EXTENT OF CARBONATION IN BUILDINGS

IN TORONTO

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EXTENT OF CARBONATION IN BUILDINGS IN TORONTO

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This legislation is designed to aid in the improvement of housing and living conditions in Canada. As a result, the Corporation has interests in all aspects of housing and urban growth and development.

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This publication is one of the many items of information published by CMHC with the assistance of federal funds.

Caution

The methodologies, the interpretations and the recommendations are those of the consultants and do not necessarily reflect the view of Canada Mortgage and Housing Corporation, which assisted in the study and its publication. The results of the study are published for information purposes and the reader is cautioned that the scientific data generated are derived from a study of selected buildings in the Toronto area.

Extrapolation of this data to most structures in Canada may be feasible, provided that the vagaries of climates and the behaviour of various structural systems and building materials in those local areas are understood.

88/003

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Executive Summary

Introduction

Carbonation occurs when concrete reacts with carbon dioxide from air or water and reduces the pH of the concrete to below 9.0. At this low pH reinforcing steel is no longer passive and corrosion of steel may occur. Carbonation is not a problem in very dry concrete or in water-saturated concrete. More massive steel-reinforced concrete structures such as roads, bridges, dams, water and sewage-treatment plants are more likely to fail due to the effects of de-icing salts, freeze-thaw effects and sulphate or alkali-reactivity damage, than to the effects of carbonation.

Carbonation of concrete has attracted considerable and recent interest in Europe and Australia, where it is known to be the cause of current structural problems. As the Canadian building stock is younger than European carbonation troubled structures, it was considered prudent to initially investigate the literature to assess the likely occurrence of future carbonation-induced decay of reinforced concrete in Canada. To this end the Corporation had already funded a literature review and analysis.[1]

As a potential problem was subsequently thought to exist in Canada, a research design has been developed and tested in Toronto and an assessment made of the impact of carbonation on concrete structures in that City.

Methodology

Major building owners such as Ontario Housing Corporation, Toronto Metropolitan Housing Authority, Public Works Canada, the Ontario Ministry of Government Services and members of the Canadian Institute of Public Real Estate Companies were interviewed and their willingness to have buildings investigated was determined. Twenty-eight buildings were eventually selected and tested with invasive but non-destructive procedures.

The classifications of building components examined were; cast-in-place balconies; vertical exposed components of cast-in-place structural elements and precast concrete facades.

[1] "Determine Potential of Carbonation of Concrete in Canada", CMHC, 1987.

A total of 348 concrete cores, each approximately 50mm diameter x 75mm long were removed, by diamond drilling, and examined by a series of testing techniques as follows: splitting tensile strength, absorption and voids, chloride ion content, carbonation depth and lime content.

A representative from IRC/NRC was retained to provide guidance in site selection, sampling procedures and assistance in analysis of the data.

Findings

The study shows that, in Toronto at least, a proportion of the building stock will experience carbonation corrosion damage within a desired service life.

Of all the building components tested, only the balconies in two already had carbonation to the depth of the specified cover to the steel reinforcement. However, one third of the balconies examined, had a rate of carbonation penetration higher than is considered desirable relative to design life expectancy.

None of the vertical cast-in-place components or pre-cast cladding units had carbonation to specified cover depths. However two structures in each category had excessively high rates of carbonation penetration relative to design life expectancy.

The lime content tests shows that ongoing carbonation may be to depths greater than those shown by the simple phenolphthalein indicator tests, which only shows when carbonation is complete. This finding will require consideration with regard to future recommendations and testing procedures.

The drilling and testing of cores by the procedures adopted was found to be technically sound and economic. Arranging and gaining access to structures presented some problems.

Conclusions

The splitting tensile and absorption and void data confirm the absence of anomalies in other data. It may not be essential to make these tests in future programmes of field study.

The chloride-ion content determinations eliminated the possibility of any anomalies in the carbonation depth test results. These tests could be made as a second and optional stage, in future field studies if shown to be necessary by the results of carbonation tests.

The lime content tests show that in some cases the carbonation depth as determined by phenolphthalein testing may be underestimated, on occasion, to a significant extent. It would therefore seem prudent to provide for this or other types of testing, in addition to the simple phenolphthalein indicator test, indicating only that the carbonation process is complete.

The study data suggests therefore, that in Toronto at least, a proportion of the building stock will experience carbonation corrosion damage within a desired service life.

Balconies appear to be the most vulnerable component with two in the survey sample with carbonation already having reached the specified reinforcement depth, and one-third of those tested likely to suffer damage within their service life.

With the vertical cast-in-place components and precast cladding, most of those examined would last their service life without damage, but two buildings had these components with carbonation depths that would result in a lower than desirable service life.

The cost of repairing corrosion damage will be very high if carbonation is allowed to proceed until it reaches the reinforcement. Accordingly it would be prudent to provide, to the industry, some guidance on the diagnostic and preventative measures which can be taken.

CONTENTS

	PAGE NO.
EXECUTIVE SUMMARY	
Introduction	
Methodology	
Findings	
Conclusions	
CONTENTS	
ABSTRACT	
INTRODUCTION	1
METHODOLOGY	1
FIELD PROCEDURE	1
LABORATORY PROCEDURES	2
Splitting Tensile Test	2
Carbonation Depth	2
Absorption and Voids	2
Chloride Ion Content	2
Lime Content Tests	2
EVALUATION OF DATA: PART 1 PHYSICAL TESTS	3
Tensile Strength	3
Absorption and Voids	3
Orientation	3
Carbonation Depth	3
Table - Estimation of Carbonation Depth in Portland Cement	4
EVALUATION OF DATA: PART 2 CHEMICAL TESTS	5
Chloride Ion Content	5
Lime Content	6
CONCLUSIONS	7
Methodology	7
Test Results	7-8
TABLE 1 - Building Sample	9
TABLE 2 - Splitting Tensile Strengths	10-12
TABLE 3 - Carbonation Depth	13-15
TABLE 4 - Absorption and Voids	16-18
TABLE 5 - Chloride Contents	19-21
TABLE 6 - Summary of Carbonation Depths	22

TABLE 7 - Summary of Splitting Tensile Tests 23

TABLE 8 - Summary of Absorption and Voids 24

TABLE 9 - Summary of Constants B 25

TABLE 10 - Splitting Tensile Tests: Statistical Summary 26

TABLE 11 - Summary of Absorption and Voids 26-27

TABLE 12 - Orientation of Building Components 28

TABLE 13 - Values of B: Statistical Summary 29

TABLE 14 - Average Chloride Contents 30

TABLE 15 - Summary of Properties 31

FIGURE 1 - Building Locations 32
FIGURE 2 - Value of B 33
FIGURE 3 - Comparison of Indicator and Lime Content Tests - **Sample 4/4** 34
FIGURE 4 - Comparison of Indicator and Lime Content Tests - **Sample 6/5** 34
FIGURE 5 - Comparison of Indicator and Lime Content Tests - **Sample 28/3** 35
FIGURE 6 - Comparison of Indicator and Lime Content Tests - **Sample 38/4** 35
FIGURE 7 - Comparison of Indicator and Lime Content Tests - **Sample 61/5** 36
FIGURE 8 - Comparison of Indicator and Lime Content Tests - **Sample 91/1** 36
FIGURE 9 - Comparison of Indicator and Lime Content Tests - **Sample 91/8** 37
FIGURE 10 - Comparison of Indicator and Lime Content Tests - **Sample 92/3** 37
FIGURE 11 - Comparison of Indicator and Lime Content Tests - **Sample 92/9** 38
FIGURE 12 - Comparison of Indicator and Lime Content Tests - **Sample 133/9** 38
FIGURE 13 - Carbonation Depth and Age - **Balconies** 39
FIGURE 14 - Carbonation Depth and Age - **Vertical Cast-in-Place Components** 39
FIGURE 15 - Carbonation Depth and Age - **Pre-cast Cladding** 39
FIGURE 16 - Carbonation Depth and Absorption 40
FIGURE 17 - Carbonation Depth and Tensile Strength 40

APPENDIX "A" 41

ABSTRACT

This report is the second phase of a multi-phase study of the potential for carbonation in Canadian buildings. It describes a survey and testing of 28 buildings in Toronto to determine depths of carbonation. An assessment of this phenomena in relationship to other concrete properties is provided.

Based on the findings it is concluded that while no epidemic of damage is expected, in the Toronto area, some buildings there will experience corrosion damage within their service life with concurrent loss of structural properties.

Extent of Carbonation in Buildings in Toronto

CMHC File: 6710-12-1

Introduction

In 1986/87 a literature review was made, and a synthesis prepared, to "Determine Potential of Carbonation of Concrete in Canada". The study concluded that there was a significant potential for carbonation in some major urban areas of Canada and recommended a further study.

It was decided to concentrate the next phase of the work in one urban area. Toronto was chosen as a suitable and convenient location. Cores were taken from a number of buildings and information developed from the tests carried out on these cores.

Methodology

Through contact with the Federal and Provincial Governments and the Ontario Ministry of Housing, a total of 134 public and residential buildings were identified as candidates for testing. From these, a sample of 32 buildings were chosen and 28 were tested. The locations were in various parts of the Metropolitan Toronto area, see figure 1, and from all compass orientations.

The buildings are listed in Table 1 by a reference number. Table 1 also lists the samples obtained.

Samples were obtained from the top surfaces of exposed balconies, vertical cast-in-place exposed concrete columns and shear walls, and from pre-cast cladding panels.

Field Procedure

All test samples were 50mm diameter cores about 75-100mm long. These were drilled from the outside exposed surfaces remote from possible salt splash using a diamond drill bit cooled with water. Immediately after drilling the cores were marked for identification and then immersed in water until tested to prevent further carbonation. Cores were taken in sets of three and the location and orientation was noted for all samples.

Laboratory Procedures

To prevent any ongoing carbonation all samples remained immersed in water until tested.

Splitting Tensile Test

In order to make tests to determine carbonation depths, the cores were split in half along a major axis. To obtain an approximate strength value the failing load was noted and the splitting tensile strength calculated according to ASTM C496-86. These results are tabulated in Table 2. A total of 348 tests were made.

Carbonation Depth

Immediately after splitting, one half of the core was re-immersed in water to prevent any ongoing carbonation and the other half tested to determine the depth of carbonation. The test procedure used was based on that given in ISO Standard DOC N77E except that with the relatively small size specimen used four depth measurements were made and averaged. These carbonation depth results are summarized in Table 3. A total of 348 tests were made.

Absorption and Voids

In order to provide further data on concrete quality, absorption and voids were determined according to the procedure given in ASTM 642-82, however the specimens were inevitably smaller than the size specified in this standard. These results are summarized in Table 4. A total of 339 tests were made.

Chloride Ion Content

A number of horizons, with selected samples, were tested by the Ministry of Transportation of Ontario method to determine the water soluble chloride-ion content of the samples. The results are summarized in Table 5. A total of 279 tests were made.

Lime Content Tests

The lime content of 30 selected samples was determined by the National Research Council of Canada using a thermo gravimetric procedure and a copy of their report is attached as Appendix A.

Evaluation of Data: Part 1 Physical Tests

Tensile Strength

To ensure that any potential surface disfigurement was kept to a minimum, cores were made deliberately small and did not meet the dimensional requirements of ASTM-C496. The strengths obtained therefore may be approximate but are examined later with other data to see if any correlation or trends can be deduced relative to the carbonation data.

This tensile strength data has been summarized in Table 7 and the results of a statistical analysis of the data are given in Table 10.

It is seen that the variation in strength, from building to building, is quite high. Although in every case the average strengths of the public buildings are higher, the difference is marginal and not significant. This data did not make a significant contribution to the findings.

Absorption and Voids

The test specimens were much smaller than the minimum size specified in ASTM-C642 but again are used to see if any correlation or trends can be deduced relative to the carbonation data.

The data has been summarized in Table 8 and the results of a statistical analysis are given in Table 11.

Again it is seen that the results are highly variable and no clear difference between the quality of concrete in public and residential buildings is seen. This data also did not make a significant contribution to the findings.

Orientation

Orientation is not thought to be a factor in the depth of carbonation found. The orientation of each building is summarized in Table 12.

Carbonation & Carbonation Depth

In previous work[1] it has been found that the formula postulated by Pihlajavaara appeared to be suitable for concrete in Canada. This formula takes into account concrete quality and the environment and a tabulation of it is given below:

Estimation of carbonation depth in Portland cement concrete. Carbonation depth = $10B\sqrt{t}$. Values of constant B.

Carbonation time (years)	Quality of Concrete and Storage Condition					
	Low strength		Middle strength		High strength	
	Outdoors (moist)	Indoors	Outdoors (moist)	Indoors	Outdoors (moist)	Indoors
	Thickness of Carbonation Layer					
	B=0.6	B=1.0	B=0.2	B=.05	B=0.1	B=0.2
1	6	10	2	5	1	2
2	9	14	3	7	1.5	3
5	13	22	4	11	2	4
10	19	32	6	16	3	6
25	30	50	10	25	5	10

The constant B has been calculated for each component of each building and the results are summarized in Table 9 and their distribution is shown in Figure 2.

Results

If a value for B of 0.25 is taken as the upper limit for a quality of concrete reasonably resistant to carbonation in Canada most of the balcony and pre-cast concrete examined in this pilot study falls within this definition, while most of the concrete cast in columns and shear walls does not.

The data has been analysed statistically and the results summarized in Table 13.

This agreement shows clearly that the pre-cast concrete is, as would be expected, superior to the cast-in-place concrete from the point of view of carbonation. The balcony concrete is more susceptible to carbonation and the cast-in-place vertical components the least susceptible. It is this last category which property owners shall consider for further testing as it is a very critical structural component.

It is noteworthy that there is no relationship between the age of any of the structures and carbonation depths. These relationships have been plotted on Figures 13 to 15. Clearly carbonation depth must relate more to concrete quality and possibly its constituents, than to age.

The cover requirements required by the Building Codes for different building components are different and have changed over the years.

For the buildings in this sample most balconies would have had, according to code, 3/4" (19mm) cover and the vertical cast-in-place components 1-1/2" (38mm) or 2" (51mm) cover. For pre-cast facade panels the minimum cover specified would probably have been 3/4" (19mm).

By comparing averages and selecting individual results which emphasize poor resistance to carbonation the following rather random picture emerges from the Toronto area pilot study.

For balconies the average value of B determined and a cover of 19mm would produce a time to corrosion of the reinforcing steel of 82 years. However, in Building 62 and Building 88 corrosion depths in those balconies have already been reached. 6 out of the 19 balconies examined or almost 1/3rd of the buildings sampled would experience corrosion within 50 years.

For vertical cast-in-place concretes 38mm and 51mm carbonation depths would be reached in 50 years for buildings having a B value of 0.53 and 0.72 respectively. Only 2 buildings fall within this category.

For pre-cast facade panels only 2 of the buildings will experience corrosion within 50 years.

A summary of average carbonation depths for each building is given in Table 6.

Evaluation of Data: Part 2 Chemical Tests

Chloride Ion Content

The quantities of chloride-ion found are, in all cases, a small fraction of the amount that would be present if calcium chloride had been added to the freshly mixed concrete, as a component of a code-approved agent. It is therefore concluded that it was not more likely present. Average chloride contents found in all the cores examined are summarized in Table 14.

Where there was a gradient in chloride ion content from the exposed face of the concrete to the interior the differences were typical of a normal distribution of variation throughout a concrete building component. In some cases there may have been some minor leaching at the exposed face and in others some exterior deposition of chlorides but neither phenomenon, if they occurred, was of a magnitude to make any significant impact on the study data.

It is concluded therefore that the chlorides found are all or virtually all background chlorides present in the materials from which the concrete was made. They will therefore have had little if any effect on the carbonation results.

Lime Content

The study test data is given in Appendix A. A significant reduction in the original H_2O and $Ca(OH)_2$ contents indicates that carbonation is taking place.

Litvan & Meyer in their paper "Carbonation of Granulated Blast Furnace Slag Cement Concrete During Twenty Years of Field Exposure" remind that phenolphthalein is an acid-base indicator, and that the colour changes resulting from that test signifies not so much the presence of carbonate as the absence of lime. Accordingly the resulting red colour of the partial area must not be interpreted as evidence of no carbonation. Accordingly the thermo gravimetric approach used in the lime content tests improves the sensitivity of analysis suggesting ongoing carbonation to depths beyond that detected by the phenolphthalein indicator.

For the purpose of this evaluation the percentage of original $Ca(OH)_2$ at the three horizons tested by IRC/NRC, has been plotted in Figures 2 to 11 together with the carbonation depth as found by the phenolphthalein indicator test.

In Figure 4 it is seen that the carbonation front as determined by phenolphthalein is close to the horizon at which virtually all the original $Ca(OH)_2$ was present. Similar results might be adduced to the data in Figure 3. In all other tests however it will be seen that a significant reduction of $Ca(OH)_2$ occurs deeper than the carbonation depth determined by phenolphthalein. This difference may be as little as 10 mm in Figure 8 but could be significantly greater as in Figure 9. Here the depth of carbonation is significantly under estimated by the phenolphthalein tests.

This data was further examined by comparing it with other data from these samples. This data is summarized in Table 15 and the relationship between carbonation depth is compared to both absorption and splitting tensile strengths on Figures 16 and 17. No consistent relationship is shown between absorption and carbonation depth. There may be a rough correlation with splitting tensile strength similar to the carbonation depth compressive strength relationship found by Parrott.[2]

[2] L.J. Parrott, "A Review of Carbonation in Reinforced Concrete", C and CA, July 1987.

The data base is too small to make any conclusions with regard to carbonation depth and building orientation.

Conclusions

Methodology

The drilling and testing of cores by the procedures adopted was found to be technically sound, and economic. Arranging and gaining access to structures does on occasion present problems.

The splitting tensile and absorption and void data was interesting in that it helped confirm a lack of anomalies in the other data. It is not considered that it would be essential to make these tests in future programmes.

The chloride-ion content determinations also eliminated the possibility of any anomalies in the carbonation depth test results. In future these tests could be made as a second and optional stage, if shown to be necessary by the results of carbonation tests.

The lime content tests show that in some cases the carbonation depth as determined by phenolphthalein may be under estimated, on occasion to a significant extent. It would therefore seem prudent to provide for this or other types of testing in addition to the simple indicator test.

Test Results

Of all the building components tested, only the balconies in two of them had carbonation to the depth of the specified cover to reinforcement. On the other hand one third of all the balconies examined had B constants higher than is considered desirable, an indicator suggesting a lower than desirable service life.

None of the vertical cast-in-place components or pre-cast cladding units had carbonation to specified cover depths and in only two structures, in each category, were there excessively high B constants.

The lime content tests show however, that ongoing carbonation depths may be greater than those shown by simple indicator tests. This may mean that the actual time to corrosion may be less than that predicted from the results of indicator tests.

The study data suggests therefore, that in Toronto at least a proportion of the building stock will experience carbonation corrosion damage within a desired service life. Balconies appear to be the most vulnerable component with two in the survey sample with carbonation already having reached the specified reinforcement depth, and one-third of those tested likely to suffer damage within their service life. With the vertical cast-in-place components and precast cladding most likely would last their service life without corrosion induced structural damage, but two buildings had these components with carbonation depths which would result in a lower than desirable service life.

If carbonation is allowed to proceed until it reaches the reinforcement in those buildings examined, the cost of repair of the resulting corrosion damage would be high. It would therefore be prudent to provide, to the industry, some guidance on the diagnostic and preventative measures which could be undertaken.

Table 1

Building Sample

Building No.	Samples Taken: Balconies	Vertical Cast-in-Place Components	Pre-Cast Panels
Public Buildings			
4	-	3	3
6	9	6	-
7	9	9	-
8	-	3	3
11	-	-	9
128	-	-	-
130	-	9	9
131	-	3	3
132	-	9	9
133	-	9	9
134	-	-	3
Residential Buildings			
28	9	9	-
29	9	3	-
38	9	-	-
44	9	9	-
61	6	6	-
62	6	6	-
66	3	3	-
67	3	3	-
69	3	3	-
75	9	9	-
78	-	-	-
79	9	9	-
81	6	-	-
86	-	-	18
88	9	9	-
91	9	-	-
92	9	9	-
94	9	9	-
98	-	-	-
100	9	-	-
105	-	-	-
TOTALS	144	138	66 = 348

Table 2

Splitting Tensile Strengths

Building No.	Component	Splitting Tensile Test (MPa) 1	2	3	Average
4	V	4.90	4.31	4.95	4.72
	PC	5.85	5.12	5.70	5.56
6	B	5.54	7.09	6.11	6.25
	B	5.42	5.36	6.10	5.63
	B	5.70	5.54	5.58	5.61
	V	2.56	3.85	1.61	2.67
	V	2.25	2.64	3.21	2.70
7	B	4.31	4.95	5.18	4.81
	B	3.27	4.05	3.86	3.73
	B	4.29	3.37	4.00	3.89
	V	3.99	4.68	3.44	4.04
	V	4.88	3.24	3.73	3.95
	V	4.32	3.31	5.03	4.22
8	V	3.43	2.96	2.08	2.82
	PC	5.49	4.90	3.31	4.57
11	PC	4.25	3.77	3.96	3.99
	PC	4.60	4.09	3.22	3.97
	PC	3.91	4.01	3.68	3.87
130	V	2.84	2.91	2.64	2.80
	V	3.18	2.94	2.63	2.92
	V	2.09	3.07	2.75	2.64
	PC	4.49	2.76	3.53	3.59
	PC	3.33	2.59	3.26	3.06
	PC	3.00	2.93	5.27	3.73
131	V	4.35	5.87	5.62	5.28
	PC	4.68	4.08	3.50	4.09
132	V	3.82	3.95	3.64	3.80
	V	3.37	3.83	1.88	3.03
	V	3.21	3.52	3.08	3.27
	PC	3.84	5.14	4.21	4.46
	PC	3.76	4.50	4.08	4.11
	PC	3.74	3.92	4.10	3.92
133	V	3.22	3.09	4.18	3.50
	V	3.99	3.97	4.33	4.10
	V	3.34	4.12	3.97	3.81
	PC	3.77	5.56	5.38	4.90
	PC	4.81	4.87	3.96	4.55
	PC	5.45	4.54	5.24	5.08
134	PC	4.36	3.99	5.43	4.59
28	B	2.91	3.13	3.67	3.24
	B	2.99	3.12	3.21	3.11
	B	6.02	3.30	4.13	4.48
	V	3.24	3.97	3.25	3.49
	V	2.42	3.17	3.79	3.13
	V	3.34	4.81	3.25	3.80

Building No.	Component	Splitting Tensile Test (MPa) 1	2	3	Average
29	B	3.37	3.67	3.70	3.58
	B	2.94	2.52	2.90	2.79
	B	2.89	3.01	4.23	3.38
	V	2.41	3.62	2.43	2.82
38	B	4.07	4.09	3.16	3.77
	B	3.24	3.12	2.84	3.07
	B	2.50	3.23	3.92	3.22
44	B	3.83	3.00	2.21	3.01
	B	2.36	2.80	1.94	2.37
	B	2.21	3.81	2.81	2.94
	V	4.23	2.61	1.94	2.93
	V	3.34	2.55	2.34	2.74
	V	2.44	2.93	3.43	2.93
61	B	3.12	4.55	3.98	3.88
	B	3.60	3.25	3.11	3.32
	V	2.94	3.34	2.92	3.07
	V	2.96	3.80	3.30	3.05
62	B	4.43	4.52	4.62	4.52
	B	4.30	4.30	5.73	4.78
	V	3.06	3.64	3.41	3.37
	V	3.70	3.73	3.72	3.72
66	B	3.49	3.84	2.90	3.41
	V	3.72	2.53	2.48	2.91
67	B	3.02	2.91	2.23	2.72
	V	2.55	2.05	3.16	2.59
69	B	4.22	2.27	2.76	3.08
	V	3.65	3.63	6.57	4.62
75	B	3.91	4.53	3.58	4.01
	B	3.23	3.16	3.04	3.14
	B	3.70	3.13	3.76	3.53
	V	2.66	2.29	2.66	2.54
	V	2.80	3.20	3.10	3.03
	V	3.17	2.52	2.23	2.64
79	B	5.46	3.57	5.82	4.95
	B	3.27	3.80	3.61	3.56
	B	3.12	1.91	1.99	2.34
	V	2.38	3.31	2.27	2.65
	V	2.90	1.97	2.62	2.50
	V	2.17	2.62	2.12	2.30
81	B	4.30	3.11	2.87	3.43
	B	3.71	4.32	3.52	3.85
86	PC	3.80	3.42	3.85	3.69
	PC	2.44	3.75	3.96	3.38
	PC	2.28	2.64	2.14	2.35
	PC	4.58	4.88	3.90	4.45
	PC	1.95	3.49	3.23	2.89
	PC	3.68	3.54	3.42	3.55

Building No.	Component	Splitting Tensile Test (MPa) 1	2	3	Average
88	B	2.59	1.28	1.22	1.70
	B	2.25	2.45	2.52	2.41
	B	1.75	3.03	2.12	2.30
	V	2.64	2.74	2.90	2.76
	V	2.93	2.67	2.79	2.80
	V	2.41	2.26	2.31	2.33
91	B	3.38	3.61	2.56	3.18
	B	2.97	4.20	2.74	3.30
	B	3.46	3.57	2.88	3.30
92	B	1.74	1.91	2.49	2.05
	B	2.41	2.74	3.25	2.80
	B	2.35	2.46	2.95	2.59
	V	3.23	2.87	2.30	2.80
	V	2.77	3.11	3.00	2.96
	V	2.82	2.69	2.65	2.72
94	B	2.39	2.69	1.63	2.24
	B	2.64	2.53	1.44	2.20
	B	2.88	3.18	3.43	3.16
	V	3.39	3.26	2.33	2.99
	V	2.73	2.12	3.24	2.70
	V	3.46	2.92	3.10	3.16
100	B	2.73	2.27	2.37	2.46
	B	3.61	3.33	2.81	3.25
	B	3.04	3.25	3.11	3.13

