EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
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CERN TE -VSC

Radiation Induced Aging Effects in Polymeric Cable Insulators at CERN. Compilation of the DSC and ATR-FTIR data on irradiated CERN cables

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2009

Summary

Abbreviations and symbols list

Abbreviation	Significance
ATR-FTIR	Attenuated Total Reflectance - Fourier Transform Infrared Spectroscopy
DSC	Differential Scanning Calorimetry
D	Irradiation dose
D_r	Dose rate
D_x	Maximum supportable dose
E_a	Activation energy
EPR (or EPDM)	Ethylene-propylene rubber
EVA	Ethylene-vinyl acetate copolymer
FR	Flame Retardants
Gy	Gray (dose unit)
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
PE	Polyethylene
PP	Polypropylene
R	Gas constant
RI	Radiation index
t_x	Life-time in specific conditions
XPE	Crosslinked polyethylene
DSC terms	
β	Heating rate (non-isothermal)
OIT	Oxidation induction time
t_{max}	Time to reach the maximum of the heat flow value (t_{max}) (isothermal DSC)
OOT	Oxidation induction temperature (non-isothermal)
OT_m	Oxidation peak temperature (non-isothermal)
DOT	Decomposition onset temperature (non-isothermal)
DT_m	Decomposition peak temperature
ΔH	Enthalpy of a chemical or physical process (isothermal & non-isothermal)
ΔH_D	Decomposition enthalpy (non-isothermal)
ΔH_m	Melting enthalpy (non-isothermal)
ΔH_{ox}	Oxidation enthalpy (isothermal & non-isothermal)
T_m	Melting temperature peak (non-isothermal DSC)

Introduction

This second part of the Report on Radiation Induced Aging Effects in Polymeric Cable Insulators at CERN [1] summarizes in a tabulated form all the experimental DSC results obtained in this work, concerning the life-time evaluation of the selected CERN cables irradiated in different conditions. Several examples of DSC curves and ATR-FTIR spectra were included to support the future polymeric materials analysis.

Information on the experimental conditions, the instruments, the basic concept of life-time evaluation using the DSC data, as well as the examples of data processing and interpretation are presented and discussed in reference [1].

Explanation of tables columns

Column title	Signification
Type/ Lab. code/ Function	CERN cable type. For the unknown types, the usual CERN name is indicated (e.g. EPR cable) / Each cable has a code-number; similar cables, differing by the production date, received different code numbers/ Function: the role of the material: e.g. insulation, jacket
Supplier/ Production date	The name of the producer (supplier) company/ production year as indicated on the cable jacket
Material	Type of the polymeric material
Radiation/ Sample form	Radiation: radiation type, e.g. γ^{137}Cs, γ^{60}Co or CERN accelerators radiations (e.g. SPE-ZS, LSS-2)/ Sample form: - strap - obtained by lathering from large diameter insulation and jacket; used to prove the effect of air on the materials - bulk-air: cable fragment exposed to irradiation without sealing of the extremities - bulk-enc: cable fragment wax sealed (encapsulated) prior irradiation, to reduce the air access
Dose rate (kGy/h)	0.4 kGy/h: γ^{137}Cs, ICPE-CA, Bucharest, RO 1.5 kGy/h: γ^{60}Co, Ionisos, Dagneaux, FR 21.1 kGy/h: γ^{60}Co, BGS, Wiehl, DE
Dose (kGy)	The doses in kGy used for cables irradiation in controlled conditions (at ICPE-CA, Bucharest, RO, Ionisos-Dagneaux, FR, BGS, Wiehl, DE) The doses indicated for PB-300 cable (aged in CERN service) were measured by a RPL dosimeter
OIT (min.)	OIT (Oxidation Induction Time), in minutes, is obtained directly from isothermal measurement, according to CERN TE/VSC/CSA Chemistry Laboratory Procedure [2] and the reference standards [3, 4]. For non-isothermal measurements, OOT (Oxidation Onset Temperature) was determined for 4 different heating rates, according to CERN TE/VSC/CSA Chemistry Laboratory Procedure [5] and reference standards [6]; the activation energy of oxidation was calculated with Kissinger's equation [7, 8] and OIT was calculated with the Gimzewski's equation [9, 10].

Column title	Signification
k (kGy^{-1}, or y^{-1})	is the kinetic constant of the OIT decrease as a function of the irradiation dose (D) or, respectively, irradiation time (t) $OIT_D = OIT_0 \cdot e^{-kD}$ where OIT_0 and OIT_D are, respectively, the OIT at 0 kGy (as received, unaged, cable) and the OIT of the material irradiated at the dose *D*; $OIT_t = OIT_0 \cdot e^{-kt}$ where OIT_t is the OIT of the material irradiated for a time *t* [1, 14]
Maximum supportable dose (kGy)	The dose corresponding to the evaluated life-end of the material (when OIT becomes zero and the material is no longer protected against the oxidation) in the specific conditions; the exponential model is used for evaluation [1, 14]
Life-time (rounded)	The irradiation time to the life-end of the material (when OIT becomes zero) in the specific conditions; the exponential model is used for evaluation [1, 14]
RI	Radiation index = $\log_{10}$ (maximum supportable dose, in Gy). The *radiation index* is defined in IEC 60544-4 [11] as the logarithm, base 10, of the absorbed dose in gray (rounded to two significant digits) at which the elongation at break is reduced to 50 % of its initial value, in specified conditions of irradiation and tests [11, 12]. In present case, the radiation index is calculated from the maximum supportable dose, i.e. the dose corresponding to zero OIT. As the mechanical properties fail after the moment of OIT reaches zero value, it is reasonable to assume that RI can be evaluated in this manner from OIT measurements [1, 14]
DSC parameters/ remarks	a) The mode of DSC measurement (isothermal or non-isothermal) and the temperature (for isothermal OIT) are specified; for non-isothermal measurements, the OIT was evaluated for a certain specified temperature, using the OOT values from 4 measurements at 4 different heating rates [5-10]. b) For the thick insulator cables, such as Silec, HV Septa, PB-300 or CLP-50, three reference positions on the transversal section were defined for the in depth degradation state characterization: S3 - on the outer side of insulator; S2 - in the central part of the insulator; S1 - on the inner side of the insulator, after the removal of the sheath between the central conductor and insulator. In each case, layers of ca. 0.3 mm were used for DSC measurements [1, 2].

1. EPR (Ethylene-propylene rubber)

1.1 Compilation of the DSC life-time evaluation data

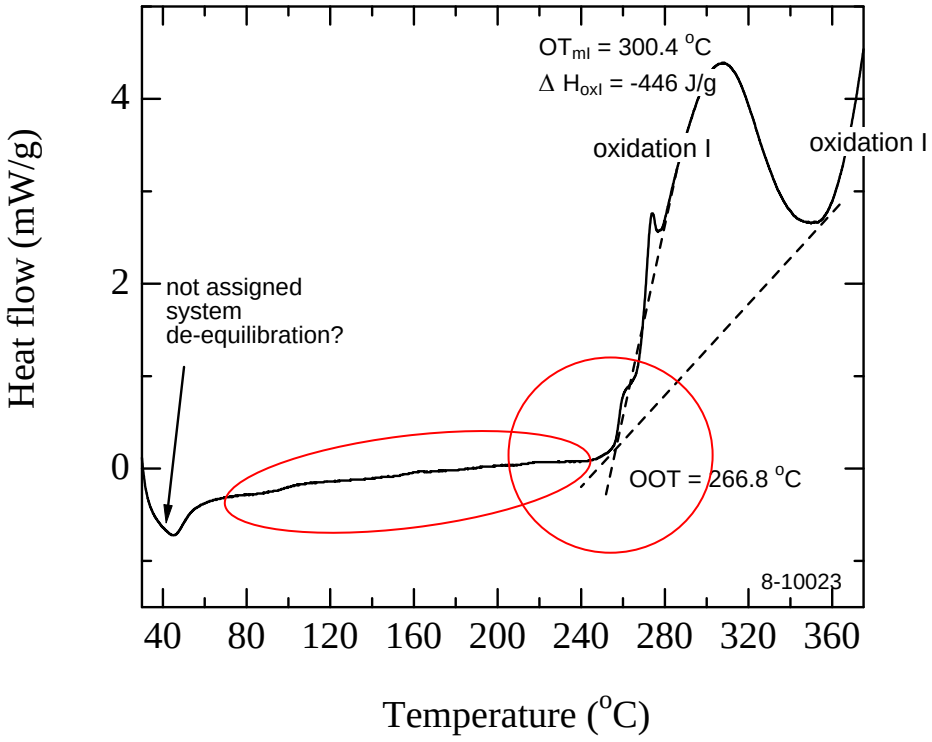
Cable data			Irradiation conditions			Laboratory measurements and results					DSC parameters/ remarks
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x (kGy)	Life-time (rounded)	RI	
EPR/ 2/ insulation	Cortaillod Cables S.A, CH/ unknown; received in lab. July 2007	**EPR**	γ^{137}Cs/ **strap**	-	0	372	**$1.36 \cdot 10^{-2}$**	**567**	**1400 h**	**5.8**	isothermal, 200 °C, air
				0.4	9.6	308					
				0.4	28.8	258					
				0.4	96	101					
			γ^{60}Co/ **bulk-air**	-	0	372	**$2.36 \cdot 10^{-3}$**	**3266**	**2200 h**	**6.5**	isothermal, 200 °C, air
				1.5	310	143					
				1.5	630	94					
			γ^{60}Co/ **bulk-N_2**		0	372	**$2.19 \cdot 10^{-3}$**	**3520**	**2350 h**	**6.5**	isothermal, 200 °C, air
				1.5	310	238					
				1.5	630	90					
EPR/ 2/ jacket	as above, received in lab. July 2007	**EPR**	γ^{137}Cs/ **strap**	-	0	424	**$1.55 \cdot 10^{-2}$**	**506**	**1250 h**	**5.7**	isothermal, 200 °C, air
				0.4	9.6	361					
				0.4	28.8	301					
				0.4	96	96					
			γ^{60}Co/ **bulk-air**	-	0	424	**$3.43 \cdot 10^{-3}$**	**2286**	**1500 h**	**6.4**	isothermal, 200 °C, air
				1.5	310	112					
				1.5	630	63					
			γ^{60}Co/ **bulk-N_2**	-	0	424	**$1.52 \cdot 10^{-3}$**	**5158**	**3450 h**	**6.7**	isothermal, 200 °C, air
				1.5	310	265					
				1.5	630	170					
EPR/ 68/ insulation	as above, received in lab. June 2008	**EPR**	SPE-ZS run 2007/ **bulk**	-	0	246	**$(6.40 \cdot 10^{-3})$*** ***0.27 year^{-1}***	(**1140**)*	**~27 years**	(**6.1**)*	isothermal, 200 °C, air
				n.a.	(42)*	188					
EPR/		**EPR**	SPE-ZS	-	0	55	**$(1.784 \cdot 10^{-2})$***	(**325**)*		(**5.5**)*	isothermal, 200 °C,

Cable data			Irradiation conditions			Laboratory measurements and results					DSC parameters/ remarks
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x (kGy)	Life-time (rounded)	RI	
68/ jacket			run 2007/ **bulk**	n.a.	n.a.	26	***0.749 years^{-1}***		**~ 8 years**		air
EPR/ 85/ insulation	as above, received in lab. Feb. 2008	**EPR**	1 year in LSS-2/ bulk	-	0	513	**(4.746·10^{-3})*** ***0.37 year^{-1}***	(**1692**)*	**~ 22 years**	(**6.2**)	isothermal, 200 °C, air
				n.a.	(70)*	368					
				-	0	246	**(4.703·10^{-3})*** ***0.33 year^{-1}***	(**1551**)*	**~ 22 years**	(**6.2**)	isothermal, 190 °C, air
				n.a.	(70)*	177					
EPR/ 85/ jacket		**EPR**	1 year in LSS-2/ bulk	-	0	55	**(7.30·10^{-3})** ***0.511 years***	(**794**)	**~ 11 years**	(**5.9**)	isothermal, 200 °C, air
				n.a.	(70)*	33					

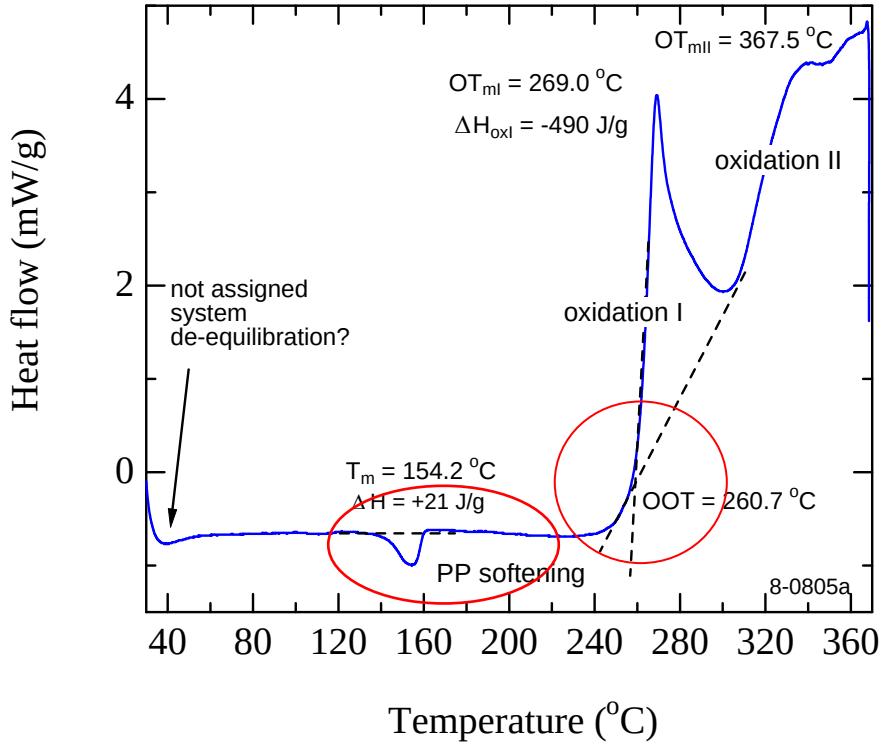
* Dose estimated (see reference [1])

1.2 Non-isothermal DSC curves

(β = 5 K/min., air)

