PUBLICATION NO. 01-033-077
01-041-077

PHOSPHOGYPSUM FOR SECONDARY ROAD CONSTRUCTION

PREPARED BY

UNIVERSITY OF MIAMI

UNDER A GRANT SPONSORED BY THE

FLORIDA INSTITUTE OF PHOSPHATE RESEARCH

BARTOW, FLORIDA

JUNE, 1989

FLORIDA INSTITUTE OF PHOSPHATE RESEARCH

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PHOSPHOGYPSUM FOR SECONDARY ROAD CONSTRUCTION

FINAL REPORT

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PERSPECTIVE

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At a time when the newspapers, radio and television seem to report almost daily that Florida faces a transportation crisis unless a greatly expanded road building and maintenance program is adopted, it is refreshing to find that it is possible to reduce the cost of some road building projects by utilizing an abundant, readily available raw material, phosphogypsum.

The question of structural properties of phosphogypsum has been fully resolved by well-documented construction projects in both Texas and Florida. Texas has taken the lead in this area and a phosphogypsum road base industry has become a reality. Recent activity in Florida has been limited to the two experimental roads described in this report.

While FIPR has taken the position that phosphogypsum can be used for road construction without adverse environmental results, a major portion of this document is devoted to reporting the results of an environmental testing program that has, to date, justified FIPR confidence that this material can be safely used in roads. The environmental testing program will be continued for at least two more years to insure that data sufficient to satisfy the most rigorous scientific review is obtained.

Phosphogypsum in roads cannot be considered the ultimate means of reducing the cost of road building in Florida, but it can have a major economic impact on road building in the counties near enough to the phosphogypsum supply that the cost of transportation to the construction site does not become excessive.

The future for phosphogypsum road building is bright and the fact that a material that was once considered as a waste can be converted into a valuable construction material should encourage all those working in this area.

ACKNOWLEDGEMENTS

The project is funded by two grants from the Florida Institute of Phosphate Research, Bartow, Florida.

The design, monitoring and testing of the roads were conducted by the University of Miami and Bureau of Materials & Research, the Florida Department of Transportation.

The Polk County and Columbia County experimental roads were constructed by the Departments of Public Works of the respective counties.

Environmental monitoring was conducted by the University of Miami in cooperation with the Florida Department of Environmental Regulation and the Florida Department of Health and Rehabilitative Services.

DISCLAIMER

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INTRODUCTION

Phosphogypsum is a by-product of the phosphate fertilizer industry. Its main constituent is calcium sulfate dihydrate. According to recent statistics, the phosphate industry in Central Florida annually produces 33 million tons of phosphogypsum and has over 500 million tons stockpiled. It is estimated that by the year 2000, Florida could accumulate over one billion tons of phosphogypsum. The continued accumulation of phosphogypsum has created urgent pressures to find useful applications for this by-product.

The population increase in Florida is one of the highest in the country. Each year many new roads and many existing roads have to be built and upgraded, respectively. However, traditional road building materials, such as limerock, shellrock, shell and clay are in short supply in many parts of Florida. Significant tonnages of aggregates used in road construction are now imported from foreign countries. The U. S. Bureau of Mines has forecasted that Florida will have to import all its aggregate by the year 2000. The lack of adequate sources of locally available rock materials has prompted William C. Kenley, County Engineer, Polk County, and Ronald W. Williams, County Commissioner, Columbia County, to take the initiative in finding alternate material for building roads.

The experimental projects are to provide alternate methods of rebuilding county and other secondary roads in Florida. It is intended to provide comparable or better material to repair or replace existing roads with the best possible utilization of locally available aggregates.

The experimental project in Polk County consists of the construction of one and one-half miles of secondary road utilizing phosphogypsum. The Parrish Road located one mile east of Fort Meade and South of U.S. 98 was selected for the experiment because the road was convenient to the supply of phosphogypsum and easily accessed from U.S. 98.

The experimental road section in Columbia County, a two-mile rural road, is known as the White Springs Road, located south of SR 136 between I-75 and U.S. 41 southwest of White Springs.

In recent years, the University of Miami had performed extensive laboratory research into the engineering properties of phosphogypsum as well as phosphogypsum mixtures with portland cement, flyash, lime and sand under the sponsorship of the Florida Institute of Phosphate Research.

Phosphogypsum when subjected to compaction can be transformed into a solid of valuable strength. Therefore, it can be used very effectively as a binder to stabilize on-site soil and to replace shell and clay in secondary road and parking lot construction.

The design, supervision and testing of the road projects were conducted by a collective effort of the University of Miami and the Florida Department of Transportation. The experimental roads were built by the Polk County Division of Public Works and the Columbia County Department of Public Works, respectively. Evaluation of the construction crews on the projects is highly positive.

The experimental projects call for a thorough environmental impact investigation which includes the pre- and post-construction sampling of air, soil and groundwater including drinking water. Environmental monitoring as described were conducted by the University of Miami, in cooperation with the Florida Department of Environmental Regulation and the Florida Department of Health and Rehabilitative Services. Test results as obtained indicated that there was no leaching occurring into the groundwater and drinking water samples. Radiation monitoring during the construction of the roads, indicated no health hazards either to the construction crews or the residents living in the areas.

Economic analysis on the construction of the experimental roads conducted by the University of Miami, indicated tremendous saving on the construction cost of utilizing phosphogypsum as compared to the traditional method of construction.

II. LABORATORY INVESTIGATION

Phosphogypsum possesses binding strength when subjected to compaction. However, phosphogypsum from different producers indicates strength variations. The aim of the laboratory tests is to investigate the engineering properties of different phosphogypsum-sand (on-site soil) mixtures. Unconfined compressive strength, moisture-density and California Bearing Ratio tests were used to ascertain the suitability of the proposed mixtures as pavement materials. All specimens were prepared in accordance with the Modified Proctor specification.

2.1 PLAIN PHOSPHOGYPSUM

The strength properties of plain phosphogypsum supplied by eight phosphate Companies in Florida (Gardinier Inc., Agrico Chemical Co., USS Agri-Chemicals, IMC, OXY, W. R. Grace, Royster, and Farmland) were studied to examine the strength variability. Figures 2.1(a) through 2.1(h) represent the relationship between compressive strength, dry density, and compaction moisture content of dihydrate phosphogypspum from these companies, respectively. The strength of specimens was tested under air-dry conditions; when subjected to soaked conditions, the specimens disintegrated.

It is seen from these figures that the maximum compressive strength of phosphogypsum from these companies generally exists at the optimum moisture content, i.e. the moisture content at which the maximum dry density is obtained. Thus, it is important to compact phosphogypsum at the optimum moisture content in order to achieve maximum strength and density values.

Also observed from these figures are the variations in maximum compressive strength. Figure 2.2 is the comparison of the compressive strength of different sources of phosphogypsum. As can be seen, the maximum compressive strength (under air-dry conditions) varies from 100 psi to up to 800 psi, although the strength of most phosphogypsum ranges between 300 and 500 psi. Thus, the source of phosphogypsum has an important effect on the compressive strength of phosphogypsum under the Modified Proctor compaction.

2.2 PHOSPHOGYPSUM AND SAND

Phosphogypsum from two different sources was used in this investigation. Dihydrate and hemihydrate phosphogypsum were supplied by Gardinier Inc. and Occidental Chemical Company, respectively. Sand (on-site soil) used for mixing with dihydrate and hemihydrate phosphogypsum were obtained from the actual construction sites at Polk and Columbia Counties,

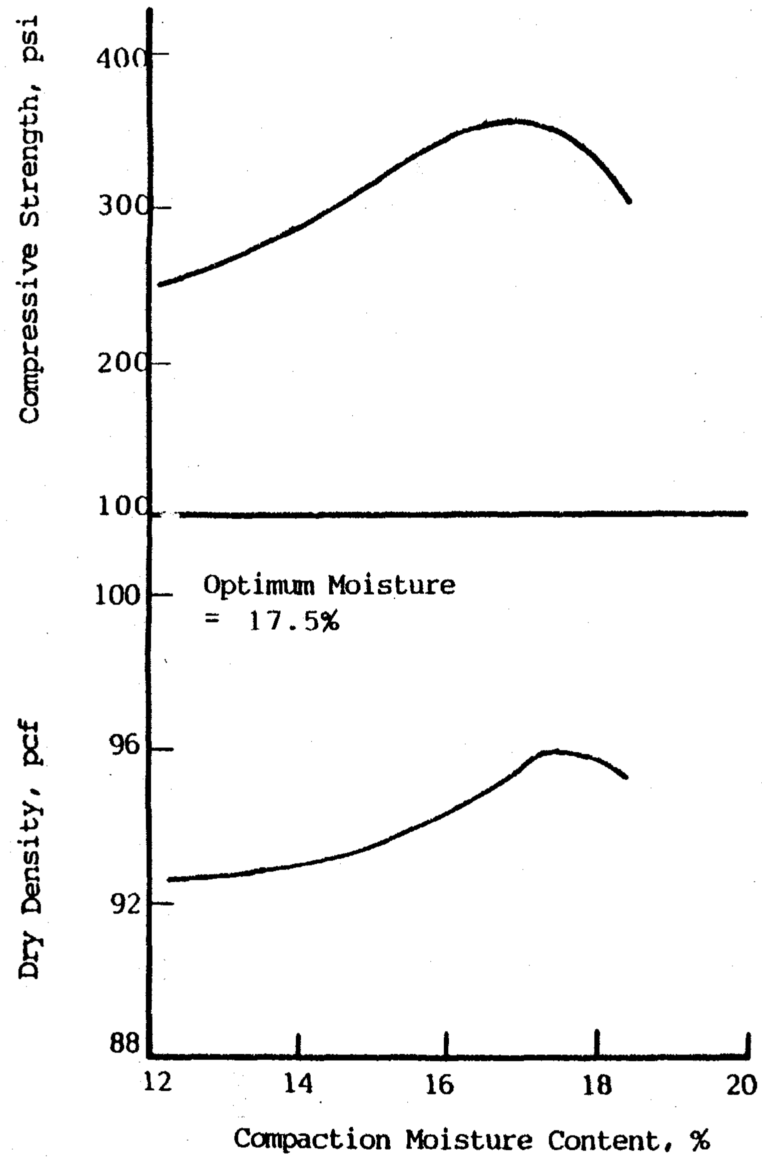


Figure 2.1(a) Moisture-density-strength relationship of Gardinier-DPG.

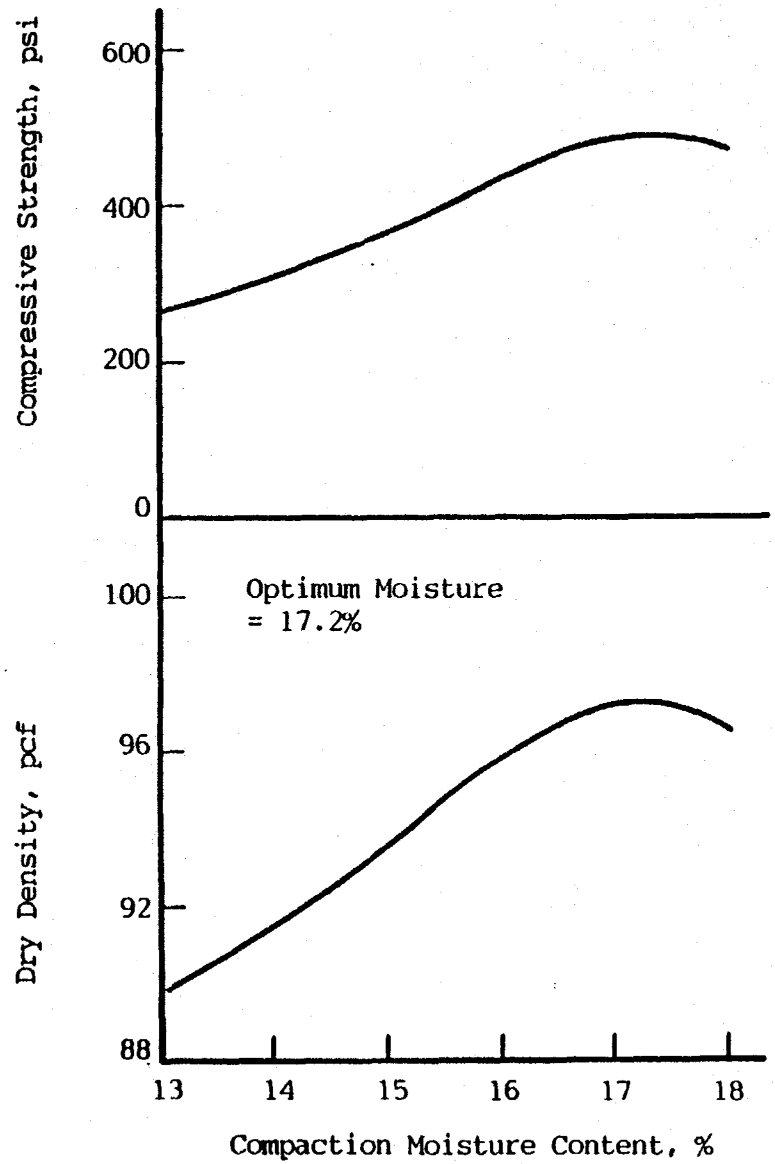


Figure 2.1 (b) Moisture-density-strength relationship of Agrico-DPG.

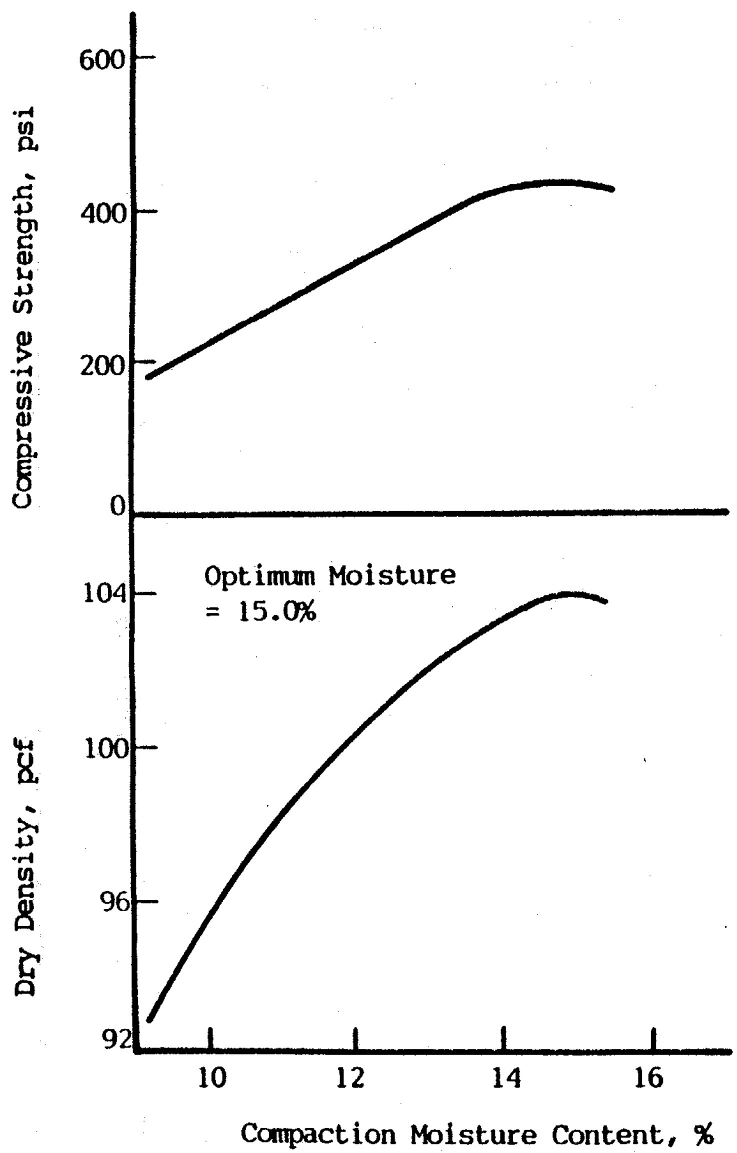


Figure 2.1 (c) Moisture-density-strength relationship of USS-DPG.

