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Thermal Properties of Automotive Polymers III-Thermal Characteristics And Flammability of Fire Retardant Polymers

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ABSTRACT

Thermal properties and flammability behavior of two grades of fire retardant polypropylene and nylon 66, and their base resins were determined using thermal gravimetric analysis, differential scanning calorimetry, and a new burn test. Similar analyses were also conducted for a nylon 6 base polymer and a nano-composite based on that polymer. Thermal gravimetric analysis showed more complex degradation patterns for the fire retardant grades as compared to the base resin. Weight loss in some cases was observed at lower temperature for the fire retardant grades. This was attributed to decomposition of ingredients present in the fire retardant. Degradation of polypropylene in air started at about a 100°C lower temperature than degradation in nitrogen. For nylon the degradation in both atmospheres occurred at approximately the same temperature. The differences in the behavior of the polymers are explained in terms of molecular structure.

Modulated Differential Scanning Calorimetry (MDSC) measurements were used to determine melting and glass transition temperatures, heats of fusion, heat capacity and thermal conductivity. Determination of these characteristics is important for quantifying flammability properties.

Both phosphorus-based and halogen-based fire retardants were modified the ignition, propagation, and melt dripping behavior of both nylon and polypropylene during burning. Because the base polypropylene resin is more flammable than nylon, the effects of fire retardants were more noticeable for polypropylene.

Performance, durability, and fire resistance of these materials will have to be evaluated in actual vehicle applications and fires before use for a broad scale basis. Incorporation of a nano-filler was found to be ineffective in imparting fire retardancy to nylon 6.

INTRODUCTION

This work was funded by General Motors pursuant to an agreement between GM and the US Department of Transportation. One of the objectives of the project is to identify or devise potentially cost effective, less flammable substitutes, for selected materials, which would not compromise other important physical properties of the materials. In this report we describe the results of a study to characterize the flammability properties of commercially available fire retardant polymers.

Polypropylenes and polyamides (nylons) are the two most widely used polymers for automotive exteriors and underhood applications [1]. The polymers are also used for parts of the heating/ventilation/and air conditioning (HVAC) system. For underhood fires, a potential fire pathway from the engine compartment to the passenger compartment is through the HVAC module. For these reasons we identified polypropylene and nylon as two polymer systems for which less flammable substitutes will be sought. The substitutes are intended not to compromise performance, durability or other important physical properties and manufacturability.

EXPERIMENTAL

Materials:

The different grades of polypropylene and nylon used in the study are shown in Table 1 along with some of their mechanical and thermal properties. The polymers were obtained from three suppliers. The properties shown in Table 1 for polypropylene and nylon 66 for base and fire retardant grades were obtained from the suppliers, while the properties for nylon 6 reference material and nano-composite were determined at GM R&D. Base polypropylene grades Pro-fax SB-786 and 8523 were obtained from Montell, while the fire retardant grades based on these base polymers, RTP 151 and RTP156, were obtained from the RTP Company (a supplier company of fully formulated plastic materials). RTP 151 contains phosphorus compounds as fire retardant additives, while the fire retardancy in RTP 156 is based on bromine antimony chemistry.

Two grades of nylon 66 were also obtained from RTP. Compound 200H contains a halogenated fire retardant additive, while compound 299 is the base polymer without fire retardant. A non-halogenated fire retardant grade of nylon 66 (Ultramid A3X2G5) was obtained from BASF, along with its base polymer (Ultramid A3K).

The flammability characteristics of two grades of nylon 6 were investigated. One of the grades is a base resin and the other is a nano-composite based on this standard resin. Nano-composites have been found to exhibit fire retardancy characteristics [2]. The nano-composite and its base polymer were obtained through the National Institute of Standards and Technology (NIST).

Modulated Differential Scanning Calorimetry (MDSC) Measurements:

Measurements were made using the MDSC 2920 module (TA Instruments) per methods described in earlier reports [3,4,5]. The instrument was calibrated prior to sample measurements using indium as a standard. Typically, a polymer sample in pellet form weighing approximately 10 mg was placed in an aluminum pan and hermetically sealed. The pan containing the sample was then placed in the MDSC nitrogen-purged cell. The sample was allowed to equilibrate at -60°C for five minutes, before starting programmed heating to 350°C, at 5°C per minute. During the run, modulation of +/- 0.5°C was programmed at time intervals of 40 seconds. MDSC measurements were used to determine the melting temperature (T_m), the glass transition temperature (T_g), Heat of fusion (ΔH_f) and the heat capacity (C_p) of the different grades of polymers investigated.

Thermal Gravimetric Analysis (TGA):

High-resolution TGA measurements were conducted using the TA Instrument 2100 module. These analyses were carried out on 13 to 15 mg samples. The samples were heated from 25 to 1000°C using a linear heating rate of 50°C /min., and a resolution factor of 4. All runs were conducted in nitrogen or air atmospheres at a flow rate of 50-ml/min. Decomposition temperature; weight loss percent and weight loss rate were determined for each decomposition peak. The amount of residue left after heating the sample to 900°C was also determined.

Flammability Test:

Sample plaques of base and fire retarded grades of polypropylene and nylon were prepared by compression molding at 20,000 psi using a heated press (PHI Company). The dimensions of the plaques were 300 mm x 100 mm x 3 mm. Polypropylene samples were molded at 193°C. Nylon 6, and nylon 66 samples were molded at 282°C. The samples were molded from pellets pre-dried in a vacuum oven at 125°C for at least 12 hours.

The flammability characteristics for the above samples were determined using an Atlas Fire Science Products HV Series Test Chamber. A lightweight aluminum sample holder and frame were specially constructed for this test (see Figure 10). The holder position could be adjusted on the frame so that the sample orientation during burning could be vertical, horizontal, or at a 45° angle. The holder and frame sat on a load cell (Tovey Engineering Inc.) to give a real time measurement of the weight of sample consumed by the fire.

A Meeker Type high temperature burner with a grid diameter of 35 mm was used as the flame source. A natural gas supply was metered into the burner at 65 to 70 mm of Hg. The flow was adjusted to give a flame 90 - 115 mm high.

Plaques were dried in a vacuum oven at 100°C for at least two hours, before weighing and mounting in the sample holder. All samples were mounted at a 45° angle for the burning run as shown in Figure 10. Sample weight loss with time data was collected using a 486 PC and Smart® software. During the test, dripping or flaming dripping were noted if they occurred. The total weight of melt dripping is measured at the end of the run. The test is terminated if the sample self-extinguishes or after five minutes of burning, whichever comes first. A water mist was used to extinguish the flame or any residual smoldering. For some of the fire retardant samples as many as eight ignitions were attempted in order to ignite the sample.

From the test, weight loss due to combustion as well as the percentage of melt dripping were calculated. The weight loss data, attributed to combustion, can be used to calculate approximate values for chemical heat flux and heat release rate [4]. Total flame travel and flame spread rates are also measured for samples that sustained fires for more than 30 seconds.

The above flammability test was developed in our laboratory. Comparison with other standard flammability tests is briefly discussed later in this report.

RESULTS & DISCUSSION

Mechanical Properties:

The types, grades, and mechanical properties of all polymer samples tested are shown in Table 1. Mechanical properties measured include: density; tensile strength, elongation and modulus; flexural modulus; heat deflection temperature; and notched Izod impact strength. The properties for all polymers except the nylon 6 were obtained from the suppliers. The properties for the nylon 6 control and nano-composite polymers were determined at our laboratories using ASTM procedures listed in Table 1. Comparing the properties of fire retardant (FR) grades with the base grades containing no fire retardant, one observes that the FR grades have higher tensile and flexural modulii, higher heat deflection temperatures, but lower notched Izod impact strength. All of these effects can be explained by the fact that the fire retardant additives generally contain hard inorganic fillers, and thus will increase the stiffness of the materials, but at the same time act as defect sites in the polymer matrix and decrease the impact strength. The important observation is that the listed physical properties of the nylon and polypropylene grades chosen for the study were not markedly affected by the presence of the fire retardants (Table 1). The only exception is nylon 6, where addition of a small concentration (3%) of nano filler leads to doubling of tensile modulus, little or no change in the impact strength value, and a large decrease in the values of tensile strength and elongation.

Modulated Differential Scanning Calorimetry (MDSC):

Some of the basic thermal properties of polymers were determined. In addition to the determination of the melting point, the glass transition temperature, and the heat of fusion, MDSC allows measurement of specific heat and thermal conductivity. Table 2 contains values of melting points, glass transition temperatures and heats of fusion determined for all polymers included in this study. The heats of fusion values were determined per gram of sample, and not per gram of polymer, since the exact compositions of the fire retardant polymers are not known. Accordingly, the reported heats of fusion values for the fire retardant polymers are all lower than those of the base polymers.