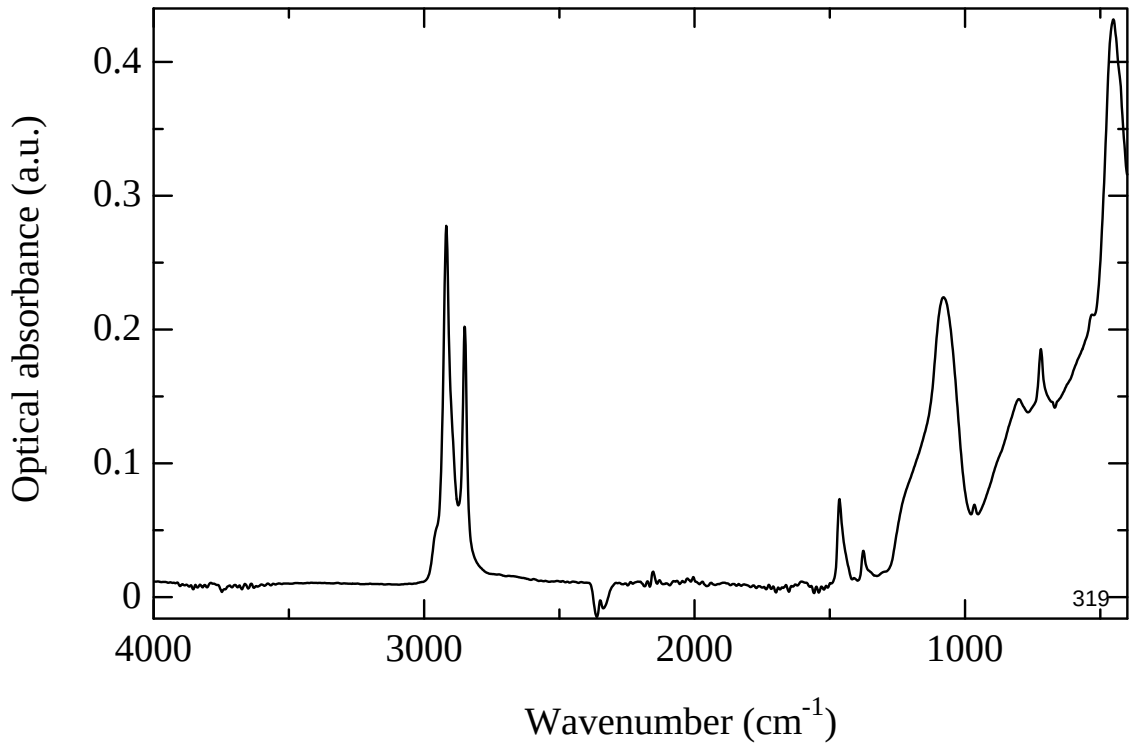


1.2.1 *- Non-isothermal DSC curve of EPR cable (Lab. code 2) insulation*

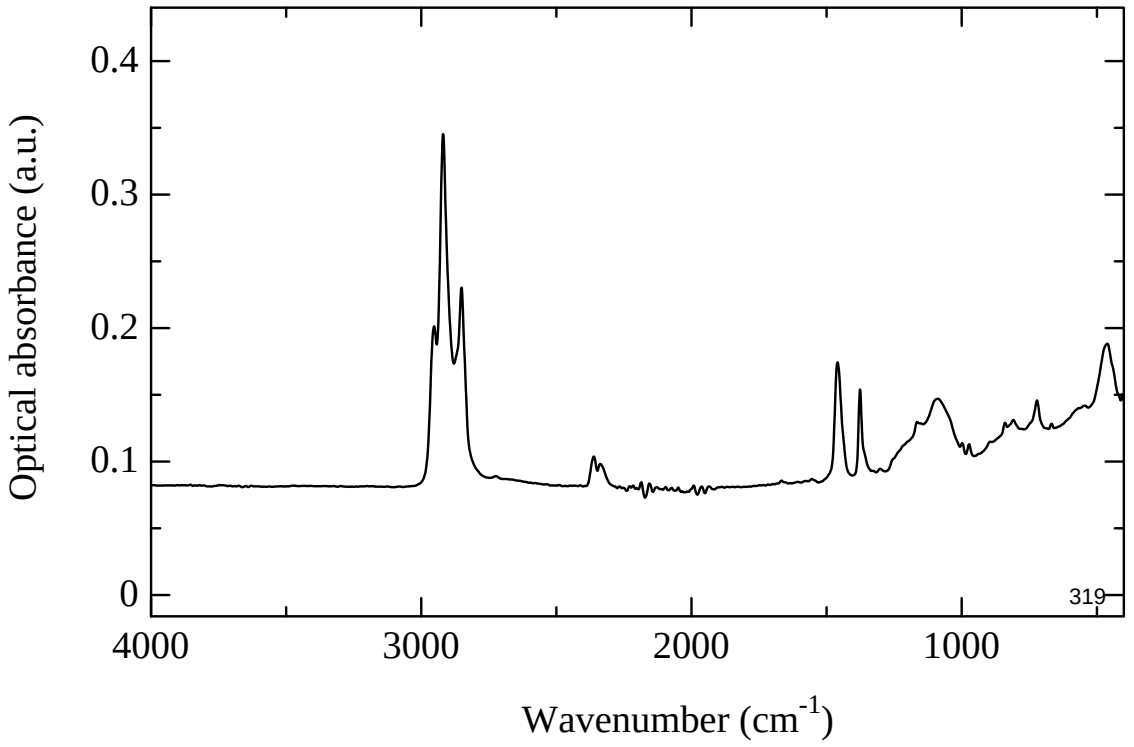


1.2.2 *- Non-isothermal DSC curve of EPR cable (Lab. code 2) jacket*

1.3 ATR-FTIR spectra



1.3.1 *- ATR-FTIR spectrum of EPR insulation of EPR cable (Lab. code: 2)*



1.3.2 *- ATR-FTIR spectrum of EPR jacket of EPR cable (Lab. code 2)*

2. EVA (Ethylene-vinyl acetate copolymer)

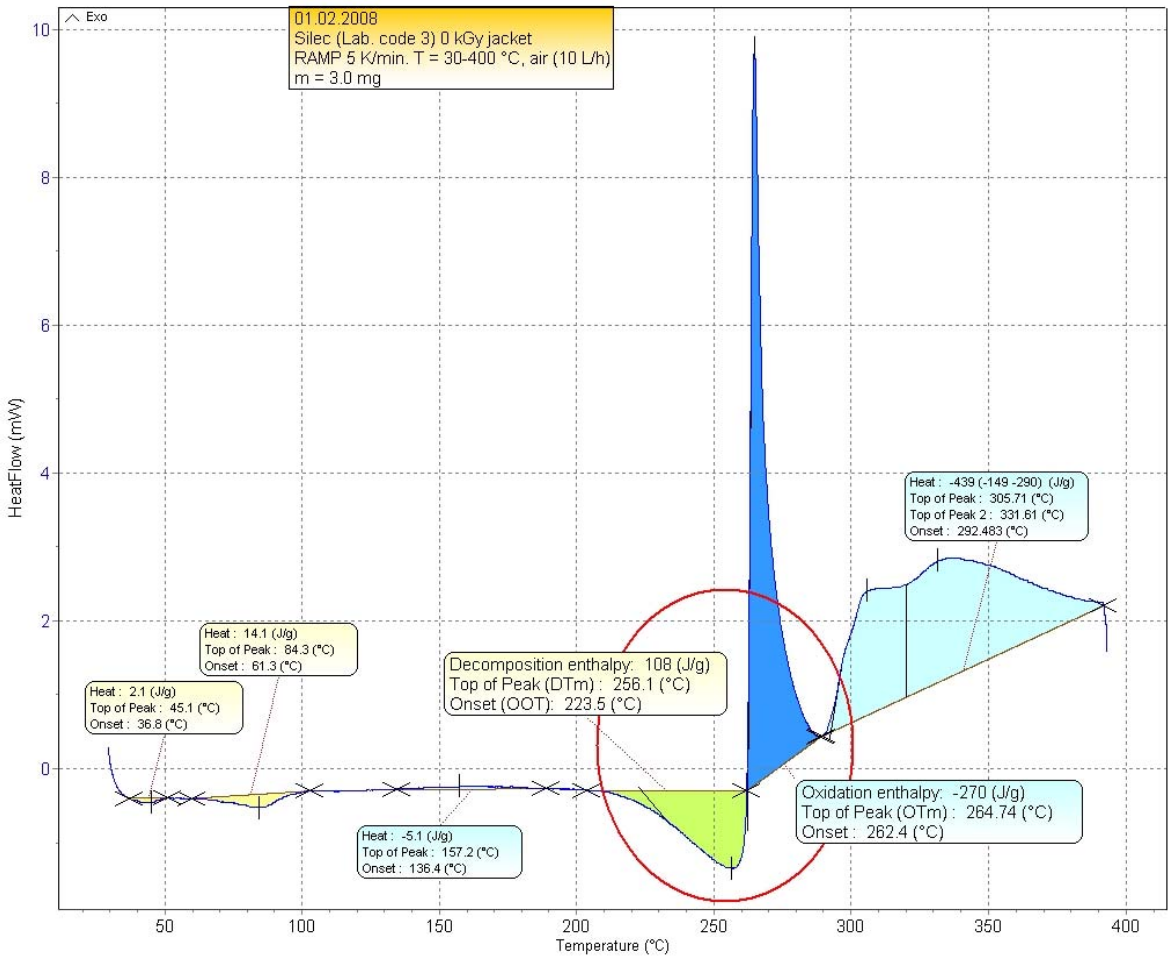
2.1 Compilation of the DSC life-time evaluation data

Cable data			Irradiation conditions			Laboratory measurements and results					DSC parameters/ remarks
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation / Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x (kGy)	Life-time (rounded)	RI	
Silec/ 1/ jacket	Silec Cable, FR/ ~1995	**EVA type I (black)**	γ^{137}Cs/ **strap**	-	0	460	**$1.16 \cdot 10^{-3}$**	**683**	**1700 h**	**5.8**	isothermal, 190 °C, air
				0.4	9.6	490					
				0.4	28.8	391					
				0.4	96	164					
			γ^{60}Co/ **bulk-air**	-	0	460	**$5.47 \cdot 10^{-3}$**	**1448**	**950 h**	**6.2**	isothermal, 190 °C, air
				1.5	310	82					
				1.5	630	18					
NG-18/ 9/ jacket	Draka Comteq, DE/ 2006w19	**EVA type I (white)**	γ^{137}Cs/ **bulk-air**	-	0	343	**$1.06 \cdot 10^{-2}$**	**720**	**1800 h**	**5.9**	isothermal, 210 °C, air
				0.4	9.6	240					
				0.4	28.8	266					
				0.4	96	201					
			γ^{60}Co/ **bulk-air**	-	0	343	**$9.42 \cdot 10^{-3}$**	**810**	**2000 h**	**5.9**	isothermal, 210 °C, air
				1.5	310	8					
				1.5	630	1.9					
			γ^{60}Co/ **bulk-enc.**	-	0	343	**$8.27 \cdot 10^{-3}$**	**922**	**2300 h**	**6.0**	isothermal, 210 °C, air
				1.5	310	21					
				1.5	630	2.8					
CC-50/ 22/ jacket	Draka Comteq, DE/ 2002	**EVA type I (brown)**	γ^{60}Co/ **bulk-enc.**	-	0	369	**$9.28 \cdot 10^{-3}$**	**830**	**550 h**	**5.9**	isothermal, 210 °C, air
				1.5	310	12					
				1.5	630	1.3					
			γ^{60}Co/ **bulk-enc.**	-	0	152	**$8.96 \cdot 10^{-3}$**	**760**	**500 h**	**5.9**	OIT at 210 °C as calculated from non-isothermal measurements
				1.5	310	5.5					
				1.5	630	0.7					
CBH-50/ 23/ jacket	Draka Comteq, DE/ 2006	**EVA type I (red)**	γ^{60}Co/ **bulk-enc.**	-	0	706	**$2.949 \cdot 10^{-3}$**	**2831**	**1900 h**	**6.5**	isothermal, 210 °C, air
				1.5	310	101					
				1.5	630	161					

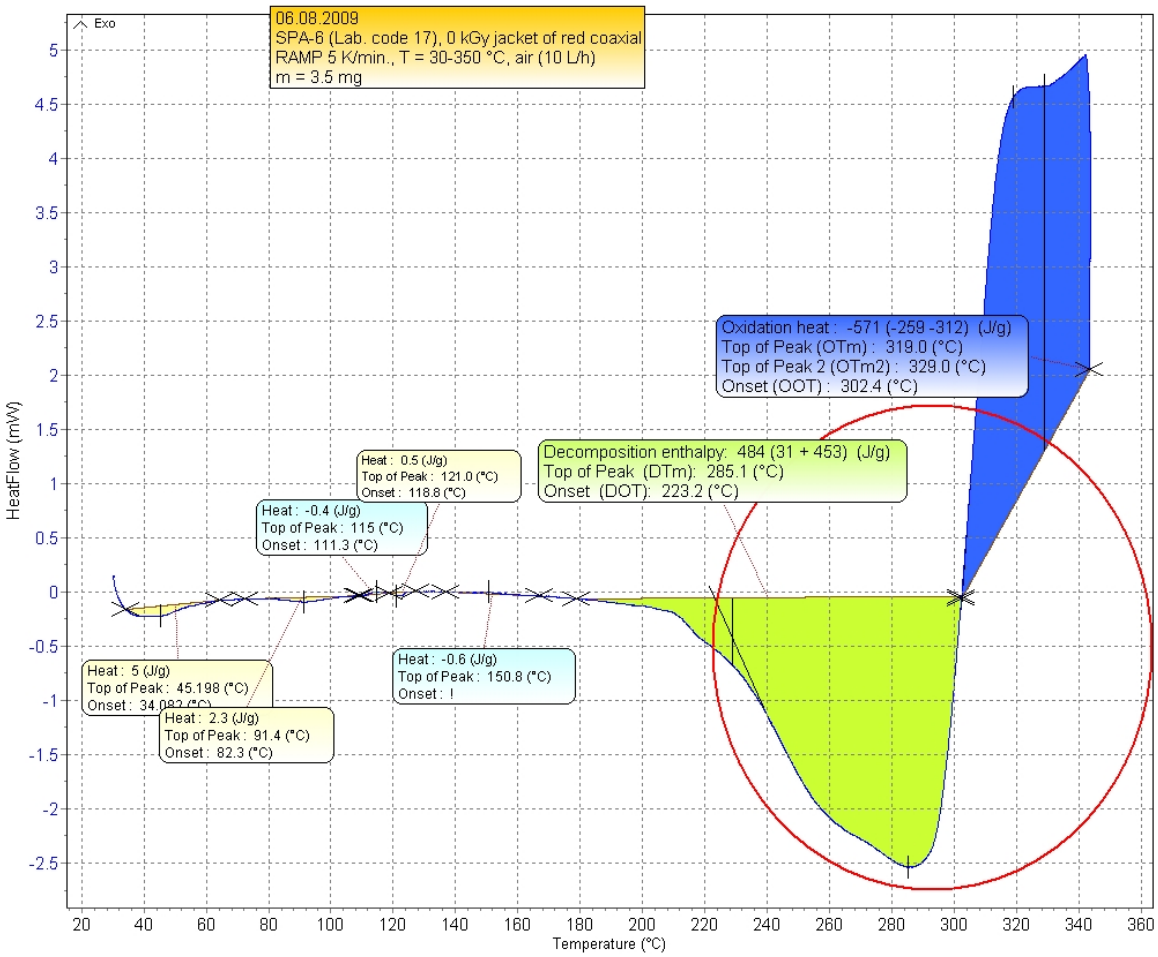
Cable data			Irradiation conditions			Laboratory measurements and results					DSC parameters/ remarks
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation / Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x (kGy)	Life-time (rounded)	RI	
	w49										
SVAR-3/ 38b/ jacket	Raydex	**EVA type II (red)**	γ^{60}Co/ **bulk-air**	-	0	5834	**$1.01 \cdot 10^{-3}$**	**10352**	**6900 h**	**7.0**	OIT at 210 °C as calculated from non-isothermal measurements
				1.5	3000	278					
			γ^{60}Co/ **bulk-air**	-	0	5834	**$1.43 \cdot 10^{-4}$**	**19919**	**950 h**	**7.3**	OIT at 210 °C as calculated from non-isothermal measurements
				21.1	10000	573					
				21.1	20000	473					
			γ^{60}Co/ **bulk-enc.**	-	0	5834	**$1.55 \cdot 10^{-4}$**	**18377**	**850 h**	**7.3**	OIT at 210 °C as calculated from non-isothermal measurements
				21.1	10000	1213					
TFA-3/ 39/ jacket	Draka Multimedia DE 1998 (J98-0535)	**EVA type II (orange)**	γ^{60}Co/ **bulk-air**		0	2475	**$2.995 \cdot 10^{-3}$**	**3212**	**2150 h**	**6.5**	OIT at 210 °C as calculated from non-isothermal measurements
				1.5	310	790					
				1.5	630	398					

