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Engineering Properties of Geologic Materials

From

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Final Report

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Engineering Properties of Eagle Ford Shale, Taylor Marl, and Bentonite from the SSC Project

1. Introduction

This is the Final Report for Consultant Agreement No. SP-3134 with the Earth Technology Corporation, Long Beach, California. It includes data on mineralogy, natural water content, total unit weight, dry unit weight, Atterberg plastic and liquid limits, undrained shear strength, undrained modulus, residual friction angle, swelling pressure, recompression index, swelling index, and deterioration characteristics of Eagle Ford shale and Taylor Marl specimens prepared from NX core size samples. A limited number of measurements were made on a Bentonite sample.

This report includes results of 22 Atterberg plastic and liquid limit tests, 25 unconsolidated undrained triaxial compression tests, 5 drained reversal direct shear tests, 31 oedometer tests, 34 duplicate environmental controlled deterioration tests, and mineralogy determinations. Natural water content was determined for specimens used for all tests.

2. Geologic Materials

NX-core samples of Eagle Ford shale (EFS), Taylor marl (TM), and Bentonite (BEN), which were received from the Earth Technology Corporation, are listed in Table 1. This table includes information on Boring Number and Depth of Samples, as well as the date they were received. These samples were inspected when received, resealed if necessary, and stored in a

For Eagle Ford shale, s_u = 677-1811 kPa, E_u = 250-571 MPa and E_u/s_u = 258-414; for Taylor shale, s_u = 885-1670 kPa, E_u = 223-530 MPa, and E_u/s_u = 213-304; and for Bentonite s_u = 536 kPa, E_u = 83 MPa, and E_u/s_u = 154. The values of s_u(UU), E_u(UU) and E_u(UU)/s_u(UU) for EFS and TM are plotted against natural water content in Figs. 1, 2, 3 and 4.

6. Drained Reversal Direct Shear Tests

Direct shear test results are summarized in Table 5 and are presented in Appendix BI, Figs. B1-B5. Reconstituted pre-cut specimens were used to determine residual friction angle of Eagle Ford shale, Taylor marl and Bentonite. Each 60 x 60 mm square and 10 mm high specimen half was one-dimensionally consolidated. All drained direct shear tests were carried out under an effective normal pressure of 690 kPa. One set of specimen halves was consolidated under 690 kPa, whereas a second set was consolidated under 2758 kPa, unloaded and allowed to swell under 690 kPa, before being assembled and sheared. A linear relationship was used to define residual shear strength-effective normal stress relationship in the range of zero to 690 kPa. The values of the residual friction angle, ϕ'_r, are 5-6°, 4-6°, and 7-8° for Eagle Ford shale, Taylor marl, and Bentonite, respectively. The measured magnitude of ϕ'_r for Bentonite which is rather high and is greater than those for EFS and TM, is surprising. Additional tests are required to clarify this result.

After reaching the residual shear condition by a cumulative shear displacement of 50 mm, the specimen was removed from the shear box and separated along the shear plane. In every case highly polished and slickensided shear surfaces were exposed.

7. Oedometer Tests

Oedometer test results are summarized in Table 6, and void ratio-log pressure as well as swelling pressure-log time curves are presented in Appendix CI, Figs. C1-C30. All tests were carried out on 45 mm diameter and 12 mm high intact specimens. The swelling pressure, σ_{si} was measured at the specimen void ratio e_i. Table 6 includes the values of natural water content w_o, specimen void ratio e_i, as well as swelling pressure σ_{si}. The values of σ_{si} are in the range of 0.8-20 tsf (77-1900 kPa), and 0.9-4.0 tsf (86-383 kPa) for Eagle Ford shale and Taylor marl, respectively. The magnitude of swelling pressure at void ratios slightly smaller than or larger than e_i can be computed using the following equation:

$$\sigma_s = \sigma_{si} \exp \left(2.3 \frac{e_i - e}{C_s} \right)$$

where C_s is the swelling index. The values of σ_{si} for Eagle Ford shale and Taylor marl are plotted against natural water content in Fig. 5.

Most oedometer tests were unloaded after reaching the swelling pressure, σ_{si}, using either load control or deformation control, and a swelling curve was defined. The values of the swelling index C_s are summarized in Table 6 and are plotted against natural water content in Fig. 6.

A number of oedometer tests were subjected to incremental loading after reaching the swelling pressure σ_{si}. The intention was to measure compressibility of Eagle Ford shale and Taylor marl. Maximum effective vertical pressures of 64-126 tsf (6-12 MPa) were reached in these tests. However, it appears from the e-log σ'_v curves in Appendix CI that for Eagle

Ford shale as well as Taylor marl the in situ preconsolidation pressure σ'_p was not reached. Thus, the loading data provide information on the recompression index, C_r, the values of which are listed in Table 6 and summarized against natural water content in Fig. 7. The recompression e-log σ'_v curves are non-linear. Therefore, two values of C_r are listed in Table 6.

8. Environmental Controlled Deterioration Tests

Deterioration test results are summarized in Table 7 and are presented in terms of water content against relative humidity as well as suction pressure, and water content against time in Appendix DI, Figs. D1-D29. The suction pressure u_s in tsf is computed using the following equation:

$$u_s = 1391 \ln (RH/100)$$

All specimens were first subjected to RH = 99% and allowed to come to equilibrium. Then relative humidity was decreased to 87%, and after primary drying it was further reduced to RH = 45%. Following primary drying at RH = 45% the cycle was reversed and RH was increased to 87% and then to 99%. All duplicate specimens of Eagle Ford shale and Taylor marl were subjected to one full dry-wet cycle, except one set each of Eagle Ford shale and Taylor marl which was subjected to three full dry-wet cycles. In Table 7 the deterioration test results are summarized in terms of final water content under each relative humidity. In Figs. 8-9 water content of Eagle Ford shale and Taylor marl against number of exposures to dry (RH = 45%) and wet (RH = 99%) conditions are plotted. These results indicate that softening accelerated after the third dry-wet cycle.

All specimens of Eagle Ford shale and Taylor marl slightly softened, but remained intact upon the first exposure to RH = 99%. However, as they were dried at RH = 87%, microfissures started to open up along the bedding planes, and they widened as RH was further decreased to 45%. No further fissuring was observed during wetting to RH = 87% and then at RH = 99%. However, during the second drying cycle the fissures widened and some specimens split into pieces. Further fissuration, cracking, and splitting was observed during the third drying cycle.

Eagle Ford shale and Taylor marl are moderately fissile shales (Eagle Ford shale being relatively more fissile than Taylor marl) with natural water contents (15-17%) and liquid limits (90-160%) that lead to an equilibrium relative humidity, ERH, of around 95%. Equilibrium relative humidity is the RH at which shale neither gains or loses moisture, thus remaining unchanged. Both Eagle Ford shale and Taylor marl are expected to deteriorate when they are subjected to environments drier than 95%, and they can soften if exposed to environments wetter than 95%.

Duplicate specimens of a sample of Bentonite were subjected to two dry-wet cycles. Fissures parallel and normal to bedding planes developed as soon as the Bentonite samples were subjected to any drying, and they deteriorated after the second cycle of drying. Deterioration test data on Bentonite are shown in Table 7 and Fig. 10.

Table 1 List of Samples Received

Boring	Depth (ft)	Material	Date Received
BE7A	36.15 - 37.15	Taylor Marl	1/29/90
BE7A	82.33 - 83.00	Taylor Marl	1/29/90
BE7A	166.80 - 167.40	Taylor Marl	1/29/90
BE7A	167.4 0 - 168.15	Taylor Marl	1/29/90
BE7A	206.59 - 207.77	Taylor Marl	1/29/90
BE7A	305.90 - 306.35	Taylor Marl	1/29/90
BF1	211.70 - 212.30	Eagle Ford Shale	1/29/90
BF8	38.00 - 39.20	Taylor Marl	1/29/90
BF8	78.30 - 79.05	Taylor Marl	1/29/90
BF8	106.95 - 107.50	Taylor Marl	1/29/90
BI3	264.40 - 265. 60	Eagle Ford Shale	1/29/90
BI3	265.60 - 266.60	Eagle Ford Shale	1/29/90
BI4	171.60 - 174.00	Taylor Marl	1/29/90
BI4	176.10 - 177.70	Eagle Ford Shale	1/29/90
BI6	224.00 - 225.50	Eagle Ford Shale	1/29/90
BIR41	180.20 - 184.10 (I of IV)	Eagle Ford Shale	1/29/90
BIR41	180.20 - 184.10 (III of IV)	Eagle Ford Shale	1/29/90
BIR41	211.50 - 215.00	Eagle Ford Shale	1/29/90
BE6	33.65 - 34.30	Taylor Marl	2/15/90
BE6	53.50 - 54.30	Taylor Marl	2/15/90
BE6	112.80 - 113.55	Taylor Marl	2/15/90
BF7	169.35 - 170.85	Taylor Marl	2/15/90
BIR13	216.75 - 217.60	Eagle Ford Shale	3/22/90
BIR13	240.90 - 242.40	Eagle Ford Shale	3/22/90
BIR14	217.00 - 217.80	Eagle Ford Shale	3/22/90
BIR14	217.80 - 218.80	Eagle Ford Shale	3/22/90
BIR14	292.00 - 293.00	Eagle Ford Shale	3/22/90
BIR43	116.90 -117.85	Bentonite	3/22/90
BIR43	184.00 - 185.20	Eagle Ford Shale	3/22/90
BIR43	216.30 - 217.65	Eagle Ford Shale	3/22/90

Table 1 (Cont.) List of Samples Received

Boring	Depth (ft)	Material	Date Received
BIR43	311.50 - 312.45	Eagle Ford Shale	3/22/90
BIR43	312.45 - 313.40	Eagle Ford Shale	3/22/90
BIR44	183.00 - 184.10	Eagle Ford Shale	3/22/90
BIR44	209.10 - 210.10	Eagle Ford Shale	3/22/90
BIR44	210.10 - 211.10	Eagle Ford Shale	3/22/90
BIR44	260.50 - 261.90	Eagle Ford Shale	3/22/90
B1527	229.50 - 230.50	Eagle Ford Shale	4/17/90
B1533	204.90 - 206.00	Eagle Ford Shale	4/17/90
B1533	206.10 - 206.90	Eagle Ford Shale	4/17/90
B1540	211.10 - 212.35	Eagle Ford Shale	4/17/90
B1540	212.35 - 213.00	Eagle Ford Shale	4/17/90
B1540	255.75 - 257.00	Eagle Ford Shale	4/17/90
B1737	181.50 - 182.00	Eagle Ford Shale	4/17/90
B22-90	190.00 - 191.15	Eagle Ford Shale	4/17/90
B1807	201.75 - 202.85	Eagle Ford Shale	4/17/90
BIR45	176.00 - 177.80	Eagle Ford Shale	4/17/90
BIR45	177.90 - 179.00	Eagle Ford Shale	4/17/90
BIR45	233.90 -234.80	Eagle Ford Shale	4/17/90

Table 2A Whole Sample Mineralogy

Material	Bore Hole	Depth	Clay	Qtz	Plag	K-spar	Apa	Calc	Pyr
TM	BE7A	82.33-83.00	41	19	4	2	5	29	0.5
EFS	BI6	224.0-225.5	55	33	4	4	3		1

Numbers represent mineral abundance in weight percent
Clay = Total clay minerals, Qtz = Quartz, Plag = plagioclase feldspar, K-spar = Potassium feldspar, Apa = Apatite, Calc = Calcite, Pyr = pyrite.

Table 2B Clay Mineralogy (< 2 μm)

Material	Bore Hole	Depth	ILL	Kaol	Smect	Smectite Hydration State	Development of Hydroxy Interlayer in Smectite
TM	BE7A	82.33-83.00	19	22	58	$2H_2O$	Minor
EFS	BI6	224.0-225.5	37	32	31*	$2H_2O$	Minor

Numbers represent mineral abundance in weight percent
ILL = Illite, Kaol = Kaolinite, Smect = Smectite,

* This smectite is actually randomly interstratified illite/smectite with ≈ 30 % Illite layers.

Table 3 Index Properties of Core Samples

Material	Bore Hole	Depth (ft)	w_o (%)	Total Unit Wt pcf	Dry Unit Wt pcf	L L (%)	P L (%)	P I (%)
EFS	BI4	176.10 - 177.70	16.4	136	117	95*	23	72
EFS	BI6	224.00 - 225.50	16.5	135	116	93*	25	68
EFS	BI6	224.00 - 225.50	16.9	136	116	94	27	67
TM	BE7A	82.33 - 83.00	17.7	132	112	112	22	90
TM	BE7A	167.40 - 168.15	14.6	--	--	105	21	84
EFS	BF1	211.70 - 212.30	16.5	131	112	91	27	64
TM	BF8	38.00 - 39.20	23.3	124	101	102	24	78
TM	BF8	78.30 - 79.05	19.9	131	109	115	22	93
TM	BF8	106.95 - 107.50	17.8	133	113	116	23	93
TM	BE6	33.65 - 34.30	19.2	132	111	105	23	82
TM	BE6	53.55 - 54.30	18.5	132	111	124	23	101
EFS	BI3	264.40 - 265.60	16.6	132	113	121	29	92
EFS	BIR13	216.75 - 217.60	18.4	128	108	126	29	87
EFS	BIR13	240.90 - 242.40	17.8	135	115	102	27	75
EFS	BIR14	292.00 - 293.00	15.1	137	119	86	26	60
EFS	BIR41	180.20 - 184.10	15.4	132	114	111	26	85
EFS	BIR41	180.20 - 184.10	16.7	127	109	93**	26	67

Note: All the samples prepared by air-drying and then pulverizing by ball milling except those marked with asterisk.

* Sample oven dried and then pulverized by ball milling

** Sample air dried and then pulverized by mortar and pestle (ASTM)

Table 3 (Cont.) Index Properties of Core Samples

Material	Bore Hole	Depth (ft)	w_o (%)	Total Unit Wt pcf	Dry Unit Wt pcf	L L (%)	P L (%)	P I (%)
BEN	BIR43	116.90 -117.85	39.6	113	81	200	48	152
EFS	BIR43	312.45 - 313.40	16.0	136	117	84	27	57
EFS	BIR44	183.00 - 184.10	16.5	137	118	123	27	96
EFS	BIR44	210.10 - 211.10	15.6	136	118	104	27	77
EFS	BIR45	233.90 - 234.80	14.3	139	122	111	26	85
EFS	B1533	204.90 - 206.00	14.9	137	119	---	---	---
EFS	B1533	204.90 - 206.00	15.1	137	119	---	---	---

Note: All the samples prepared by air-drying and then pulverizing by ball milling except those marked with asterisk.

* Sample oven dried and then pulverized by ball milling

** Sample air dried and then pulverized by mortar and pestle (ASTM)

Table 4 Summary of UU Test Results

Test No.	Bore Hole	Depth (ft)	Material	w_o (%)	L L (%)	P L (%)	σ_3 kPa	q_u kPa	E_u MPA	E_u/s_u	t_f mins
UU1	BI4	176.10 - 177.70	EFS	16.4	95	23	1379	2850	368	258	22
UU2	BI6	224.00 - 225.50	EFS	16.8	94	27	1379	2930	389	265	15
UU3	BI6	224.00 - 225.50	EFS	16.9	94	27	2758	3493	538	308	22
UU4	BI6	224.00 - 225.50	EFS	16.5	94	27	2758	2920	437	299	16
UU5	BI6	224.00 - 225.50	EFS	16.9	94	27	689	2921	437	299	20
UU6	BE7A	82.33 - 83.00	TM	17.9	112	22	1379	2984	318	213	20
UU7	BE7A	82.33 - 83.00	TM	17.7	112	22	1379	2888	350	242	25
UU8	BF8	106.95 - 107.50	TM	17.8	116	23	2758	3340	500	299	20
UU9	BF8	78.30 - 79.05	TM	19.4	115	22	2758	3287	500	304	18
UU10	BF8	78.30 - 79.05	TM	19.9	114	22	689	3070	389	253	25
UU11	BF8	38.00 - 39.20	TM	23.3	108	24	689	1895	233	246	22
UU12	BF8	38.00 - 39.20	TM	22.8	108	24	2758	1770	233	263	17
UU13	BE6	33.65 - 34.30	TM	19.2	105	23	1378	1778	233	262	22
UU14	BE6	53.55 - 54.30	TM	18.5	124	23	1378	2392	269	225	18
UU15	BIR43	116.90 -117.85	BEN	39.6	200	48	1378	1072	83	154	25
UU16	BIR13	216.75 - 217.60	EFS	18.4	126	29	1378	1354	280	414	15
UU17	BIR13	240.90 - 242.40	EFS	17.8	102	27	1378	1637	250	305	16
UU18	BIR14	292.00 - 293.00	EFS	15.1	86	26	1378	3617	500	276	22

EFS = Eagle Ford Shale, TM = Taylor Marl, BEN = Bentonite

Table 4 (Cont.) Summary of UU Test Results

Test No.	Bore Hole	Depth (ft)	Material	w_o (%)	L L (%)	P L (%)	σ_3 kPa	q_u kPa	E_u MPA	E_u/s_u	t_f mins
UU19	BIR43	312.45 - 313.40	EFS	16.0	84	27	2758	2412	466	386	18
UU 20	BIR43	312.45 - 313.40	EFS	15.8	84	27	1379	2875	437	304	18
UU21	BIR44	183.00 - 184.10	EFS	16.5	123	27	2758	2955	538	364	15
UU22	BIR44	210.10 - 211.10	EFS	15.6	104	27	2758	3623	571	315	18
UU23	BIR45	233.90 - 234.80	EFS	14.4	--	--	1378	3005	444	296	15
UU24	B1533	204.90 - 206.00	EFS	14.9	--	--	1378	3090	444	287	18
UU25	B1533	204.90 - 206.00	EFS	15.1	--	--	2758	3204	500	312	24

EFS = Eagle Ford Shale, TM = Taylor Marl, BEN = Bentonite

Table 5 Summary of Drained Reversal Direct Shear Tests

Test No.	Material	Bore Hole	Depth (FT)	L L (%)	P L (%)	P I (%)	σ'_{vmax} (kPa)	σ'_{vc} (%)	ϕ'_r (o)
DS1	EFS	BI6	224.00 - 225.50	94	27	67	690	690	5~6
DS2	TM	BE7A	82.33 - 83.00	112	22	90	690	690	4
DS3	EFS	BI6	224.00 - 225.5	94	27	67	2758	690	5~6
DS4	BEN	BIR43	116.90 - 217.85	200	48	152	2758	690	7~8
DS5	TM	BE7A	82.33 - 83.00	112	22	90	2758	690	5~6

EFS = Eagle Ford Shale, TM = Taylor Marl, BEN = Bentonite

Table 6 Summary of Oedometer Tests

Bore Hole	Depth (ft)	Mate-rial	Test No.	w_o (%)	e_i	σ_{si} (TSF)	C_s	C_r
BI 3	264.40 - 265.60	EFS	EFS-7a*	16.9	0.482	20.0	----	
BI 3	264.40 - 265.60	EFS	EFS-8	16.6	0.522	8.0	0.04	
BF1	211.70 - 212.30	EFS	EFS-9a*	16.6	0.488	3.6	----	
BF1	211.70 - 212.30	EFS	EFS-10	16.3	0.528	2.0	0.03	
BIR 41	180.20 - 184.10	EFS	EFS-13a*	15.4	0.506	6.7	----	
BIR 41	180.20 - 184.10	EFS	EFS-14	16.7	0.579	1.6	0.03	
BI 4	176.10 - 177.70	EFS	EFS-17**	16.4	0.463	4.2	0.03-0.06	0.02-0.07
BI 4	176.10 - 177.70	EFS	EFS-18**	16.6	0.495	2.0	0.03-0.06	0.03-0.09
BI 4	176.10 - 177.70	EFS	EFS-17a*	16.6	0.482	5.2	----	
BIR 13	240.90 - 242.40	EFS	EFS-23a*	16.6	0.522	1.2	----	
BIR 13	240.90 - 242.40	EFS	EFS-24	17.1	0.532	0.9	0.04	
BIR 14	217.00 - 217.80	EFS	EFS-25a*	17.1	0.625	0.8	----	
BIR 14	217.00 - 217.80	EFS	EFS-26	17.8	0.528	2.0	0.03	
BIR 43	184.00 - 185.20	EFS	EFS-27a*	17.9	0.530	1.5	----	
BIR 43	184.00 - 185.20	EFS	EFS-28	17.3	0.516	1.3	0.01	
BIR 43	216.30 - 217.60	EFS	EFS-47a*	16.6	0.509	2.4	----	
BIR 43	216.30 - 217.60	EFS	EFS-48	17.1	0.497	1.7	0.01	
BIR 44	209.10 - 210.10	EFS	EFS-49a*	15.3	0.439	11.2	----	
BIR 44	209.10 - 210.10	EFS	EFS-50	15.2	0.422	7.0	0.01	
BIR 44	260.50 - 261.9	EFS	EFS-61***	15.4	0.513	1.5	0.04-0.06	0.05-0.08
BI 4	171.60 - 174.10	TM	TM-9a	17.5	0.546	3.9	----	
BI 4	171.60 - 174.10	TM	TM-10	17.2	0.550	1.5	0.02	
BF 8	106.95 - 107.50	TM	TM-11a*	18.5	0.565	3.0	----	
BF 8	106.95 - 107.50	TM	TM-12**	18.2	0.530	4.0	0.02-0.04	0.02-0.07

* Test in Rigid Frame. ** Recompressed to 64 TSF. *** Recompressed to 126 TSF

Table 6 (Cont.) Summary of Oedometer Tests

Bore Hole	Depth (ft)	Mate-rial	Test No.	w_o (%)	e_l	σ_{sl} (TSF)	C_s	C_r
BE 6	33.65 - 34.30	TM	TM-15a*	18.9	0.558	0.9	----	
BE7A	206.59 - 207.77	TM	TM-21a*	14.2	0.509	3.9	----	
BE 6	112.80 - 113.55	TM	TM-33a*	15.5	0.536	1.5	----	
BE 6	112.80 - 113.55	TM	TM-34	15.4	0.519	3.5	0.01	
BE 6	112.80 - 113.55	TM	TM-37***	15.5	0.558	2.9	0.02-0.04	0.03-0.06
BF 7	169.35 - 170.85	TM	TM-35a*	16.3	0.589	1.6	----	
BF 7	169.35 - 170.85	TM	TM-36	16.8	0.498	2.0	0 .01	

* Test in Rigid Frame, ** Recompressed to 64 TSF, *** Recompressed to 126 TSF

Table 7 Summary of Deterioration Test Results

Bore Hole	Depth (ft)	Mate-rial	Test No.	w_o (%)	Equilibrium Water Content (%) RH (%) 99	87	45	87	99
BIR 41	211.50 - 215.00	EFS	EFS-3	15.6	16.05	14.43	11.64	13.42	17.68
BIR 41	211.50 - 215.00	EFS	EFS-4	15.6	16.30	14.44	11.57	13.37	18.20
BIR 41	180.20 - 184.10	EFS	EFS-5	16.2	16.42	15.11	12.05	13.69	18.41
BIR 41	180.20 - 184.10	EFS	EFS-6	16.3	16.37	15.06	12.36	14.03	17.94
BIR 41	180.20 - 184.10	EFS	EFS-15	16.2	16.33	15.08	12.50	14.09	17.20
BIR 41	180.20 - 184.10	EFS	EFS-16	16.3	16.36	15.08	12.31	14.00	17.42
BI 3	264.40 - 265.60	EFS	EFS-11	16.4	16.65	15.36	12.58	14.37	17.78
BI 3	264.50 - 265.60	EFS	EFS-12	16.4	16.70	15.56	13.18	14.76	17.96
BI 4	176.10 - 177.70	EFS	EFS-19	16.6	16.18	15.16	12.53	14.09	16.83
BI 4	176.10 - 177.70	EFS	EFS-20	16.6	16.65	15.36	12.45	14.21	17.45
BF 1	211.70 - 212.30	EFS	EFS-21	16.5	16.59	15.23	12.09	13.91	16.47
BF 1	211.70 - 212.30	EFS	EFS-22	16.5	16.72	14.89	10.71	13.07	16.44
BF 1	211.70 - 212.30	EFS	EFS-21#	16.5	16.47	14.34	12.12	14.06	16.80
BF 1	211.70 - 212.30	EFS	EFS-22#	16.5	16.44	13.73	10.76	13.34	16.89
BF 1	211.70 - 212.30	EFS	EFS-21##	16.5	16.80	14.43	12.23	13.74	18.61
BF 1	211.70 - 212.30	EFS	EFS-22##	16.5	16.89	13.81	10.93	12.92	19.54
BIR 14	217.00 - 217.80	EFS	EFS-29	18.7	19.36	16.71	13.84	15.22	20.87
BIR 14	217.00 - 217.80	EFS	EFS-30	18.7	19.59	16.16	12.60	14.63	19.29
BIR 43	184.00 - 185.20	EFS	EFS-31	18.5	19.84	16.13	12.95	14.85	20.61
BIR 43	184.00 - 185.20	EFS	EFS-32	18.5	20.41	15.87	12.33	14.50	22.70
BIR 43	216.30 - 217.65	EFS	EFS-33	16.7	17.46	14.99	11.97	13.61	17.75
BIR 43	216.50 - 217.65	EFS	EFS-34	16.7	17.52	15.10	12.04	13.73	18.38
BIR 43	311.00 - 312.00	EFS	EFS-35	15.7	17.18	13.54	10.12	11.98	17.81
BIR 43	311.00 - 312.00	EFS	EFS-36	15.7	17.60	13.57	10.10	11.97	17.68

Second Cycle ## Third Cycle

Table 7 (Cont.) Summary of Deterioration Test Results

Bore Hole	Depth (ft)	Mate-rial	Test No.	w_o (%)	Equilibrium Water Content (%) RH (%) 99	87	45	87	99
BIR 44	209.10 - 210.10	EFS	EFS-37	15.3	16.31	13.76	10.43	12.28	16.57
BIR 44	209.10 - 210.00	EFS	EFS-38	15.3	16.56	13.77	10.41	12.29	16.90
BIR 44	260.50 - 261.90	EFS	EFS-39	15.1	15.96	13.65	10.43	12.12	15.82
BIR 44	260.50 - 261.90	EFS	EFS-40	15.1	15.73	13.33	9.80	11.75	16.49
B 1527	229.50 - 230.50	EFS	EFS-41	15.7	16.36	14.32	11.21	12.87	16.57
B 1527	229.50 - 230.50	EFS	EFS-42	15.7	16.56	14.29	11.05	12.79	16.53
B 1533	204.90 - 206.00	EFS	EFS-43	13.0	14.16	11.76	9.58	10.77	14.79
B 1533	204.90 - 206.00	EFS	EFS-44	13.0	14.00	11.27	7.88	9.64	14.18
B 1540	211.10 - 212.35	EFS	EFS-45	16.5	17.83	15.07	12.19	13.85	18.13
B 1540	211.10 - 212.35	EFS	EFS-46	16.5	17.85	14.90	11.55	13.49	18.94
B 1540	255.75 - 257.00	EFS	EFS-51	16.6	17.66	14.87	11.54	13.31	17.13
B 1540	255.75 - 257.00	EFS	EFS-52	16.6	17.74	14.68	10.92	12.88	17.11
B 22-90	190.00 - 191.15	EFS	EFS-53	15.7	16.77	14.11	11.00	12.76	16.47
B 22-90	190.00 - 191.15	EFS	EFS-54	15.7	17.01	13.98	10.57	12.47	16.57
B 1807	201.75 - 202.85	EFS	EFS-55	16.4	17.77	14.60	11.13	12.91	17.54
B 1807	201.75 - 202.85	EFS	EFS-56	16.4	17.95	14.60	11.57	13.22	18.04
BIR 45	176.00 - 177.80	EFS	EFS-57	16.3	17.10	14.14	10.63	12.63	16.55
BIR 45	176.00 - 177.80	EFS	EFS-58	16.3	17.19	14.15	10.71	12.56	16.58
BIR 45	233.90 - 234.80	EFS	EFS-59	16.0	17.40	14.76	11.69	13.23	17.10
BIR 45	233.90 - 234.80	EFS	EFS-60	16.0	17.60	14.54	11.39	13.08	17.75

Table 7 (Cont.) Summary of Deterioration Test Results

Bore Hole	Depth (ft)	Mate-rial	Test No.	w_o (%)	Equilibrium Water Content (%) RH (%) 99	87	45	87	99
BIR 43	116.90 - 117.85	BEN	BEN-2	43.0	42.93	37.54	33.82	36.75	40.26
BIR 43	116.90 - 117.85	BEN	BEN-3	43.0	43.02	38.04	35.07	37.51	41.01
BIR 43	116.90 - 117.85	BEN	BEN-2#	43.0	40.26	37.03	33.95	36.32	42.83
BIR 43	116.90 - 117.85	BEN	BEN-3#	43.0	41.01	37.64	35.19	37.19	44.26
BF 8	38.00 - 39.20	TM	TM-5	23.8	23.48	20.02	16.47	18.63	23.90
BF 8	38.00 - 39.20	TM	TM-6	27.0	26.98	24.06	20.95	22.73	27.59
BI 4	171.60 - 174.10	TM	TM-7	18.0	18.01	16.82	14.17	15.74	19.82
BI 4	171.60 - 174.10	TM	TM-8	18.0	18.45	17.18	14.76	16.20	19.68
BE 7A	206.59 - 207.77	TM	TM-19	14.3	14.95	13.33	11.36	12.56	15.29
BE 7A	206.59 - 207.77	TM	TM-20	14.3	14.90	13.46	11.48	12.68	15.50
BE 7A	36.15 - 37.15	TM	TM-17	24.8	23.69	20.01	17.33	18.93	23.50
BE 7A	36.15 - 37.15	TM	TM-18	24.8	24.71	20.97	18.11	19.87	24.37
BE 7A	167.40 - 168.15	TM	TM-23	14.8	15.10	13.93	11.93	13.18	15.58
BE 7A	167.40 - 168.15	TM	TM-24	14.8	15.28	13.68	11.08	12.54	15.13
BI 4	171.60 - 174.10	TM	TM-25	17.2	17.28	15.33	11.72	13.64	16.68
BI 4	171.60 - 174.10	TM	TM-26	17.2	17.57	15.37	11.81	13.80	17.04
BI 4	171.60 - 174.10	TM	TM-25#	17.2	16.68	14.25	11.69	13.56	17.30
BI 4	171.60 - 174.10	TM	TM-26#	17.2	17.04	14.37	11.78	14.07	18.47
BI 4	171.60 - 174.10	TM	TM-25##	17.2	17.30	14.03	11.42	13.26	19.64
BI 4	171.60 - 174.10	TM	TM-26##	17.2	18.47	14.48	11.89	13.76	21.75
BE 7A	167.40 - 168.15	TM	TM-29	14.6	15.13	13.30	10.08	11.63	14.33
BE 7A	167.40 - 168.15	TM	TM-30	14.6	14.80	13.36	10.42	11.91	14.27
BE 6	53.55 - 54.35	TM	TM-31	18.8	18.97	16.02	13.38	15.24	18.53
BE 6	53.55 - 54.35	TM	TM-32	18.8	19.42	15.64	12.35	14.55	14.17

Second Cycle ## Third Cycle

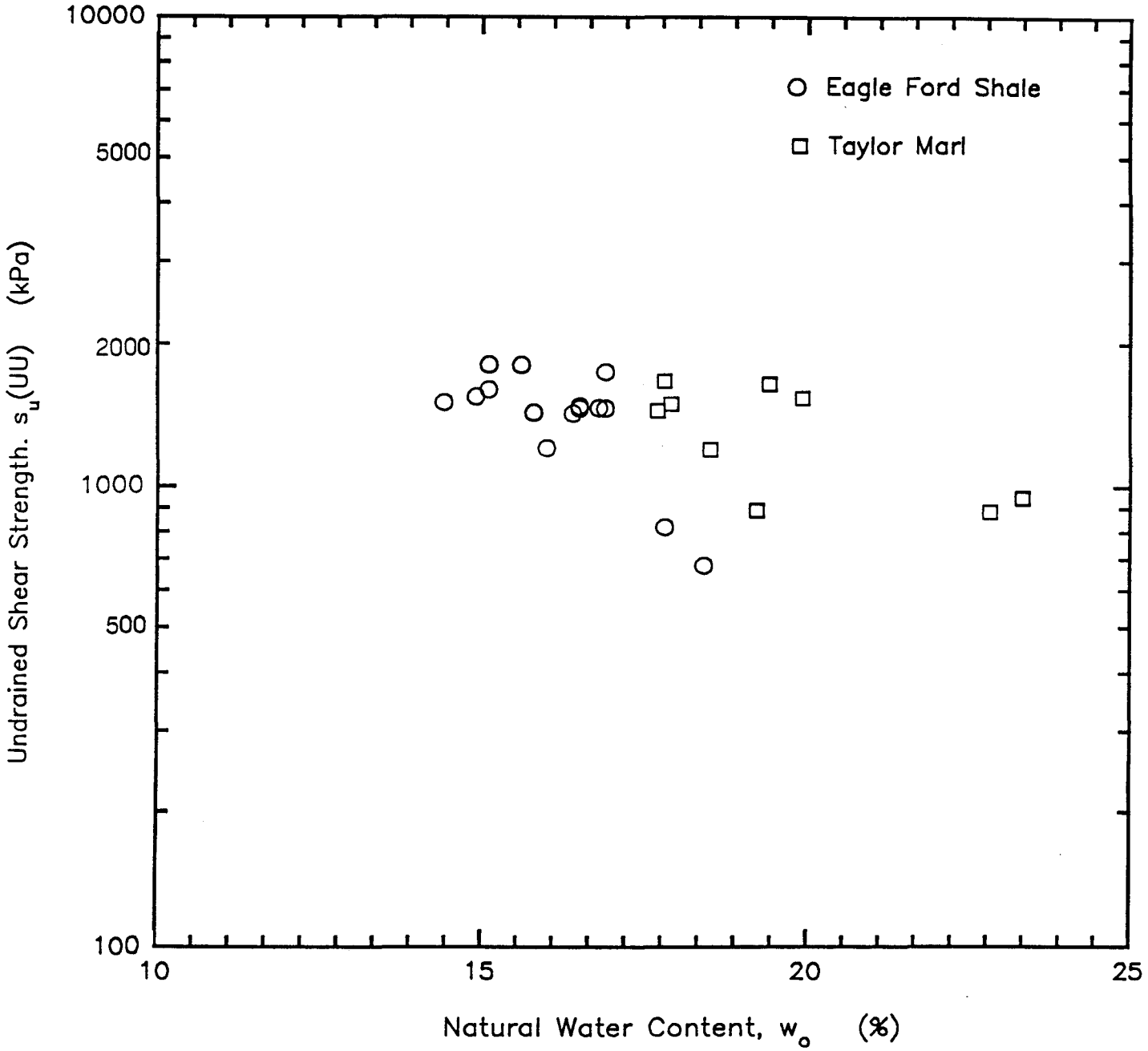


Fig. 1 Undrained Shear Stength, s_u(UU) vs Natural Water Content

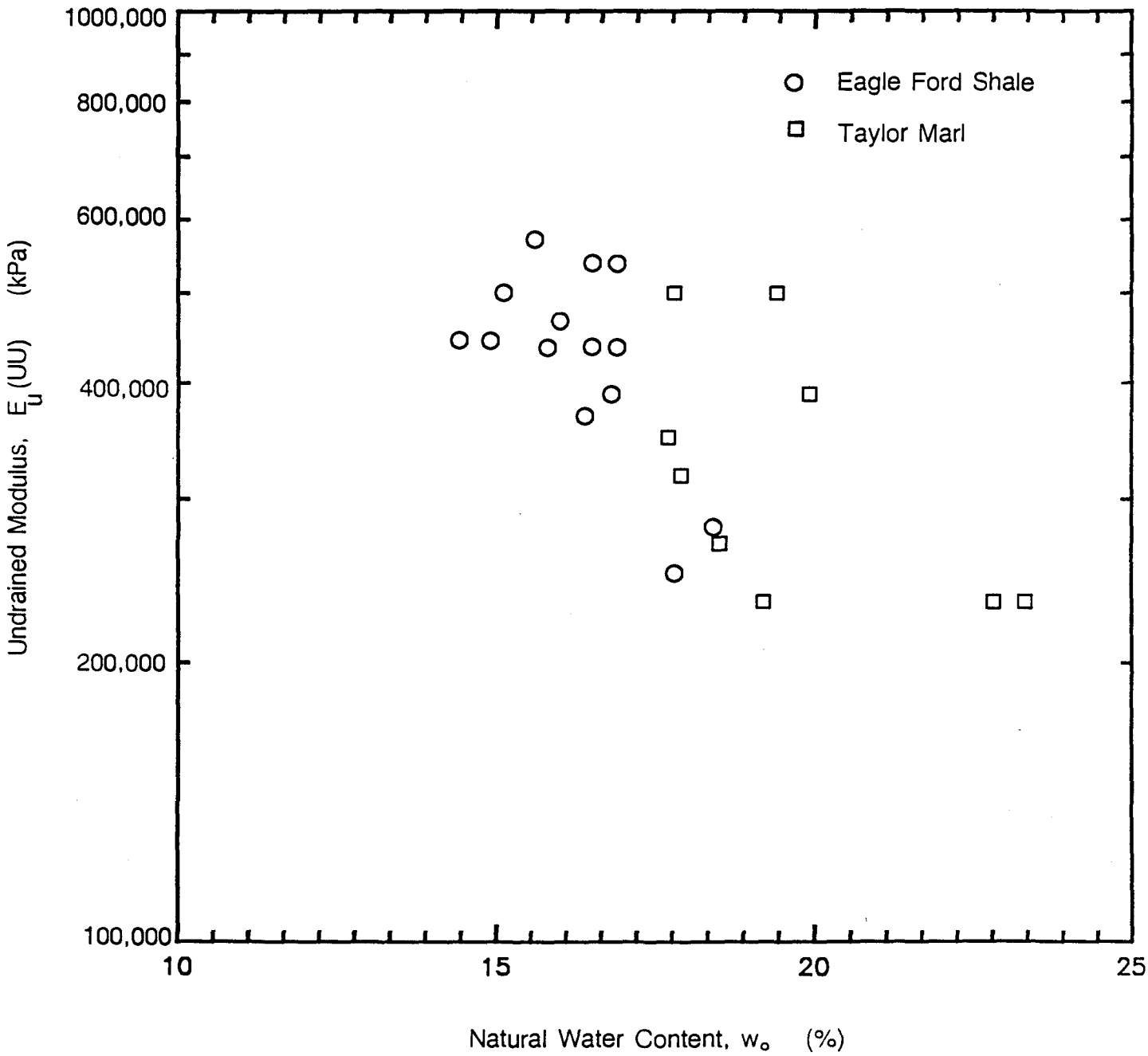


Fig. 2 Undrained Modulus, E_u(UU) vs Natural Water Content

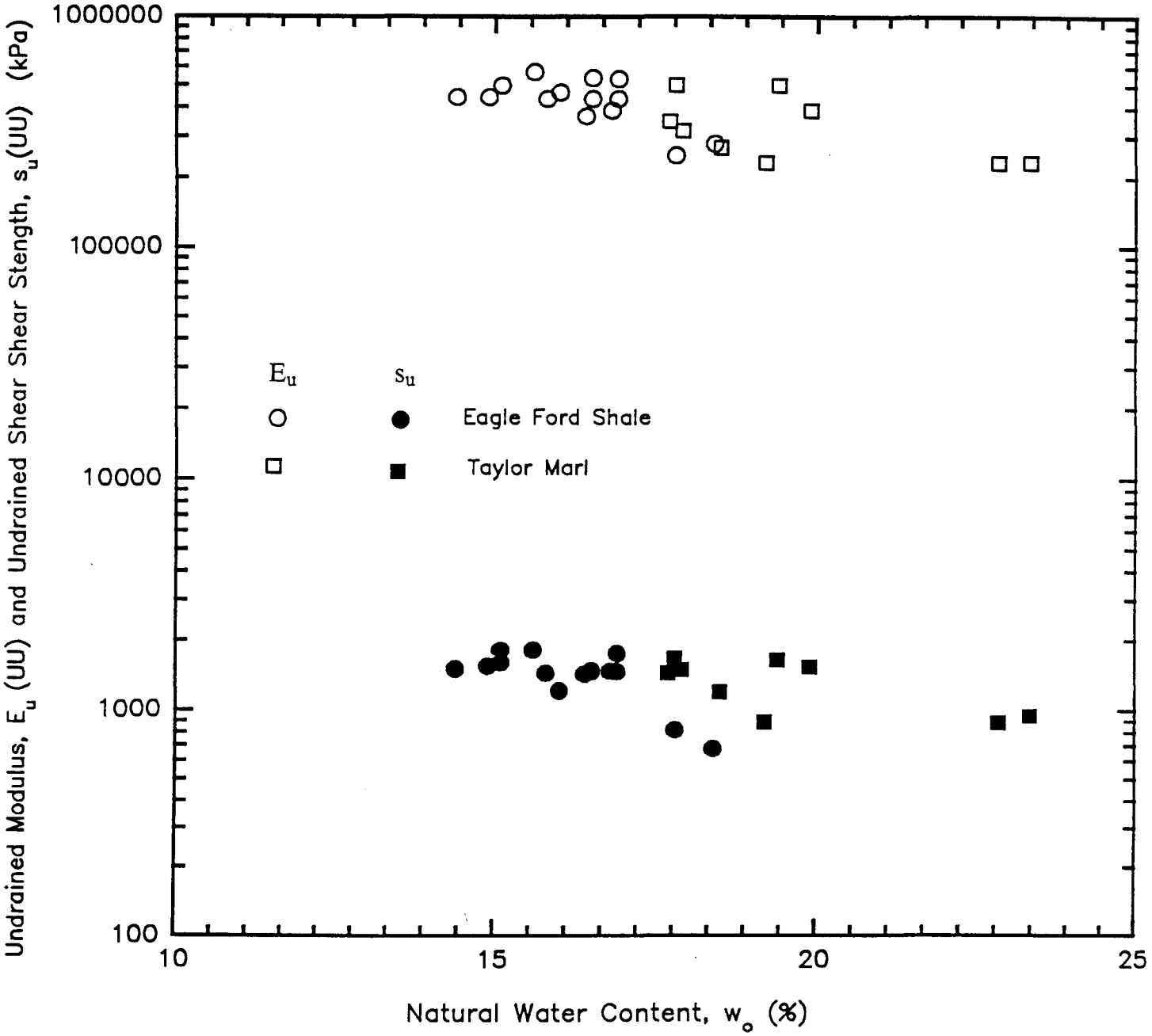


Fig. 3 E_u(UU) and s_u(UU) vs Natural Water Content

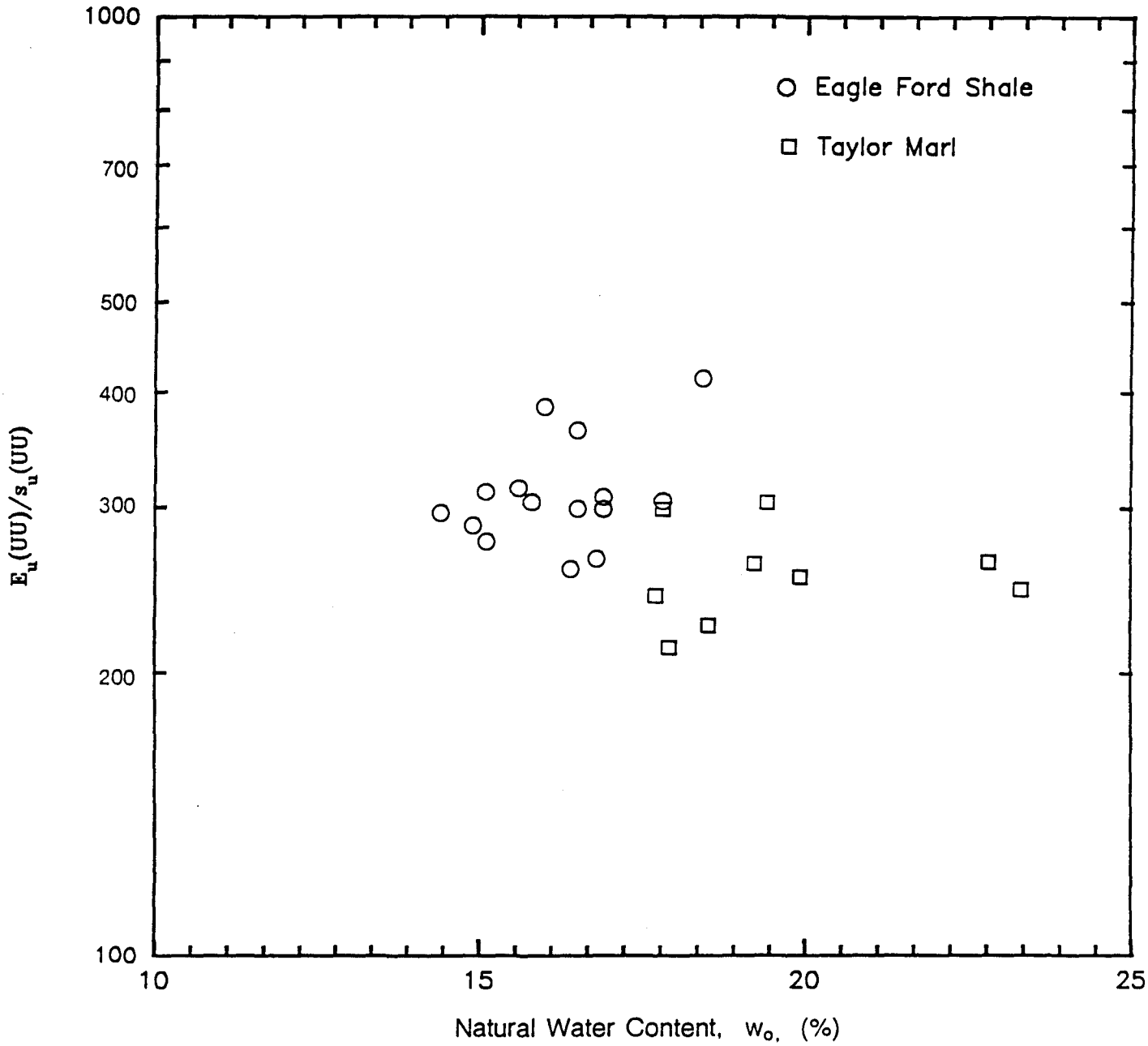


Fig. 4 $E_u(UU)/s_u(UU)$ vs Natural Water Content

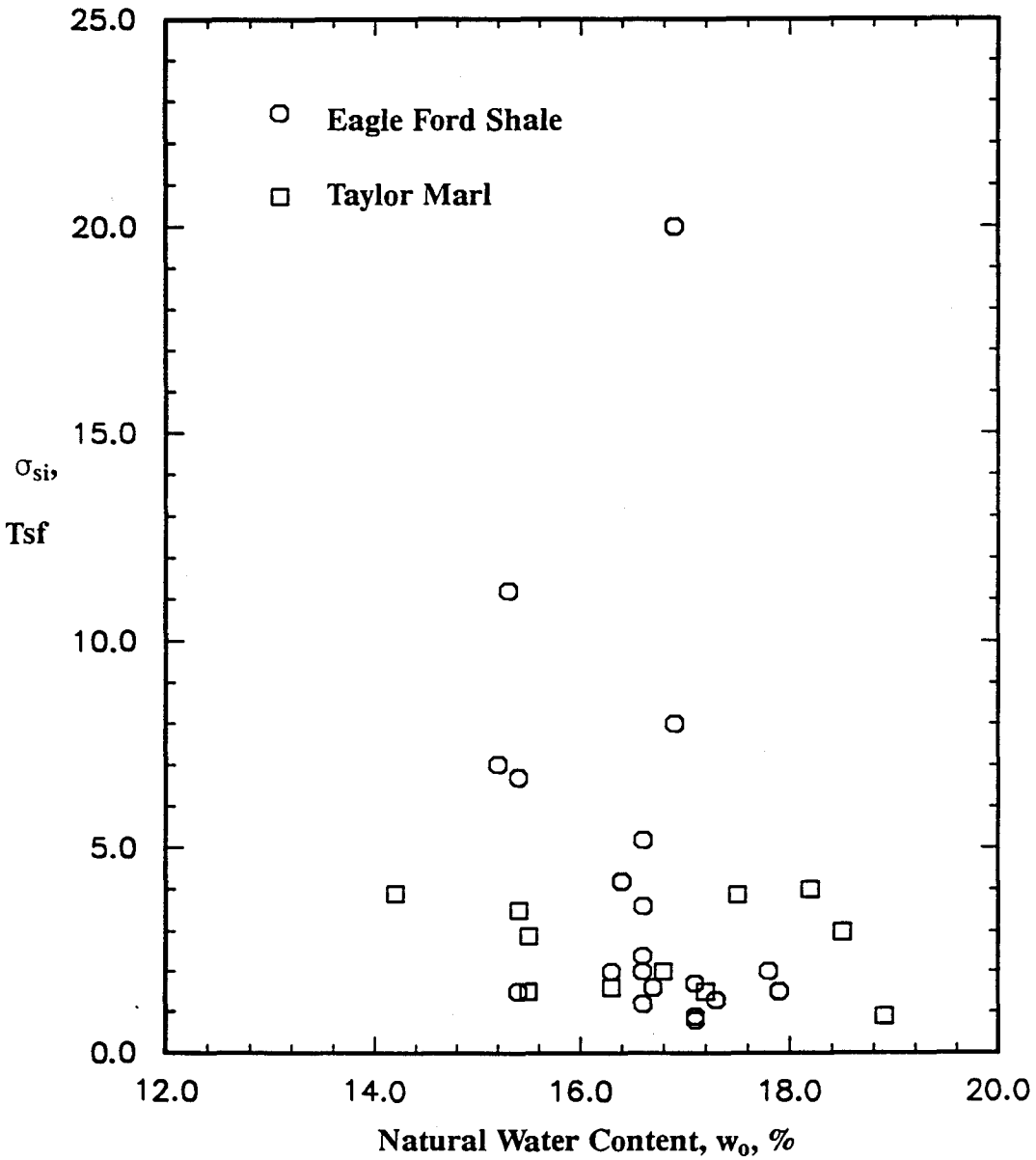


Fig. 5 Swelling Pressure vs Natural Water Content

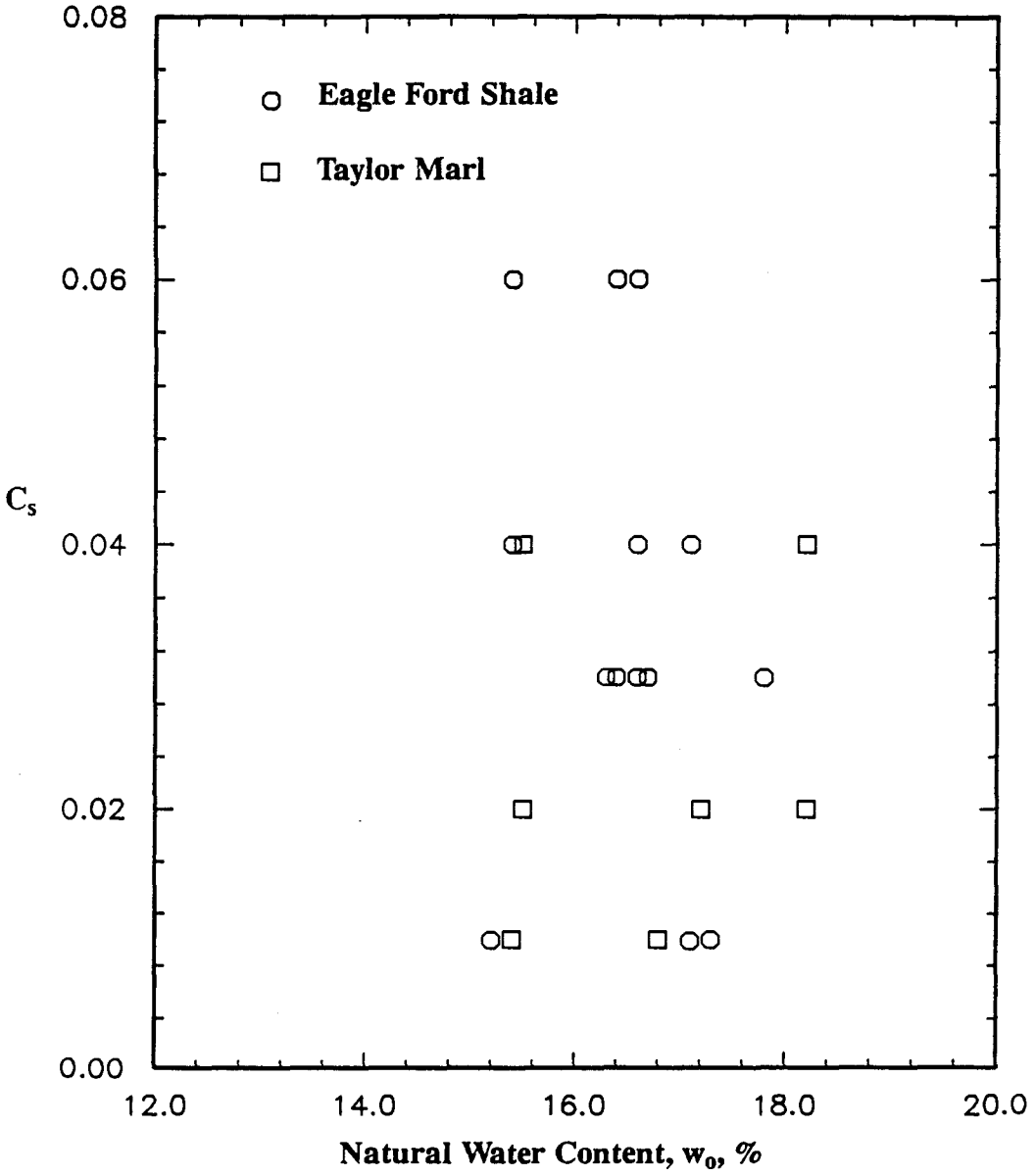


Fig. 6 Swelling Index vs Natural Water Content

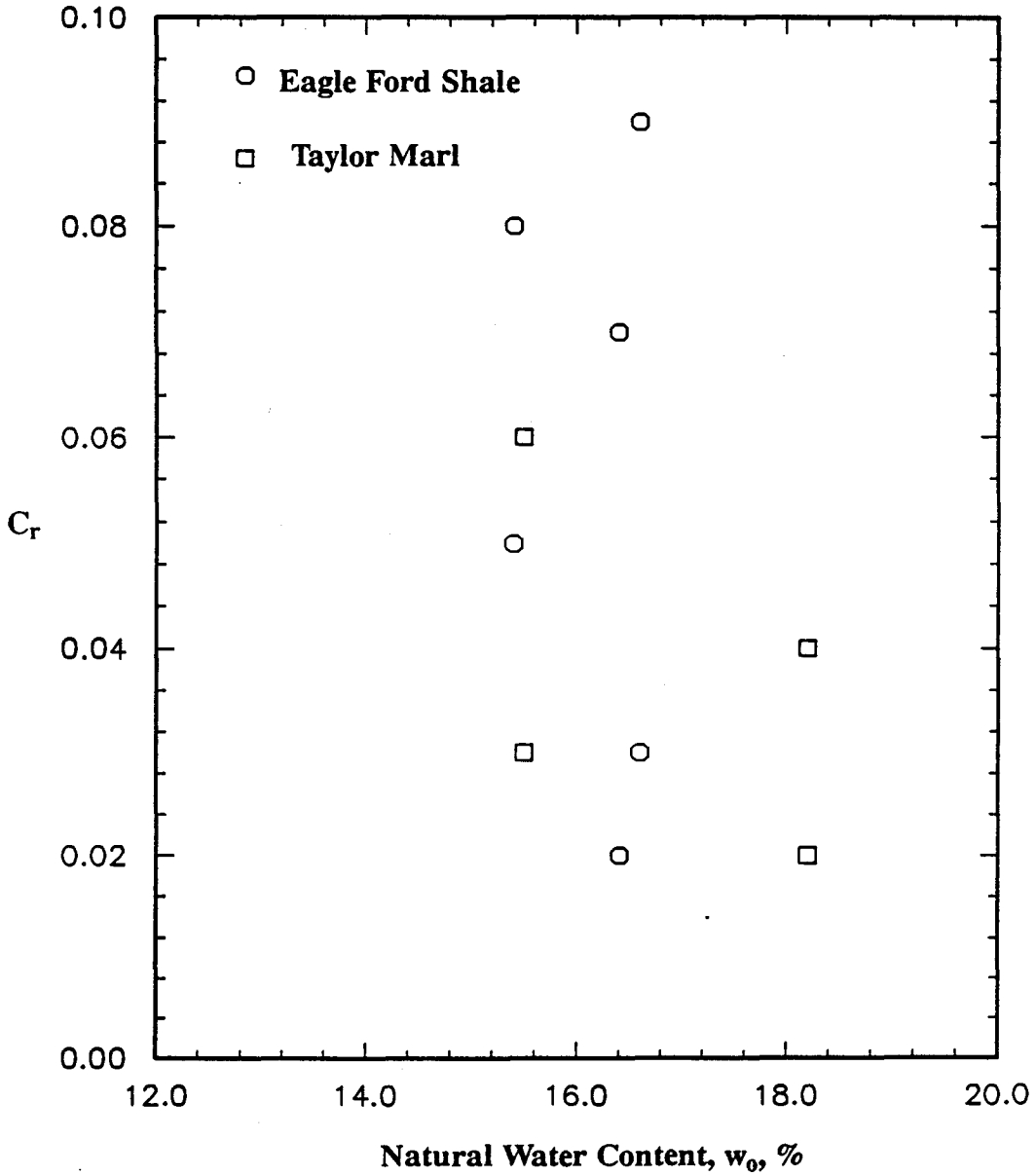


Fig. 7 Recompression Index vs Natural Water Content

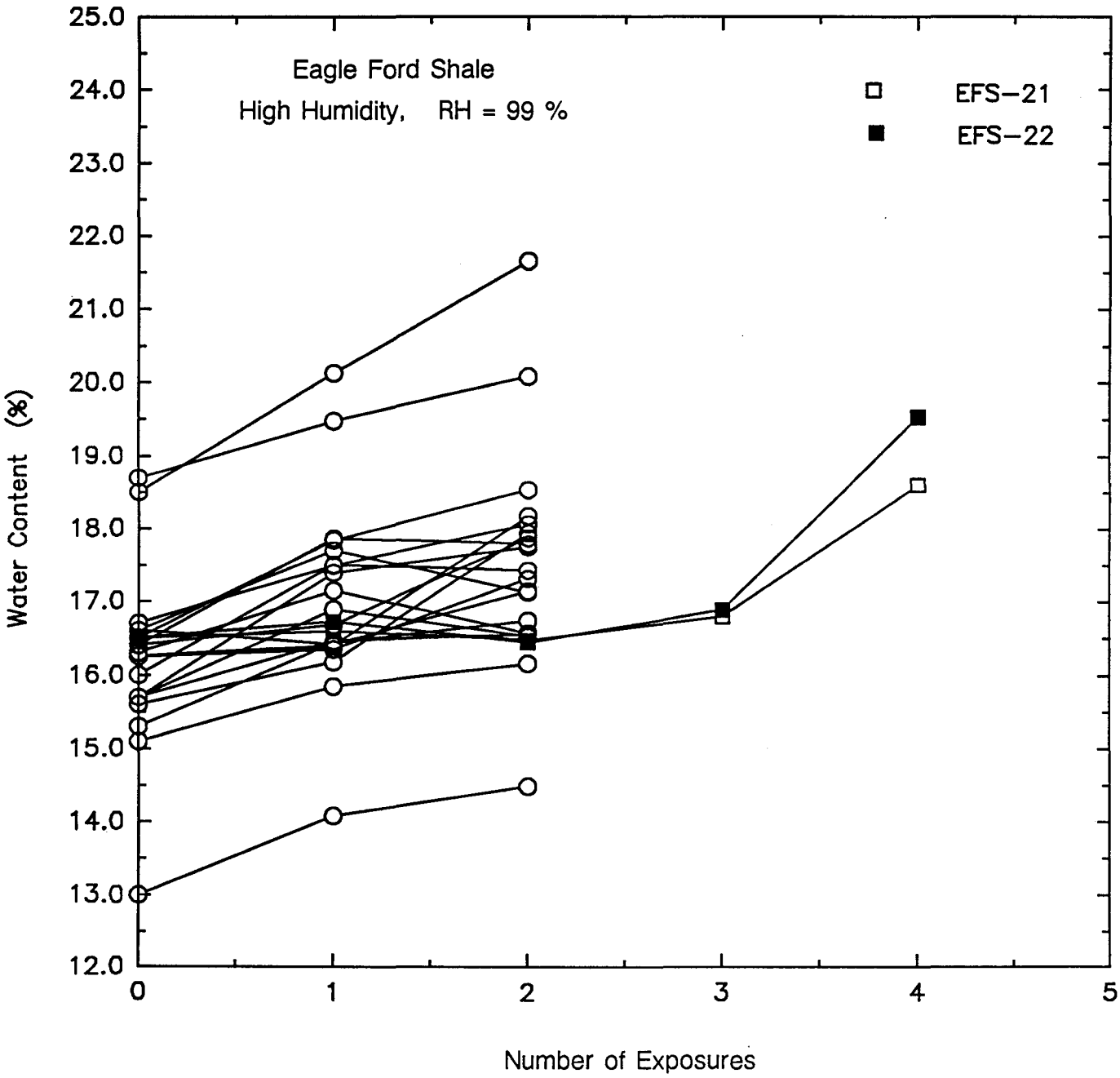


Fig. 8a Water Content vs Number of Environmental Exposures

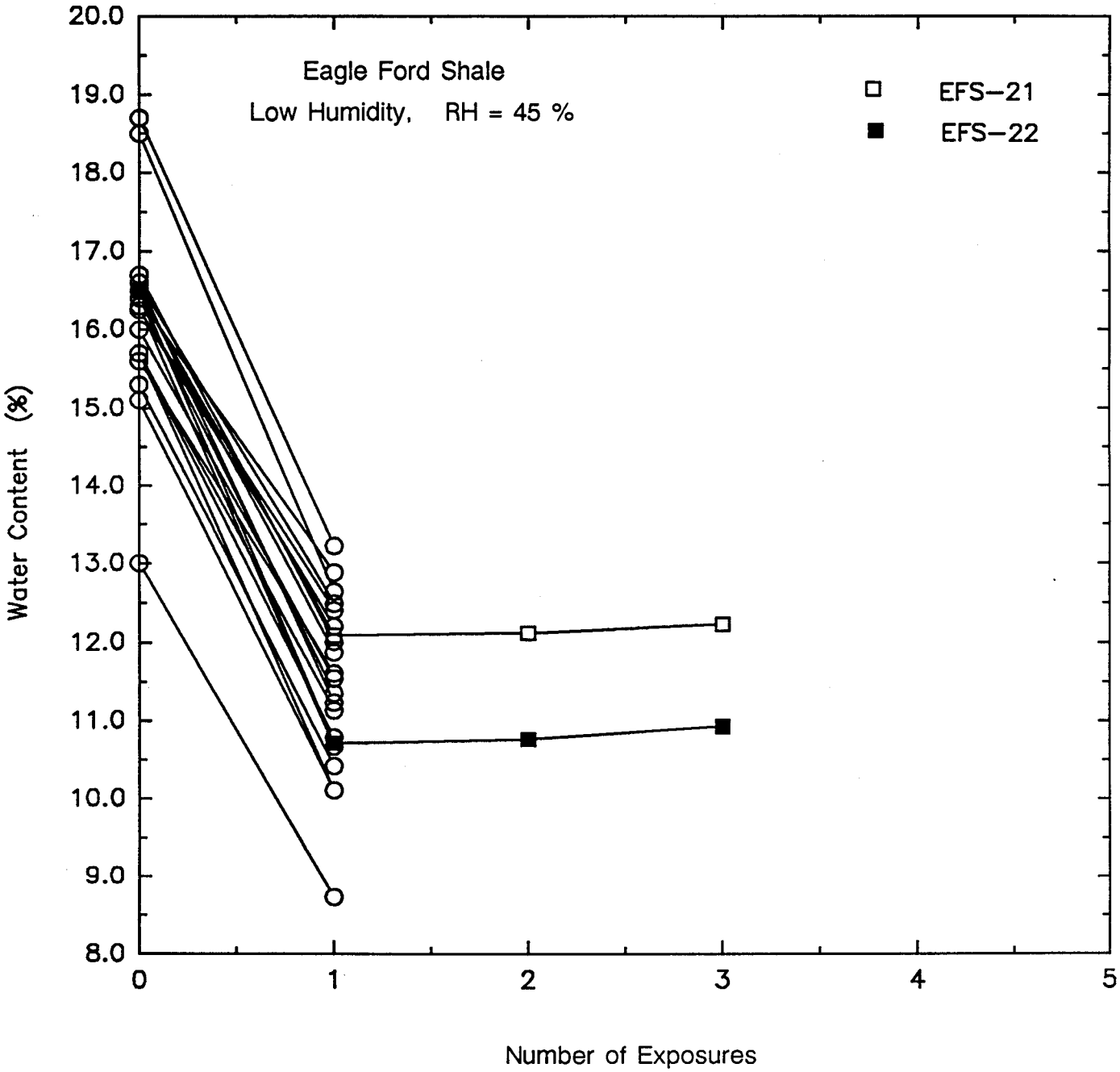


Fig. 8b Water Content vs Number of Environmental Exposures

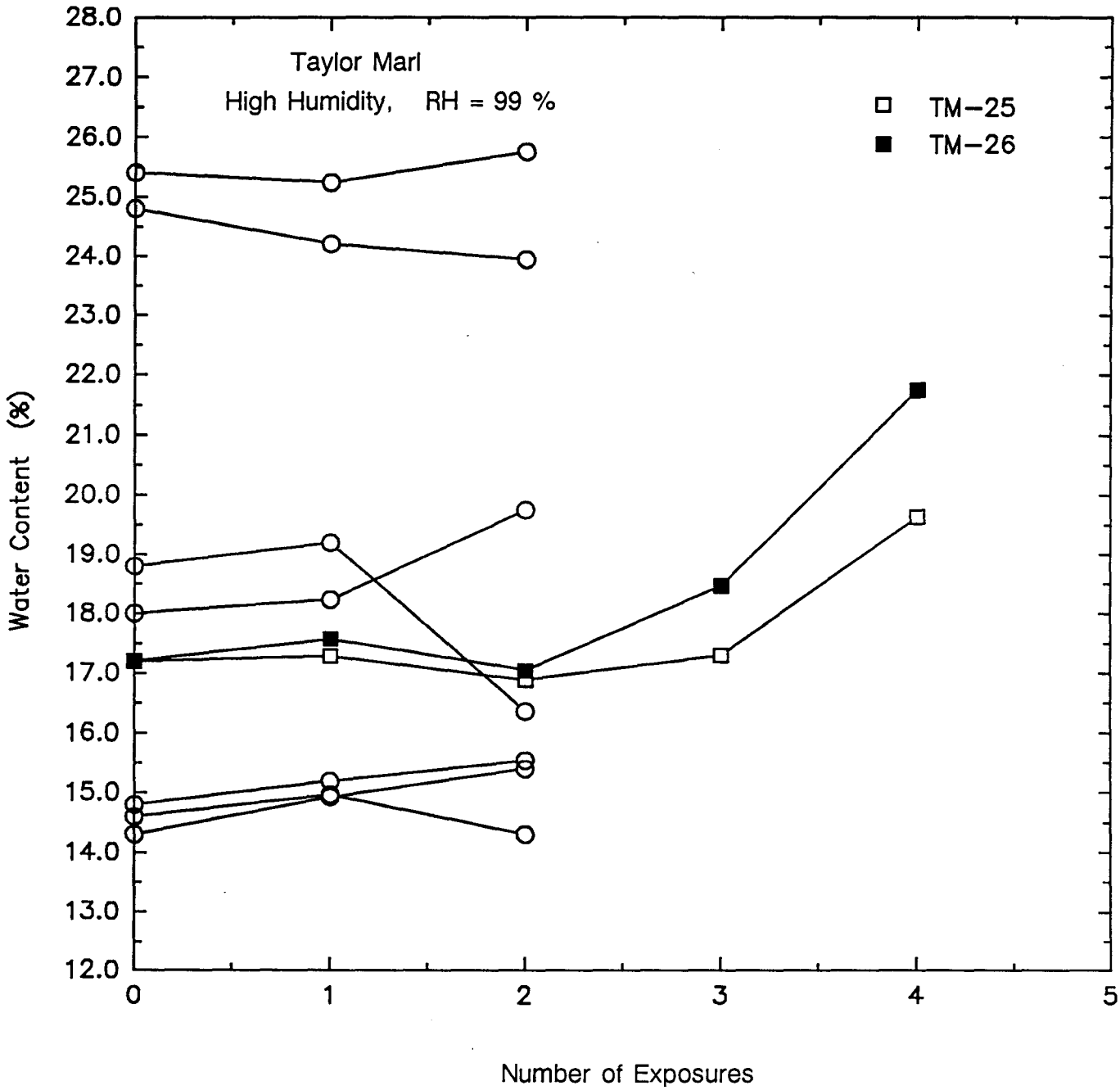


Fig. 9a Water Content vs Number of Environmental Exposures

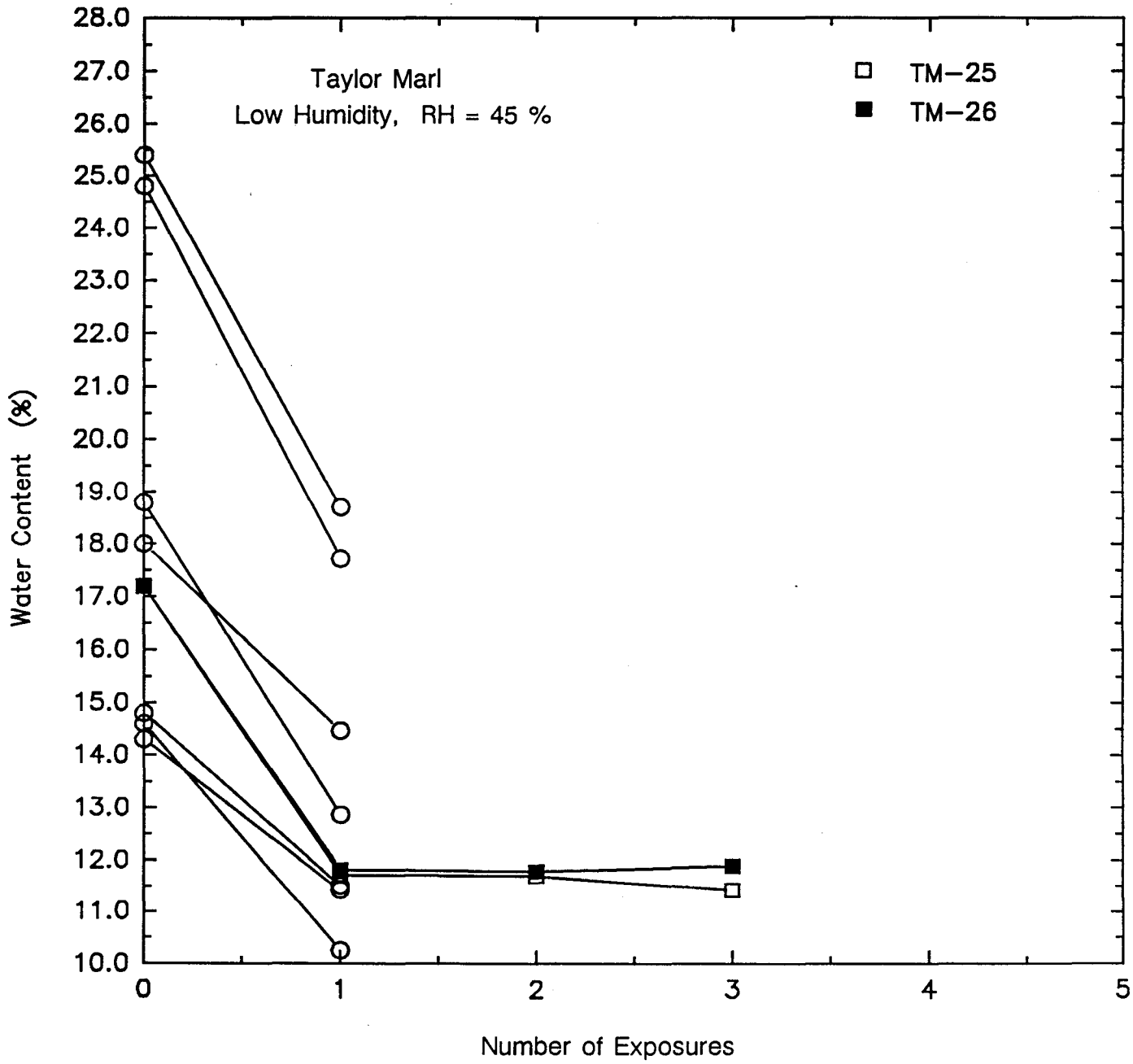


Fig. 9b Water Content vs Number of Environmental Exposures

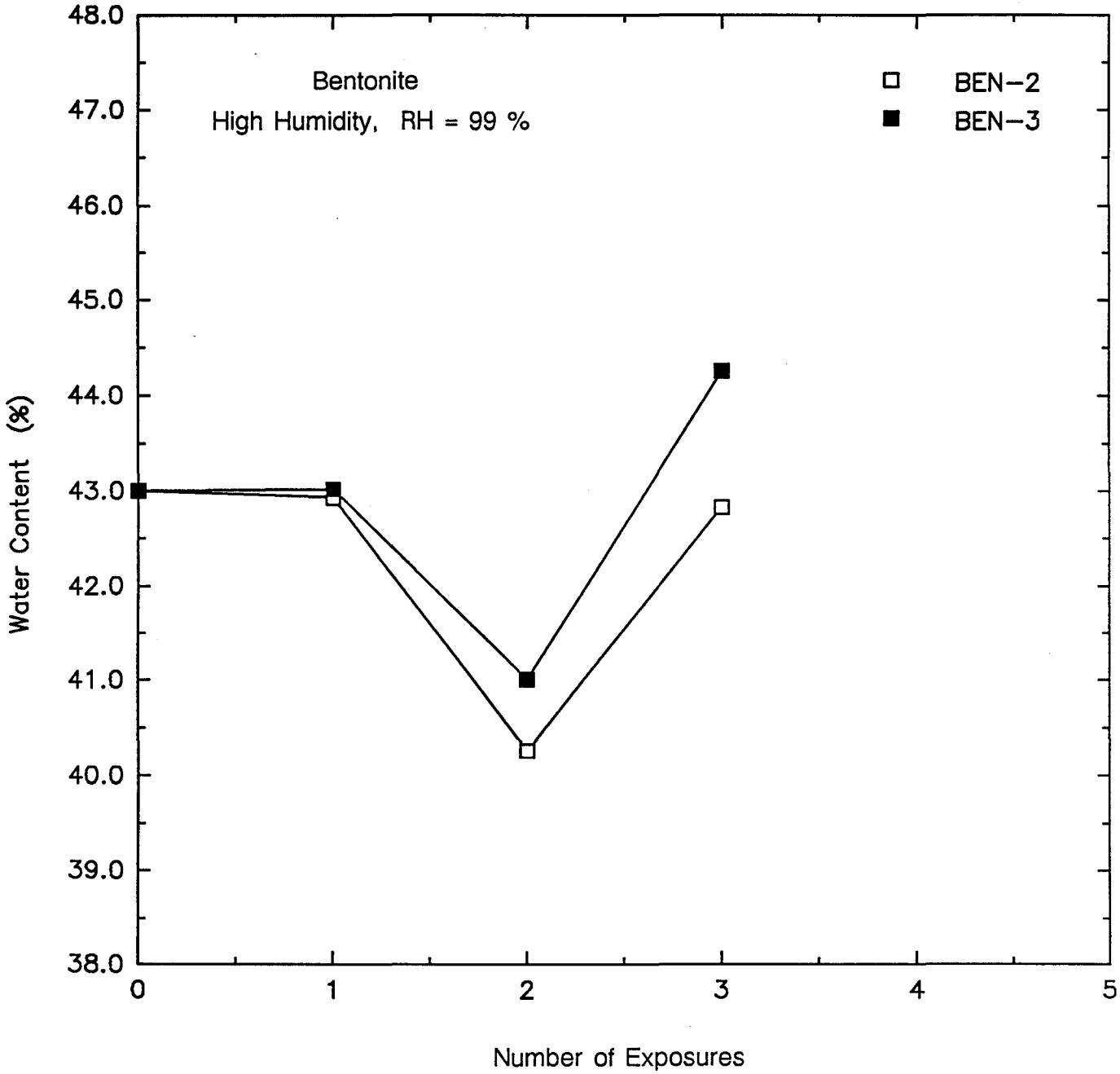


Fig. 10a Water Content vs Number of Environmental Exposures

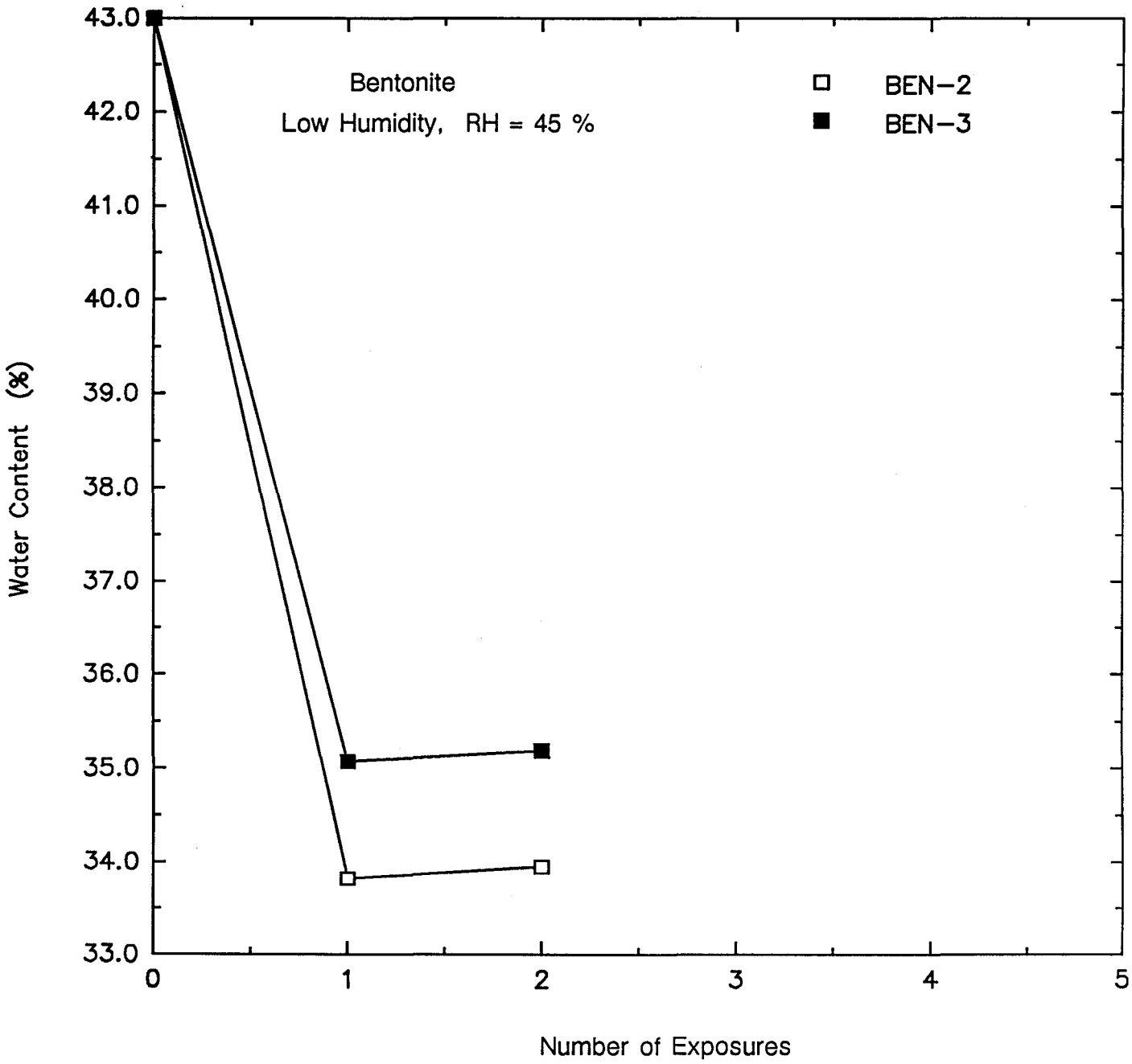


Fig. 10b Water Content vs Number of Environmental Exposures

APPENDIX AI

Figs. A1-A25

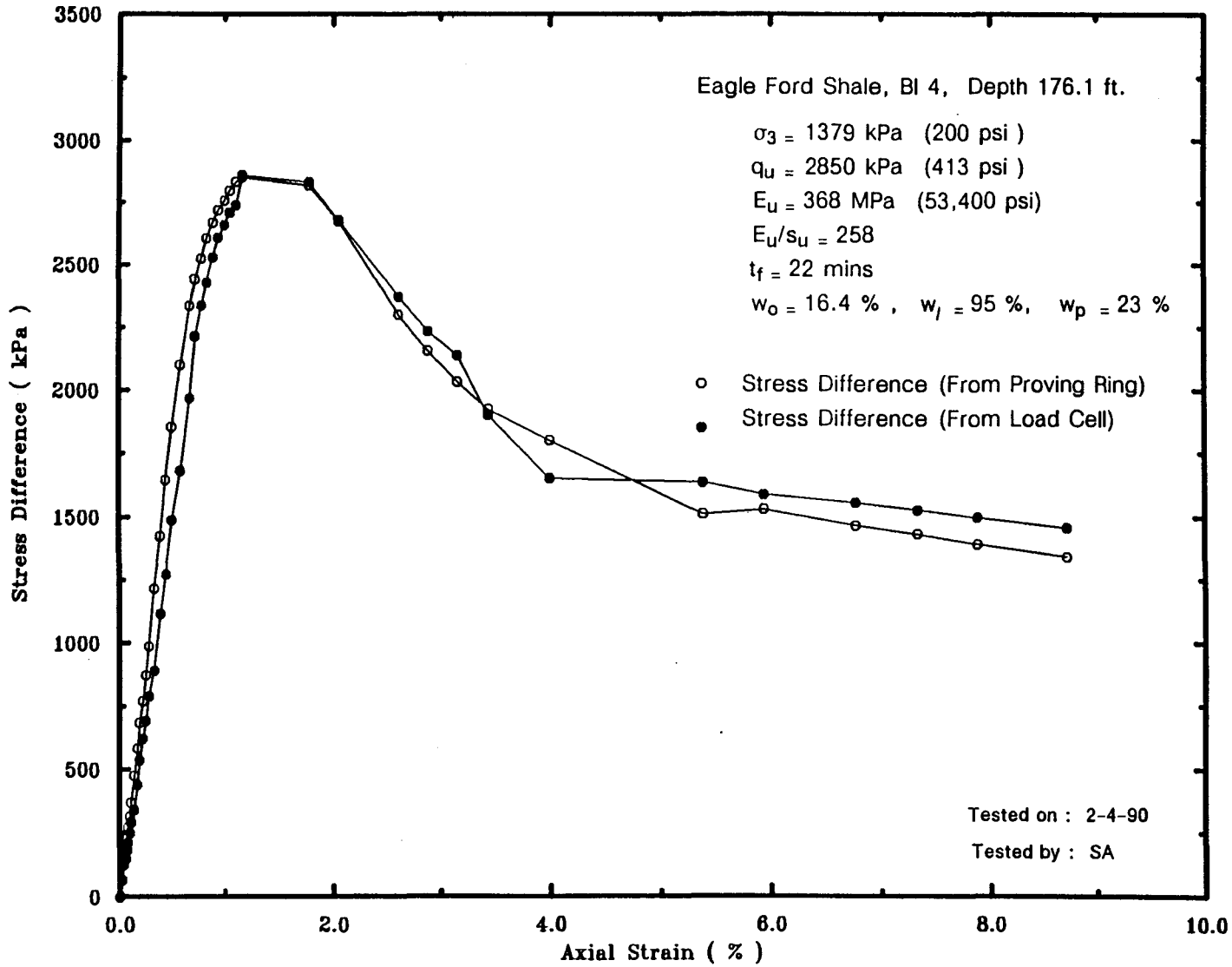
Stress-Strain Curves

for Unconsolidated Undrained Triaxial Compression Tests

on Eagle Ford Shale, Taylor Marl and Bentonite

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU1



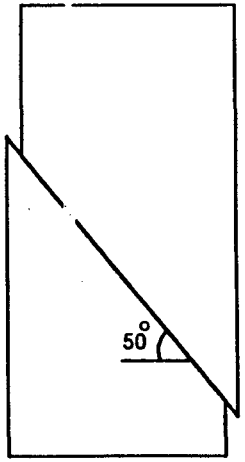
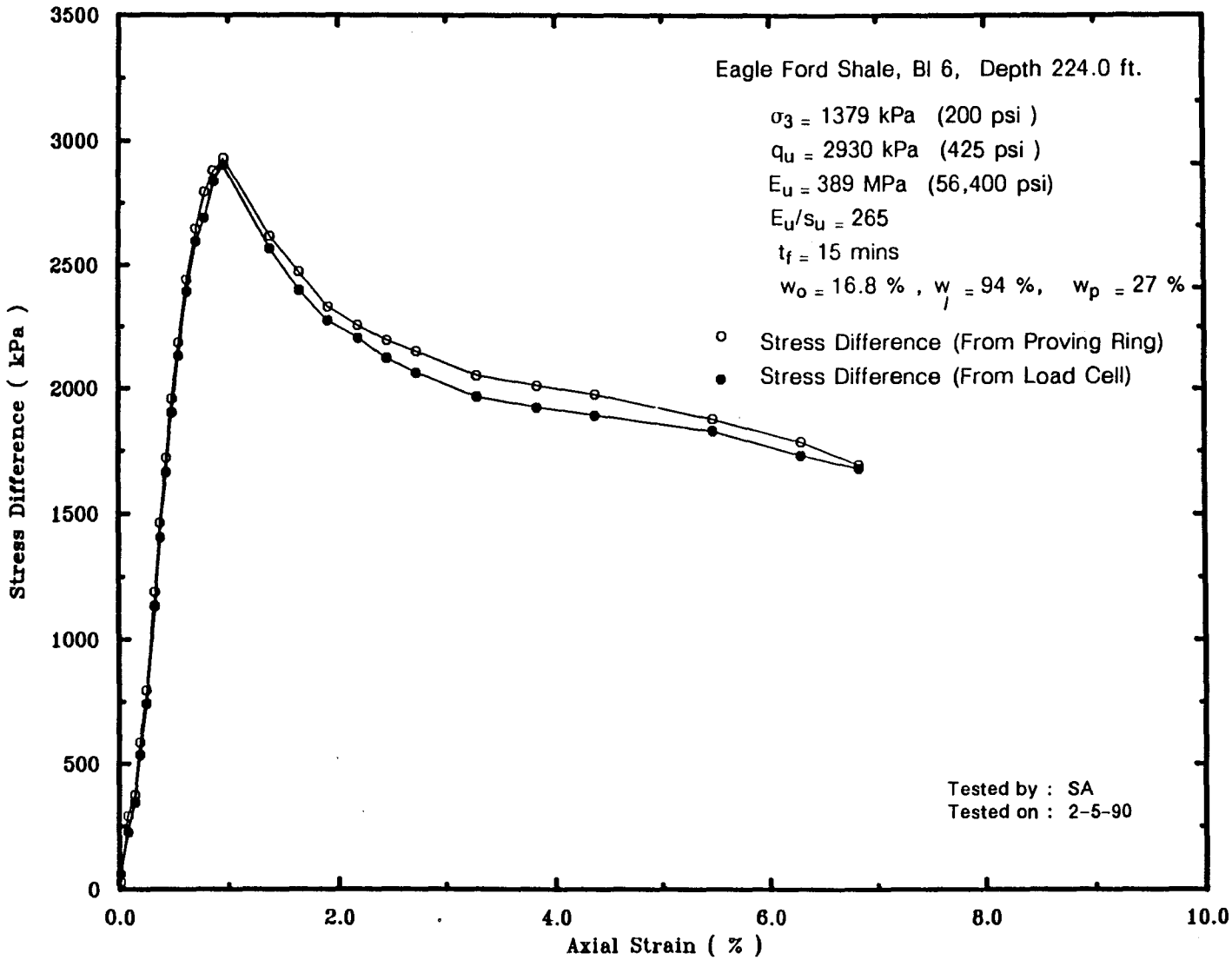


Fig. A1 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU2



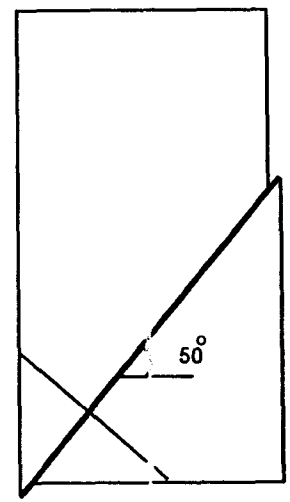
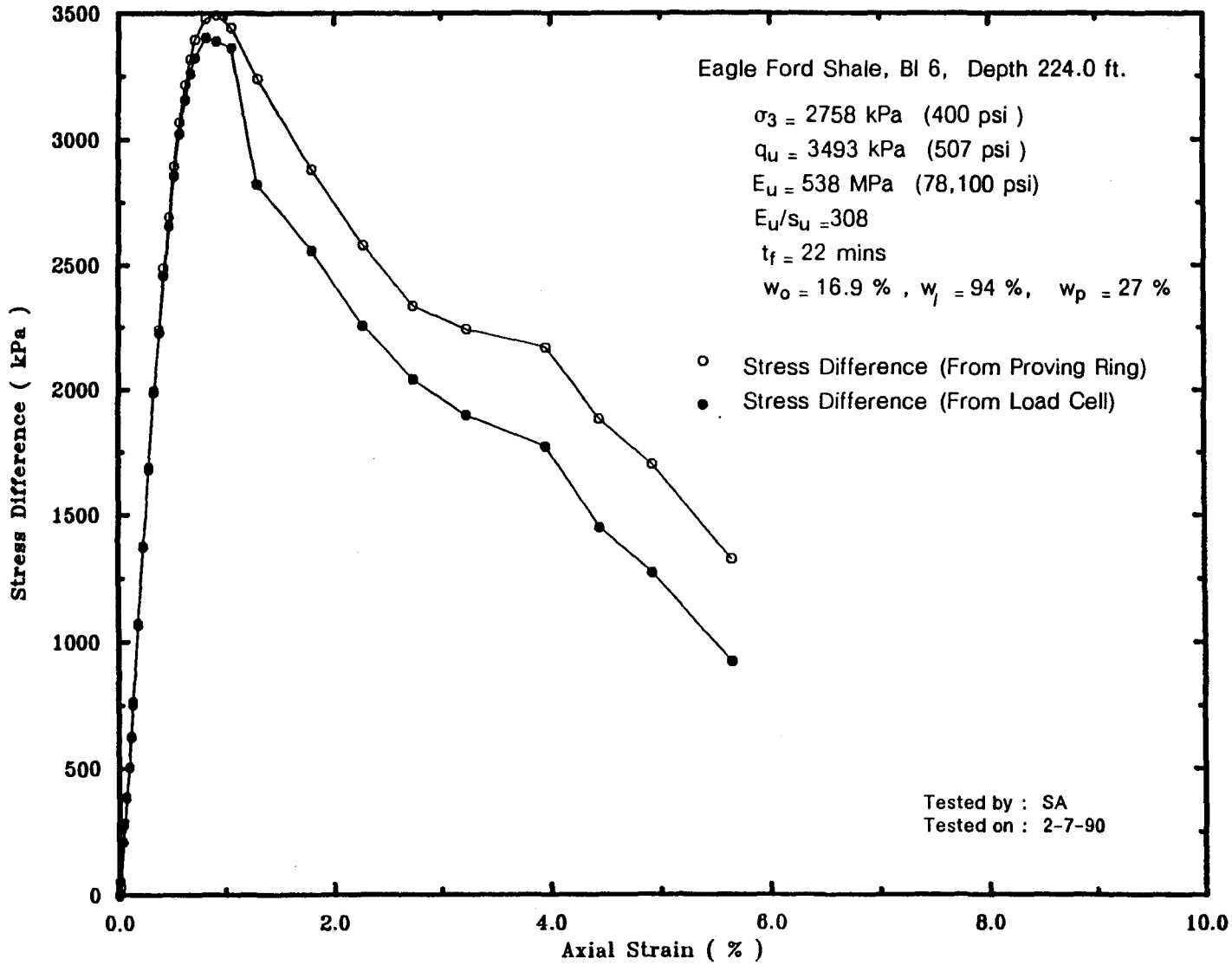


Fig. A2 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU3



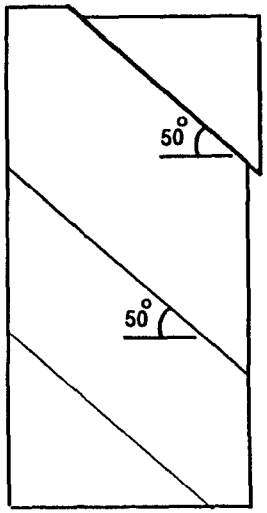
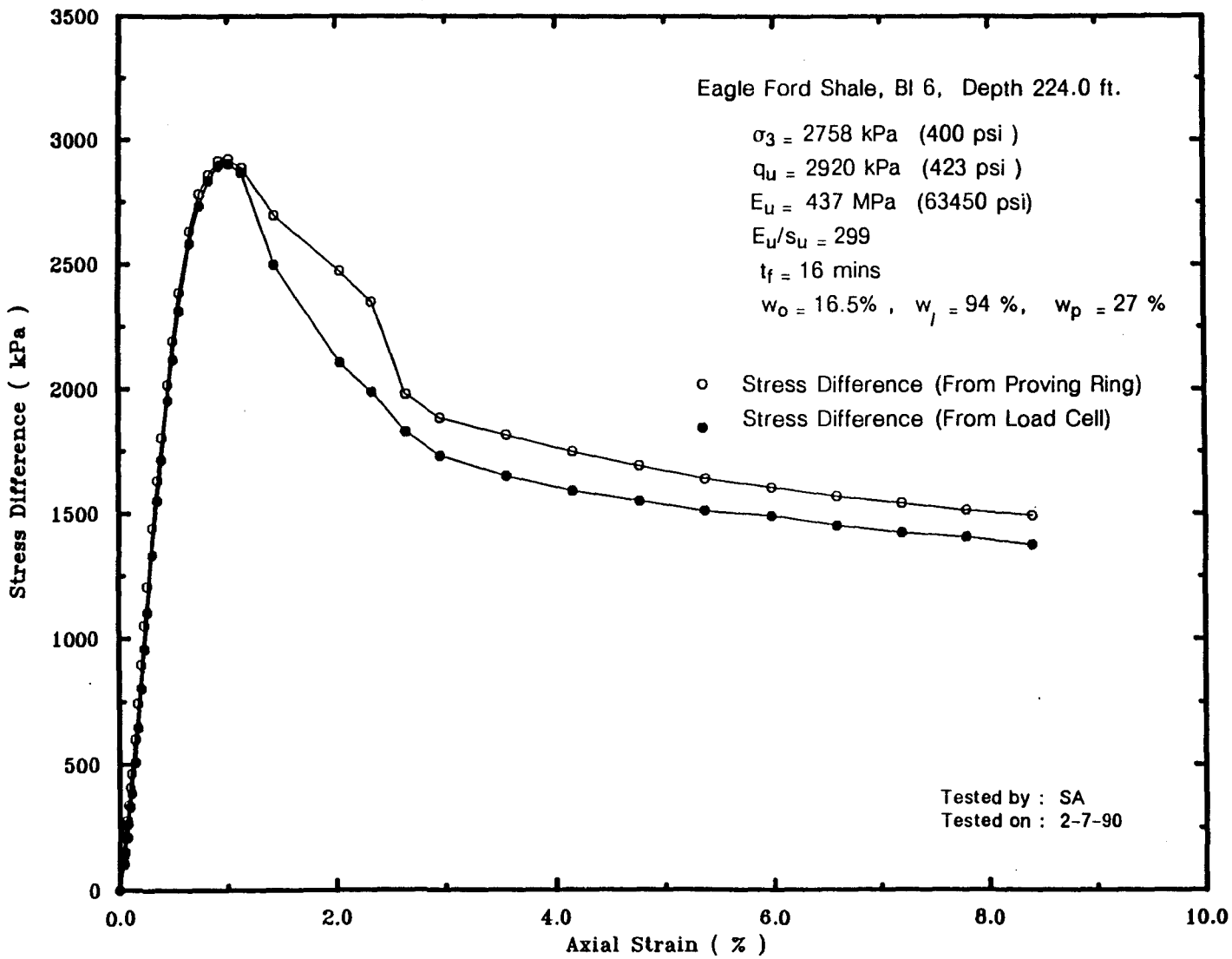


Fig. A3 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU4



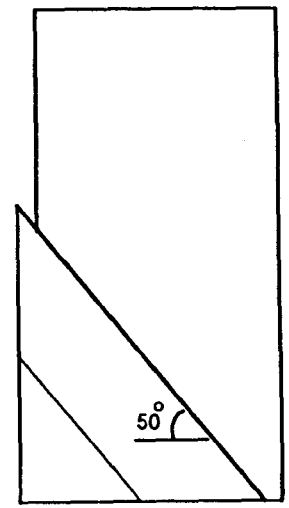


Fig. A4 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU5

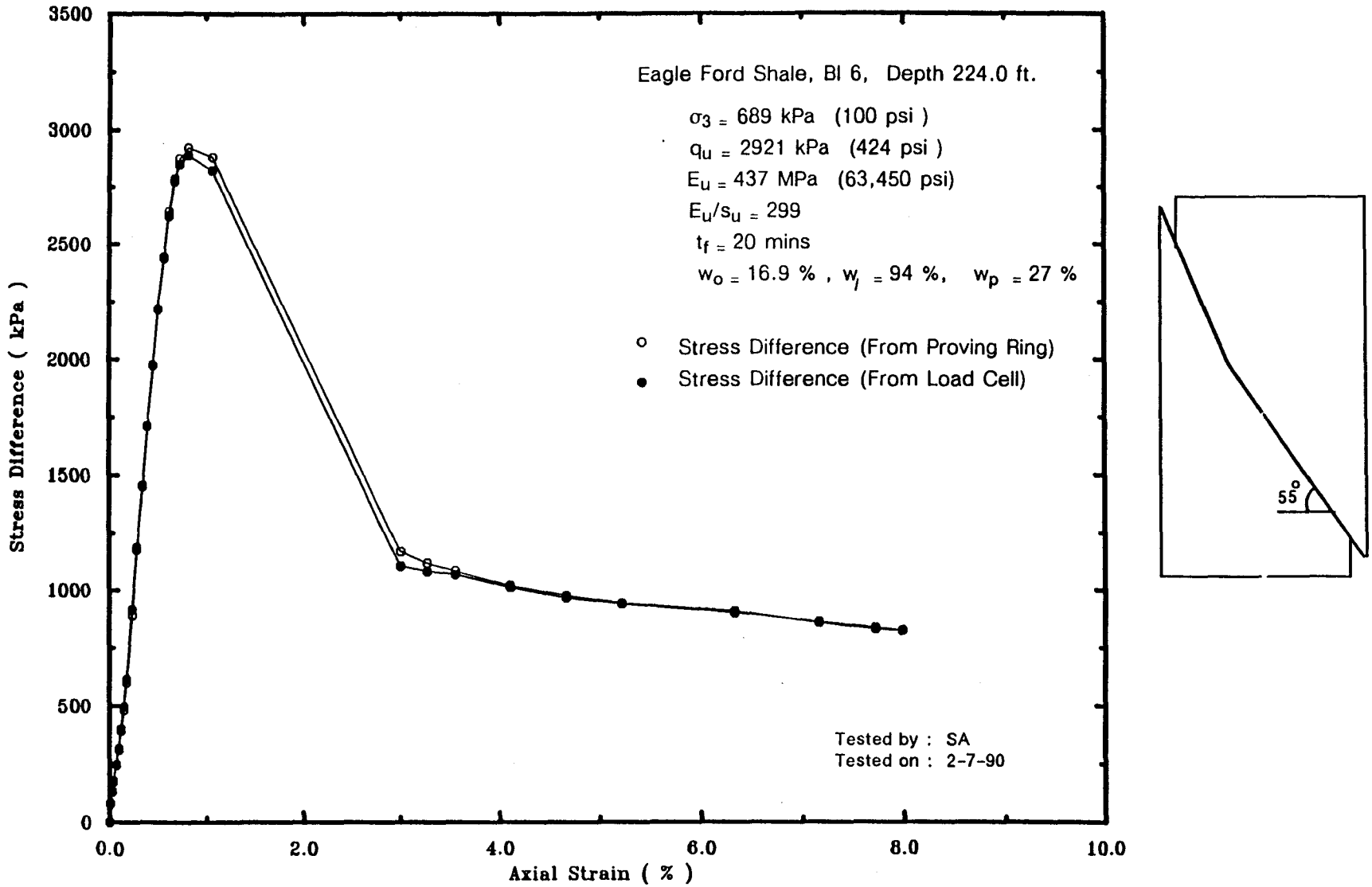


Fig. A5 Stress Difference vs Axial Strain

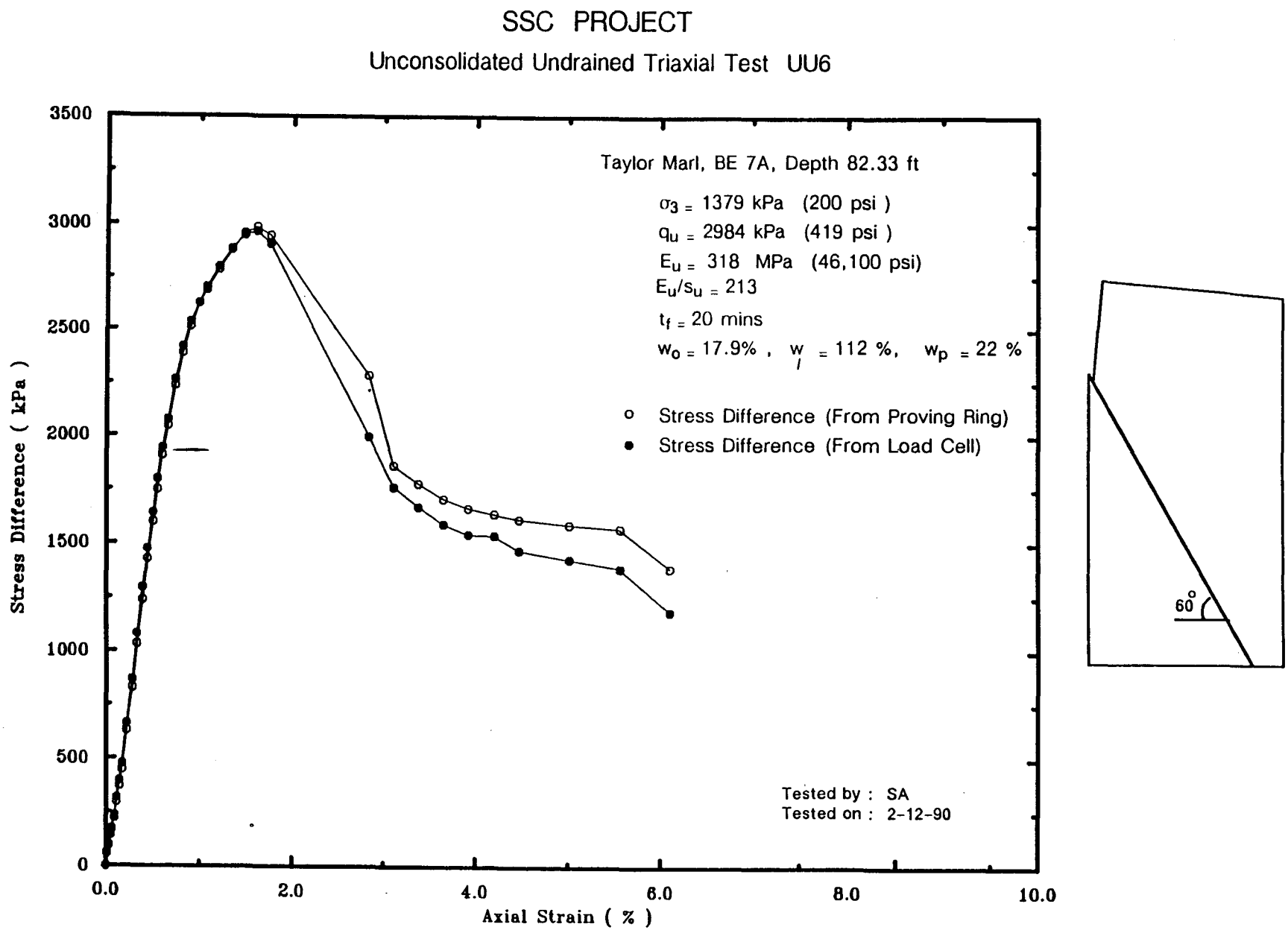
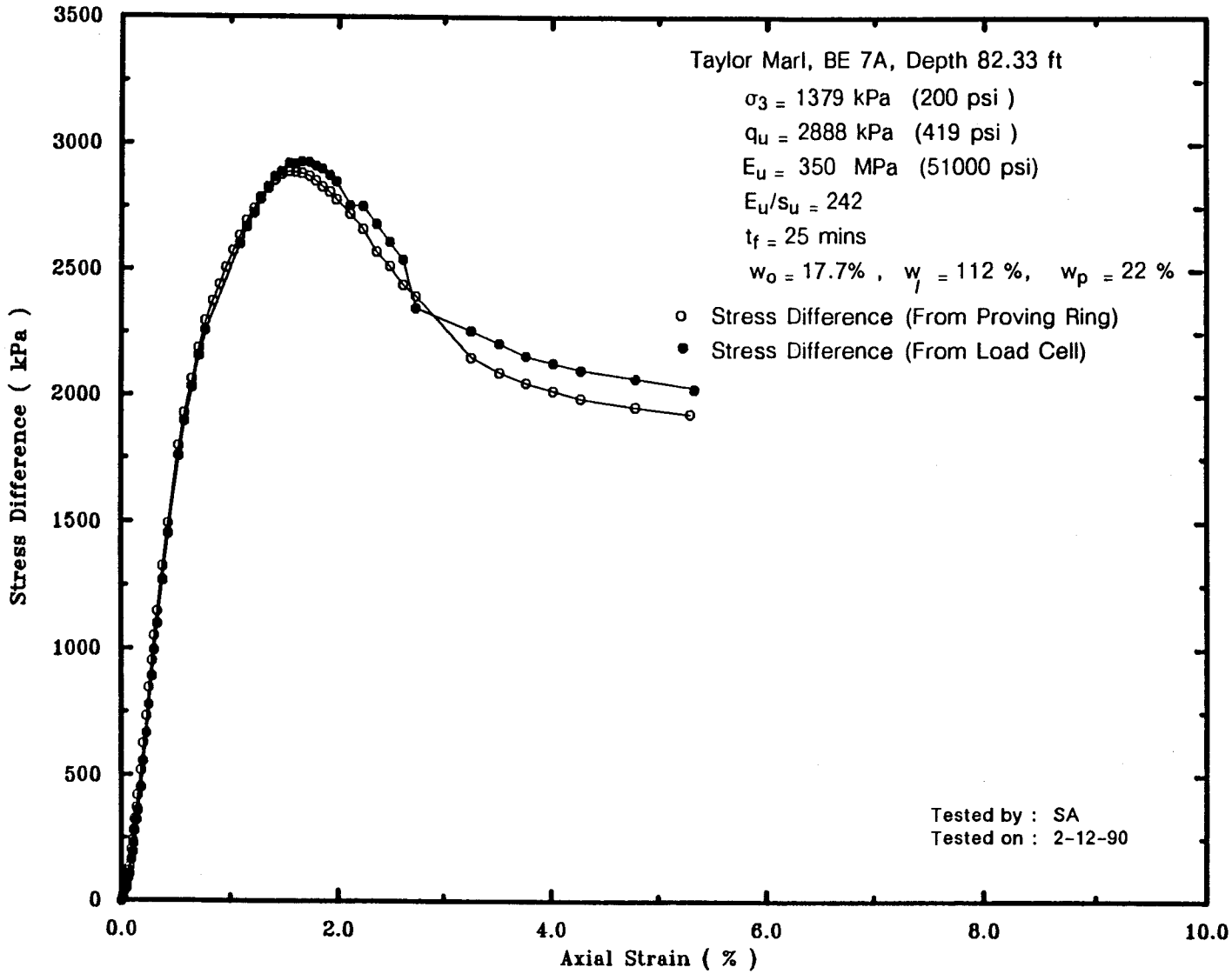


Fig. A6 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU7



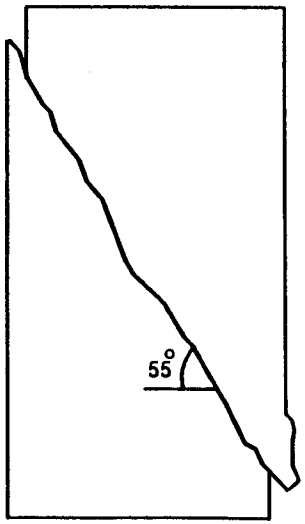
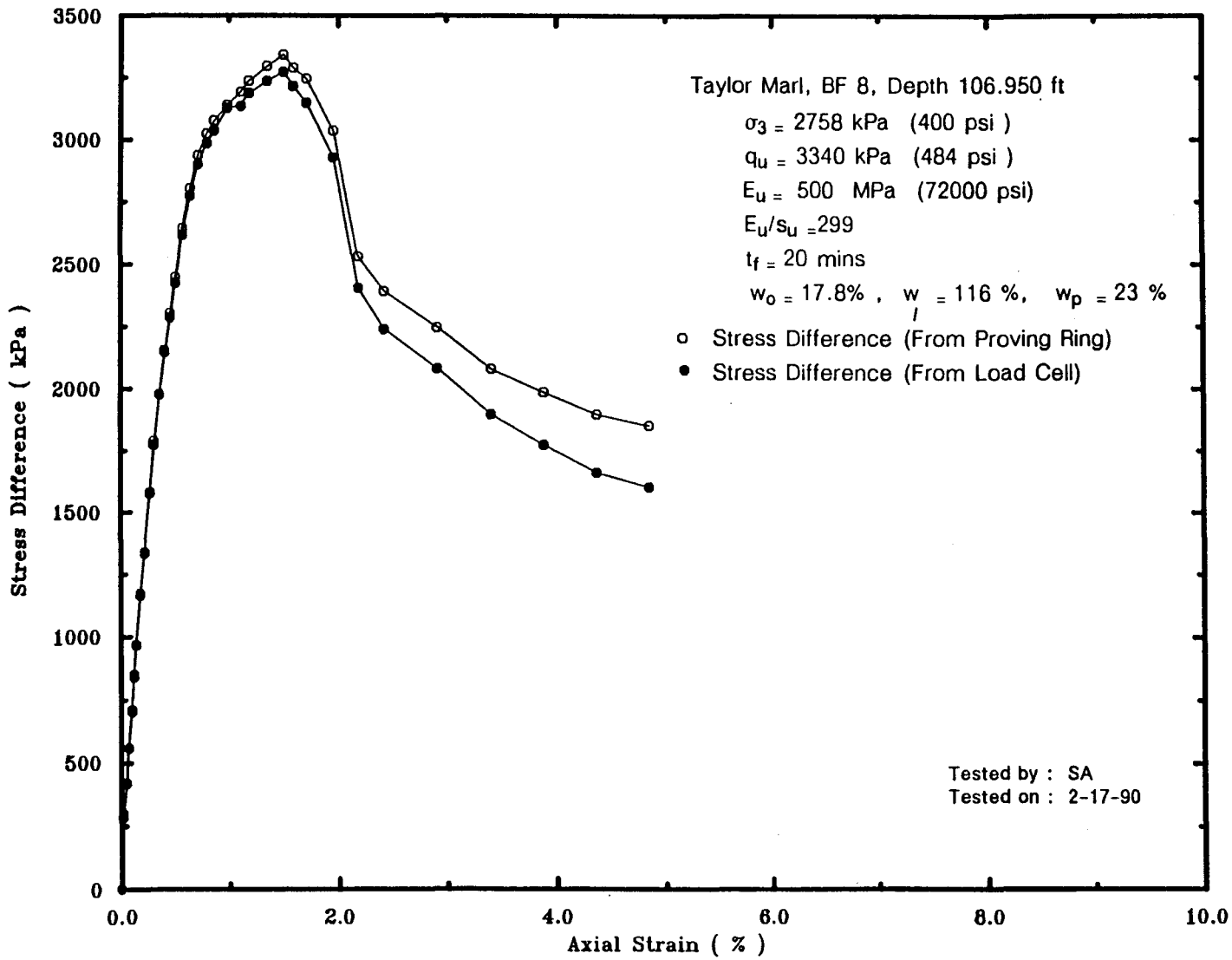


Fig. A7 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU8



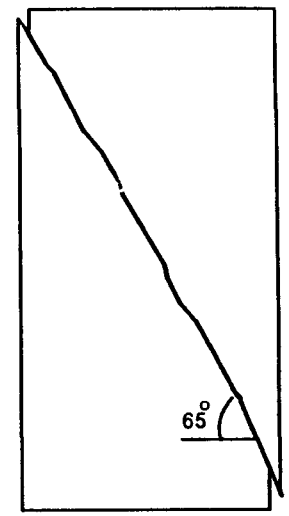
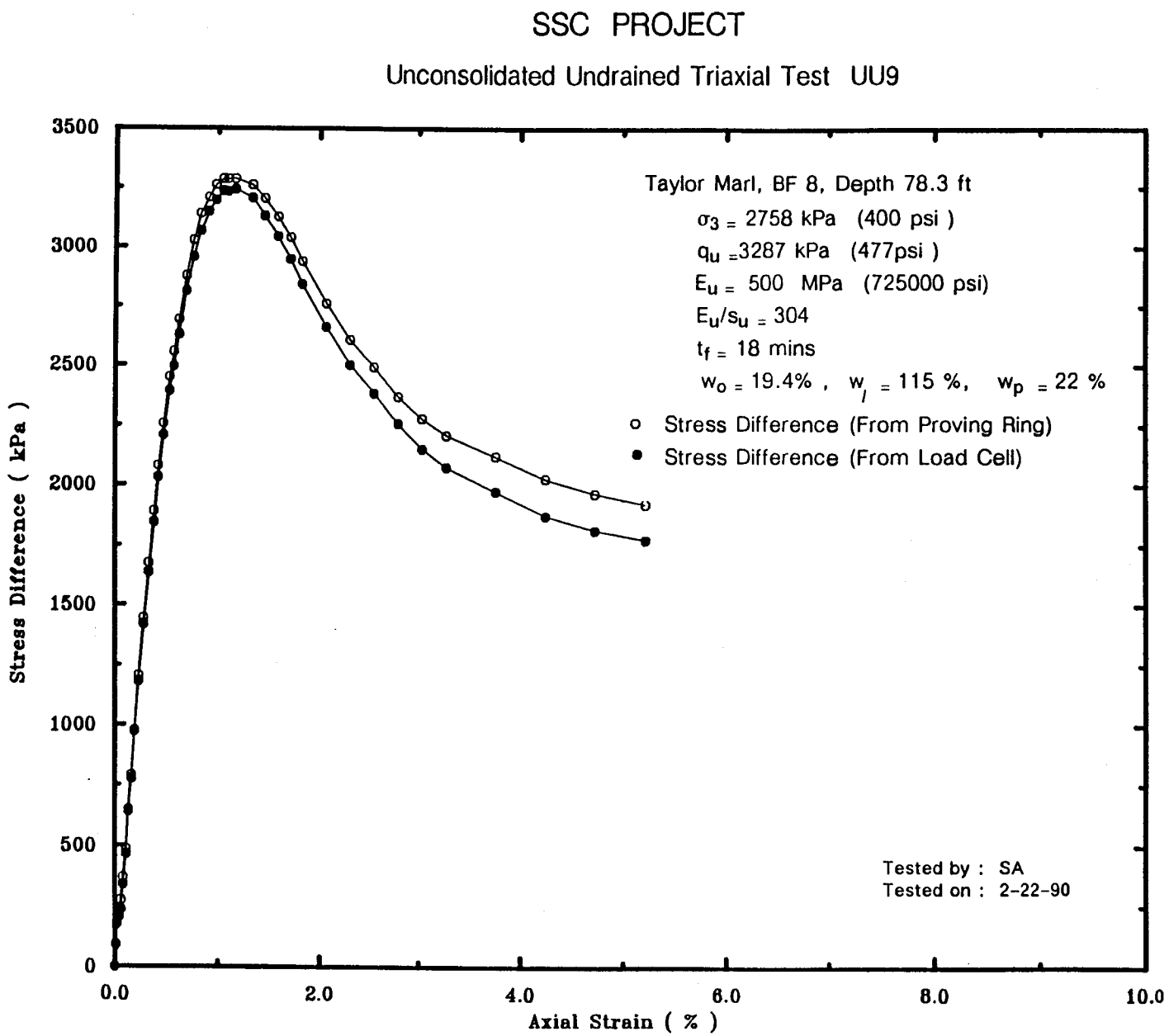


Fig. A8 Stress Difference vs Axial Strain



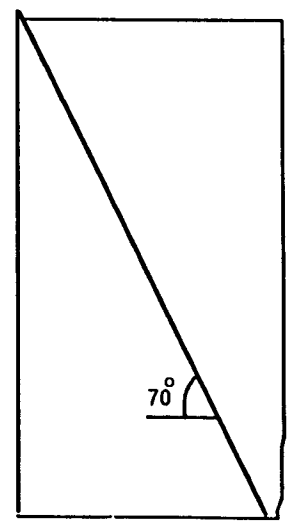
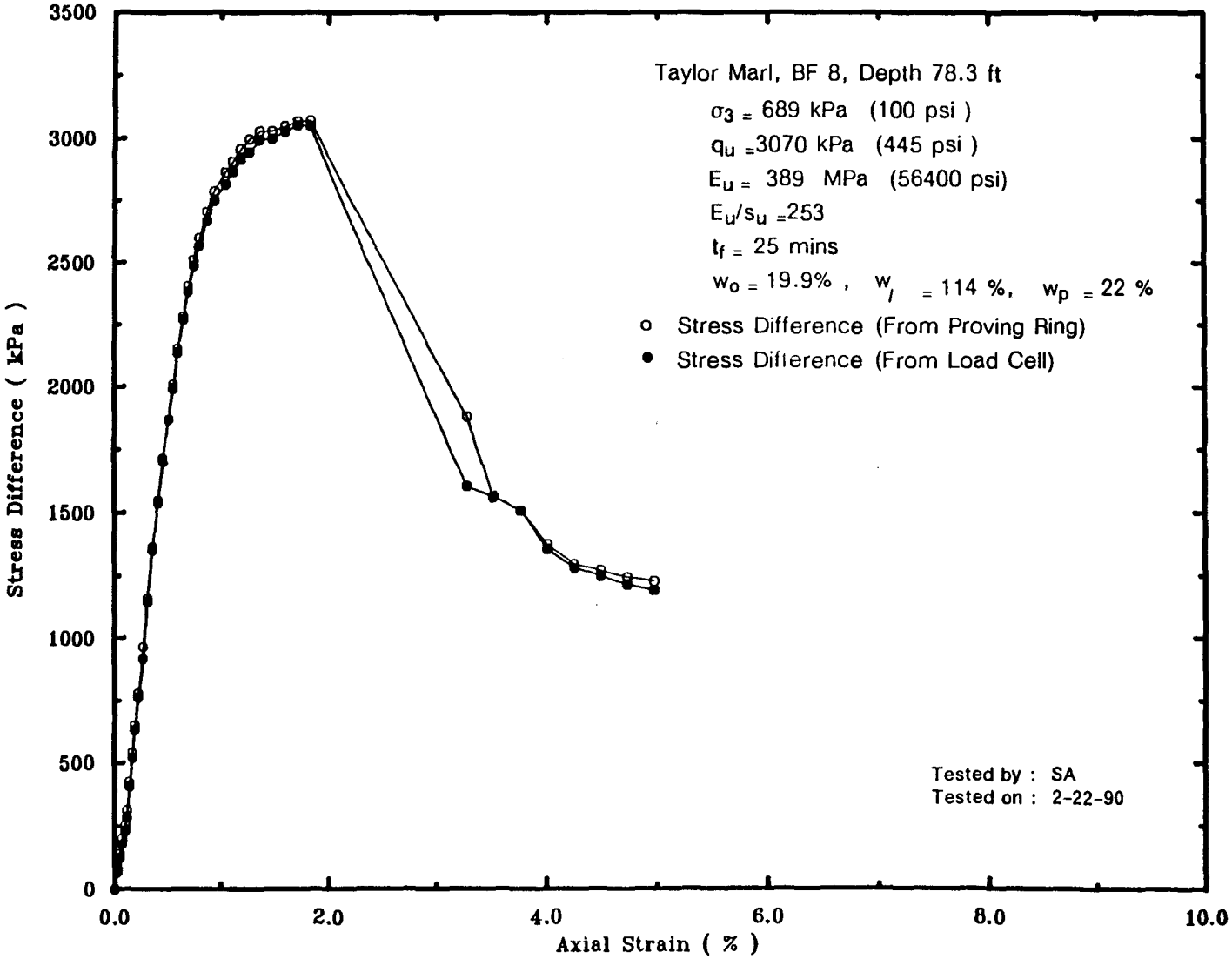


Fig. A9 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU10



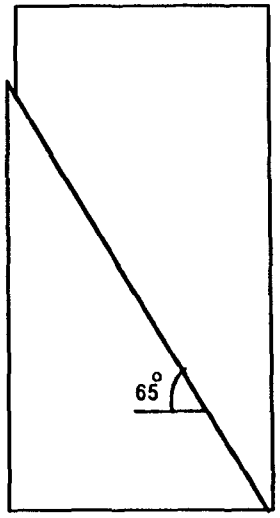
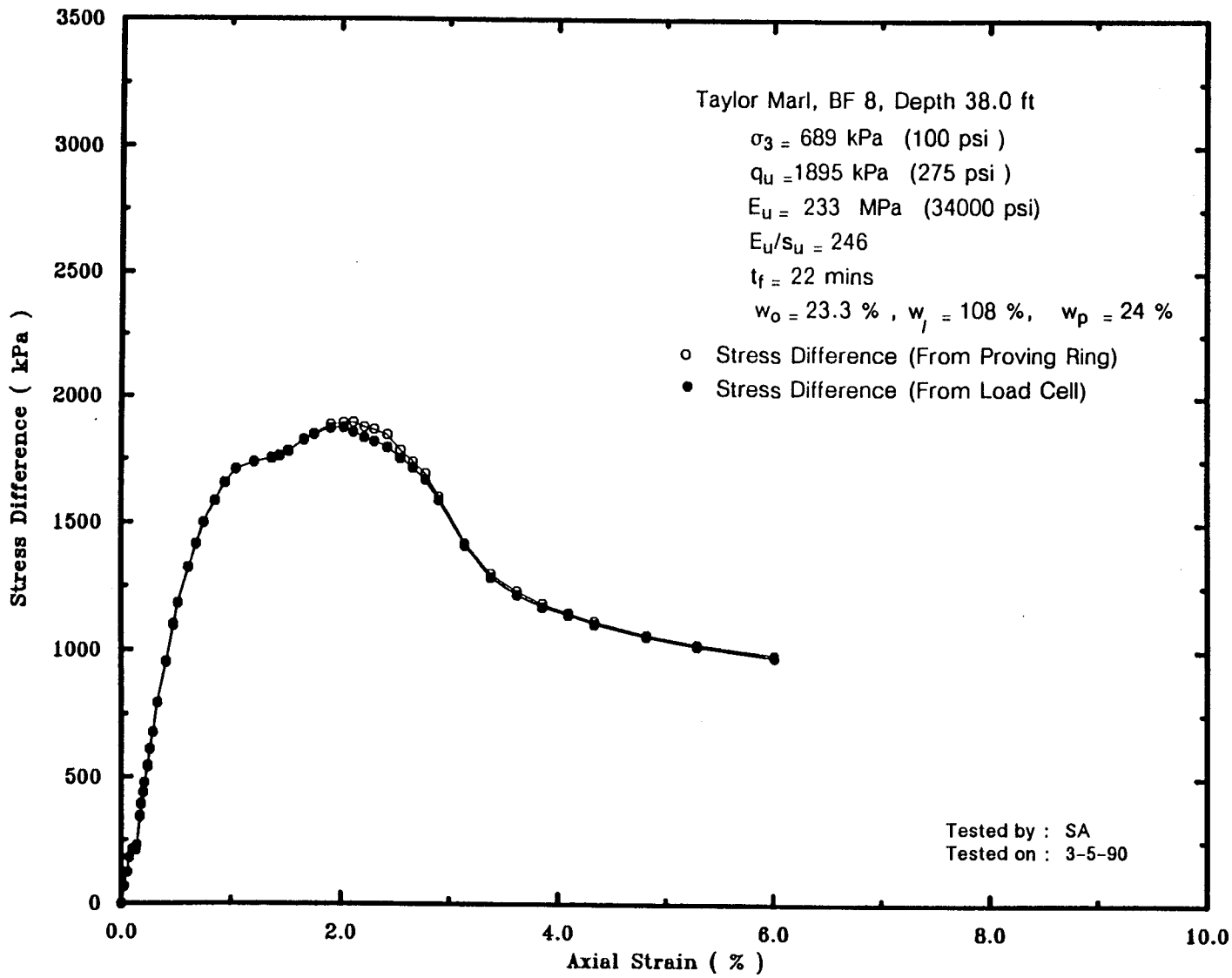


Fig. A10 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU11



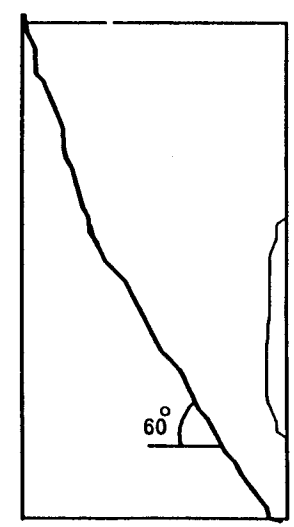
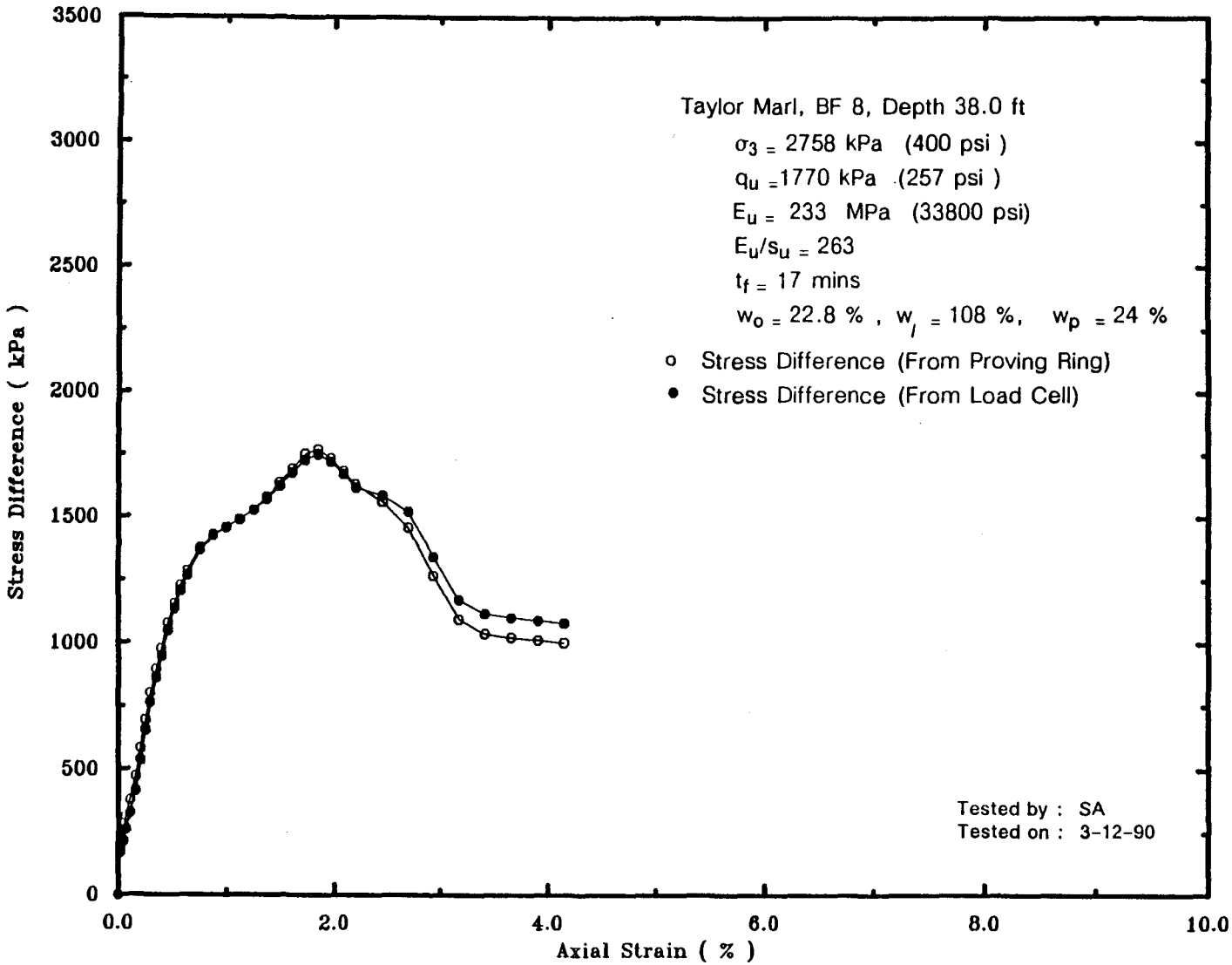


Fig. A11 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU12



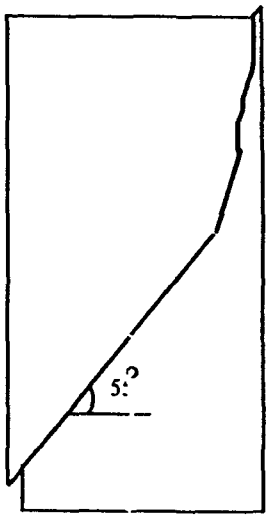
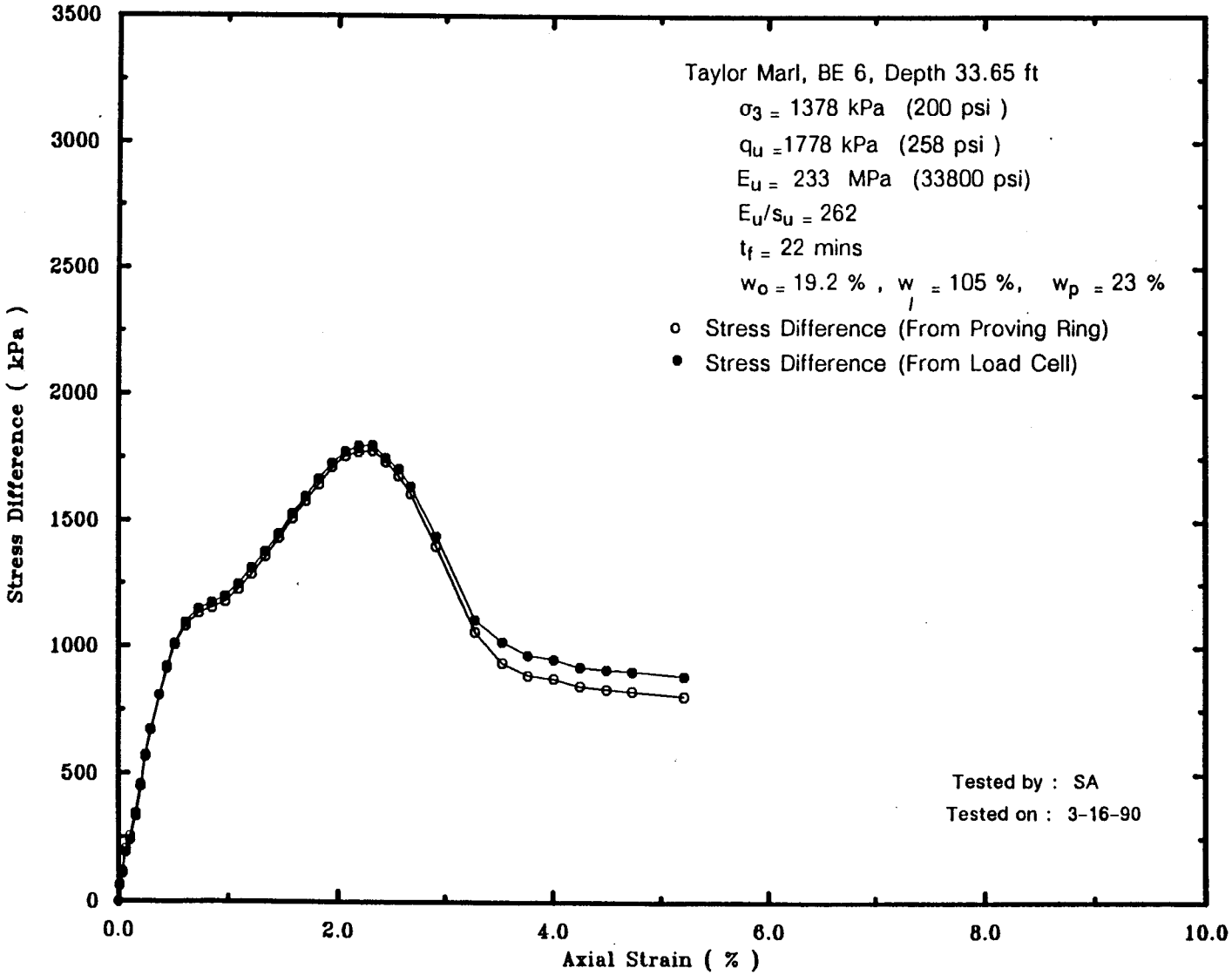


