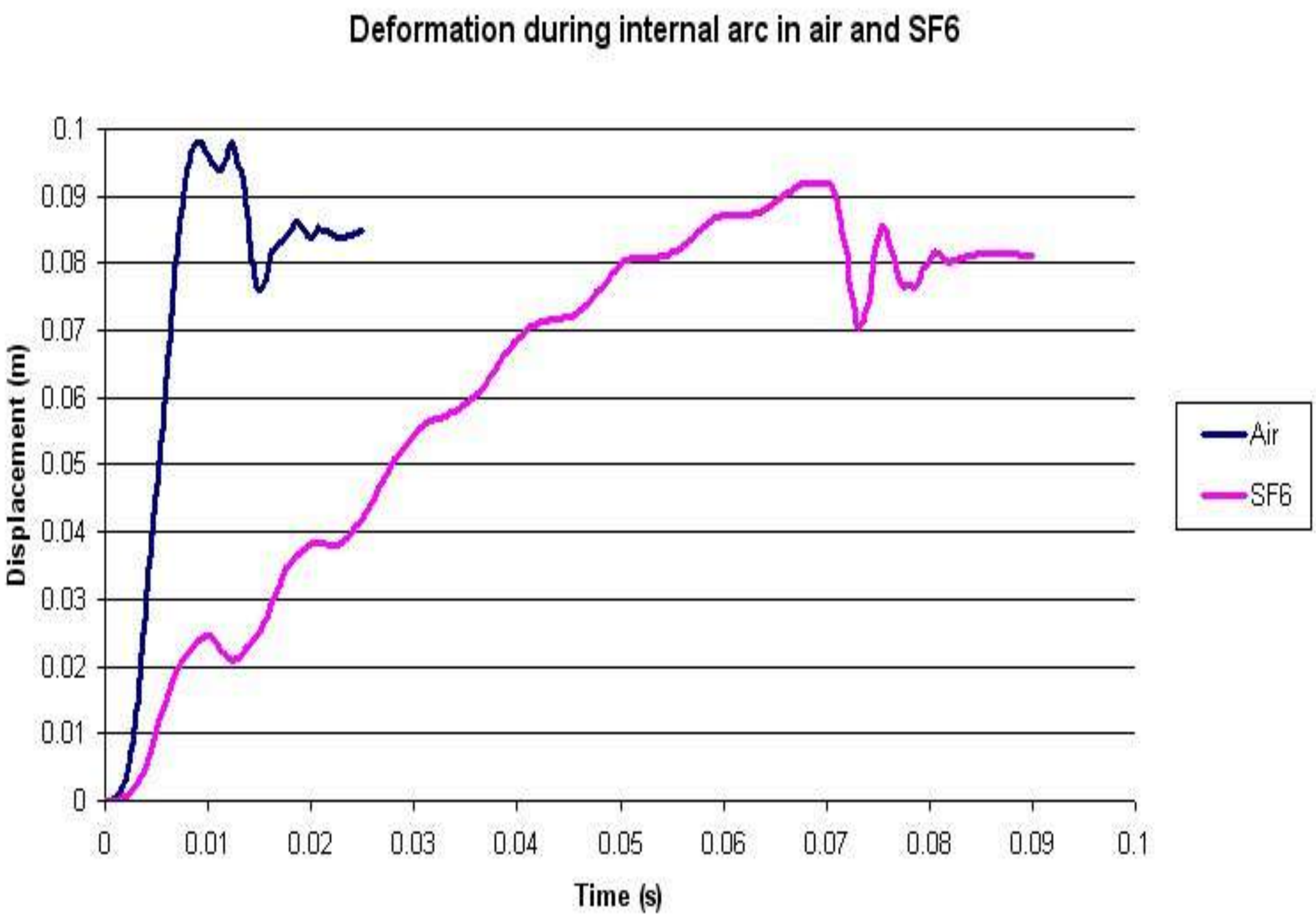
- Greater the thickness, the longer the burn through time
- Larger the arc current, the shorter the burn through time
- Aluminium enclosures burn through faster than steel enclosures
- Risk for personnel is very small: estimation of the probability of personnel being injured from the direct hit of a burn-through of 1E-5 per substation and year.