2.2 Non-isothermal DSC curves

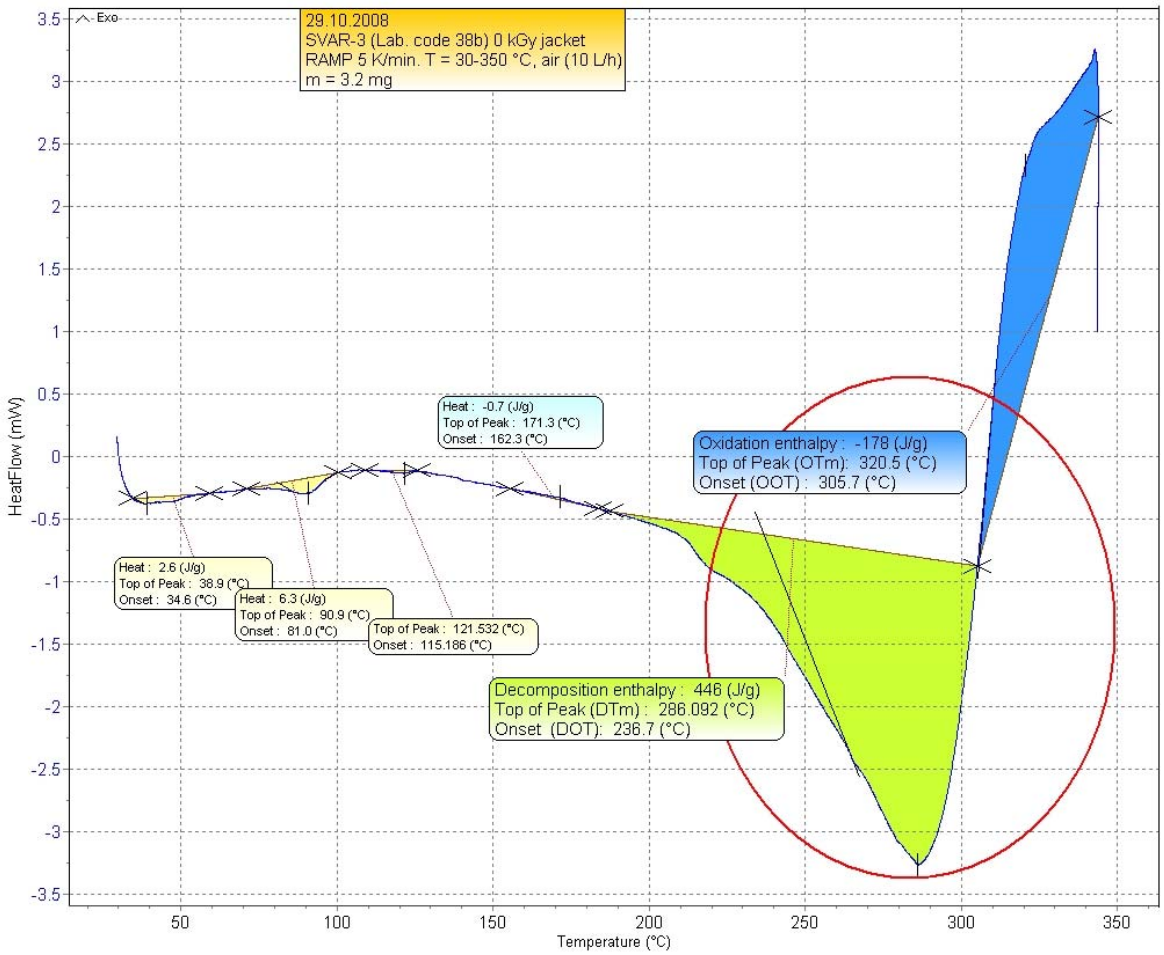
(β = 5 K/min., air)



2.2.1 *- Non-isothermal DSC curve of Silec cable (Lab. code 1) jacket*

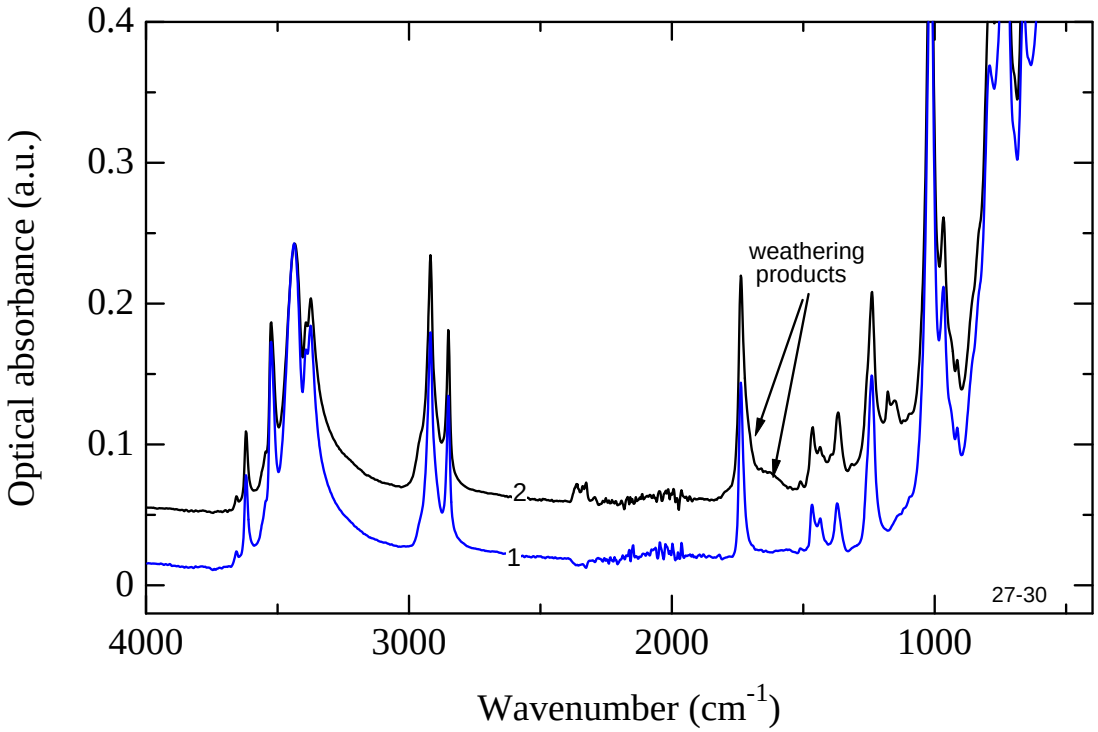


2.2.2 *- Non-isothermal DSC curve of SPA-6 cable (Lab. code 17) jacket of red coaxial*

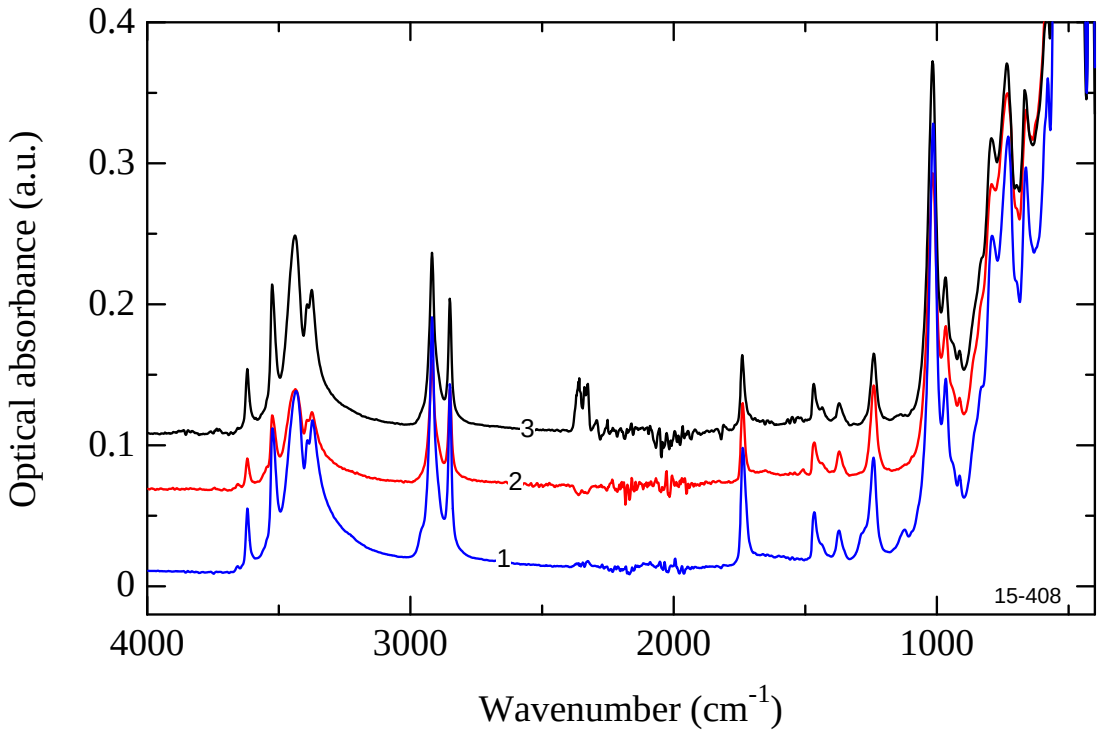


2.2.3 *- Non-isothermal DSC curve of SVAR-3 cable (Lab. code 38b) jacket*

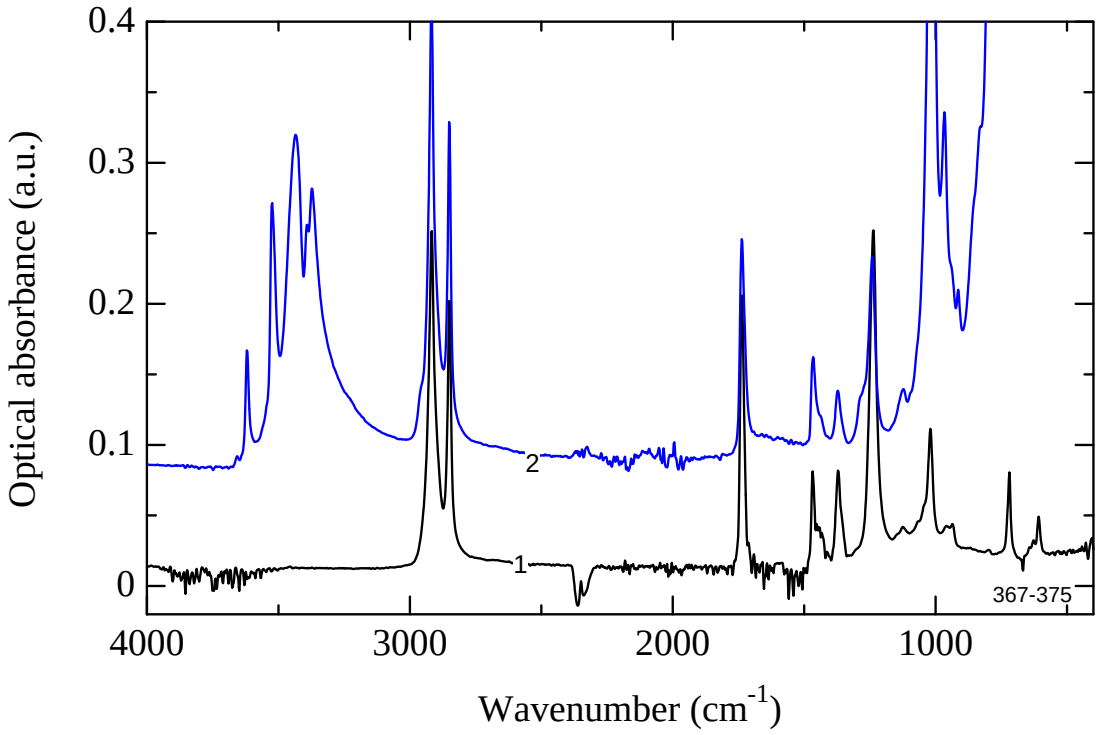
2.3 ATR-FTIR spectra



2.3.1 *- ATR-FTIR spectra of different EVA jacket materials: 1 - inner part; 2 - outer part, weathered (yellowish)*



