ITT AO/1-5245/07/NL/Sfe

FINAL PRESENTATION

Development of high current, high voltage and high temperature cable suitable for Electric Propulsion.

axon' CABLE & INTERCONNECT

ASTRIUM AN EADS COMPANY

esa ESTEC

NOV. 24 2011

I. Introduction

Problematic :

- No space qualified cable available for Electric Propulsion (EP) applications requiring high temperature, high current and high voltage capabilities.
- dynamic interface imposed by a pointing mechanism, this demands the additional feature of flexibility in the selected cable.
- PTFE, polyimide etc., although having excellent dielectric capabilities, they are fundamentally limited to operation at temperatures below approximately 200 degrees Celsius.

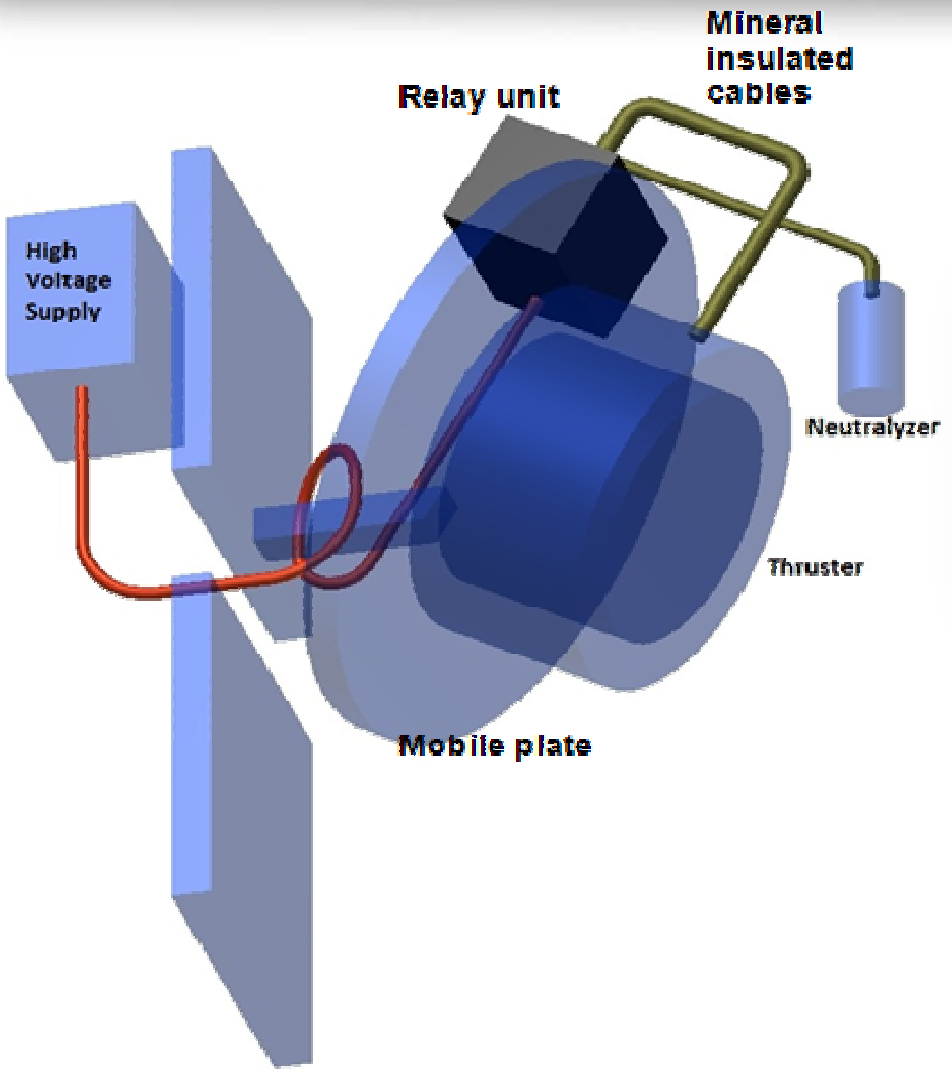
Two principle objectives :

1 - The first one is to identify and investigate the most promising insulation materials that could be used in the manufacture of high temperature and high voltage cables.

2 - The second objective is to manufacture sample lots of the cable, subject it to thermal, vacuum, dielectric electrical strength, partial discharge and environment testing with the ultimate objective of identifying a cable that will enable space qualification.

Current system

INSIDE THE SATELLITE



SPACE ENVIRONMENT

II. REQUIREMENTS

Physical & electrical requirements

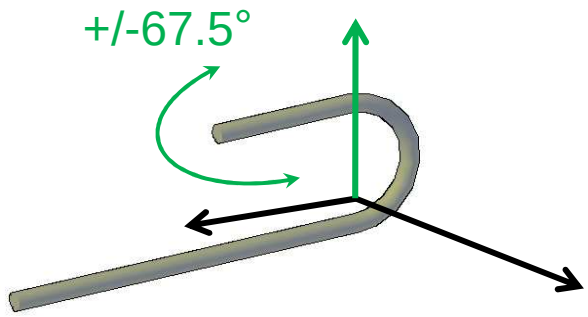
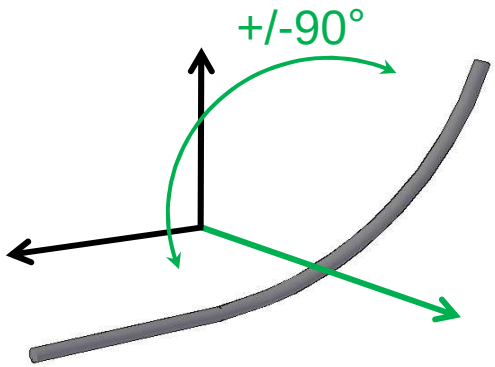
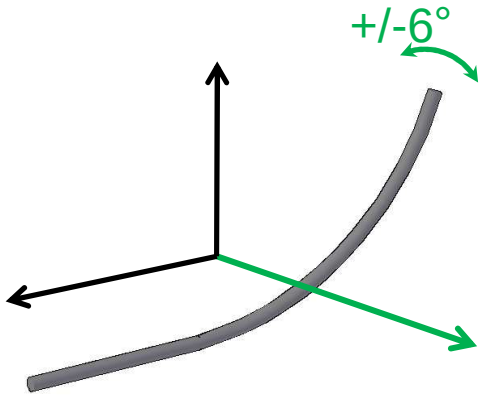
Max. continous operating voltage	5 kV
Max. operating current	12 A
Conductor gauges	AWG 20 – AWG 4
Immunisation	ESD
Radiation resistance	200 MRad

Thermal requirements

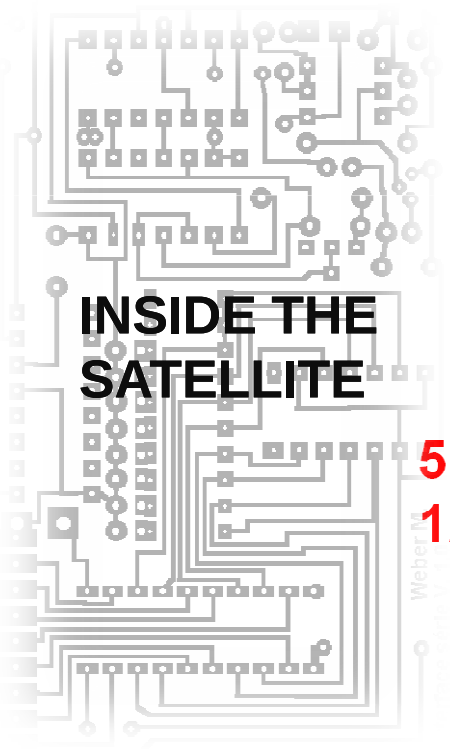
		Static application	Dynamic application
Operating temperature	min °C	-50	-20
	max°C	280	120
Non operating temperature	min °C	-100	-50
	max °C	200	120

II. REQUIREMENTS

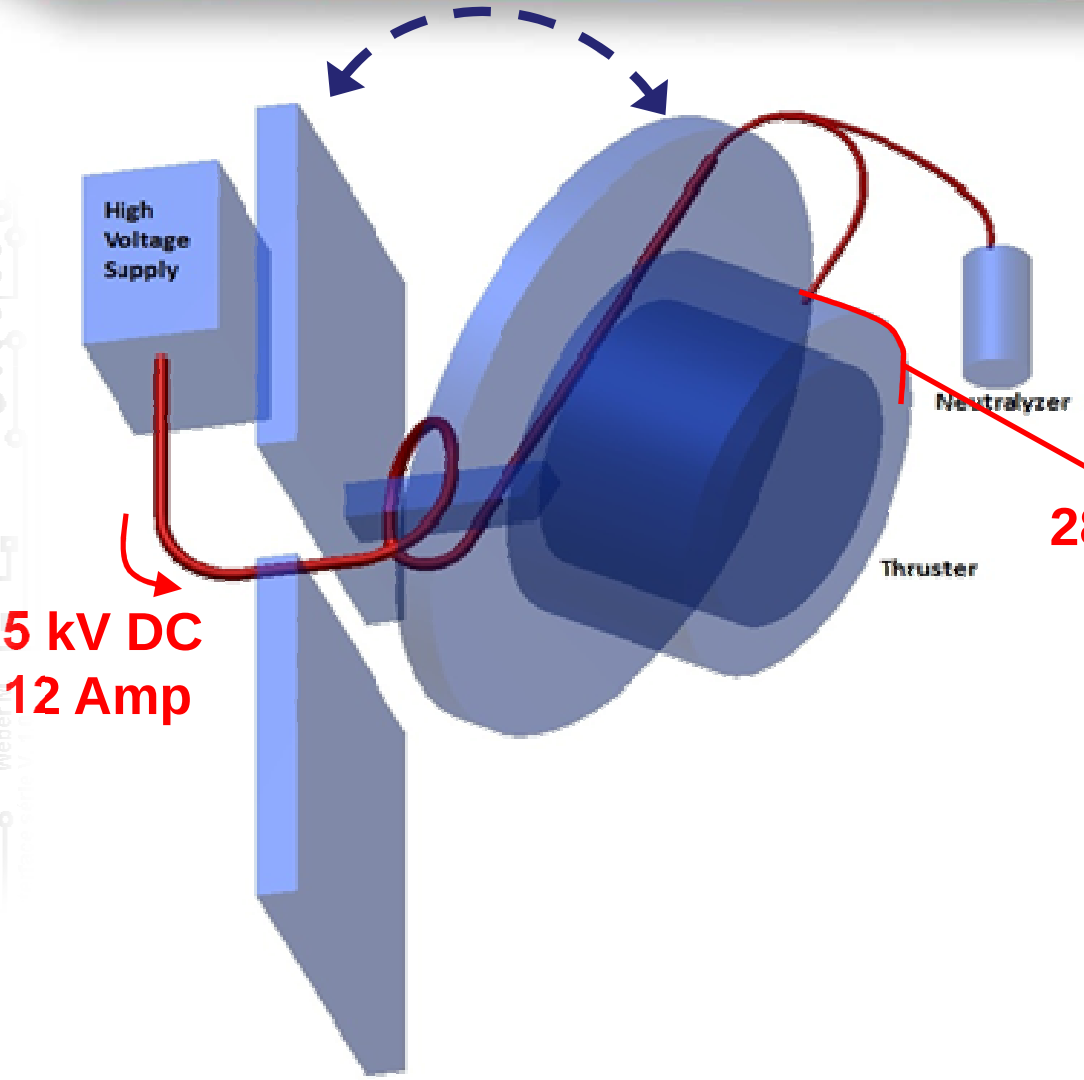
Geometrical Requirements

non-operating modus		daily operation
+/-67.5° on a first axis	**+/- 90° on a second axis**	**Max +/- 45° within an overall +/- 6° range**
		
Linear displacement of the cable, due to rotation movement : 40mm.		
Minimum bending radius shall be a ratio of 5 between bend radius and cable diameter.		