3) Mechanical stress on the switch

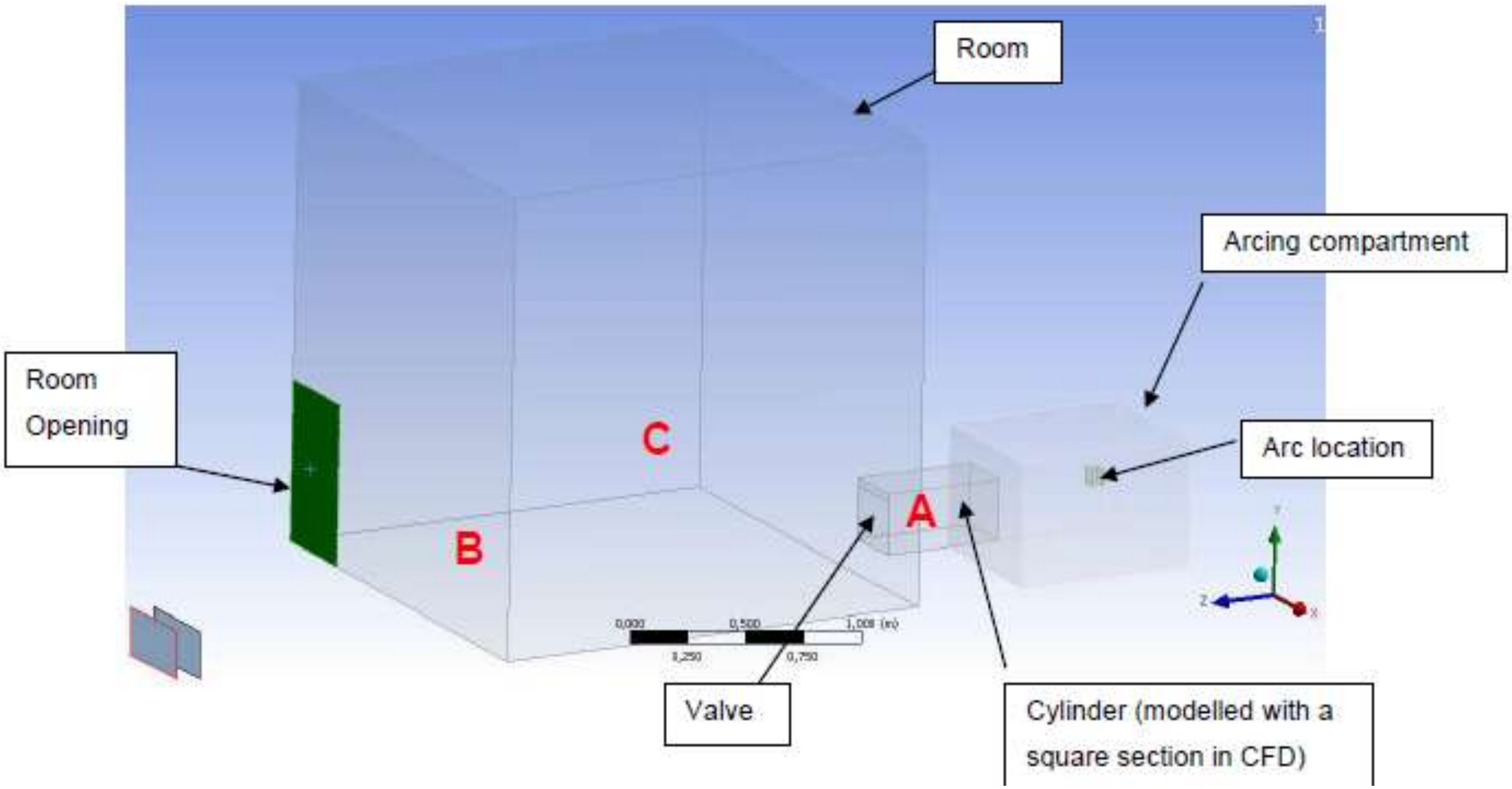
- First calculate the expected pressure rise inside the switch
- Then use existing FEA to evaluate the mechanical stress on the enclosure
- Calculation of deformation of enclosure by FEA stress analysis can be done both for welded and bolted enclosures