2.3.2 *- ATR-FTIR spectra of different EVA jacket materials: 1 - cable CC-50 (Lab. code 22, EVA type I)); 2 - cable TFA-3 (Lab. code 39, EVA type II); 3 - cable SVAR-3 (Lab. code 38b, radiation resistant, EVA type II)*



2.3.3 *- ATR-FTIR spectra of ELVAX 3182 (28 % vinyl acetate, DuPont; from TE/VSC Laboratory polymer samples collection), spectrum 1; for comparison, the ATR-FTIR spectrum of the jacketing material of cable CC-50 (Lab. code 22, spectrum 2)*

3. LDPE (Low density polyethylene)

3.1 Compilation of the DSC life-time evaluation data

Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
Silec/ 1/ insulation	Silec Cable FR/ ~1995	**LDPE**	γ^{137} Cs/ **strap**	-	0	45	**$4.27 \cdot 10^{-2}$**	**130**	**325 h**	**5.1**	isothermal, 190 °C, air
				0.4	9.6	34					
				0.4	28.8	8.7					
				0.4	96	0.8					
			γ^{60} Co/ **bulk-air**	-	0	45	**$1.22 \cdot 10^{-3}$**	**4587**	**3050 h**	**6.7**	isothermal, 190 °C, air
				1.5	310	23.5					
				1.5	630	26					
			γ^{60} Co/ **bulk-enc**.	-	0	45	**$1.08 \cdot 10^{-3}$**	**5182**	**3450 h**	**6.7**	isothermal, 190 °C, air
				1.5	310	29					
				1.5	630	25					
HV Septa/ 3/ insulation	Draka Comteq DE/ 2006	**LDPE**	γ^{137} Cs/ **strap**		0	296	**$8.87 \cdot 10^{-2}$**	**84**	**210 h**	**4.9**	isothermal, 190 °C, air
				0.4	9.6	111					
				0.4	28.8	24					
				0.4	96	0					
			γ^{60} Co/ **bulk-air**	-	0	296	**$3.93 \cdot 10^{-3}$**	**1903**	**1250 h**	**6.3**	isothermal, 190 °C, air;/ pos. S1, S2; in pos. S3, D_x < 300 kGy
				1.5	630	28					
			γ^{60} Co/ **bulk-enc**.	-	0	296	**$3.71 \cdot 10^{-3}$**	**2016**	**1350 h**	**6.3**	isothermal, 190 °C, air/ pos. S1, S2; in pos. S3, D_x < 300 kGy
				1.5	630	32					
HV Septa/ 66/ insulation	Draka Comteq DE/ 2006?	**LDPE**	run 2007 in PS Section 31/ **bulk**	-	0	283	***2.31 y^{-1}***	**-**	**~ 3 years**	**-**	isothermal, 190 °C, air/ pos. S3
				n.a.	n.a.	28					
				-	0	283	***0.94 y^{-1}***	**-**	**~8 years**	**-**	isothermal, 190 °C, air/ pos.
				n.a.	n.a.	111					

Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
											S1, S2
HV Septa/ 67/ insulation	Draka Comteq DE/ 2006?	**LDPE**	run 2007 in SPS-ZS/ **bulk**	-	0	283	***2.81 y^{-1}***	**-**	**~ 2.5 years**	**-**	isothermal, 190 °C, air/ pos. S3
				n.a.	n.a.	17					
				-	0	283	***2.35 y^{-1}***	**-**	**~ 3 years**	**-**	isothermal, 190 °C, air/ pos. S1, S2
				n.a.	n.a.	27					
HV Septa/ 86/ insulation	Draka Comteq, DE/ unknown	**LDPE**	1 y in LSS-2/ **bulk**		0	269	***2.92 y^{-1}***	**-**	**~ 2.5 years**	**-**	isothermal, 190 °C, air/ pos. S3
				n.a.	n.a.	14.5					
				-	0	269	***2.65 y^{-1}***	**-**	**~ 3 years**	**-**	isothermal, 190 °C, air/ pos. S1, S2
				n.a.	n.a.	19					
PB-300 4/ insulation	unknown/ stored in CERN ~ 30 years	**LDPE**	γ^{137} Cs/ **strap**	-	0	104	**$4.04 \cdot 10^{-2}$**	**159**	**400 h**	**5.2**	isothermal, 190 °C, air
				0.4	9.6	76					
				0.4	28.8	33					
				0.4	96	0					
			γ^{60} Co/ **bulk-air**	-	0	104	**$3.6 \cdot 10^{-3}$**	**1787**	**1200 h**	**6.3**	isothermal, 190 °C, air
				1.5	310	37					
				1.5	630	12					
			γ^{60} Co/ **bulk-enc**.	-	0	104	**$4.05 \cdot 10^{-3}$**	**1589**	**1050 h**	**6.2**	isothermal, 190 °C, air
				1.5	310	19					
				1.5	630	11					
PB-300/ 5/ insulation	unknown/ stored in CERN ~ 30 years	**LDPE**	PS Septum SEH 23R/ **bulk**	-	0	104	**$2.60 \cdot 10^{-2}$**	**247**	unknown irradiation time	**5.4**	isothermal, 190 °C, air/ *excessively small dose (!), as it was communicated*
				n.a.	0.748	102					
PB-300/ 6/ insulation	unknown/ stored in CERN ~ 30 years	**LDPE**	PS Septum SEH 23T/ **bulk**	-	0	104	**$3.96 \cdot 10^{-1}$**	**16**	unknown irradiation time	**4.2**	isothermal, 190 °C, air/ *excessively small dose (!),*
				n.a.	0.726	78					

Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
											as it was communicated
PB-300/ 7/ insulation	unknown/ stored in CERN ~ 30 years	**LDPE**	PS Septum SEH 31 R/ **bulk**	-	0	104	**$8.71 \cdot 10^{-2}$**	**74**	unknown irradiation time	**4.9**	isothermal, 190 °C, air/ *excessively small dose (!), as it was communicate*
				n.a.	0.800	97					
PB-300/ 8/ insulation	unknown/ stored in CERN ~ 30 years	**LDPE**	PS Septum SEH 31T/ **bulk**	-	0	104	unknown dose and irradiation time				isothermal, 190 °C, air
				n.a.	n.a.	93					
PB-300/ 4/ jacket	unknown/ stored in CERN ~ 30 years	**LDPE**	γ^{137}Cs/ **strap**	-	0	229	**$2.69 \cdot 10^{-2}$**	**269**	**670 h**	**5.4**	isothermal, 190 °C, air
				0.4	9.6	216					
				0.4	28.8	105					
				0.4	96	17					
		LDPE	γ^{60}Co/ **bulk-air**, inner part	-	0	229	**$7.74 \cdot 10^{-2}$**	**933**	**620 h**	**6.0**	isothermal, 190 °C, air
				1.5	310	10					
				1.5	630	3.3					
NG-18/ 9/ insulation (white)	Draka Comteq DE/ 2006w19	**LDPE**	γ^{137}Cs/ **bulk-air**	-	0	148	**$1.27 \cdot 10^{-1}$**	**53**	**130 h**	**4.7**	isothermal, 190 °C, air
				0.4	9.6	40					
				0.4	28.8	4					
				0.4	96	0					
			γ^{137}Cs/ **bulk-enc.**	-	0	148	**$7.63 \cdot 10^{-2}$**	**89**	**220 h**	**4.9**	isothermal, 190 °C, air
				0.4	9.6	46					
				0.4	28.8	19					
				0.4	96	11					
			γ^{60}Co/ **bulk-air**	-	0	148	**-**	**<310**	**<200 h**	-	isothermal, 190 °C, air
				1.5	310	0					
				1.5	630	0					
			γ^{60}Co/ **bulk-**	-	0	148	**-**	**<310**	**<200 h**	-	isothermal, 190 °C, air
				1.5	310	0					

Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
			enc.	1.5	630	0					

Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
NG-18/ 9/ insulation (brown)	Draka Comteq DE/ 2006w19	**LDPE**	γ^{137}Cs/ **bulk-air**	-	0	157	**$1.53 \cdot 10^{-1}$**	**45**	**110 h**	**4.7**	isothermal, 190 °C, air
				0.4	9.6	31					
				0.4	28.8	2.2					
				0.4	96	0					
			γ^{137}Cs/ **bulk-enc.**	-	0	157	**$8.46 \cdot 10^{-2}$**	**81**	**200 h**	**4.9**	isothermal, 190 °C, air
				0.4	9.6	31					
				0.4	28.8	9					
				0.4	96	4.5					
			γ^{60}Co/ **bulk-air**	-	0	157	**-**	**<300**	**<750 h**	**-**	isothermal, 190 °C, air
				1.5	310	0					
				1.5	630	0					
			γ^{60}Co/ **bulk-enc.**	-	0	157	**-**	**<300**	**<750 h**	**-**	isothermal, 190 °C, air
				1.5	310	0					
				1.5	630	0					
CLP-50/ 16/ insulation	Draka Comteq DE/ 2003	**LDPE**	γ^{137}Cs/ **strap**	-	0	124	**$7.35 \cdot 10^{-2}$**	**90**	**225 h**	**5.0**	isothermal, 190 °C, air/ heterogeneous material*
				0.4	9.6	33					
				0.4	28.8	16					
				0.4	96	0					
			γ^{137}Cs/ **bulk-air**; S3	-	0	124	**$1.109 \cdot 10^{-1}$**	**60**	**150 h**	**4.8**	isothermal, 190 °C, air/ heterogeneous material*
				0.4	9.6	11.6					
				0.4	28.8	5.9					
				0.4	96	0					
			γ^{137}Cs/ **bulk-air**, S2	-	0	124	**$1.785 \cdot 10^{-2}$**	**370**	**925 h**	**5.6**	isothermal, 190 °C, air/
				0.4	9.6	68					

Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
				0.4	28.8	57					heterogeneous material*
				0.4	96	0					
			γ^{137}Cs/ **bulk-air,** S1	-	0	124	**$3.296 \cdot 10^{-2}$**	**201**	**500 h**	**5.3**	isothermal, 190 °C, air/ heterogeneous material*
				0.4	9.6	84					
				0.4	28.8	12					
				0.4	96	8					

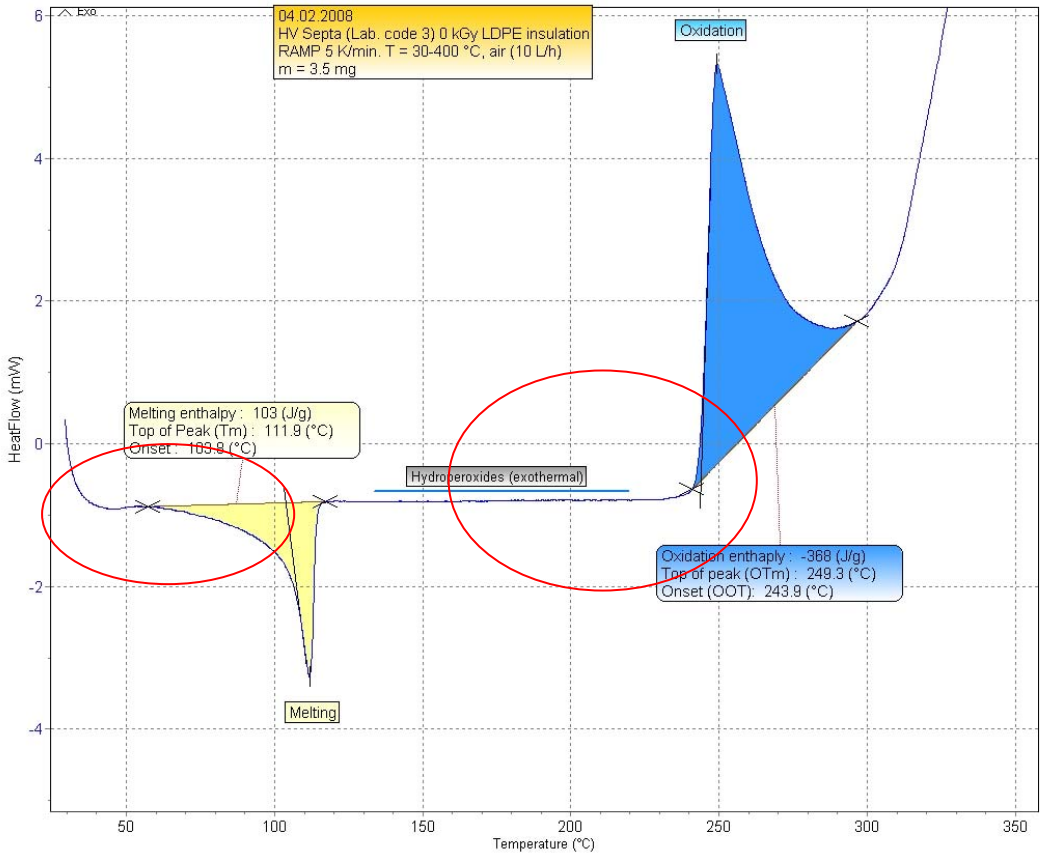
Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
CLP-50/ 16/ insulation	Draka Comteq DE/ 2003	**LDPE**	γ^{137} Cs/ **bulk-enc.**, S3	-	0	124	**$5.754 \cdot 10^{-2}$**	**115**	**300 h**	**5.1**	isothermal, 190 °C, air/ heterogeneous material*
				0.4	9.6	26					
				0.4	28.8	35					
				0.4	96	0					
			γ^{137} Cs/ **bulk-enc.**, S2	-	0	124	**$1.895 \cdot 10^{-2}$**	**377**	**950 h**	**5.6**	isothermal, 190 °C, air/ heterogeneous material*
				0.4	9.6	176					
				0.4	28.8	52					
				0.4	96	34					
SPA-6/ 17/ insulation of blue-jacketed coaxial	Draka Comteq DE/ 2004 w23	**LDPE**	γ^{137} Cs/ **bulk-air**	-	0	96	**$3.319 \cdot 10^{-2}$**	**191**	**480 h**	**5.3**	isothermal, 190 °C, air/ heterogeneous material
				0.4	9.6	(10)					
				0.4	28.8	21					
				0.4	96	4.7					
SPA-6/ 17/ insulation of red-jacketed coaxial	Draka Comteq DE/ 2004 w23	**LDPE**	γ^{137} Cs/ **bulk-air**	-	0	68	**$2.282 \cdot 10^{-2}$**	**263**	**650 h**	**5.4**	isothermal, 190 °C, air/ heterogeneous material
				0.4	9.6	25					
				0.4	28.8	10.6					
				0.4	96	9.9					
			γ^{137} Cs/ **bulk-enc.**	-	0	68	**$2.226 \cdot 10^{-2}$**	**275**	**675 h**	**5.4**	isothermal, 190 °C, air/ heterogeneous material
				0.4	9.6	42					
				0.4	28.8	24					
				0.4	96	12					
			γ^{60} Co/ **bulk-enc.**	-	0	68	**$6.39 \cdot 10^{-3}$**	**940**	**630 h**	**6.0**	isothermal, 190 °C, air/ heterogeneous material
				1.5	310	(0)					
				1.5	630	10.6					
CC-50/ 23/ insulation	Draka Comteq DE/ 2006 w49	**LDPE**	γ^{60} Co/ **bulk-air**	-	0	51	**n.a.**	**<300**	**n.a.**	**n.a.**	isothermal, 190 °C, air
				1.5	310	0					
				1.5	630	0					
			γ^{60} Co/ **bulk-enc.**	-	0	51	**$3.259 \cdot 10^{-3}$**	**1756**	**1200 h**	**6.2**	isothermal, 190 °C, air
				1.5	310	7.4					
				1.5	630	10					

Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
PH-5SJ/ 35/ insulation (blue)	Nexans CH/ 2004 w37	**LDPE**	γ^{60} Co/ **bulk-enc.**	-	0	713	**$1.183 \cdot 10^{-2}$**	**707**	**480 h**	**5.8**	isothermal, 190 °C, air
				1.5	310	8.4					
				1.5	630	0					
				1.5	630	0.6					
PH-5SJ/ 35/ insulation (black)	Nexans CH/ 2004 w37	**LDPE**	γ^{60} Co/ **bulk-enc.**	-	0	584	**$8.472 \cdot 10^{-3}$**	**963**	**650 h**	**6.1**	isothermal, 190 °C, air
				1.5	310	5.9					
				1.5	630	7.4					

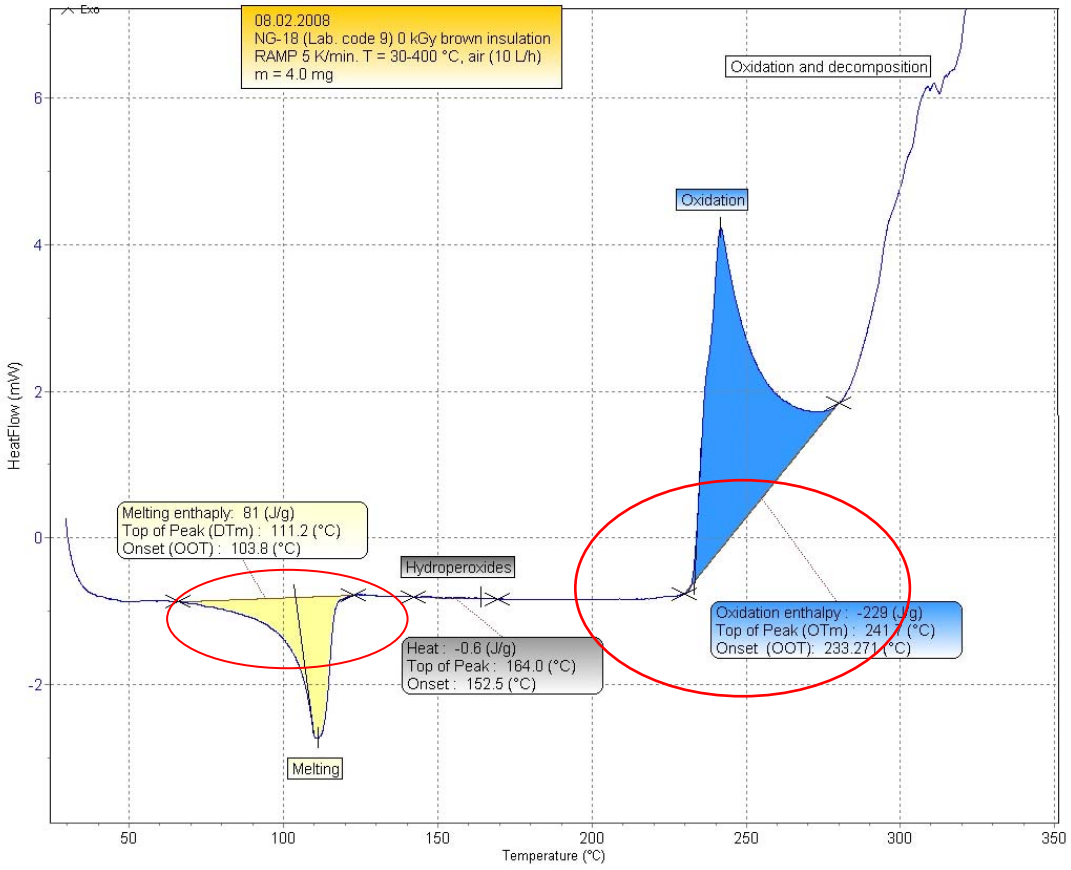
* antioxidant lost during the storage of both un-irradiated (r.t., no light) and irradiated material (refrigerator, ~ 4 °C) or inhomogeneous antioxidant distribution

3.2 Non-isothermal DSC curves

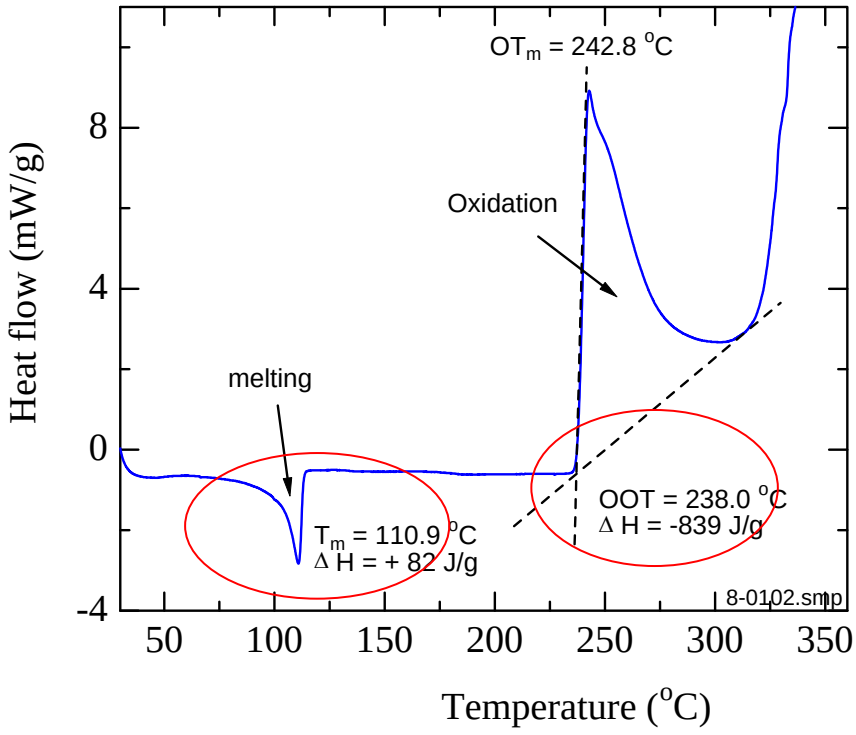
(β = 5 K/min., air)



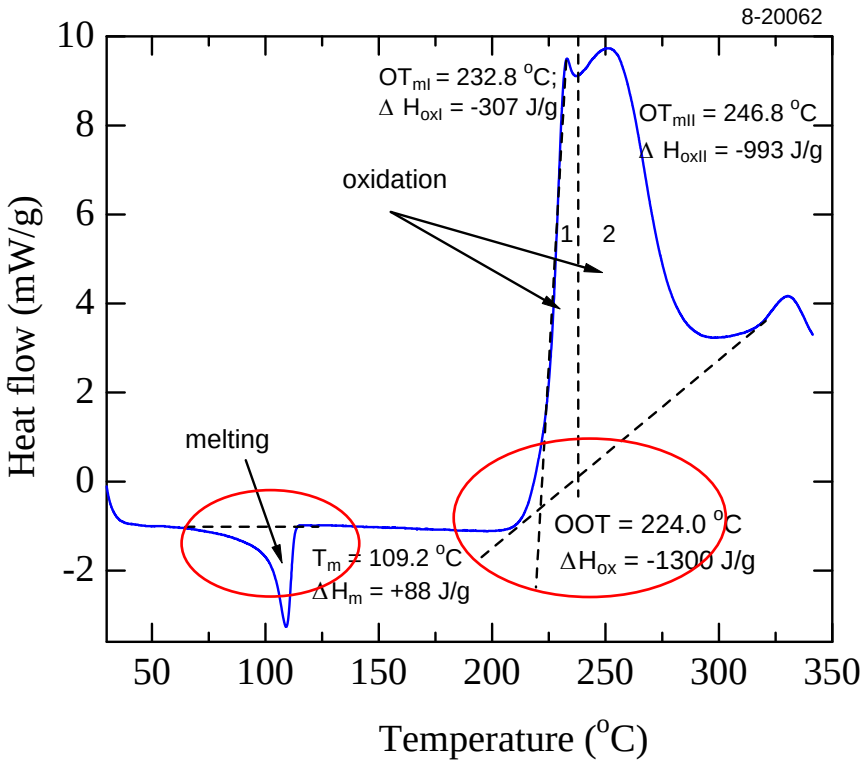
3.2.1 *- DSC non-isothermal curve of HV Septa (Lab. code 3) insulation;* ***LDPE*** *(LE6006)*



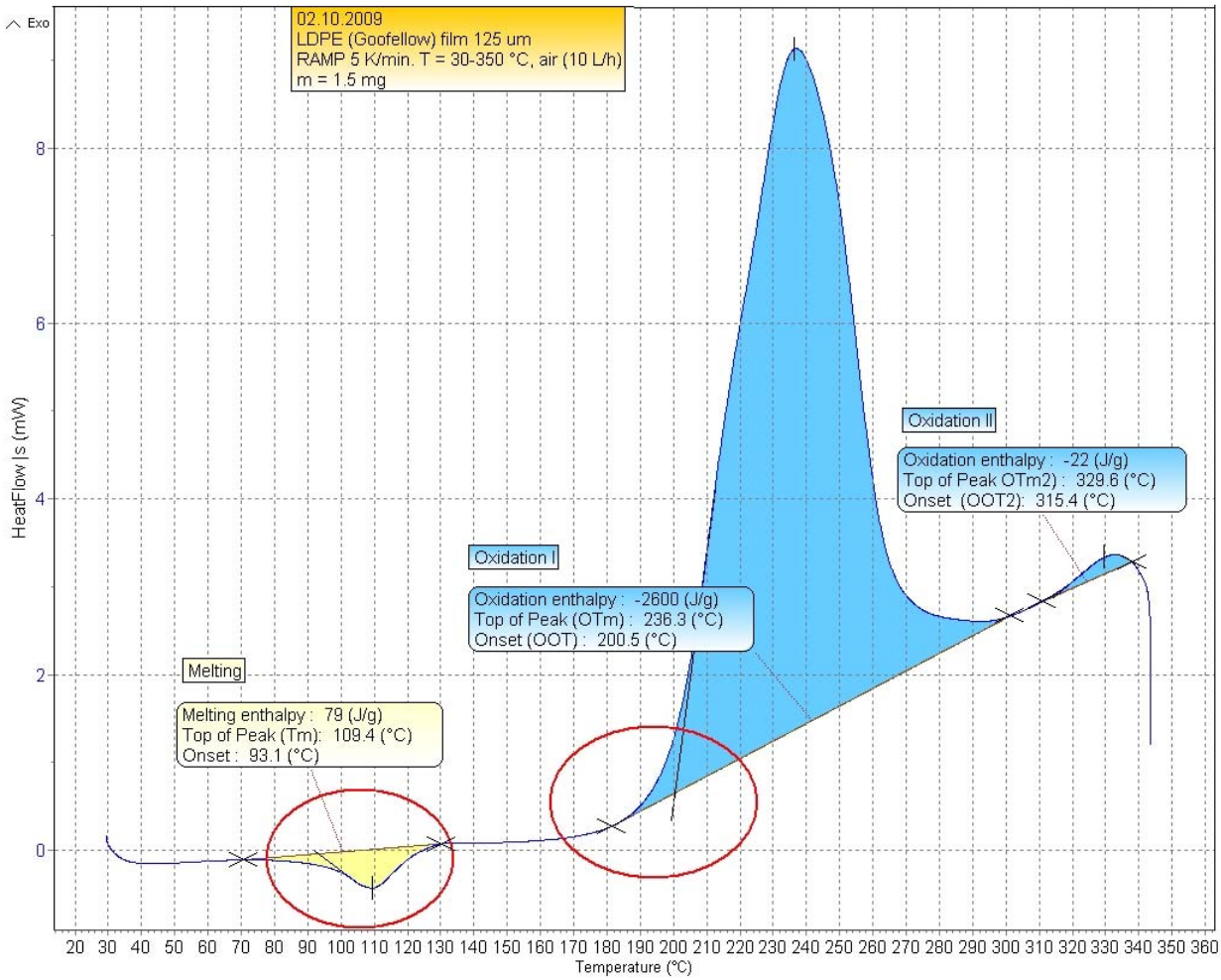
3.2.2 *- DSC non-isothermal curve of NG-18 (Lab. code 9) brown insulation;* ***LDPE*** *(LE6006 + masterbatch)*



3.2.3 *- DSC non-isothermal curve of Silec (Lab. code 1) insulation; crosslinked PE (****XPE****)*