Improved system



INSIDE THE SATELLITE



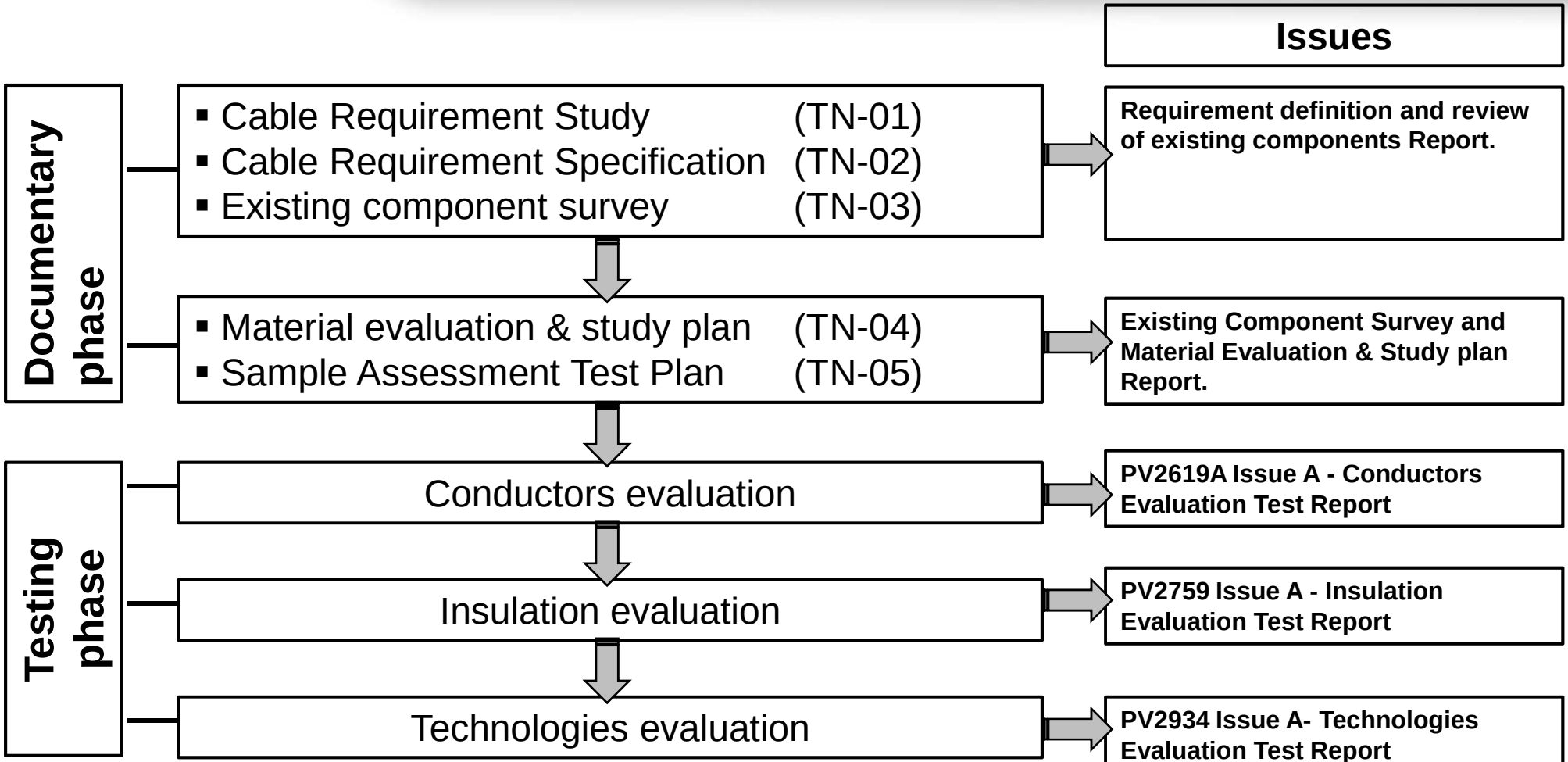
5 kV DC
12 Amp

200 MRad

280 C

SPACE ENVIRONMENT

PROJECT PROGRESS CHART



TN01-TN03

- Cable Requirement Study (TN-01 & TN-02)

Survey by Astrium of the needs of several thruster users in order to define generic requirements (SNECMA, Alta, Thales, Qinetiq etc.)

- Existing component survey (TN-03)

Materials component survey about conductors materials and their physical limits (Tin,Silver, Nickel plating, Copper, Copper Alloy…), a generic survey on polymeric materials and fibers and a generic survey on existing cable solutions.

→ 92 pages report : **Requirement definition and review of existing components.**

TN04-TN05

- Material evaluation and study plan (TN-04)

1- Reflection on the possible cable construction techniques focused on metallic and insulation materials that might be considered for the final product.
Presentation of the advantages and drawbacks of many materials (both metals and plastics).

2 - Study approach explanation

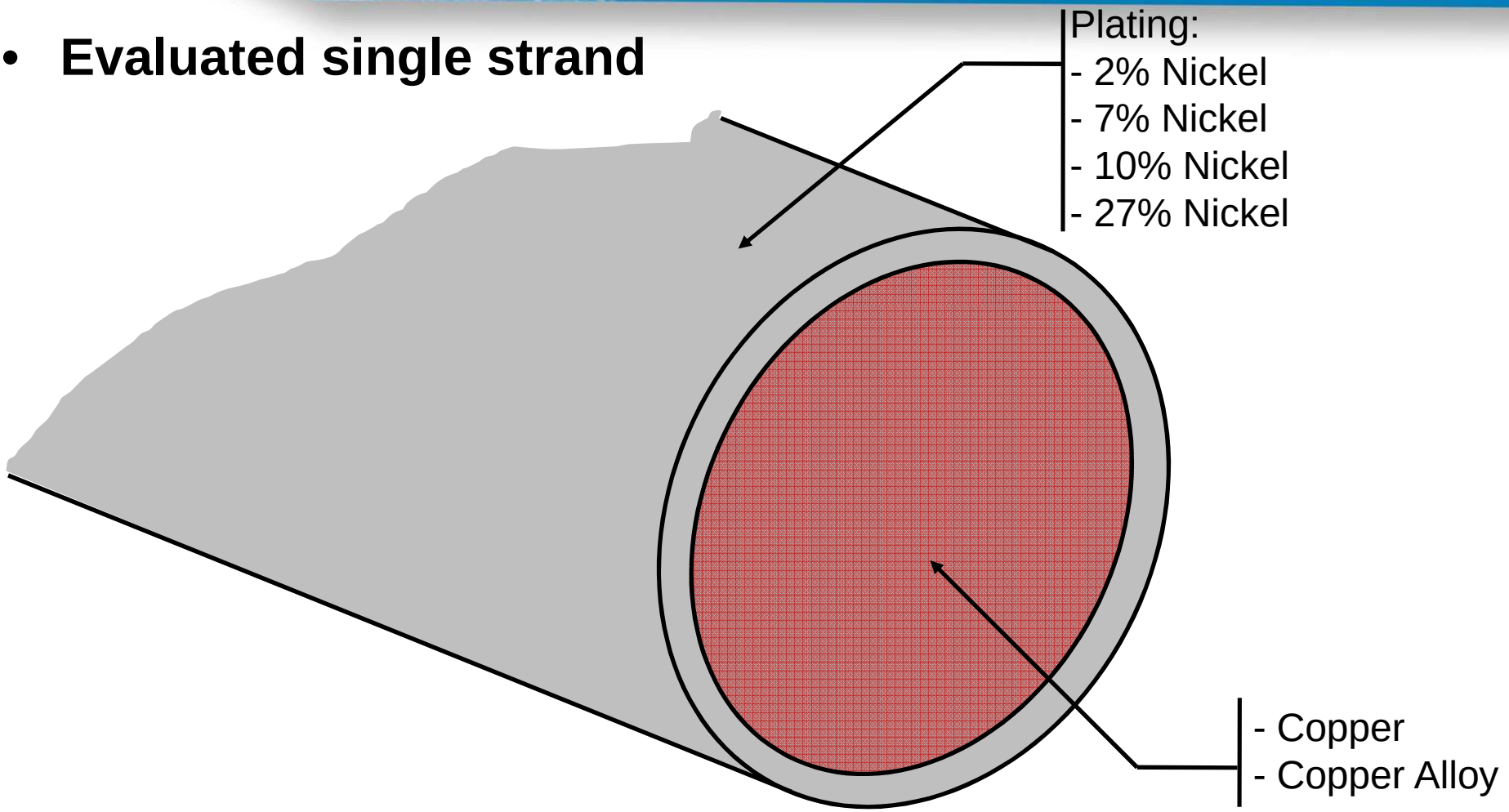
- Sample Assessment Test Plan (TN-05)

→ 110 pages report : **Existing Component Survey and Material Evaluation & Study plan.**

III. Conductors evaluation

III. Conductors evaluation

- **Evaluated single strand**



III. Conductors evaluation

- **Evaluated single strand**

AWG	Material	Plating	Length (m)	Diameter (mm)	Section (mm^2)
2401	Percon ™ 24	27% Ni	Acc. to norm	0.511	0.205
2401	Percon ™ 24	10% Ni	Acc. to norm	0.511	0.205
2401	Percon ™ 24	7 % Ni	Acc. to norm	0.511	0.205
2401	Nickel plated copper	27% NI	Acc. to norm	0.511	0.205
2401	Nickel plated copper	1.5% NI	Acc to norm	0.511	0.205

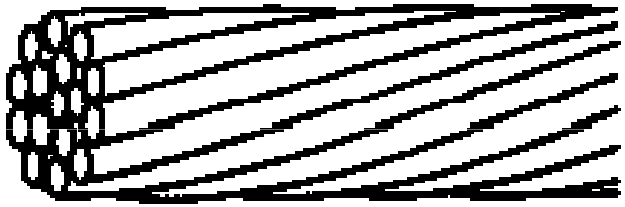
→Conclusion page 35 of Test Report PV2619A.

The selected material for the evaluation of the conductor constructions is the 10% Nickel plated PERCON24®

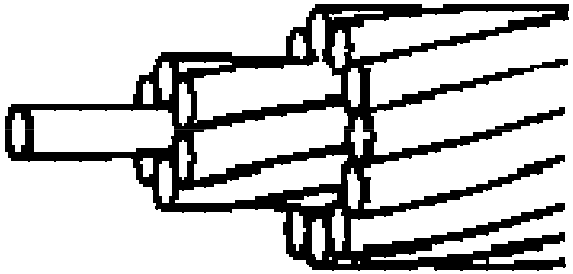
III. Conductors evaluation

- **Examples of conductor constructions**

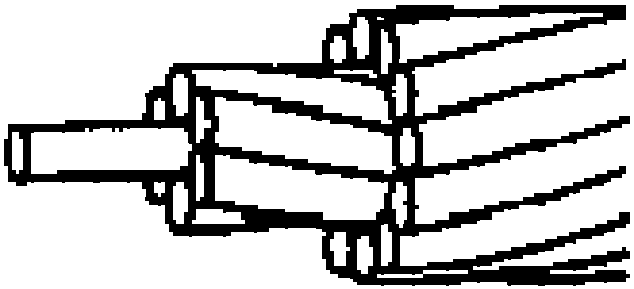
Bunched



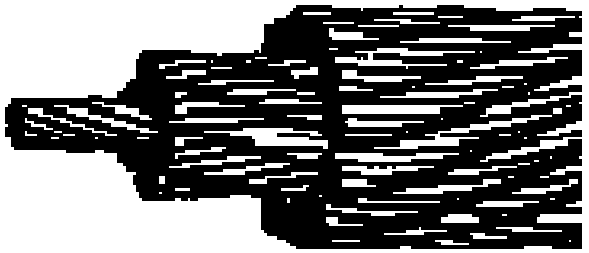
Unilay



Concentric



Ropelay



III. Conductors evaluation

- **Evaluated constructions**

AWG	Material	Plating	Construction	Diameter (mm)	Section (mm^2)
19 x 0.511 (24)	Percon24®	10% Ni	Unilay	2.555	3.89
19 x 0.511 (24)	Percon24®	10% Ni	Concentric	2.555	3.89
7 x 7 x 0.320 (28)	Percon24®	10% Ni	Ropelay	2.583	4.073
37 x 0.361 (27)	Percon24®	10% Ni	Concentric	2.828	3.787