The melting point data show two melting regions for all polypropylene samples indicating that all of them are made of copolymers of ethylene and propylene (Table 2). An example is also shown in Figure 1, for the Profax SB 786 sample. The melting peak at 122°C indicates the presence of polyethylene moiety, while the peaks at 160° and 164°C denote the presence of polypropylene blocks. For Nylon 66 the melting point for all grades falls between 260 to 262°C, and for nylon 6, between 216 and 219°C. Glass transition temperatures for polypropylene are around 0 °C (-8 to 2°C). In addition, fire retardant samples RTP 151 and RTP 156 exhibit another transition at 72 and 74°C, respectively, probably related to the presence of the fire retardant additives. Nylon samples exhibit a glass transition at temperatures between 46 and 64°C. The large variations in the Tg values of the nylon samples indicate that some of them, with the lower Tg values, are plasticized either by absorbed water or by additives contained in the fire retardants. The nano-composite nylon 6 sample exhibits another transition at -1°C that can be attributed to the freezing of the small concentration of water present in the sample. Both nylon 6 and the montmorillonite aluminum silicate nano filler (general formula $Al_2O_3.4SiO_2.H_2O$) are known to be hygroscopic.

The heat capacities of the different samples measured at temperatures ranging from -50 to 300°C are shown in Table 3. The heat capacity values for all polymer grades are comparable. In general the heat capacities of the fire retardant grades are lower than those of the base polymer grades. This is to be expected since a significant portion of the constituents of a fire retardant are inorganic additives, which have lower heat capacity values. Slopes of the heat capacity versus temperature were determined for the different samples in three temperature regions namely, below Tg, above Tg but below melting, and above melting. The data is shown in Table 4. For all samples, the slope of the rate of change in heat capacity with temperature, is much lower for the melt than the solid polymer. The slopes are generally equal or slightly higher above Tg than below Tg, the exceptions being the nylon 66 samples from BASF, Ultramid A3K, and A3X2G5, where the heat capacity curve with temperature shows appreciable flattening in the temperature region above Tg and below melting (see Figure 2).

Thermal conductivity measurements were carried out per procedures described by Abu-Isa in a previous report [5]. The thermal conductivity values for the samples, measured at 30°C, are shown in Table 5, and Figure 3. They are all within the expected range for polymeric samples. Unfilled nylon, being more polar, has slightly higher thermal conductivity values than unfilled polypropylene samples. Fire retardant grades of the polymers also have slightly higher thermal conductivity values than their base polymer counterparts.

Thermal Gravimetric Analysis (TGA):

Thermal gravimetric analysis measurements were conducted, in a nitrogen atmosphere and in air, for all fire retardant and base polymer grades, using a high-resolution module. The results are detailed in Tables 6 and 7. In all cases, degradation takes place over a temperature range. However, degradation in nitrogen takes place in a narrower temperature range than degradation in air. This is demonstrated in Figures 4 & 5 for a standard grade of polypropylene (Profax 8523), for which degradation in nitrogen takes place in a narrow temperature range of 400 to 470°C, whereas in air the range is 290 to 580°C. A similar situation is also observed for nylon 6 as seen in Figures 6 and 7. An explanation for the observed wide range of degradation temperatures is char formation. The char formed during earlier stages of degradation remains stable and does not decompose further until higher temperatures are reached in an air atmosphere. Addition of fire retardants complicates the patterns of degradation as seen in Figures 8 & 9 for phosphorus based fire retarded polypropylene (RTP 151). Degradation starts to occur at 239°C. The lower degradation temperatures can be attributed to the fire retardant additive. A complex degradation pattern is observed when the sample is heated in air. Also, decomposition takes place over a very wide temperature range (230 to 700°C)

The following are general observations concerning the degradation of these polymers. The major peak in the degradation of polypropylene takes place about 100 °C lower in an air atmosphere as compared to a nitrogen atmosphere. In contrast, for nylon samples, the major degradation peak occurs at about the same temperature in both atmospheres. The explanation is that polypropylene has a tertiary hydrogen on the backbone of the polymer, which readily reacts with oxygen to form a hydroperoxide that starts accelerated degradation [6]. Nylon does not have a tertiary hydrogen structure. This explains the similar behavior in the degradation of nylon in nitrogen and air, and the higher temperature of degradation in air for nylon samples compared to polypropylene samples.

Sample Flammability:

Flammability measurements were conducted for molded slabs of the polymers using a procedure similar to the one described in GM 9833P flammability test for engine compartment sound absorbers. The sample holder used and the test setup are shown in Figure 10. The difference between the current test and the GM 9833P is that, in this test, the extent of fire involvement is evaluated by following the actual weight of the sample being consumed by the fire instead of merely relying on flame travel. The current test also differs from the FMVSS 302 as follows:

1. The sample was oriented at a 45-degree angle, instead of the horizontal orientation specified in FMVSS 302.

2. A more intense ignition source was used in this test. A Meeker burner 35 mm in diameter adjusted to produce 90 - 115 mm high flame was used, as opposed to a Bunsen burner, 10 mm in diameter and a flame height of 25 mm used for the FMVSS 302 test.

3. A more quantitative method for evaluation of flammability of materials was used. Flammability in this case is measured by sample weight loss with time during burning; as compared to estimation of flame travel specified in FMVSS 302. The weight loss data can be converted to heat release rate by multiplying the weight loss by heat content of the material.

Typical curves for weight loss with time during burning are shown in Figure 11 for standard polypropylene (Profax 8523), Figure 12 for standard nylon 66 (BASF A3K), and Figure 13 for fire retardant nylon 66 (BASF A3X2G5). In all these Figures, the experimental points are shown by the symbols. The line drawn is a binomial best-fit curve for the data. The curves are characterized by an induction period where the burn rate is slow, followed by a fast growing rate representing fire propagation, and finally a slower rate representing termination. The high scatter in the data for the fire retardant grade indicates a high noise to signal ratio, caused by multiple ignitions performed whenever a sample self-extinguished, and also due to slow burn rate.

The burn test results for all samples are summarized in Table 8. For polypropylene and nylon 66, the fire retardant grades show less weight loss due to burning and lower amounts of melt dripping. For nylon 6, a nano-composite sample is more flammable than the base polymer. The total weight loss for the base polymer was 3.0% as compared to 8.95% for the nano-composite. The respective percent drip values were 0.46 versus 2.00. Although cone calorimeter data shows that nano-composites exhibit enhanced flame retardancy characteristics in terms of lower heat release rate and more char formation [2], our data shows that the flame propagates faster in nano-composites as compared to base polymer.

Overall, fire retardants based on halogen or phosphorus slowed the rate of flame spread and the amount of sample consumption during fire for both polypropylene and nylon 66. They also decrease or eliminate the melt dripping during burning. The effects of the fire retardants are more noticeable for polypropylene than nylon 66, because the polypropylene base polymer is more flammable.

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Table 1: Types of polypropylene and nylon polymers investigated and their properties.

Typical Resin Property	ASTM Test Method	Polypropylene Pro-fax SB-786 (Montell)*	Polypropylene Pro-fax 8523 (Montell)*	Polypropylene 151(F.R.)** (RTP)*	Polypropylene 156(F.R.)** (RTP)*	Nylon 66 Ultramid A3K (BASF)*	Nylon 66 Ultramid A3X2G5 (F.R.)** (BASF)*	Nylon 66 200H (F.R.)** (RTP)*	Nylon 66 299X (RTP)*	Nylon 6 Standard (NIST)*	Nylon 6 Nano-Composite (NIST)*
Density(g/cm^3)	D792	0.9	0.9	1.05	1.21	1.13	1.33	1.27	1.18	1.11	1.12
Tensile Strength at Yield(MPa)	D638	26	21	23	17	85	140	43	72	42	15
Tensile Elongation at yield(%)	D638	8	8	10	10	-	-	40	10	46	2.5
Tensile Modulus (MPa)	D638	-	-	2480	1447	3197	8337	2076	3652	486	923
Flexural Modulus 1% Secant(MPa)	D790A	1200	1000	2412	1309	-	-	1585	3445	-	-
Heat Deflection Temperature(°C) (at 455 kPa)	D648	87	81	110	104	>199	250	199	188	-	-
Notched Izod Impact Strength at 23 °C(J/m)	D256A	90	No Break	53	214	53	-	187	40	337	328

* Name of the Supplier

** F.R. = Fire Retardant

Table 2: Melting point, glass transition temperature and heat of fusion of polymers as determined by modulated differential scanning calorimetry conducted in nitrogen.

Polymer type	Melting point (°C)	Glass transition temperature (°C)	Heat of Fusion (J/g of sample)
Polypropylene Pro-faxSB 786	122 , 160, 164	-3	36 , 92
Polypropylene Pro-fax8523	118 , 166	2	8 , 68
Polypropylene 151(FR)	128 , 160	(-8 , 72)	14 , 58
Polypropylene 156(FR)	124 , 166	(-4 , 74)	7 , 50
Nylon 66 Ultramid A3K	262	64	113
Nylon 66 Ultramid A3X2G5 (FR)	262	52	86
Nylon 66 200H (FR)	260	46	73
Nylon 66 299X	260	58	79
Nylon 6 Standard	219	59	129
Nylon 6 Nano- Composite	216	(-1 , 56)	103

Table 3: Heat capacities of selected polymers as determined by modulated differential scanning calorimetry conducted in nitrogen.