Table 3

Carbonation Depth

Building No.	Component	Orientation	Carbonation Depth (mm)			
			1	2	3	Average
4	V	N	7	11	8	9
	PC	N	N	N	N	N
6	B	N	4	5	3	4
	B	N	2	N	N	1
	B	S	3	1	3	2
	V	N	12	16	25	18
	V	S	11	20	12	14
7	B	N	5	N	1	2
	B	N	2	N	1	1
	B	W	2	1	5	3
	V	N	16	14	19	16
	V	N	14	21	12	16
	V	W	13	16	13	14
8	V	E	10	8	10	9
	PC	E	6	10	2	6
11	PC	W	5	5	4	5
	PC	W	6	2	5	4
	PC	S	N	6	4	3
130	V	S	12	15	21	16
	V	S	13	13	15	14
	V	S	17	15	10	14
	PC	W	21	23	20	21
	PC	W	20	18	22	20
	PC	W	21	20	20	20
131	V	W	4	45*	2	3
	PC	W	2	2	1	2
132	V	E	21	26	19	22
	V	E	23	21	24	23
	V	E	24	26	24	25
	PC	S	3	7	5	5
	PC	S	7	1	3	4
	PC	S	1	4	4	3
133	V	S	N	5	7	4
	V	S	3	10	2	5
	V	S	1	7	10	6
	PC		N	N	N	N
	PC		N	N	N	N
	PC		N	N	N	N
134	PC	W	1	2	1	1

N = Negligible

* Excluded from the averages

Building No.	Component	Orientation	Carbonation Depth (mm)			
			1	2	3	Average
28	B	S	21	21	22	21
	B	S	18	18	17	18
	B	E	6	7	5	6
	V	S	10	15	12	12
	V	S	15	19	11	15
	V	E	17	13	18	16
29	B	W	8	6	9	8
	B	E	2	2	2	2
	B	E	3	3	2	3
	V	S	23	22	20	22
38	B	W	4	5	4	4
	B	W	7	5	5	6
	B	W	1	10	3	5
44	B	S	5	4	8	5
	B	N	N	5	D	3
	B	N	N	N	N	N
	V	S	17	17	11	15
	V	N	9	13	11	11
	V	N	15	11	11	12
61	B	S	20	25	25	23
	B	N	6	13	10	10
	V	S	27	15	15	19
	V	N	21	24	21	22
62	B	E	25	24	22	24
	B	W	31	30	31	31
	V	E	25	25	25	25
	V	W	8	9	5	7
66	B	E	5	3	8	5
	V	S	8	7	10	8
67	B	S	7	7	9	8
	V	S	5	3	9	5
69	B	S	4	3	5	4
	V	E	7	8	3	5
75	B	W	N	3	2	2
	B	W	4	3	5	4
	B	E	5	4	4	4
	V	W	37	37	37	37
	V	W	32	31	31	31
	V	E	25	21	26	26
79	B	W	6	10	6	7
	B	W	7	10	7	8
	B	E	N	10	1	4
	V	W	13	13	16	14
	V	W	16	15	14	15
	V	E	16	15	15	15
81	B	N	2	2	4	3
	B	N	3	4	4	4

Building No.	Component	Orientation	Carbonation Depth (mm)			
			1	2	3	Average
86	PC(B)	N	2	3	N	2
	PC(B)	S	1	1	1	1
	PC(B)	N	3	3	7	4
	PC	N	11	6	12	10
	PC	S	13	12	15	13
	PC	N	11	8	10	10
88	B	W	21	D	21	21
	B	E	17	19	17	18
	B	E	20	16	15	17
	V	W	14	14	14	14
	V	E	12	12	10	11
	V	E	11	15	12	13
91	B	N	9	7	11	9
	B	S	9	8	11	9
	B	S	5	14	7	9
92	B	W	11	18	16	15
	B	W	14	12	14	13
	B	E	10	N	10	7
	V	W	26	28	28	27
	V	W	25	30	28	30
	V	E	29	33	28	30
94	B	S	23	16	16	18
	B	S	10	14	18	14
	B	N	20	19	20	20
	V	S	13	15	18	15
	V	S	15	18	18	17
	V	N	6	6	7	6
100	B	W	7	N	4	4
	B	E	N	N	N	N
	B	E	N	N	N	N

Table 4

Absorption and Voids

Building No.	Component	Absorption (%) 1	2	3	Average	Permeable Voids (%) 1	2	3	Average
4	V	4.6	4.7	4.1	4.5	11.8	11.7	11.0	11.5
	PC	2.6	2.6	2.7	2.6	6.8	6.9	8.0	7.2
6	B	5.2	5.2	5.8	5.4	-	12.0	13.3	12.7
	B	6.1	5.8	4.8	5.6	13.9	14.5	11.5	13.3
	B	6.2	5.3	5.5	5.7	14.1	11.0	12.6	12.6
	V	3.6	2.9	4.1	3.5	7.9	6.1	8.8	7.6
	V	3.6	3.3	3.5	3.5	7.2	7.1	7.5	7.3
7	B	4.5	4.5	4.6	4.5	11.6	11.3	11.4	11.4
	B	4.3	4.4	4.6	4.4	11.1	11.2	11.5	11.3
	B	5.5	5.2	4.8	5.2	13.3	13.3	11.9	12.8
	V	4.3	4.3	4.6	4.4	11.0	11.3	11.0	11.1
	V	4.6	4.4	4.9	4.6	11.4	11.0	12.2	11.5
	V	5.2	4.8	5.1	5.0	12.5	12.3	13.2	12.7
8	V	5.1	6.0	5.9	5.7	14.5	14.4	15.6	14.8
	PC	5.6	5.0	5.9	5.5	14.2	13.0	14.3	13.8
11	PC	4.7	5.0	5.6	5.1	11.3	12.9	13.5	12.6
	PC	4.9	4.8	4.8	4.8	12.5	12.6	12.3	12.5
	PC	4.7	4.9	4.7	4.8	11.5	11.7	12.2	11.8
130	V	6.8	6.2	5.3	6.1	16.8	14.6	13.8	15.1
	V	5.6	5.3	5.7	5.5	14.0	12.7	15.4	14.0
	V	5.4	6.1	6.5	6.0	13.7	15.6	15.0	14.8
	PC	4.9	5.0	4.8	4.9	11.9	13.8	11.9	12.5
	PC	5.1	5.3	5.3	5.2	13.7	11.8	13.2	12.9
	PC	6.1	4.9	5.0	5.3	14.2	12.1	11.7	12.7
131	V	6.0	6.5	6.4	6.3	15.4	16.1	16.2	15.9
	PC	4.3	4.4	3.4	4.0	11.4	11.3	9.1	10.6
132	V	4.9	4.9	5.3	5.0	12.7	12.3	13.1	12.7
	V	5.5	5.3	5.3	5.4	13.8	13.5	13.9	13.8
	V	5.6	4.9	4.4	5.0	14.1	13.1	11.6	12.9
	PC	5.9	4.6	4.6	5.0	14.4	11.5	11.3	12.4
	PC	3.9	4.7	4.7	4.4	9.6	11.6	11.4	10.9
	PC	5.8	6.3	4.7	5.6	13.8	14.9	11.5	12.2
133	V	4.7	5.1	5.0	4.9	13.5	11.9	12.2	12.5
	V	4.9	4.8	4.2	4.6	11.8	11.5	10.5	11.3
	V	4.7	3.7	4.7	4.4	11.2	11.4	11.8	11.5
	PC	3.4	4.1	4.0	3.8	8.5	10.2	10.5	9.7
	PC	3.7	4.0	3.6	3.8	9.5	10.4	9.5	9.8
	PC	3.9	4.1	4.0	4.0	10.1	10.3	10.2	10.2
134	PC	4.7	4.5	4.6	4.6	13.3	11.0	13.2	12.5
28	B	4.8	4.8	5.6	5.1	12.0	12.3	14.0	12.8
	B	5.3	5.1	5.1	5.2	12.9	12.8	13.2	13.0
	B	4.6	4.5	5.4	4.8	11.9	11.9	12.6	12.1
	V	5.7	5.6	6.1	5.8	13.5	13.6	15.0	14.0
	V	5.8	6.0	6.0	5.9	13.3	14.1	14.4	13.9
	V	4.5	5.1	3.8	4.5	11.3	12.8	9.5	11.2

Building No.	Component	Absorption (%) 1	2	3	Average	Permeable Voids(%) 1	2	3	Average
29	B	5.3	5.1	4.8	5.1	9.1	12.5	11.7	11.1
	B	4.8	4.5	4.8	4.7	12.8	11.6	12.4	12.3
	B	4.7	4.9	4.9	4.8	12.0	12.3	12.1	12.1
	V	5.1	5.0	5.4	5.2	12.8	12.4	12.8	12.7
38	B	5.3	4.6	4.6	4.8	12.7	11.4	11.2	11.8
	B	-	4.9	4.7	4.8	-	11.9	11.5	11.7
	B	4.9	4.5	4.6	4.7	11.7	10.8	11.2	11.2
44	B	4.5	4.4	4.6	4.5	11.6	10.8	10.8	11.1
	B	5.0	4.0	4.8	4.6	12.1	11.7	11.9	11.9
	B	4.4	4.5	4.3	4.4	10.7	10.9	11.1	10.9
	V	4.9	5.6	5.2	5.2	11.7	13.3	12.6	12.5
	V	4.2	4.3	4.4	4.3	10.6	10.7	11.6	11.0
	V	4.5	4.8	5.0	4.8	11.3	11.6	12.6	11.9
61	B	5.4	3.4	5.3	4.7	15.4	11.0	15.7	14.0
	B	5.7	5.5	5.7	5.6	14.8	13.7	13.9	14.1
	V	6.2	5.4	6.1	5.9	15.7	14.0	15.8	15.2
	V	5.5	5.7	5.5	5.6	13.9	14.2	14.0	14.0
62	B	5.8	5.1	4.9	5.3	17.3	17.3	16.4	17.0
	B	4.8	4.6	4.9	4.8	17.0	15.0	16.0	16.0
	V	6.1	5.4	7.2	6.2	15.1	14.0	16.5	15.2
	V	5.2	5.1	5.1	5.1	12.9	12.6	12.3	12.6
66	B	5.2	5.9	6.1	5.7	13.0	13.6	14.1	13.6
	V	2.7	2.4	2.4	2.5	6.5	5.7	6.2	6.1
67	B	5.2	5.1	5.7	5.3	12.4	12.0	13.9	12.8
	V	2.5	2.1	2.3	2.3	6.2	5.1	5.9	5.7
69	B	2.8	-	2.7	2.8	7.0	-	7.1	7.1
	V	1.5	1.2	1.1	1.3	3.6	3.0	2.6	3.1
75	B	4.8	5.4	4.7	5.0	12.1	13.4	12.4	12.6
	B	5.8	5.3	5.6	5.6	13.8	13.2	13.9	13.6
	B	6.0	6.0	5.1	5.7	15.1	14.5	13.2	14.3
	V	5.7	5.8	6.3	5.9	15.0	15.2	16.1	15.4
	V	6.5	5.8	6.0	6.1	15.7	14.1	14.6	14.8
	V	5.9	5.4	5.8	5.7	14.9	13.5	14.6	14.3
79	B	5.1	4.8	5.2	5.0	12.4	11.2	12.2	11.6
	B	4.4	5.0	4.5	4.6	11.3	12.4	11.5	11.7
	B	4.7	6.3	4.9	5.3	11.2	15.3	12.3	12.9
	V	1.6	2.8	1.7	2.0	4.7	9.3	4.5	6.2
	V	2.8	3.0	2.7	2.8	7.1	8.0	7.1	7.4
	V	2.2	2.8	-	2.5	6.0	7.1	-	6.6
81	B	5.6	5.8	5.8	5.7	14.0	14.1	14.0	14.0
	B	5.6	5.6	5.6	5.6	13.4	13.7	14.8	14.0
86	PC	5.6	5.6	5.7	5.6	16.0	13.3	13.4	14.2
	PC	4.9	5.6	5.4	5.3	12.1	13.6	13.2	13.0
	PC	6.9	6.6	6.5	6.7	18.4	15.4	15.5	16.4
	PC	4.0	4.3	5.8	4.7	9.9	13.9	14.6	12.8
	PC	4.8	4.8	5.6	5.1	12.7	11.5	13.2	12.5
	PC	5.5	5.8	5.8	5.7	13.4	13.2	13.6	13.4

Building No.	Component	Absorption (%) 1	2	3	Average	Permeable Voids (%) 1	2	3	Average
88	B	4.2	-	5.8	5.0	17.4	-	15.7	16.6
	B	5.2	5.3	5.3	5.3	13.3	14.2	13.4	13.6
	B	5.4	5.4	3.1	4.6	14.3	13.7	8.5	12.2
	V	5.7	5.8	3.7	5.1	13.9	14.3	9.2	12.5
	V	5.9	5.5	6.2	5.9	14.9	17.5	15.8	16.1
	V	6.2	5.8	6.1	6.0	15.0	14.3	14.8	14.7
91	B	7.0	6.8	6.2	6.7	17.3	16.1	15.1	16.2
	B	5.5	5.7	5.1	5.4	14.2	14.8	13.1	14.0
	B	6.1	5.4	5.4	5.6	15.1	13.2	14.2	14.2
92	B	6.8	6.7	6.6	6.7	15.8	16.7	16.7	16.4
	B	6.4	5.8	6.5	6.2	15.6	14.2	16.0	15.3
	B	5.9	7.4	6.0	6.4	14.9	16.6	15.1	15.5
	V	7.5	6.5	5.8	6.6	17.8	15.7	14.1	15.9
	V	6.0	5.8	6.2	6.0	13.3	14.5	14.8	14.2
	V	6.3	6.7	6.6	6.5	15.6	16.3	16.0	16.0
94	B	5.2	5.2	5.7	5.4	12.8	12.9	13.6	13.1
	B	4.9	5.4	5.4	5.2	12.2	13.3	13.7	13.1
	B	4.7	5.6	6.0	5.4	12.6	14.1	13.9	13.5
	V	5.5	5.4	5.8	5.6	13.5	13.5	13.7	13.6
	V	5.8	5.5	5.9	5.7	14.5	13.2	14.1	14.0
	V	5.6	5.0	6.5	5.7	13.7	12.4	15.4	13.8
100	B	6.7	5.6	1.8	4.7	16.0	14.1	8.8	13.0
	B	4.9	4.6	4.6	4.7	11.4	11.3	11.4	11.4
	B	5.0	5.6	4.8	5.1	12.2	13.9	11.5	12.5

Table 5

Chloride Contents

BUILDING	BUILDING COMPONENT	CORE	HORIZON (MM FROM OUTSIDE FACE)		
			0 - 10	30 - 40	60 - 70
6	V	1	0.016	0.012	0.014
		2	0.016	0.015	0.011
		3	0.012	0.017	0.012
7	V	10	0.013	0.012	0.044
		11	0.010	0.017	0.025
		12	0.022	0.023	0.020
28	B	4	0.021	0.017	0.026
		5	0.026	0.035	0.027
		6	0.020	0.020	0.029
29	B	7	0.031	0.017	0.016
		8	0.037	0.016	0.021
		9	0.028	0.020	0.016
	V	10	0.019	0.031	0.052
		11	0.014	0.023	0.010
		12	0.007	0.017	0.011
38	B	1	0.025	0.016	0.007
		2	0.018	0.007	0.013
		3	0.008	0.006	0.023
44	B	7	0.025	0.008	0.005
		8	0.011	0.012	0.012
		9	0.007	0.006	0.023
61	B	1	0.011	0.022	0.020
		2	0.011	0.035	0.045
		3	0.008	0.034	0.043
	V	10	0.010	0.019	0.028
		11	0.021	0.022	0.022
		12	0.019	0.025	0.029
62	V	4	0.020	0.042	0.035
		5	0.024	0.030	0.026
		6	0.023	0.027	0.024
	B	7	0.011	0.040	0.040
		8	0.012	0.034	0.030
		9	0.005	0.042	0.037

BUILDING	BUILDING COMPONENT	CORE	HORIZON (MM FROM OUTSIDE FACE)		
			0 - 10	30 - 40	60 - 70
66	B	1	0.012	0.012	0.010
		2	0.010	0.012	0.012
		3	0.012	0.012	0.012
67	B	1	0.008	0.008	0.004
		2	0.008	0.010	0.008
		3	0.011	0.013	0.010
69	B	1	0.029	0.028	0.019
		2	0.034	0.029	0.026
		3	0.033	0.021	0.022
	V	4	0.030	0.034	0.030
		5	0.044	0.051	0.054
		6	0.054	0.070	0.059
75	B	7	0.024	0.031	0.020
		8	0.041	0.027	0.034
		9	0.028	0.023	0.025
	V	10	0.005	0.008	0.008
		11	0.005	0.008	0.009
		12	0.010	0.010	0.009
81	B	1	0.020	0.012	0.009
		2	0.017	0.014	0.008
		3	0.039	0.014	0.010
86	B(PC)	1	0.017	0.011	0.012
		2	0.015	0.012	0.010
		3	0.021	0.010	0.012
	V(PC)	4	0.011	0.009	0.010
		5	0.011	0.009	0.013
		6	0.005	0.008	0.007
88	B	7	0.017	0.045	0.025
		8	0.017	0.024	0.036
		9	0.015	0.038	0.017
92	V	10	0.023	0.030	0.027
		11	0.033	0.027	0.013
		12	0.026	0.036	0.035
94	B	1	0.034	0.028	0.026
		2	0.027	0.033	0.033
		3	0.028	0.026	0.031

BUILDING	BUILDING COMPONENT	CORE	HORIZON (MM FROM OUTSIDE FACE)		
			0-10	30 - 40	60 - 70
100	B	4	0.011	0.009	0.009
		5	0.011	0.008	0.012
		6	0.011	0.009	0.012
130	V	7	0.008	0.014	0.013
		8	0.016	0.013	0.013
		9	0.008	0.014	0.013
	PC	13	0.009	0.016	0.017
		14	0.012	0.012	0.012
		15	0.007	0.009	0.010
131	V	1	0.036	0.031	0.037
		2	0.038	0.027	0.029
		3	0.028	0.025	0.023
132	V	4	0.021	0.019	0.023
		5	0.017	0.022	0.018
		6	0.011	0.025	0.014
133	V	4	0.017	0.017	0.026
		5	0.012	0.009	0.013
		6	0.015	0.017	0.015
	PC	10	0.027	0.012	0.017
		11	0.012	0.009	0.013
		12	0.015	0.017	0.015

Table 6

Summary of Carbonation Depths

Building No.	Age (Years)	Average Depth of Carbonation (mm) Balconies	Vertical cast-in-place Concrete	Pre-cast
4	27	-	9	N
6	12	2	16	-
7	20	2	15	-
8	20	-	9	6
11	16	-	-	4
130	22	-	15	20
131	16	-	3	2
132	25	-	23	4
133	22	-	5	N
134	16	-	-	1
28	16	15	14	-
29	20	4	22	-
38	20	5	-	-
44	16	N	13	-
61	20	17	21	-
62	20	28	16	-
66	18	5	8	-
67	18	8	5	-
69	18	4	5	-
75	17	3	31	-
79	16	6	15	-
81	23	4	-	-
86	16	-	-	2(B)
		-	-	11(W)
88	18	19	13	-
91	21	9	-	-
92	15	12	28	-
94	18	17	13	-
100	17	1	-	-
Average		8	14	5
Range		N-28	3-31	N-20
				2
				N-6

Note: 1. For the precast wall panels, if the results for buildings 130 and 86 are discarded, the results become:

2. (B) Balconies, (w) Wall panels

Table 7

Summary of Splitting Tensile Tests

Building No.	Average Tensile Strength (MPa)		
	Balconies	Vertical Cast-in-place Concrete	Pre-cast
4	-	4.72	5.56
6	5.83	2.69	-
7	4.14	4.07	-
8	-	2.82	4.57
11	-	-	3.94
130	-	2.79	3.46
131	-	5.28	4.09
131	-	3.37	4.14
133	-	3.80	4.82
134	-	-	4.59
28	3.61	3.49	-
29	3.25	2.82	-
38	3.35	-	-
44	2.77	2.87	-
61	3.60	3.06	-
62	4.65	3.55	-
66	3.41	2.91	-
67	2.72	2.59	-
69	3.08	4.62	-
75	3.56	2.74	-
79	3.62	2.48	-
81	3.64	-	-
86	-	-	3.14(B) 3.63(W)
88	2.14	2.63	-
91	3.26	-	-
92	2.48	2.83	-
94	2.53	2.95	-
100	2.95	-	-

Table 8

Summary of Absorptions and Voids

Building No.	Absorption (%)			Voids (%)		
	Balconies	Cast-in-place concrete	Pre-cast	Balconies	Cast-in-place concrete	Precast
4	-	4.5	2.6	-	11.5	7.2
6	5.6	3.5	-	12.9	7.5	-
7	4.7	4.7	-	11.8	11.8	-
8	-	5.7	5.5	-	14.8	13.8
11		-	-	4.9	-	-
130						
130	-	5.9	5.1	-	14.6	12.7
131	-	6.3	4.0	-	15.9	10.6
132	-	5.1	5.0	-	13.1	11.8
133	-	4.6	3.9	-	11.8	9.9
134	-	-	4.6	-	-	12.5
28	5.0	5.4	-	12.6	13.4	-
29	4.9	5.2	-	11.8	12.7	-
38	4.8	-	-	11.6	-	-
44	4.5	4.8	-	11.3	11.8	-
61	5.2	5.8	-	14.1	14.6	-
62	5.1	5.7	-	16.5	13.9	-
66	5.7	2.5	-	13.6	6.1	-
67	5.3	2.3	-	12.8	5.7	-
69	2.8	1.3	-	7.1	2.6	-
75	5.4	5.9	-	13.5	14.8	-
79	5.0	2.4	-	12.1	6.7	-
81	5.7	-	-	14.0	-	-
86	-	-	5.9	-	-	14.5
	-	-	5.2	-	-	12.9
88		5.0	5.3	-	14.1	14.4
		-				
91	5.9	-	-	14.8	-	-
92	6.4	6.4	-	15.7	15.4	-
94	5.3	5.7	-	13.2	13.8	-
100	4.8	-	-	12.3	-	-

Table 9

Summary of Constants B

Building No.	Age (Years)	Balconies	Vertical cast-in-place Concrete	Pre-cast
4	27	-	0.17	Nil
6	12	0.06	0.35	-
7	20	0.05	0.34	-
8	20	-	0.20	0.13
11	16	-	-	0.10
130	22	-	0.32	0.43
131	16	-	0.08	0.05
132	25	-	0.46	0.08
133	22	-	0.11	Nil
134	16	-	-	0.03
28	16	0.38	0.35	-
29	20	0.09	0.49	-
38	20	0.11	-	-
44	16	Nil	0.33	-
61	20	0.38	0.47	-
62	20	0.63	0.36	-
66	18	0.12	0.19	-
67	18	0.19	0.12	-
69	18	0.09	0.12	-
75	17	0.07	0.75	-
79	16	0.15	0.38	-
81	23	0.08	-	-
86	16	-	-	0.05
		-	-	0.28
88	18	0.45	0.31	-
91	21	0.20	-	-
92	15	0.31	0.72	-
94	18	0.40	0.31	-
100	17	0.02	-	-

Table 10

Splitting Tensile Tests: Statistical Summary

	Balconies	Vertical Cast-in-place Concrete		Pre-cast
Without Public Building	N = 17 $\bar{x}$ = 3.21 s = 0.59	N = 13 $\bar{x}$ = 3.04 s = 0.57	**Public Buildings**	N = 8 $\bar{x}$ = 4.39 s = 0.64
All Buildings	N = 19 $\bar{x}$ = 3.39 s = 0.83	N = 21 $\bar{x}$ = 3.21 s = 0.79		N = 10 $\bar{x}$ = 4.19 s = 0.72

Table 11

Summary of Absorptions and Voids

Absorption (%)

	Balconies	Cast-in-place concrete		Pre-cast
Excluding Public Building	N = 17 $\bar{x}$ = 5.1 s = 0.76	13 4.5 1.72	**Public Buildings**	8 4.5 0.92
All Buildings	N = 19 $\bar{x}$ = 5.1 s = 0.76	21 4.6 1.42		10 4.7 0.95

Voids (%)

	Balconies	Cast-in-place concrete		Pre-cast
Excluding Public Building	N = 17	13	**Public Buildings**	8
	$\bar{x}$ = 13.0	11.2		11.4
	s = 2.08	4.32		2.08
All Buildings	N= 19	21		10
	$\bar{x}$ = 12.9	11.8		11.8
	s = 1.98	3.76		2.11

Table 12

Orientation of Building Components

Building No.	Balconies				Vertical Cast-In-Place Concrete				Precast Concrete			
	N	S	E	W	N	S	E	W	N	S	E	W
4					9				N			
6	3	2			18	14						
7	2			3	16			14				
8							9				6	
11										3		5
130						15						20
131								3				2
132							23			4		
133						5						
134												1
28		20	6			14	16					
29			3	8		22						
38				5								
44	2	5			12	15						
61	10	23			22	19						
62			24	31			25	7				
66			5			8						
67		8				5						
69		4					5					
75			4	3			26	34				
79			4	8			15	15				
81	4											
86									3	1		B
87									10	13		W
88			18	21			14	14				
91	9	9										
92			7	14			30	29				
94	20	16			6	16						
100			N	4								
Avgs.	7	11	8	11	14	13	18	17	7	5	6	7

Table 13

Values of B: Statistical Summary

	Balconies	Cast-In-Place Vertical Concrete		Pre-Cast Concrete
Excluding Public Buildings	N = 17	13	**Public Buildings**	8
	$\bar{x}$ = 0.21	0.38		0.10
	s = 0.18	0.20		0.14
With Public Buildings	N = 19	21	**All Buildings**	10
	$\bar{x}$ = 0.20	0.33		0.11
	s = 0.17	0.18		0.14

Table 14

Average Chloride Contents

BUILDING COMPONENT: BALCONIES

BUILDING	PUBLIC(P) OR RESIDENTIAL(R)	HORIZON (MM FROM OUTSIDE FACE) 0 - 10	30 - 40	60 - 70
28	R	0.022	0.024	0.027
29	R	0.032	0.018	0.018
38	R	0.017	0.010	0.010
44	R	0.014	0.009	0.013
61	R	0.010	0.030	0.029
62	R	0.009	0.039	0.036
66	R	0.011	0.012	0.011
67	R	0.009	0.010	0.007
69	R	0.032	0.026	0.022
75	R	0.031	0.027	0.026
81	R	0.025	0.013	0.009
88	R	0.016	0.037	0.026
94	R	0.030	0.029	0.030
100	R	0.011	0.009	0.011
BUILDING COMPONENTS: VERTICAL CAST-IN-PLACE CONCRETE				
6	P	0.013	0.015	0.012
7	P	0.015	0.017	0.030
29	R	0.013	0.024	0.024
61	R	0.017	0.022	0.026
62	R	0.022	0.033	0.028
69	R	0.043	0.052	0.048
75	R	0.007	0.009	0.009
92	R	0.027	0.031	0.025
130	P	0.011	0.014	0.013
131	P	0.034	0.028	0.030
132	P	0.016	0.022	0.018
133	P	0.015	0.014	0.018
BUILDING COMPONENTS: PRE-CAST CONCRETE				
86	R	0.018	0.011	0.011
		0.009	0.009	0.010
130	P	0.009	0.012	0.013
133	P	0.018	0.013	0.015