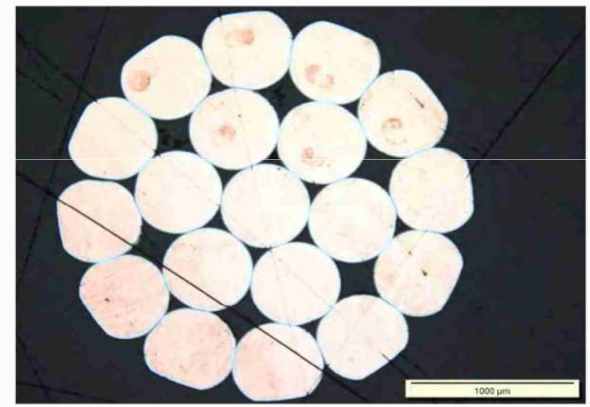
III. Conductors evaluation

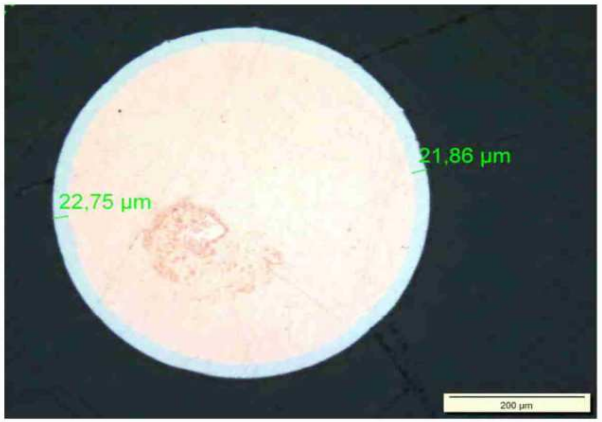
- **Critical thermal tests**
  - → Thermal stability (short term ageing)
    - 400°C
    - 450°C
    - 500°C
  - → Long term ageing
    - 350°C
  - → Temperature elevation under amperage variation
    - 50°C
    - 100°C
    - 150°C
    - 200°C
    - 260°C
    - 300°C
- **Characterization tests**
  - → Mechanical
    - Alternate bending
    - Elongation, Breaking load….
  - → Electrical
    - Linear resistance

III. Conductors evaluation

- Selected conductor

19x0.511 Unilay





- Results statement

✓ Good mechanical stability when exposed to very high temperature (short exposition)

✓ Good mechanical and electrical stability when exposed for long time to high temperature

✓ Design recommended for High voltage application

✓ Good flex life

IV. Insulation evaluation

IV. Insulation evaluation

- **Potential materials list (according to TN04-TN05 issue)**

	Temperature	High temp.	voltage	Out-gass.	Radiation		
	-100°C	260-300°C	5 kV DC		200 MRad	bending	Deployment
						+/- 6°	+/-90° max
Thermoplastic polyimide	✓	TBE	✓	✓	✓	✓	TBE
Thermoset Polyimide resin	✓	✓	x	✓	✓	✓	TBE
Polyimide tape	✓	✓	✓	✓	✓	✓	TBE
PEEK	✓	x	✓	✓	✓	✓	TBE
PEEK HT G22	✓	✓	✓	✓	✓	✓	TBE
PEEK HT ST45	✓	✓	✓	✓	✓	✓	TBE
Vicote ™ HT	✓	✓	✓	TBE	✓	✓	TBE
OXPEKK CE	✓	✓	✓	✓	✓	✓	TBE
RTP PEEK + Nanotube blend	✓	x	x	TBE	✓	✓	TBE
PBI film	✓	✓	✓	✓	✓	✓	TBE
PBI solvent based resin	✓	✓	x	✓	✓	x	TBE

IV. Insulation evaluation

- Rejected materials and reasons why

Thermoset Polyimide solvent based resin	▪ **The process does not allow to realize a coating on wires or cables with a diameter bigger than 3 mm.** ▪ **Machines not adapted to process rigid wires with a diameter > 3mm (more for thin wires).** ▪ **Curing very difficult.**
PEEK	▪ **Limited temperature.** ▪ **More rigid than its by-products: PEEK HT G22 – PEEK ST G45 – OXPEKK CE.**
Vicote ™ HT	▪ **Process not compatible with a continuous process(Evaporation time and curing are way too long).** ▪ **Possibility to realize only a thin coating with too low mechanical properties.** ▪ **Machines and processes not adapted for diameters >3mm.**
RTP Nanotubes charged PEEK	▪ **Limited temperature.** ▪ **Difficult to extrude in thin layers.** ▪ **Conductivity not controlled.**

IV. Insulation evaluation

- Rejected materials and reasons why.

PBI film	▪ **Properties identical to the Kapton tape (no significant reason to use instead of Kapton tape).**
Thermoset PBI solvent based resin	▪ **Fragile once it is cured**
OXPEKK C03 DRT	▪ **The process does not allow to realize a coating on wires or cables with a diameter bigger than 3 mm.** ▪ **Machines not adapted to process rigid wires with a diameter > 3mm (more for thin wires).** ▪ **Curing very difficult.**
OXPEKK C	▪ **Limited temperature.** ▪ **More rigid than its by-products: PEEK HT G22 – PEEK ST G45 – OXPEKK CE.**

IV. Insulation evaluation

- Selected materials and applicable process

Trade name	Chemical nature	Thermoplastic extrusion	Taping	Coating
AURUM PL450C	Thermoplastic polyimide	✓	X	X
PEEK HT G22	Poly Ether Ketone (PEK)	✓	X	X
PEEK HT ST45	PEKEKK	✓	X	X
OXPEKK CE	PEKK	✓	X	X

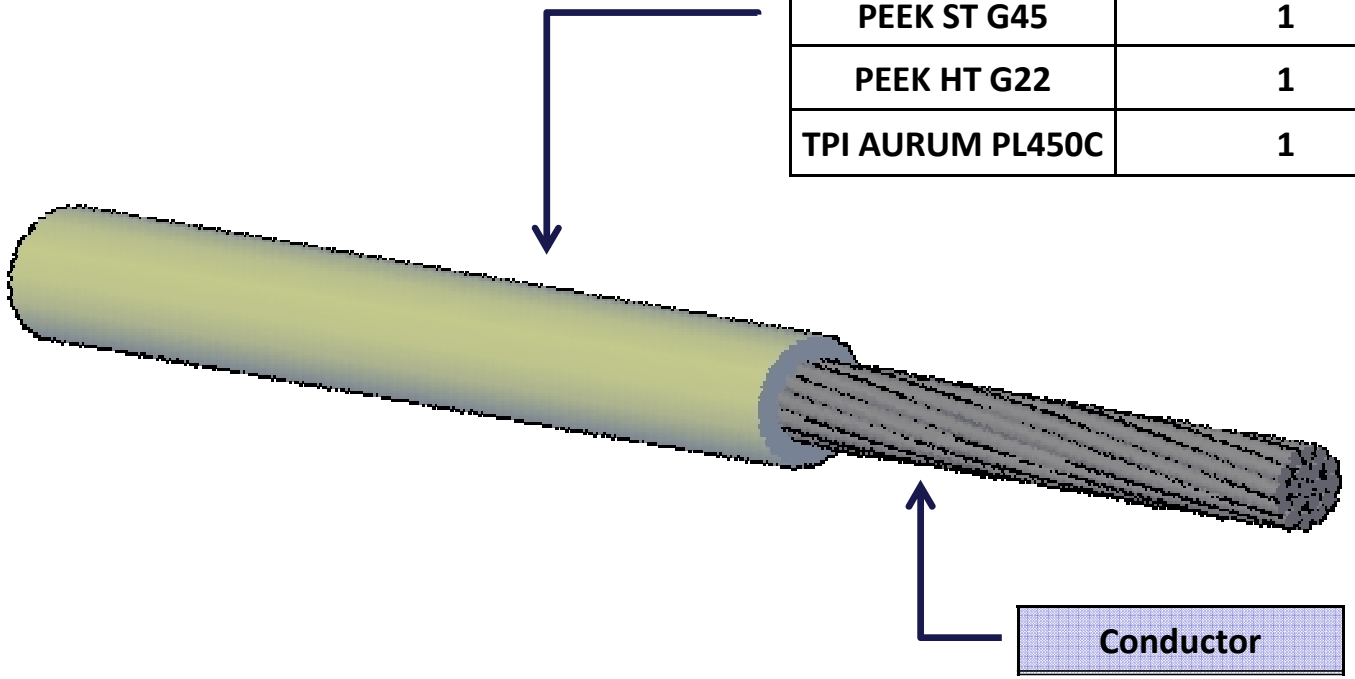
IV. Insulation evaluation

Aurum PL450C	PEEK STG 45	PEEK HT G22	OXPEKK-CE
- Same family as Kapton®. - Low Outgassing - Very high radiation resistance. - Excellent electrical resistance. - Maximum température rating : 240°C. - Melting point: 388°C - Tg : 245°C - Density : 1.33	- New material based on PEEK. - Low Out-gassing - Low flammability - Improved thermal properties - Improved mechanical properties. - Maximum temperature rating : 260°C. - Melting point : 387°C - Tg : 162°C - Density : 1.30	- Material based on PEEK. - Low Out-gassing - Low flammability - Improved thermal properties - Maximum temperature rating : 260°C - Melting point : 373°C - Tg : 163°C - Density : 1.30	-Material based on PEEK. - Low Out-gassing - Low flammability - Improved thermal properties - Maximum temperature rating : 260°C - Melting point : 360°C - Tg : 163°C - Density : 1.31

IV. Insulation evaluation

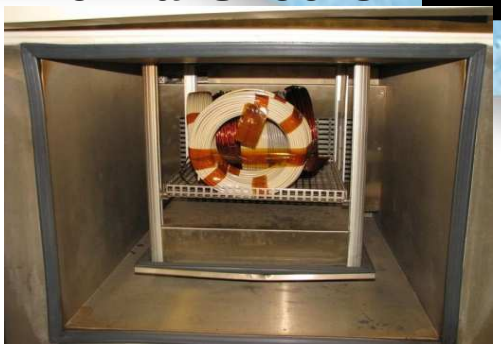
- Samples construction

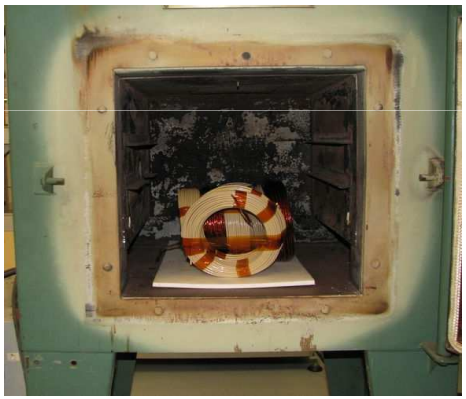
Insulating material	Thickness (mm)
OXPEKK CE	1
PEEK ST G45	1
PEEK HT G22	1
TPI AURUM PL450C	1



IV. Insulation evaluation

Thermal Shocks





280 °C Thermal Ageing

Material insulation evaluation

Test serie
§ 1.2.5.

Thermal Shocks Test without high voltage
§ 1.3.9.3.

Overload Resistance
§ 1.2.5.10.

280°C thermal ageing without high voltage
§ 1.3.9.5.

Cold bend test ESCC 3901 para.9.12. Deviation § 1.2.5.9

Voltage test

Out-gassing test
§ 1.2.5.7.

Wrapp test at ambiant temp.
§ 1.2.5.9.