	Heat capacity J/(g-°C) at temperature:										
Polymer type	-50 (°C)	-40 (°C)	-20 (°C)	0 (°C)	20 (°C)	40 (°C)	60 (°C)	80 (°C)	100 (°C)	200 (°C)	300 (°C)
Polypropylene Pro-faxSB786	1.010	1.031	1.121	1.233	1.357	1.473	1.600	1.750	1.937	2.155	2.413
Polypropylene Profax 8523	1.337	1.404	1.501	1.628	1.737	1.894	1.968	2.140	2.382	2.442	2.740
Polypropylene 151(FR)	0.846	0.854	0.879	0.952	1.018	1.084	1.491	1.225	1.307	1.537	1.789
Polypropylene 156(FR)	1.293	1.320	1.416	1.568	1.658	1.760	1.873	2.051	2.157	2.322	2.506
Nylon 66 Ultramid A3K	1.446	1.451	1.536	1.651	1.748	1.838	1.997	2.191	2.343	2.652	2.979
Nylon 66 Ultramid A3X2G5 (FR)	1.164	1.167	1.229	1.312	1.378	1.441	1.562	1.659	1.754	2.122	2.038
Nylon 66 200H (FR)	1.050	1.071	1.142	1.222	1.303	1.413	1.529	1.571	1.639	2.017	1.991
Nylon 66 299X	1.187	1.225	1.265	1.367	1.461	1.557	1.812	1.895	2.014	2.770	2.736
Nylon 6 Standard	1.048	1.081	1.149	1.229	1.317	1.421	1.558	1.732	1.847	3.982	2.487
Nylon 6, Nanocomposite	1.198	1.188	1.257	1.404	1.547	1.656	1.804	1.953	2.069	4.191	2.729

Table 4: Heat capacity slopes for polymers at different temperature ranges (J/g-°C-°C).

Polymer type	Slope (-20 to 0)°C	Slope (50 to 70)°C	Slope (200 to220)°C
Polypropylene Pro-faxSB 786	0.0066	0.0078	0.0028
Polypropylene Pro-fax8523	0.0063	0.0066	0.0028
Polypropylene 151(FR)	0.0069	0.0084	0.0061
Polypropylene 156(FR)	0.0075	0.0068	0.0029
	Slope (-10 to 10)°C	**Slope (150 to 170)°C**	**Slope (290 to 310)°C**
Nylon 66 Ultramid A3K	0.0063	0.0006	0.0018
Nylon 66 Ultramid A3X2G5 (FR)	0.0045	0.0019	0.0006
Nylon 66 200H (FR)	0.0025	0.0022	0.0004
Nylon 66 299X	0.0060	0.0071	0.0047
Nylon 6 Standard	0.0051	0.0091	0.0010
Nylon6 Nano- Composite	0.0048	0.0071	N/A

Table 5: Thermal conductivity of polymers as determined by modulated differential scanning calorimetry conducted in nitrogen at 30 °C.

Polymer type	Thermal conductivity (W/m-°C)
Polypropylene Profax SB 786	0.12
Polypropylene Profax 8523	0.12
Polypropylene 151(FR)	0.17
Polypropylene 156(FR)	0.16
Nylon 66 Ultramid A3K	0.18
Nylon 66 Ultramid A3X2G5	0.21
Nylon 66 200H (FR)	0.15
Nylon 66 299X	0.15
Nylon 6 Standard	0.14
Nylon 6 Nano-composite	0.16

Table 6: Thermalgravimetric analysis of polymers in nitrogen.

Polymer type	Initial weight loss			Major weight loss			Secondary weight loss			Residue
	Temp (°C)	wt loss (%)	wt loss (%)/°C	Temp (°C)	wt loss (%)	wt loss (%)/°C	Temp (°C)	wt loss (%)	wt loss (%)/°C	(%)
Polypropylene Pro-faxSB786	426	99.92	9.98	426	99.92	9.98				0.07
Polypropylene Pro-fax 8523	429	99.91	13.13	429	99.91	13.13				0.06
Polypropylene 151(FR)	238	8.83	0.35	434	78.61	4.84				7.61
Polypropylene 156(FR)	328	54.69	5.49	328	54.69	5.49	398	24.81	0.58	3.76
Nylon 66 Ultramid A3K	409	16.90	0.95	427	58.06	3.69	585	18.03	0.18	6.69
Nylon 66 Ultramid A3X2G5 (FR)	383	44.60	1.10	383	44.60	1.10	450	25.44	0.58	33.65
Nylon 66 200H (FR)	374	63.25	10.16	374	63.25	10.16	468	20.16	0.94	4.79
Nylon 66 299X	338	15.27	0.86	413	71.64	1.47	585	12.46	0.16	0.42
Nylon 6 Standard	417	98.70	6.41	417	98.70	6.41				0.53
Nylon 6 Nano- Composite	398	20.05	1.71	419	70.80	3.69				6.25

Table 7: Thermal gravimetric analysis of polymers in air.

	Initial weight loss			Major weight loss			Secondary weight loss			Residue
Polymer type	Temp (°C)	wt loss (%)	wt loss (%)/°C	Temp (°C)	wt loss (%)	wt loss (%)/°C	Temp (°C)	wt loss (%)	wt loss (%)/°C	(%)
Polypropylene Pro-faxSB786	309	84.85	6.56	309	84.85	6.56				0.00
Polypropylene Pro-fax 8523	312	89.72	11.41	312	89.72	11.41	429	5.83	0.21	0.26
Polypropylene 151(FR)	242	5.60	0.31	335	18.64	0.92	347	13.83	0.97	2.21
Polypropylene 156(FR)	328	42.42	3.65	328	42.42	3.65	517	10.61	0.19	2.89
Nylon 66 Ultramid A3K	403	15.54	0.75	424	58.93	4.61	526	19.68	0.4	0.00
Nylon 66 Ultramid A3X2G5 (FR)	370	2.77	0.16	417	30.11	1.53	461	9.98	0.28	31.18
Nylon 66 200H (FR)	368	52.90	8.80	368	52.90	8.80	534	24.62	1.98	0.28
Nylon 66 299X	327	13.65	0.78	431	40.91	2.26	421	21.35	2.49	0.24
Nylon 6 Standard	403	29.01	3.07	415	53.28	2.35	578	12.19	0.14	0.10
Nylon 6 Nano- Composite	411	90.66	4.88	411	90.66	4.88				3.58

Table 8: Flammability properties of polymers using Meeker type high temperature burner.

Polymer type	Average rate of flame travel(in/min)	Number of ignitions	%Drip	%Mass lost	Flame travel(in)	Observations
Polypropylene Pro-faxSB786	2.20	1	11.00	16.20	8.30	Flammable, Dripping with flammability
Polypropylene Pro-fax 8523	5.85	1	27.50	29.90	11.00	Flammable, Dripping with flammability
Polypropylene 151(FR)	0.18	5	0.67	1.39	1.50	Flaming for 5 seconds without dripping
Polypropylene 156(FR)	0.28	5	1.15	3.16	2.50	Dripping after 35 seconds, the drips were non- flaming
Nylon 66 Ultramid A3K	1.73	1	7.72	9.00	2.50	Flammable, Dripping with flammability
Nylon 66 Ultramid A3X2G5 (FR)	0.00	8	0.00	2.88	0.50	Non- flammable, No dripping
Nylon 66 200H (FR)	0.00	9	0.00	2.47	0.50	Non- flammable, No dripping
Nylon 66 299X	0.09	8	0.45	3.26	1.00	Flaming while lighting, No dripping
Nylon 6 Standard	0.09	4	0.46	3.94	1.50	8 drops at second ignition
Nylon 6 Nano- Composites	0.40	2	2.00	8.95	4.00	Flammable, with few drops

Figure 1: Modulated differential calorimetry run for polypropylene Profax SB 786 conducted in nitrogen.