Fig. A12 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU13



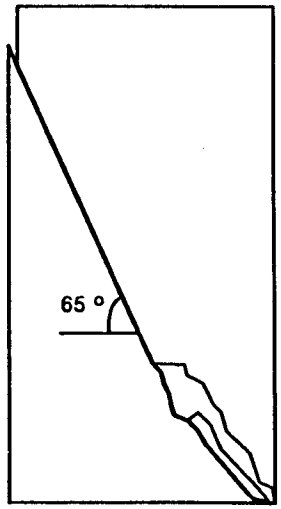
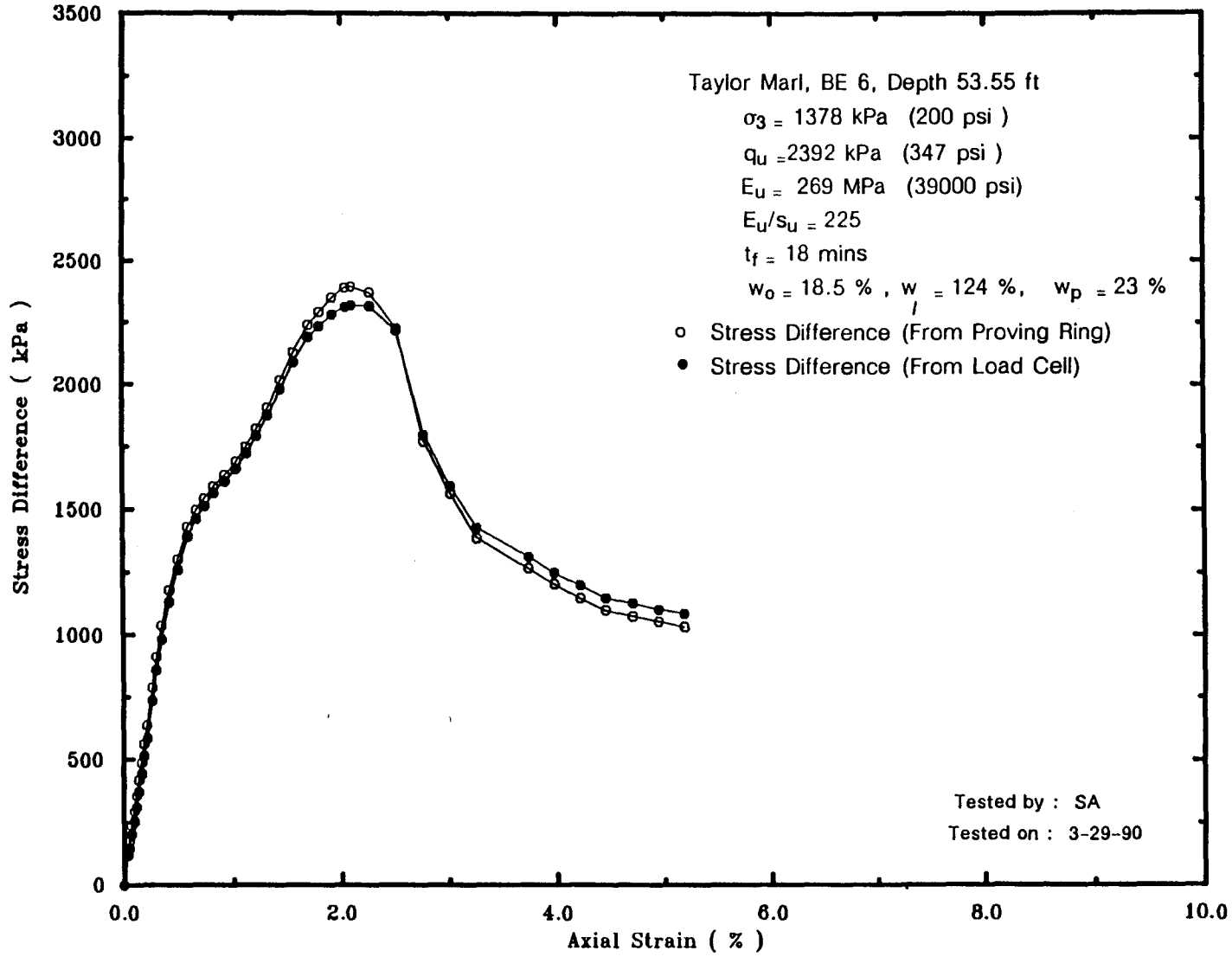


Fig. A13 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU14



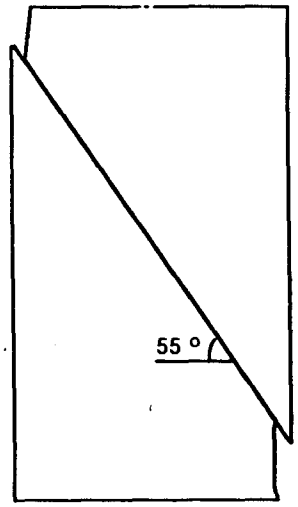
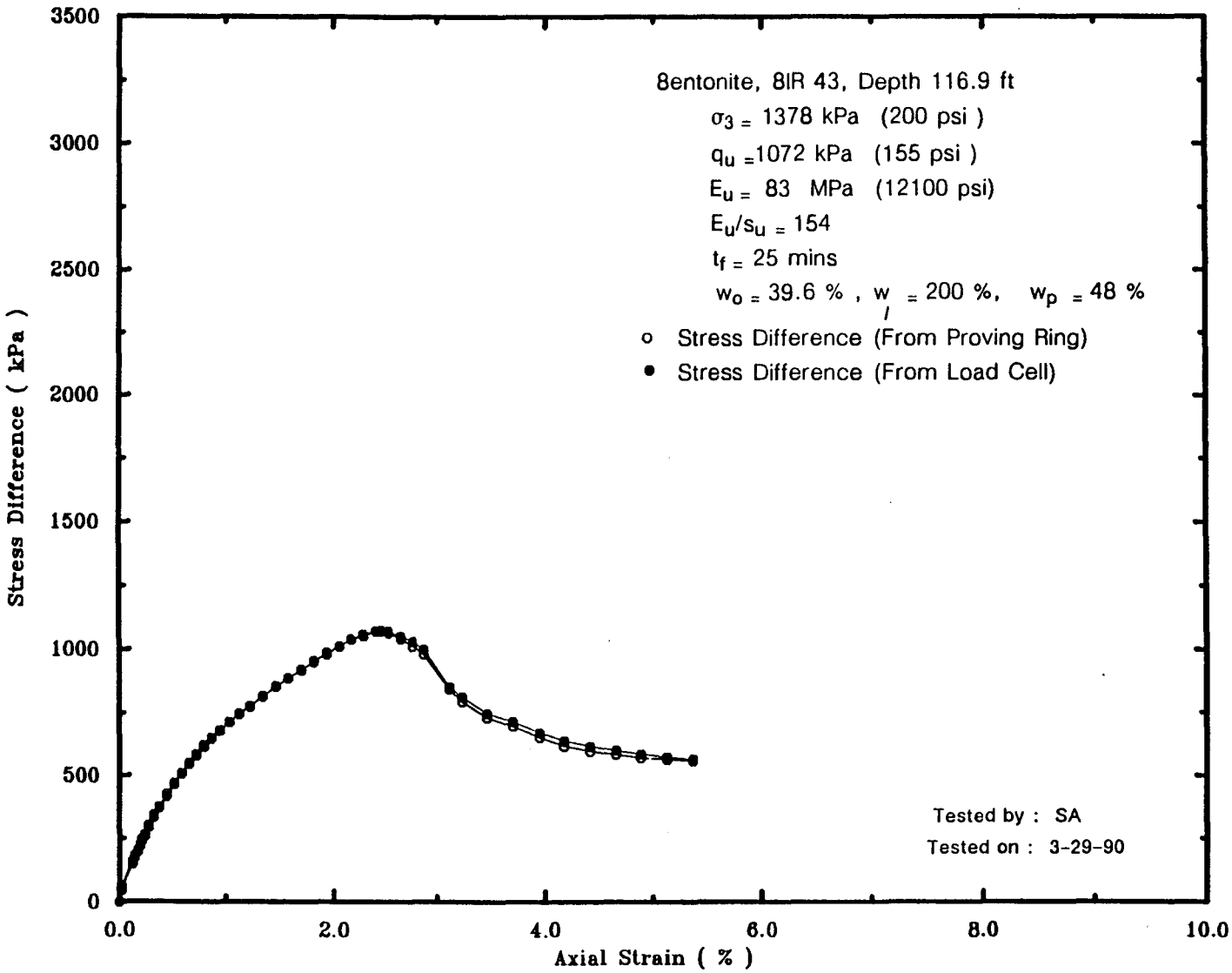


Fig. A14 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU15



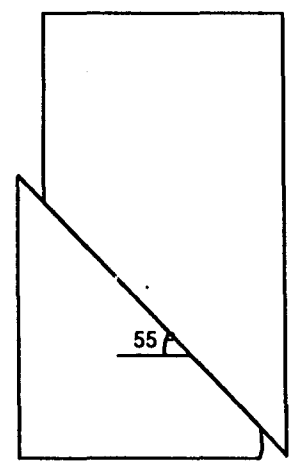
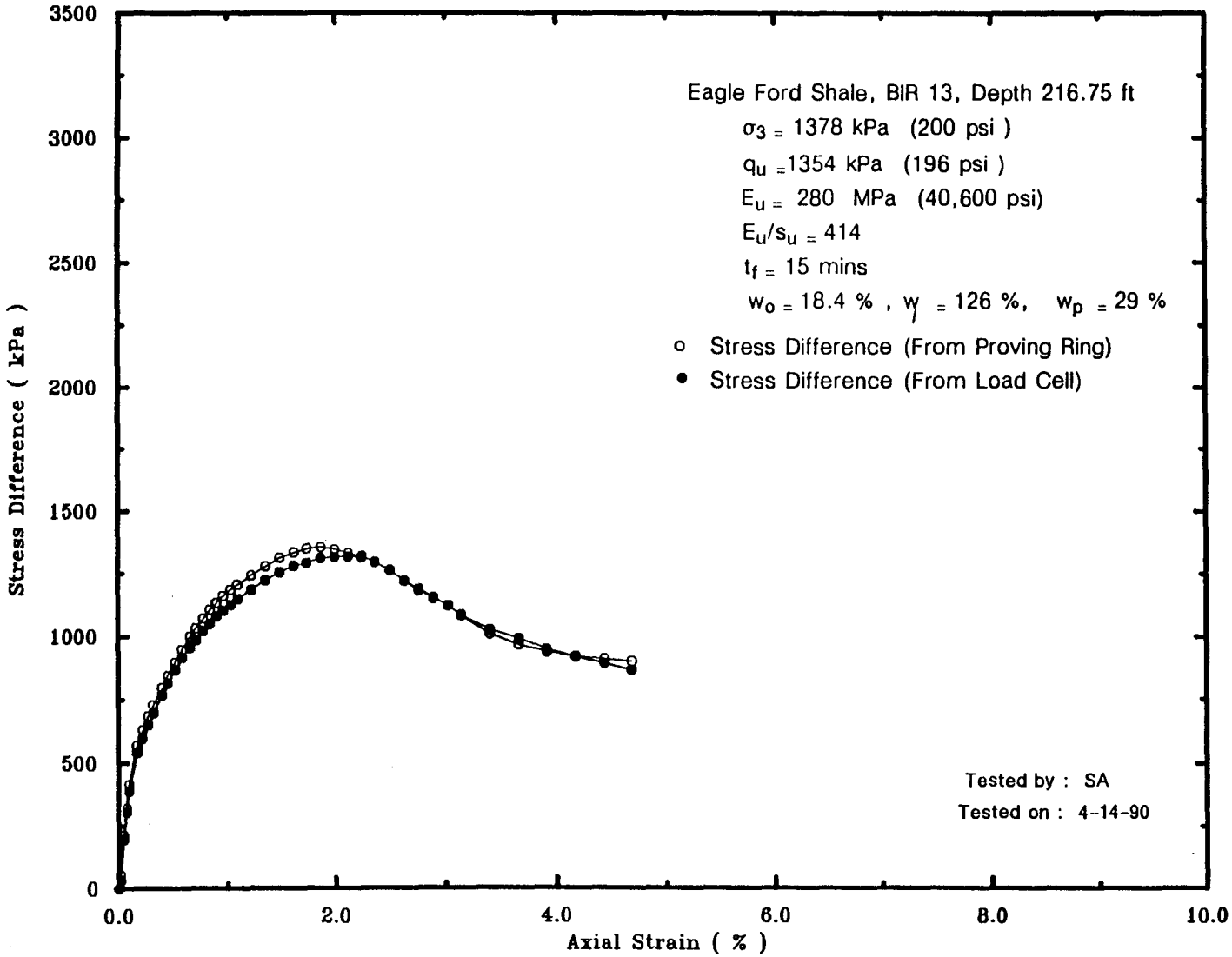


Fig. A15 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU16



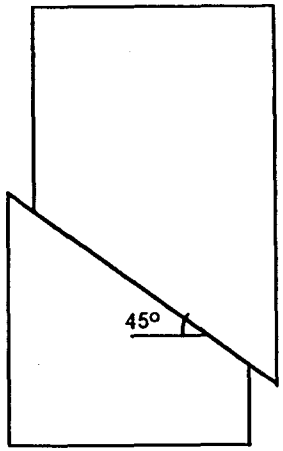
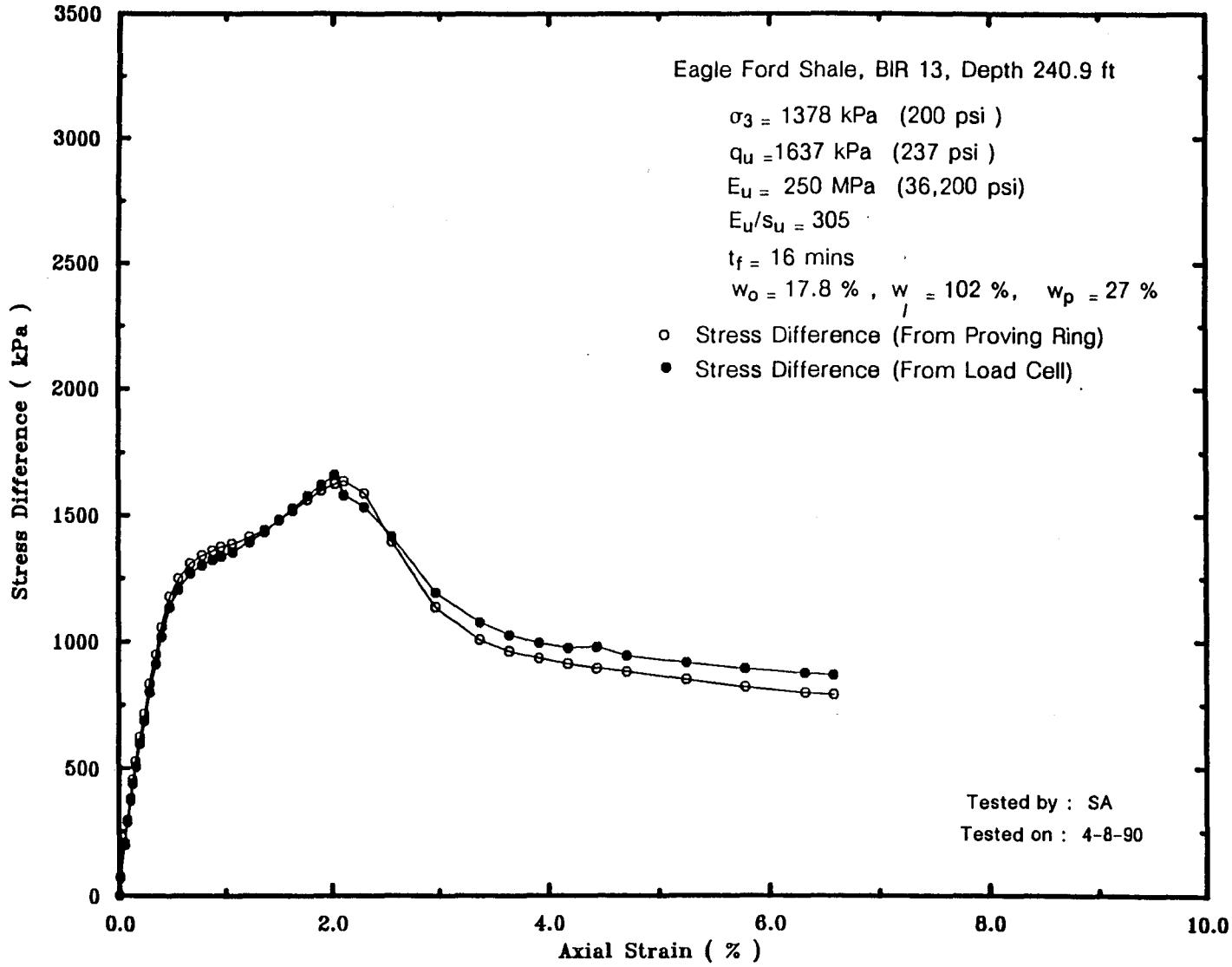


Fig. A16 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU17



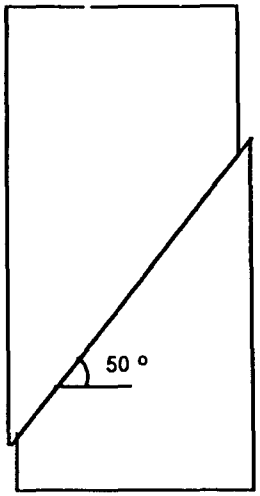
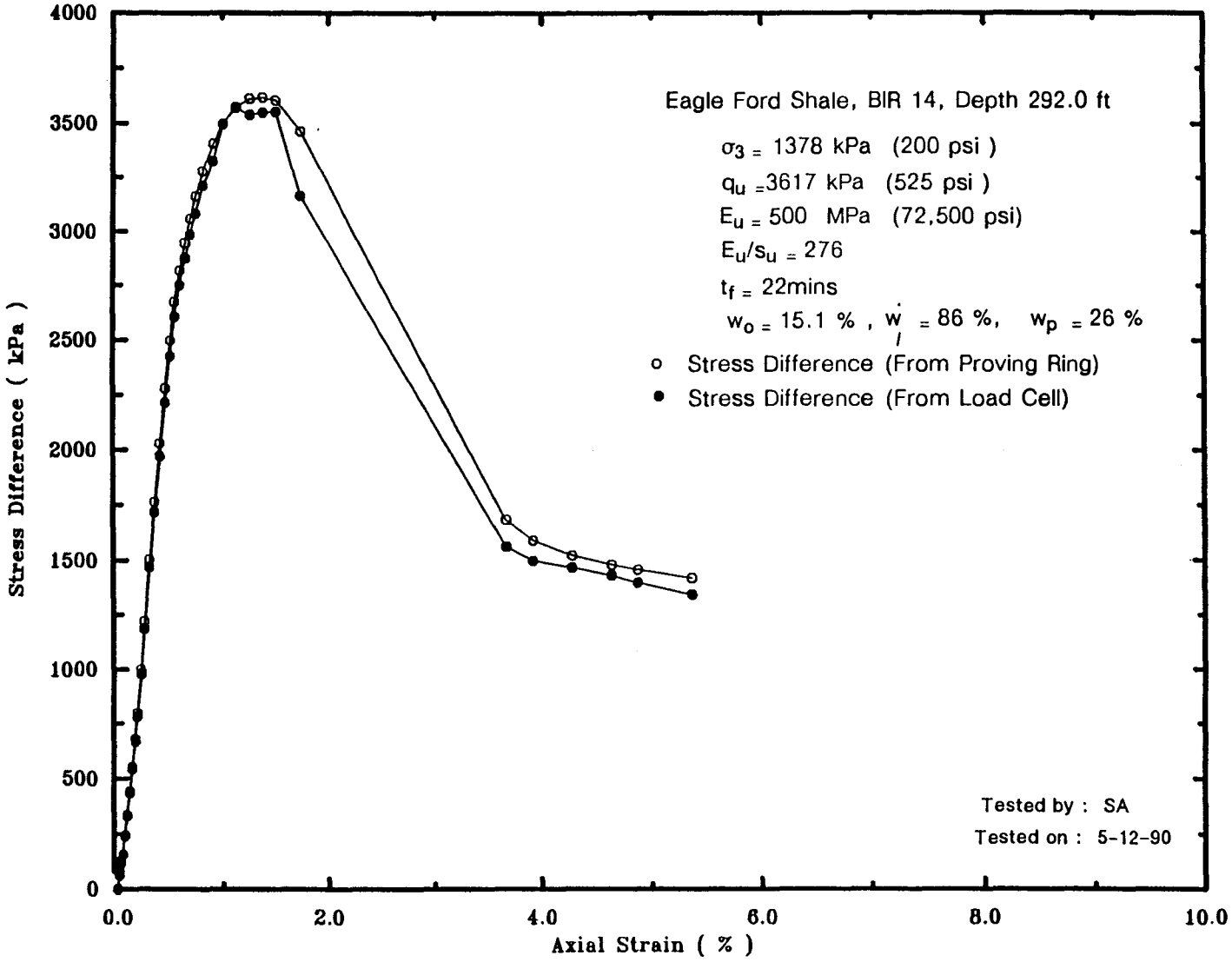


Fig. A17 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU18



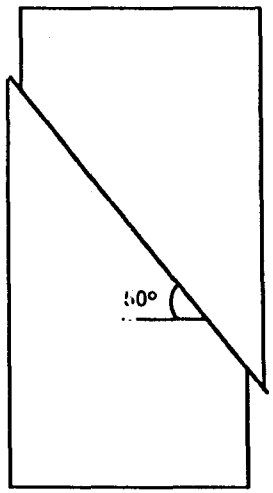
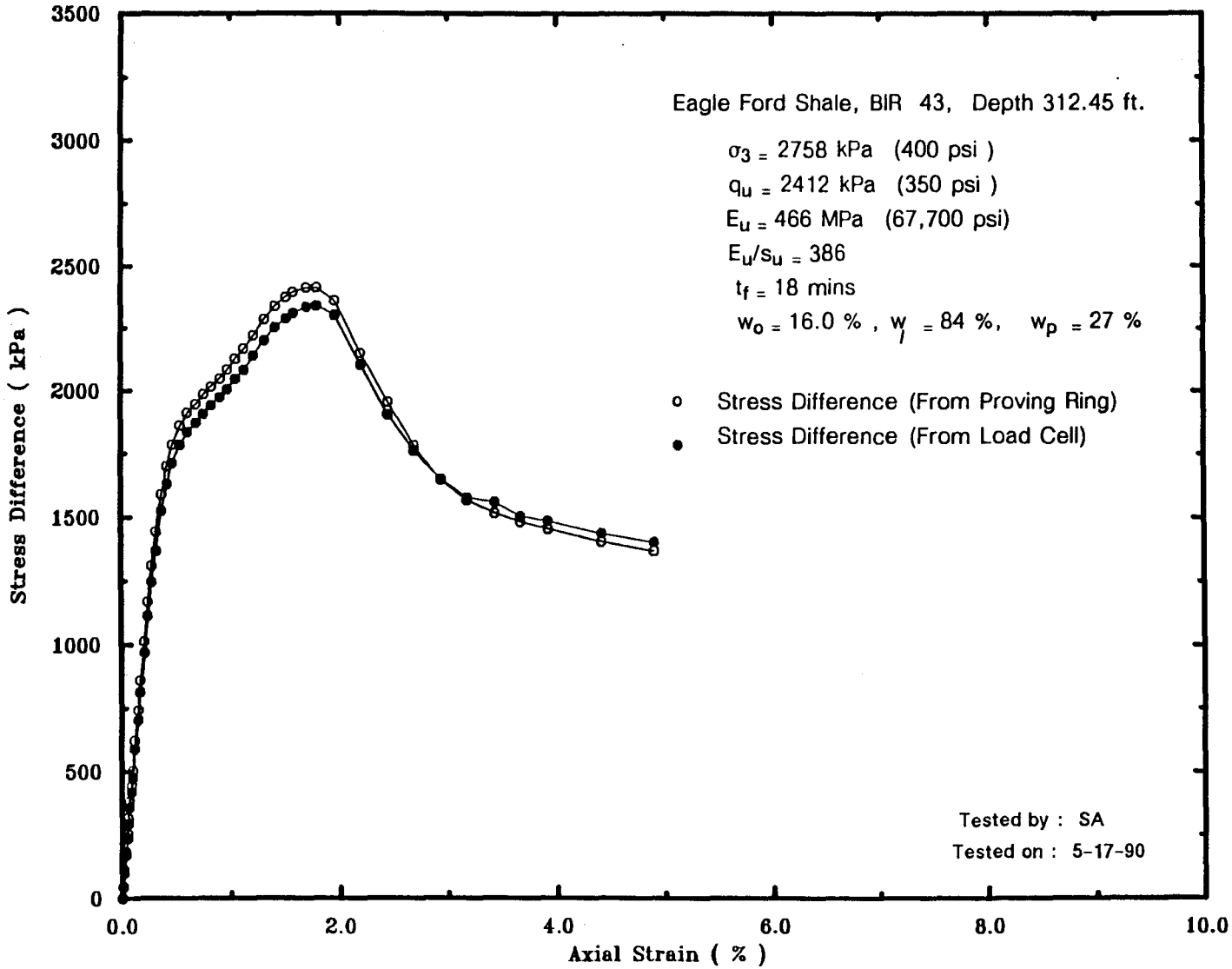


Fig. A18 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU19



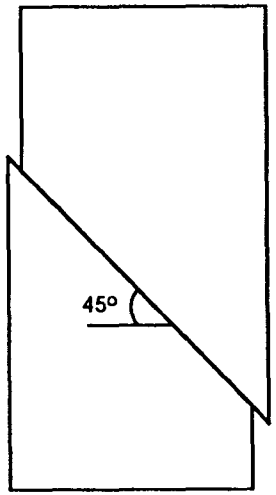
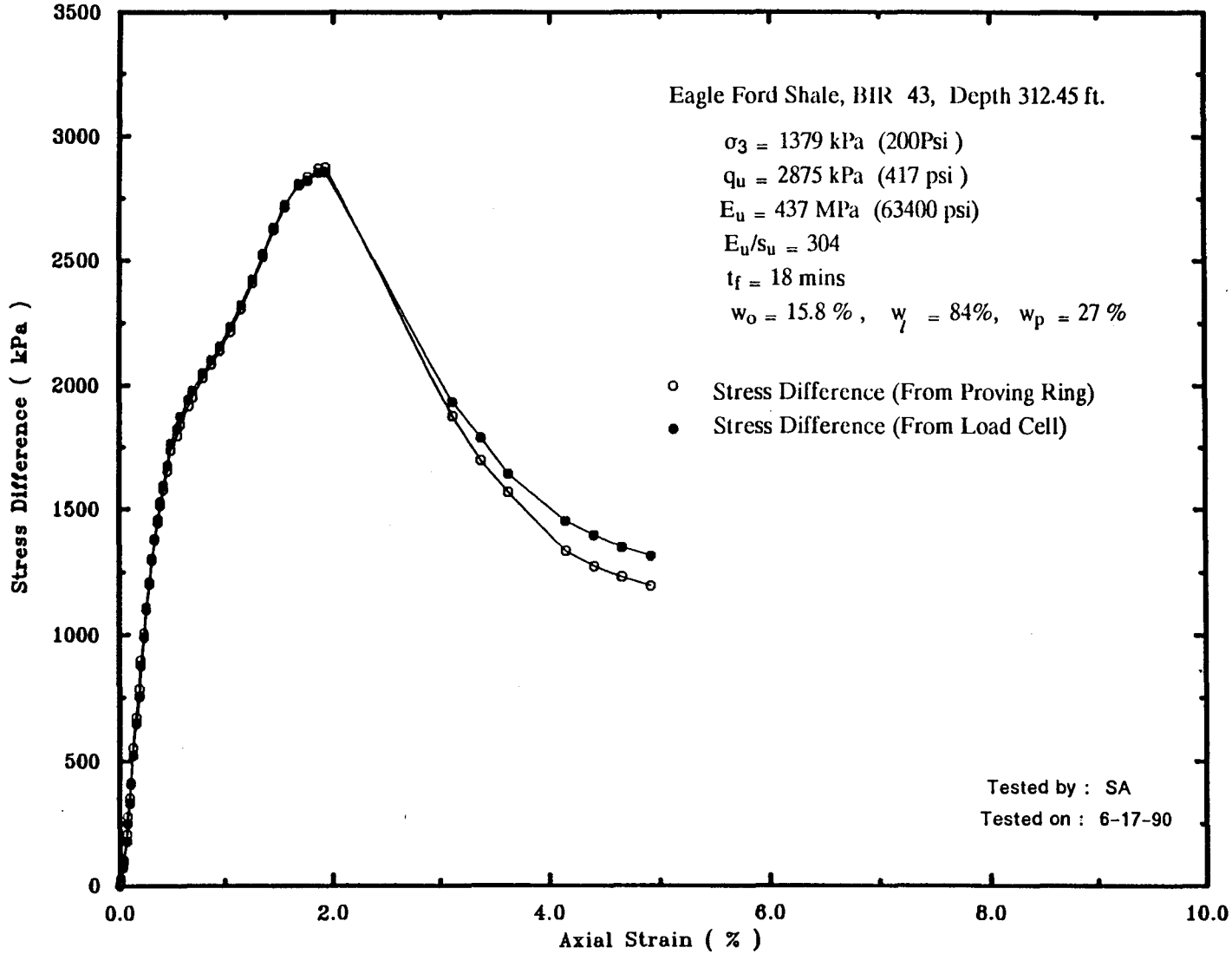


Fig. A19 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU20



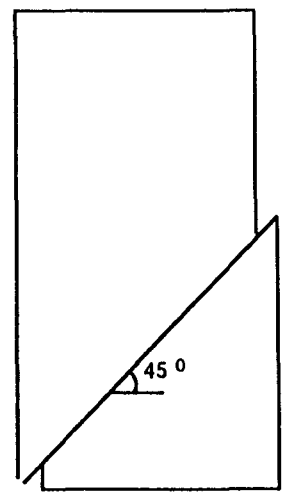
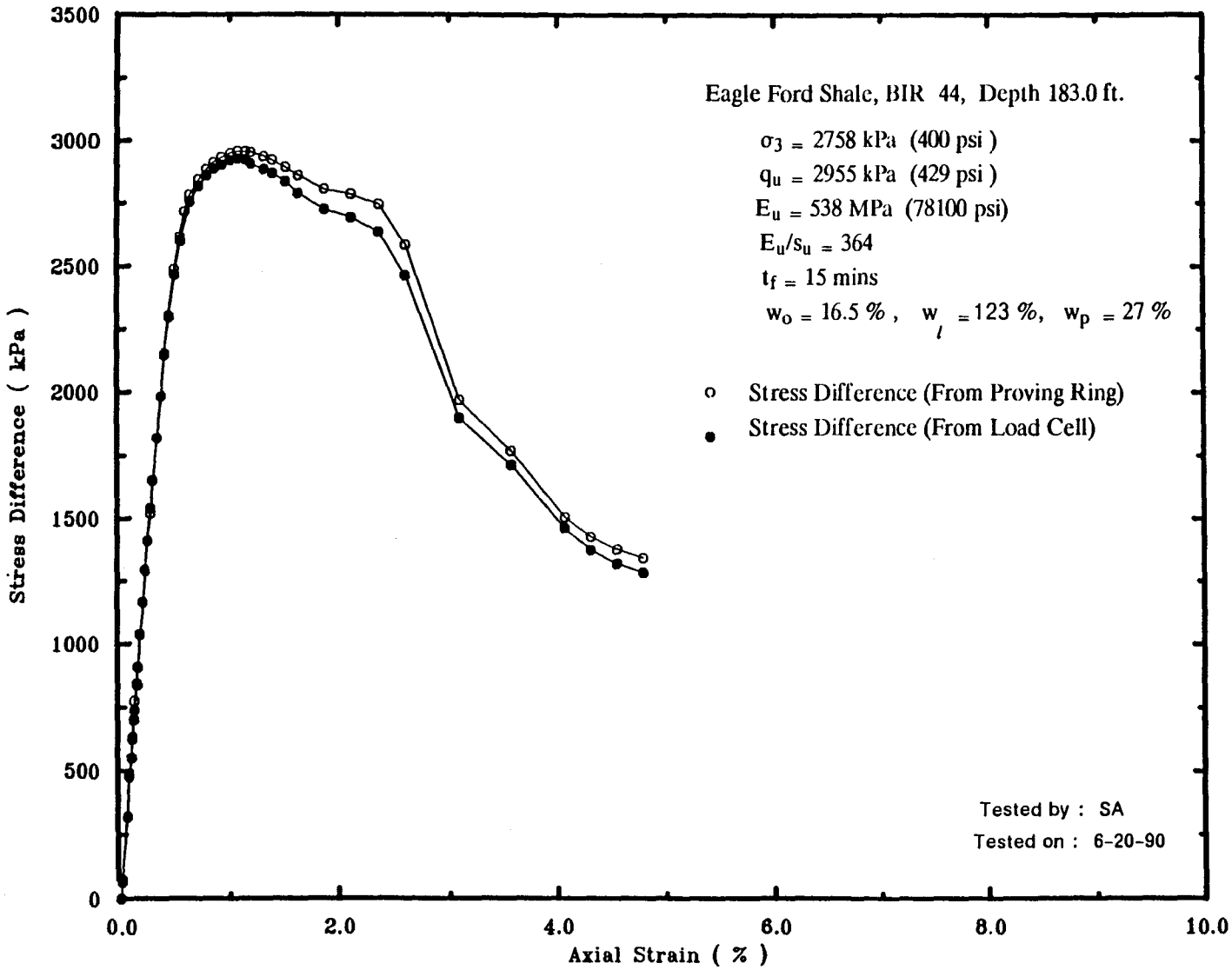


Fig. A20 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU21



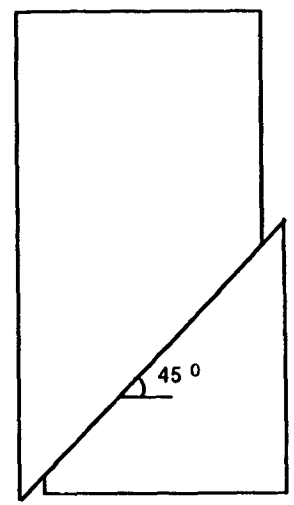
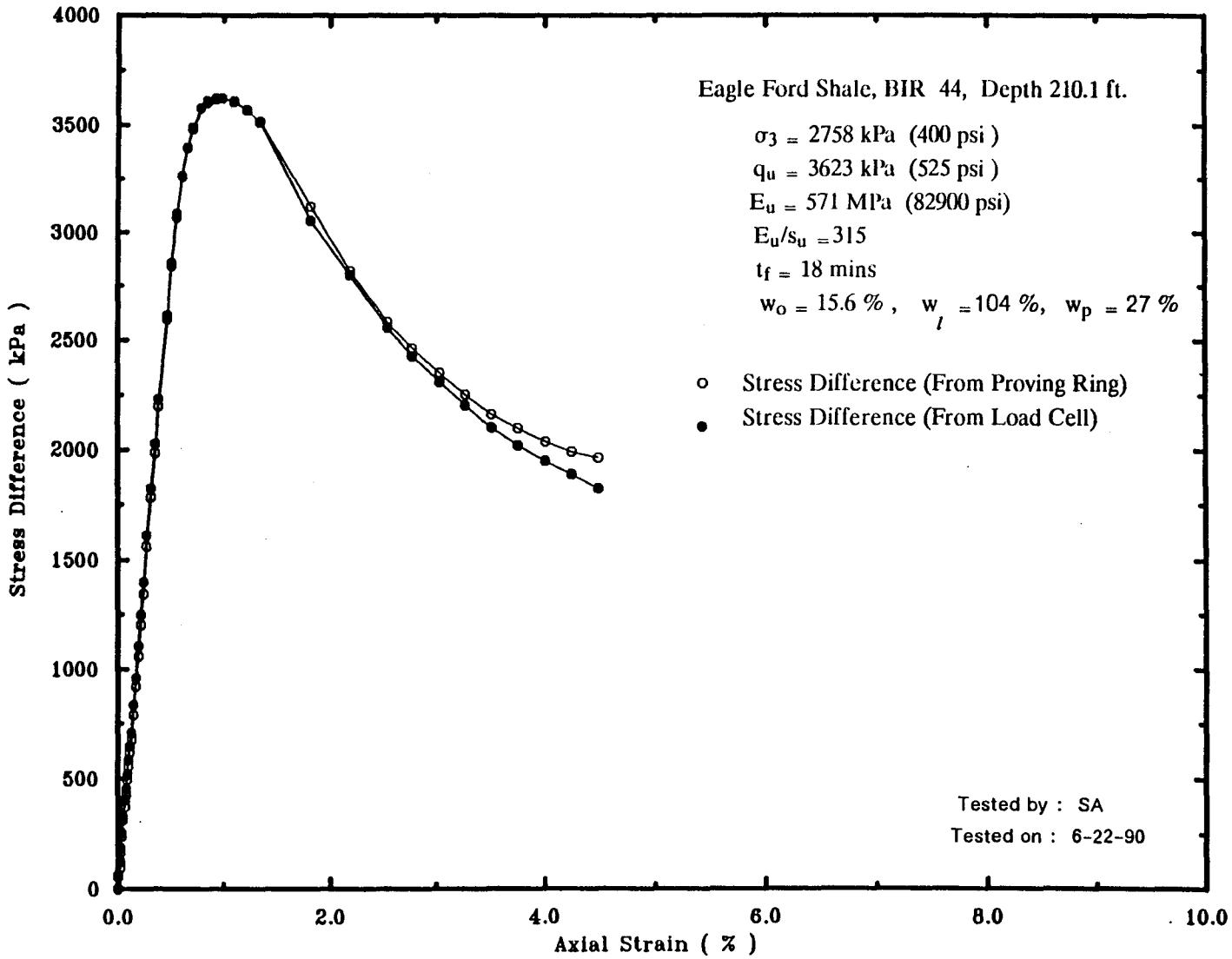


Fig. A21 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU22



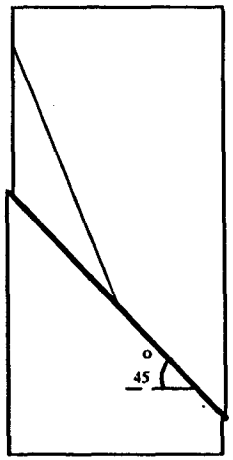
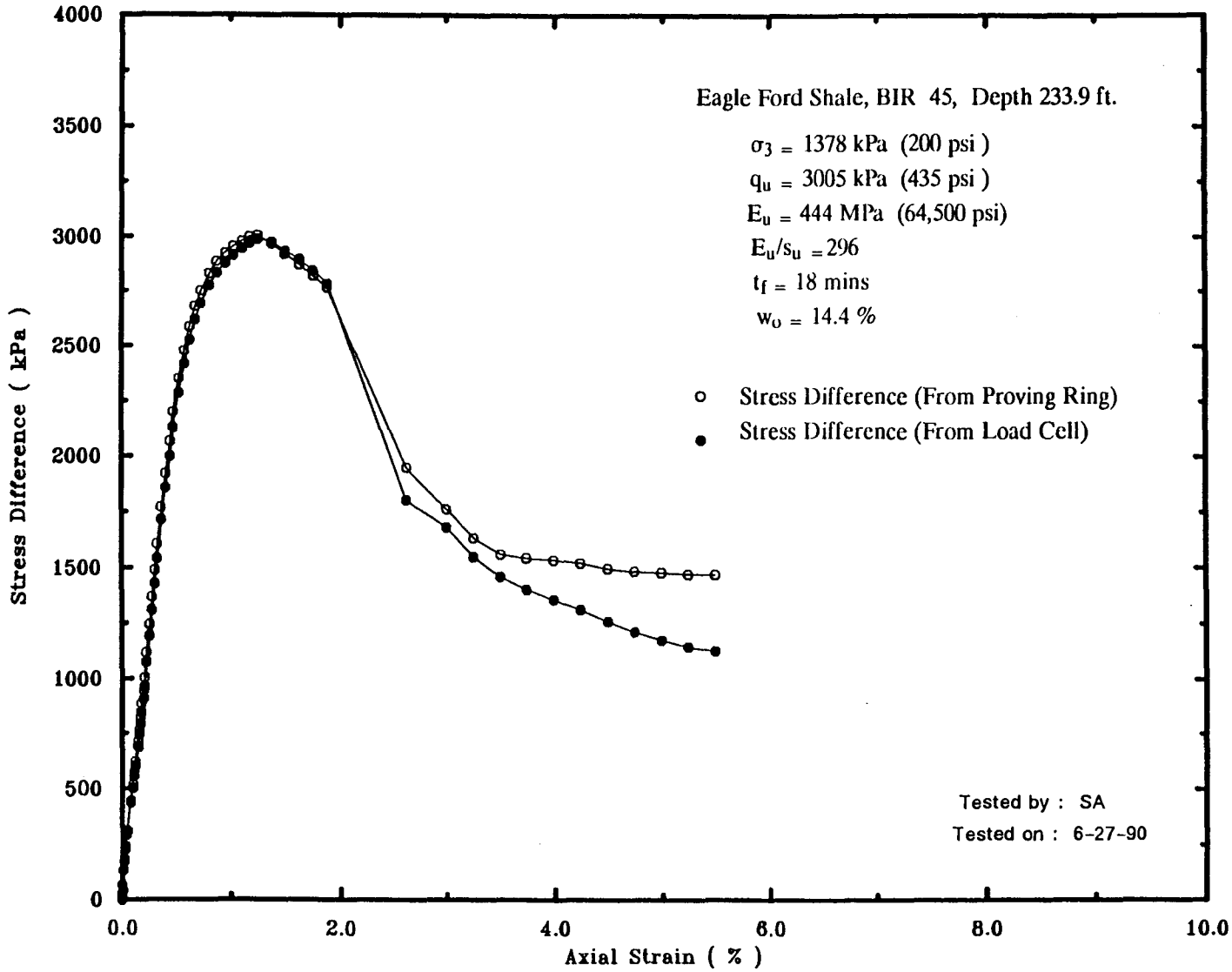


Fig. A22 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU23



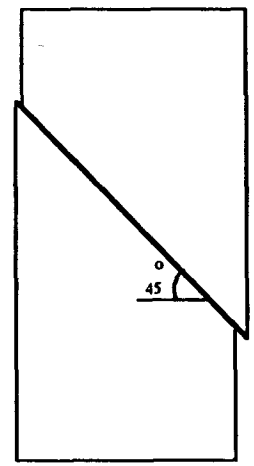
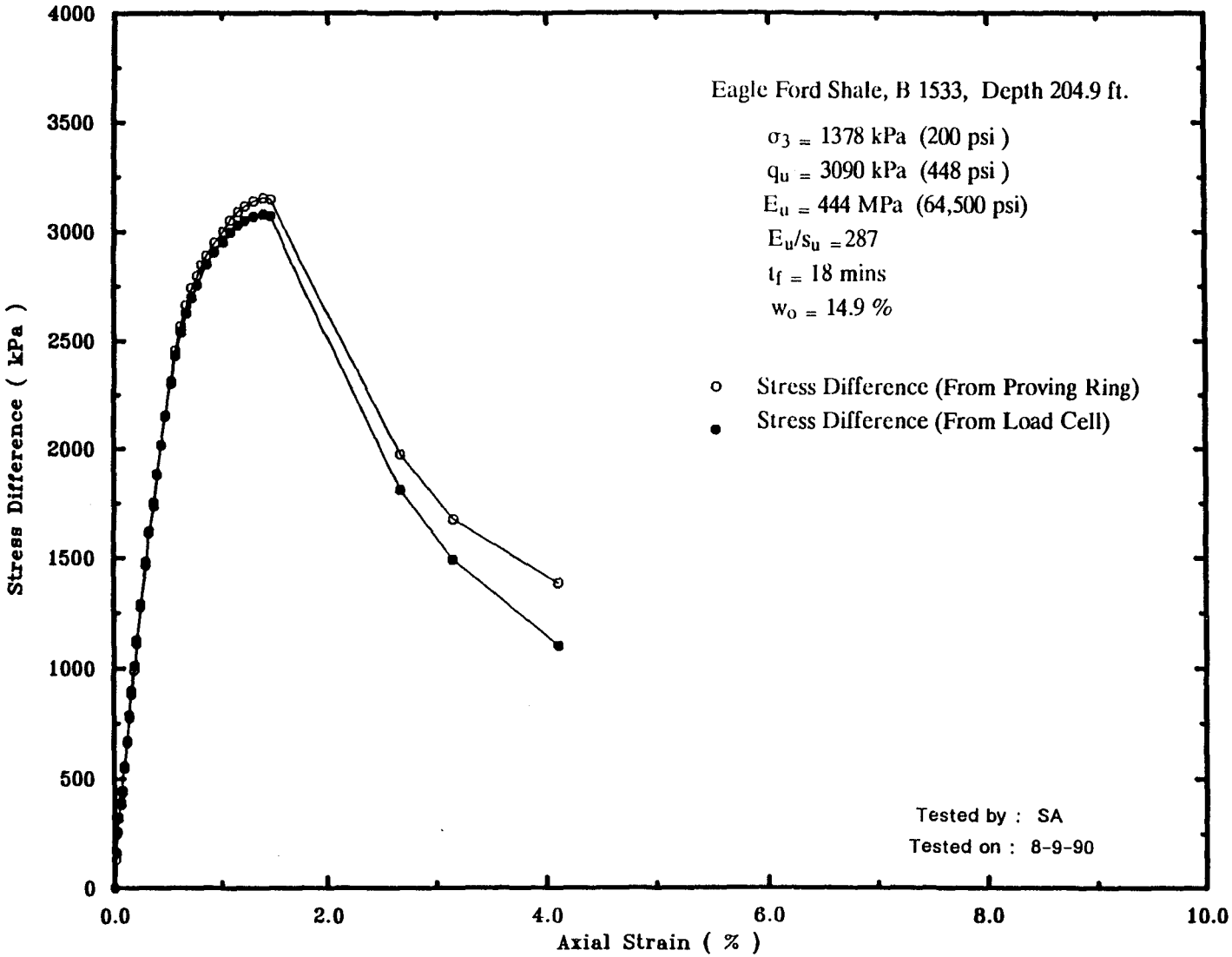


Fig. A23 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU24



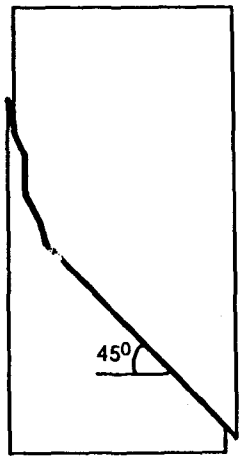
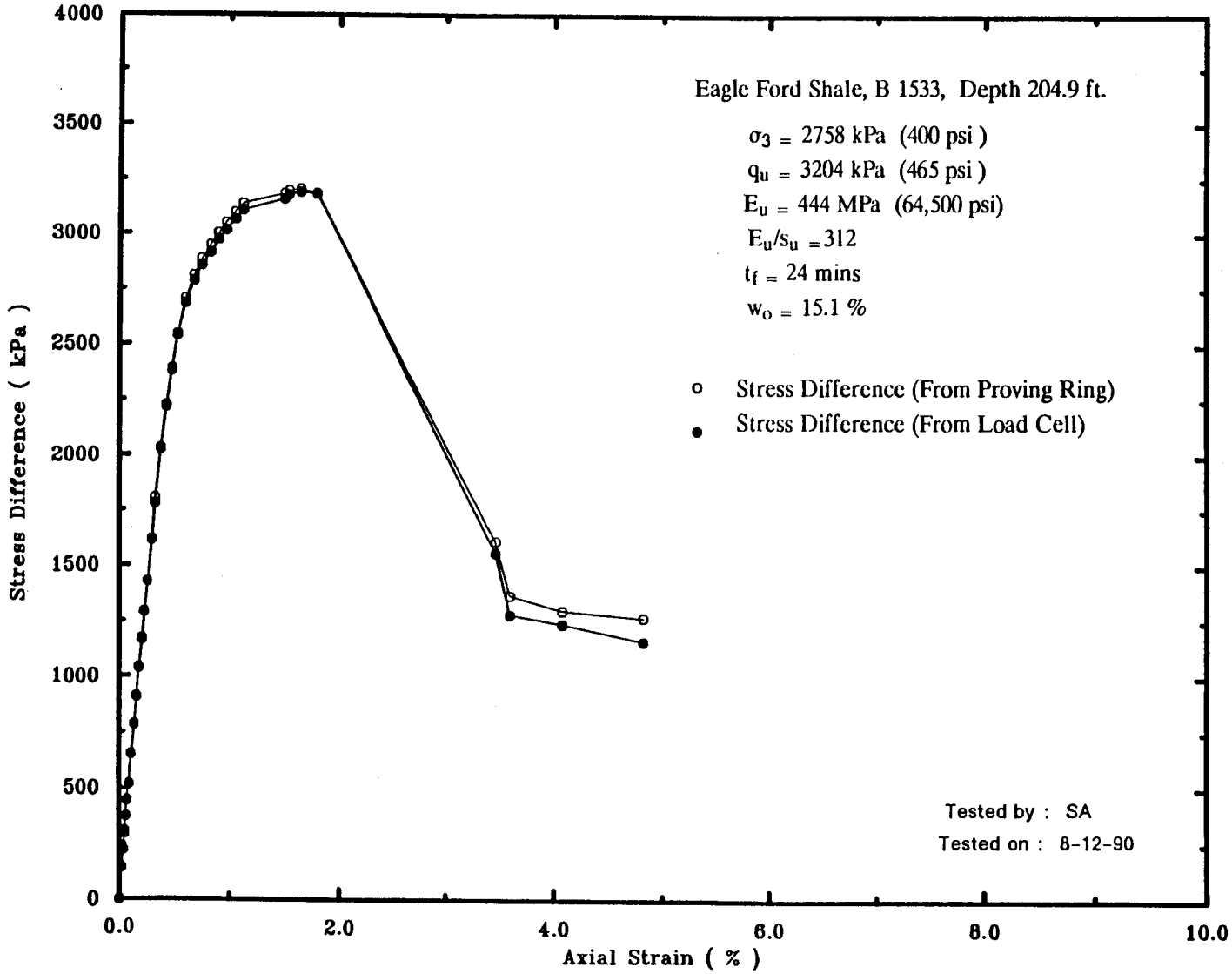