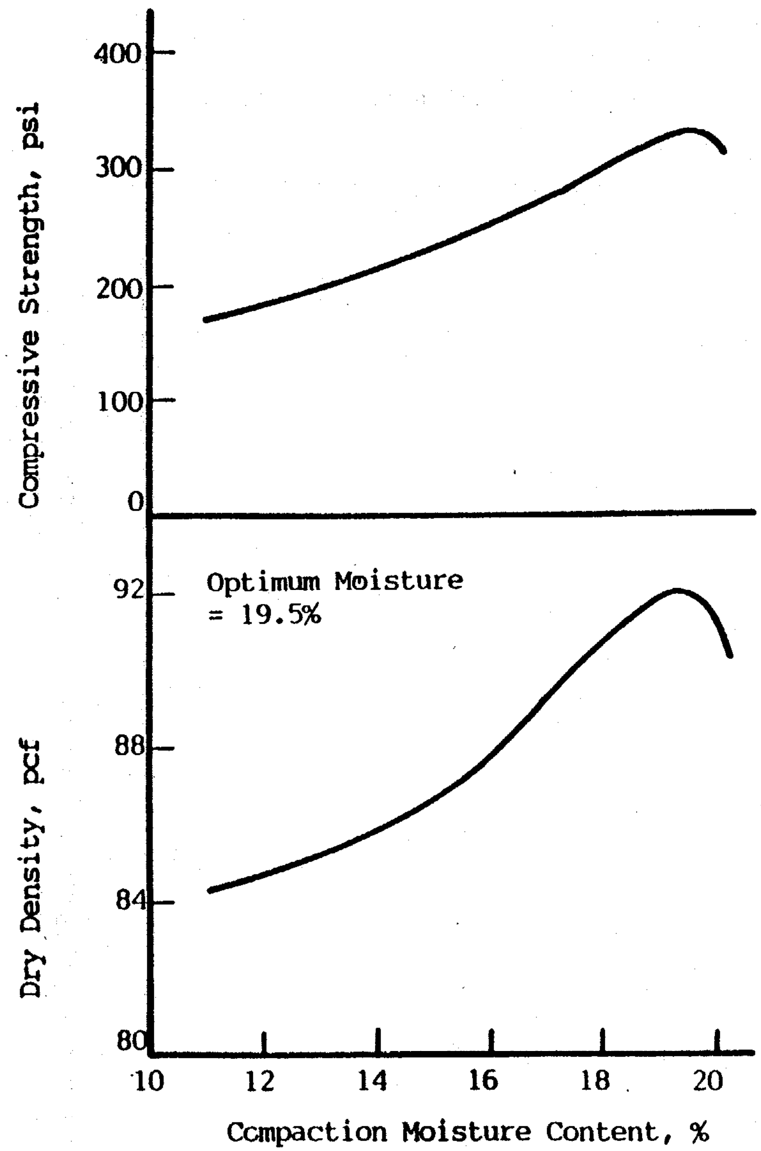


Figure 2.1(d) Moisture-density-strength relationship of Oxy-DPG.

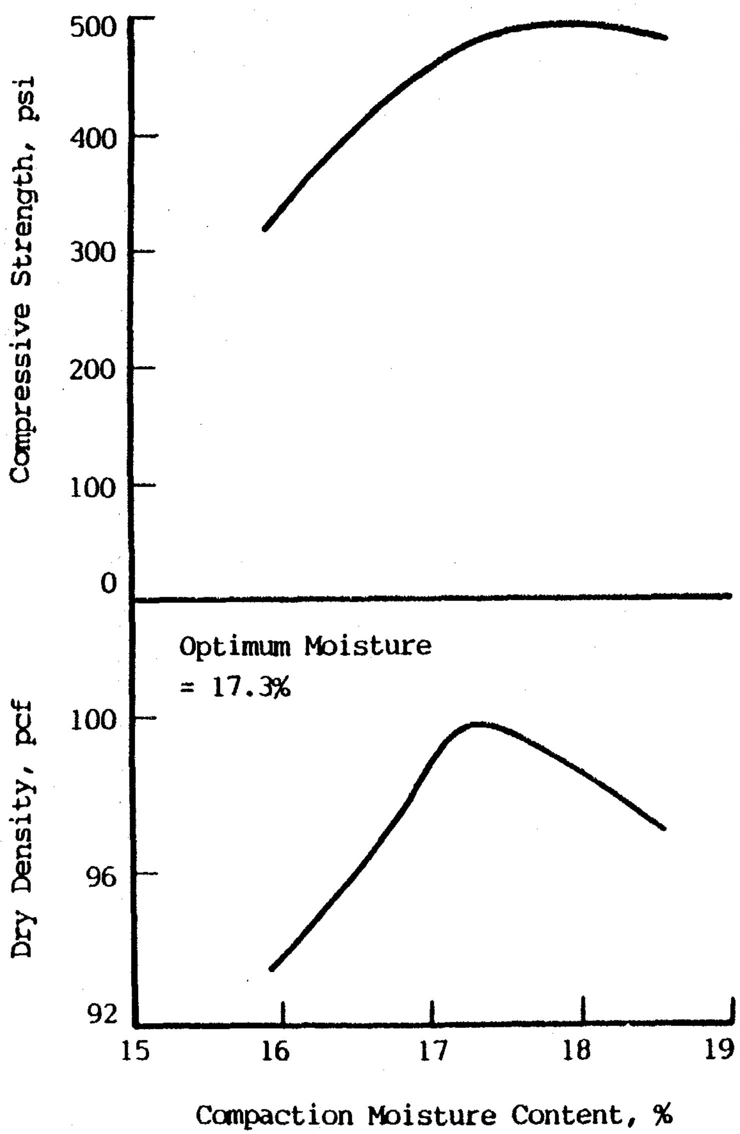


Figure 2.1(e) Moisture-density-strength relationship of IMC-DPG.

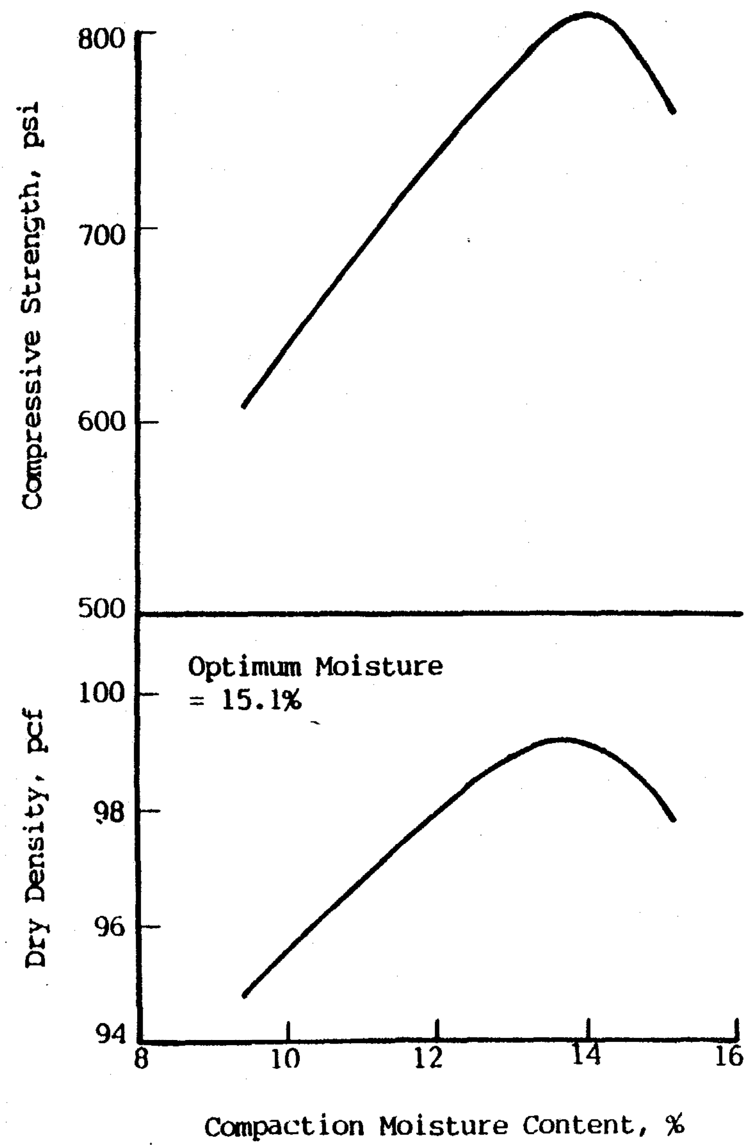


Figure 2.1(f) Moisture-density-strength relationship of Grace-DPG.

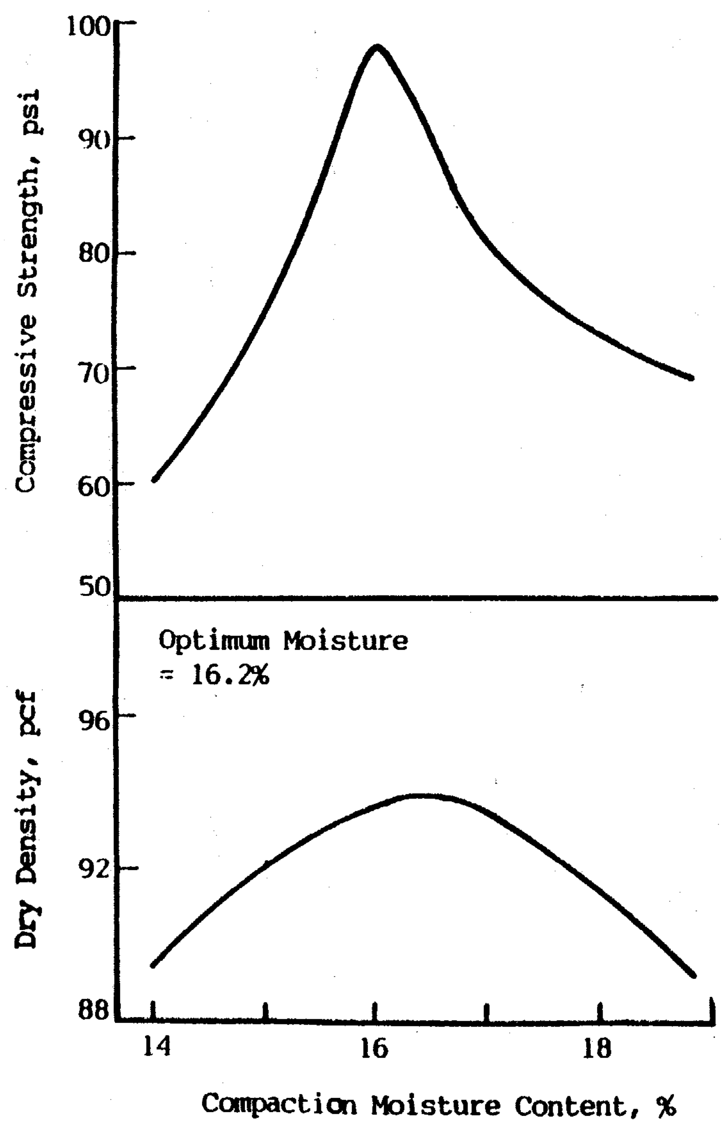


Figure 2.1(g) Moisture-density-strength Relationship of Royster-DPG.

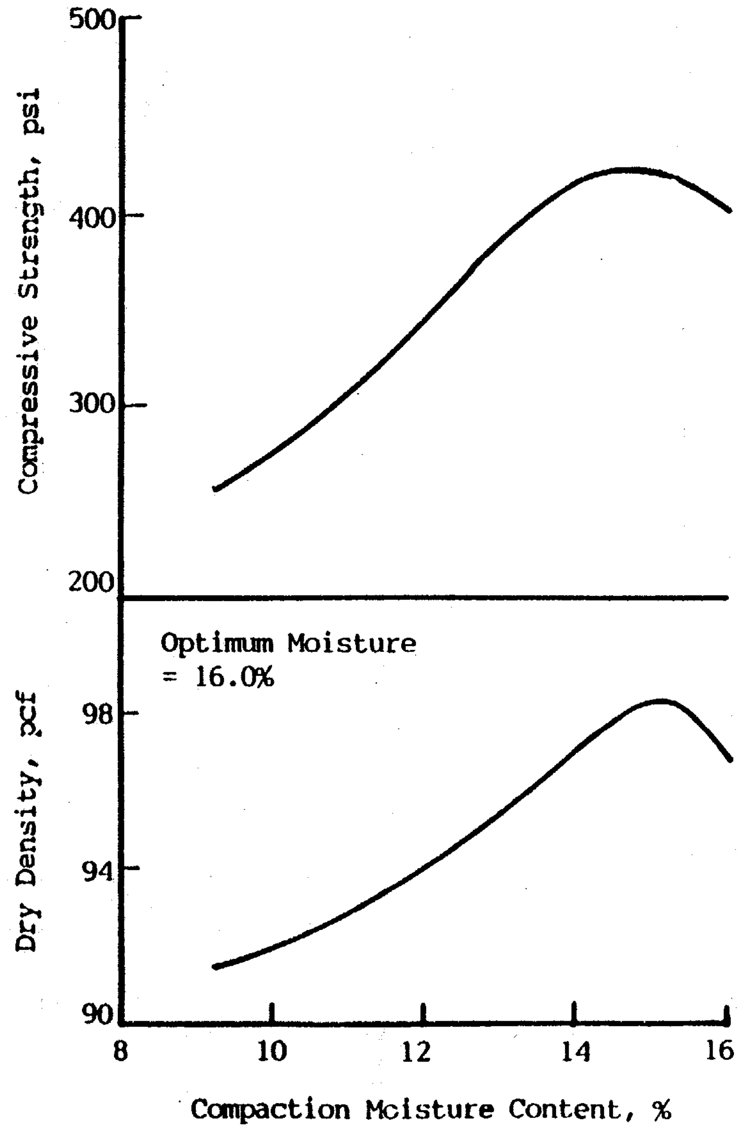


Figure 2.1(h) Moisture-density-strength Relationship of Farmland-DPG.