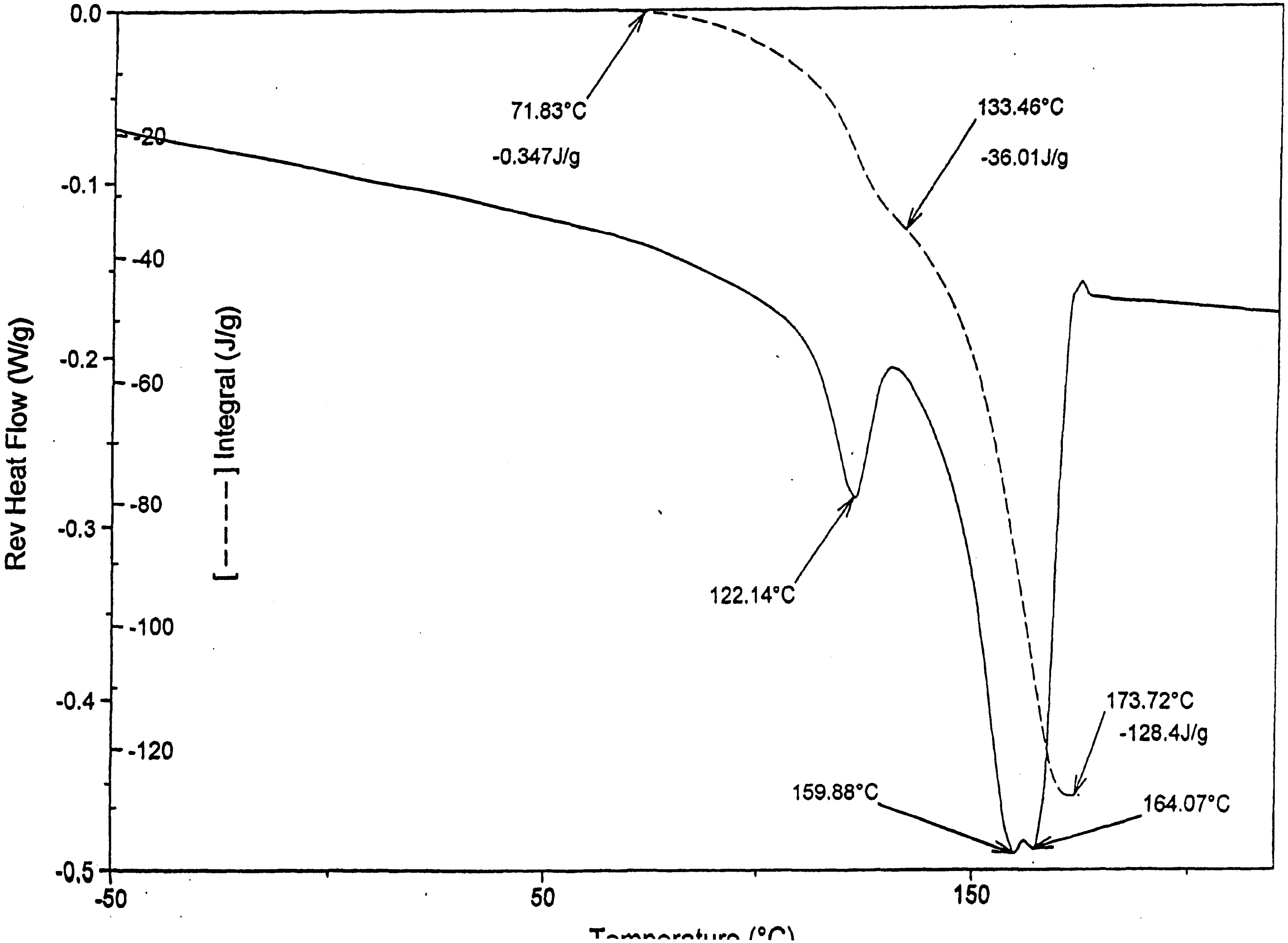


Figure 2: Heat capacity versus temperature for nylon 66 Ultramid A3K.

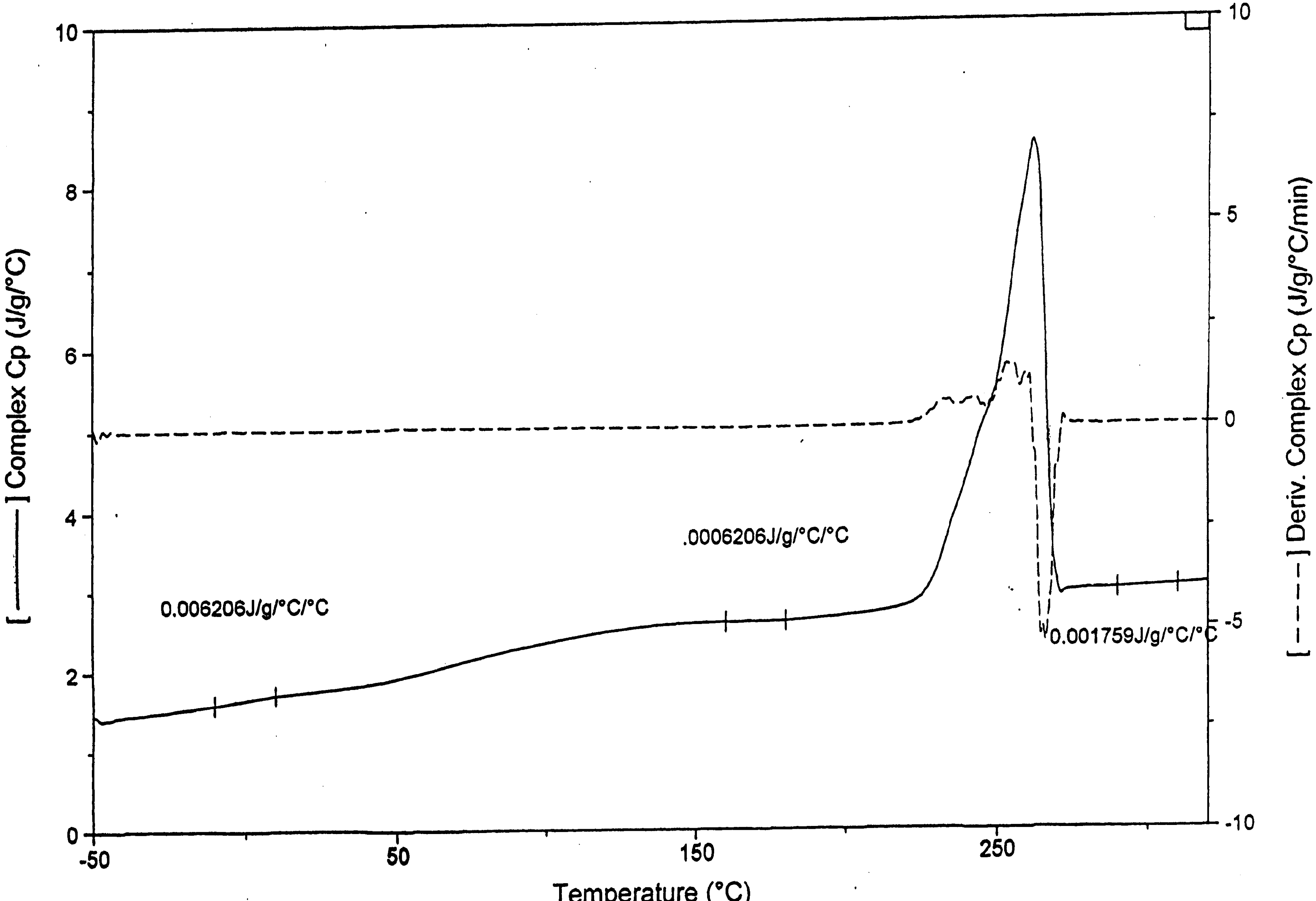


Figure 3: Thermal conductivity of standard and fire retardant polymers.

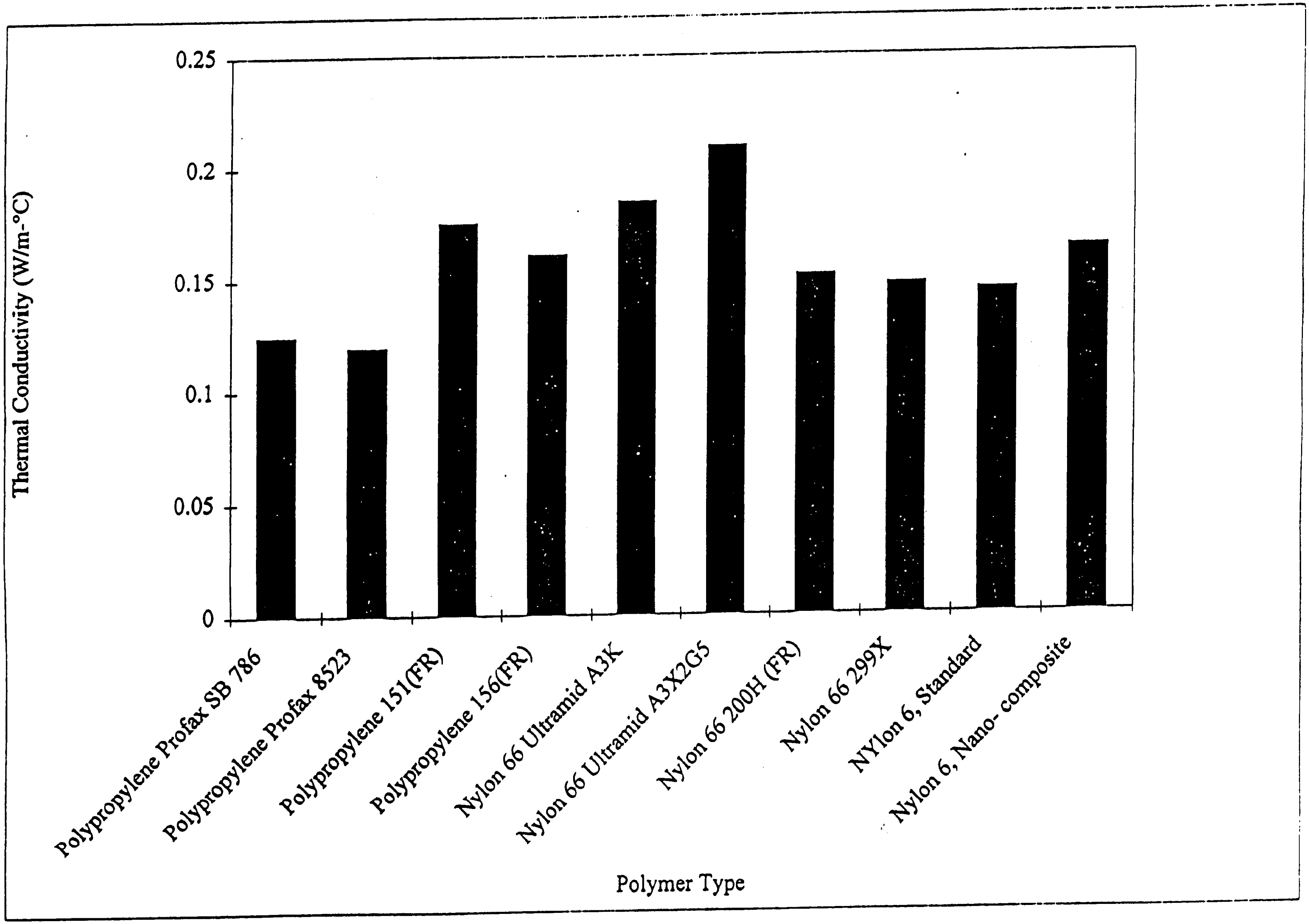


Figure 4: High resolution thermal gravimetric analysis of polypropylene Profax 8523 conducted in nitrogen.