Standard electrical tests
Standard mechanical tests

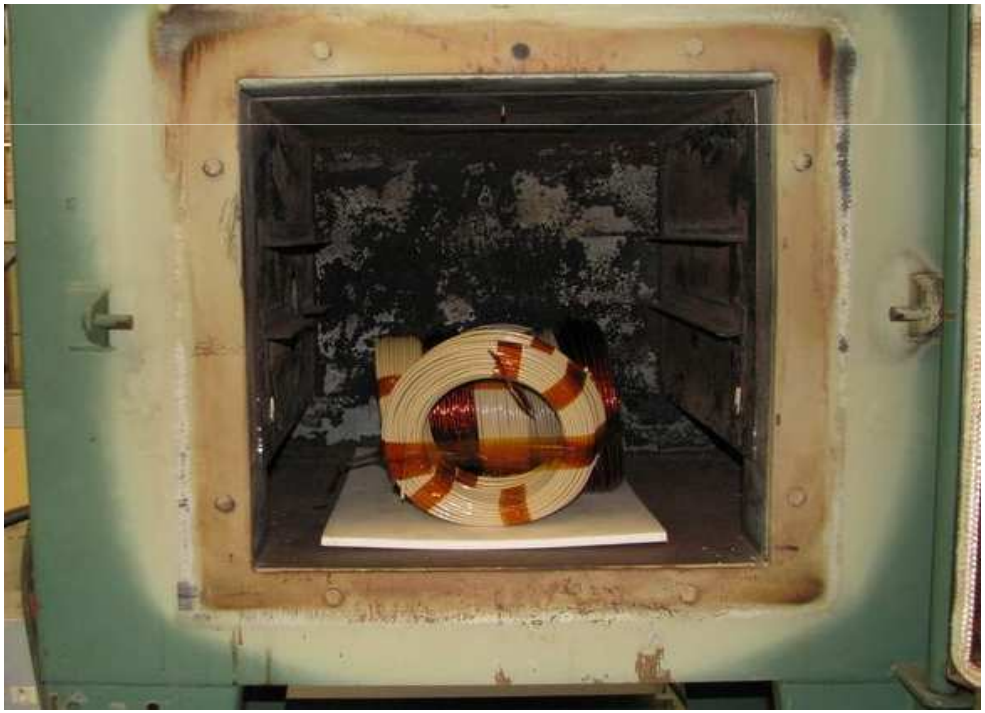
Test serie
§ 1.2.5.

Report and conclusions

IV. Insulation evaluation

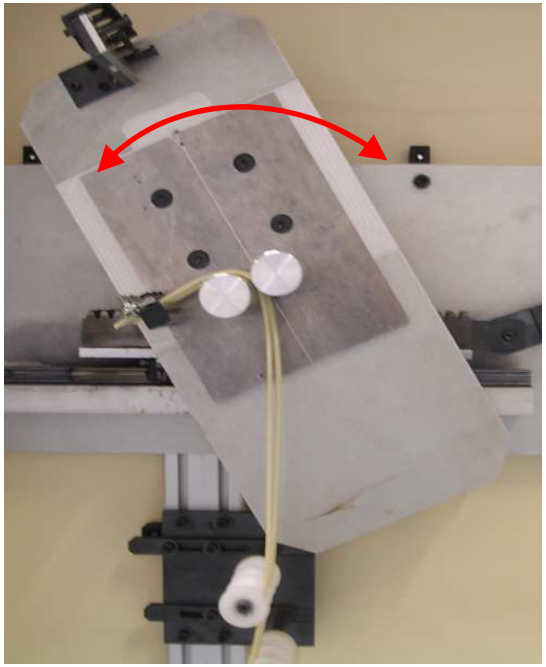
- **Ageing Tests**

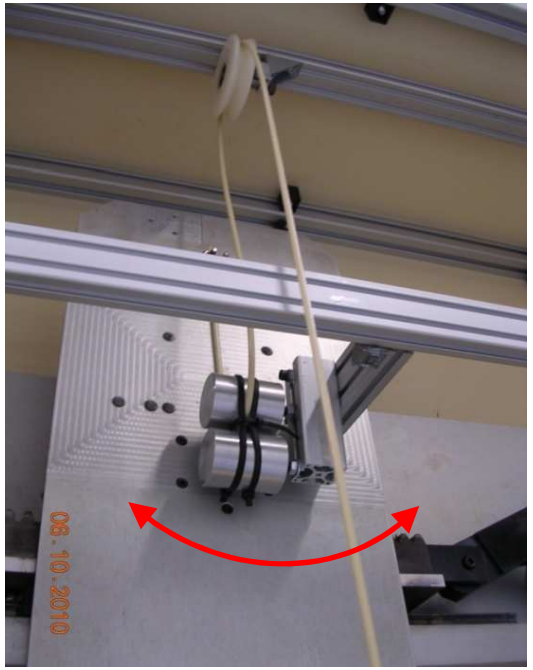
Thermal shocks (100 cycles)	280°C 100h thermal ageing



IV. Insulation evaluation

Flex Life (+/- 6°)	Flex life (+/- 90°)	Flex life (+/- 67.5°)





IV. Insulation evaluation

Dielectric breakdown at high temperature

Sample between 2 metallic plates

Metallic plates to ground potential

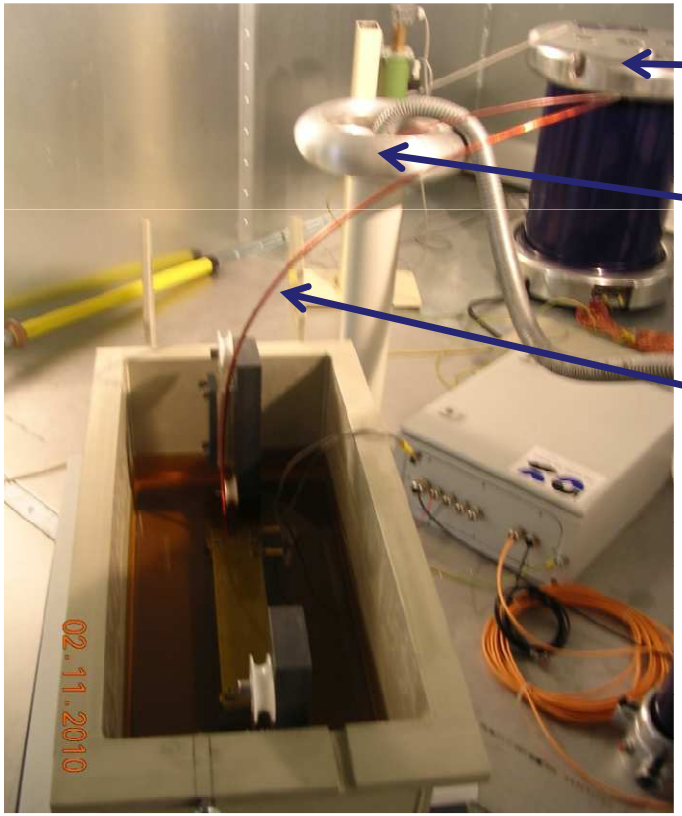
Oven

Samples extremities connected to HV

High voltage electrode

IV. Insulation evaluation

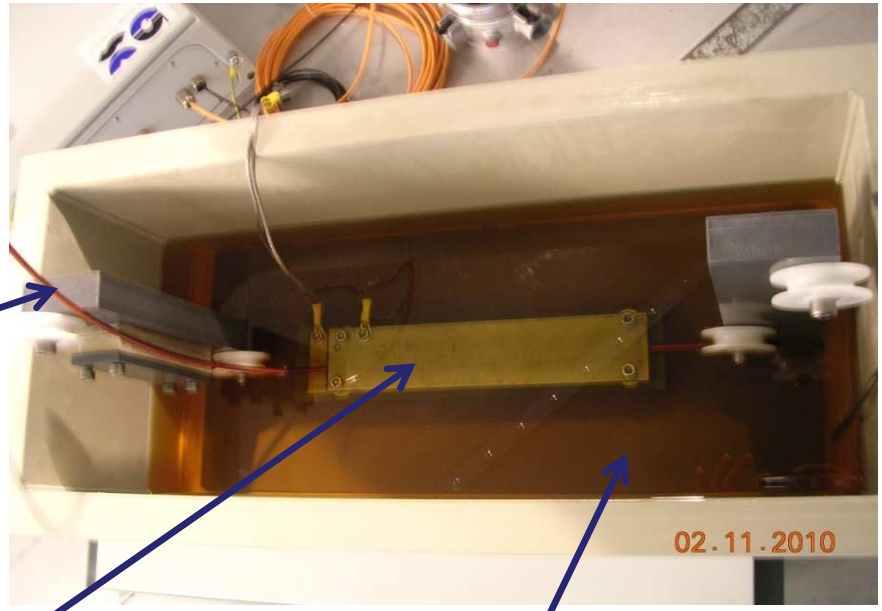
Partial discharges measurement



HV Transf.

HV Electrode

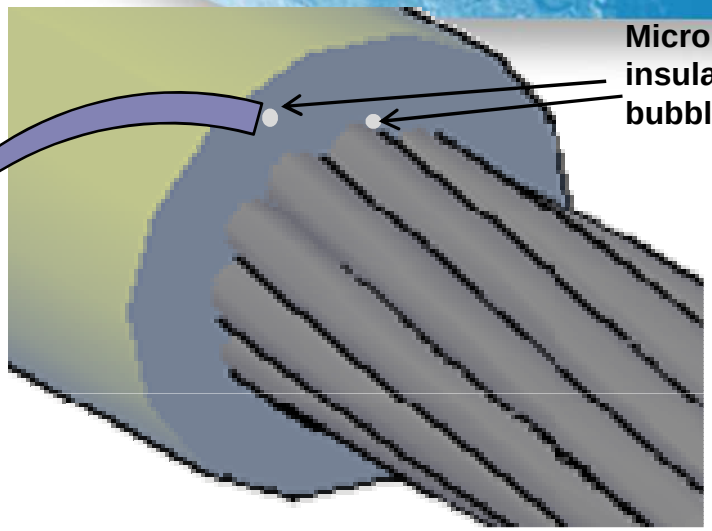
Sample (to HV)



Flat electrodes (to ground pot.)

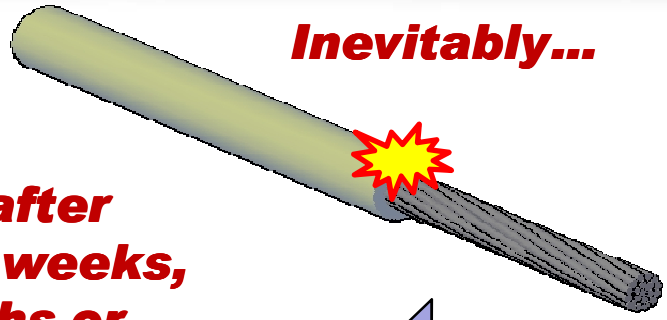
Dielectric fluid

PARTIAL DISCHARGE MEASUREMENT



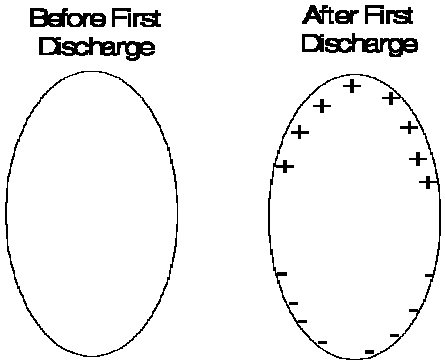
Micro defects inside the insulation : voids, bubbles, cavities.

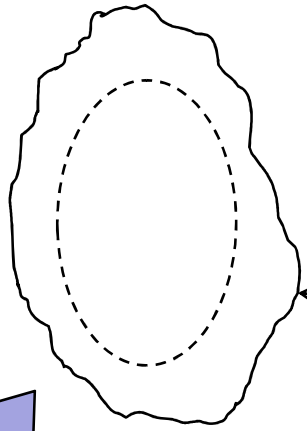
Inevitably…



Cavity after several weeks, months or years…

Cavity before and after discharge





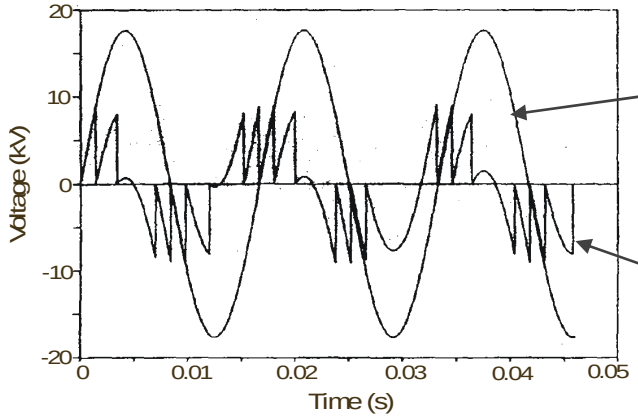
Cavity growth due to PD erosion!