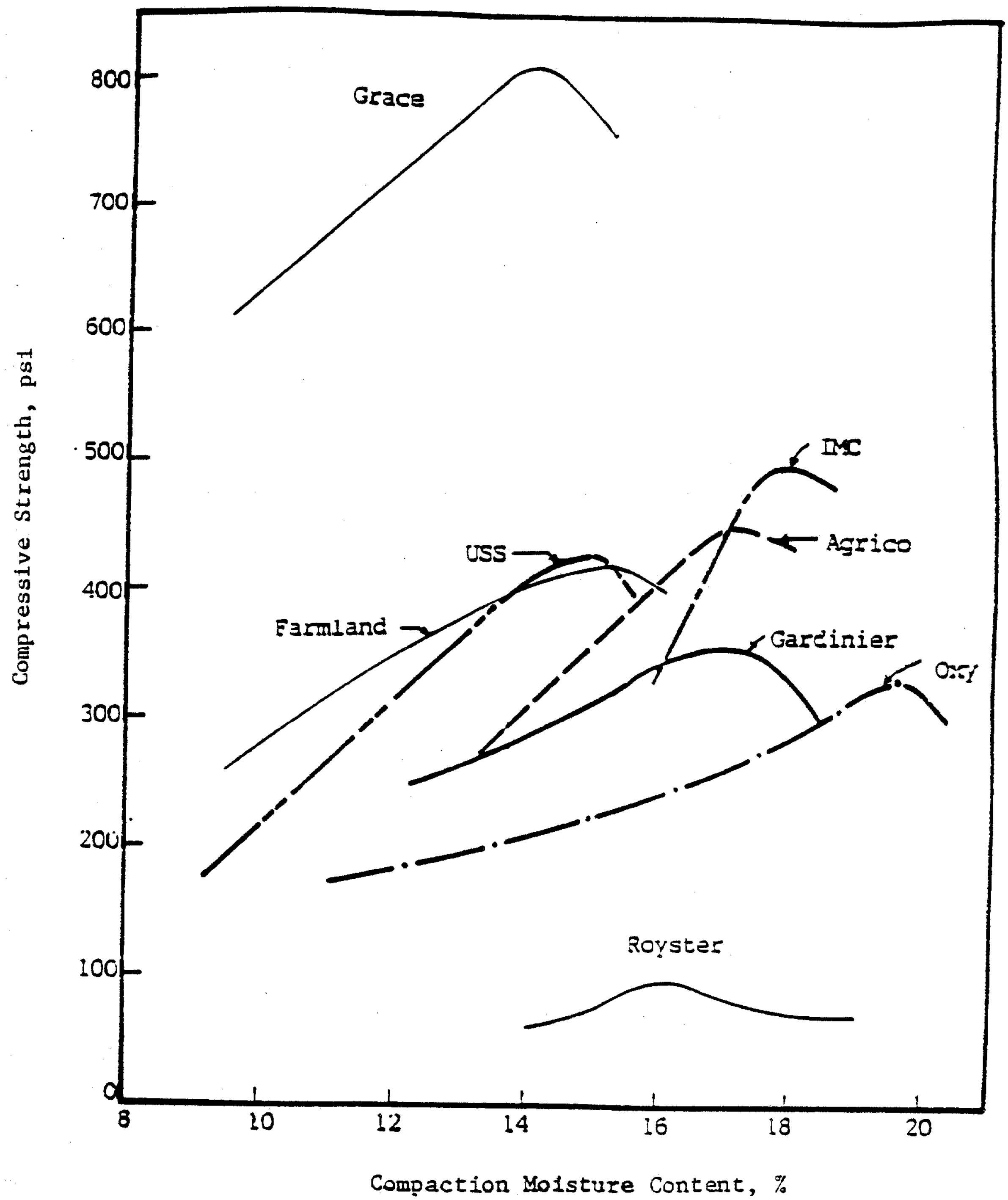


Figure 2.2: Comparison of compressive strength of 8 sources of DPG (Modified Proctor, air-dry testing).

respectively. Grain size distributions of phosphogypsum and sand are shown in Figures 2.3 and 2.4. According to the AASHO soil classification system these two different kinds of sand are classified as A-3 soil.

2.2.1 Moisture Density Relation

The moisture density test was performed in accordance with ASTM Specification D 1557-70. Specimens prepared for this test were 4.0 in. in diameter and 4.58 in. in height. Moisture content was obtained after subjecting the samples to a temperature of 60 degree Celsius in a convection oven for 24 hours. This low temperature which was required to prevent the calcination of phosphogypsum, was selected on the basis of ASTM Specification D 2216-71. Three samples were used in all cases to obtain an average of the moisture content.

It can be observed from Figure 2.5 that the dry density of the mixtures increases from phosphogypsum to sand ratio of 1:3 to the ratio 1:2 where it reaches a maximum dry density of about 2.01 (g/cm). Further reducing the amount of sand in the mixture to the ratio of 1:1 causes a decrease in the dry density. This decrease can be attributed to the fact that excess of phosphogypsum (which has a lower specific gravity) causes an opposite trend with the consequent reduction in the dry unit weight.

Moisture-density relationships for hemihydrate phosphogypsum and Columbia County sand mixtures are shown in Figure 2.6. It can be observed from the figure that the dry density increases with the amount of hemihydrate phosphogypsum in the mixtures. For a ratio of 2:l of hemihydrate phosphogypsum to sand mixture, the optimum moisture content is around 9.5%, whereas the maximum dry density is 2.07 (g/cm).

2.2.2 Unconfined Compression

Unconfined compressive strength was performed on specimens 2.0 in. in diameter and 4.0 in. height, prepared in accordance with the Modified Proctor (ASTM D 2166-65). Results of unconfined compression tests conducted immediately after compaction and under sealed curing at different time intervals, were investigated.

Compressive strength of specimens consisting of one part of phosphogypsum to two parts of sand is very low when tested immediately after compaction, as shown in Figure 2.7. The compressive strength of the mixtures increased continuously with time when cured under sealed conditions, as shown in Figures 2.8, 2.9 and 2.10 for the phosphogypsum to sand ratios of 1:3, 1:2 and 1:1, respectively. After comparing the strength of different mixtures, it is observed that the 1:2 of phosphogypsum-sand mixture with moisture content of 7% at compaction, has the