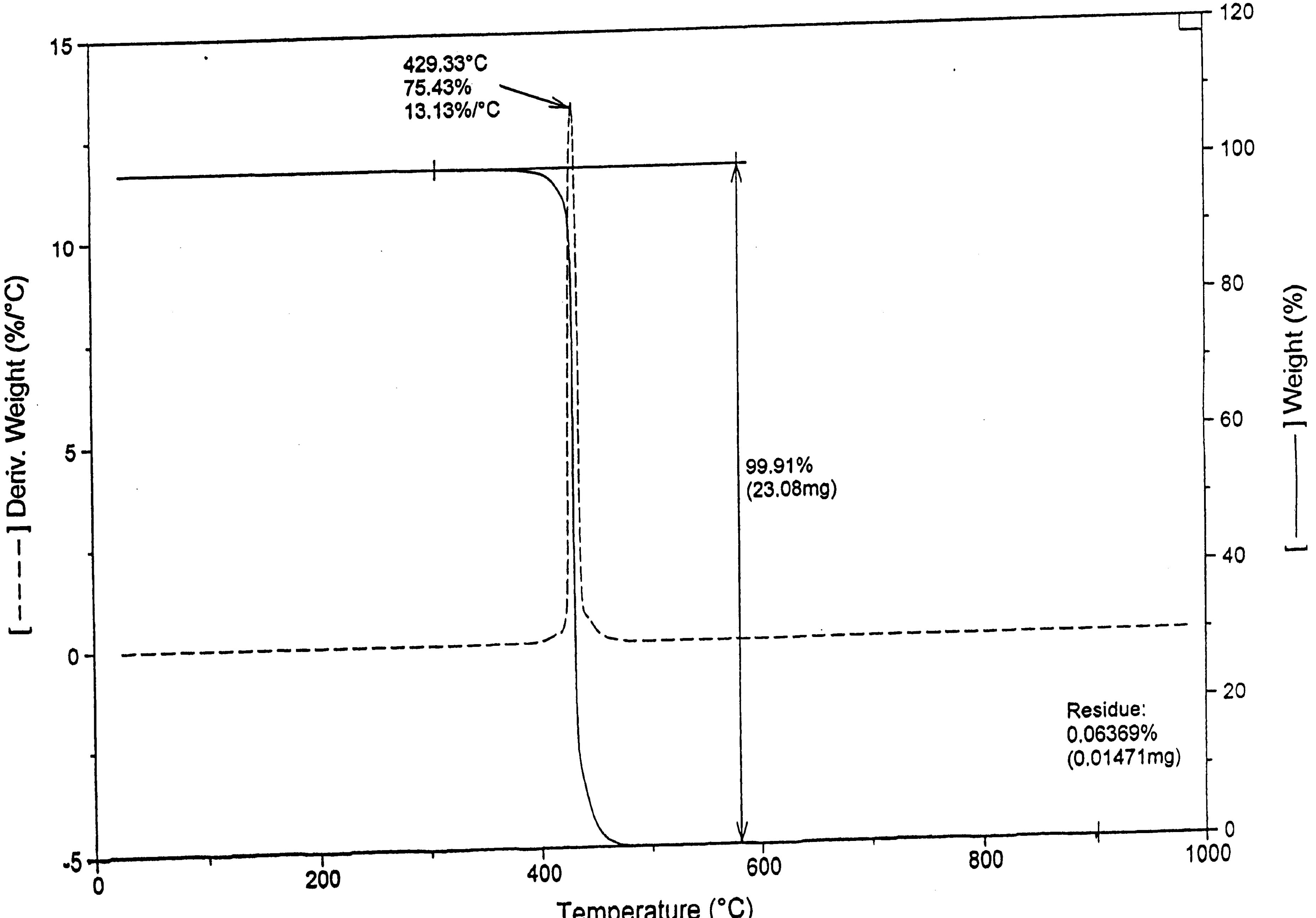


Figure 5: High resolution thermal gravimetric analysis of polypropylene Profax 8523 conducted in air.

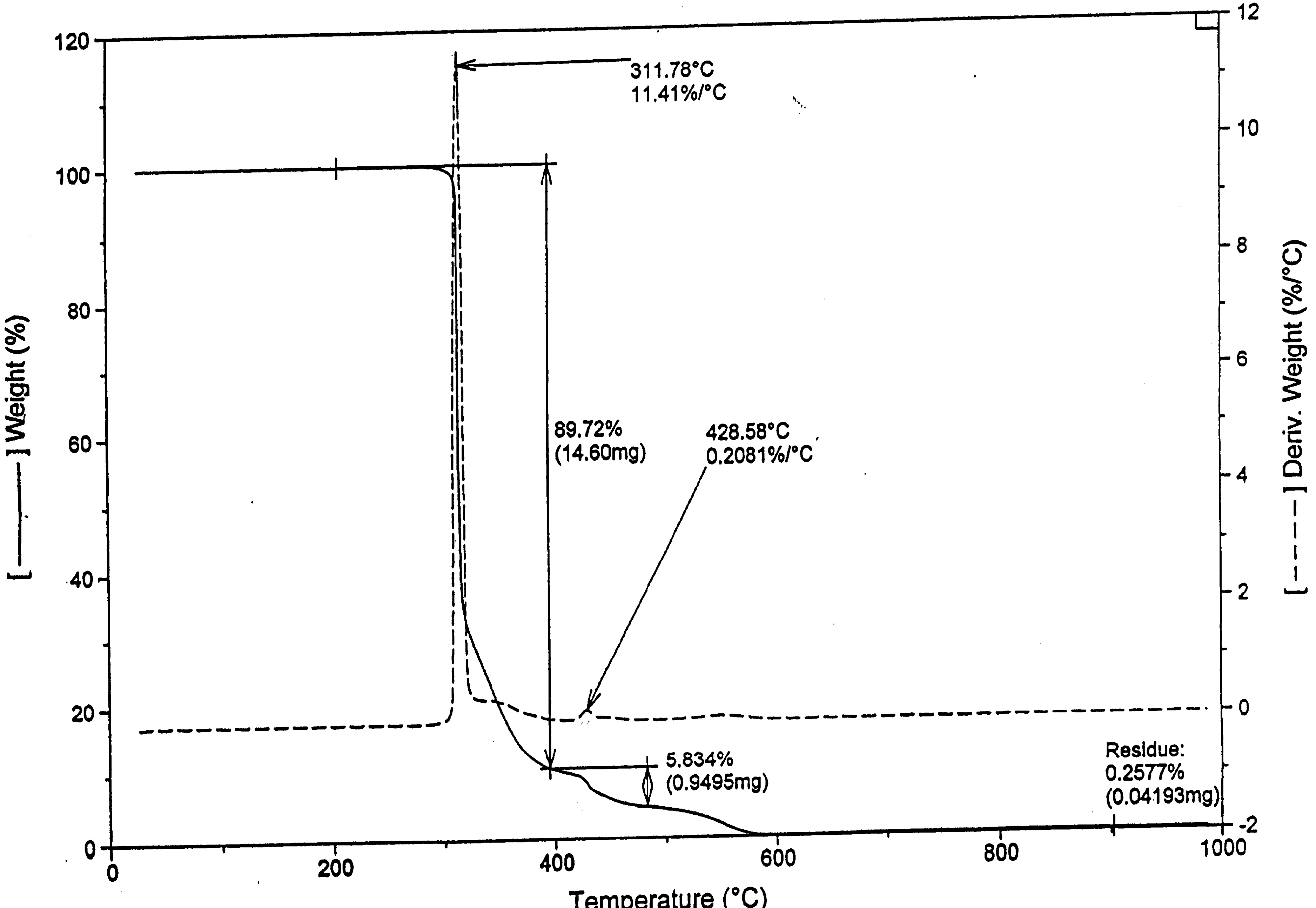


Figure 6: High resolution thermal gravimetric analysis of standard nylon 6 conducted in nitrogen.