Table 15

Summary of Properties

Building	Sample	Component	Orientation	Splitting Tensile Strength (MPa)	Absorption %	Carbonation Depth (mm)
6	6/5	V	S	2.64	3.3	2.0
61	61/5	V	S	3.34	5.4	15
91	91/1	B	N	3.38	7.0	9
	91/8	B	S	3.57	5.4	14
92	92/3	B	W	2.49	6.6	16
	92/9	V	W	2.30	5.8	28
133	133/9	V	S	3.97	4.7	10

NOTES: V - vertical cast-in-place
B - Balcony
S - South
N - North
w - West

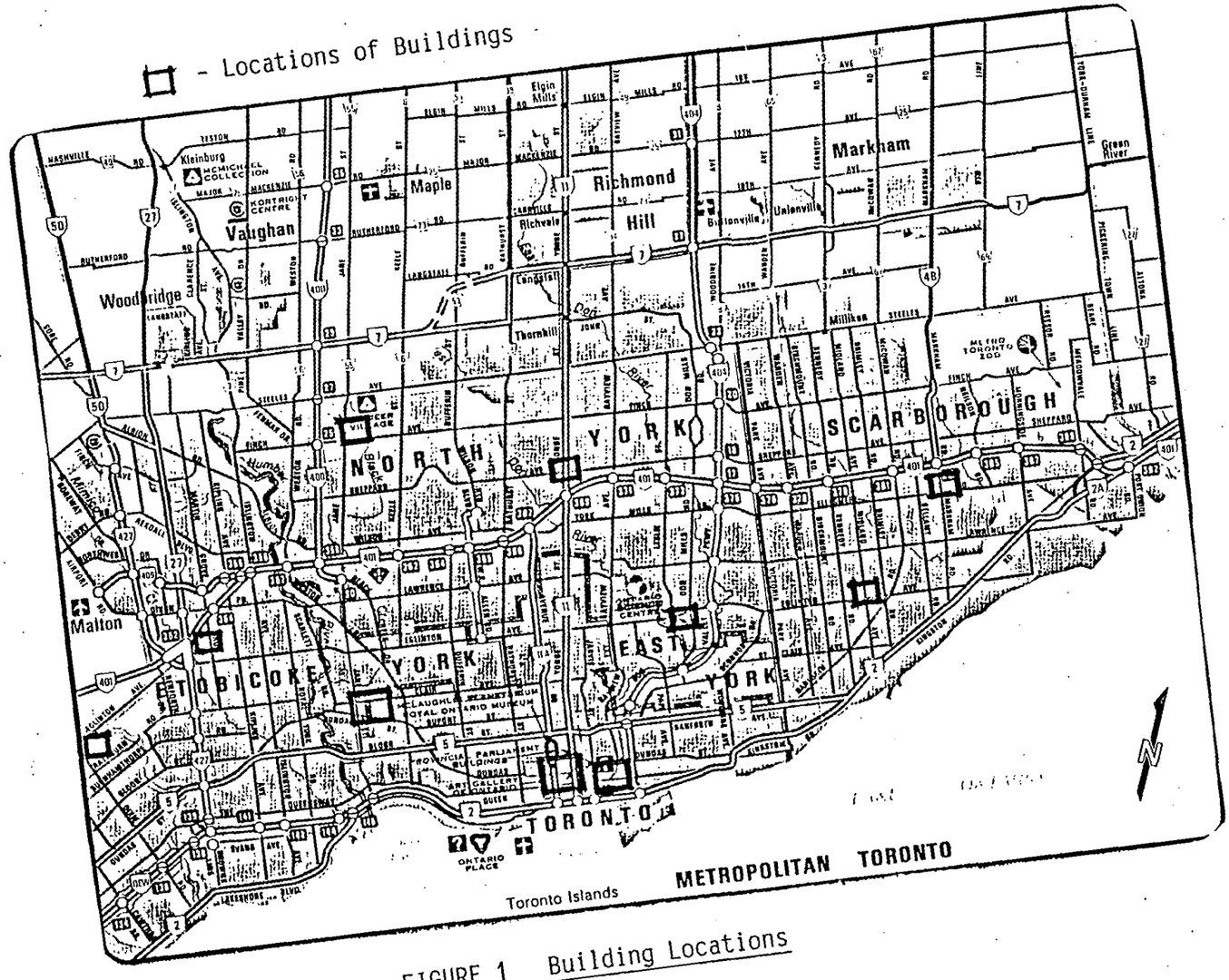
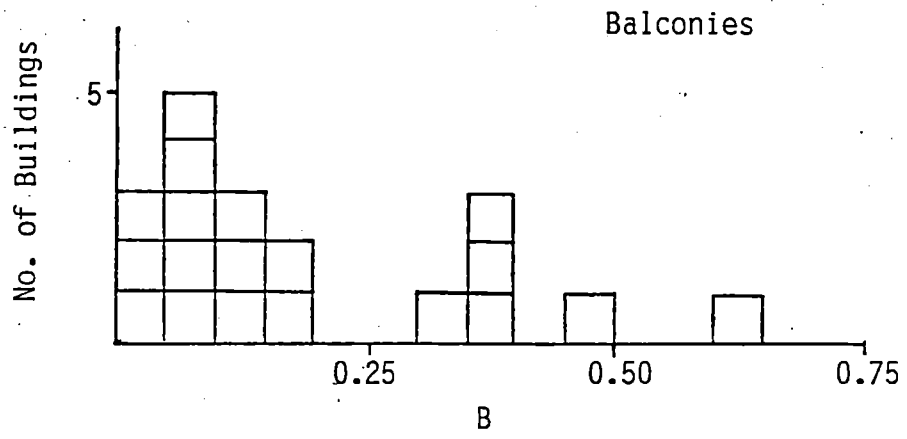
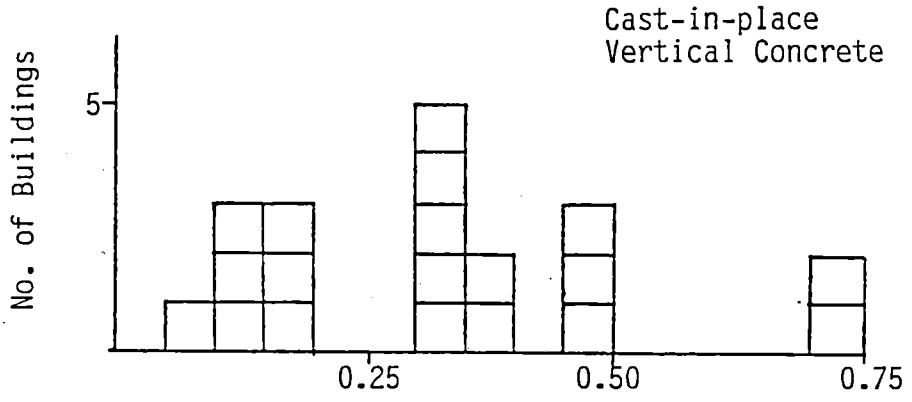


FIGURE 1 Building Locations





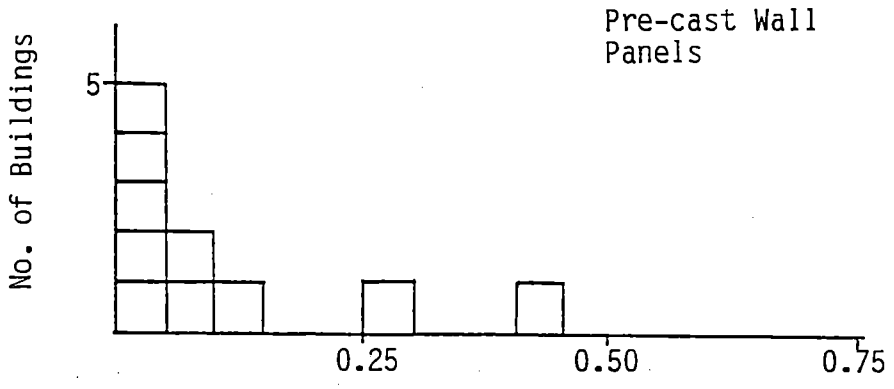


FIGURE 2: VALUES OF B

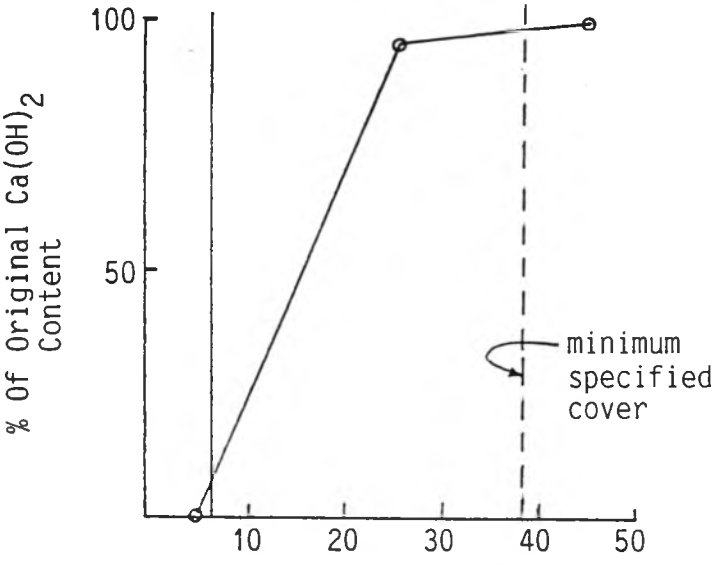


FIG 3
Sample 4/4

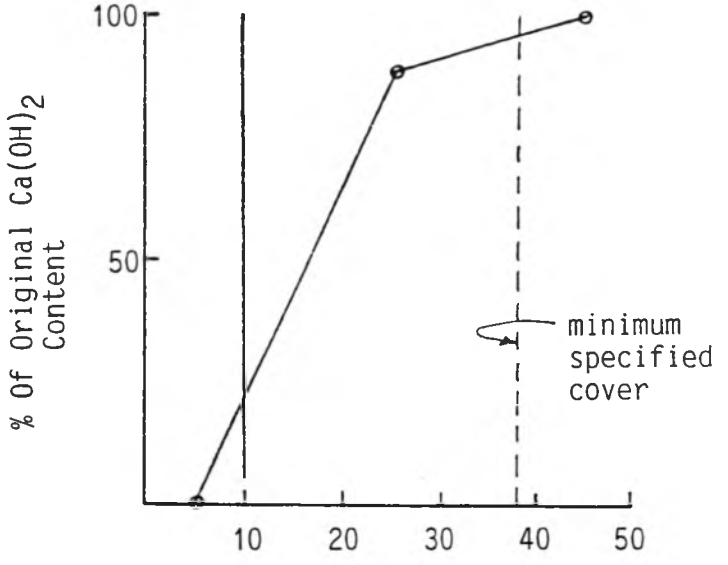


FIG 4
Sample 6/5

Vertical line and shaded area shows depth
of carbonation as determined by phenolphthalein

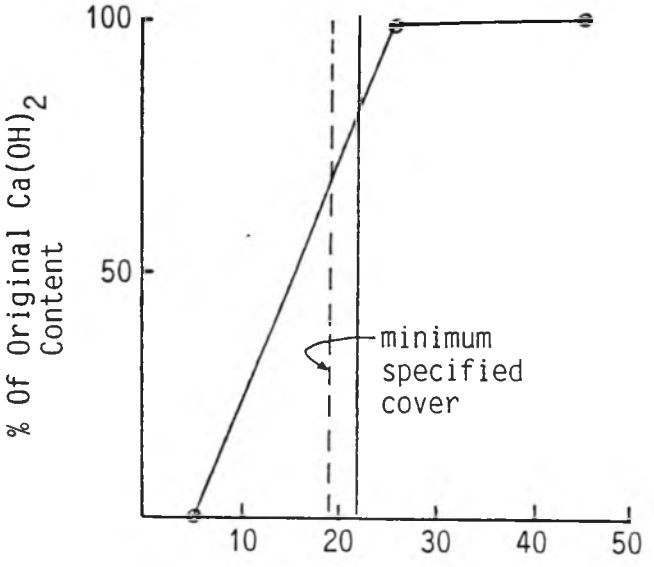


FIG 5
Sample 28/3

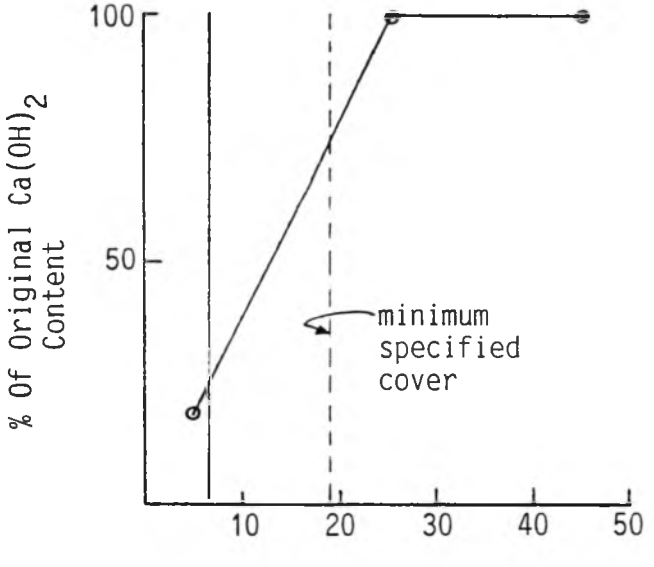


FIG 6
Sample 38/4

Vertical line and shaded area shows depth of carbonation as determined by phenolphthalein

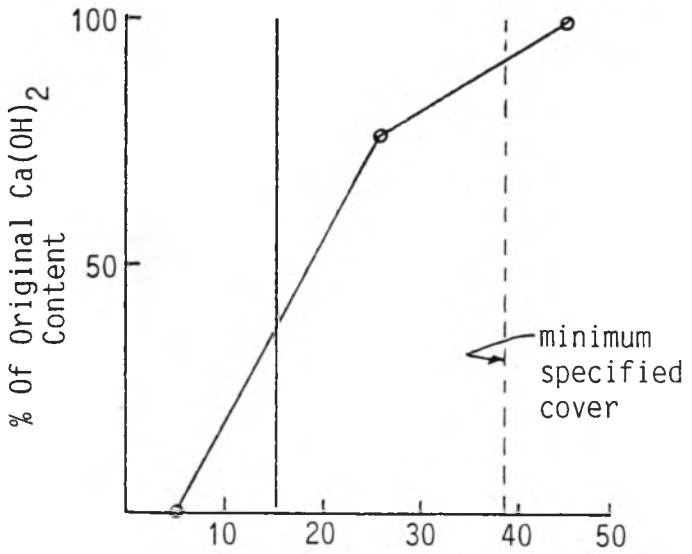


FIG 7
Sample 61/5

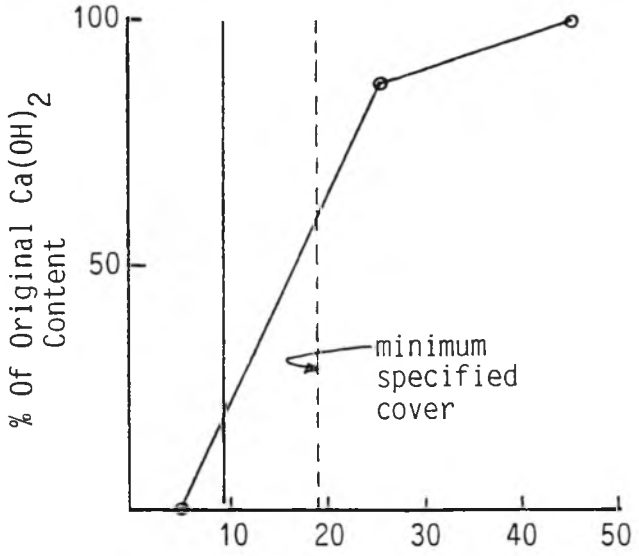


FIG 8
Sample 91/1

Vertical line and shaded area shows depth of carbonation as determined by phenolphthalein

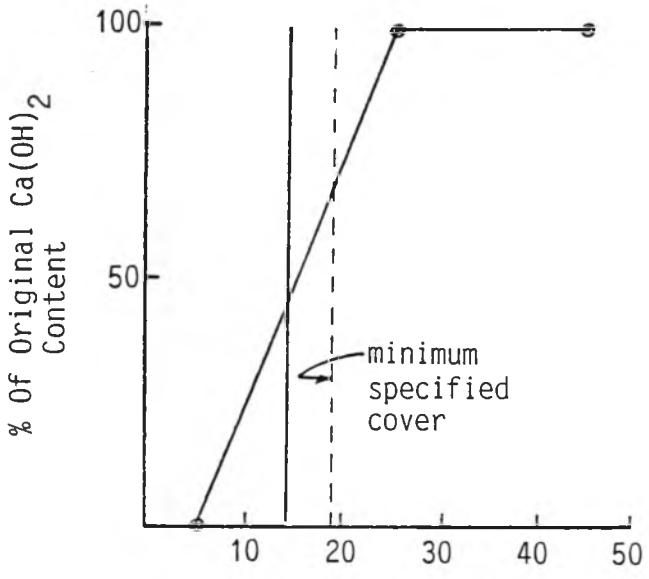


FIG 9
Sample 91/8

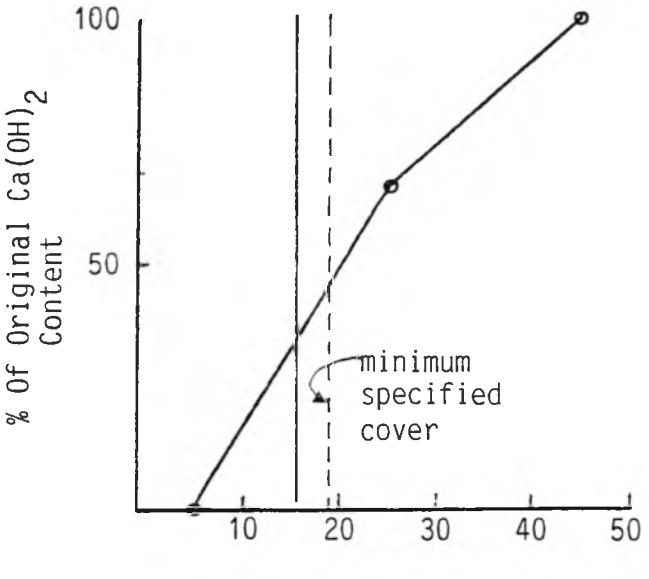


FIG 10
Sample 92/3

Vertical line and shaded area shows depth of carbonation as determined by phenolphthalein

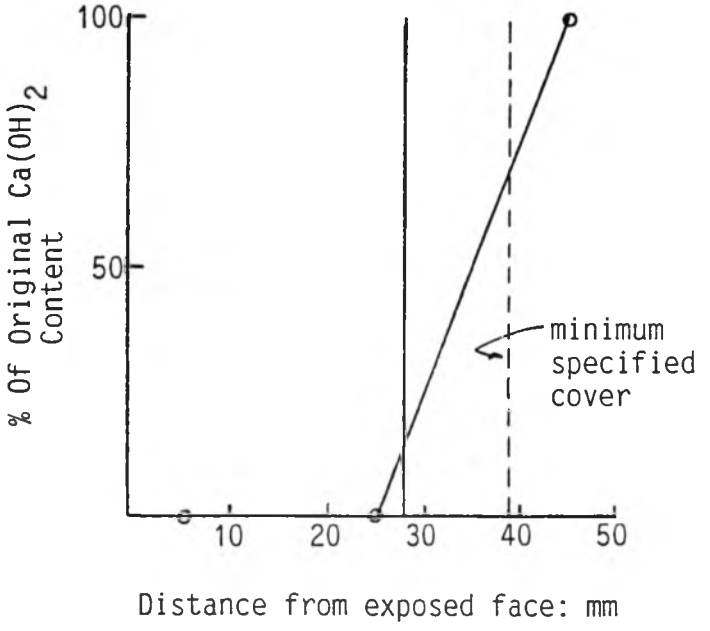


FIG 11

Sample 92/9

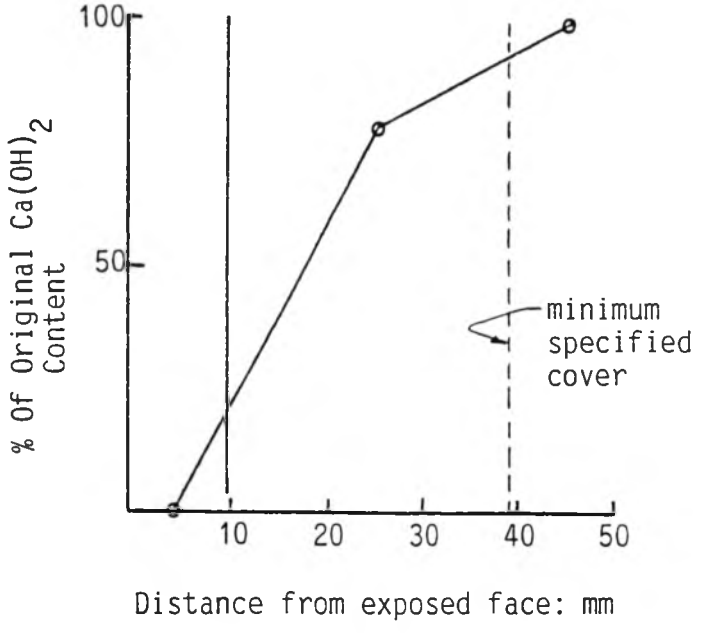


FIG 12

Sample 133/9

Vertical line and shaded area shows depth of carbonation as determined by phenolphthalein