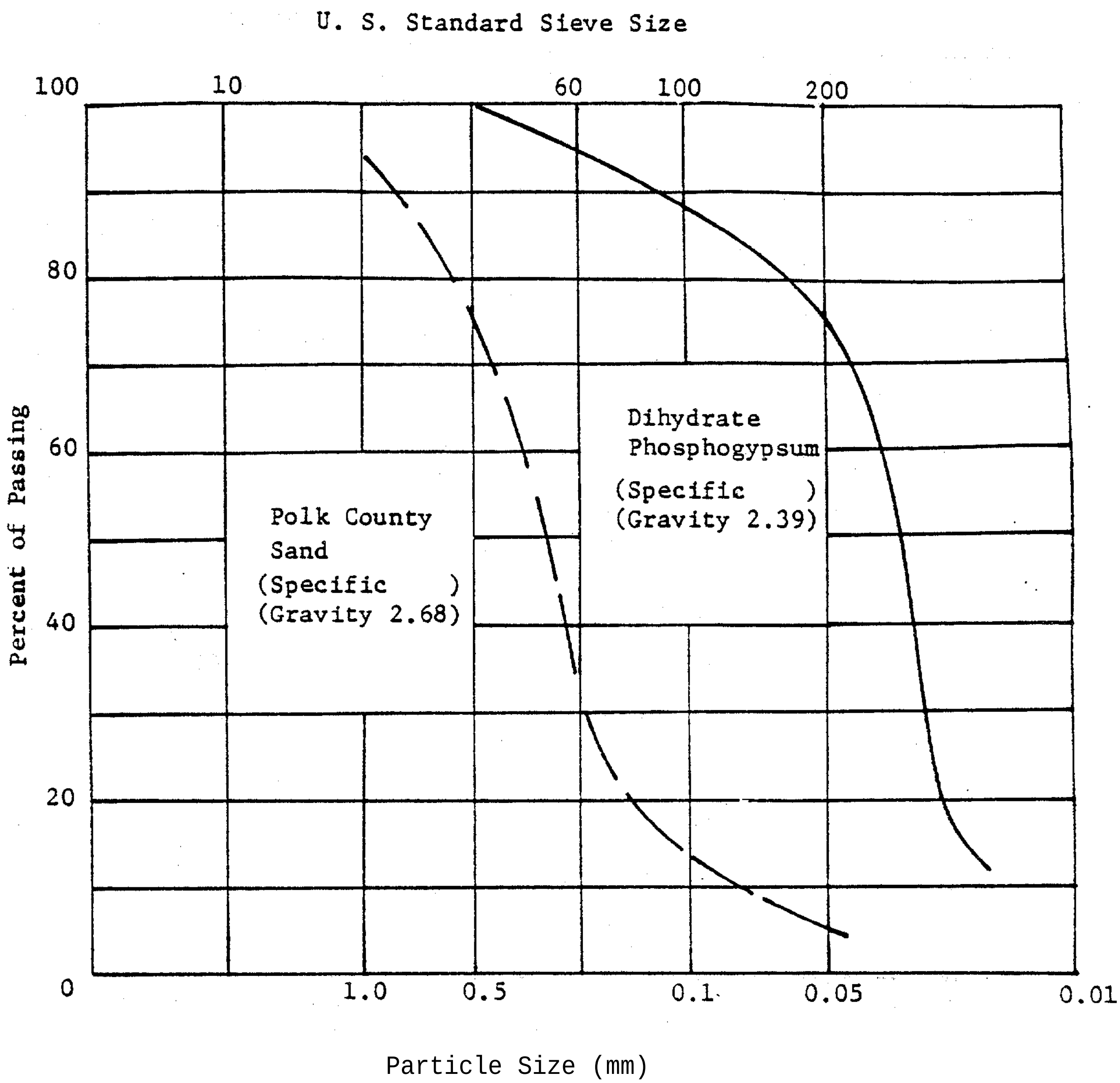


Figure 2.3 Grain Size Distribution

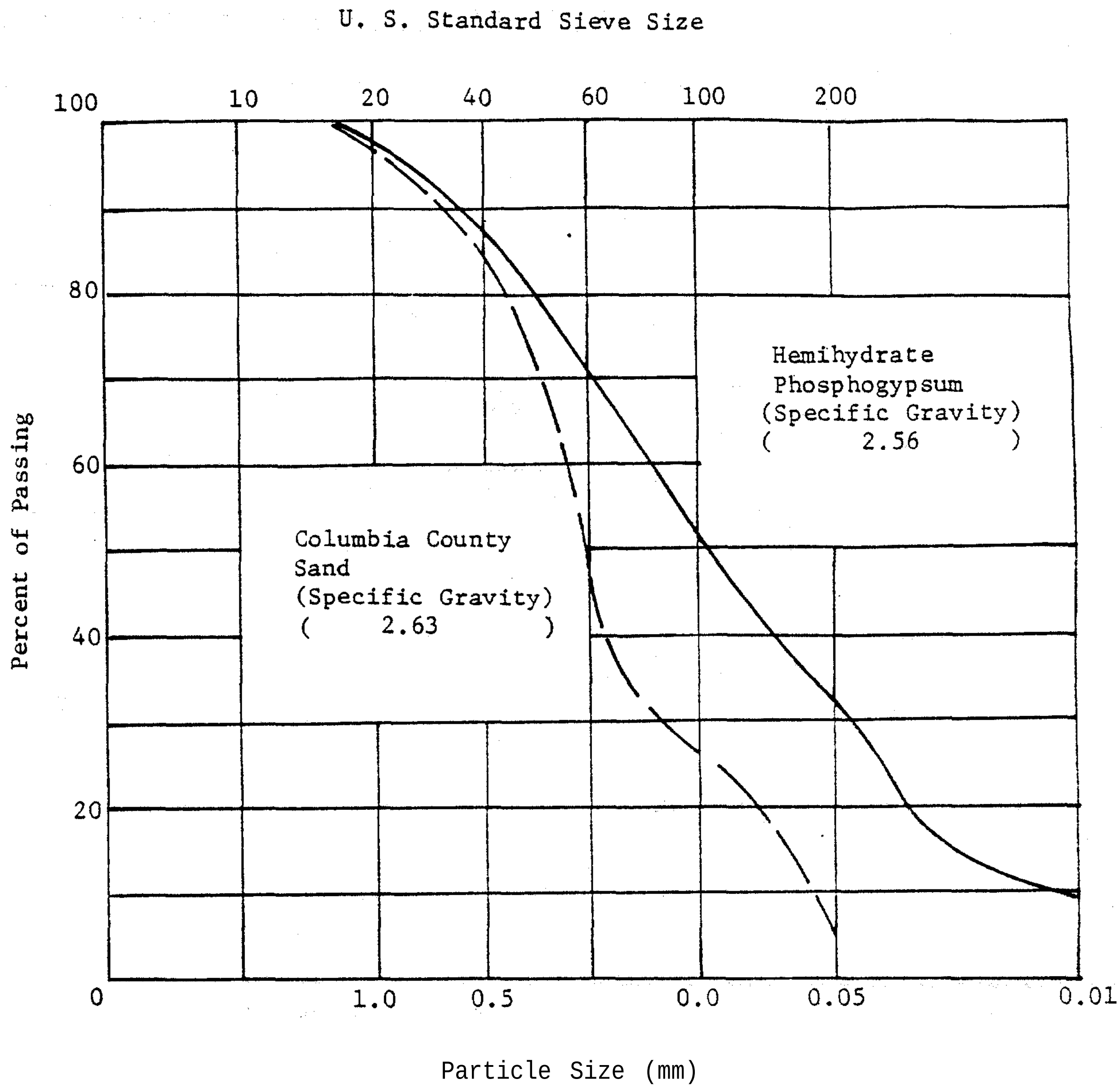


Figure 2.4 Grain Size Distribution

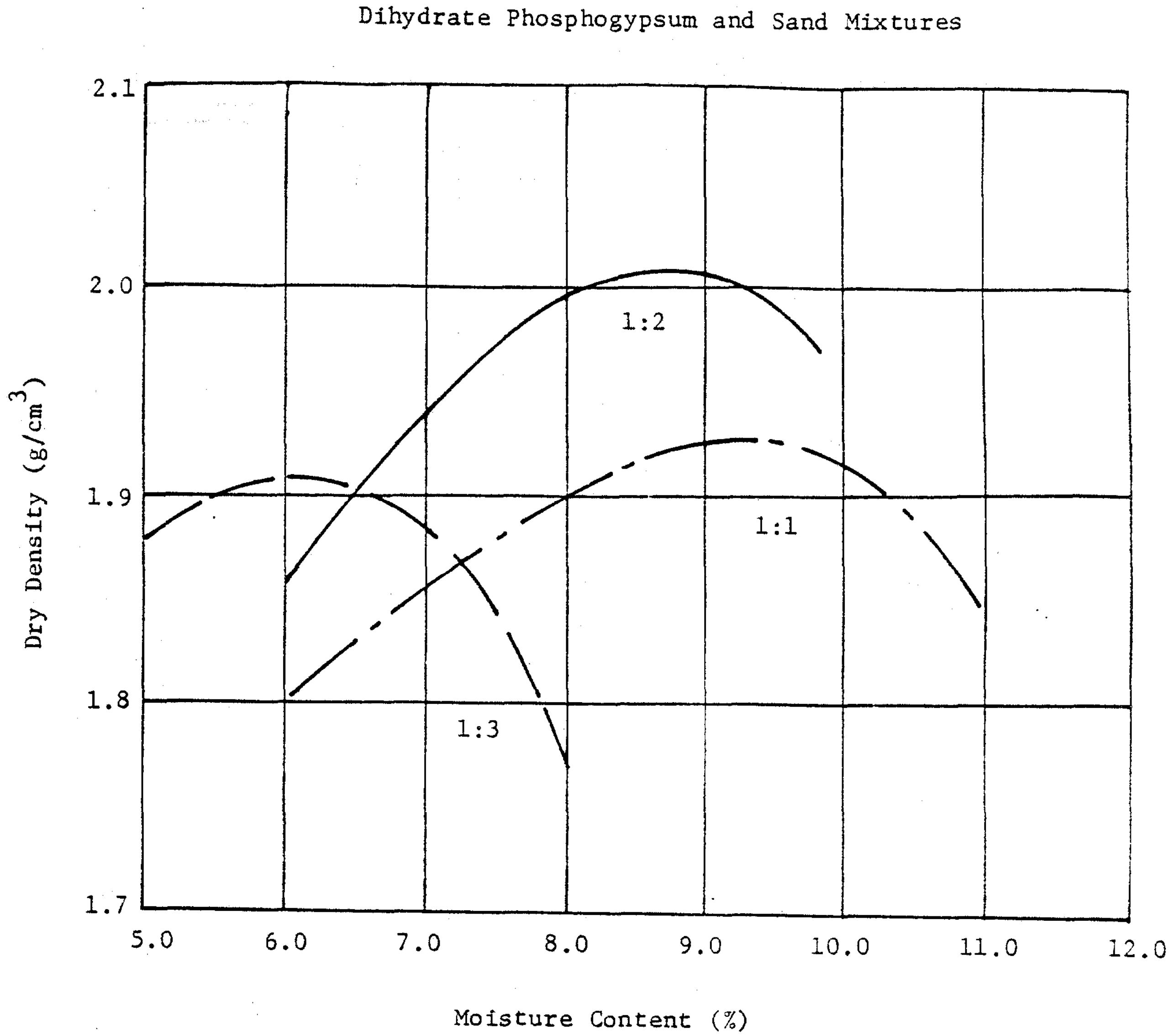


Figure 2.5 Moisture Density Relationship

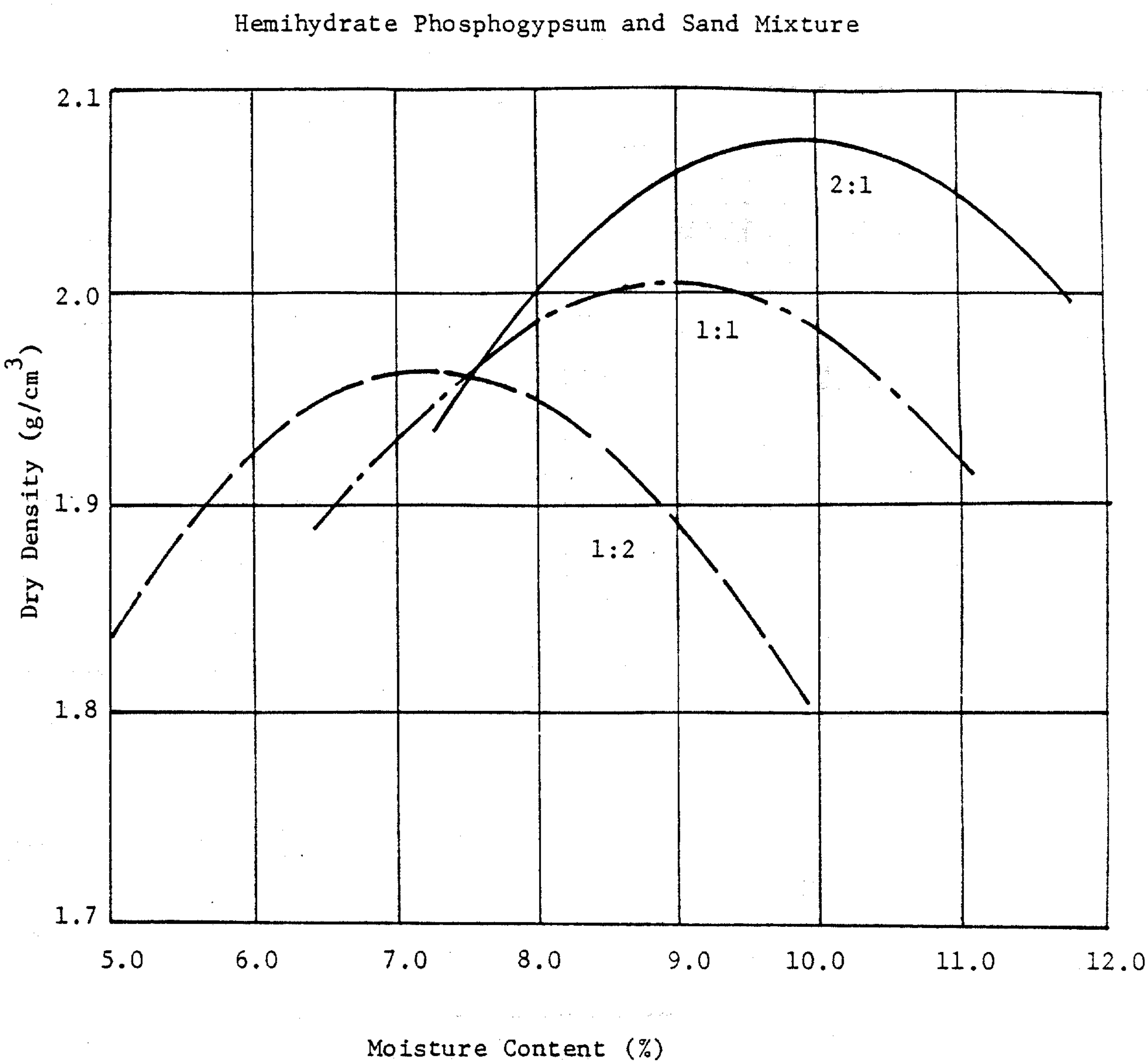


Figure 2.6 Moisture Density Relationship

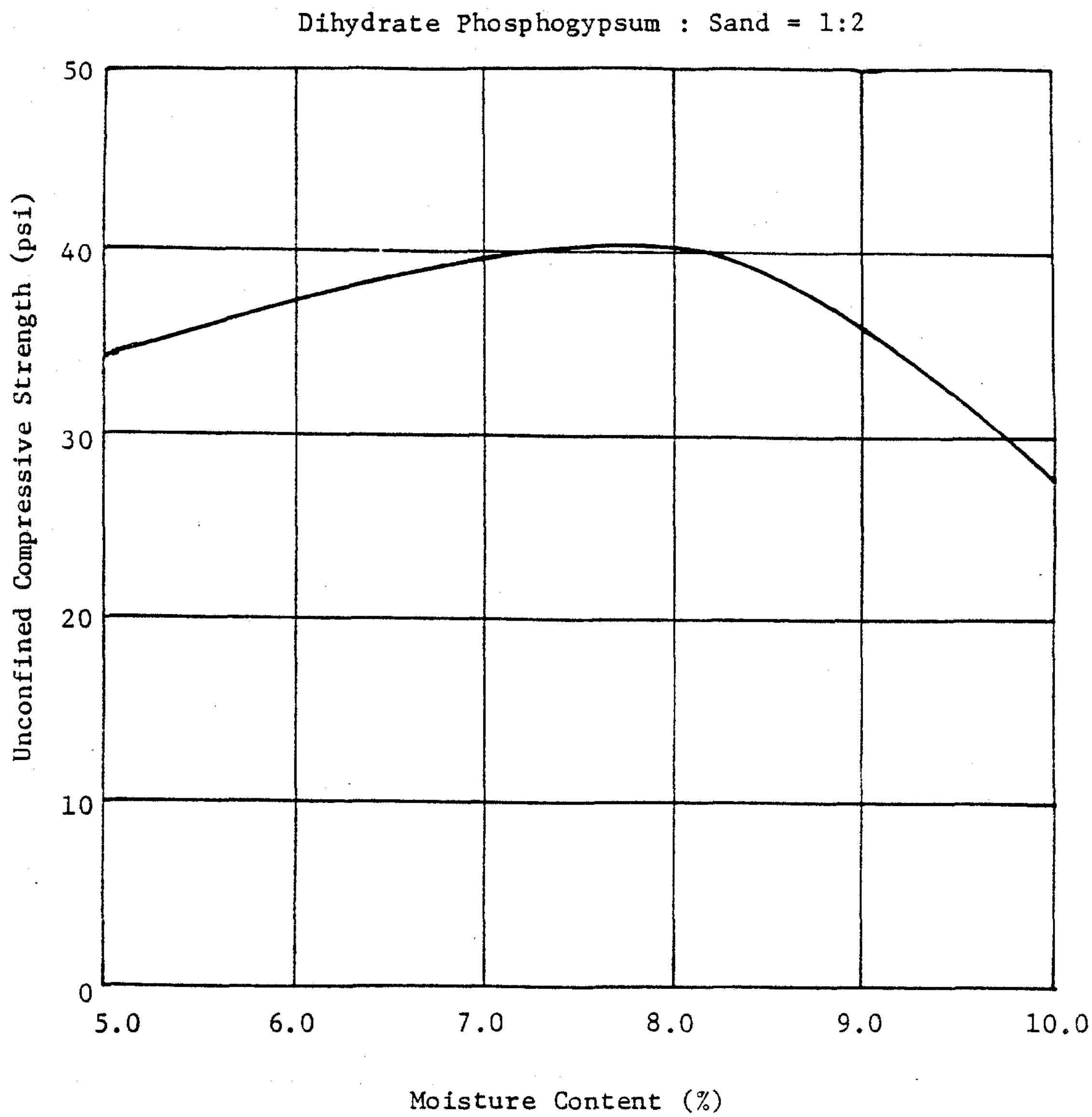


Figure 2.7 Compressive Strength Versus Moisture Content Immediately After Compaction.