PARTIAL DISCHARGE MEASUREMENT

- ***Partial discharge testing can detect:***
  - Insulation defects that may have occurred during cable system installation or the manufacturing process
  - Insulation deterioration due to normal service operating conditions

Partial discharge testing is a <u>PREDICTIVE</u> qualitative analysis tool that can warn of a potential <u>UPCOMING</u> system failure.

Typical Discharge Pattern



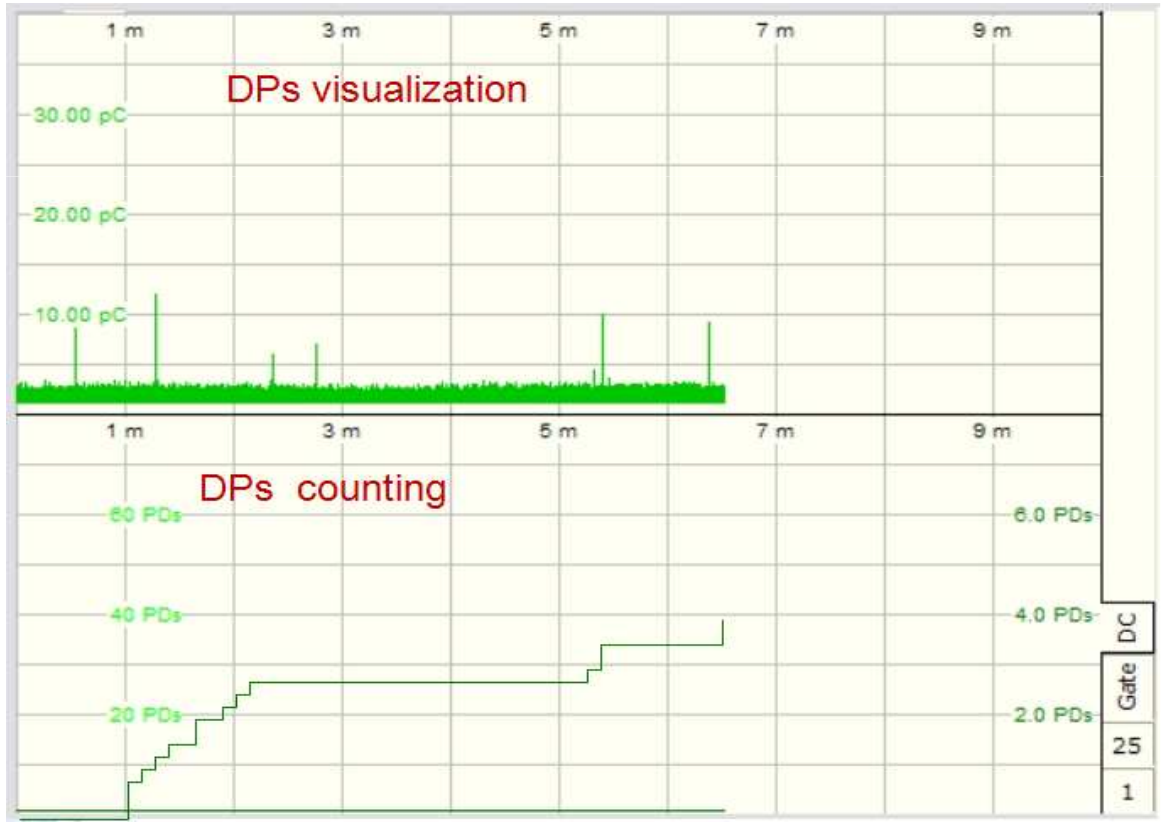
Applied Voltage

Field in Cavity

PARTIAL DISCHARGE MEASUREMENT

Real time display

Recording/counting display



- Critical tests

Ageing tests

- Thermal Shocks
- 280°C thermal ageing

Mechanical tests

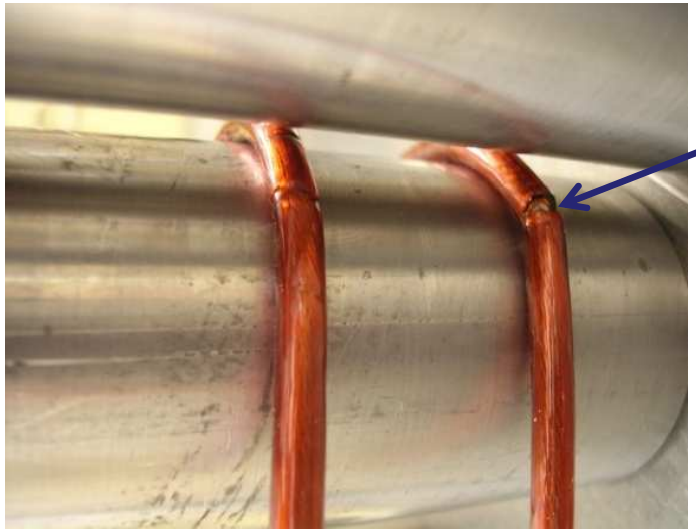
- Wrapp test at ambiant temperature
- +/-90° alternate bending

Electrical tests

- Dielectric breakdown at high temperature

IV. Insulation evaluation

Tests results – failed materials : AURUM PL450C



Serious cracks in +/- 90° bending test.

Cracks and deformations during 280°C thermal ageing.

Tests results – failed materials : OXPEKK CE

Material is OK after thermal shocks ageing but become very brittle after 280°C thermal ageing.

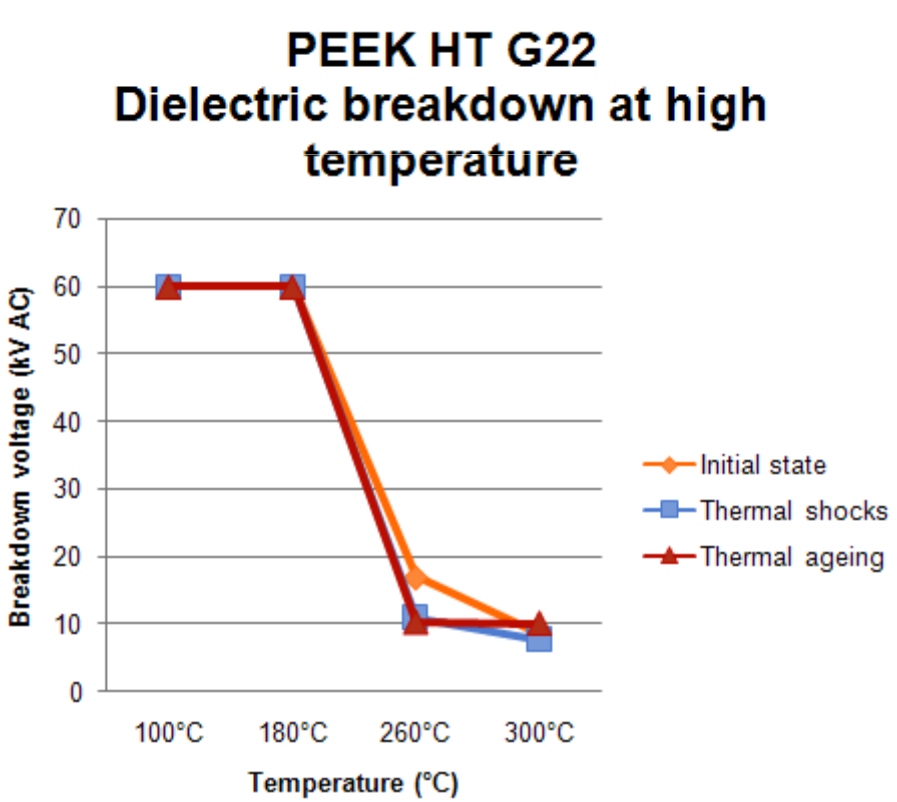
Picture shows damage after wrap test at ambient temperature and after 280°C thermal ageing.

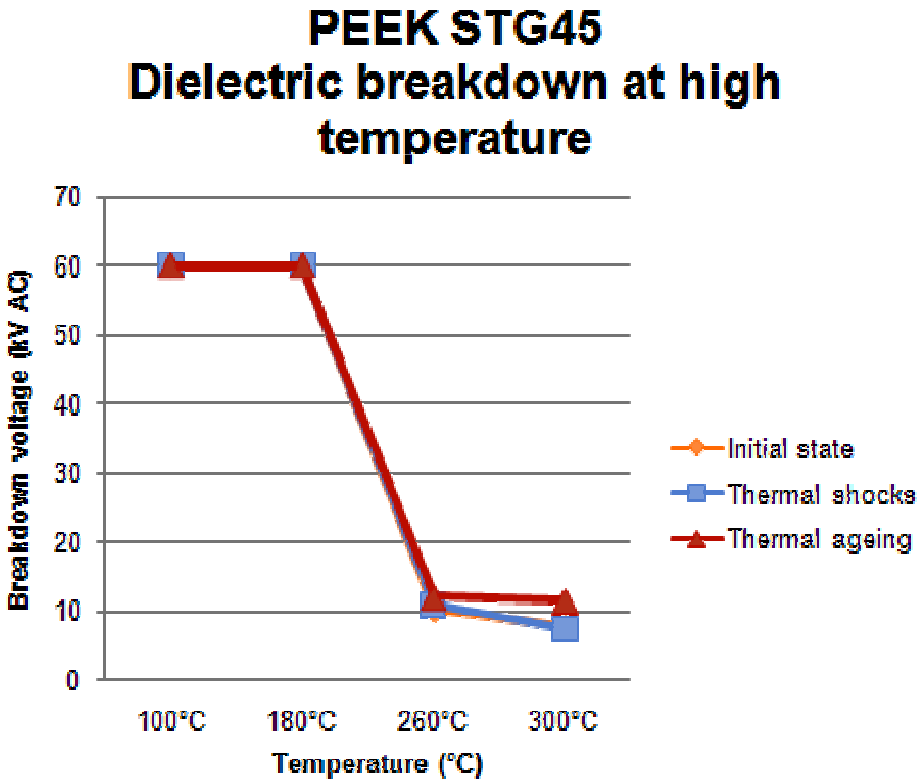
REJECTED

IV. Insulation evaluation

- Tests results on remaining materials

PEEK HT G22	PEEK ST G45





IV. Insulation evaluation

- Tests results – materials still in the race

PEEK ST G45	
Mechanical tests	
Initial state	**OK**
After Thermal Shocks	**OK**
After 280°C thermal ageing	**OK**
Electrical tests	
Initial state	**OK**
After Thermal Shocks	**OK**
After 280°C thermal ageing	**OK**
Wrap tests (cold and ambient temperature)	**OK**
Abrasion (500 cycles – 1 kg)	**OK**
Overload resistance	**---**

PEEK HT G22	
Mechanical tests	
Initial state	**OK**
After Thermal Shocks	**OK**
After 280°C thermal ageing	**OK**
Electrical tests	
Initial state	**OK**
After Thermal Shocks	**OK**
After 280°C thermal ageing	**OK**
Wrap tests (cold and ambient temperature)	**OK**
Abrasion (500 cycles – 1 kg)	**OK**
Overload resistance	**---**

IV. Insulation evaluation

- Tests results – materials still in the race

OVERLOAD RESISTANCE			
PEEK HT G22			
Durat°	Temp.	Amp.	Results
30 min	250°C	97 A	OK.
15 min	400°C	124 A	Melting. No smoke. No burning.Conductor exposed.

PEEK ST G45			
Durat°	Temp.	Amp.	Results
30 min	250°C	98 A	OK.
15 min	400°C	124 A	Melting.No smoke. No burning. Conductor exposed.

Melting starts at 380°C

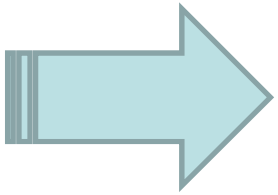
Selection of the final insulation material

Processing

- PEEK ST G45 slightly better than HT G22.