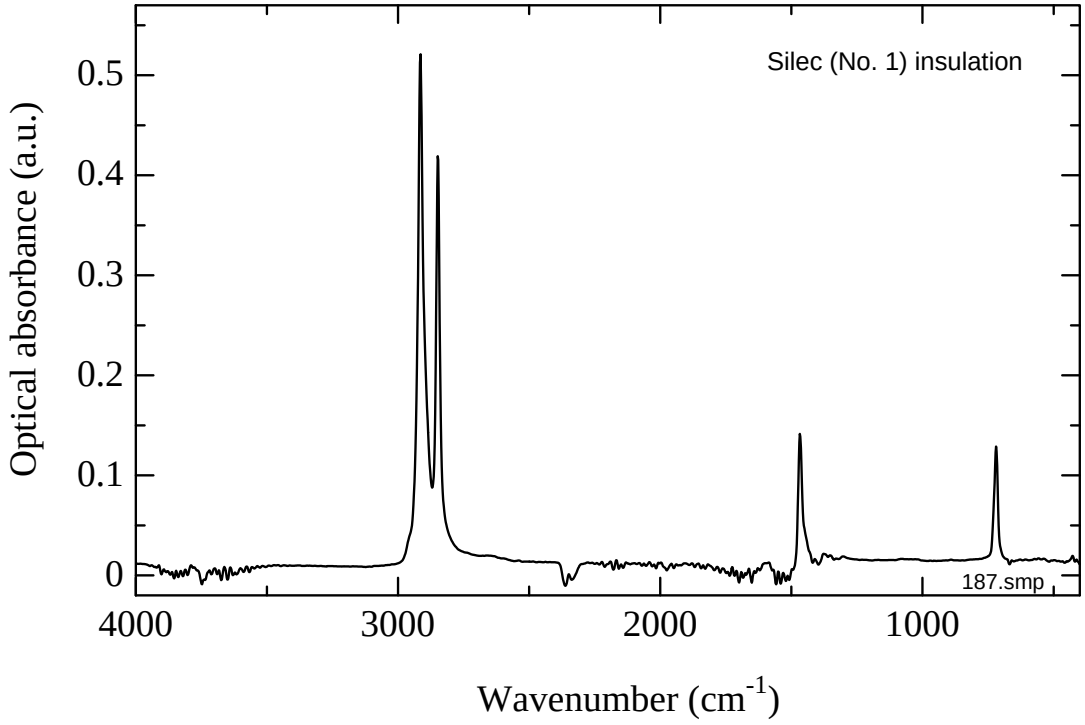


3.2.4 *- DSC non-isothermal curve of CBH-50 (Lab. code 23) insulation; crosslinked PE (**XPE**)*

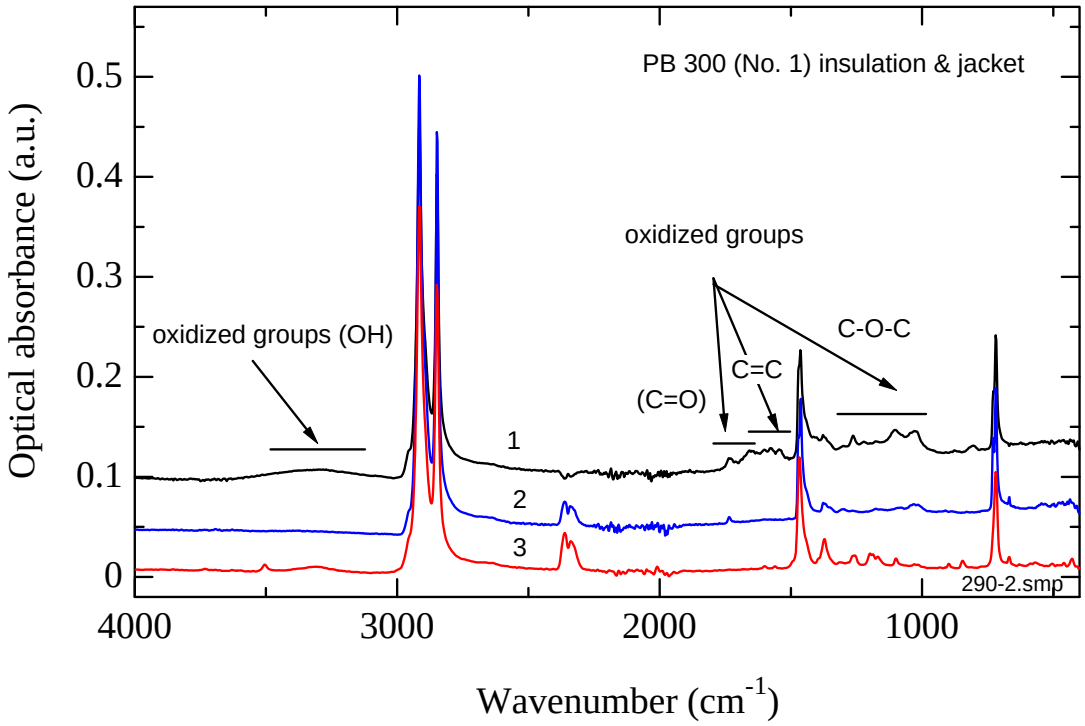


3.2.5 *- DSC non-isothermal curve of pure (unstabilised) LDPE Goodfellow film 125 um (Lab. code 87)*

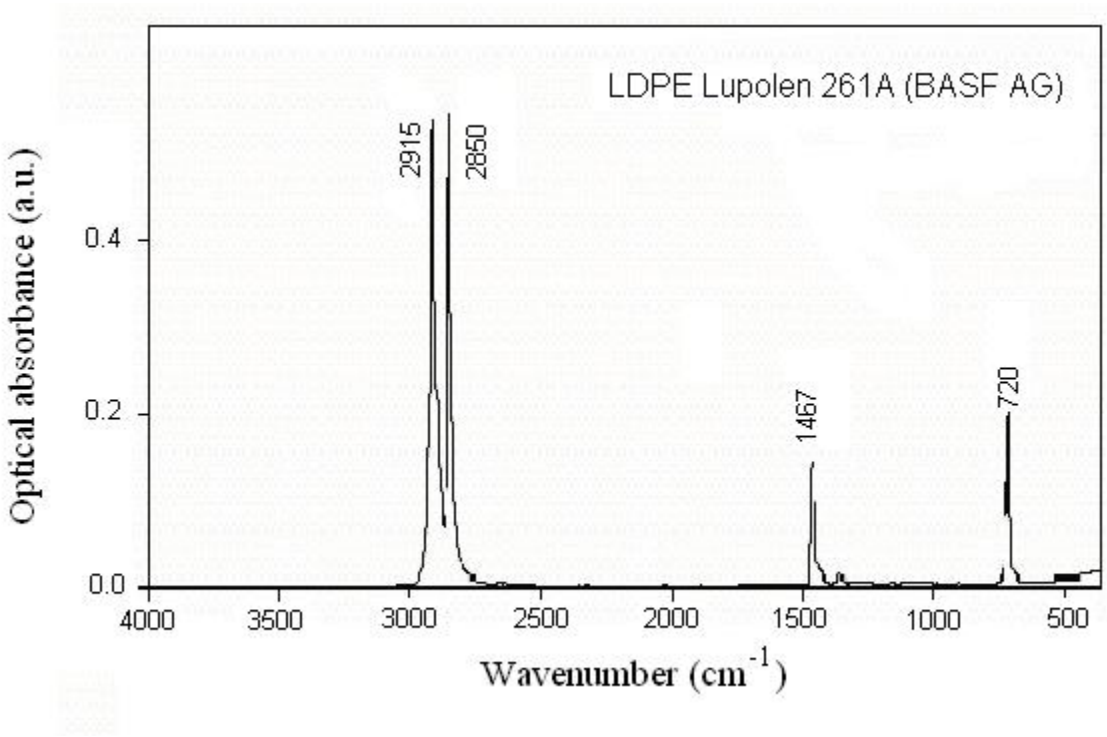
3.3 ATR-FTIR spectra



3.3.1 *- ATR-FTIR spectra of cable Silec (Lab. code 1) LDPE insulation*



3.3.2*- ATR-FTIR spectra of LDPE materials in PB 300 cable (Lab. code:4): 1 - jacket (outer part), oxidation traces (storage effect); 2 - jacket (inner part); 3 - insulation*



3.3.3 *- ATR-FTIR spectrum of LDPE (Lupolen 261A, BASF AG) [2]*

4. HDPE (High density polyethylene)

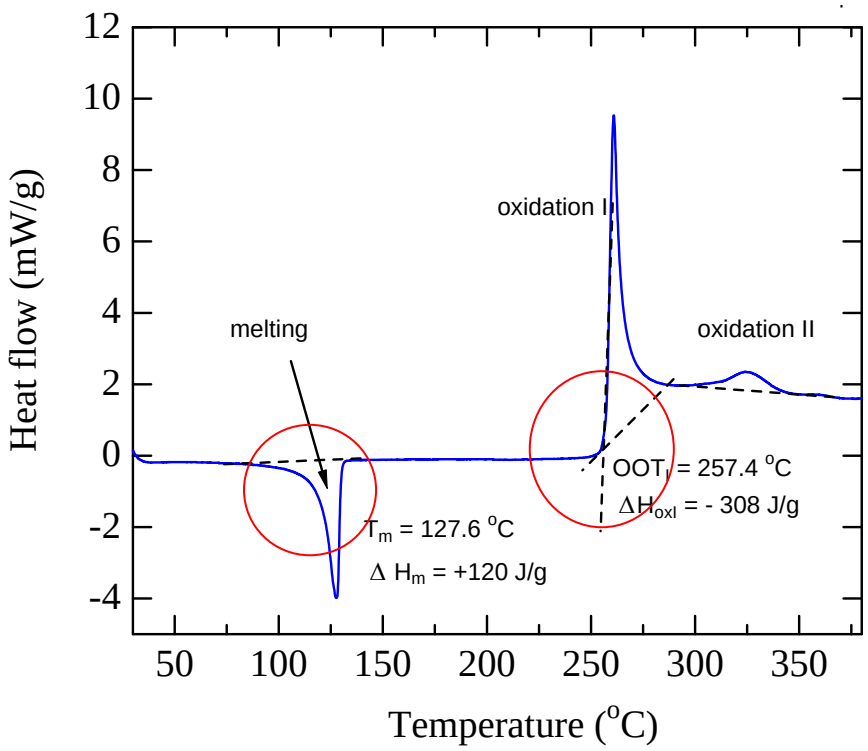
4.1 Compilation of the DSC life-time evaluation data

Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ Sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
SPA-6/ 17/ twisted pairs insulation (blue)	Draka Comteq/ 2004 w23	**HDPE**	γ^{137}Cs/ **bulk-air**	-	0	757	**$3.152 \cdot 10^{-2}$**	**267**	**668 h**	**5.4**	isothermal, 200 °C, air
				0.4	9.6	464					
				0.4	28.8	225					
				0.4	96	41					
			γ^{137}Cs/ **bulk-enc.**	-	0	757	**$1.789 \cdot 10^{-2}$**	**471**	**1178 h**	**5.7**	isothermal, 200 °C, air
				0.4	9.6	459					
				0.4	28.8	347					
				0.4	96	152					
			γ^{60}Co/ **bulk-air**	-	0	757	**$1.856 \cdot 10^{-2}$**	**454**	**303 h**	**5.7**	isothermal, 200 °C, air
				1.5	310	2.4					
				1.5	630	0*					
			γ^{60}Co/ **bulk-enc.**	-	0	757	**$4.973 \cdot 10^{-3}$**	**1693**	**1129 h**	**6.2**	isothermal, 200 °C, air
				1.5	310	0* 1.9					
				1.5	630	33					
SPA-6/ 17/ twisted pairs insulation (black)	Draka Comteq/ 2004 w23	**HDPE**	γ^{137}Cs/ **bulk-air**	-	0	516	**$2.826 \cdot 10^{-2}$**	**284**	**710 h**	**5.5**	isothermal, 200 °C, air
				0.4	9.6	344					
				0.4	28.8	232					
				0.4	96	34					
			γ^{137}Cs/ **bulk-enc**.	-	0	516	**$1.405 \cdot 10^{-2}$**	**572**	**1430 h**	**5.8**	isothermal, 200 °C, air
				0.4	9.6	366					
				0.4	28.8	256					
				0.4	96	145					

*brittle material

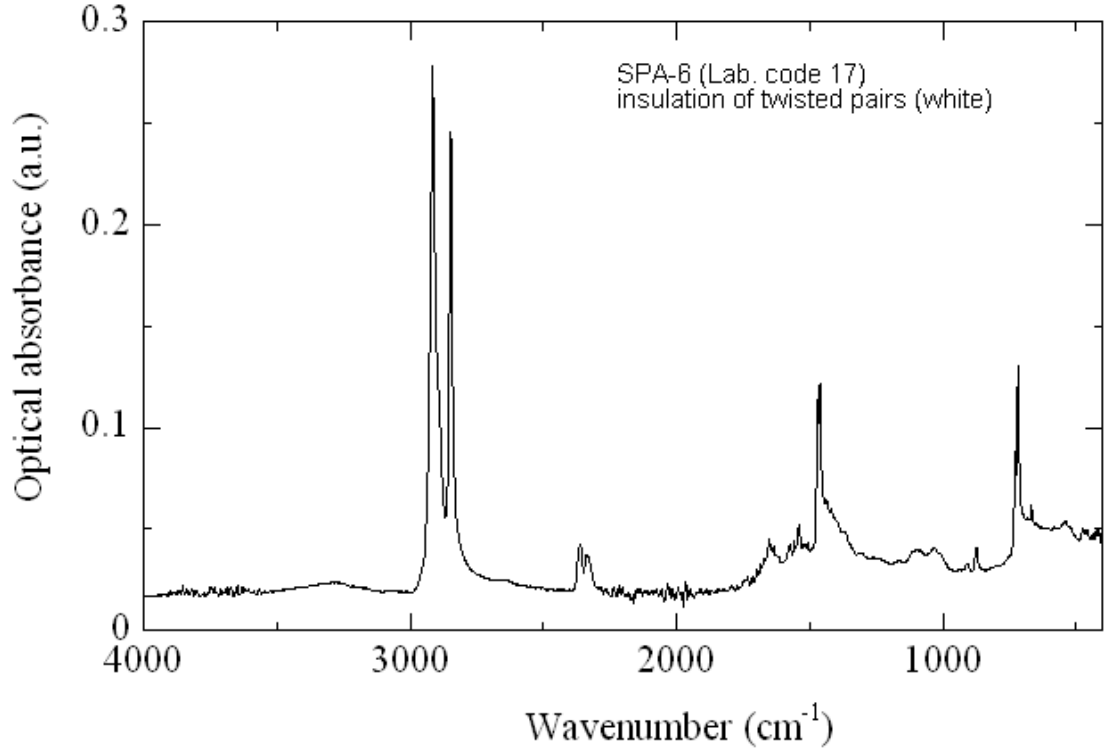
4.2 Non-isothermal DSC curves

(β = 5 K/min., air)