Fig. A24 Stress Difference vs Axial Strain

SSC PROJECT

Unconsolidated Undrained Triaxial Test UU25



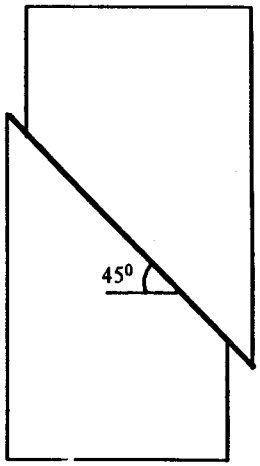


Fig. A25 Stress Difference vs Axial Strain

APPENDIX BI

Figs. B1-B5

Shear Stress - Horizontal Displacement Curves

for Drained Reversal Direct Shear Tests

on precut specimens of Eagle Ford Shale, Taylor Marl and Bentonite

SSC PROJECT

Drained Reversal Direct Shear Test DS1

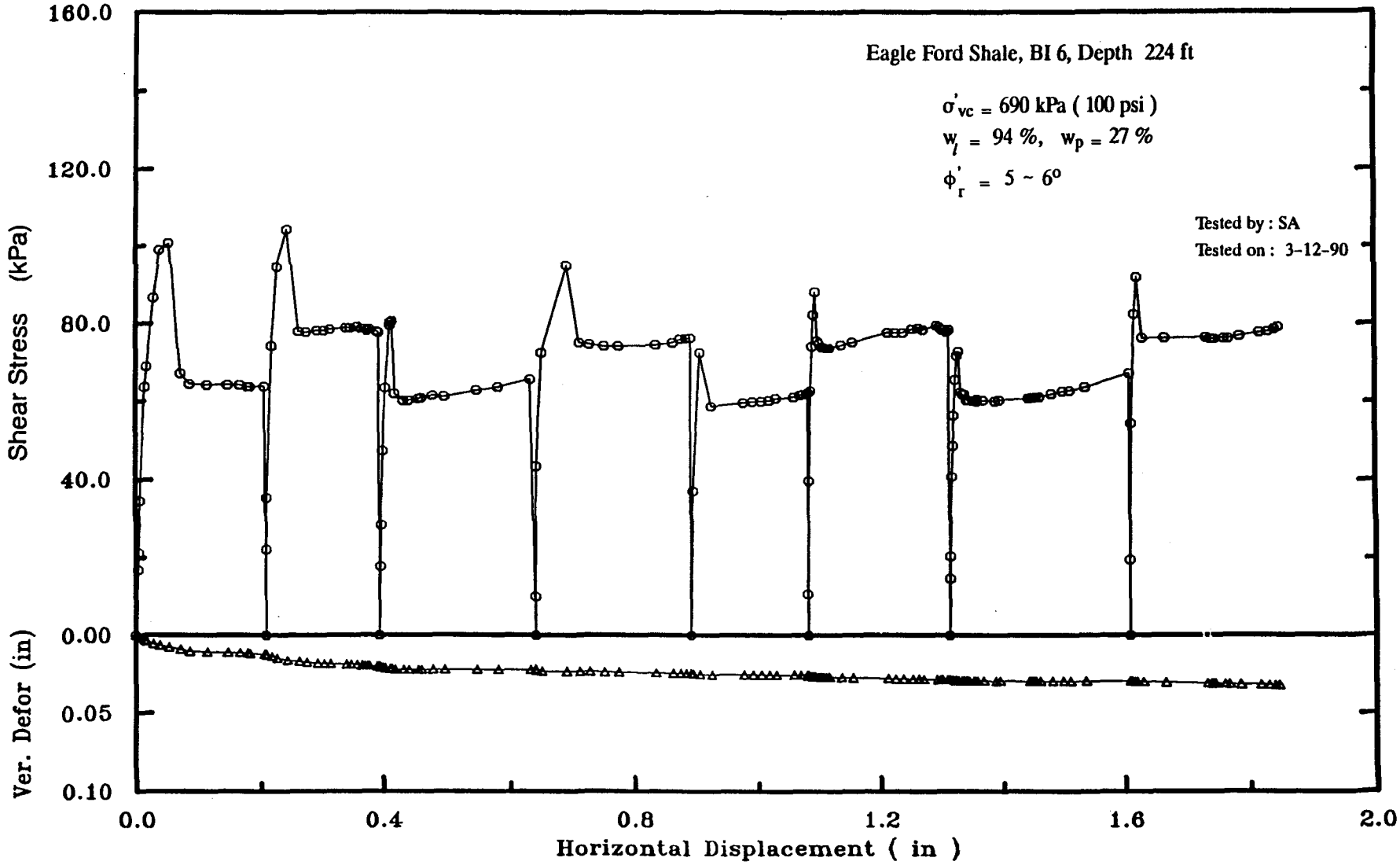


Fig. B1 Shear Stress and Vertical Deformation vs Horizontal Displacement

SSC PROJECT

Drained Reversal Direct Shear Test DS2

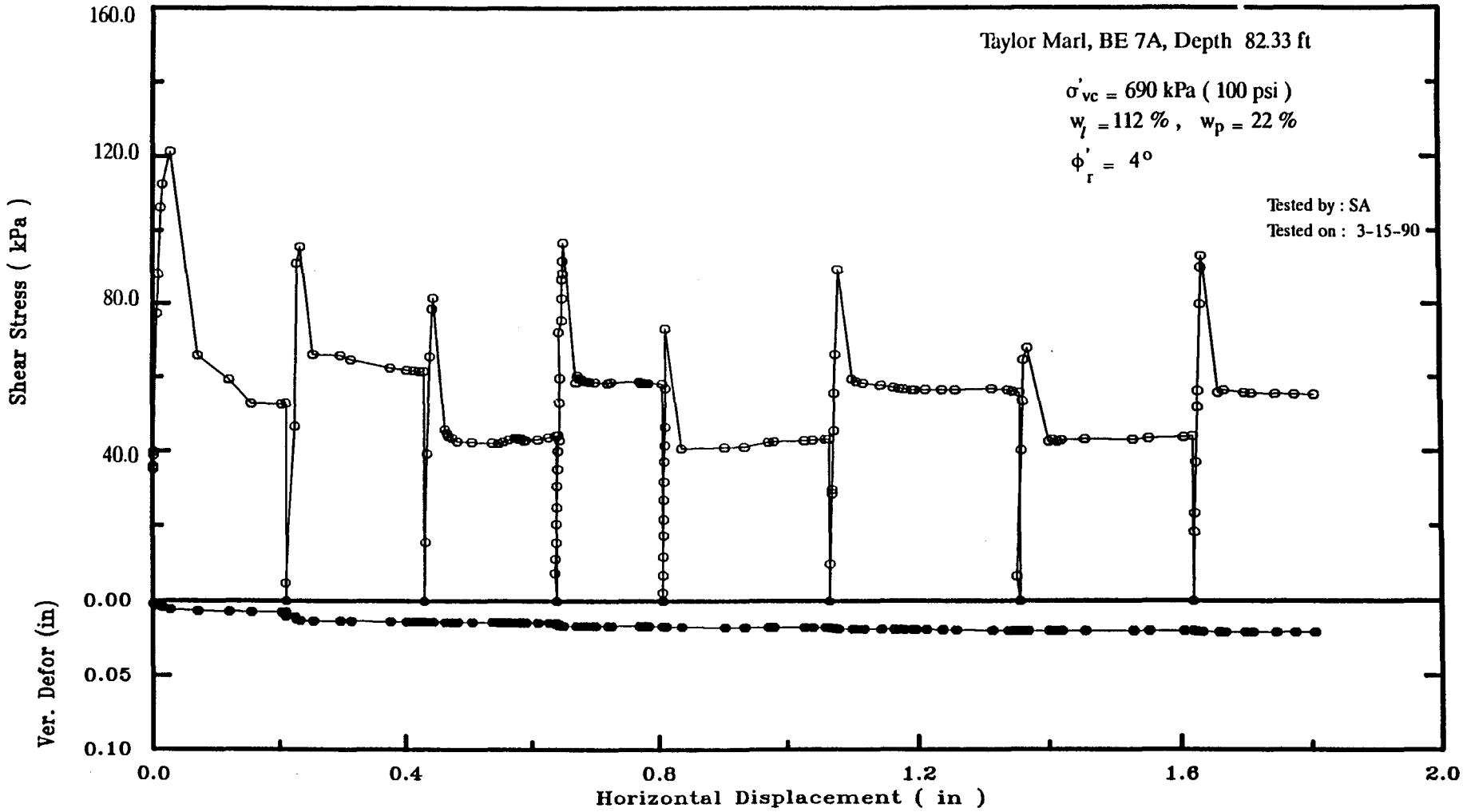


Fig. B2 Shear Stress and Vertical Deformation vs Horizontal Displacement

SSC PROJECT

Drained Reversal Direct Shear Test DS3

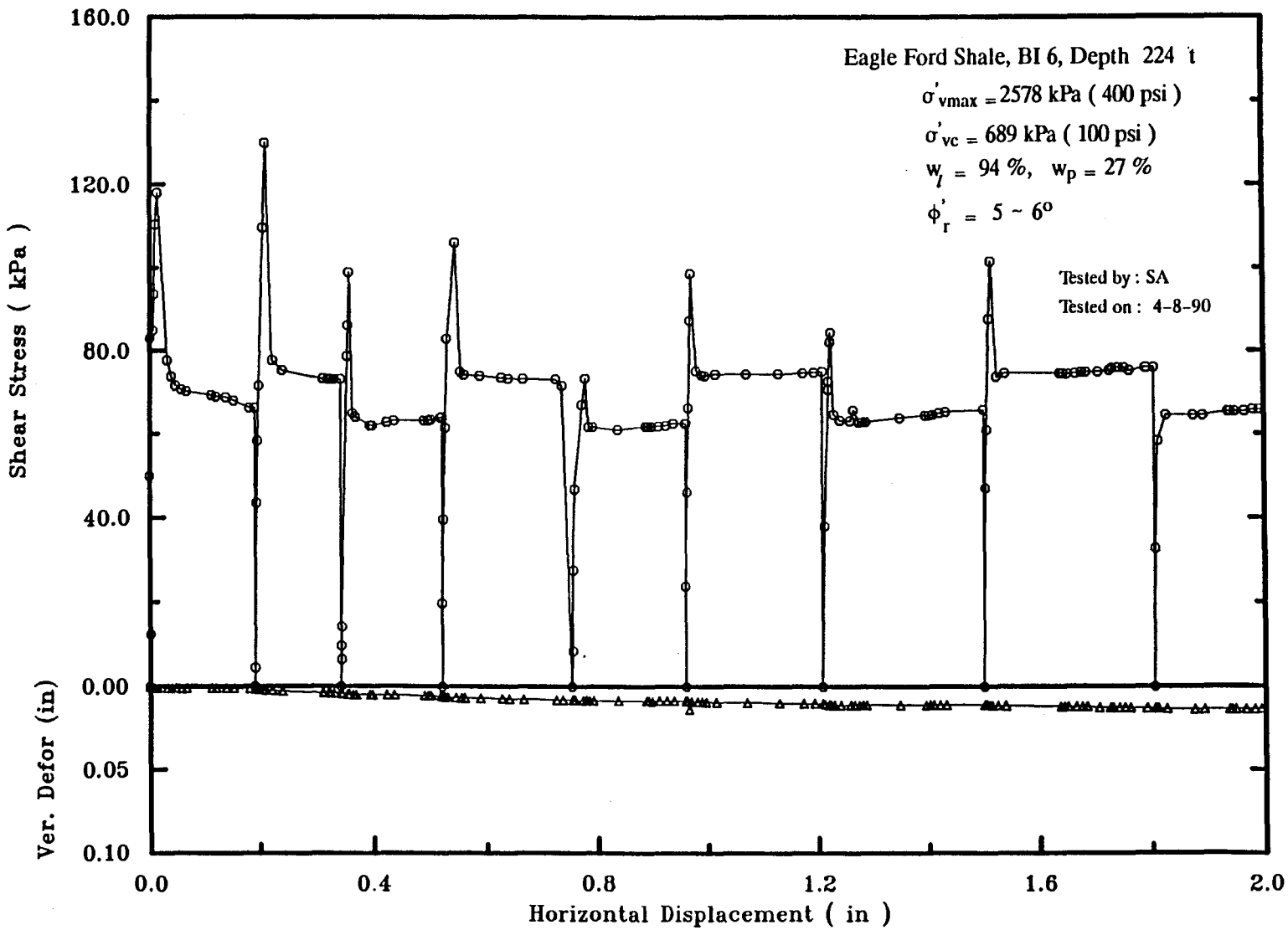


Fig. B3 Shear Stress and Vertical Deformation vs Horizontal Displacement

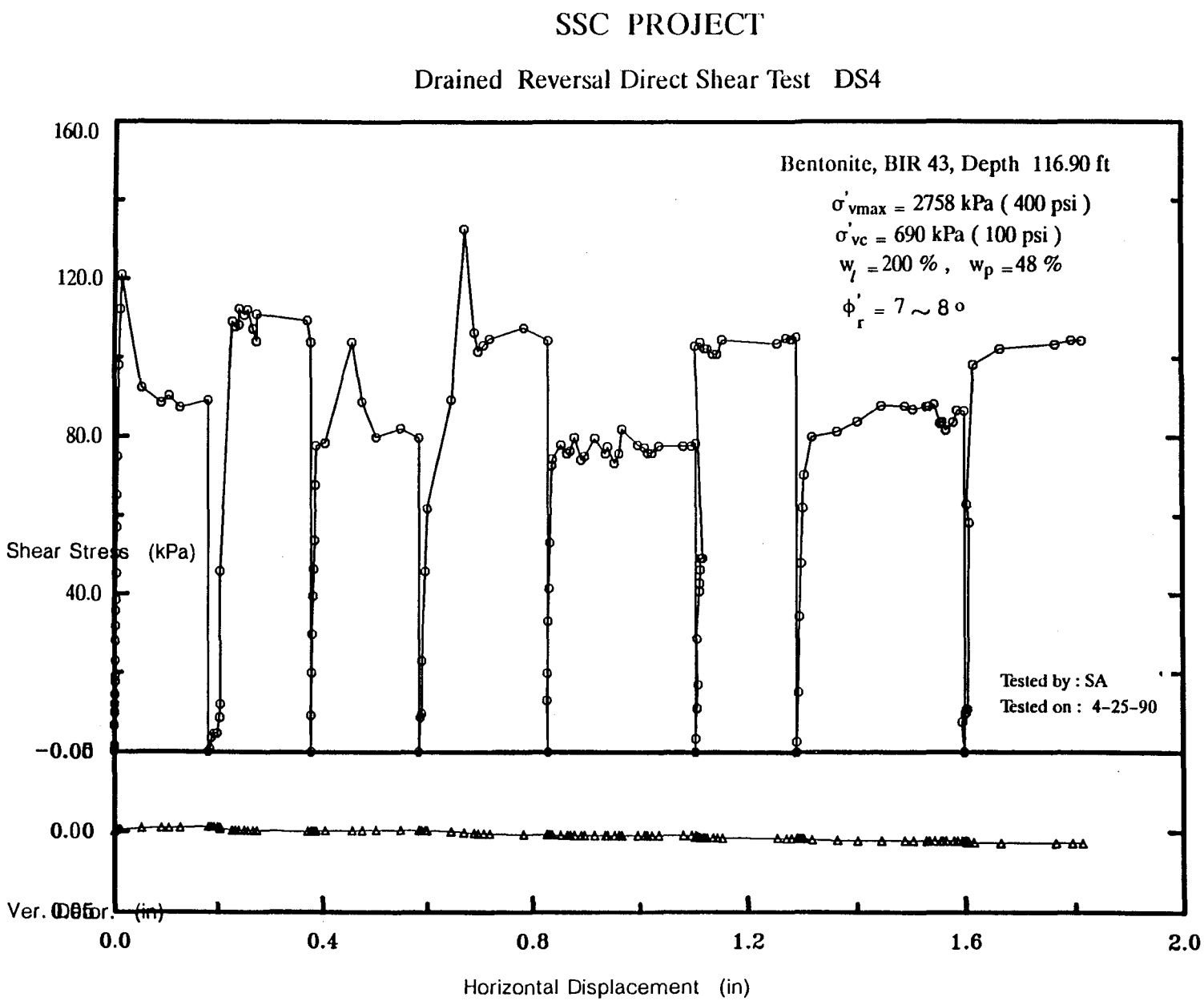


Fig. B4 Shear Stress and Vertical Deformation vs Horizontal Displacement

SSC PROJECT

Drained Reversal Direct Shear Test DS5

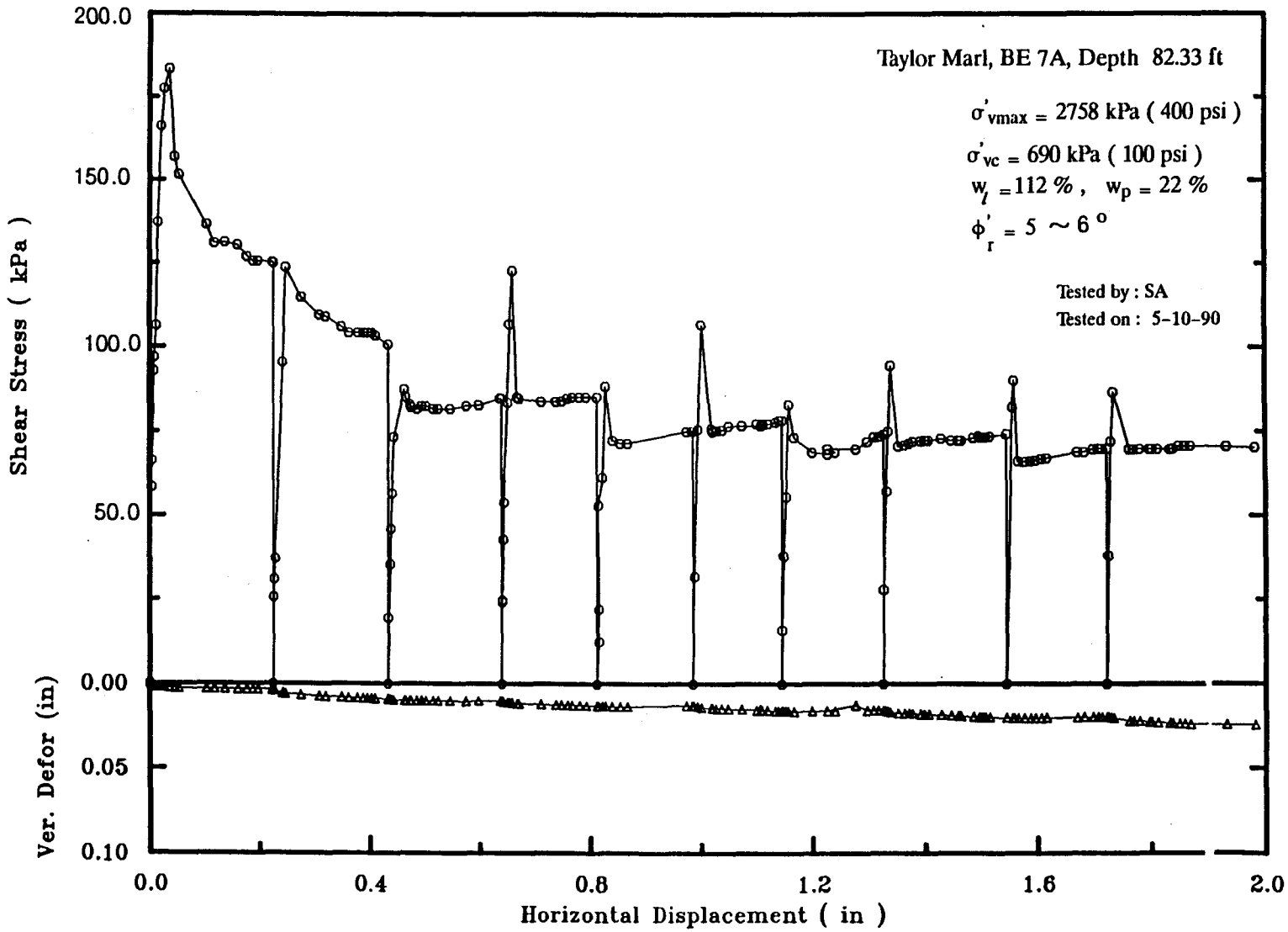


Fig. B5 Shear Stress and Vertical Deformation vs Horizontal Displacement

APPENDIX CI

Figs. C1-C30

Void Ratio - Log Pressure Relationships

and Time-rate of Swelling Pressure Development

for Oedometer Tests on Eagle Ford Shale and Taylor Marl

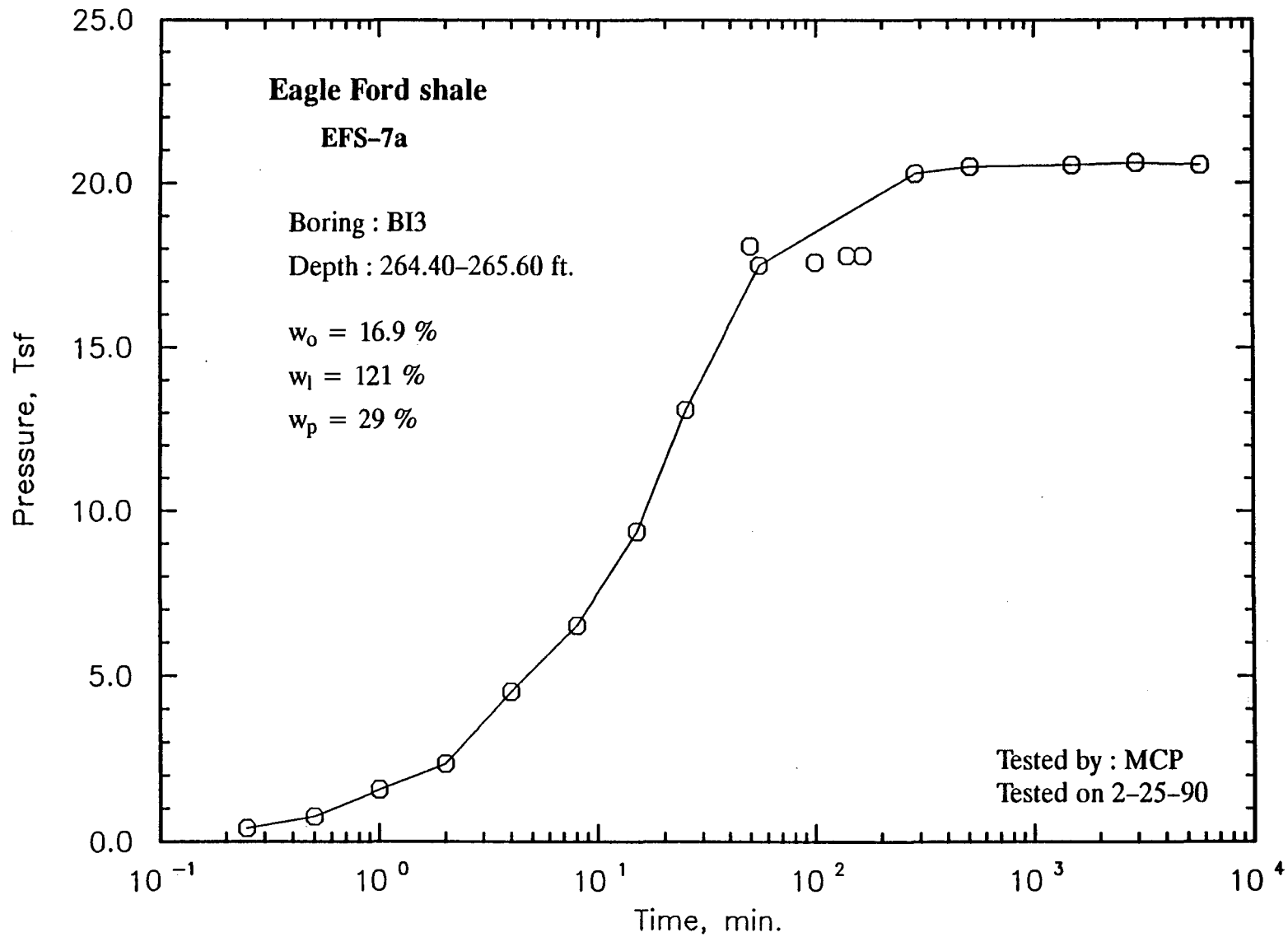


Fig. C1 Time–Rate of Swelling Pressure Development

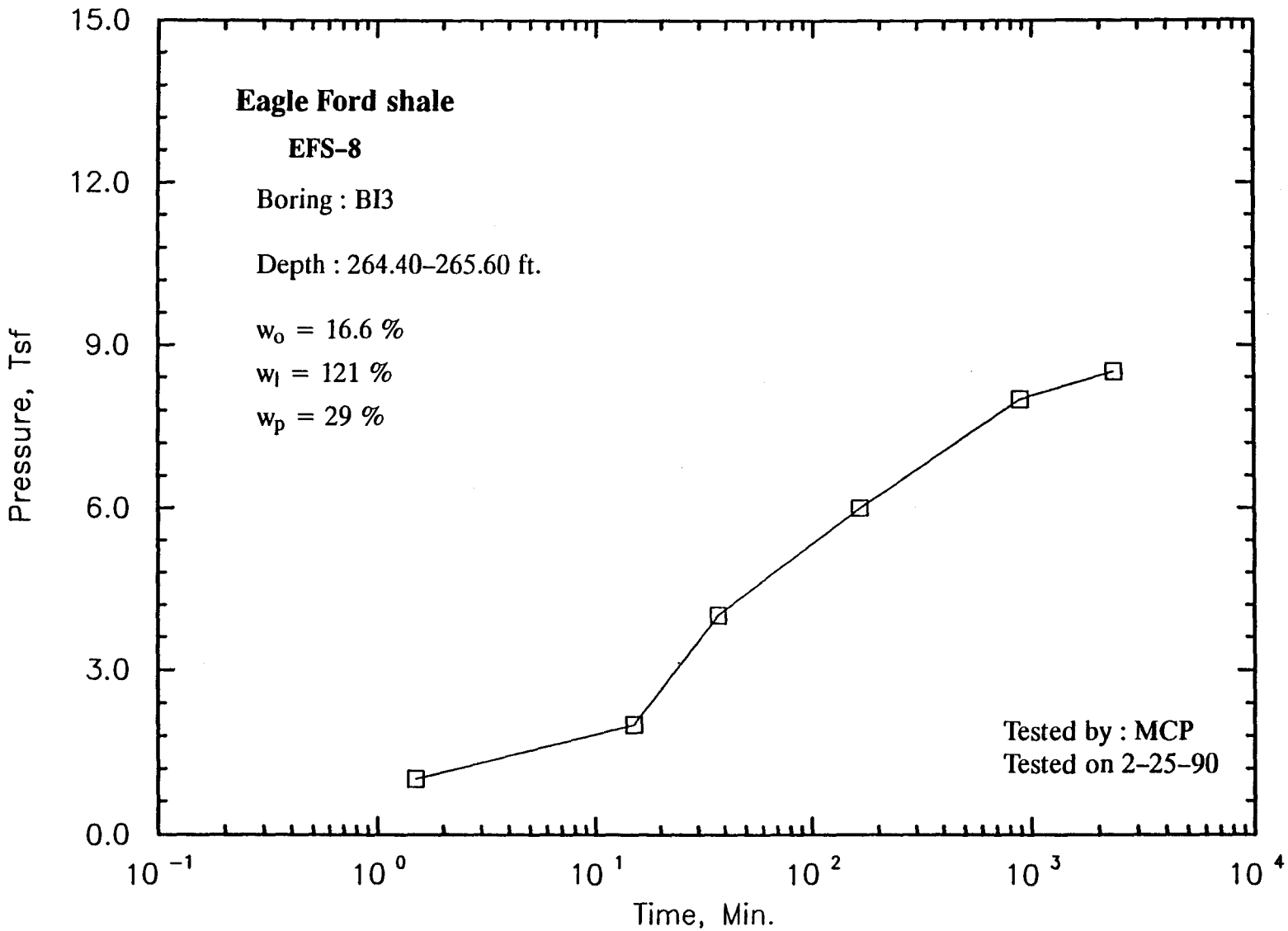


Fig. C2a Time-Rate of Swelling Pressure Development

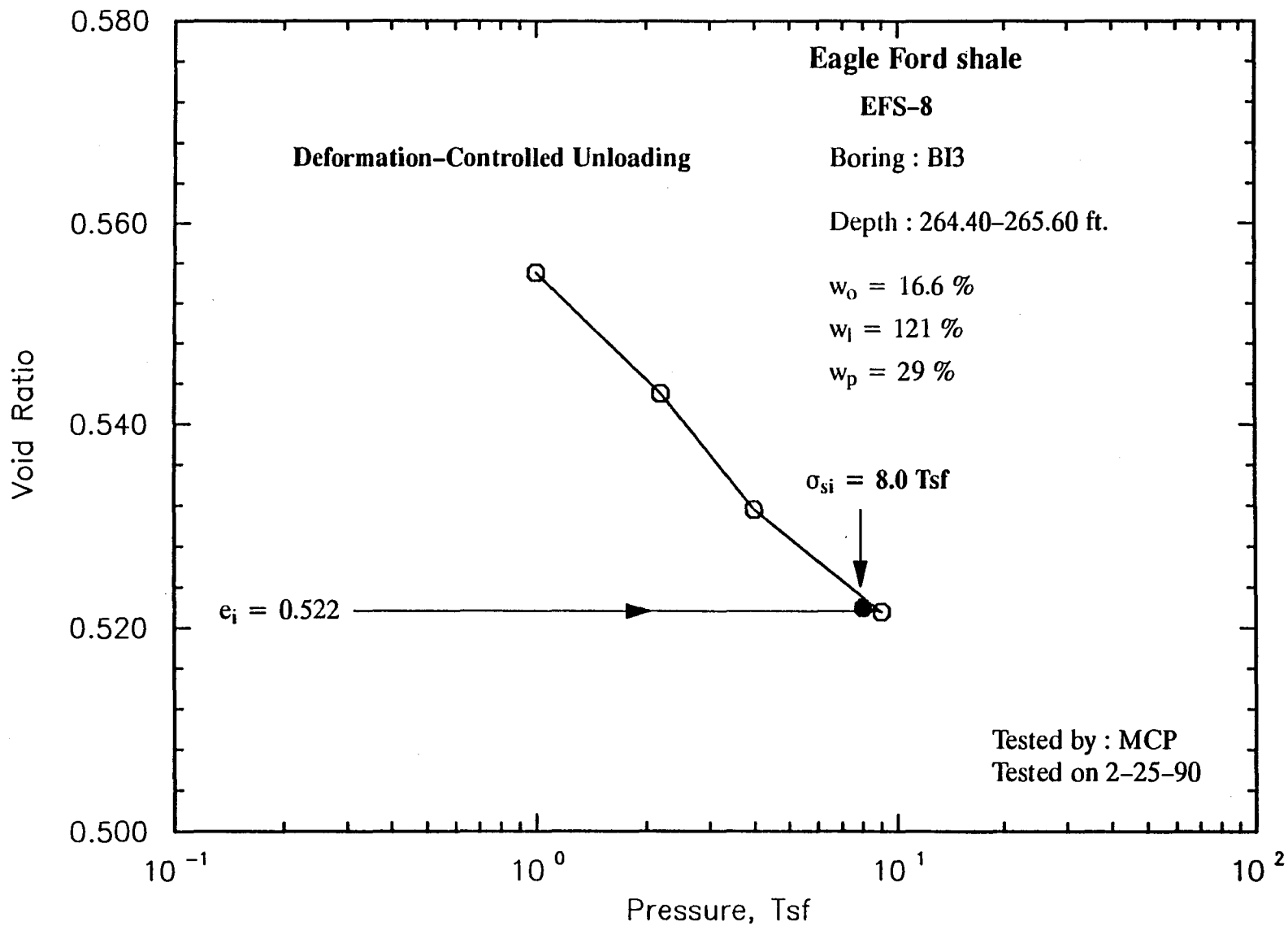


Fig. C2b Void Ratio – Log Pressure Relationship

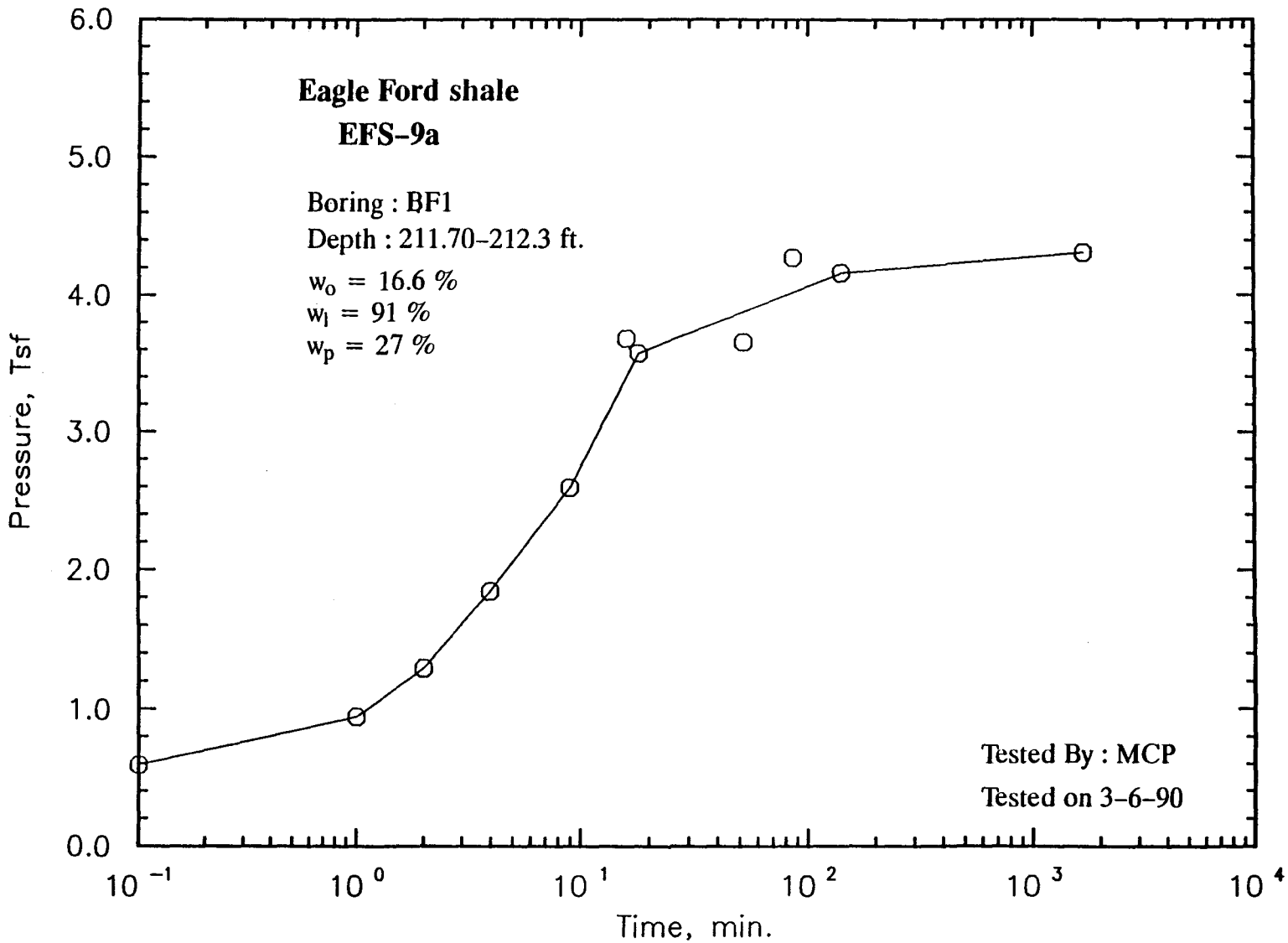


Fig. C3 Time-Rate of Swelling Pressure Development

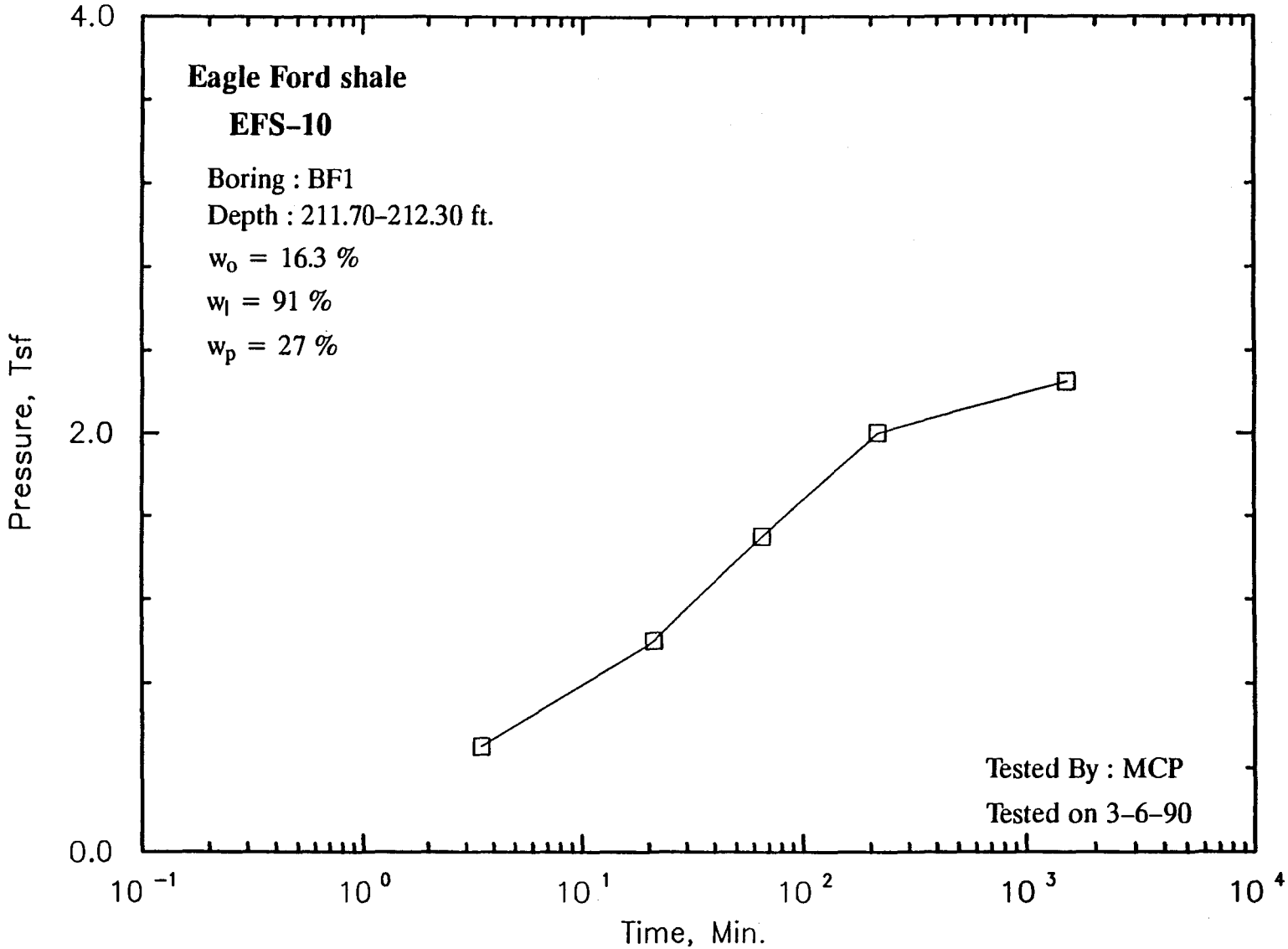


Fig. C4a Time-Rate of Swelling Pressure Development

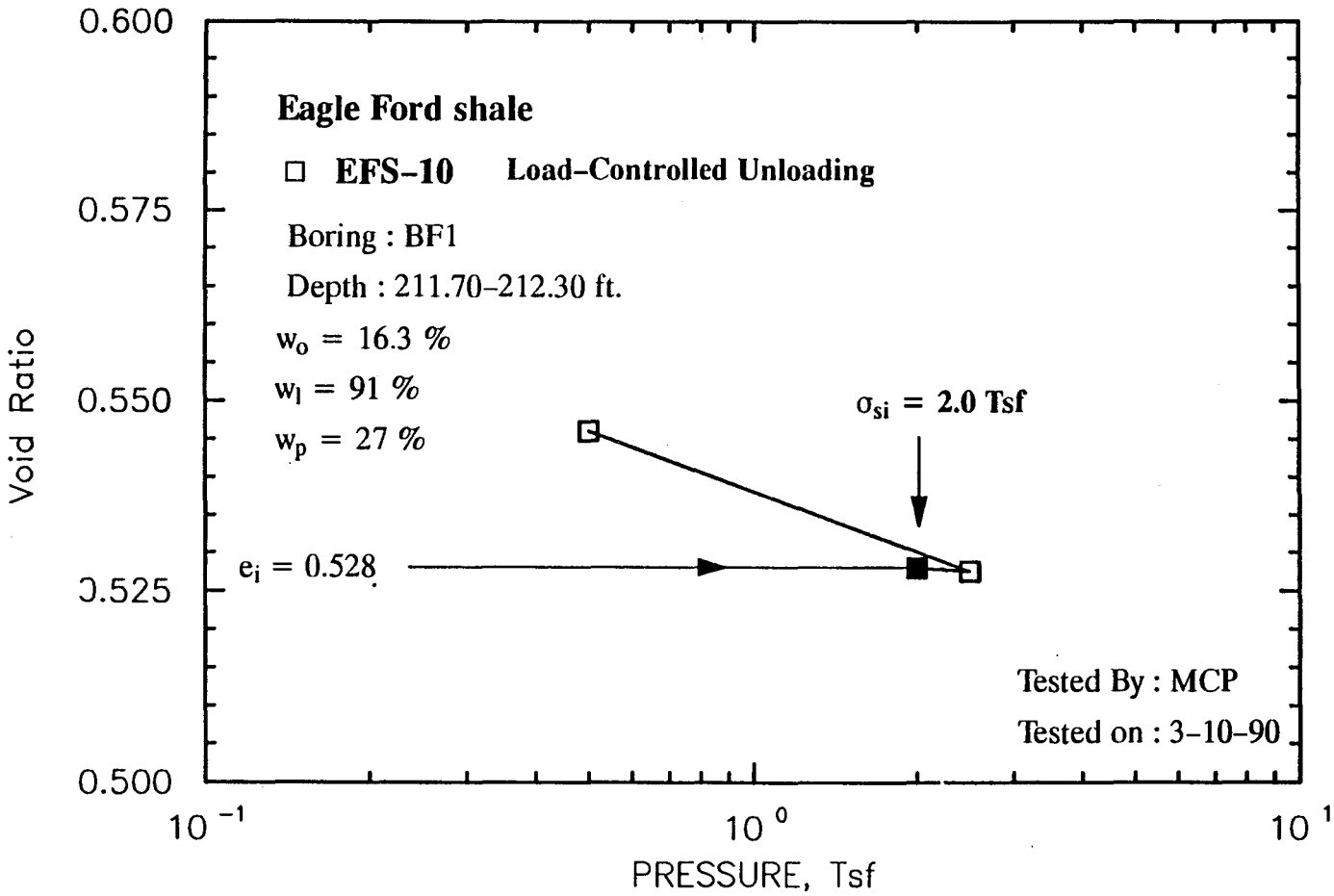


Fig. C4b Void Ratio – Log Pressure Relationship

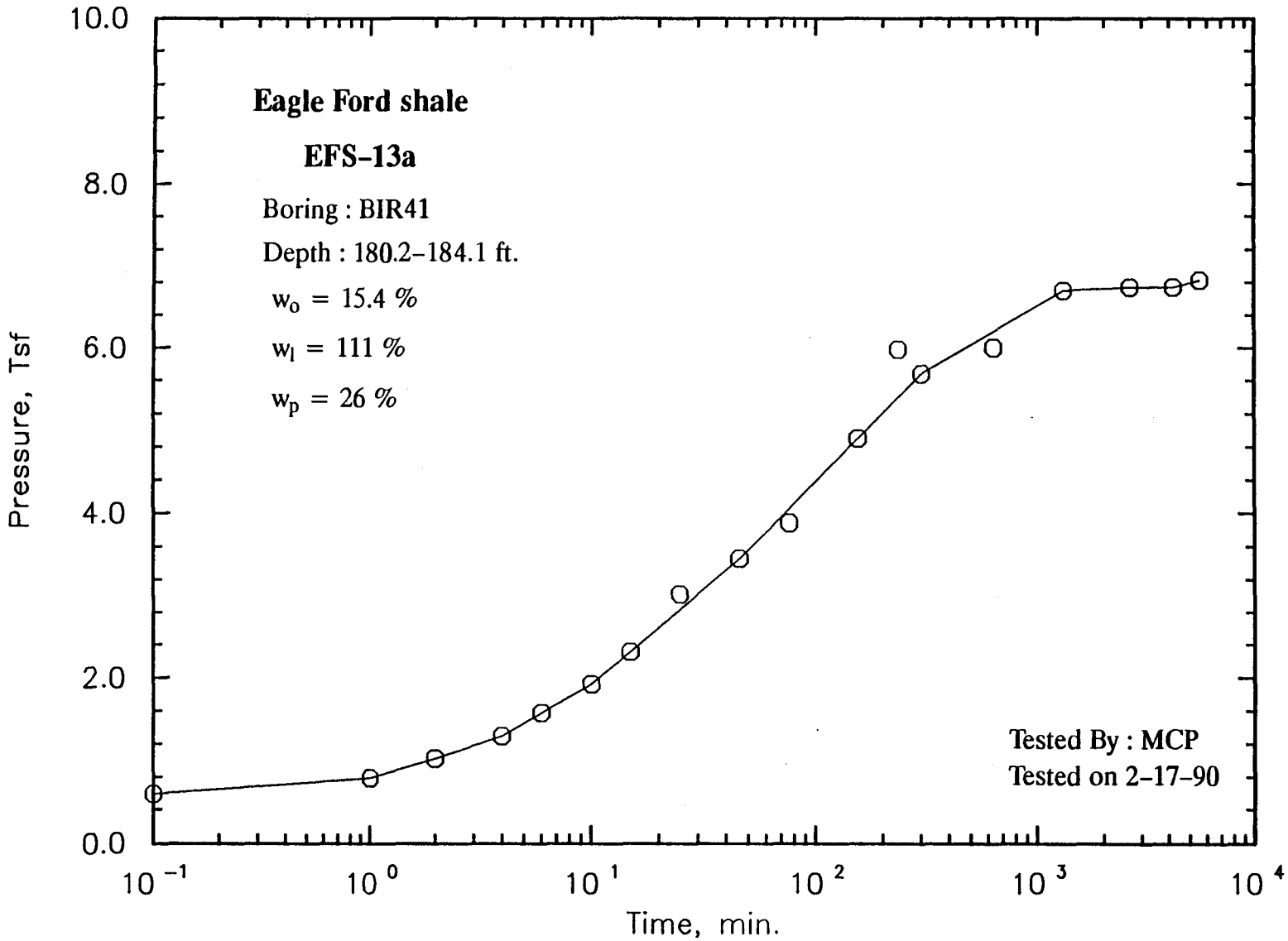


Fig. C5 Time–Rate of Swelling Pressure Development

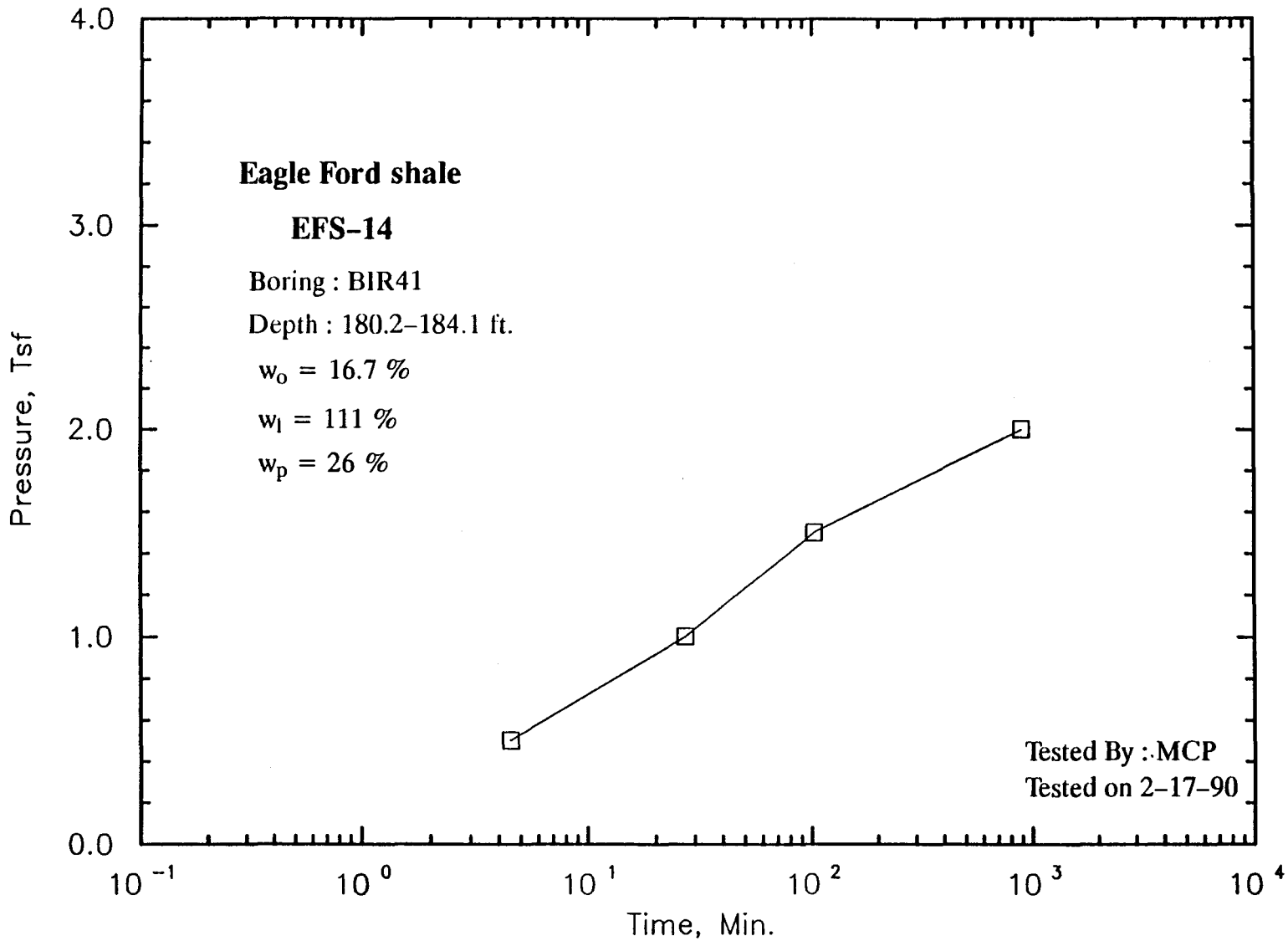


Fig. C6a Time–Rate of Swelling Pressure Development

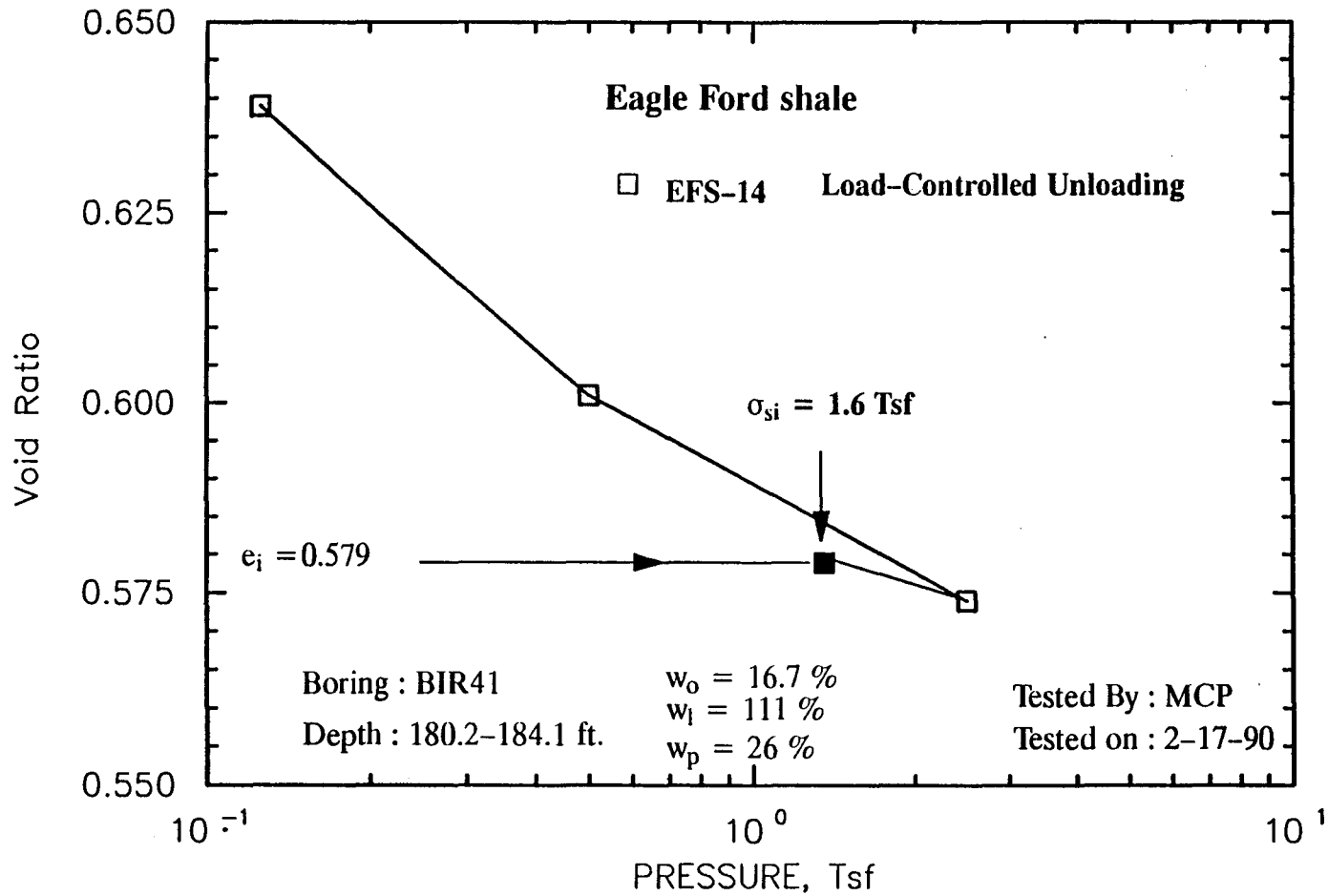


Fig. C6b Void Ratio – Log Pressure Relationship

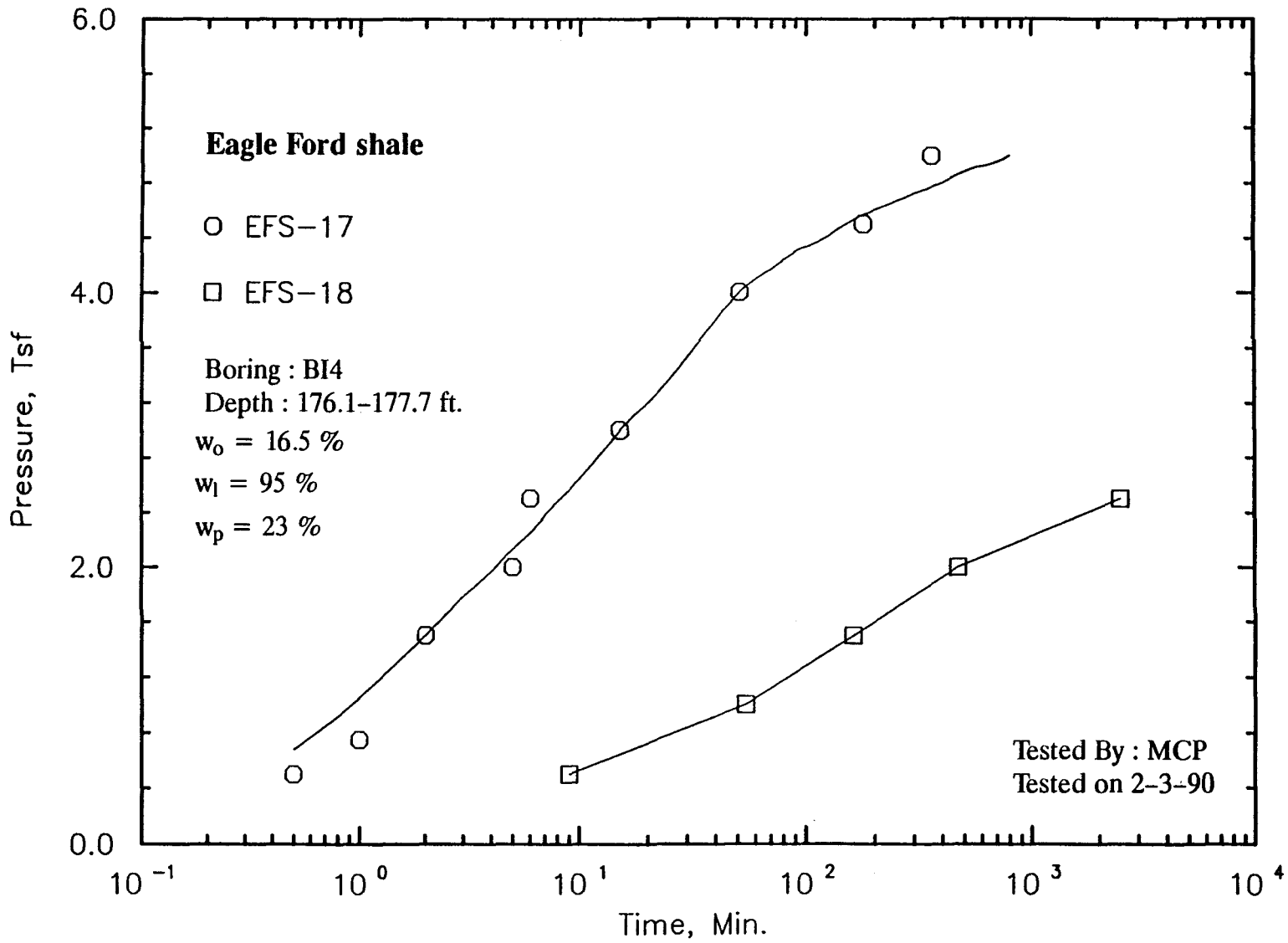


Fig. C7a Time-Rate of Swelling Pressure Development

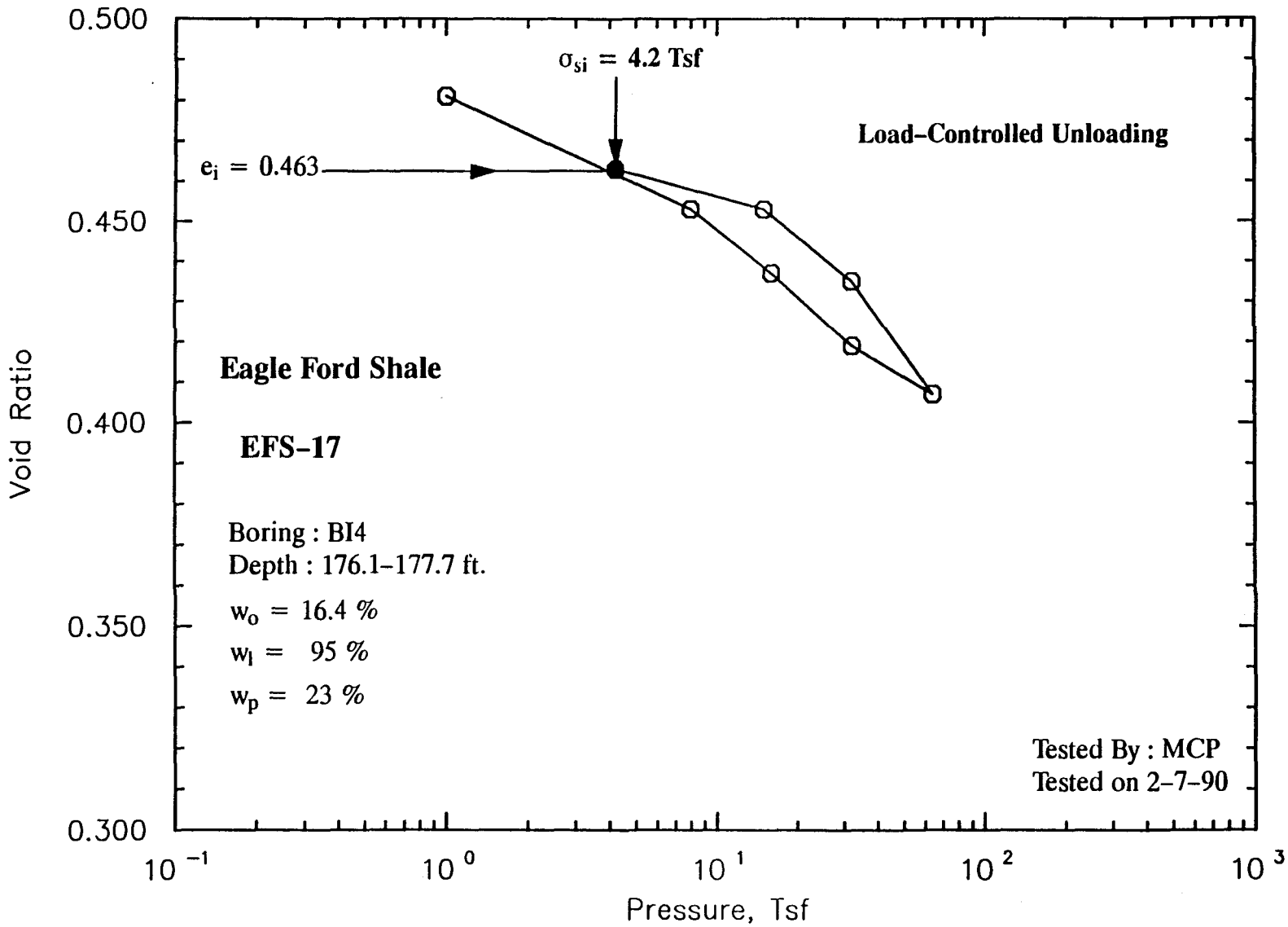


Fig. C7b Void Ratio - Log Pressure Relationship

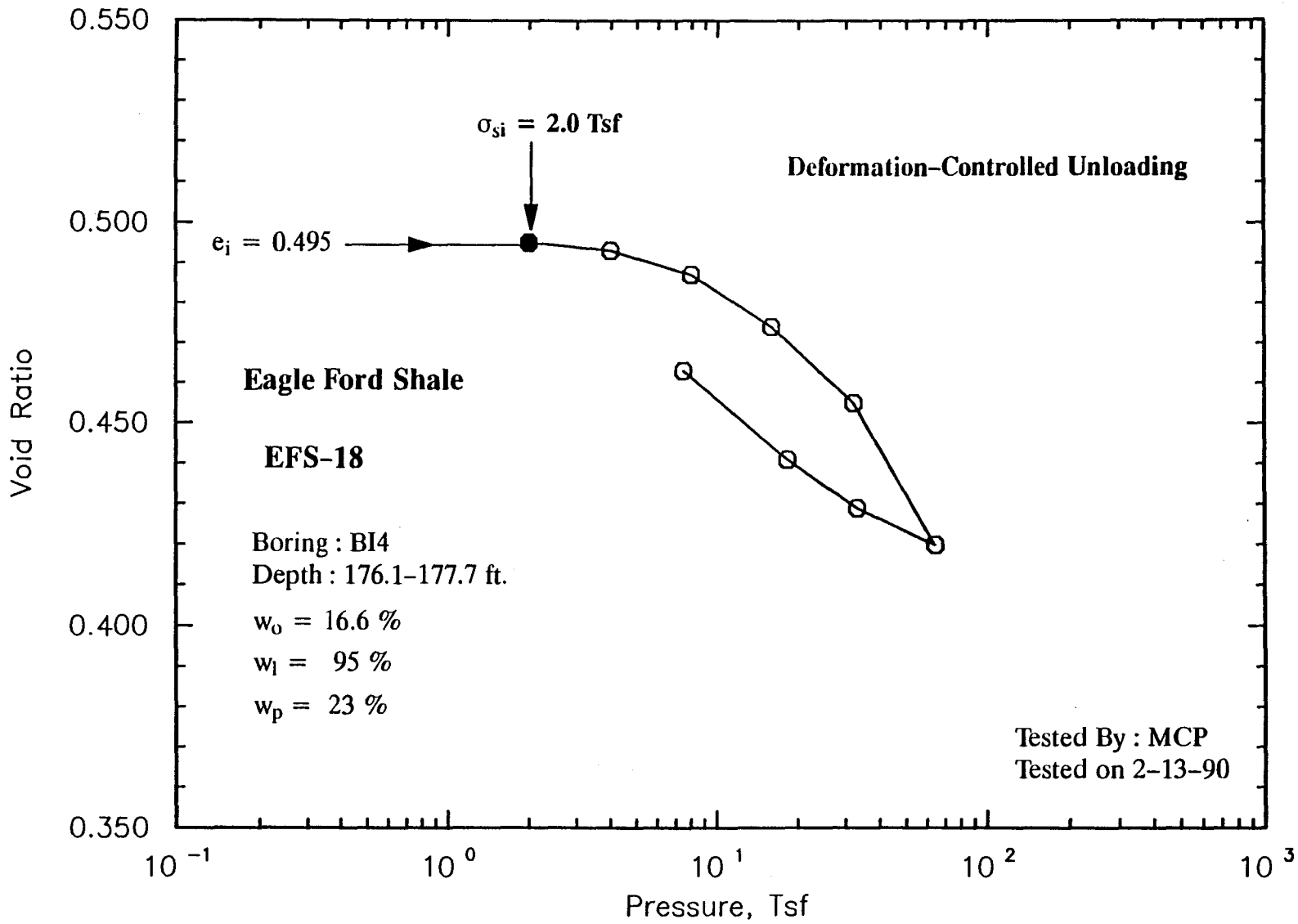


Fig. C7c Void Ratio - Log Pressure Relationship

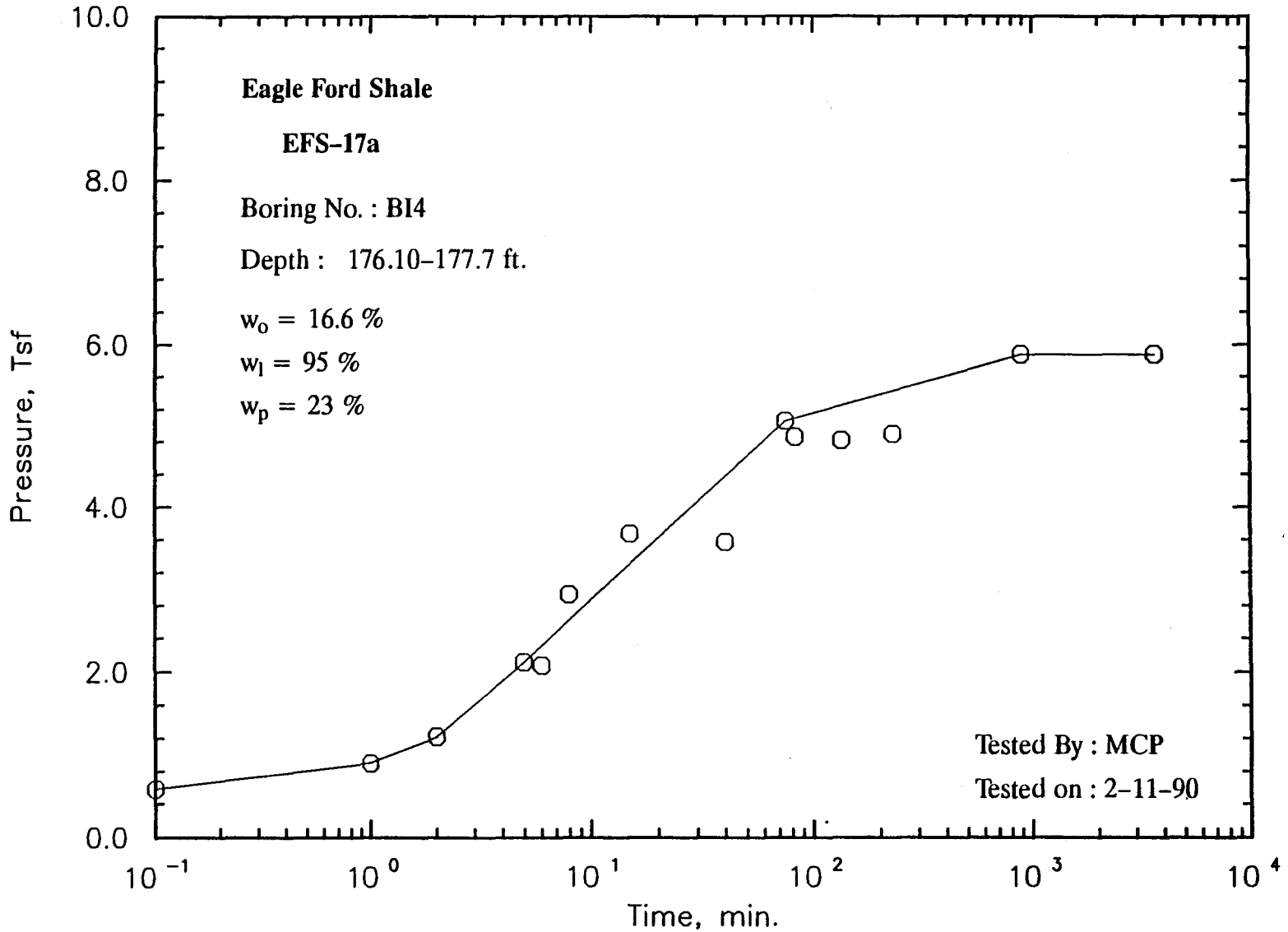


Fig. C8 Time-Rate of Swelling Pressure Development

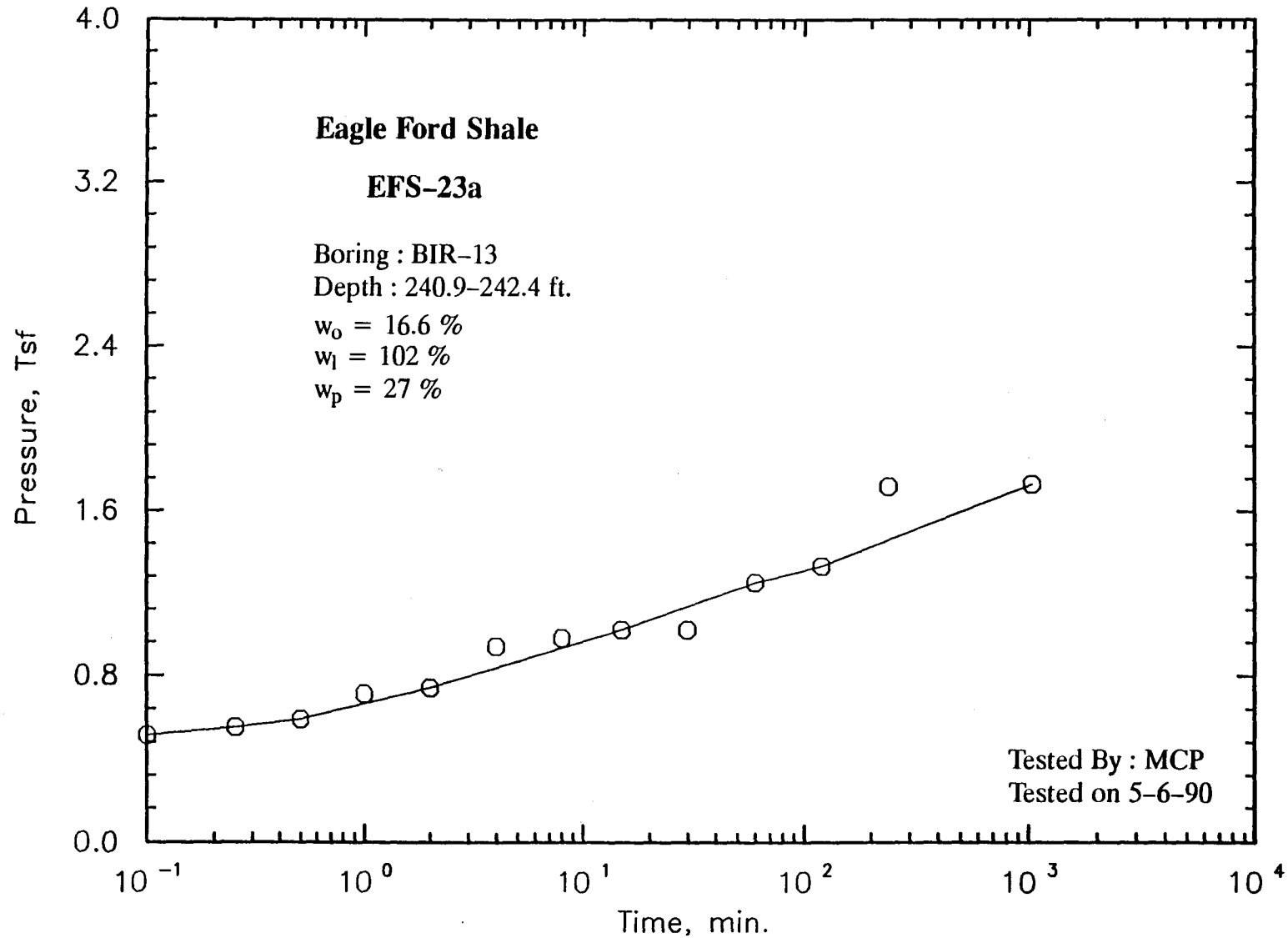


Fig. C9 Time-Rate of Swelling Pressure Development

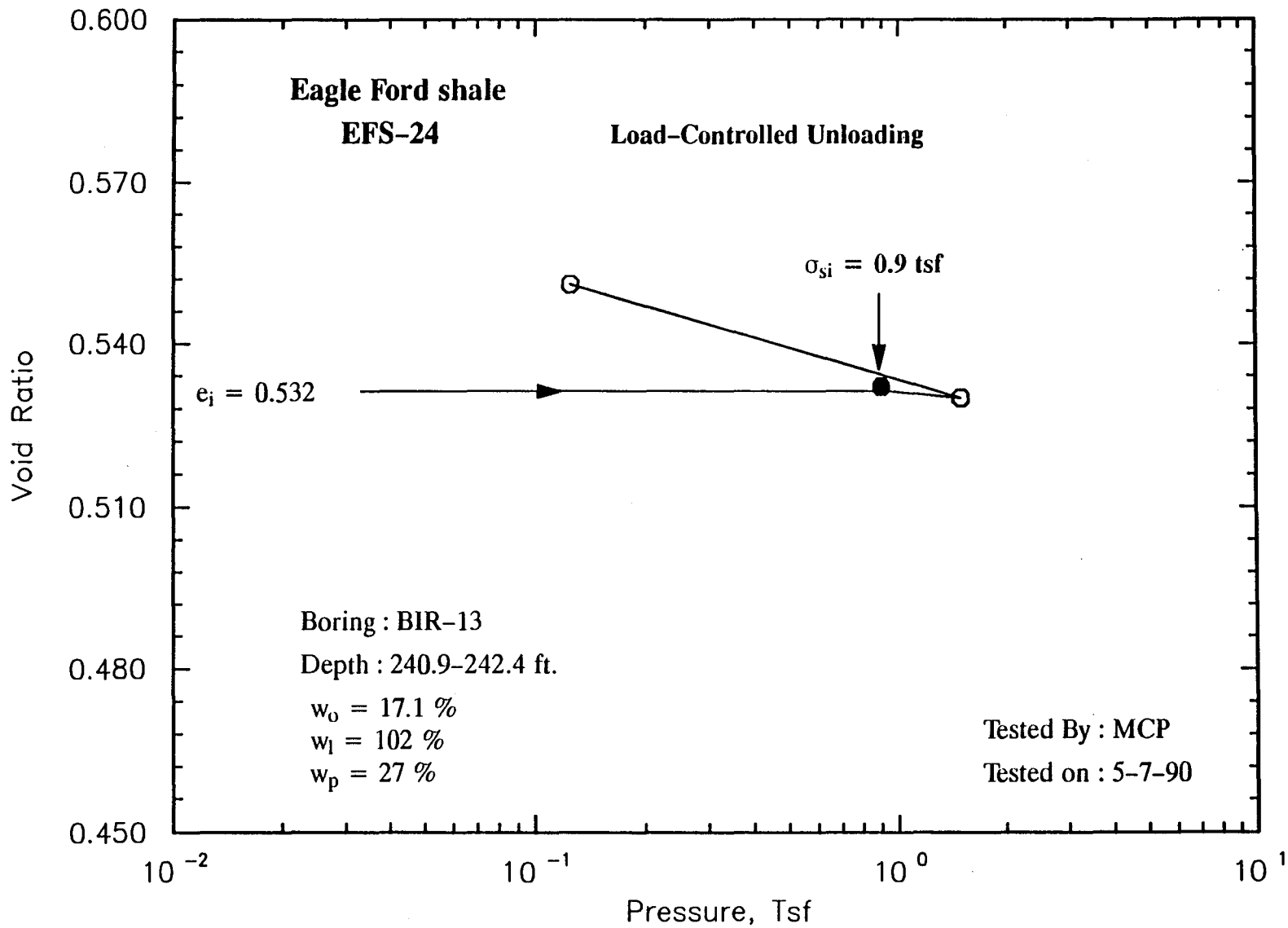


Fig. C10 Void Ratio - Log Pressure Relationship

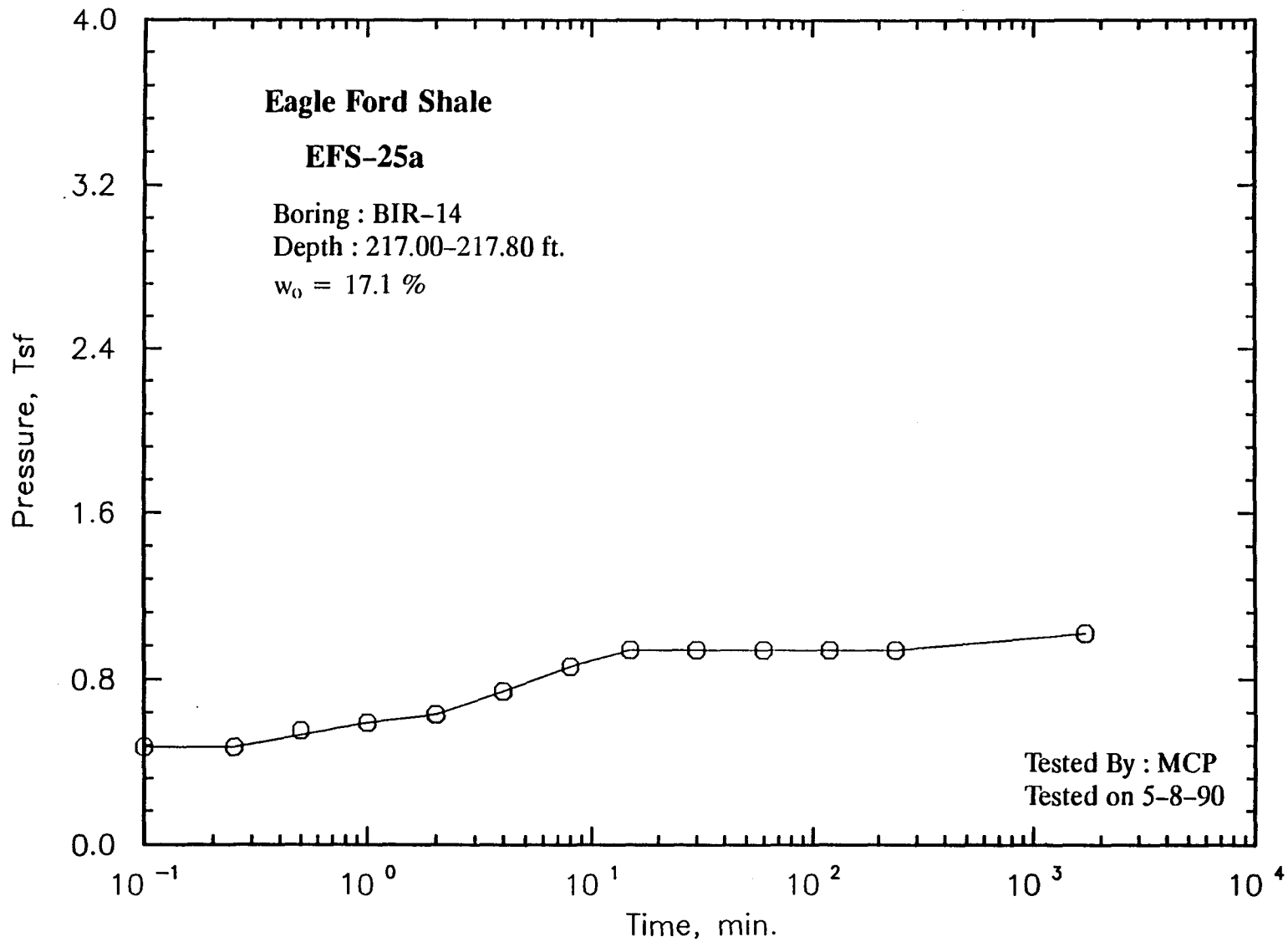


Fig. C11 Time-Rate of Swelling Pressure Development

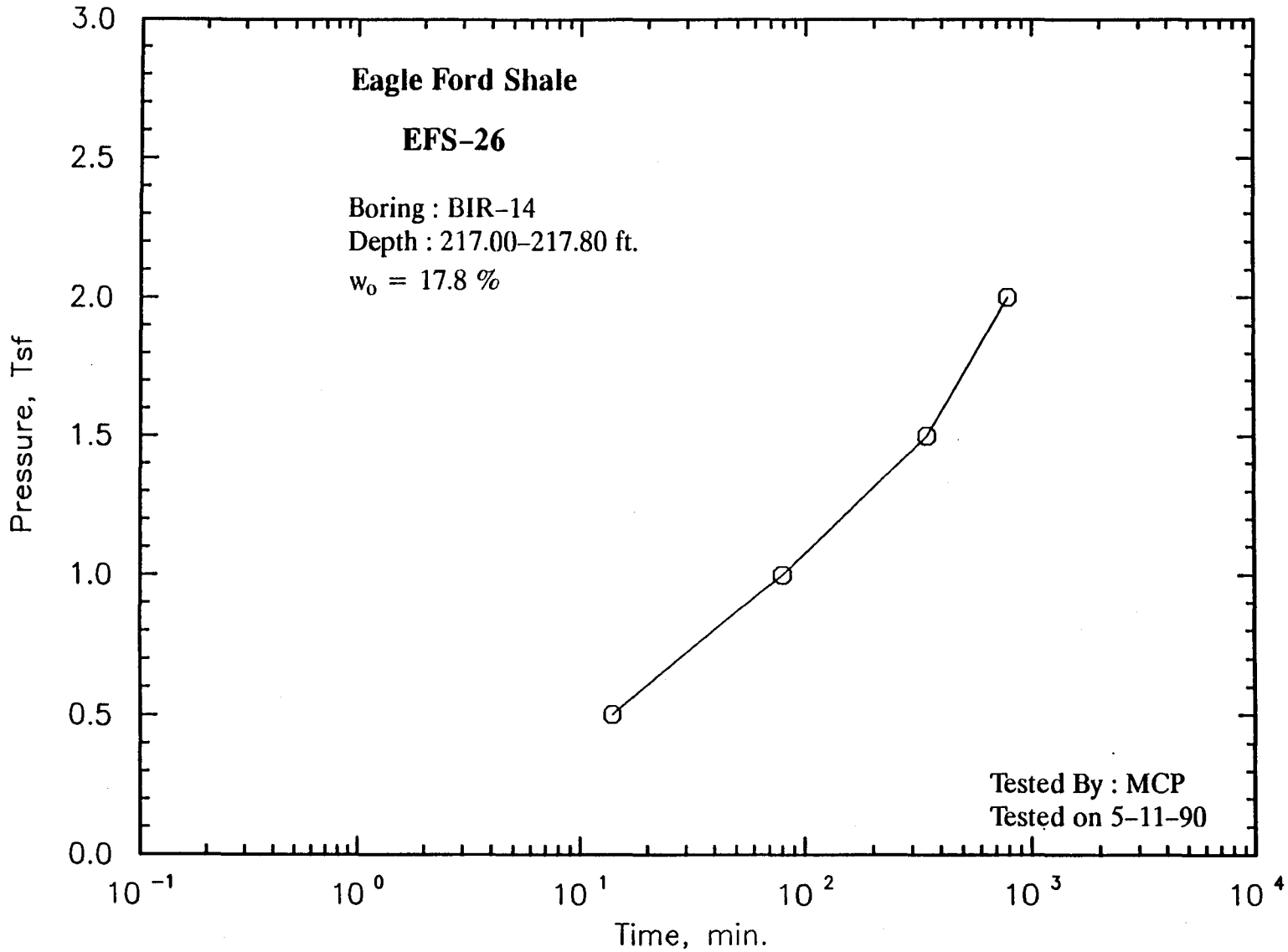


Fig. C12a Time-Rate of Swelling Pressure Development

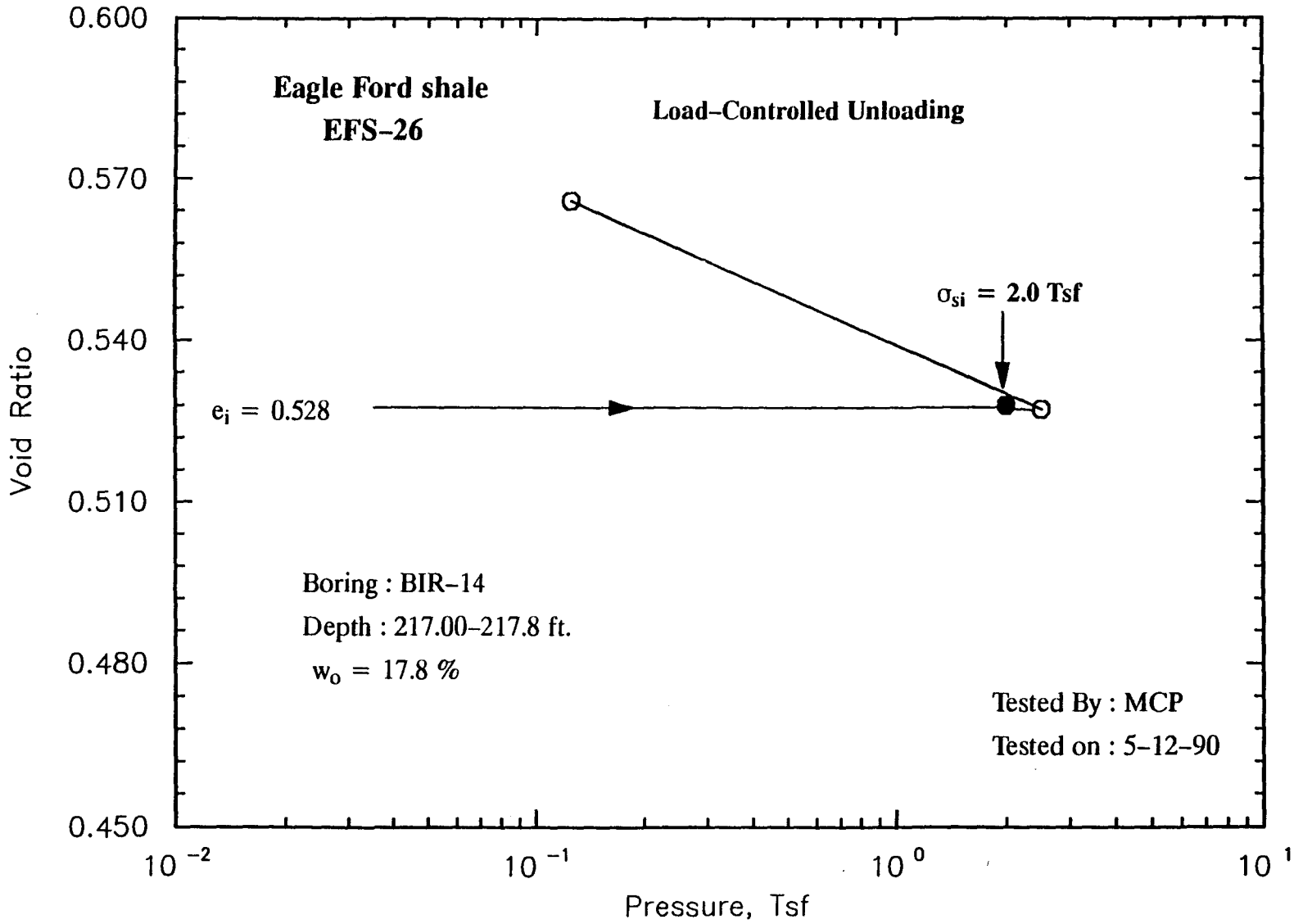


Fig. C12b Void Ratio – Log Pressure Relationship

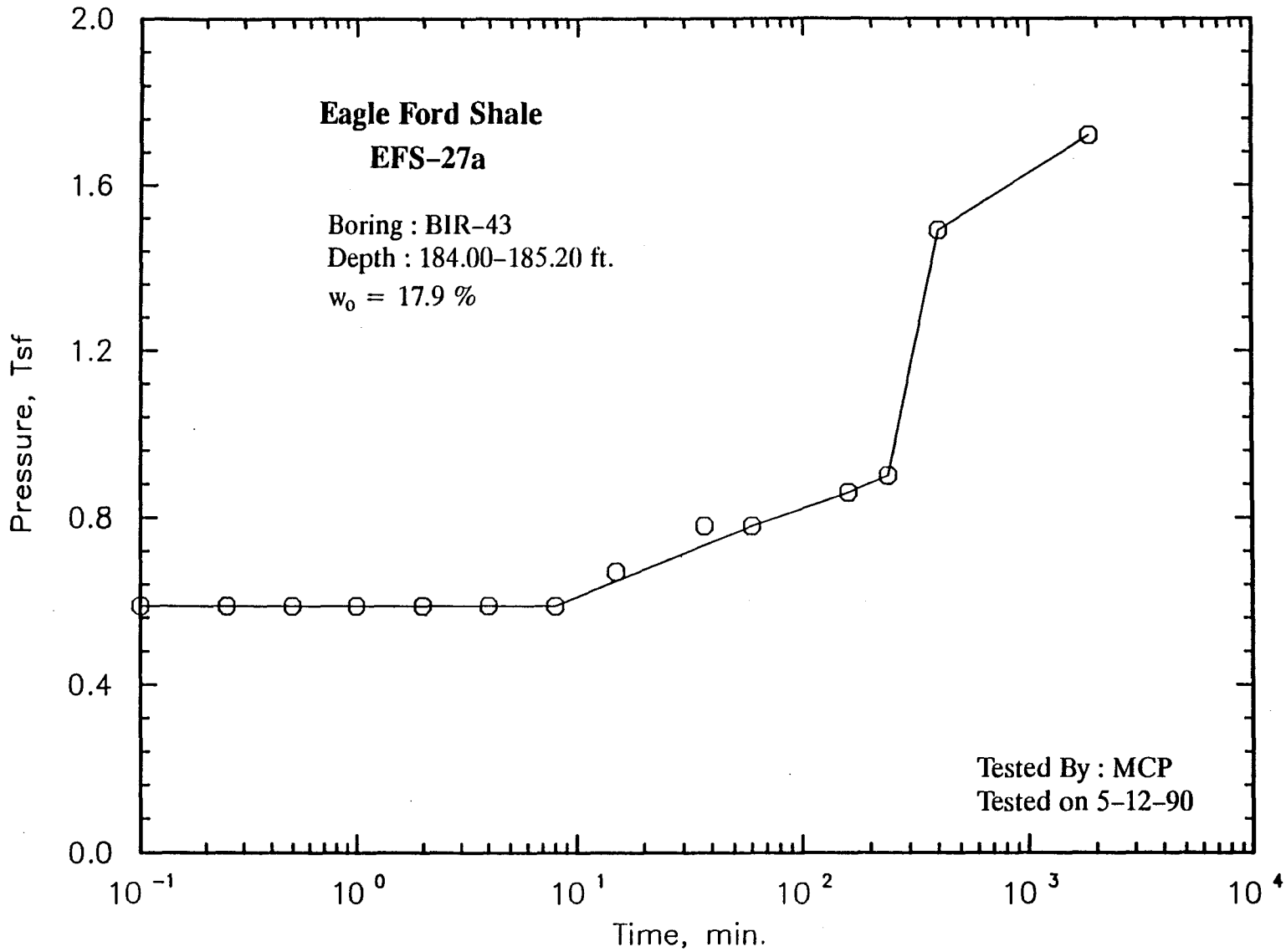


Fig. C13 Time-Rate of Swelling Pressure Development

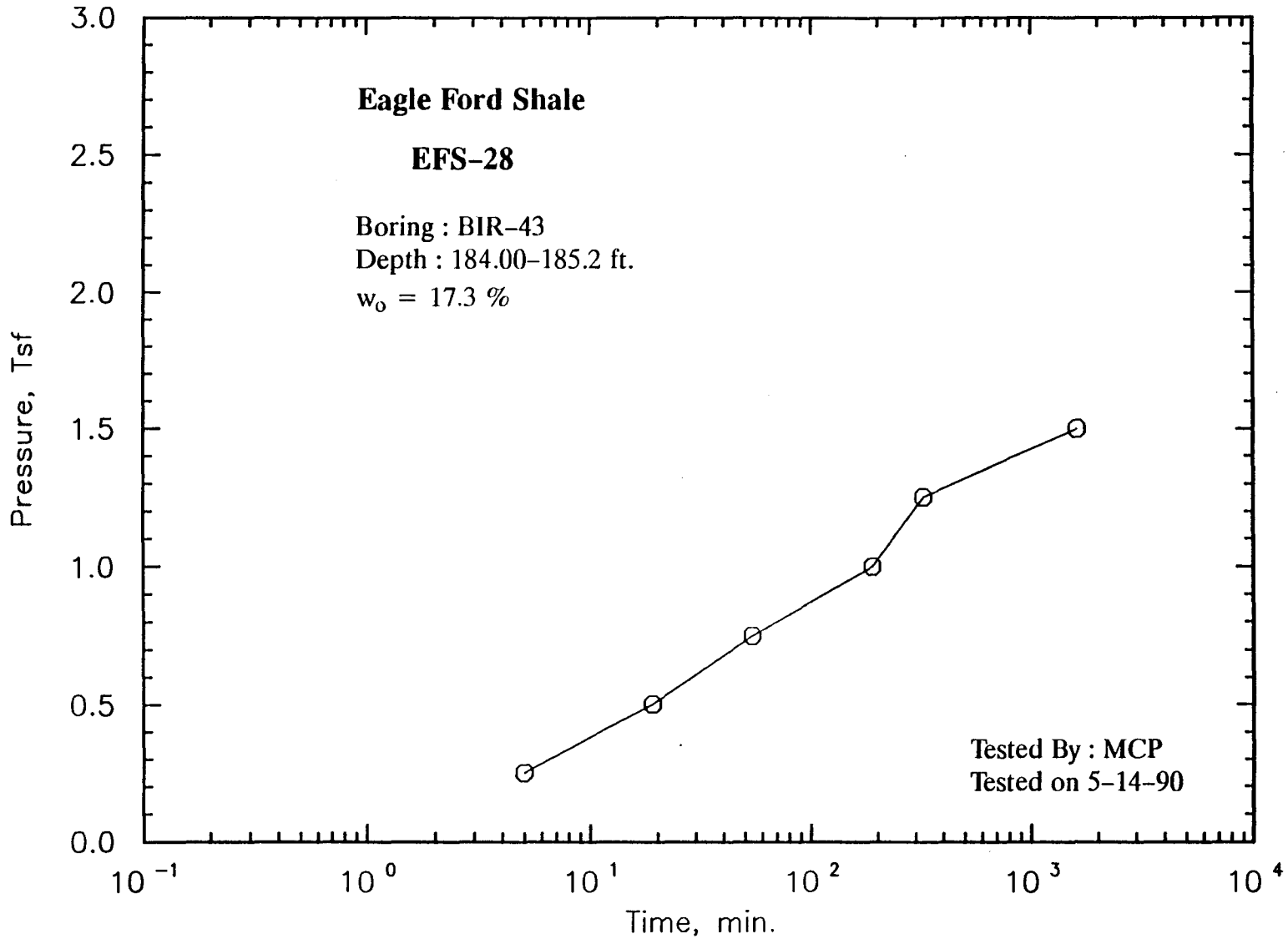


Fig. C14a Time-Rate of Swelling Pressure Development

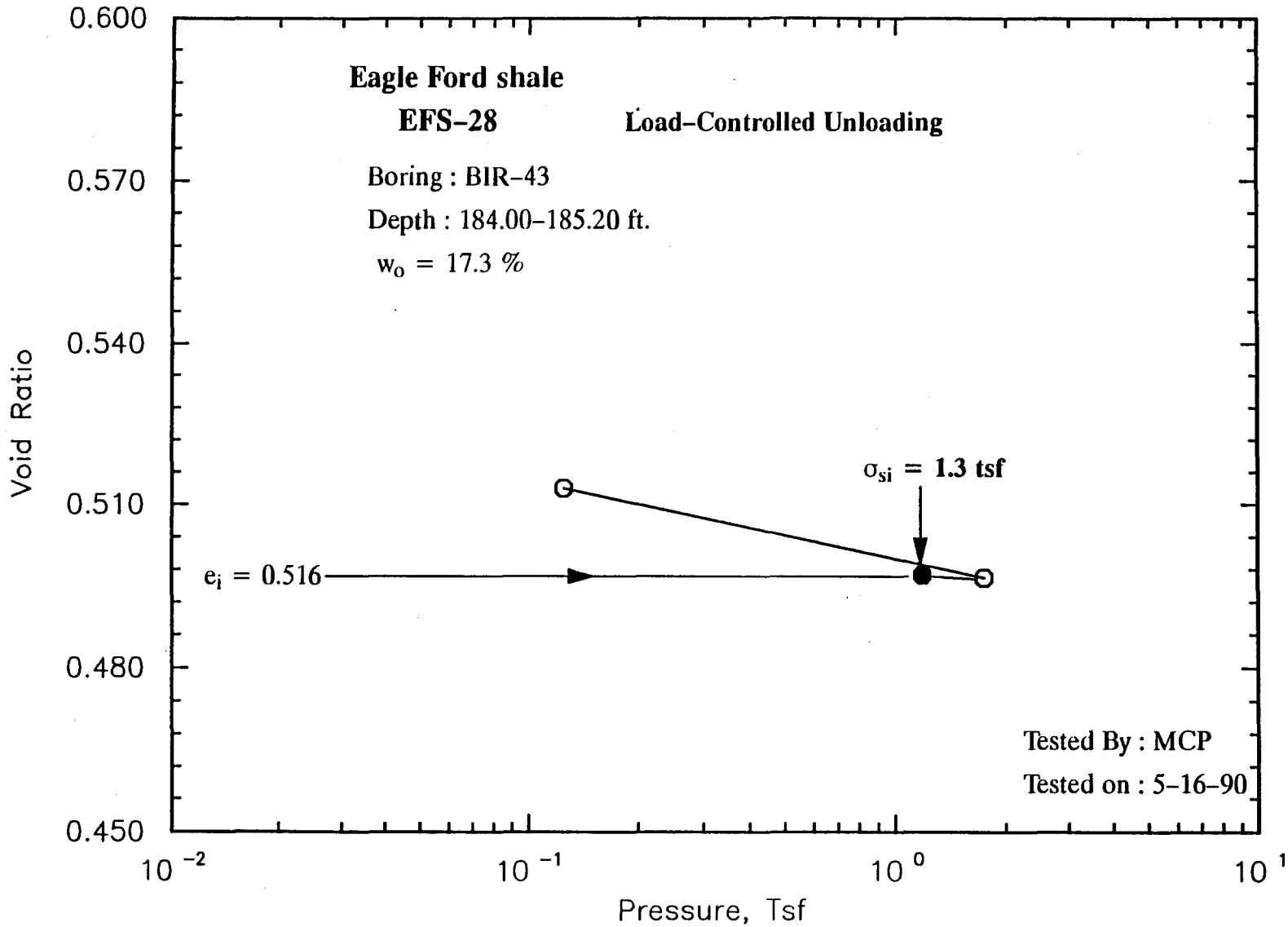


Fig. C14b Void Ratio – Log Pressure Relationship

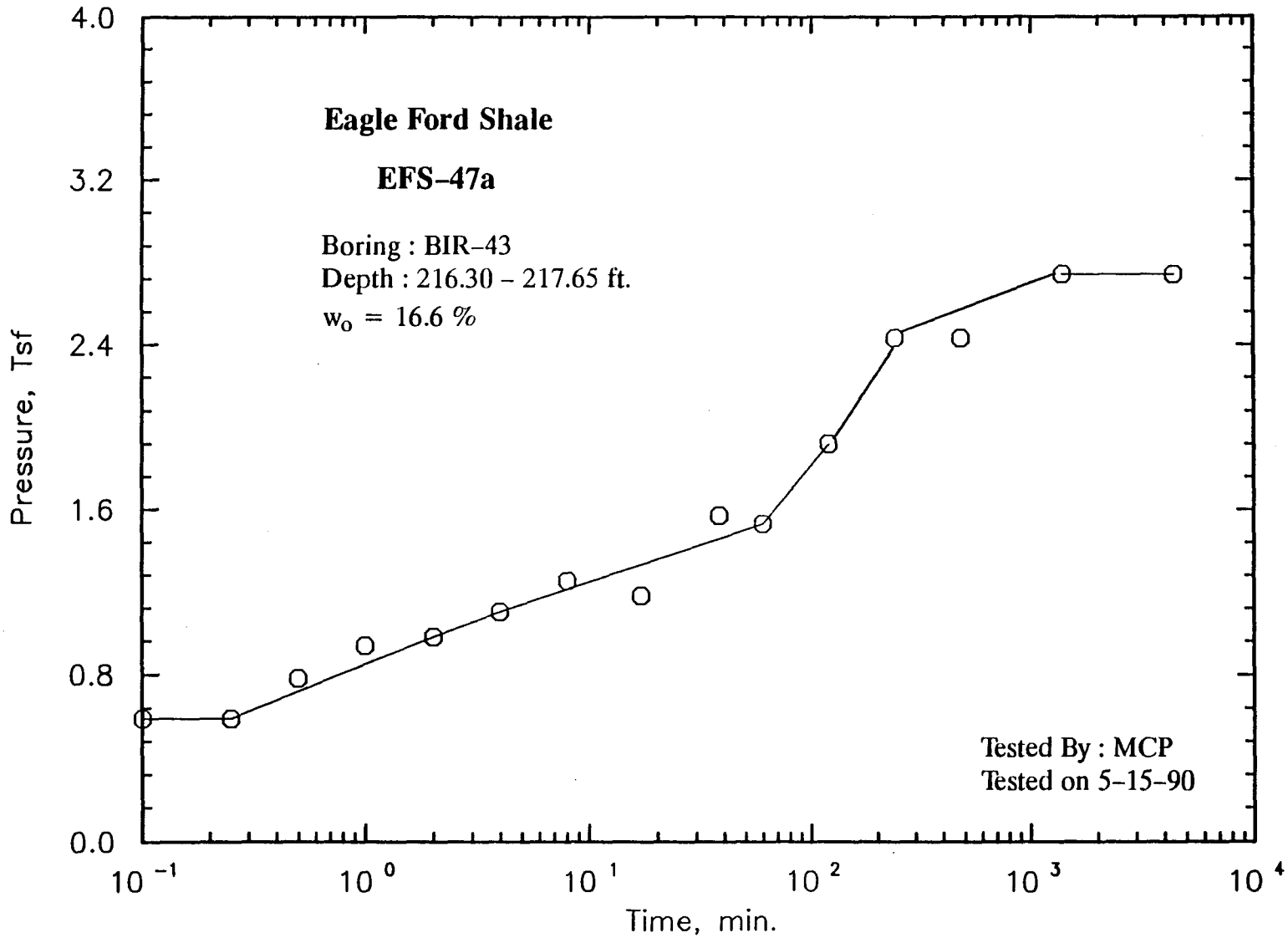


Fig. C15 Time-Rate of Swelling Pressure Development

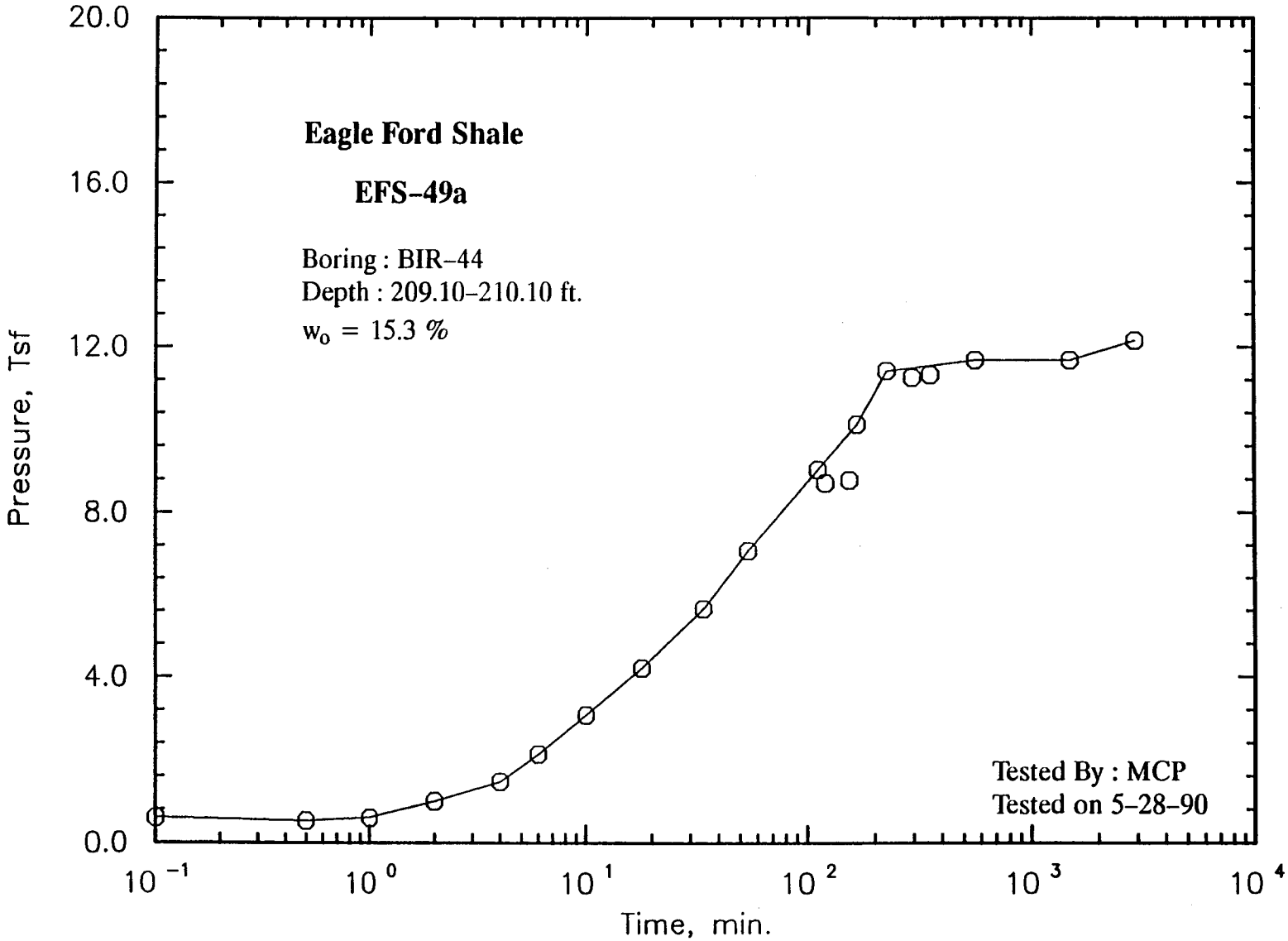


Fig. C16 Time-Rate of Swelling Pressure Development

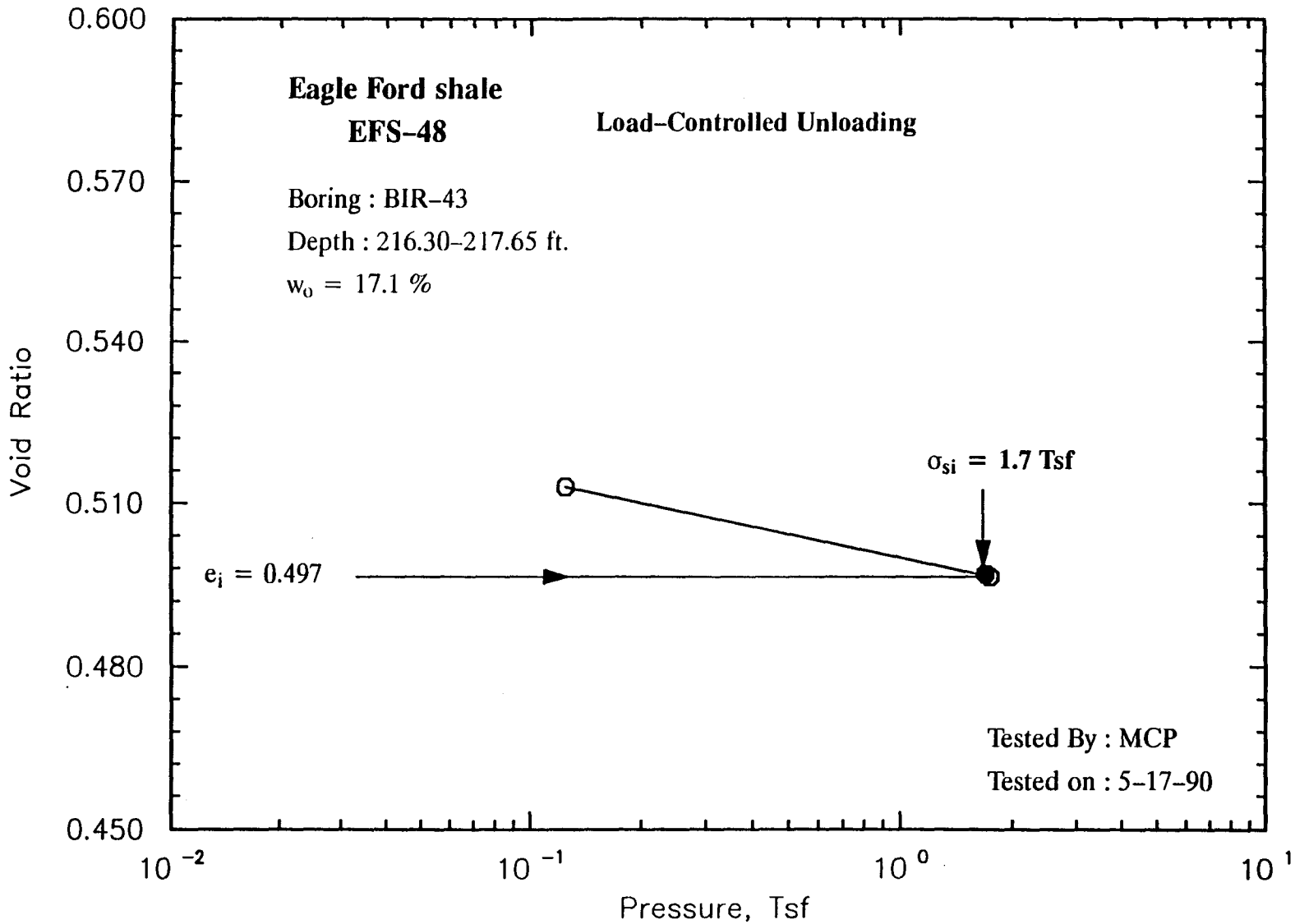


Fig. C17 Void Ratio – Log Pressure Relationship

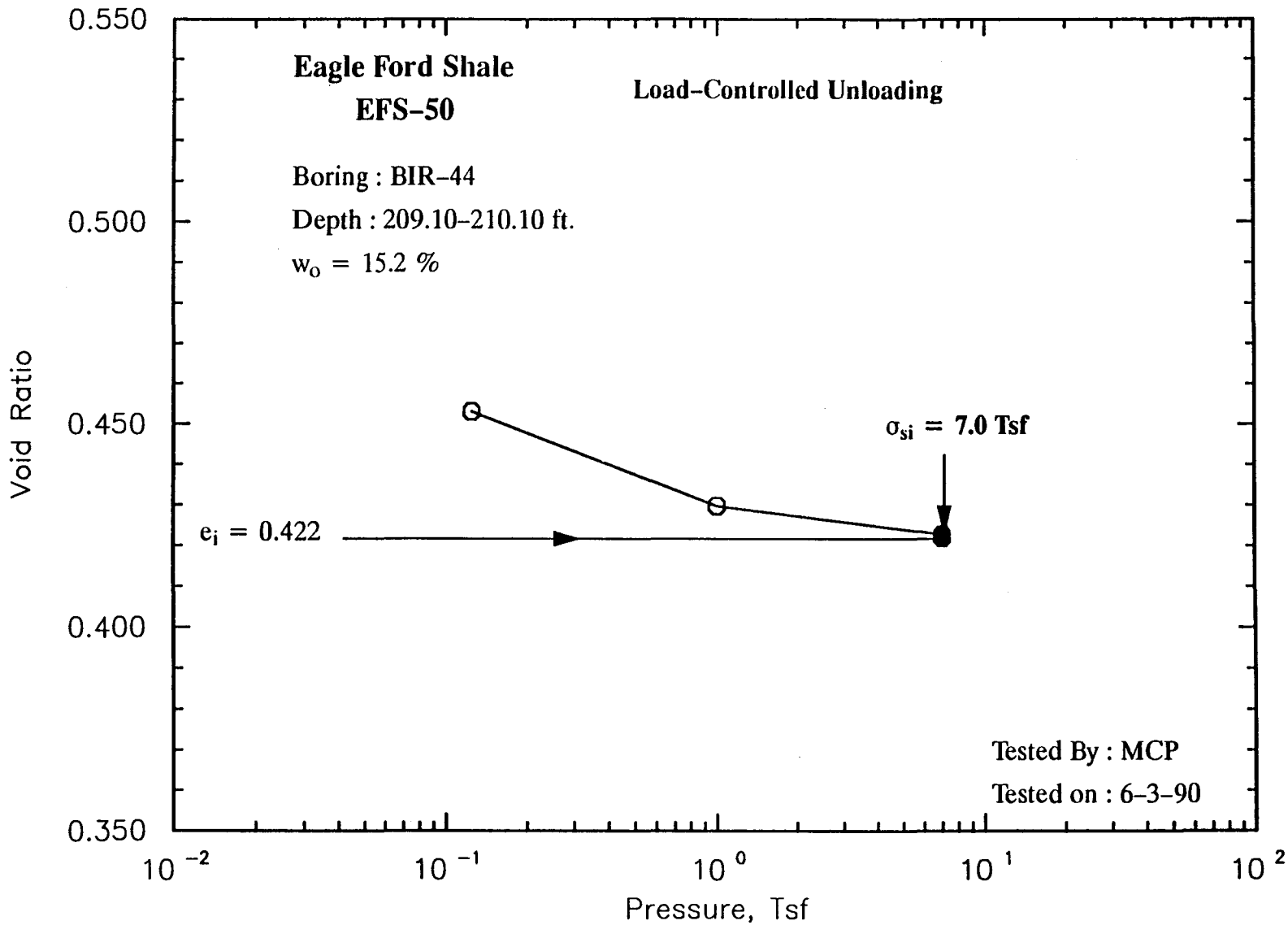


Fig. C18 Void Ratio – Log Pressure Relationship

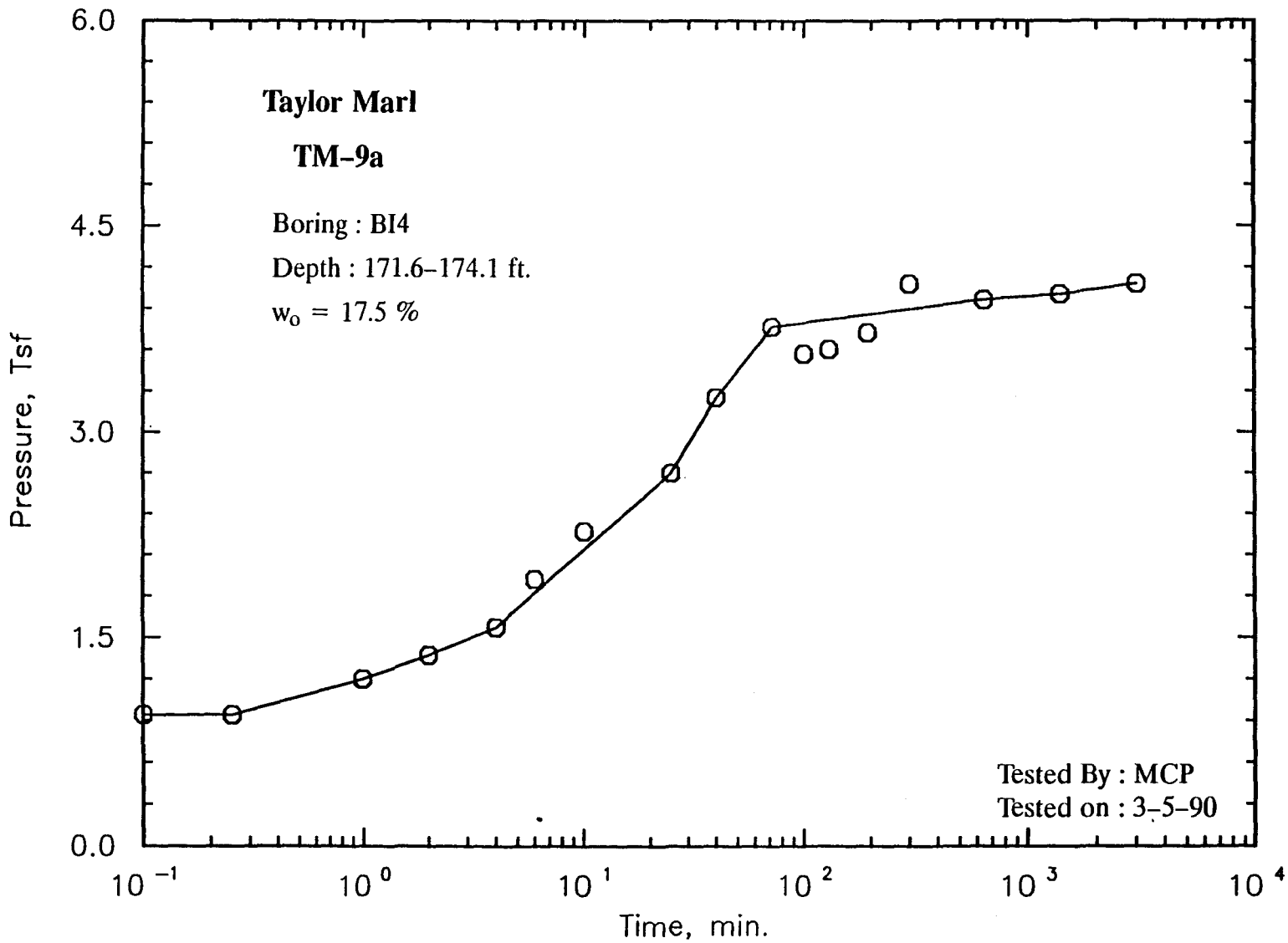


Fig. C19 Time–Rate Of Swelling Pressure Development

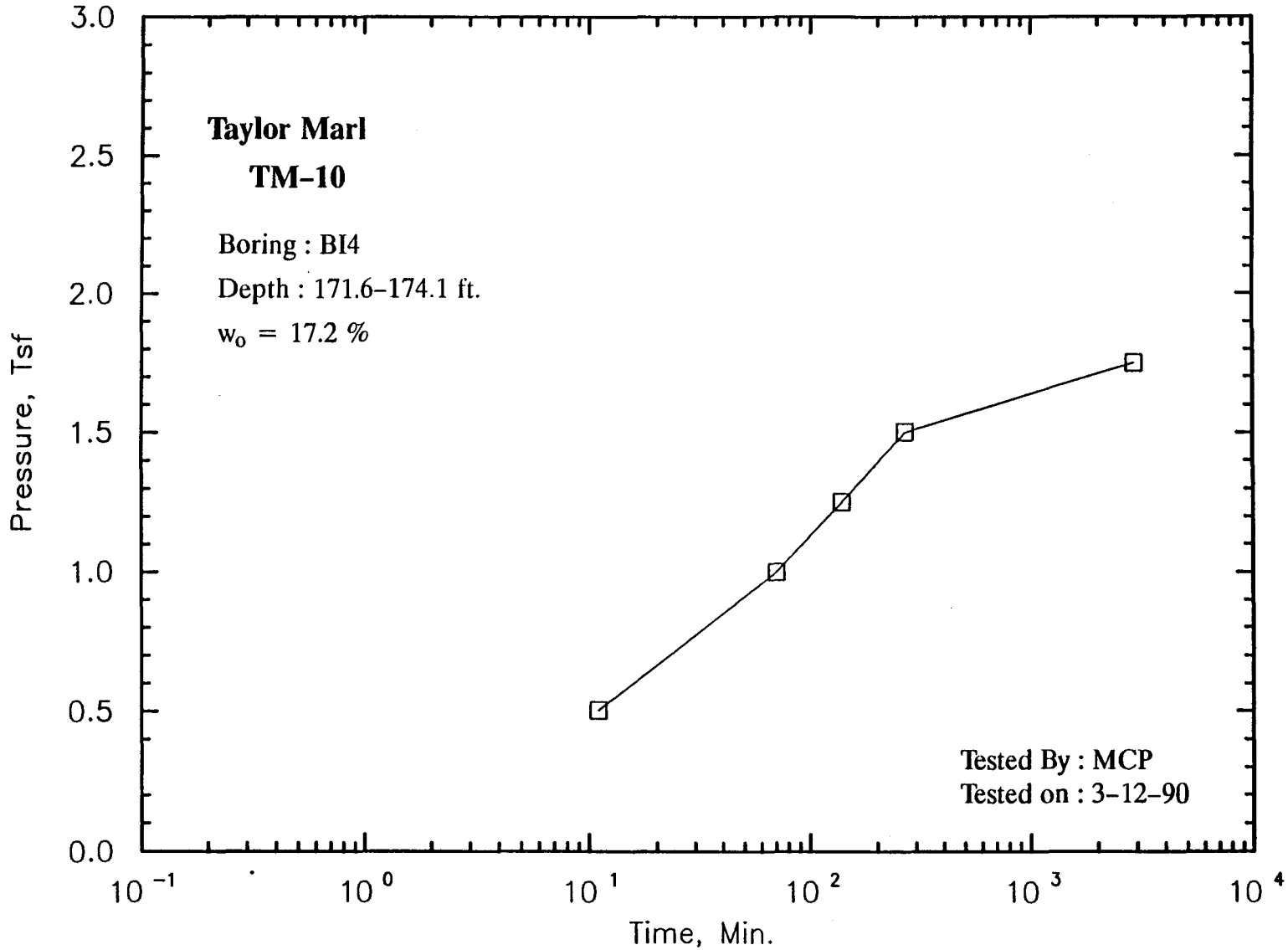


Fig. C20a Time-Rate Of Swelling Pressure Development

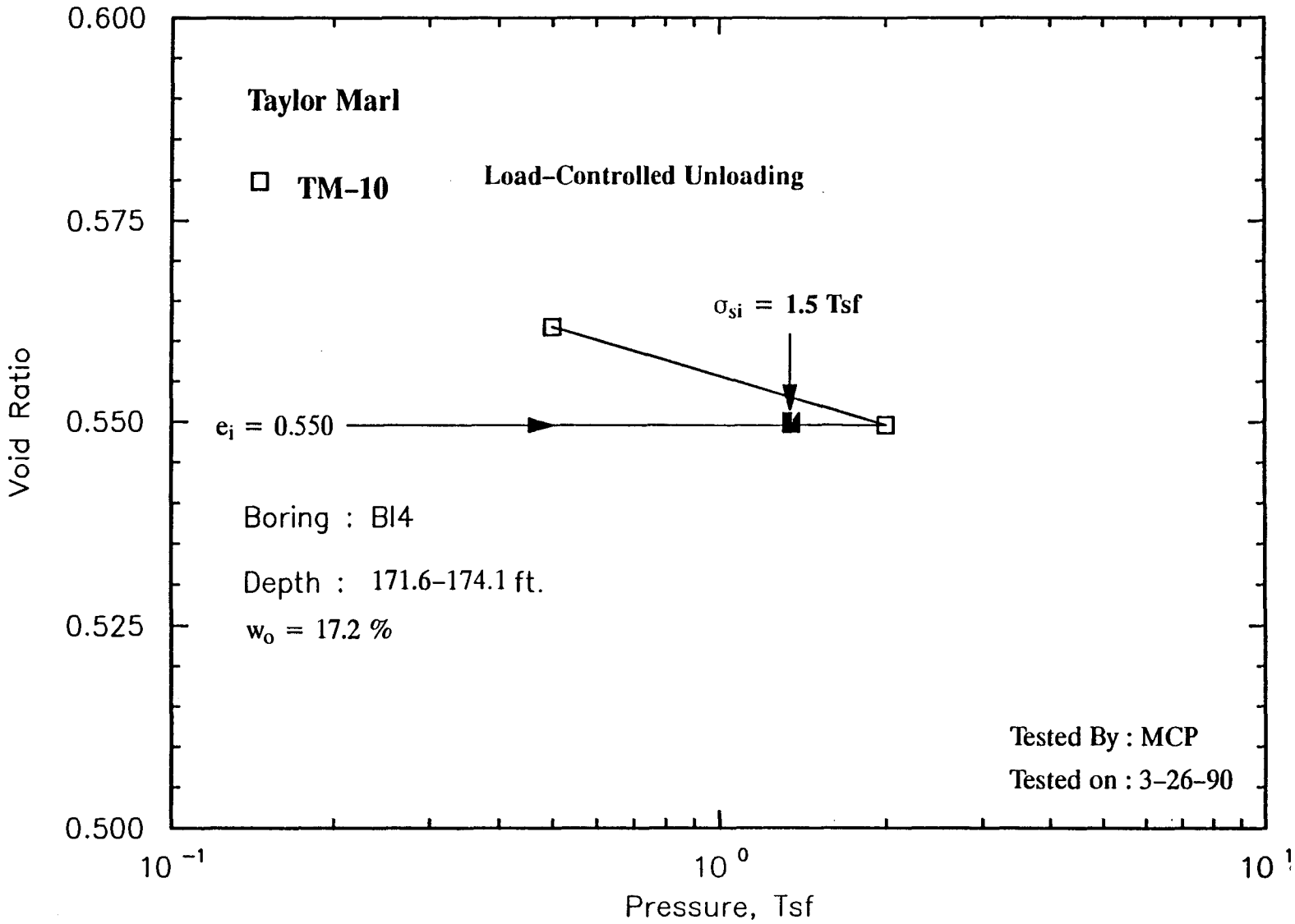


Fig. C20b Void Ratio – Log Pressure Relationship

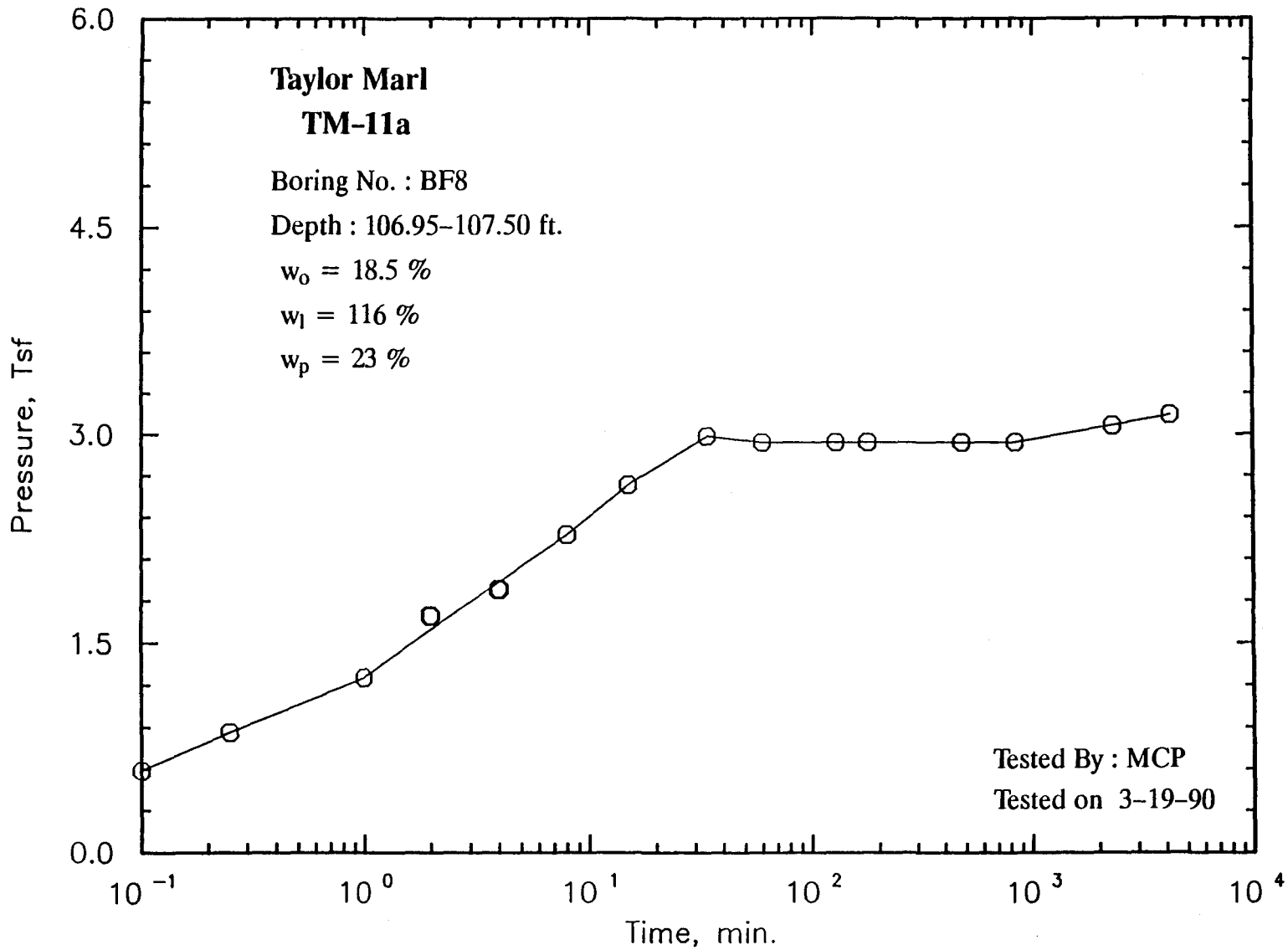