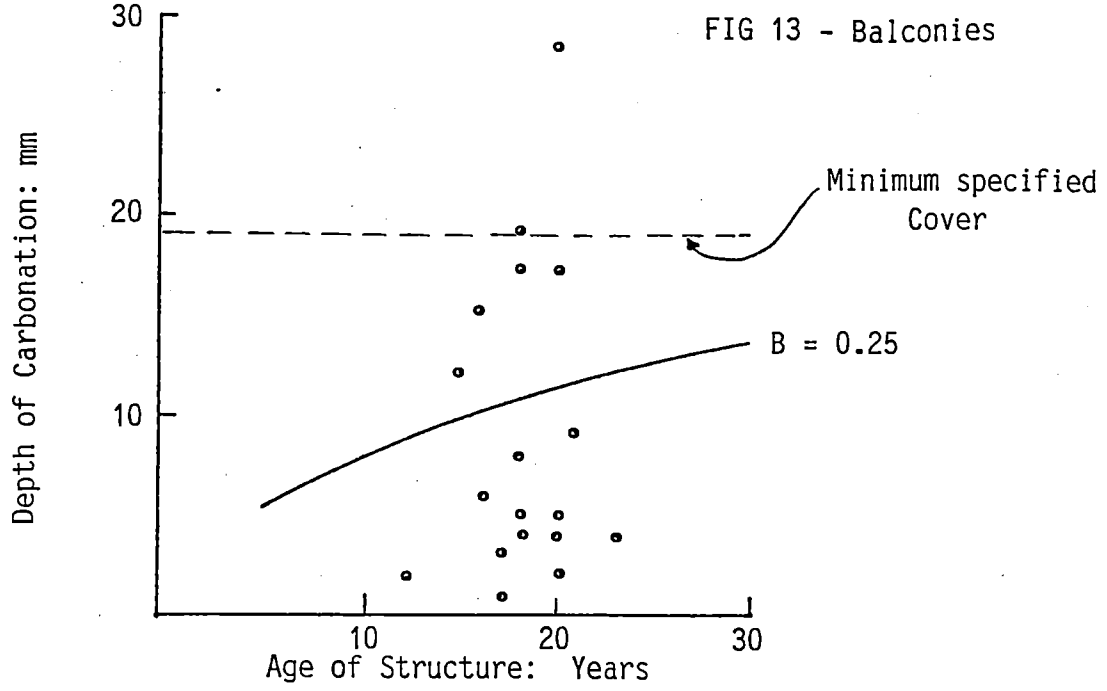


FIG 13 - Balconies

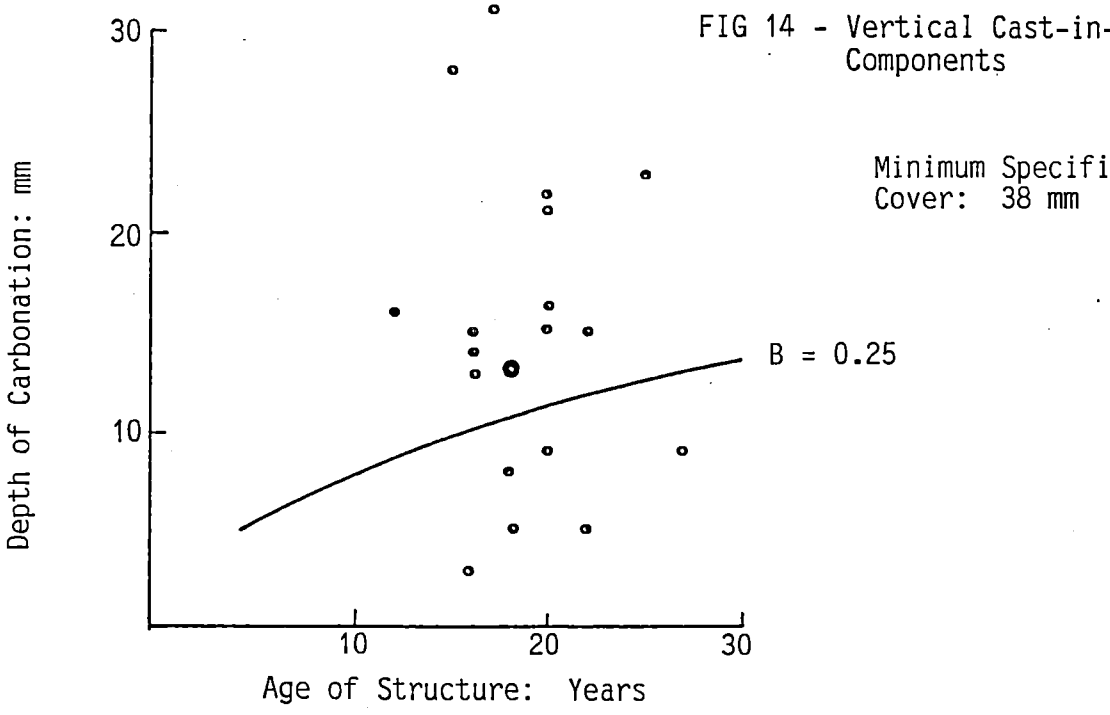


FIG 14 - Vertical Cast-in-place Components

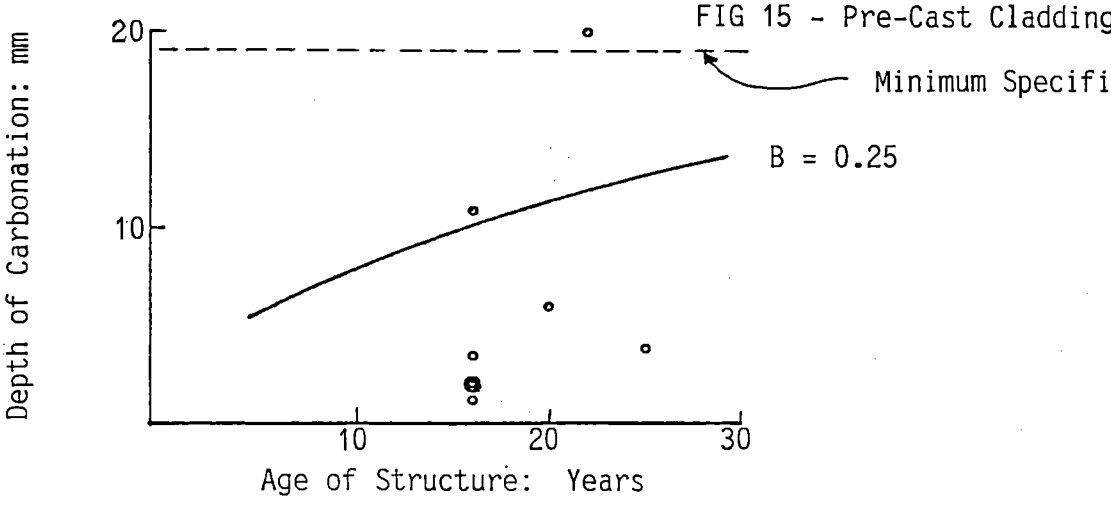


FIG 15 - Pre-Cast Cladding

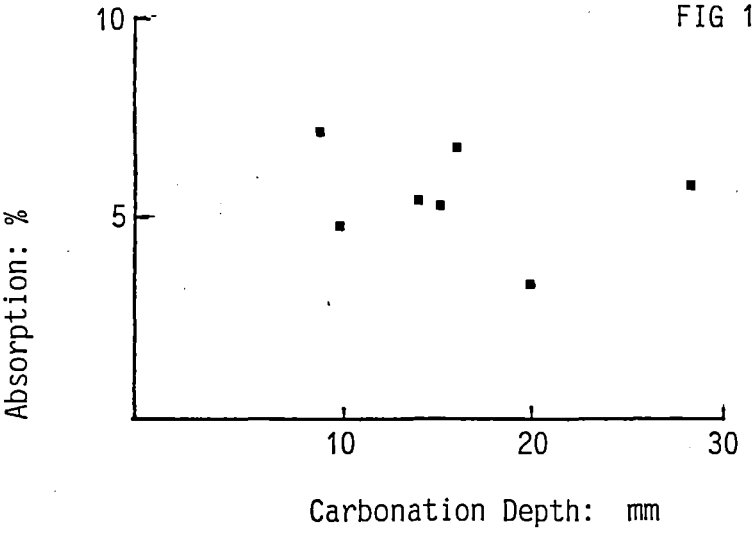


FIG 16 - Carbonation Depth and Absorption

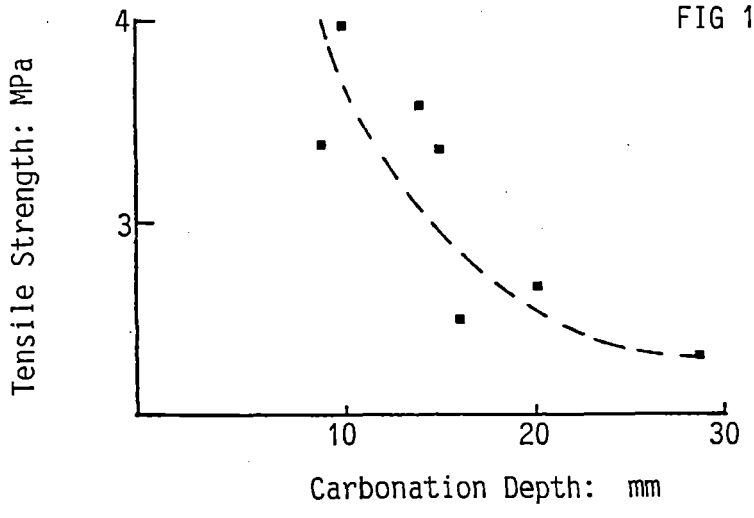


FIG 17 - Carbonation Depth and Tensile Strength

APPENDIX "A"

National Research Council Canada
Conseil national de recherches Canada

Institute for Research in Construction
Institut de recherche en construction

CLIENT REPORT

for

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Suite 214, 208 Evans Avenue
Toronto, Ontario M8Z 1J7

Determination of the Lime and Carbonate Content of Concrete Core Specimens

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Approved J.J. Beaudoin
Section Head

Approved W.A. Dalgliesh
Head, Quality Assurance

Report No. CR-5864.1
Report date: 8 December 1989
Contract No. CR-5864
Reference: Application for test dated 24 February 1989
Section: Materials

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Canada

DETERMINATION OF THE LIME AND CARBONATE CONTENT OF CONCRETE CORE SPECIMENS

Introduction

The lime and carbonate content of concrete core specimens, received from John A. Bickley Associates, were determined by Thermogravimetric Analysis.

Specimens

The cores received were registered in our laboratory as follows:

Original Code Number	IRC Code Number
4/4	D 135
6/5	D 136
28/3	D 137
38/4	D 138
61/5	D 139
91/1	D 140
91/8	D 141
92/3	D 142
92/9	D 143
133/9	D 144

With a water-cooled diamond saw 10 mm thick slices were cut off from the samples. The 0 to 10, the 20 to 30 and 40 to 50 mm sections (the reference point being the external surface) were selected for the analysis. These specimens were identified by adding to their code numbers the suffix 10, 30 and 50, respectively.

Without removing the coarse aggregates the specimens were dried and pulverized in a Buhler grinder.

The specimens to be analyzed were kept in a sealed vial until tested.

Thermogravimetry

Specimens, 50 mg in weight, were heated in a DuPont Model 9900 instrument at 20°C/min in a stream of nitrogen gas (100 mL/min).

Results

The results of the thermogravimetric analysis are shown in a graphical form in Figures 1 through 30.

The absolute weight loss percent (ordinate on the left hand side) as a function of temperature and the first derivative of the weight percent lost (ordinate on the right hand side) as a function of the temperature are given.

Due to a computer error the Run Date is incorrect.

The results are presented also in a tabular form (Table 1).

The peak of the derivative that occurs between 450 and 550°C is due to decomposition of $Ca(OH)_2$ in hydrated tricalcium silicate. The peak at approximately 780°C indicates the decomposition of $CaCO_3$.

The areas below the peaks were integrated and the obtained values are directly proportioned to the $Ca(OH)_2$ and $CaCO_3$ concentrations in the specimens.

Comments

Because there is no method available to remove reliably from the concrete all aggregate, which may contain $CaCO_3$, the values given in Table 1 indicate the total $CaCO_3$ concentrations, not only that resulting from the carbonation of lime with atmospheric CO_2.

The extent of carbonation can be estimated from the weight losses at around 450°C. As a first approximation one may assume that at the peaks obtained by testing the code 50 specimens represent the lime content of, or close to, that originally present in the hydrated cement. Accepting the lime content of code 50 specimens as reference, the decrease at a given horizon is the measure of the extent of carbonation.

TABLE 1. RESULTS OF CARBONATION TESTS ON CONCRETE CYLINDERS

SAMPLE NO.	WEIGHT LOSS EXPRESSED AS % OF ORIGINAL SAMPLE WEIGHT				
	PEAK AT 450 DEG. C		PEAK AT 800 DEG. C		IGNITED WT AT 1000 DEG. C
	AS H2O	AS Ca(OH)2	AS CO2	AS CaCO3	
D135-10	0.00	0.00	26.76	60.88	68.68
D135-30	0.48	1.97	20.86	47.46	73.96
D135-50	0.50	2.05	23.22	52.83	71.66
D136-10	0.00	0.00	14.06	31.99	82.54
D136-30	0.41	1.69	10.46	23.80	84.81
D136-50	0.46	1.90	9.66	21.98	84.95
D137-10	0.00	0.00	21.78	49.55	74.27
D137-30	0.20	0.80	27.72	63.06	67.37
D137-50	0.20	0.81	25.69	58.44	69.25
D138-10	0.08	0.34	21.11	48.03	73.36
D138-30	0.51	2.11	18.98	43.18	76.42
D138-50	0.43	1.77	21.84	49.69	73.49
D139-10	0.00	0.00	28.29	64.36	68.22
D139-30	0.23	0.93	29.85	67.91	66.03
D139-50	0.30	1.22	25.99	59.13	70.02
D140-10	0.00	0.00	29.19	66.41	66.94
D140-30	0.16	0.68	23.66	53.83	71.43
D140-50	0.19	0.77	27.68	62.97	68.52
D141-10	0.00	0.00	30.50	69.39	65.87
D141-30	0.14	0.56	27.42	62.38	68.55
D141-50	0.13	0.55	28.55	64.95	67.45
D142-10	0.00	0.00	23.67	53.85	73.00
D142-30	0.22	0.90	26.62	60.56	69.27
D142-50	0.33	1.36	21.75	49.48	73.95
D143-10	0.00	0.00	22.56	51.32	74.28
D143-30	0.00	0.00	25.35	57.67	70.82
D143-50	0.24	0.97	26.82	61.02	69.14
D144-10	0.00	0.00	25.03	56.94	71.66
D144-30	0.27	1.11	27.26	62.02	69.05
D144-50	0.34	1.40	23.46	53.37	72.50

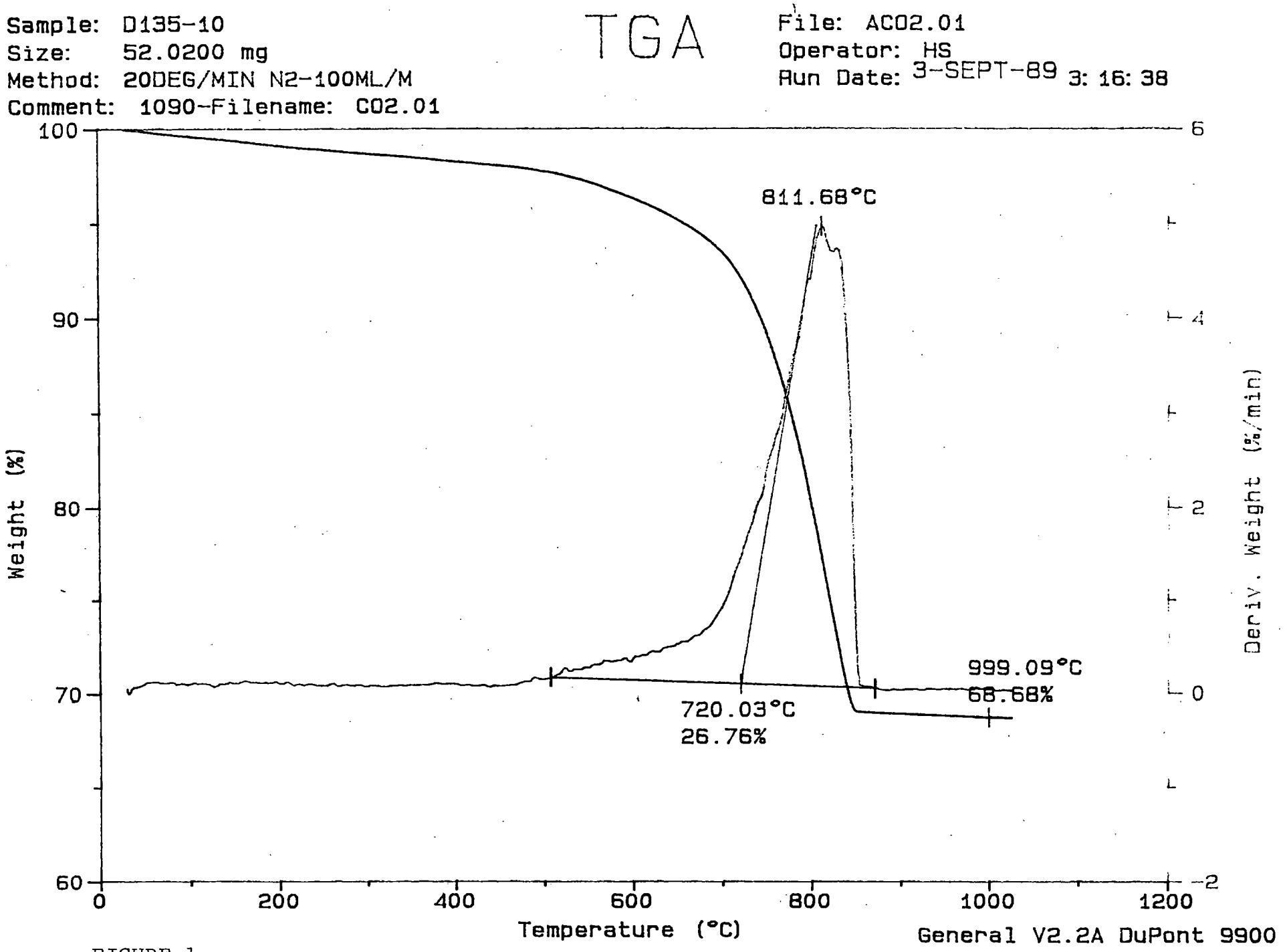
Sample: D135-10
Size: 52.0200 mg
Method: 20DEG/MIN N2-100ML/M
Comment: 1090-Filename: C02.01
TGA
File: AC02.01
Operator: HS
Run Date: 3-SEPT-89 3:16:38
811.68°C
999.09°C
68.68%
720.03°C
26.76%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 1

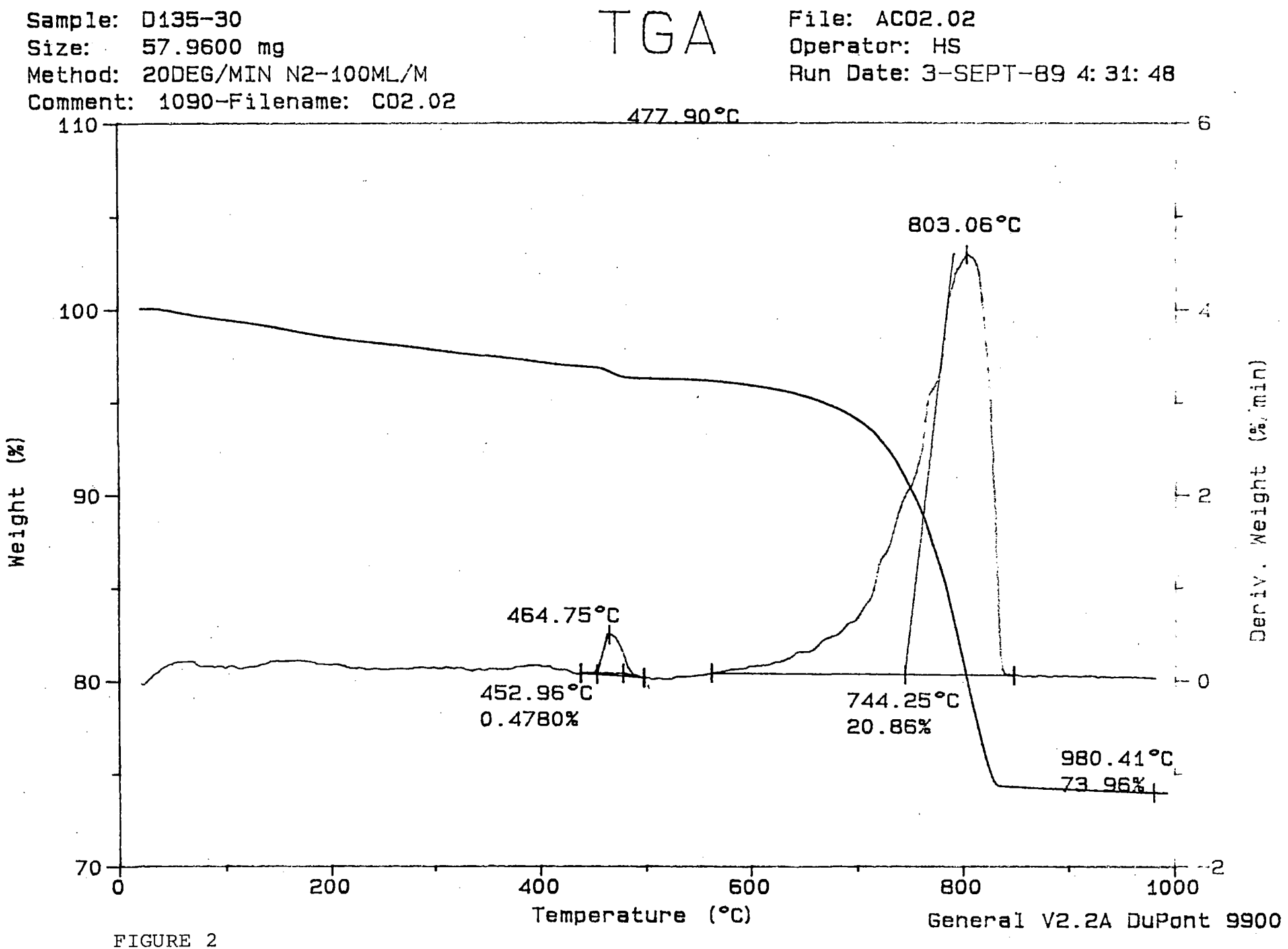
Sample: D135-30
Size: 57.9600 mg
Method: 20DEG/MIN N2-100ML/M
Comment: 1090-Filename: C02.02
TGA
File: AC02.02
Operator: HS
Run Date: 3-SEPT-89 4:31:48
477.90°C
803.06°C
464.75°C
452.96°C
0.4780%
744.25°C
20.86%
980.41°C
73.96%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 2

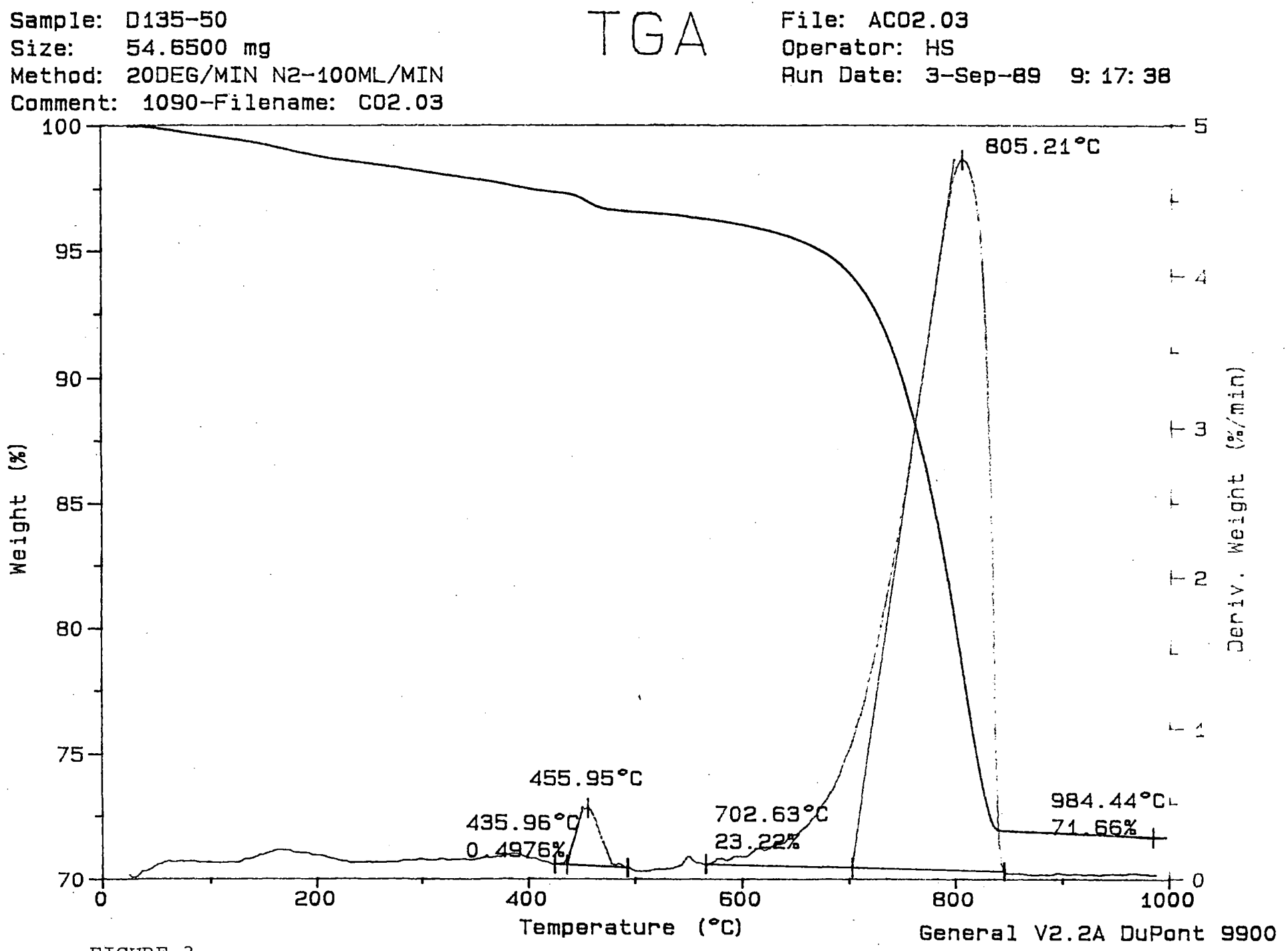
Sample: D135-50
Size: 54.6500 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.03
TGA
File: AC02.03
Operator: HS
Run Date: 3-Sep-89 9:17:38
805.21°C
455.95°C
435.96°C
0.4976%
702.63°C
23.22%
984.44°C
71.66%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 3

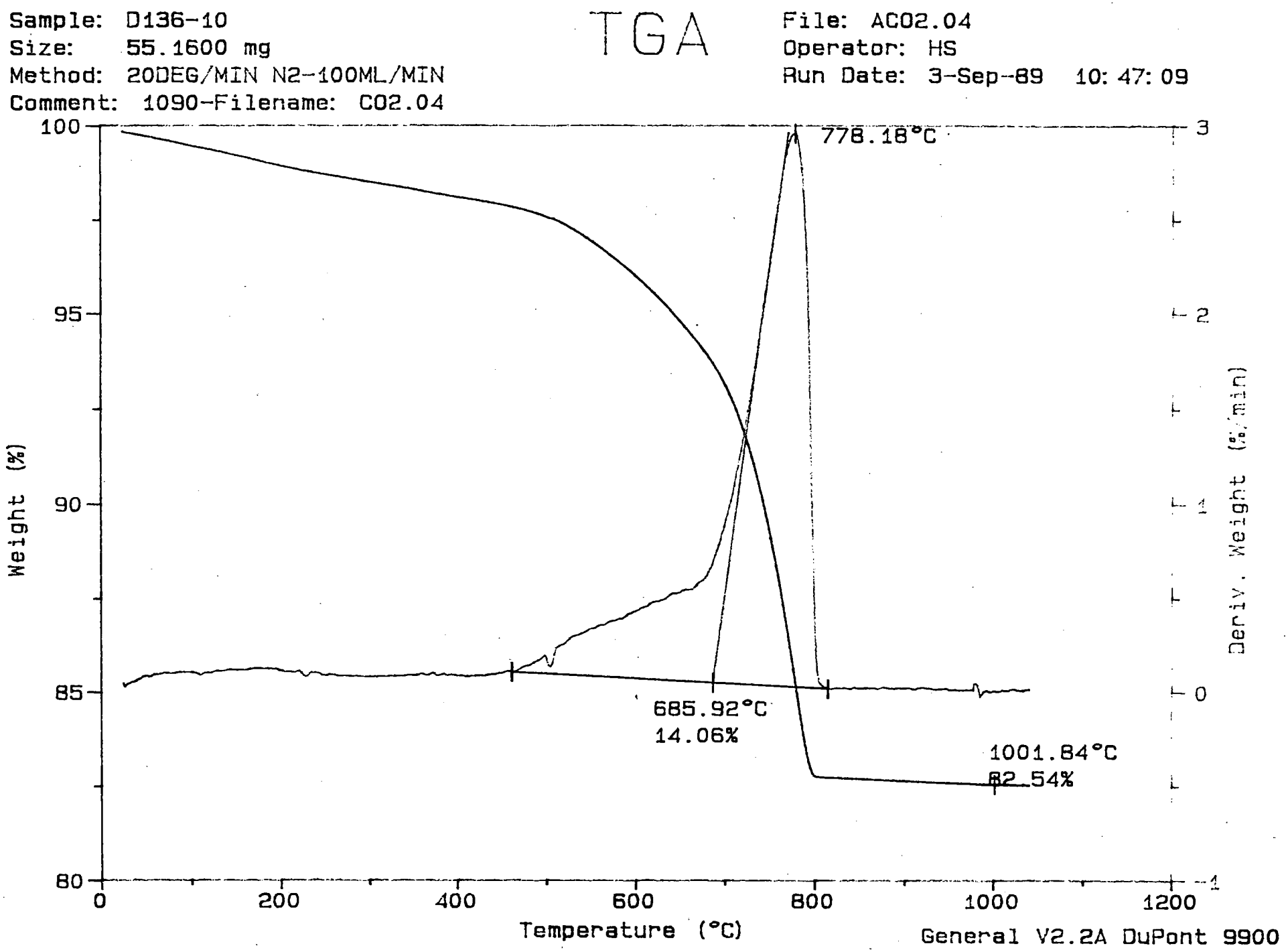
Sample: D136-10
Size: 55.1600 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.04
TGA
File: AC02.04
Operator: HS
Run Date: 3-Sep-89 10:47:09
778.18°C
685.92°C
14.06%
1001.84°C
82.54%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 4