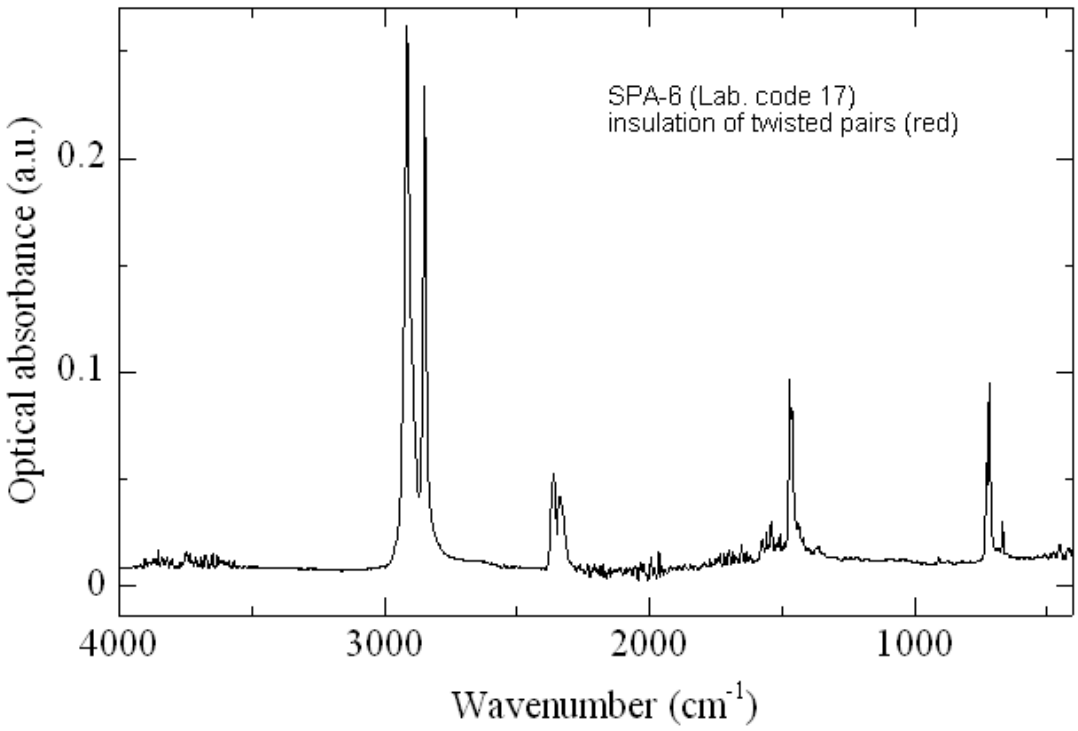


4.2.1 *- DSC non-isothermal curve of SPA-6 (Lab. code 17) HDPE insulation of twisted pairs*

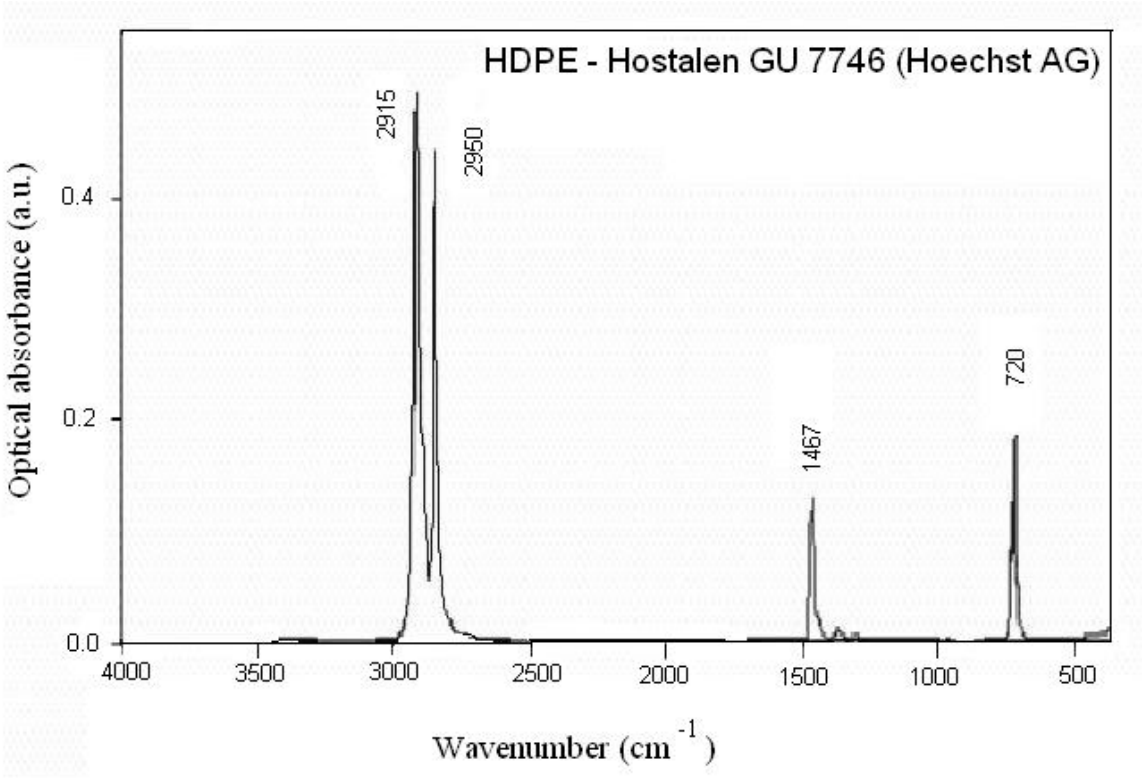
4.3 ATR-FTIR spectra



***4.3.1** - ATR-FTIR spectra of cable SPA-6 (Lab. code 17) HDPE insulation of white twisted pairs*



***4.3.2** - ATR-FTIR spectra of cable SPA-6 (Lab. code 17) HDPE insulation of red twisted pairs*



4.3.3 *- ATR-FTIR spectrum of HDPE (Hostalen GU 7746, Hoechst AG) [2]*

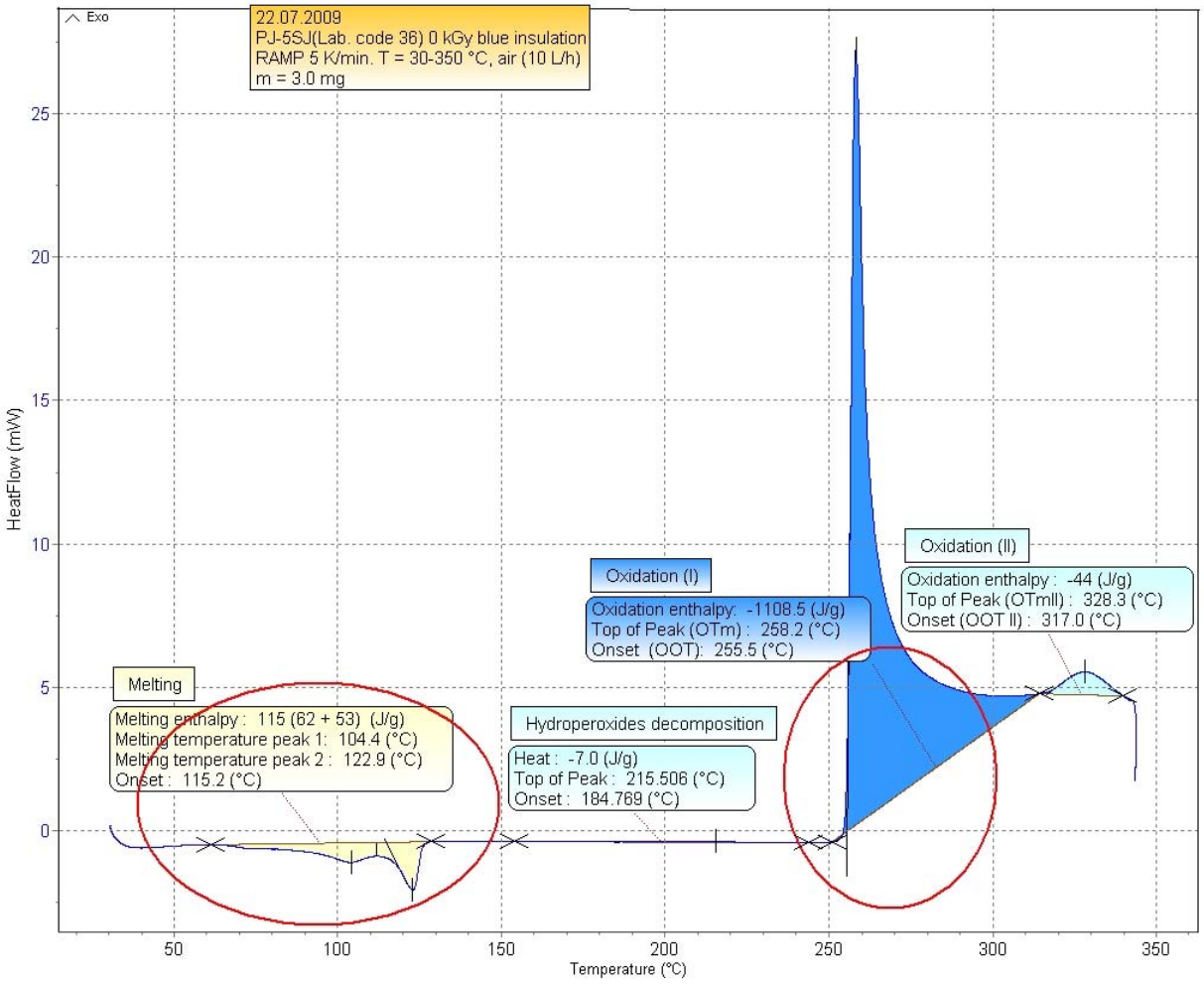
5. Bimodal polyethylene

5.1 Compilation of the DSC life-time evaluation data

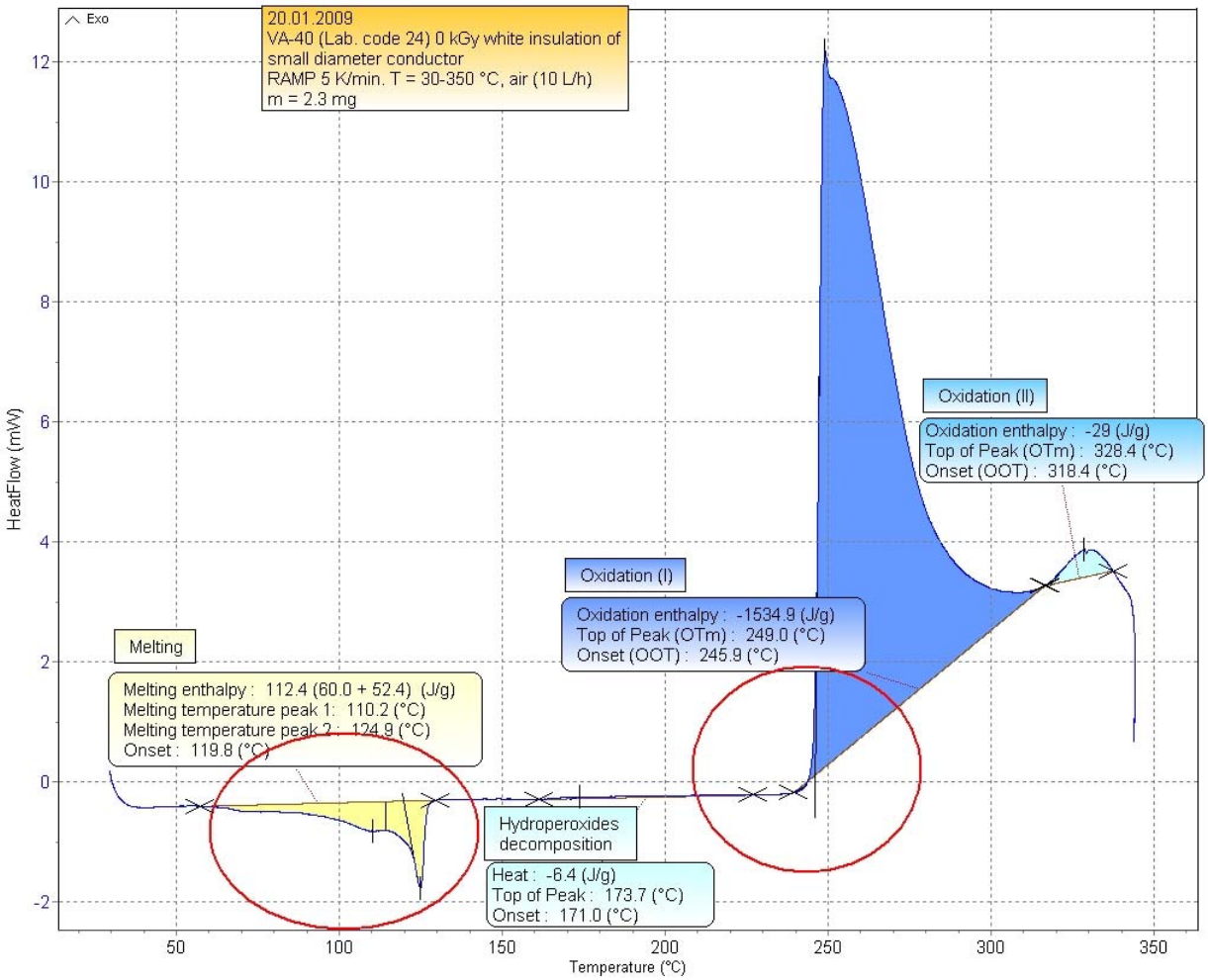
Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
PJ-5SJ/ 36/ insulation (blue)	Technikabel IT/ 2005 w39	**bimodal PE**	γ^{60}Co/ **bulk-air**	-	0	870	**$1.698 \cdot 10^{-2}$**	**504**	**340**	**5.7**	isothermal, 190 °C, air
				1.5	310	4.5					
				1.5	630	0					
			γ^{60}Co/ **bulk-enc.**	-	0	870	**$1.744 \cdot 10^{-2}$**	**491**	**330**	**5.7**	isothermal, 190 °C, air
				1.5	310	3.9					
				1.5	630	0					
PJ-5SJ/ 36/ insulation (black)	Technikabel IT/ 2005 w39	**bimodal PE**	γ^{60}Co/ **bulk-air**	-	0	634	**$1.348 \cdot 10^{-2}$**	**611**	**400**	**5.8**	isothermal, 190 °C, air
				1.5	310	3					
				1.5	630	0.23					
			γ^{60}Co/ **bulk-enc.**	-	0	634	**$1.266 \cdot 10^{-2}$**	**651**	**430**	**5.8**	isothermal, 190 °C, air
				1.5	310	5.6					
				1.5	630	0.32					

5.2 Non-isothermal DSC curves

(β = 5 K/min., air)