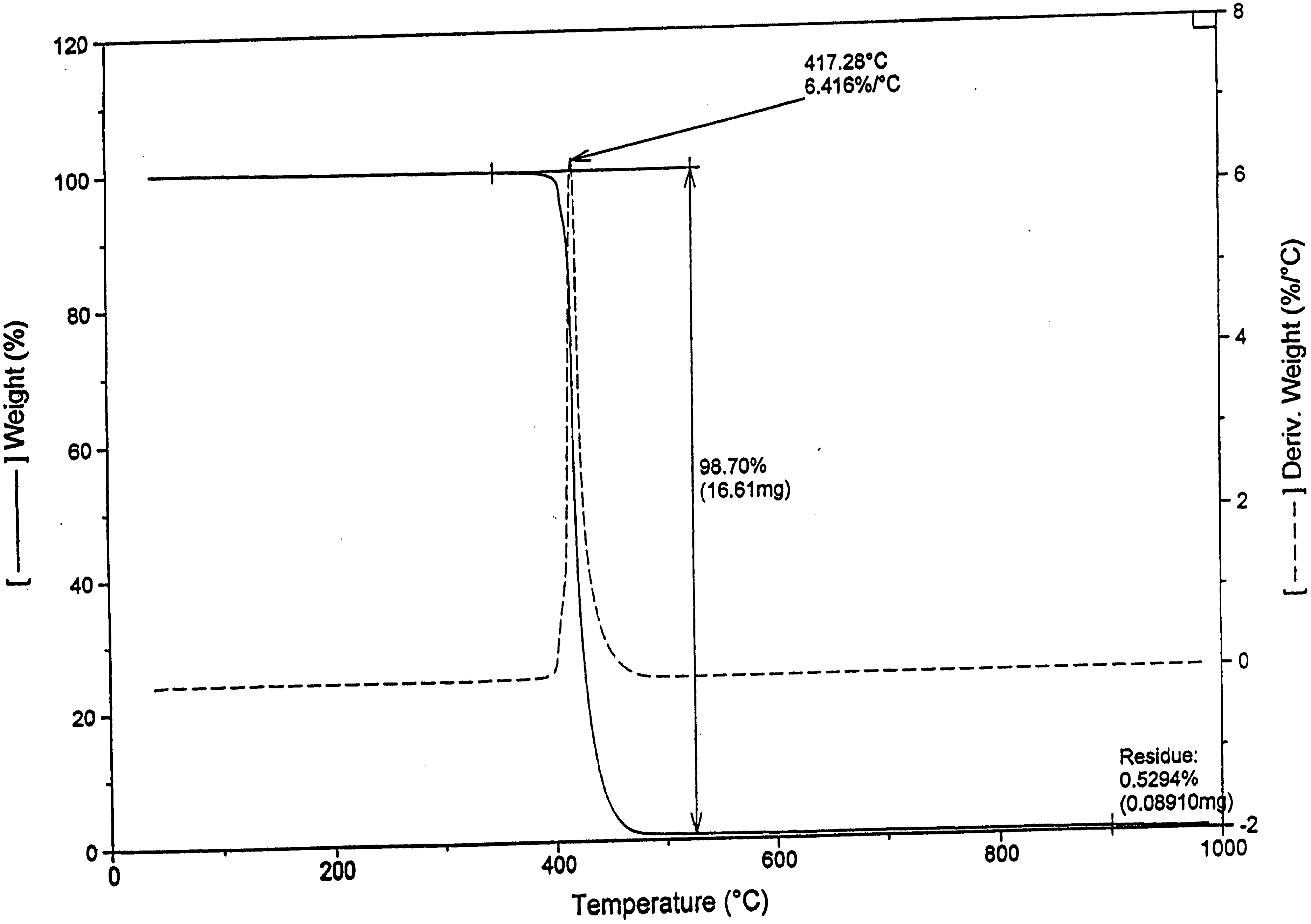


Figure 7: High resolution thermal gravimetric analysis of standard nylon 6 conducted in air.

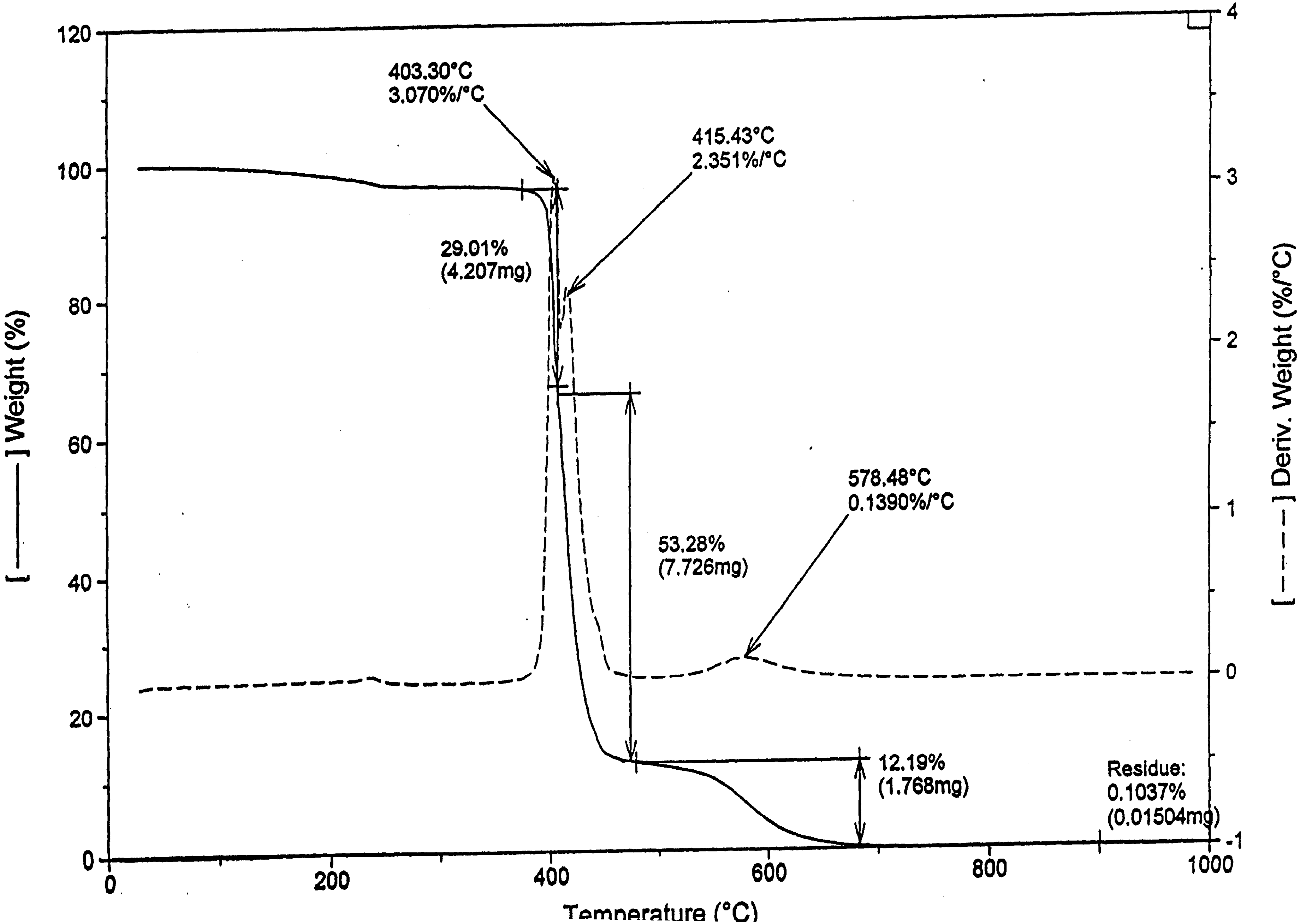


Figure 8: High resolution thermal gravimetric analysis of fire retardant polypropylene RTP 151 conducted in nitrogen.