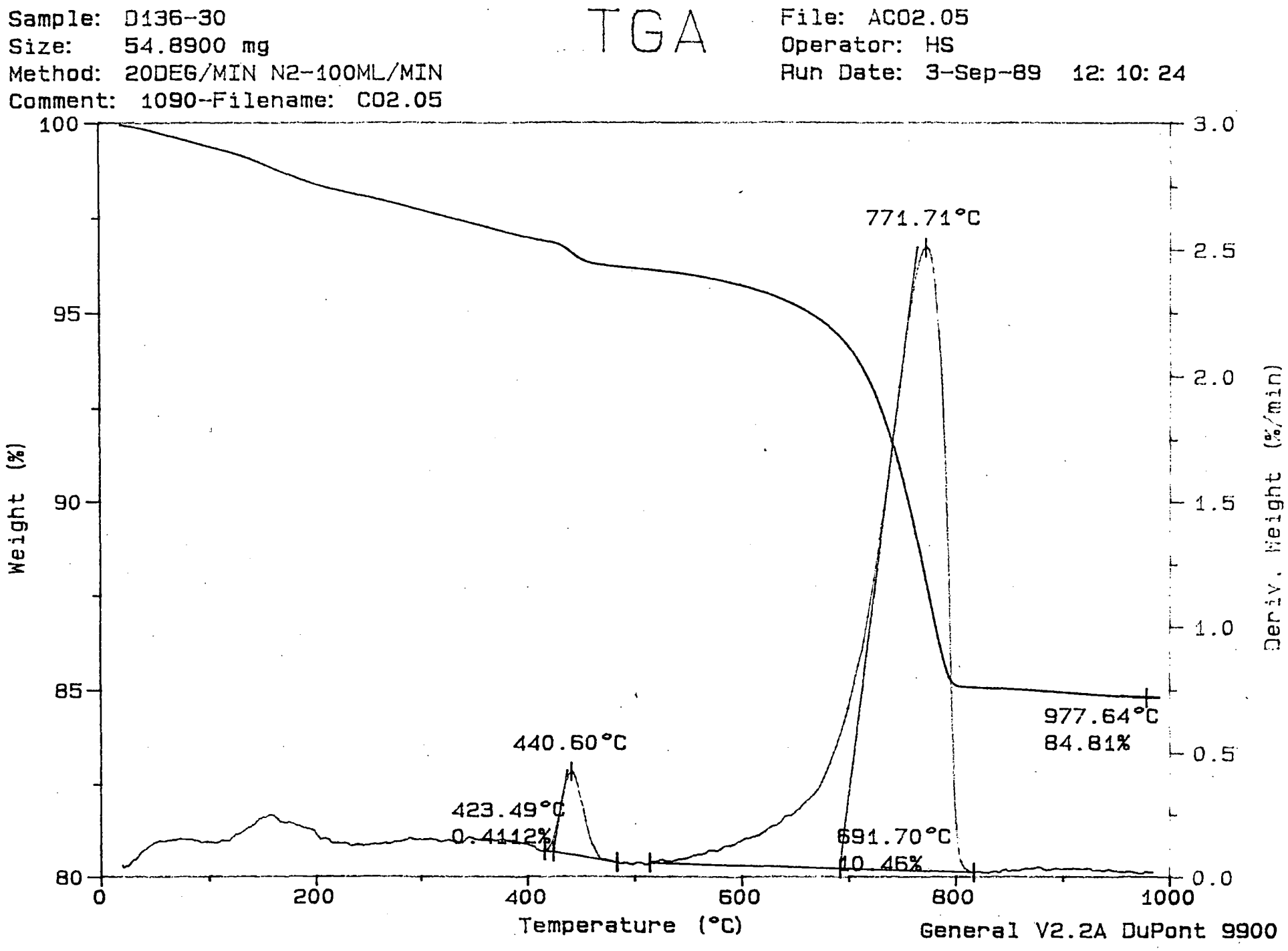
Sample: D136-30
Size: 54.8900 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.05
TGA
File: AC02.05
Operator: HS
Run Date: 3-Sep-89 12:10:24
771.71°C
977.64°C
84.81%
440.60°C
423.49°C
0.4112%
691.70°C
10.46%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 5

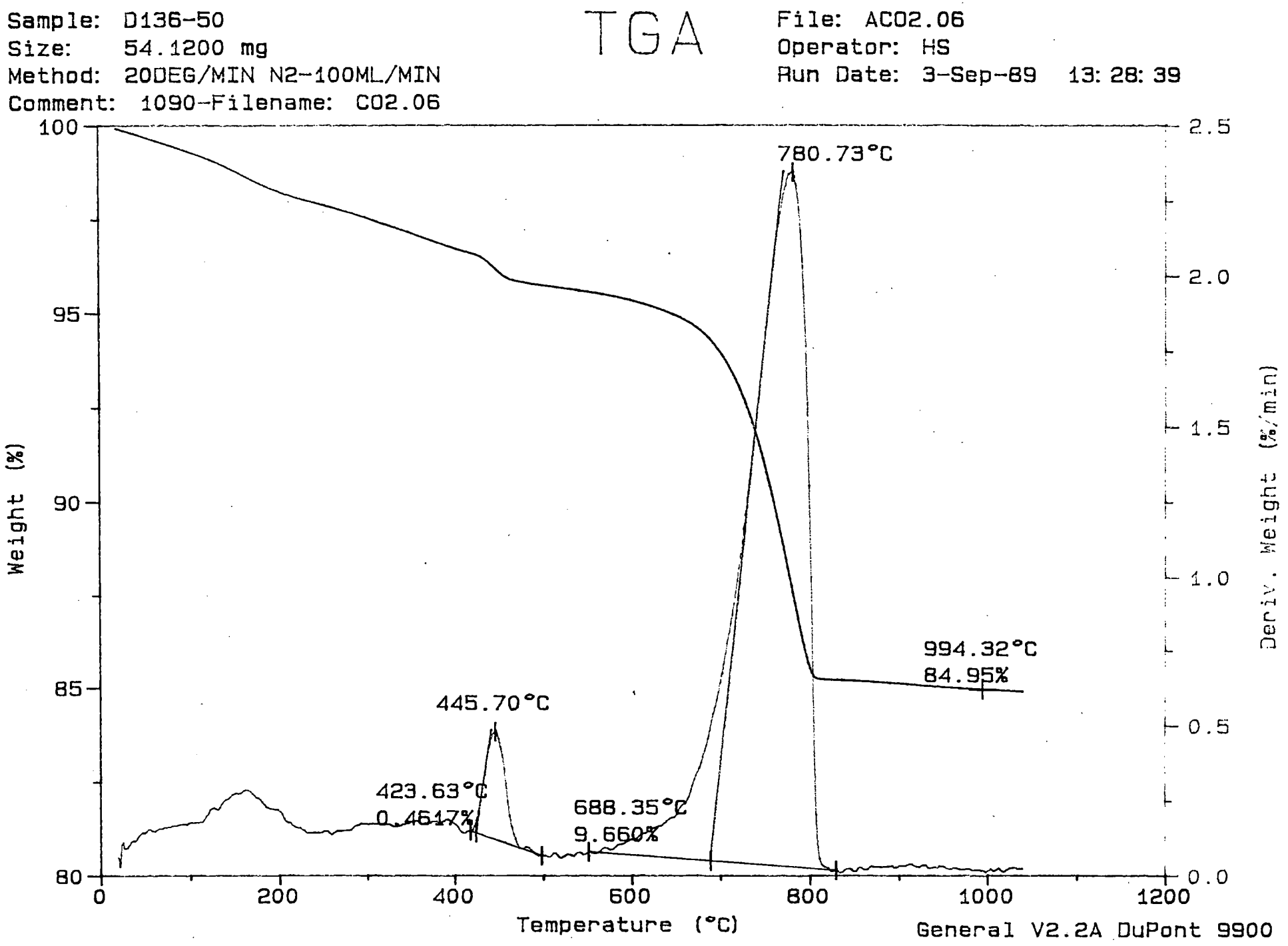
Sample: D136-50
Size: 54.1200 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.06
TGA
File: AC02.06
Operator: HS
Run Date: 3-Sep-89 13:28:39
780.73°C
994.32°C
84.95%
445.70°C
423.63°C
0.4617%
688.35°C
9.660%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 6

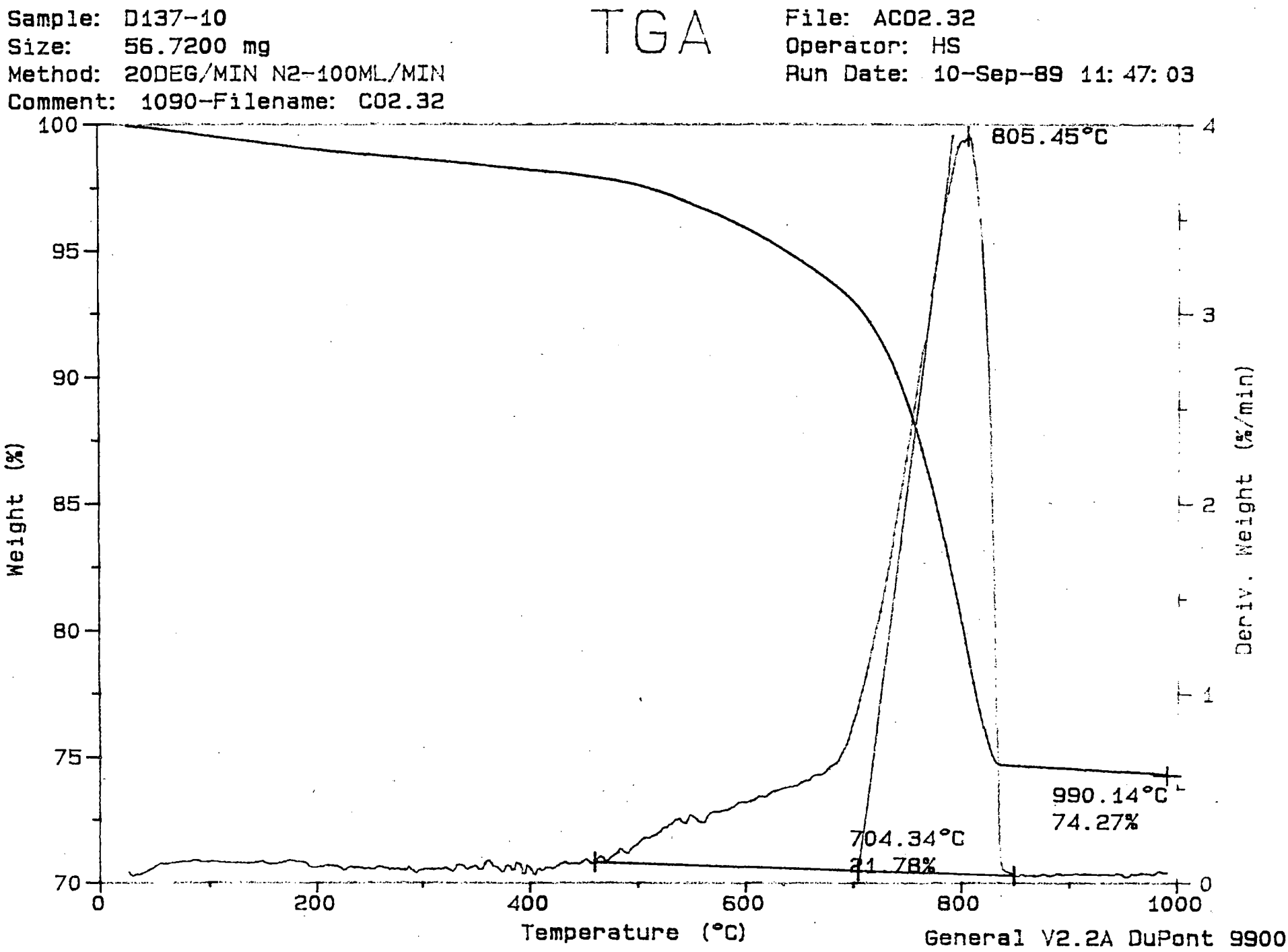
Sample: D137-10
Size: 56.7200 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.32
TGA
File: AC02.32
Operator: HS
Run Date: 10-Sep-89 11:47:03
805.45°C
990.14°C
74.27%
704.34°C
21.78%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 7

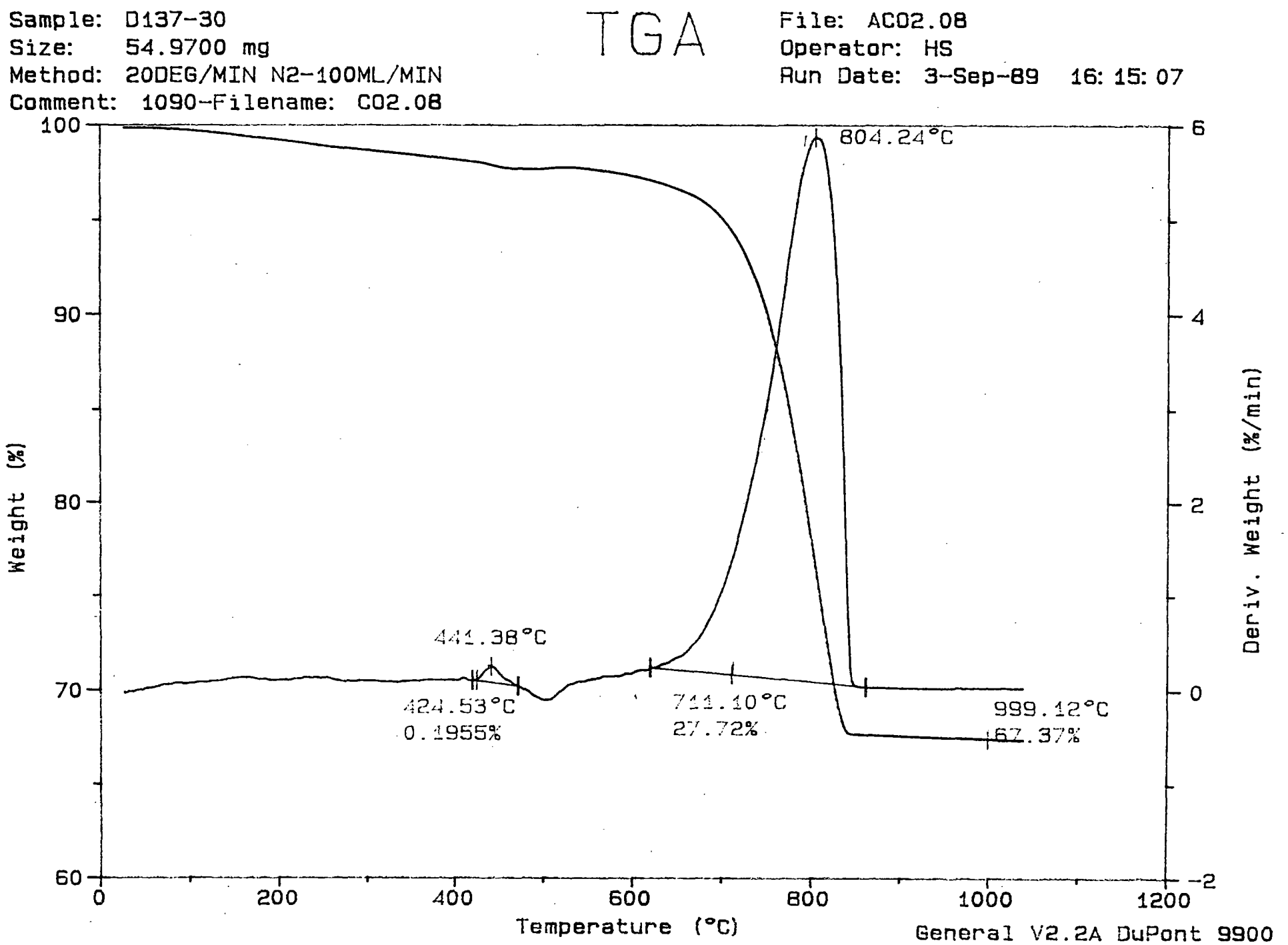
Sample: D137-30
Size: 54.9700 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.08
TGA
File: AC02.08
Operator: HS
Run Date: 3-Sep-89 16:15:07
804.24°C
441.38°C
424.53°C
0.1955%
711.10°C
27.72%
999.12°C
67.37%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 8

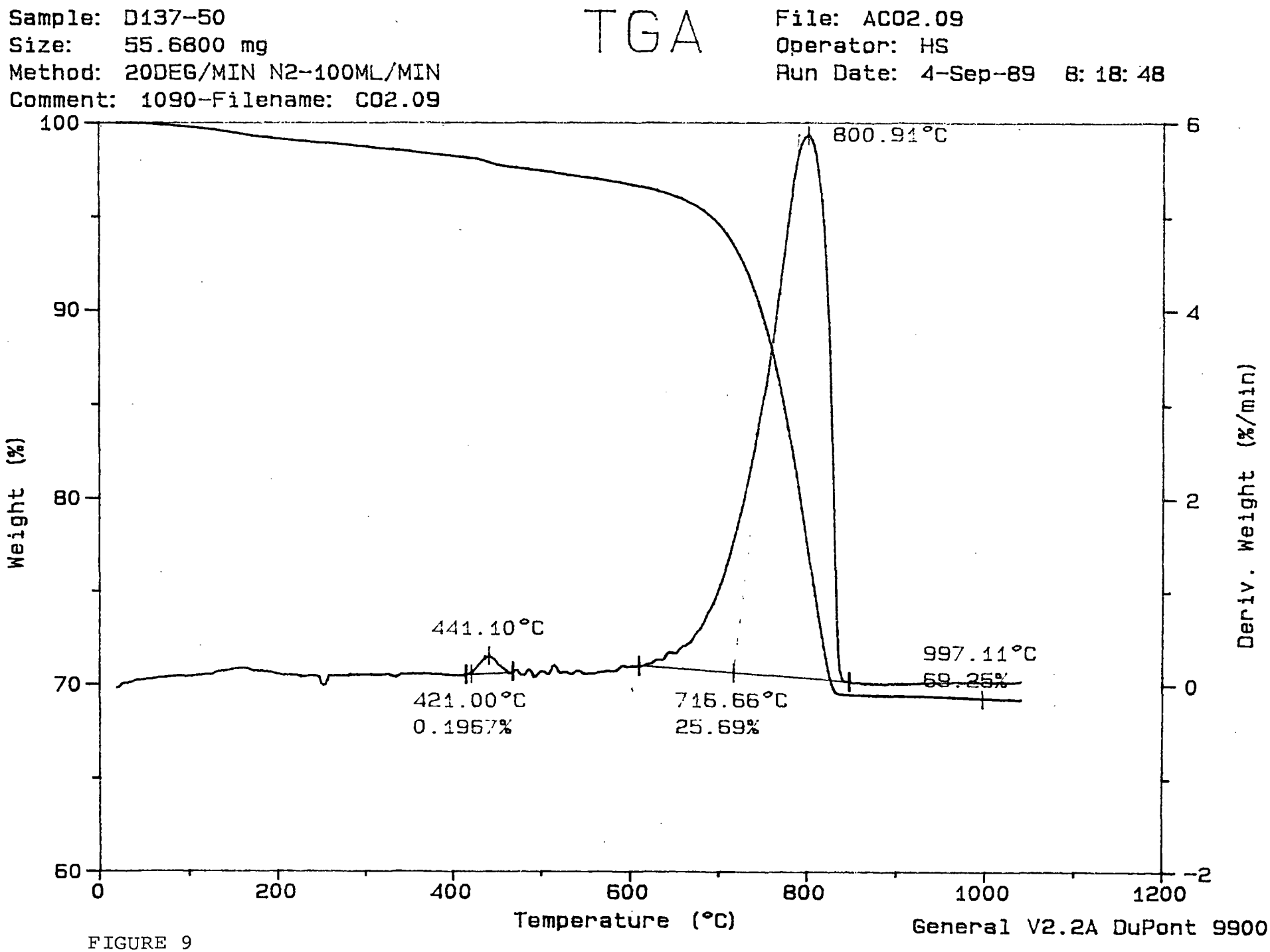
Sample: D137-50
Size: 55.6800 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.09
TGA
File: AC02.09
Operator: HS
Run Date: 4-Sep-89 8:18:48
800.91°C
441.10°C
421.00°C
0.1967%
716.66°C
25.69%
997.11°C
69.25%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 9

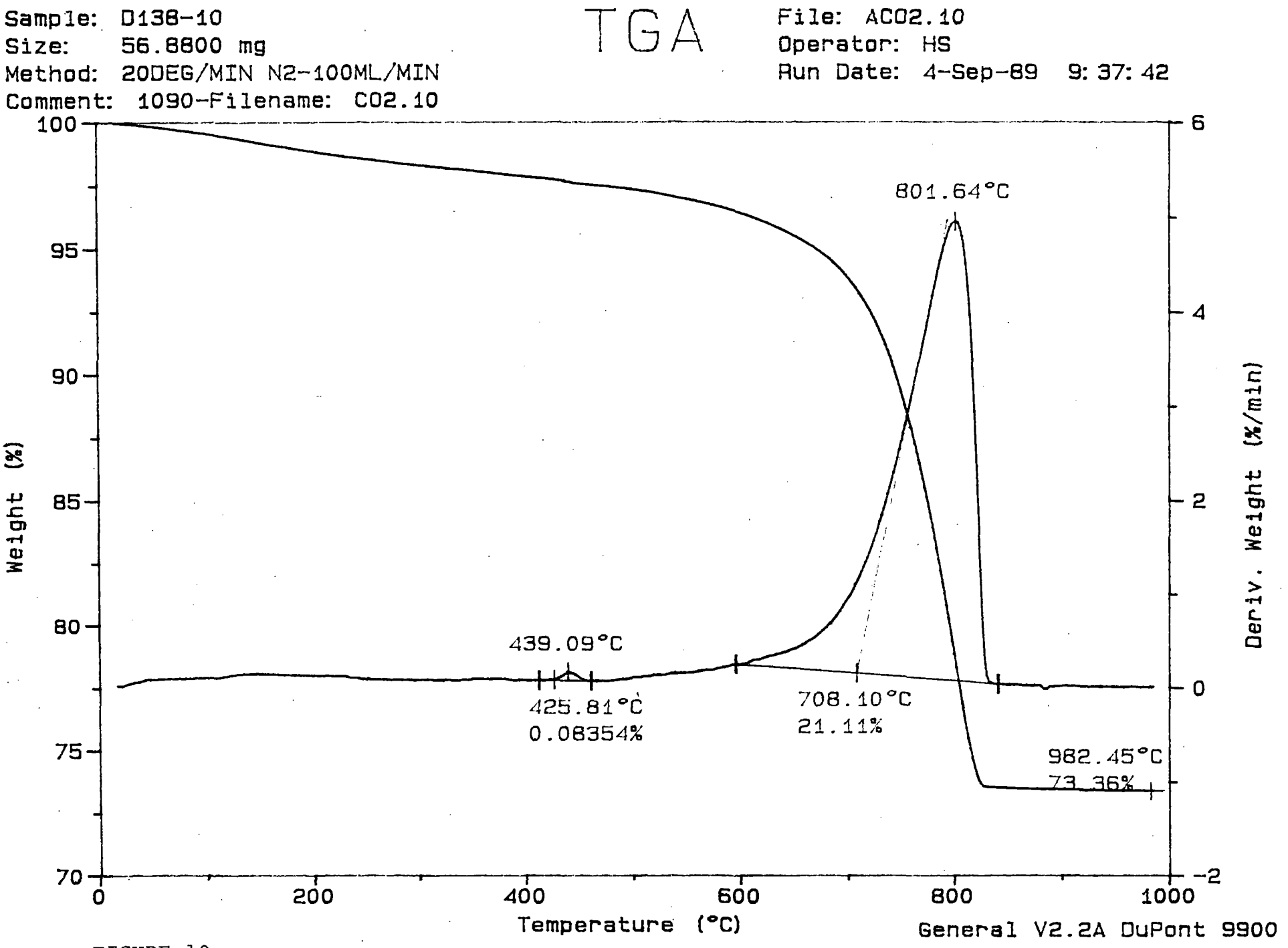
Sample: D138-10
Size: 56.8800 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.10
TGA
File: AC02.10
Operator: HS
Run Date: 4-Sep-89 9:37:42
801.64°C
439.09°C
425.81°C
0.08354%
708.10°C
21.11%
982.45°C
73.36%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 10

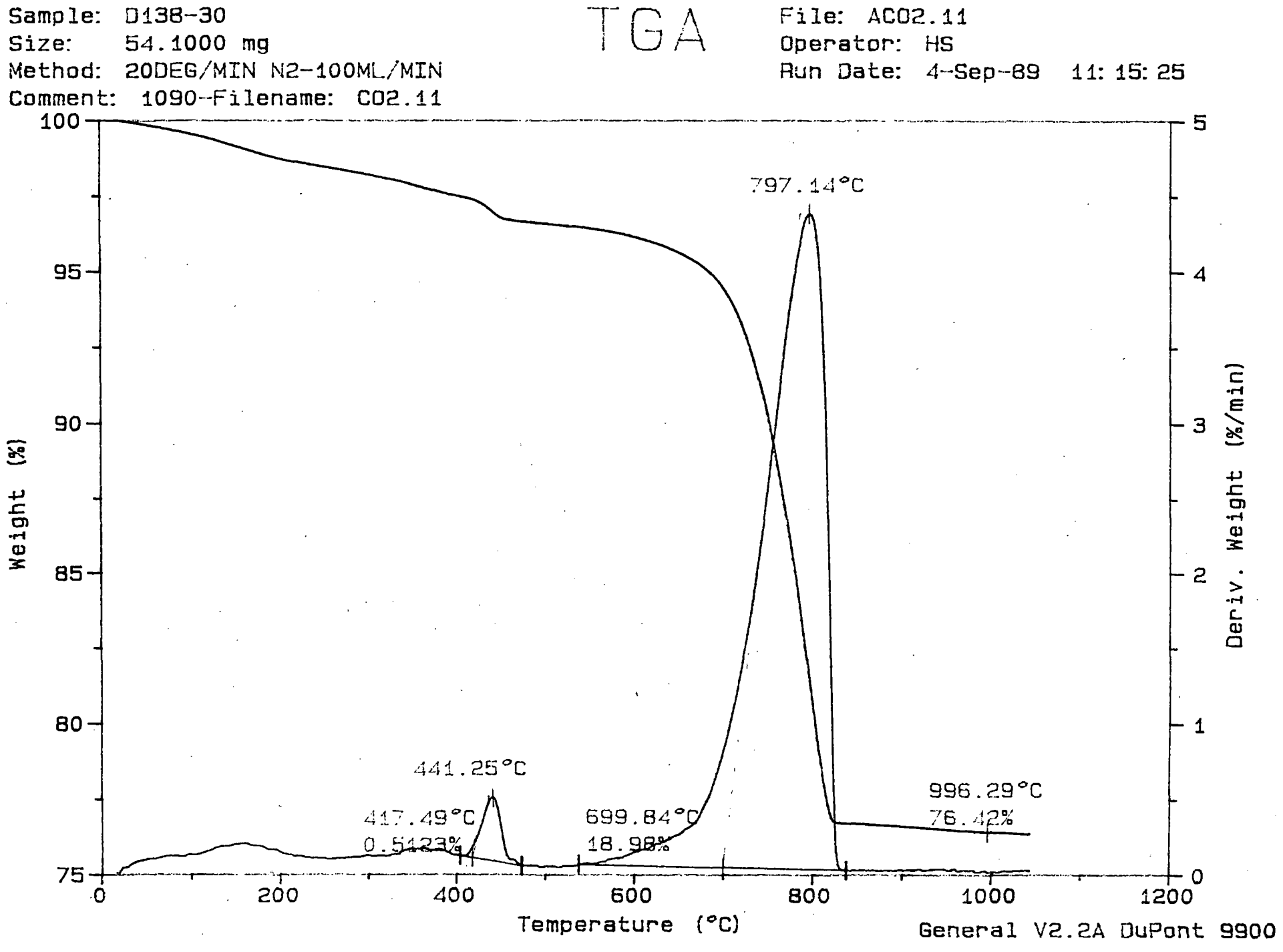
Sample: D138-30
Size: 54.1000 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090--Filename: CO2.11
TGA
File: ACO2.11
Operator: HS
Run Date: 4-Sep-89 11:15:25
797.14°C
441.25°C
417.49°C
0.5123%
699.84°C
18.98%
996.29°C
76.42%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 11