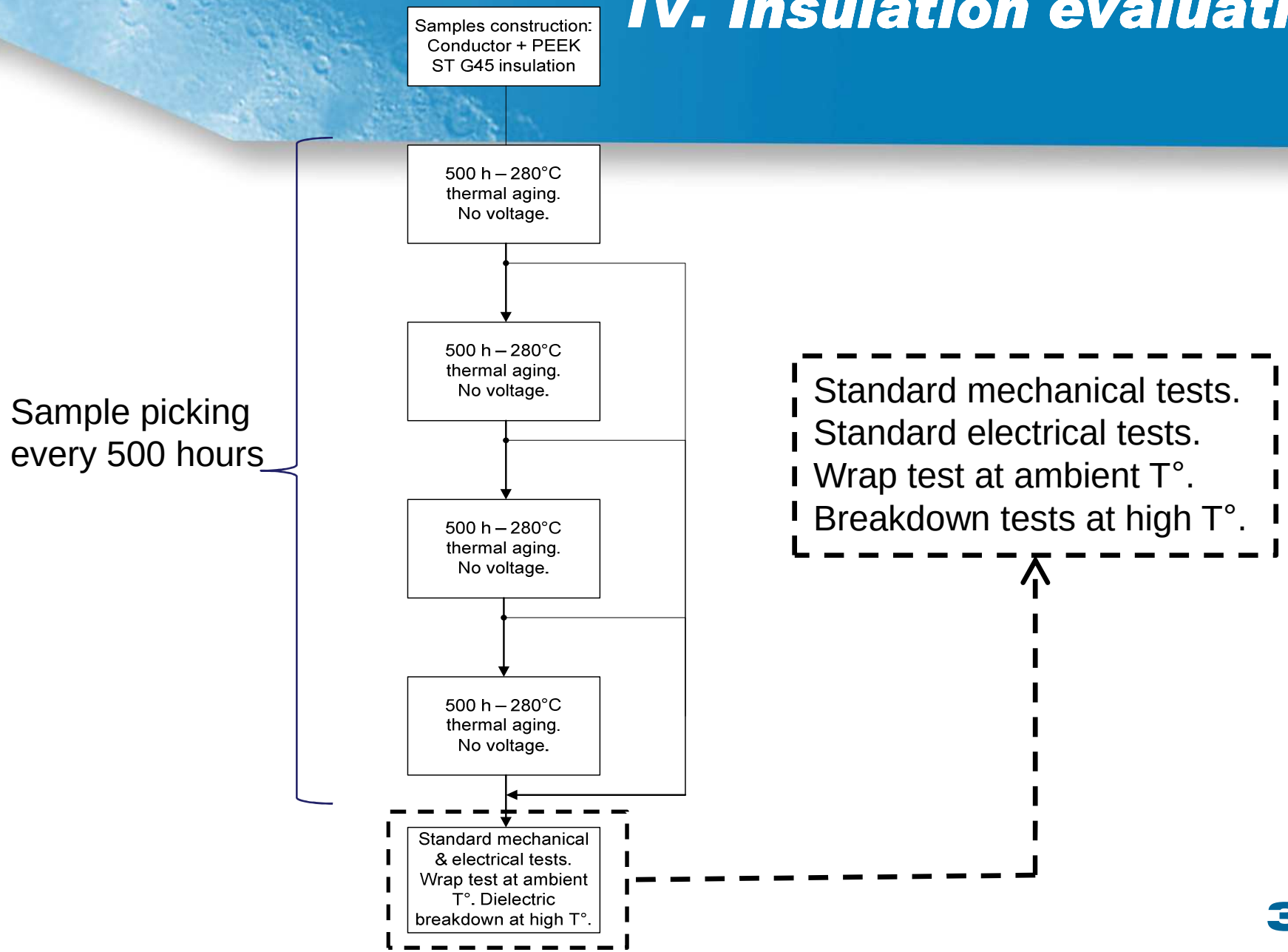
Temperature

- PEEK ST G45 has higher temperature resistance than HT G22.
- Better behavior during overload test.



Launching of a **2000 hours** ageing test at 280°C with PEEK STG45 insulated samples.

IV. Insulation evaluation

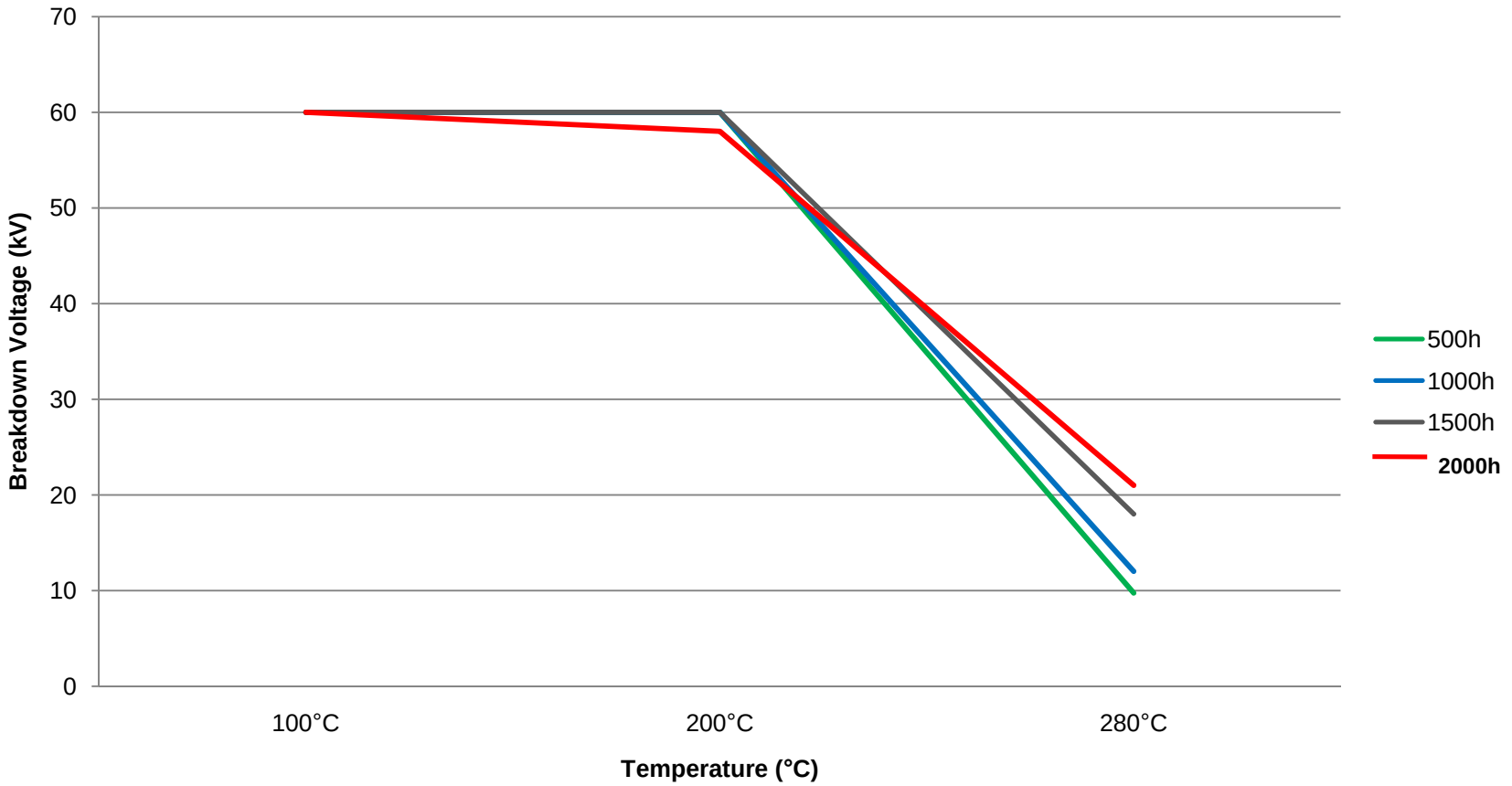


IV. Insulation evaluation

Ageing in hours	Aspect		Elongation (%)	Tensile strength (daN)	Voltage test	Wrap test + voltage test	Bending test +/-6°	Observation
500 hours	✓	Ech 1	13,95	10,66	✓	✓	✓	
		Ech 2	15,38	10,54				
		Ech 3	15,14	10,20				
		Mini	13,95	10,20				
		Max	15,38	10,66				
		Moy	**14,82**	**10,47**				
1000 hours	✓	Ech 1	13,35	10,10	✓	X	✓	
		Ech 2	14,67	10,18				
		Ech 3	14,63	9,83				
		Mini	13,35	9,83				
		Max	14,67	10,18				
		Moy	**14,22**	**10,04**				
1500 hours	✓	Ech 1	17,62	9,73	✓	X	✓	**The samples are very brittle.**
		Ech 2	19,24	10,14				
		Ech 3	19,53	10,10				
		Mini	17,62	9,73				
		Max	19,53	10,14				
		Moy	**18,80**	**9,99**				
2000 hours	✓	Ech 1	13,11	10,20	✓	X	✓	**The samples are very brittle.**
		Ech 2	13,69	10,03				
		Ech 3	17,28	10,60				
		Mini	18,55	10,29				
		Max	18,49	10,50				
		Moy	**14,69**	**10,28**				

IV. Insulation evaluation

PEEK STG 45 Breakdown voltage at high temperatures on 500 to 2000 hours aged samples



Mechanical behavior

These results show that the aged (more than 1000 hours) material can only withstand low amplitude bending solicitation.
When it is exposed to high amplitude bending manipulation, it breaks.

Mechanical tests

Electrically, the material still keeps interesting properties on the whole temperature range.
Breakdown voltages are higher than 10 kV DC at 300°C.

Test Report PV2759A (Draft).

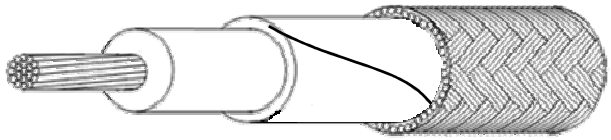
V. Technologies evaluation

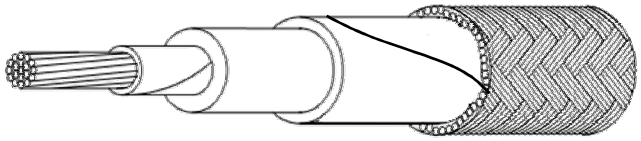
V. Technologies evaluation

- Materials for technologies evaluation
  - Conductor
    - 19X0.511 Unilay 10% Ni plated Percon24
  - Insulation materials
    - PEEK ST G45
    - Polyimide tape Kapton® type HN
  - Semi-conductive material
    - Semi-conductive Kapton® tape
  - Shielding
    - Nickel plated Copper

V. Technologies evaluation

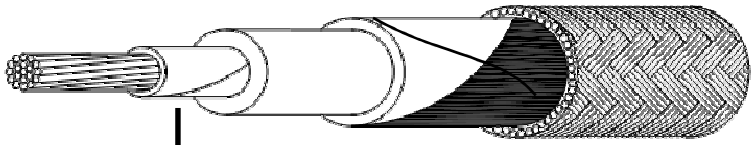
Samples construction

1. 

2. 

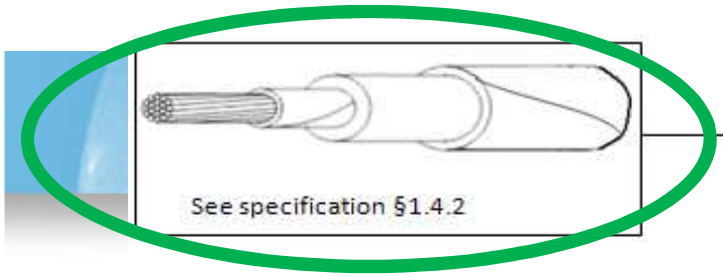
I. Preliminary tests:
- Dielectric breakdown at high temperature at initial state.