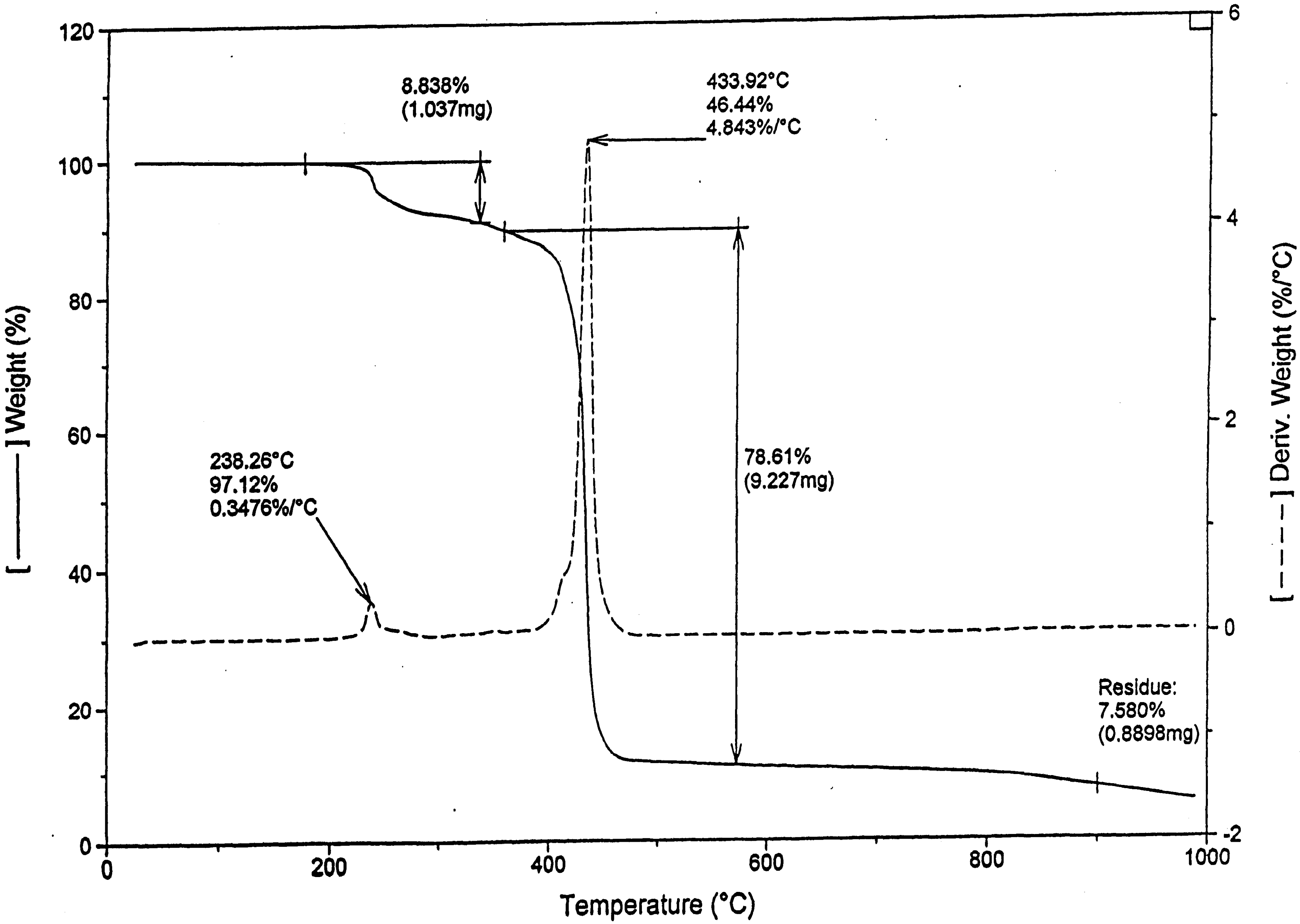


Figure 9: High resolution thermal gravimetric analysis of fire retardant polypropylene RTP 151 conducted in air.

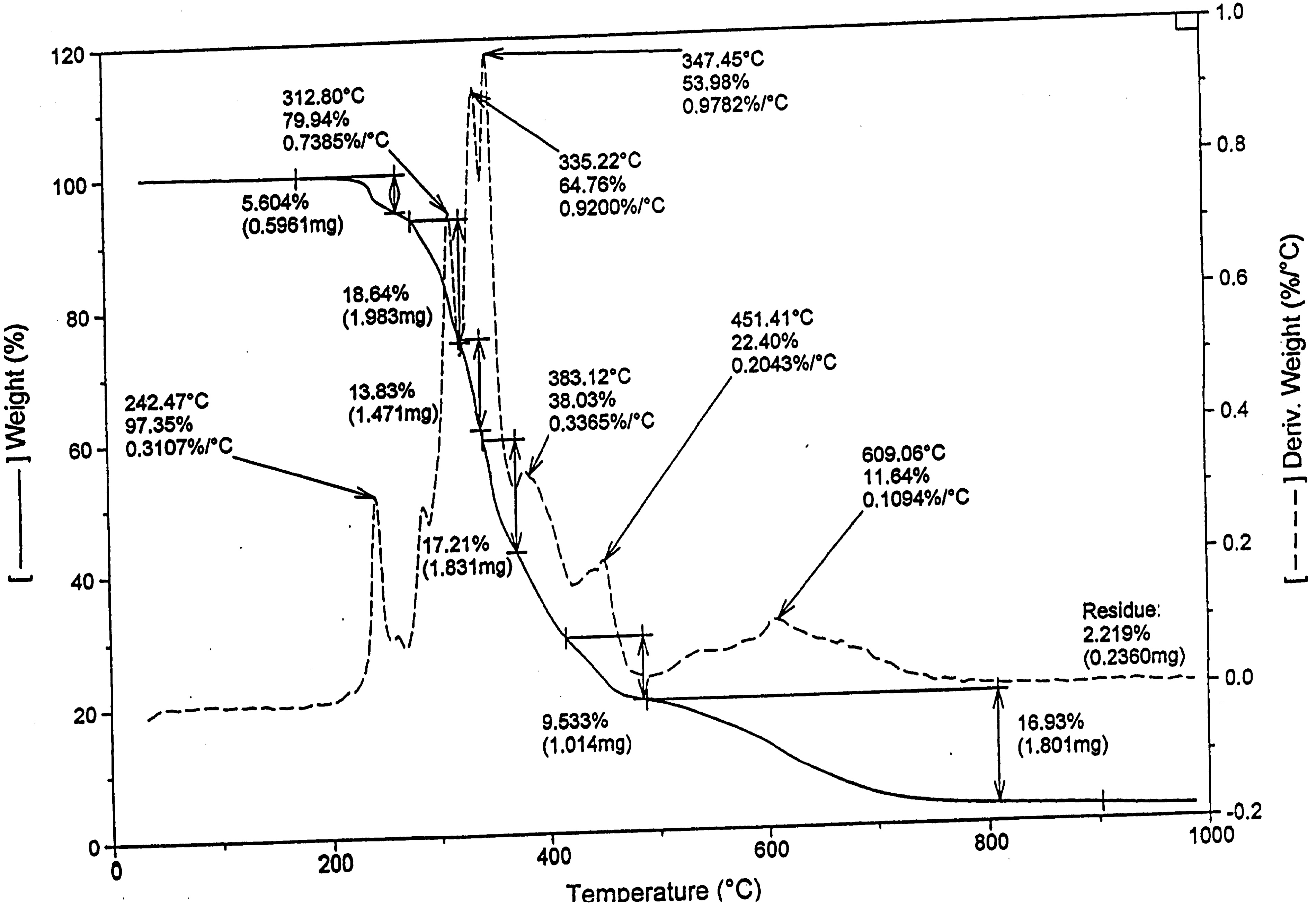
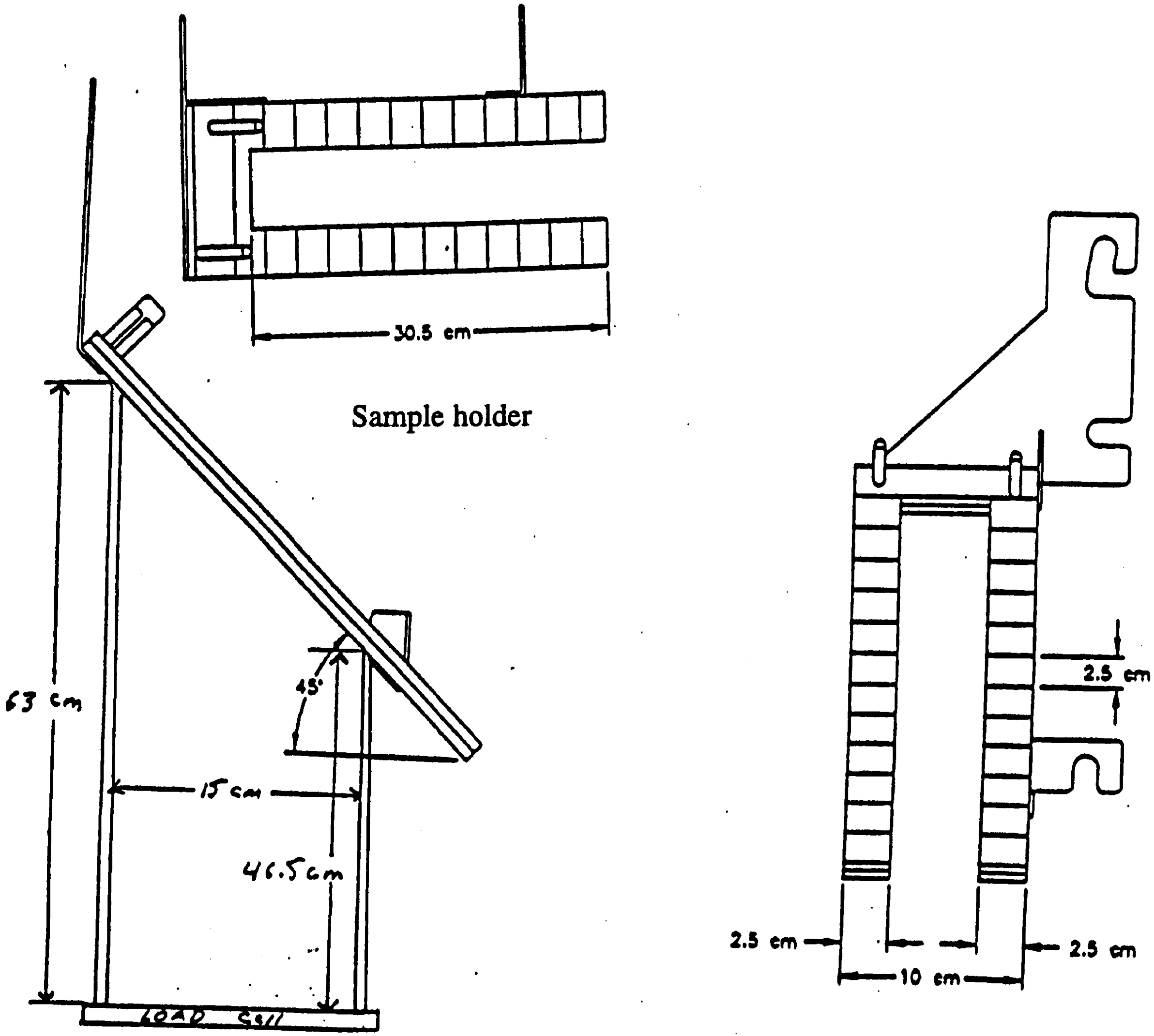


Figure 10: Flammability test apparatus.