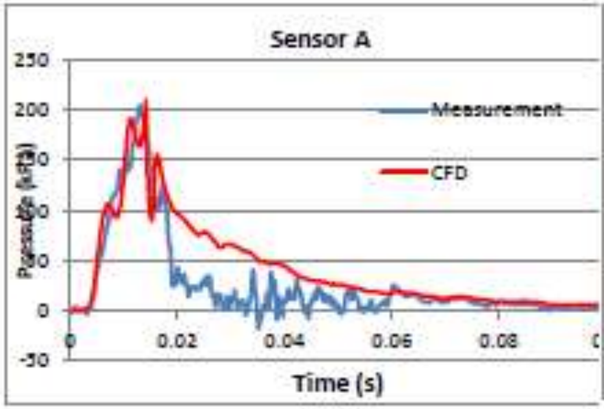


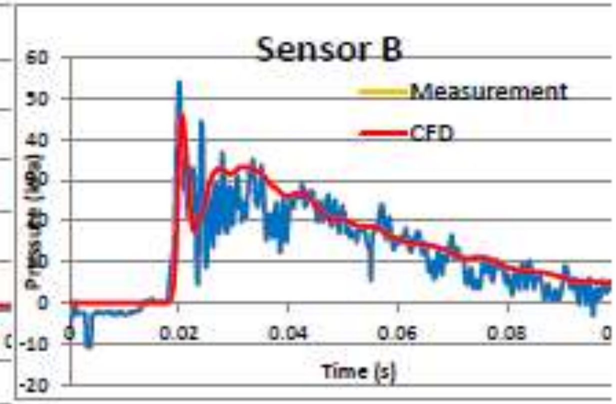
Mechanical stress on the switch: Air vs SF6

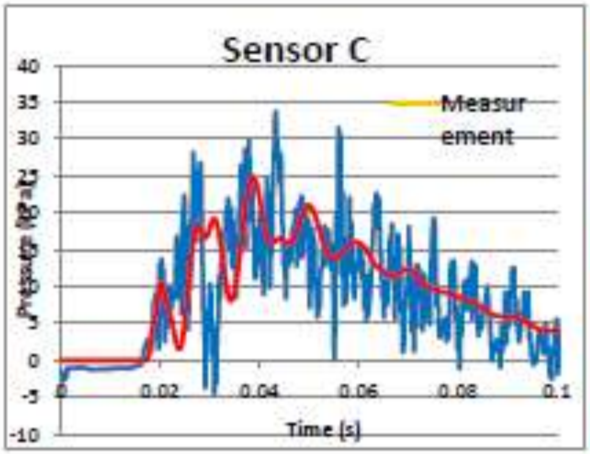


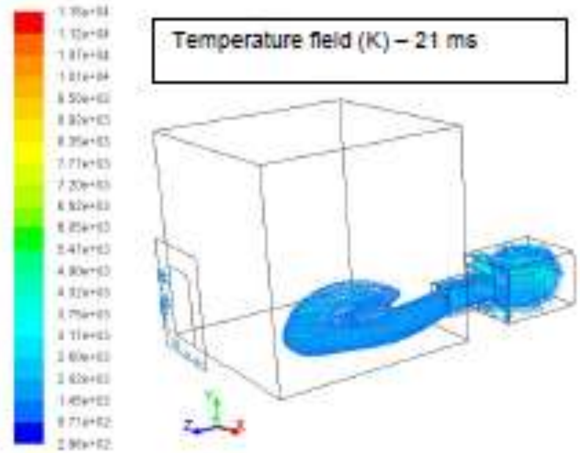
4) Mechanical stress on the installation room