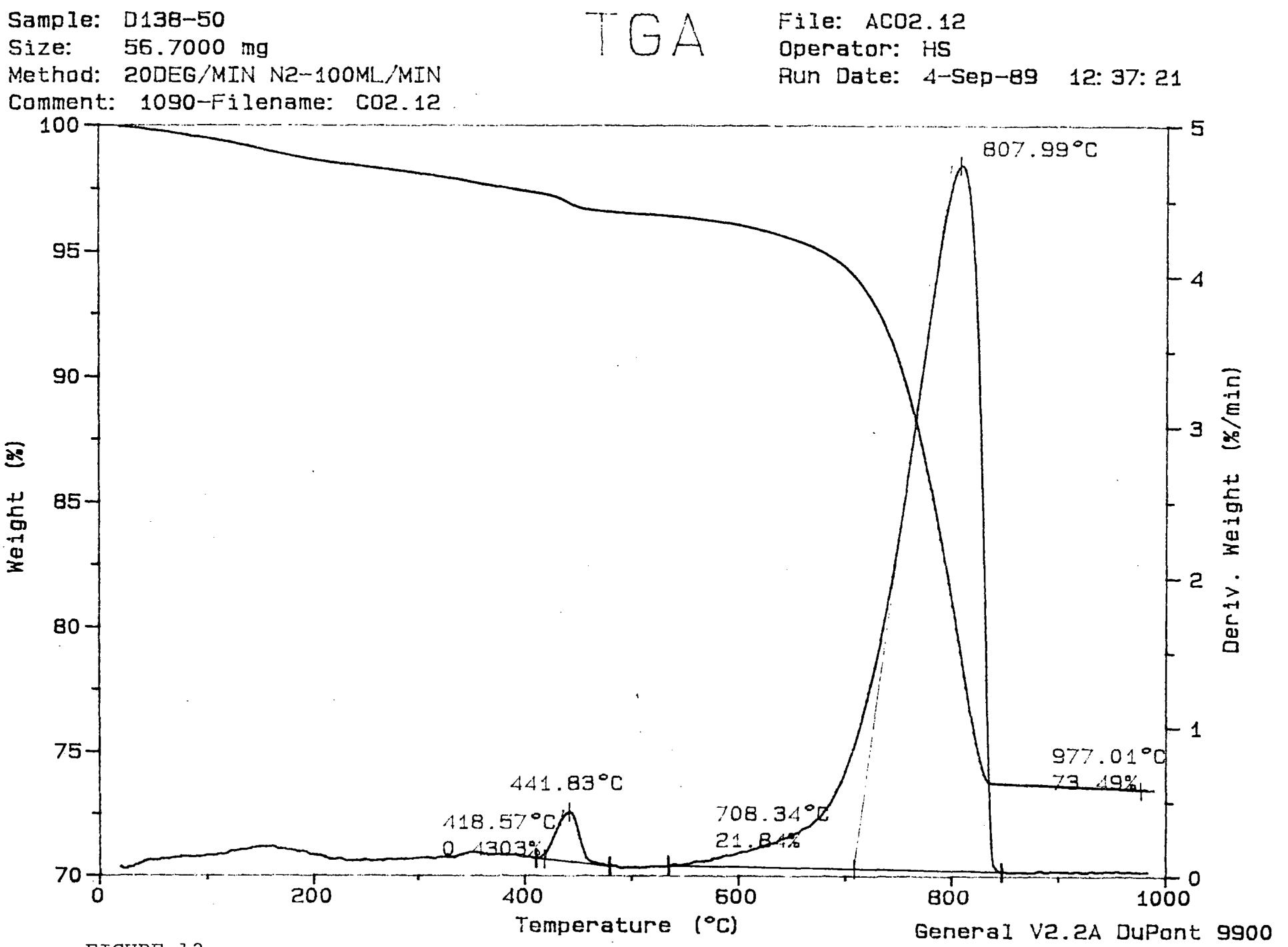
Sample: D138-50
Size: 56.7000 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.12
TGA
File: AC02.12
Operator: HS
Run Date: 4-Sep-89 12:37:21
807.99°C
441.83°C
418.57°C
0.4303%
708.34°C
21.84%
977.01°C
73.49%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 12

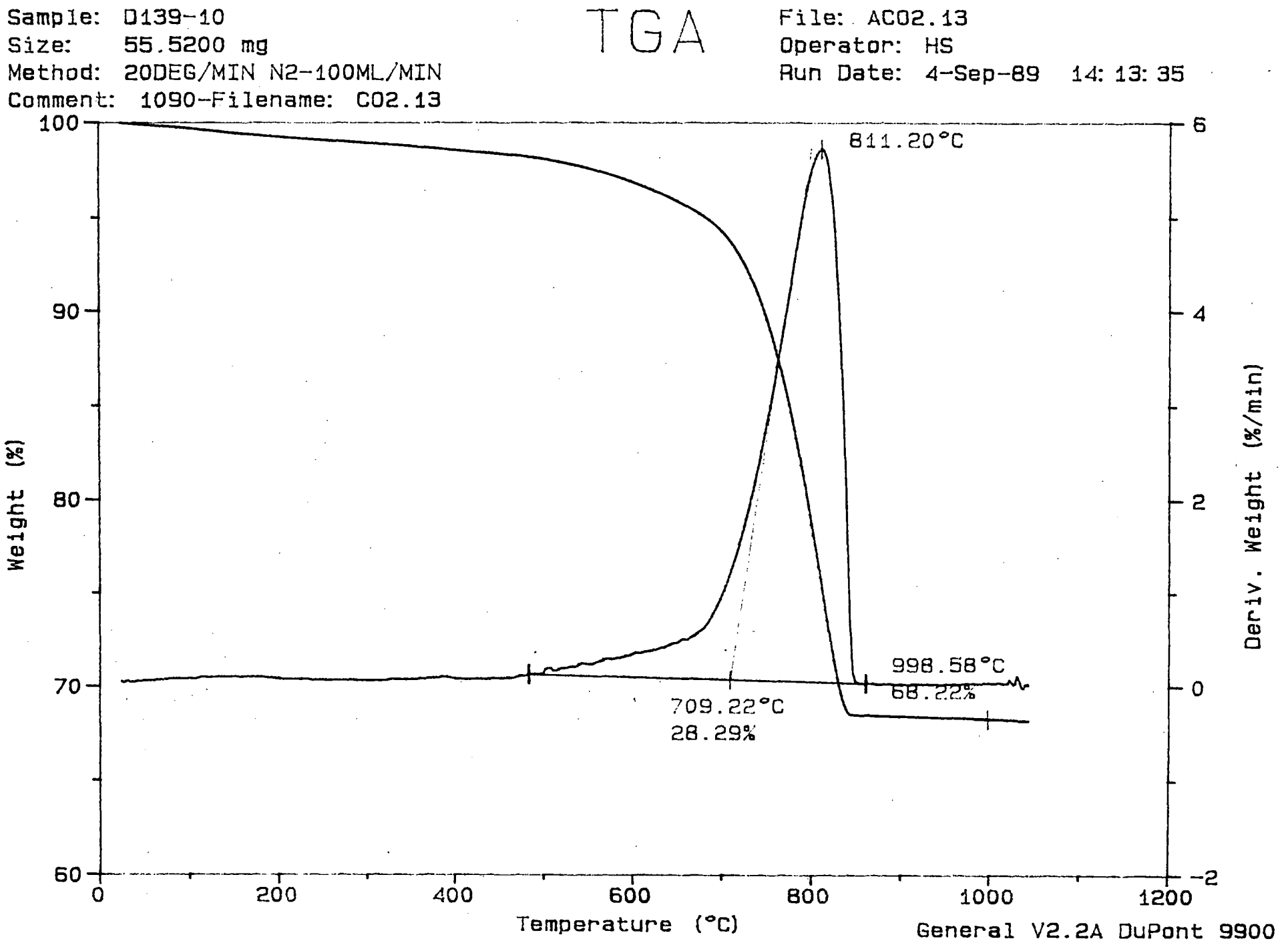
Sample: D139-10
Size: 55.5200 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.13
TGA
File: AC02.13
Operator: HS
Run Date: 4-Sep-89 14:13:35
811.20°C
998.58°C
68.22%
709.22°C
28.29%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 13

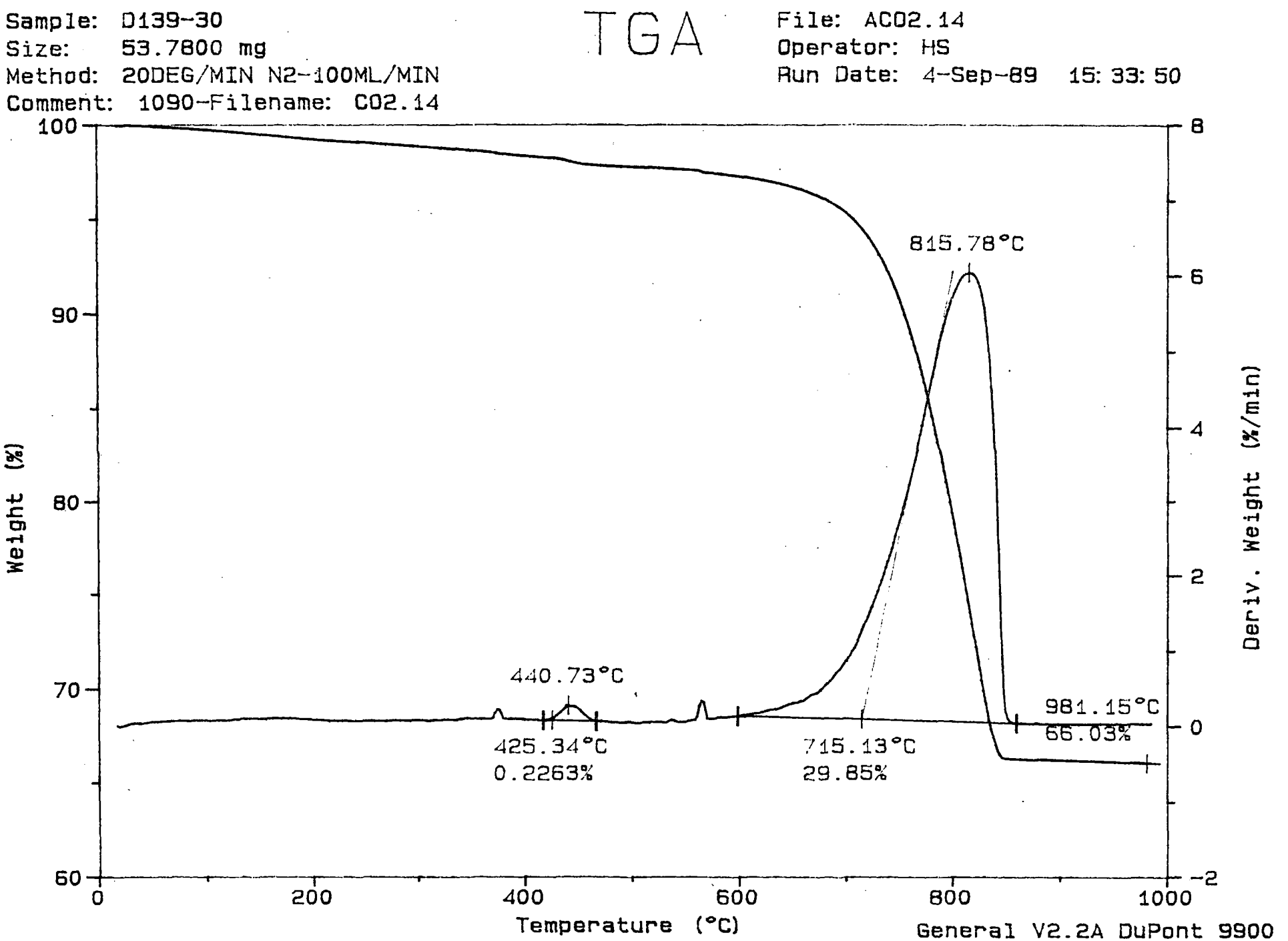
Sample: D139-30
Size: 53.7800 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.14
TGA
File: AC02.14
Operator: HS
Run Date: 4-Sep-89 15:33:50
100
90
80
70
60
Weight (%)
8
6
4
2
0
-2
Deriv. Weight (%/min)
815.78°C
440.73°C
425.34°C
0.2263%
715.13°C
29.85%
981.15°C
66.03%
0
200
400
600
800
1000
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 14

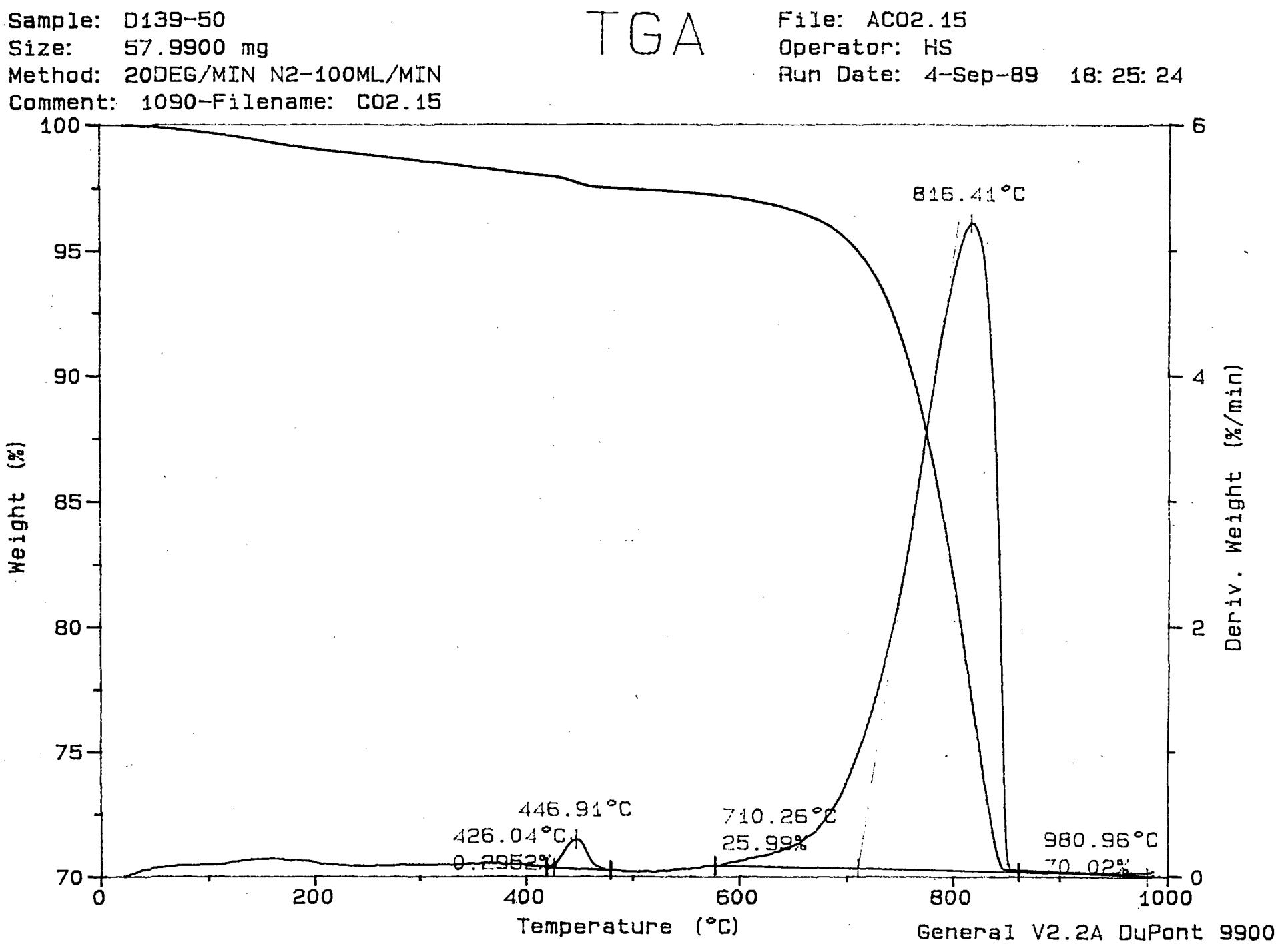
Sample: D139-50
Size: 57.9900 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.15
TGA
File: AC02.15
Operator: HS
Run Date: 4-Sep-89 18:25:24
816.41°C
446.91°C
426.04°C
710.26°C
25.99%
980.96°C
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 15

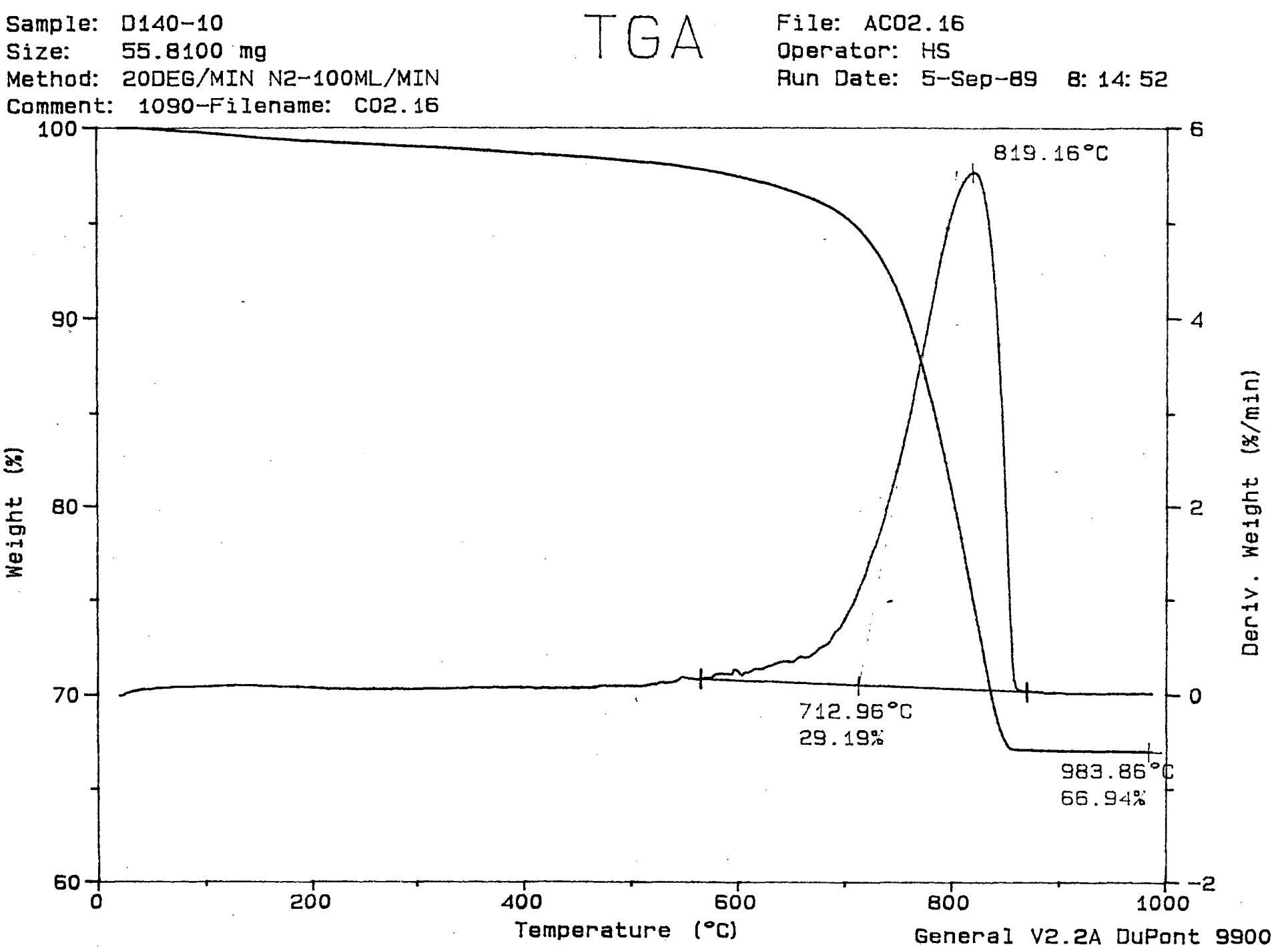
Sample: D140-10
Size: 55.8100 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.16
TGA
File: AC02.16
Operator: HS
Run Date: 5-Sep-89 8:14:52
819.16°C
712.96°C
29.19%
983.86°C
66.94%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 16

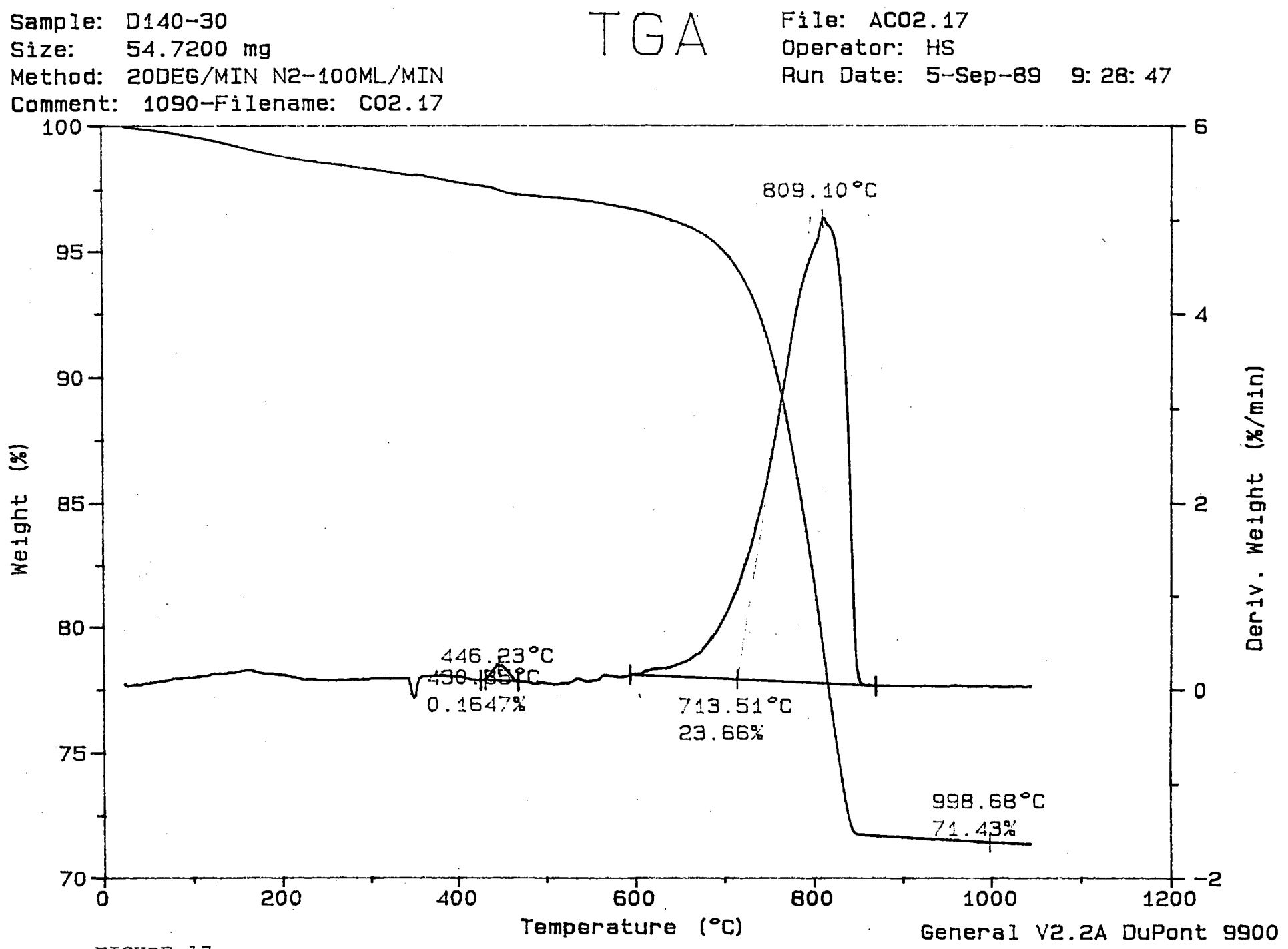
Sample: D140-30
Size: 54.7200 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.17
TGA
File: AC02.17
Operator: HS
Run Date: 5-Sep-89 9:28:47
809.10°C
446.23°C
0.1647%
713.51°C
23.66%
998.68°C
71.43%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 17