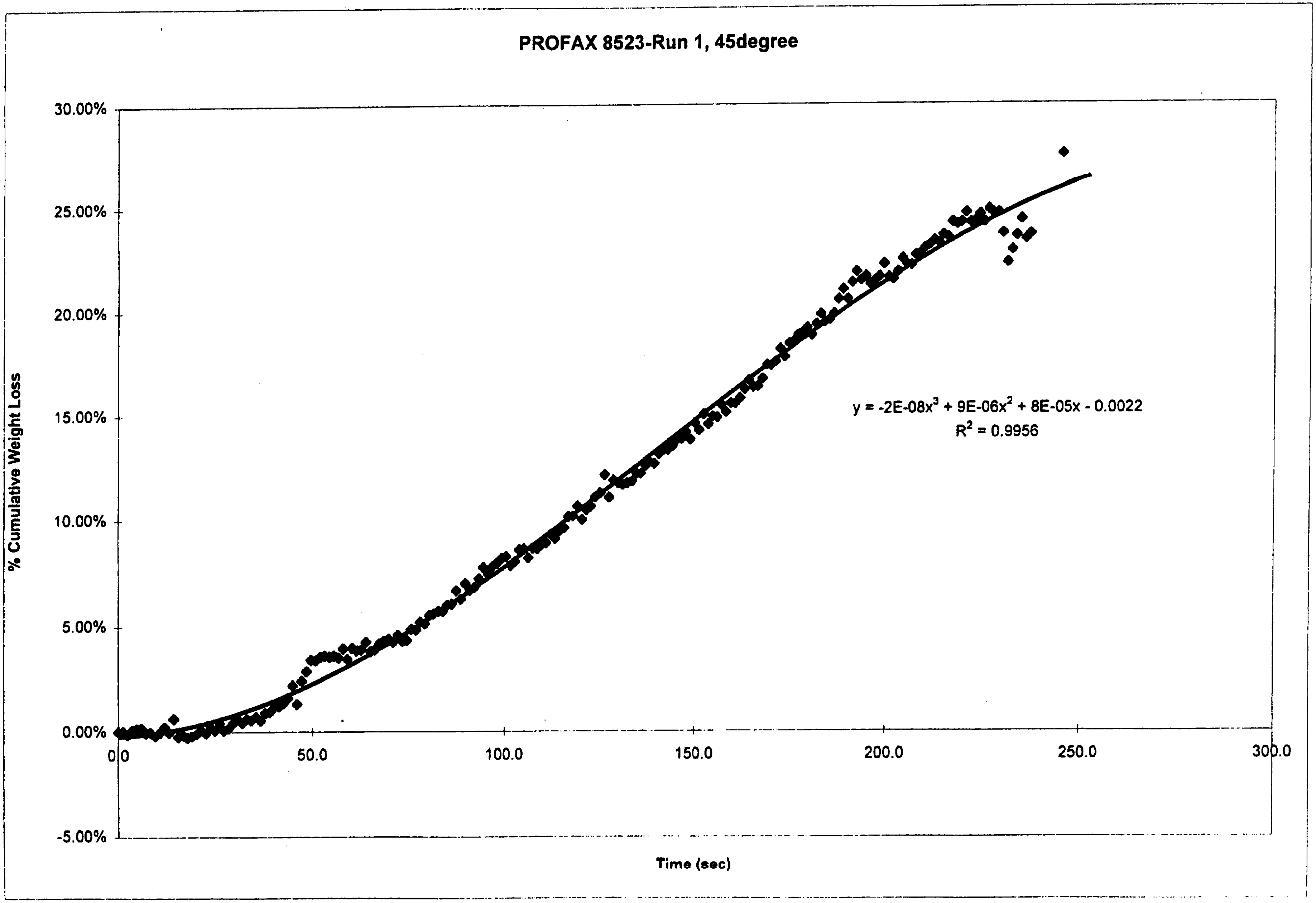


Sample holder

Sample holder placed in test stand at 45° angle

sample holder with positioning arms

Figure 11: Cumulative weight loss(%) due to combustion versus time(sec) for polypropylene Profax 8523.



$y = -2E\text{-}08x^3 + 9E\text{-}06x^2 + 8E\text{-}05x - 0.0022$

$R^2 = 0.9956$

Figure 12: Cumulative weight loss(%) due to combustion versus time(sec) for nylon 66 Ultramid A3K.

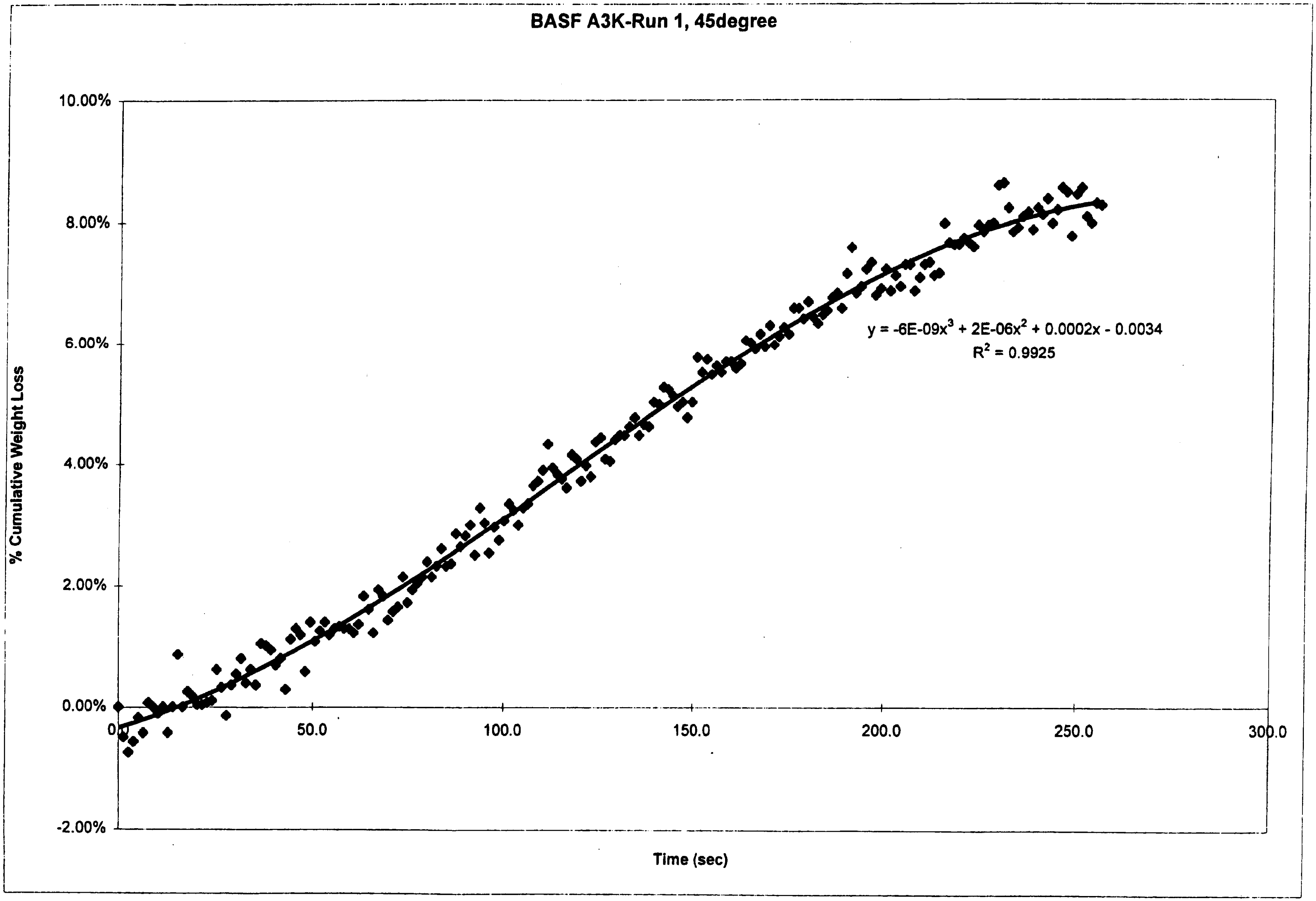


Figure 13: Cumulative weight loss(%) due to combustion versus time(sec) for nylon 66 Ultramid A3X2G5.