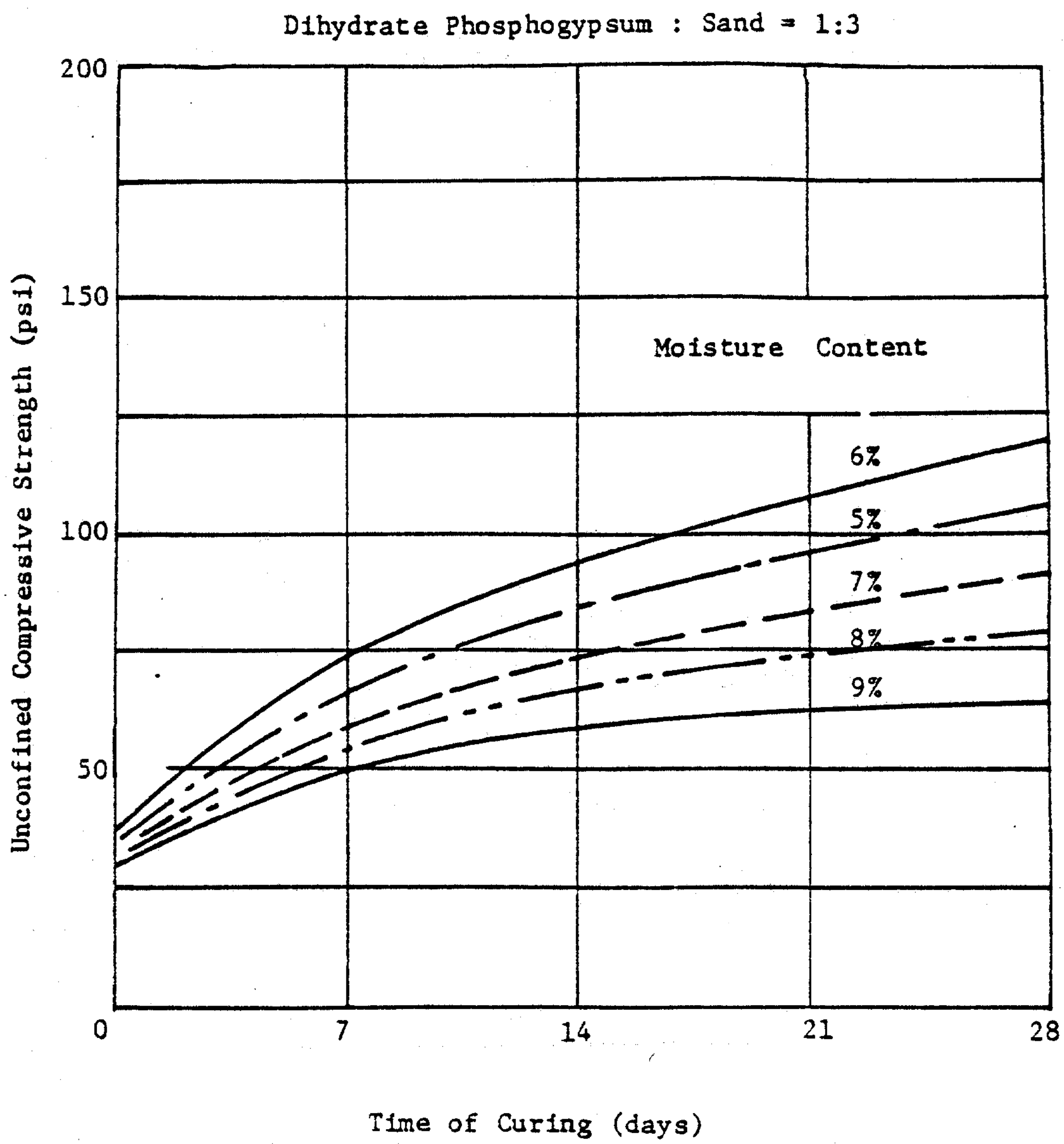


Figure 2.8 Unconfined Compressive Strength Versus Time of Curing

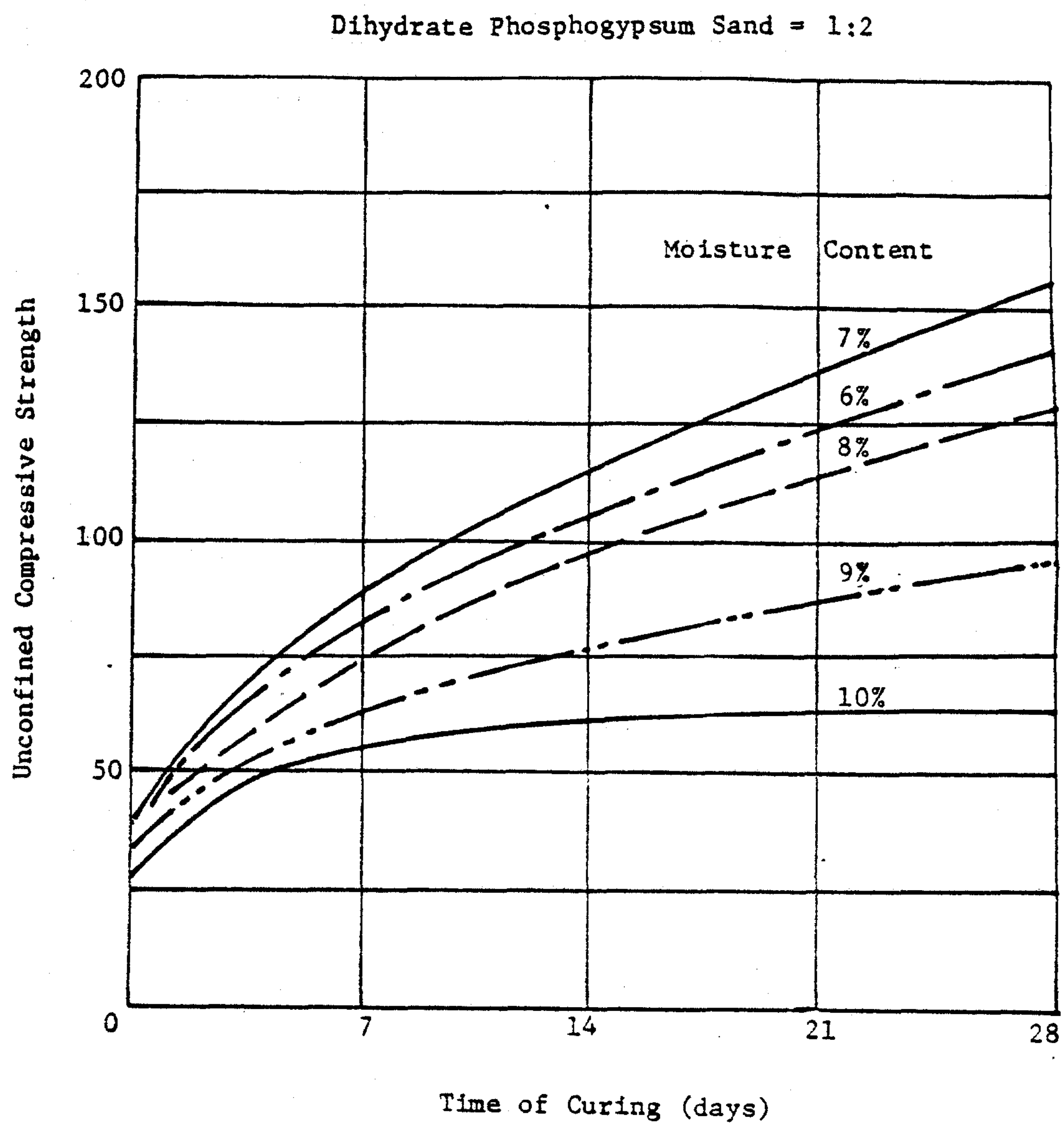


Figure 2.9 Unconfined Compressive Strength Versus Time of Curing

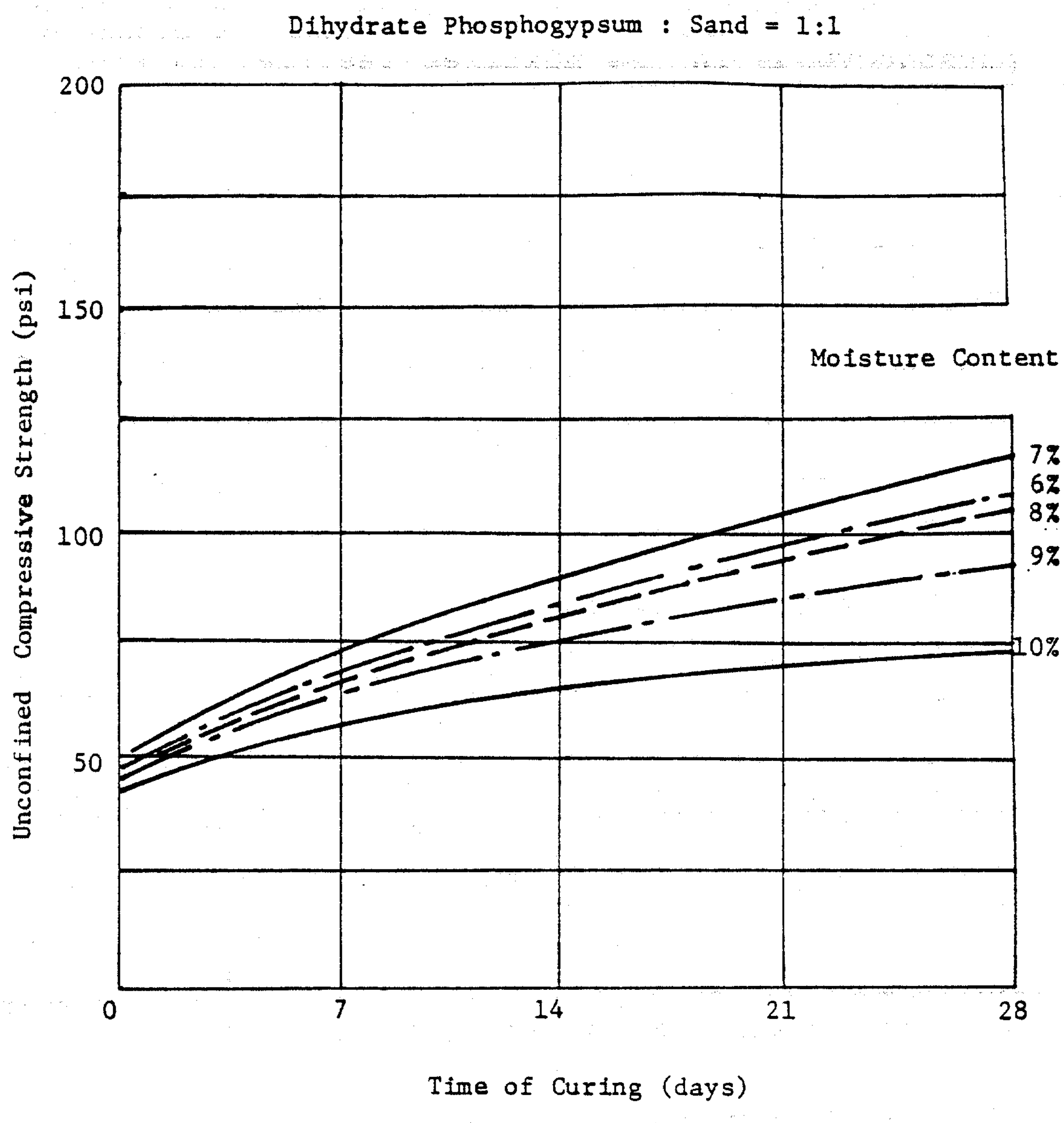


Figure 2.10 Unconfined Compressive Strength Versus Time of Curing

highest strength. Higher contents of phosphogypsum in the mixture decreases unconfined compressive strength.

Unconfined compressive strengths of phosphogypsum and sand mixtures under soaked conditions were also studied. Test results indicated that dihydrate phosphogypsum and sand cylindrical specimens were not water resistant, i.e, they collapsed when they were immersed in water. On the other hand, the mixtures of hemihydrate phosphogypsum and Columbia County sand showed good water resistance under soaked conditions as, shown in Figure 2.11. It can also be observed that increasing the amount of hemihydrate phosphogypsum in the mixtures resulted in higher compression strength under soaked conditions.

2.2.3 Effect of Compaction Energy

The specimens used for this study were prepared separately in accordance with the Standard and Modified Proctor Compaction Methods, but tested under air dry condition. The mixture chosen consisted of one part of dihydrate phosphogypsum to two parts of Polk County sand. Test results, shown in Figure 2.12, indicate that compaction efforts have a marked effect on strength properties of the mixtures. The specimens compacted in accordance with the Modified Proctor method possess much higher compressive strengths as compared to those of the Standard Proctor method.

2.2.4 Laboratory CBR Test

Laboratory CBR tests for the phosphogypsum mixtures were conducted immediately after compaction. Specimens were prepared in accordance with the Modified Proctor method (ASTM D 1883). The general trend of CBR values for phosphogypsum mixtures as expected, is similar to that of unconfined compression tests. Test results as shown in Figure 2.13 indicate that the mixture of dihydrate phosphogypsum and sand in the ratio of 1:2 gives the highest CBR value when compared with other mixing proportions The CBR values of hemihydrate phosphogypsum and sand mixtures increase with the hemihydrate phosphogypsum content in the mixtures, as shown in Figure 2.14. It can be concluded that the hemihydrate phosphogypsum possesses much higher binding strength than that of dihydrate phosphogypsum.

2.2.5 Field Samples for CBR Test

Based on laboratory test results, several mixtures were selected for field CBR tests by constructing a small pavement outdoor. The pavements compacted with a vibratory plate type compactor, were 2 ft. by 3 ft., and 5 in. in thickness. Mixture proportions and moisture contents of the pavements are shown in Tables 2.1 and 2.2 for dihydrate phosphogypsum-sand and hemihydrate phosphogypsum-sand mixtures, respectively. Field