Fig. C21 Time–Rate of Swelling Pressure Development

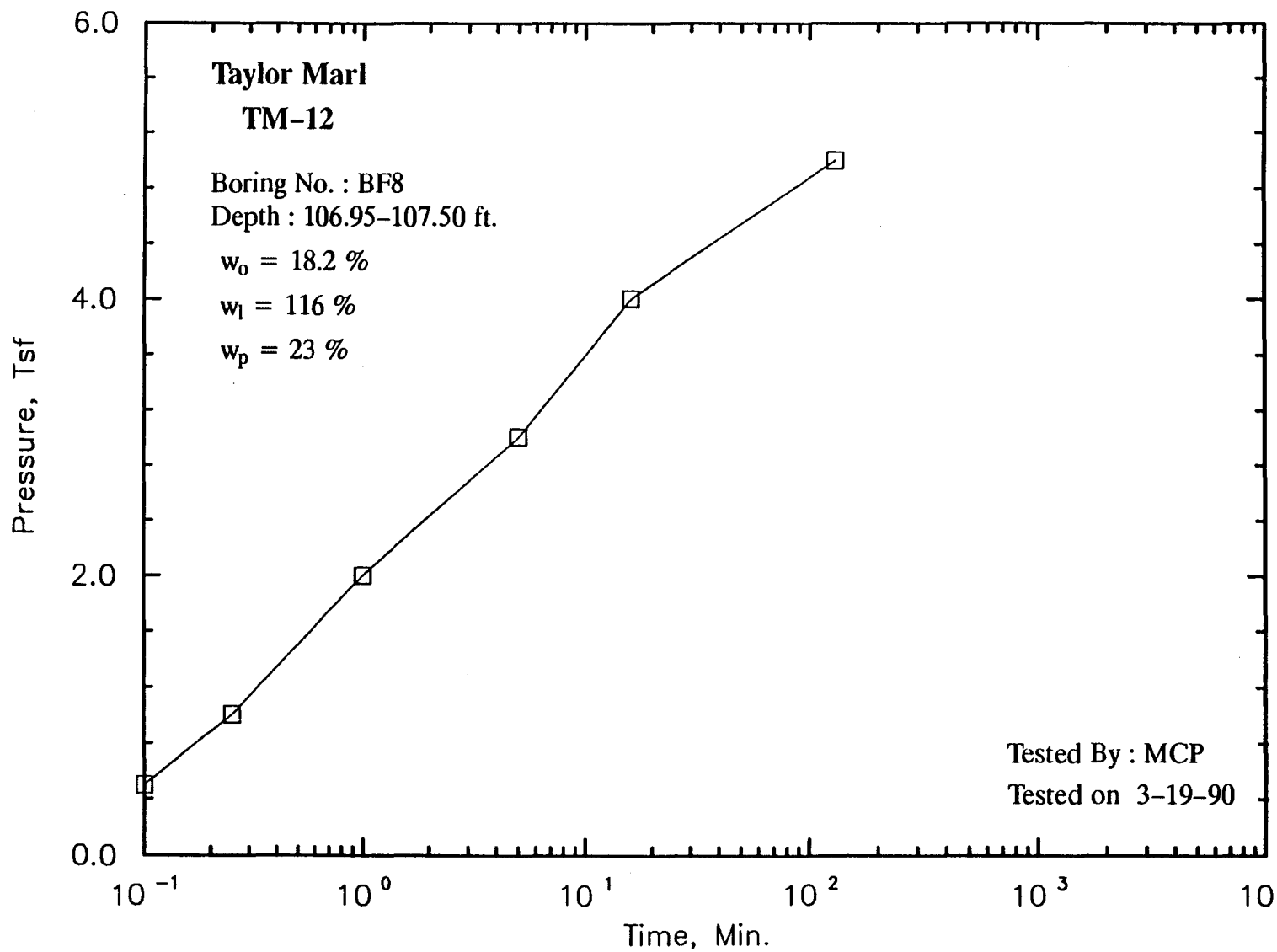


Fig. C22a Time-Rate of Swelling Pressure Development

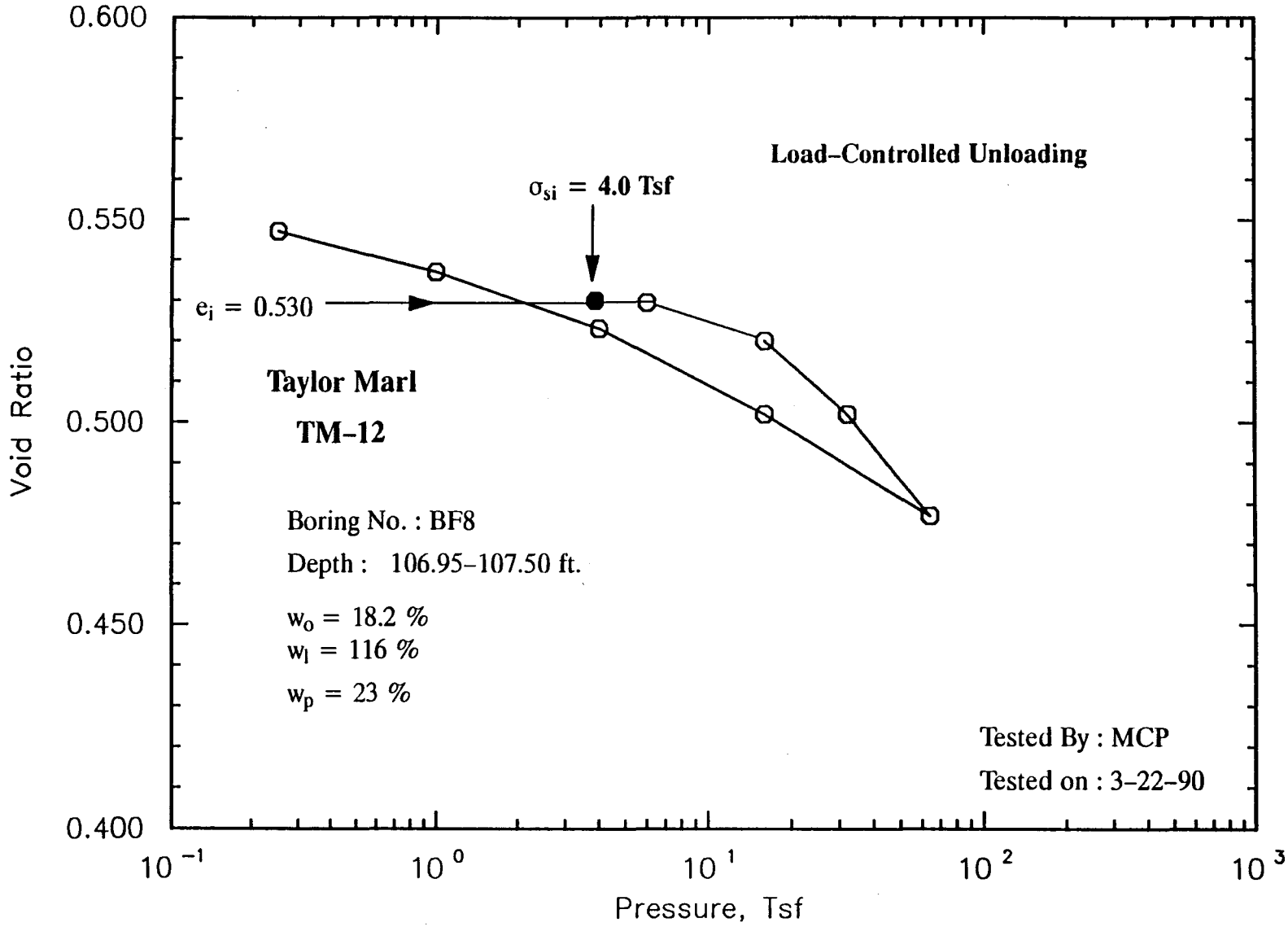


Fig. C22b Void Ratio – Log Pressure Relationship

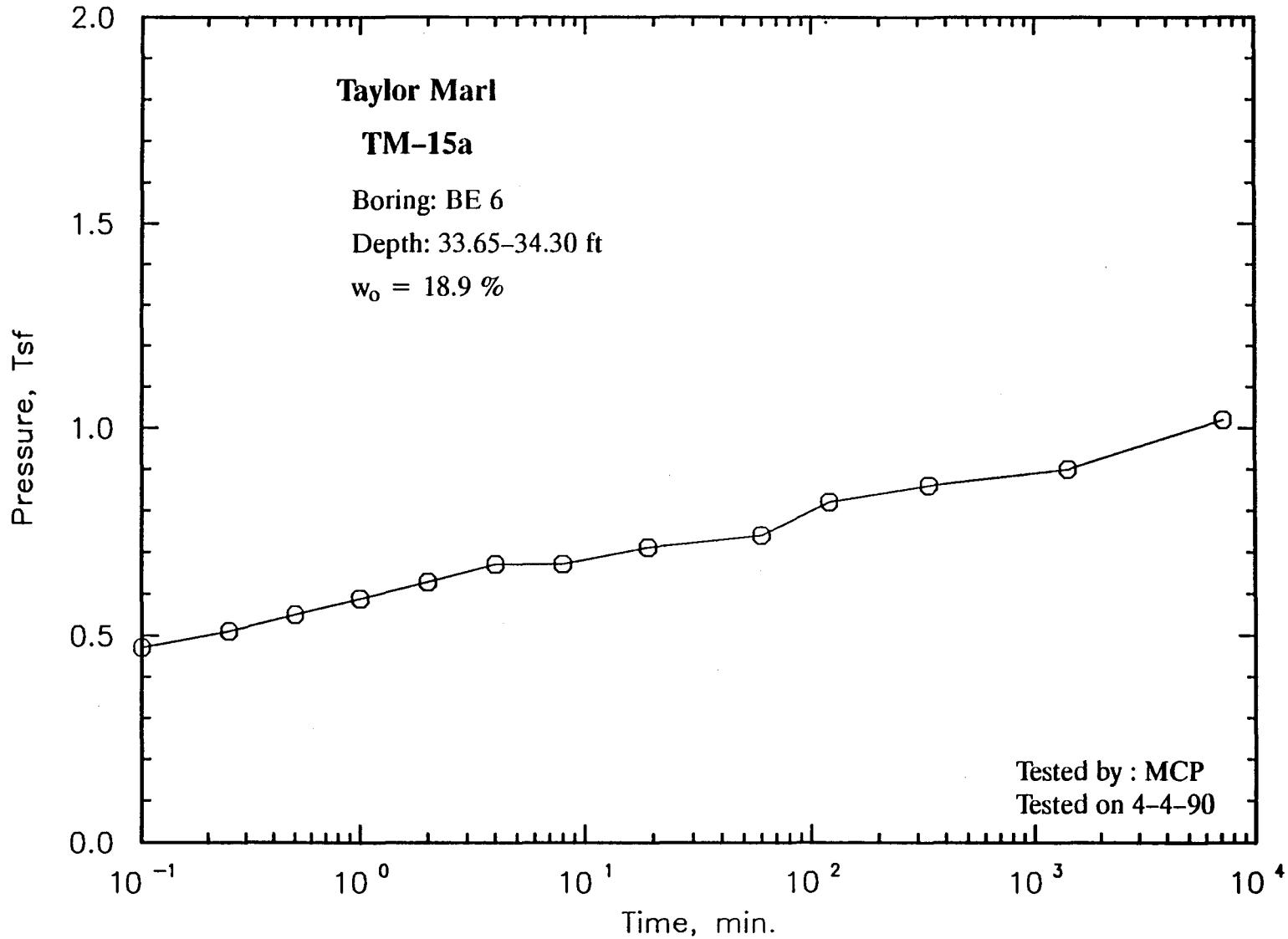


Fig. C23 Time-Rate of Swelling Pressure Development

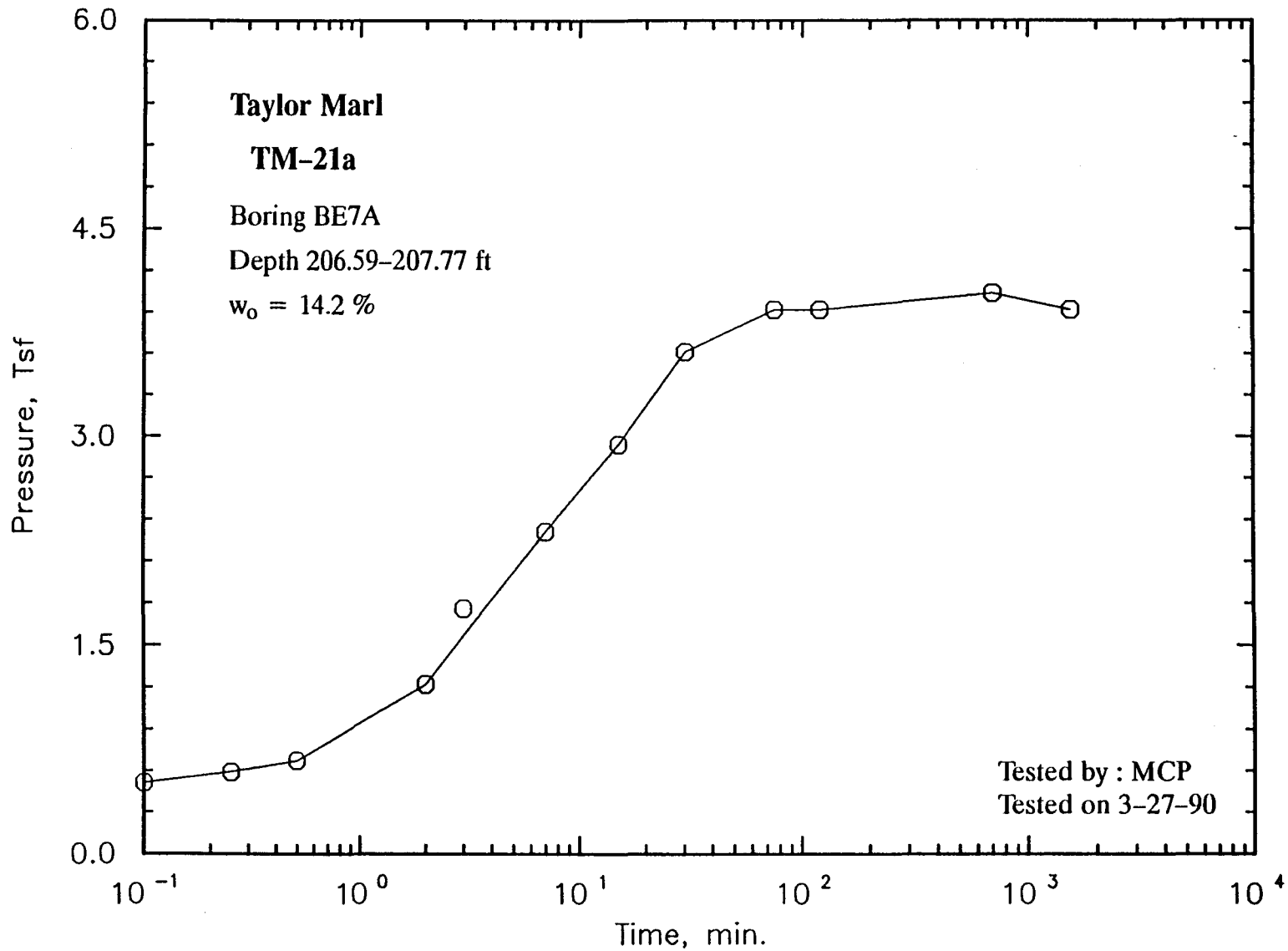


Fig. C24 Time–Rate of Swelling Pressure Development

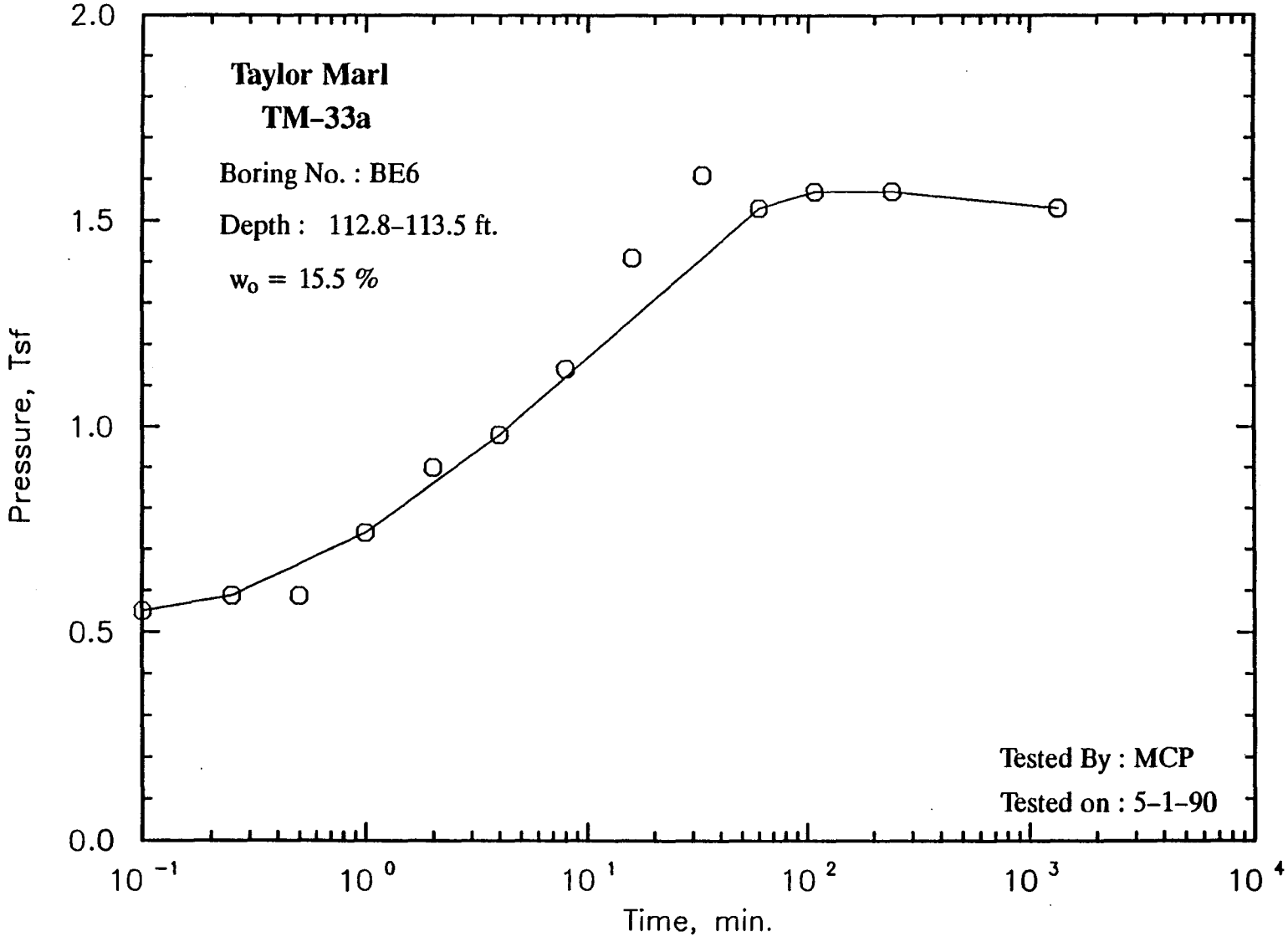


Fig. C25 Time-Rate of Swelling Pressure Development

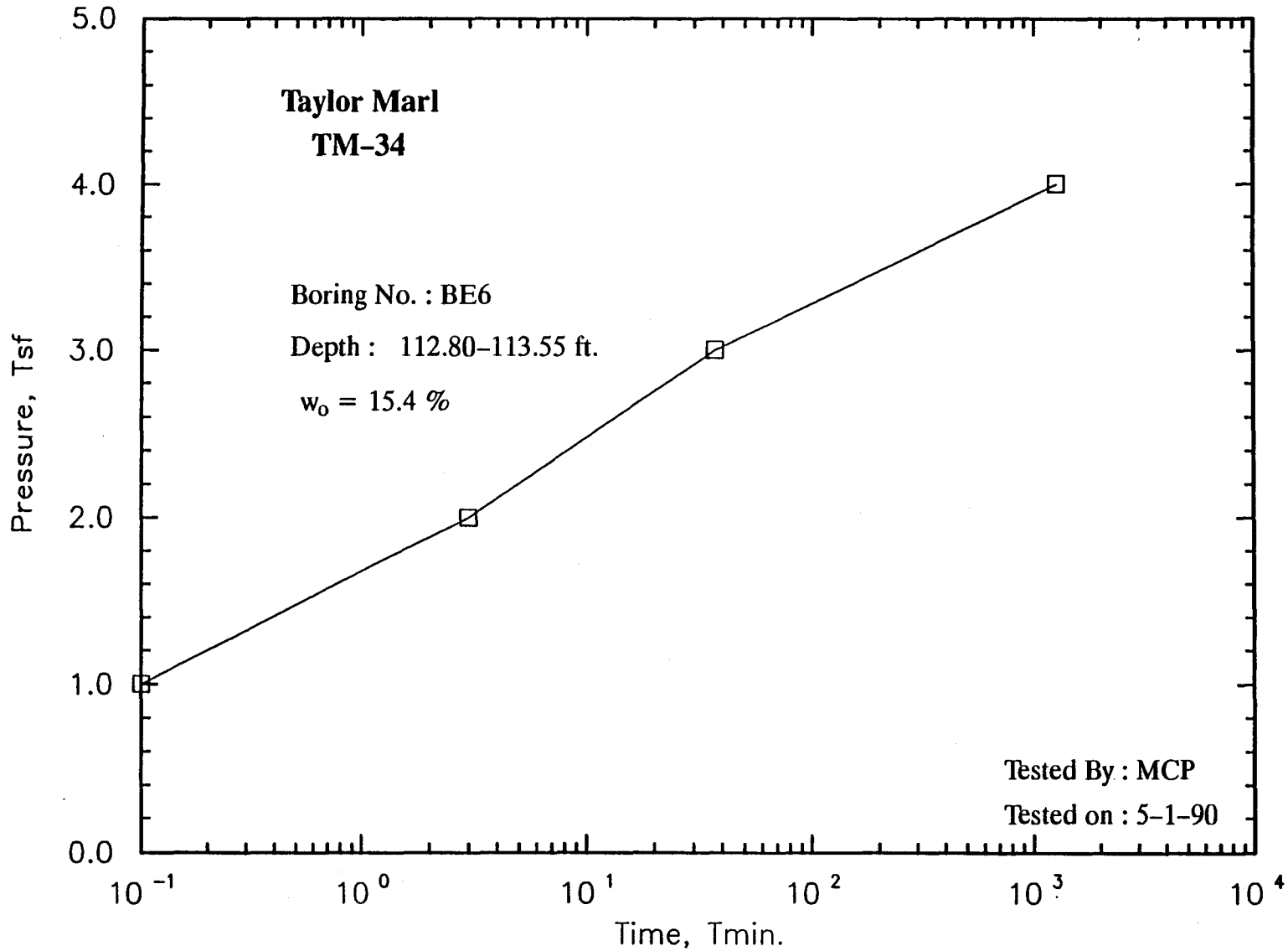


Fig. C26a Time-Rate of Swelling Pressure Development

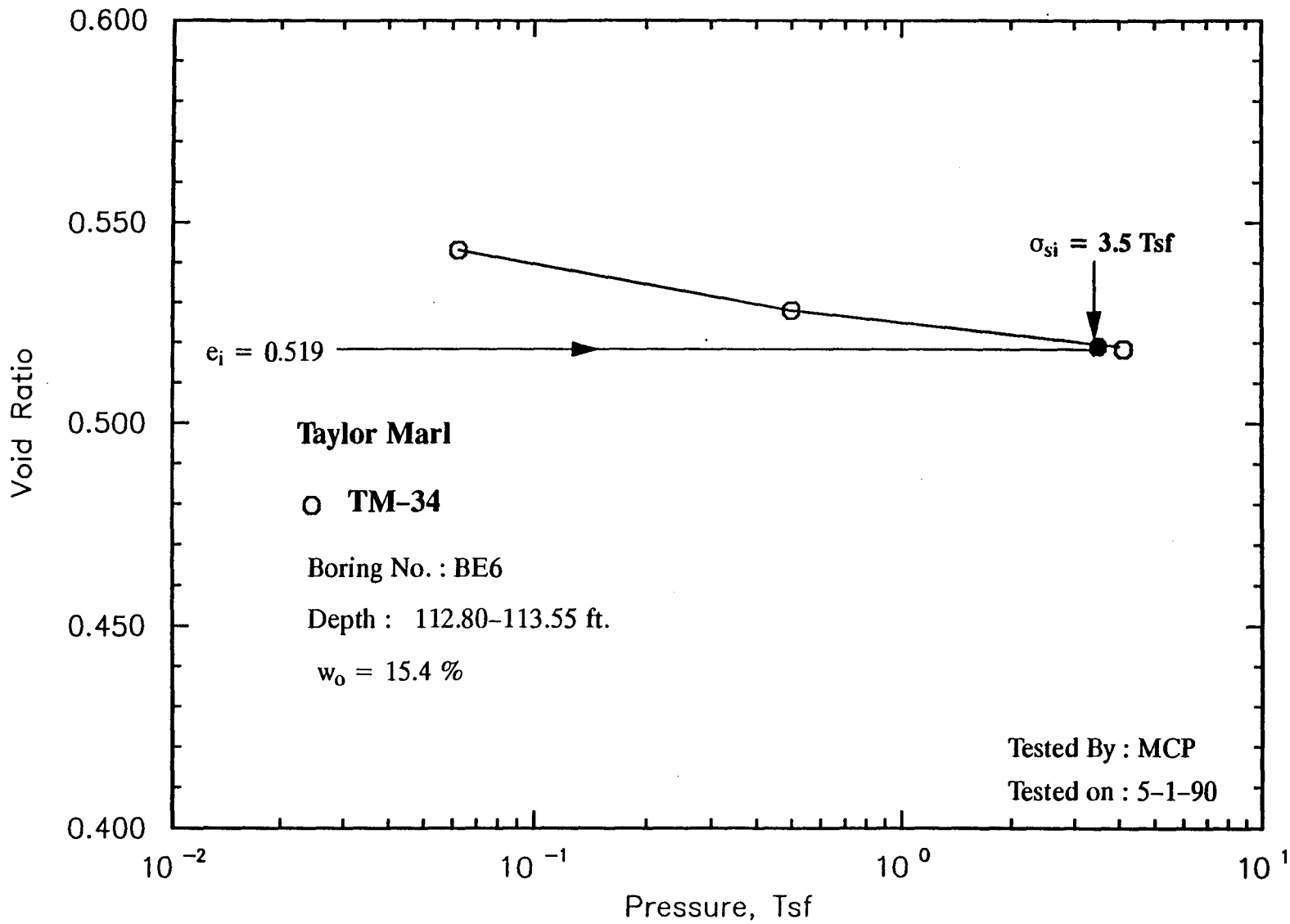


Fig. C26b Void Ratio - Log Pressure Relationship

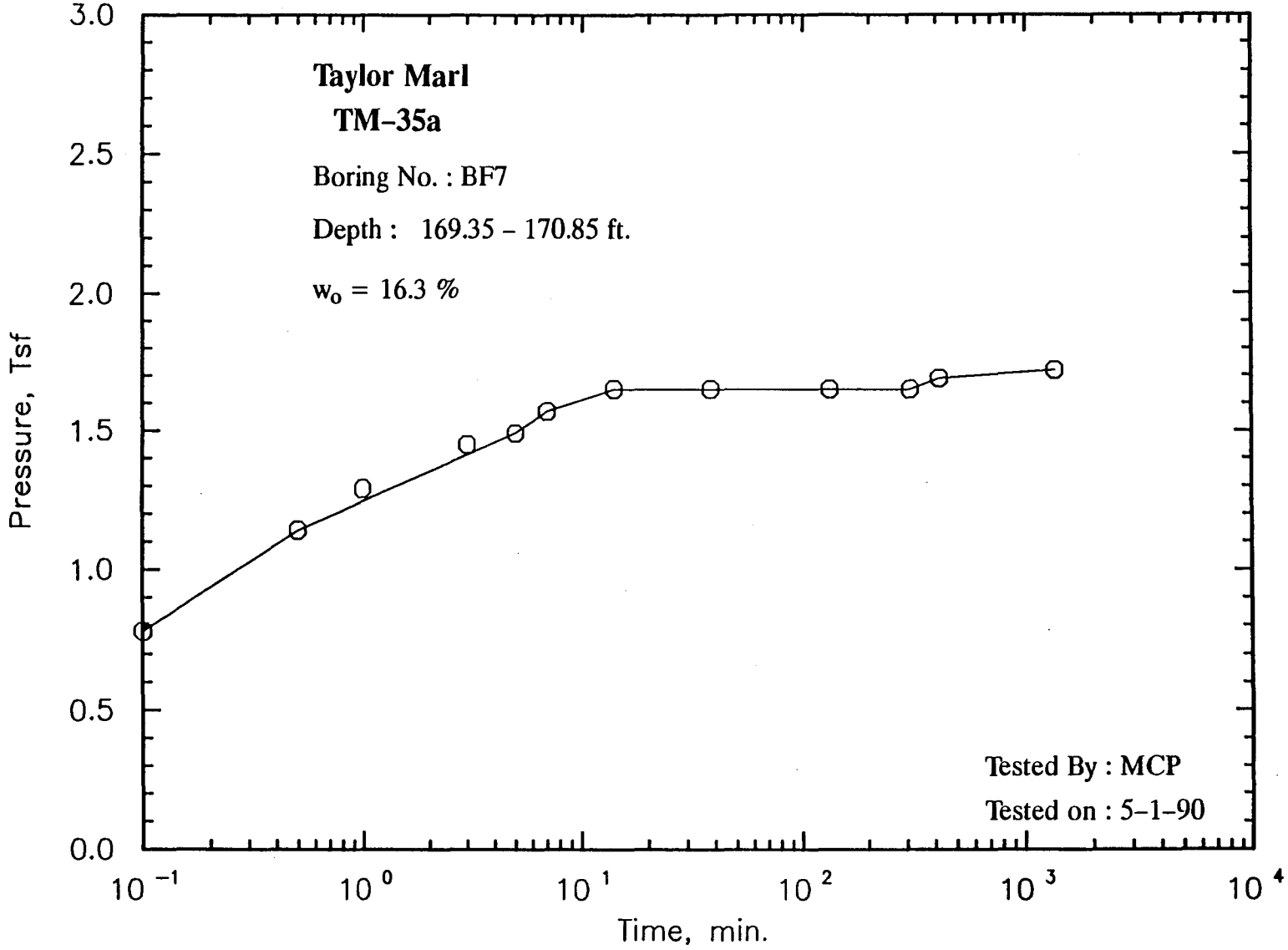


Fig. C27 Time-Rate of Swelling Pressure Development

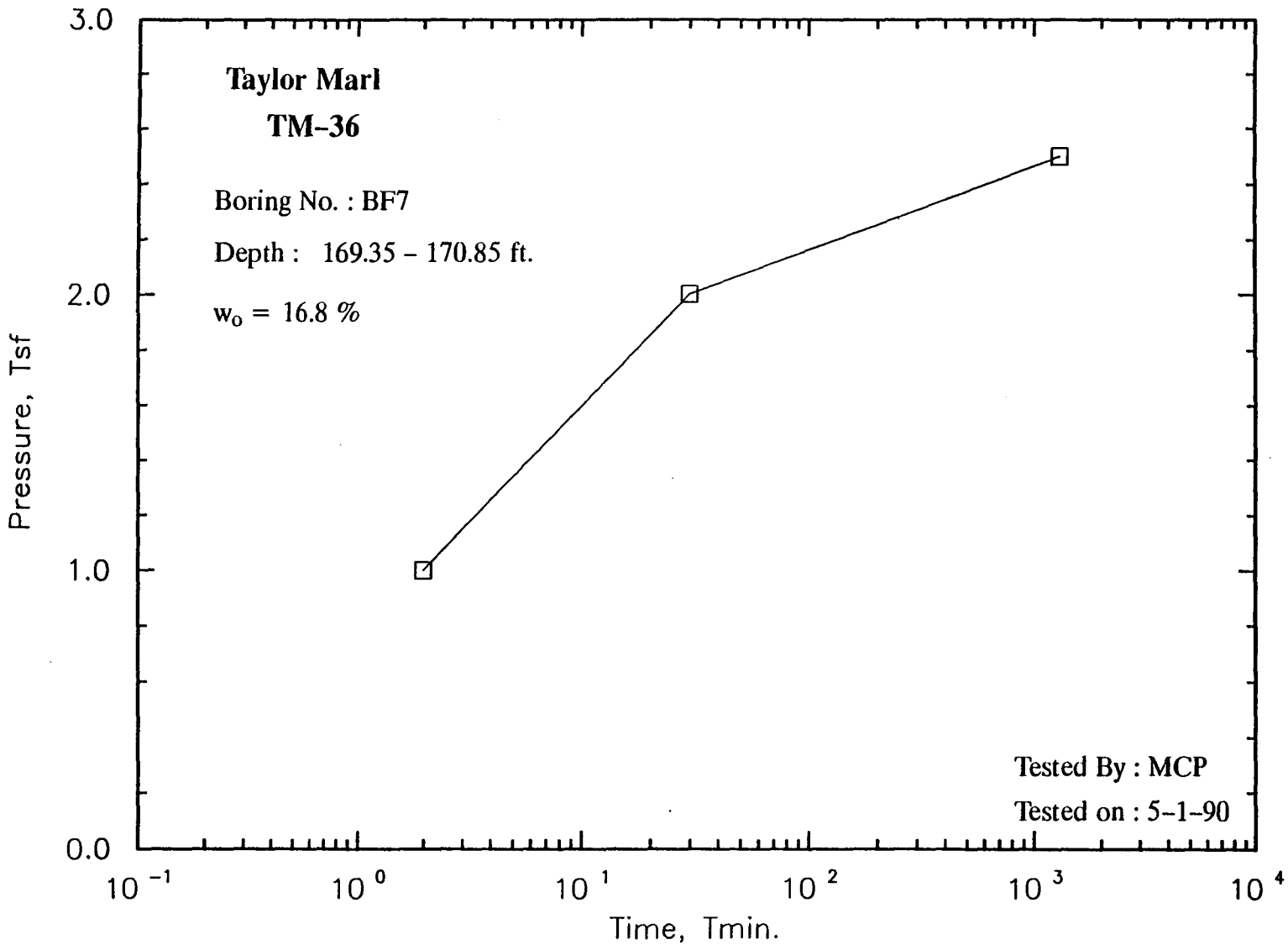


Fig. C28a Time-Rate of Swelling Pressure Development

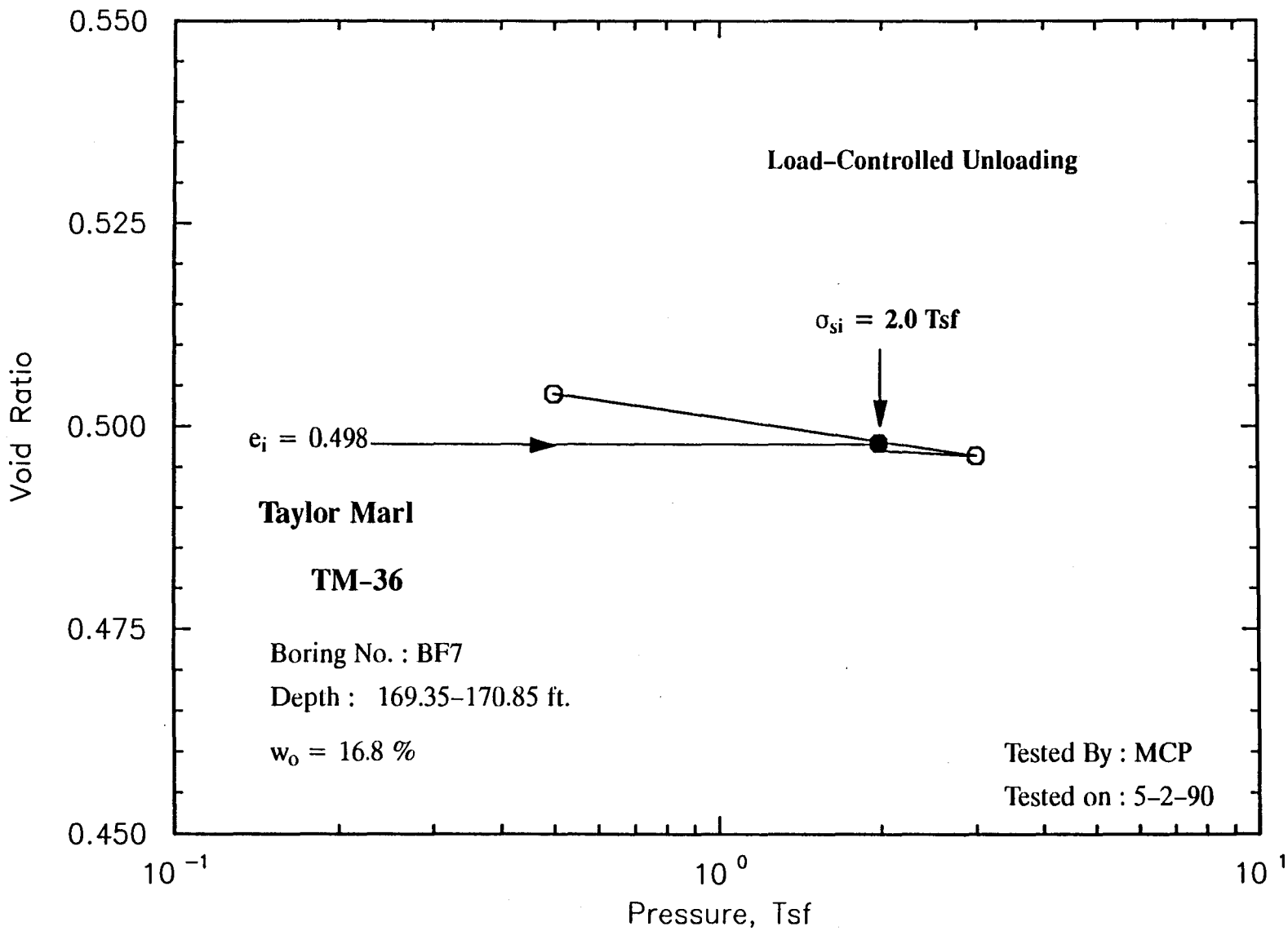


Fig. C28b Void Ratio - Log Pressure Relationship

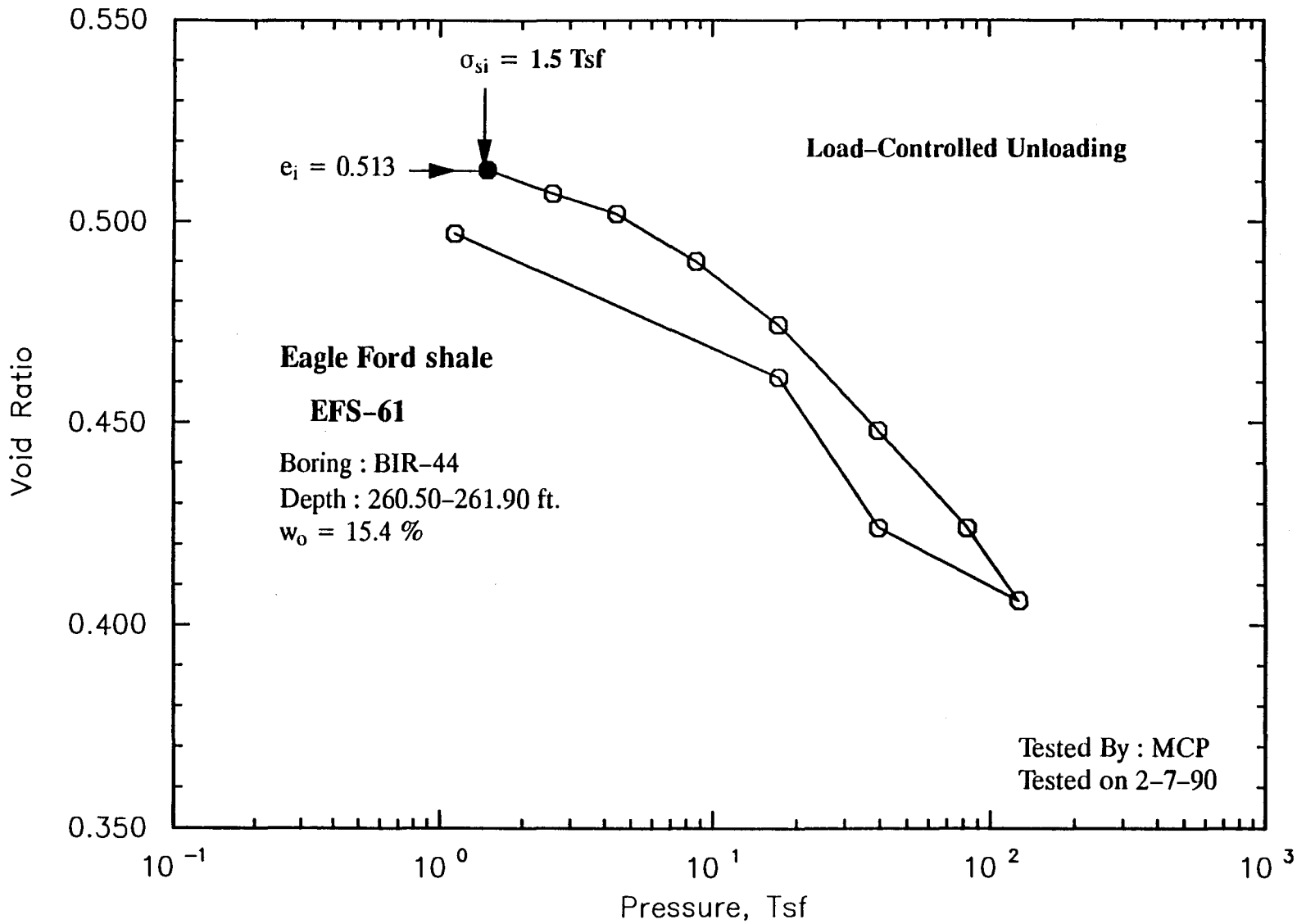


Fig. C29 Void Ratio – Log Pressure Relationship

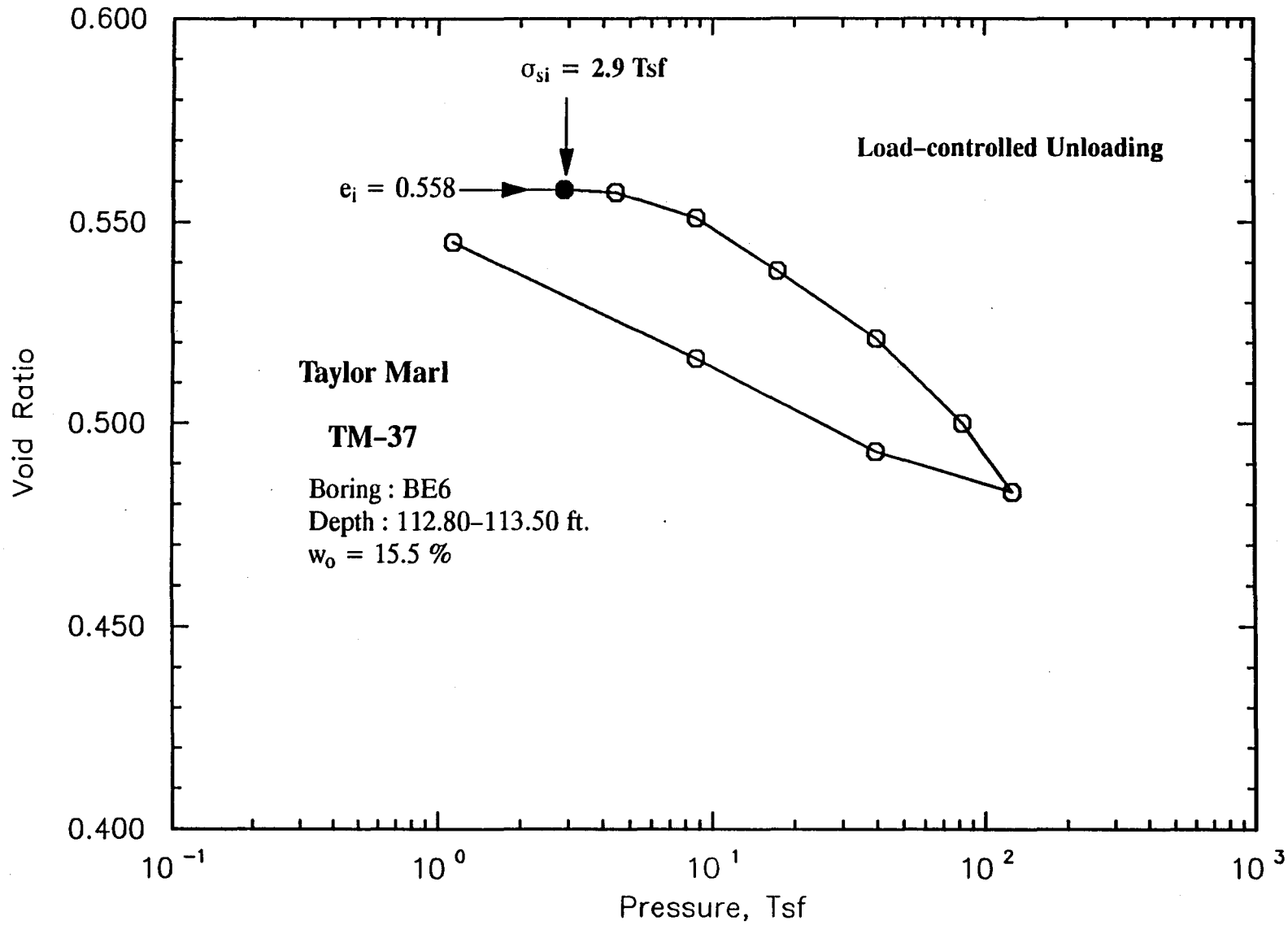


Fig. C30 Void Ratio - Log Pressure Relationship

APPENDIX DI

Figs. D1-D29

Water Content - Log Computed Suction Pressure (and RH),

and Water Content - Log Time Relationships

for Deterioration Tests on Eagle Ford Shale, Taylor Marl and Bentonite

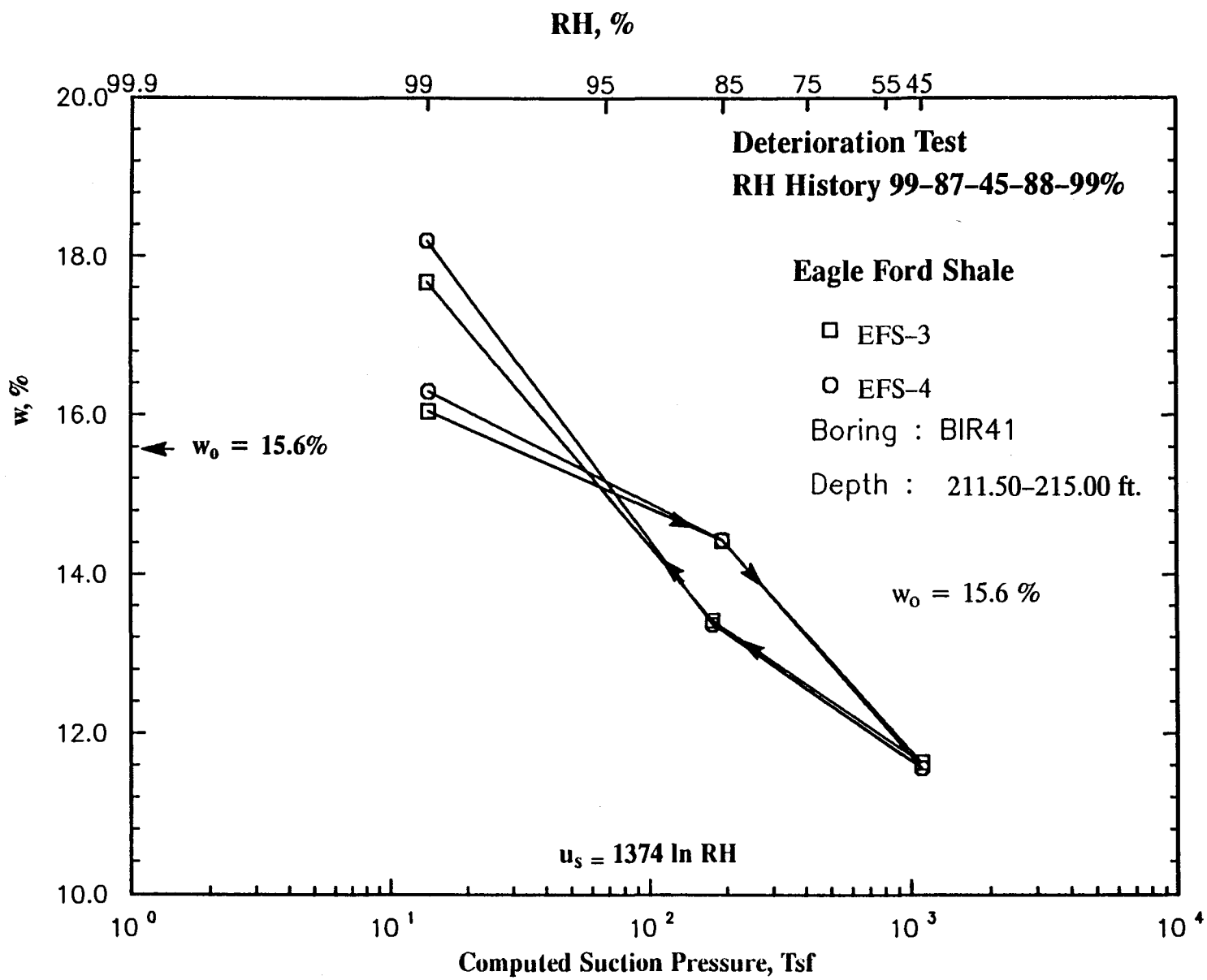


Fig. D1 Water Content – Relative Humidity Relationship

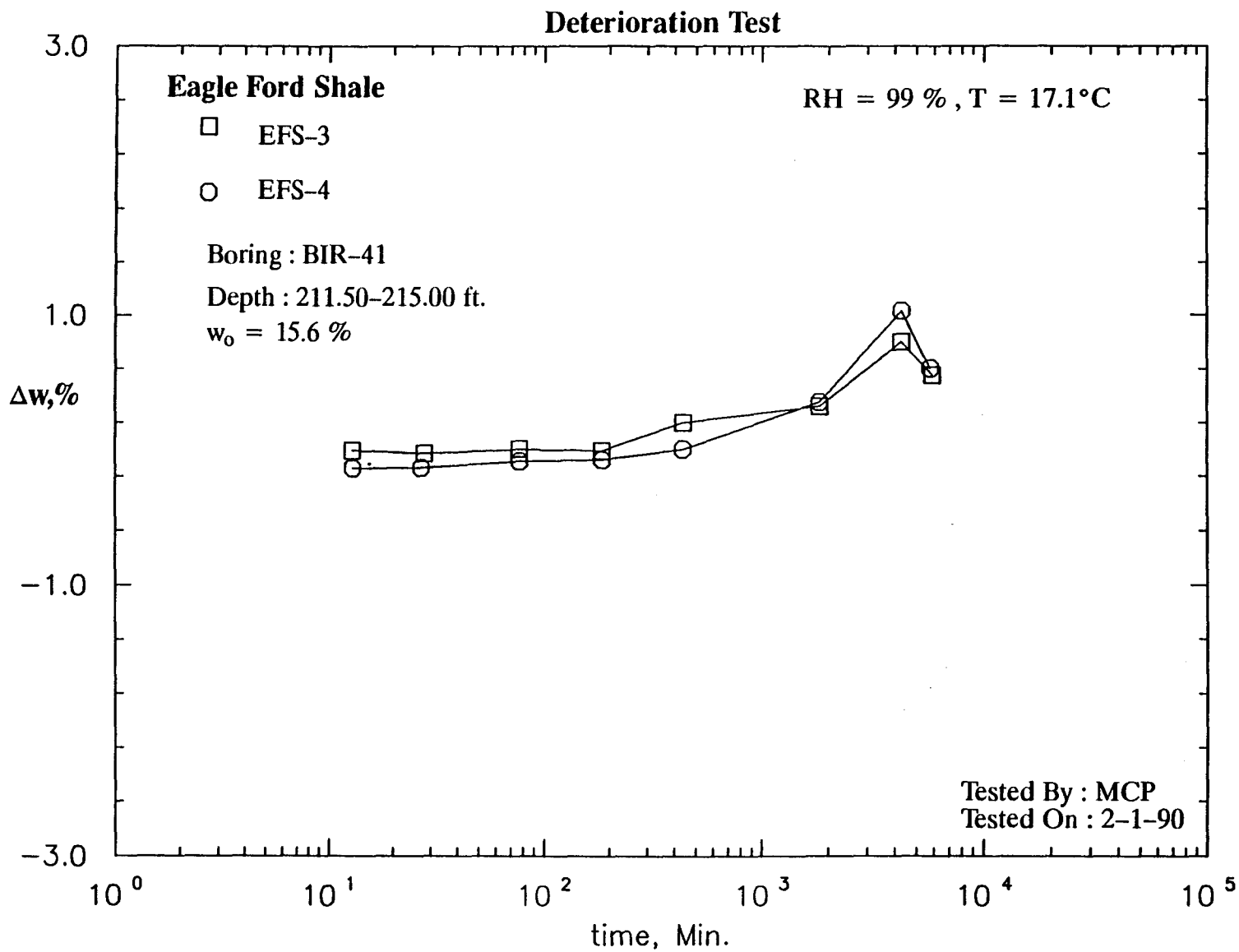


Fig. D1a Water Content Change – Log time Relationship

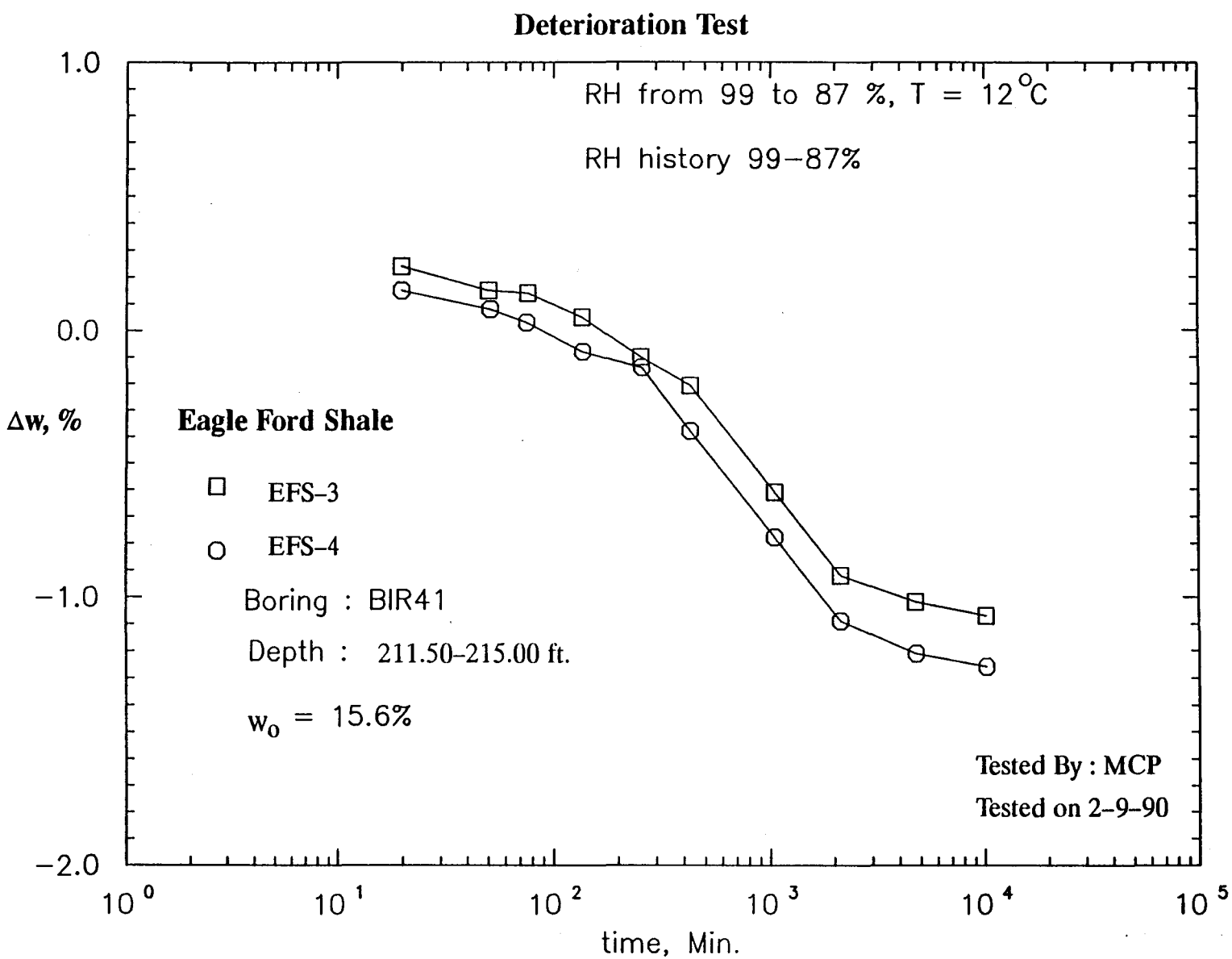


Fig. D1b Water Content Change – Log time Relationship

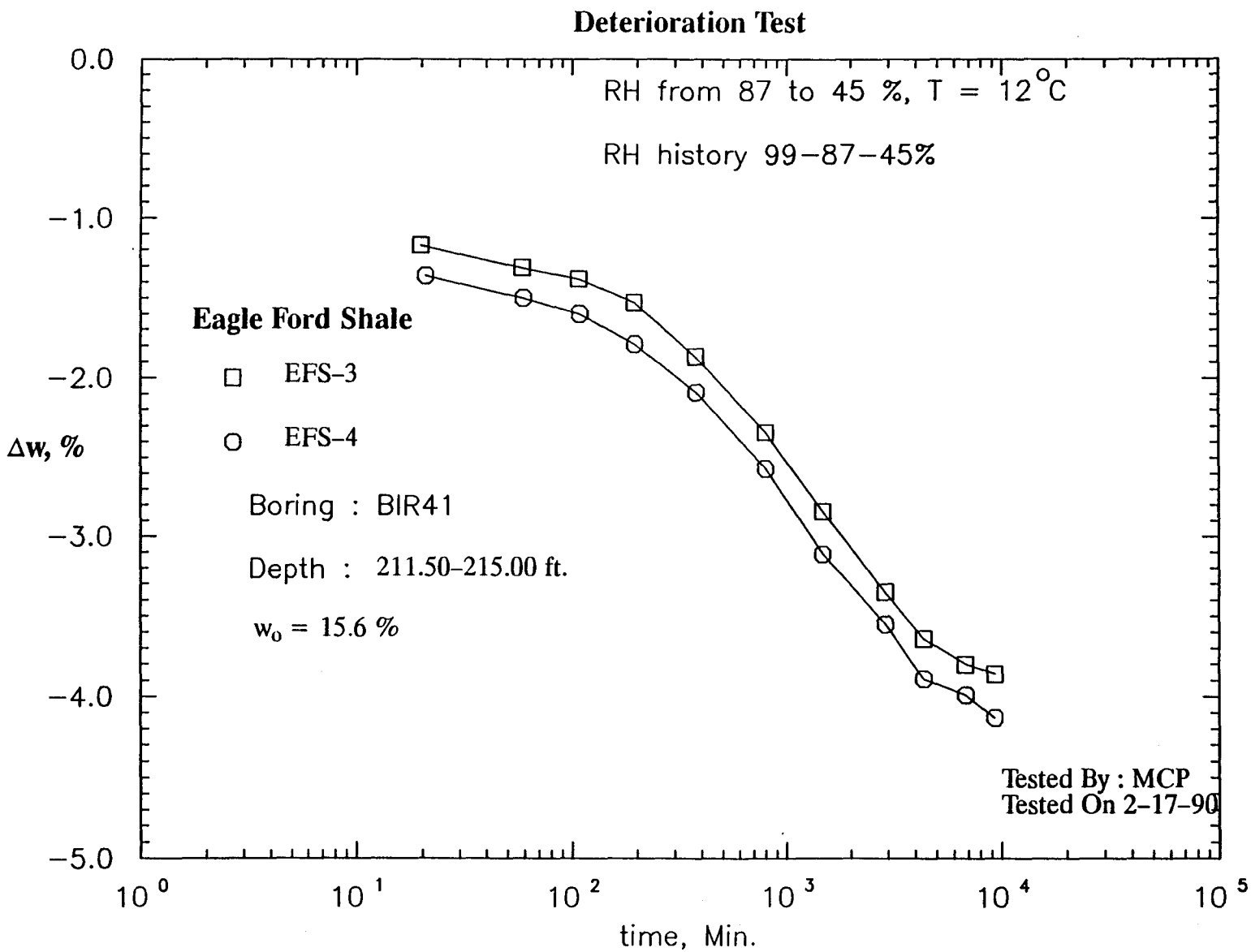


Fig. D1c Water Content Change – Log time Relationship

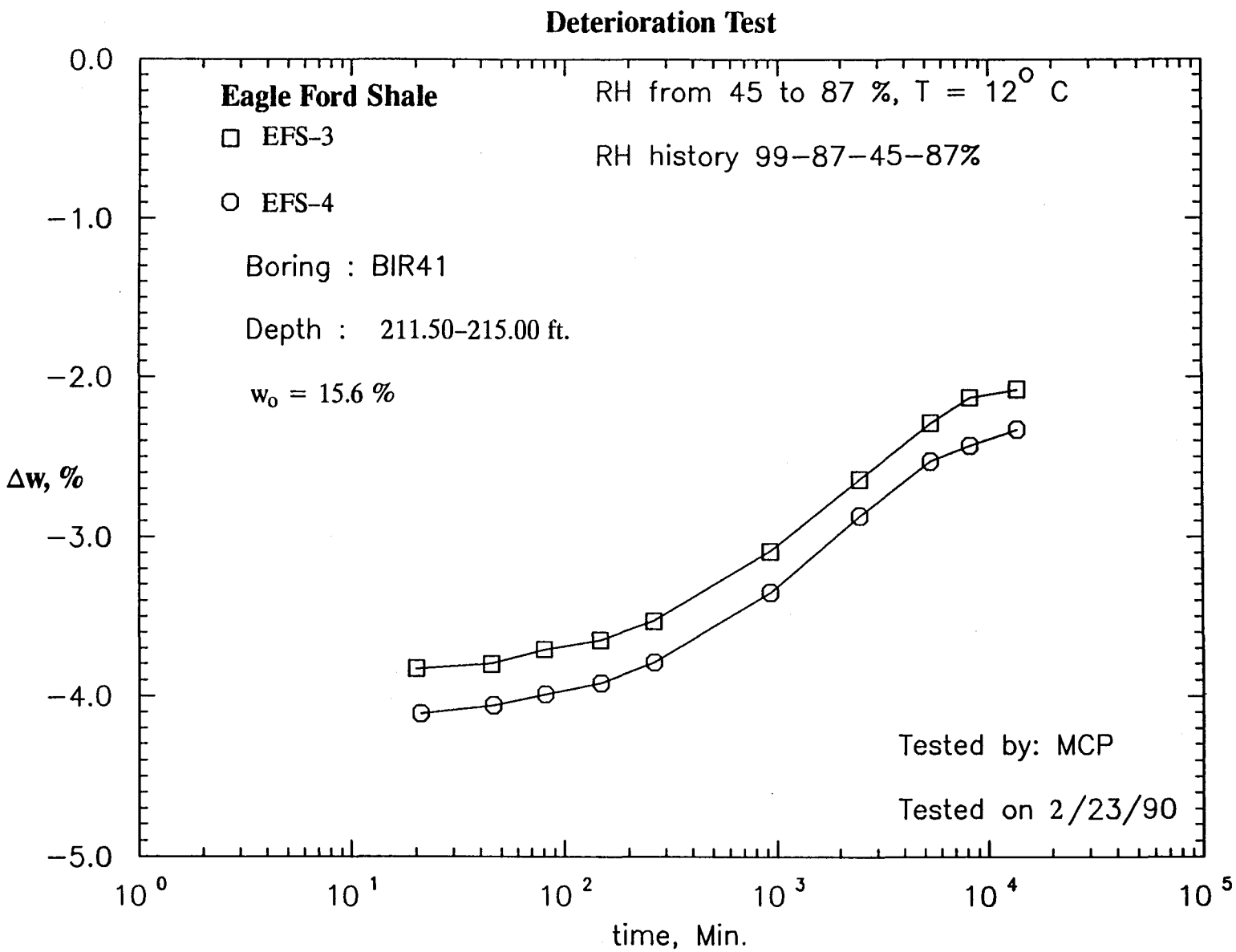


Fig. D1d Water Content Change – Log time Relationship

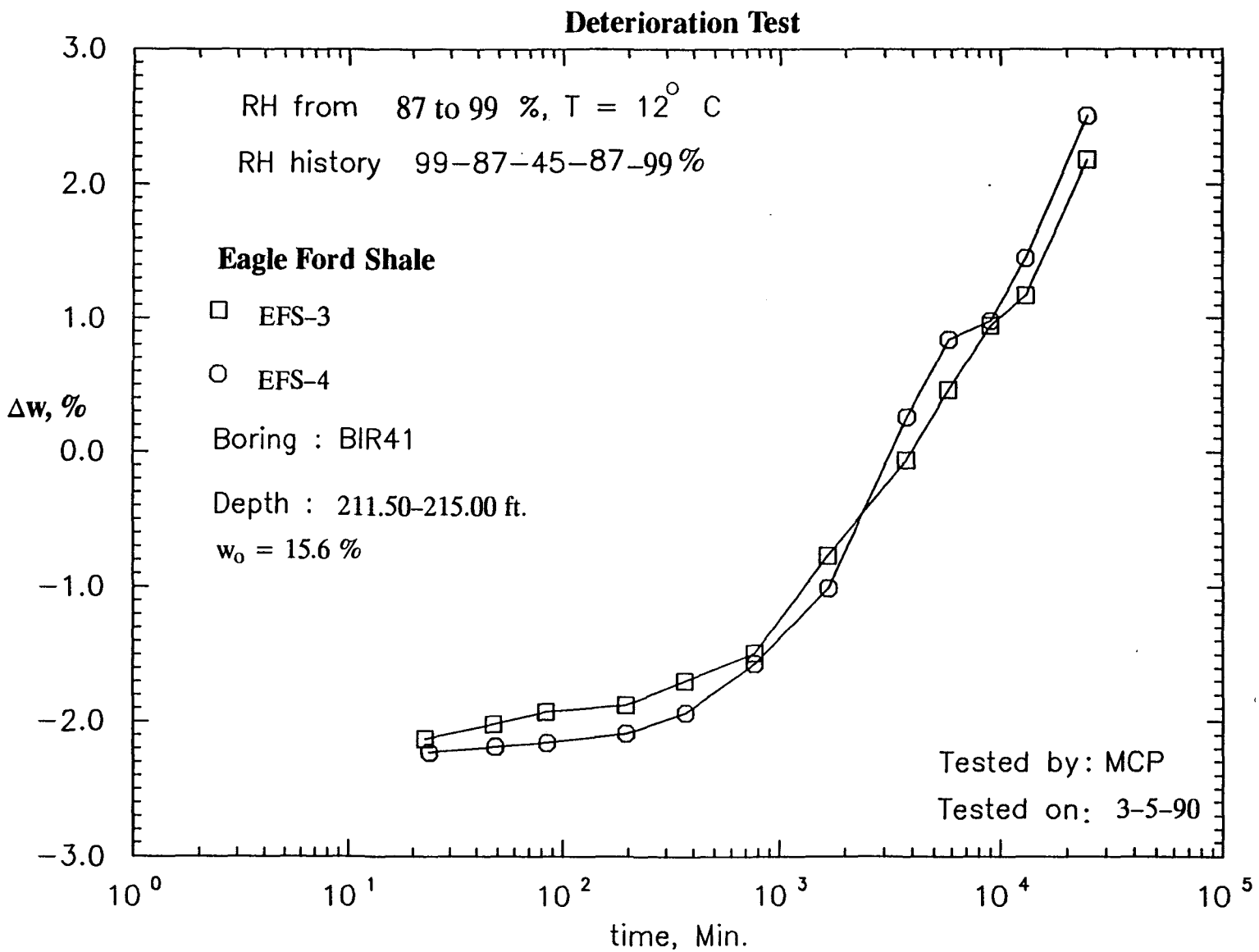


Fig. D1e Water Content Change – Log time Relationship

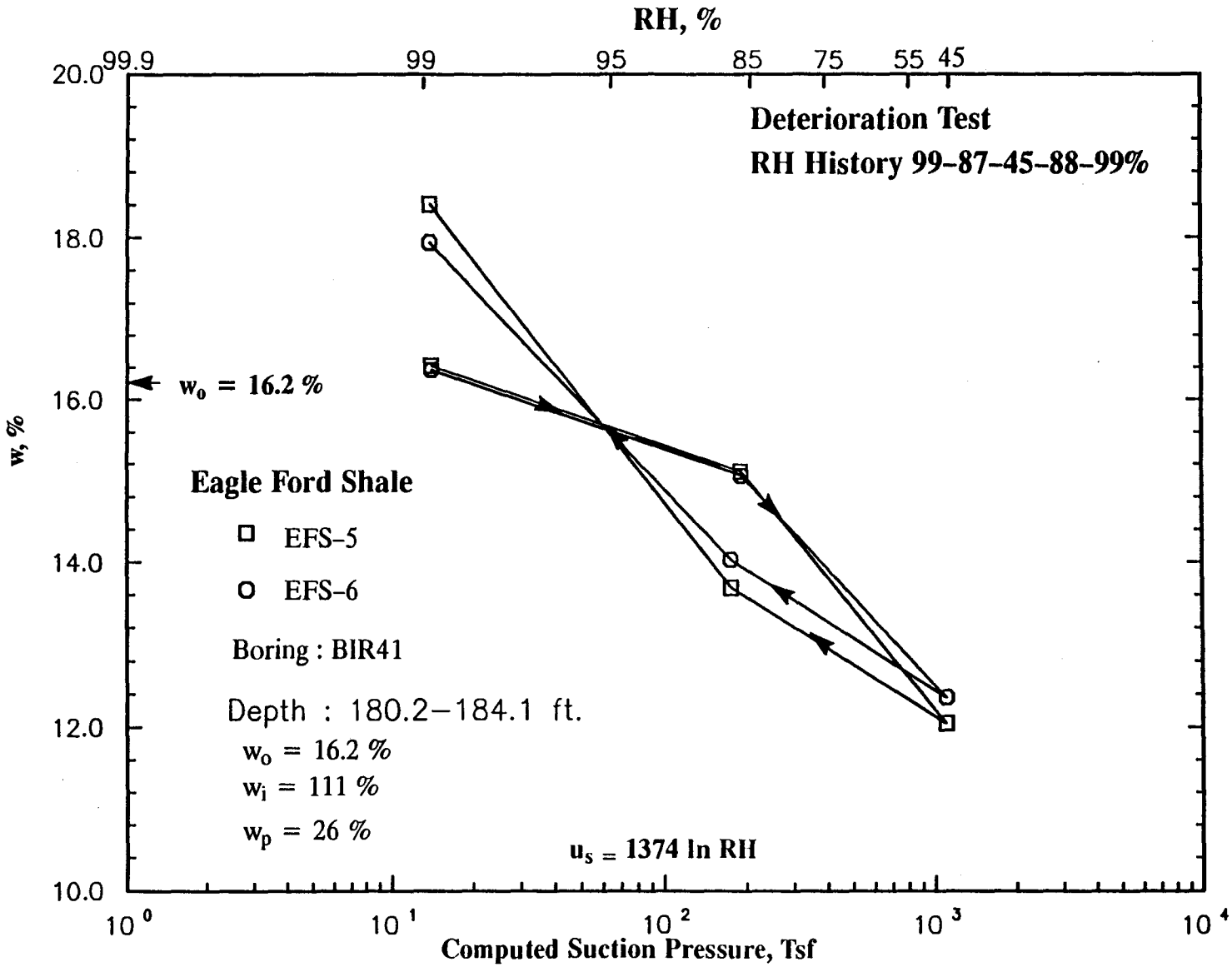


Fig. D2 Water Content – Relative Humidity Relationship

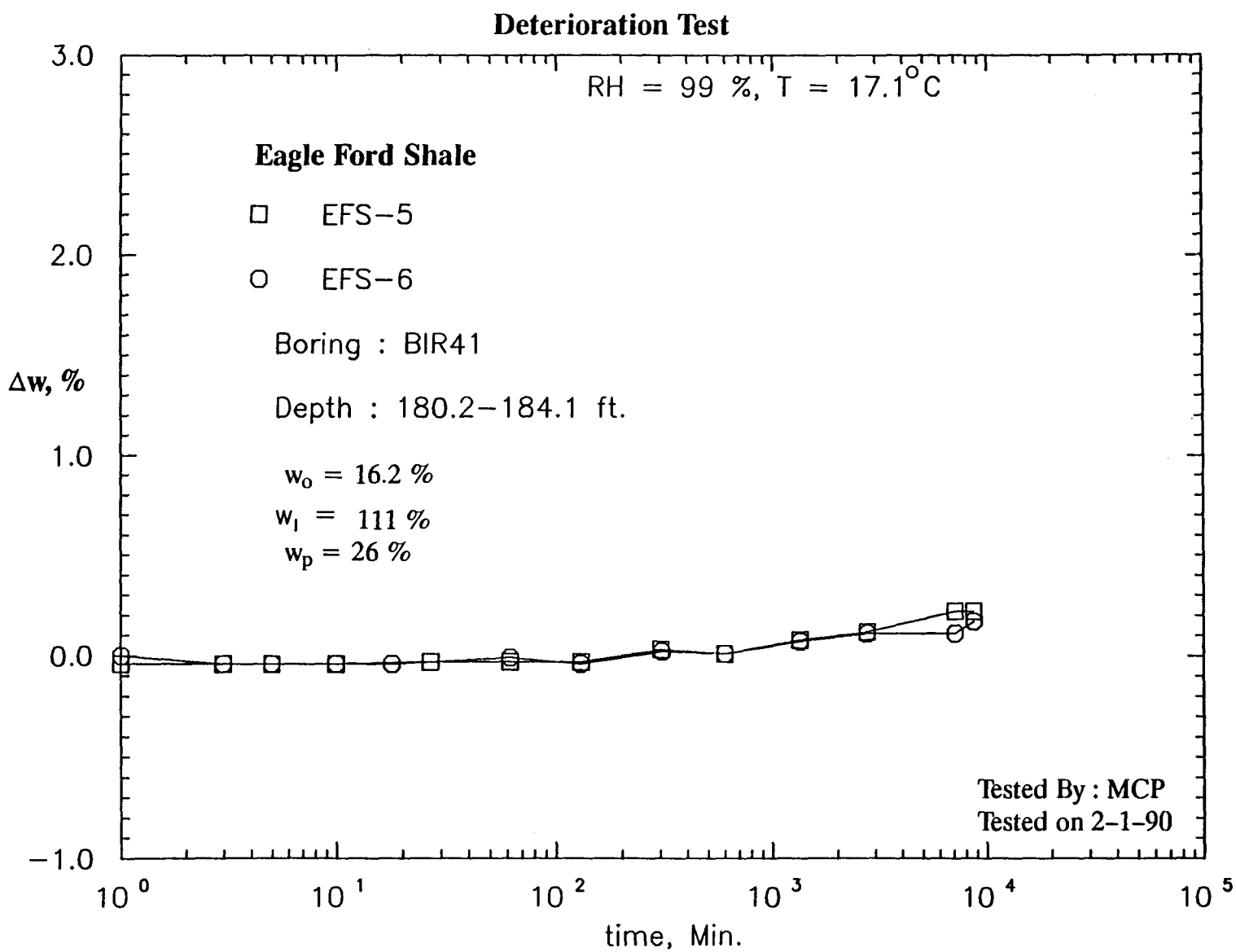


Fig. D2a Water Content Change - Log time Relationship

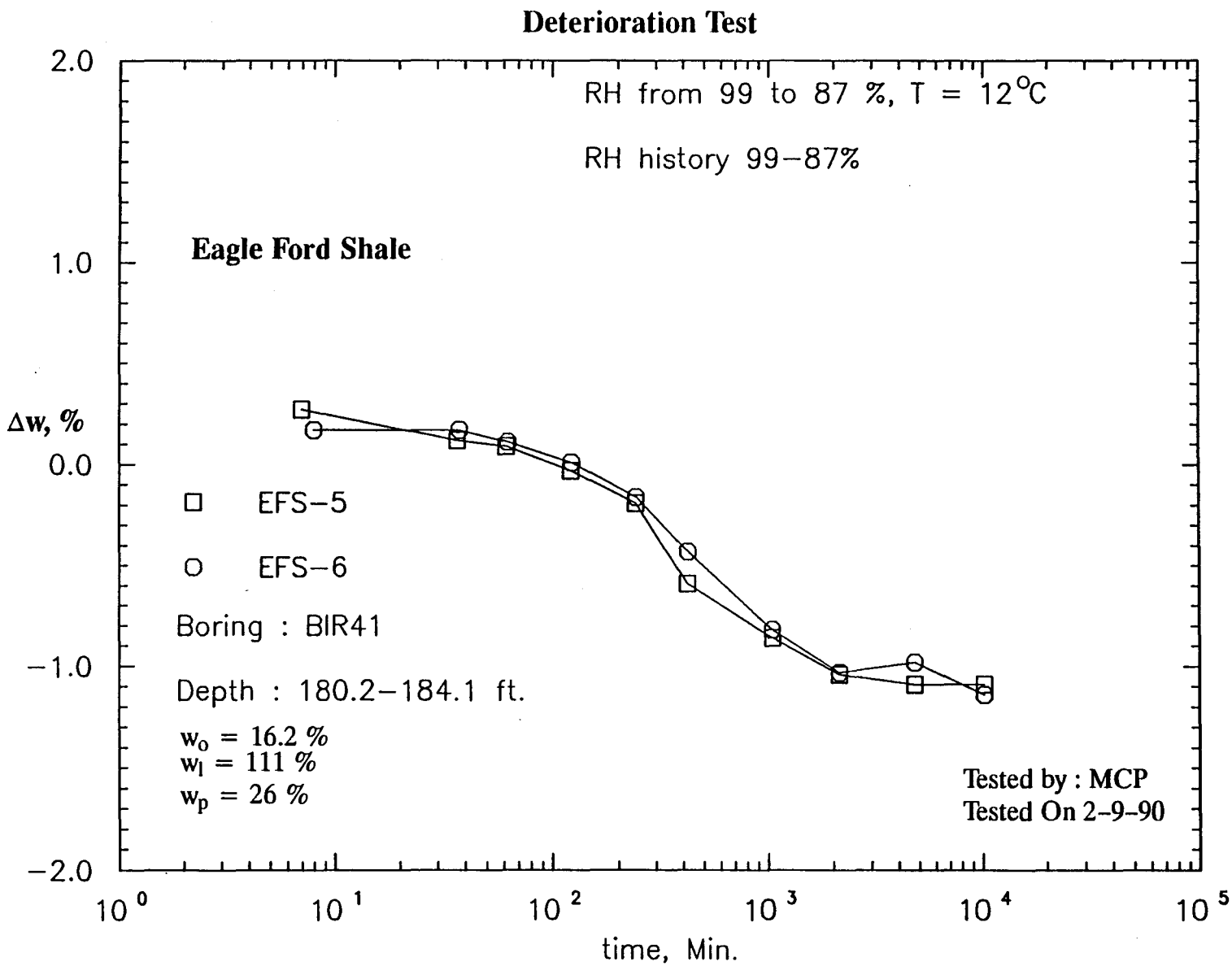


Fig. D2b Water Content Change – Log time Relationship

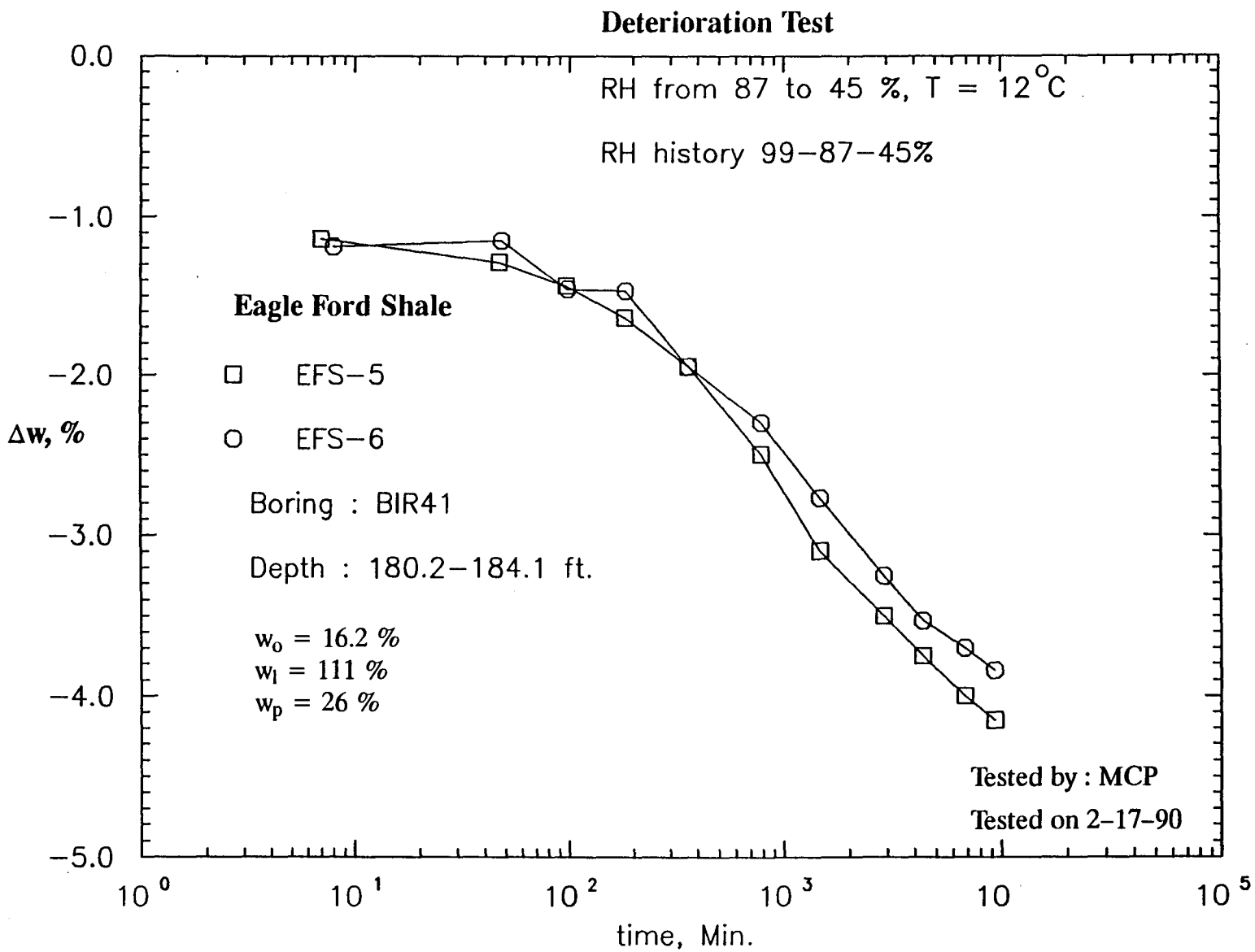


Fig. D2c Water Content Change – Log time Relationship

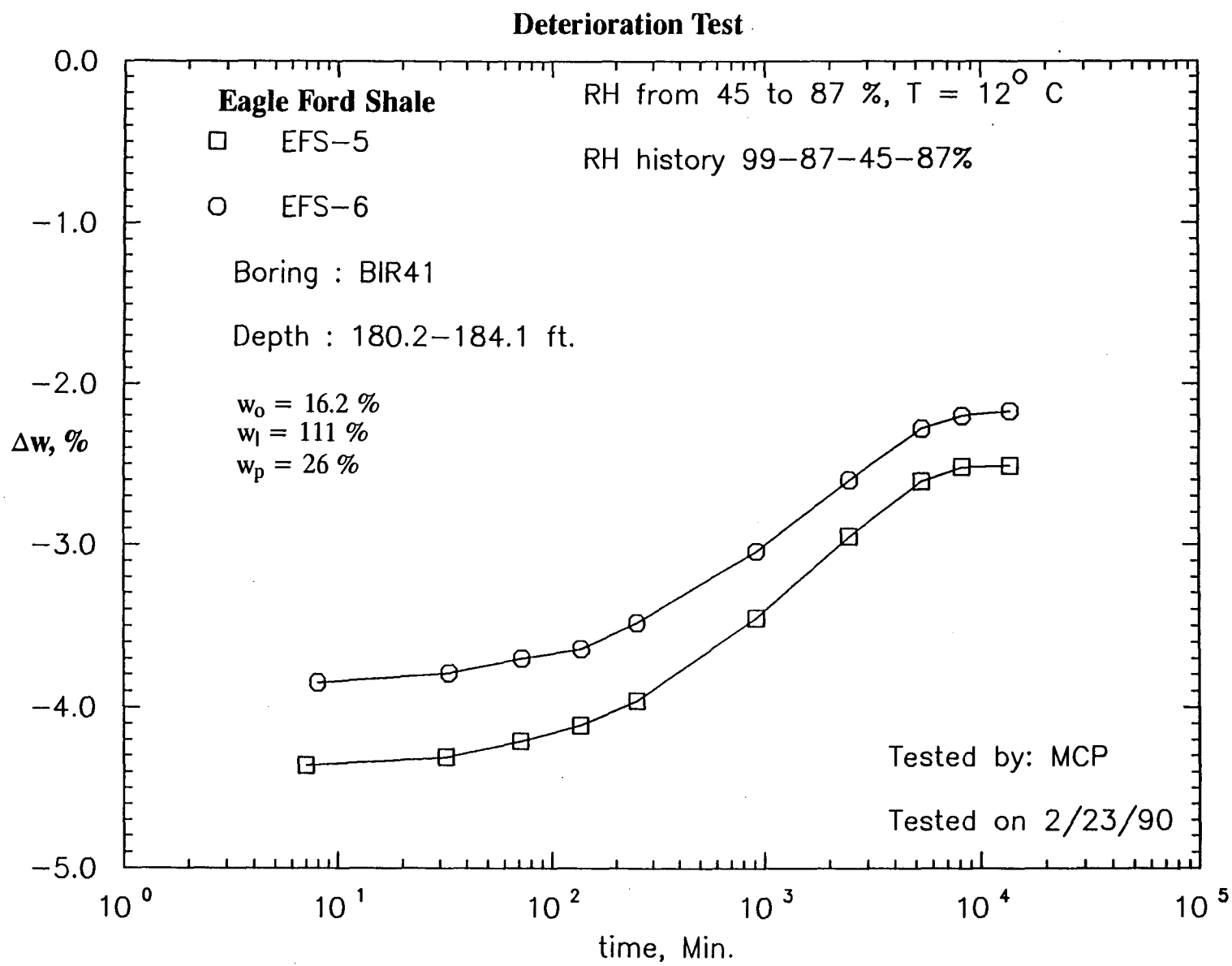


Fig. D2d Water Content Change – Log time Relationship

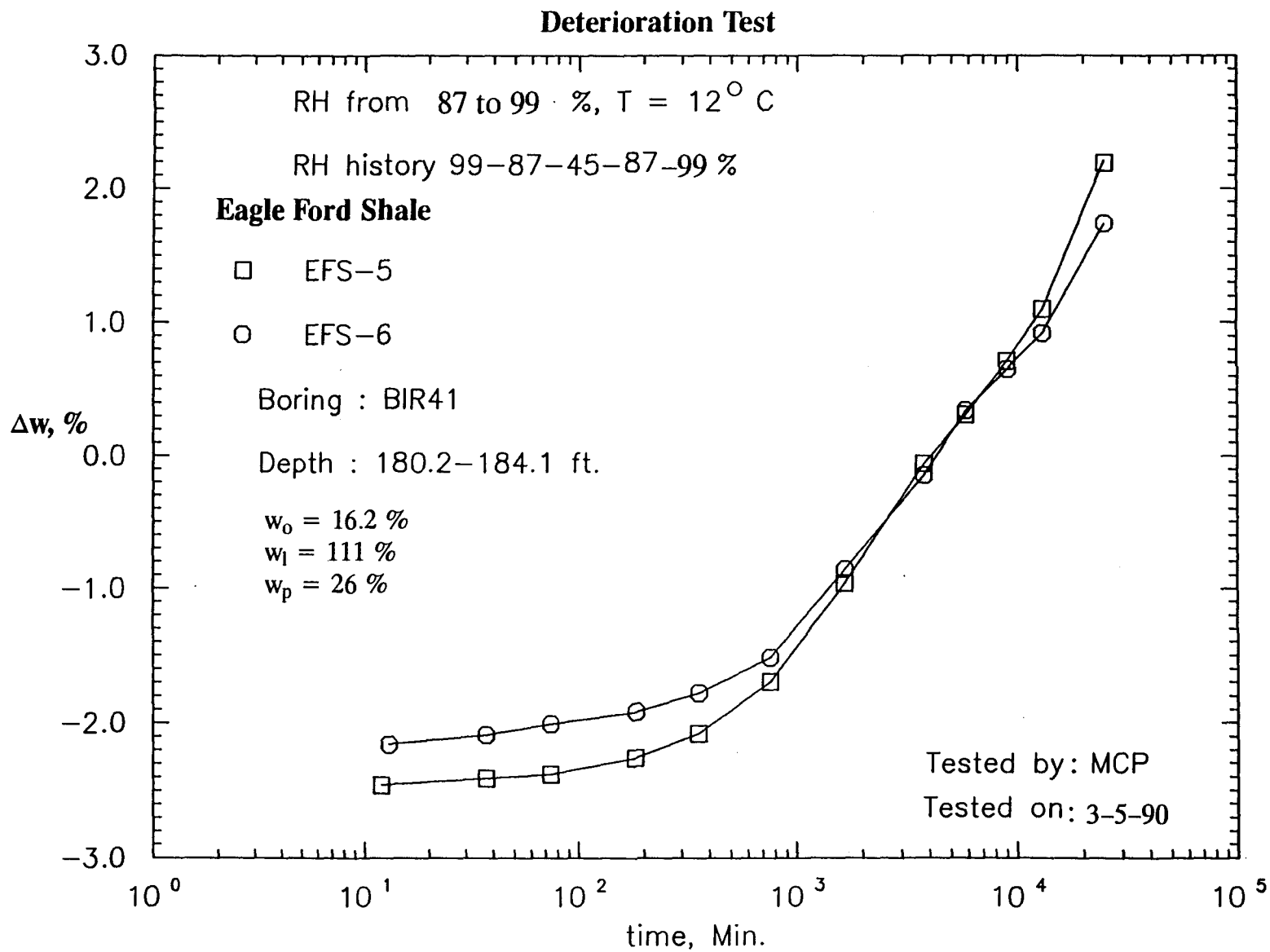


Fig. D2e Water Content Change – Log time Relationship

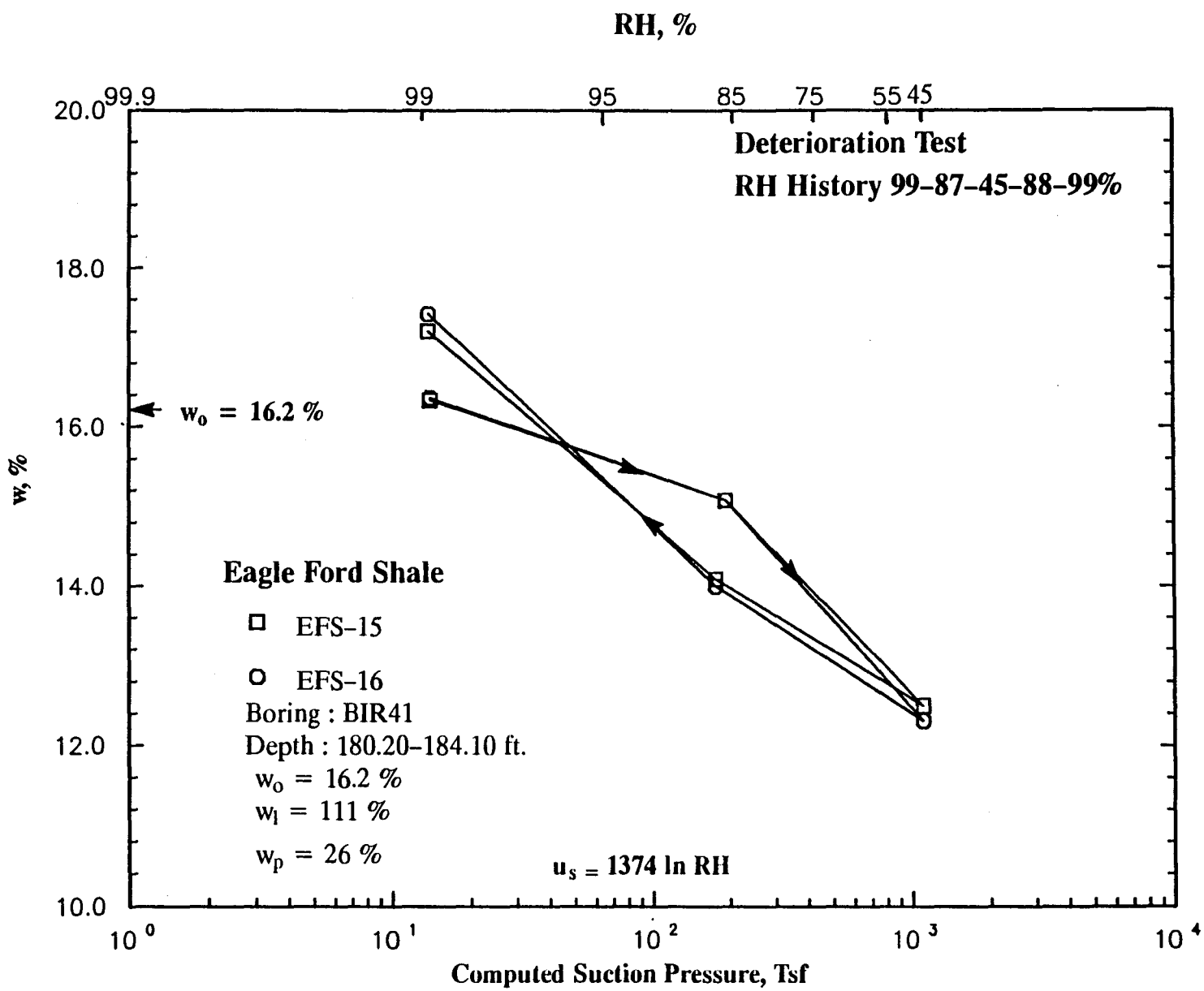


Fig. D3 Water Content – Relative Humidity Relationship

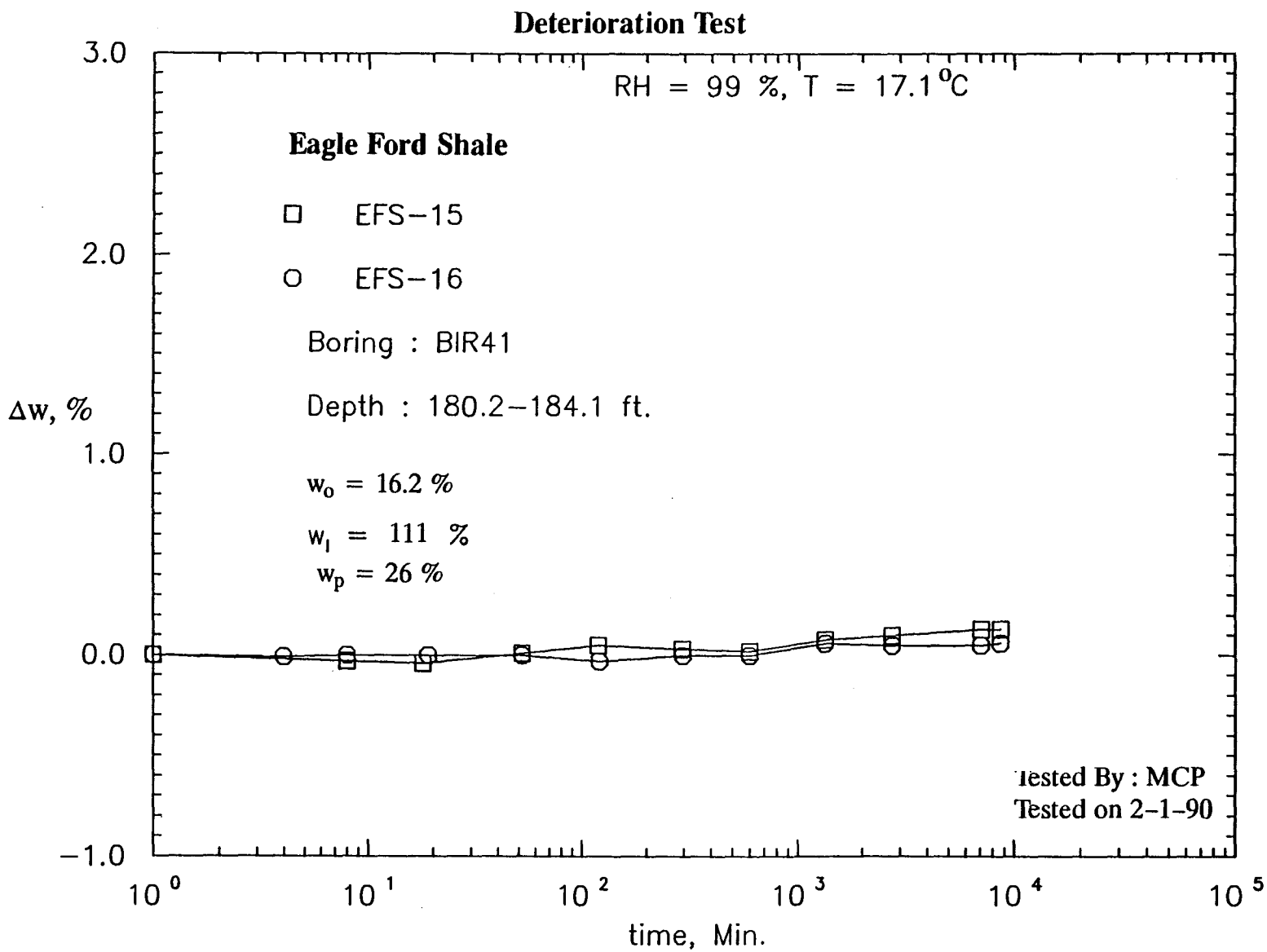


Fig. D3a Water Content Change – Log time Relationship

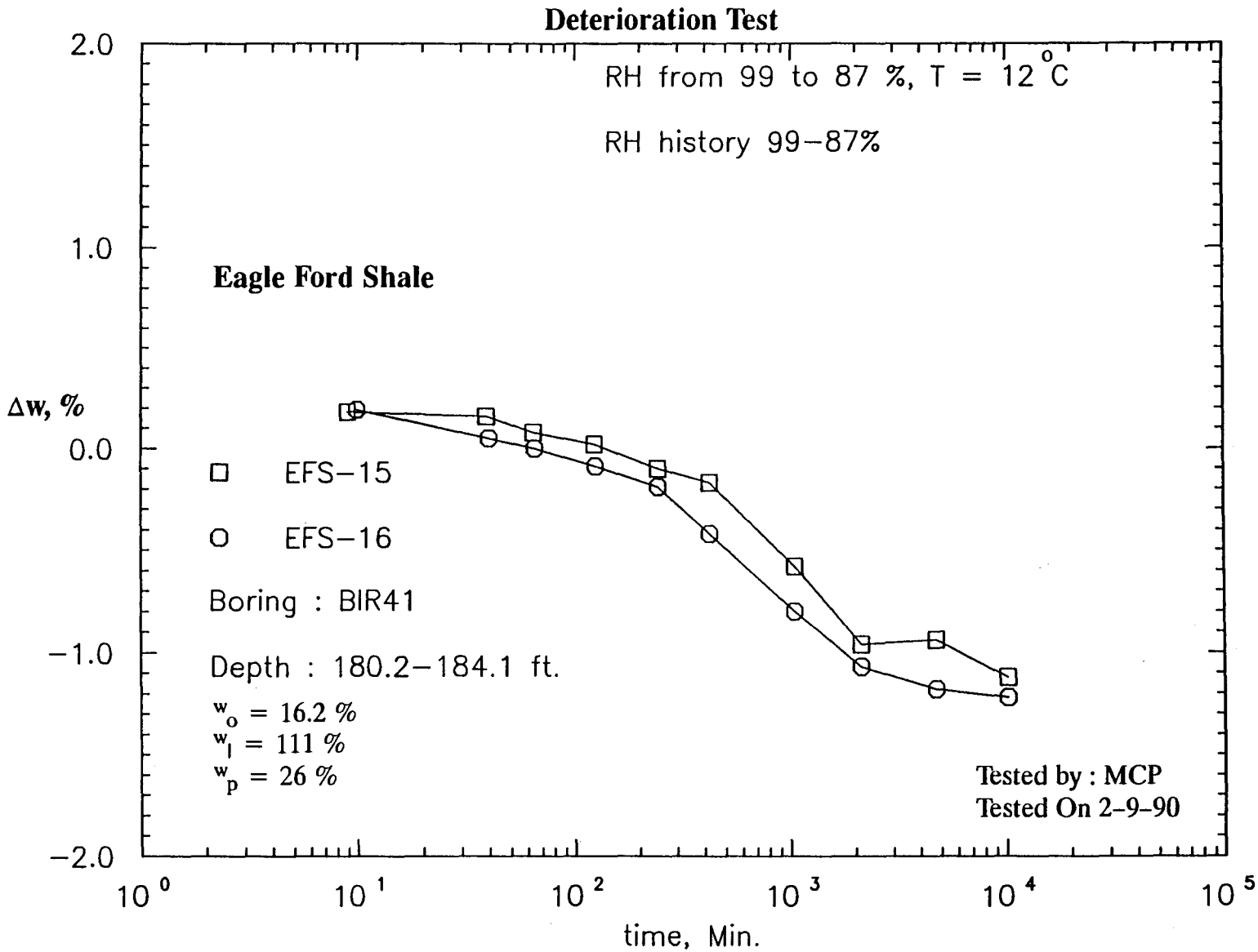


Fig. D3b Water Content Change – Log time Relationship

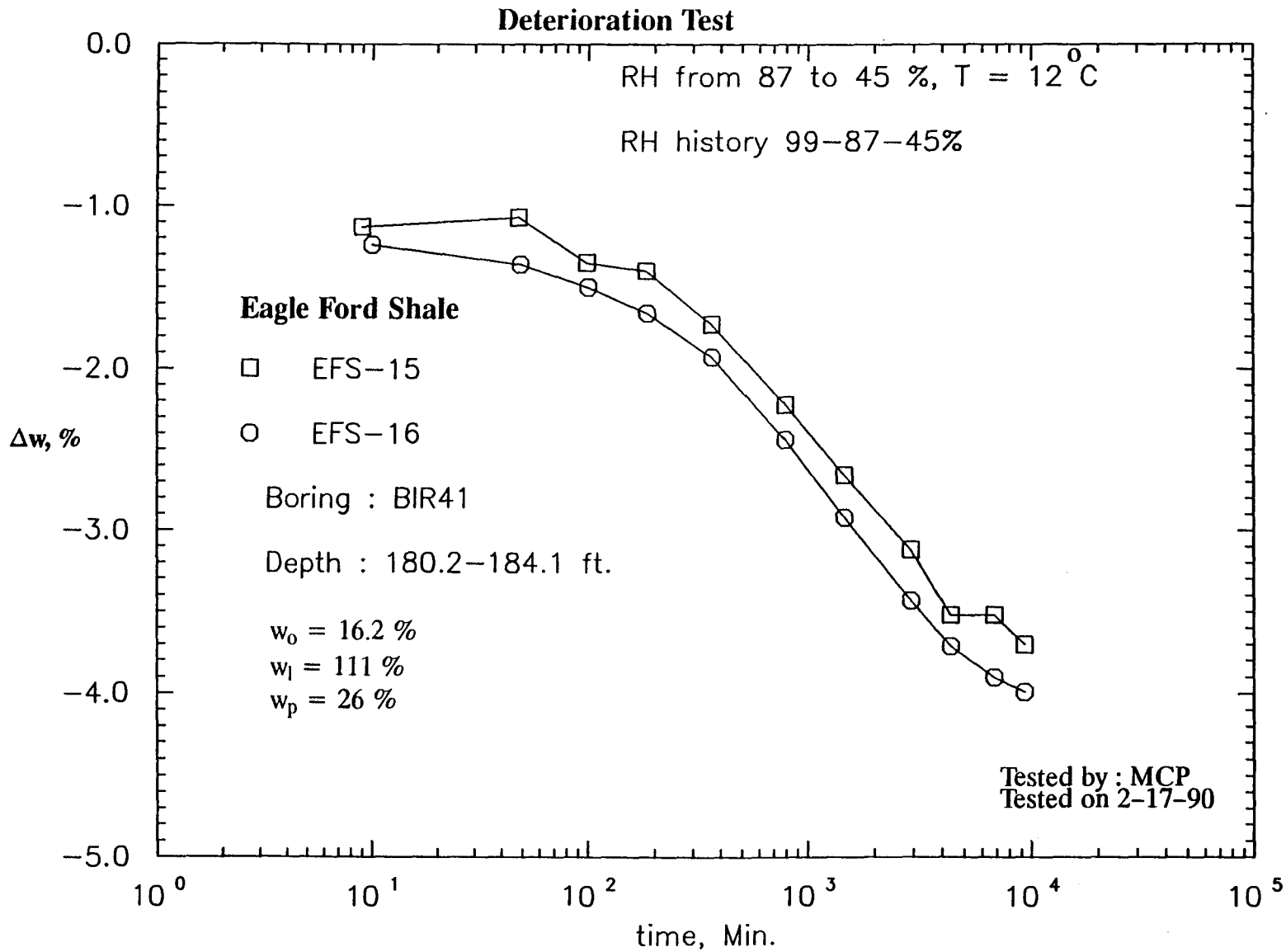


Fig. D3c Water Content Change – Log time Relationship

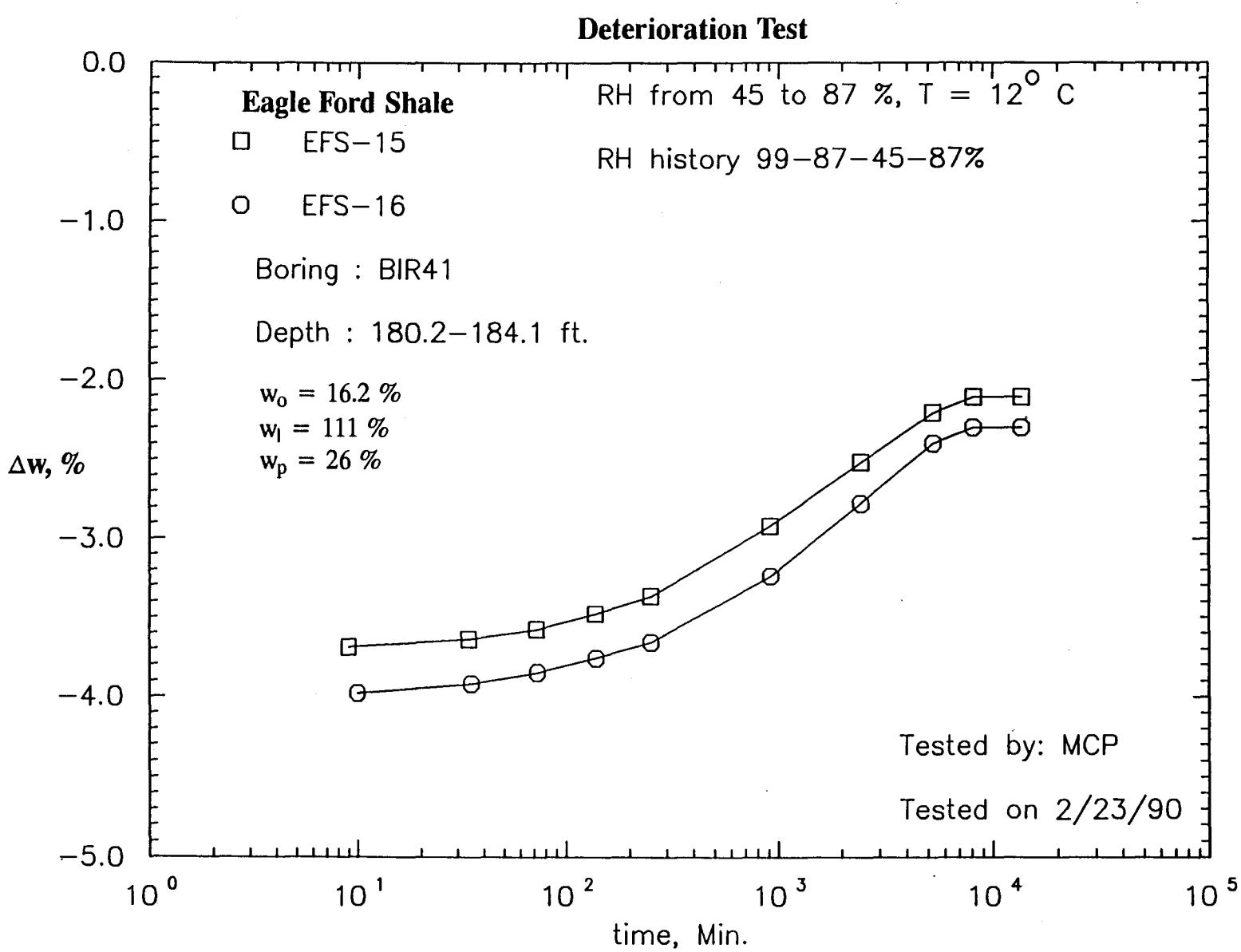


Fig. D3d Water Content Change – Log time Relationship

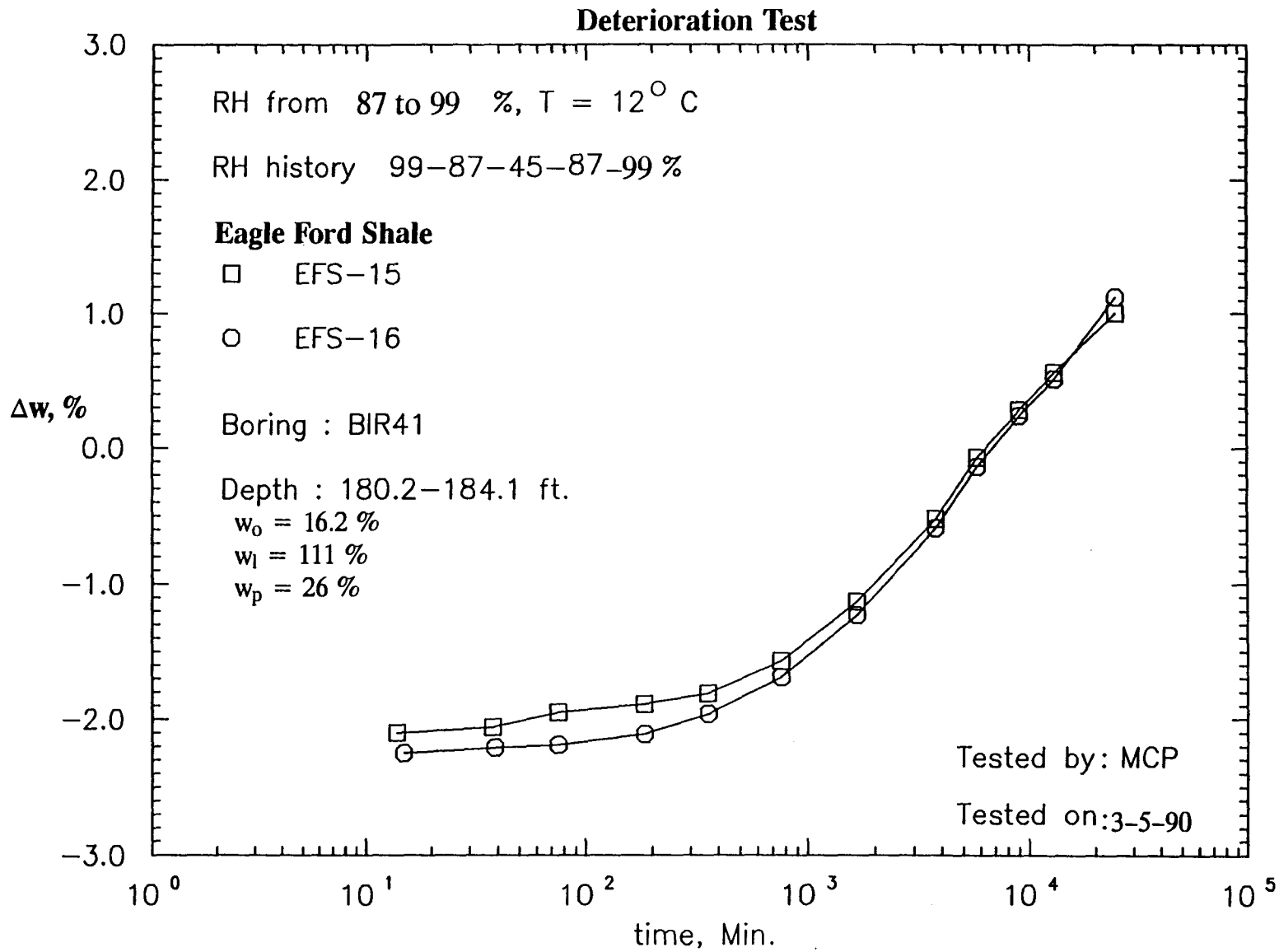


Fig. D3e Water Content Change – Log time Relationship

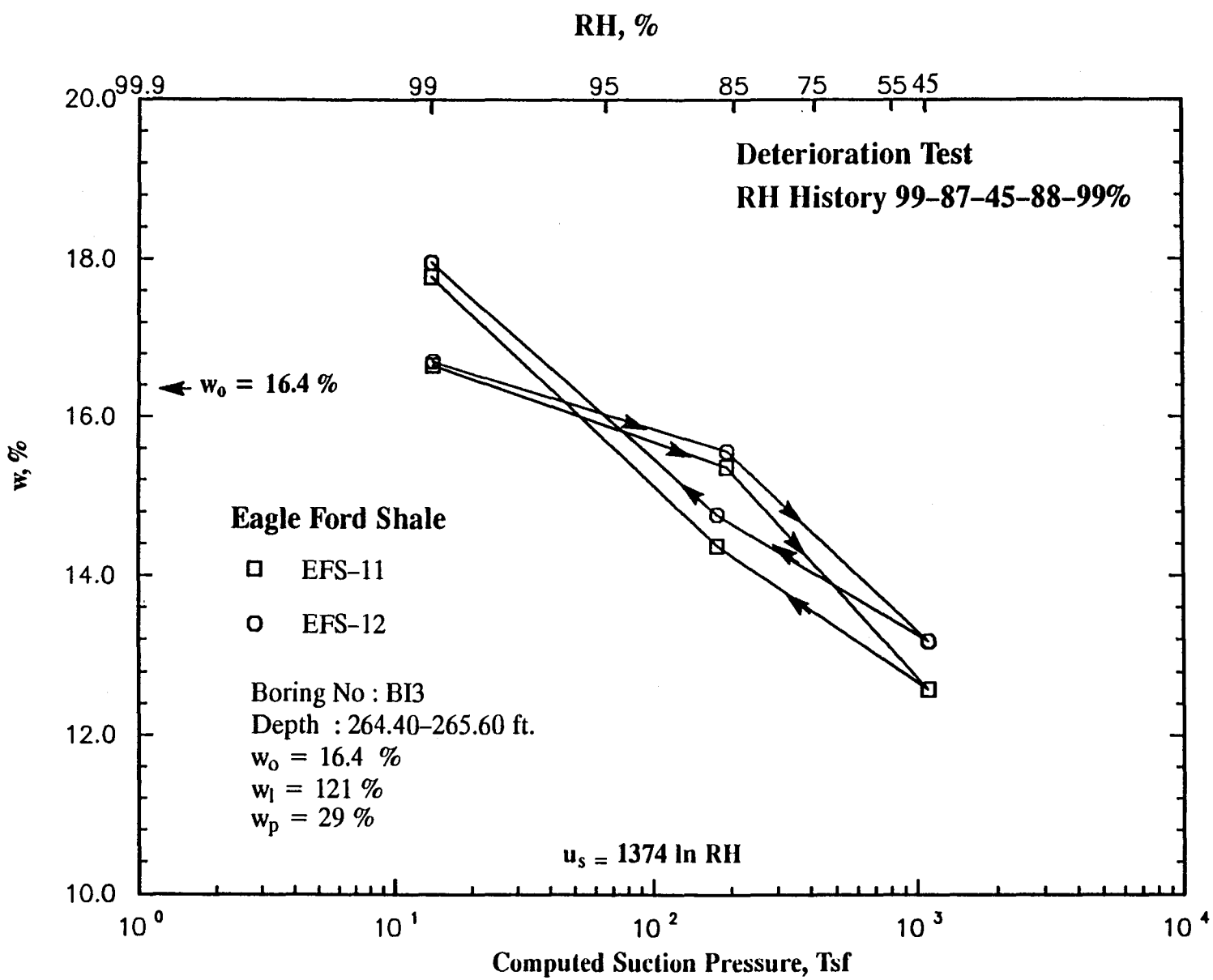


Fig. D4 Water Content – Relative Humidity Relationship

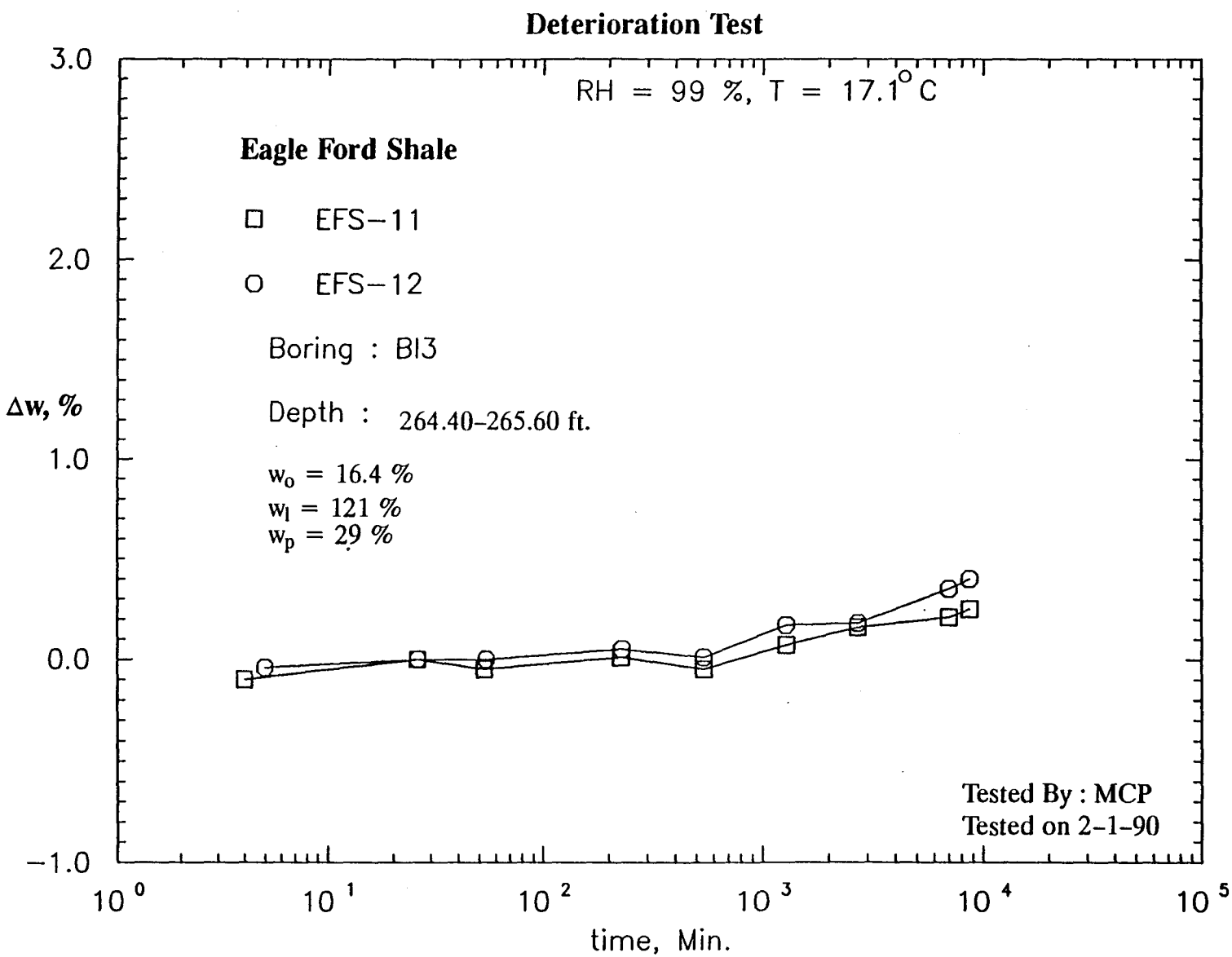


Fig. D4a Water Content Change – Log time Relationship

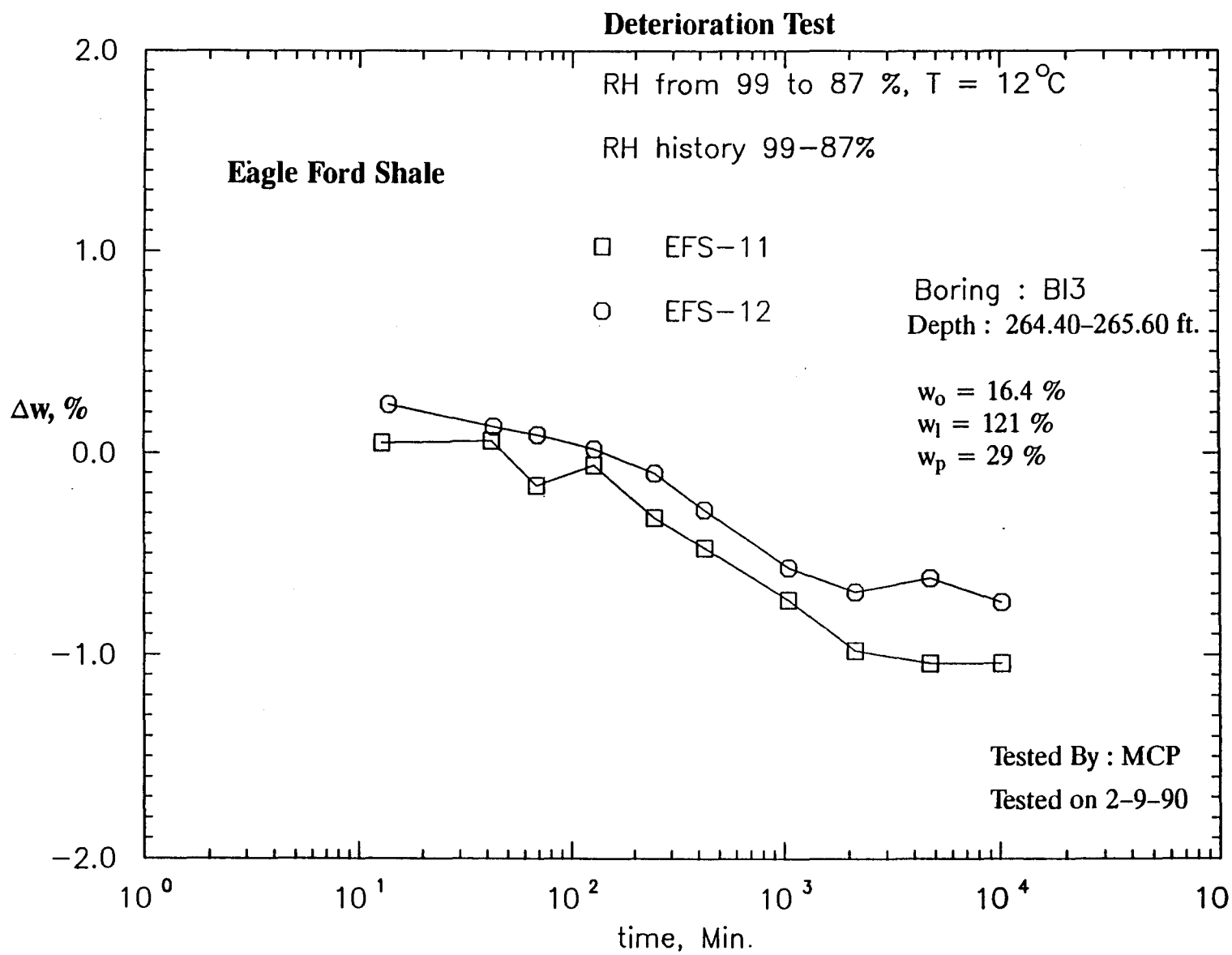


Fig. D4b Water Content Change – Log time Relationship

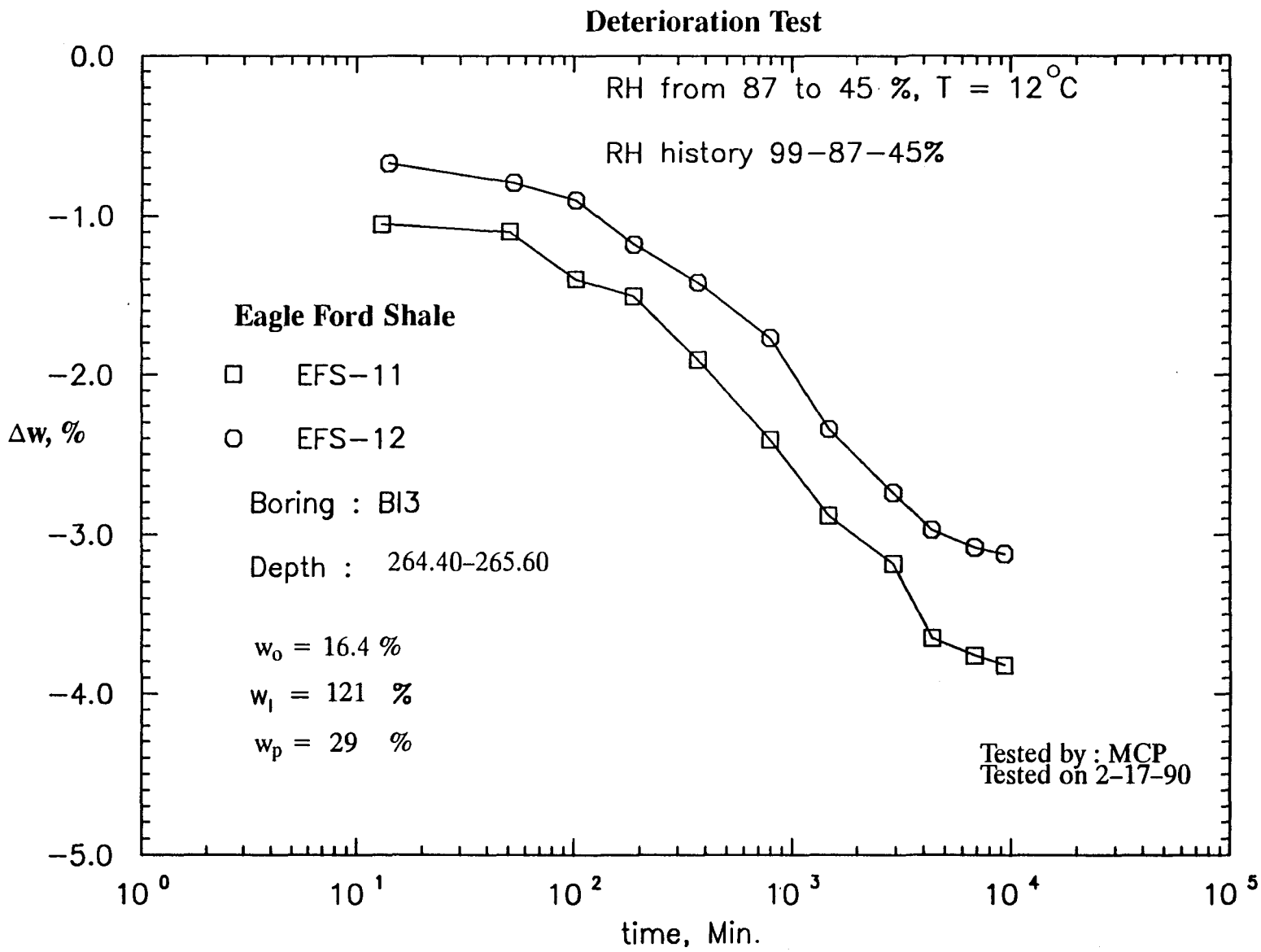


Fig. D4c Water Content Change – Log time Relationship

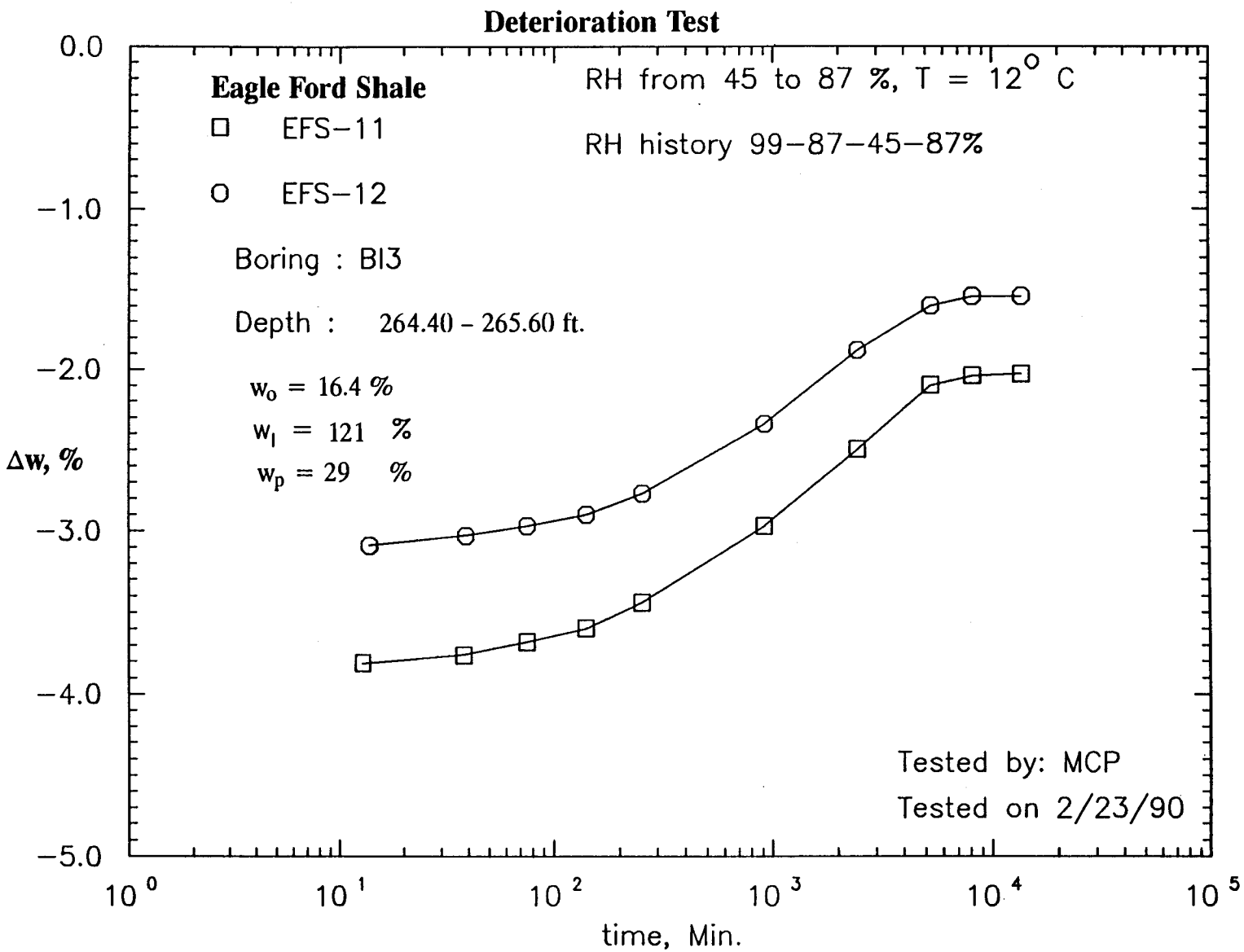


Fig. D4d Water Content Change – Log time Relationship

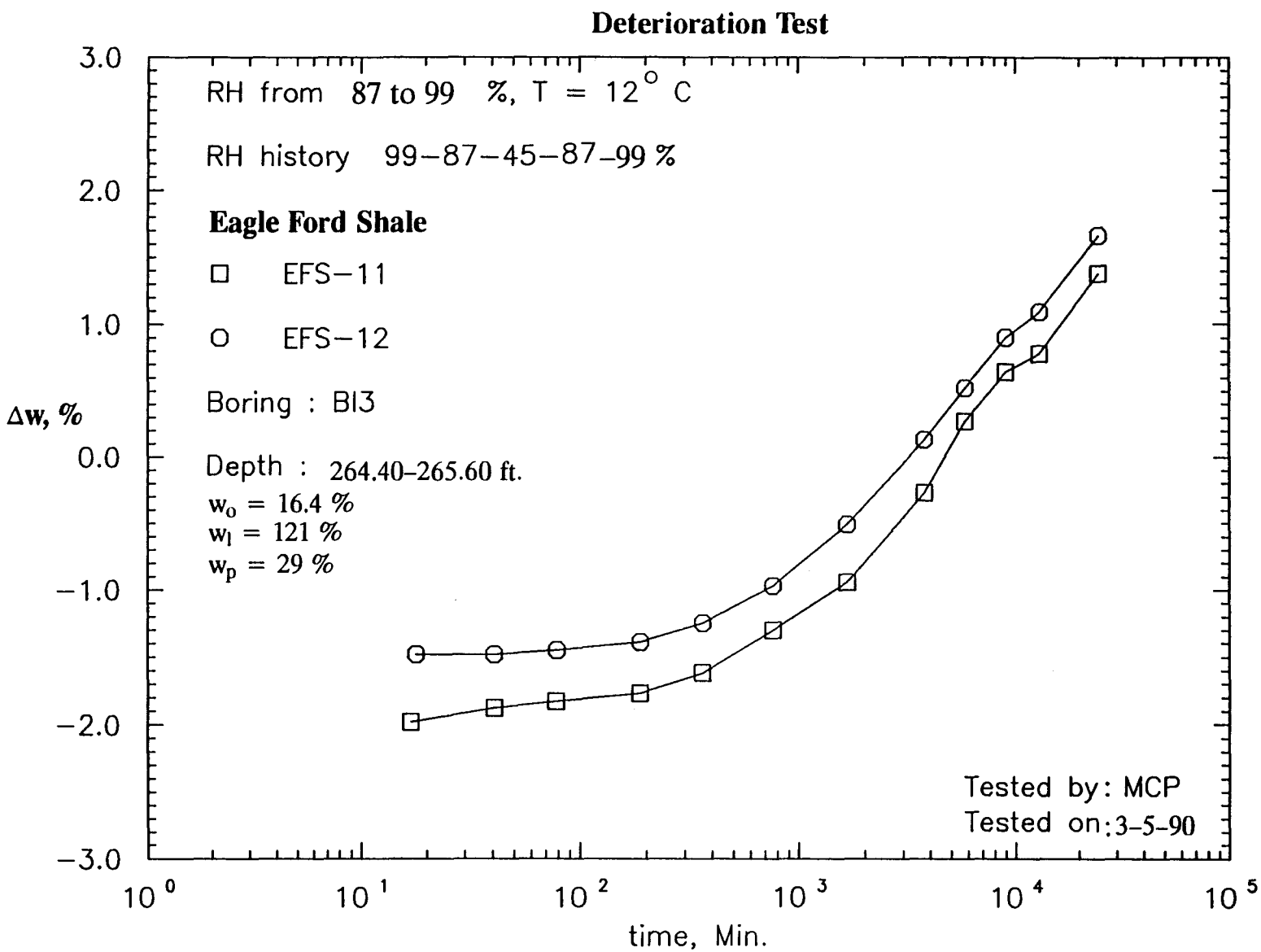


Fig. D4e Water Content Change – Log time Relationship

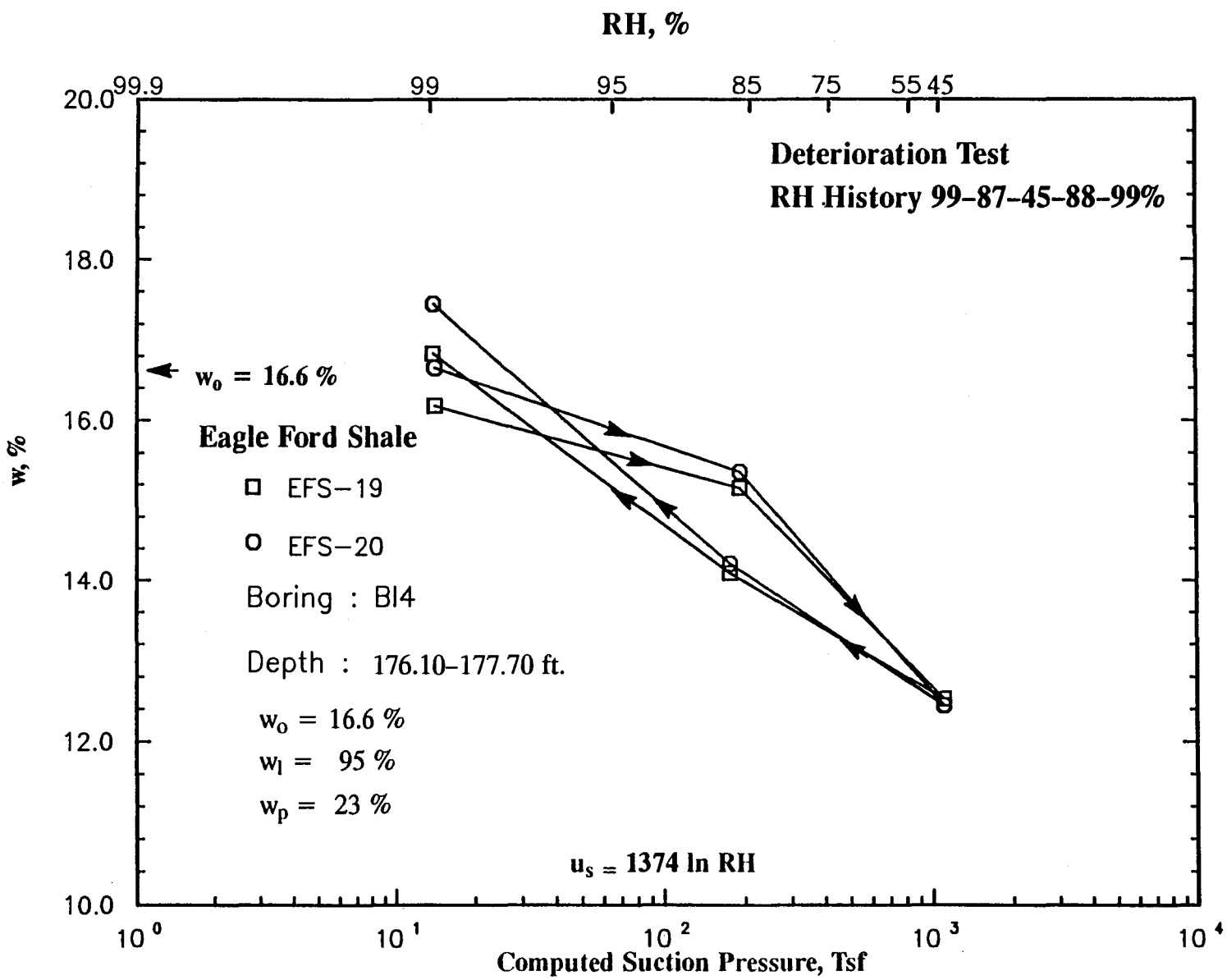


Fig. D5 Water Content – Relative Humidity Relationship

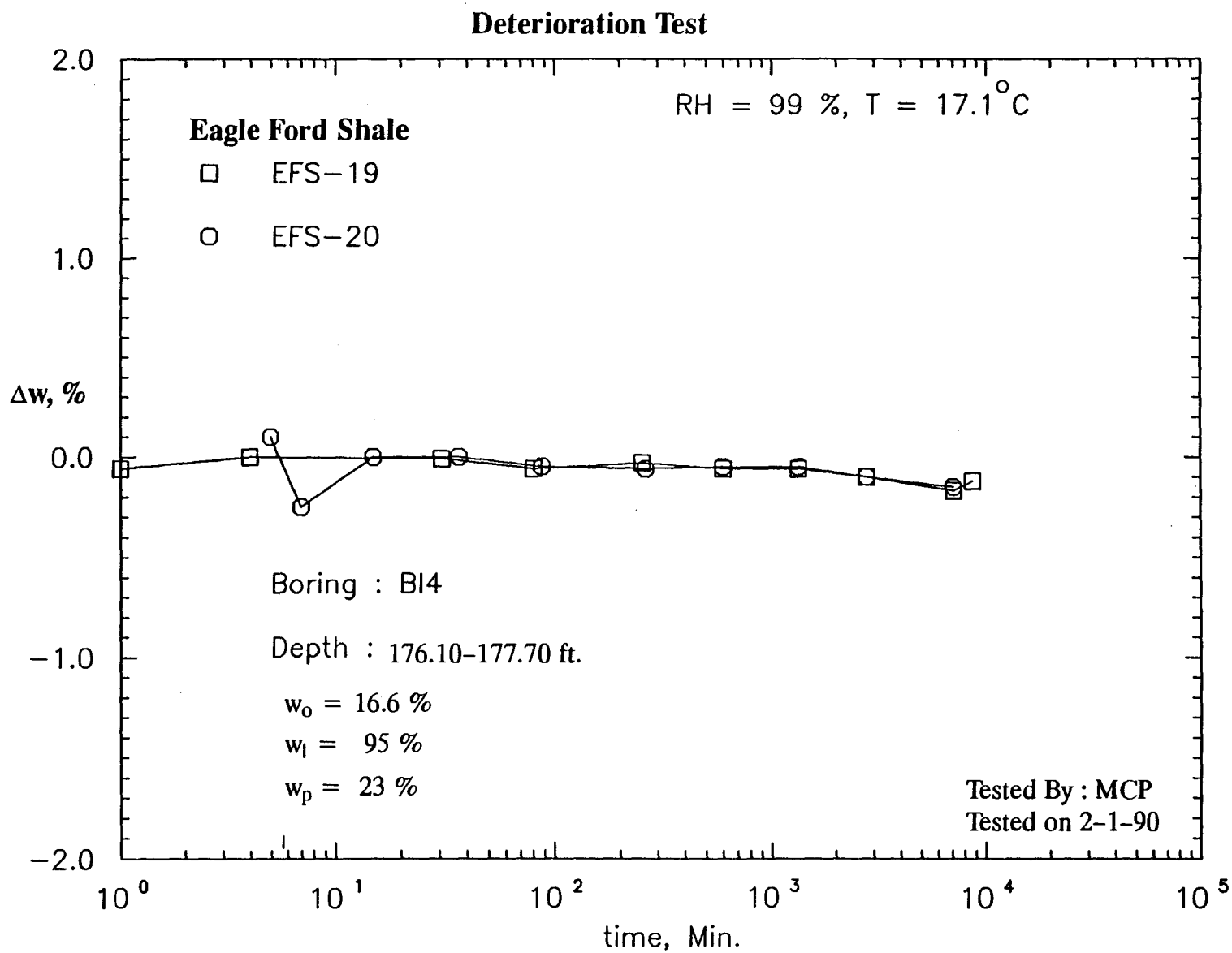


Fig. D5a Water Content Change – Log time Relationship

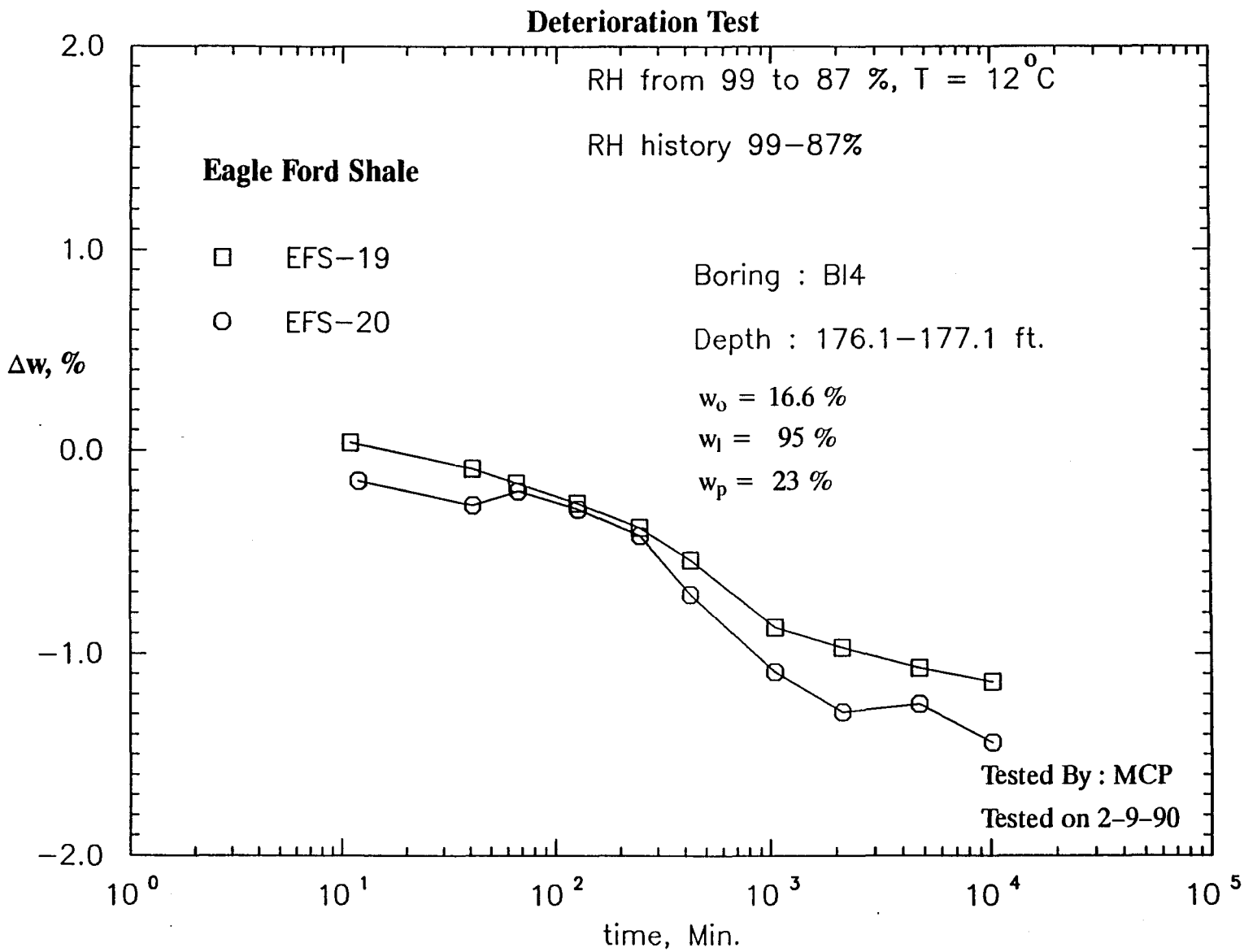