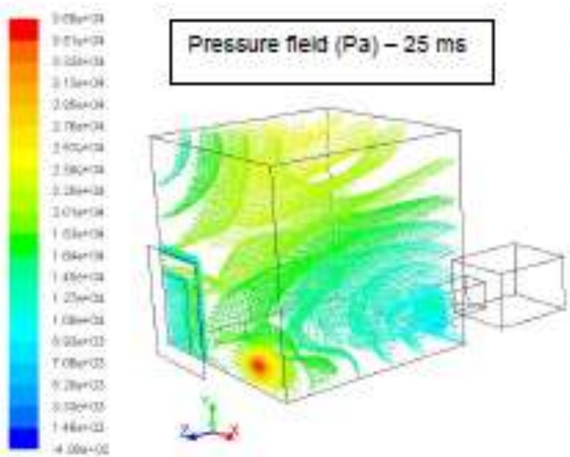


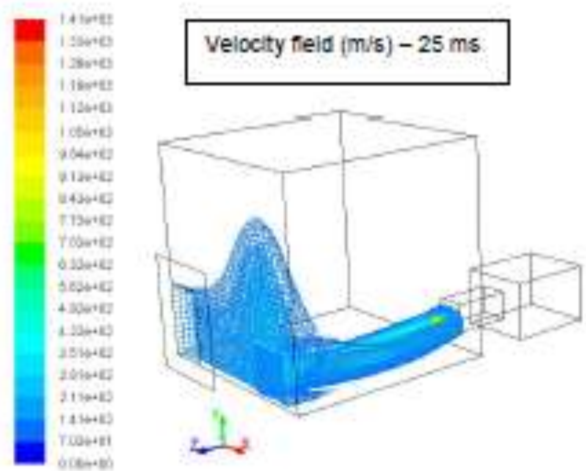

Sensor A
Measurement
CFD
Time (s)
250
200
0
-50
0.02
0.04
0.06
0.08


Sensor B
Measurement
CFD
Time (s)
60
50
40
0
-10
-20
0.02
0.04
0.06
0.08


Sensor C
Measur
ement
Time (s)
40
35
30
0
-5
-10
0.02
0.04
0.06
0.08
0.1


Temperature field (K) – 21 ms


Pressure field (Pa) – 25 ms


Velocity field (m/s) – 25 ms

Wall withstand

Wall type	Permitted overpressure in the room
Brick wall (solid brick, perforated brick, gas concrete)	3 up to 10 mbar
Armoured (reinforced) brick wall	25 mbar
Ready-mix concrete components	50 mbar
Job-mixed-concrete	≥ 70 mbar
Concrete room cell construction	160 mbar

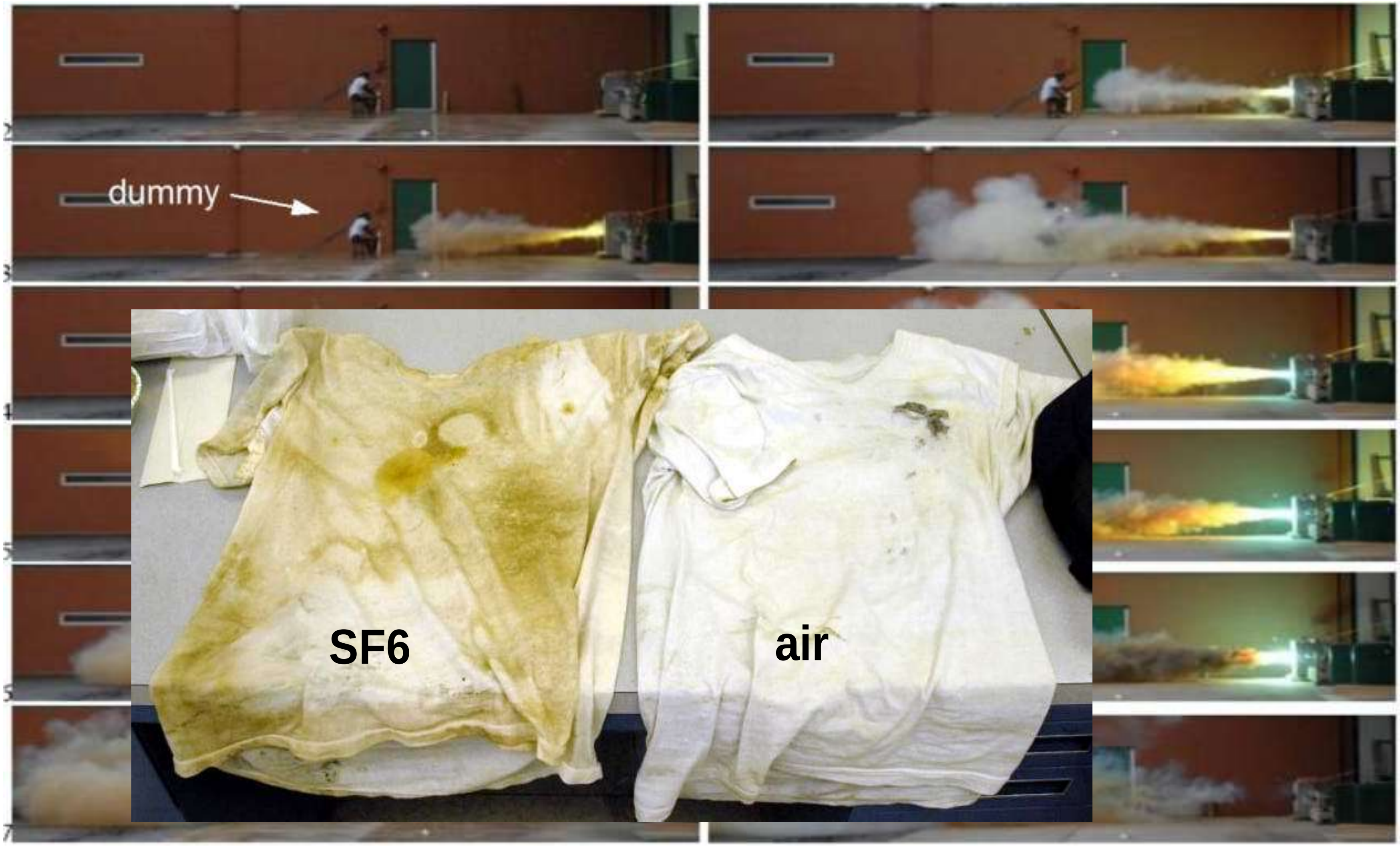
I.-F. Primus, Störlichtbogenfeste Gebäudekonzepte – geprüfte Konstruktionsprinzipien – Nachweise durch Störlichtbogenprügungen, Handbuch zur VDE-Seminarveranstaltung, VDE Bezirk Kurpfalz, März 1999