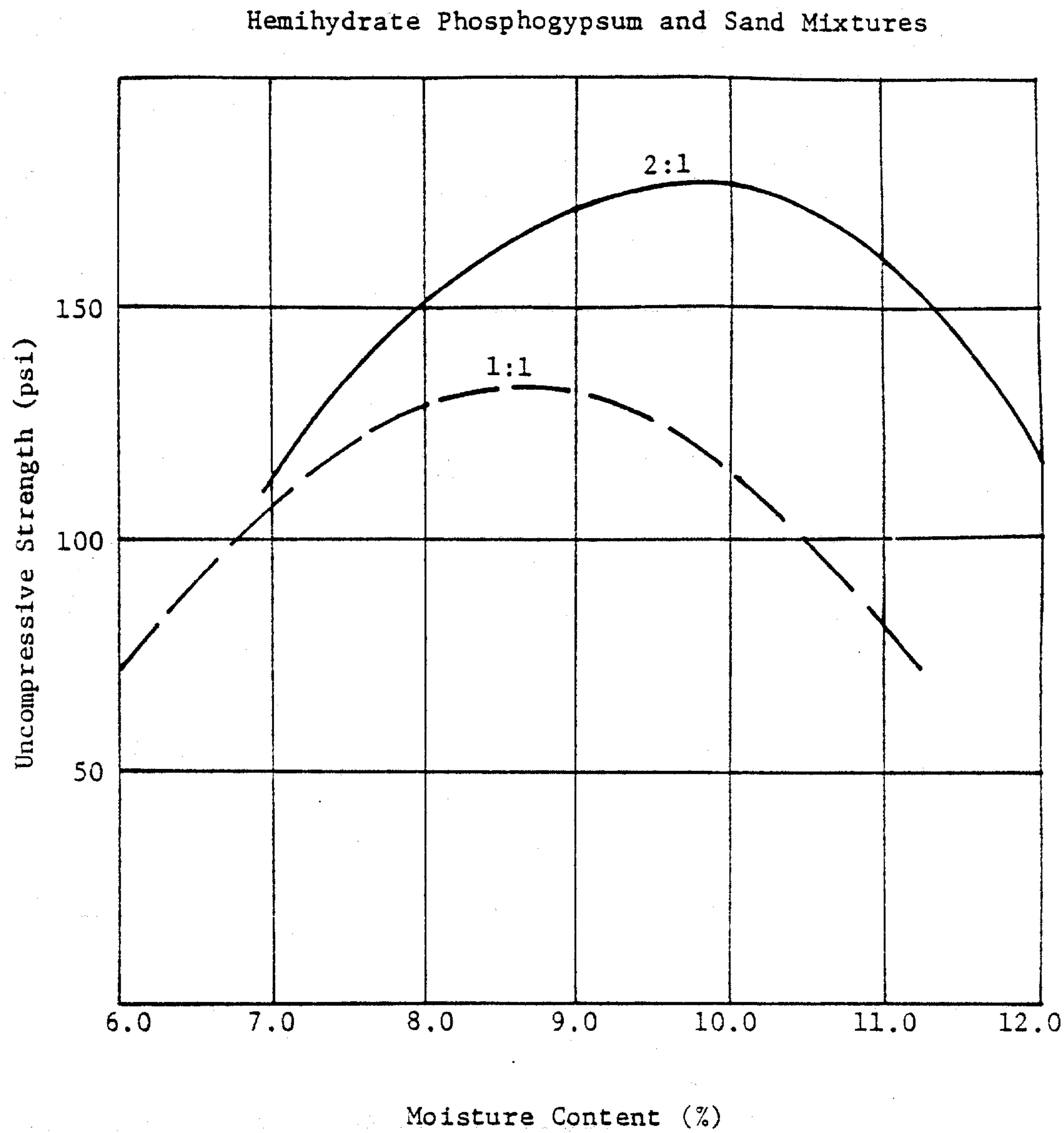


Figure 2.11 Moisture Density Relationship, Tested in Soaked Conditions

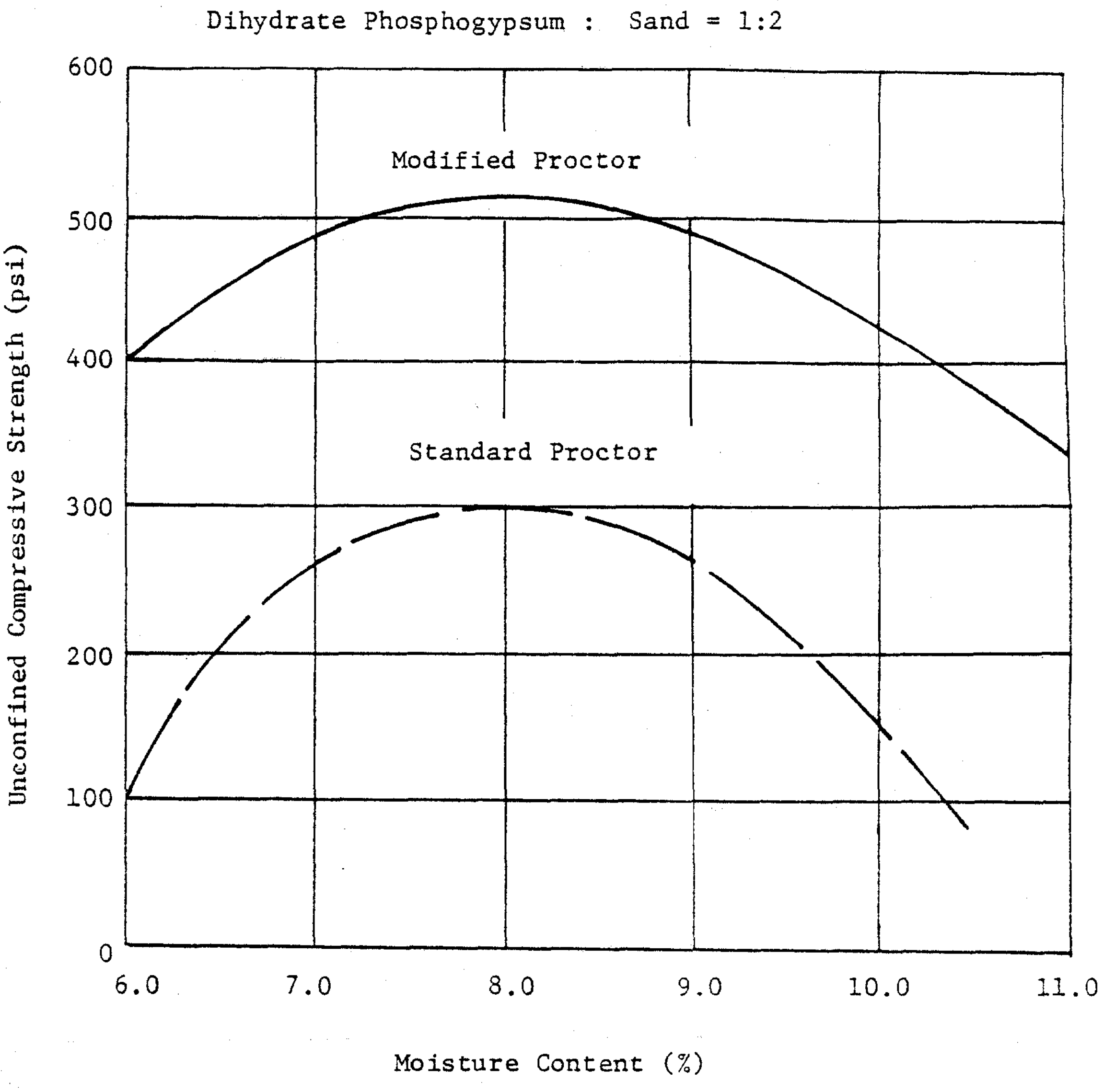


Figure 2.12 Compressive Strength and Moisture Content Relationship as Affected by Two Different Compactive Methods, Tested in Air-Dry Conditions

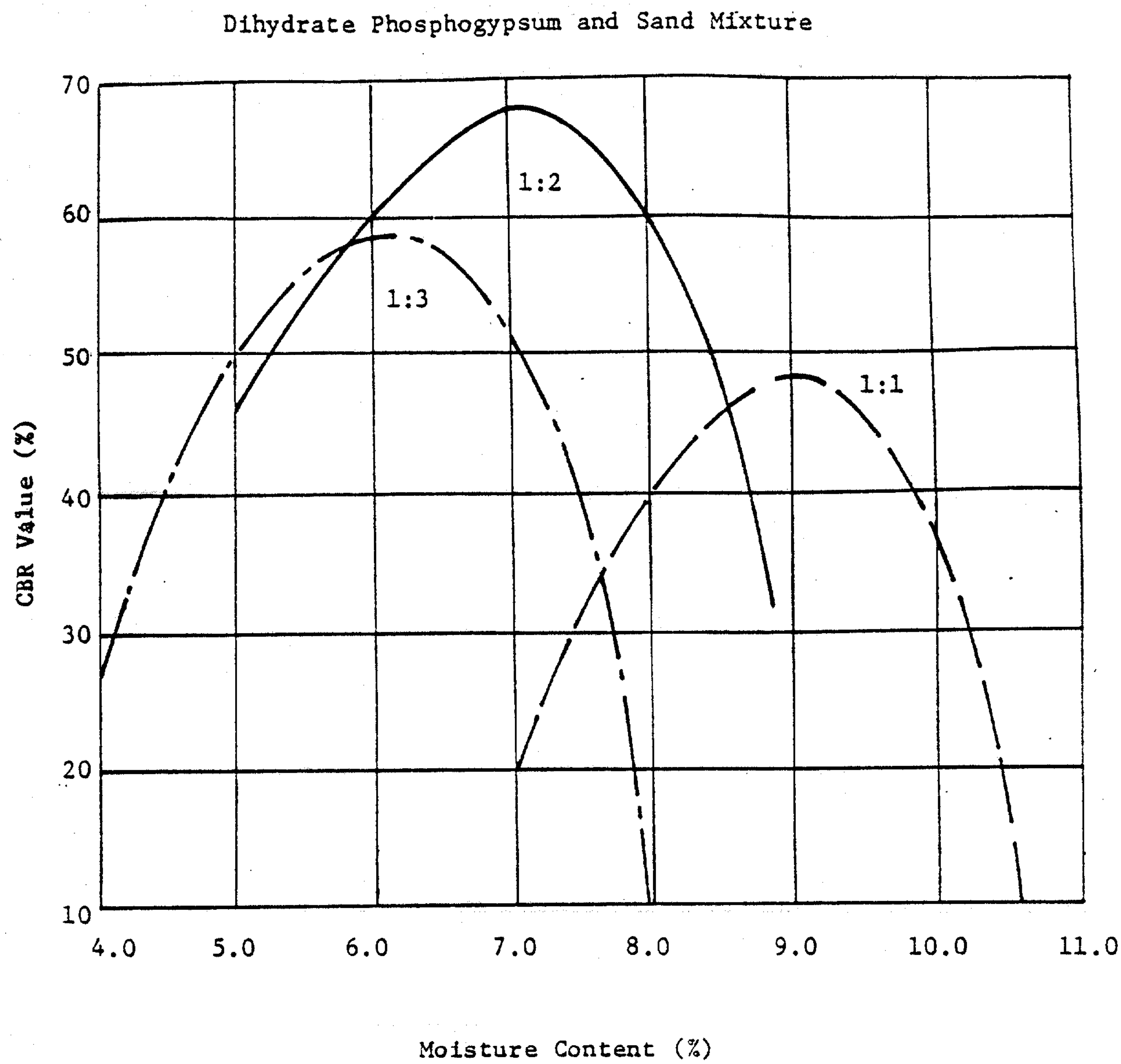


Figure 2.13 CBR Test Conducted Immediately After Compaction

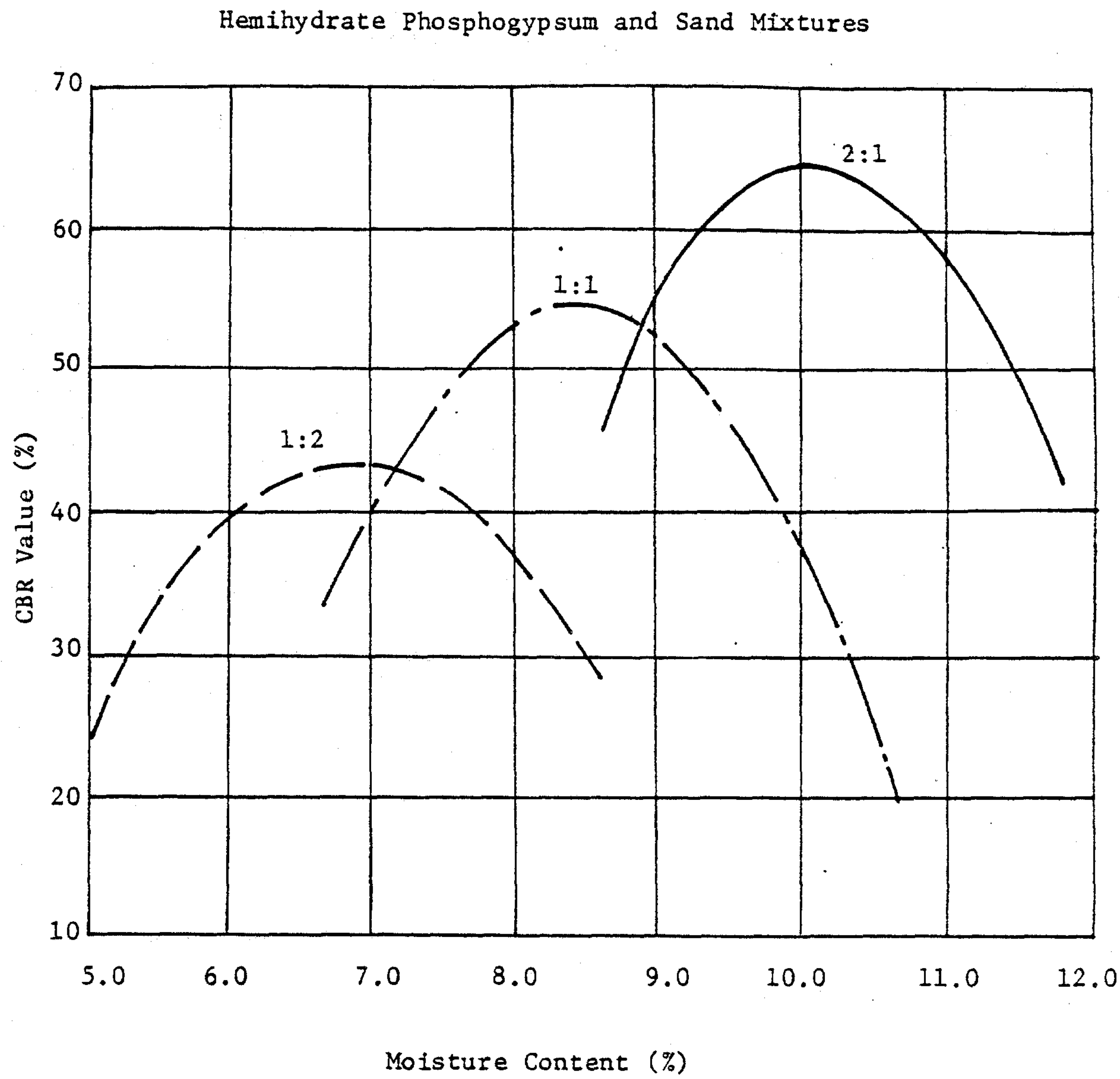


Figure 2.14 CBR Test Conducted Immediately After Compaction

Table 2.1

Mixture Proportions and Moisture Contents of Small Pavements Containing Dihydrate Phosphogypsum and Polk County Sand

Mixture No.	Dihydrate Phosphogypsum (%)	Polk County Sand (%)	RC-70 (%)	Moisture at Compaction (%)	Moisture at Testing (%)
1	--	100	--	5.5	--
2	100	--	--	18	4.5
3	33.3	66.6	--	10	3.2
4	32.5	65.4	2	10	3.2

Table 2.2

Mixture Proportions and Moisture Contents of Small Pavements Containing Hemihydrate Phosphogypsum and Columbia County Sand.

Mixture No.	Dihydrate Phosphogypsum (%)	Columbia County Sand (%)	Moisture at Compaction (%)	Moisture at Testing (%)
1	--	100	6.5%	4.0
2	50	50	11	3.6
3	66.6	33.3	12.5	3.0
4	100	--	22	4.0

test results of dihydrate phosphogypsum and sand mixtures are shown in Figure 2.15. Field CBR value of dihydrate phosphogypsum and sand mixture is much higher than that of either sand or phosphogypsum as shown in the figure. The addition of RC-70 in the phosphogypsum and sand mixture also improved the bearing capacity of the pavement.

Figure 2.16 shows field test results of hemihydrate phosphogypsum and sand mixtures. Field CBR value increases with the hemihydrate phosphogypsum content in the mixtures. For the mixture with 100% hemihydrate phosphogypsum CBR value of the pavement exceeds 100%.