Fig. D5b Water Content Change – Log time Relationship

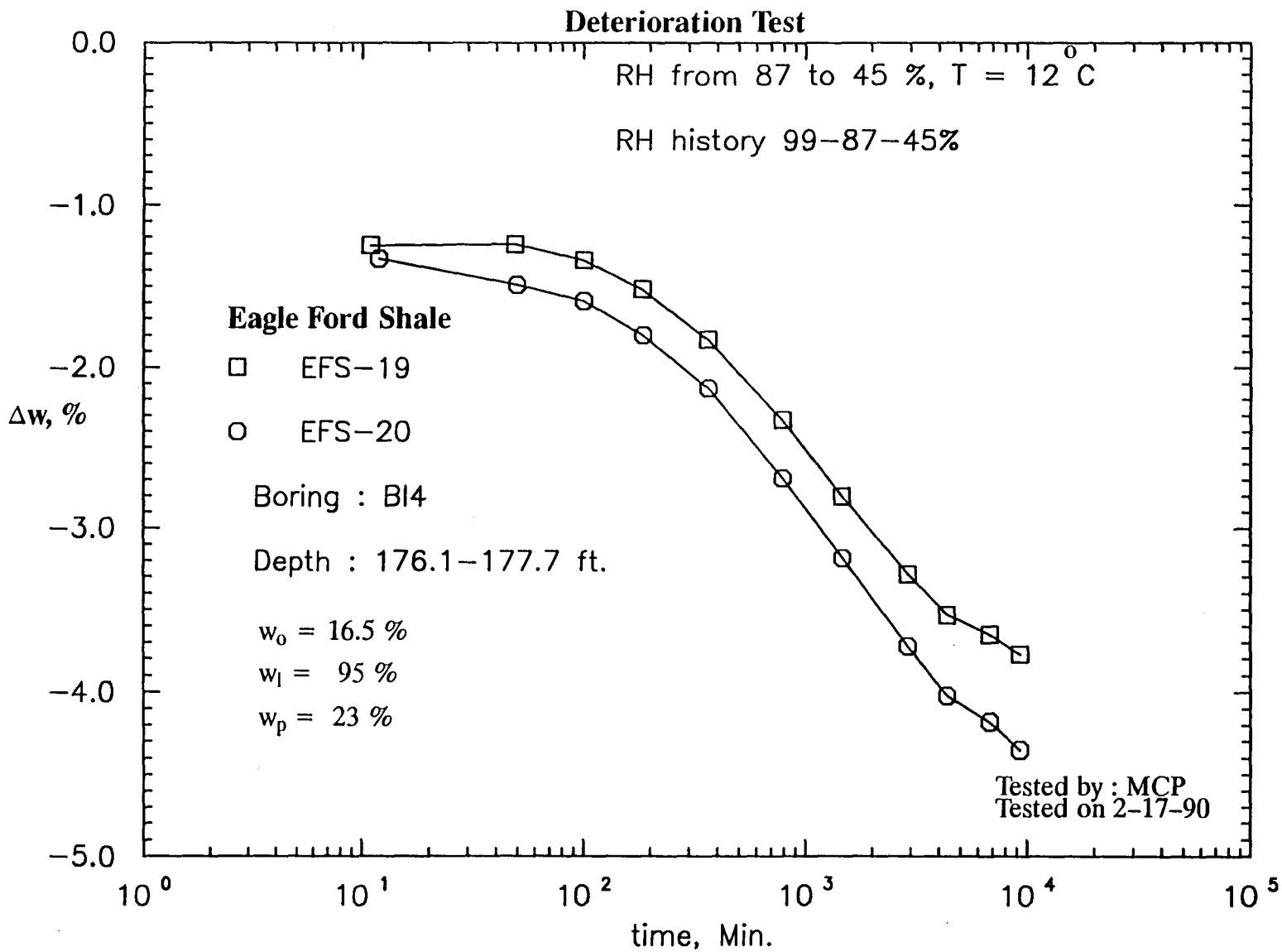


Fig. D5c Water Content Change – Log time Relationship

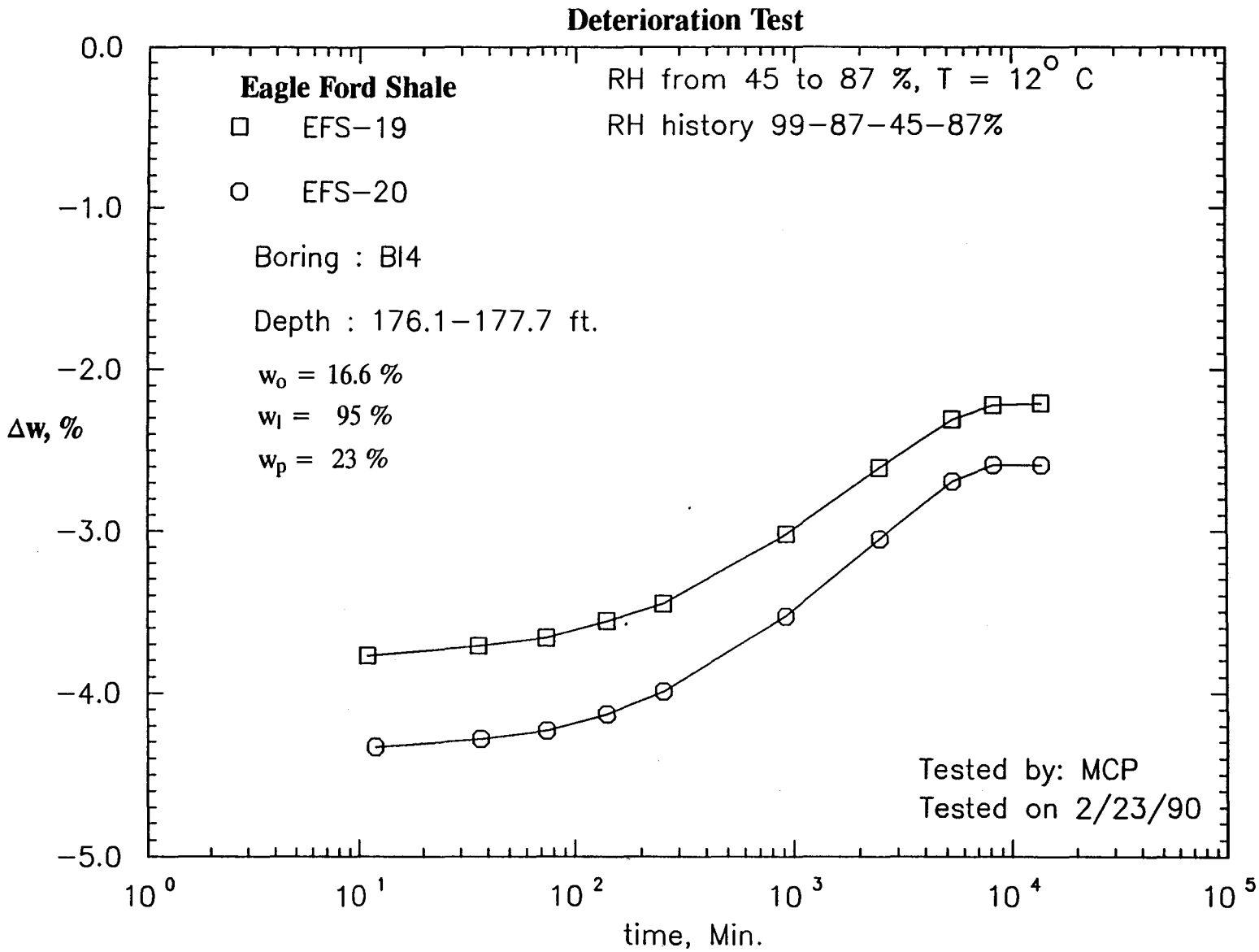


Fig. D5d Water Content Change – Log time Relationship

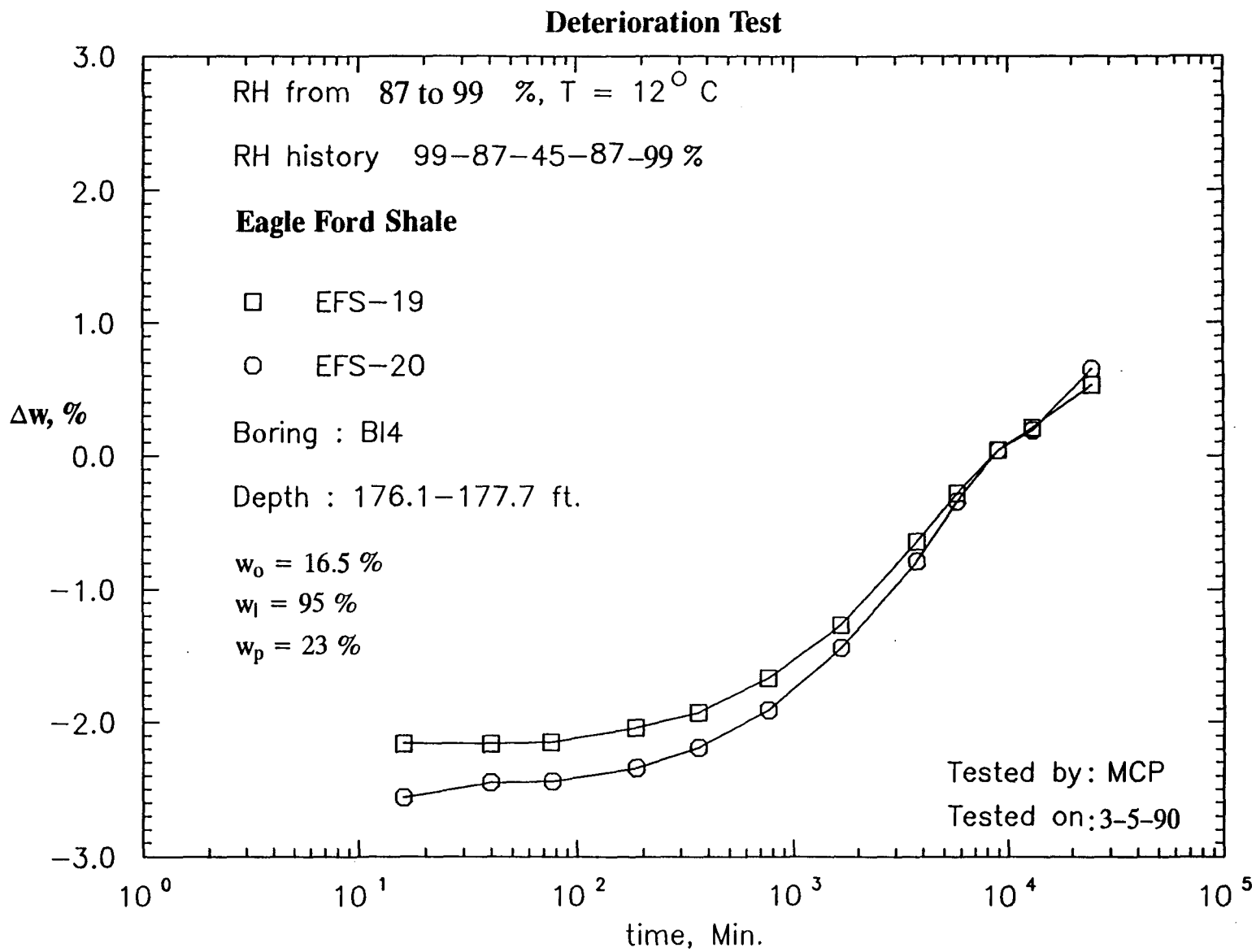


Fig. D5e Water Content Change – Log time Relationship

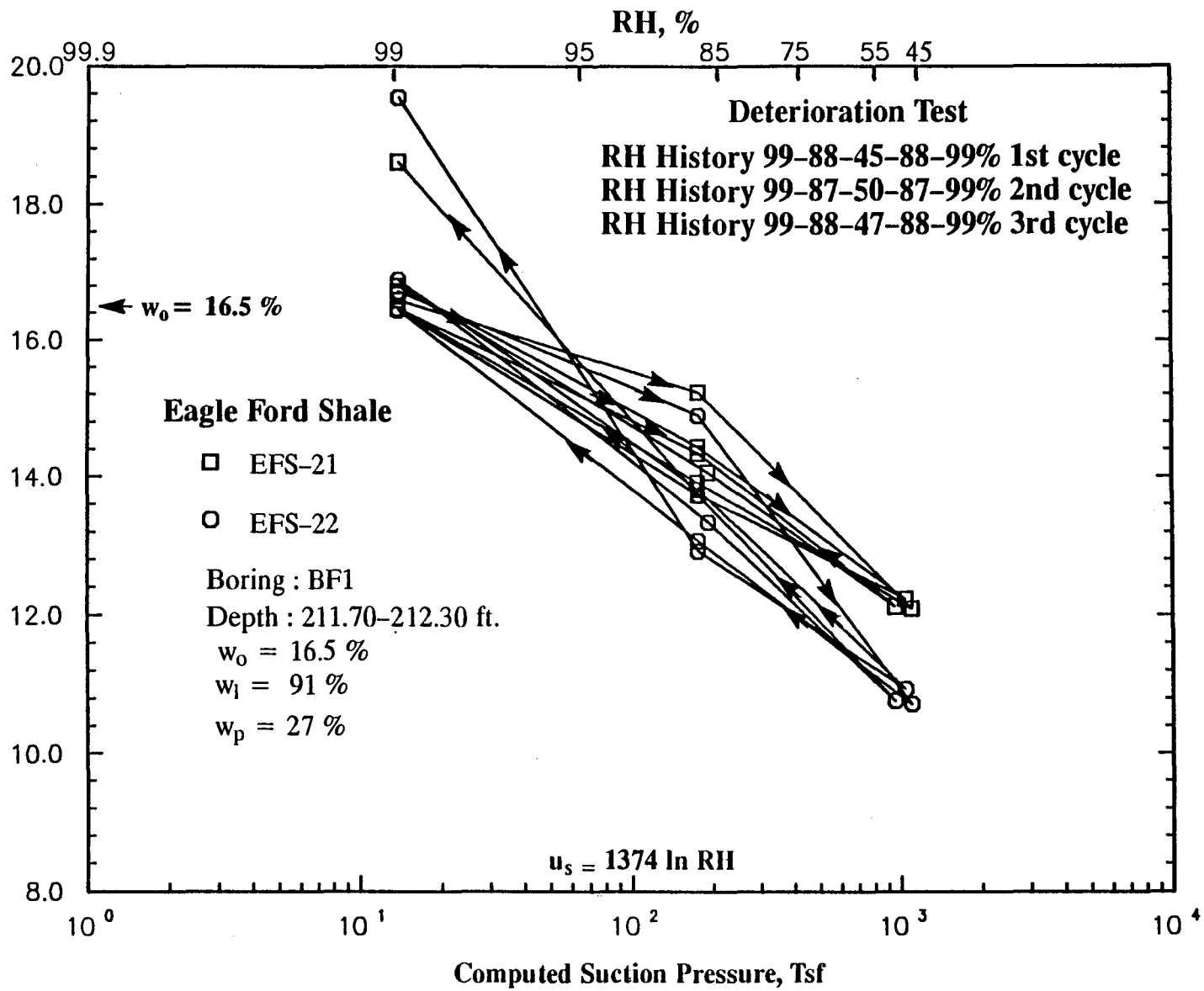


Fig. D6 Water Content – Relative Humidity Relationship

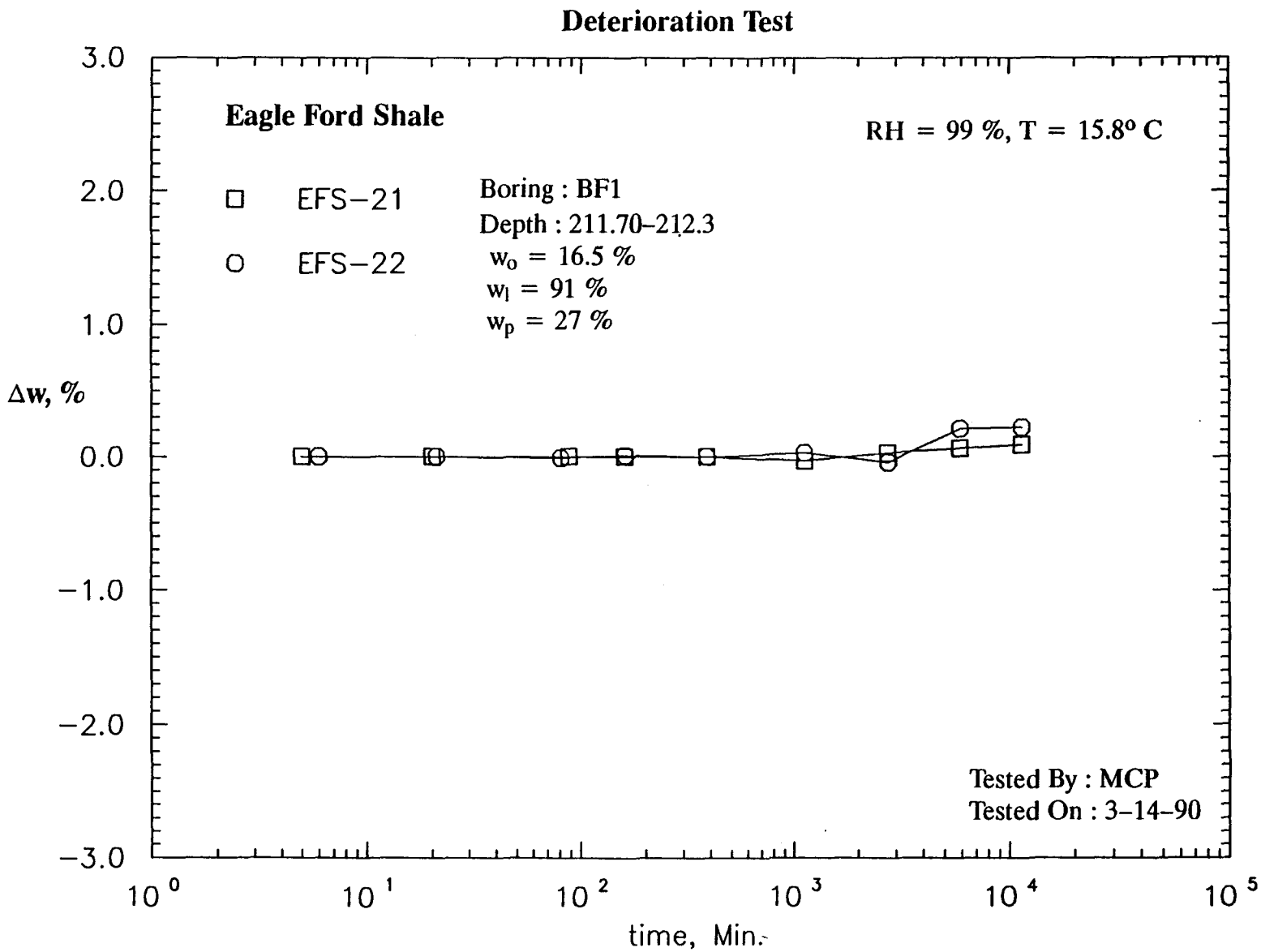


Fig. D6a Water Content Change – Log time Relationship

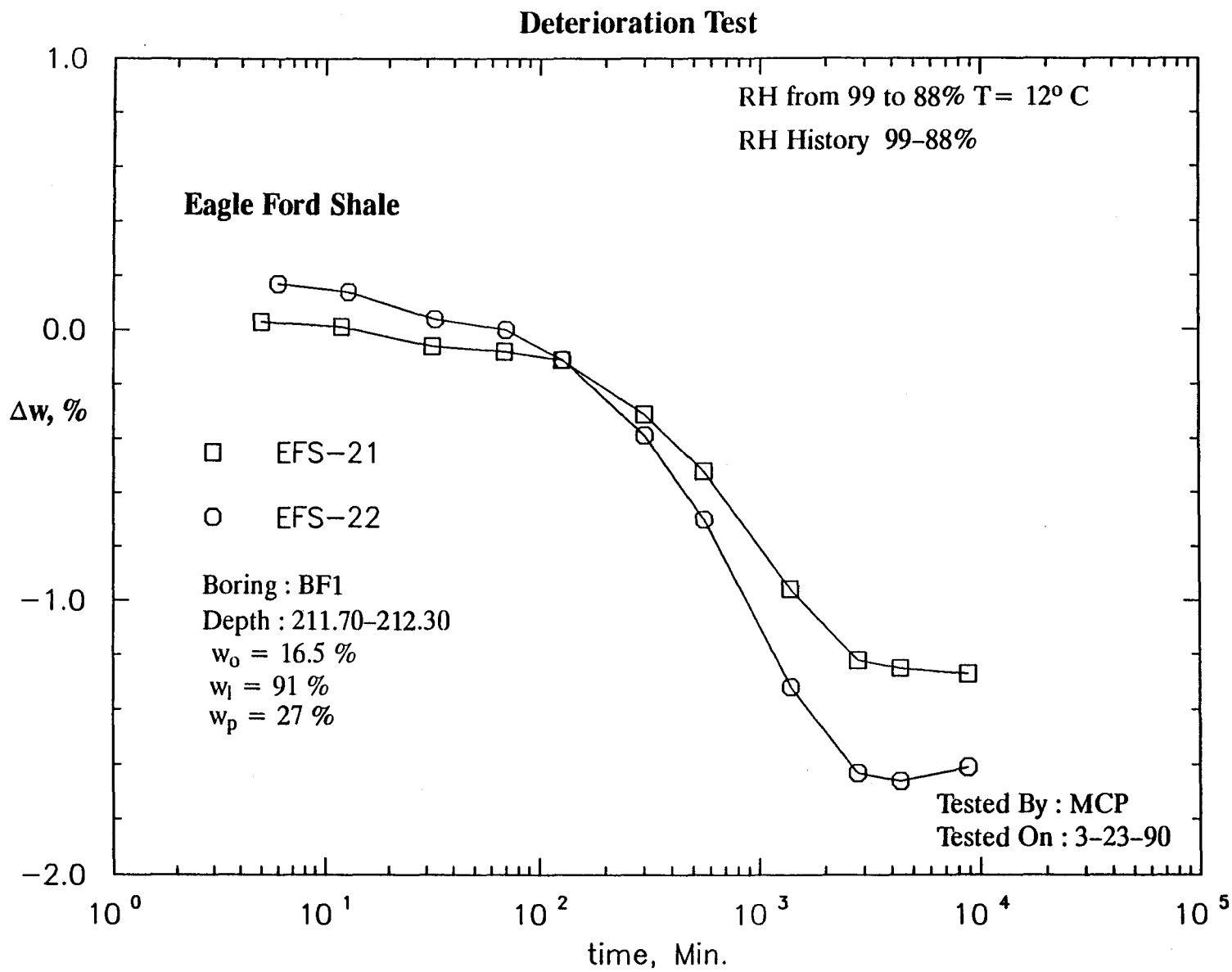


Fig. D6b Water Content Change – Log time Relationship

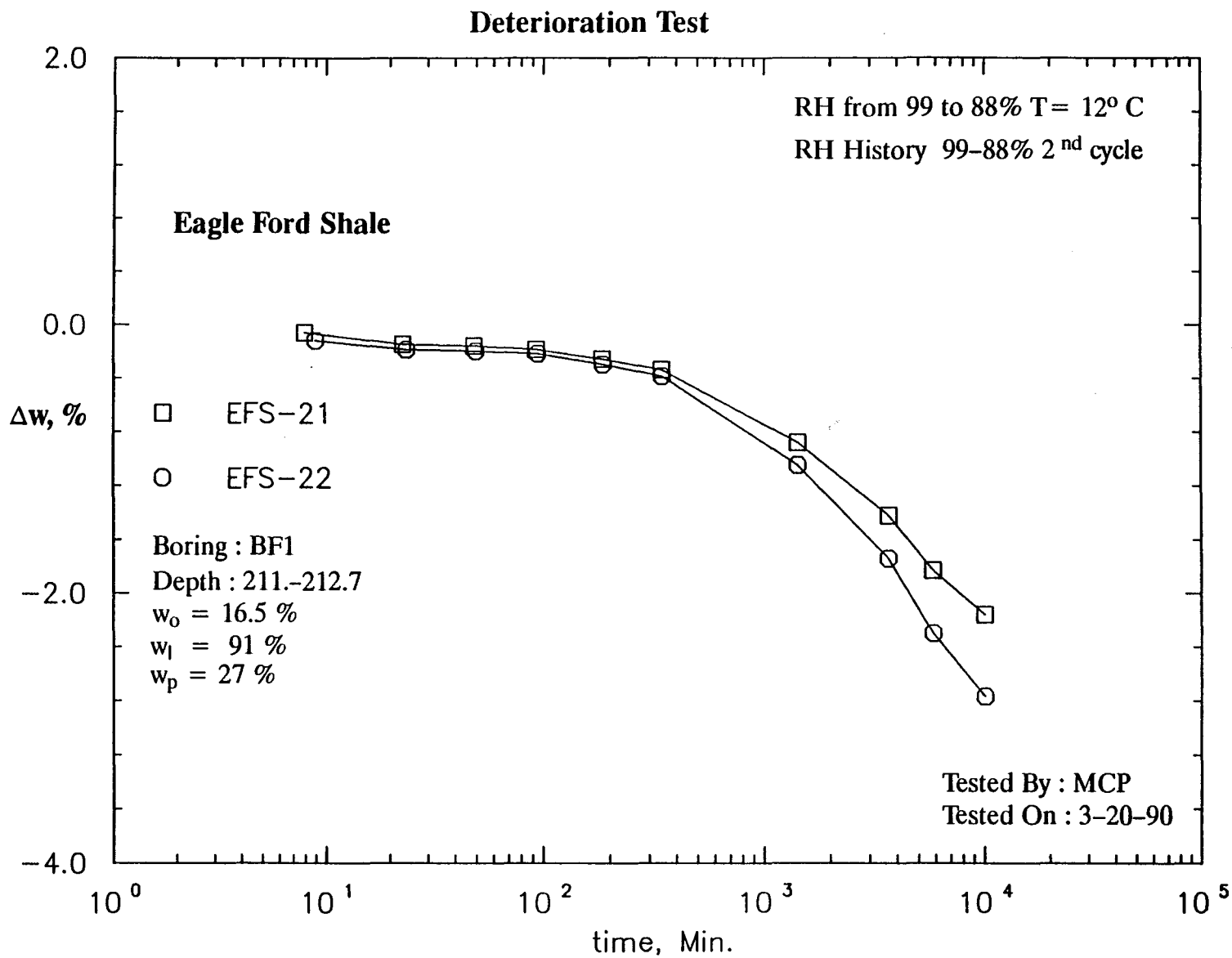


Fig. D6c Water Content Change – Log time Relationship

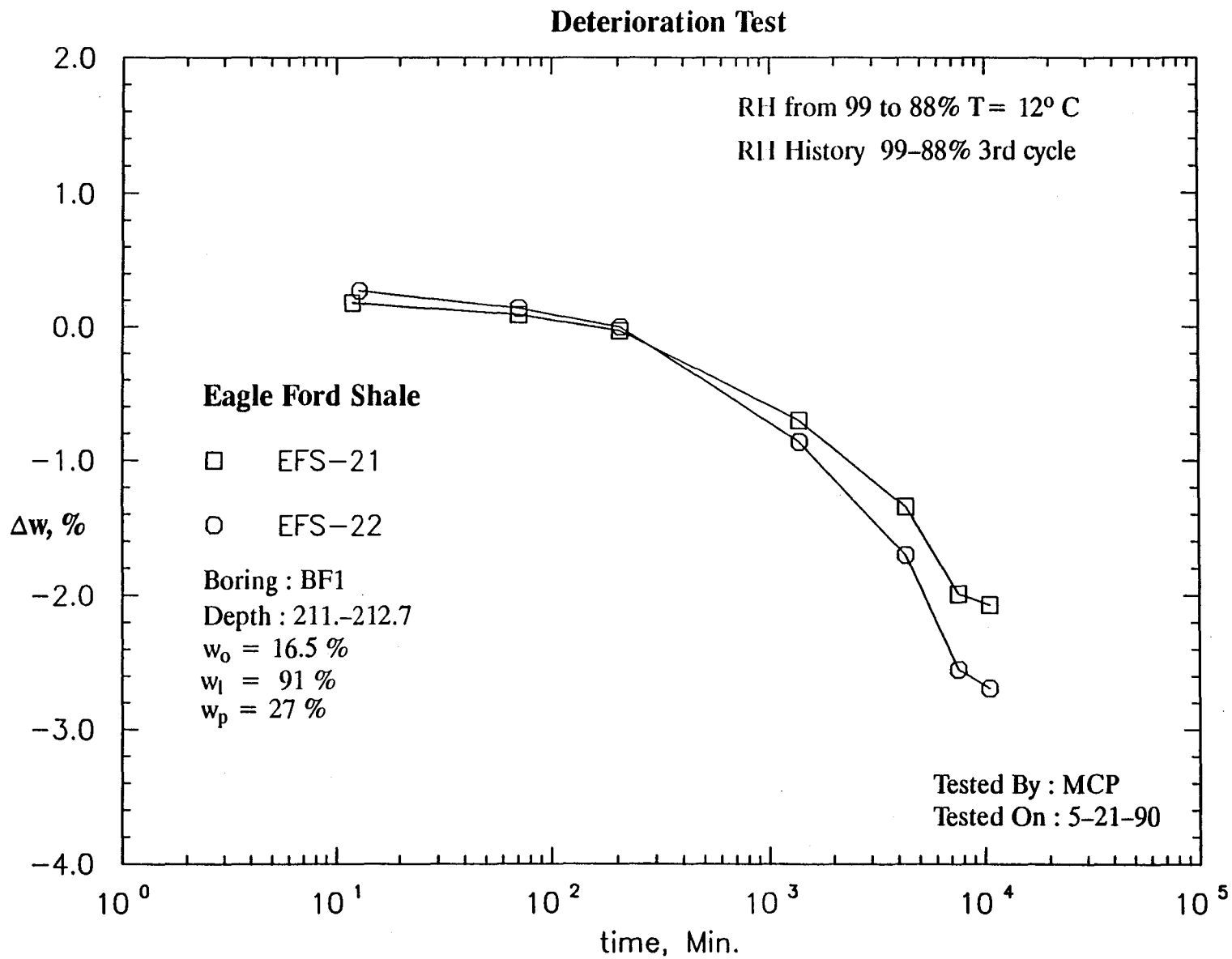


Fig. D6d Water Content Change – Log time Relationship

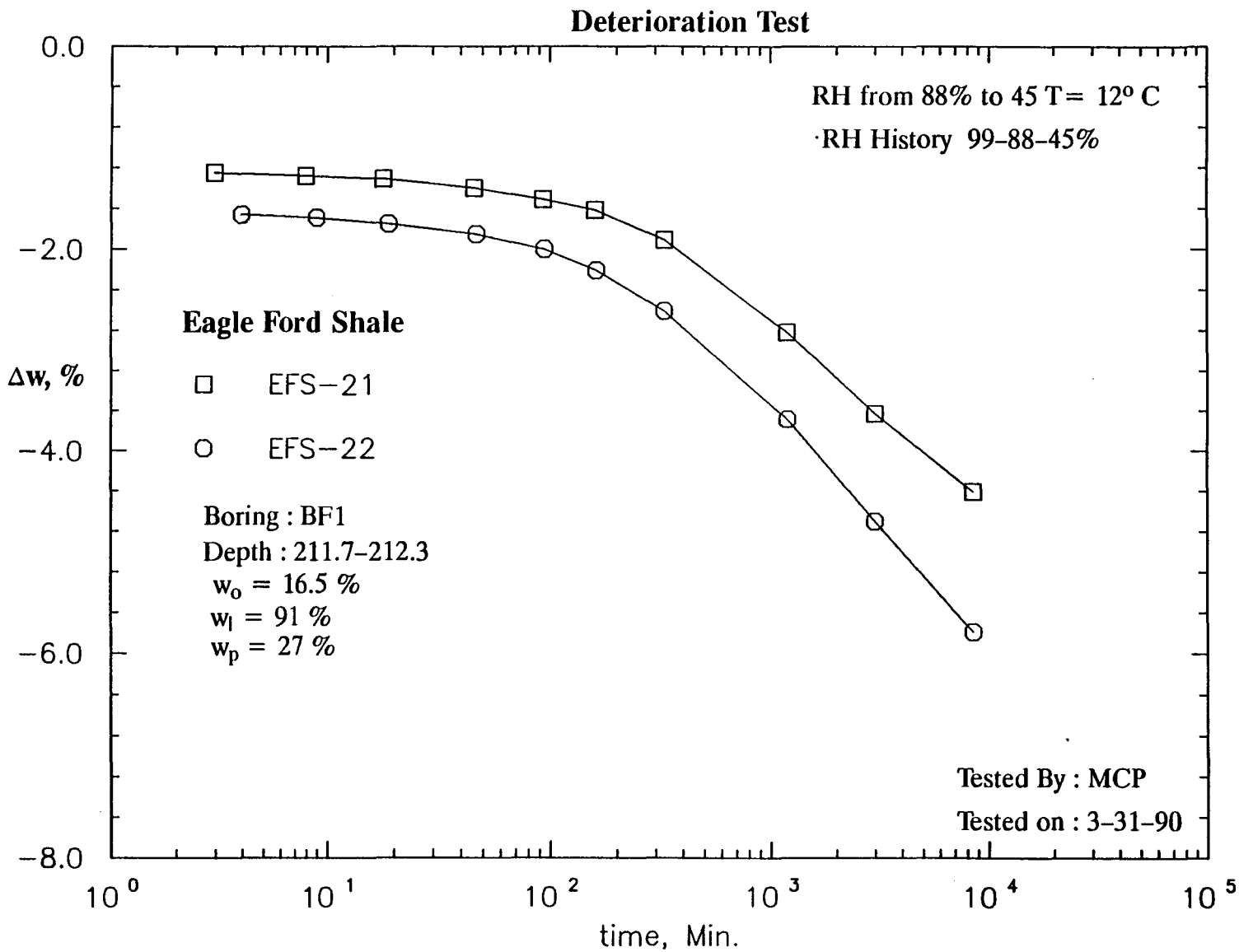


Fig. D6e Water Content Change - Log time Relationship

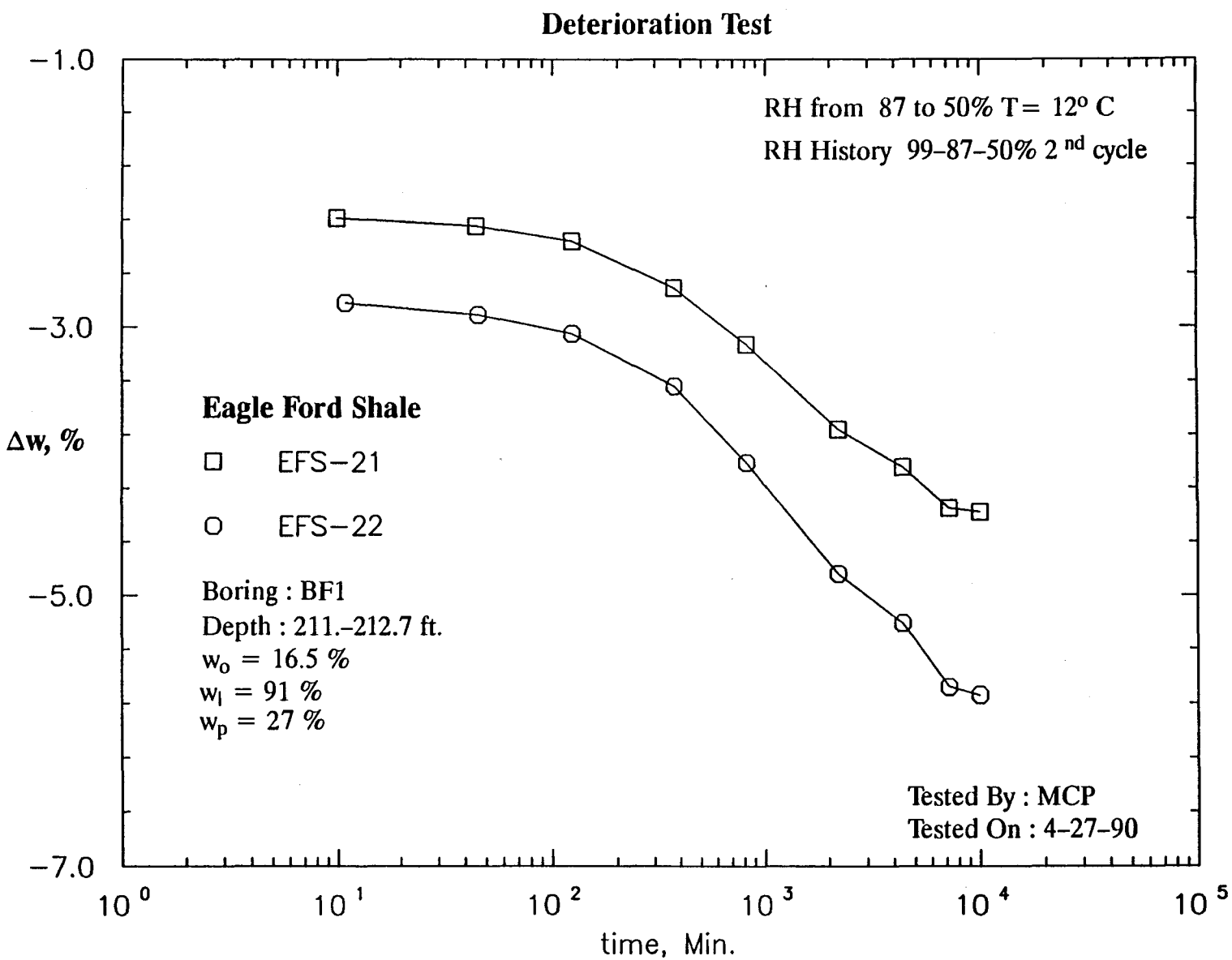


Fig. D6f Water Content Change – Log time Relationship

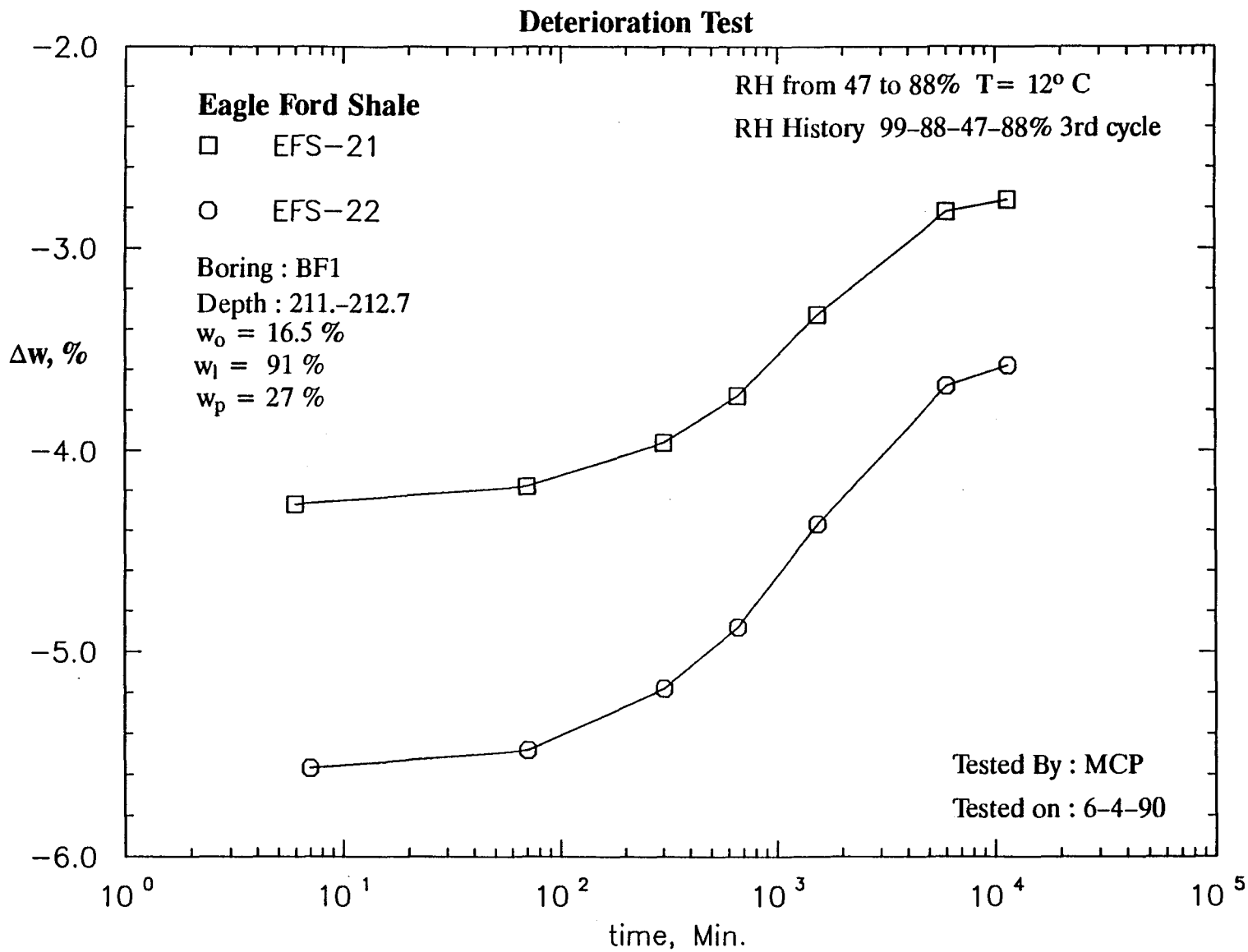


Fig. D6j Water Content Change – Log time Relationship

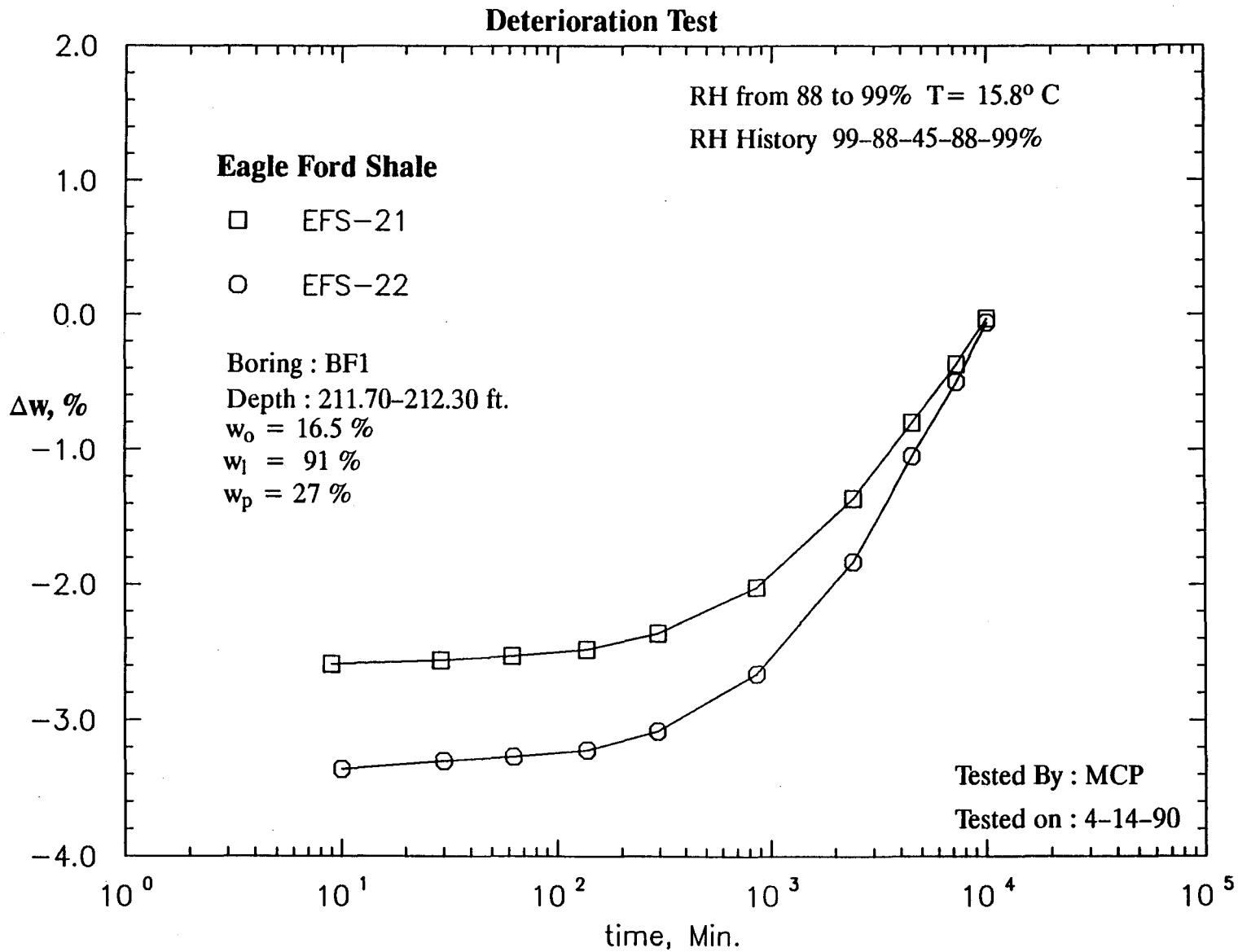


Fig. D6k Water Content Change – Log time Relationship

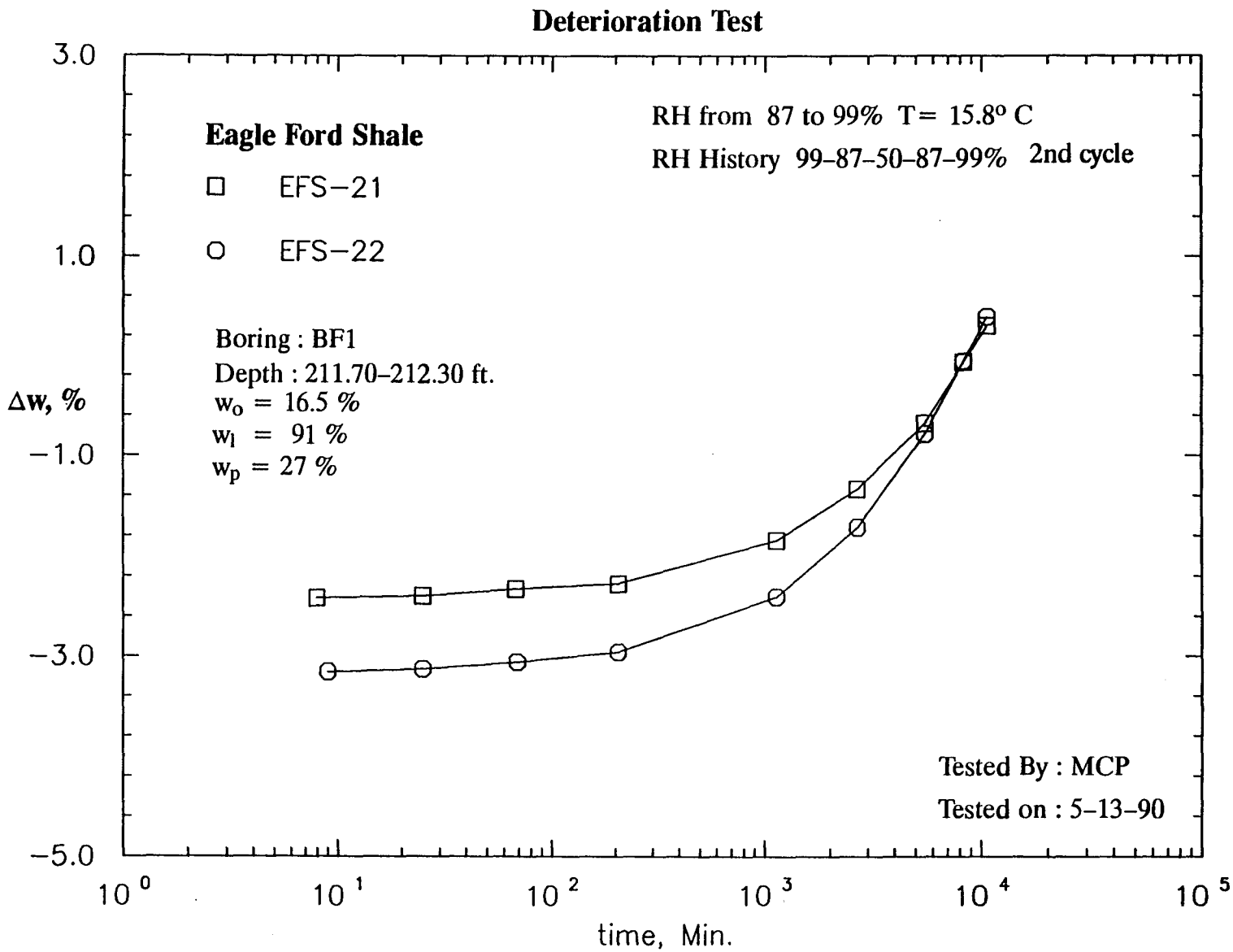


Fig. D6l Water Content Change – Log time Relationship

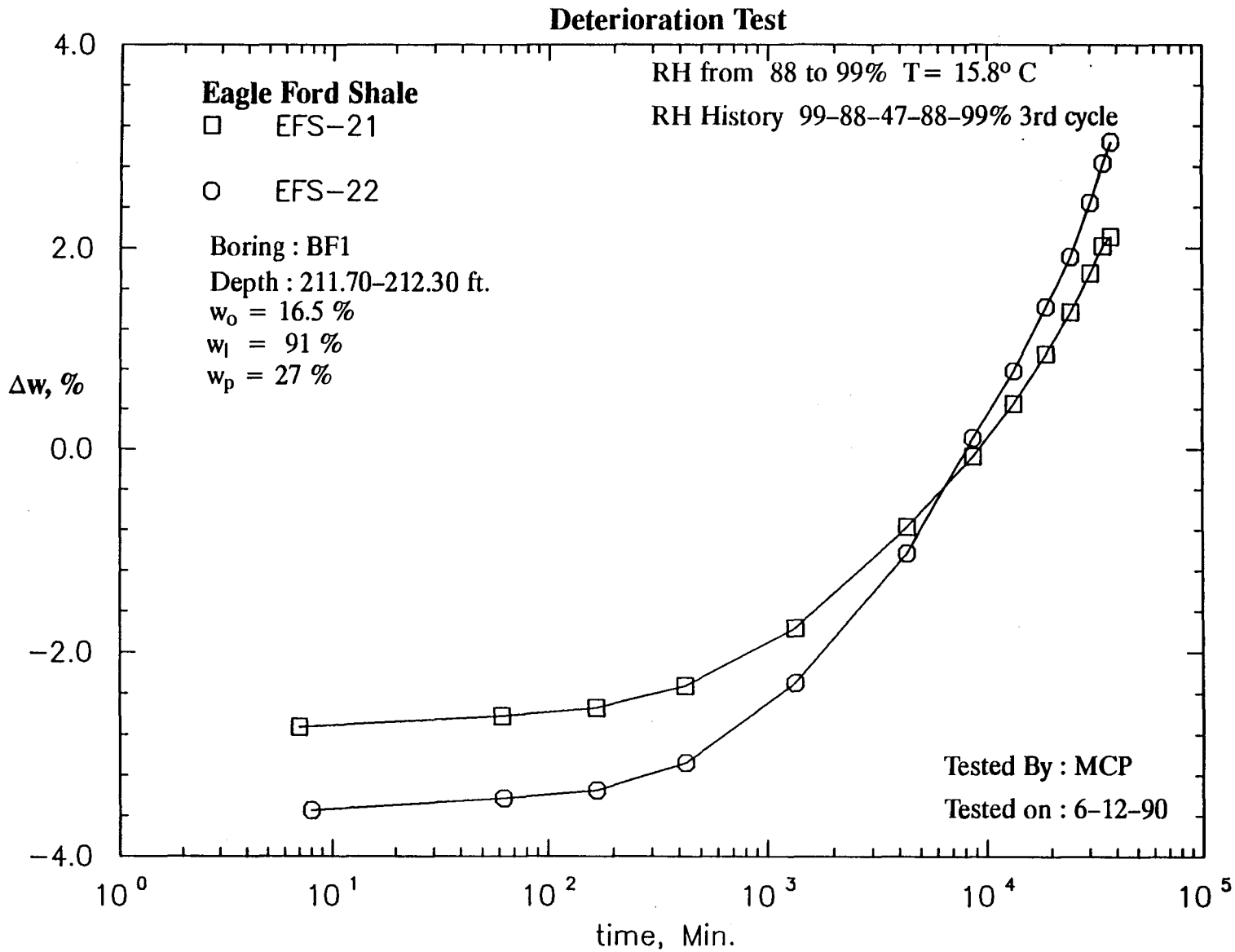


Fig. D6m Water Content Change – Log time Relationship

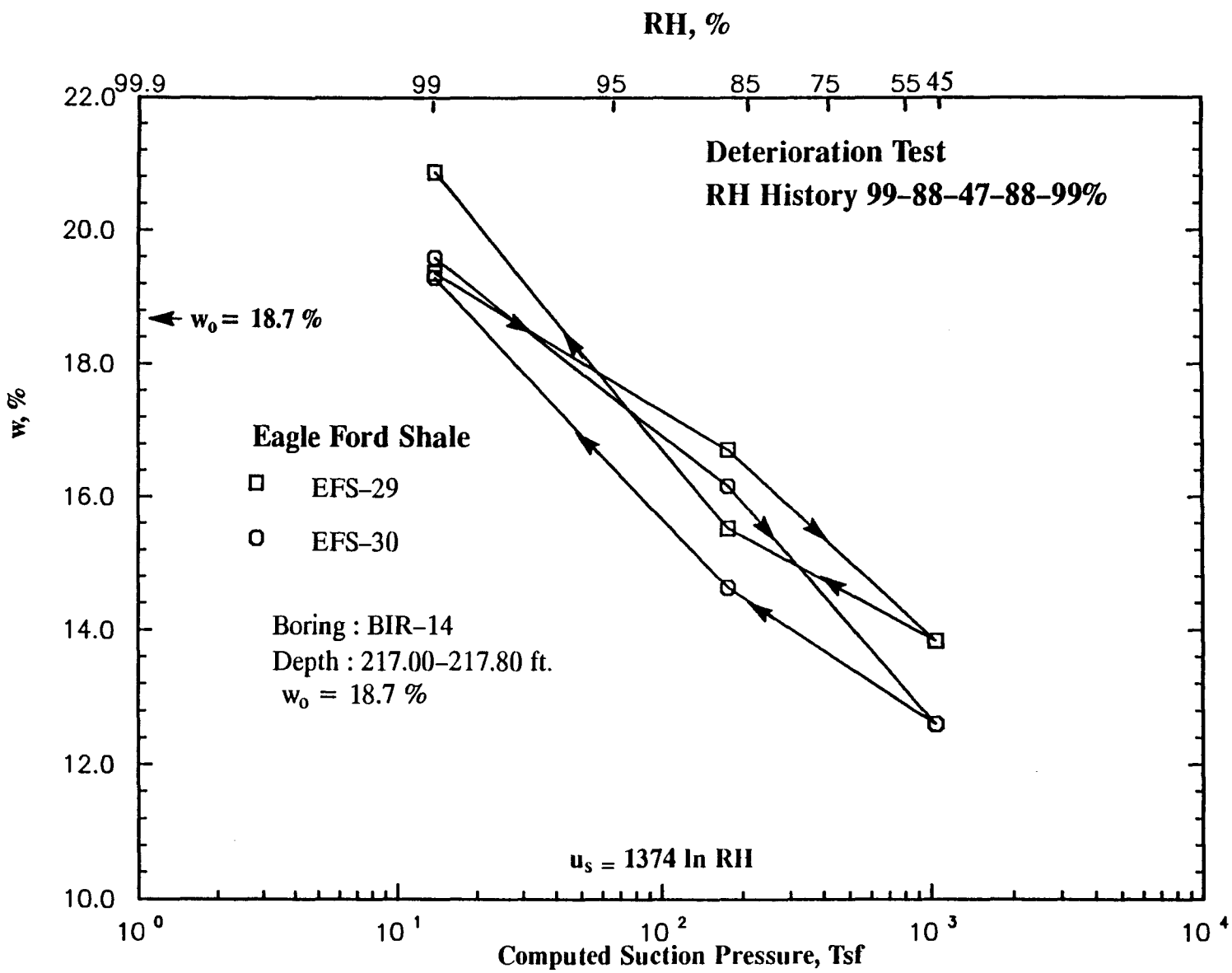


Fig. D7 Water Content – Relative Humidity Relationship

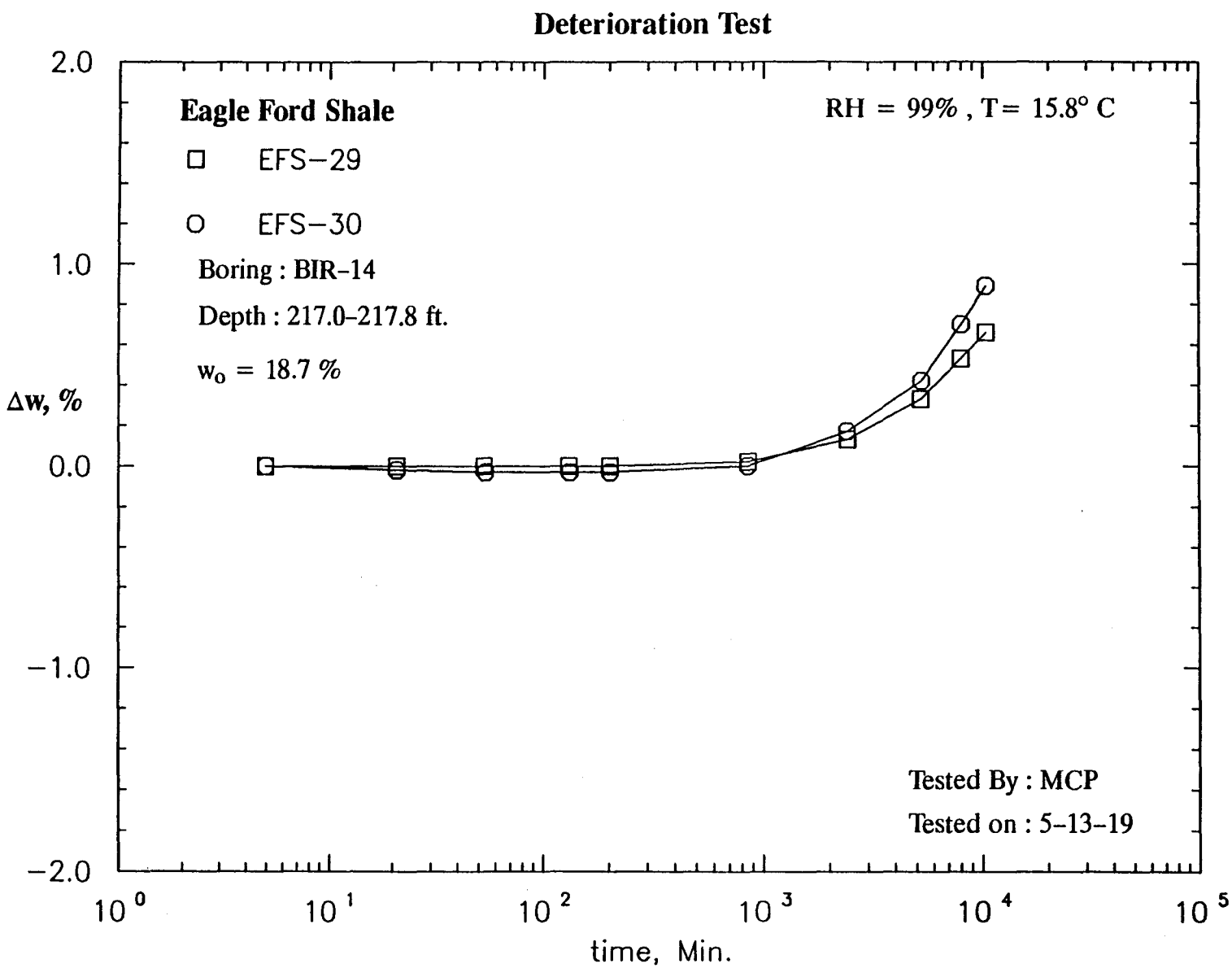


Fig. D7a Water Content Change – Log time Relationship

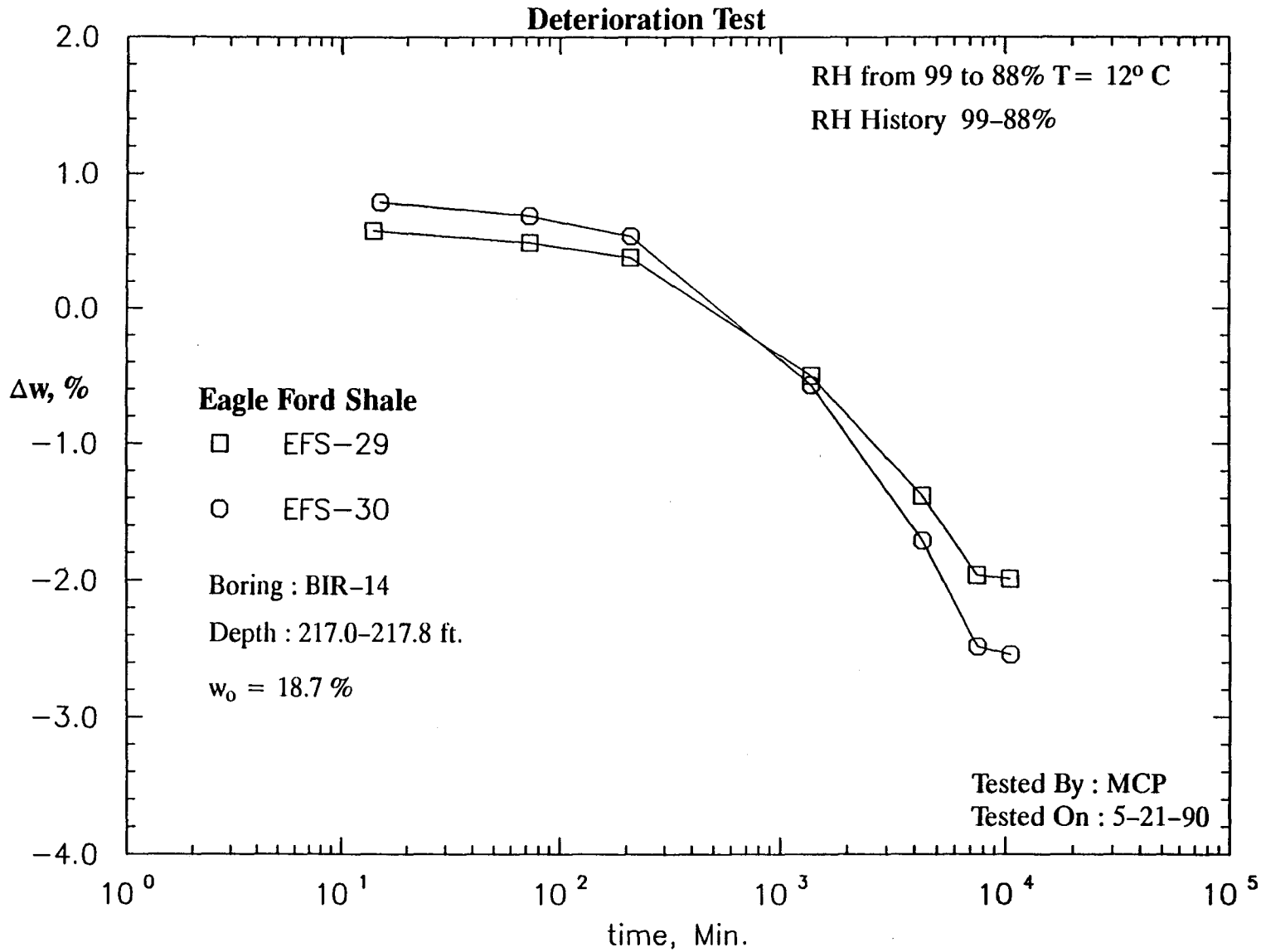


Fig. D7b Water Content Change – Log time Relationship

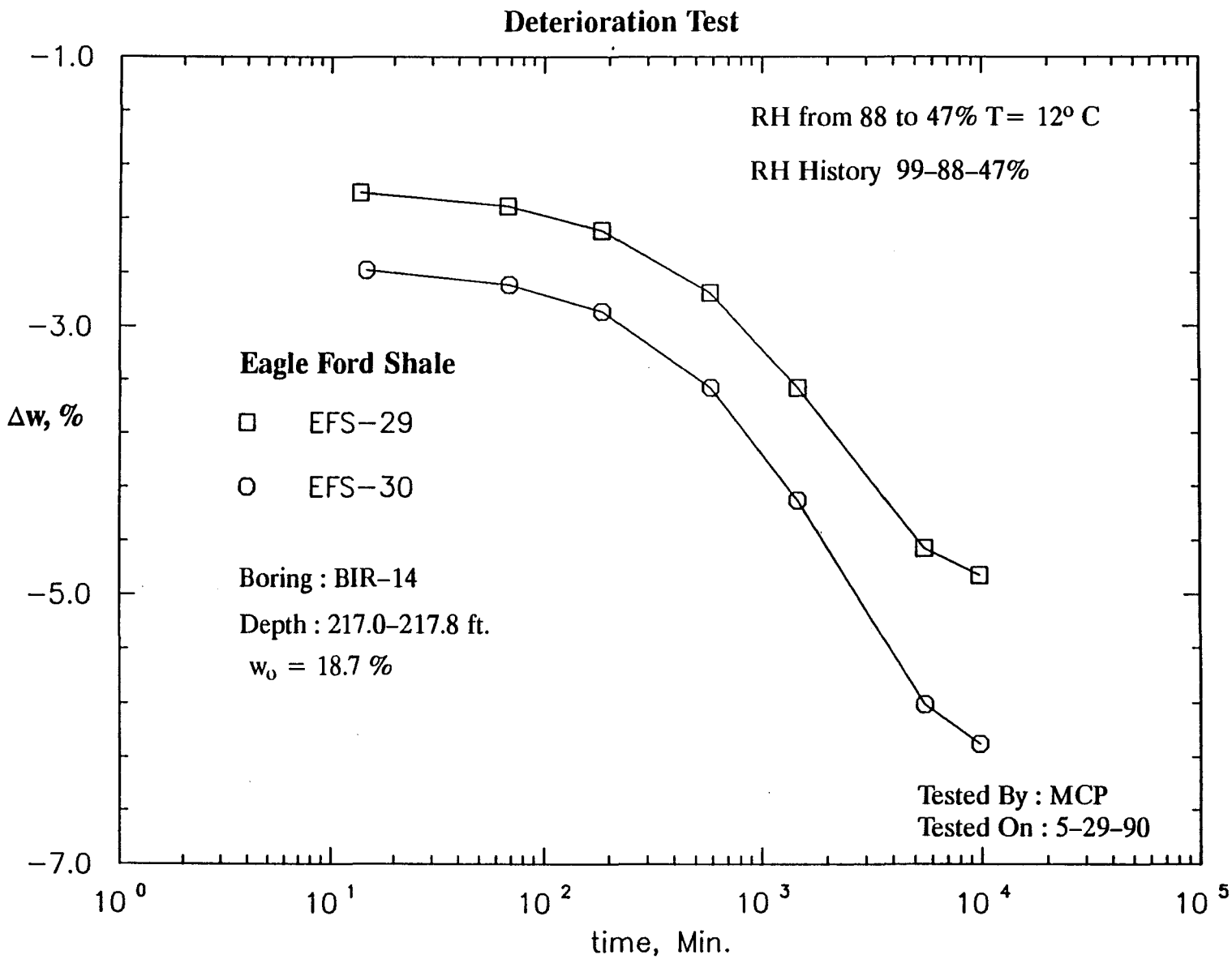


Fig. D7c Water Content Change – Log time Relationship

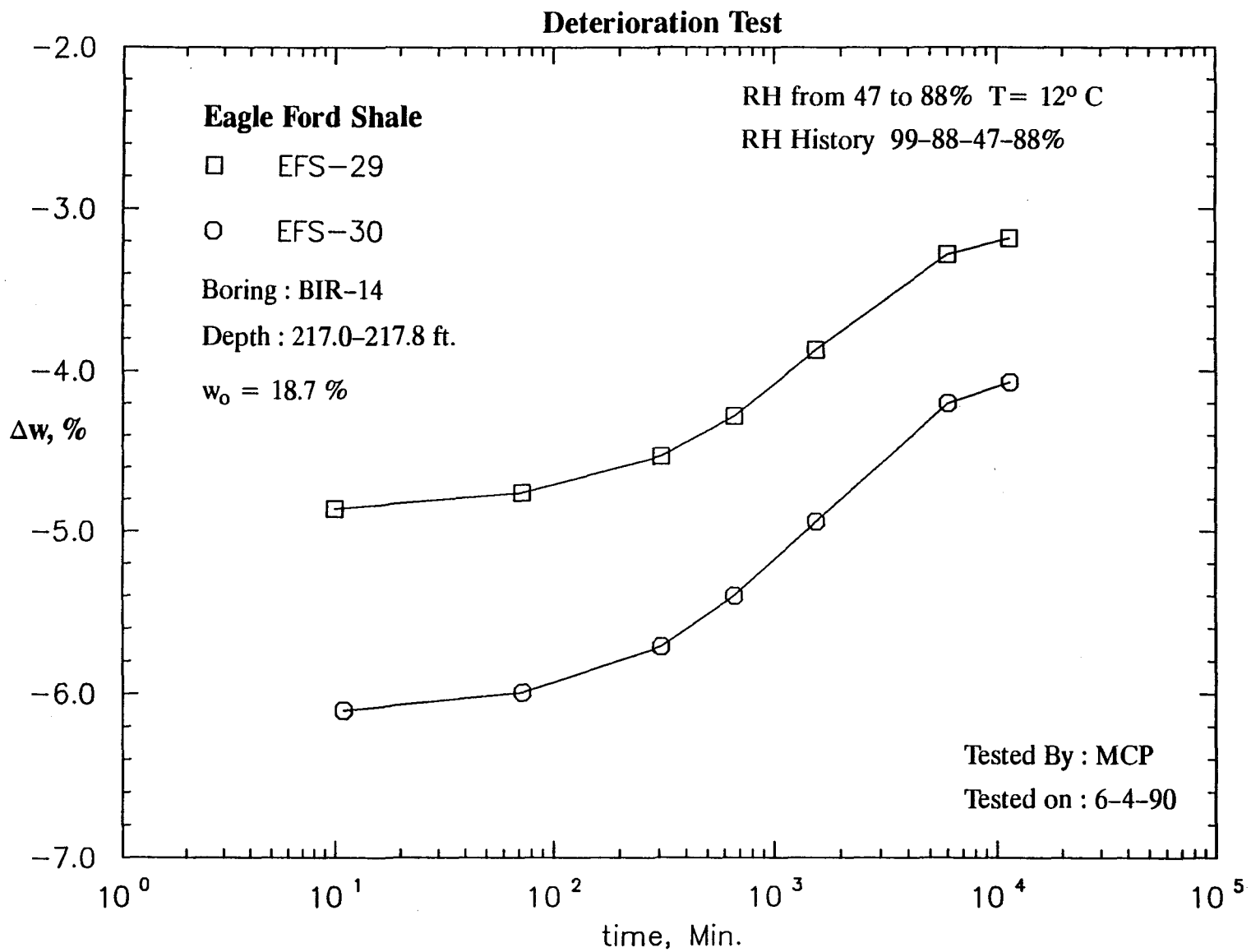


Fig. D7d Water Content Change – Log time Relationship

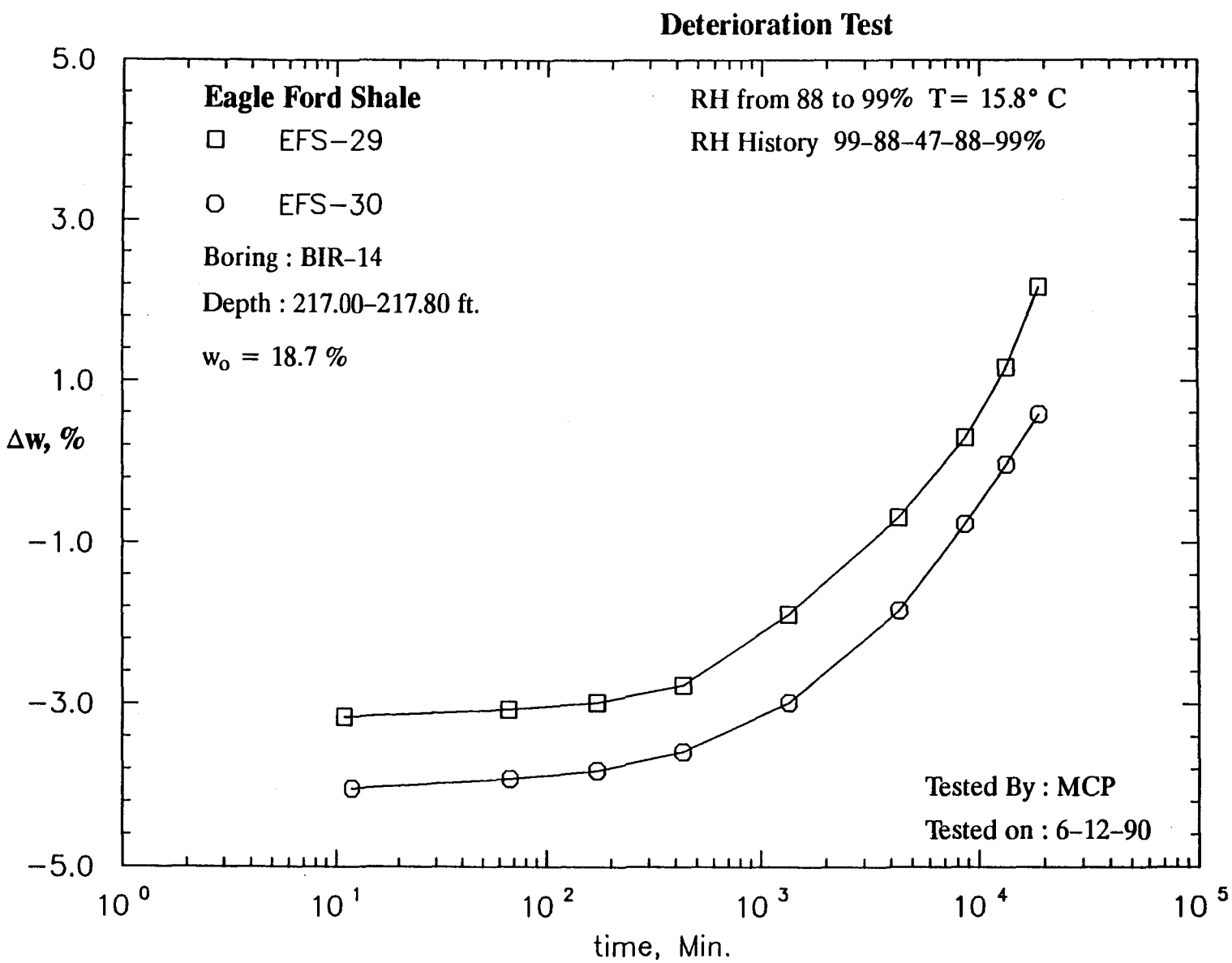


Fig. D7e Water Content Change - Log time Relationship

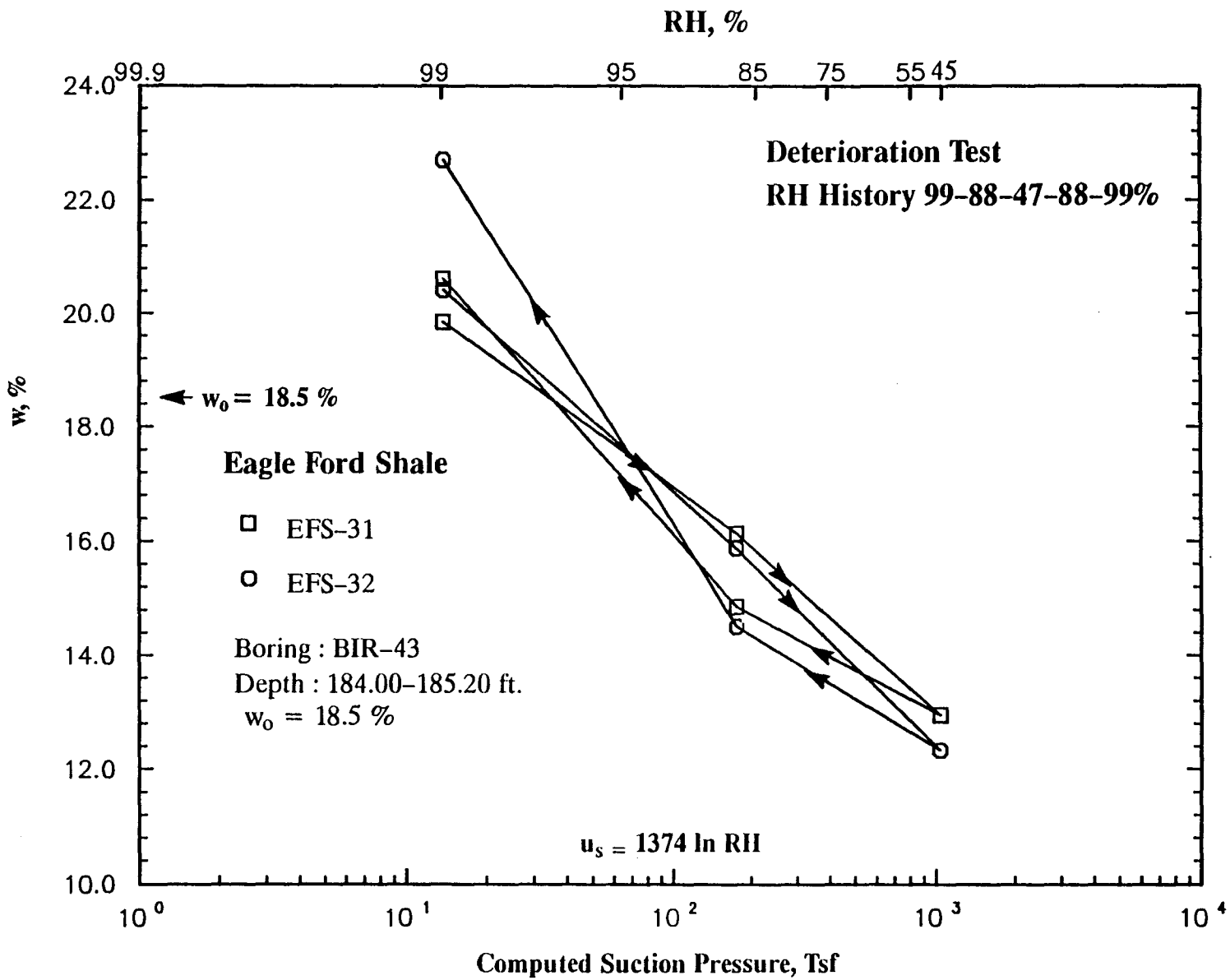


Fig. D8 Water Content – Relative Humidity Relationship

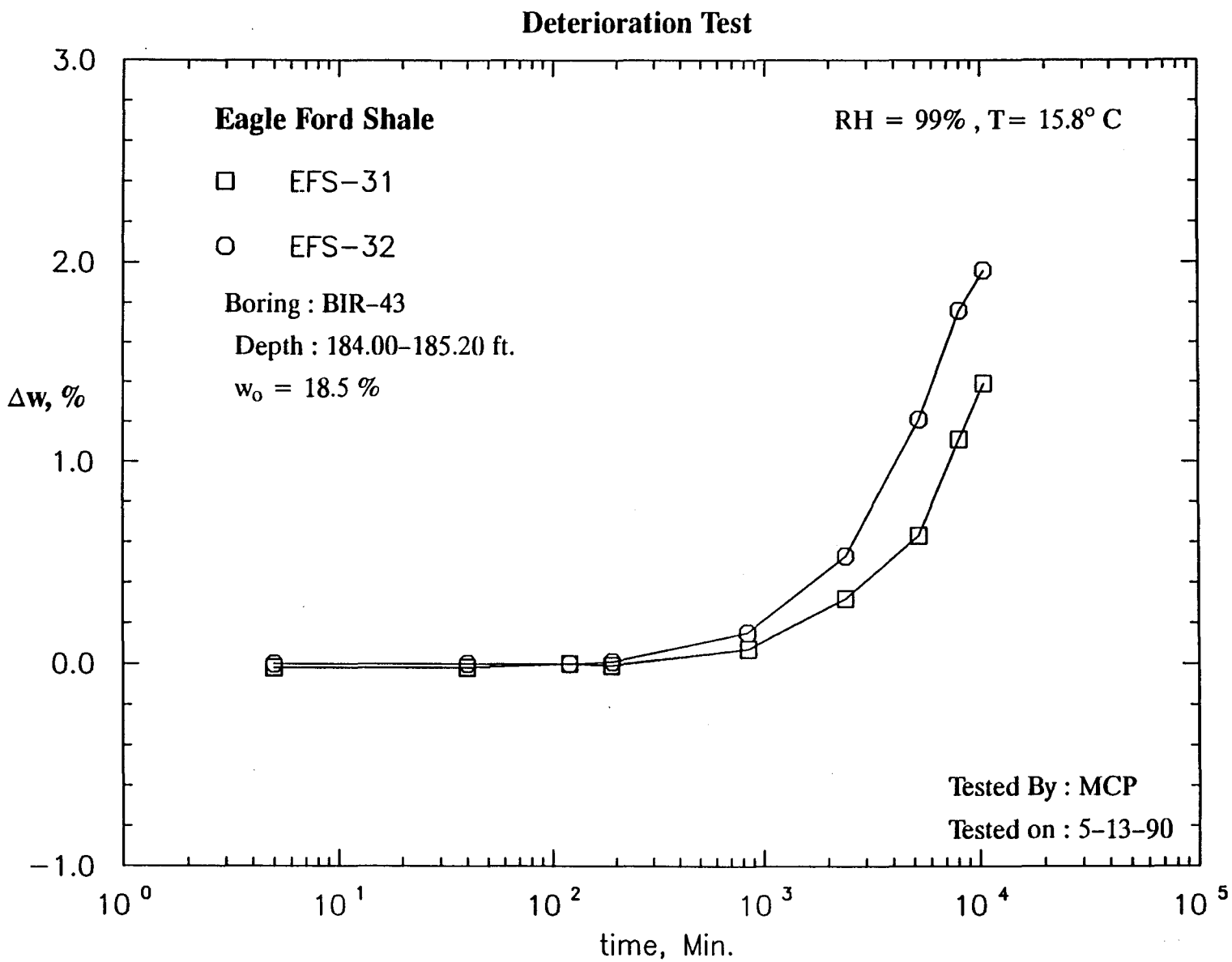


Fig. D8a Water Content Change – Log time Relationship

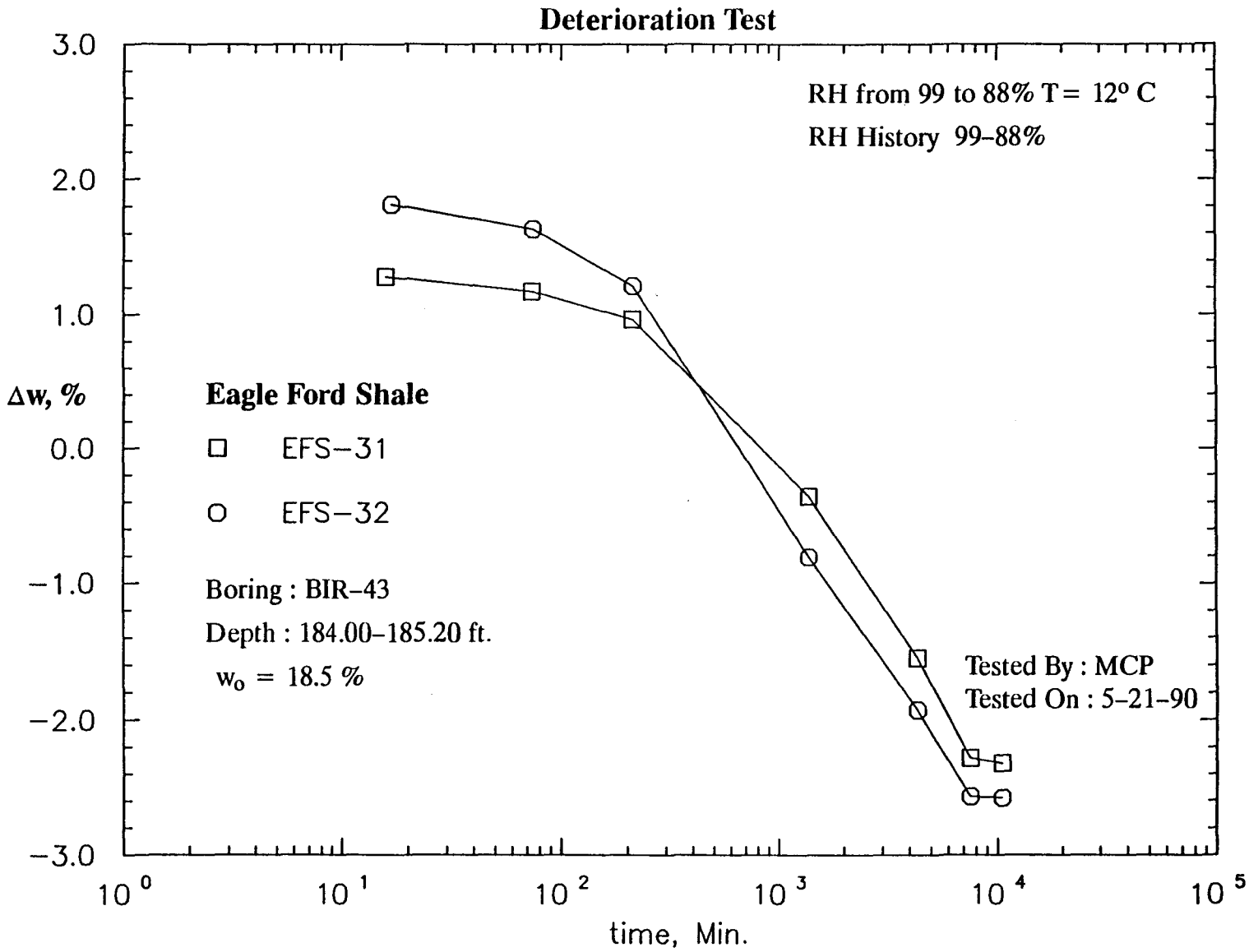


Fig. D8b Water Content Change - Log time Relationship

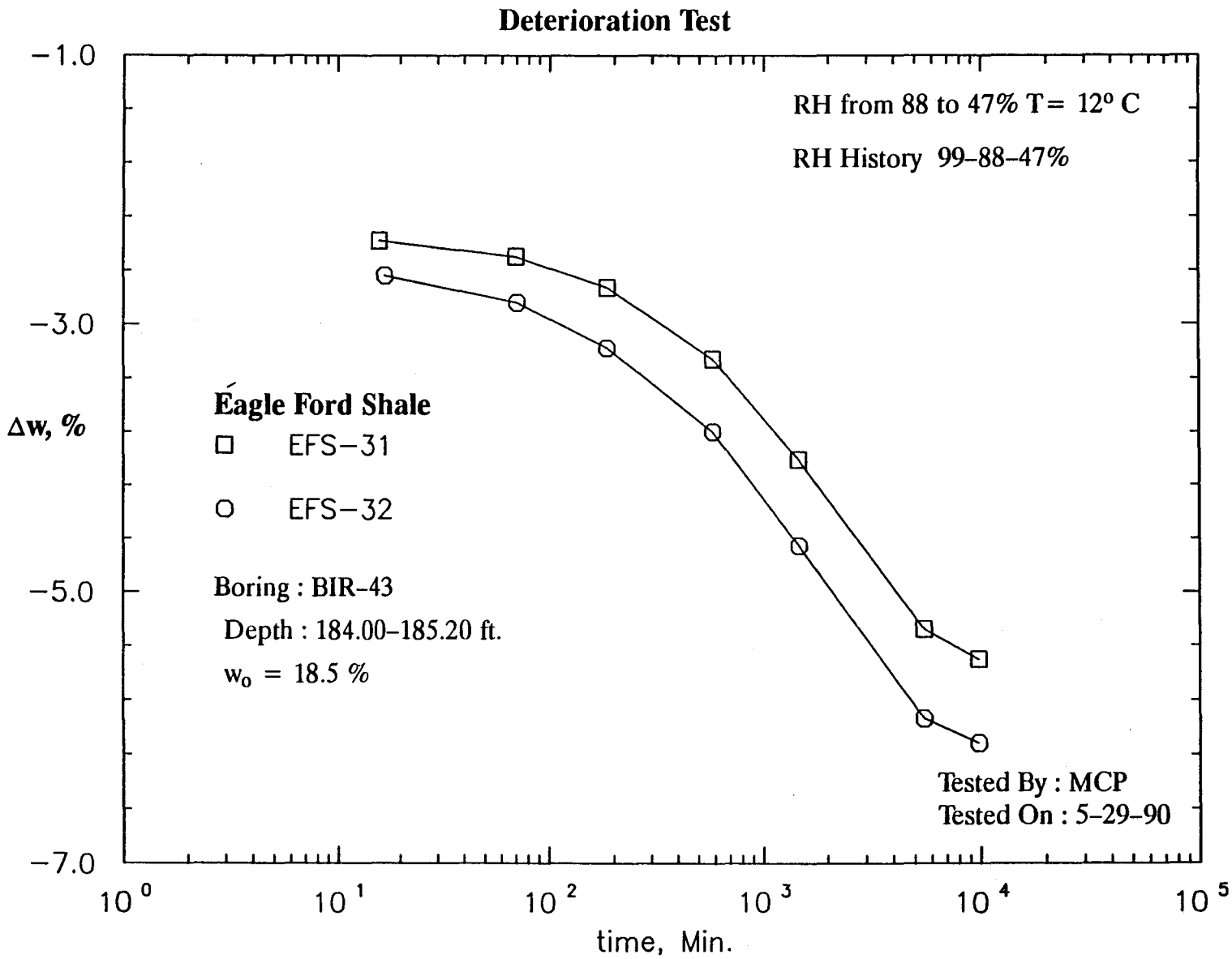


Fig. D8c Water Content Change – Log time Relationship

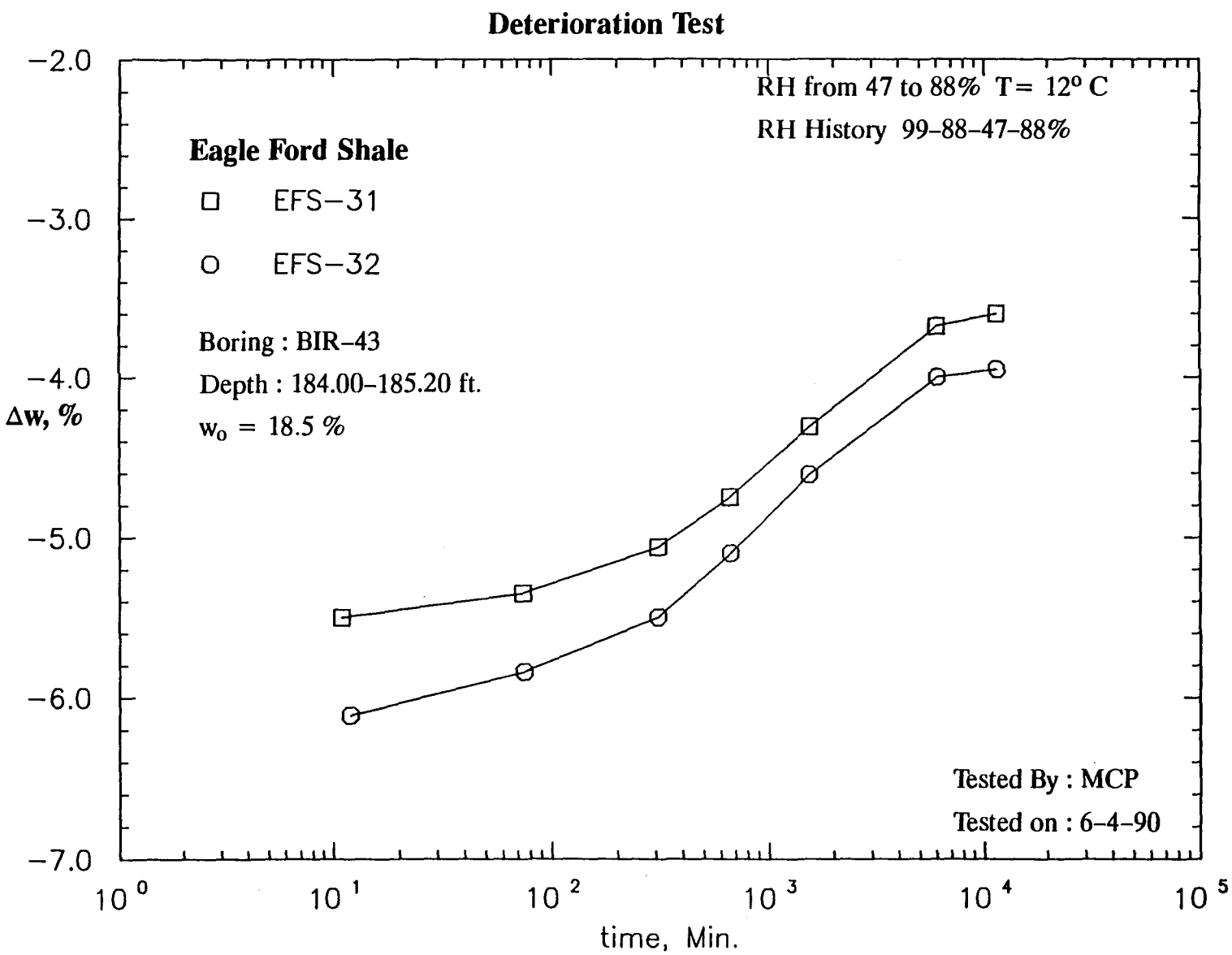


Fig. D8d Water Content Change - Log time Relationship

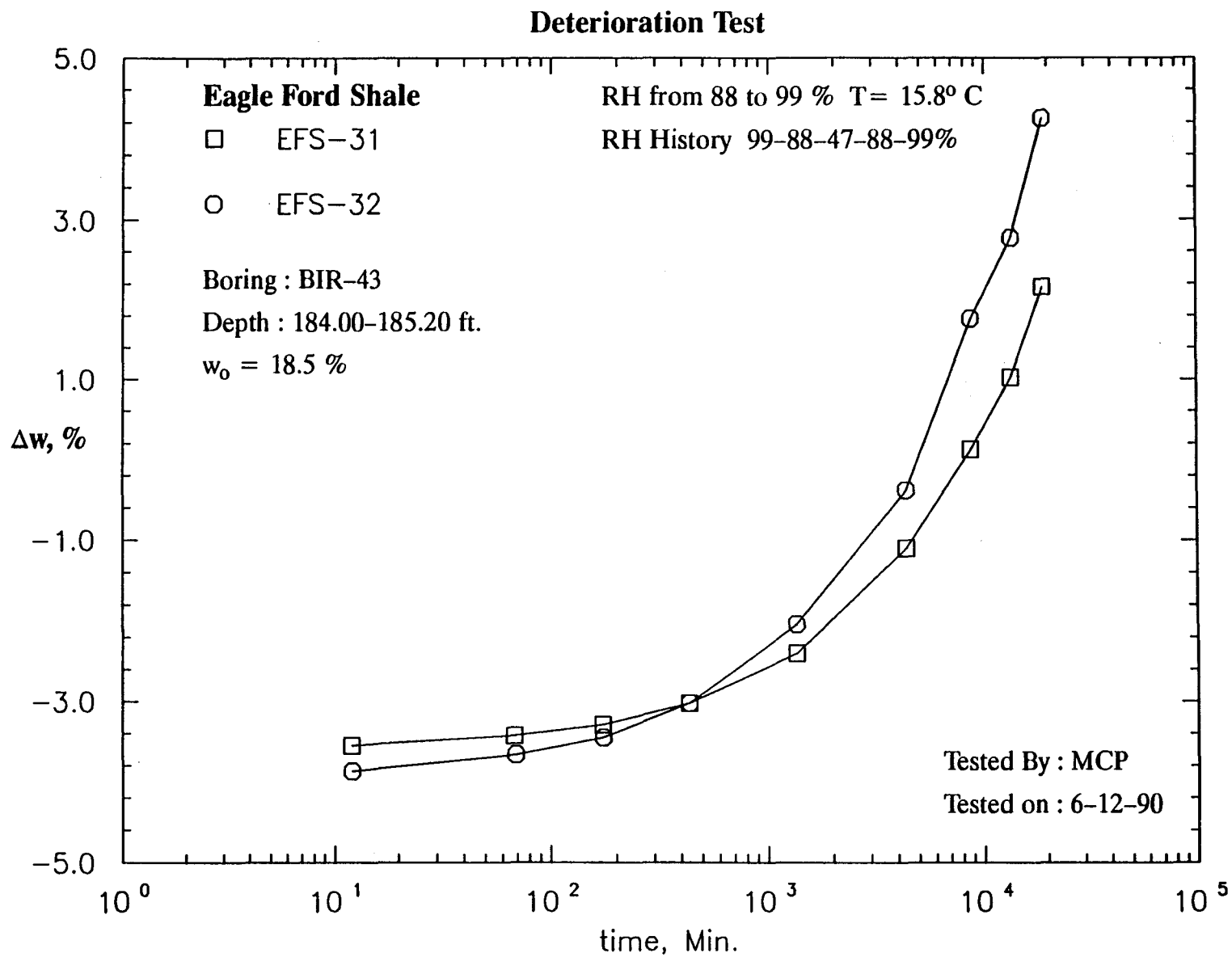


Fig. D8e Water Content Change – Log time Relationship

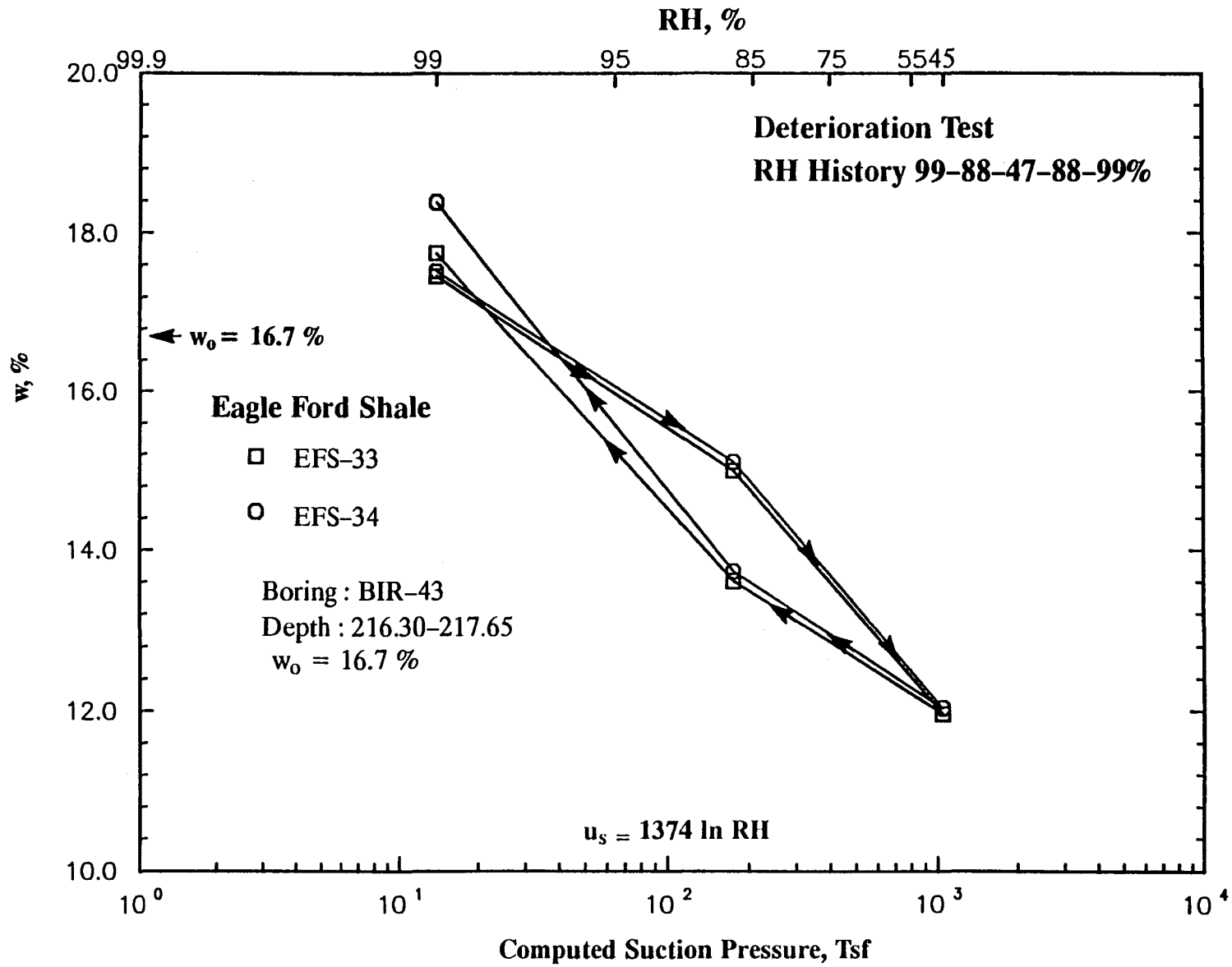


Fig. D9 Water Content – Relative Humidity Relationship

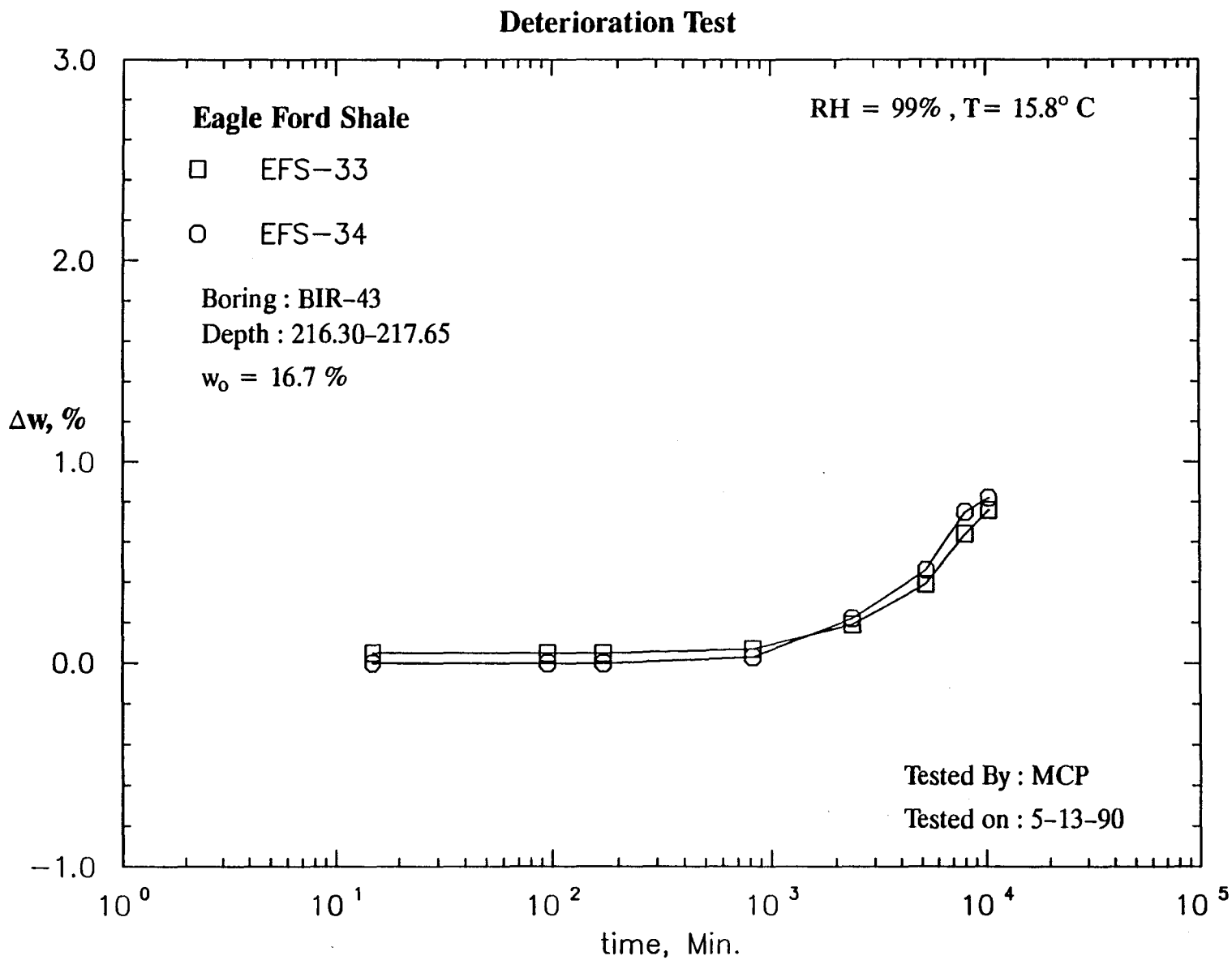


Fig. D9a Water Content Change – Log time Relationship

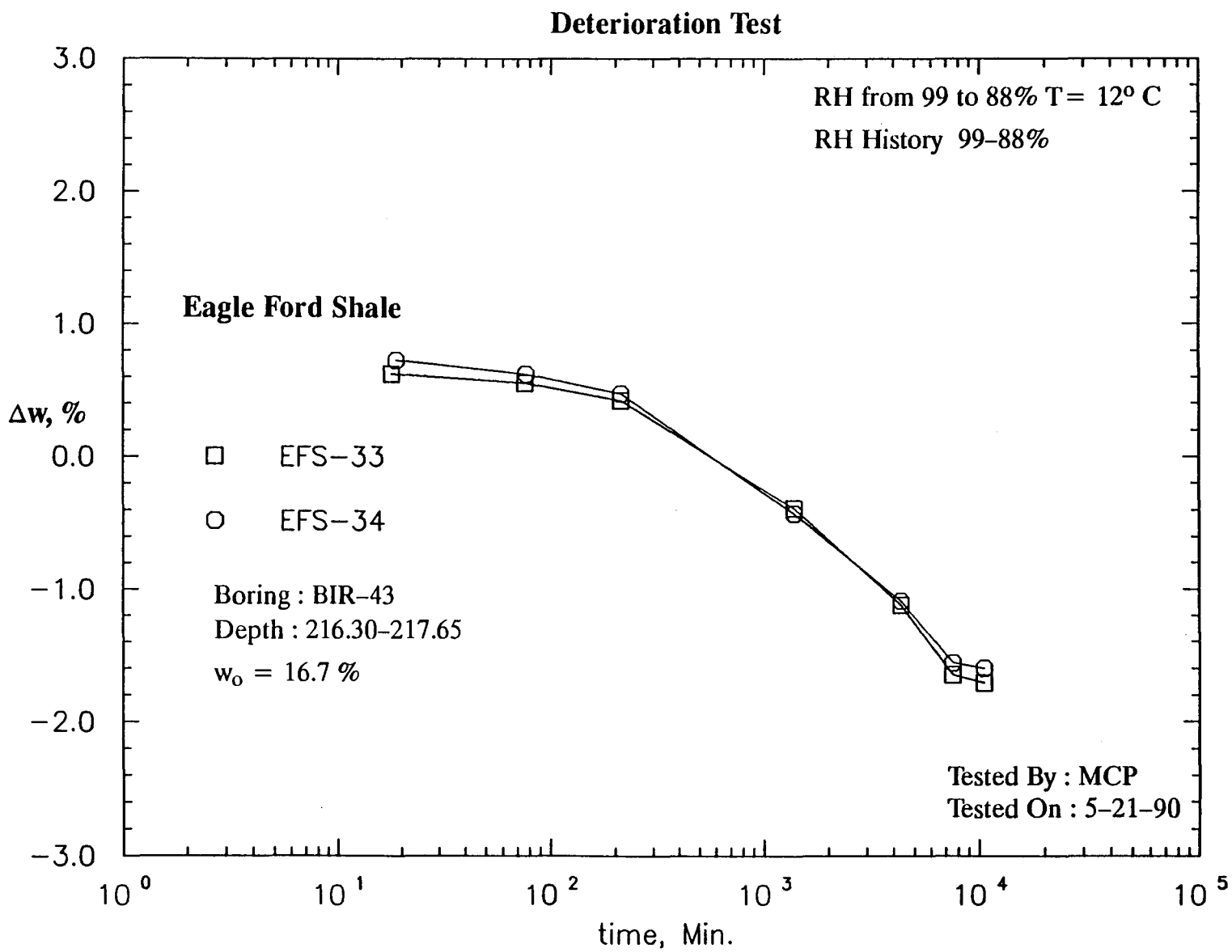


Fig. D9b Water Content Change – Log time Relationship

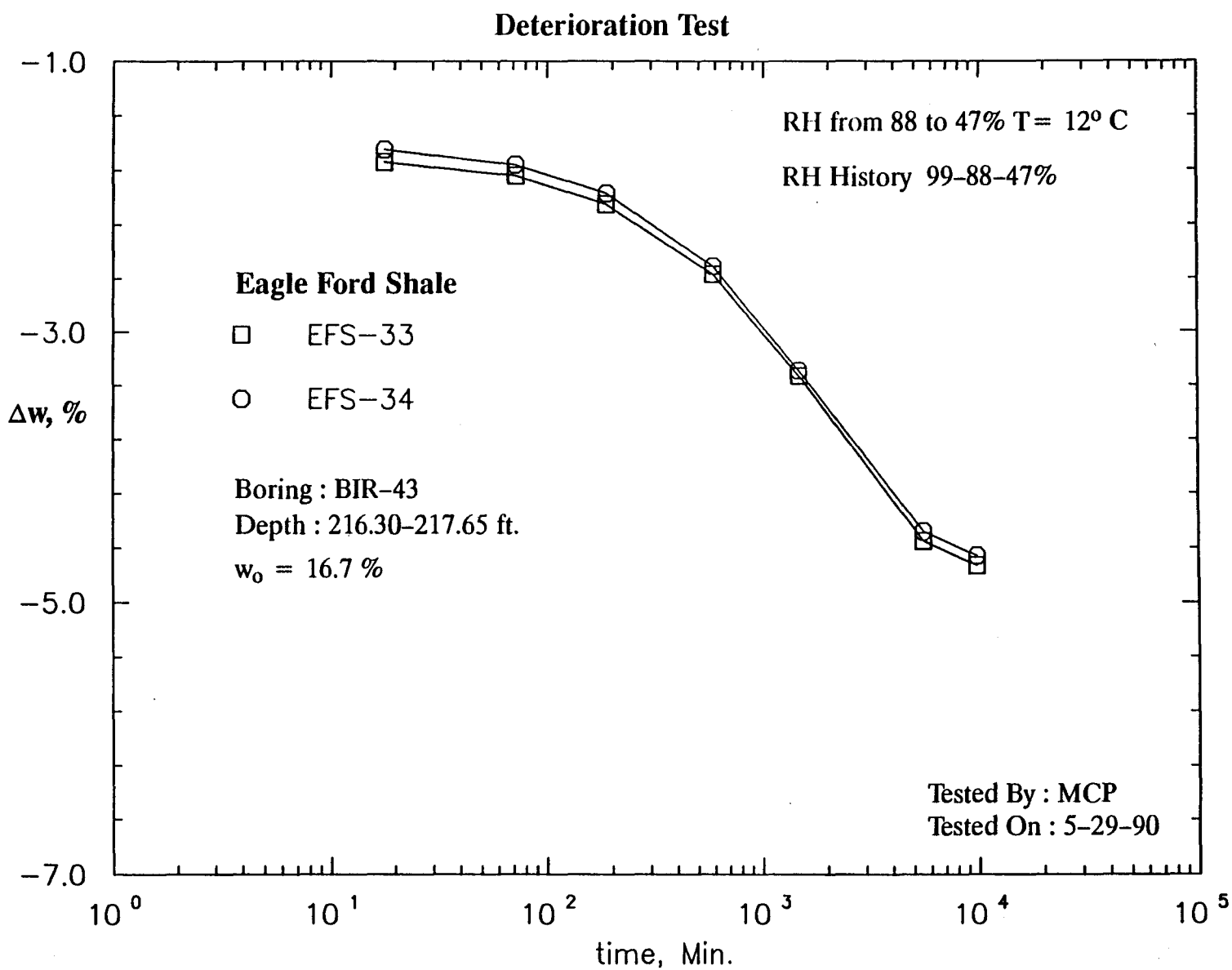


Fig. D9c Water Content Change - Log time Relationship

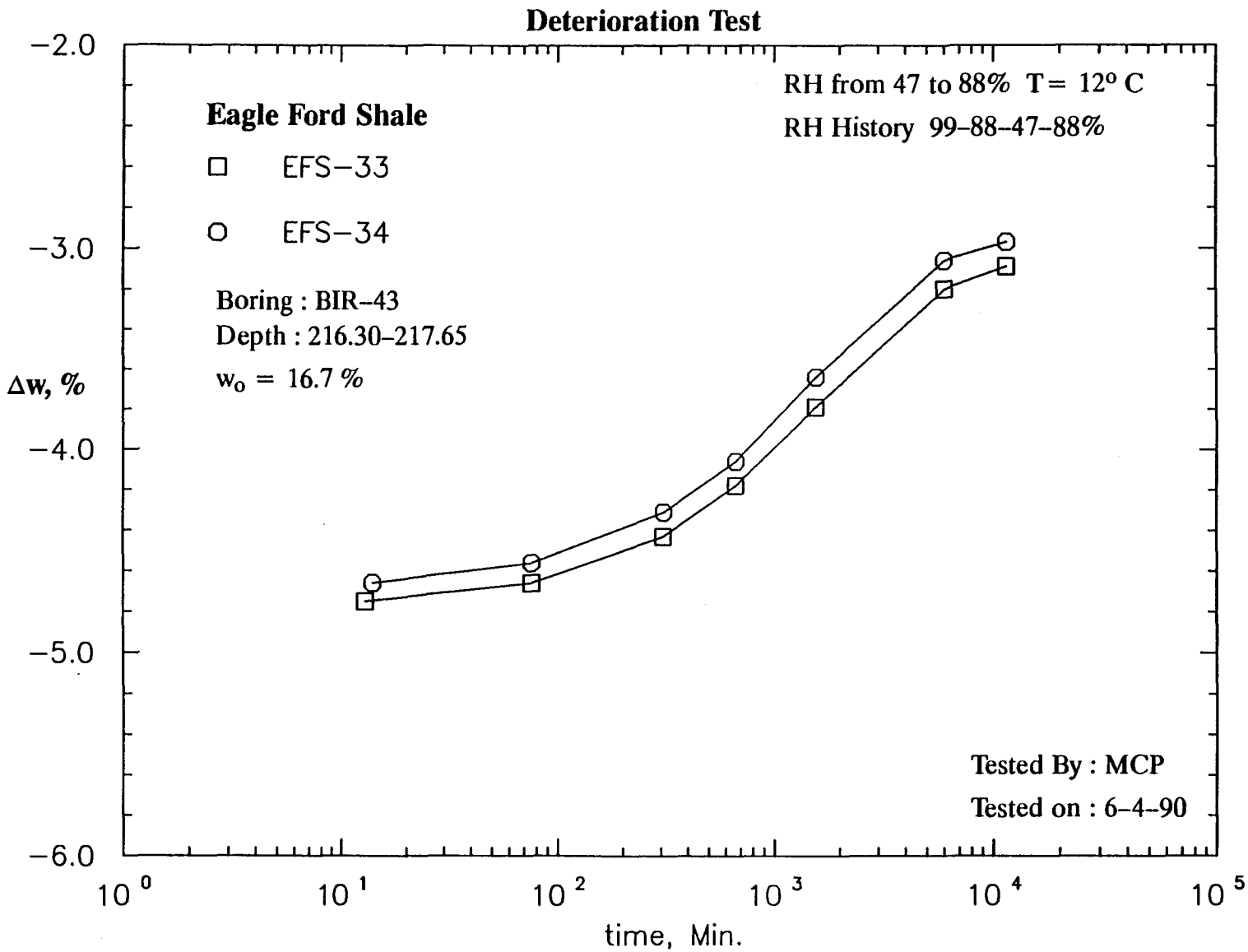


Fig. D9d Water Content Change – Log time Relationship

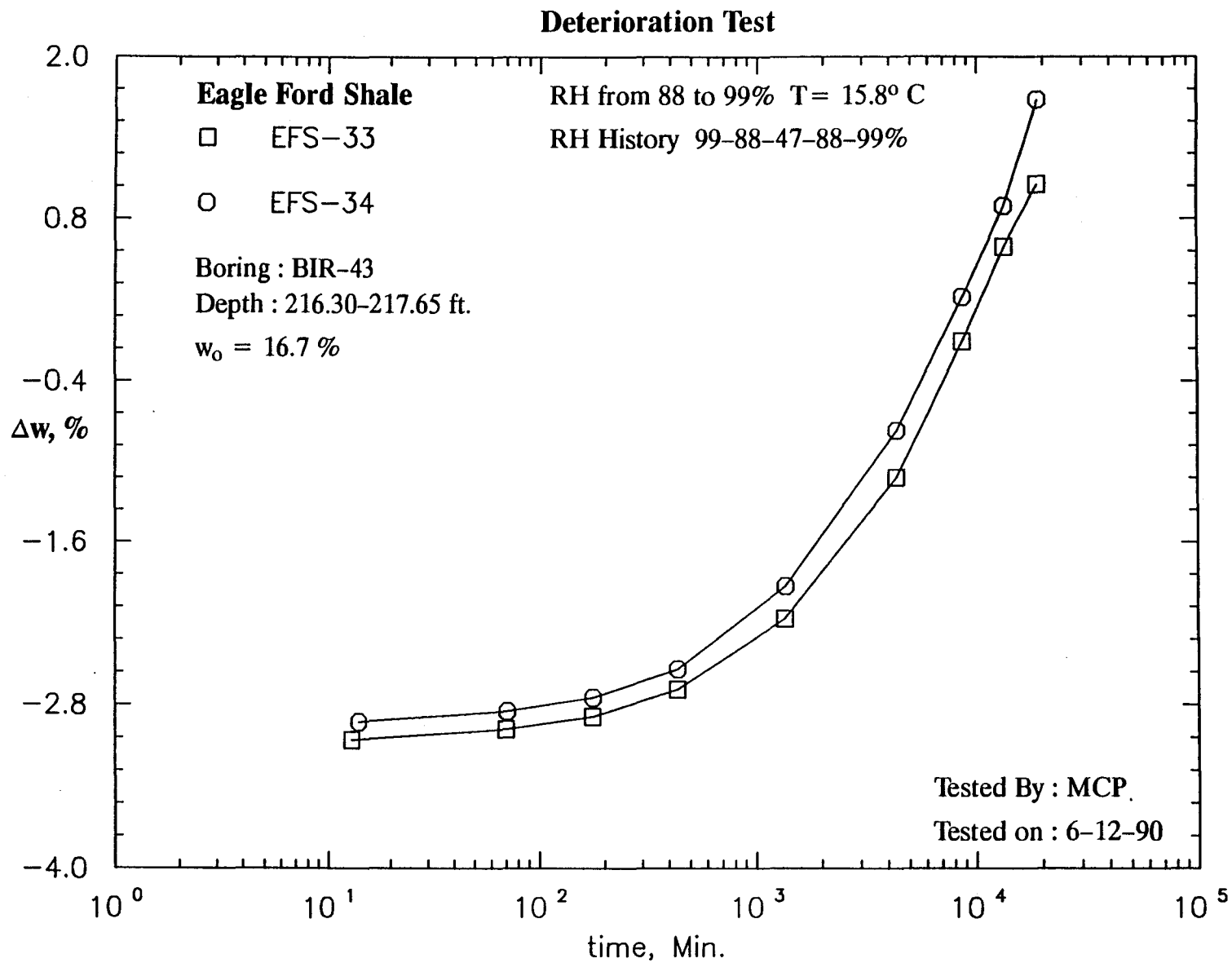


Fig. D9e Water Content Change – Log time Relationship

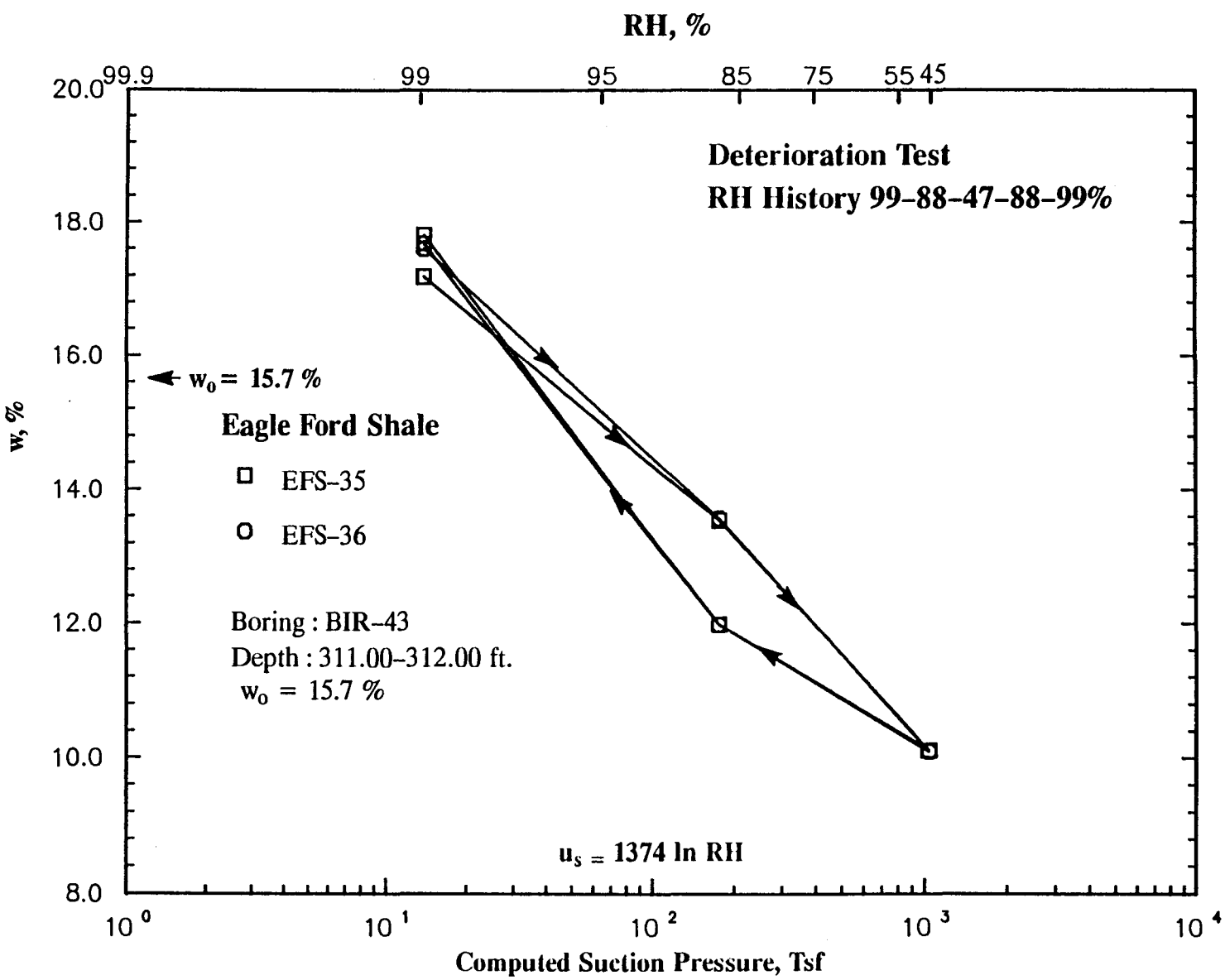


Fig. D10 Water Content – Relative Humidity Relationship

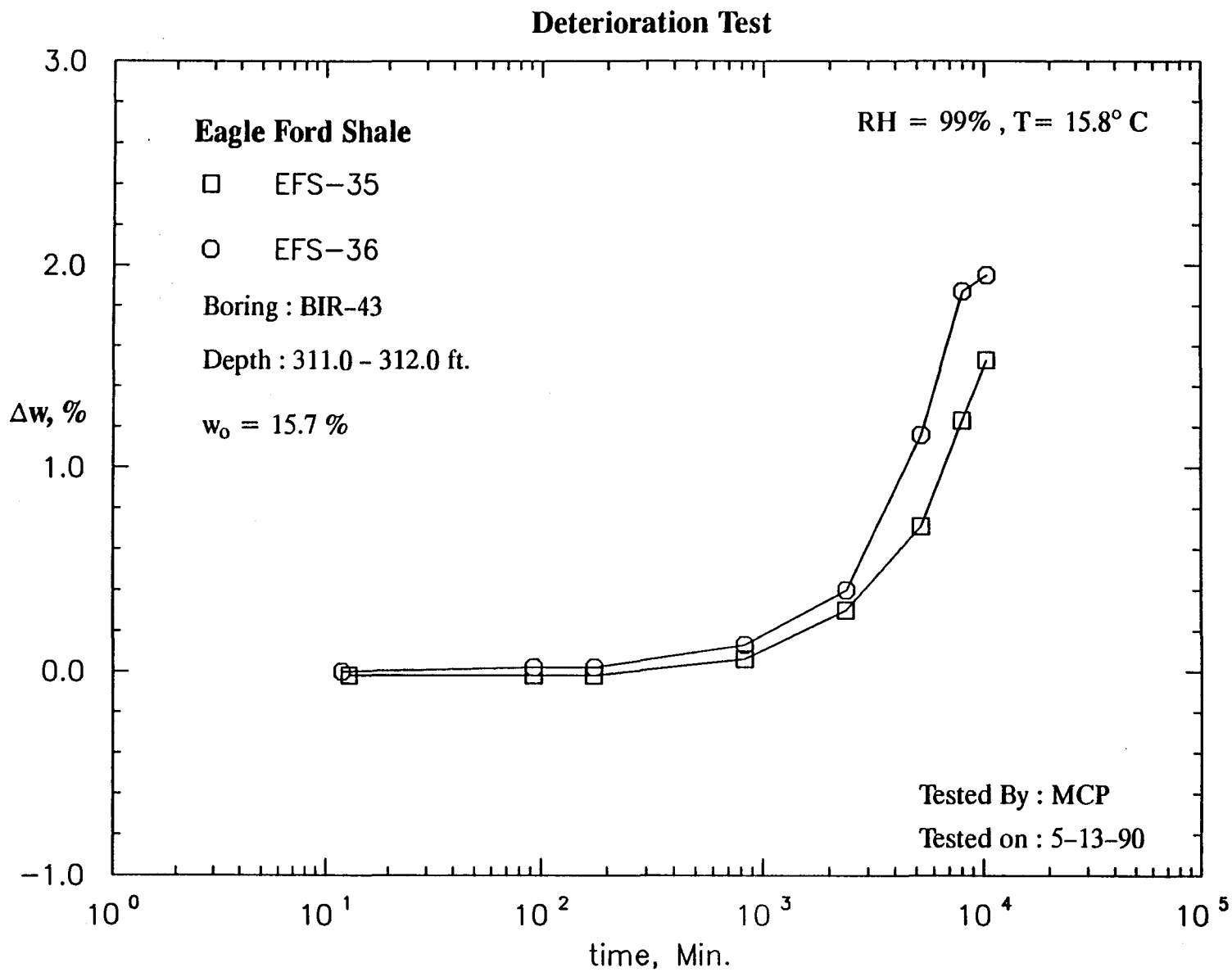


Fig. D10a Water Content Change – Log time Relationship

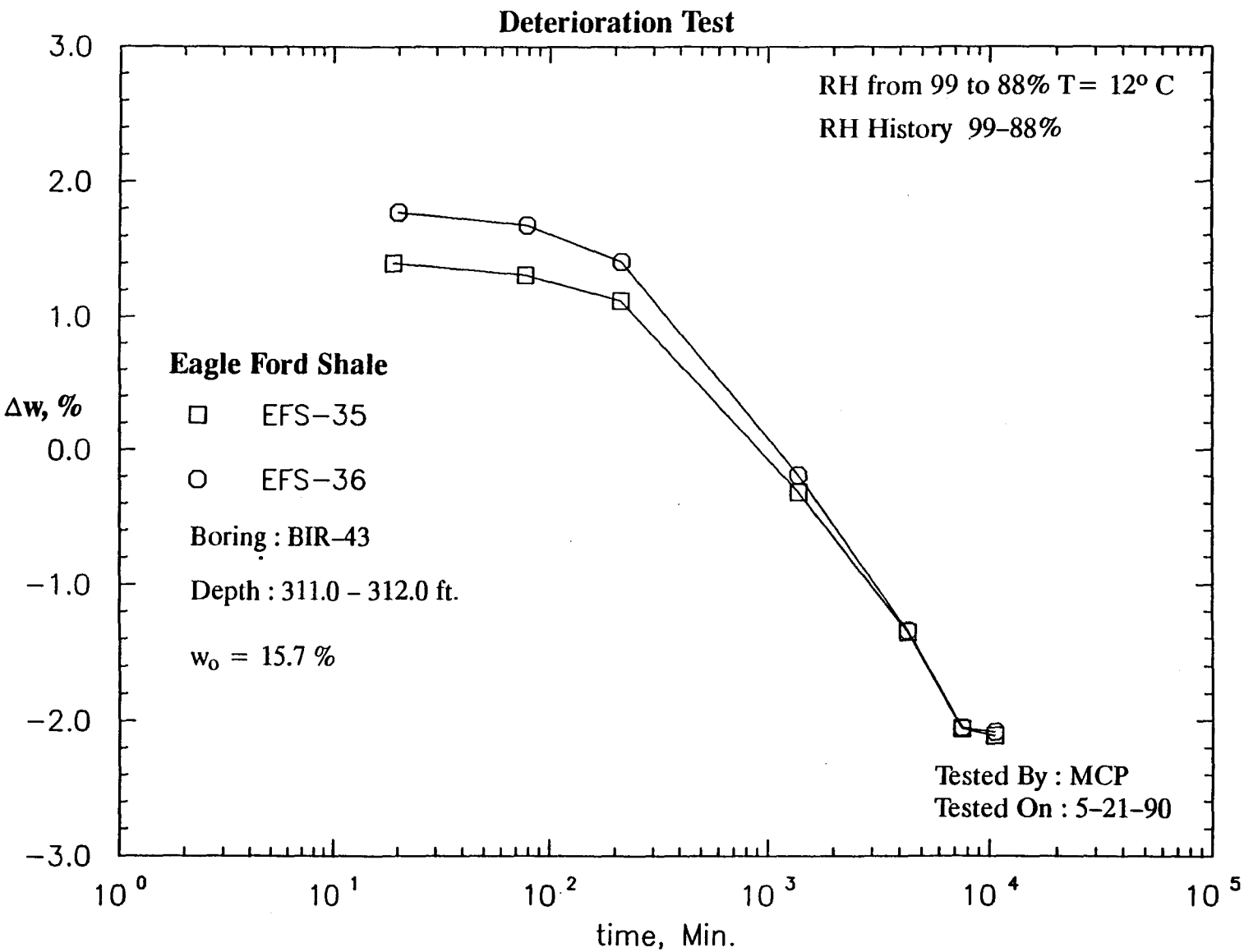


Fig. D10b Water Content Change – Log time Relationship

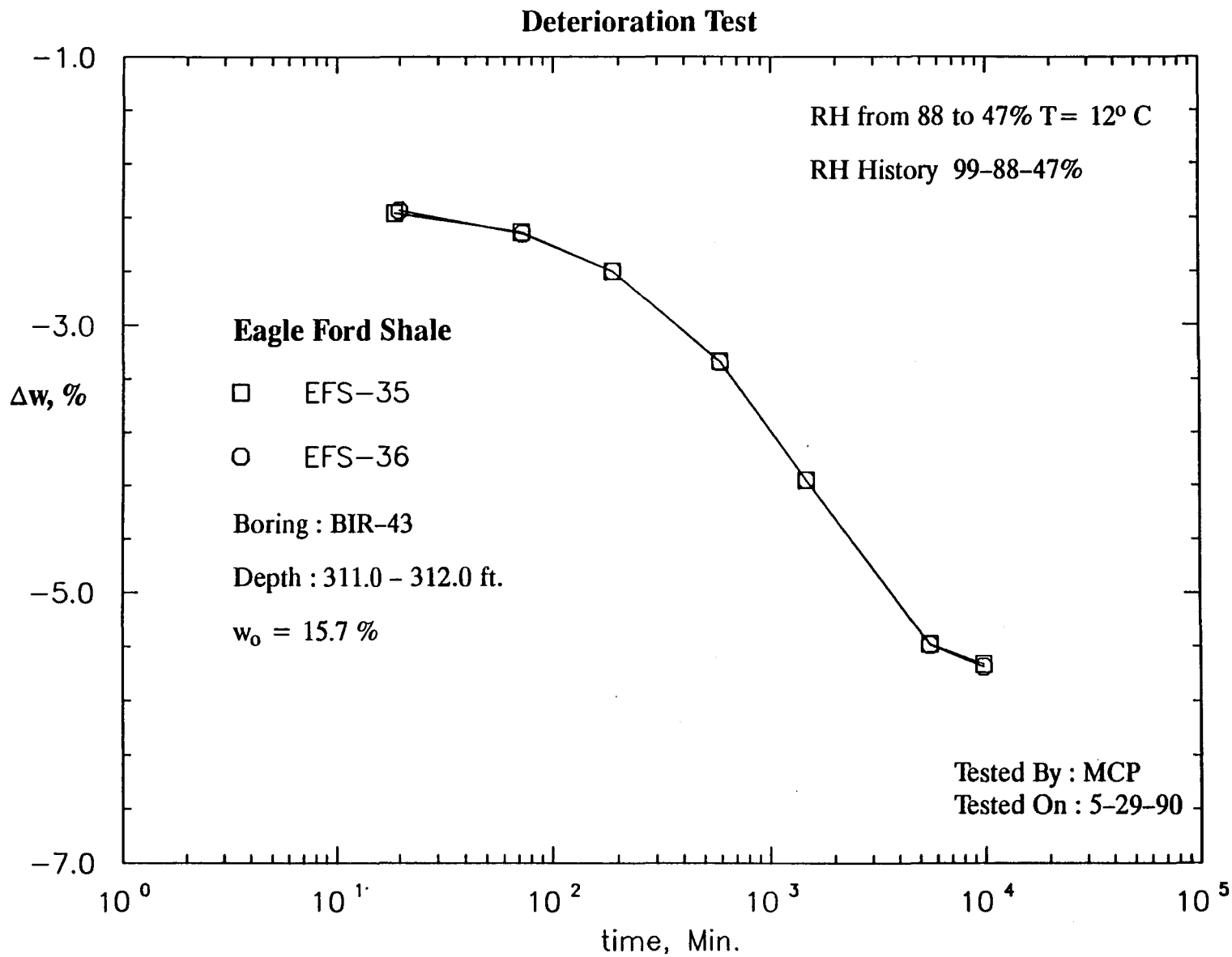


Fig. D10c Water Content Change – Log time Relationship

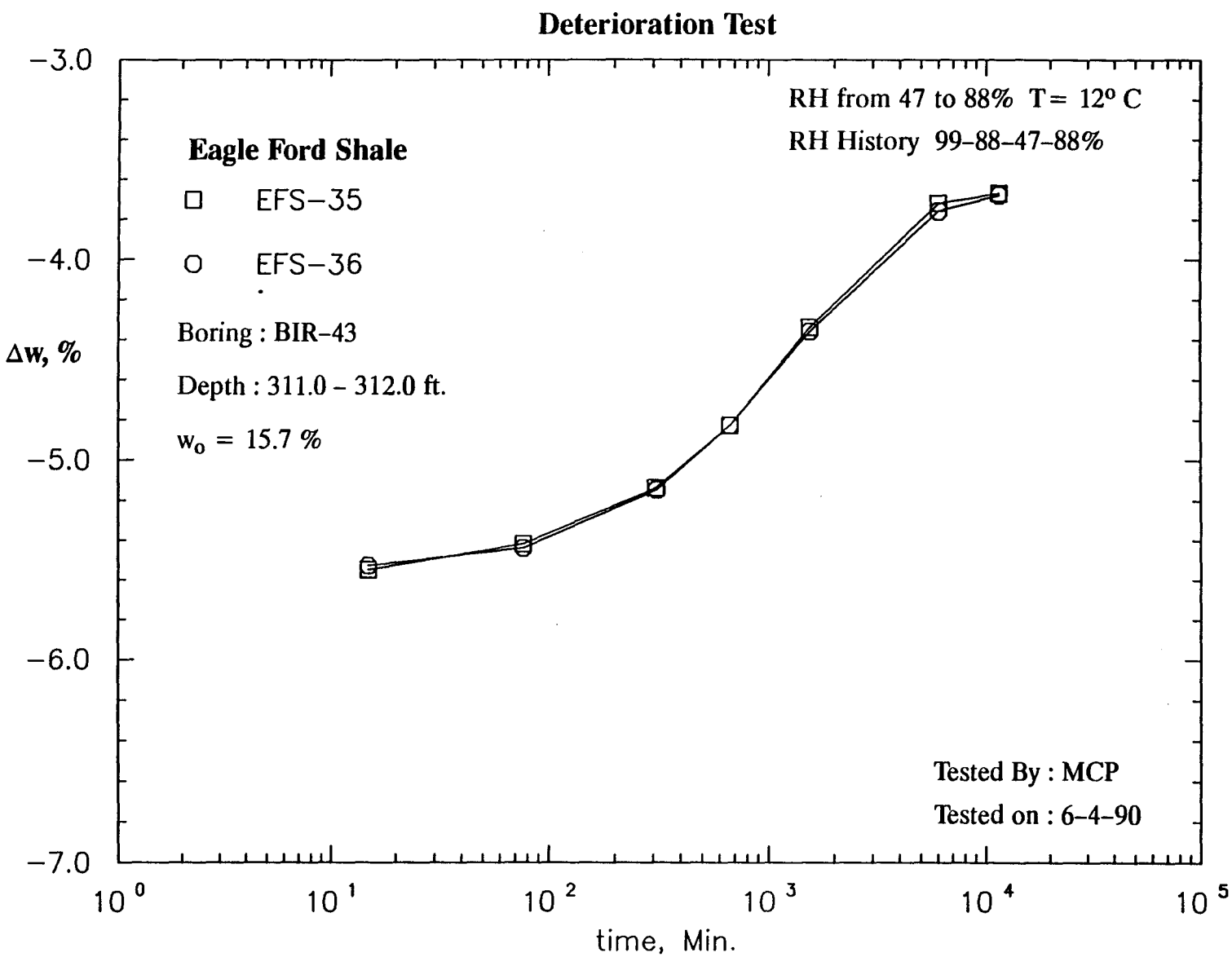


Fig. D10d Water Content Change - Log time Relationship

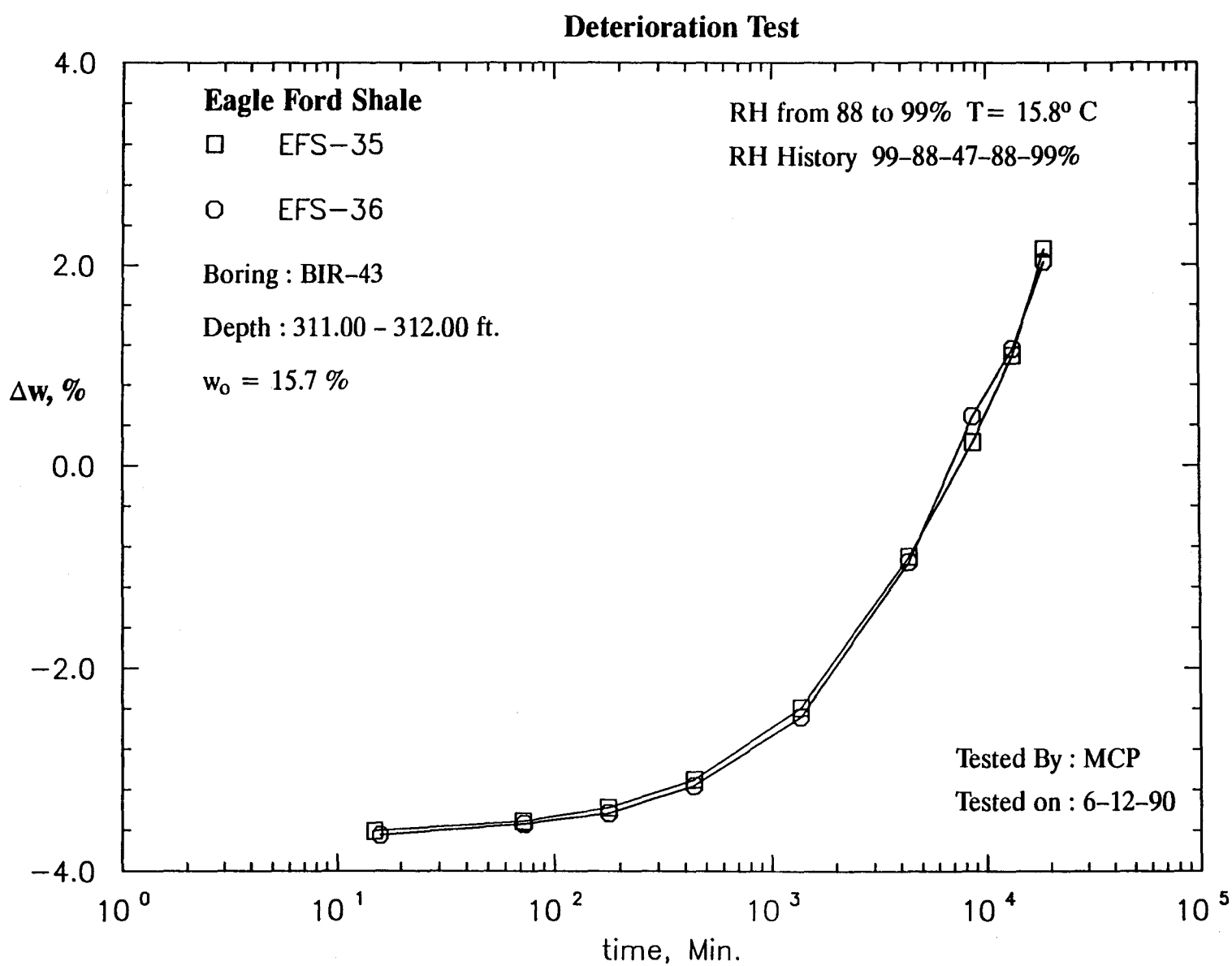


Fig. D10e Water Content Change - Log time Relationship

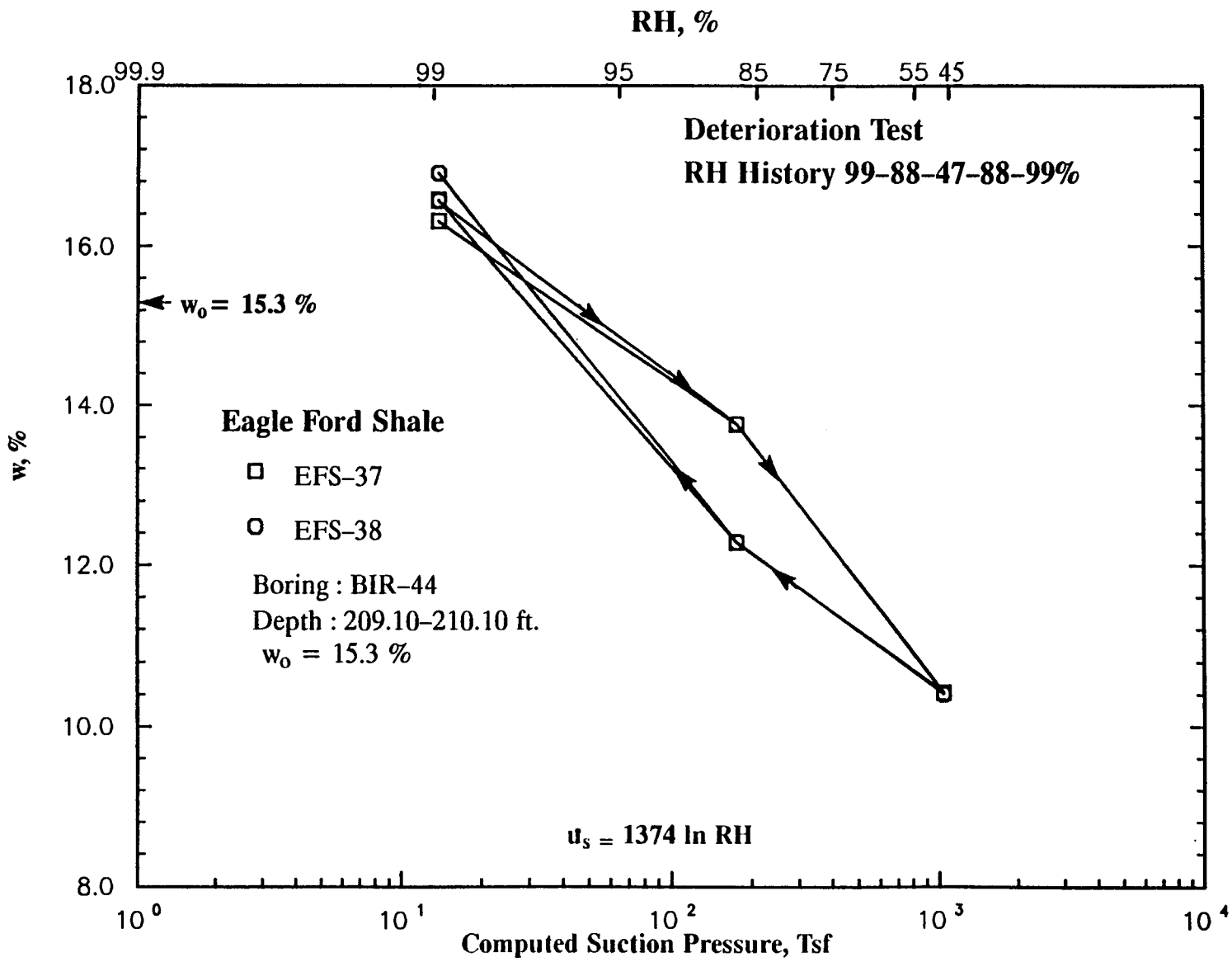


Fig. D11 Water Content – Relative Humidity Relationship

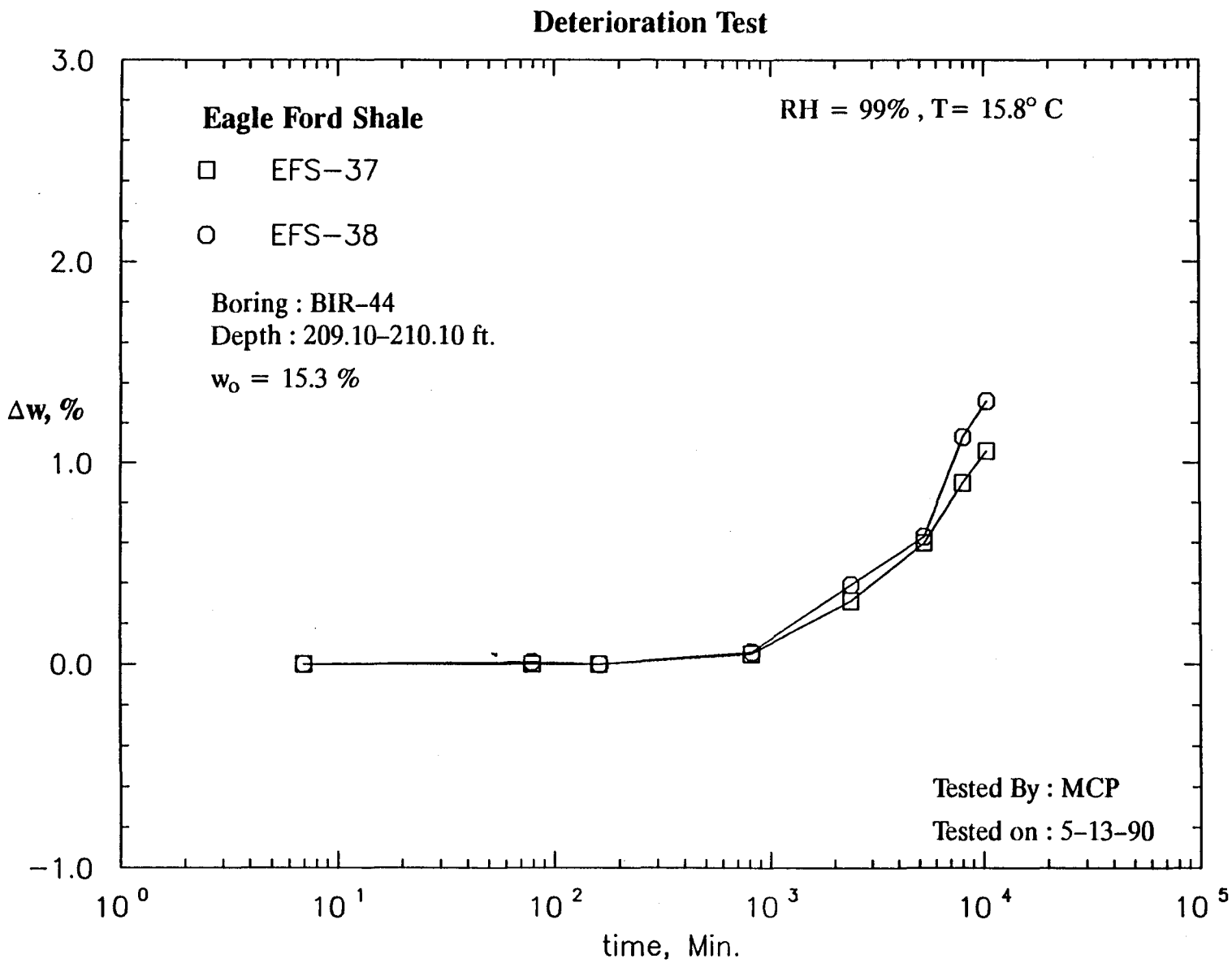


Fig. D11a Water Content Change - Log time Relationship

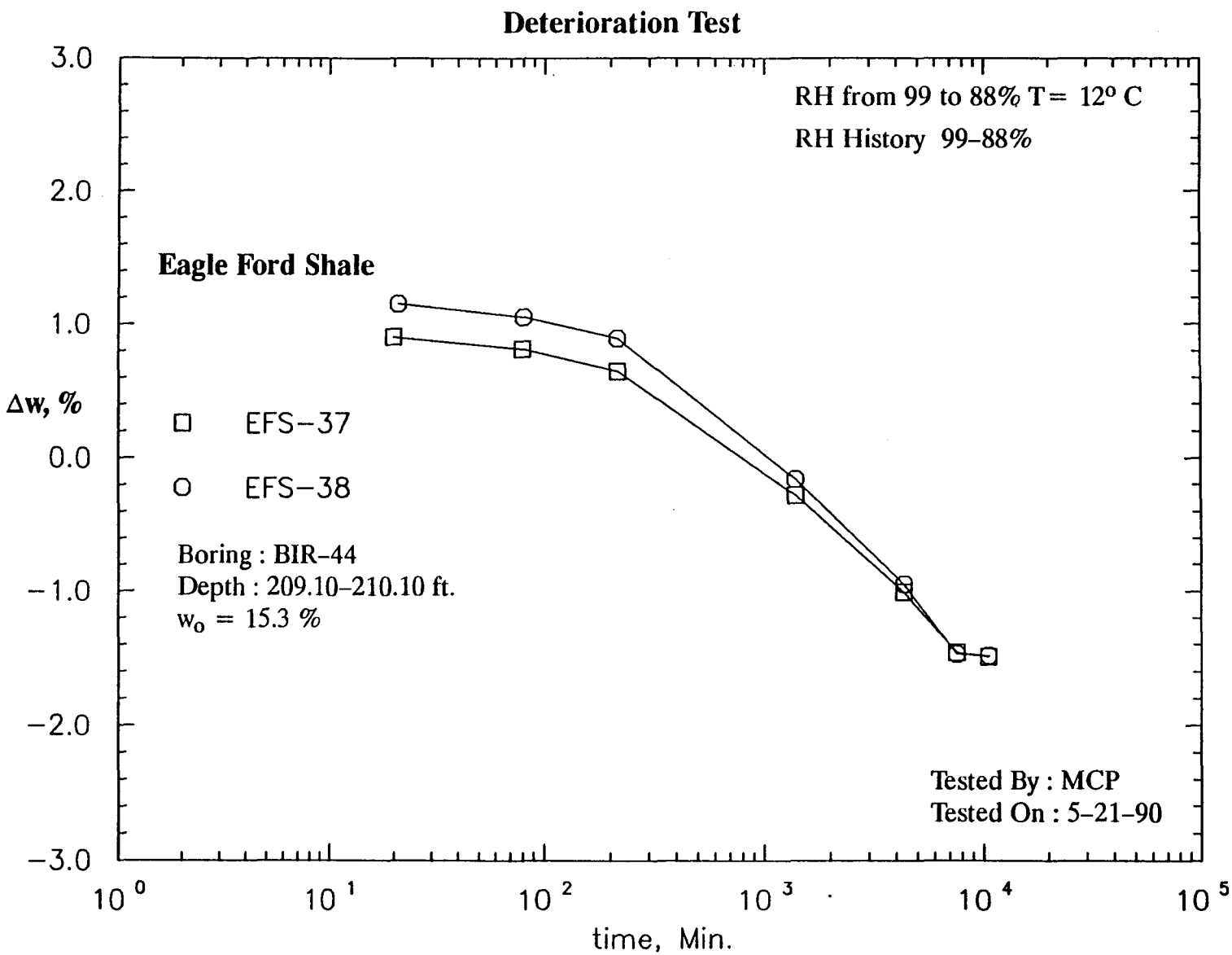