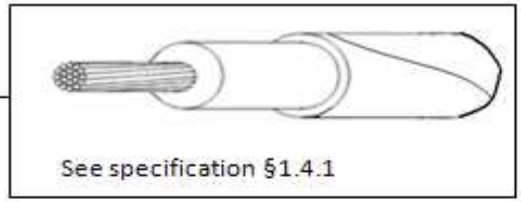
II. Selection of the best of both
- Technologies evaluation tests.



Low noise tests.
Shielding tests.

Depends on results of 1 & 2.





Selected assembly

Dielectric breakdown test at high temperature

Selection of one insulation combination

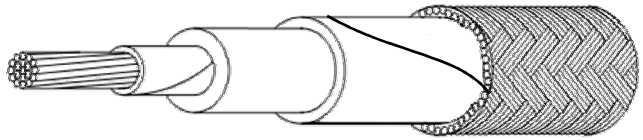
Manufacturing of the final cable construction using previously selected insulation combination.

Technologies evaluation

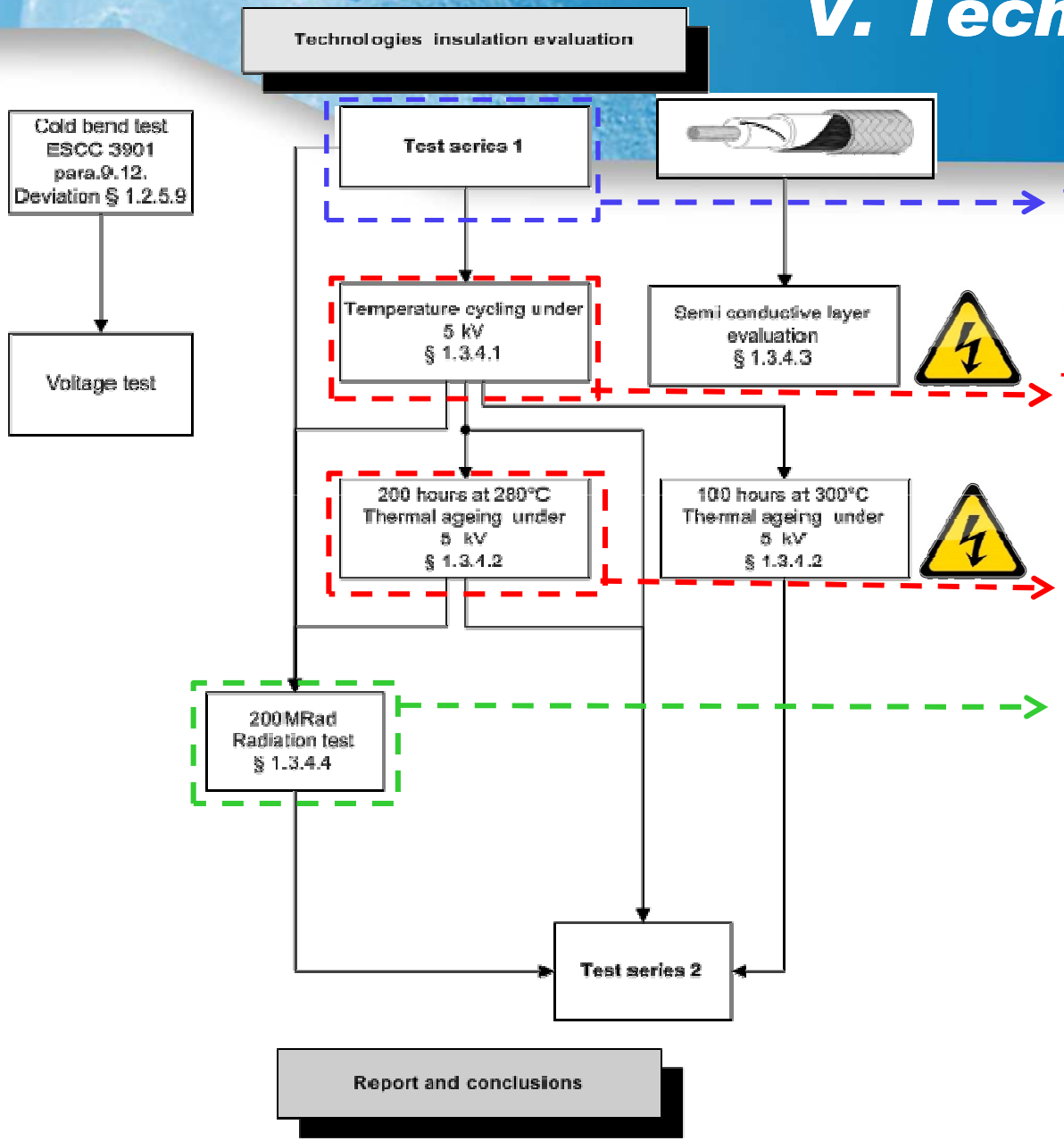
(Chart III)

SELECTION OF THE MORE EFFICIENT CONSTRUCTION BASED ON DIELECTRIC BREAKDOWN RESULTS AT HIGH TEMPERATURES.

Sample construction for technologies evaluation :



V. Technologies evaluation



Test series including mechanical and electrical characterization at each ageing stage.

Temperature cycling at 5 kV DC.

280°C thermal ageing at 5 kV DC.

200 Mrad radiation test on samples issued from each ageing phase.

V. Technologies evaluation

Mechanical and standard electrical tests results – after each ageing phase – before 200 MRad radiation.

	Aspect	Voltage test	Wrap test + voltage test	Bending test +/-6°	Bending test +/-90°	Bending test +/-67°
Initial state	Compliant	Compliant	Compliant	Compliant	Compliant	Compliant
After Temperature cycling / HV	Compliant	Compliant	Compliant	Compliant		
After 280°C thermal ageing / HV	Compliant	Compliant	Compliant	Compliant		
After 300°C thermal ageing / HV	X	X	X	X		

V. Technologies evaluation

Material aspect after 100 hours exposure at 300°C.

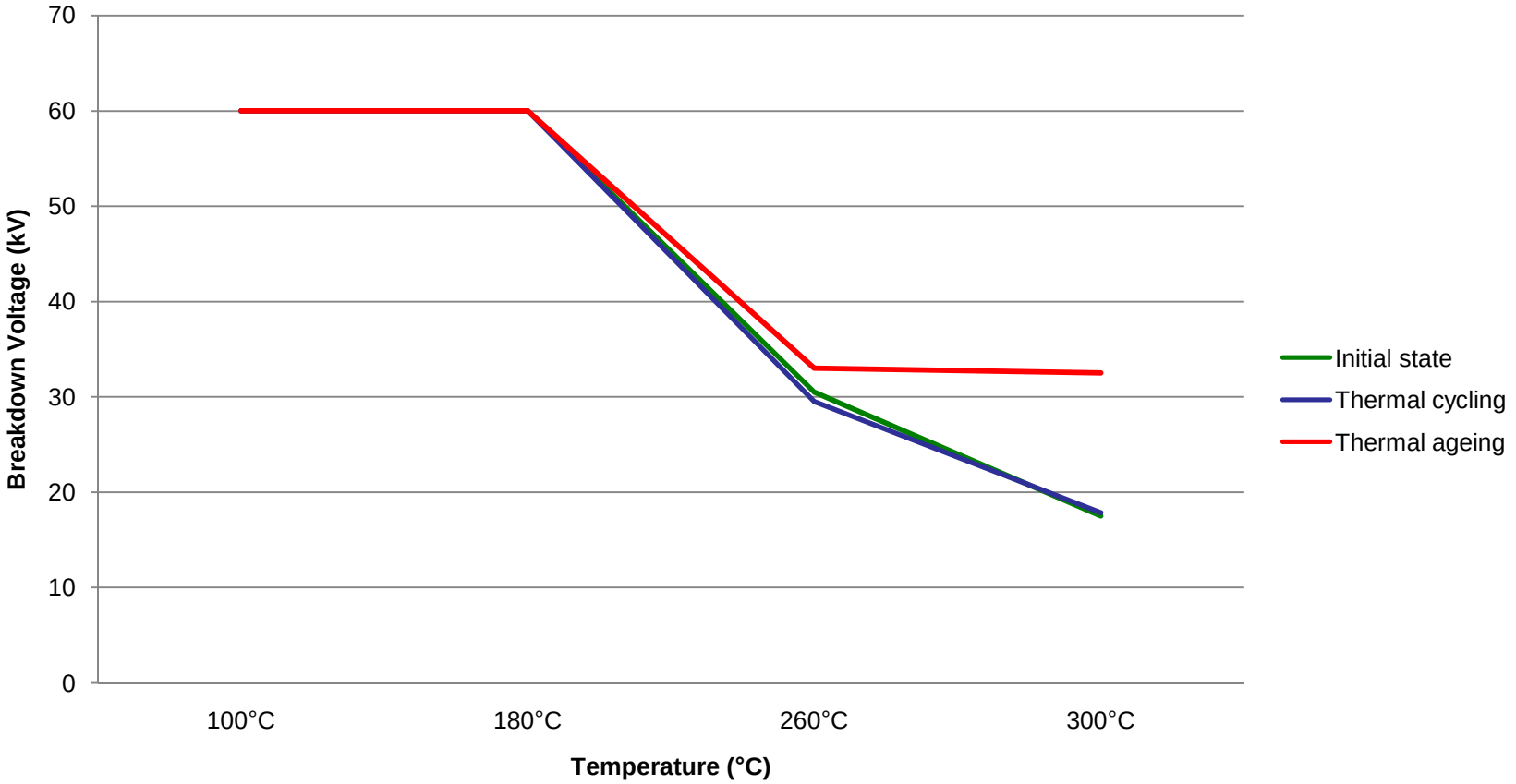
V. Technologies evaluation

Mechanical and standard electrical tests results – after each ageing phase – <u>after</u> 200 MRad radiation.

	POST-IRRADIATION RESULTS					
	Aspect	Voltage test	Wrap test + voltage test	Bending test +/-6°	Bending test +/-90°	Bending test +/-67°
Initial state	Compliant	Compliant	Compliant	Compliant		
After Temperature cycling / HV	Compliant	Compliant	Compliant	Compliant		
After 280°C thermal ageing / HV	Compliant	Compliant	Compliant	Compliant		