Dihydrate Phosphogypsum and Sand Mixtures

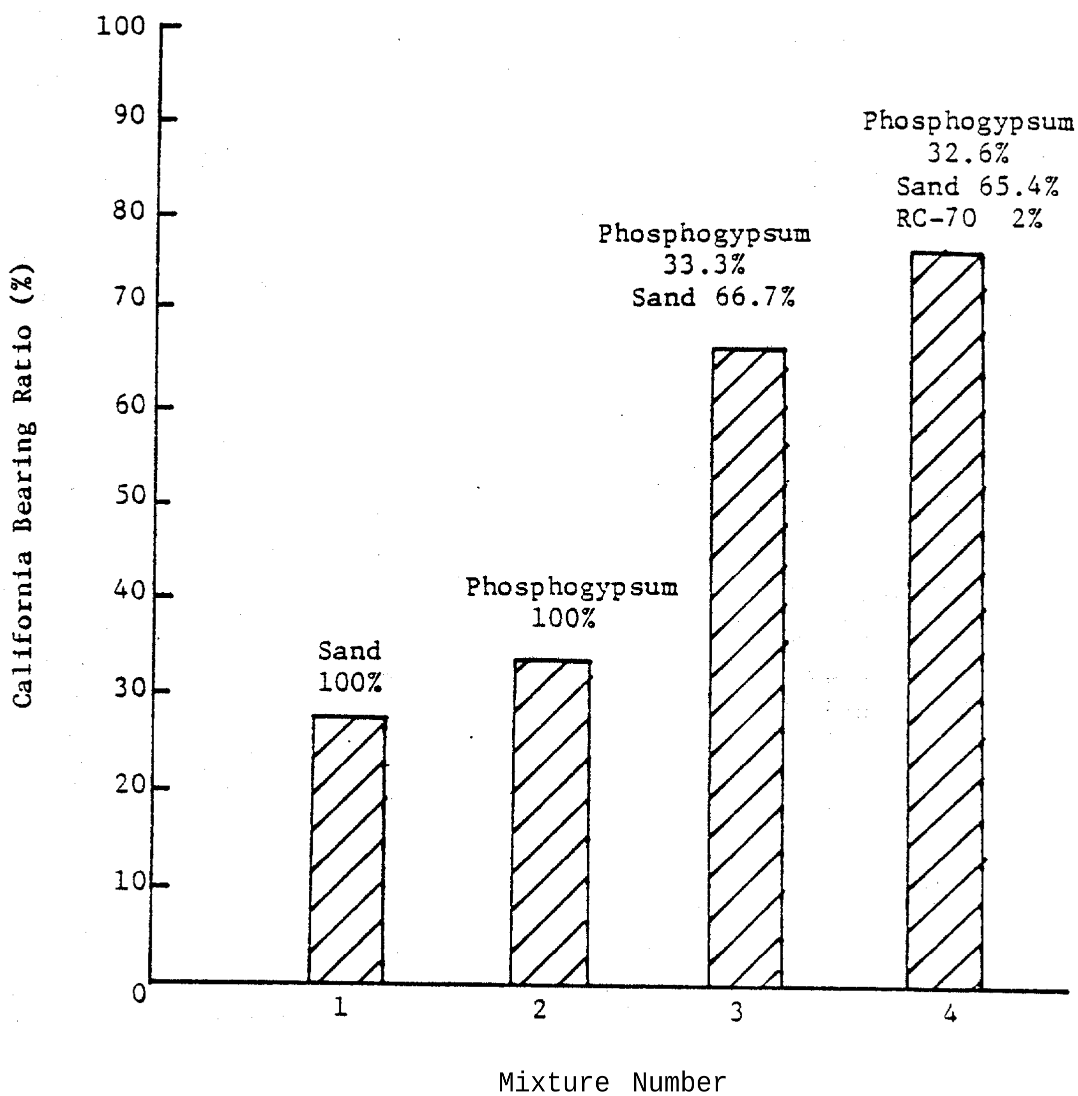


Figure 2.15 Field California Bearing Ratio Tests

Hemihydrate Phosphogypsum and Sand Mixtures

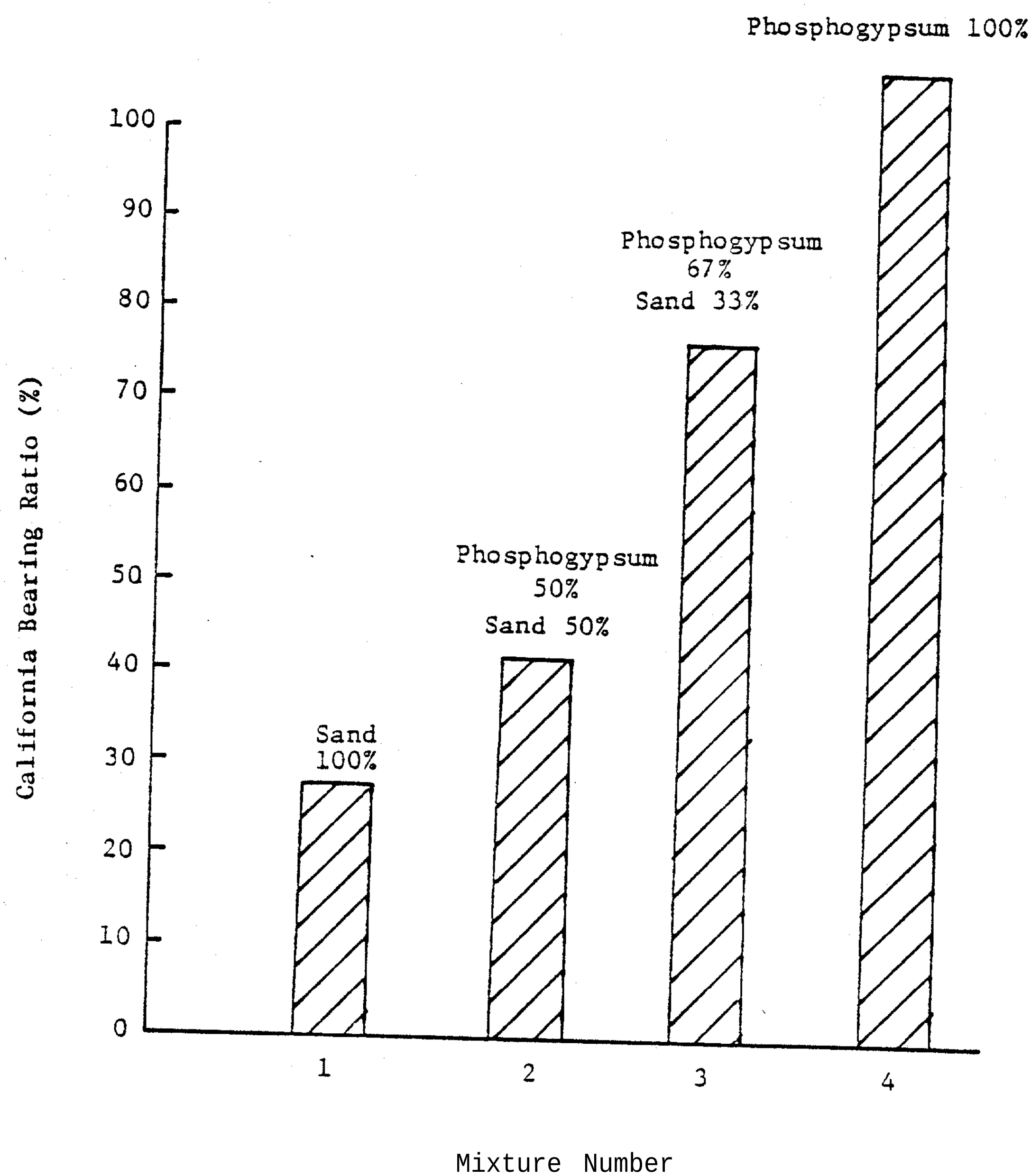


Figure 2.16 Field California Bearing Ratio Tests

III. EXPERIMENTAL ROADS DESIGN AND CONSTRUCTION

3.1 GENERAL CONSTRUCTION PROCEDURE

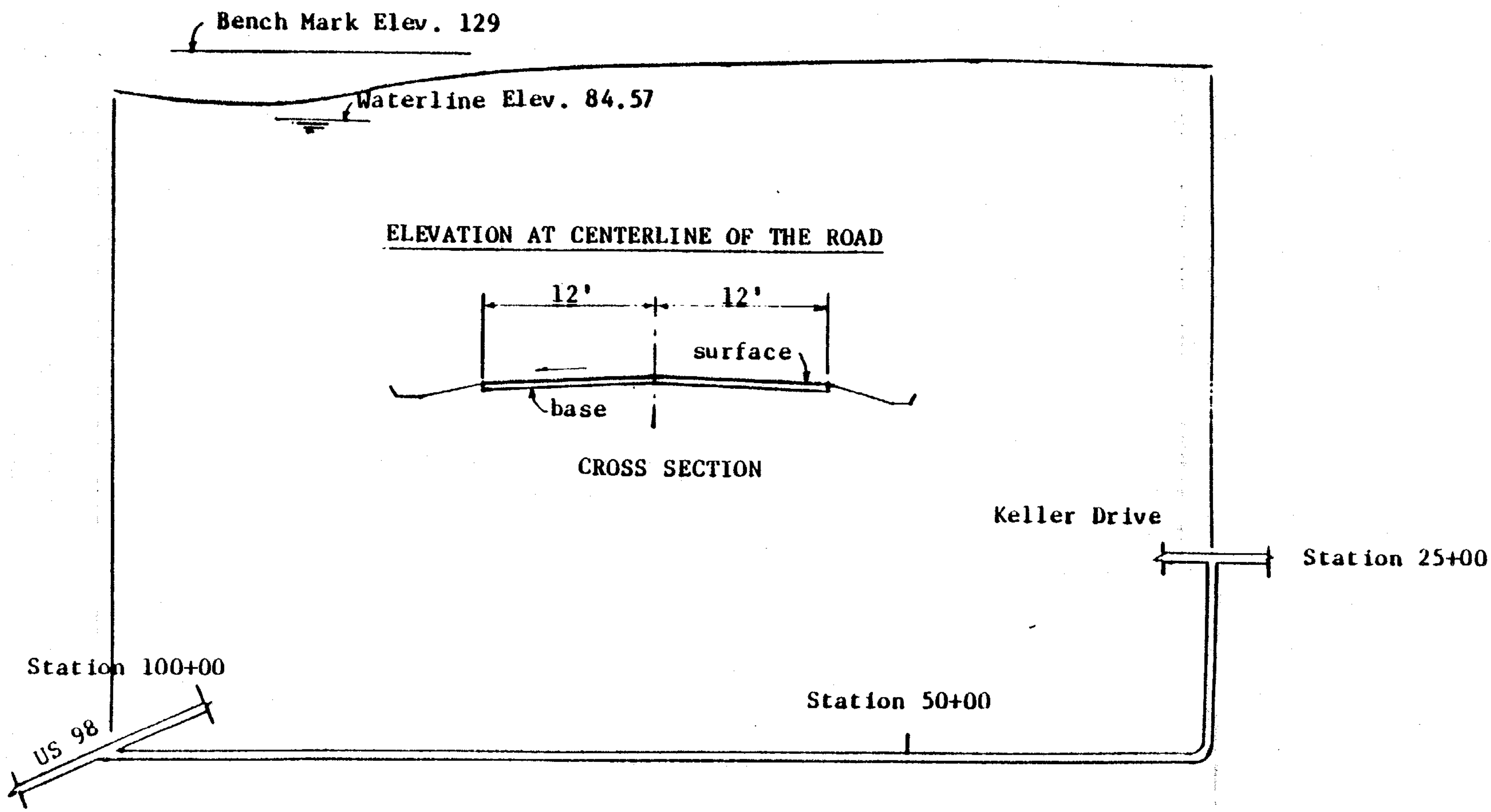
The existing road surface layer is leveled with a motor grader and compacted with a steel drum roller. Phosphogypsum at its natural moisture content is delivered by means of dump trucks. The phosphogypsum is discharged at the construction site and evenly spread by means of a bulldozer and a motor grader to meet the appropriate lift thickness. A pulvimixer is brought to the site to thoroughly mix the phosphogypsum with the subgrade material. The depth of the mixed layer is selected according to the mix constituent proportions called for in the design specifications. The importance of pulverizing the mixture constituents and thoroughly blending them should be emphasized. Final results depend on mix uniformity and moisture content. Moisture content in the mixture can be either increased by spraying water on the road surface or decreased by scarifying the surface layer for drying under the sun. Following the mixing phase, the road cross-section profile is shaped according to the design- drawings. Sloping of the road surface is important to avoid rainwater ponding on the pavement.

The road is initially compacted using a sheepsfoot roller. This roller was applied until it roiled on the surface without penetrating the base. Subsequently, the road is compacted by a steel roller and a pneumatic tire compactor. The higher the compaction effort the better: however the weight component is most important because of the materials fineness. The pneumatic tire compactor has the functions of compacting any low spots not properly compacted by the steel roller, and of smoothing the top surfaces.

3.2 ROAD DESIGN AND CONSTRUCTION

3.2.1 Polk County Experimental Road

The experimental road is shown in Figure 3.1. The first section of the road, Station 90+00 to l00+00, was tested for subgrade bearing after compaction. Test results indicated that the Florida bearing value and the California bearing ratio were 88 and 17, respectively which were low and therefore, required stabilization. On September 12, 1986. 3" of phosphogypsum supplied by U.S. Agri-Chemicals was spread on the road and mixed with a pulvimixer to a depth of approximately 12" of loose mixture. This is the procedure that would have been used with clay as a subgrade stabilizer. The mixture was then compacted



THE PARRISH ROAD

Figure 3.1

at 90 percent Modified Proctor and opened to traffic for several days. During this period of time, several rains occurred and no particular problems were encountered by the traffic using the road. A second 3" of phosphogypsum was then spread on the stabilized road base and mixed to a depth of approximately 10". The mixture was again compacted at 98 percent Modified Proctor. The Florida bearing value of the road was substantially improved from the value of 88 to 168 and the CBR from 17 to 133.

The next section of the road, Station 66+00 to 90+00, consisted mostly of clayey soil. This section was constructed by adding a single application of 3" of phosphogypsum to the existing road and mixing to a depth of 15". The section was compacted initially by a sheepsfoot roller. The pneumatic roller and steel wheel roller were subsequently used to complete the compaction.

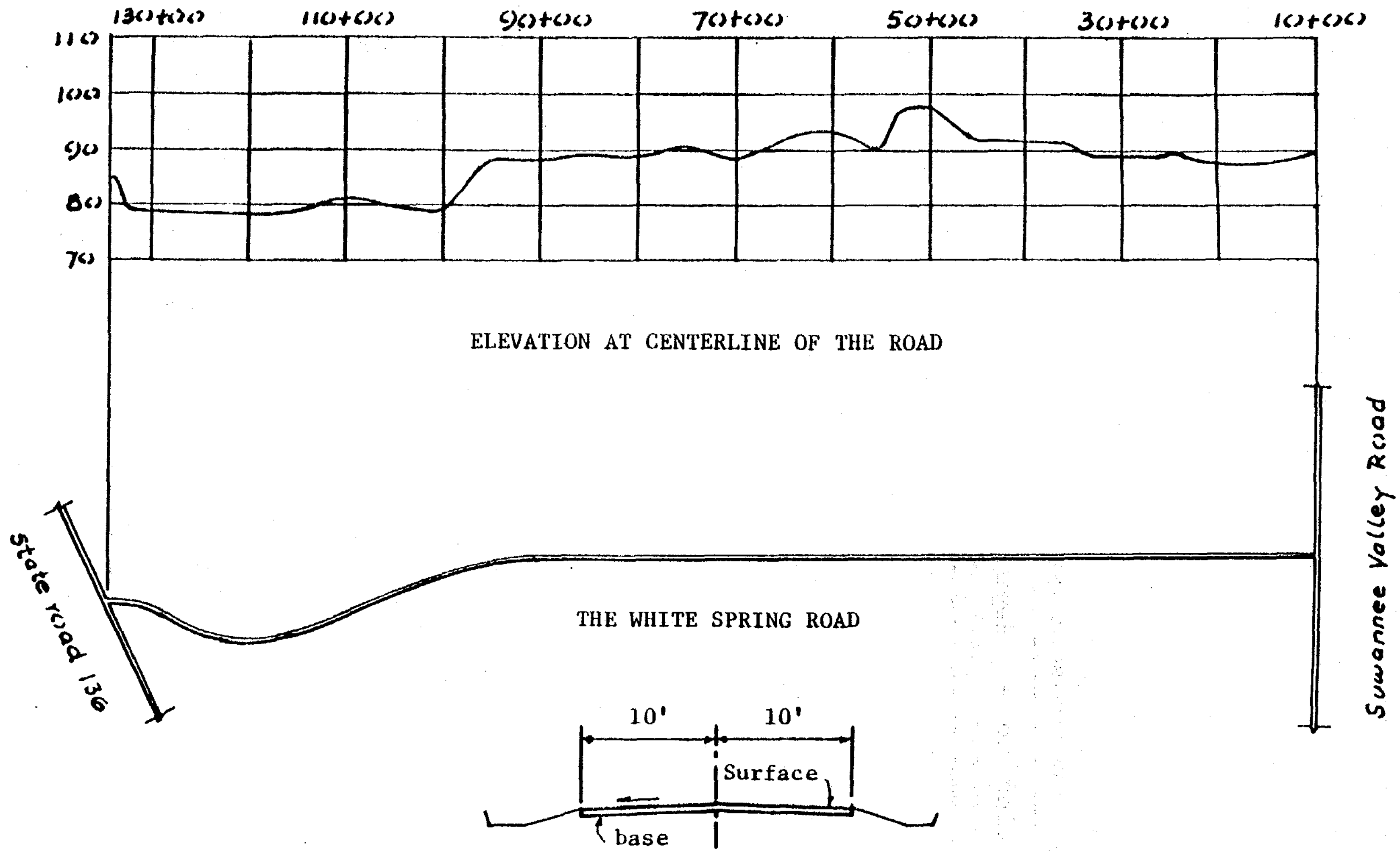
The third section, Station 25+00 to 66+00, was constructed by placing a single 6" lift of phosphogypsum on the existing road and mixing to a depth of approximately 15". The sheepsfoot roller was again used for the first part of the compactive effort and followed with the steel wheel roller and the pneumatic tire roller. Moisture content in the soil during the compaction was maintained at less than 10%.