Fig. D11b Water Content Change - Log time Relationship

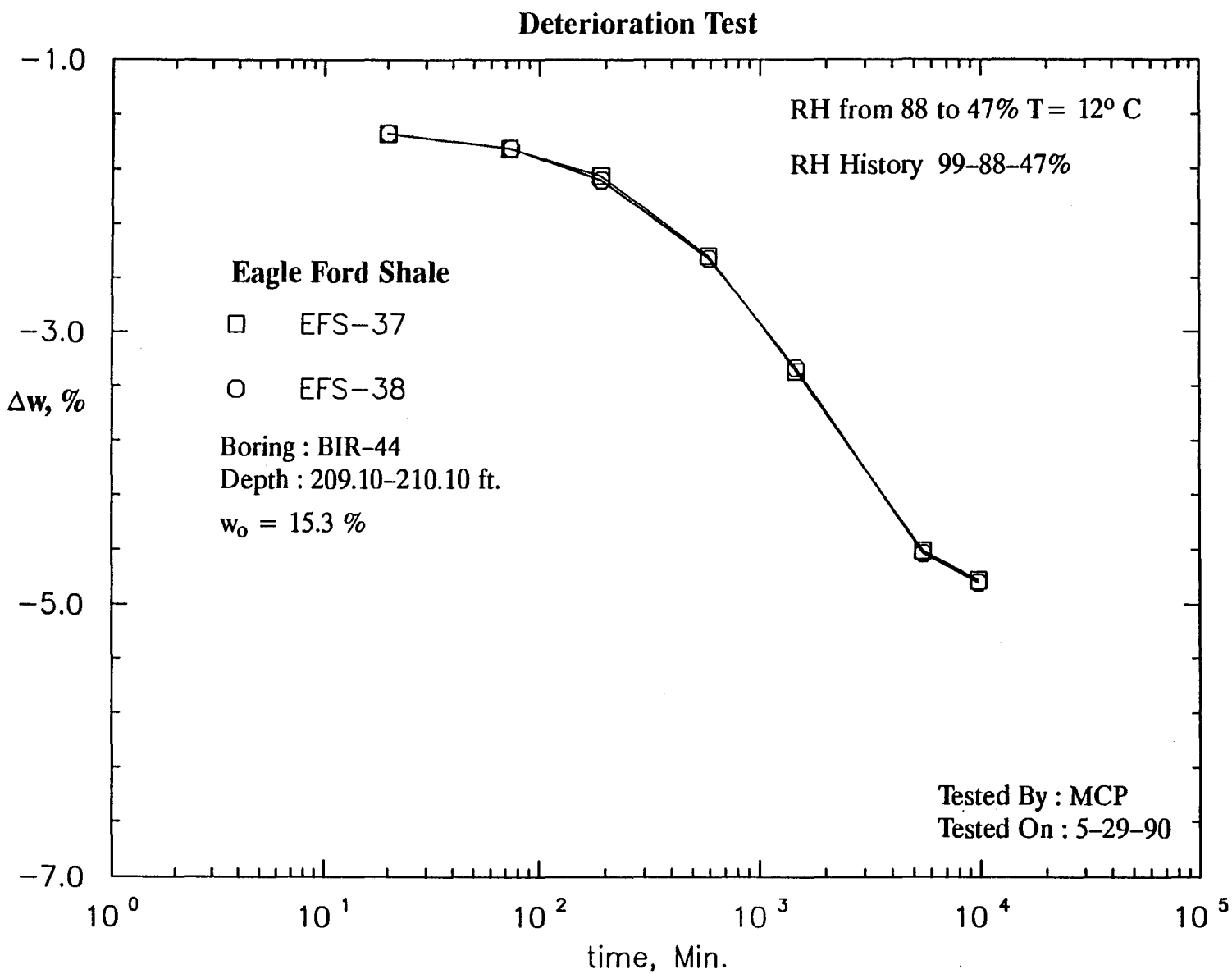


Fig. D11c Water Content Change - Log time Relationship

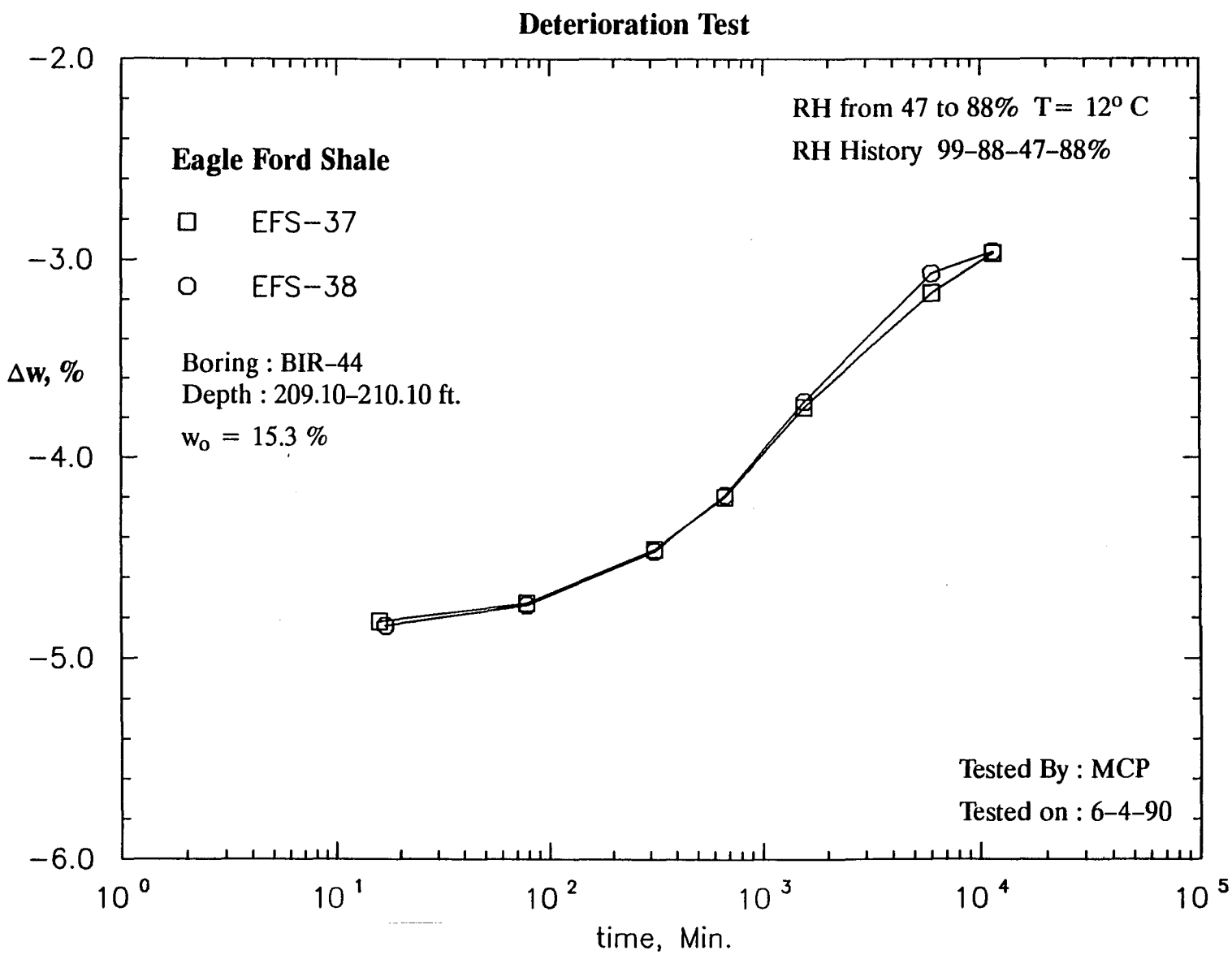


Fig. D11d Water Content Change – Log time Relationship

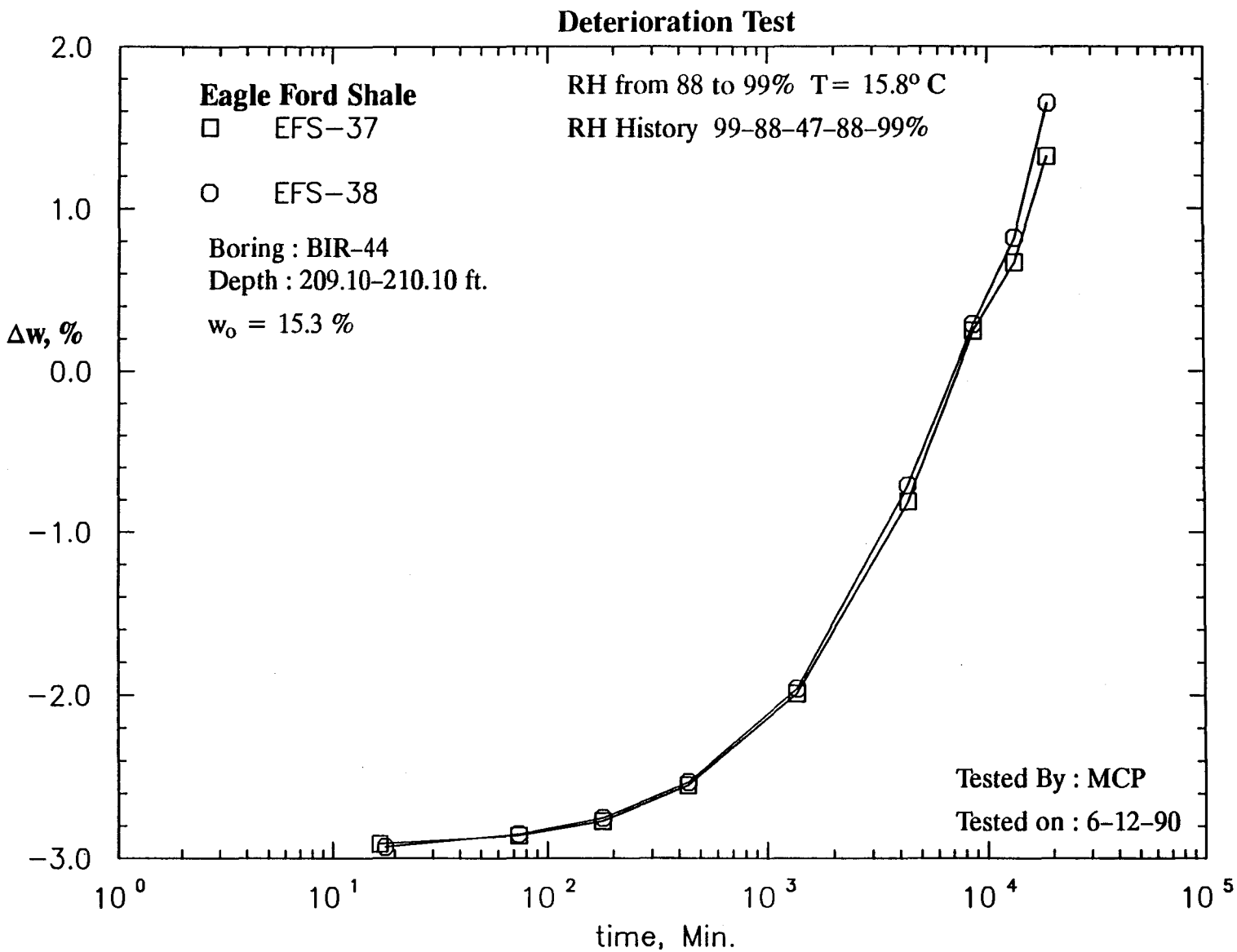


Fig. D11e Water Content Change – Log time Relationship

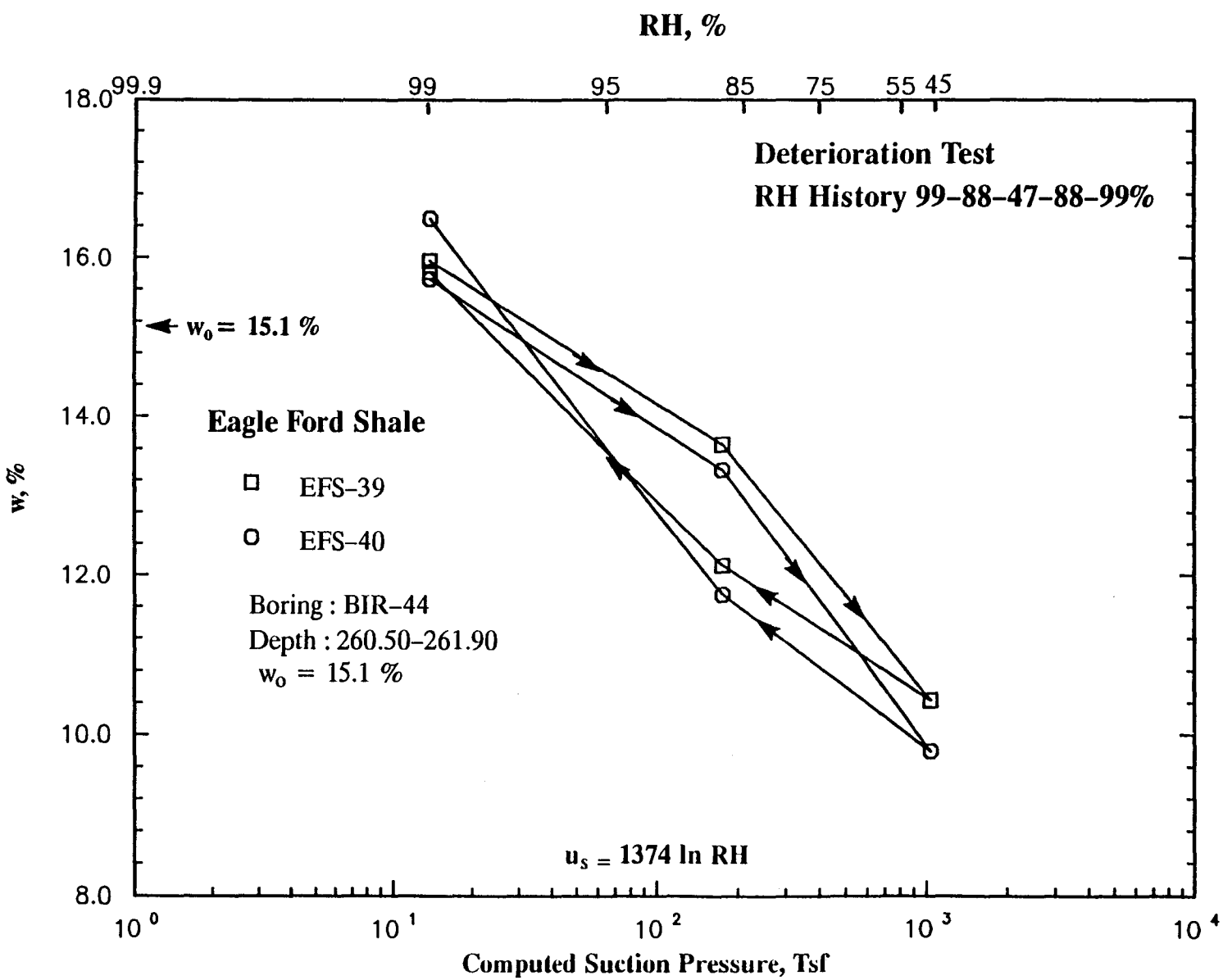


Fig. D12 Water Content – Relative Humidity Relationship

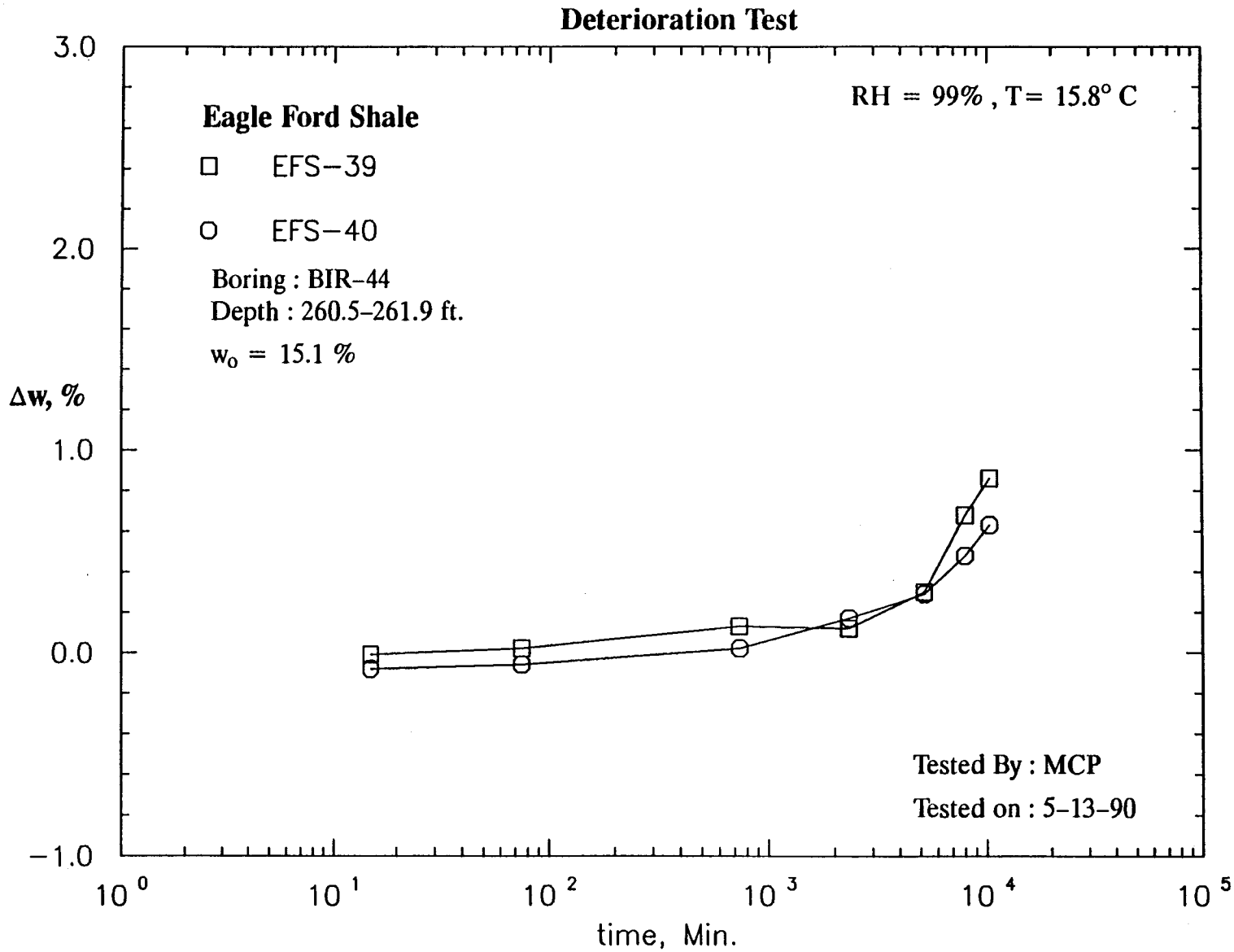


Fig. D12a Water Content Change – Log time Relationship

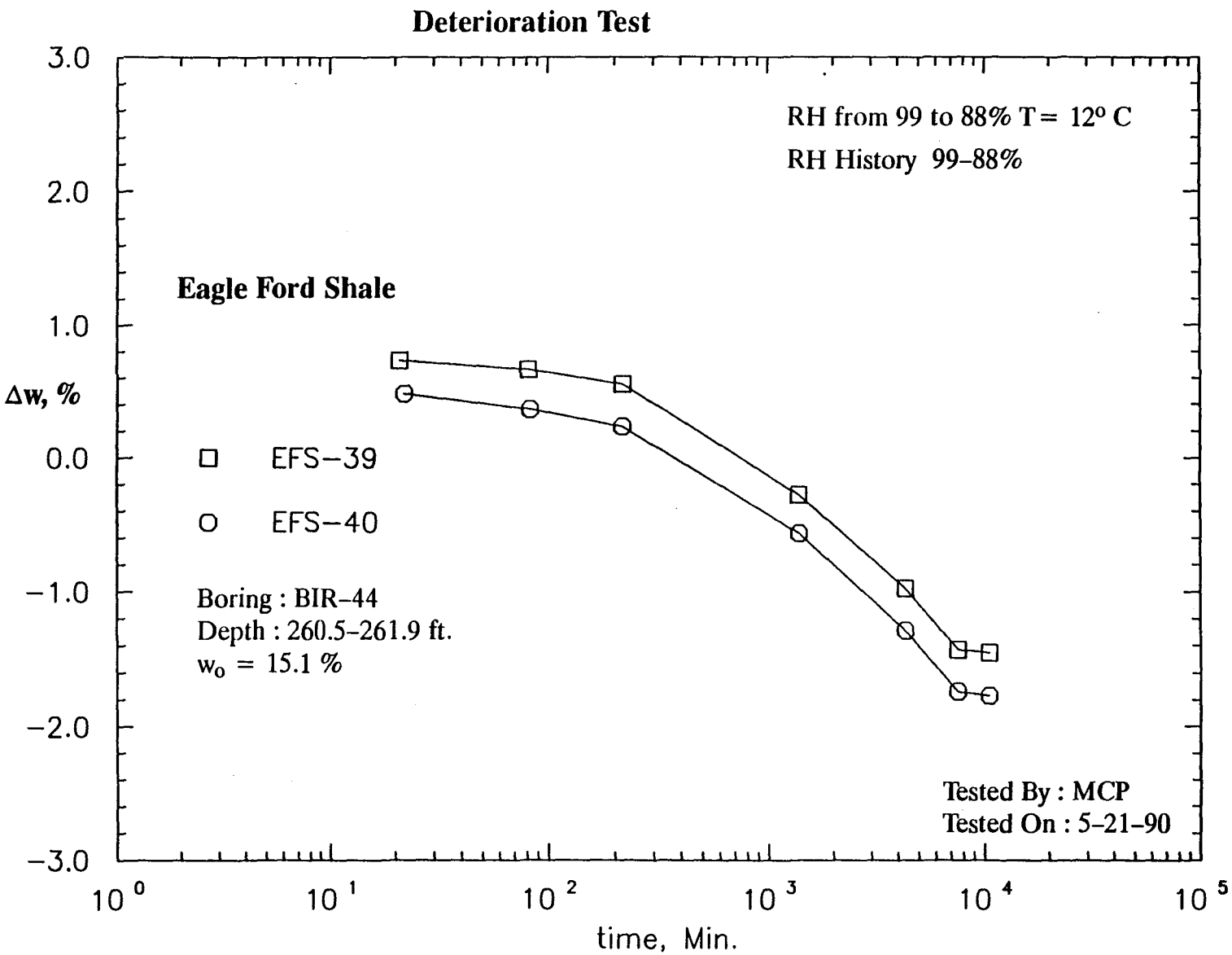


Fig. D12b Water Content Change – Log time Relationship

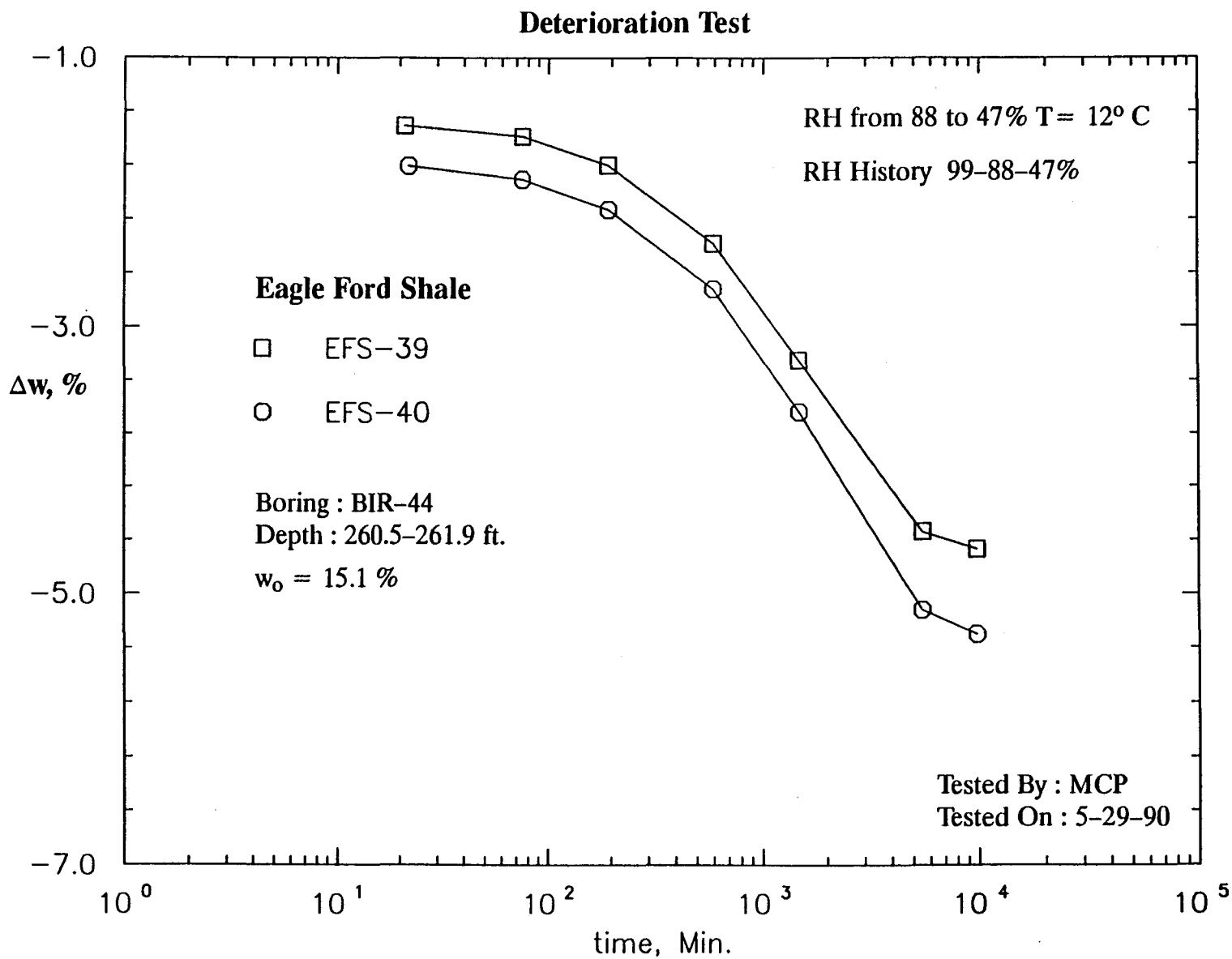


Fig. D12c Water Content Change – Log time Relationship

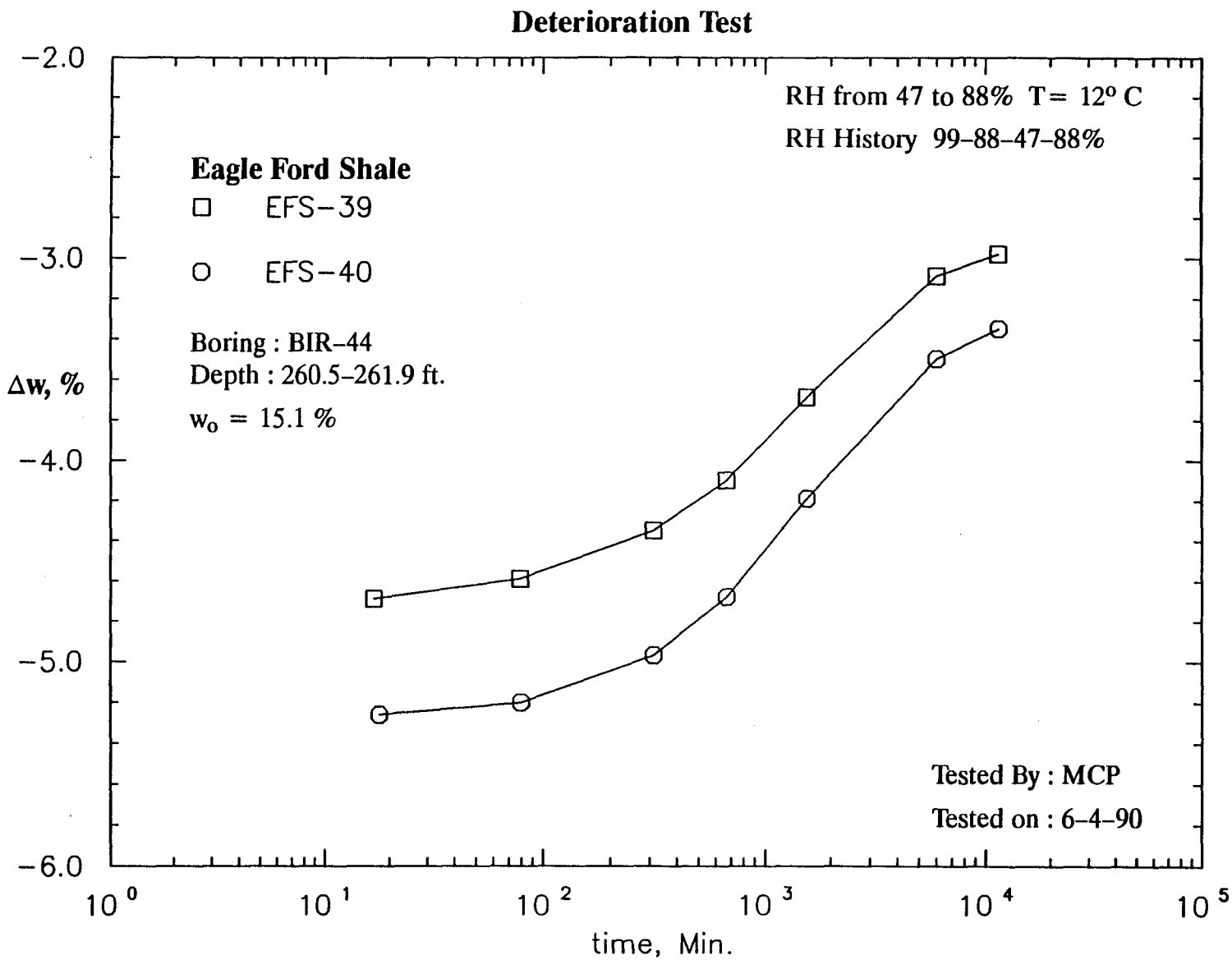


Fig. D12d Water Content Change – Log time Relationship

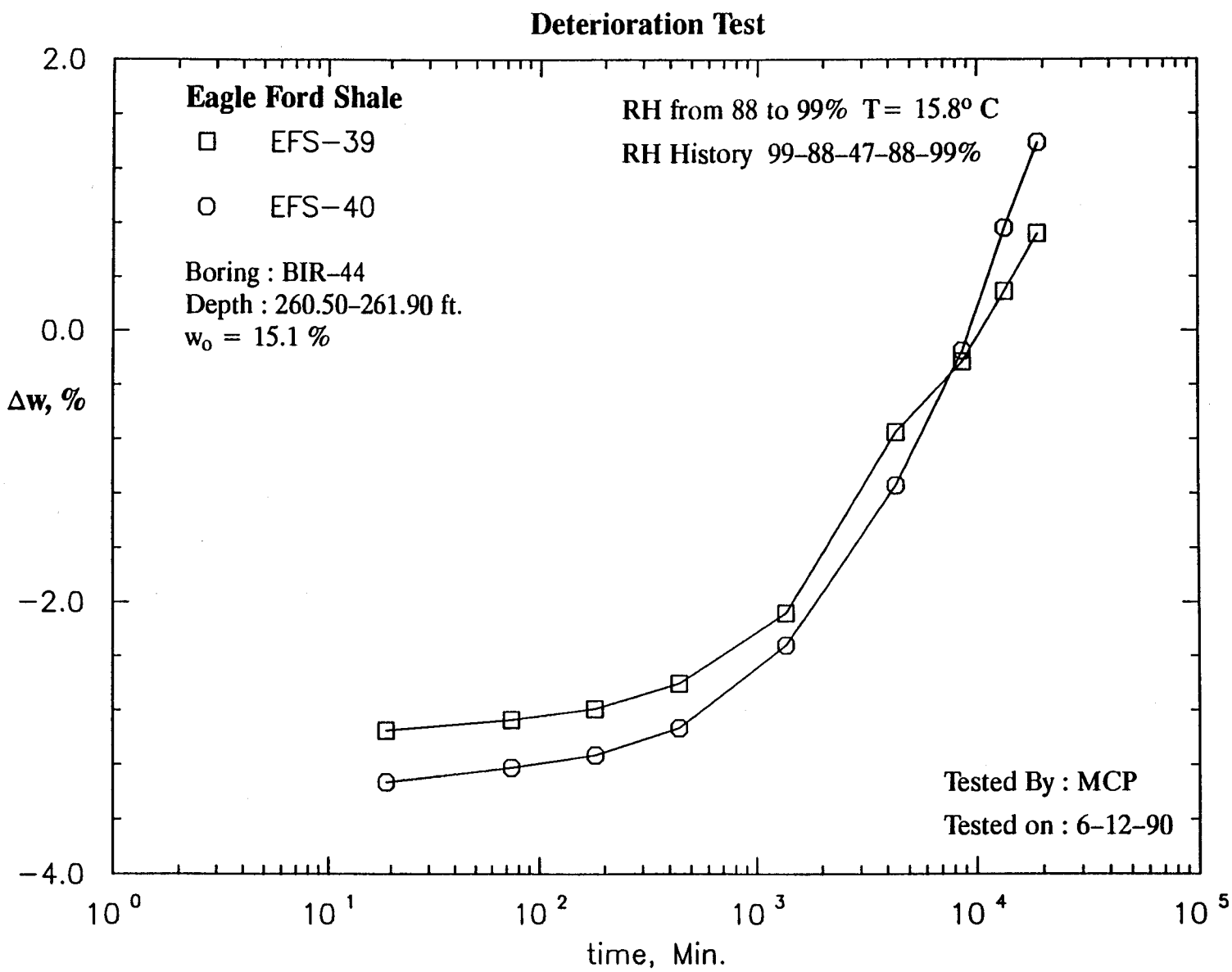


Fig. D12e Water Content Change – Log time Relationship

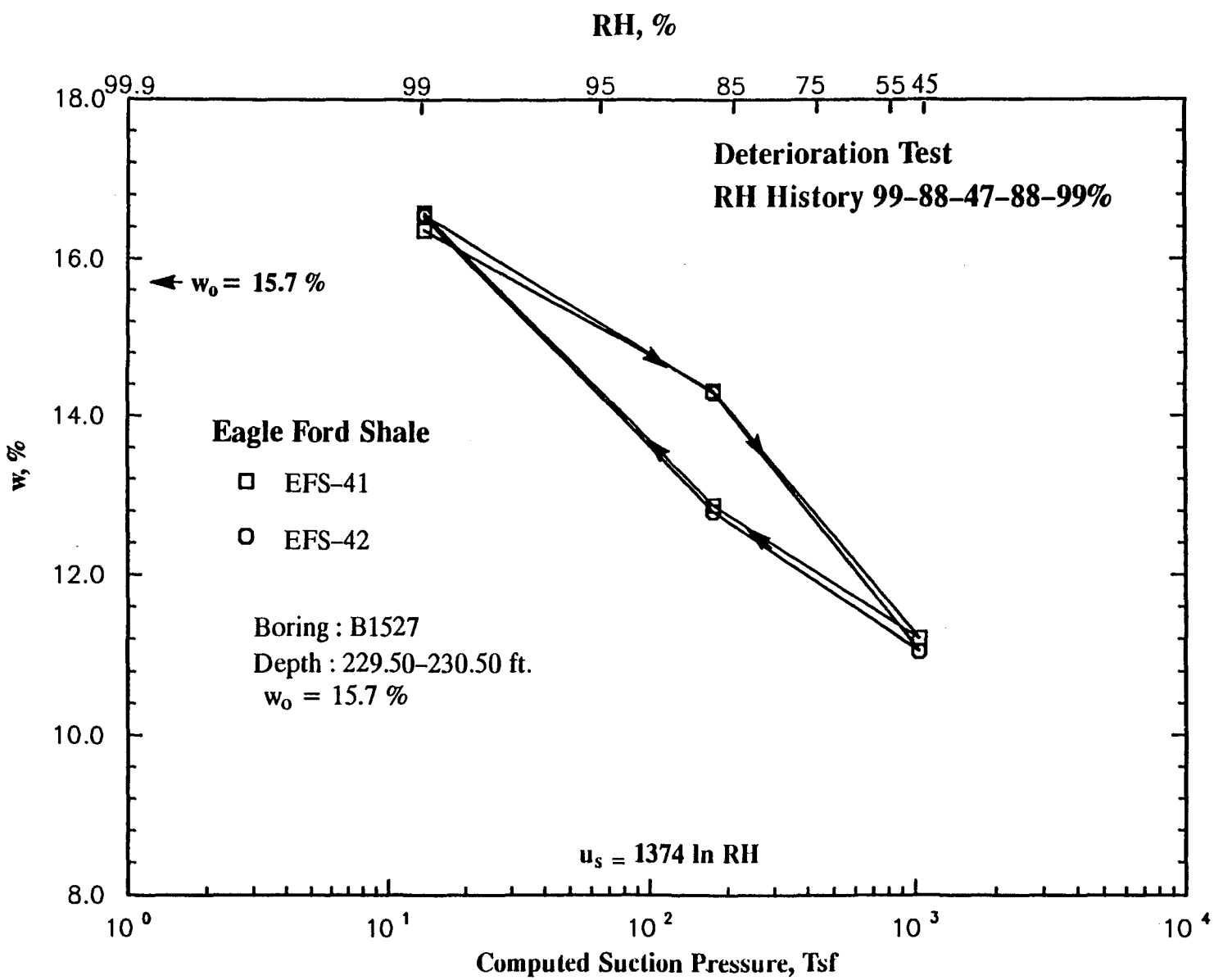


Fig. D13 Water Content – Relative Humidity Relationship

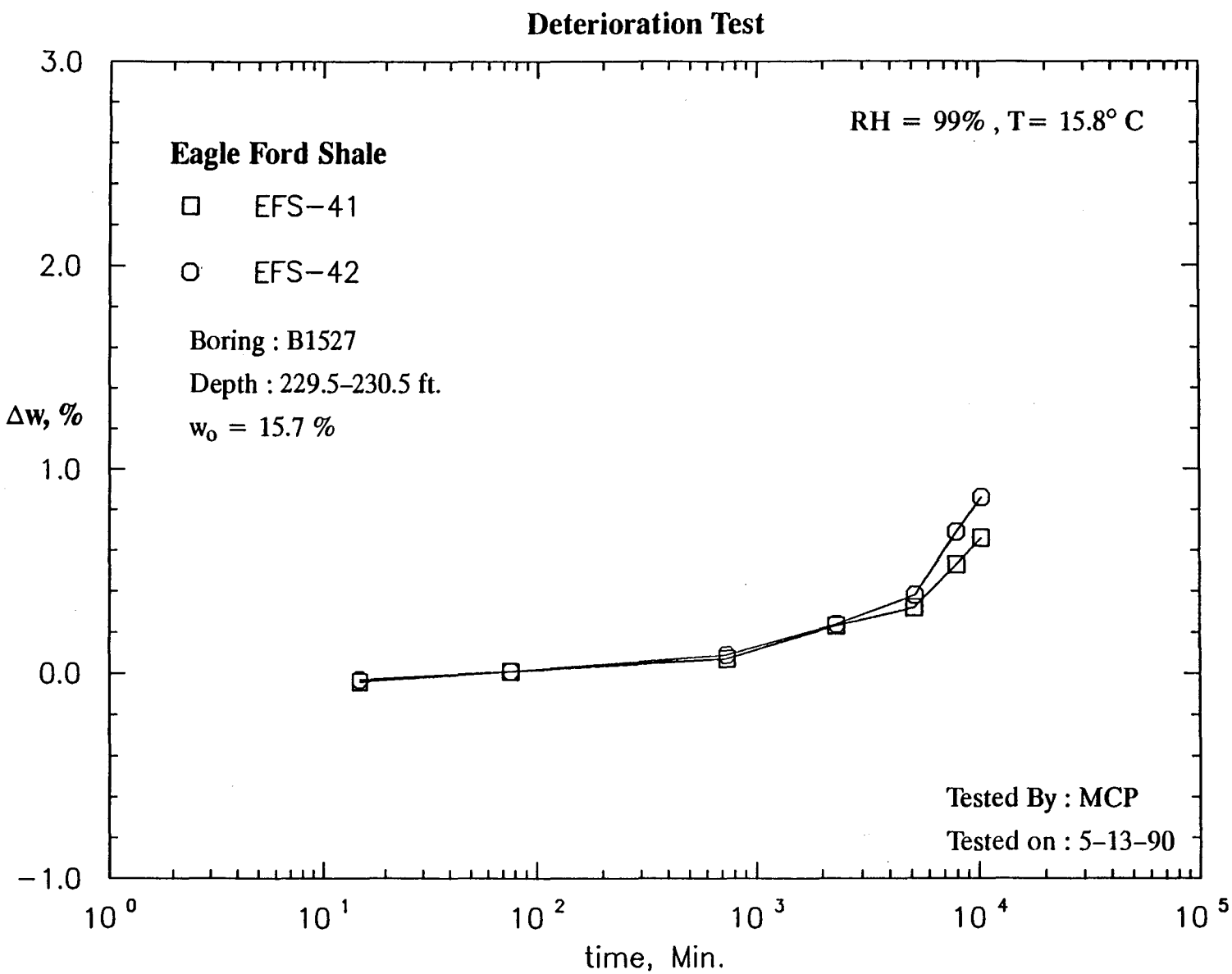


Fig. D13a Water Content Change – Log time Relationship

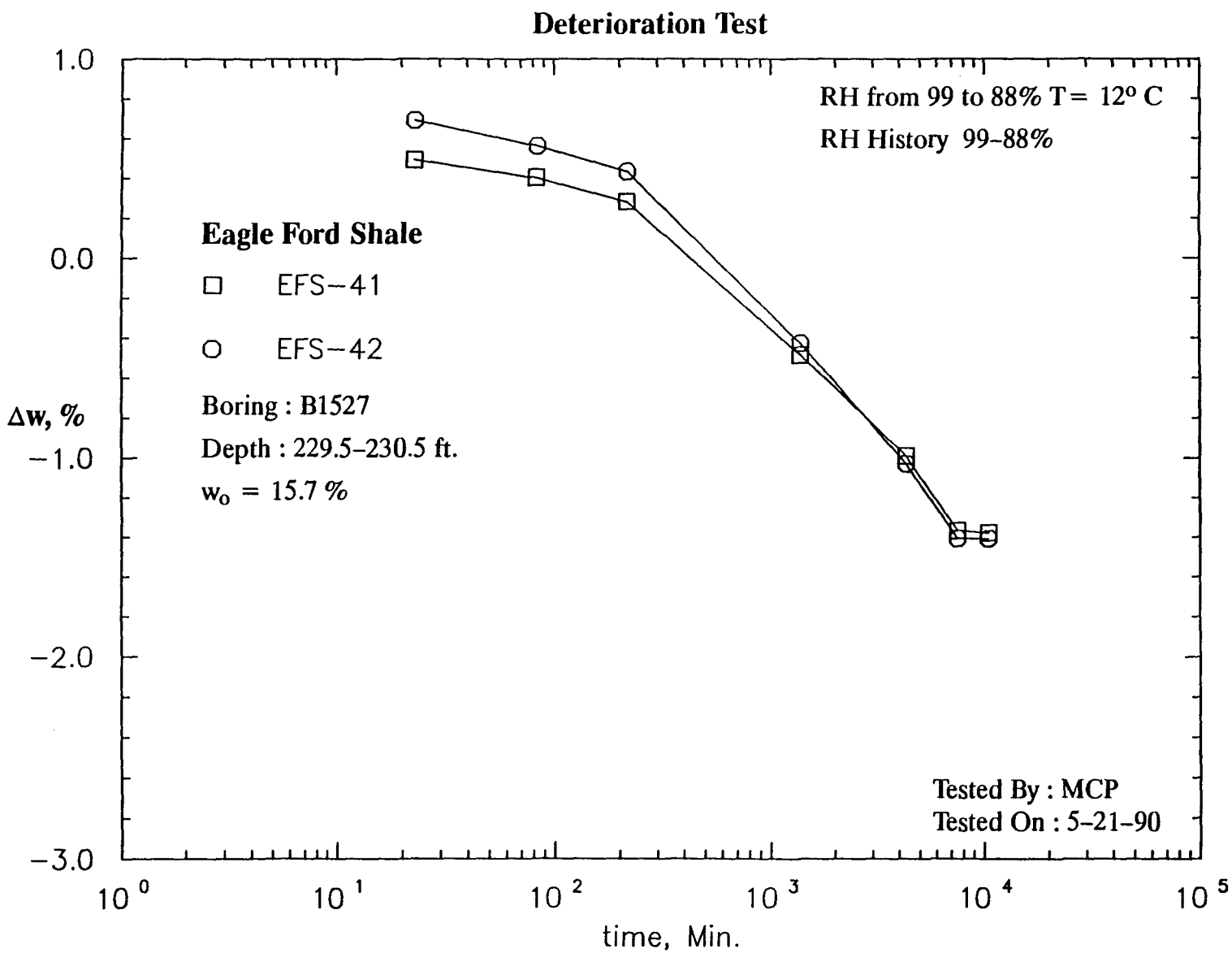


Fig. D13b Water Content Change – Log time Relationship

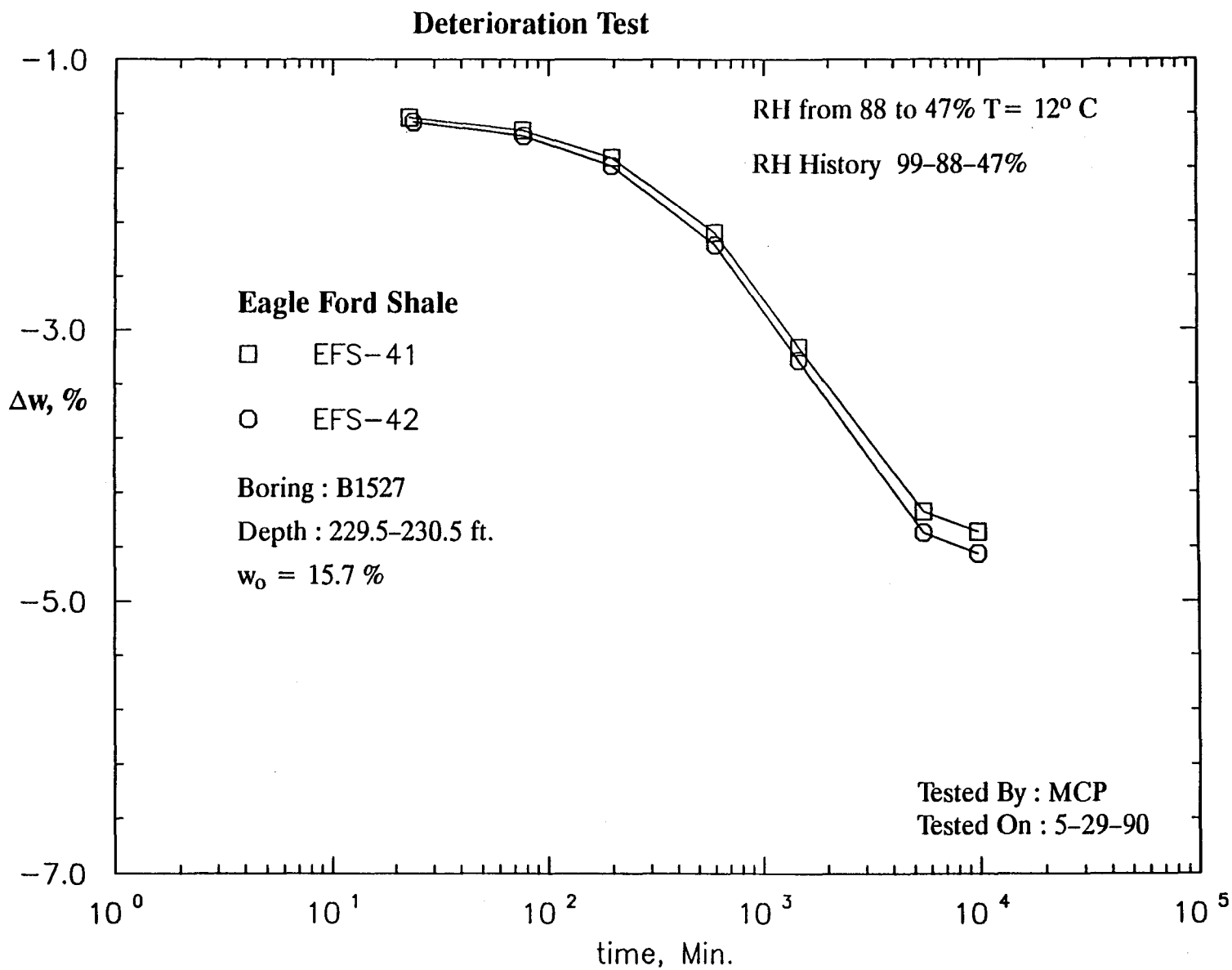


Fig. D13c Water Content Change – Log time Relationship

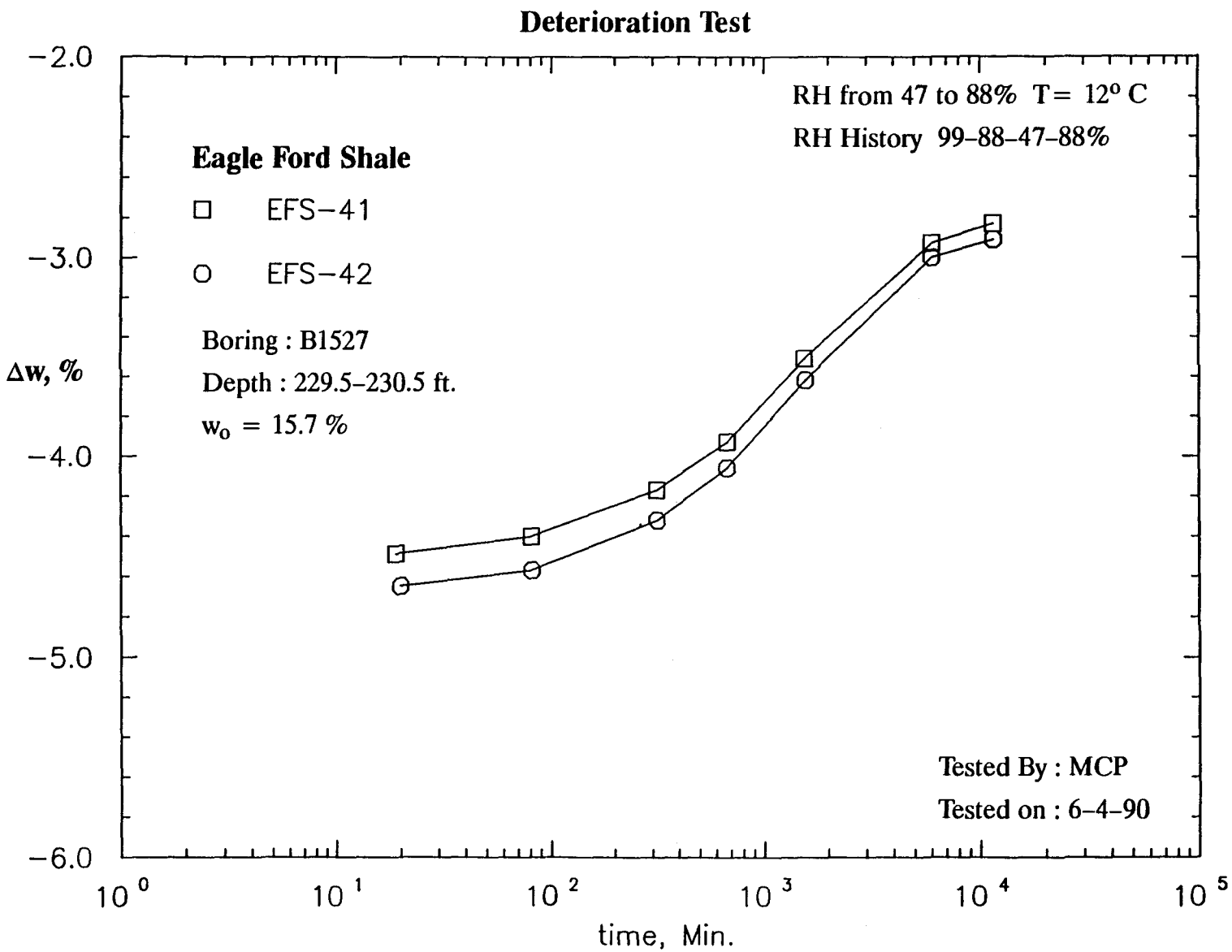


Fig. D13d Water Content Change – Log time Relationship

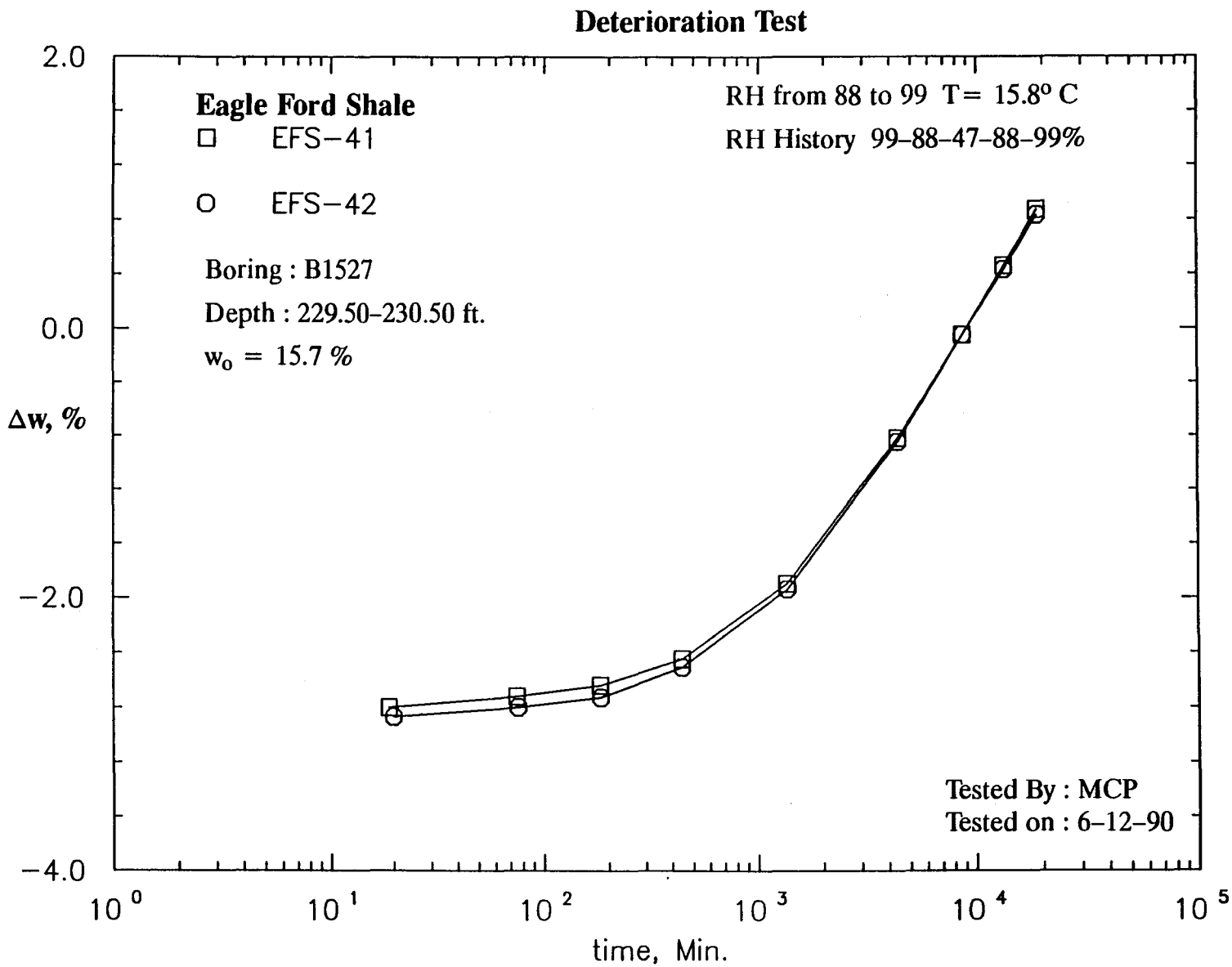


Fig. D13e Water Content Change – Log time Relationship

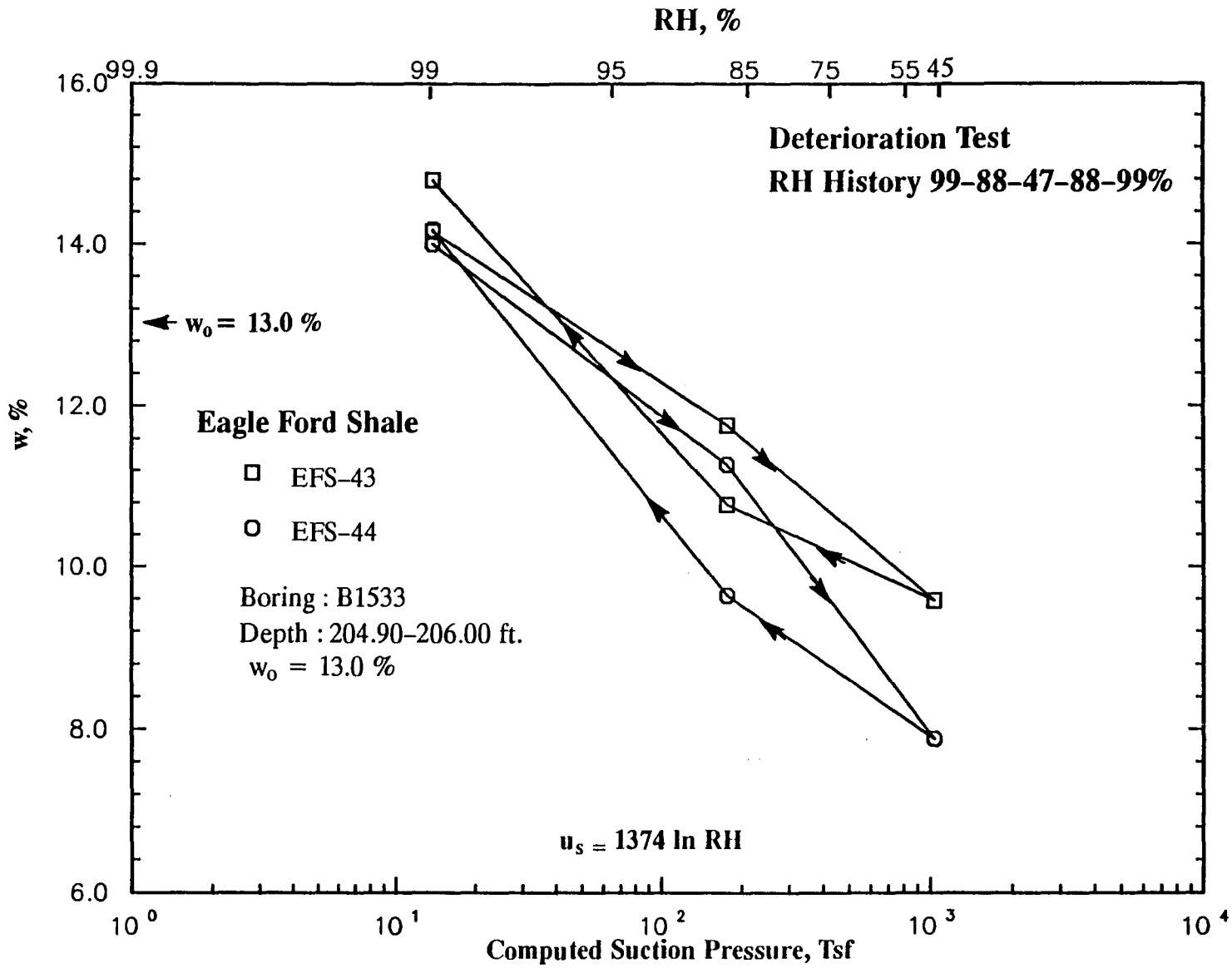


Fig. D14 Water Content – Relative Humidity Relationship

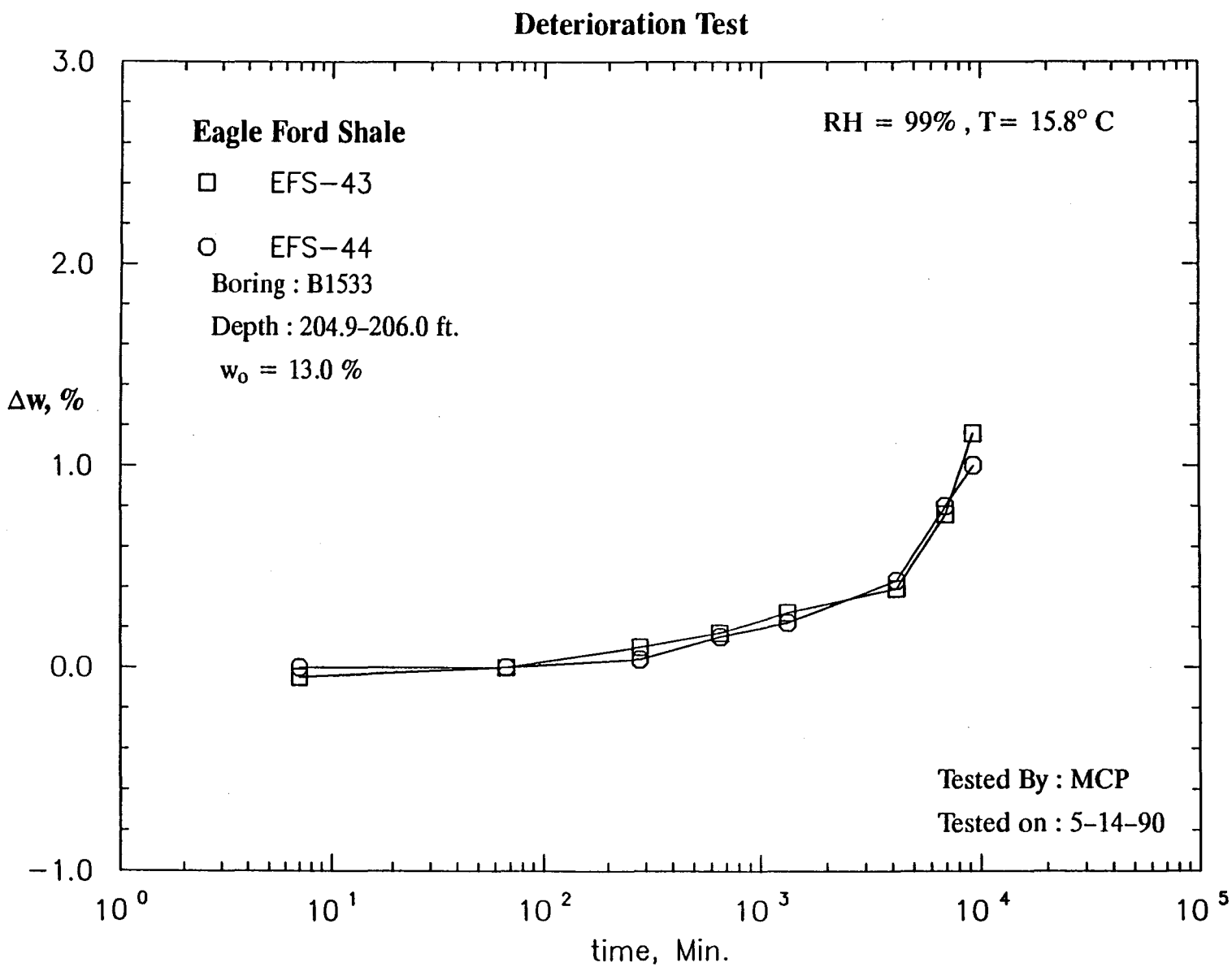


Fig. D14a Water Content Change – Log time Relationship

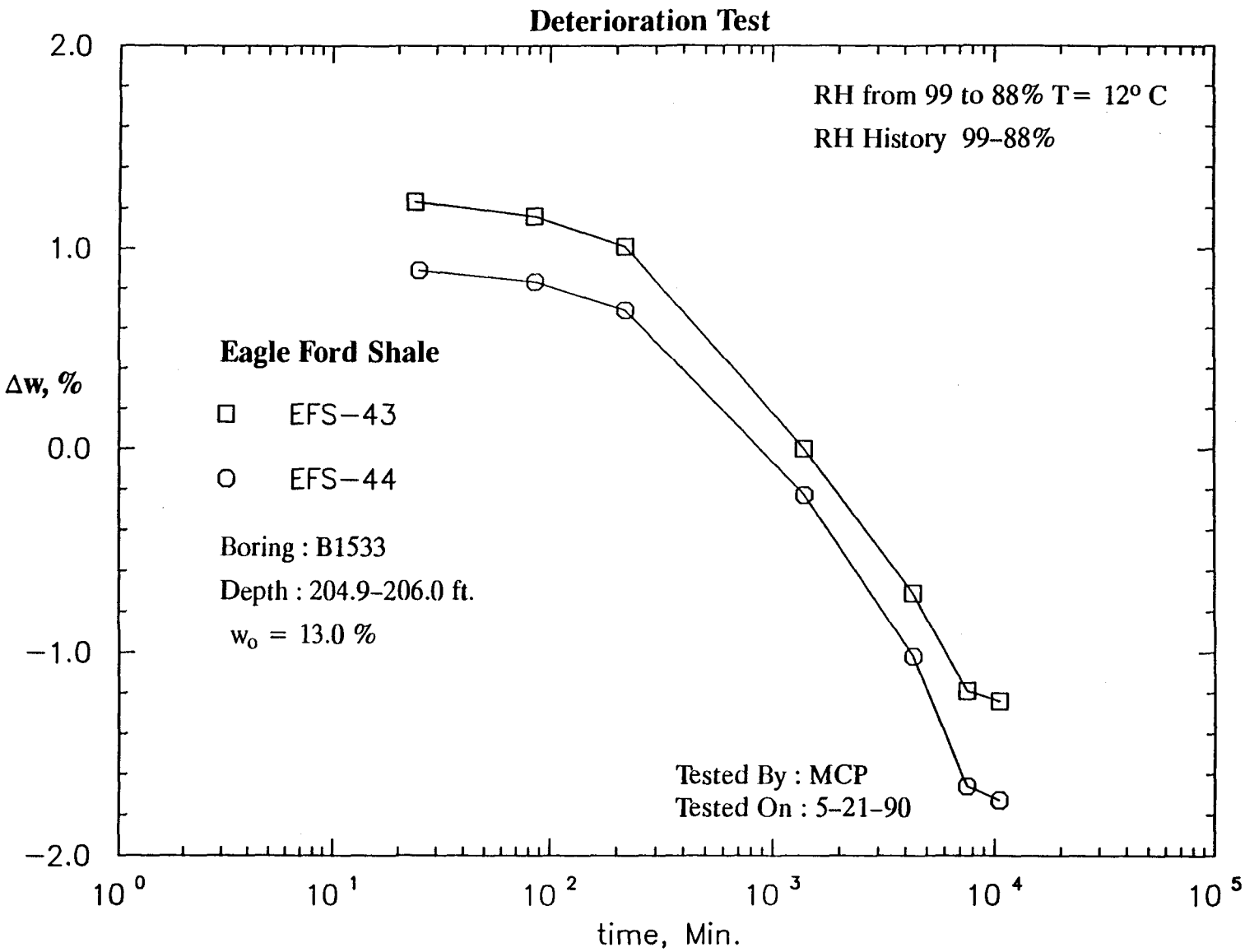


Fig. D14b Water Content Change - Log time Relationship

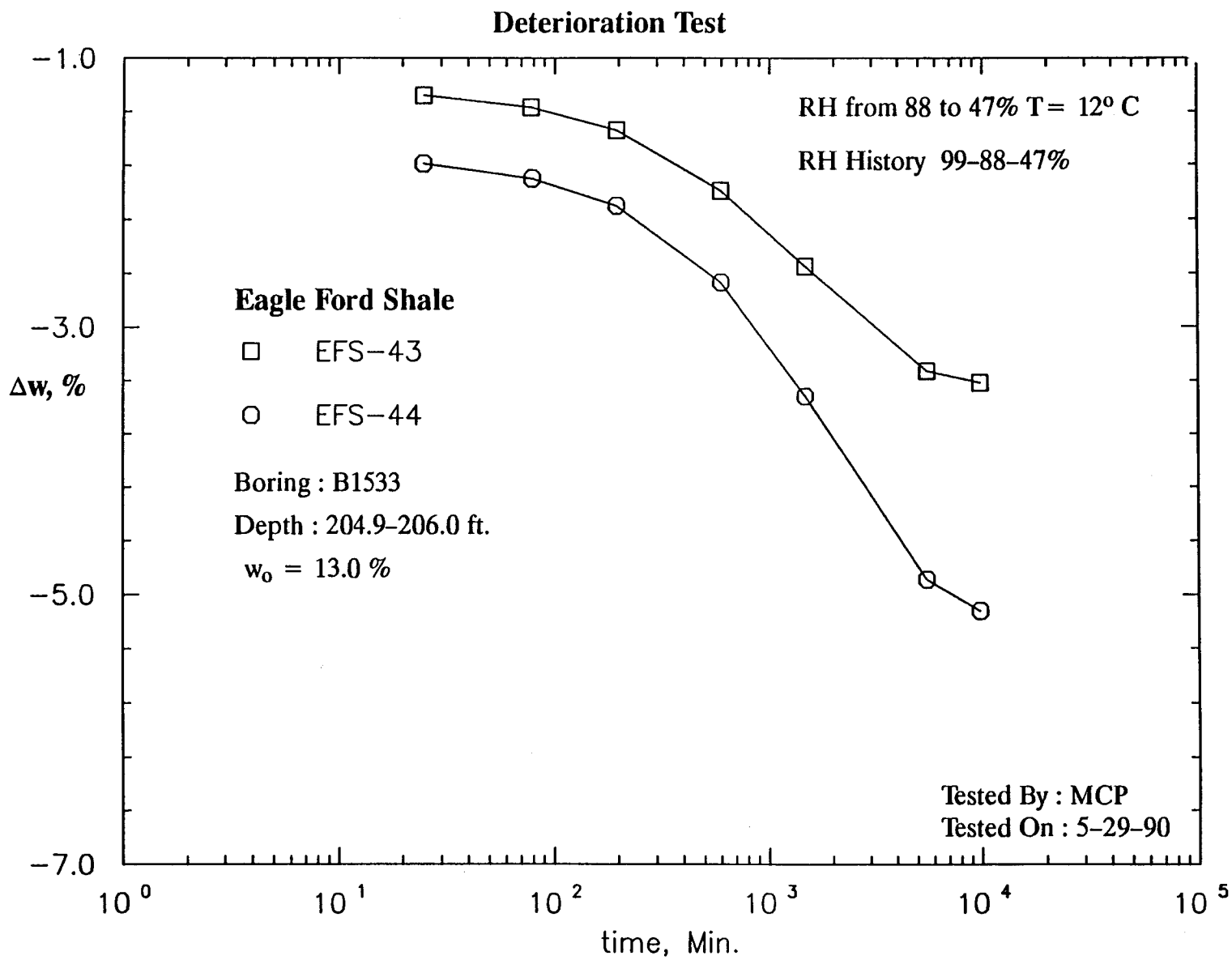


Fig. D14c Water Content Change – Log time Relationship

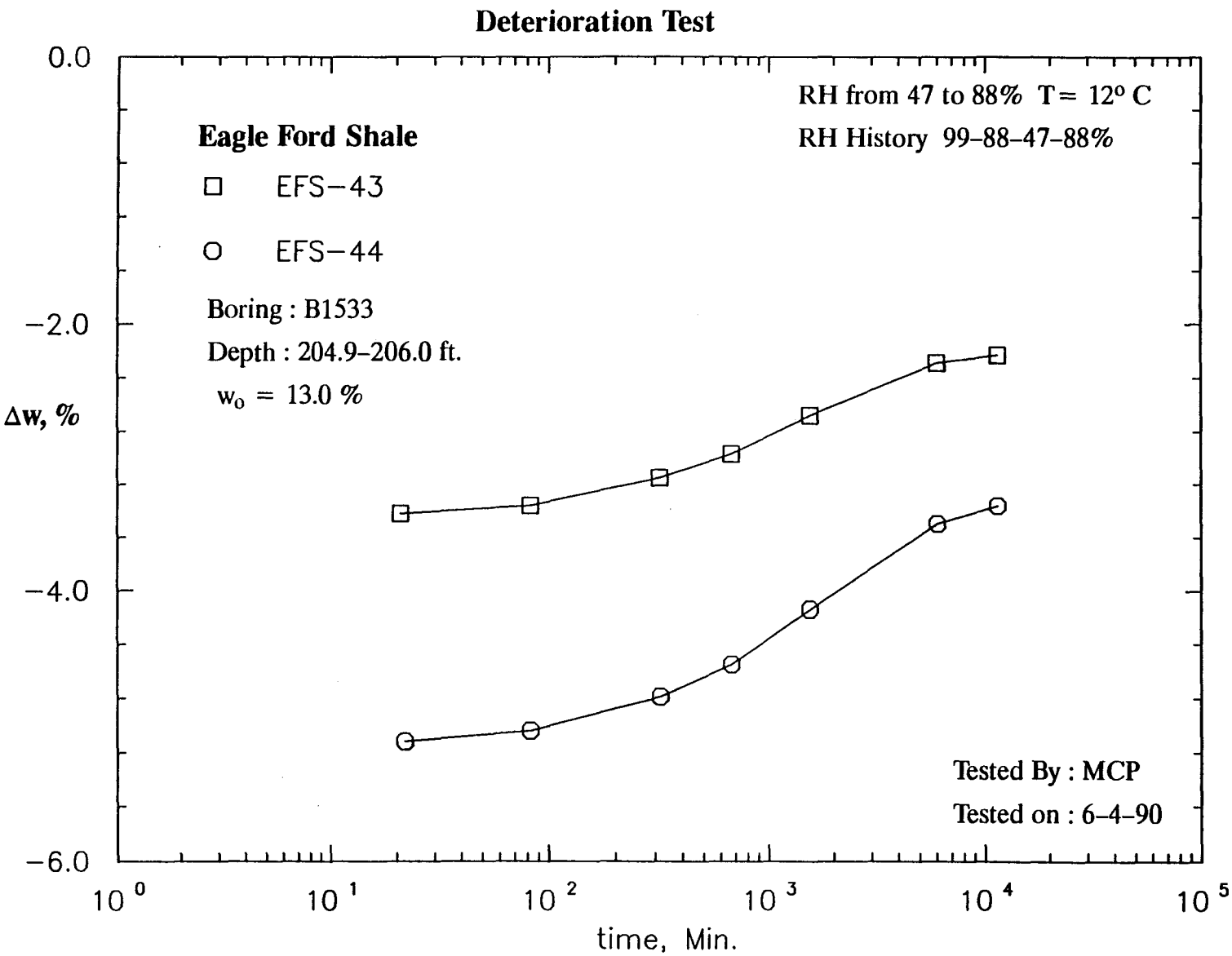


Fig. D14d Water Content Change - Log time Relationship

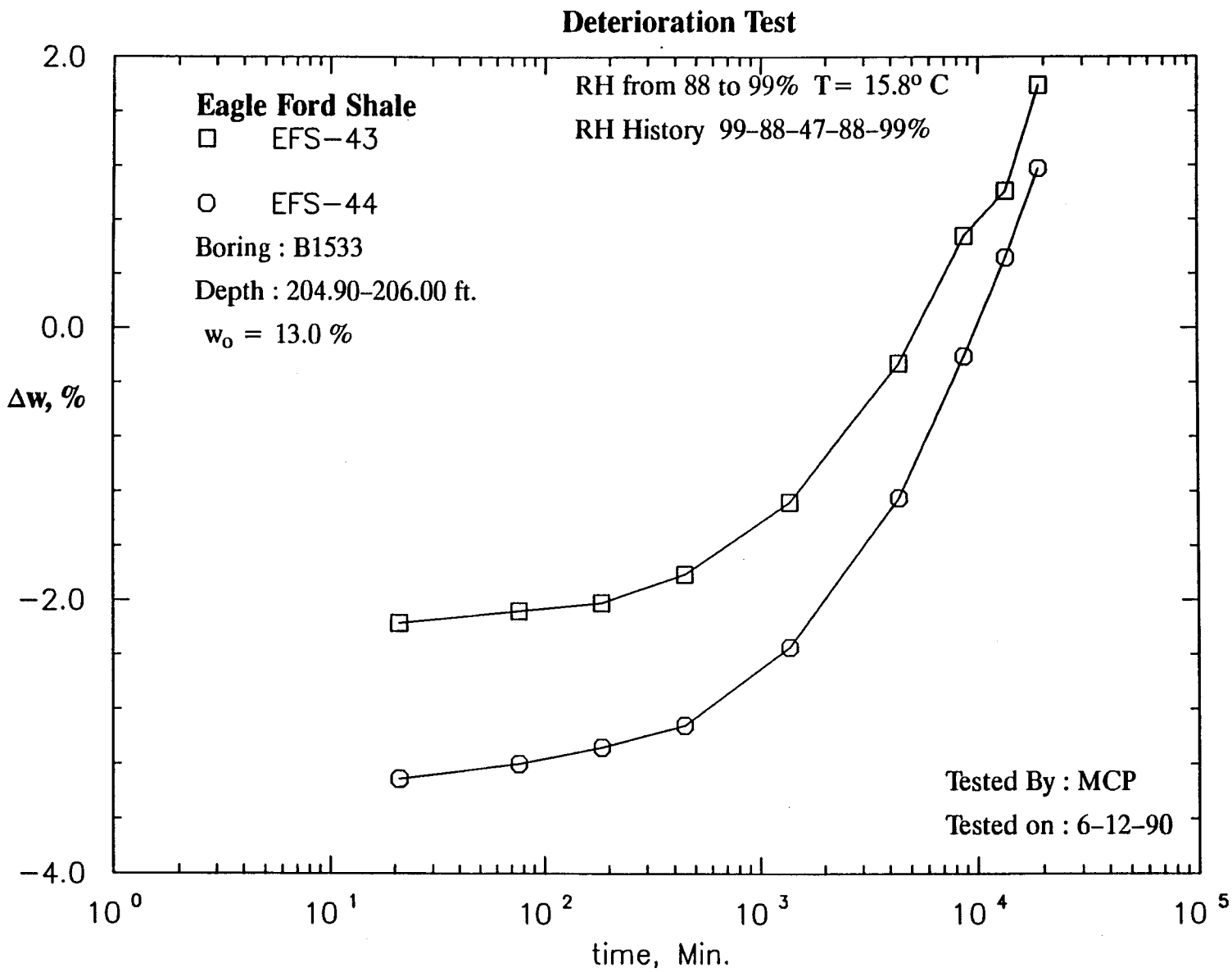


Fig. D14e Water Content Change – Log time Relationship

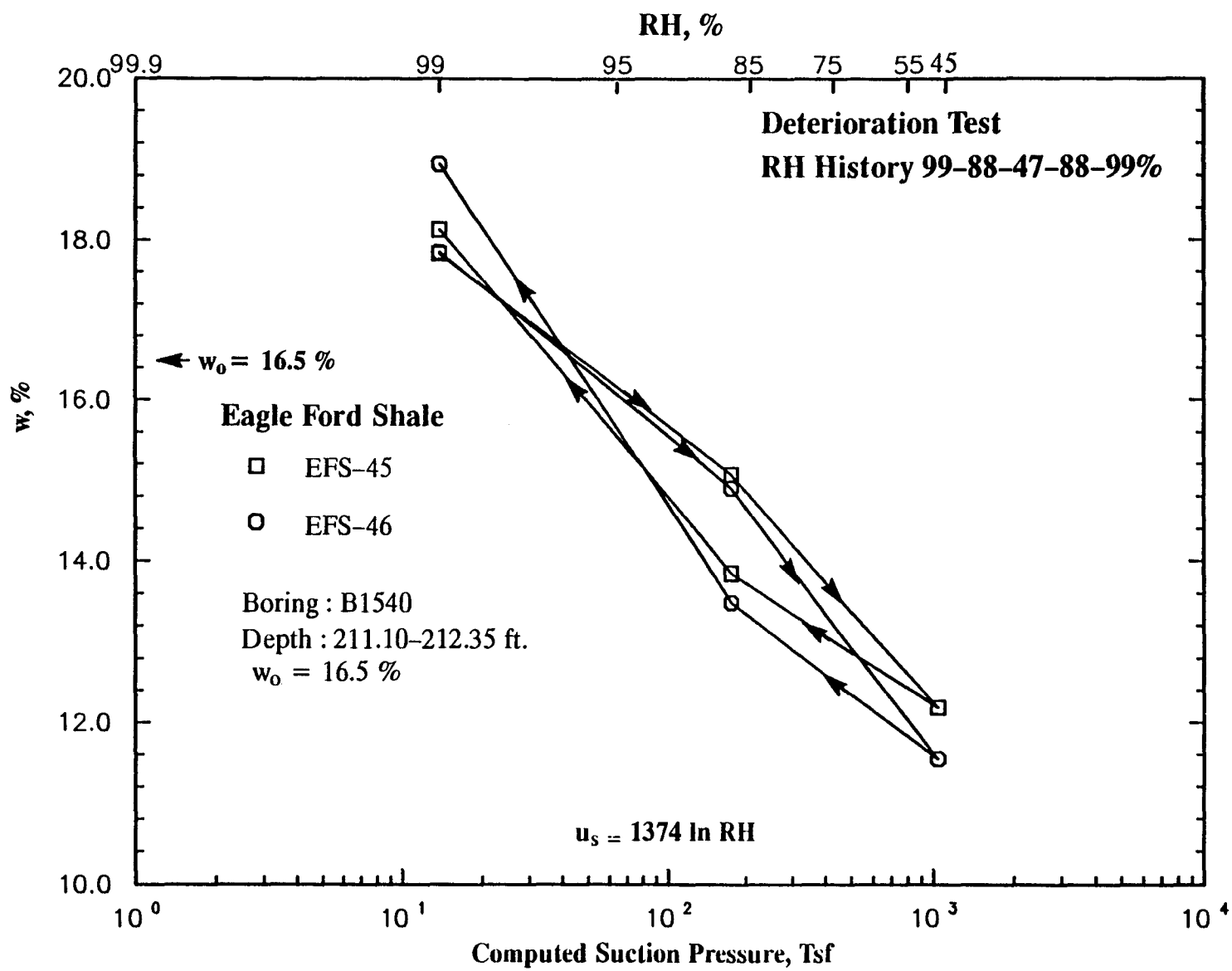


Fig. D15 Water Content – Relative Humidity Relationship

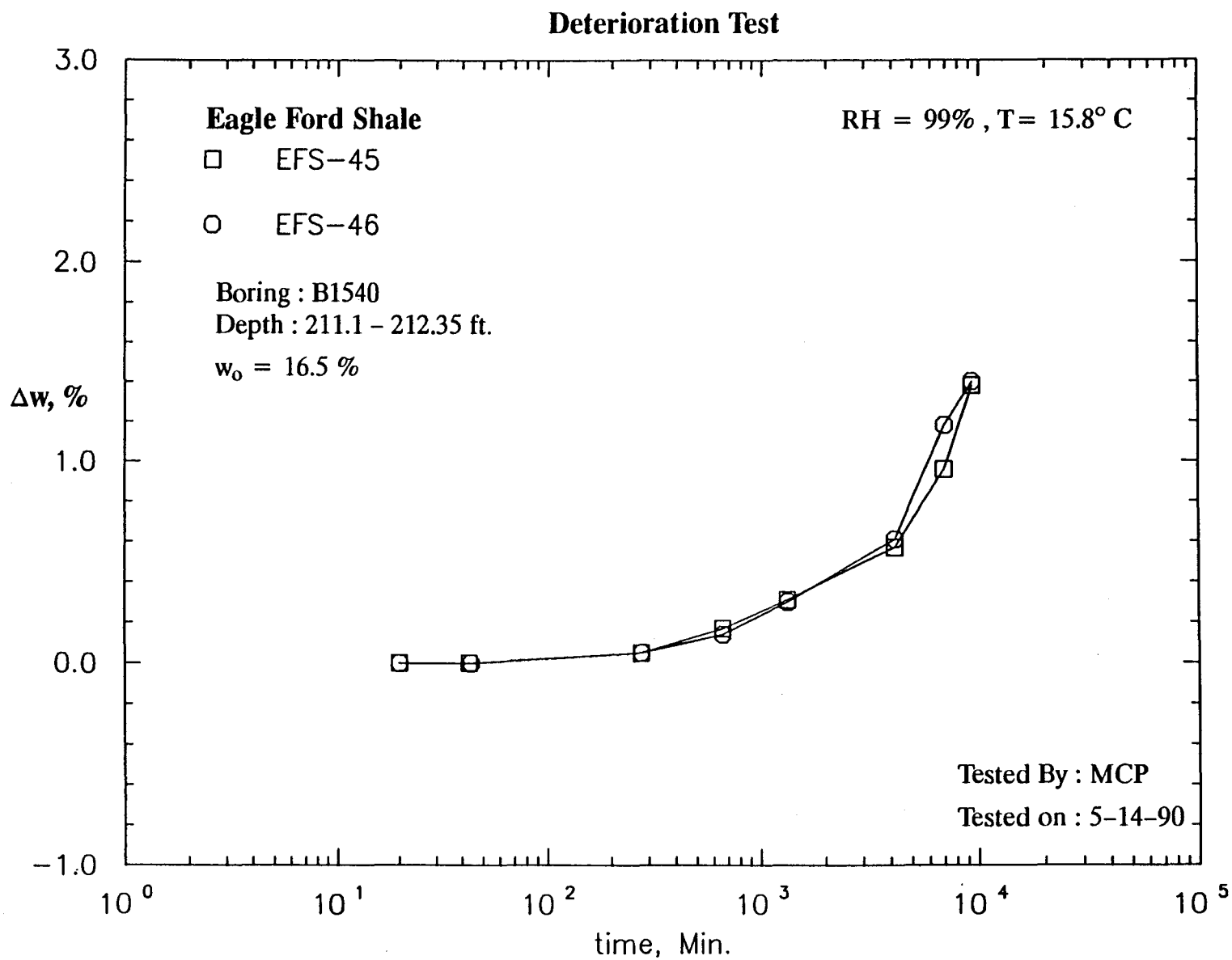


Fig. D15a Water Content Change – Log time Relationship

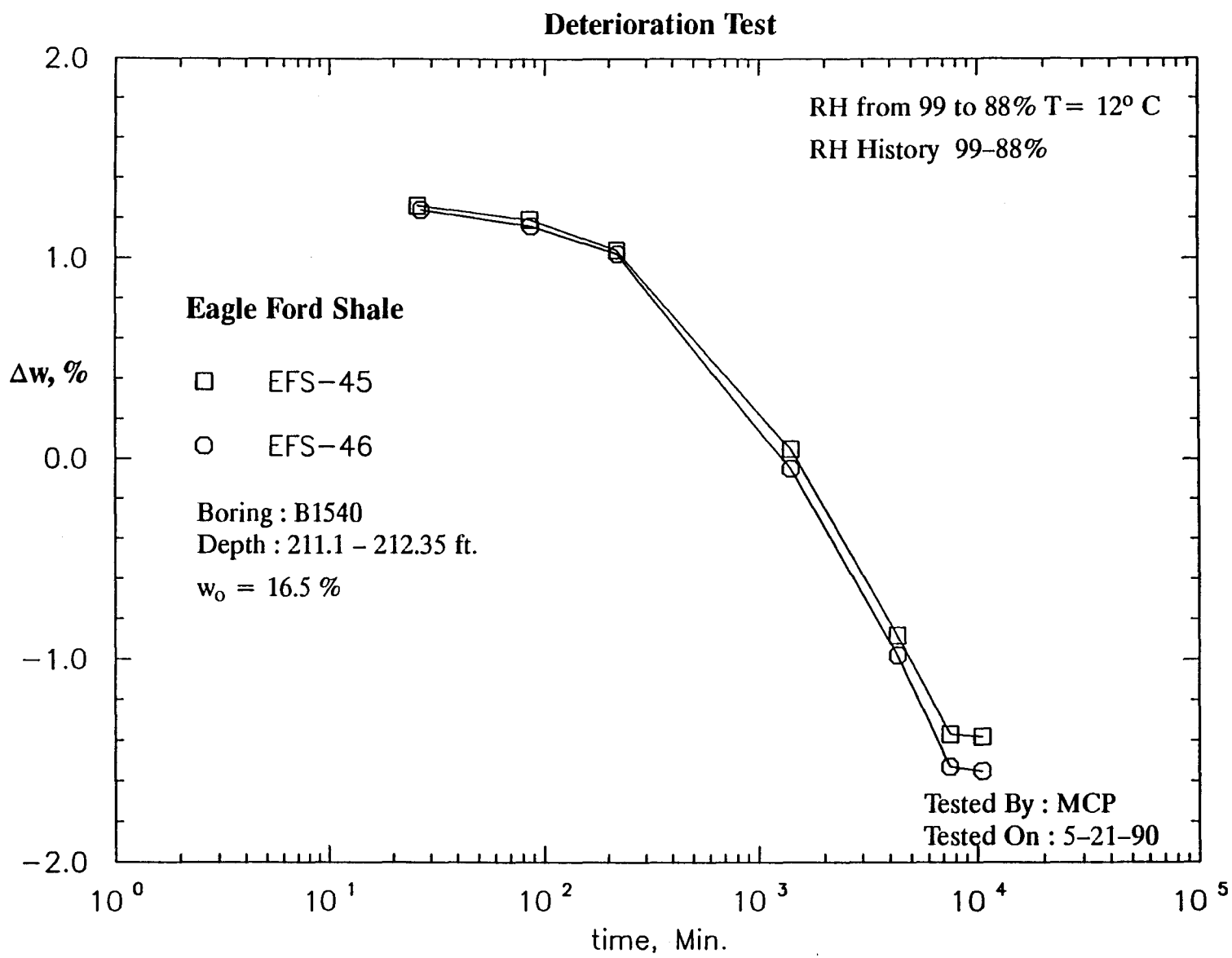


Fig. D15b Water Content Change – Log time Relationship

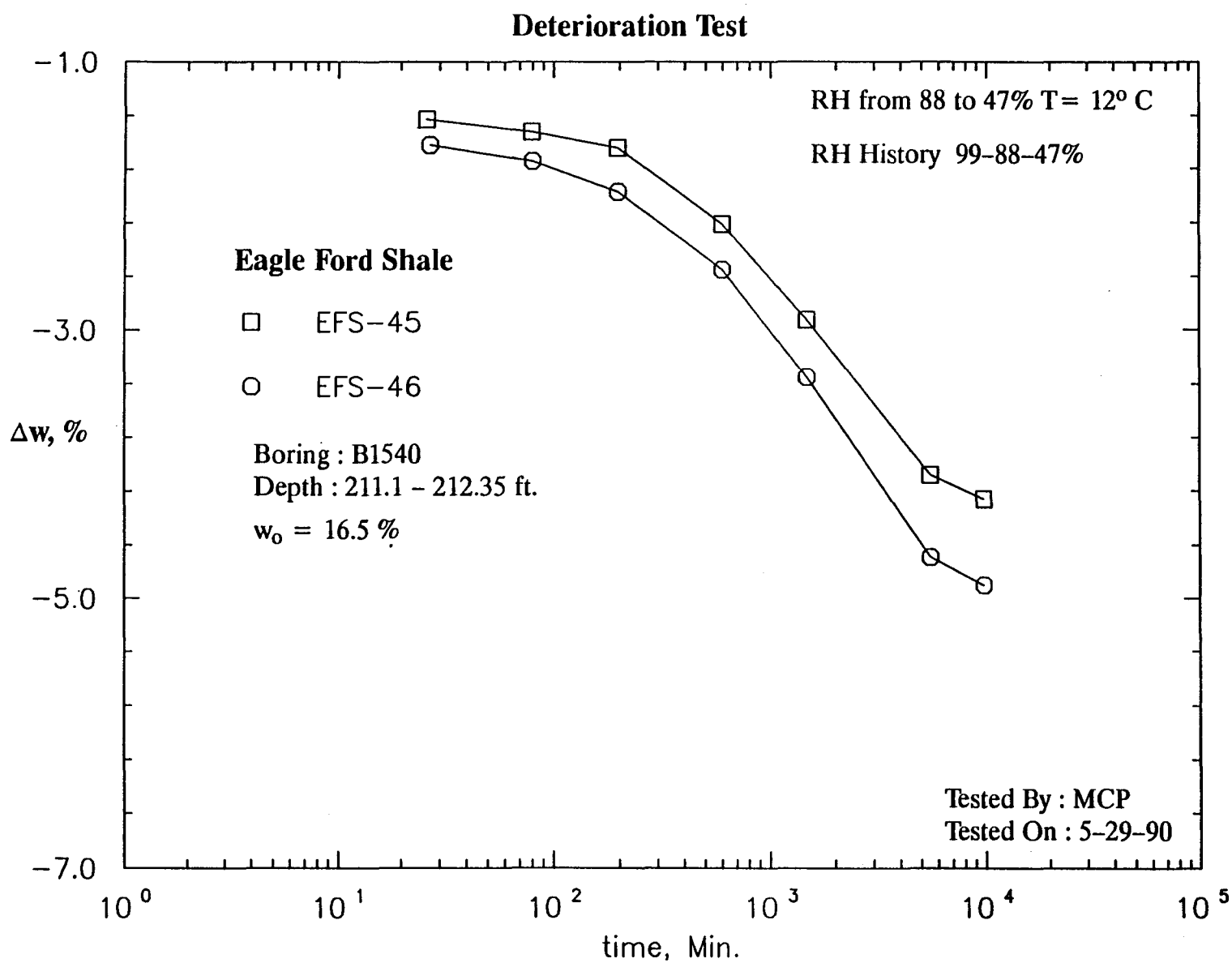


Fig. D15c Water Content Change - Log time Relationship

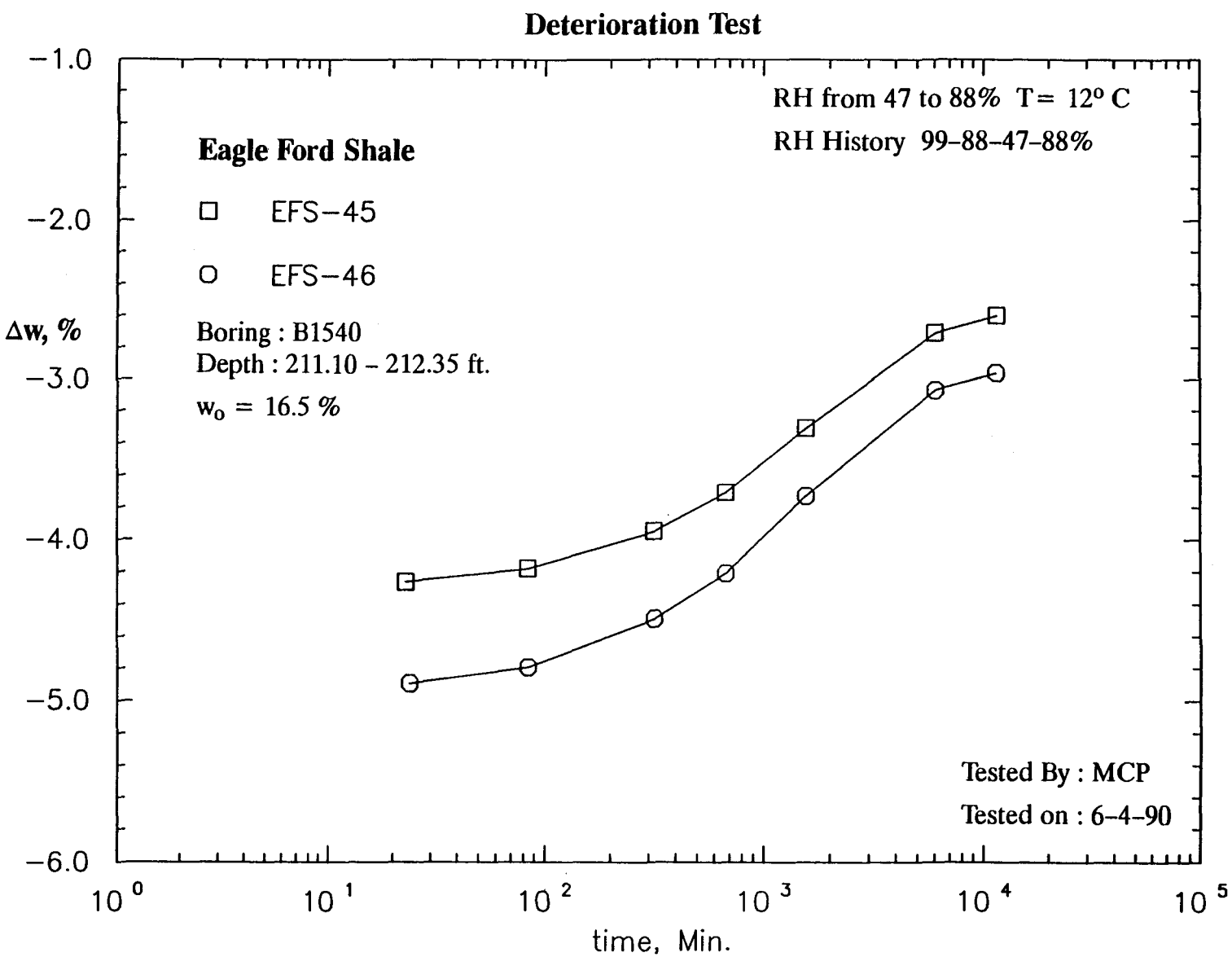


Fig. D15d Water Content Change - Log time Relationship

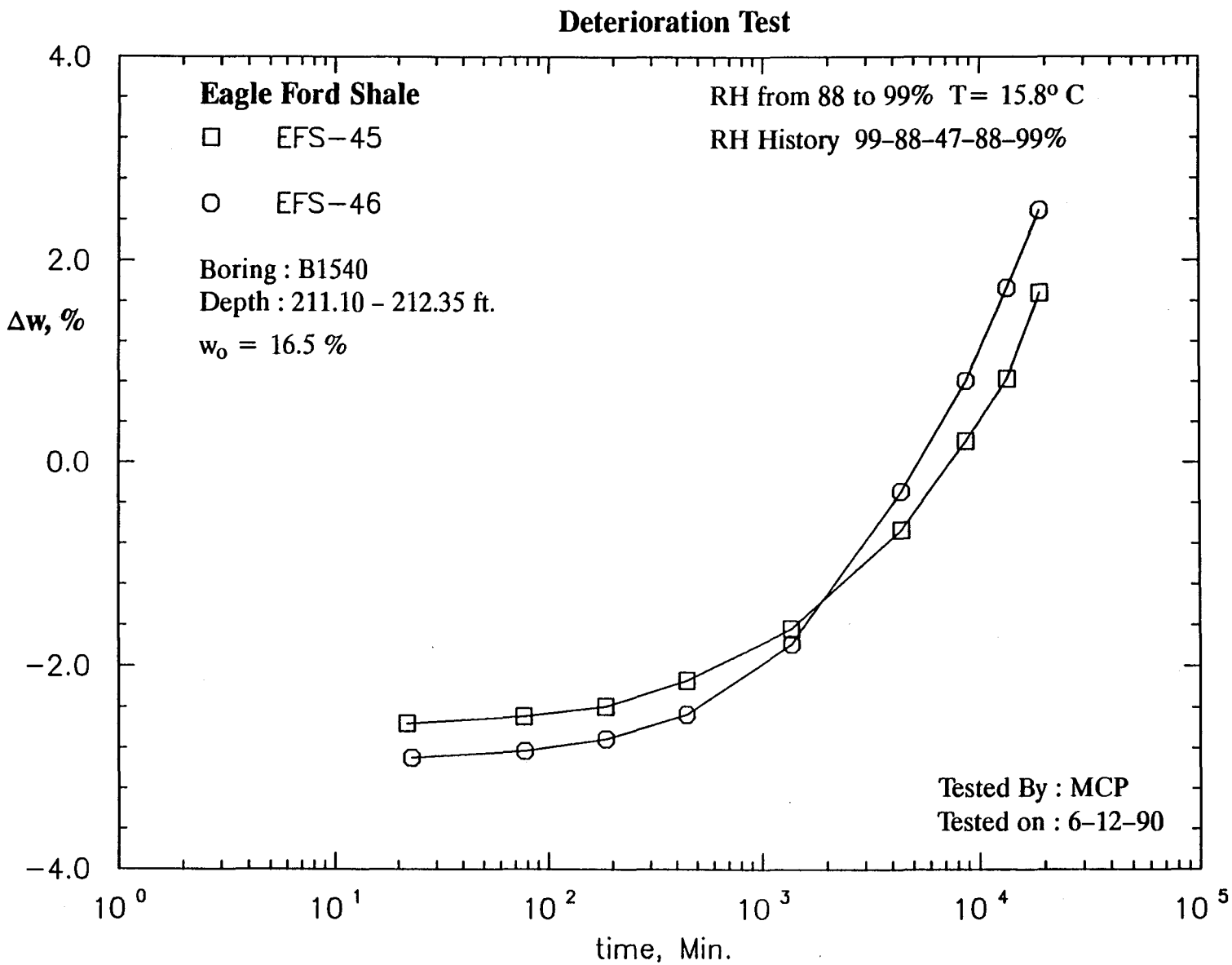


Fig. D15e Water Content Change – Log time Relationship

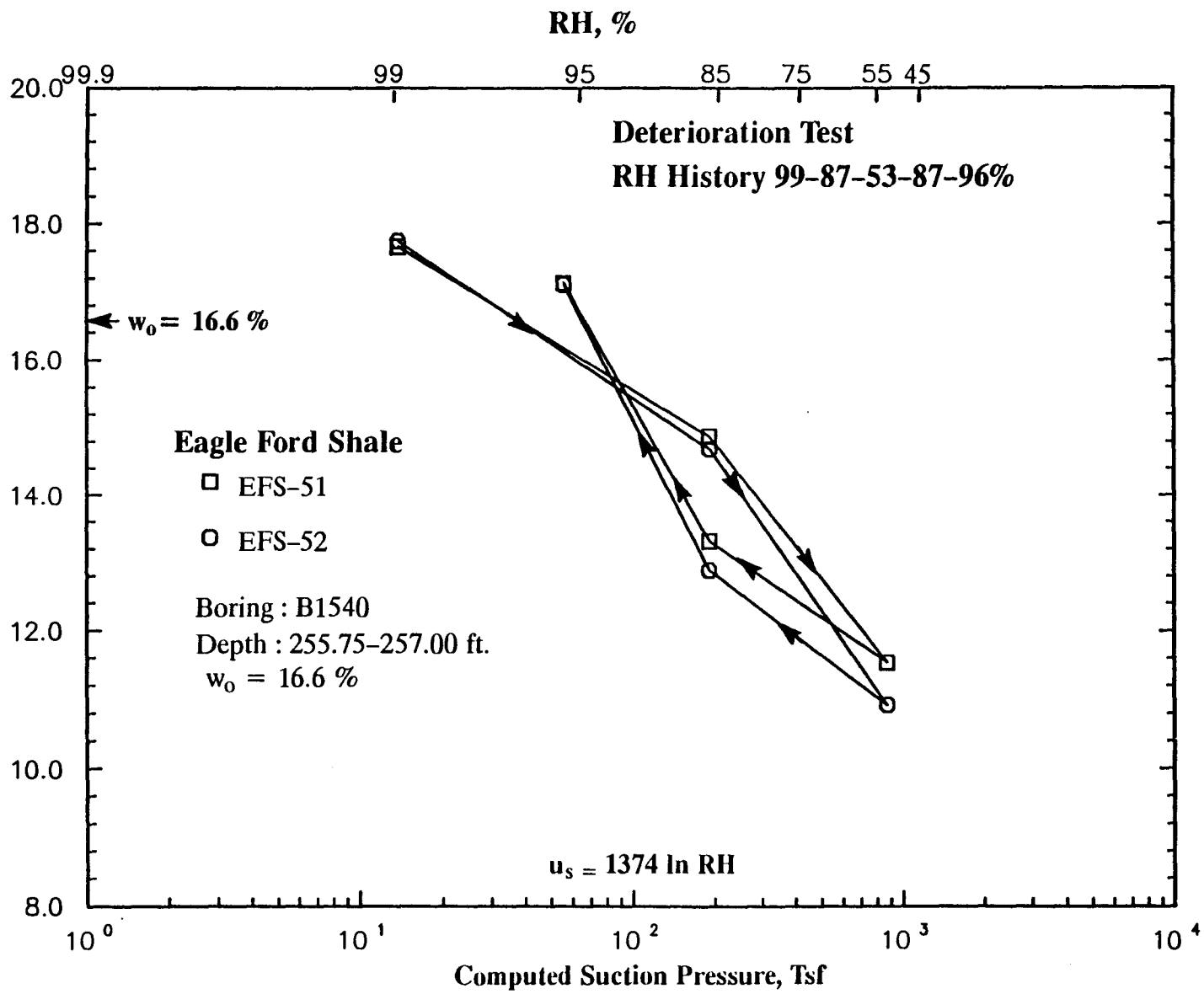


Fig. D16 Water Content – Relative Humidity Relationship

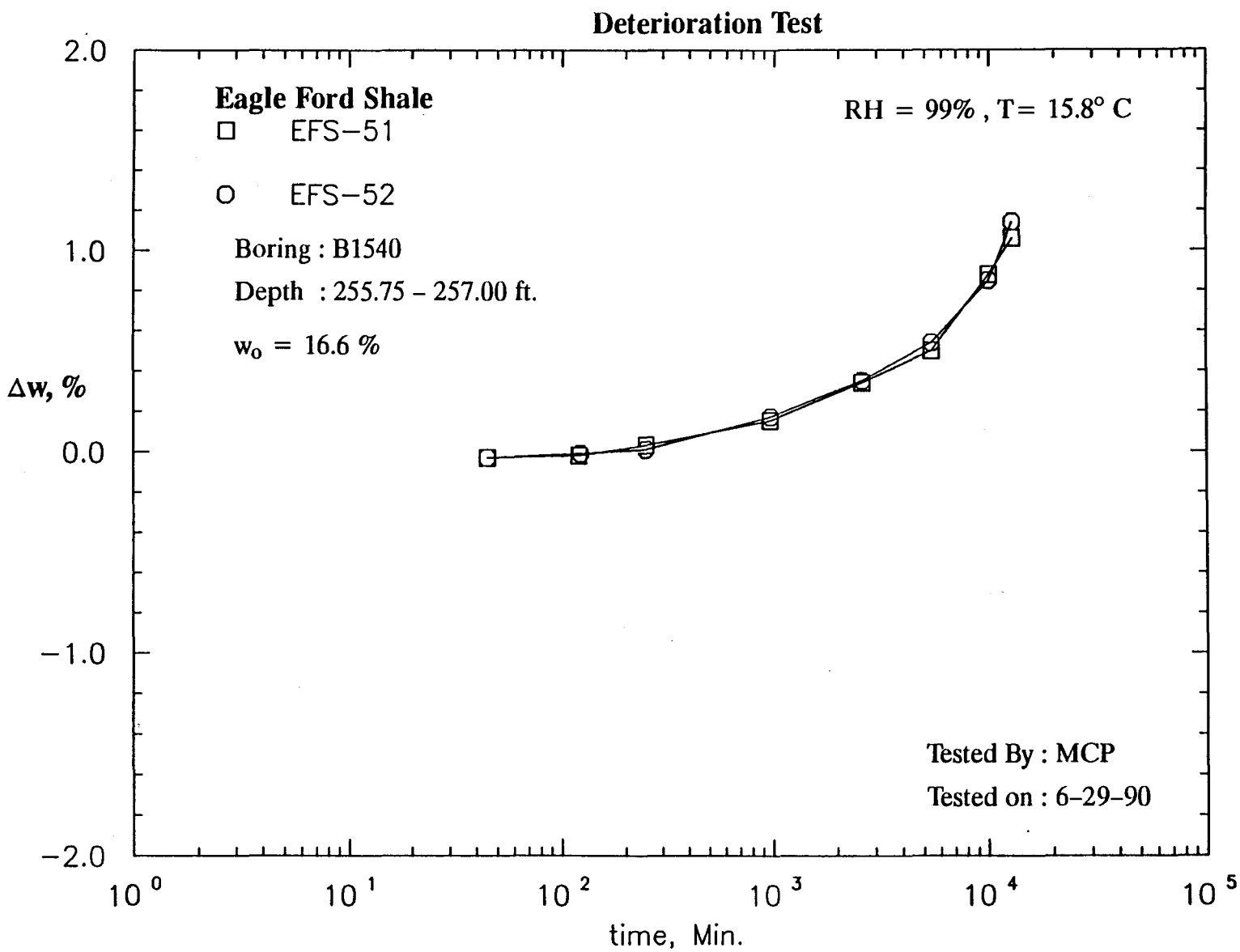


Fig. D16a Water Content Change – Log time Relationship

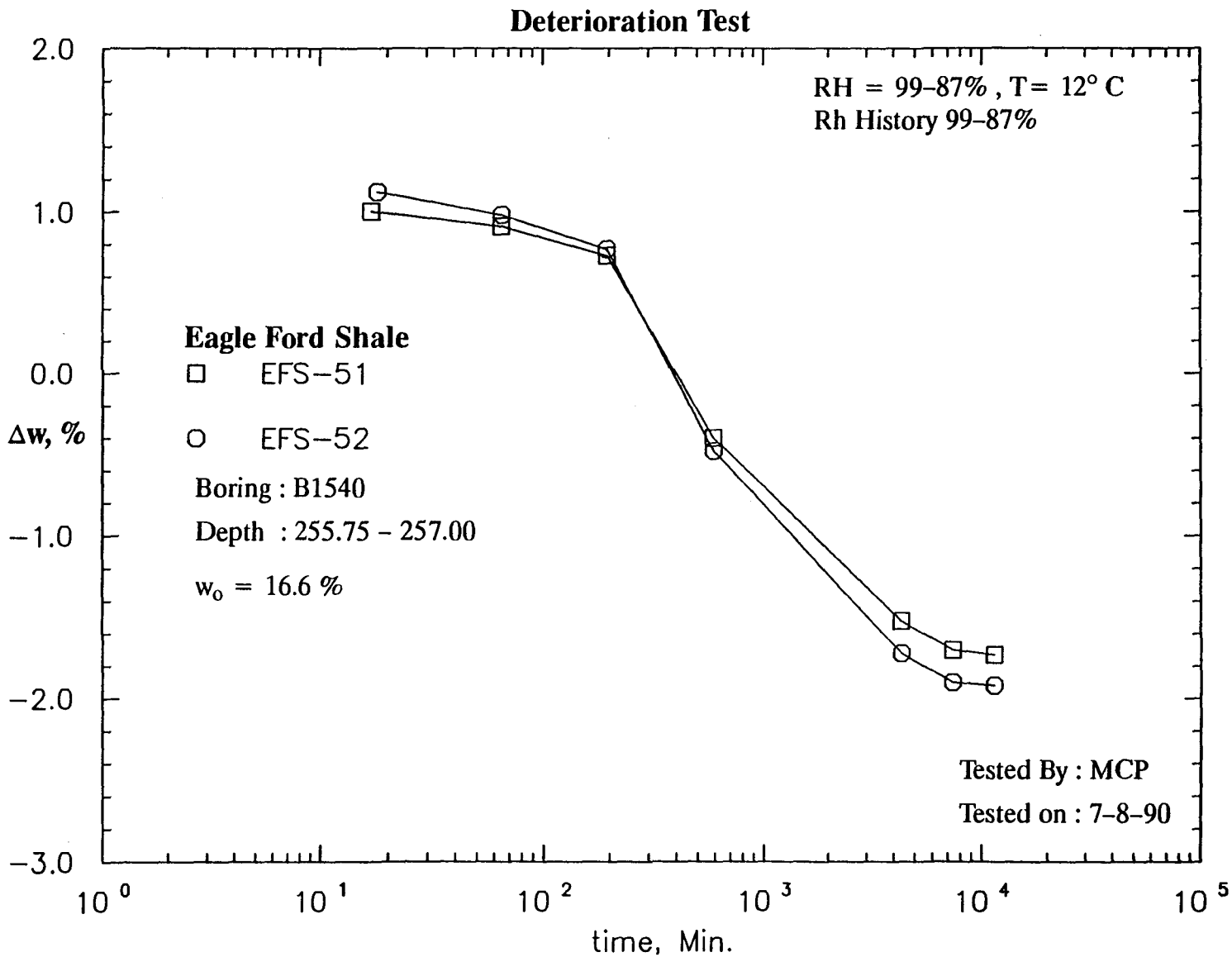


Fig. D16b Water Content Change - Log time Relationship

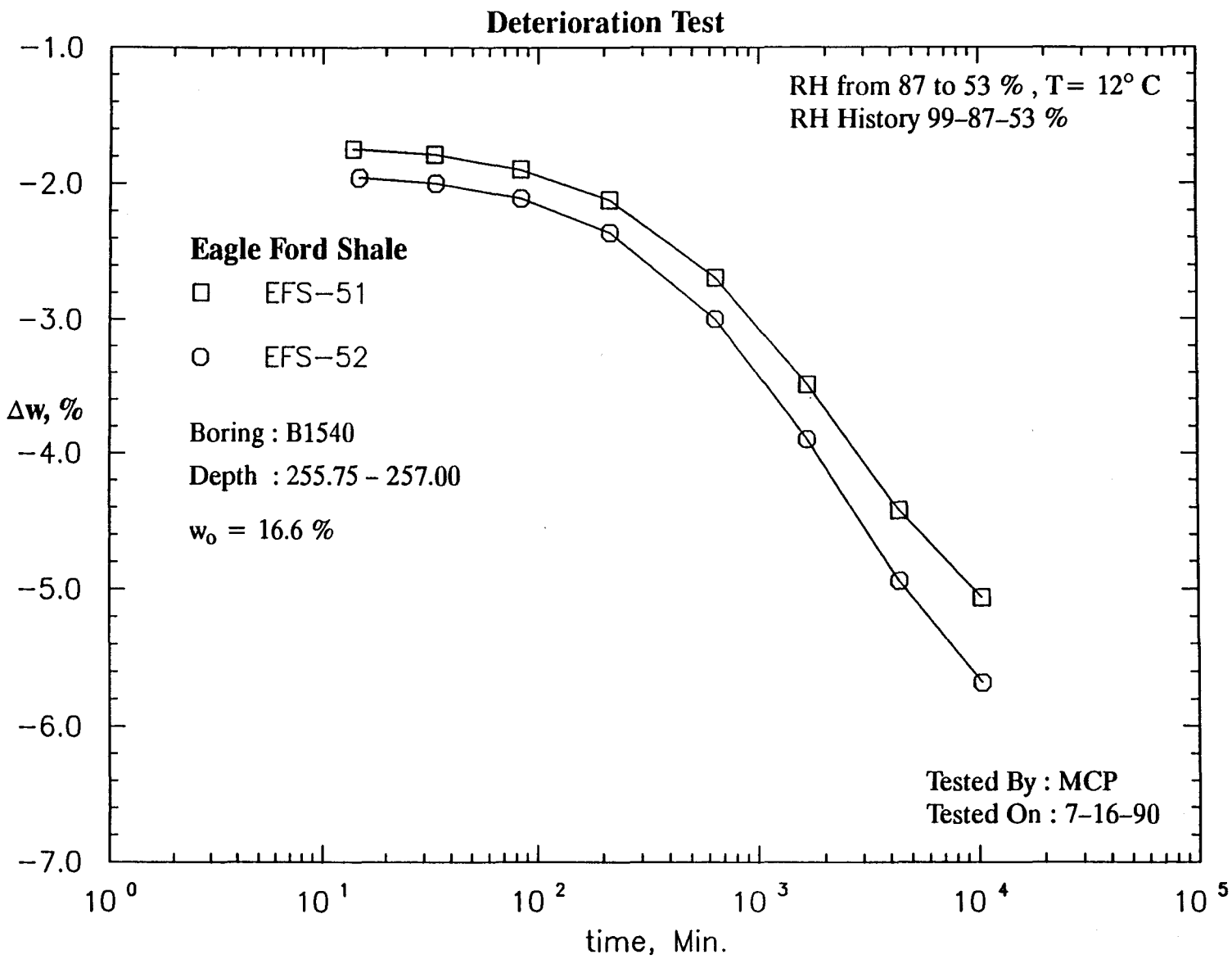


Fig. D16c Water Content Change – Log time Relationship

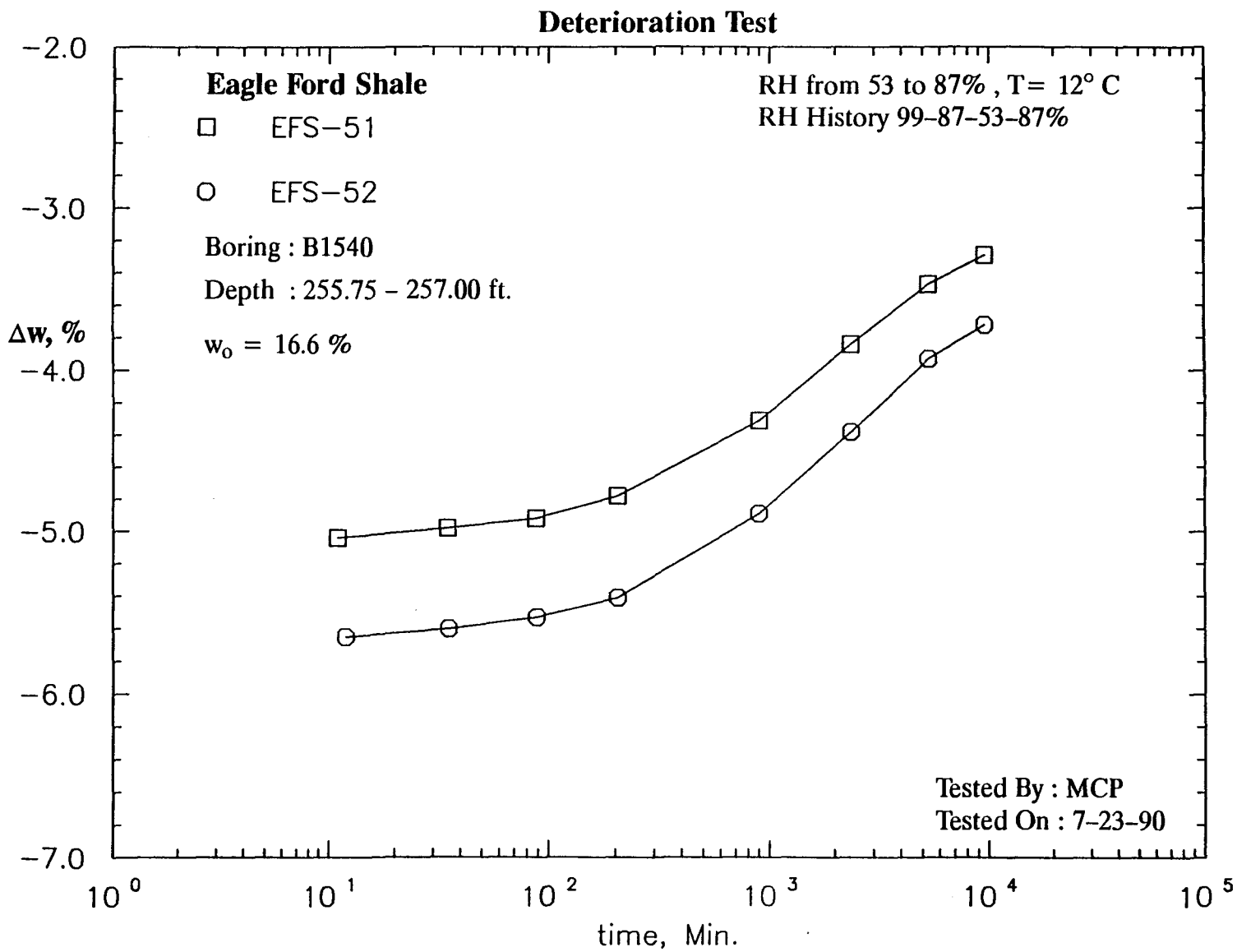


Fig. D16d Water Content Change - Log time Relationship

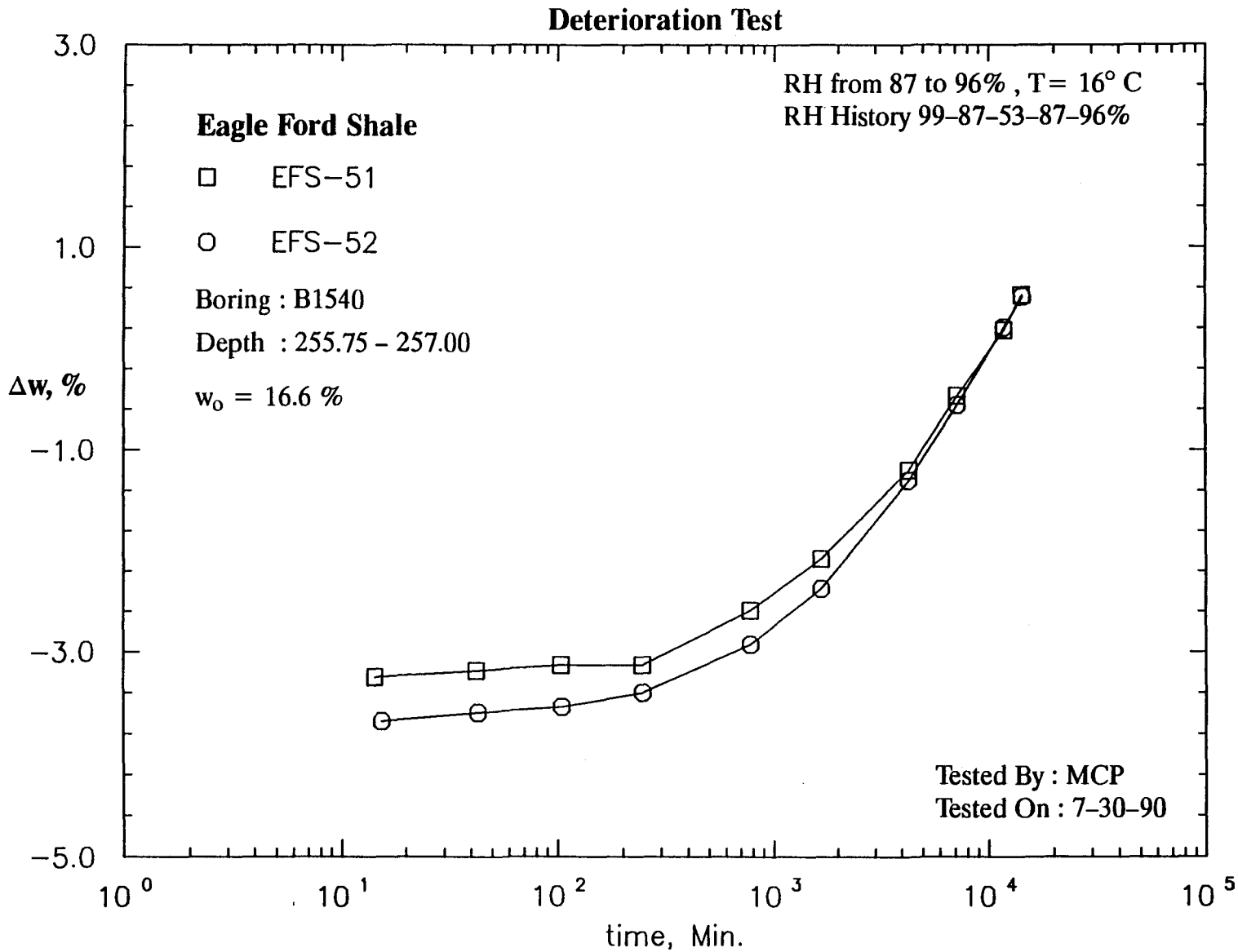


Fig. D16e Water Content Change – Log time Relationship

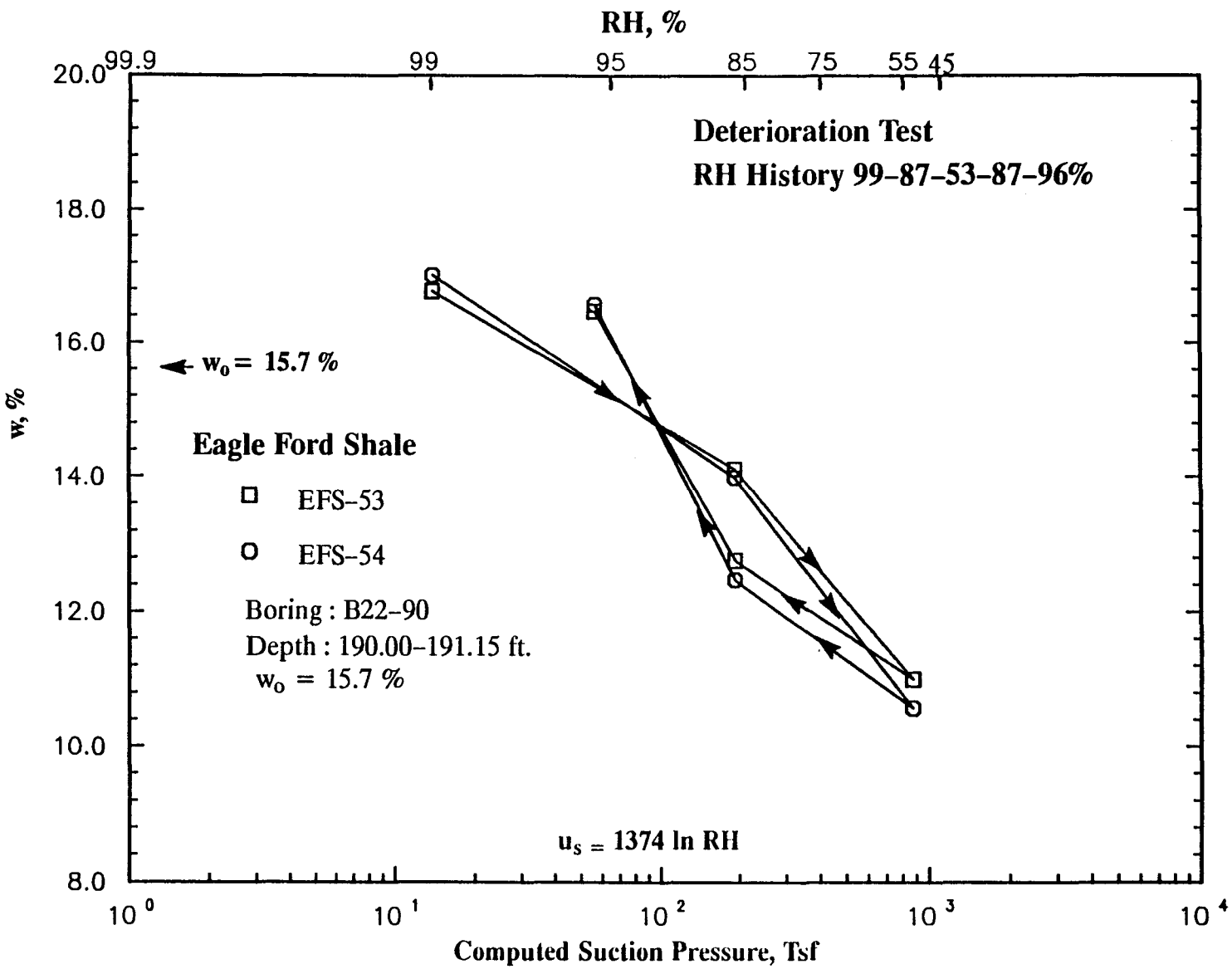


Fig. D17 Water Content - Relative Humidity Relationship

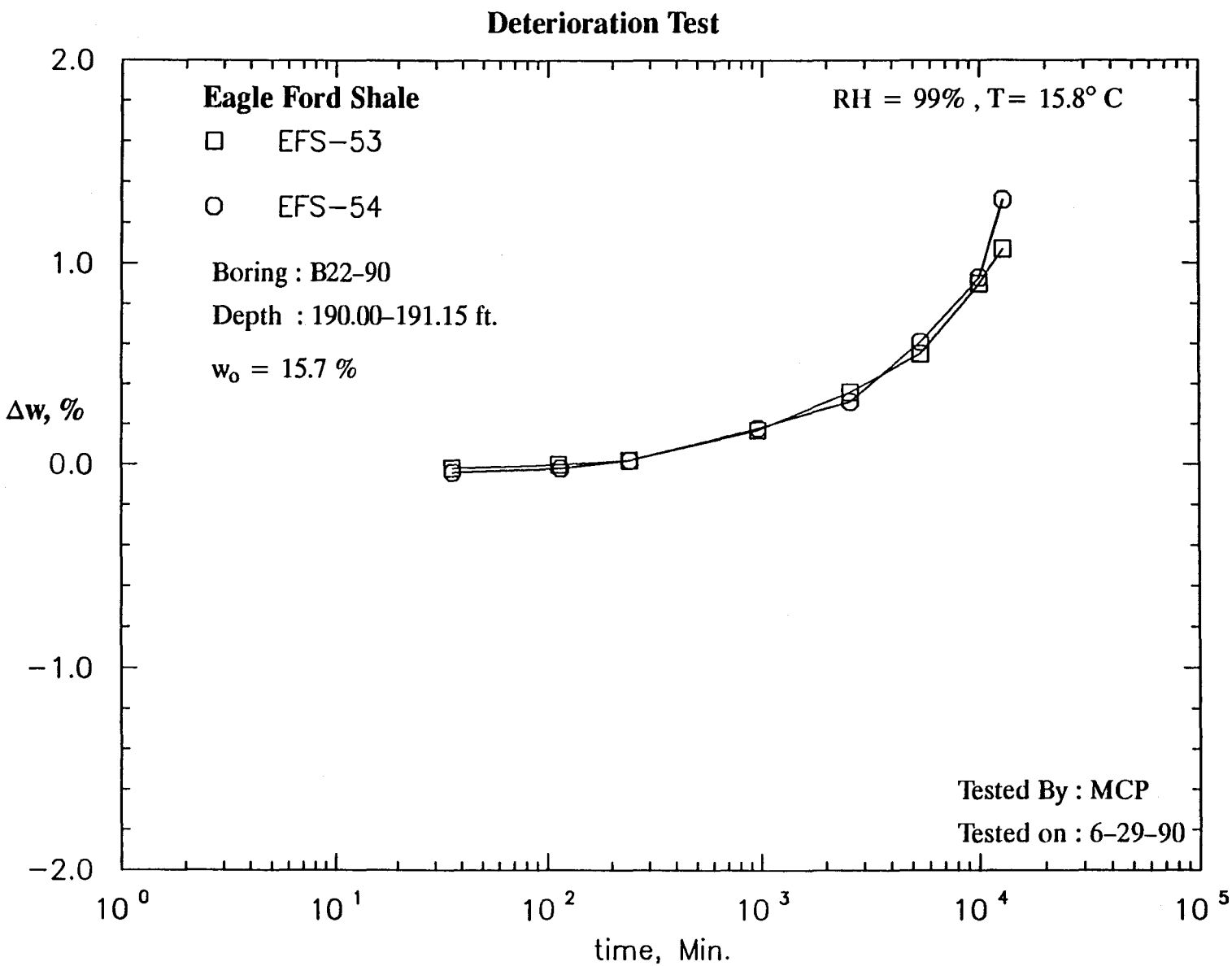


Fig. D17a Water Content Change – Log time Relationship

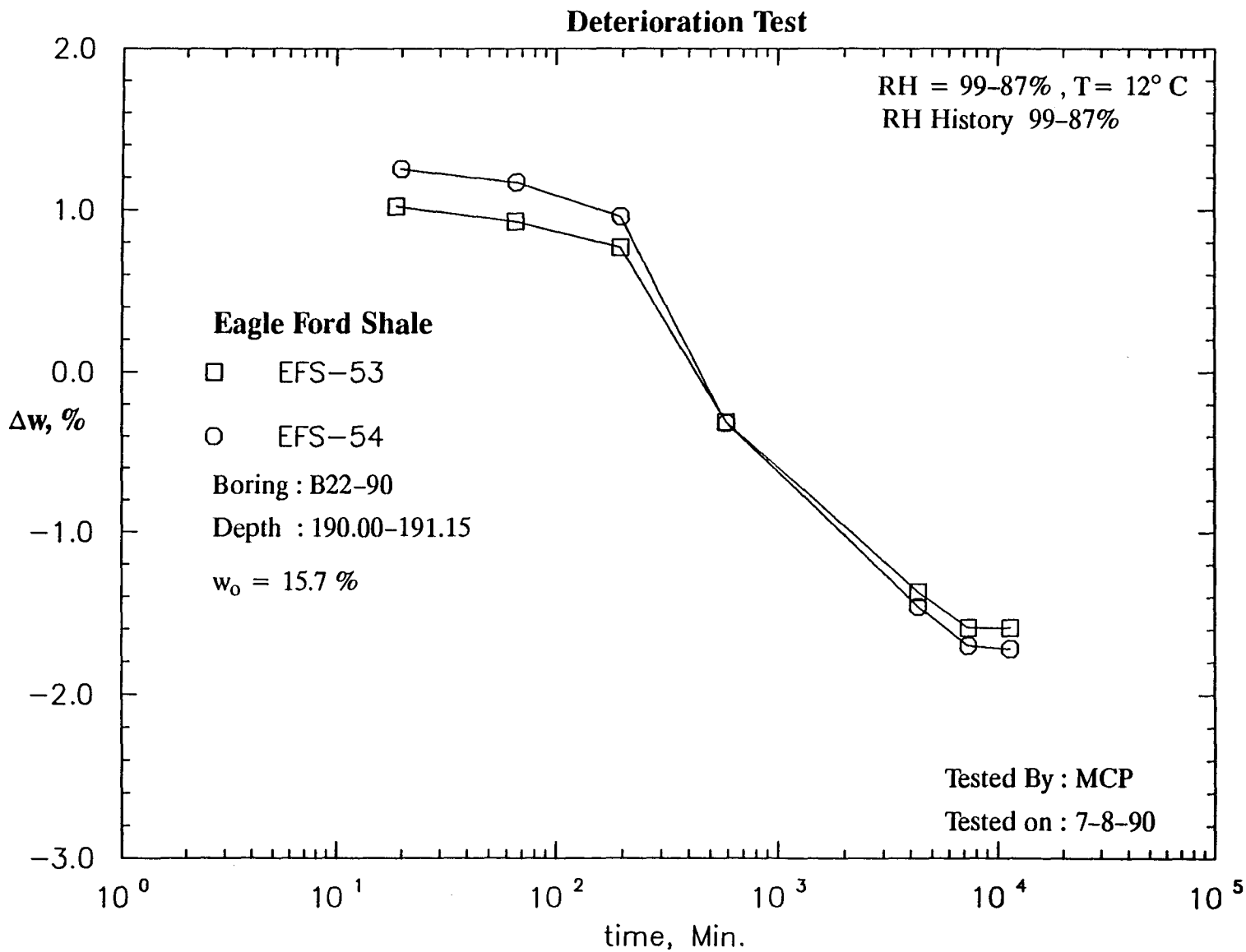


Fig. D17b Water Content Change – Log time Relationship

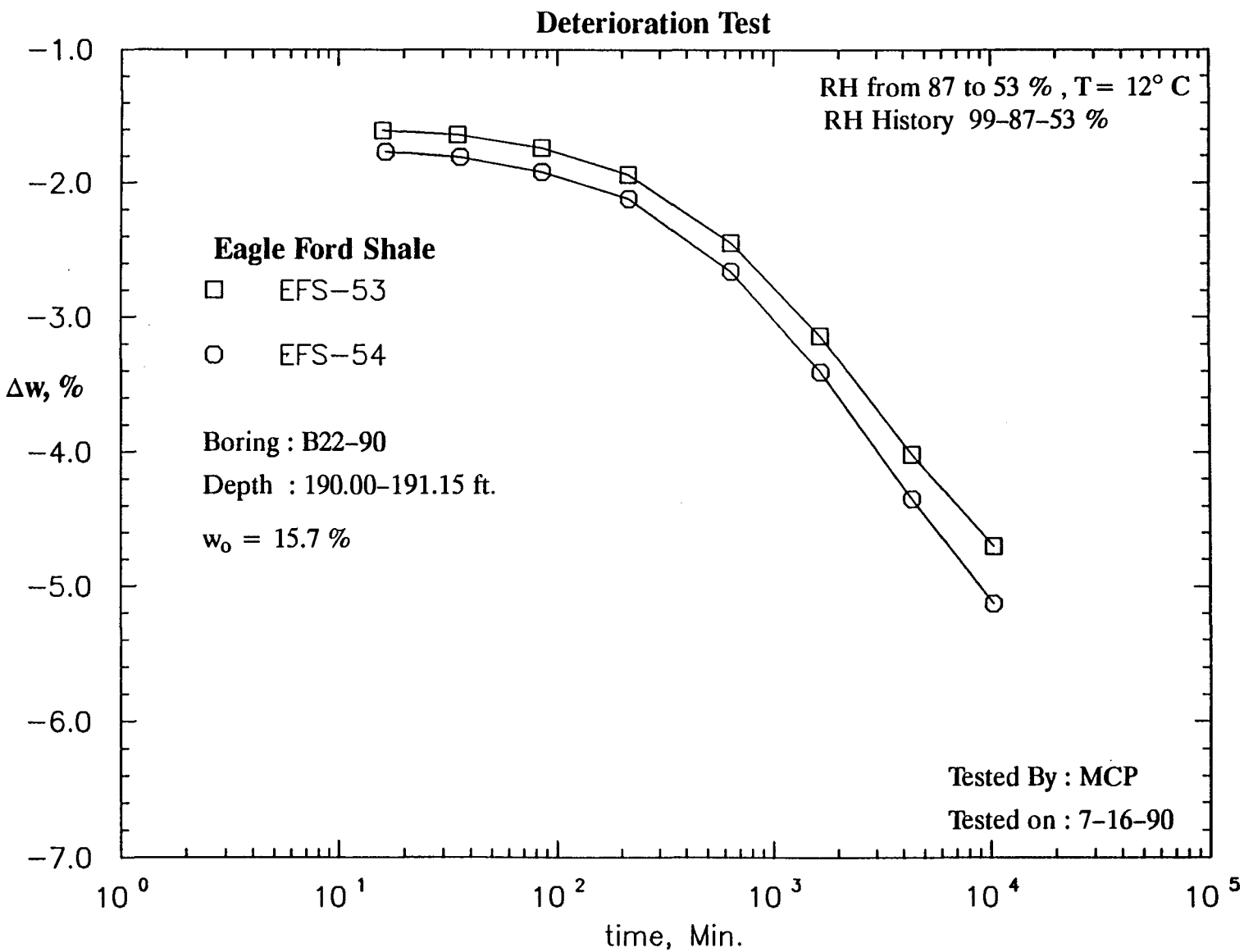


Fig. D17c Water Content Change – Log time Relationship

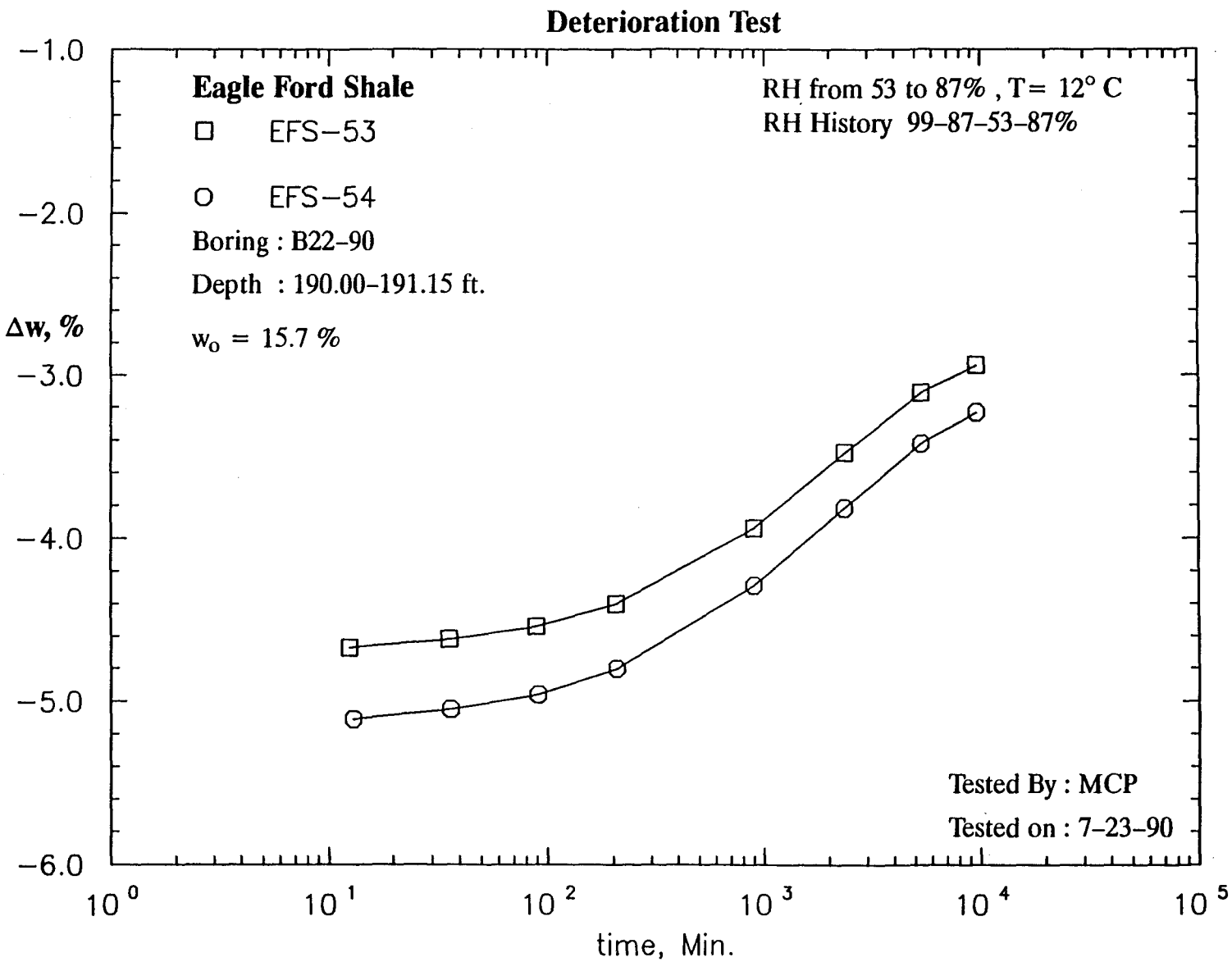


Fig. D17d Water Content Change – Log time Relationship

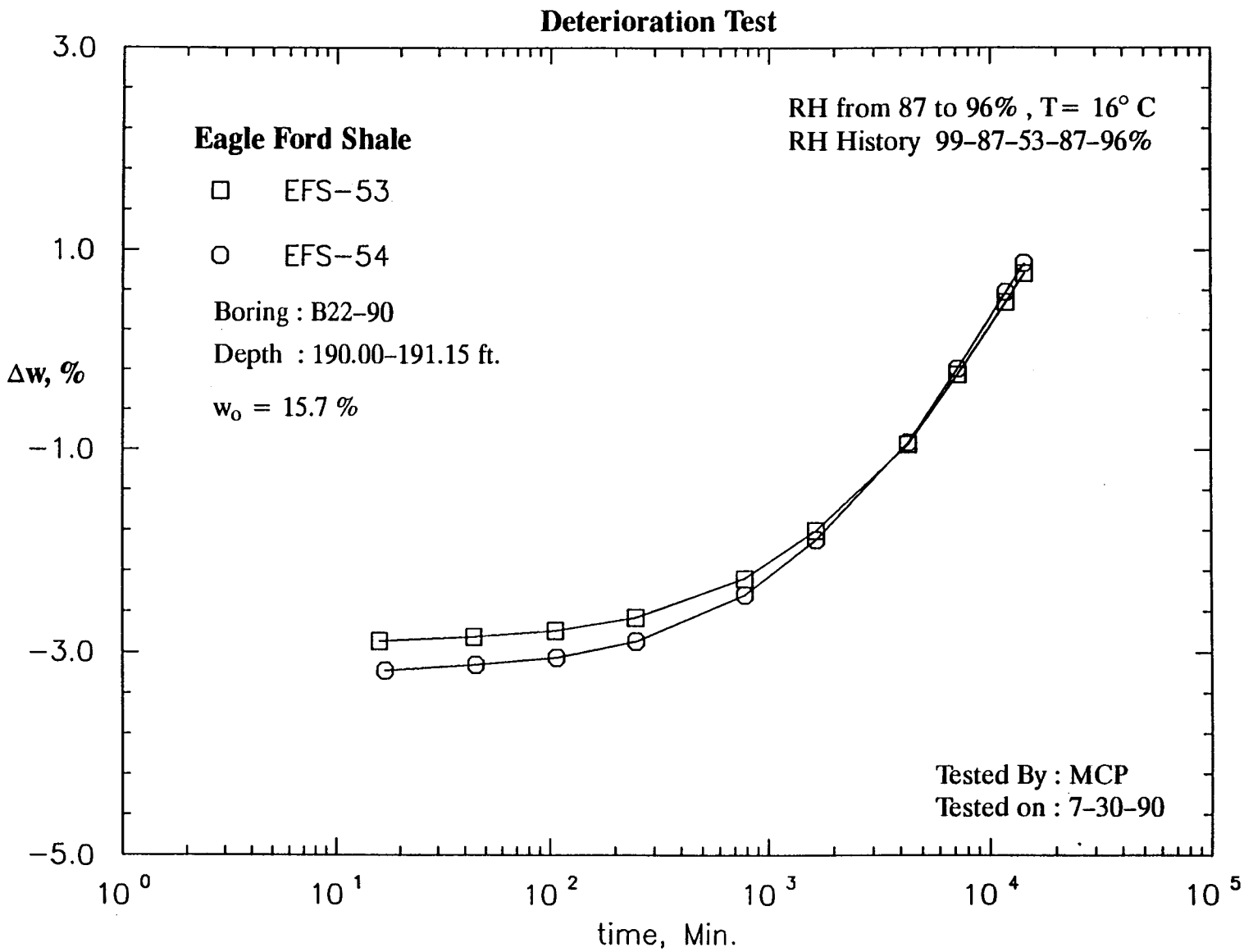


Fig. D17e Water Content Change – Log time Relationship

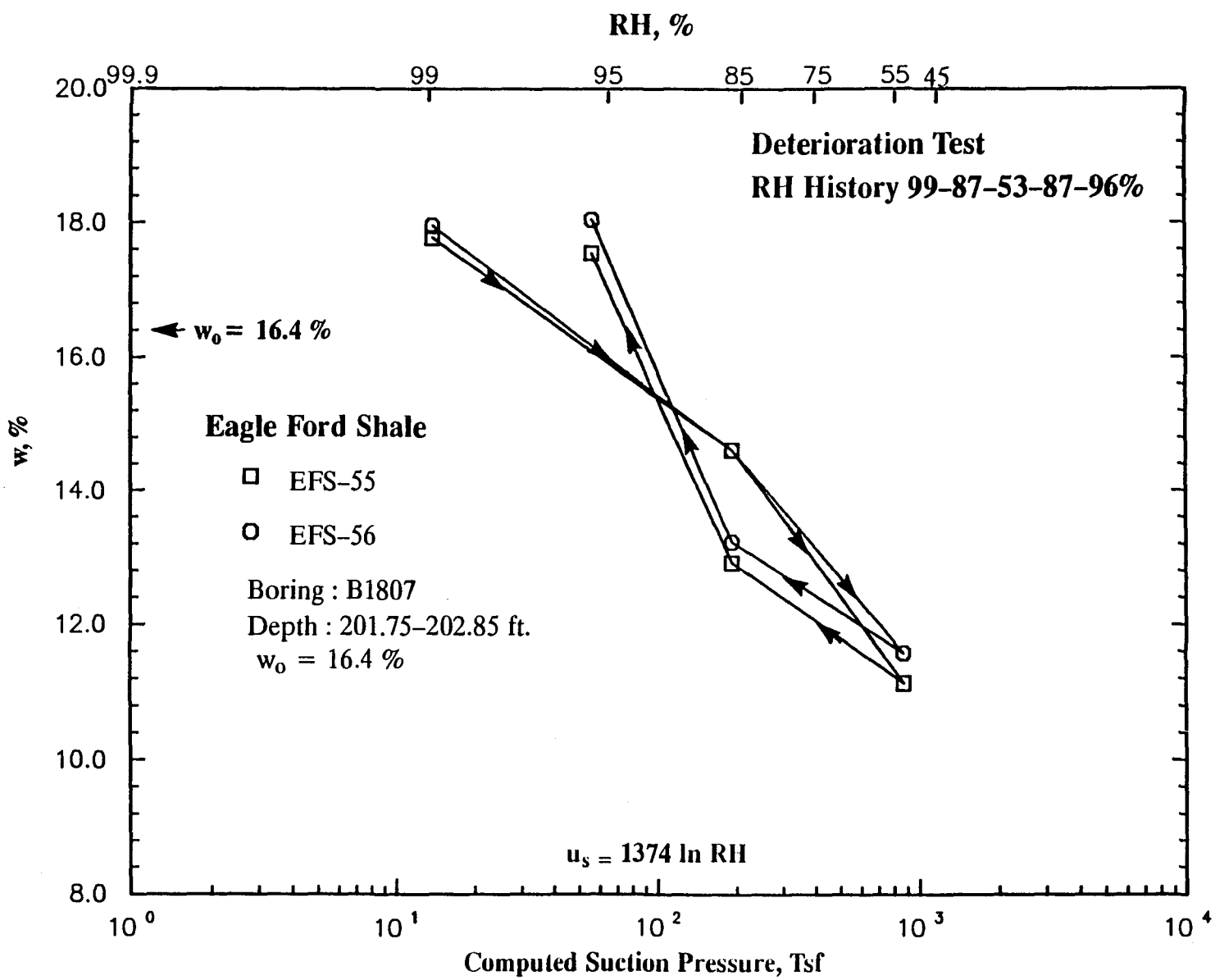


Fig. D18 Water Content – Relative Humidity Relationship