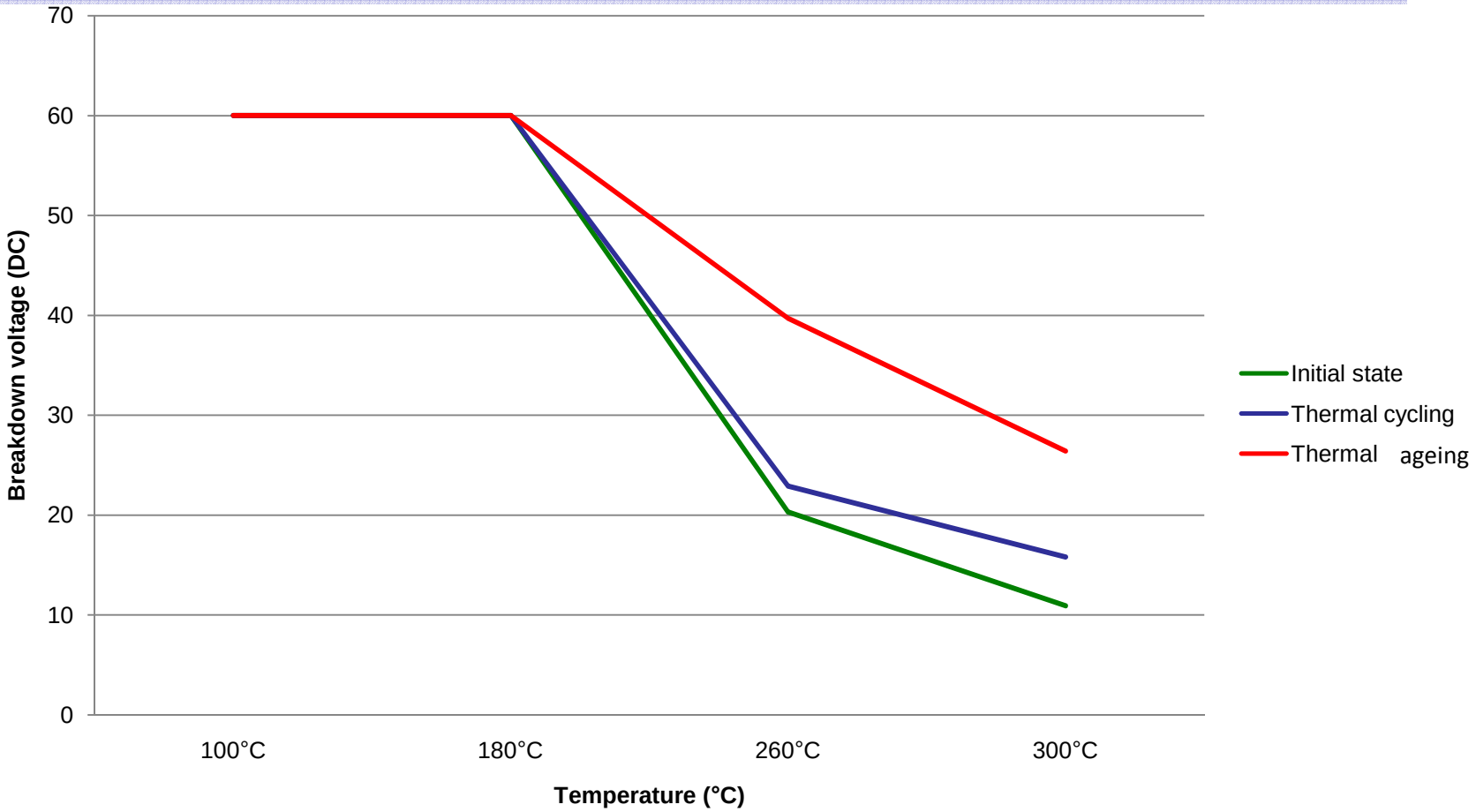
V. Technologies evaluation

High temp. Breakdown tests results – after each ageing phase – <u>before</u> radiation.



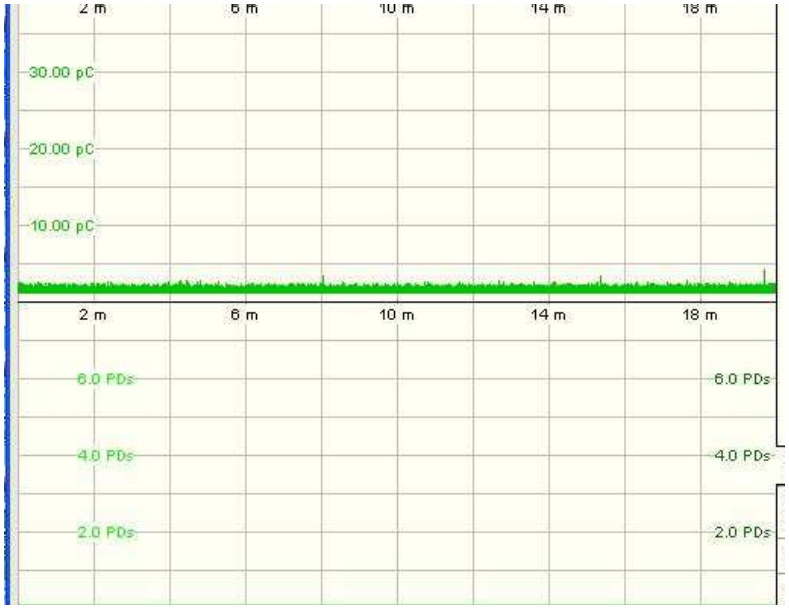
V. Technologies evaluation

High temp. Breakdown electrical tests results – after each ageing phase – <u>after</u> radiation.



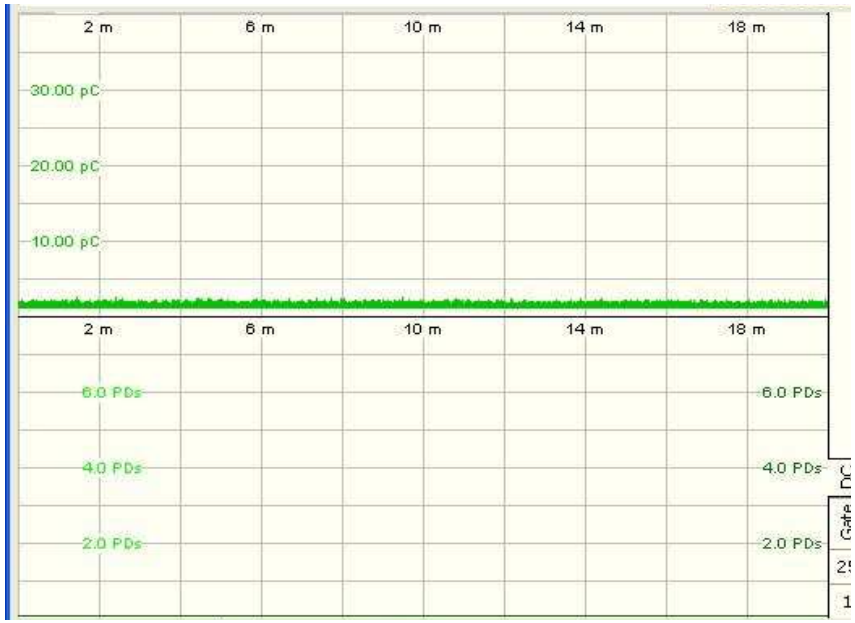
PARTIAL DISCHARGES MEASUREMENTS
BEFORE 200 Mrad radiation exposure.

2.5 kV AC



Initial state

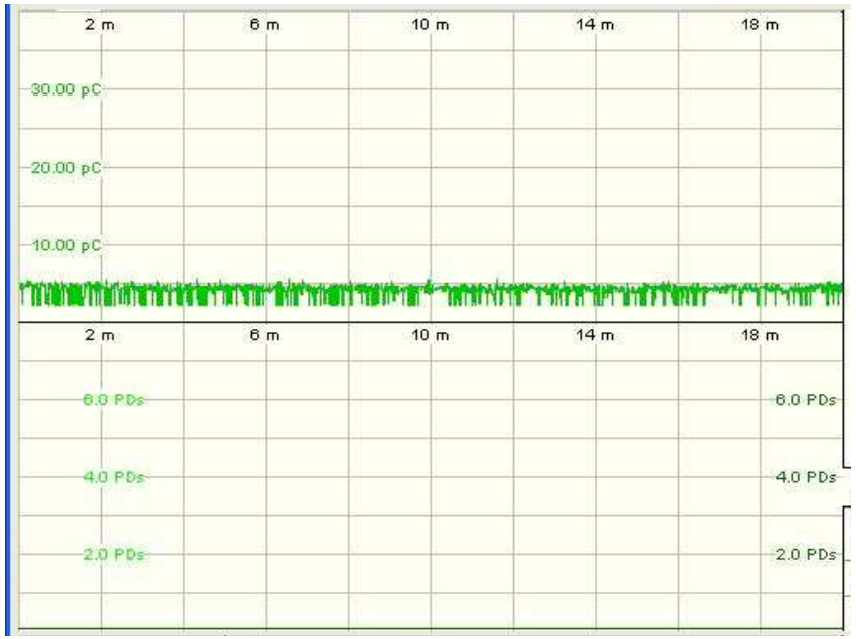
2.5 kV AC



280°C Thermal Ageing

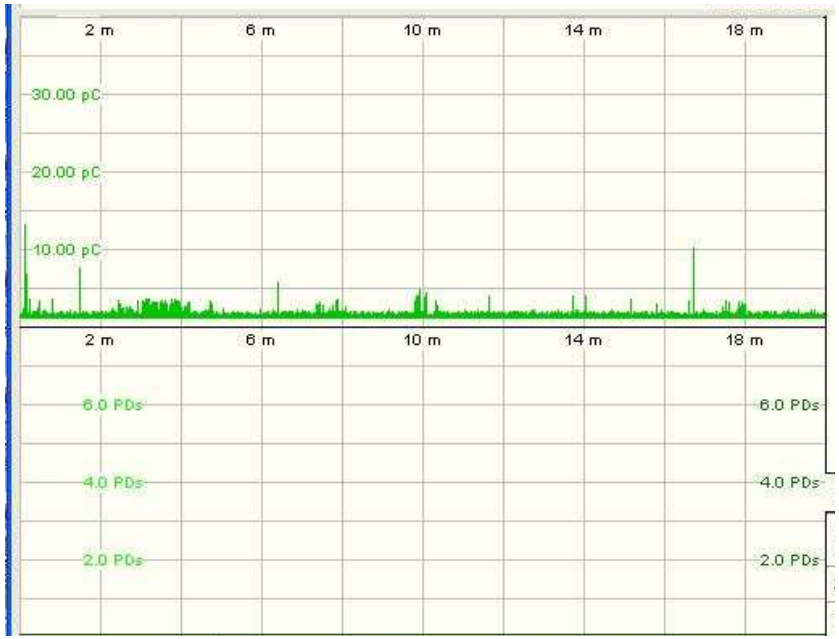
PARTIAL DISCHARGES MEASUREMENTS
AFTER 200 Mrad radiation exposure.

2.5 kV AC



Initial state
+ 200 Mrad

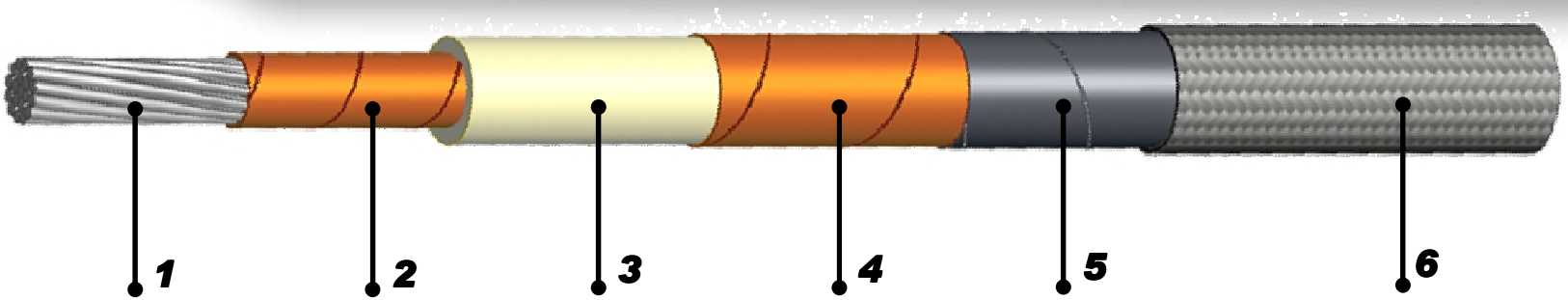
2.5 kV AC



280°C Thermal Ageing
+ 200 Mrad

VI. Synthesis

VI. SYNTHESIS



Construction	
1	19X0.511 Unilay 10% nickel plated PERCON 24®.
2	2 X Kapton® tape 100 HN with 50% covering.
3	PEEK STG45 extruded insulation Thickness : 1 mm.
4	2 X Kapton® tape 200 HN with 50% covering.
5	Optional : 1 X Kapton® semi conductive tape XC10E7.
6	10 % Nickel plated PERCON24 braided shielding.

VI. SYNTHESIS

2000 hours 280°C

- Samples OK after 500h.
- Brittle after 1000 hours but still OK for +/-6° bending.
- Electrically compliant even after 2000 hours.

100 hours 300°C

- Material highly damaged.

Thermal cycling/thermal ageing 280°C

- Samples OK.
- Still able to withstand a wrap test and keep compliant electrical resistance.

VI. SYNTHESIS

Radiation 200 MRad

- Samples OK (slight degradation due to radiation exposure).
- Not significant effect on the insulation.

Mechanical & electrical

- High amplitude bending tests OK at initial state.
- After 2000 h at 280°C, bending test at +/-6° are OK.
- After 2000 h at 280°C, electrical resistance has not significantly changed.

Test reports

- Conductors Evaluation Test report PV2619 Issue A
- Insulation Evaluation Test report PV2759 Issue A
- Technologies Evaluation Test Report PV2934 Issue A

THANK YOU FOR YOUR (LONG) ATTENTION