- Pressure on building walls as a result of an internal arc is a critical load for building design.
- Dynamic load, spatially defined, using CFD to calculate
- Analytical models can be used (simple and enhanced) but Kp have to be carefully chosen.

4) Air vs SF_6

- **Environmental reasons** to replace SF_6 by Air during internal arc testing of SF_6 insulated switchgear.
- Solid (metal-sulphides and -fluorides) as well as gaseous SF_6 decomposition products **very poisonous**.
- **Test labs** wish to **minimize** their emission of clean SF_6, a greenhouse gas, and certainly polluted SF_6.

Air vs SF_6 (cont)



SF6 Air

Air vs SF_6: pressure rise in arcing and exhaust volume

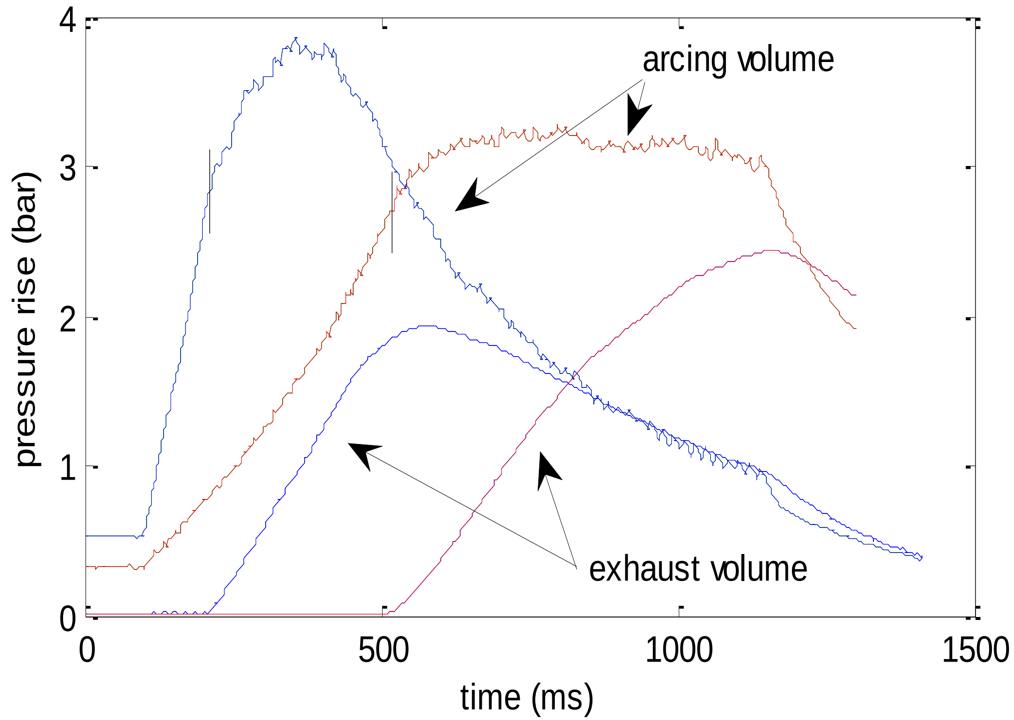
- **Arc compartment**:

  The mechanical stress of the fault arc compartment is higher when filled with air instead of SF6 due to the faster and higher pressure rise in air.