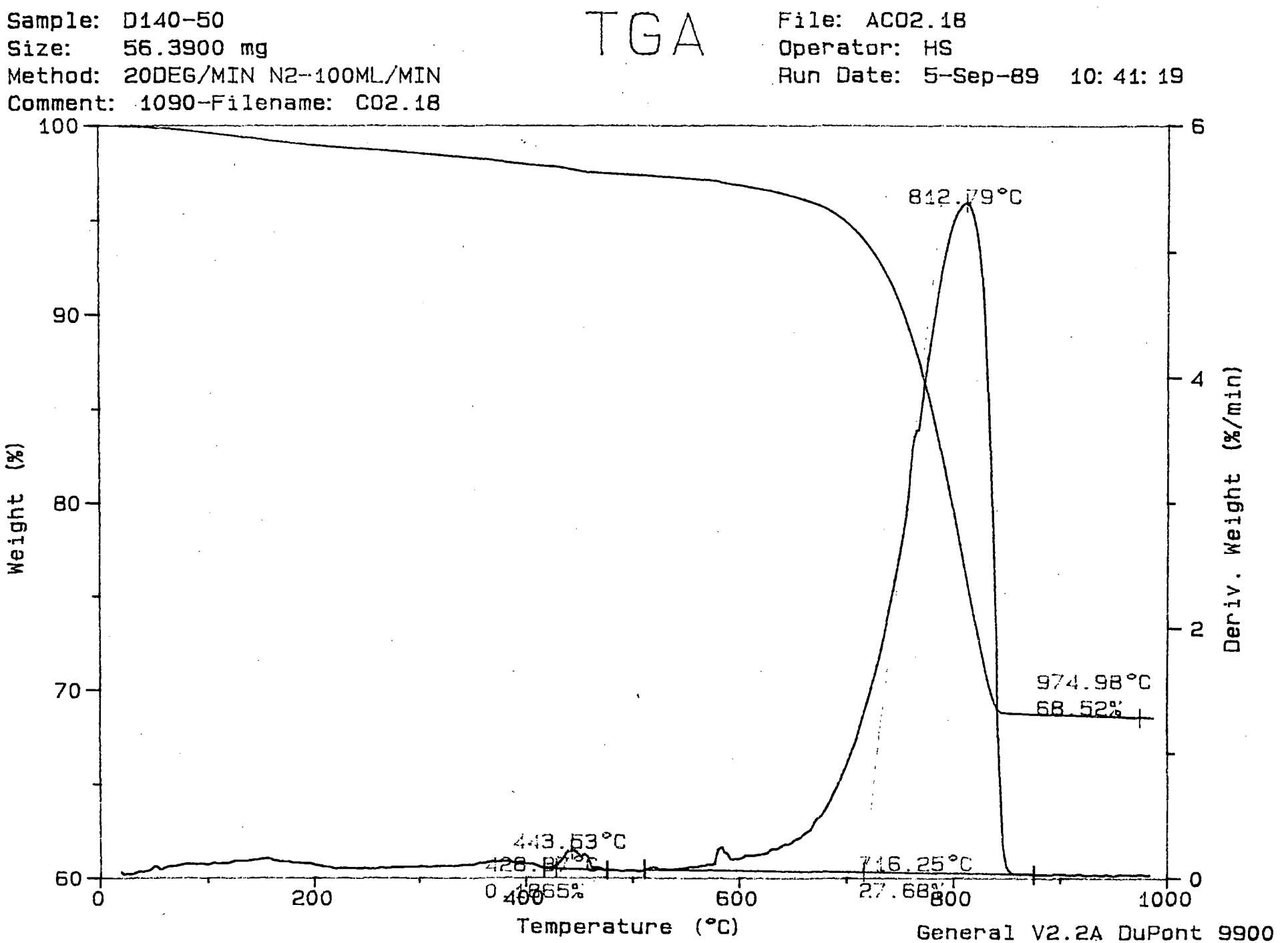
Sample: D140-50
Size: 56.3900 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.18
TGA
File: AC02.18
Operator: HS
Run Date: 5-Sep-89 10:41:19
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
812.79°C
974.98°C
68.52%
443.53°C
716.25°C
27.68%
General V2.2A DuPont 9900

FIGURE 18

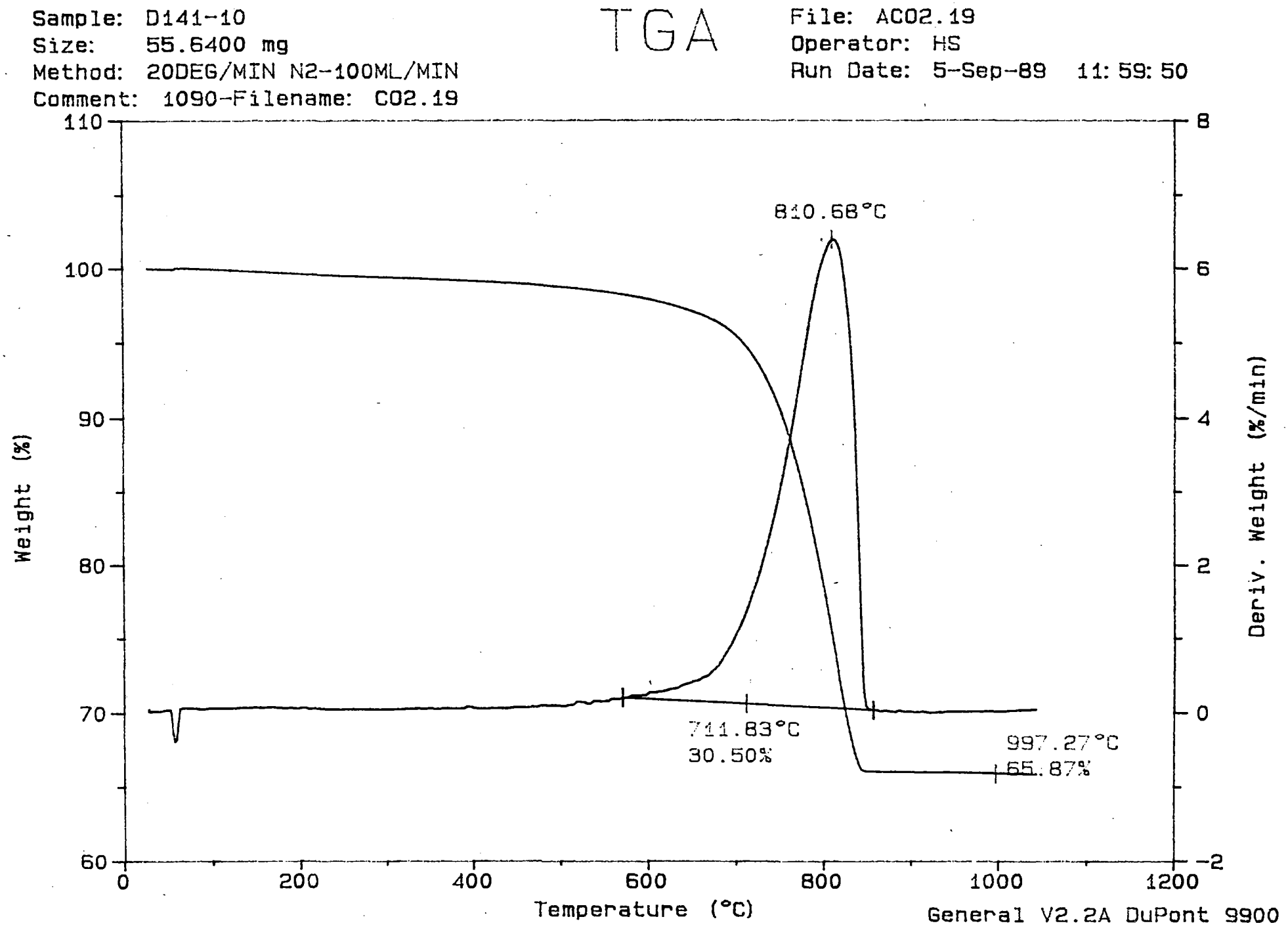
Sample: D141-10
Size: 55.6400 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.19
TGA
File: AC02.19
Operator: HS
Run Date: 5-Sep-89 11:59:50
810.68°C
711.83°C
30.50%
997.27°C
65.87%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 19

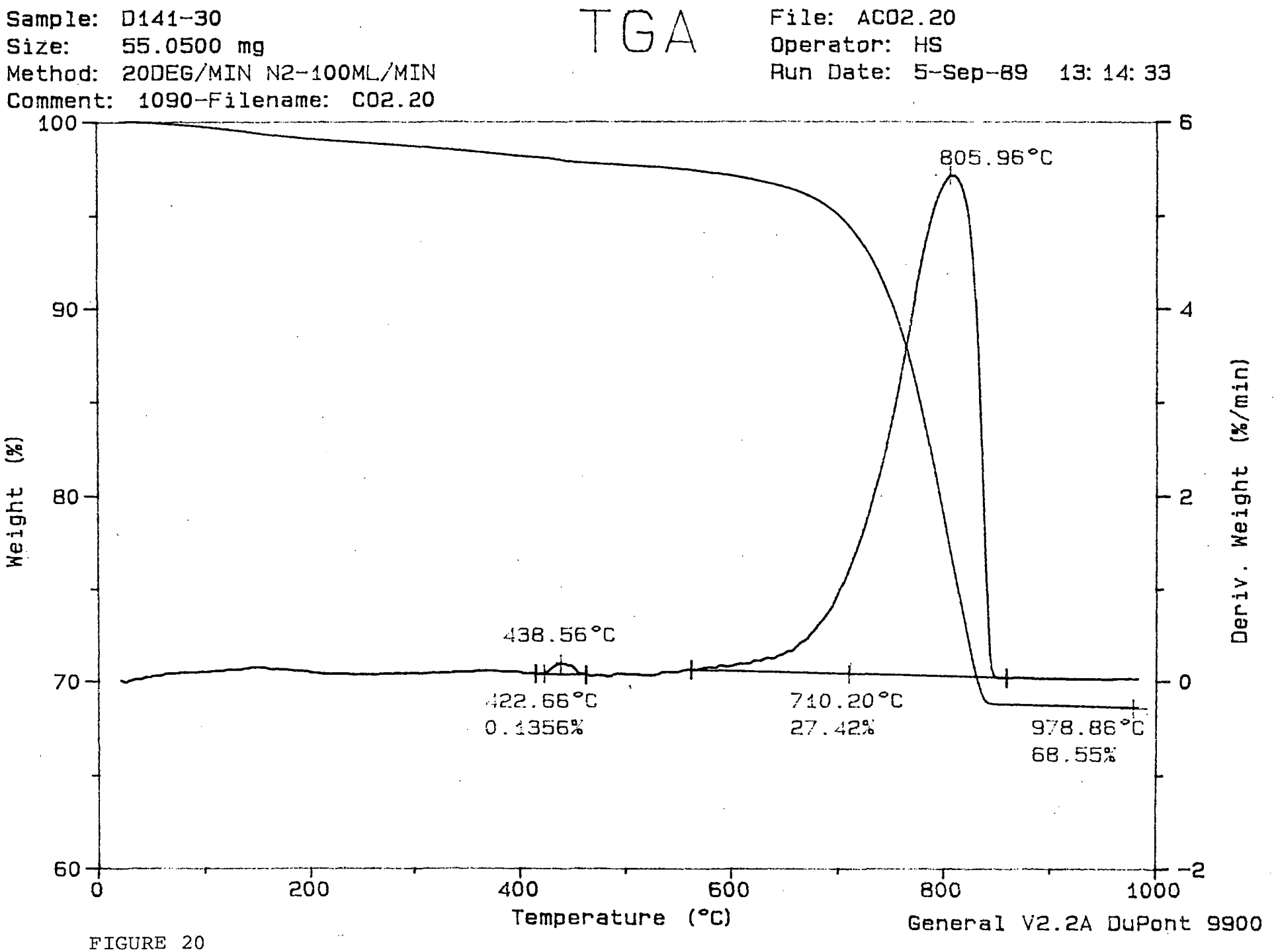
Sample: D141-30
Size: 55.0500 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.20
TGA
File: AC02.20
Operator: HS
Run Date: 5-Sep-89 13:14:33
805.96°C
438.56°C
422.66°C
0.1356%
710.20°C
27.42%
978.86°C
68.55%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 20

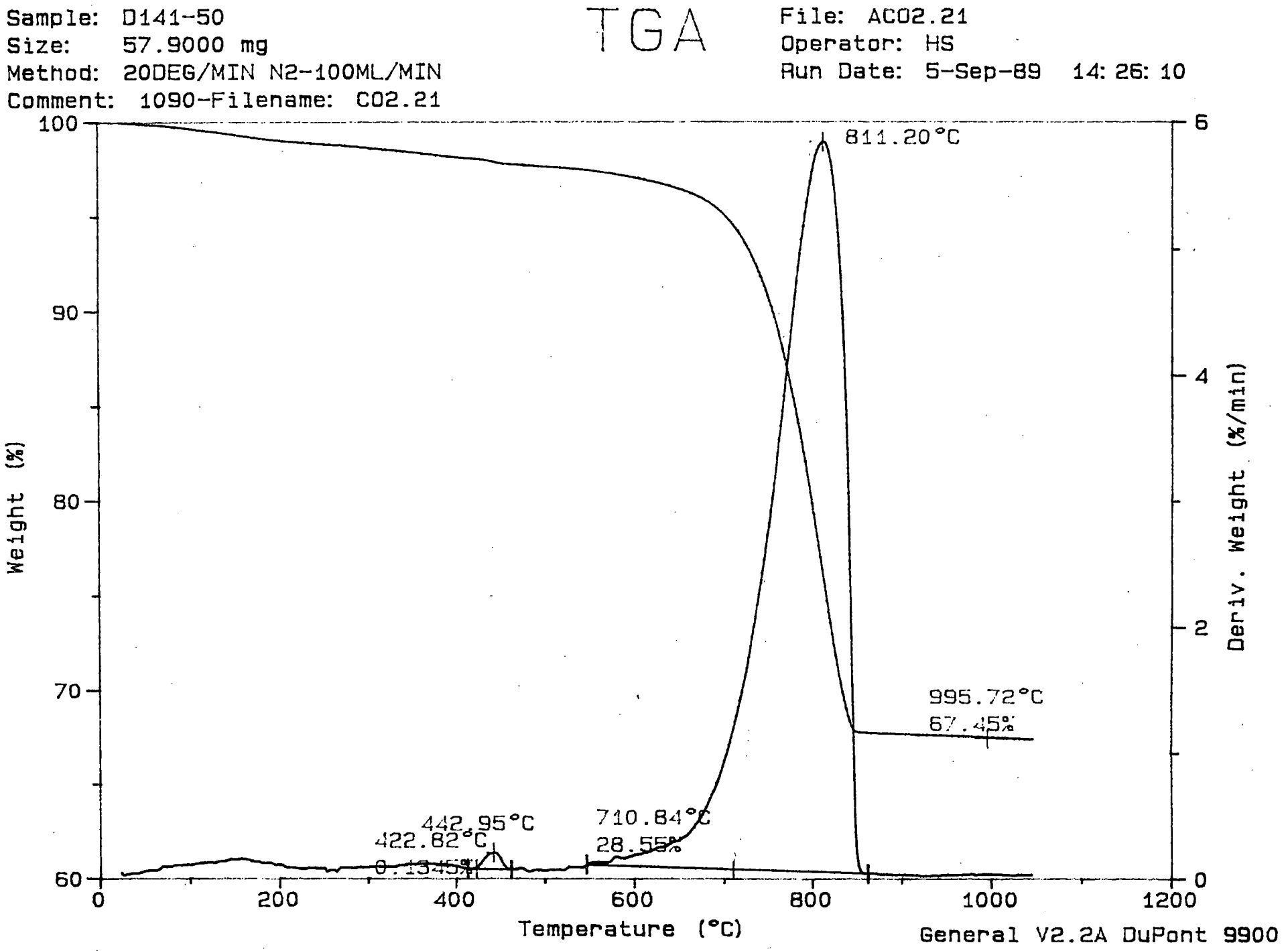
Sample: D141-50
Size: 57.9000 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.21
TGA
File: AC02.21
Operator: HS
Run Date: 5-Sep-89 14:26:10
811.20°C
995.72°C
67.45%
442.95°C
422.82°C
710.84°C
28.55%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 21

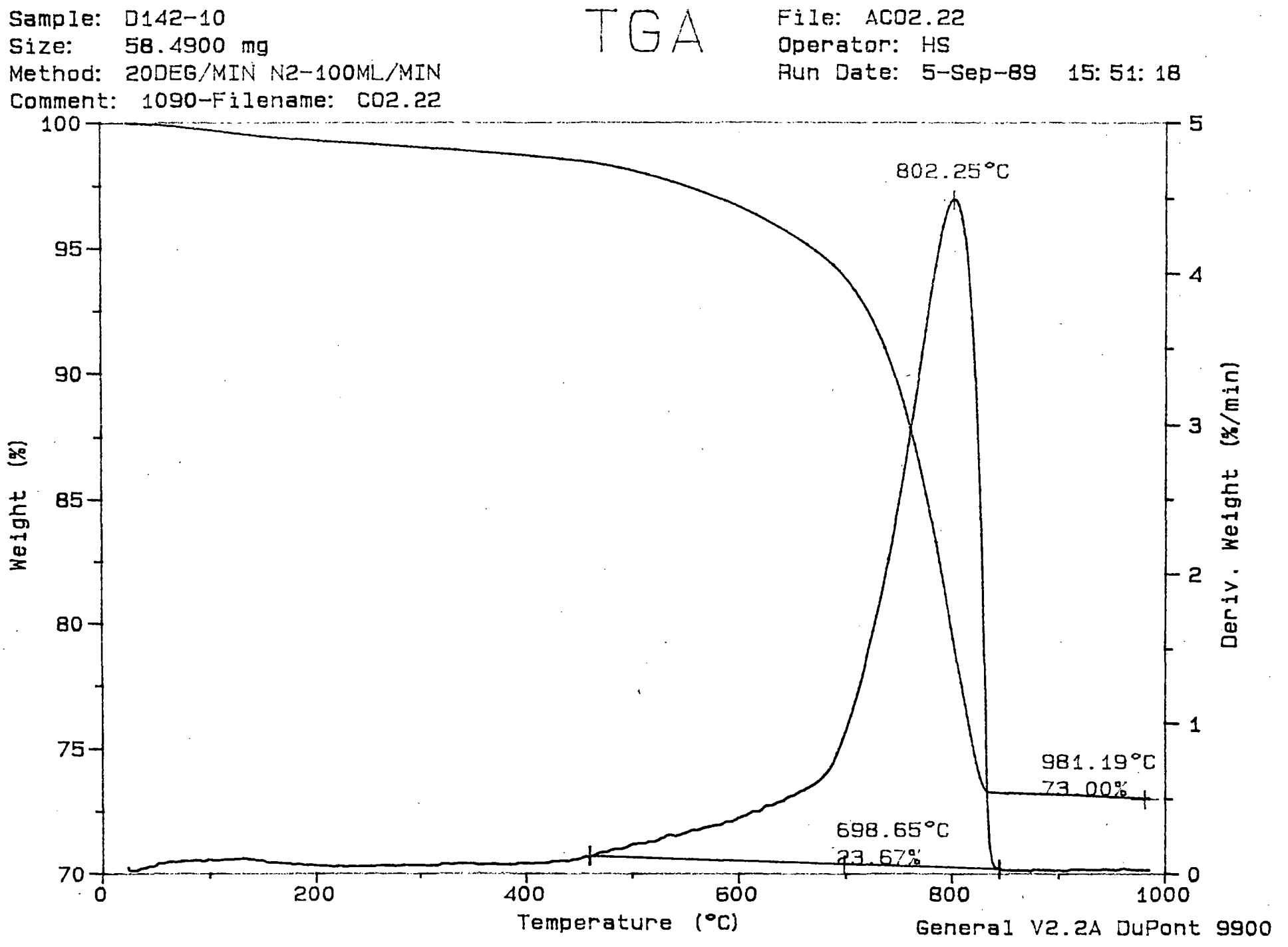
Sample: D142-10
Size: 58.4900 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.22
TGA
File: AC02.22
Operator: HS
Run Date: 5-Sep-89 15:51:18
802.25°C
981.19°C
73.00%
698.65°C
23.67%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 22

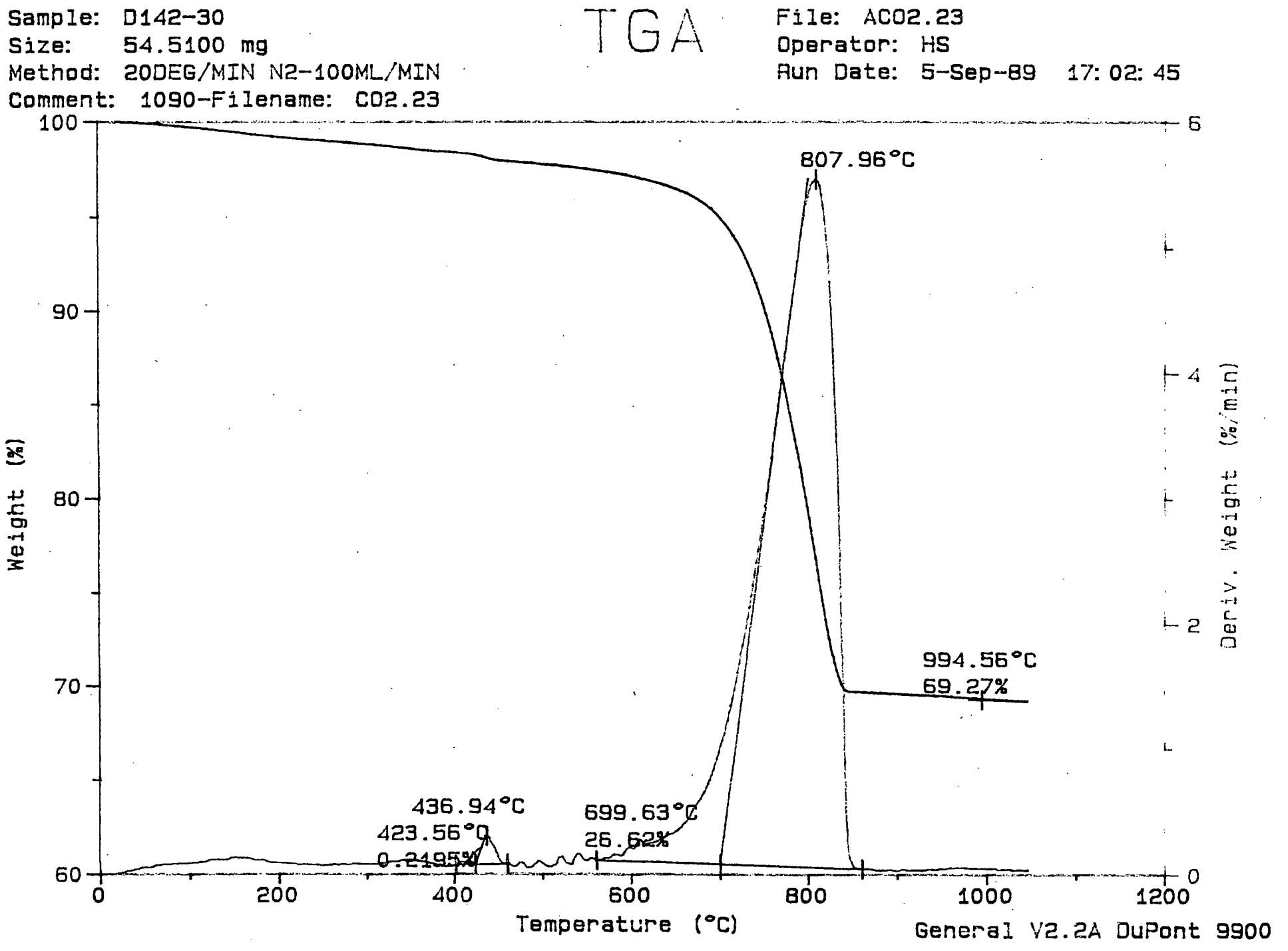
Sample: D142-30
Size: 54.5100 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.23
TGA
File: AC02.23
Operator: HS
Run Date: 5-Sep-89 17:02:45
807.96°C
994.56°C
69.27%
436.94°C
423.56°C
0.2195%
699.63°C
26.62%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 23

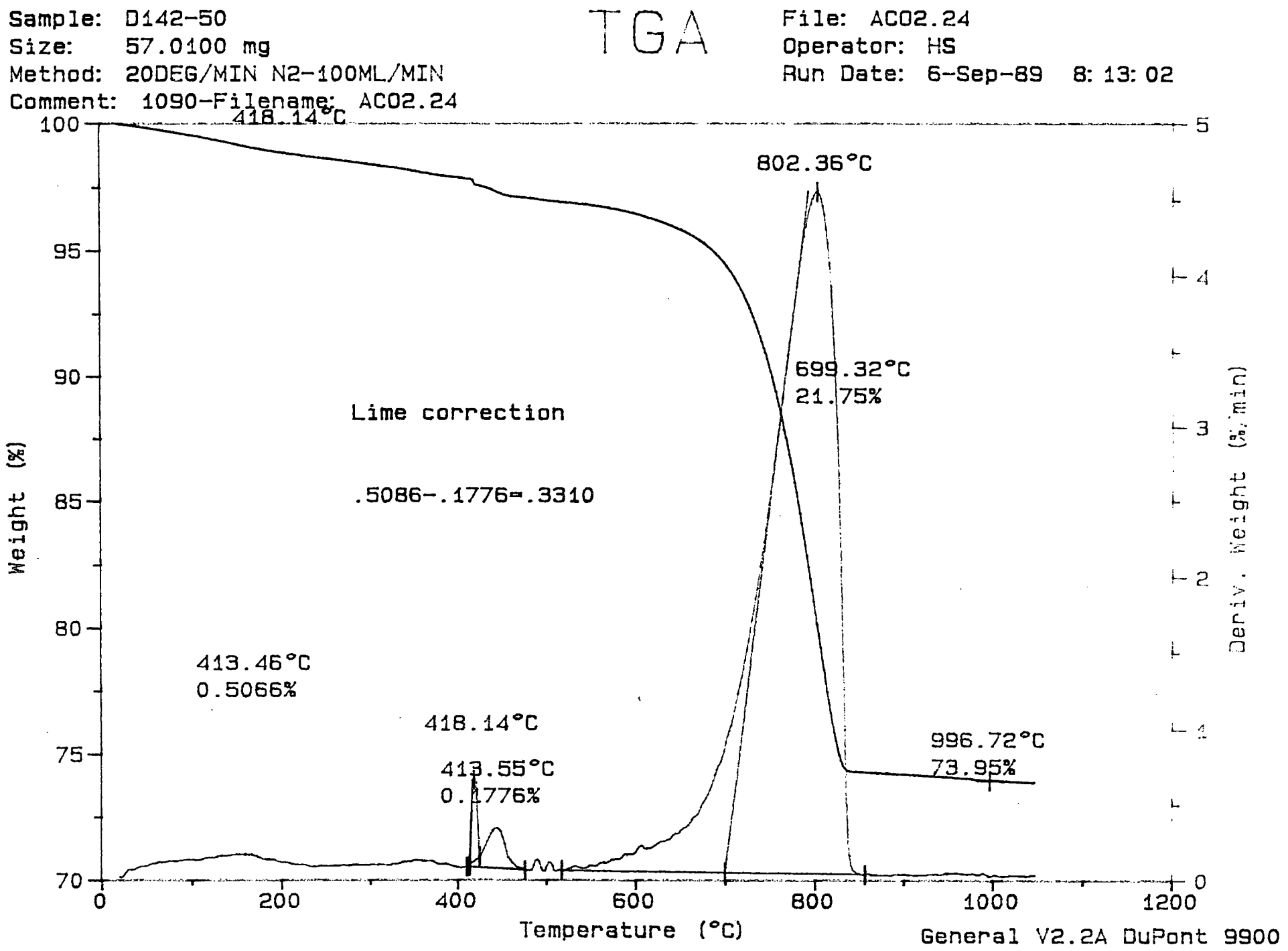
Sample: D142-50
Size: 57.0100 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: AC02.24
TGA
File: AC02.24
Operator: HS
Run Date: 6-Sep-89 8:13:02
418.14°C
802.36°C
699.32°C
21.75%
Lime correction
.5086-.1776=.3310
413.46°C
0.5066%
418.14°C
413.55°C
0.1776%
996.72°C
73.95%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 24