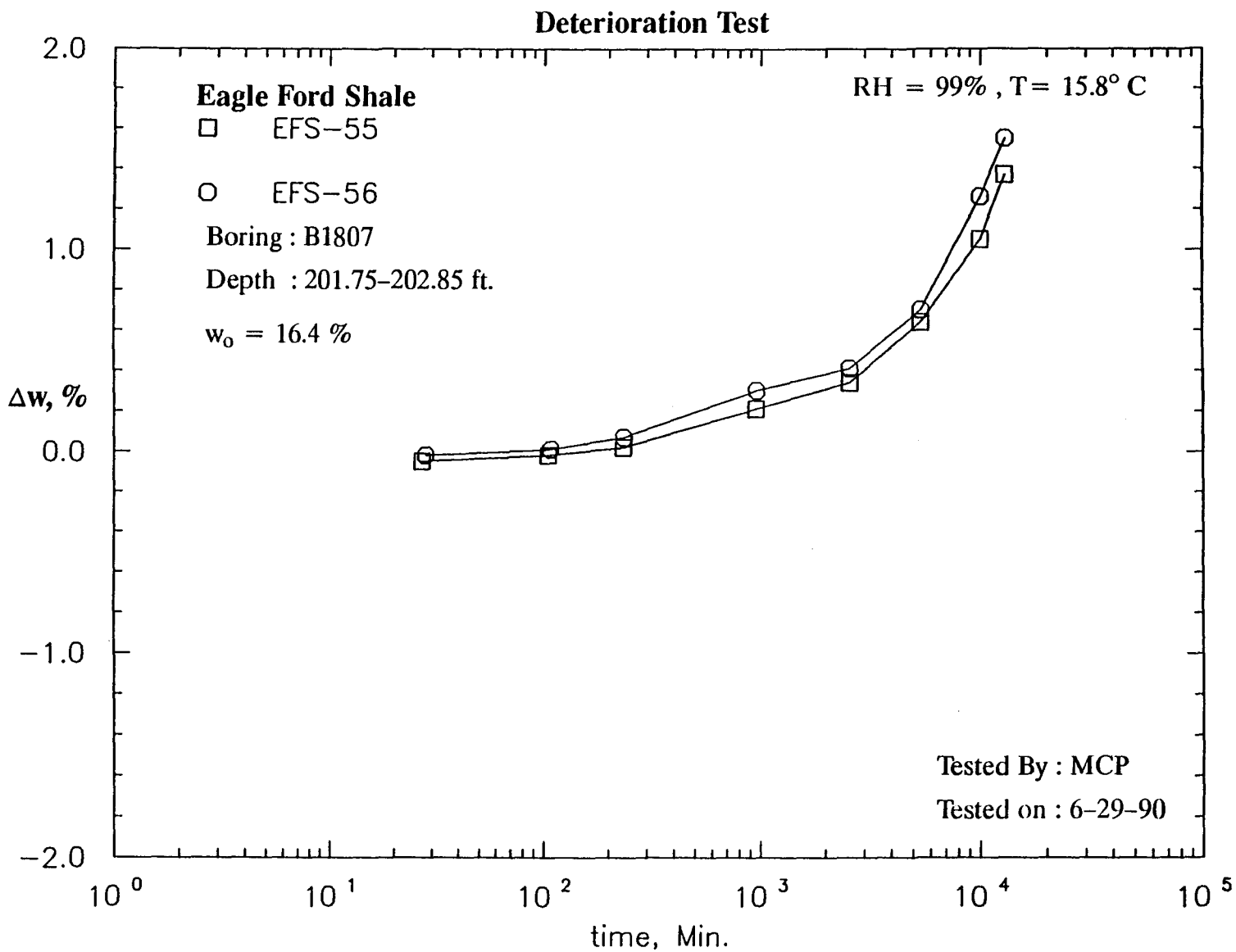


Fig. D18a Water Content Change - Log time Relationship

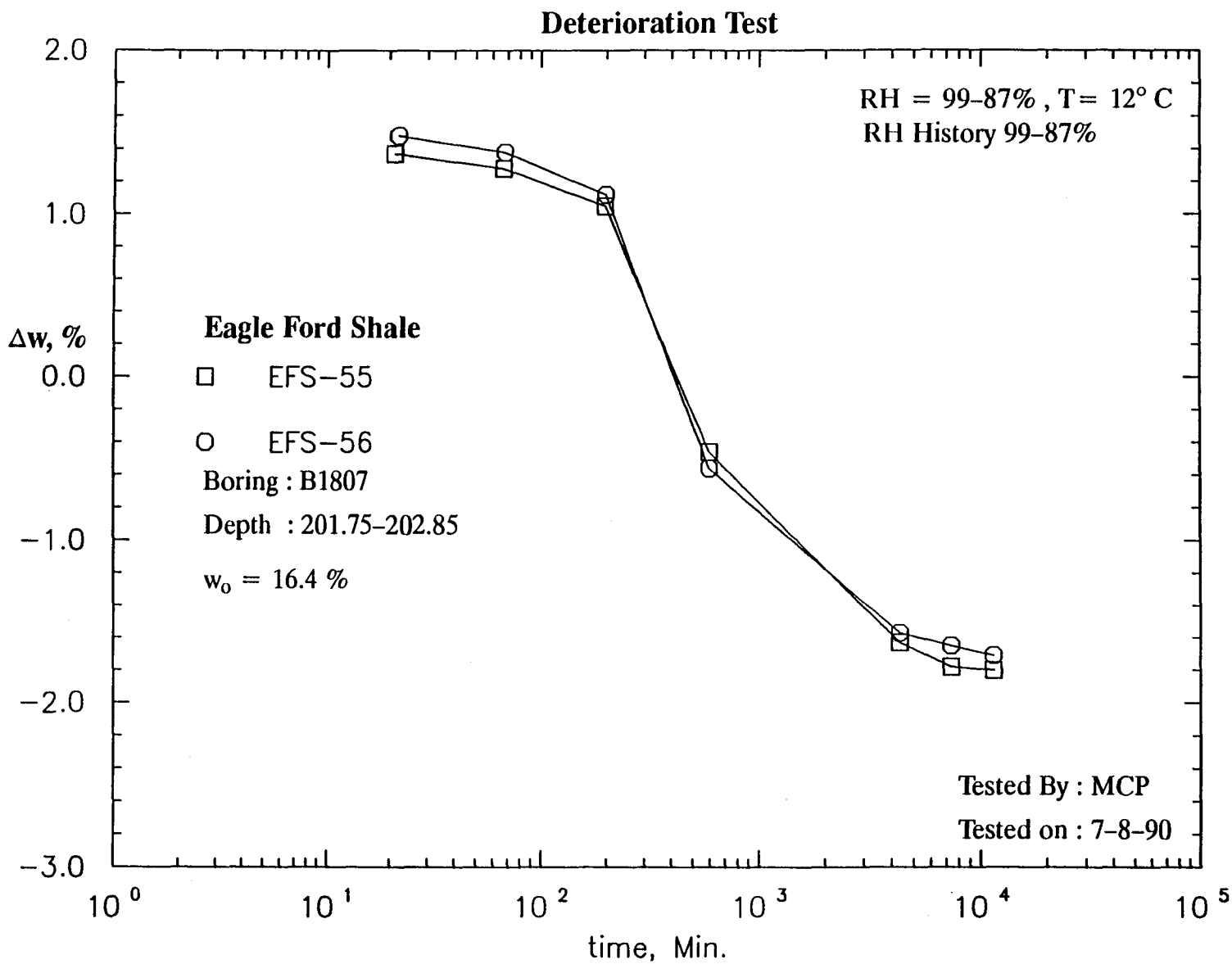


Fig. D18b Water Content Change – Log time Relationship

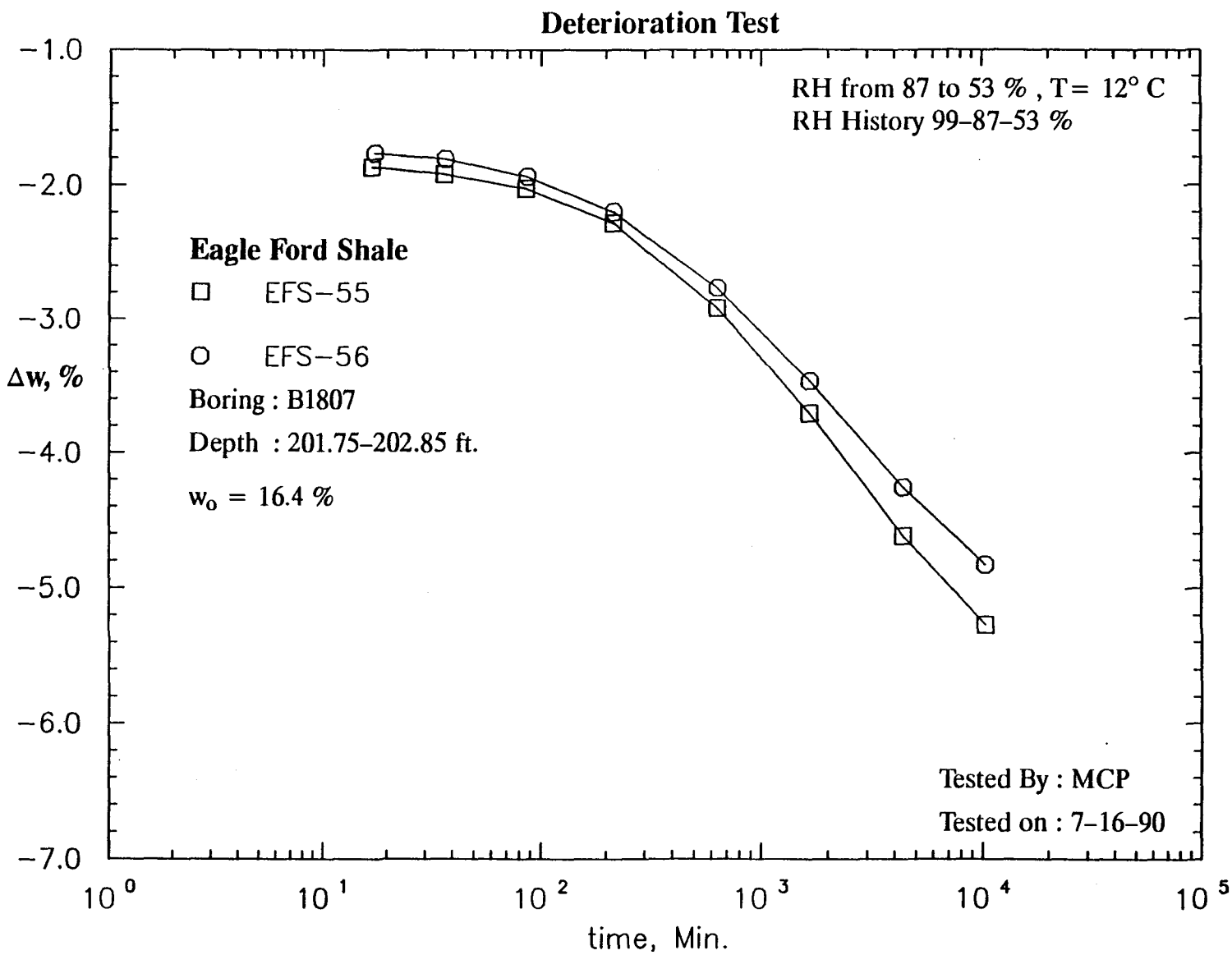


Fig. D18c Water Content Change – Log time Relationship

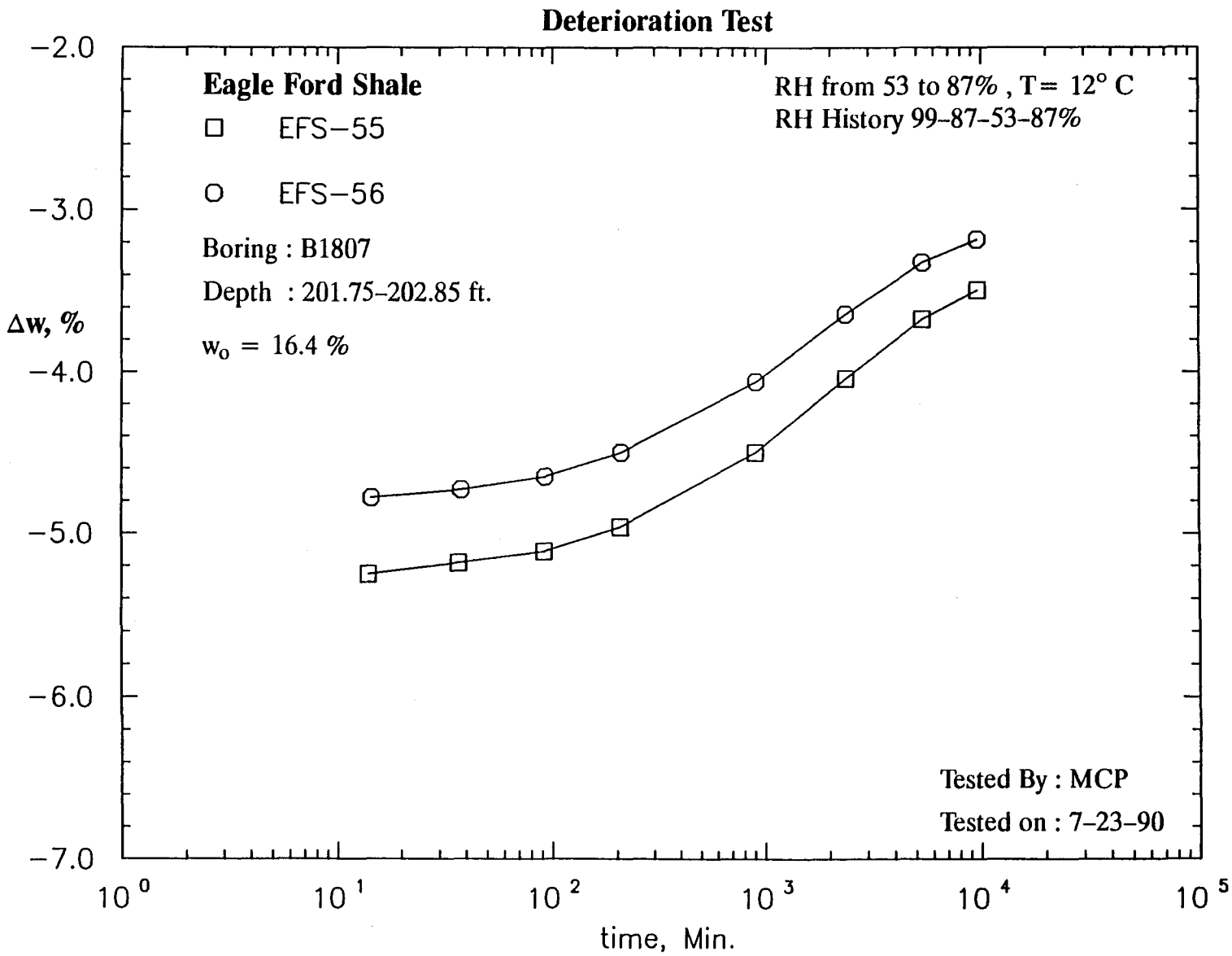


Fig. D18d Water Content Change – Log time Relationship

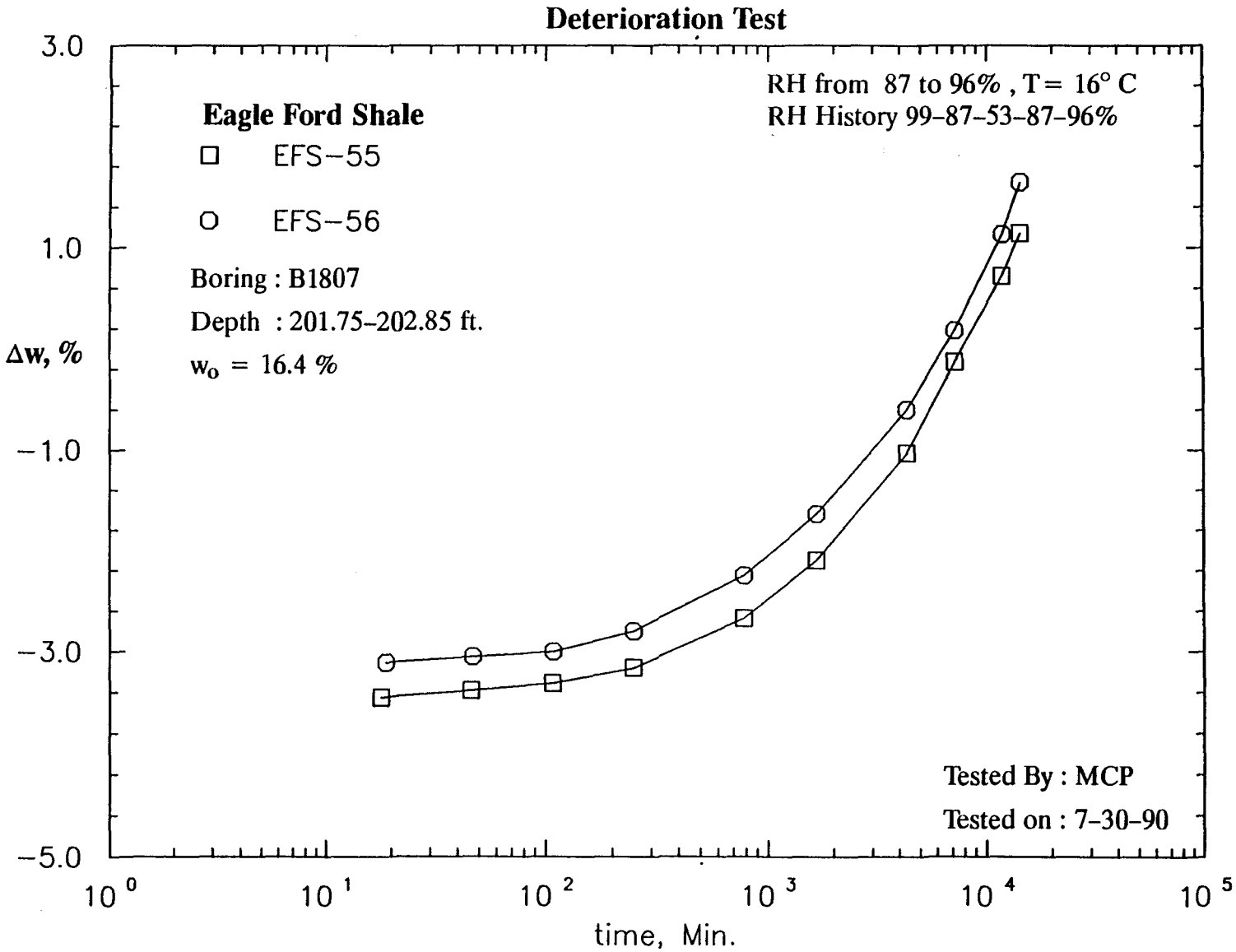


Fig. D18e Water Content Change – Log time Relationship

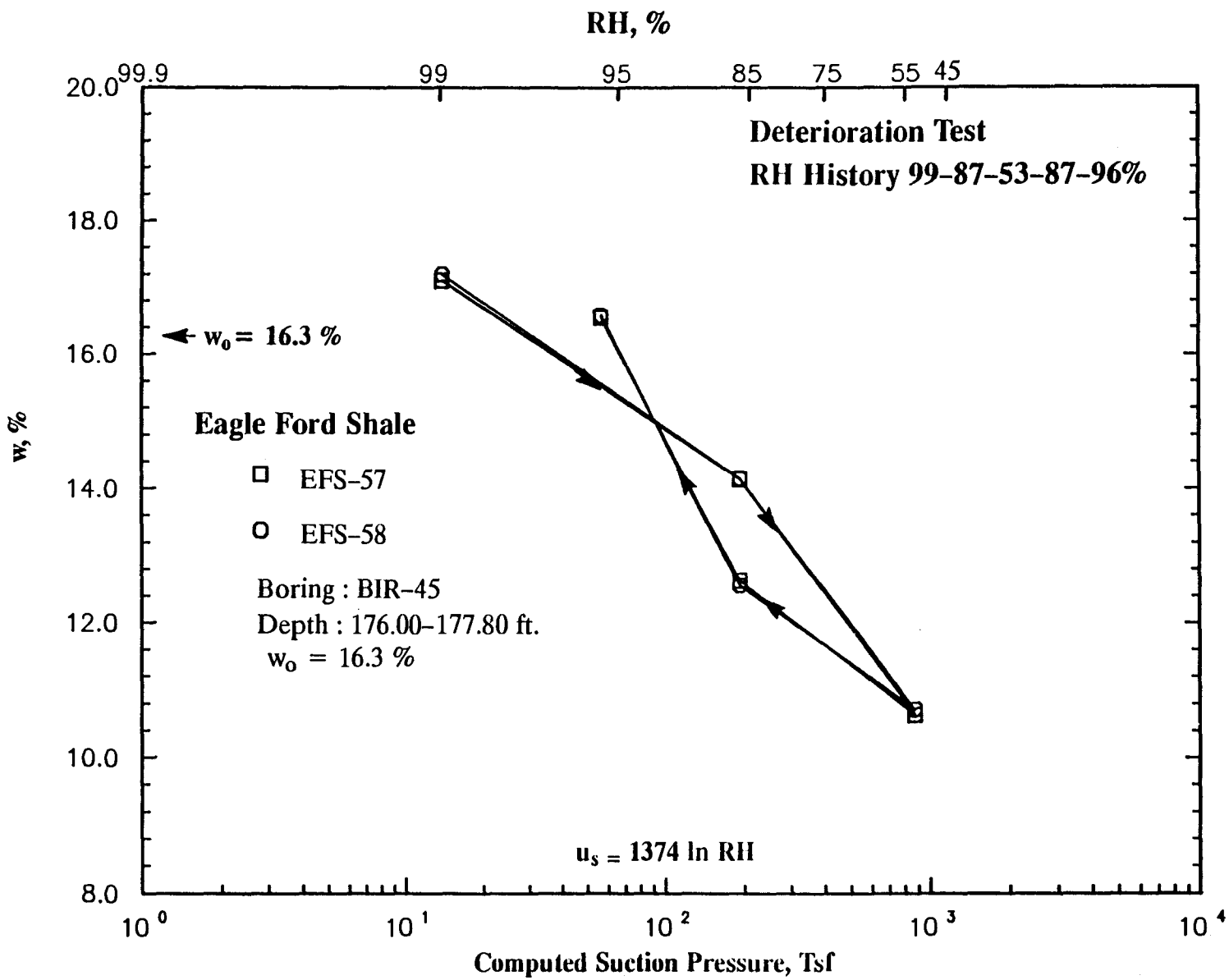


Fig. D19 Water Content – Relative Humidity Relationship

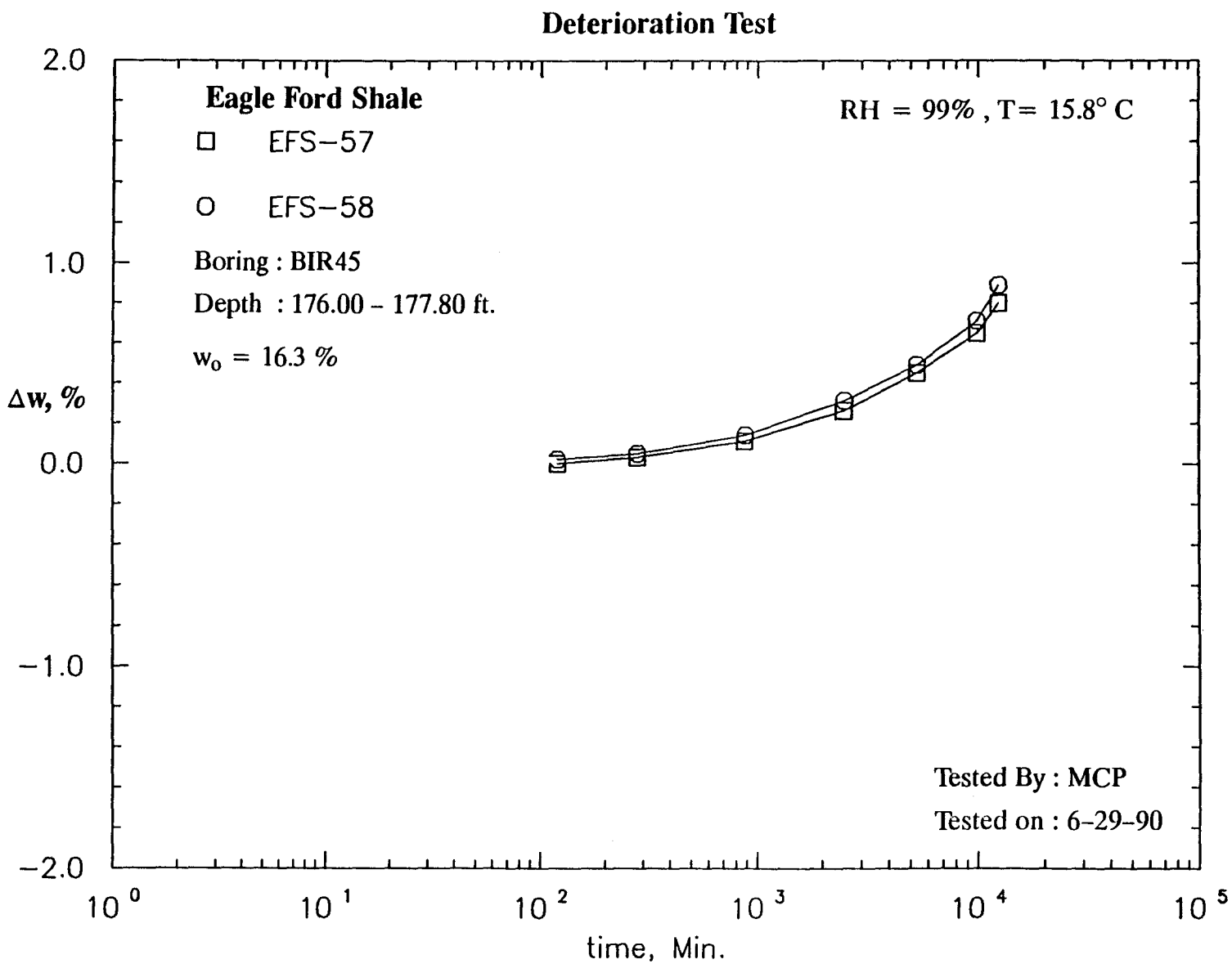


Fig. D19a Water Content Change – Log time Relationship

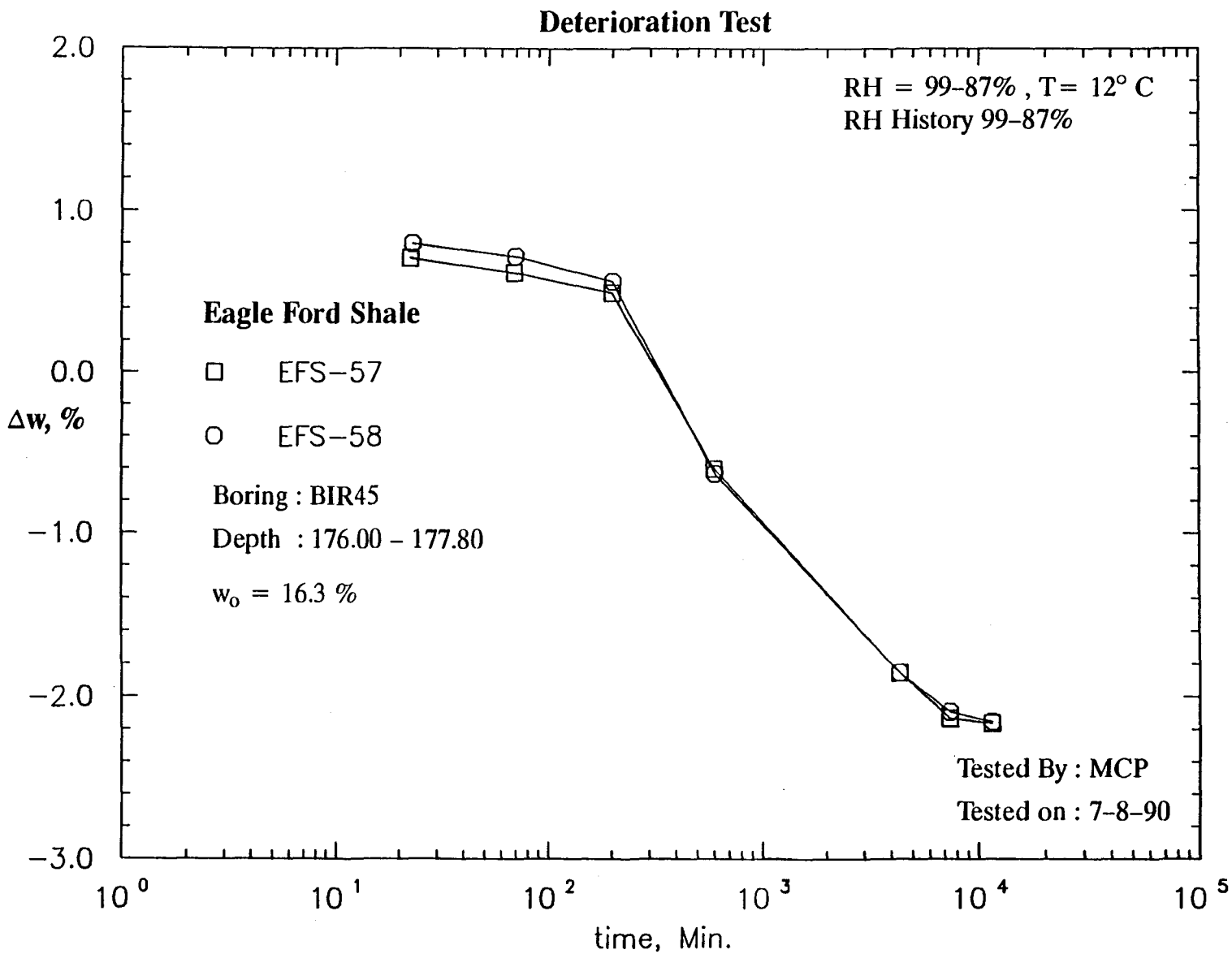


Fig. D19b Water Content Change – Log time Relationship

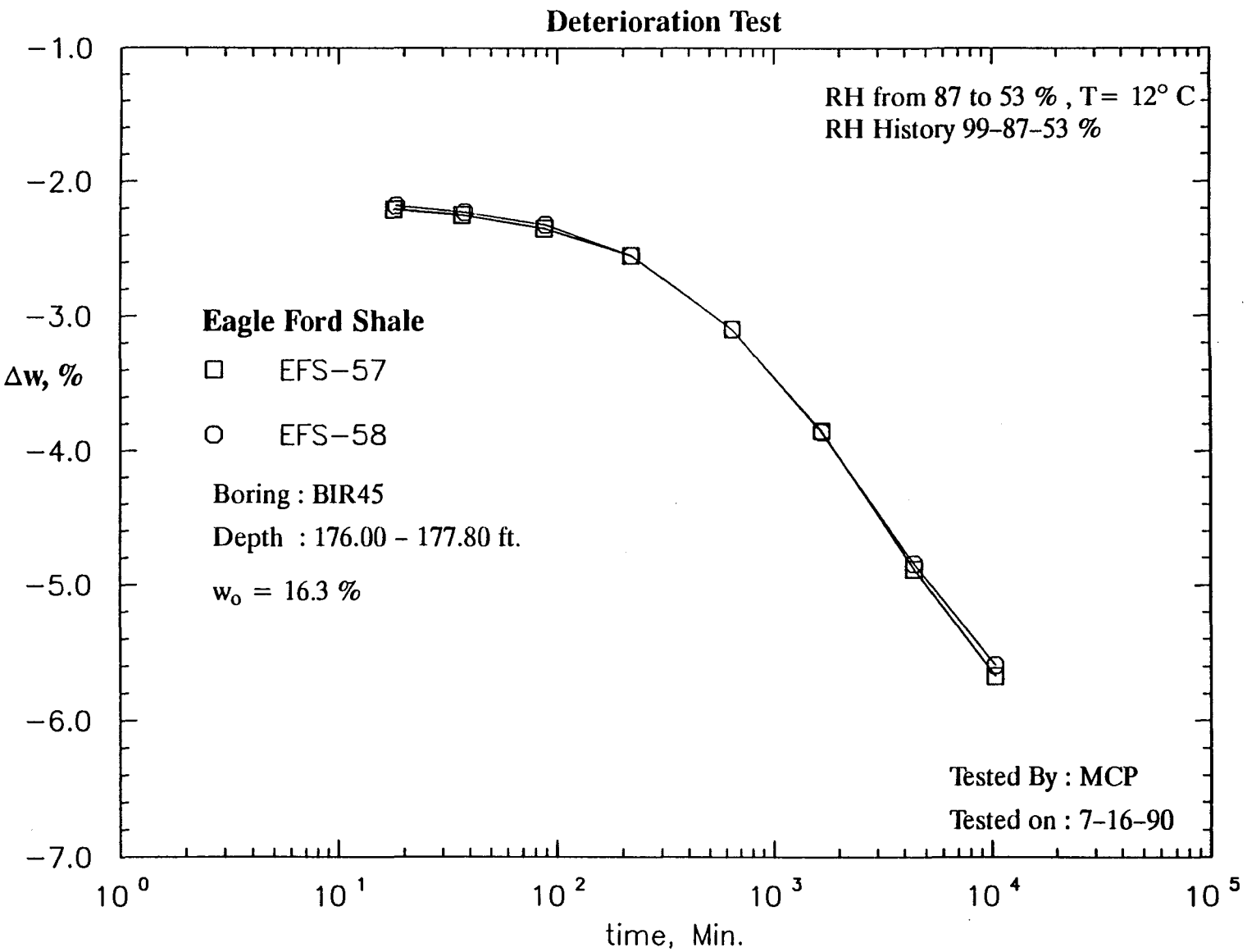


Fig. D19c Water Content Change - Log time Relationship

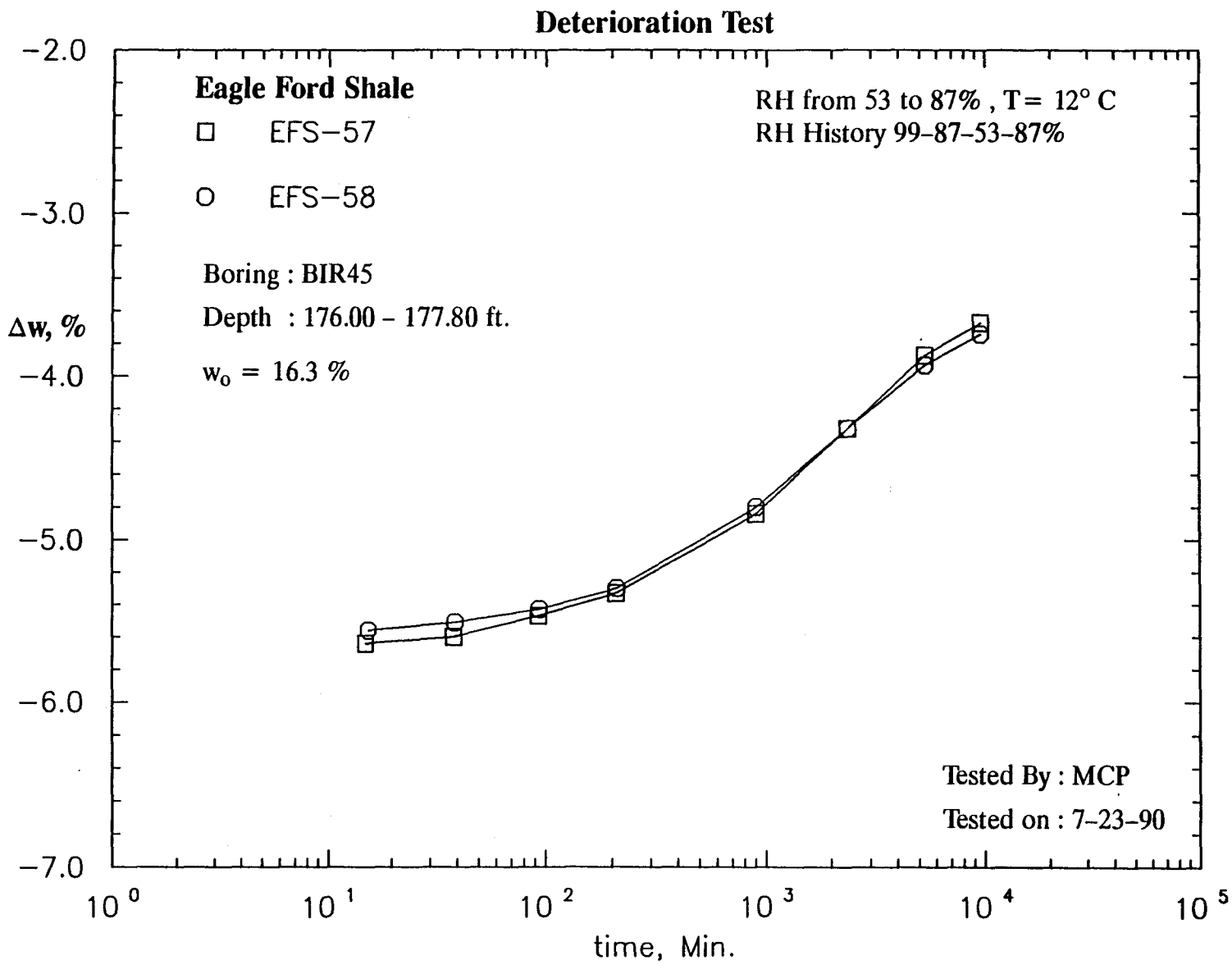


Fig. D19d Water Content Change – Log time Relationship

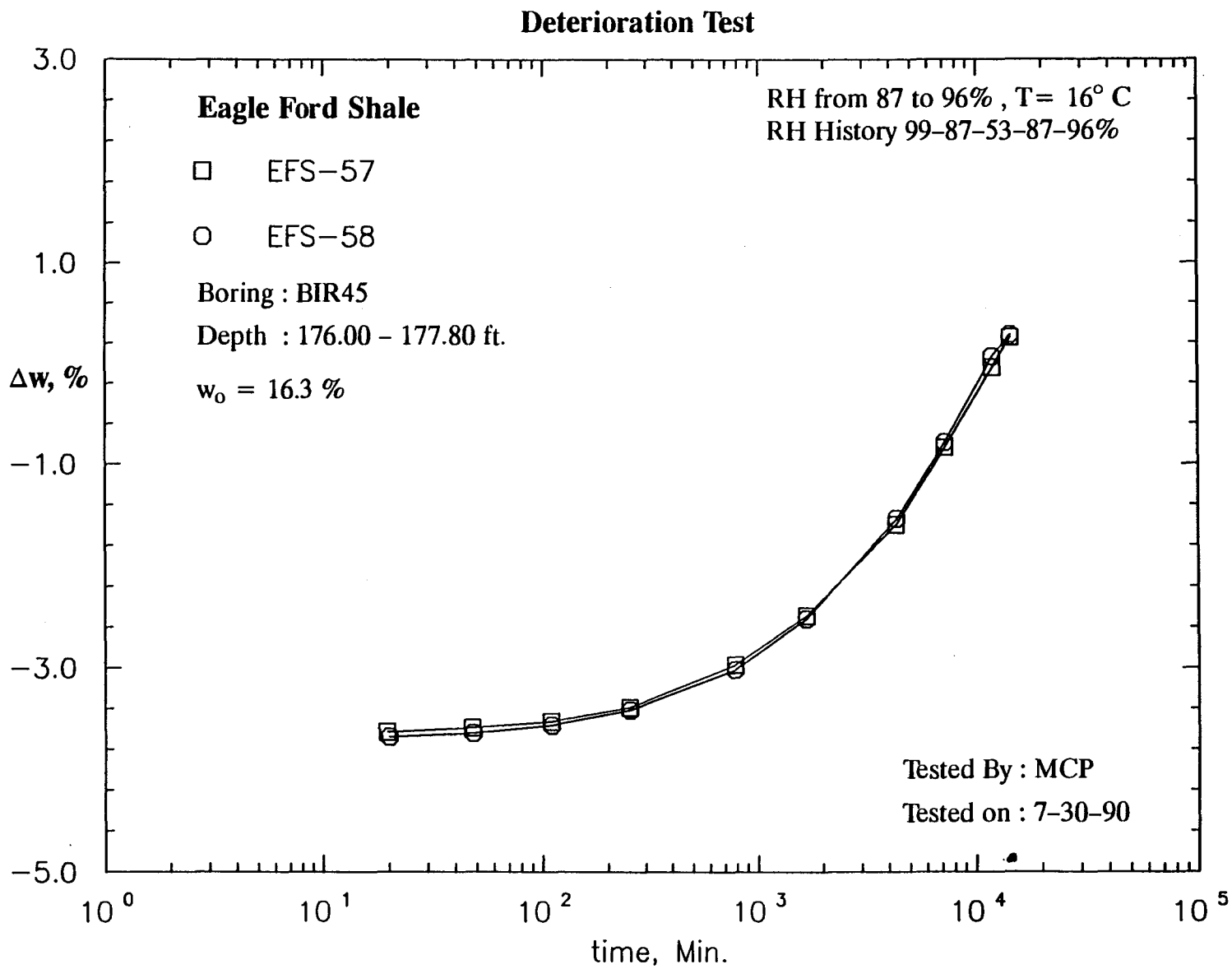


Fig. D19e Water Content Change – Log time Relationship

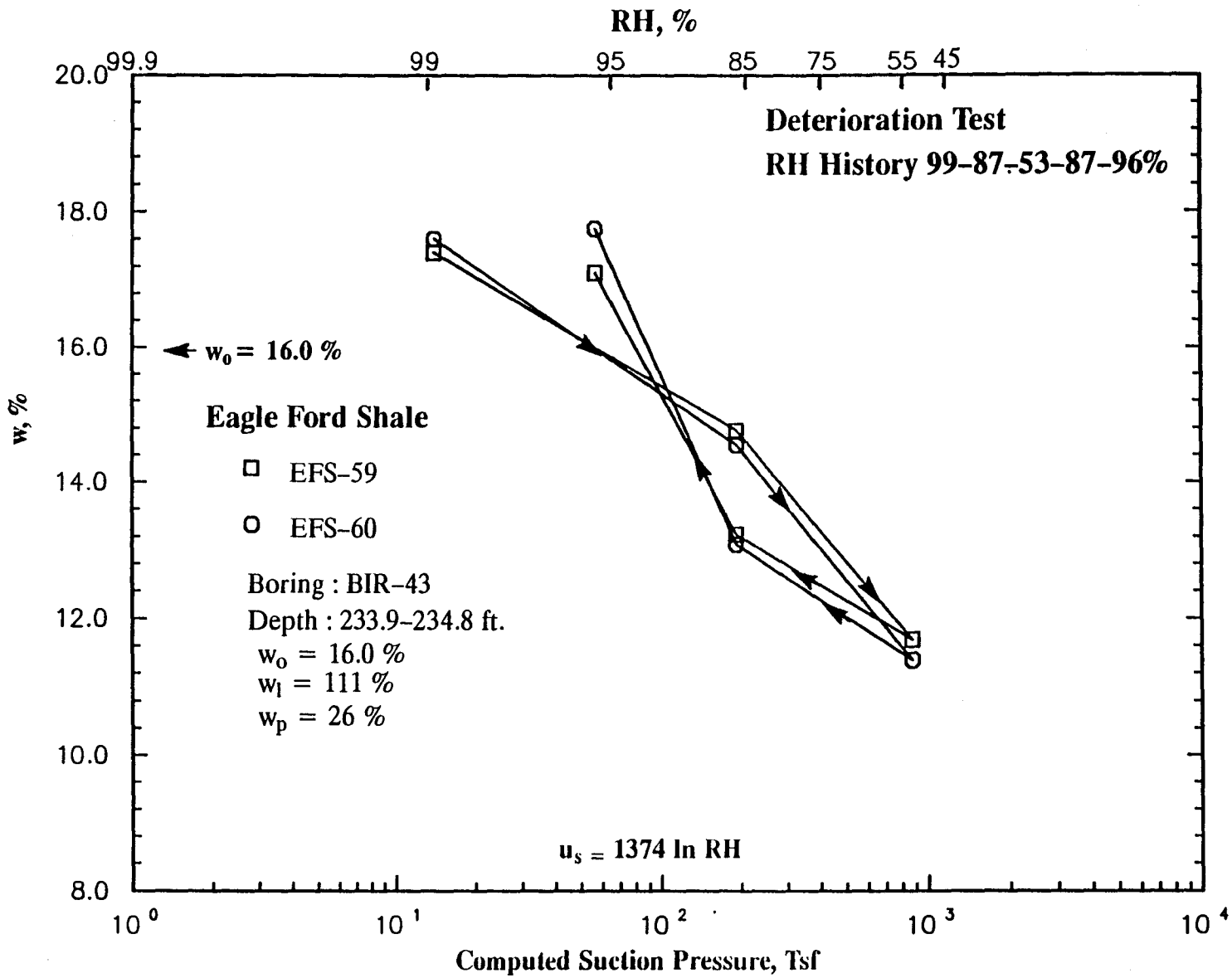


Fig. D20 Water Content – Relative Humidity Relationship

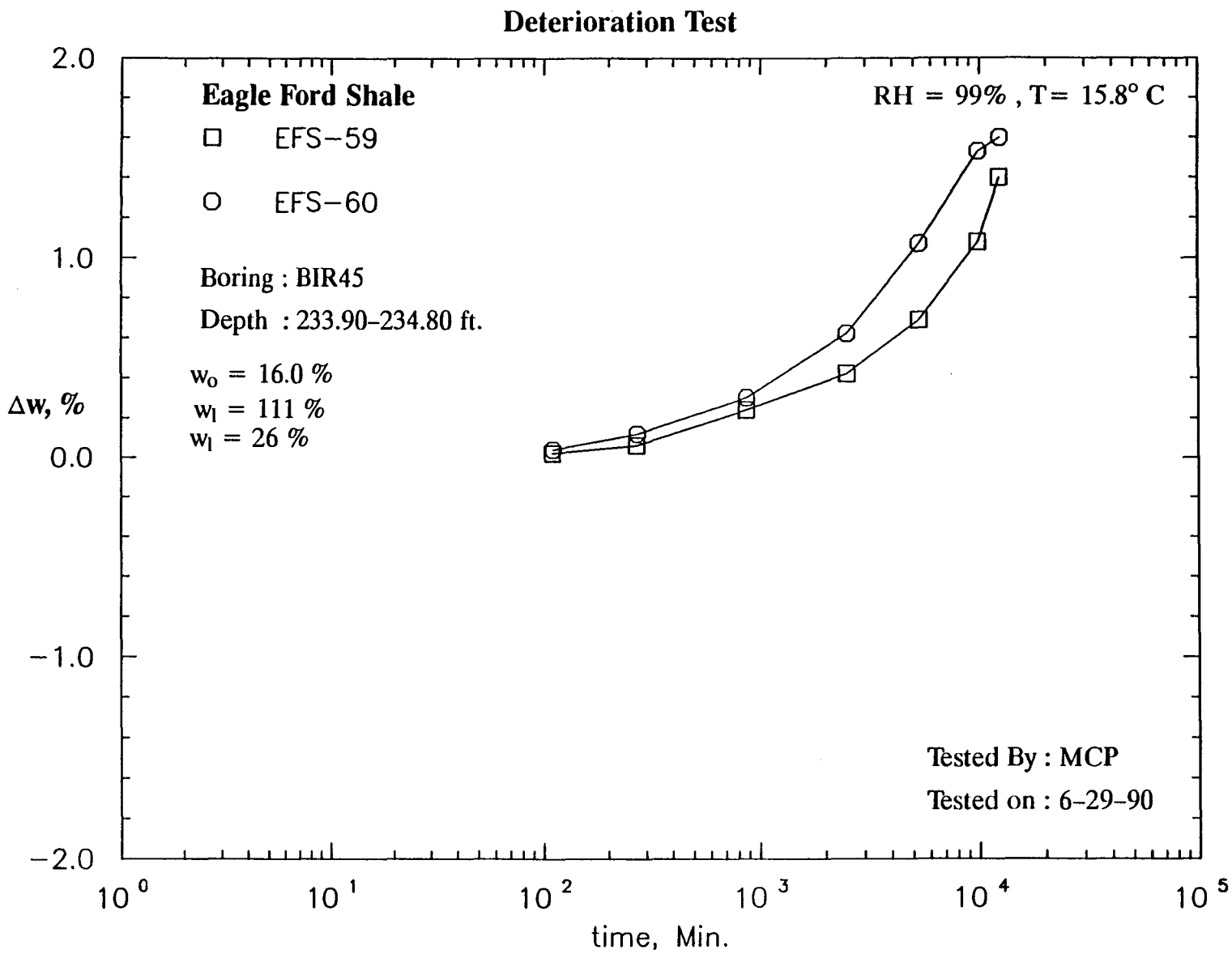


Fig. D20a Water Content Change – Log time Relationship

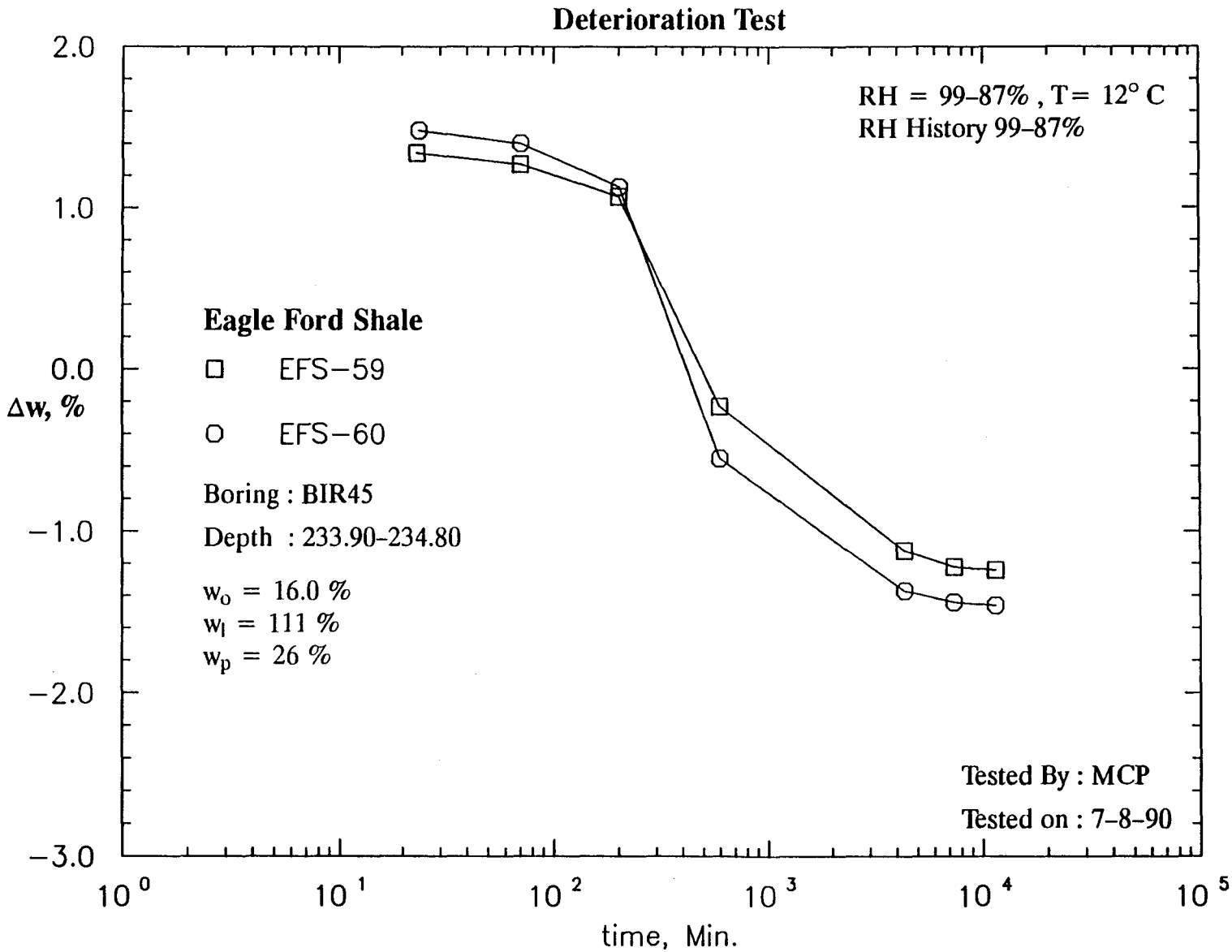


Fig. D20b Water Content Change – Log time Relationship

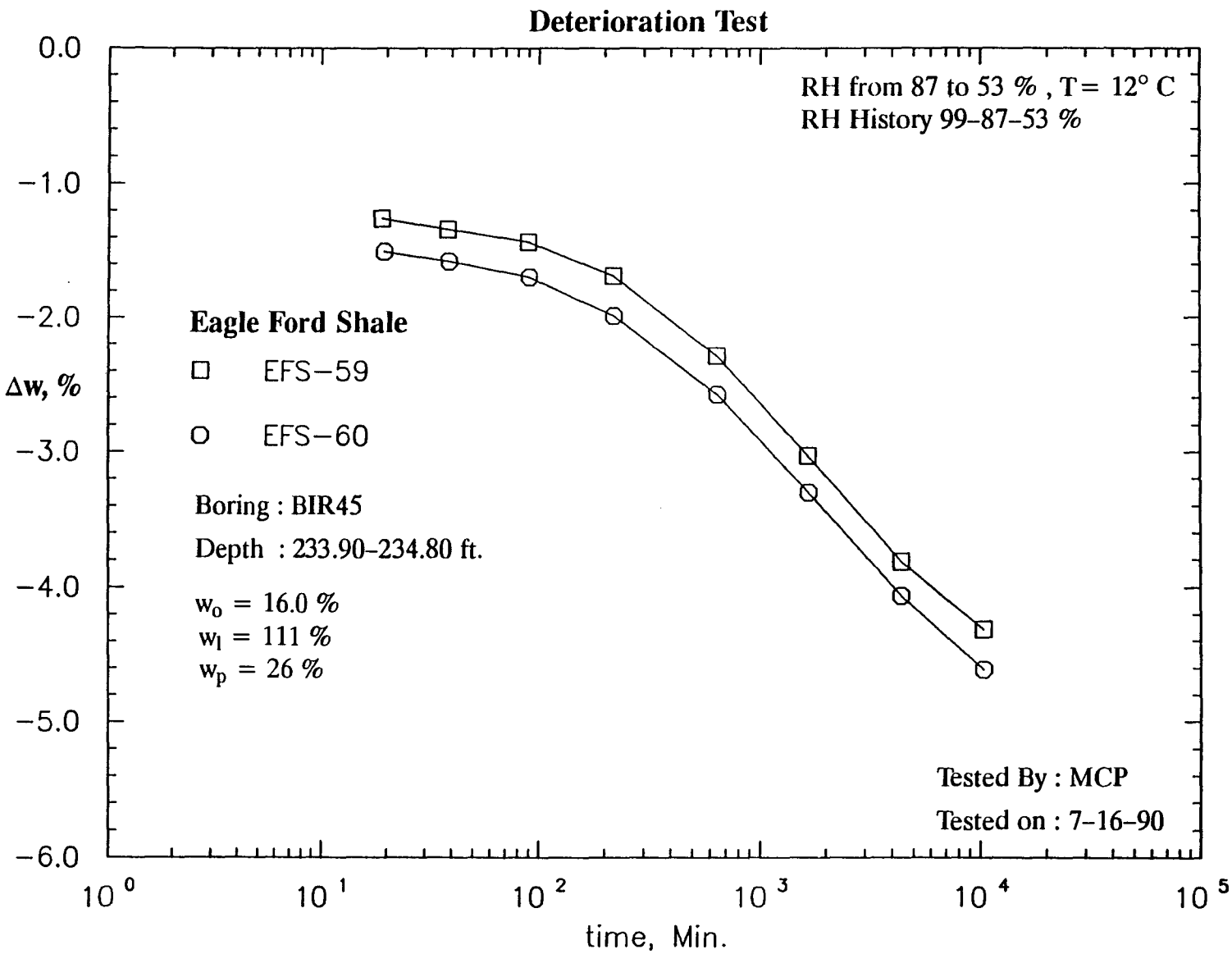


Fig. D20c Water Content Change – Log time Relationship

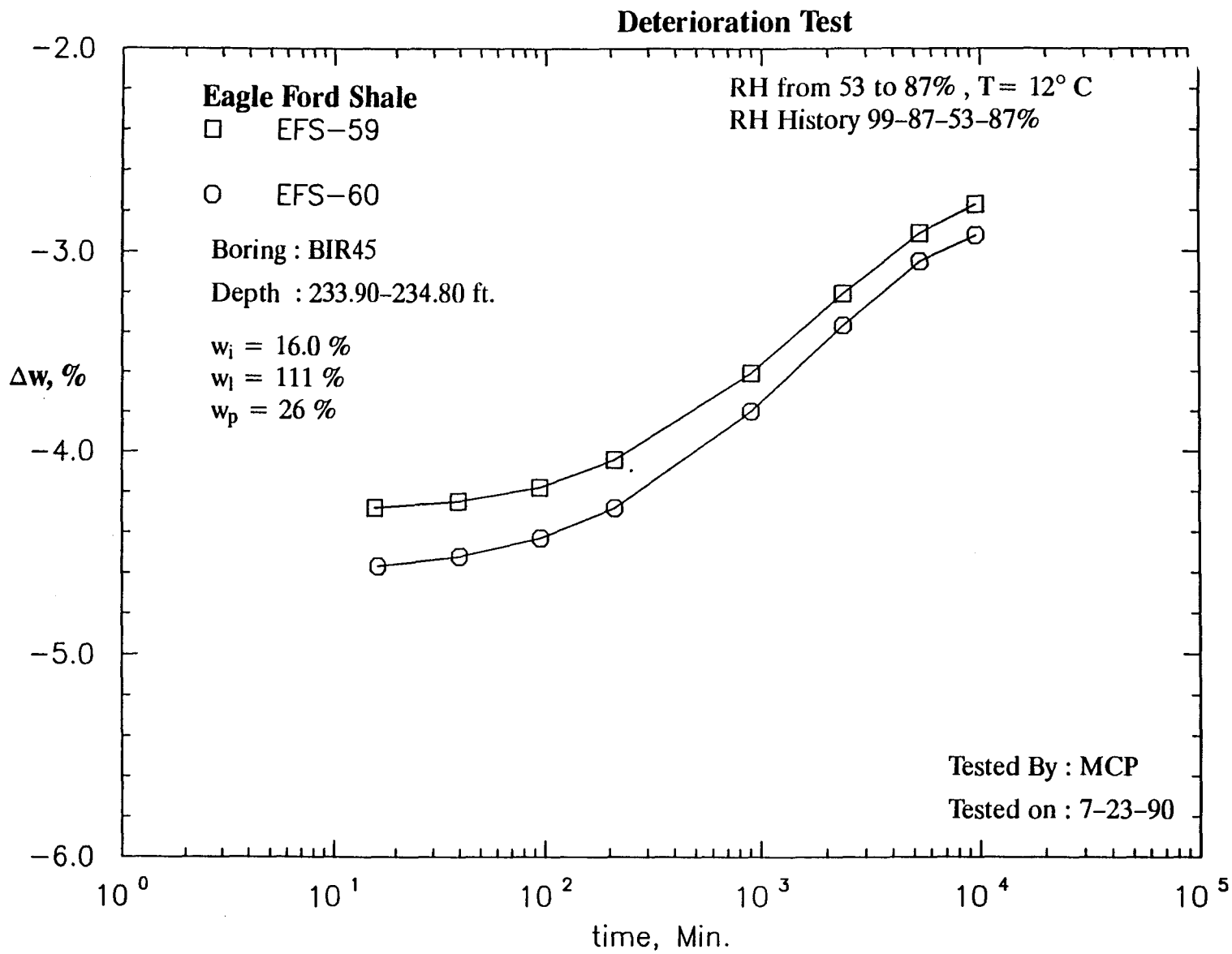


Fig. D20d Water Content Change - Log time Relationship

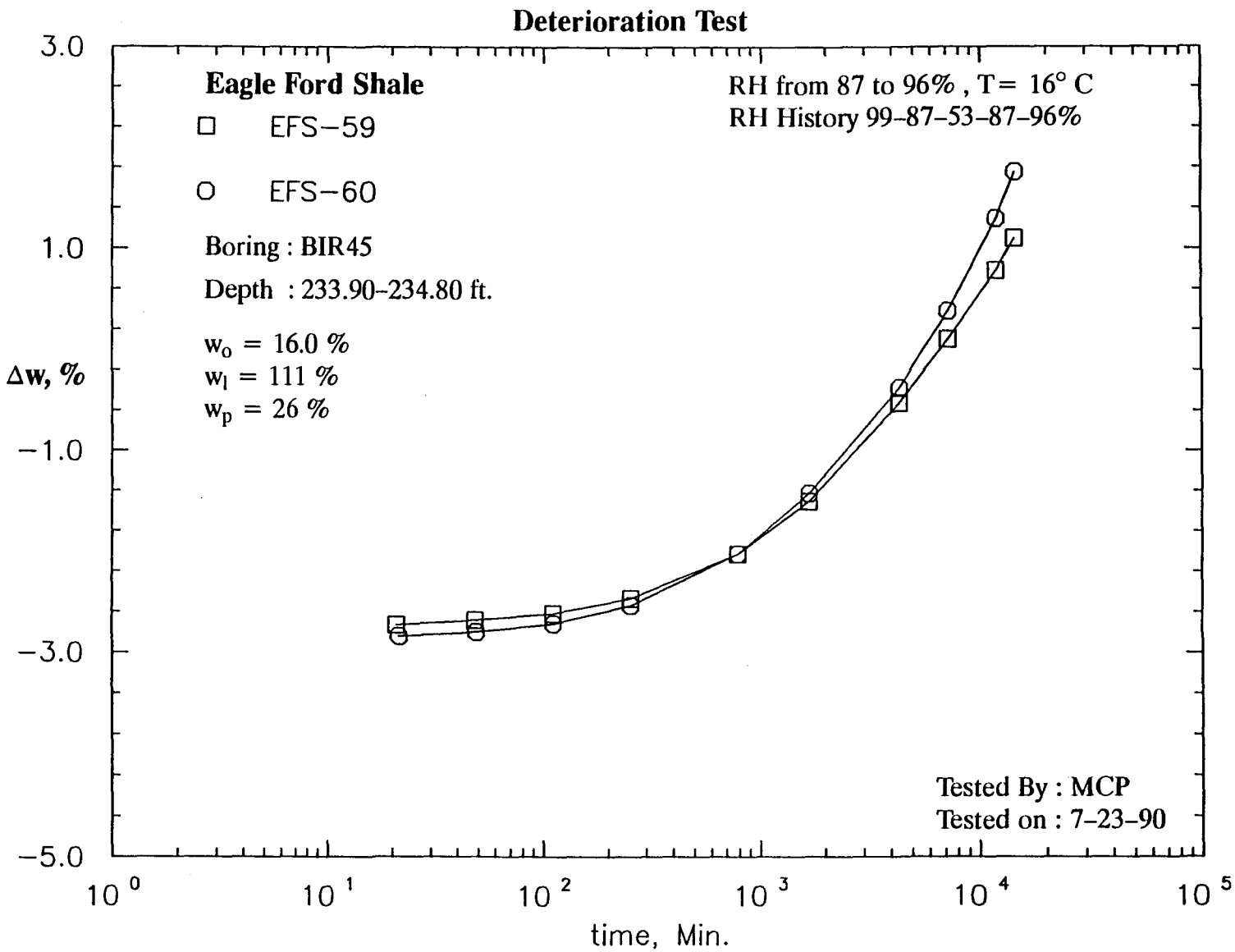


Fig. D20e Water Content Change – Log time Relationship

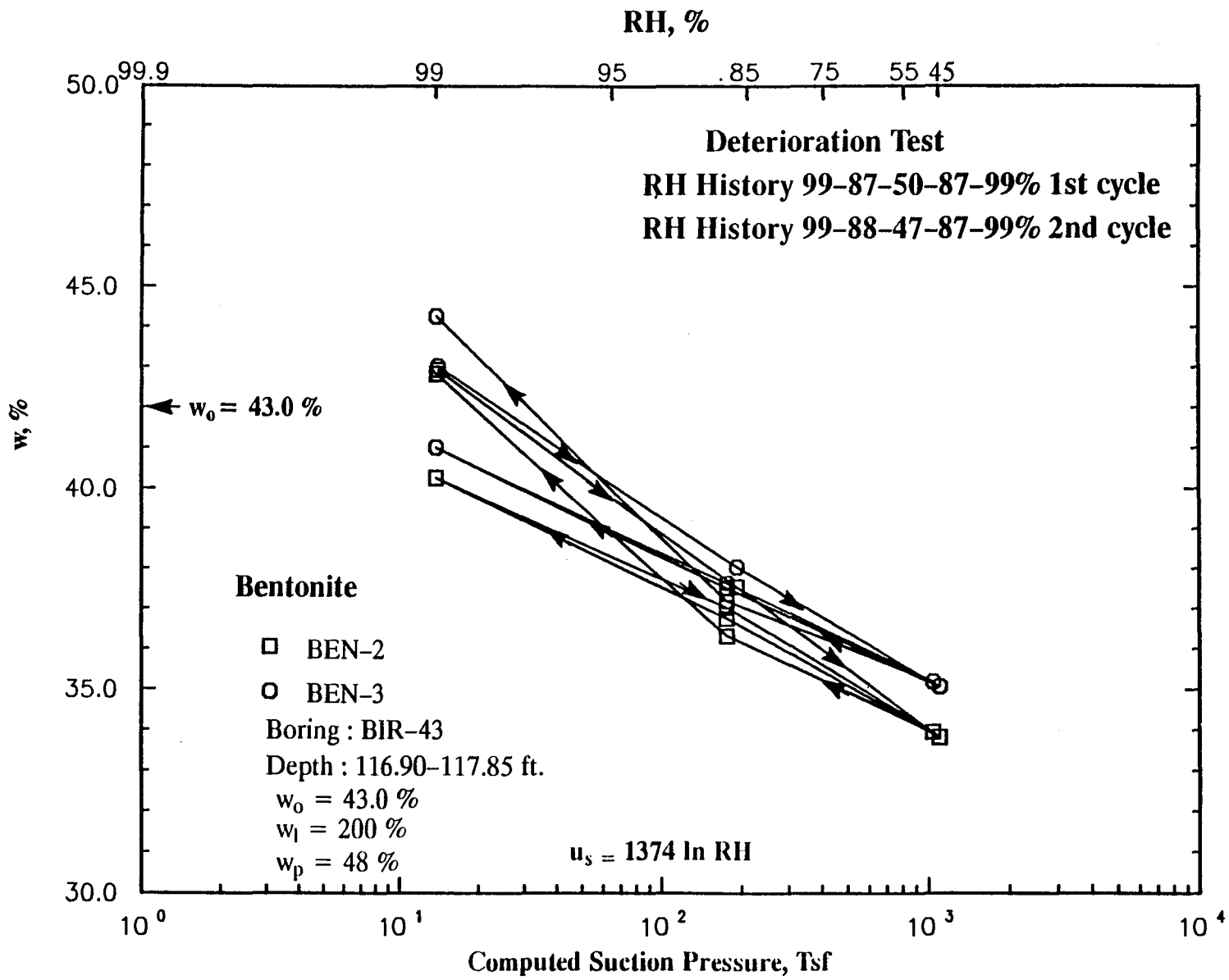


Fig. D21 Water Content – Relative Humidity Relationship

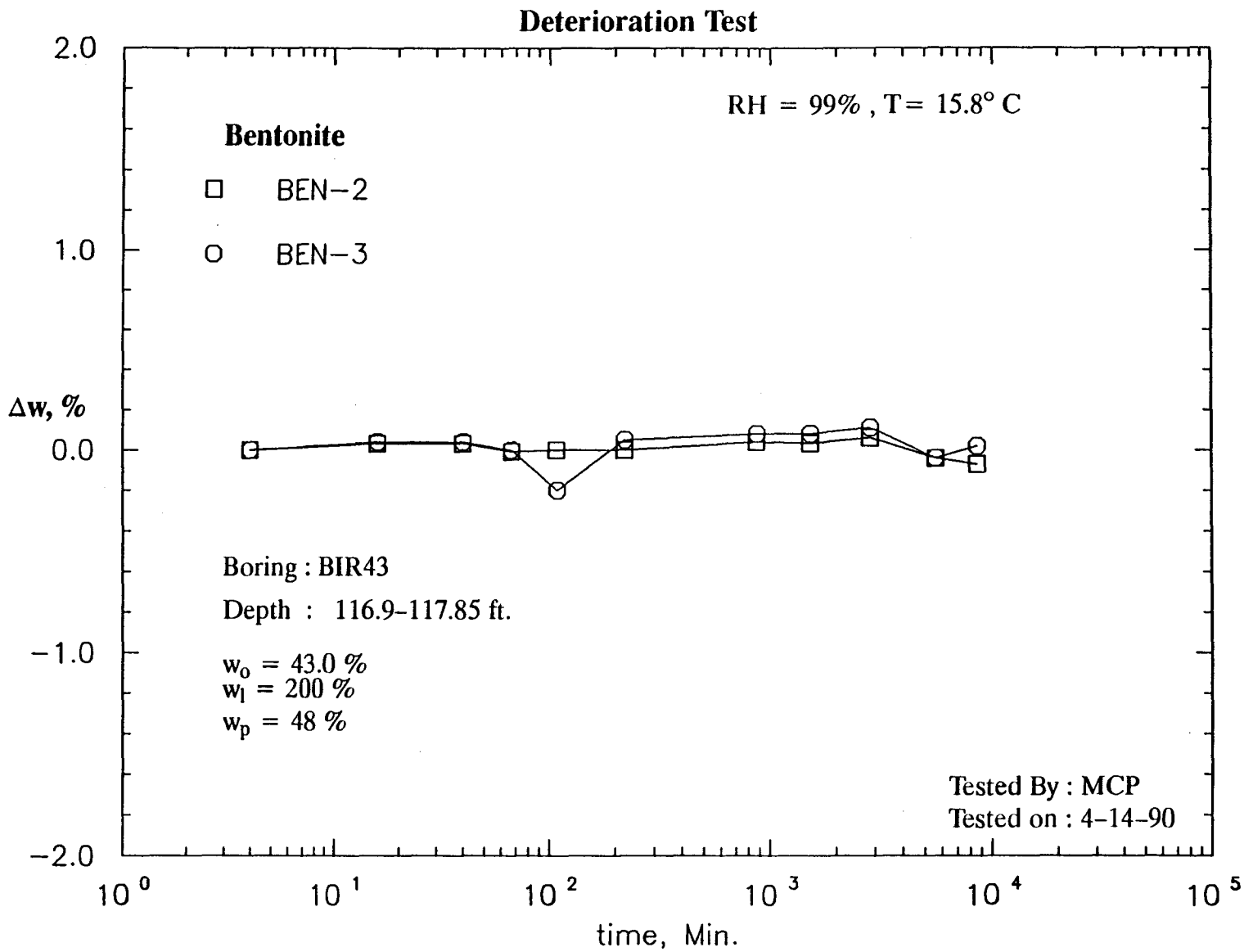


Fig. D21a Water Content Change – Log time Relationship

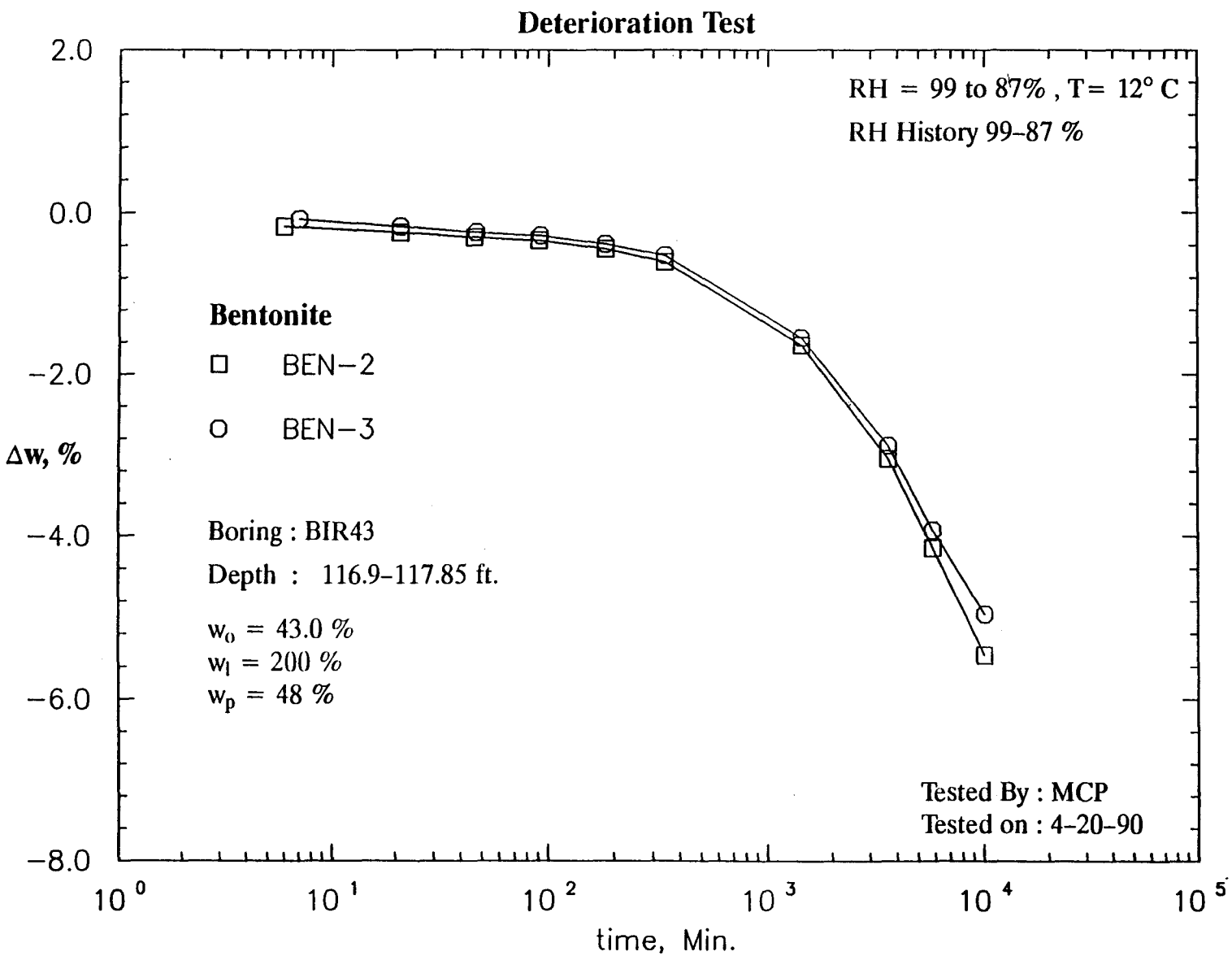


Fig. D21b Water Content Change – Log time Relationship

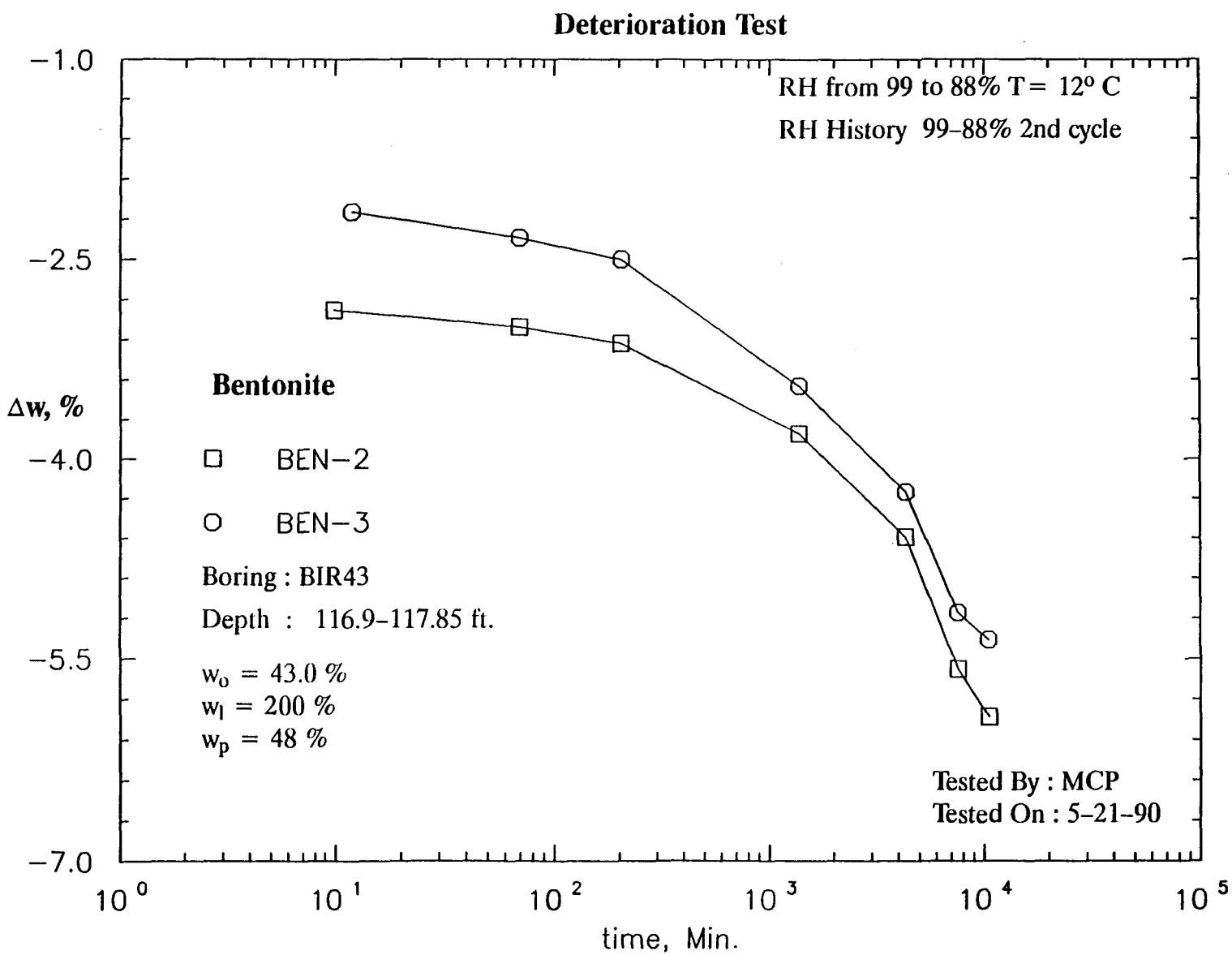


Fig. D21c Water Content Change – Log time Relationship

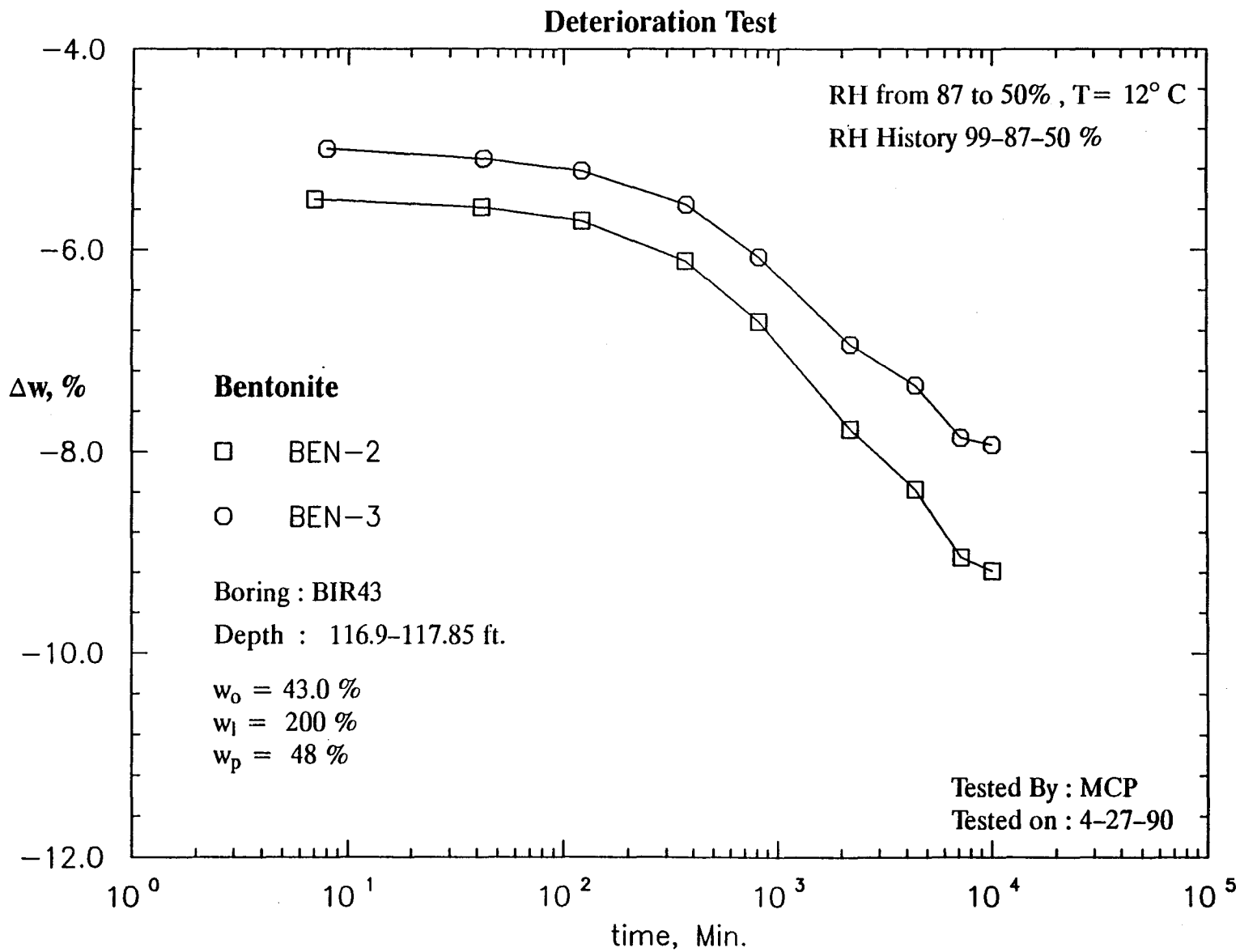


Fig. D21d Water Content Change – Log time Relationship

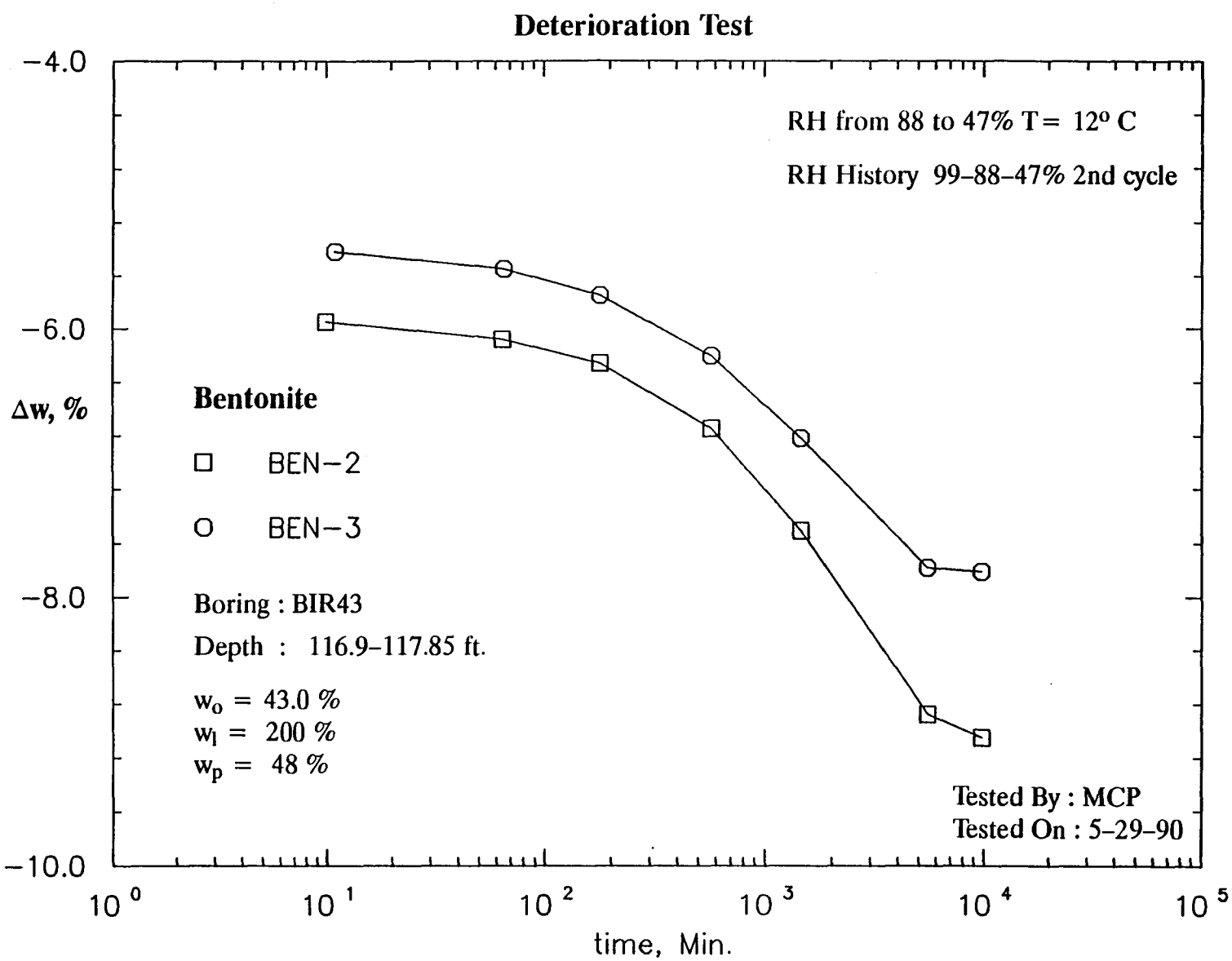


Fig. D21e Water Content Change – Log time Relationship

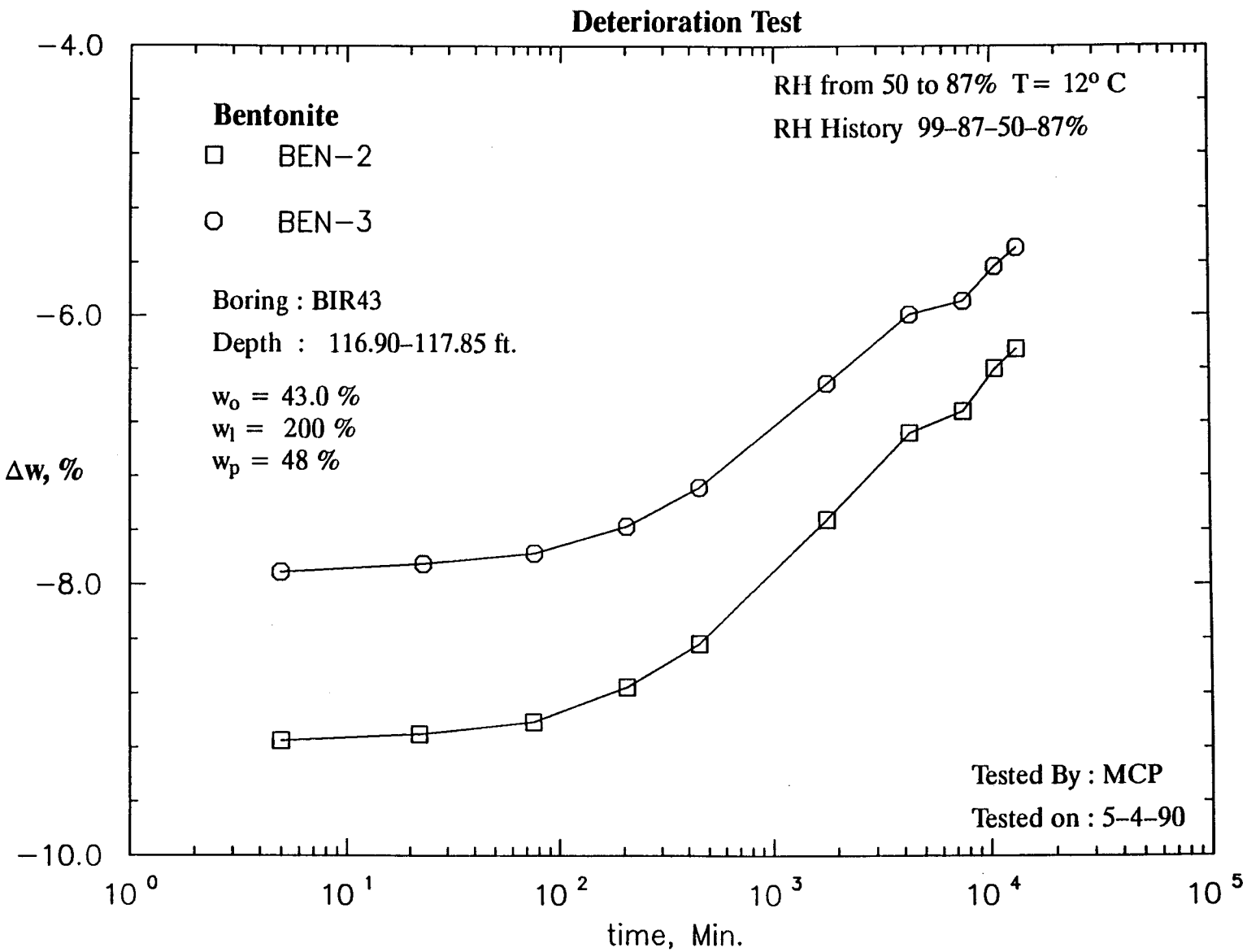


Fig. D21f Water Content Change - Log time Relationship

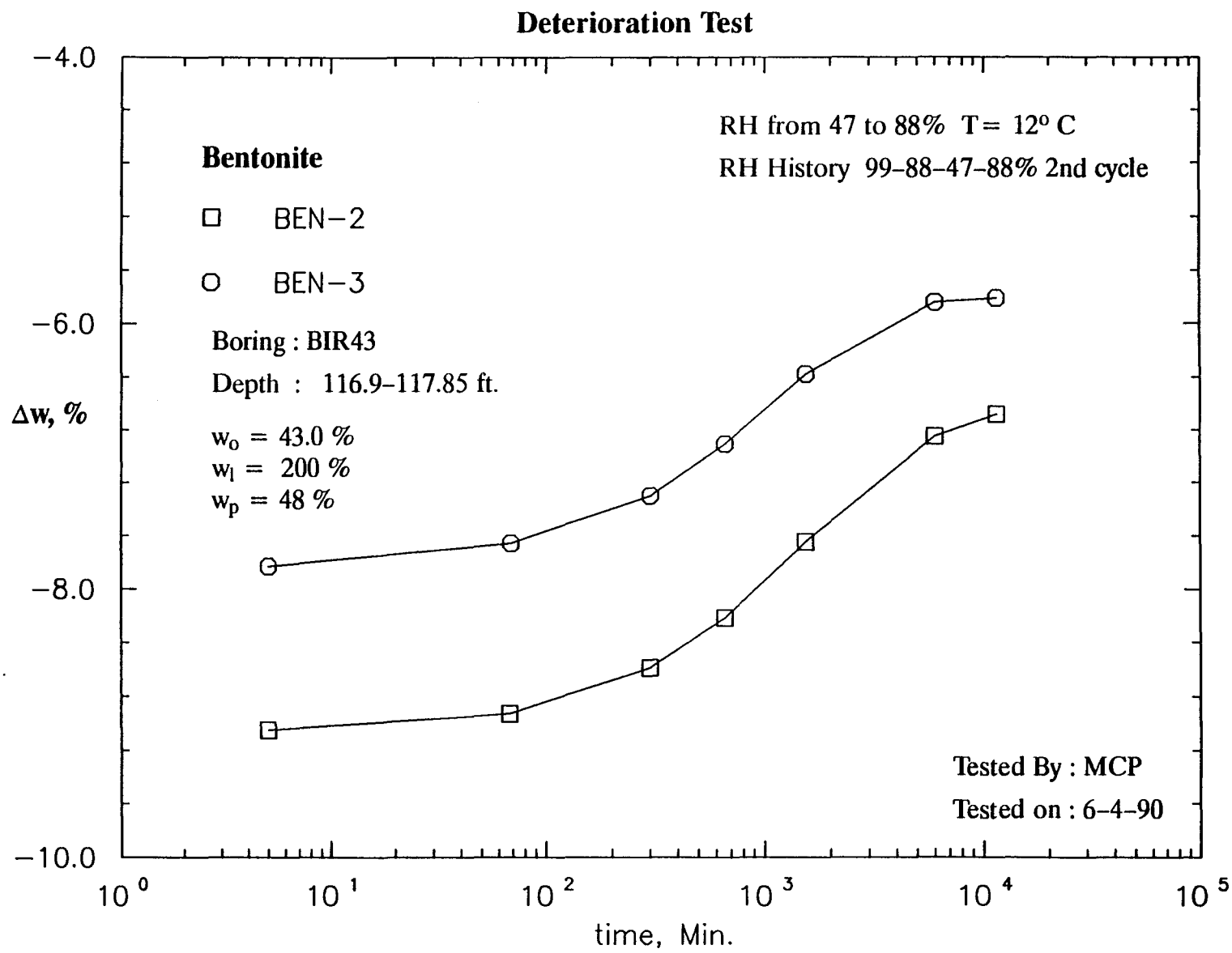


Fig. D21g Water Content Change – Log time Relationship

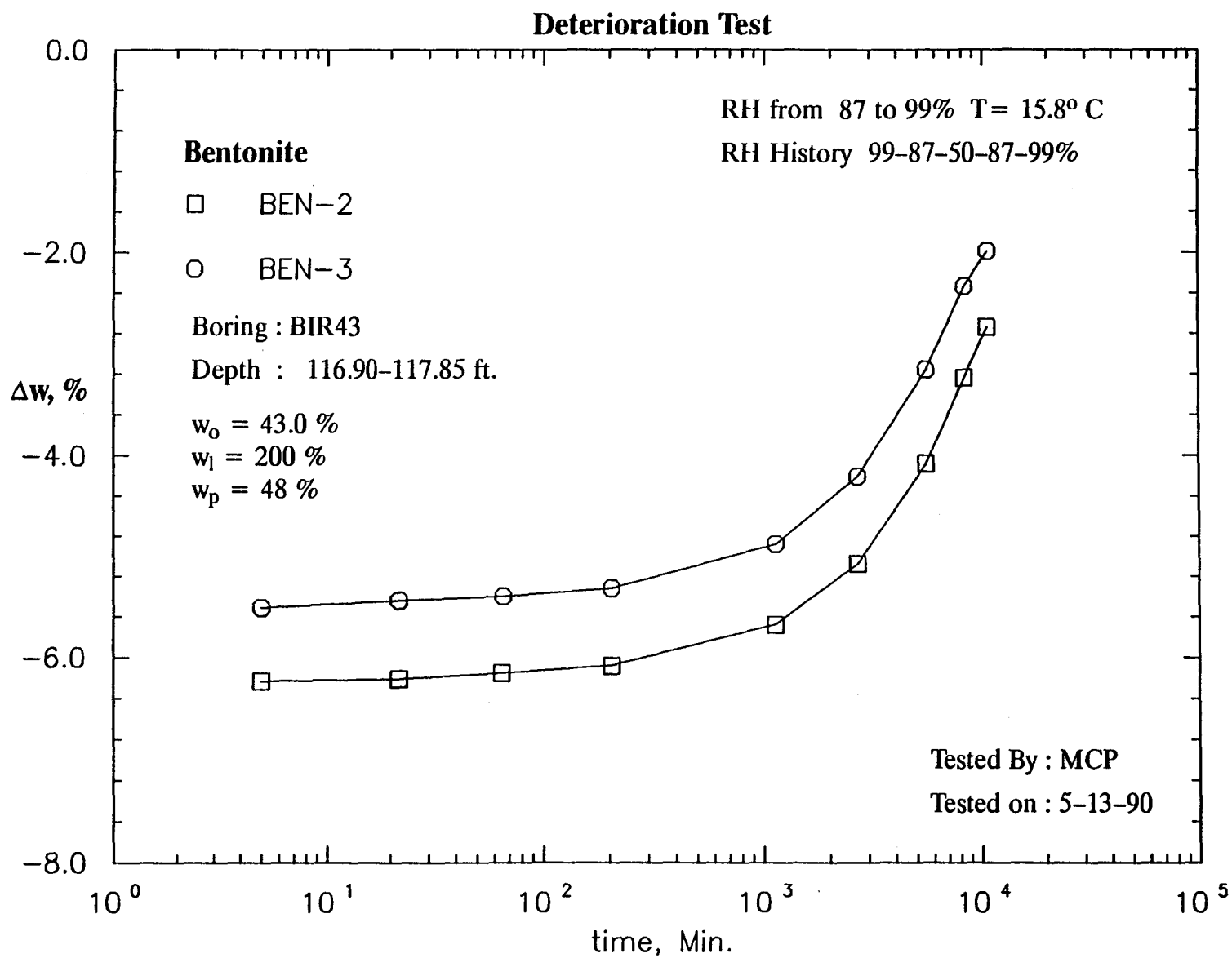


Fig. D21h Water Content Change – Log time Relationship

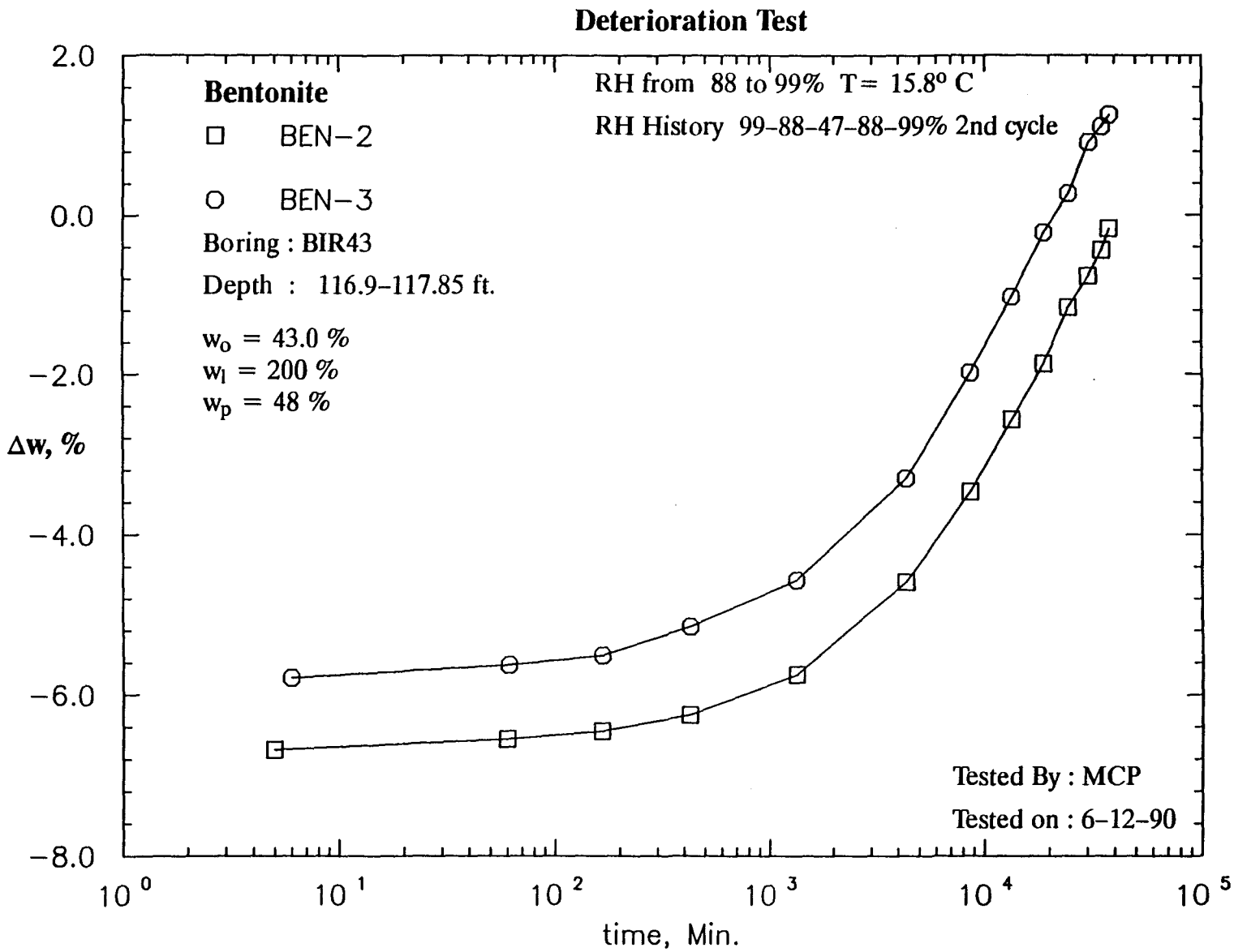


Fig. D21i Water Content Change – Log time Relationship

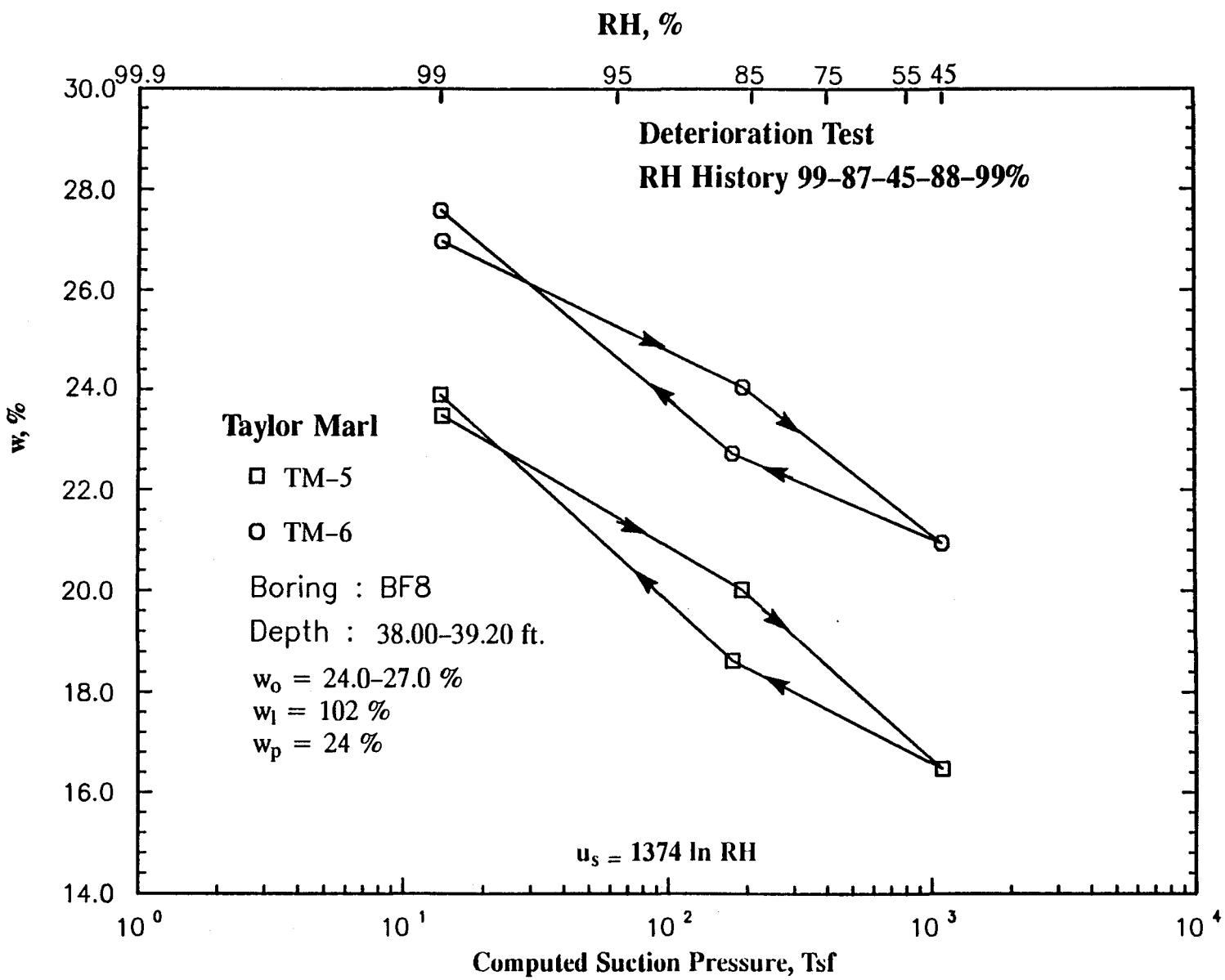


Fig. D22 Water Content – Relative Humidity Relationship

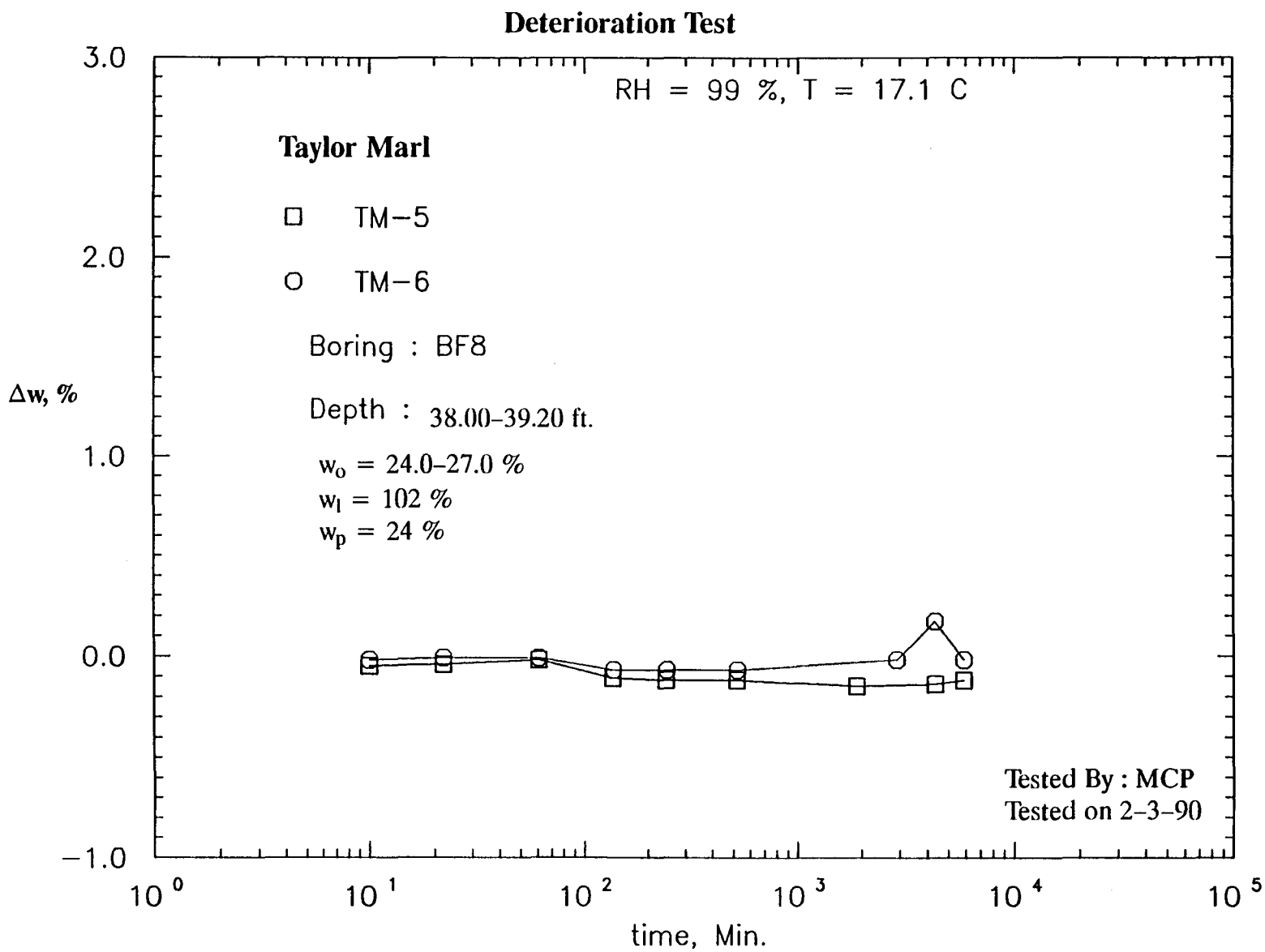


Fig. D22a Water Content Change – Log time Relationship

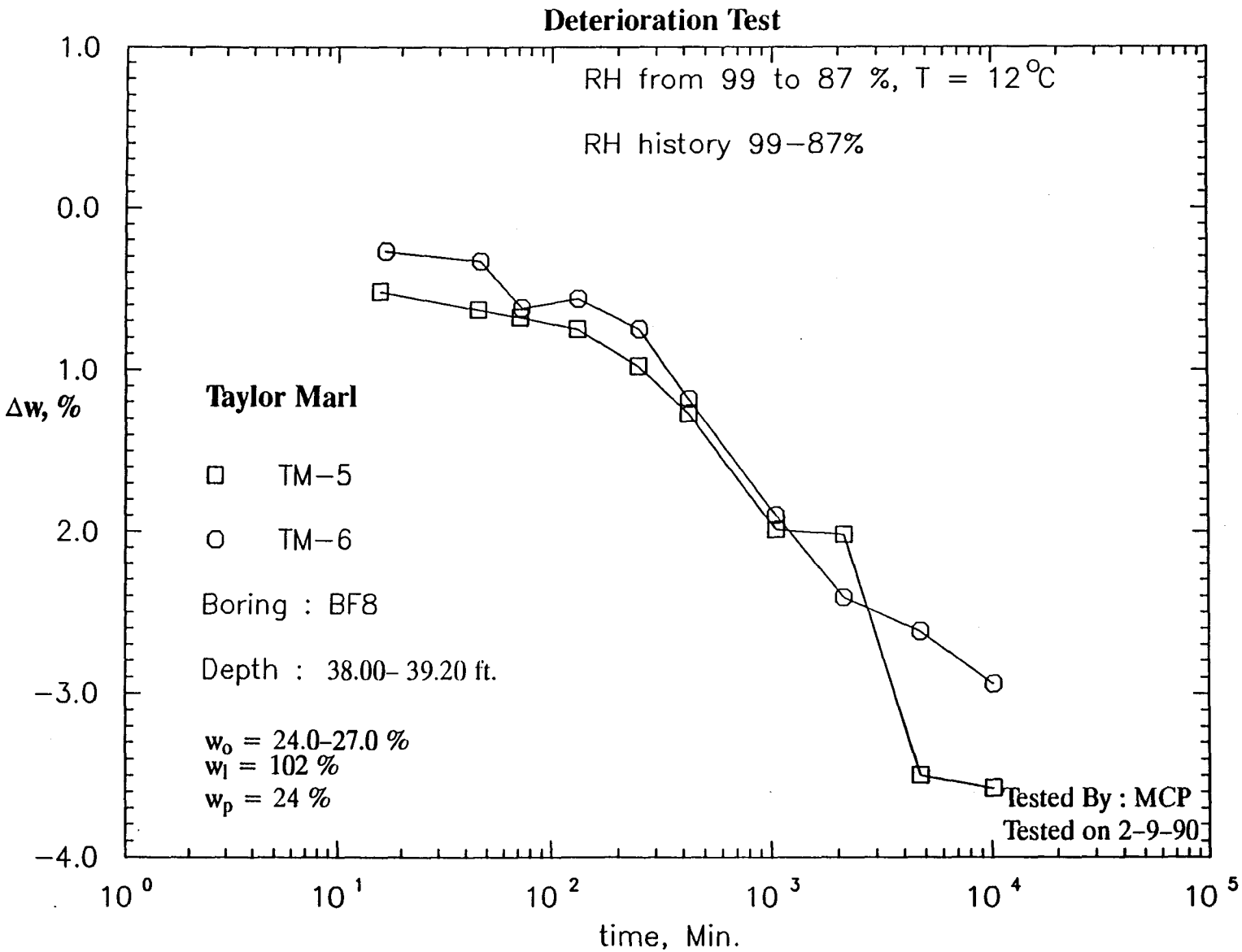


Fig. D22b Water Content Change – Log time Relationship

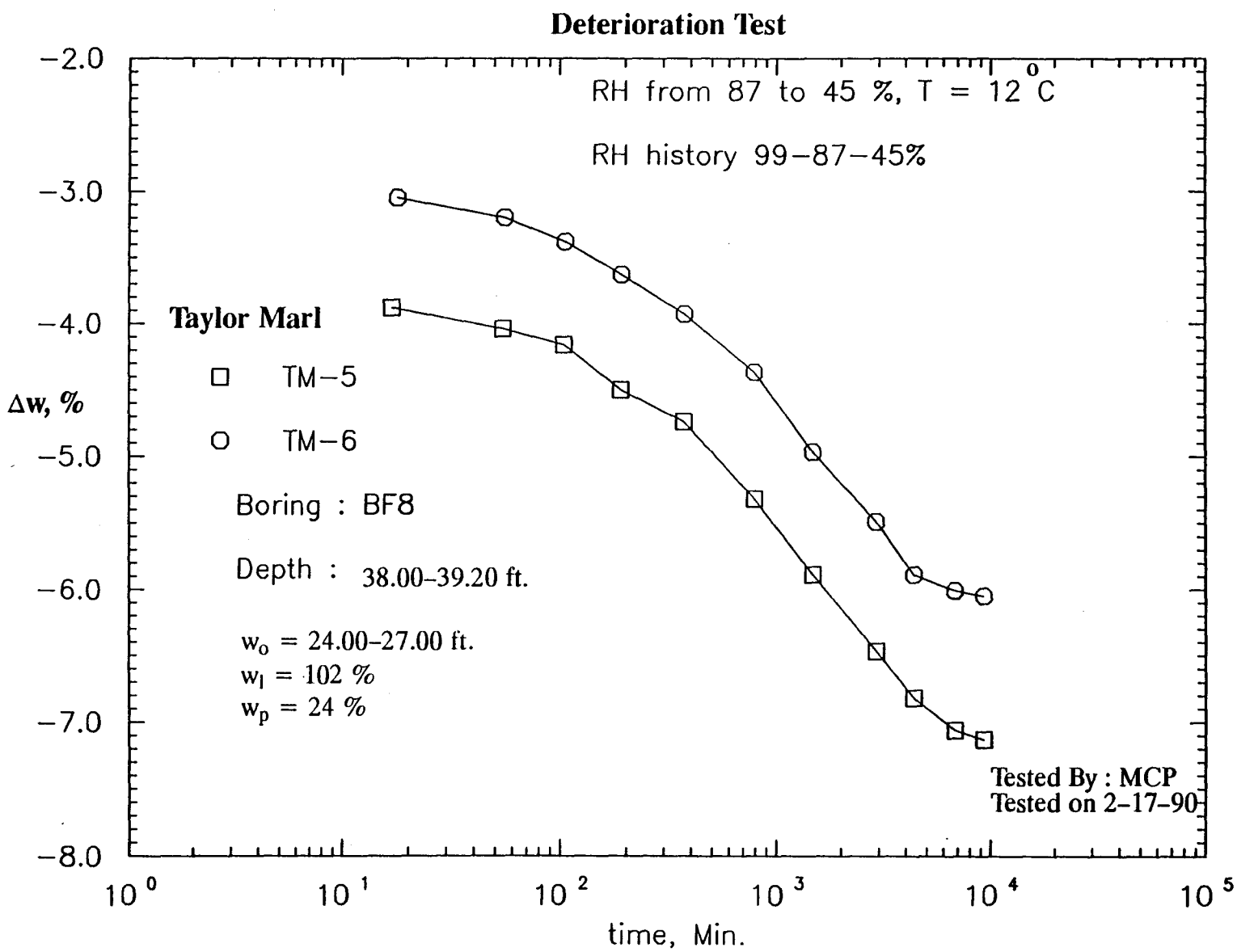


Fig. D22c Water Content Change – Log time Relationship

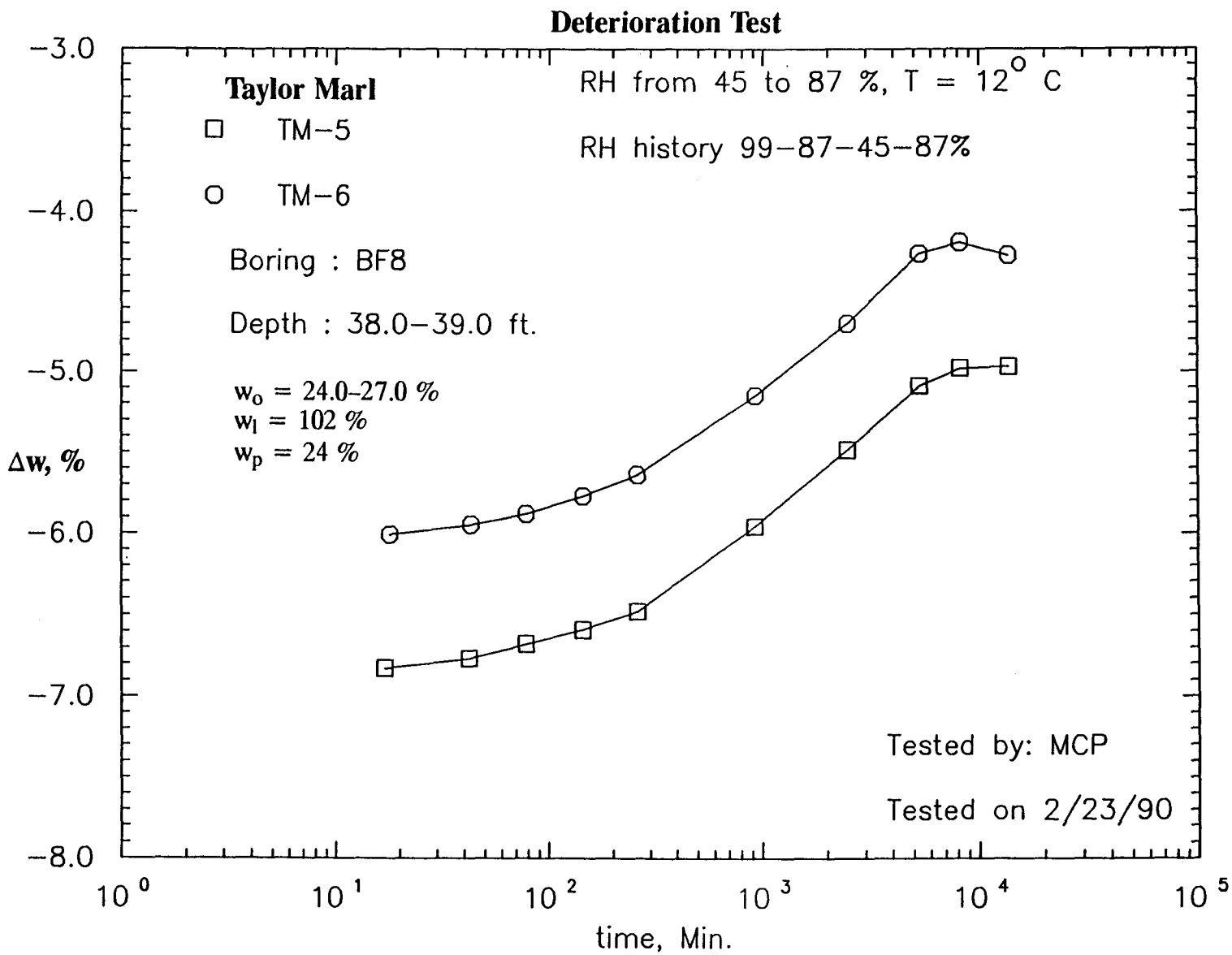


Fig. D22d Water Content Change – Log time Relationship

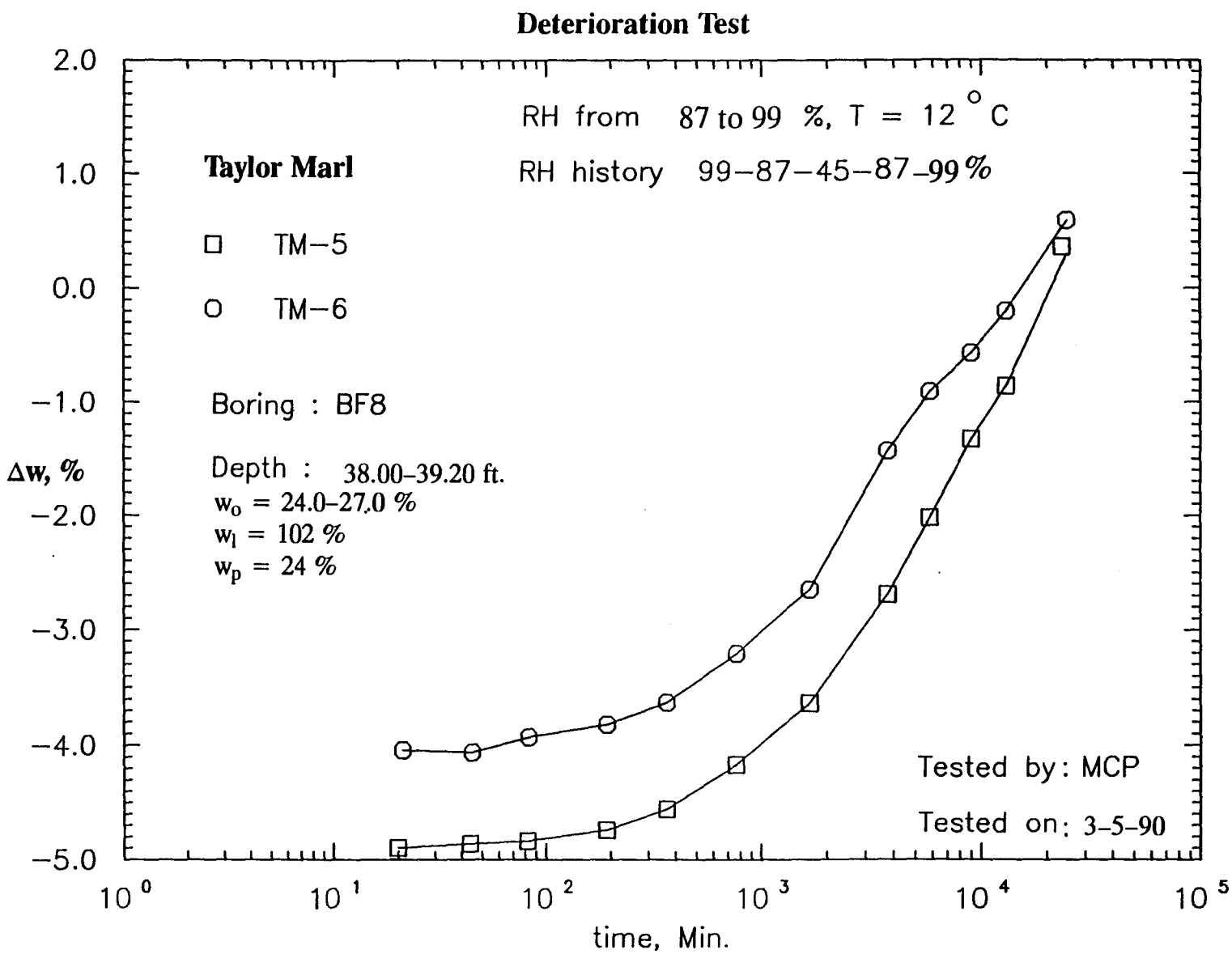


Fig. D22e Water Content Change – Log time Relationship

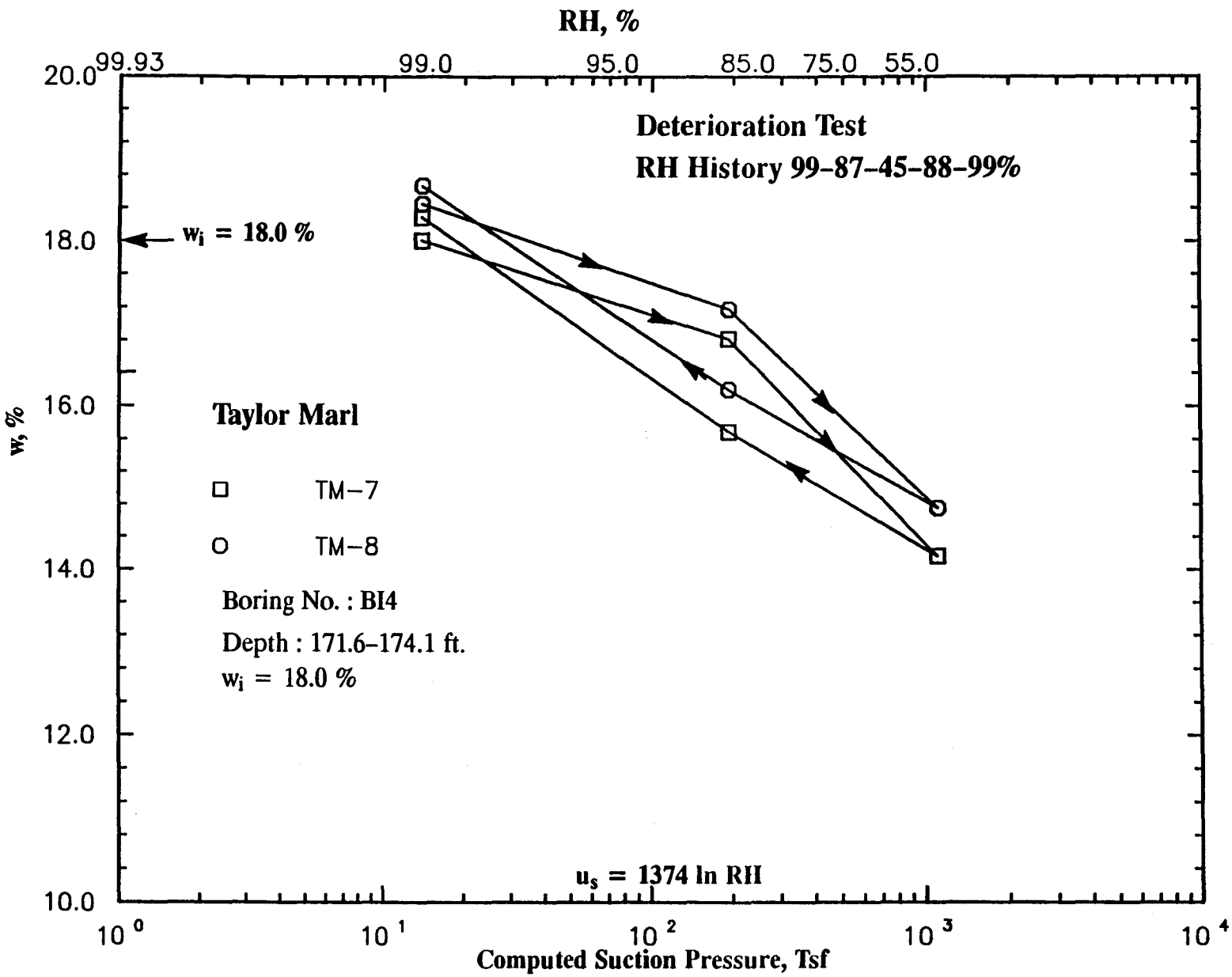


Fig. D23 Water Content – Relative Humidity Relationship

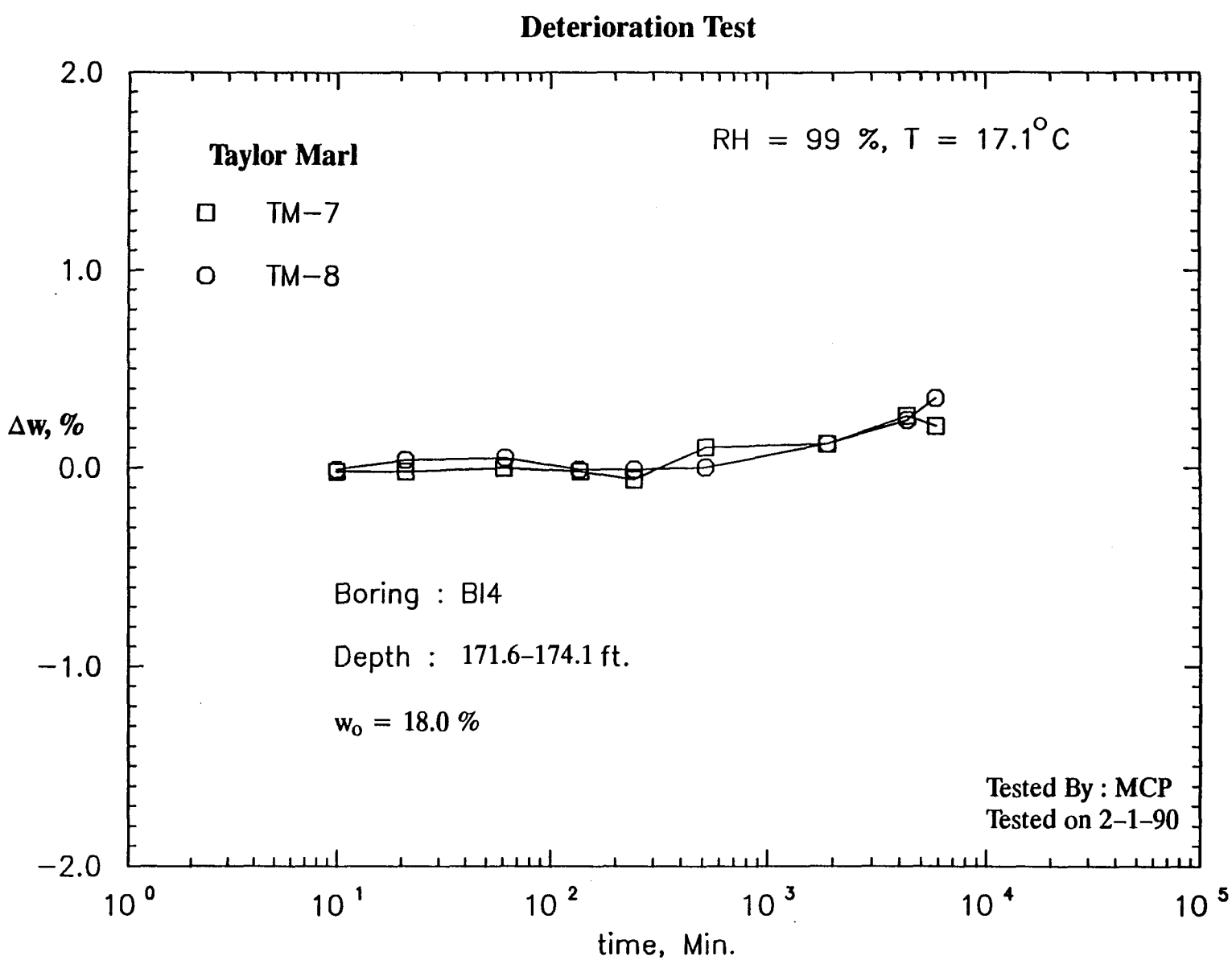


Fig. D23a Water Content Change – Log time Relationship

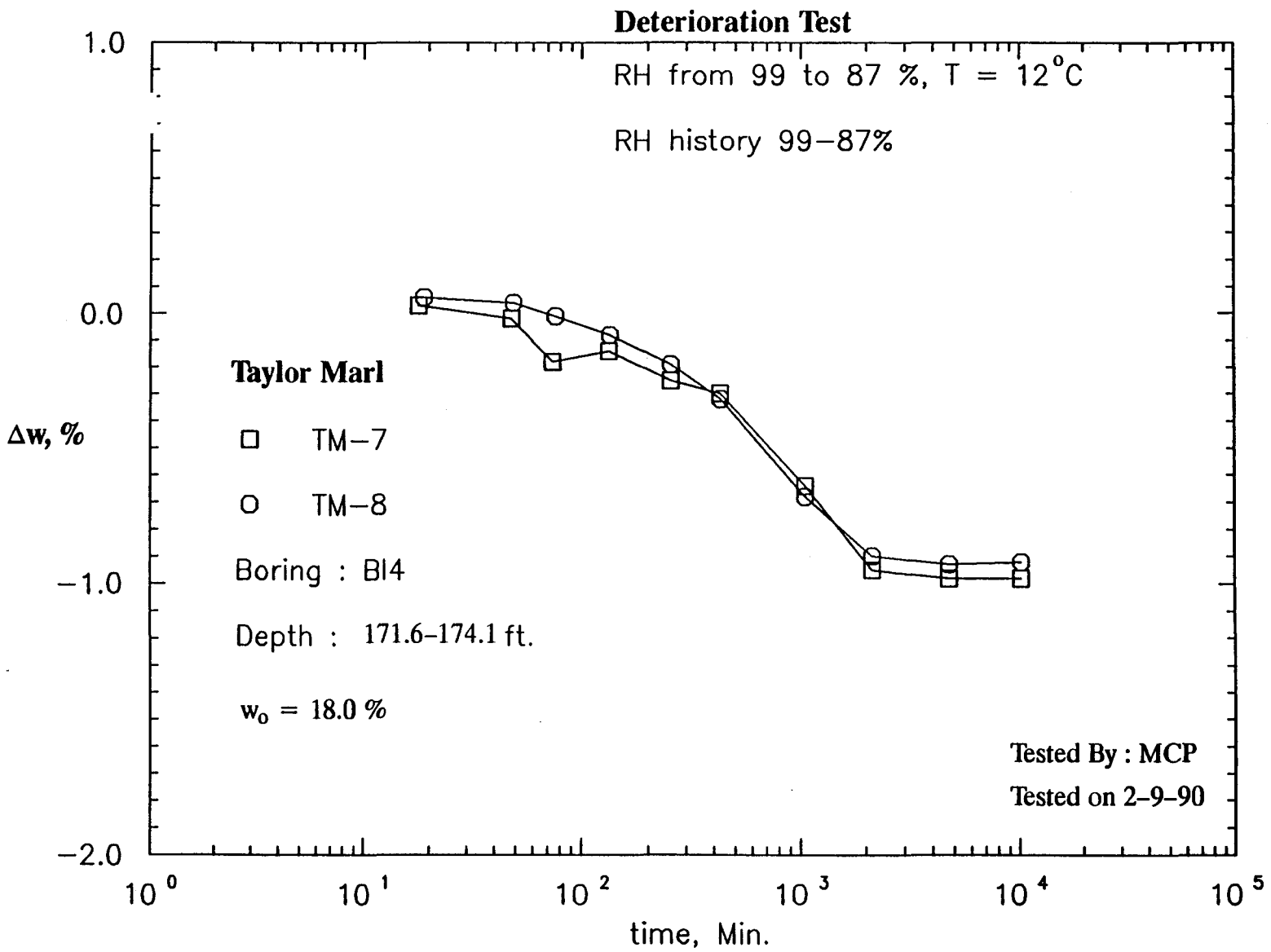


Fig. D23b Water Content Change – Log time Relationship

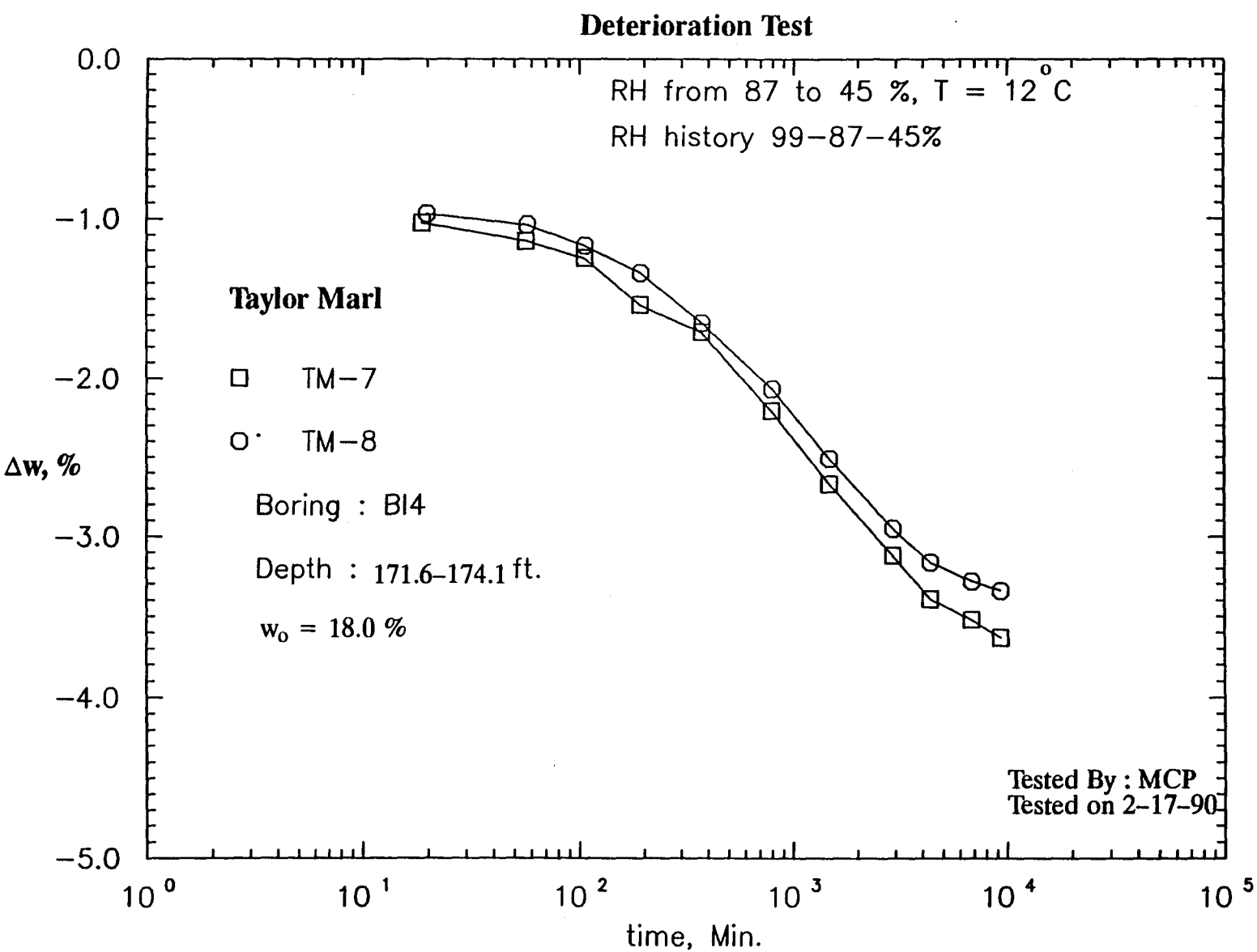


Fig. D23c Water Content Change – Log time Relationship

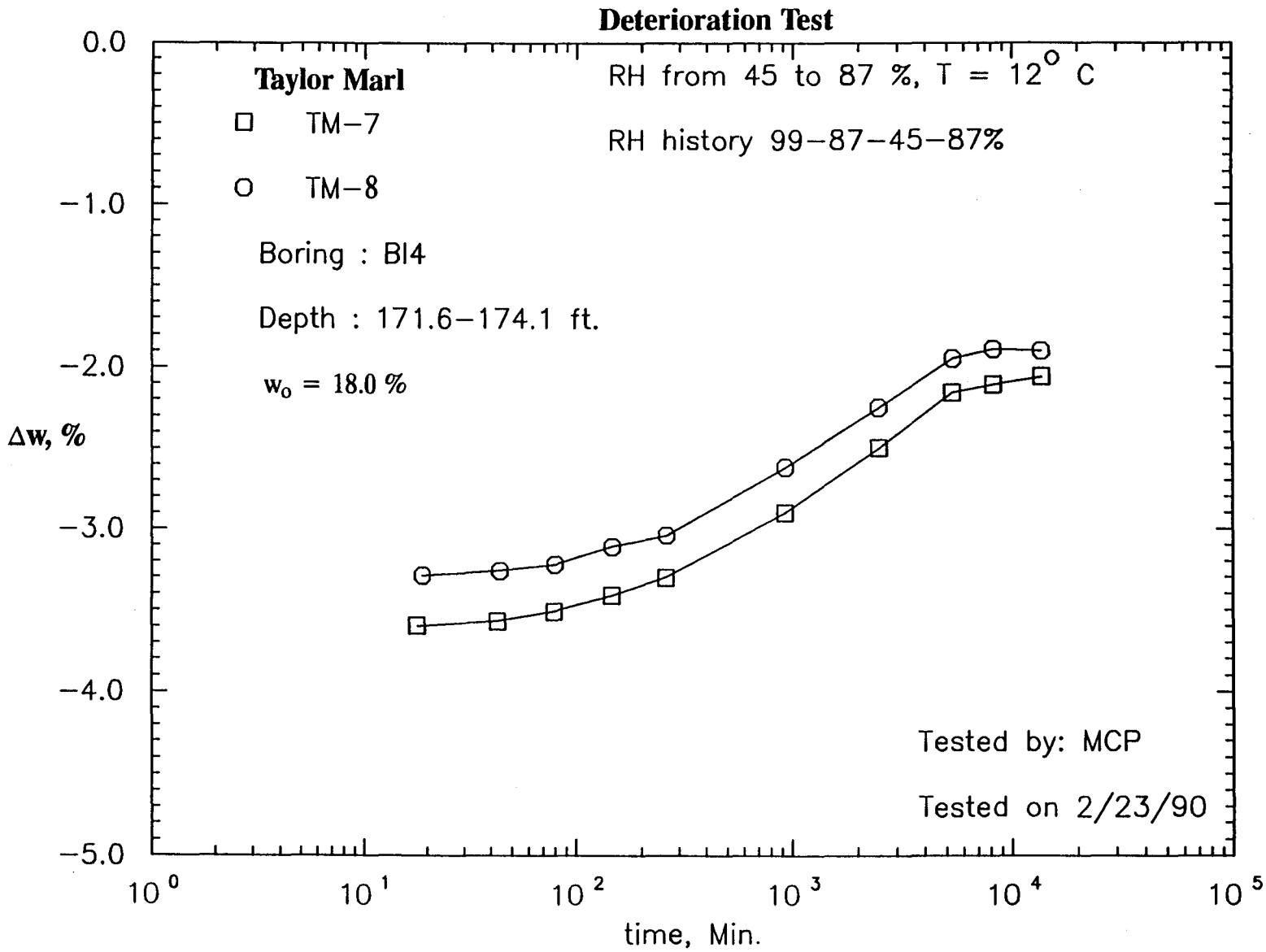


Fig. D23d Water Content Change – Log time Relationship

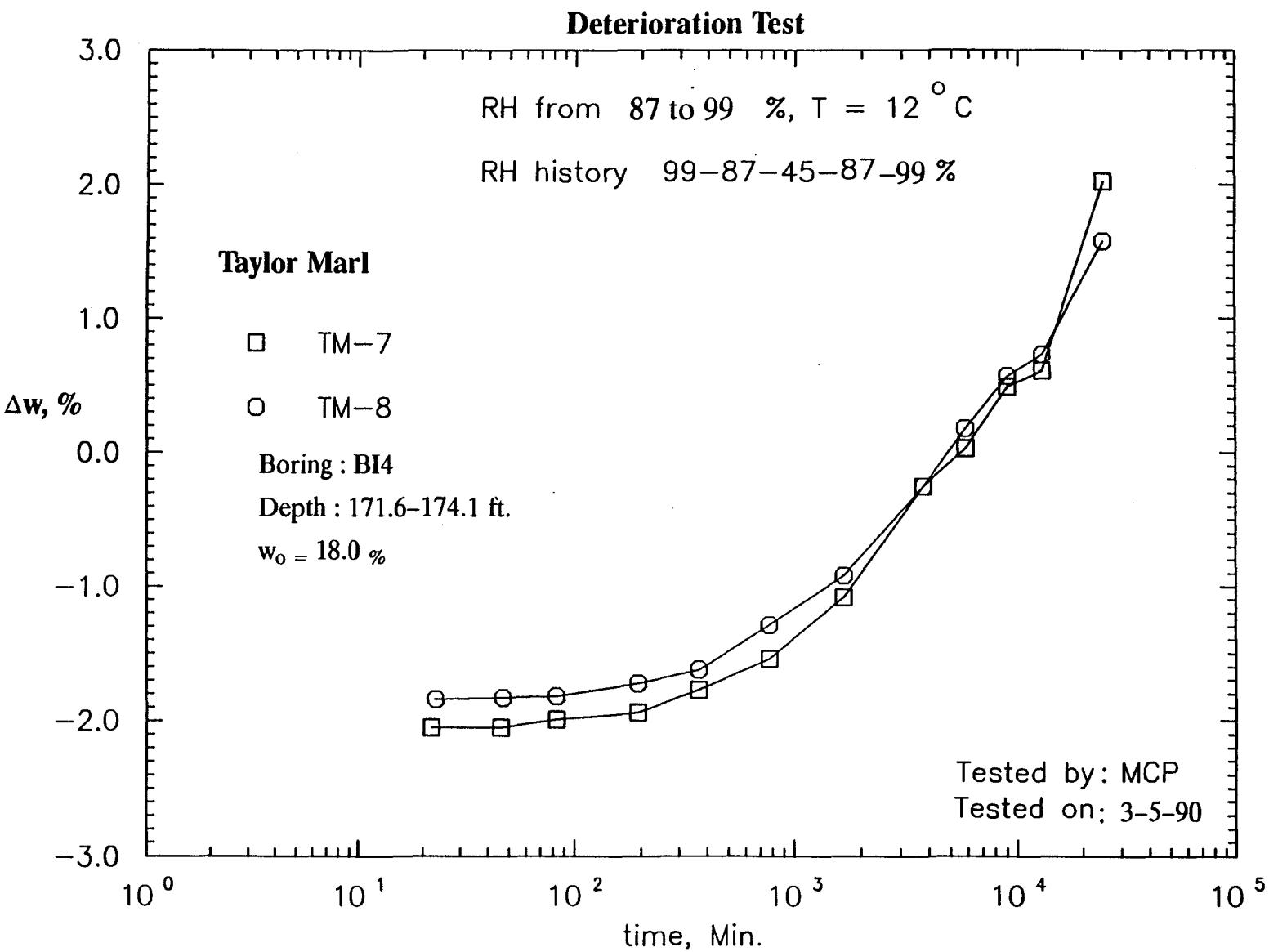


Fig. D23e Water Content Change – Log time Relationship

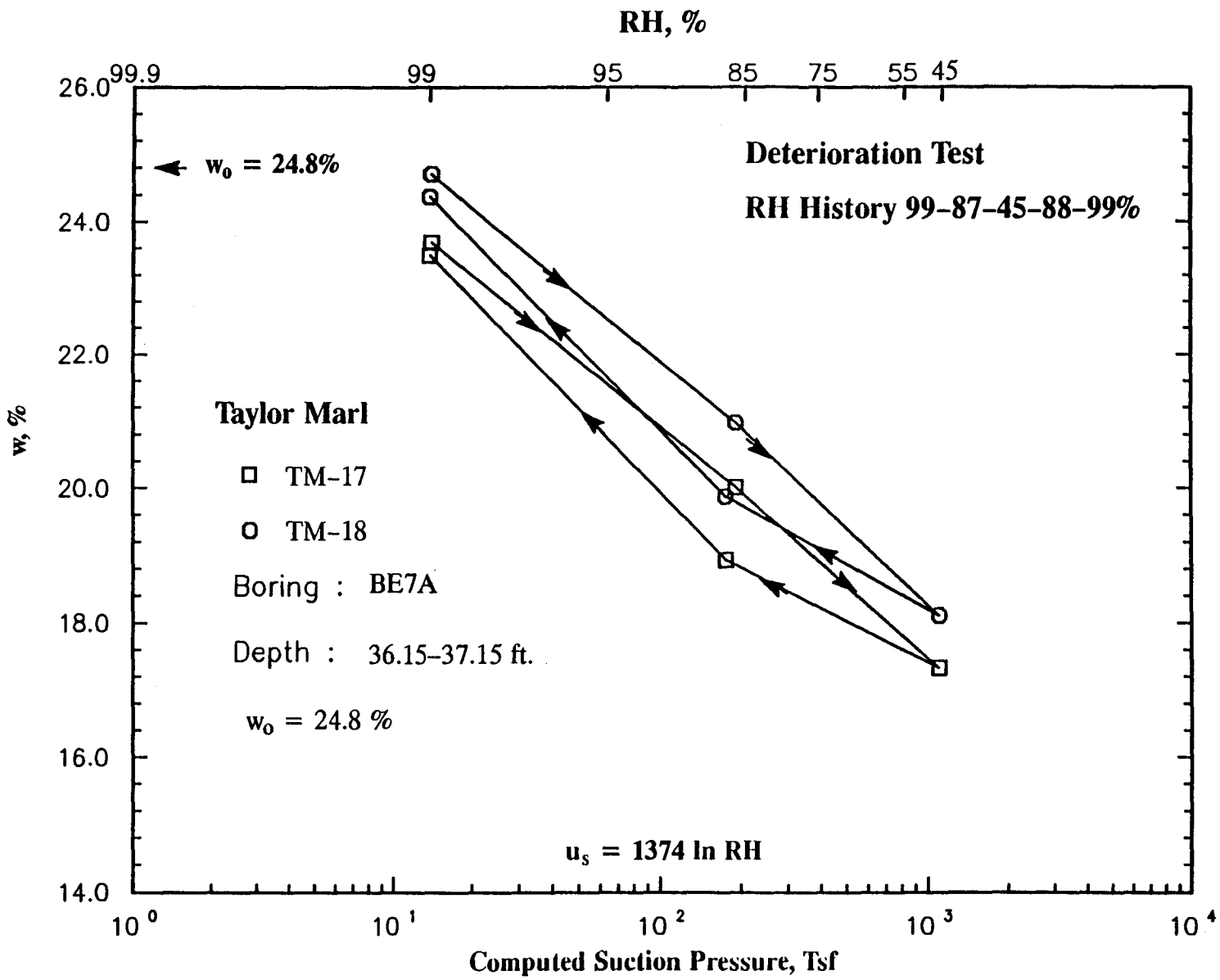


Fig. D24 Water Content – Relative Humidity Relationship

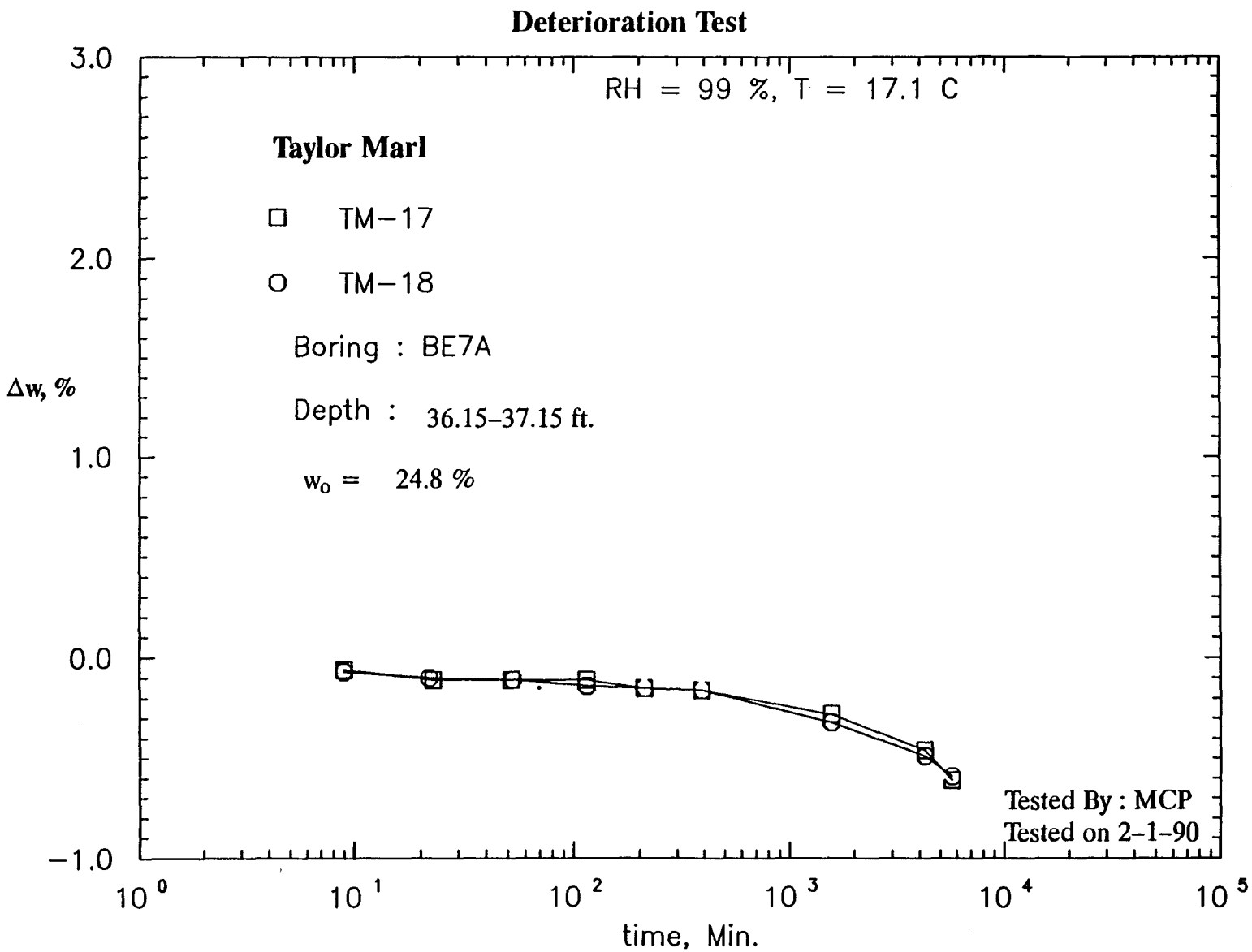