- **Exhaust compartment:**

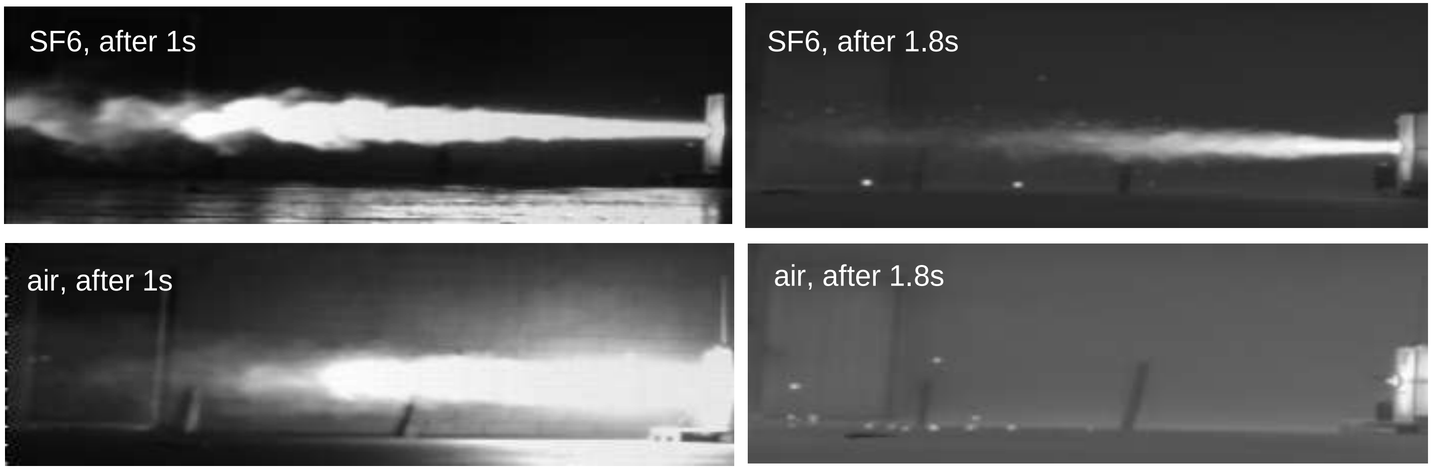
  With air, the exhaust gas gives a lower peak pressure in the adjacent compartment than with SF6; hence the mechanical stress is also smaller.

Air vs SF_6: pressure rise in arcing and exhaust volume



Pressure rise in arcing- and exhaust volume for air-filled (blue) and SF_6 filled (red) arcing volume (1 s arc duration). Vertical markers: pressure relief action (diaphragm burst).

Air vs SF_6



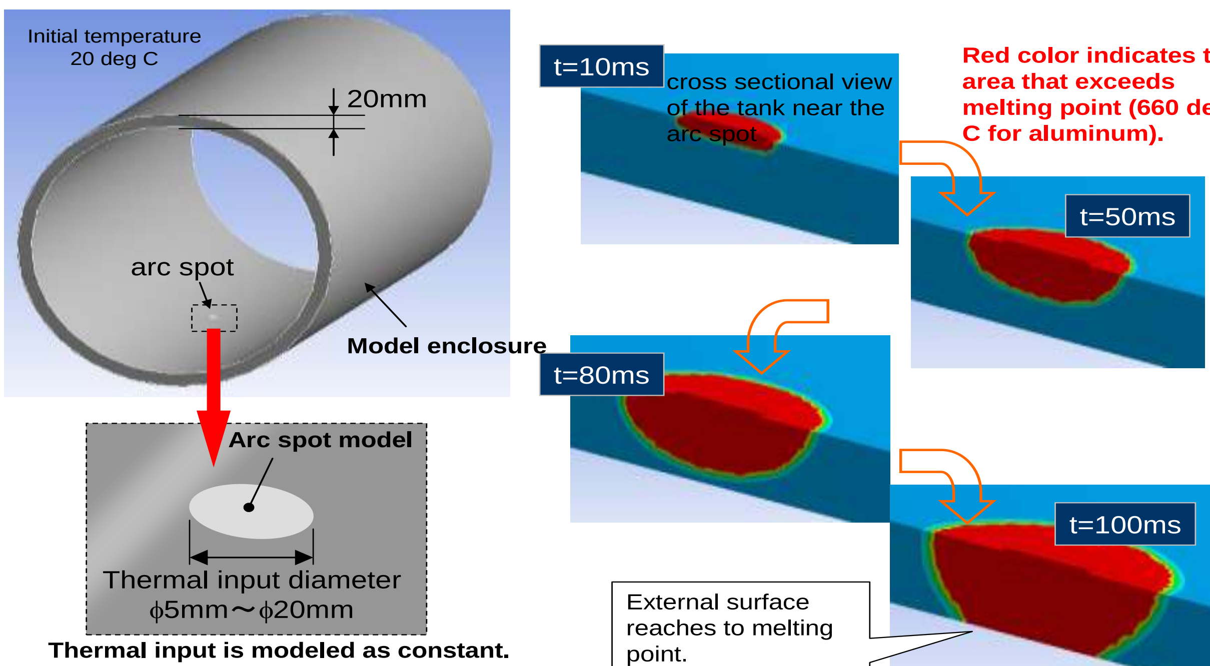
Photographic impressions of the release of hot gases as a result of arcing in SF_6 and air