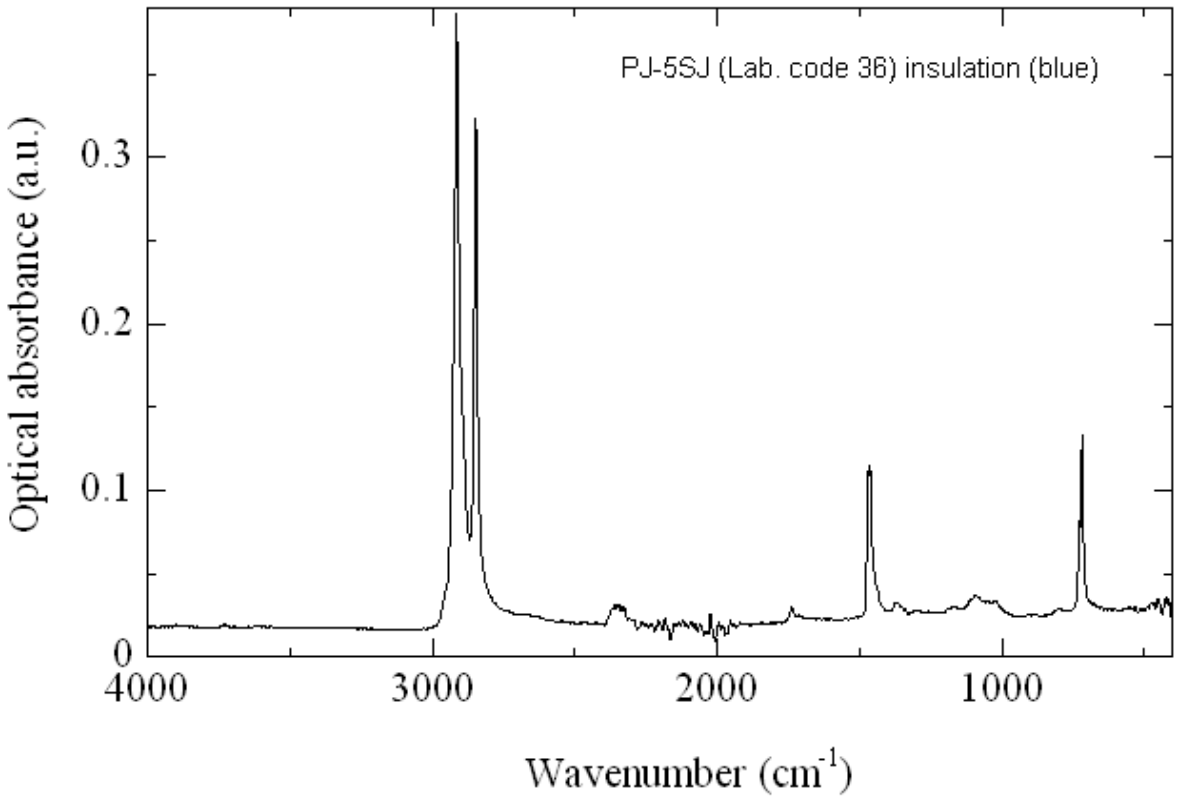


5.2.1 *- DSC non-isothermal curve of bimodal blue insulation in PJ-5SJ cable (Lab. code 36)*

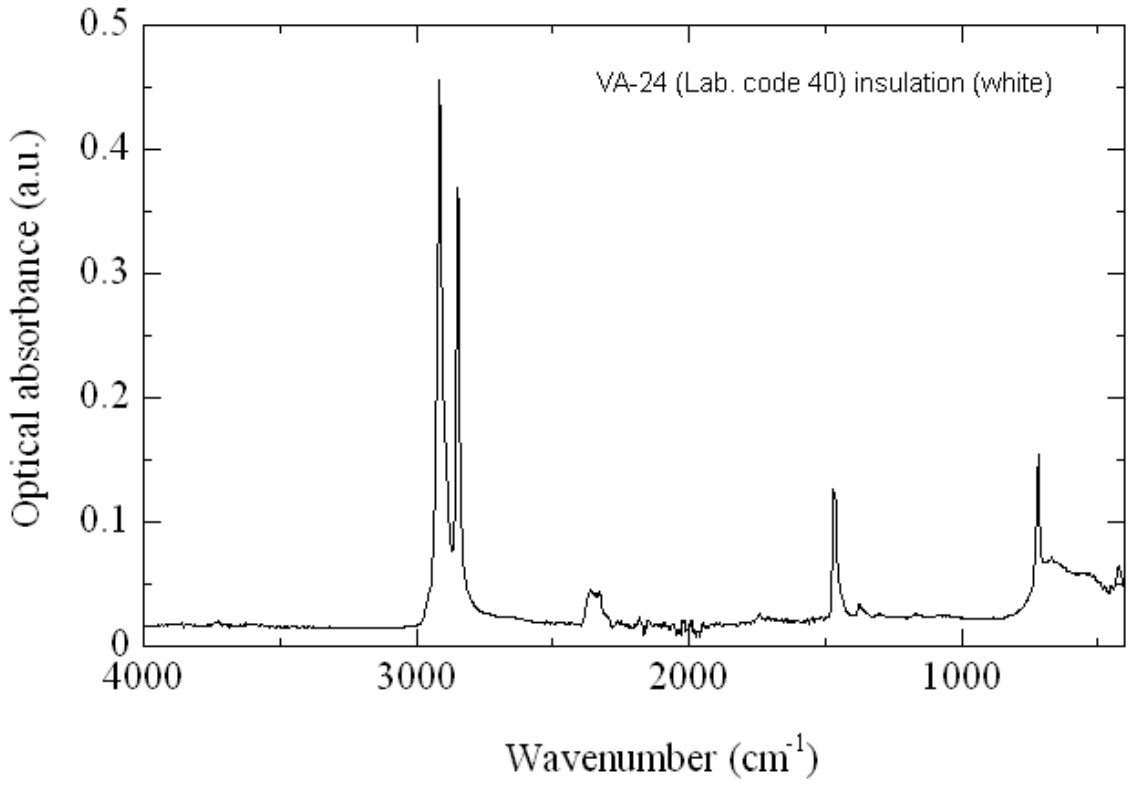


5.2.2 *- DSC non-isothermal curve of bimodal white insulation in VA-24 cable (Lab. code 40)*

5.3 ATR-FTIR spectra



5.3.1 *- ATR-FTIR spectrum of bimodal PE insulation (blue) in PJ-5SJ cable (Lab. code 36)*



5.3.2 *- ATR-FTIR spectrum of bimodal PE insulation (white) in VA-24 cable (Lab. code 40)*

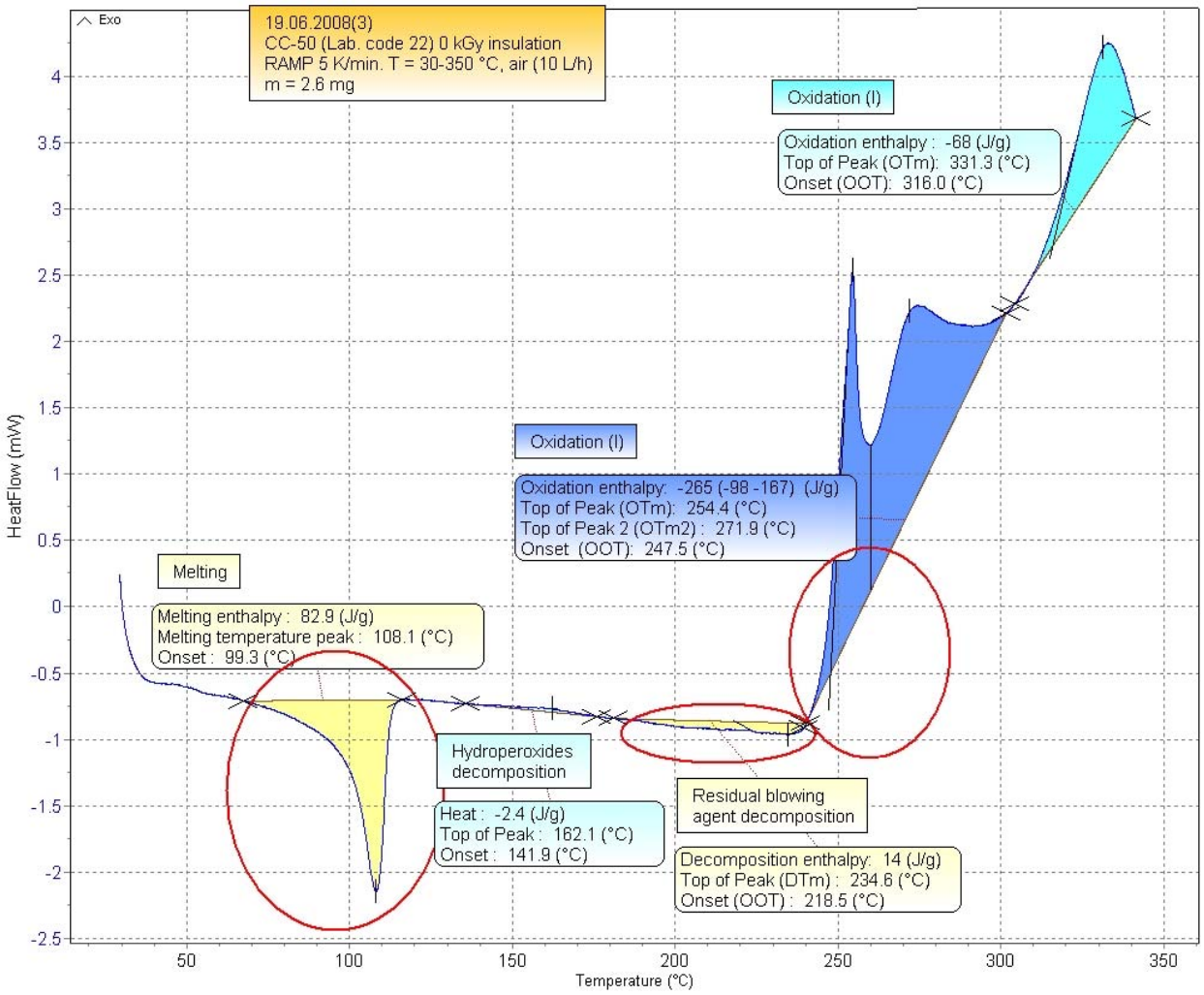
6. PE foam (PE cell)

6.1 Compilation of the DSC life-time evaluation data

Cable data			Irradiation conditions			Laboratory measurements and results					
Type/ Lab. code/ Function	Supplier/ production date	Material	Radiation/ sample form	Dose rate kGy/h	Dose (kGy)	OIT (min.)	k' (kGy^{-1})	Maximum supportable dose, D_x(kGy)	Life-time (rounded)	RI	DSC parameters/ remarks
CC-50/ 22/ Insulation	Draka Comteq DE/ 2002	**PE foam**	γ^{60} Co/ **bulk-air**	-	0	336	**$7.072 \cdot 10^{-3}$**	**1076**	**700 h**	**6.0**	isothermal, 200 °C, air
				1.5	310	6.1					
				1.5	630	9.5					
			γ^{60} Co/ **bulk-enc.**	-	0	336	**$5.996 \cdot 10^{-3}$**	**1269**	**850 h**	**6.1**	isothermal, 200 °C, air
				1.5	310	18					
				1.5	630	13					
			γ^{60} Co/ **bulk-air**	-	0	335	**$6.606 \cdot 10^{-3}$**	**1151**	**770 h**	**6.1**	OIT at 200 °C as calculated from non-isothermal measurements
				1.5	310	9.5					
				1.5	630	11					
			γ^{60} Co/ **bulk-enc.**	-	0	335	**$6.320 \cdot 10^{-3}$**	**1203**	**800 h**	**6.1**	OIT at 200 °C as calculated from non-isothermal measurements
				1.5	310	22					
				1.5	630	9.1					

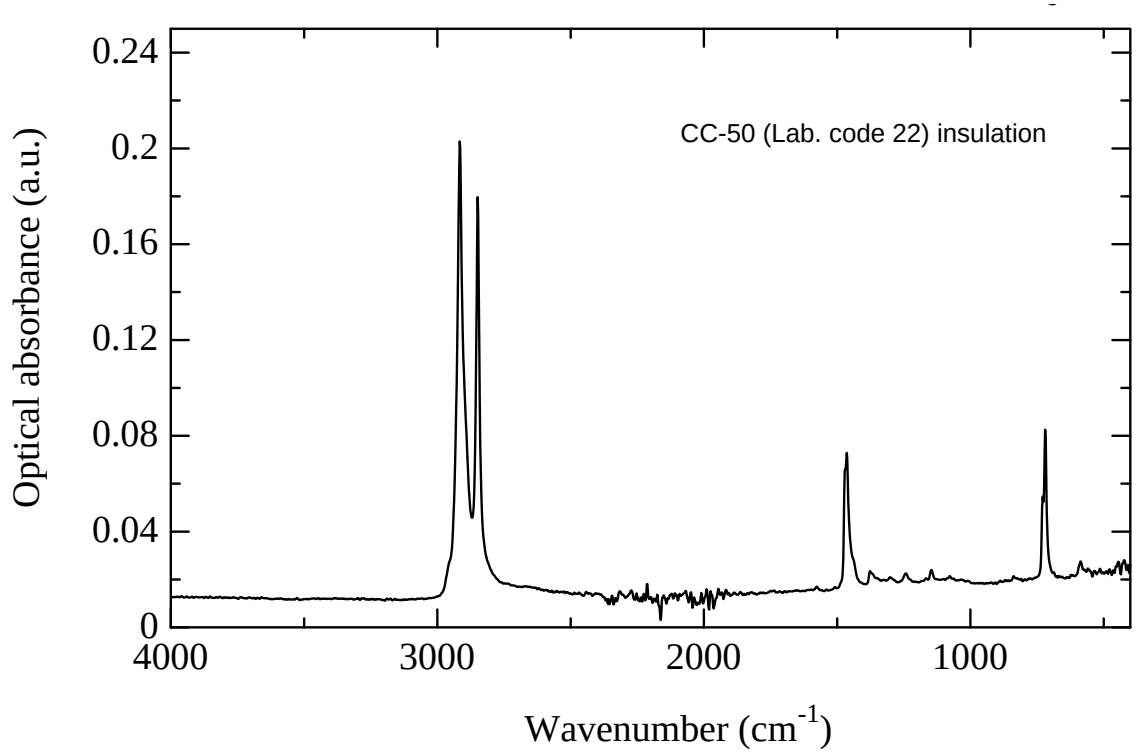
6.2 Non-isothermal DSC curves

(β = 5 K/min., air)



6.2.1 *- DSC non-isothermal curve of PE foam insulation in CC-50 cable (Lab. code 22)*

6.3 ATR-FTIR spectra



6.3.1 *- ATR-FTIR spectrum of PE foam insulation in CC-50 cable (Lab. code 22)*

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