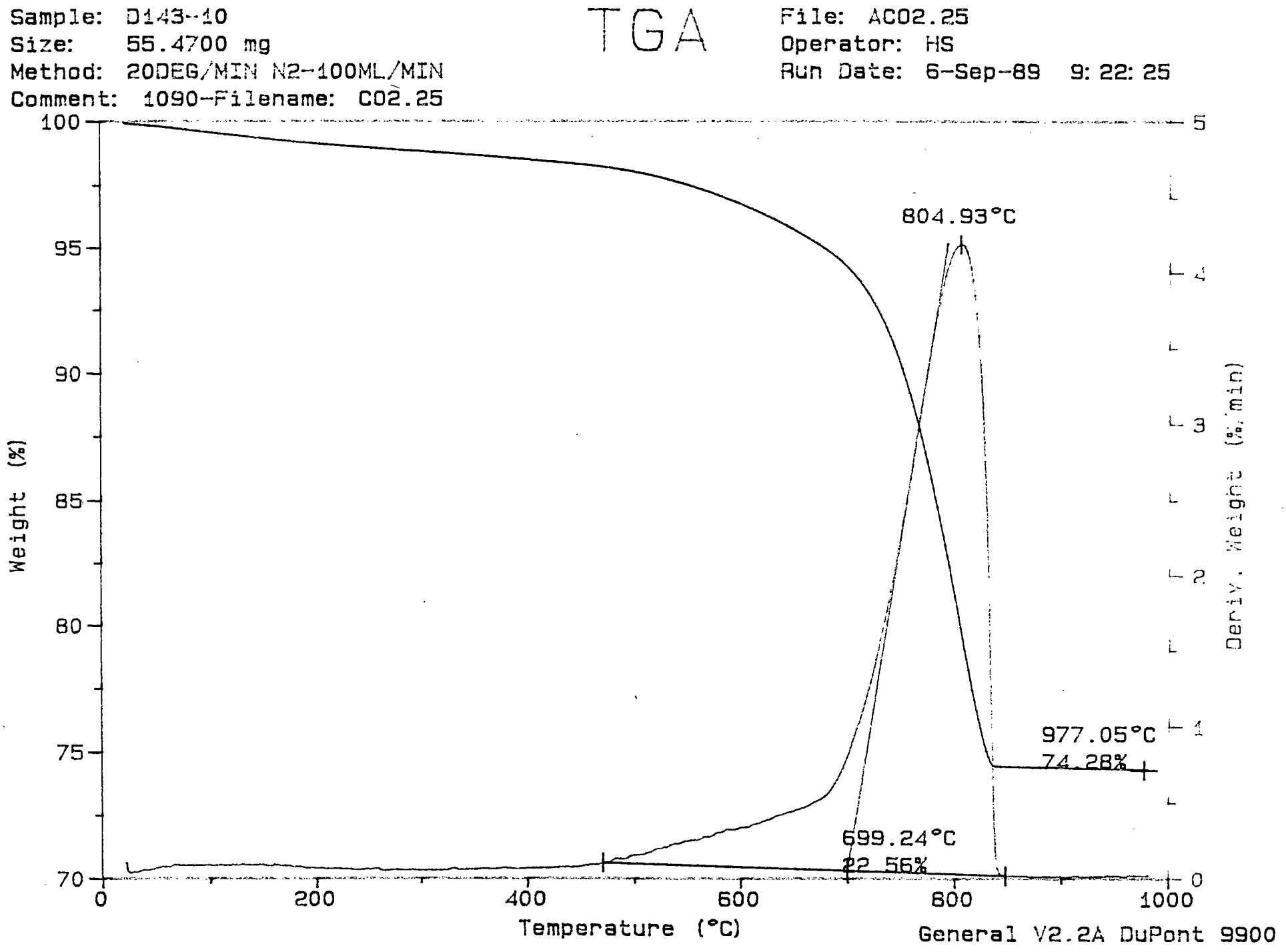
Sample: D143-10
Size: 55.4700 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.25
TGA
File: AC02.25
Operator: HS
Run Date: 6-Sep-89 9:22:25
804.93°C
977.05°C
74.28%
699.24°C
22.56%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 25

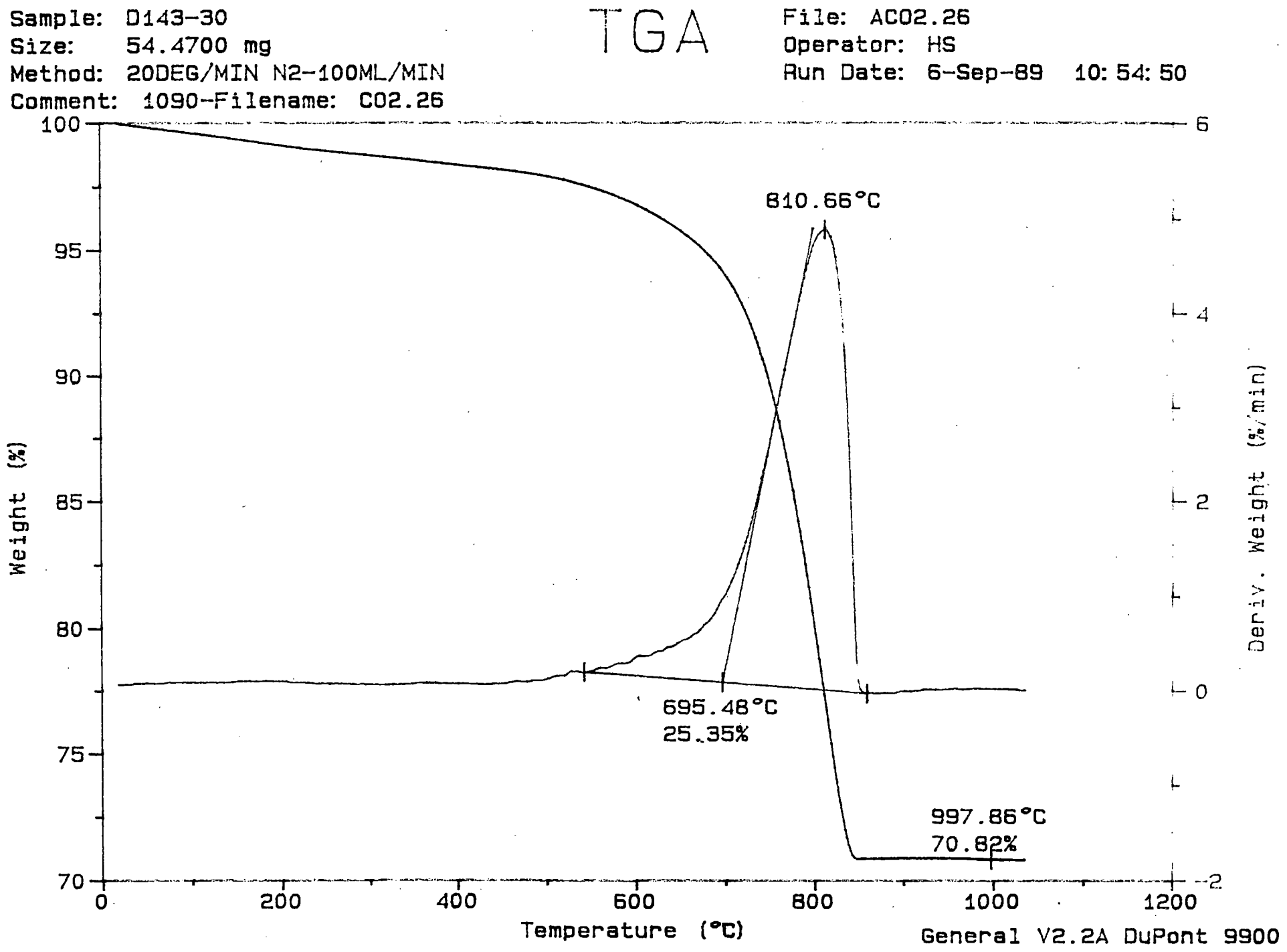
Sample: D143-30
Size: 54.4700 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.26
TGA
File: AC02.26
Operator: HS
Run Date: 6-Sep-89 10:54:50
810.66°C
695.48°C
25.35%
997.86°C
70.82%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 26

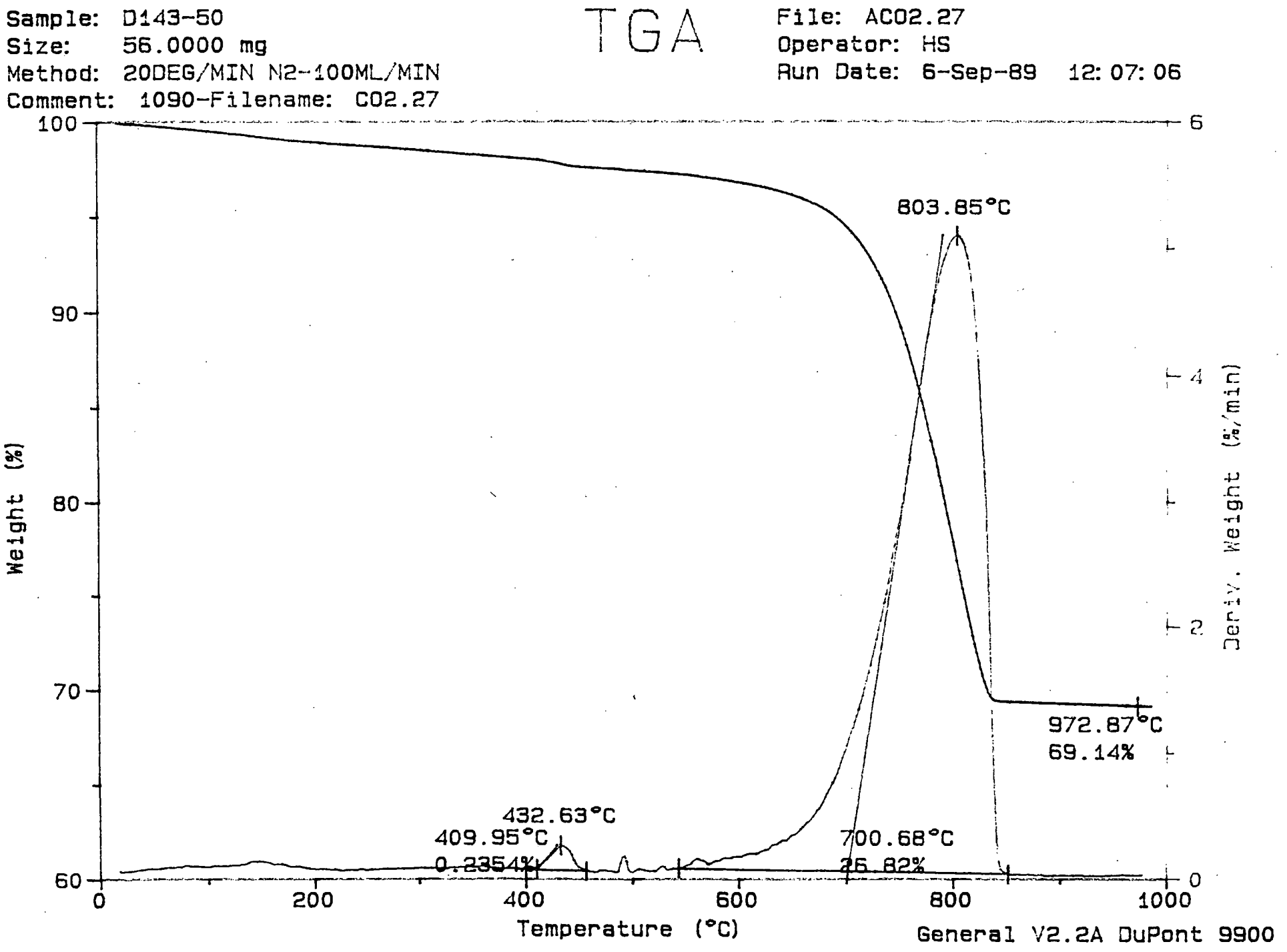
Sample: D143-50
Size: 56.0000 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.27
TGA
File: AC02.27
Operator: HS
Run Date: 6-Sep-89 12:07:06
803.85°C
972.87°C
69.14%
432.63°C
409.95°C
0.2354%
700.68°C
26.82%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 27

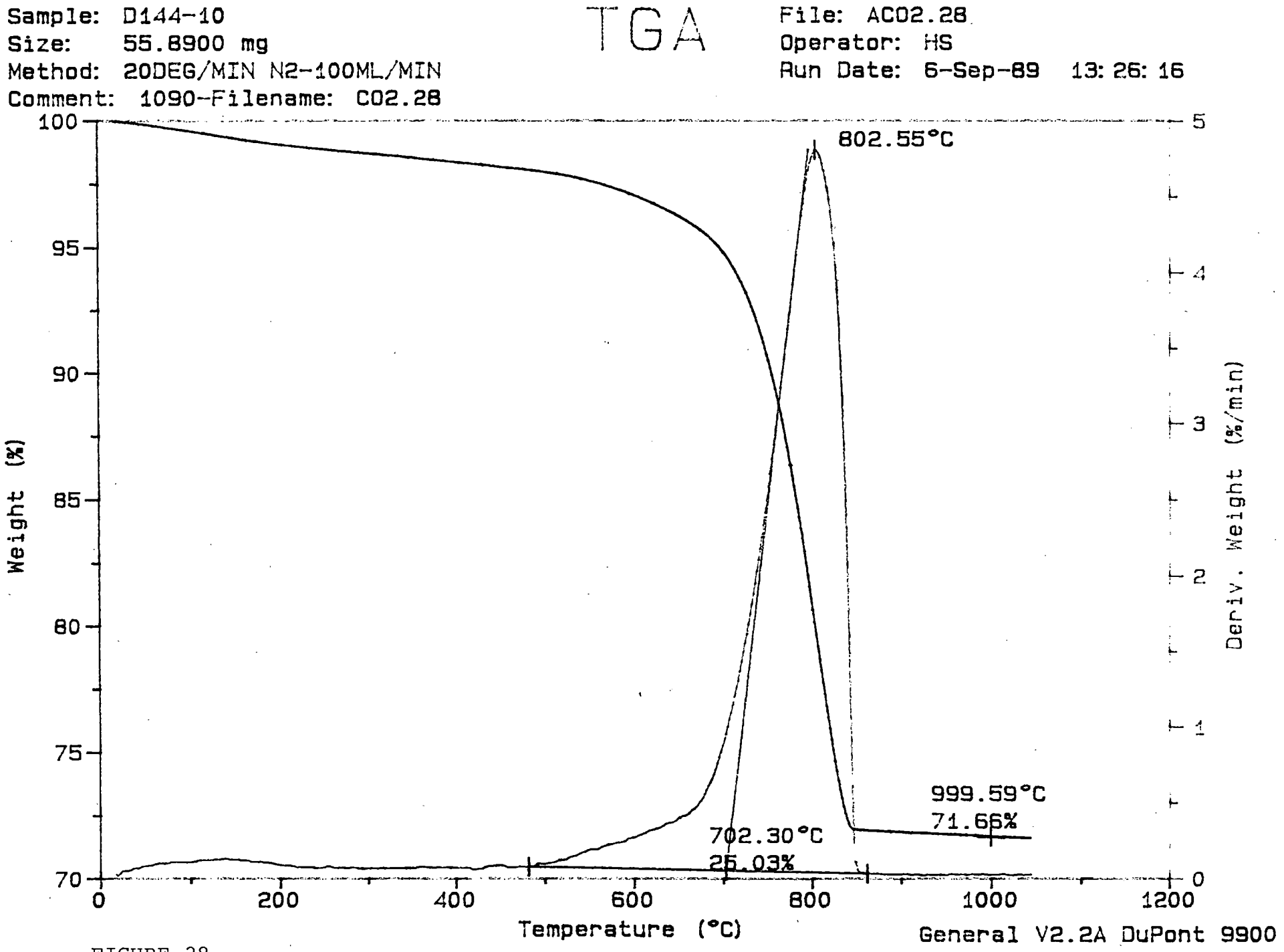
Sample: D144-10
Size: 55.8900 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.28
TGA
File: AC02.28
Operator: HS
Run Date: 6-Sep-89 13:26:16
802.55°C
999.59°C
71.66%
702.30°C
25.03%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 28

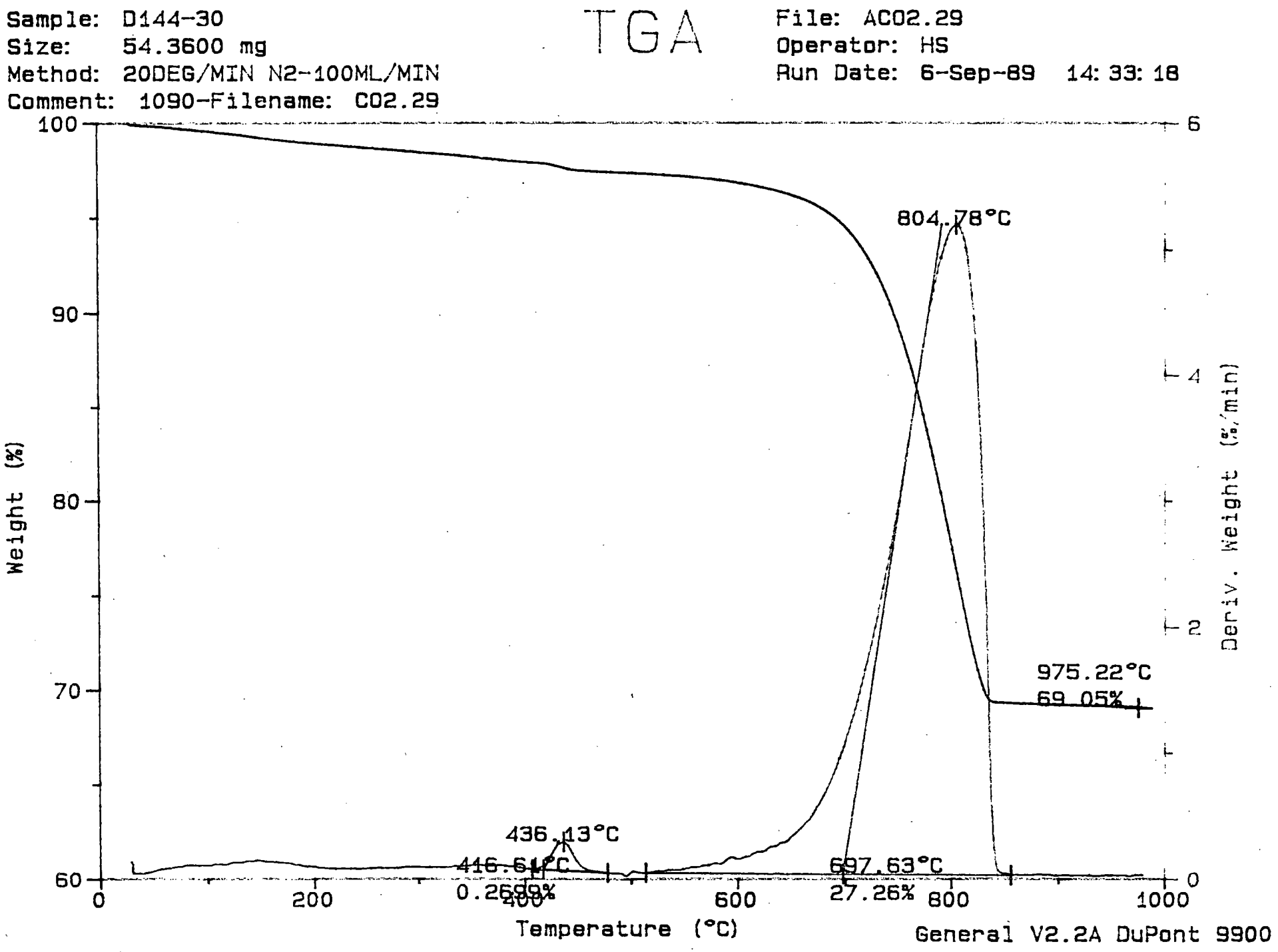
Sample: D144-30
Size: 54.3600 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.29
TGA
File: AC02.29
Operator: HS
Run Date: 6-Sep-89 14:33:18
100
90
80
70
60
Weight (%)
6
4
2
0
Deriv. Weight (%/min)
804.78°C
975.22°C
69.05%
436.13°C
416.61°C
0.26%
697.63°C
27.26%
0
200
400
600
800
1000
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 29

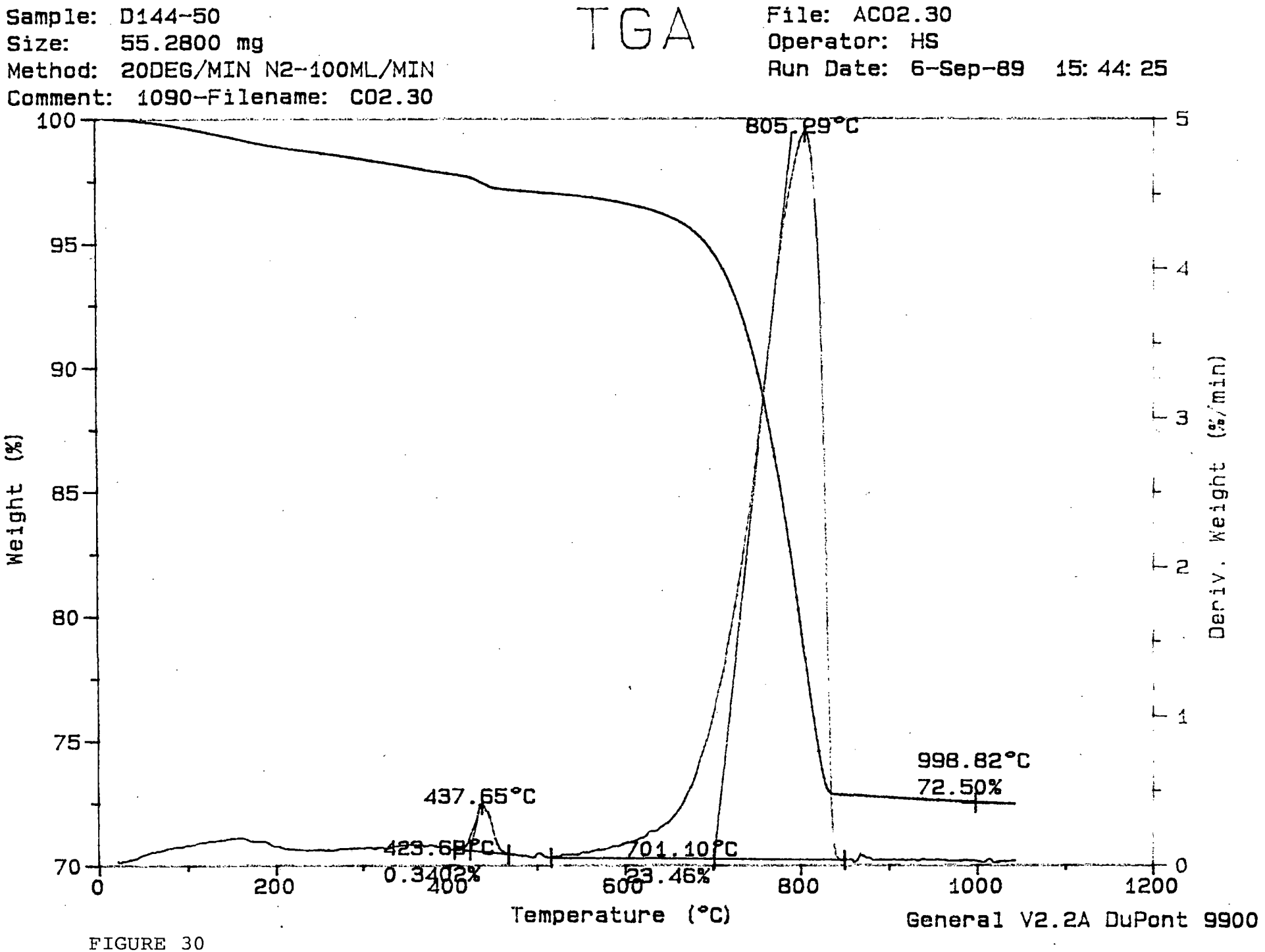
Sample: D144-50
Size: 55.2800 mg
Method: 20DEG/MIN N2-100ML/MIN
Comment: 1090-Filename: C02.30
TGA
File: AC02.30
Operator: HS
Run Date: 6-Sep-89 15:44:25
805.29°C
437.65°C
423.68°C
0.3402%
701.10°C
23.46%
998.82°C
72.50%
Weight (%)
Deriv. Weight (%/min)
Temperature (°C)
General V2.2A DuPont 9900

FIGURE 30