Fig. D24a Water Content Change – Log time Relationship

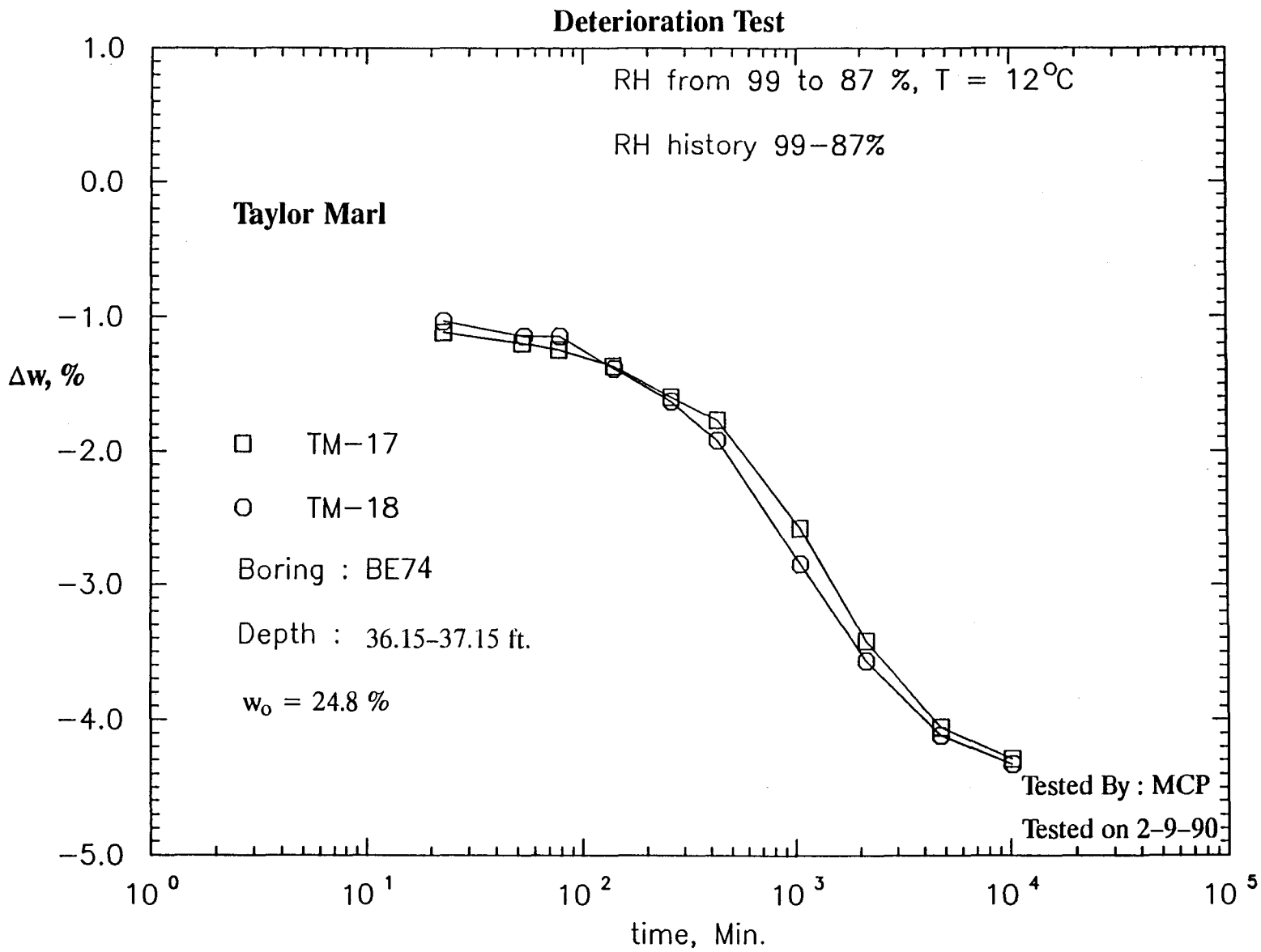


Fig. D24b Water Content Change – Log time Relationship

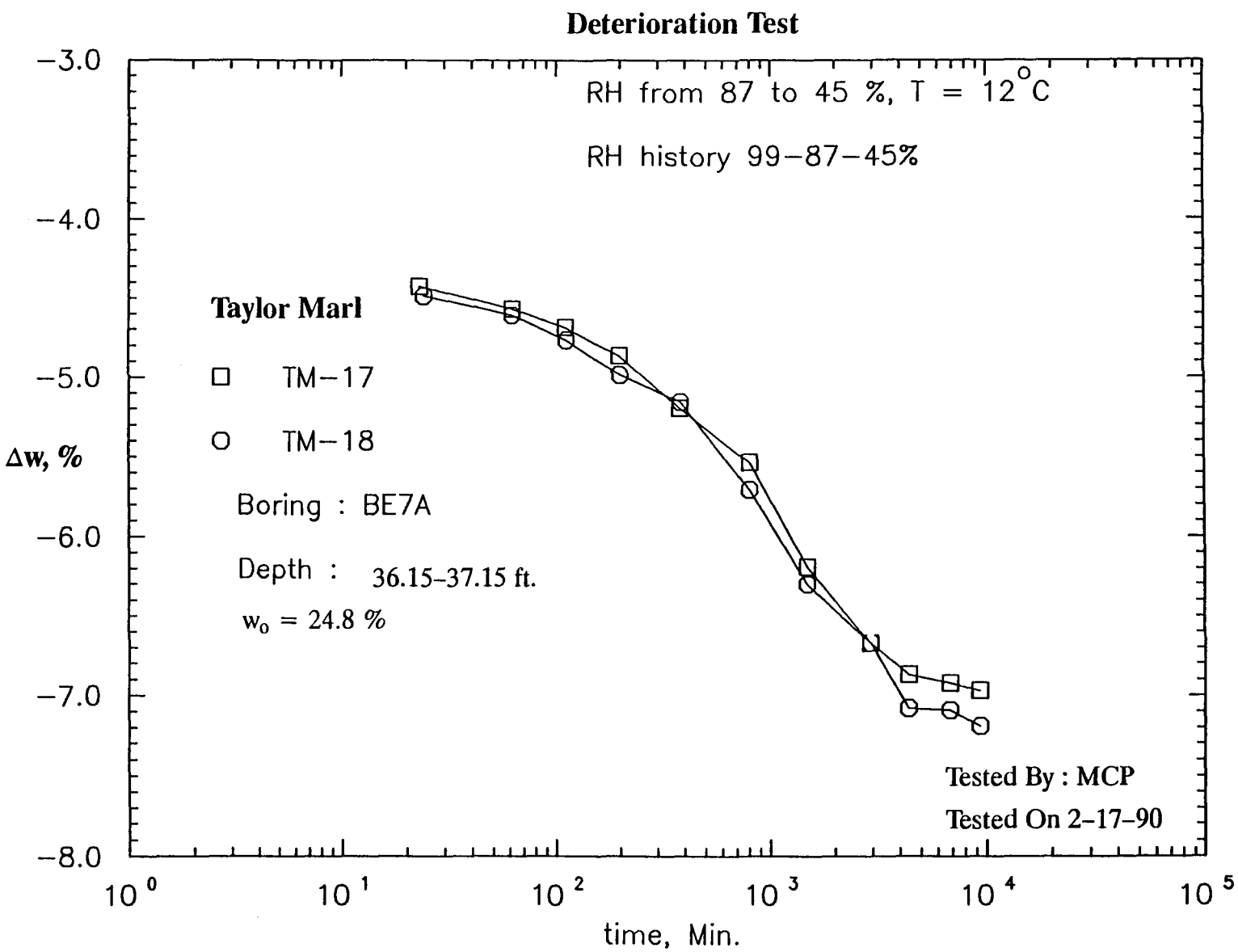


Fig. D24c Water Content Change – Log time Relationship

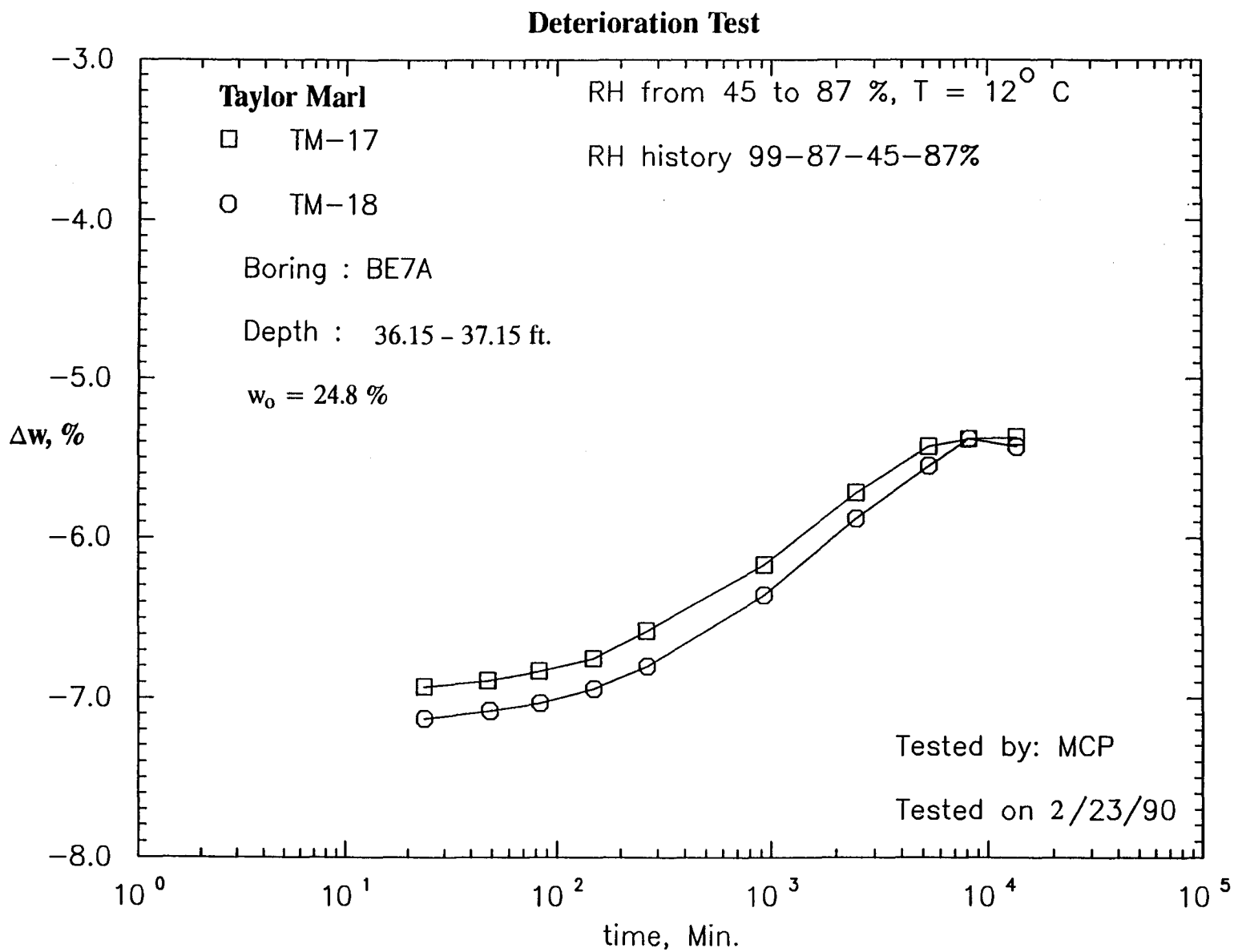


Fig. D24d Water Content Change - Log time Relationship

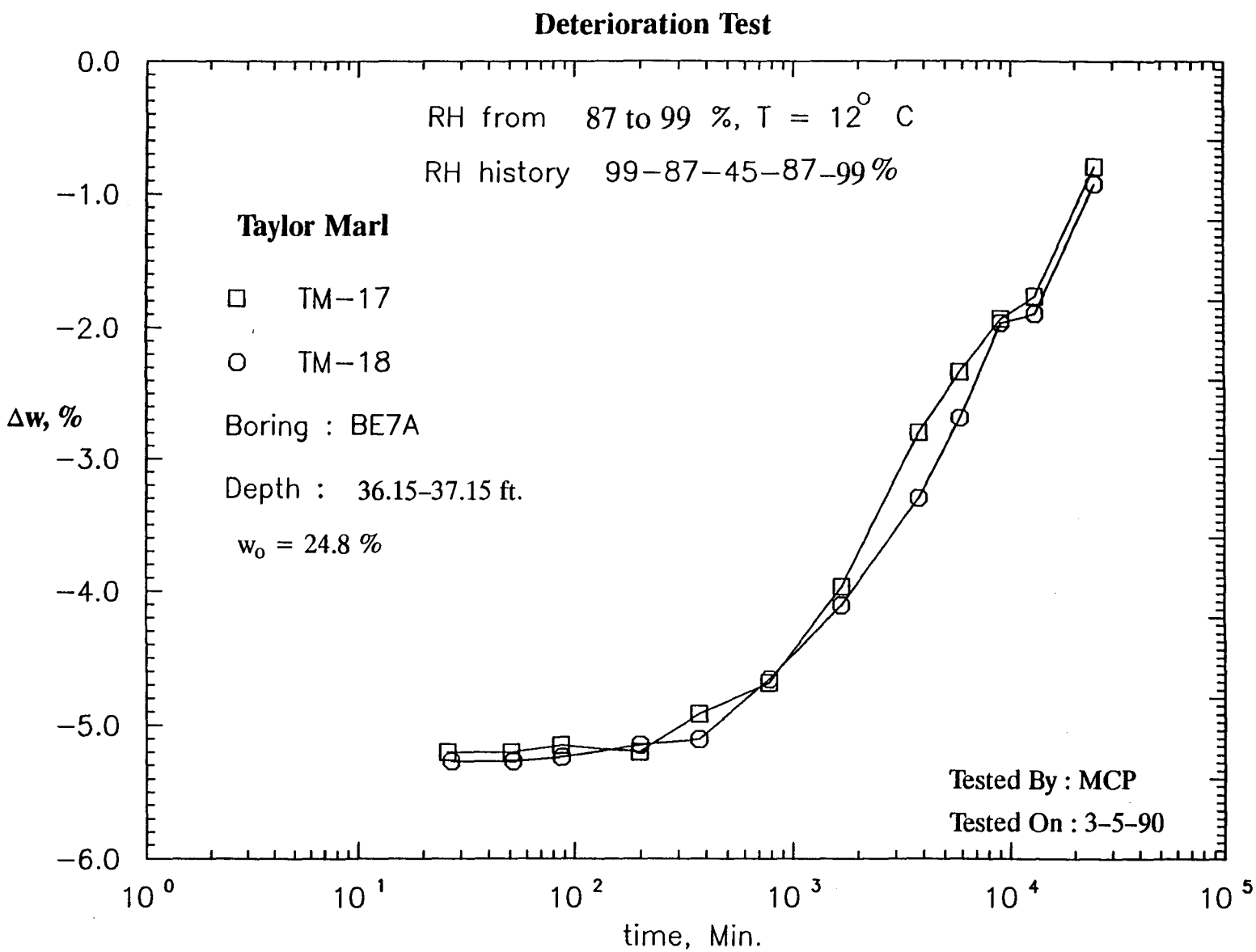


Fig. D24e Water Content Change – Log time Relationship

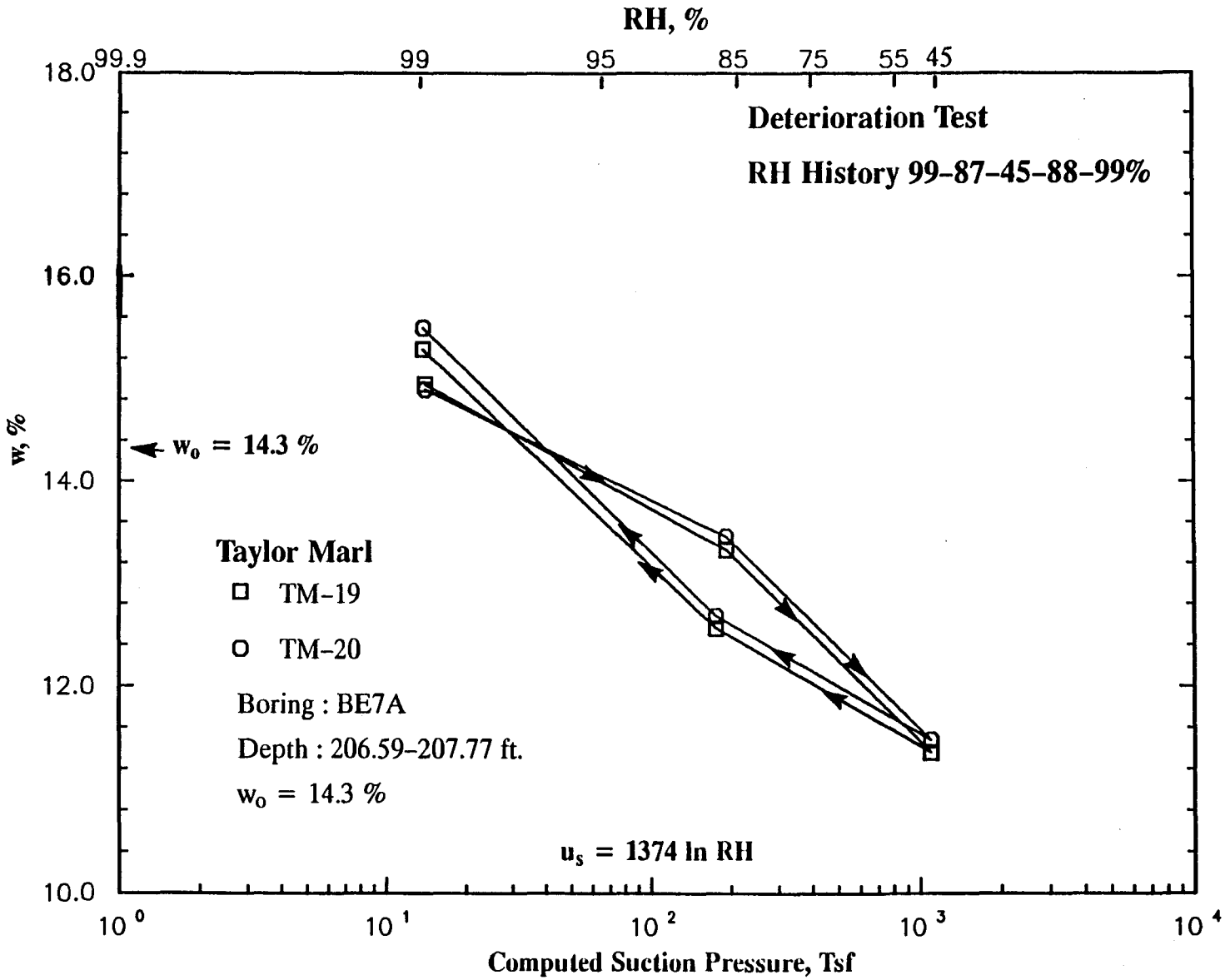


Fig. D25 Water Content – Relative Humidity Relationship

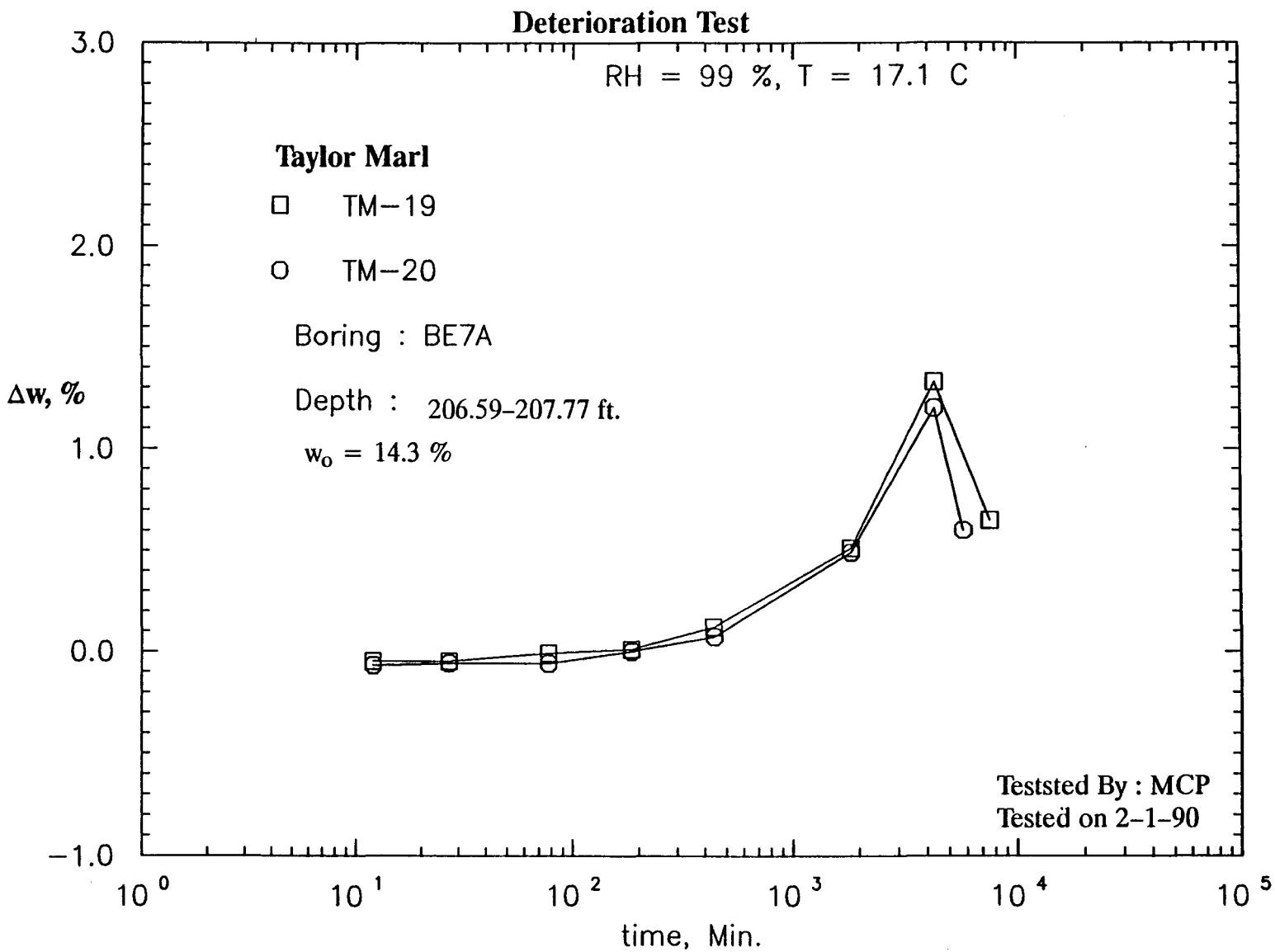


Fig. D25a Water Content Change – Log time Relationship

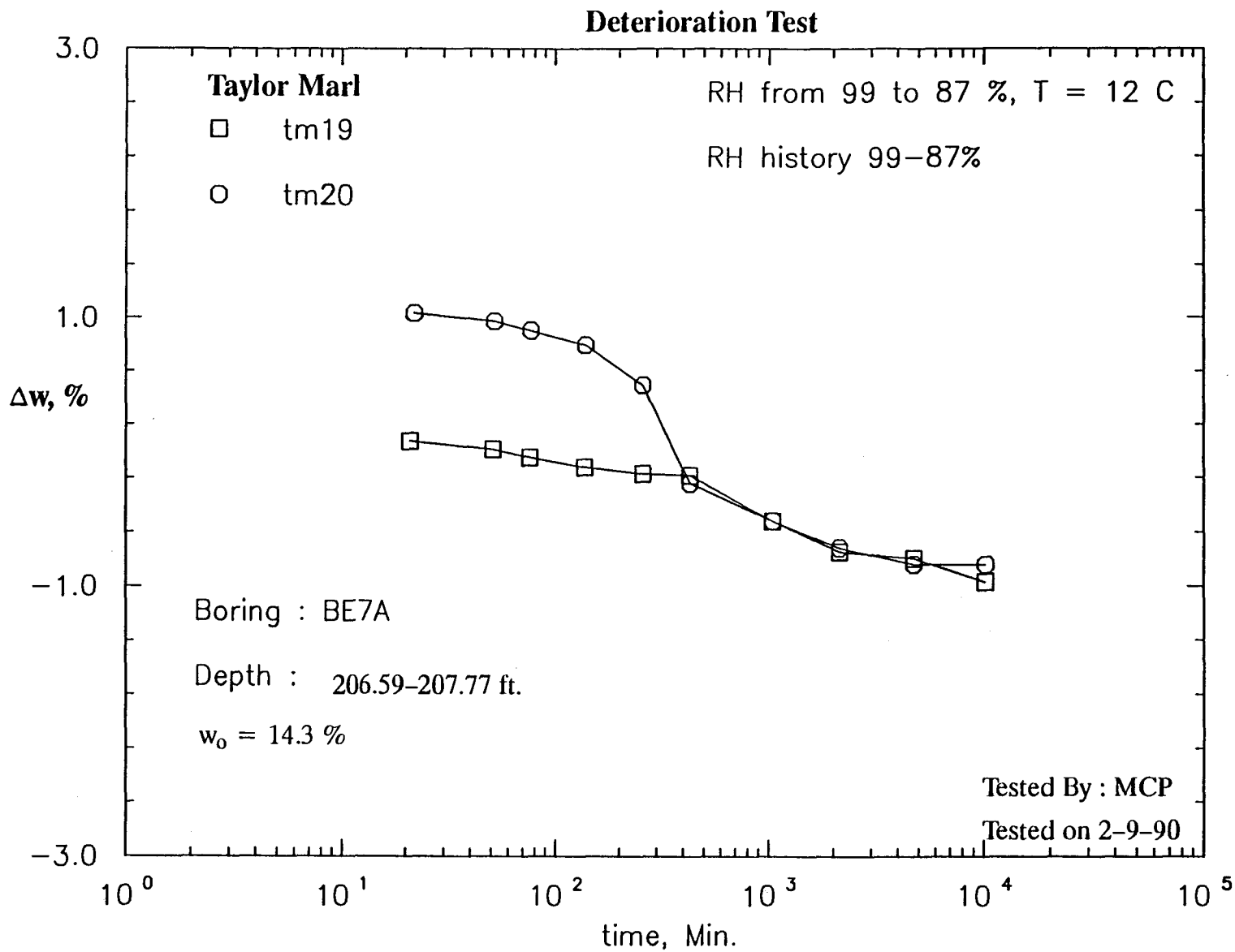


Fig. D25b Water Content Change – Log time Relationship

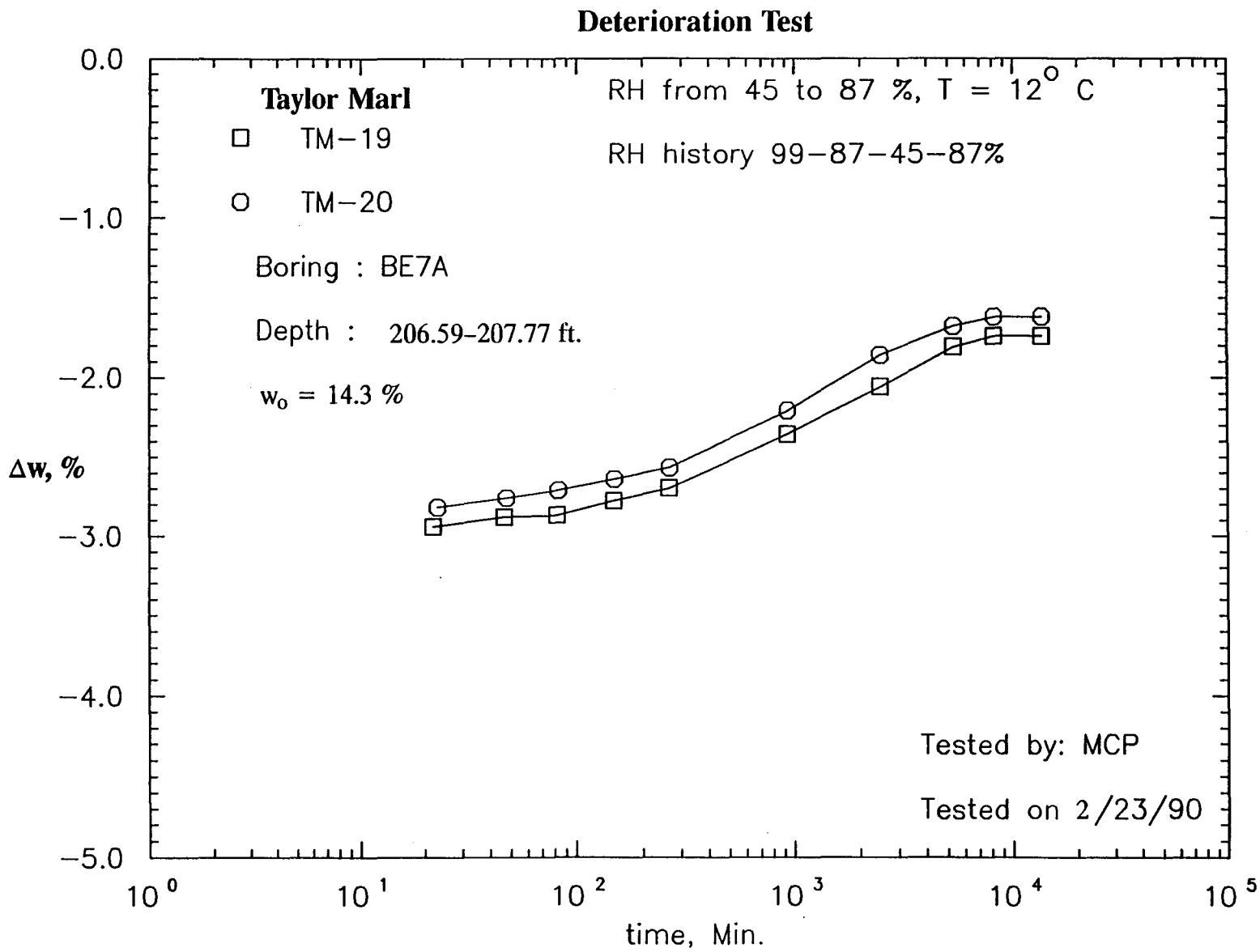


Fig. D25d Water Content Change – Log time Relationship

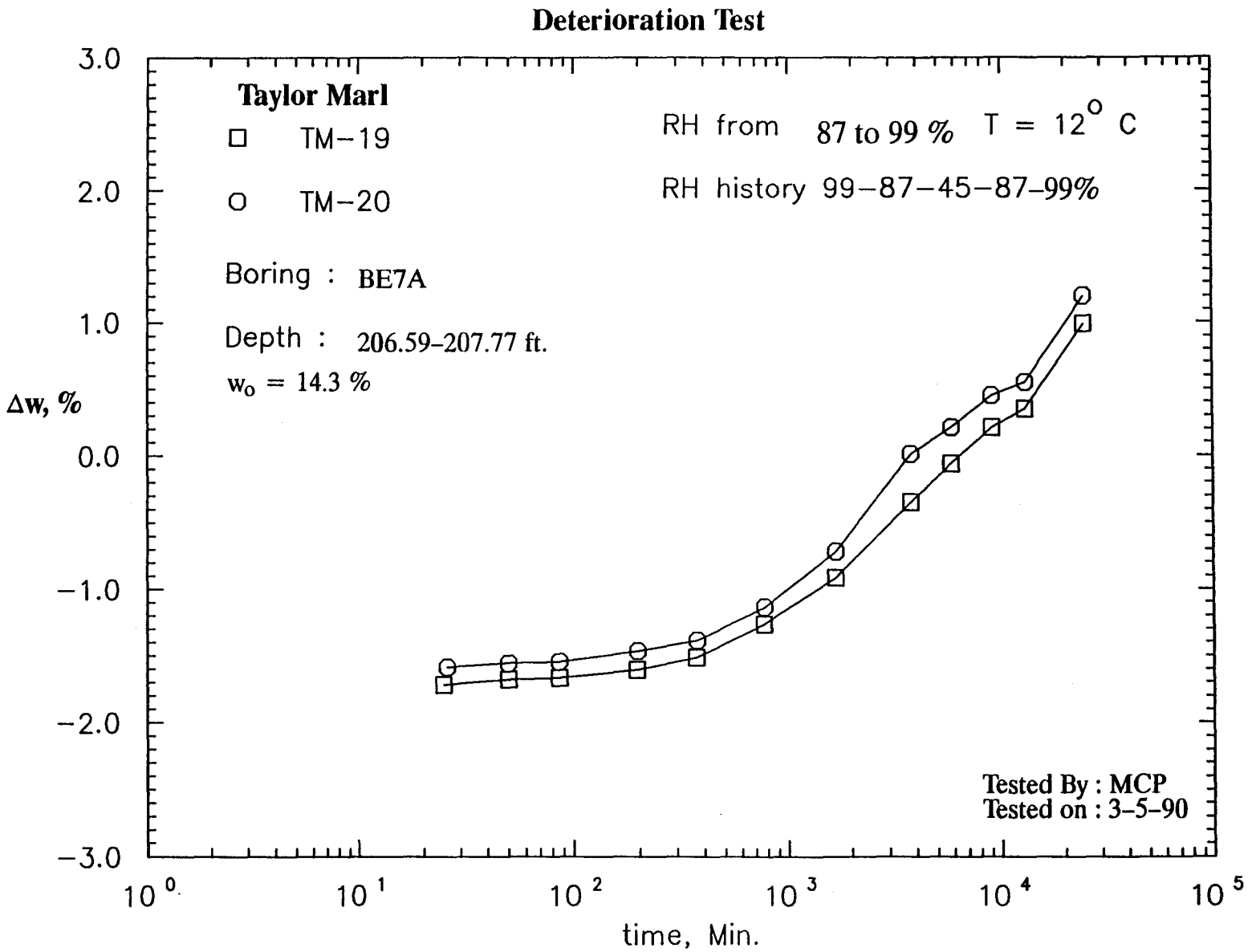


Fig. D25e Water Content Change – Log time Relationship

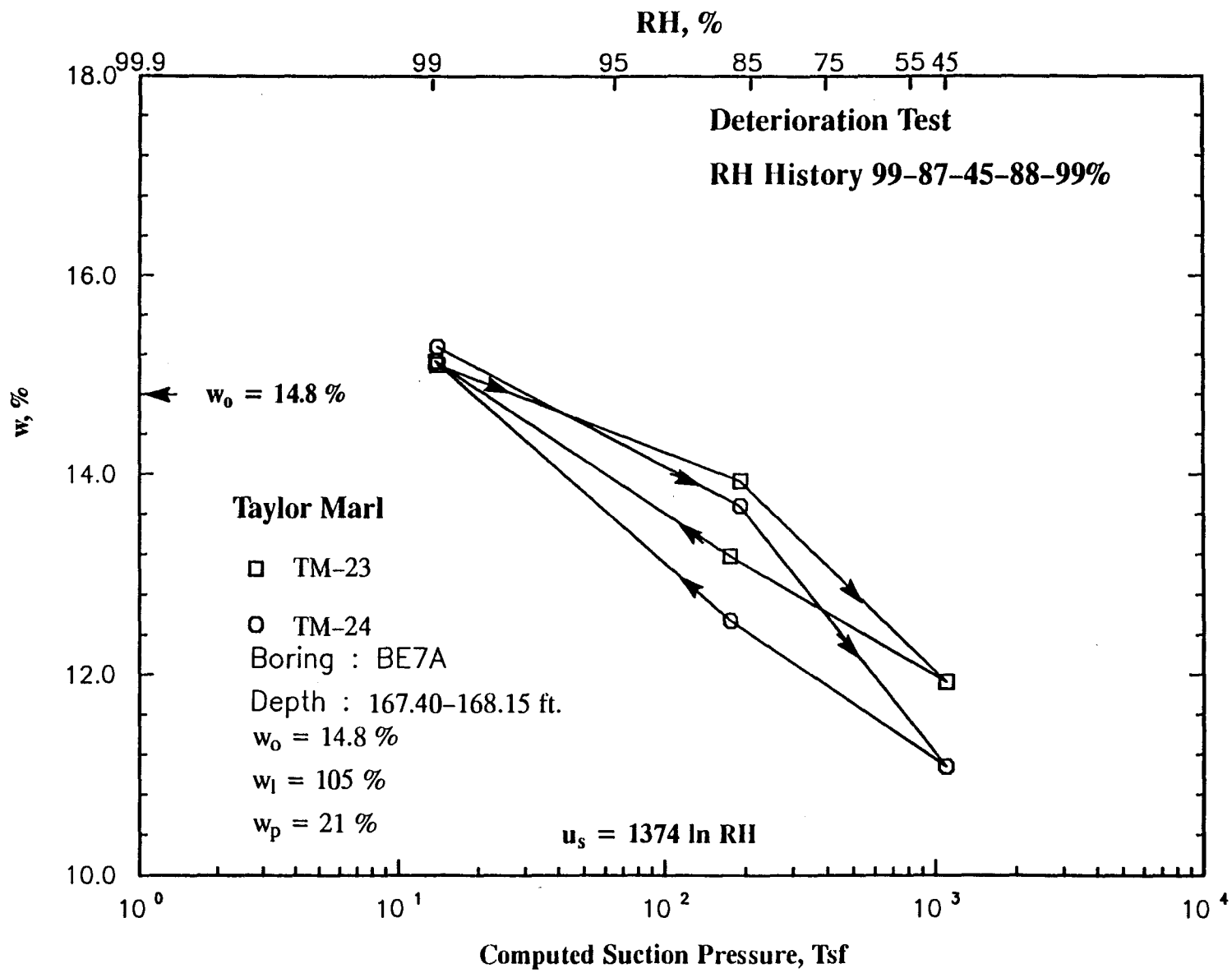


Fig. D26 Water Content – Relative Humidity Relationship

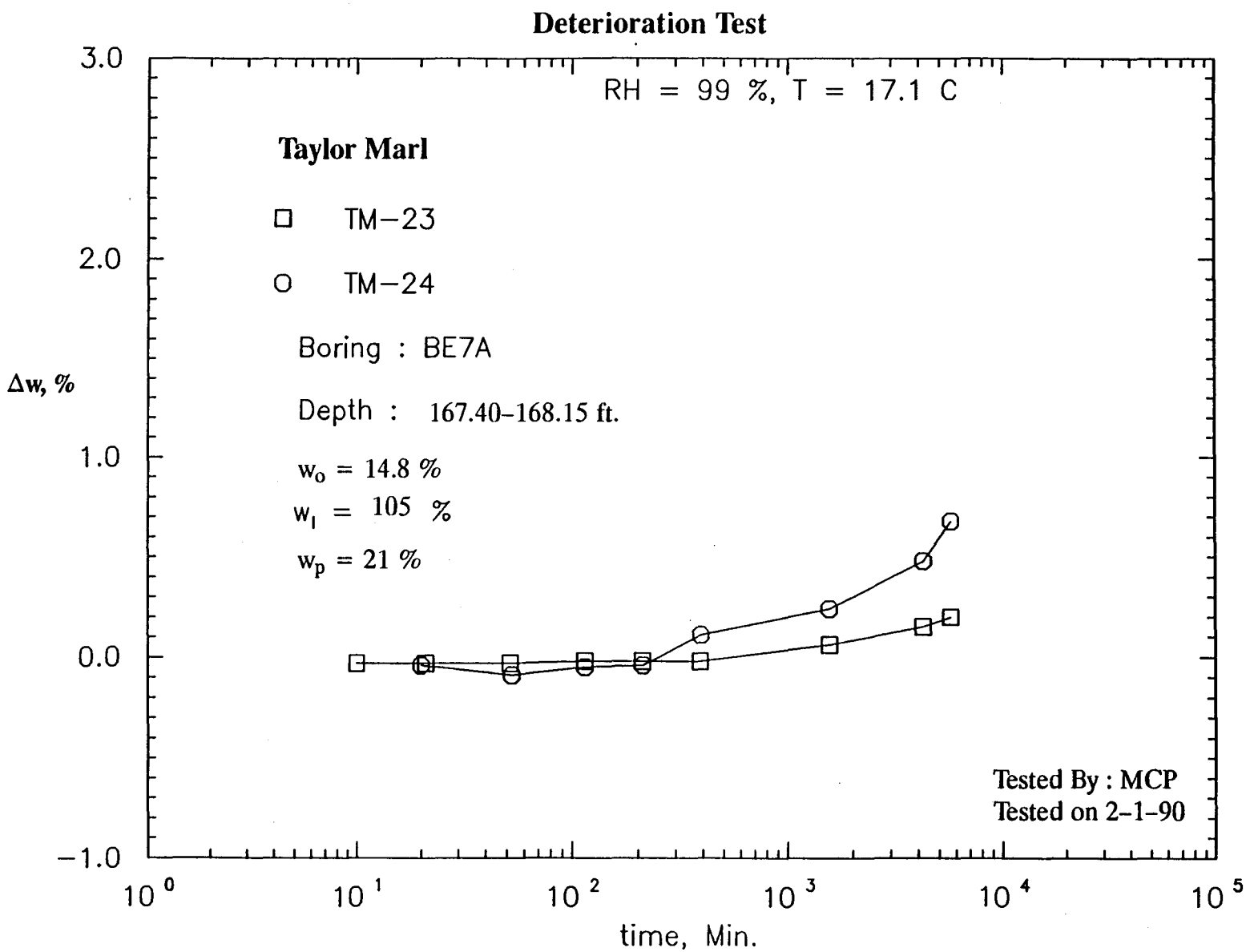


Fig. D26a Water Content Change – Log time Relationship

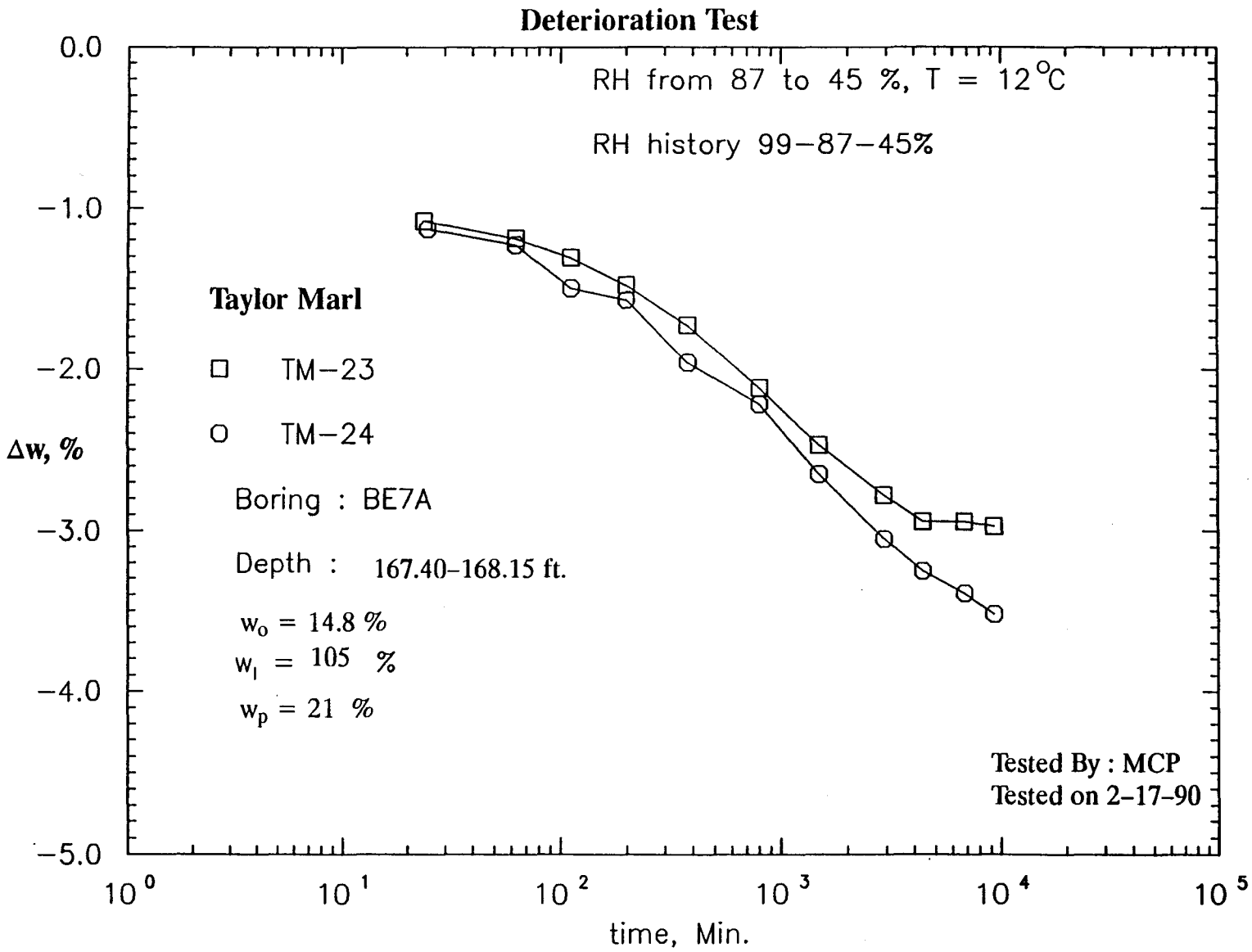


Fig. D26c Water Content Change – Log time Relationship

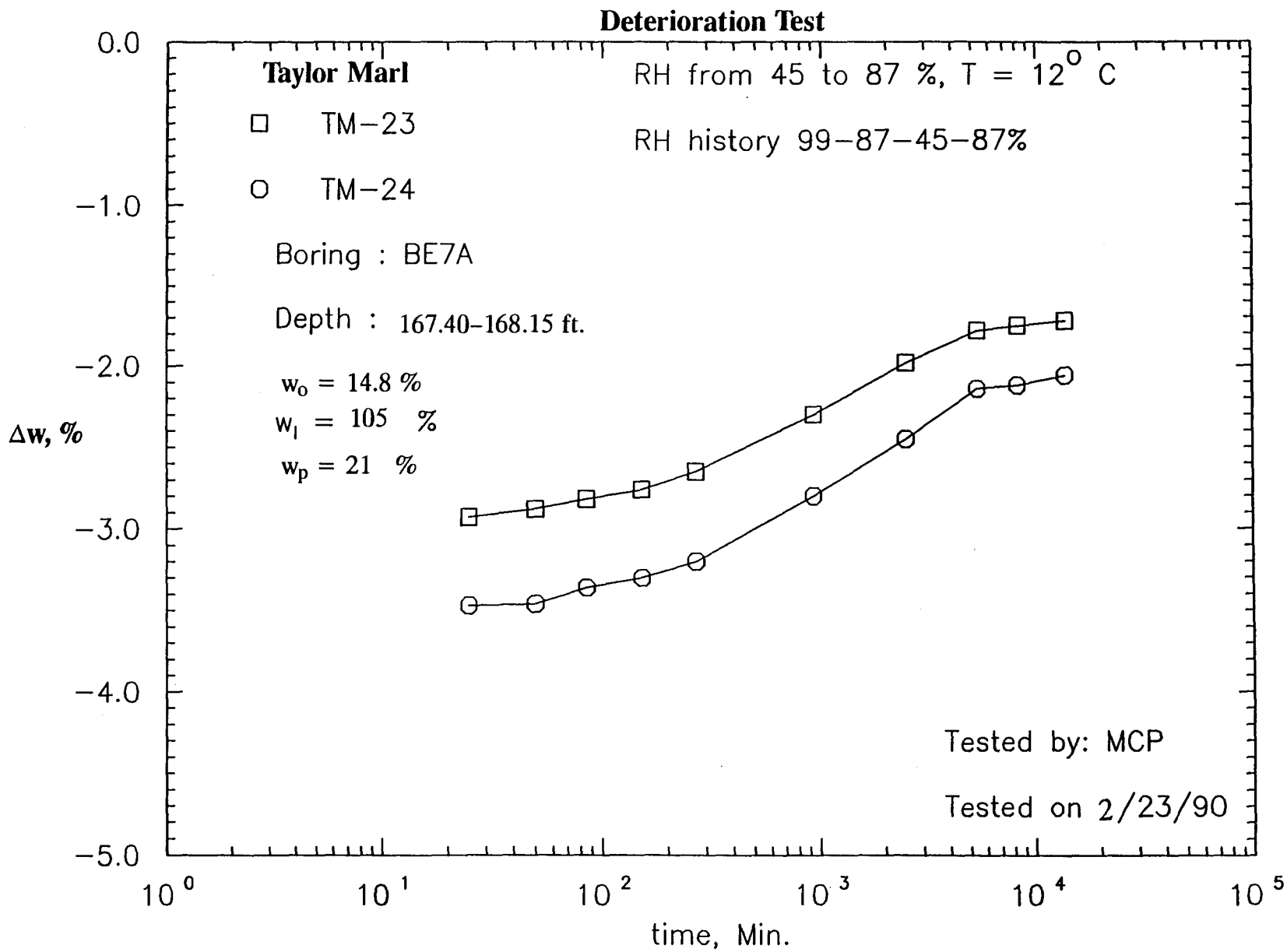


Fig. D26d Water Content Change – Log time Relationship

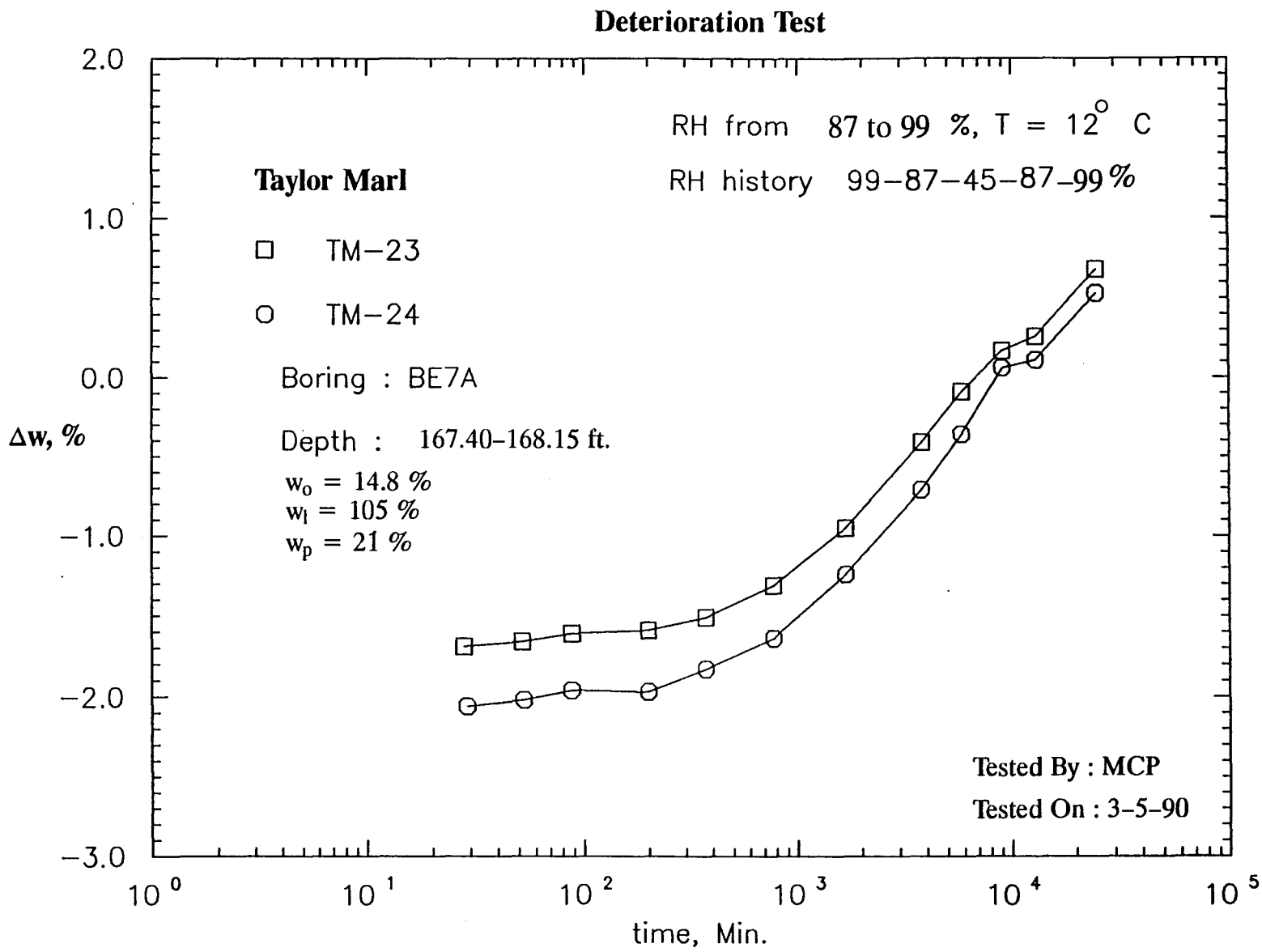


Fig. D26e Water Content Change – Log time Relationship

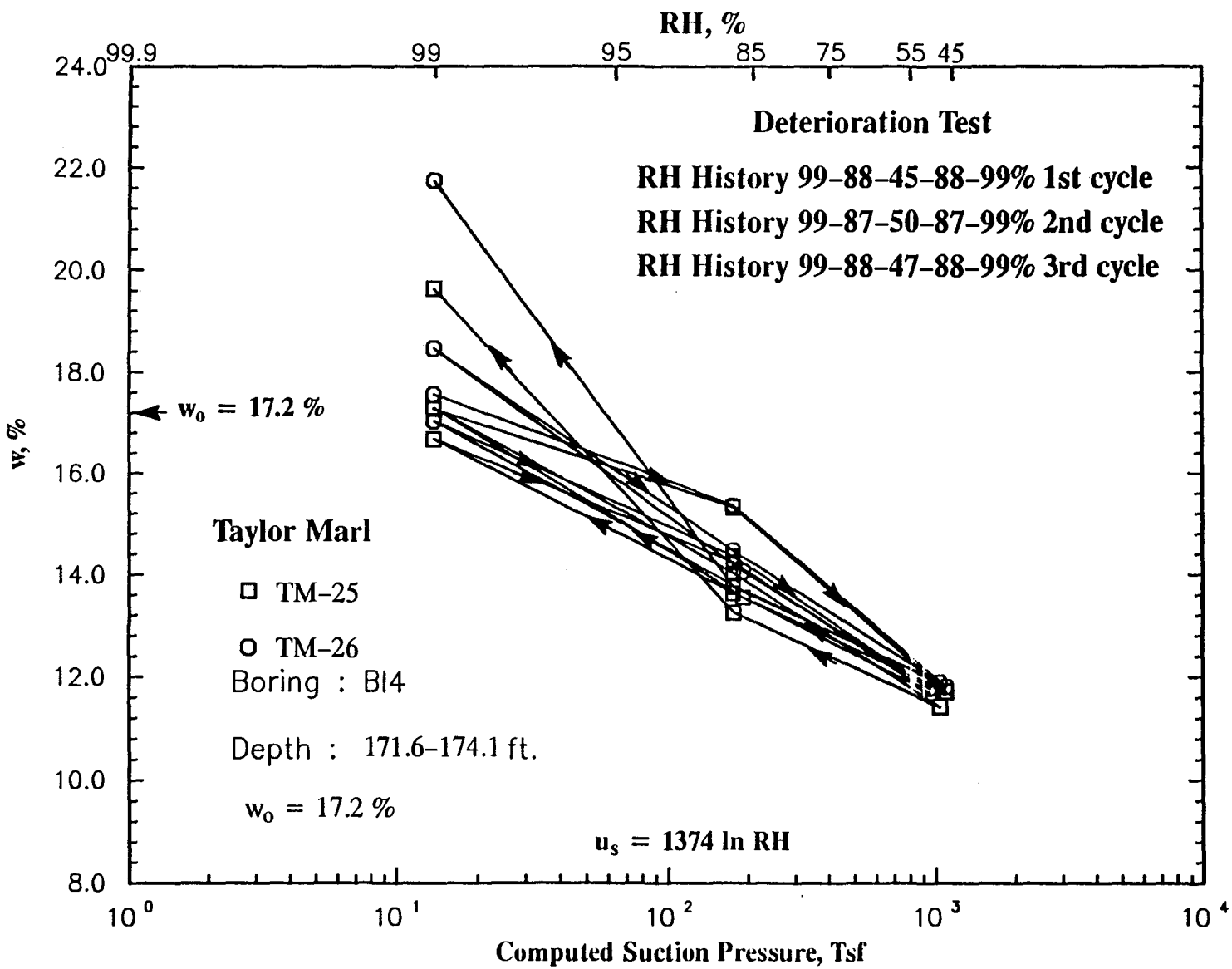


Fig. D27 Water Content – Relative Humidity Relationship

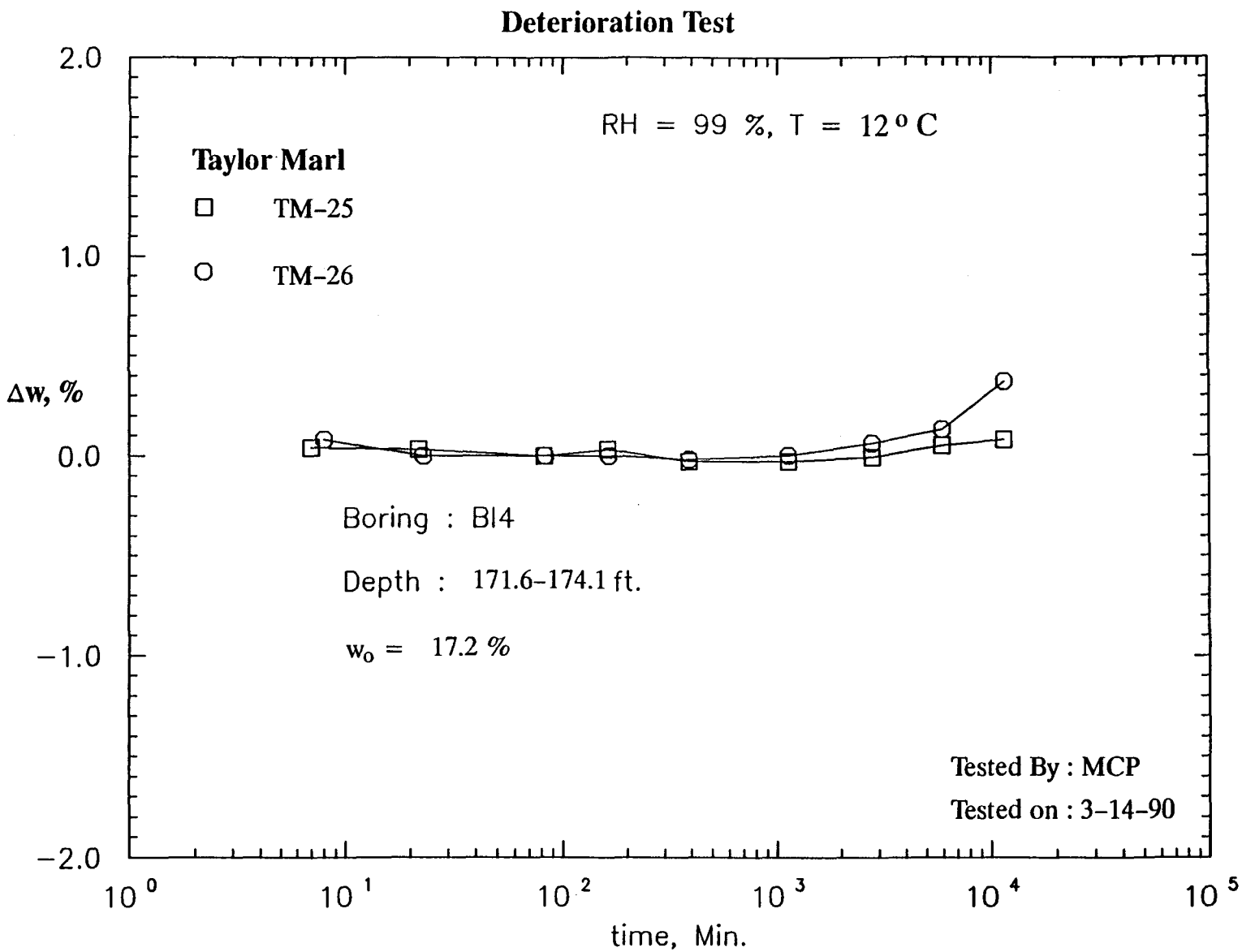


Fig. D27a Water Content Change – Log time Relationship

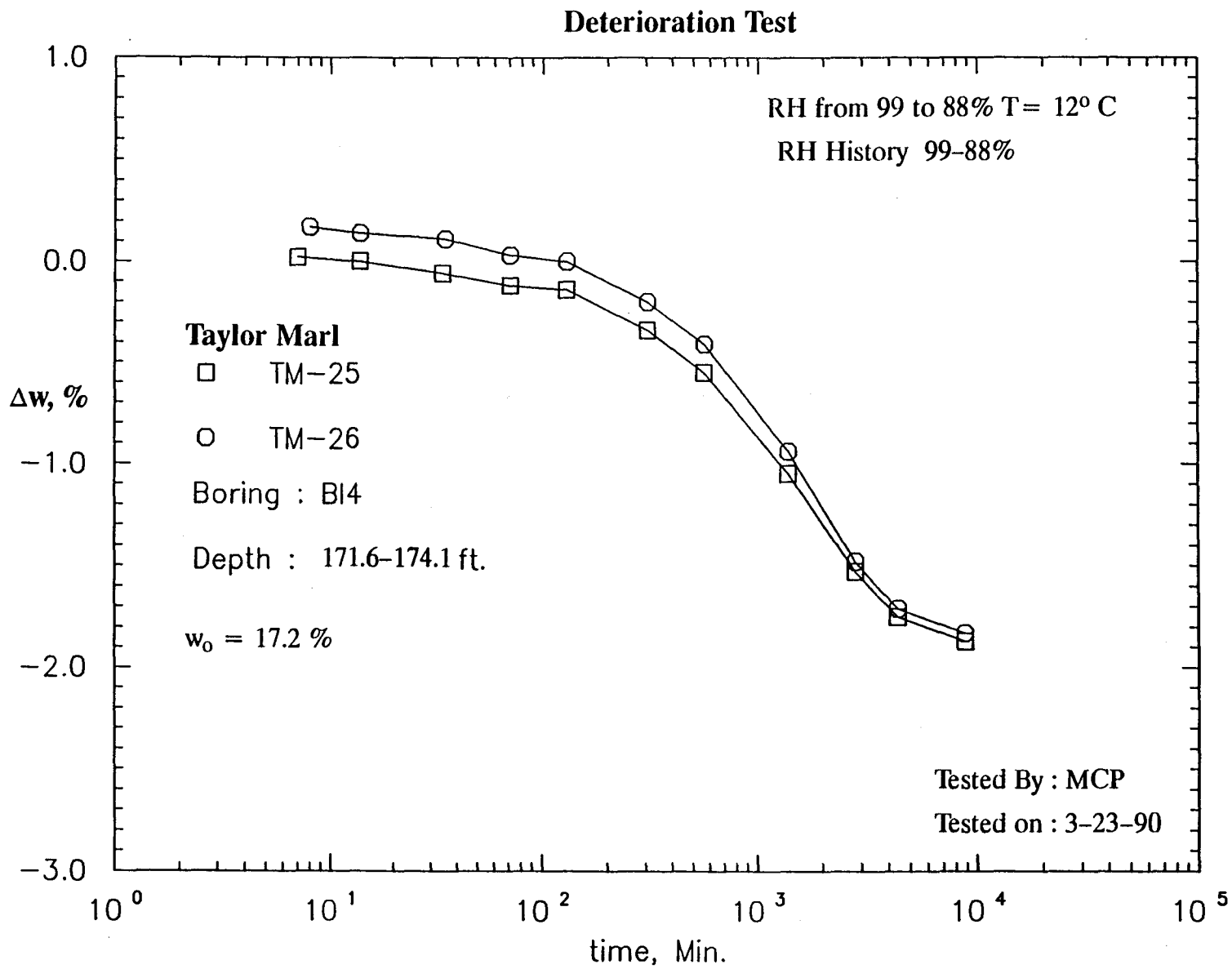


Fig. D27b Water Content Change - Log time Relationship

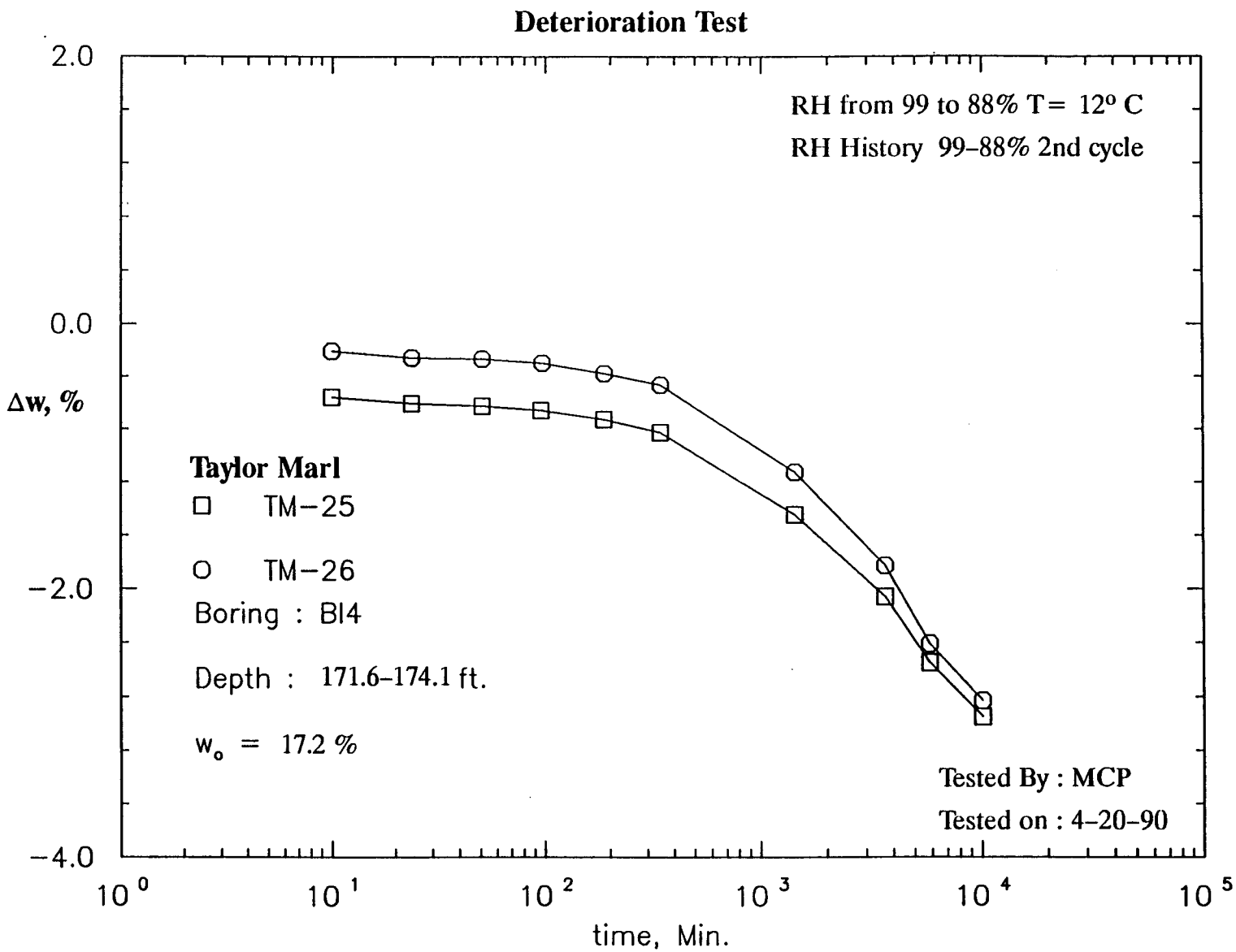


Fig. D27c Water Content Change – Log time Relationship

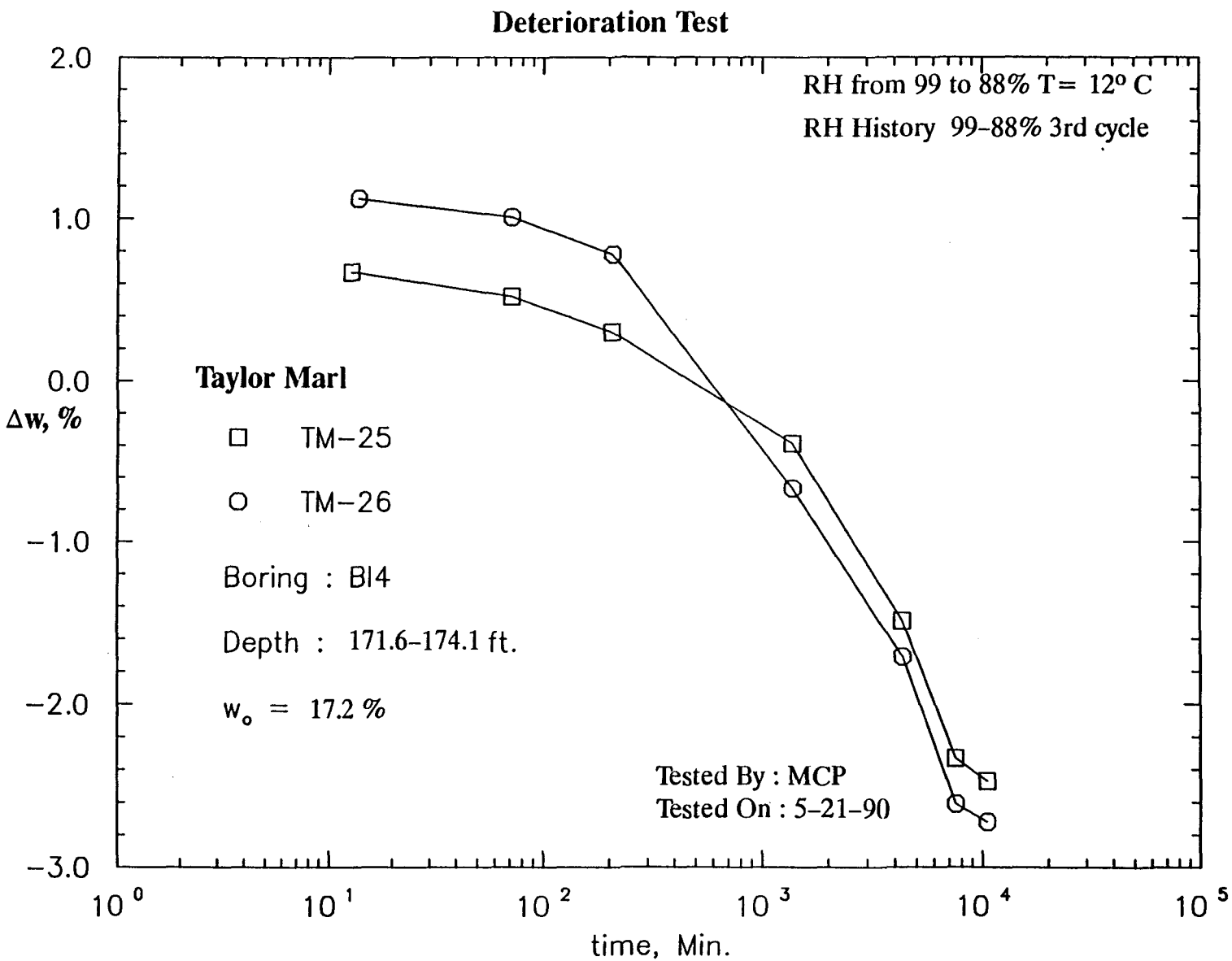


Fig. D27d Water Content Change - Log time Relationship

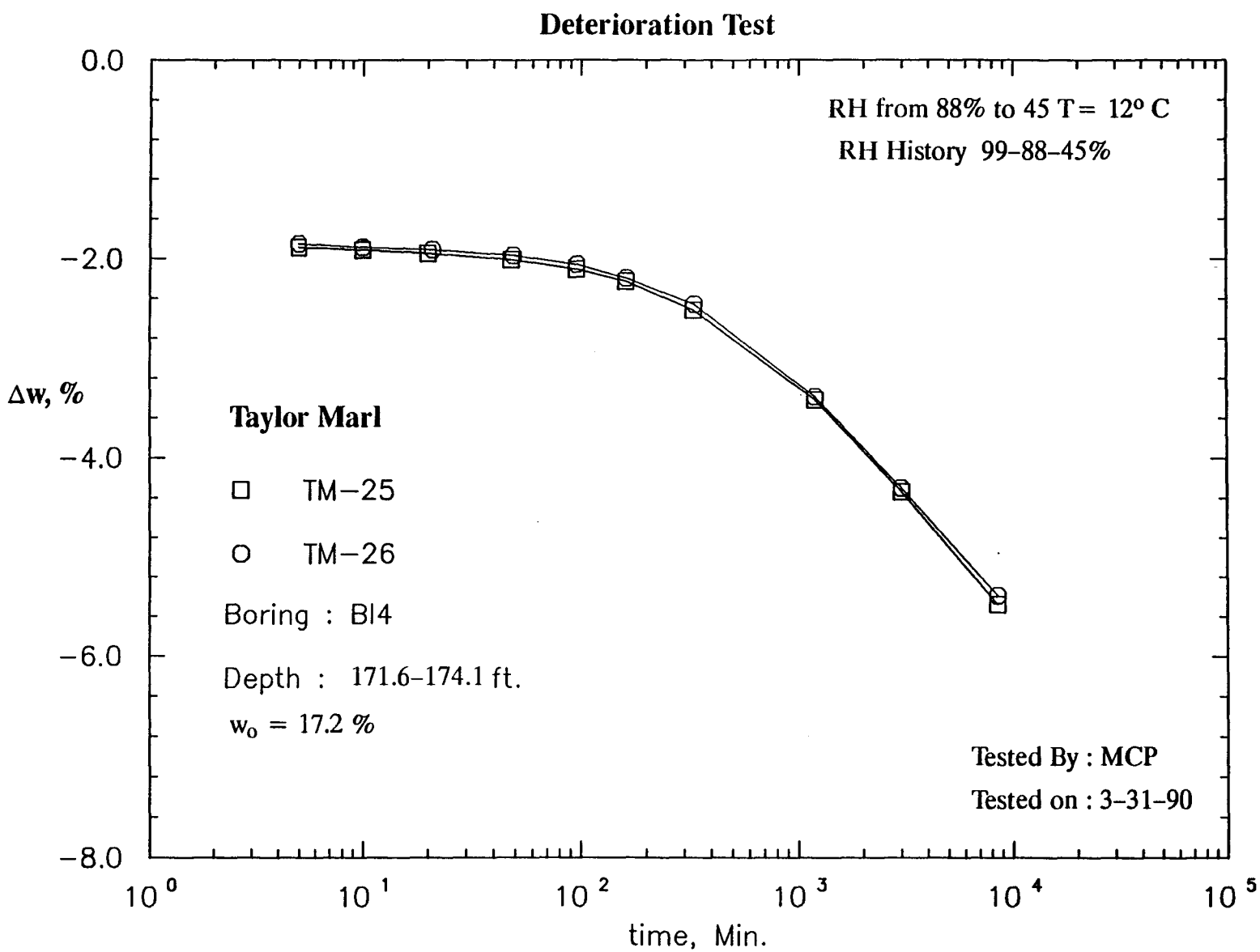


Fig. D27e Water Content Change – Log time Relationship

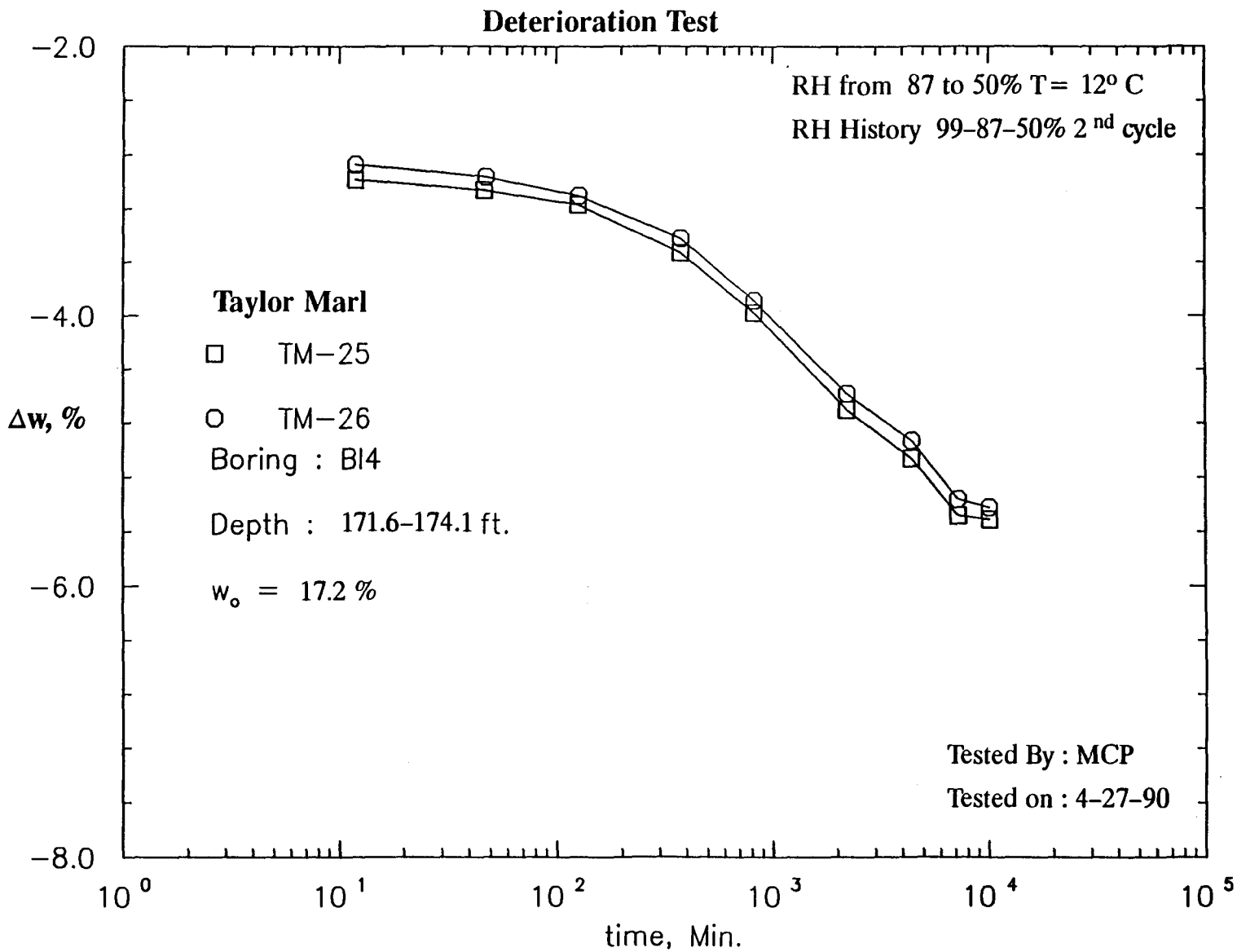


Fig. D27f Water Content Change – Log time Relationship

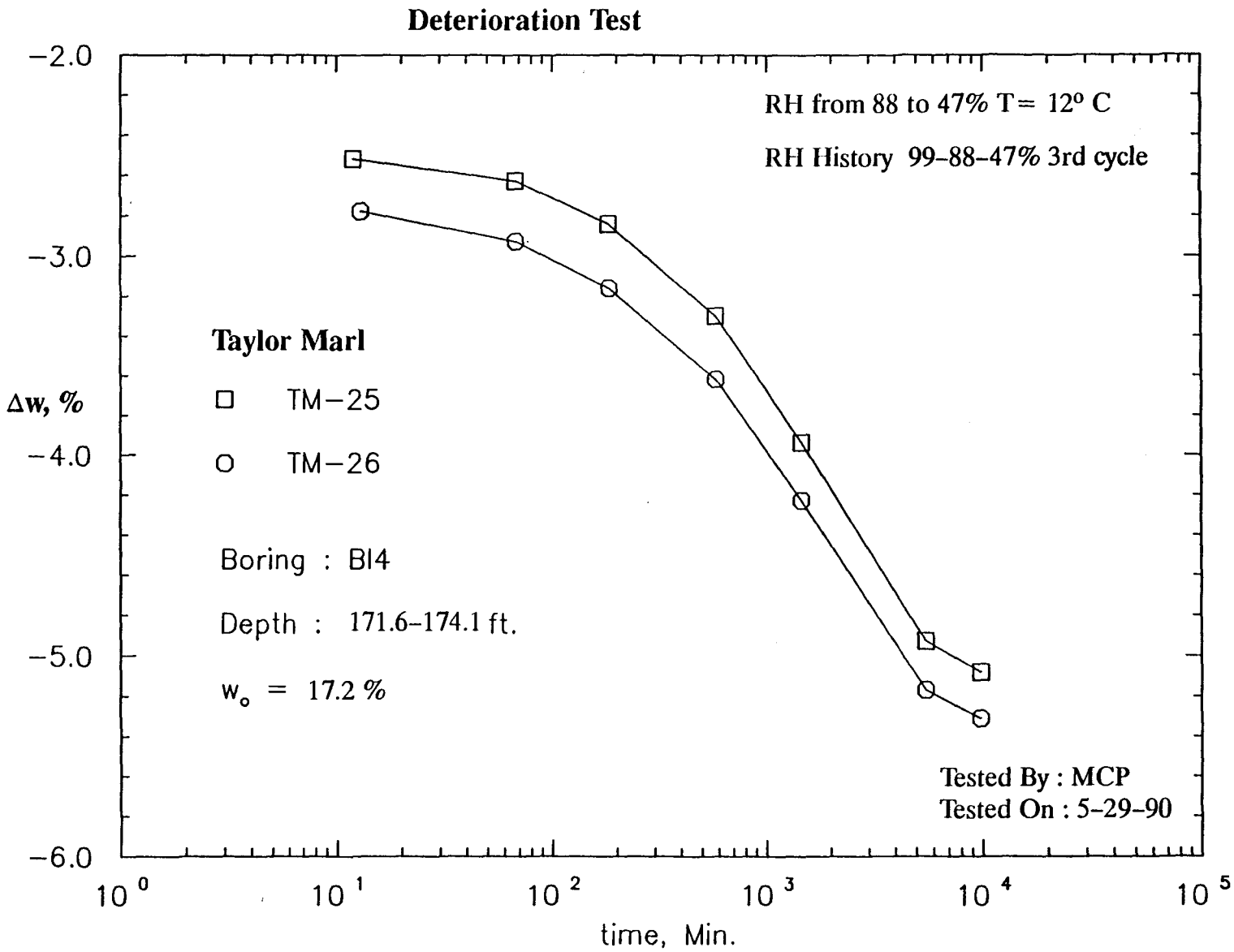


Fig. D27g Water Content Change - Log time Relationship

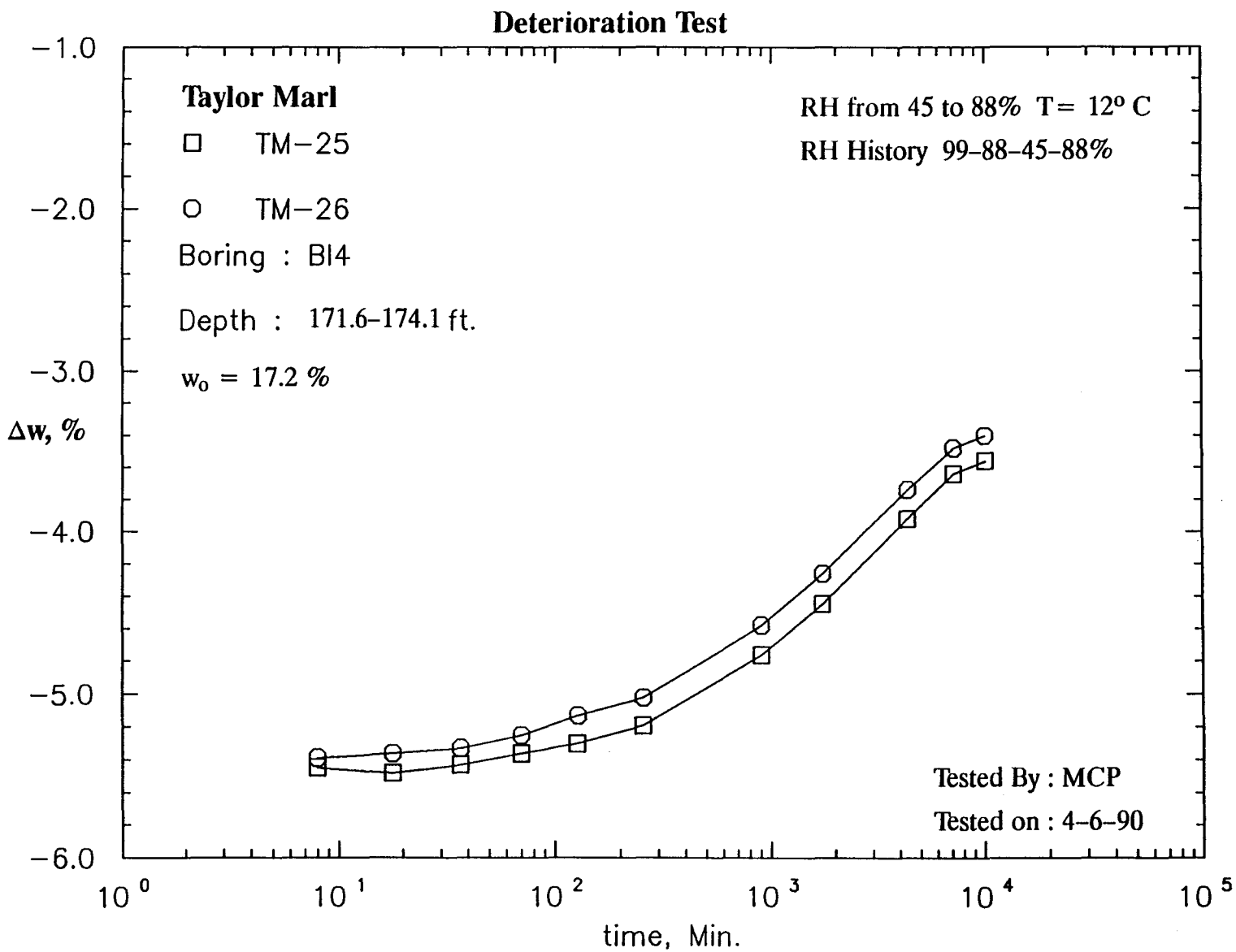


Fig. D27h Water Content Change – Log time Relationship

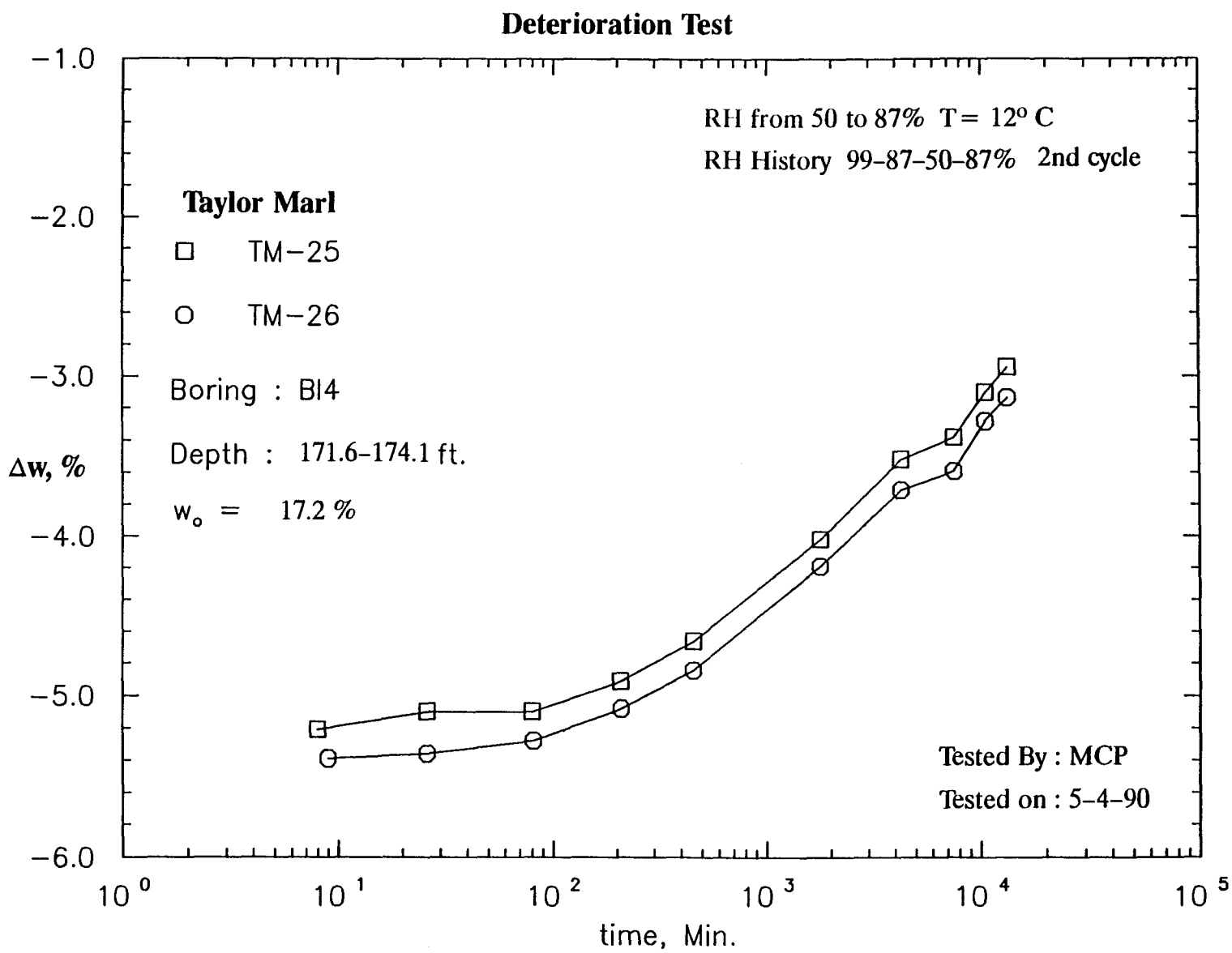


Fig. D27i Water Content Change - Log time Relationship

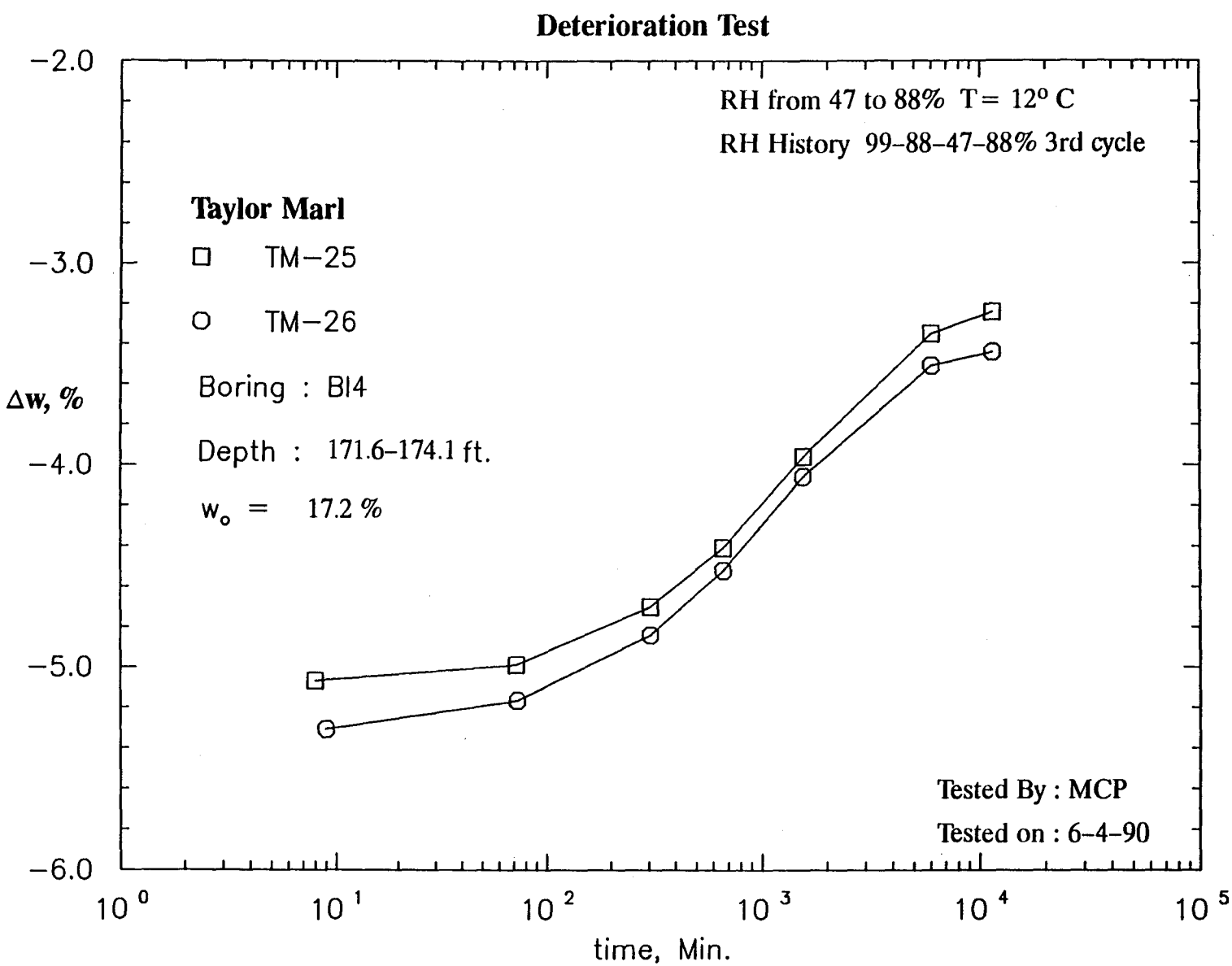


Fig. D27j Water Content Change – Log time Relationship

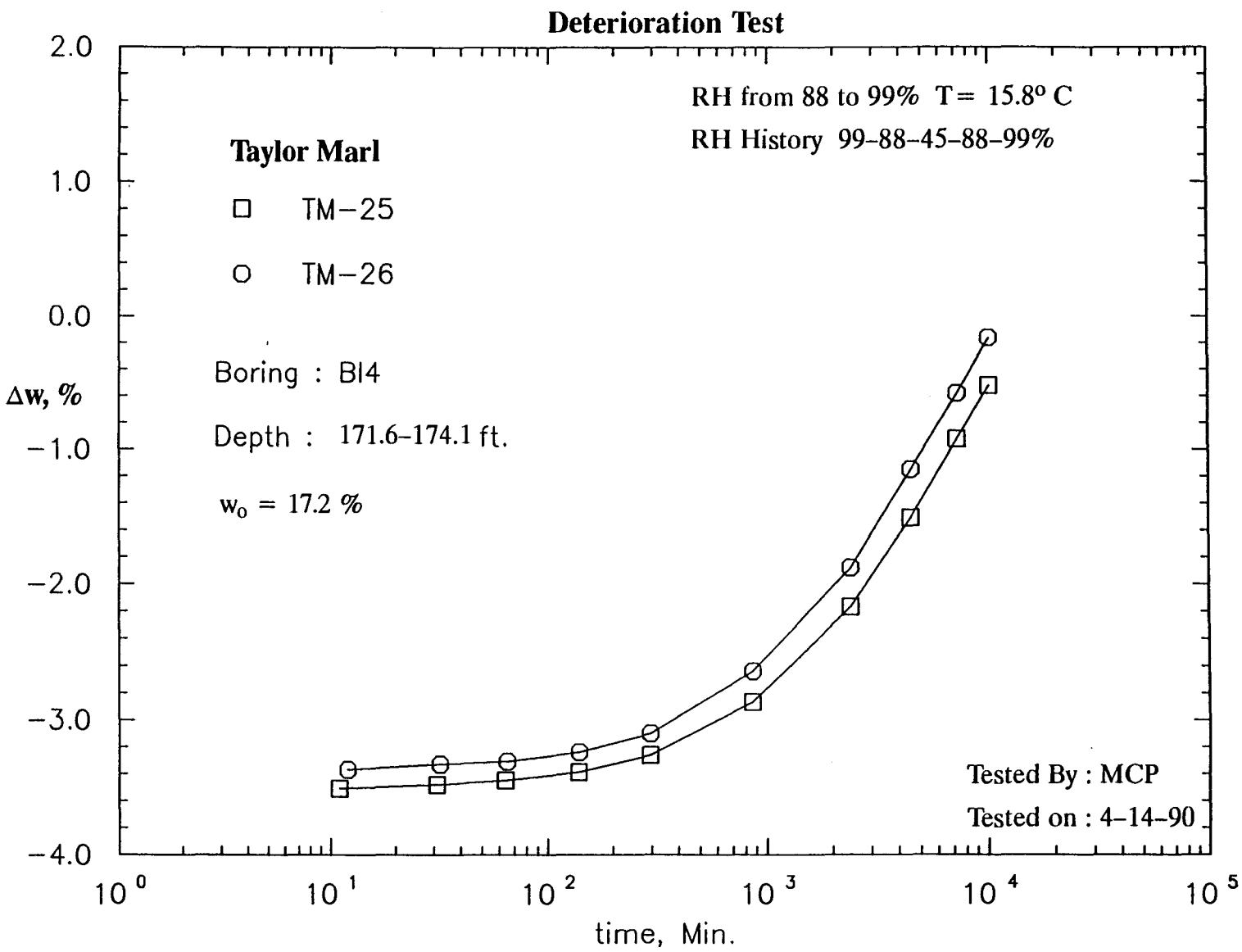


Fig. D27k Water Content Change – Log time Relationship

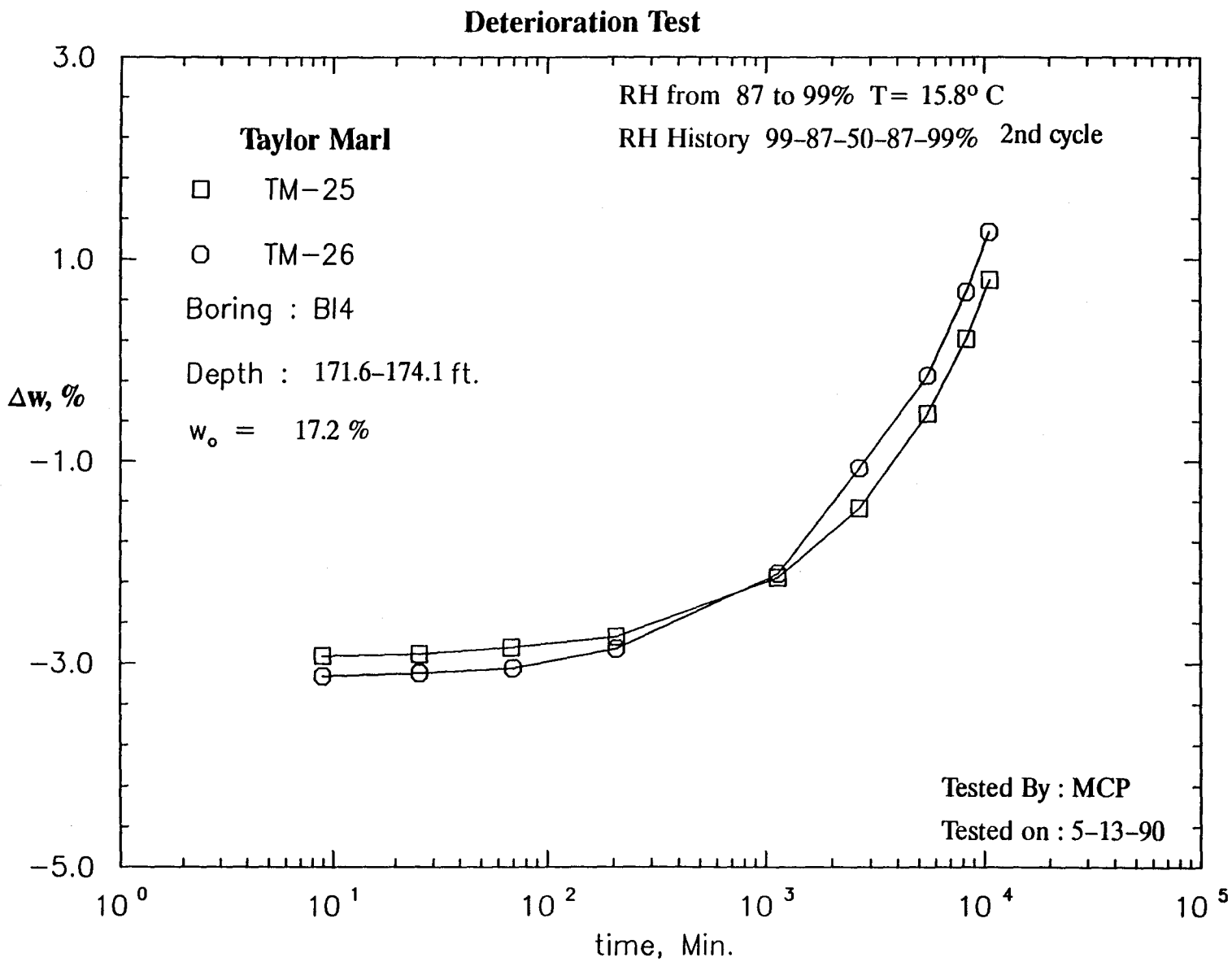


Fig. D27l Water Content Change - Log time Relationship

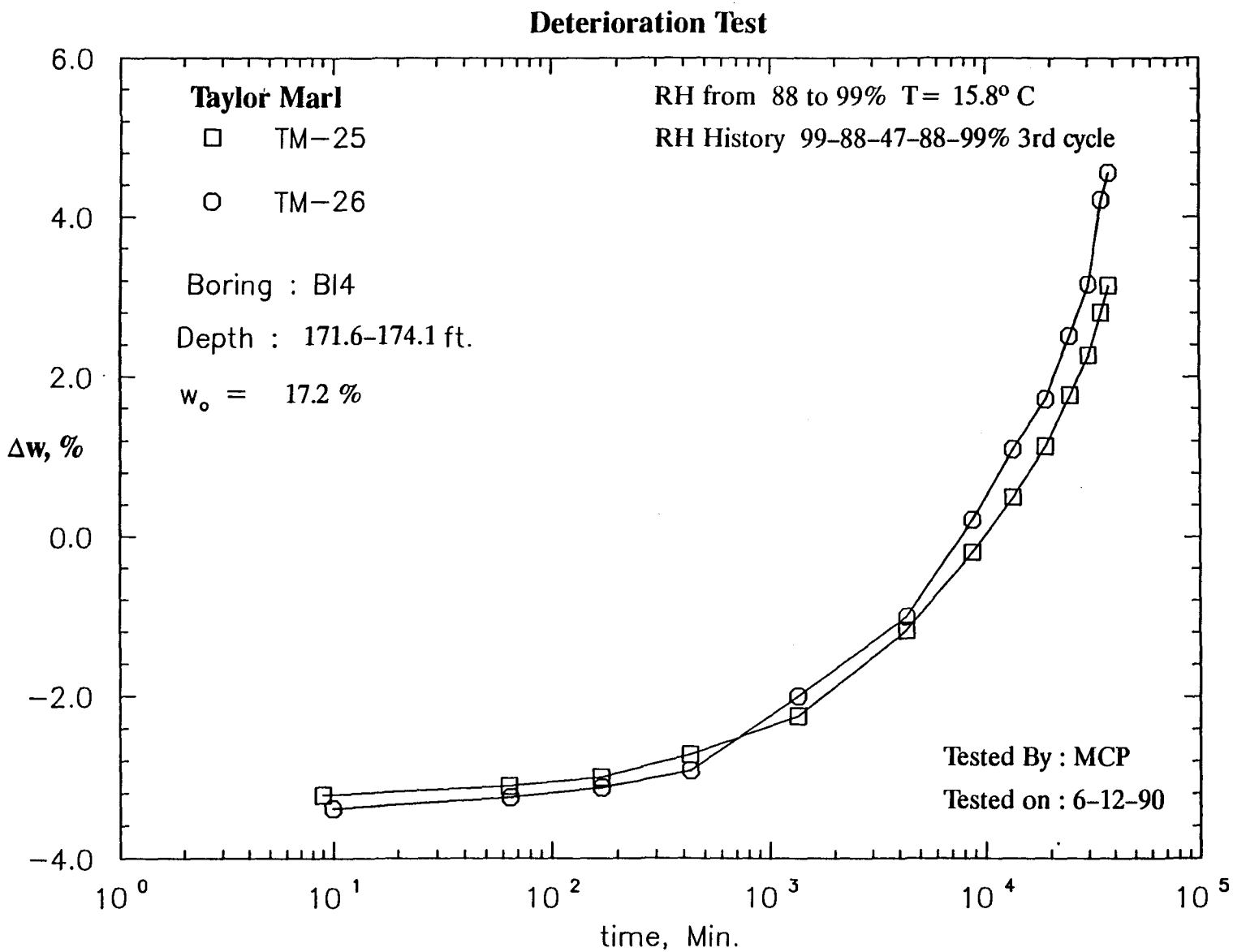


Fig. D27m Water Content Change – Log time Relationship

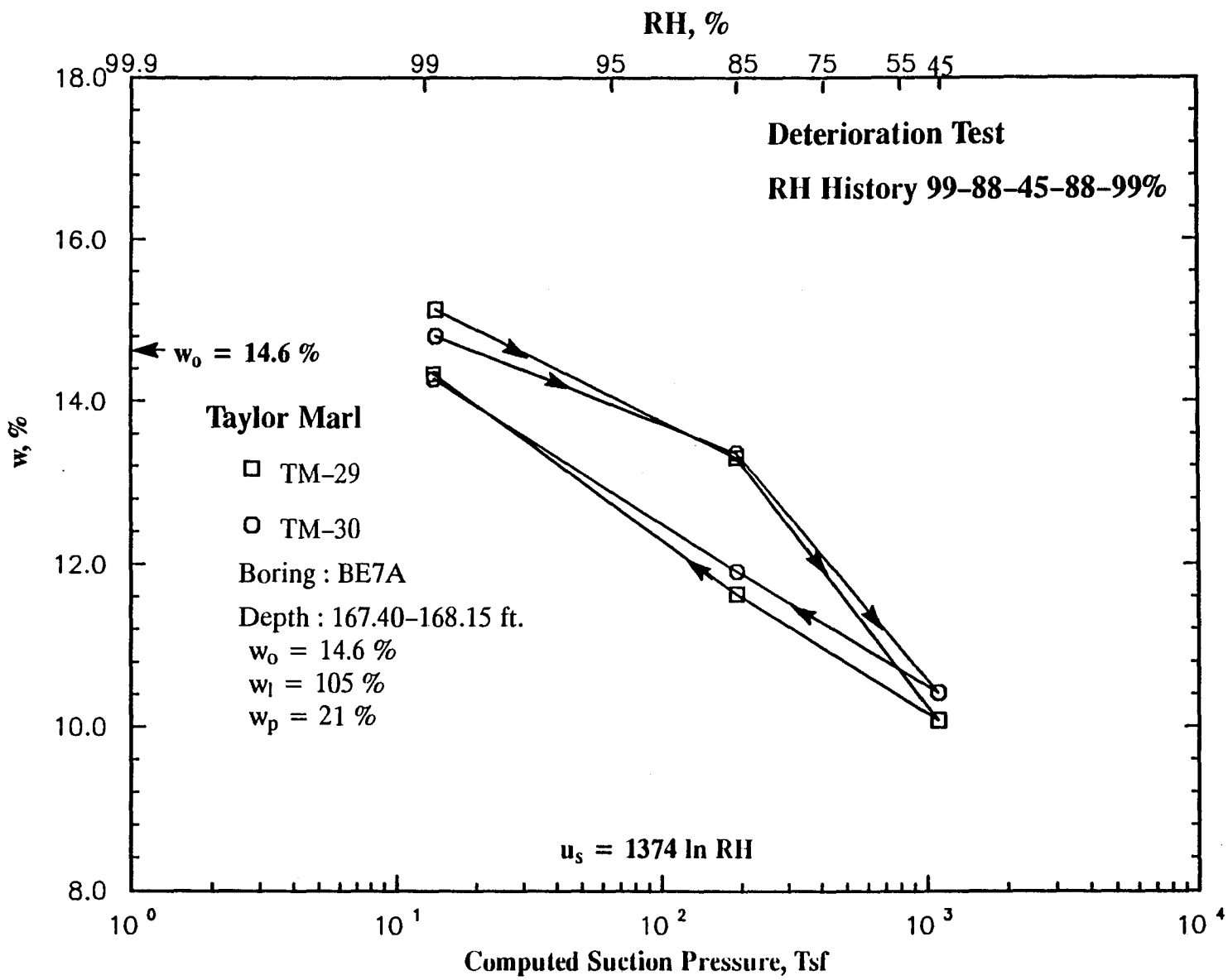


Fig. D28 Water Content – Relative Humidity Relationship

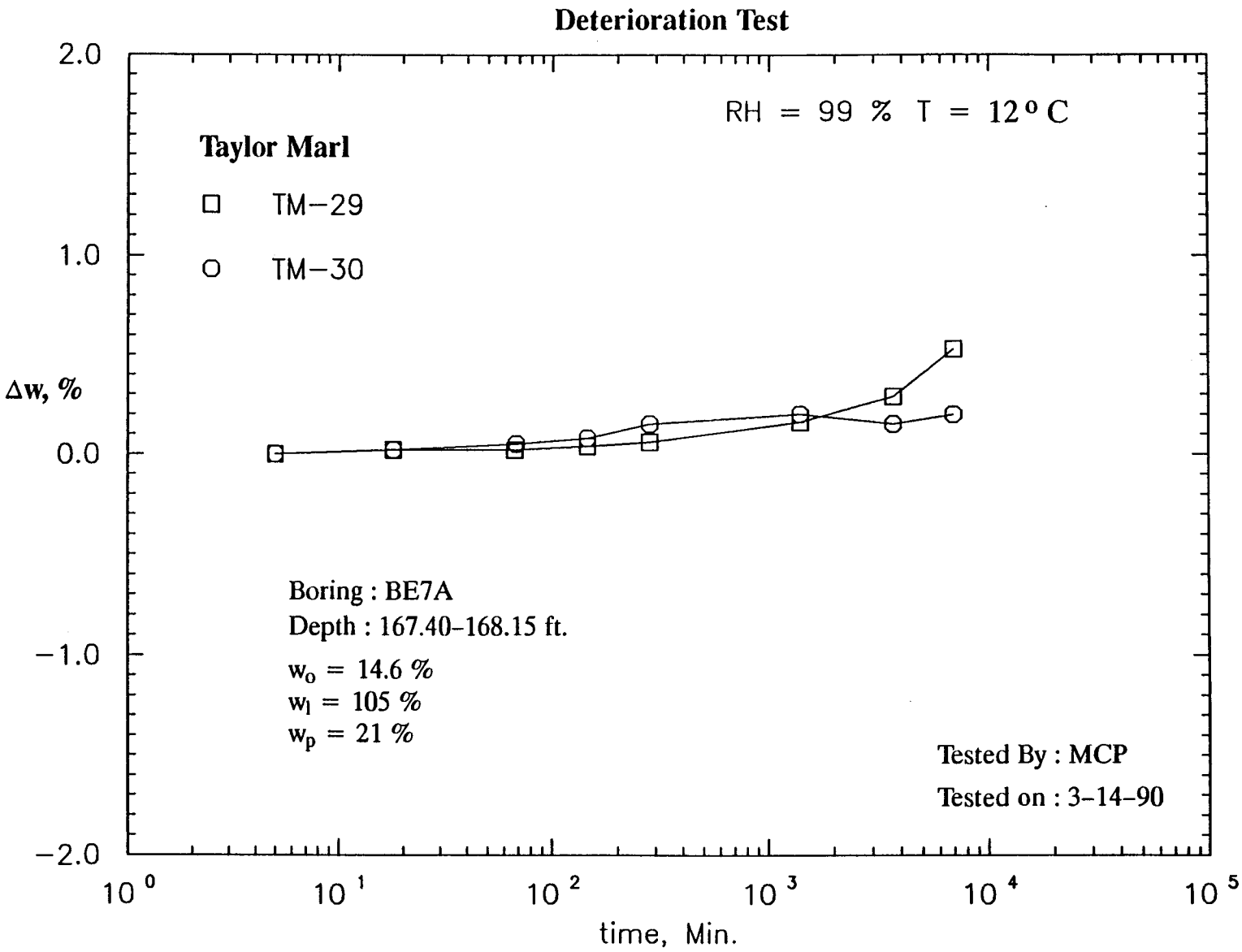


Fig. D28a Water Content Change – Log time Relationship

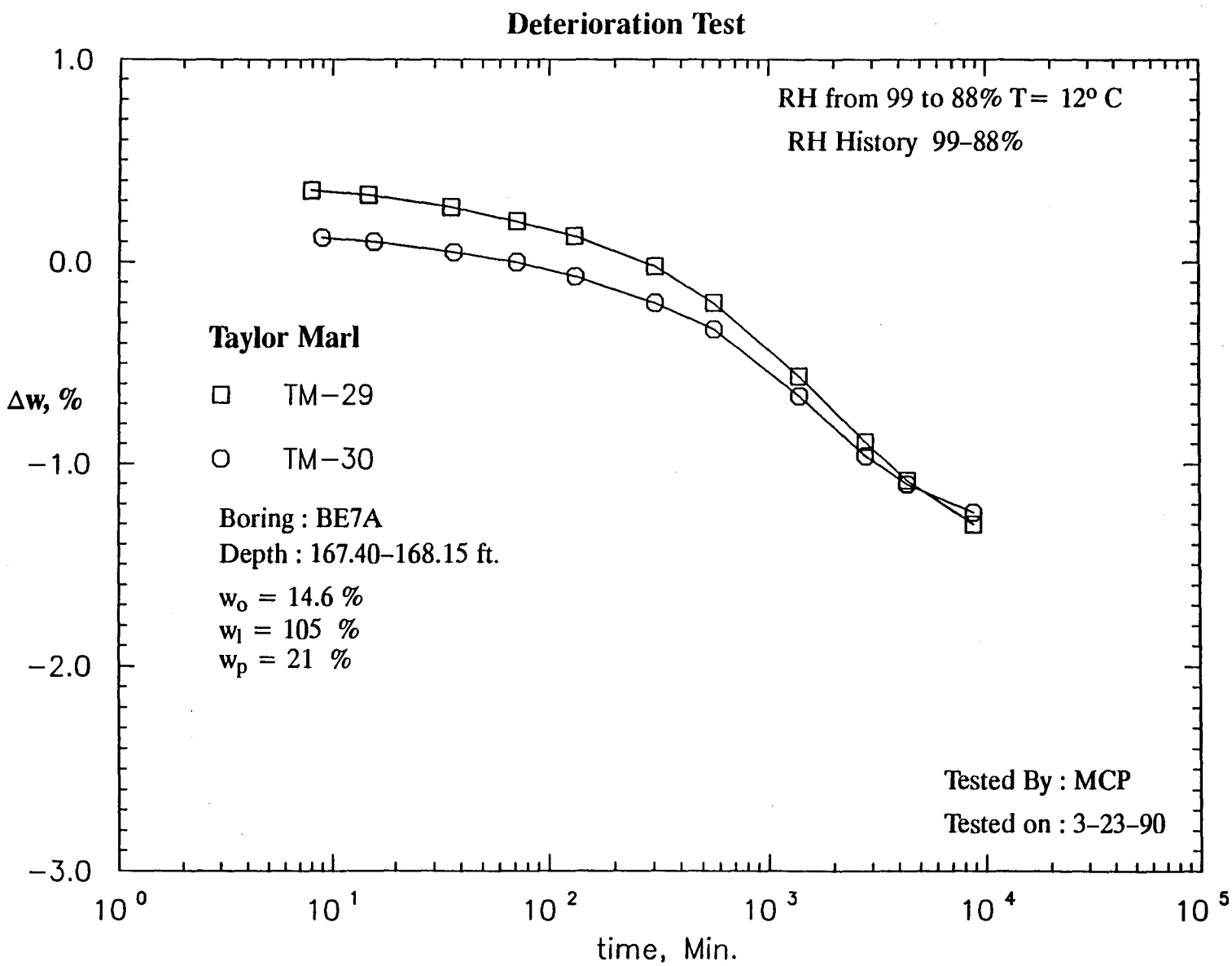


Fig. D28b Water Content Change - Log time Relationship

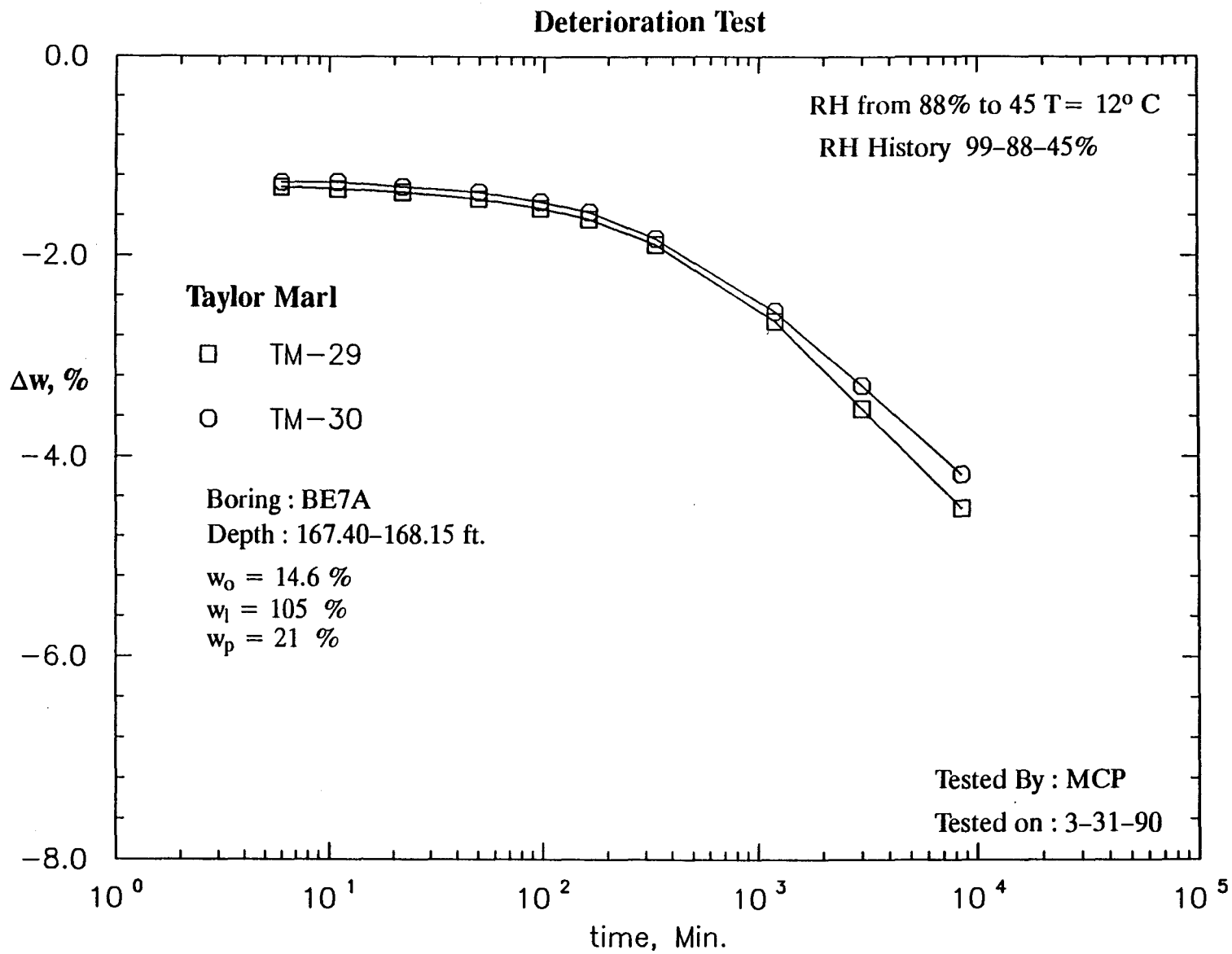


Fig. D28c Water Content Change – Log time Relationship

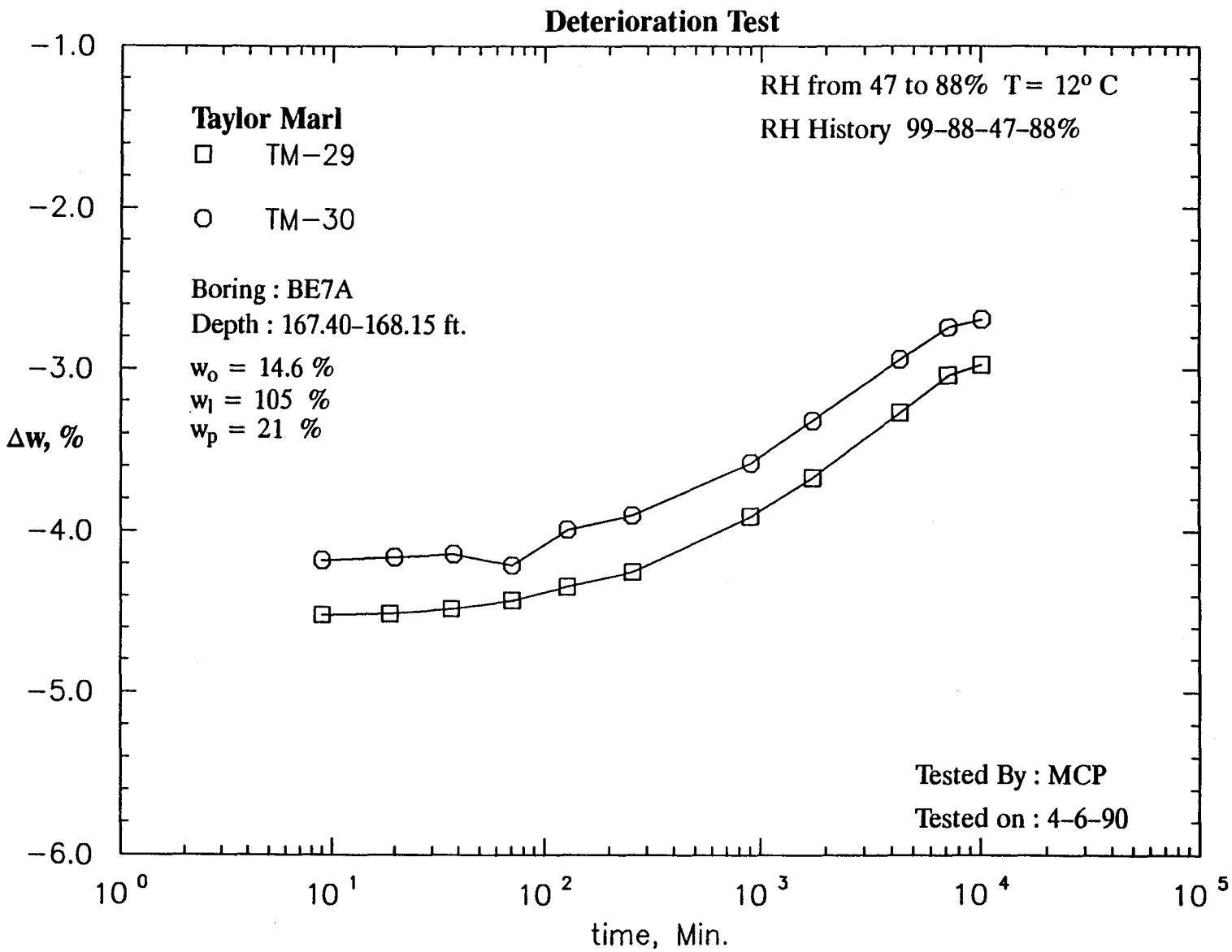


Fig. D28d Water Content Change - Log time Relationship

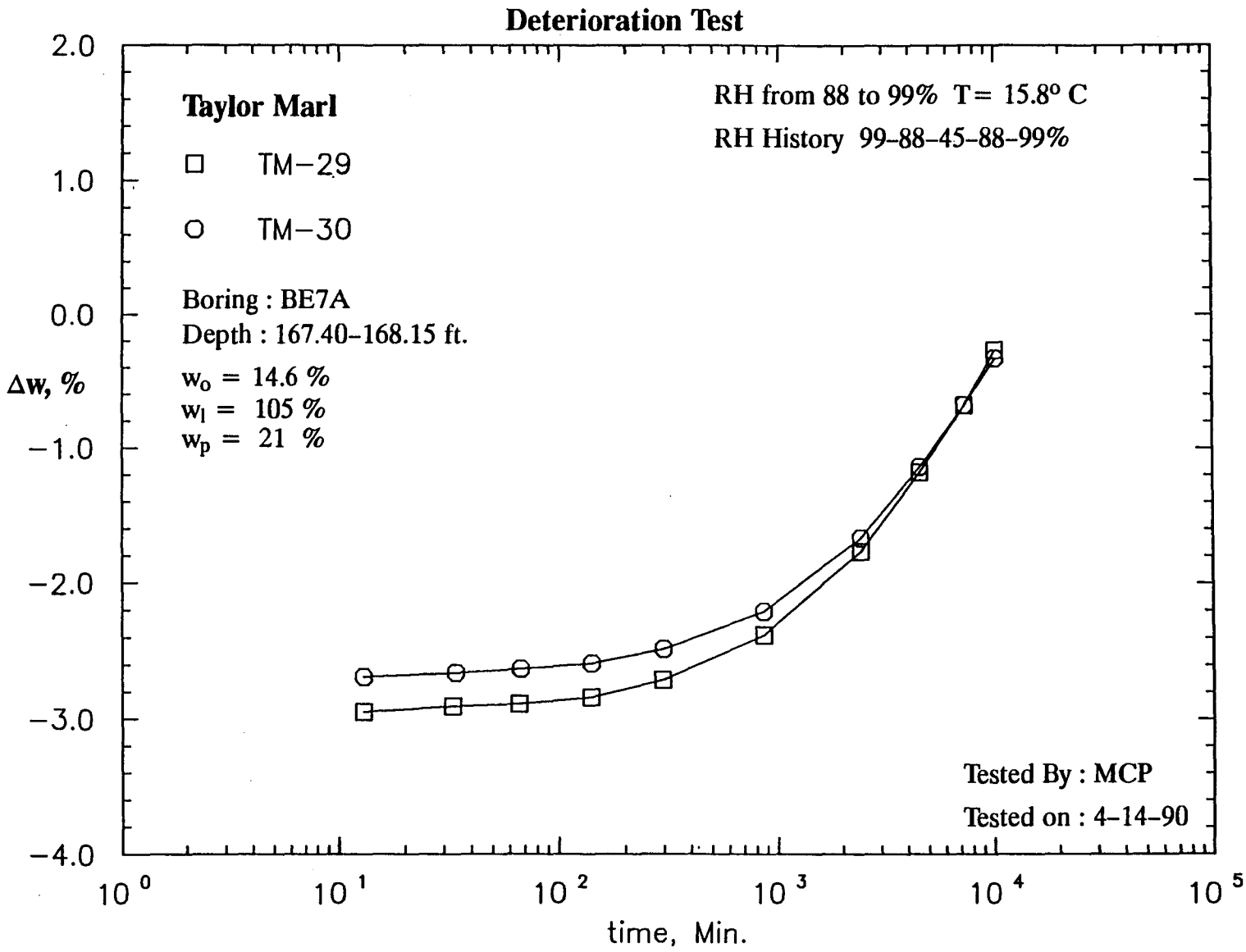


Fig. D28e Water Content Change – Log time Relationship

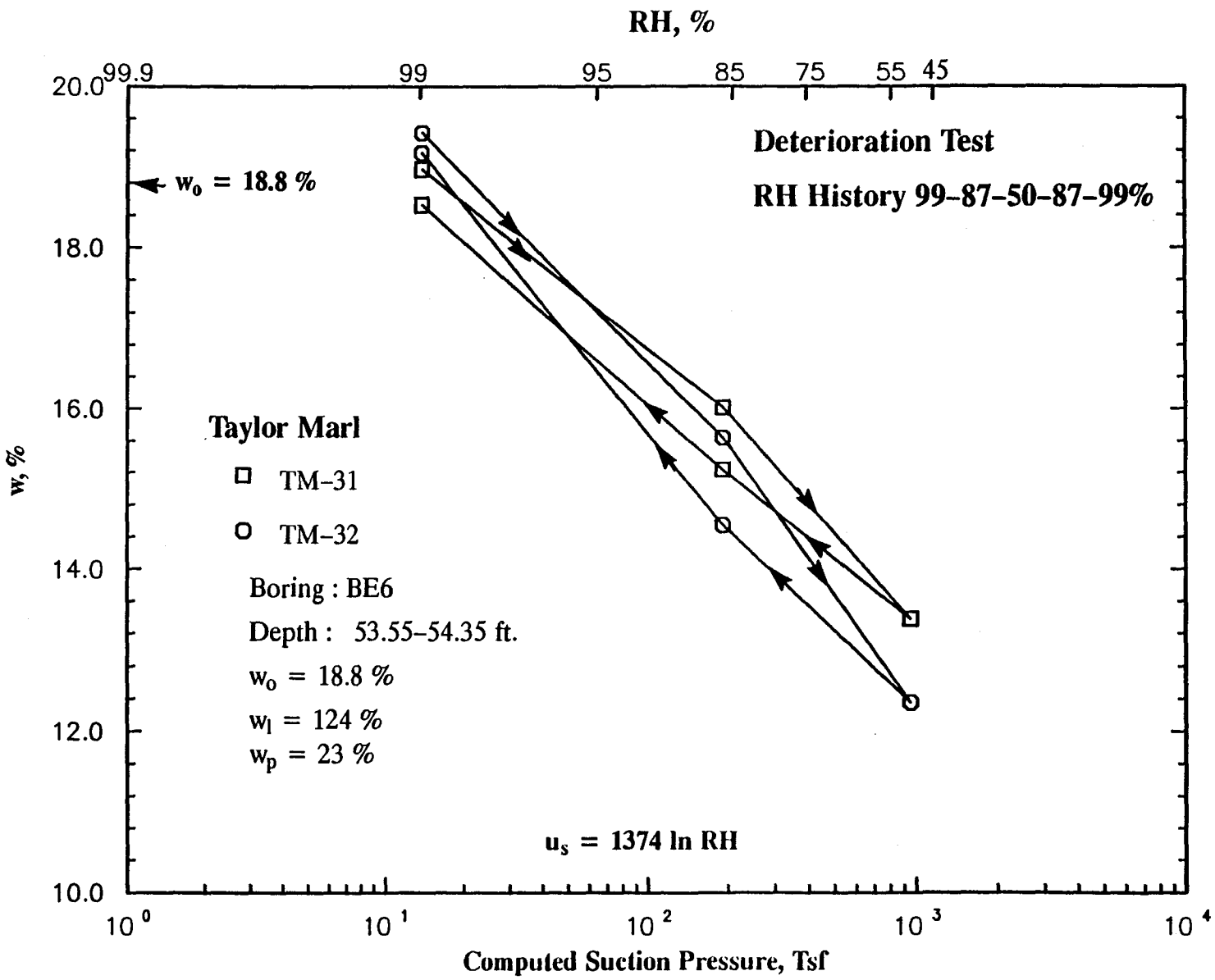


Fig. D29 Water Content – Relative Humidity Relationship

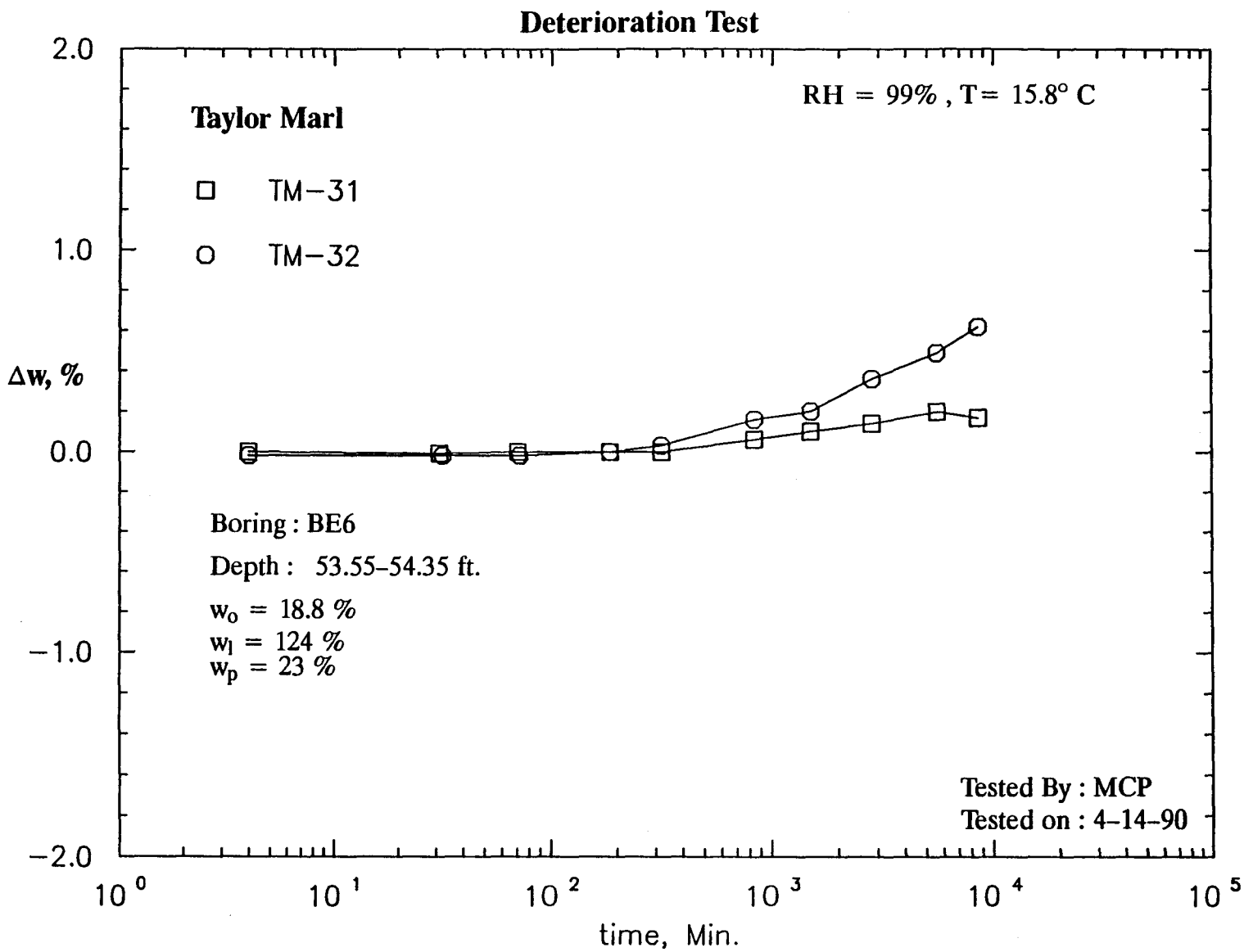


Fig. D29a Water Content Change – Log time Relationship

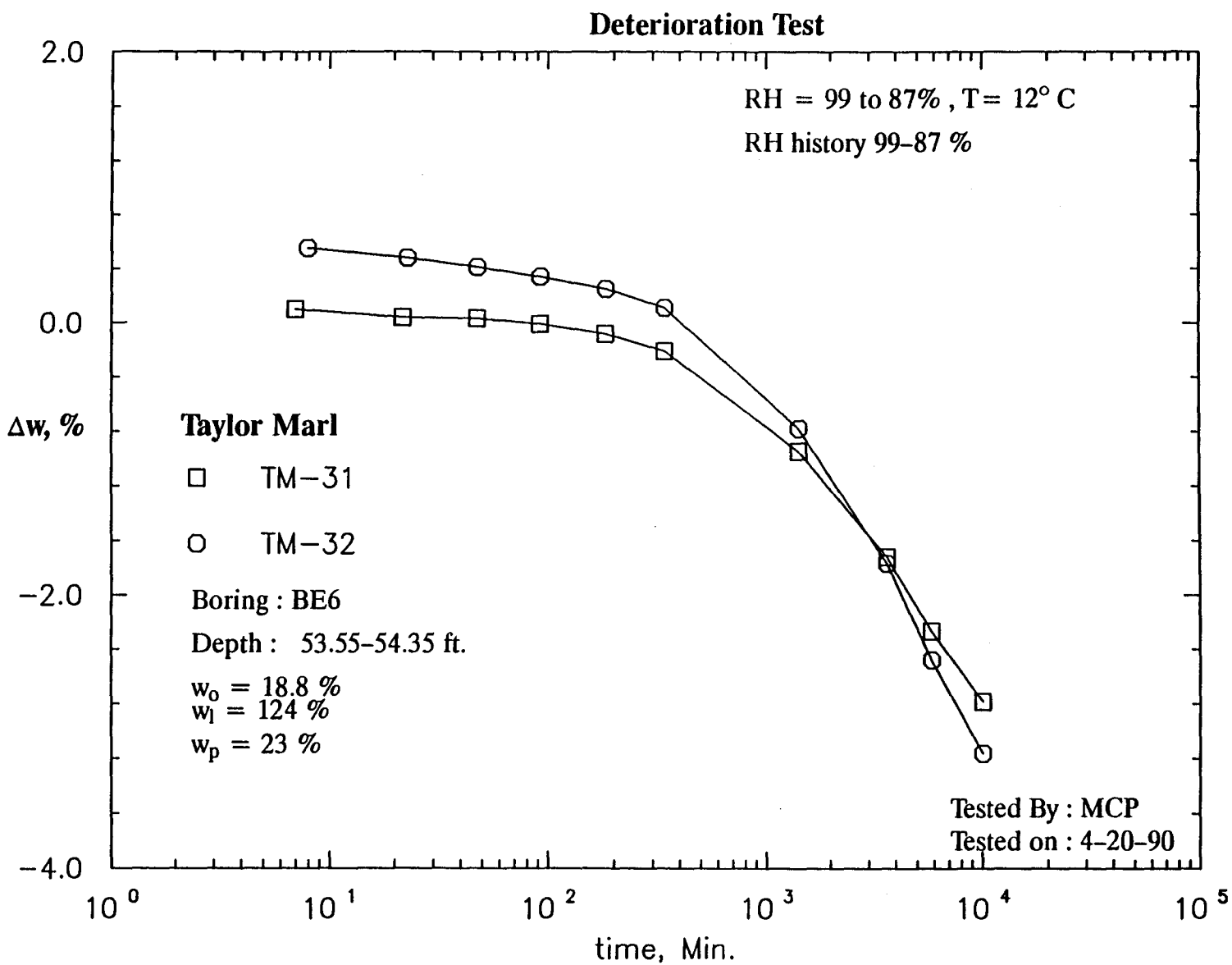


Fig. D29b Water Content Change – Log time Relationship

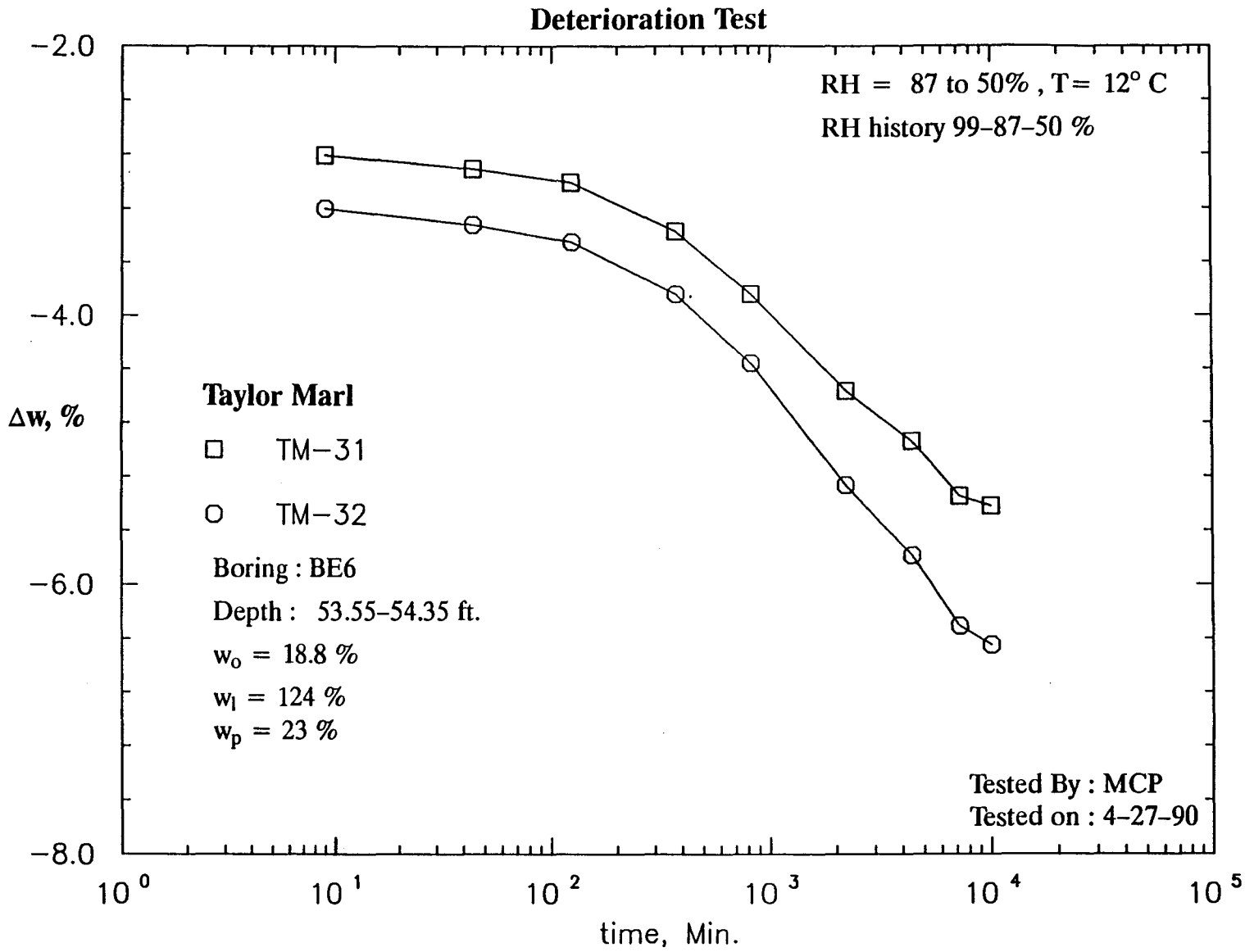


Fig. D29c Water Content Change – Log time Relationship

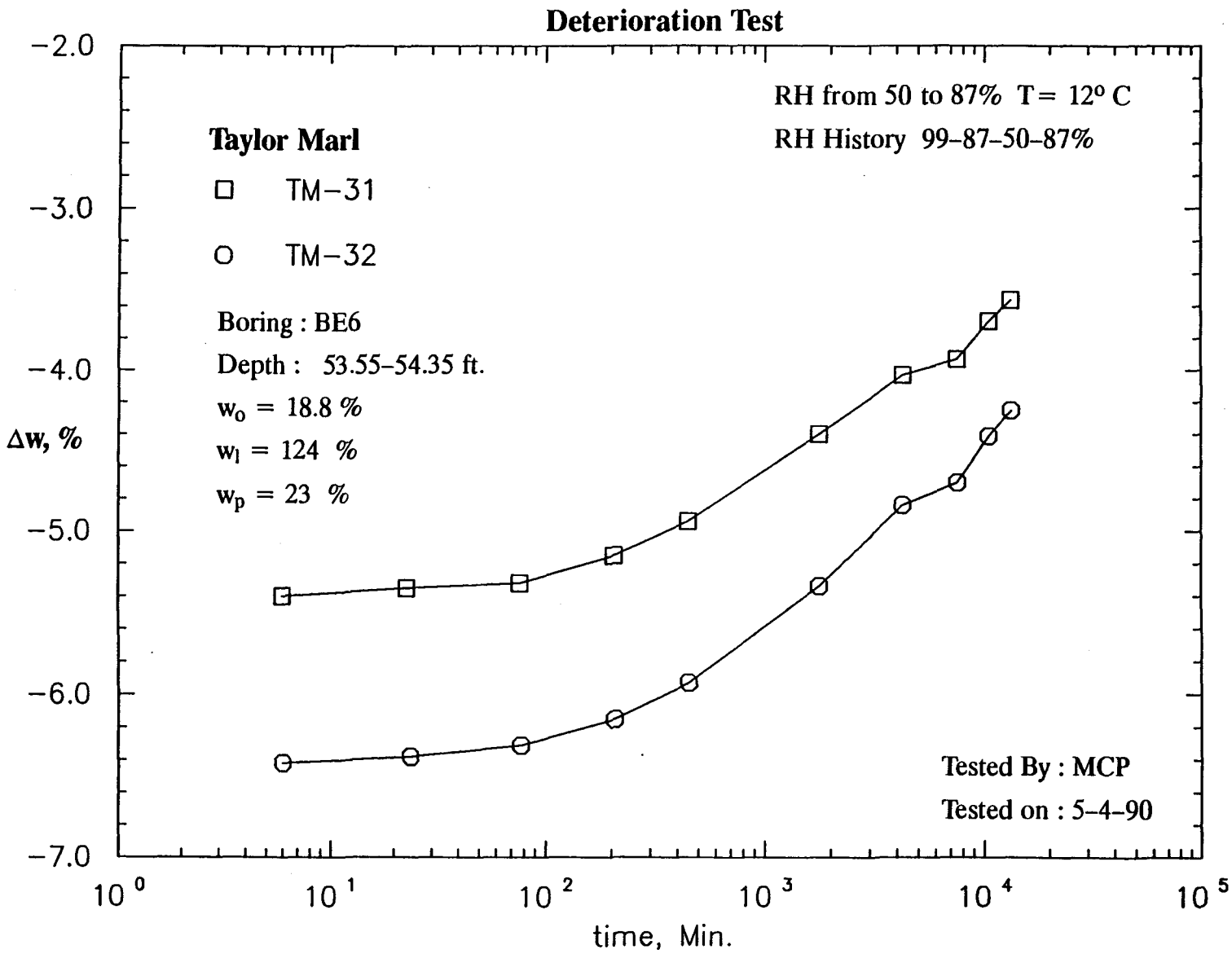


Fig. D29d Water Content Change – Log time Relationship

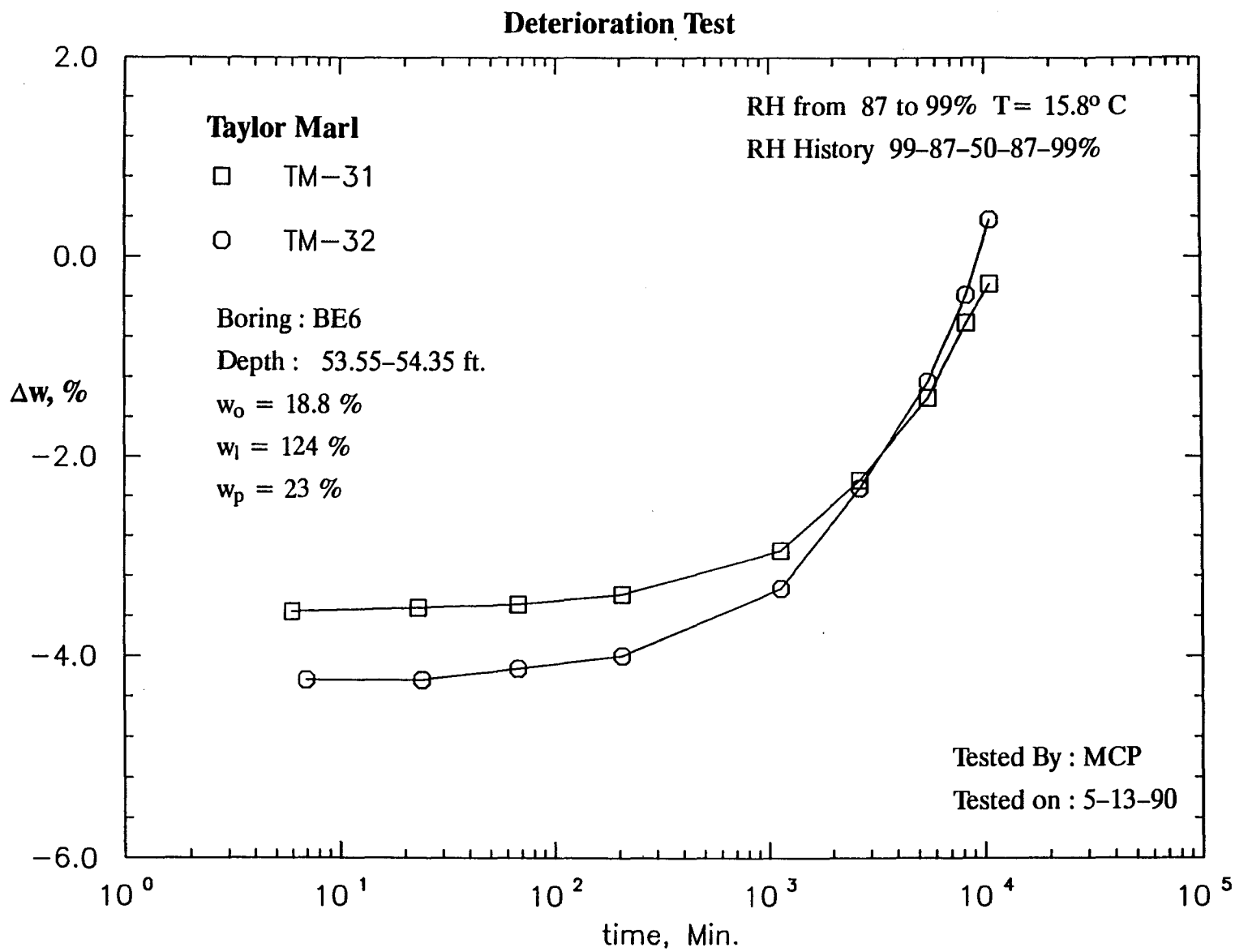


Fig. D29e Water Content Change – Log time Relationship