- **Cotton-pad indicators :**

  Air and SF6 give the same direction and flow distribution of the gas exhaust in the installation room. The probability of indicator ignition might be comparable

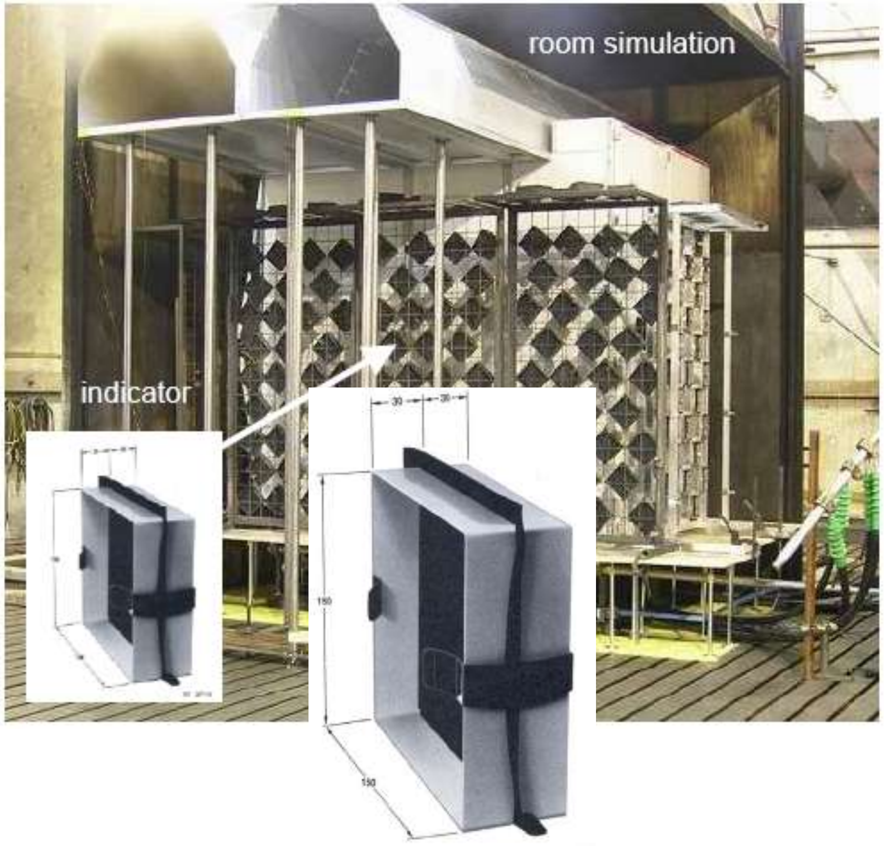
Air vs SF_6: Burn through

- For the burn-through behaviour, the effect of replacing SF_6 with Air is not obvious.
- In the qualitative approach developed by the WG - in theory burn-through time in SF_6 will likely be shorter than in air.
- However, no sufficient test data or experiment is available today to validate this claim.



Internal Arc tests for MV switchgear

- Proof Internal arc withstand is most often requested
- The ignition of the arc is initiated by a fuse-wire
- The switchgear pass the test if cotton-pad indicators are not burned



Comparison:

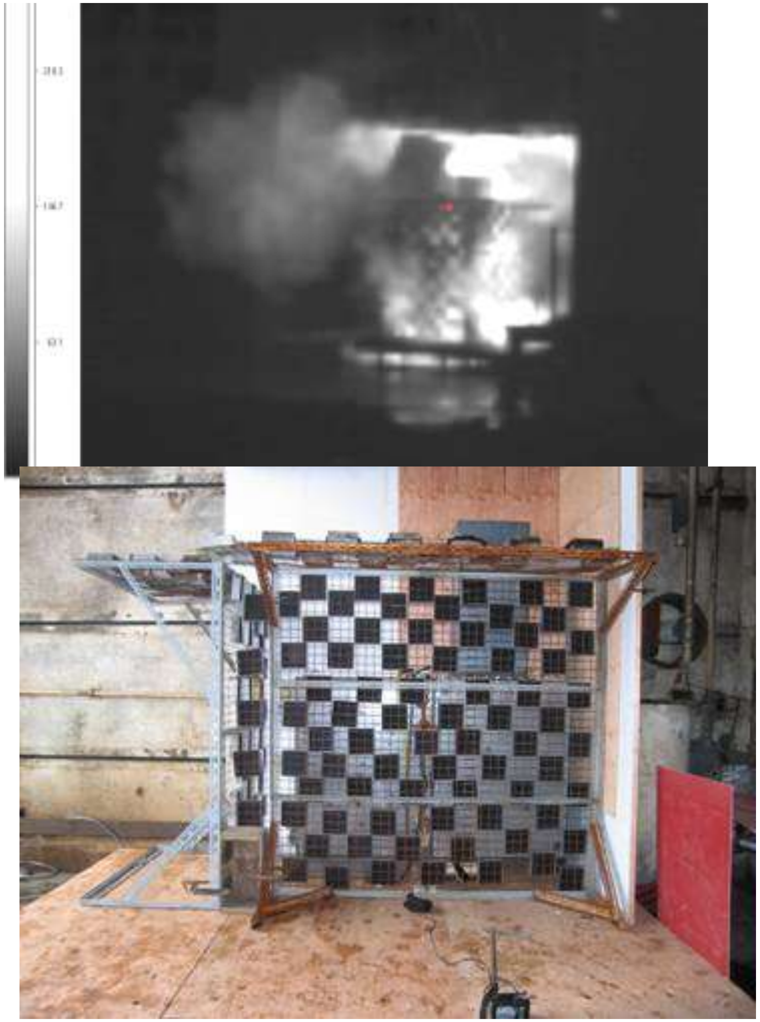
No cable compartment

No chimney with arc absorber

Smaller room height

Comparison (cont):

Flame, Burned Indicators



Smoke only, no Burned Indicators

Tests for HV metal-enclosed switchgear

- The IEC 62271-203 for HV metal-enclosed switchgear allows for the extrapolation of internal arc tests by calculation for other enclosures and currents
- This extrapolation would be based on original test results by the manufacturer
- Tests are more difficult to perform than in MV switchgear and there are generally not requested.
- Manufacturers use “design rules” and calculation programs based on previous internal arc tests

Design Reviews – similar design

Medium Voltage

Item	Design parameter	Validation criterion
(1)	(2)	(3)
1	Phase to phase clearance	≤
2	Phase to earth distance	same
3	Net enclosure/compartment volume	≥
4	Rated pressure of insulating gas, if applicable; see note 1	≤
5	Cross-section of conductors	≥
6	Raw material of conductors (Al or Cu or their alloys)	same
7	Location of the point of arc initiation	same
8	Insulating material exposed to the arc	same
9	Exhaust area	≥
10	Exhaust opening pressure	≤
11	Strength of fixing elements of relief device (flap)	≤
12	Strength of the enclosure/ compartment	≥
13	Thickness of the enclosure walls	≥
14	Strength of the doors and covers	≥
15	IP degree of protection of enclosure	≥
16	Short-circuit current	≤
17	Arc duration	≤

High Voltage

item	Design parameter	Validation criterion
(1)	(2)	(3)
1	Phase to phase clearance	≤
2	Phase to earth distance	≤
3	Enclosure/compartment volume	≥
4	Pressure of insulating gas	≤
5	Cross-section of conductors	≥
6	Raw material of conductors (Al or Cu)	Same
7	Location of the point of arc initiation	Same
8	Distance from the arc initiation point to the expected nearest obstacle	≥
9	Insulating material exposed to the arc	Same
10	Exhaust/ventilation opening area	≥
11	Exhaust opening pressure	≤
12	Pressure relief design	Same
13	Strength of the enclosure/ compartment	≥
14	Thickness of the enclosure walls	≥
15	Raw material of enclosure (Al or Steel)	Same
16	Manufacturing type of enclosure (casting, plate welding, etc.)	Same
17	Short-circuit current	≤
18	Arc duration	≤

Conclusion

- A3.24 WG findings suggest that simulations can’t replace type tests, but they could be used for interpolation between the known tests
- Internal arc test must be done on a similar design to get the correct energy input data. It is very important to measure the pressure rise during the tests
- WG provides calculation tools to predict Pressure rise and mechanical stresses.
- WG gives guidance to perform an internal arc simulation review between the switchgear manufacturer and the user.

Conclusion

- Based on the results, WG conclude that relevant differences exist in the behaviour of fault arcs in SF_6 and in air
- Replacing SF_6 by air in internal arc testing leads to comparable or higher pressure rise in the arcing compartment.
- Pressure rise in exhaust compartment or switchgear room may be higher in tests with SF_6 -filled then with air
- No conclusions exist on other criteria to pass internal arc test such as the ignition of the cotton indicators and enclosure burn through. Needs further detailed investigation.
- Replacement of SF_6 with air provides mixed results. Each case must be evaluated separately.

Questions?

nuzelac@gwelec.com