Cutback asphalt RC-70 was applied at a rate of 0.2 gal/sq. yd. to seal the finished base surface of the entire road. The section, Station 50+00 to 100+00 was then covered with a tack coat and subsequently a 1" asphalt surface.

The remaining section of the road, Station 25+00 to 50+00, was spread with a layer of fine sand.

3.2.2 Columbia County Experimental Road

The experimental road is shown in Figure 3.2. The base materials used in the first section of the road, Station 10+00 to 60+00, consisted of phosphogypsum and sand mixture of approximately 1 to 2 ratio. Truck loads of dihydrate phosphogypsum from Occidental Chemical Co., were hauled to the site in November 1986 and spread to an average depth of 5 inches. It was mixed into the existing soil (A-3 fine sand according to ASSHTO classification) with a rotomixer to a depth of about 14 inches. A total of three passes of the rotomixer was made to achieve uniform blending of the mixture. Before compaction of the mixture could be achieved, continuous rainfall and wet weather persisted for about two months. It was late January 1987 when the compaction operation resumed. After the long delay the phosphogypsum road base was initially scarified to lower the moisture content under the sun and subsequently graded to proper slope. The road base was then compacted by a steel wheeled roller and followed by a pneumatic tire roller.



CROSS SECTION

Figure 3.2

The base materials used for Station 60+00 to 81+00, and Station 81+00 to 95+00 consisted of blends of phosphogypsum and sand of approximately 1:1 and 2:1, respectively. Again a rotomixer was used to blend phosphogypsum and sand together, and compacted by a steel wheeled roller and pneumatic tire roller.

A short section of the road Station 95+00 to 100+00, was built with 100% dihydrate phosphogypsum which was hauled to the site and spread along the 500 foot section to an average depth of 12 inches. The road was shaped by a motor grader and compacted by a steel wheeled roller and pneumatic tire roller.

A laboratory investigation, described in Chapter II, indicates that phosphogypsum is sensitive to water. Road surfaces built with 100% phosphogypsum tend to become slippery and sometimes muddy when subjected to continuous rainfall. Therefore, it is advisable to avoid the rainy season for road base construction.

To seal and protect the finished base surface, cutback asphalt RC-30 was spread on the surface and subsequently a prime coat of liquid hot asphalt and sand/asphalt screenings were placed and rolled. The completed wearing surface consists of 1 to 2 inches of Type III asphalt concrete, sloping from the center of the pavement to both edges.

IV. TESTS OF EXPERIMENTAL ROADS

4.1 LABORATORY TESTS

On-site mixtures were taken to the laboratory for determining the moisture density and California Bearing Ratio. Specimens for the tests were prepared in accordance with the Modified Proctor specifications. Phosphogypsum used in the Polk County and Columbia County projects was supplied by U. S. Agri-Chemicals and Occidental Chemical Co., respectively. Figures 4.1 and 4.2 show moisture-density relationships of the 1:2 phosphogypsum-soil mixtures as compared to that of the on-site soil for Polk County and Columbia County roads, respectively. The improvement on the optimum density as shown in the figures is in the order of 6 to 7% for the use of phosphogypsum in the mixture.

Figures 4.3 and 4.4 show the moisture - CBR relationships of the 1:2 phosphogypsum-soil mixtures as compared to that of the on-site soil for Polk County and Columbia County roads, respectively. The improvement on the bearing capacity as shown in the figures is as much as 100% for the use of phosphogypsum in the mixtures.

Laboratory test data also indicate the importance of controlling moisture content at the time of compaction. Maximum density and bearing capacity can only be achieved by the use of optimum moisture content in the mixtures.

4.2 FIELD MONITORING AND TESTING

Field supervision and testing were performed during the base construction stage. It consisted of nuclear density measurements, moisture determinations, Clegg Impact Tests and California Ratio Tests. Following the application of the Type III asphalt concrete wearing surface, dynaflect testing was conducted at the Columbia County project. Dynaflect tests conducted at the Polk County road was approximately two years after the completion of the road.

4.2.1 Nuclear Density Tests

Initially, compaction requirements were established at 98% of the laboratory Modified Proctor, as presented in Figures 4.1 and 4.2, but the requirement was later reduced to 95% due to the difficulties in controlling moisture content as well as achieving

Polk County Road

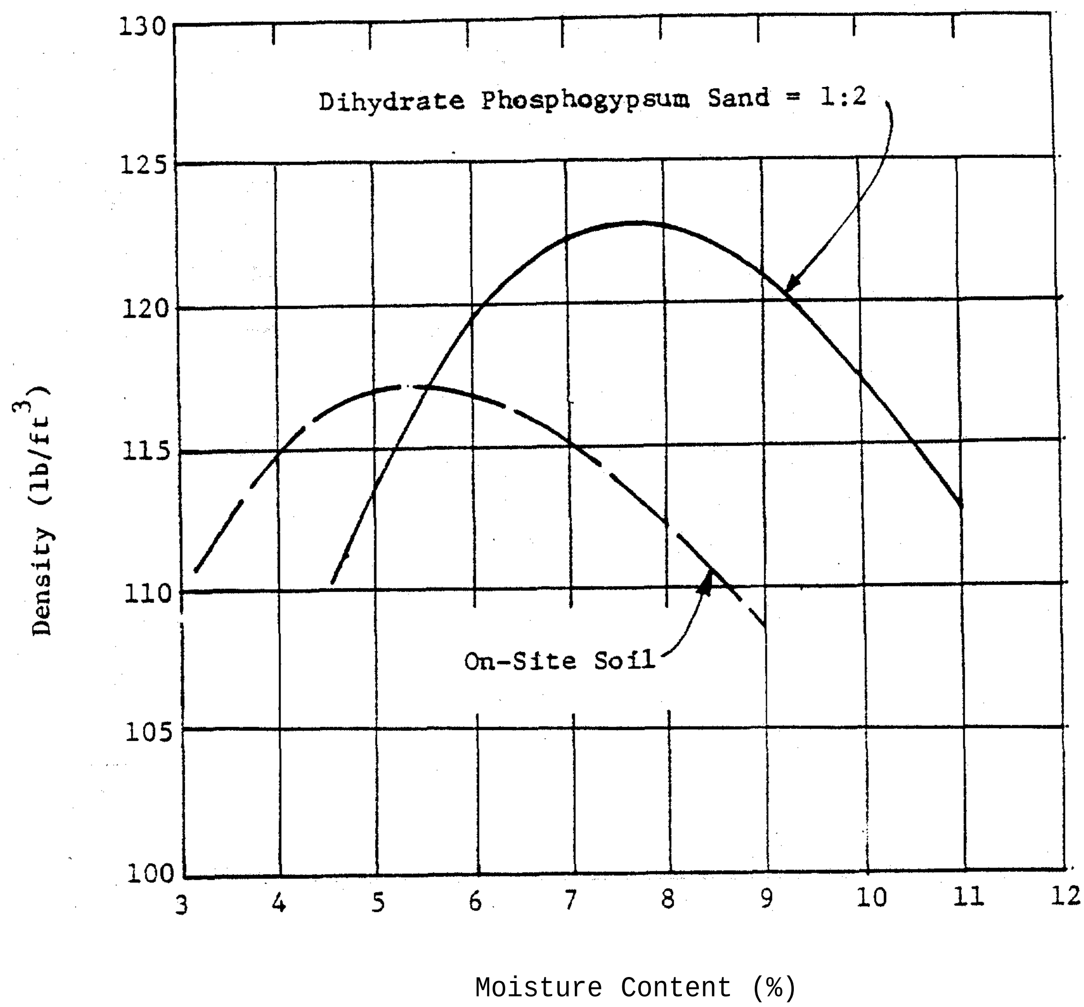


Figure 4.1 Moisture Density Relationship

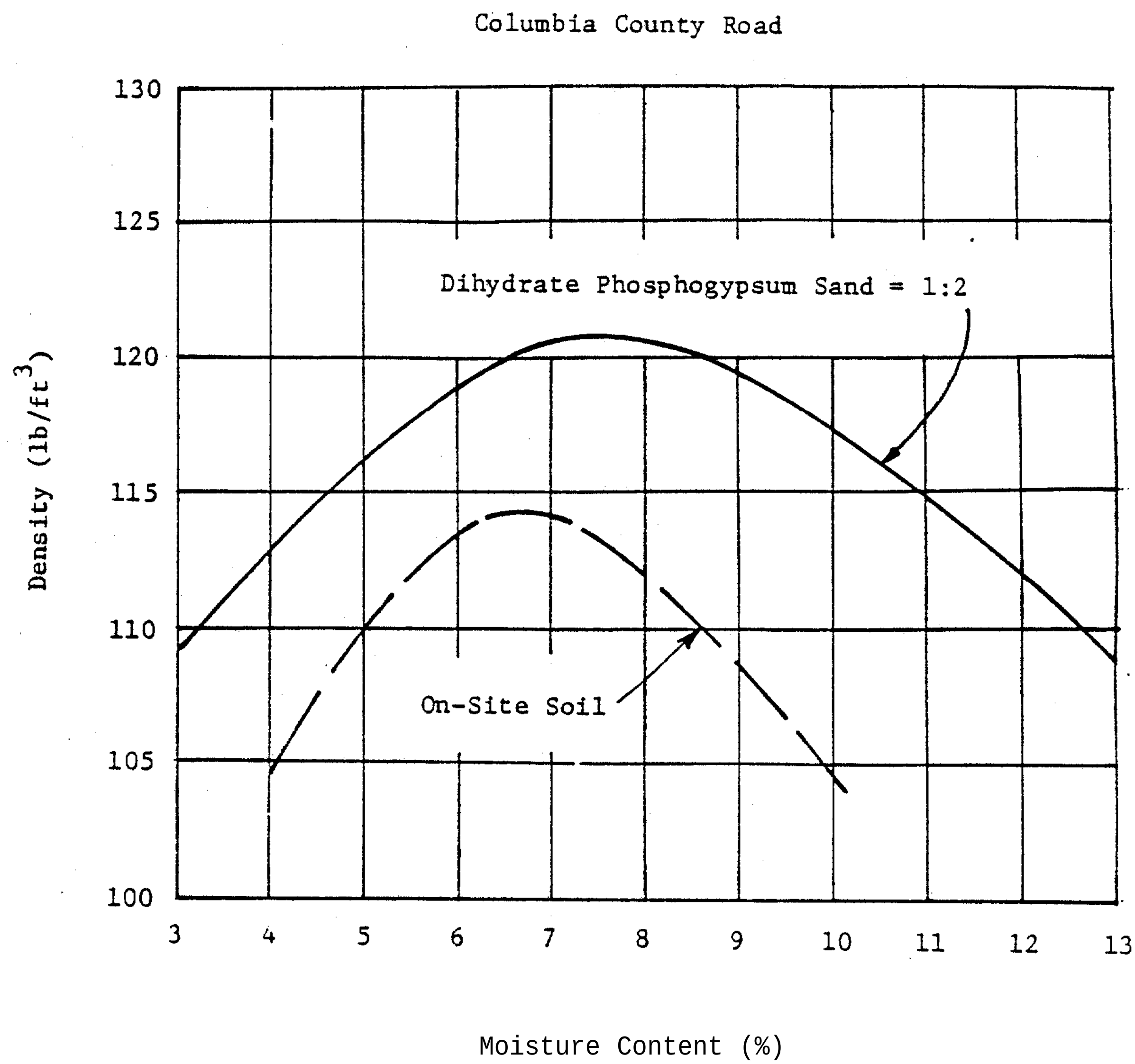
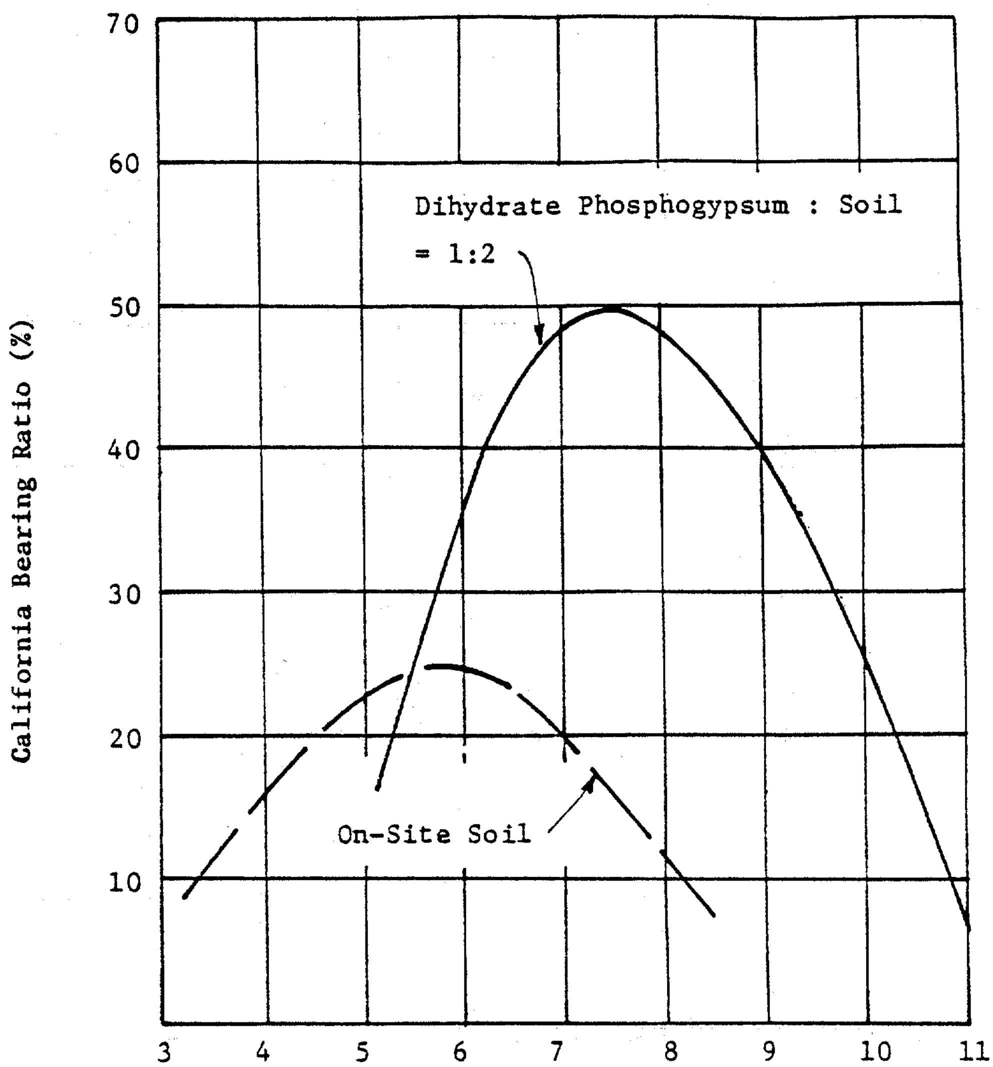


Figure 4.2 Moisture Density Relationship

Polk County Road



Moisture Content

Figure 4.3 Moisture and CBR Relationships

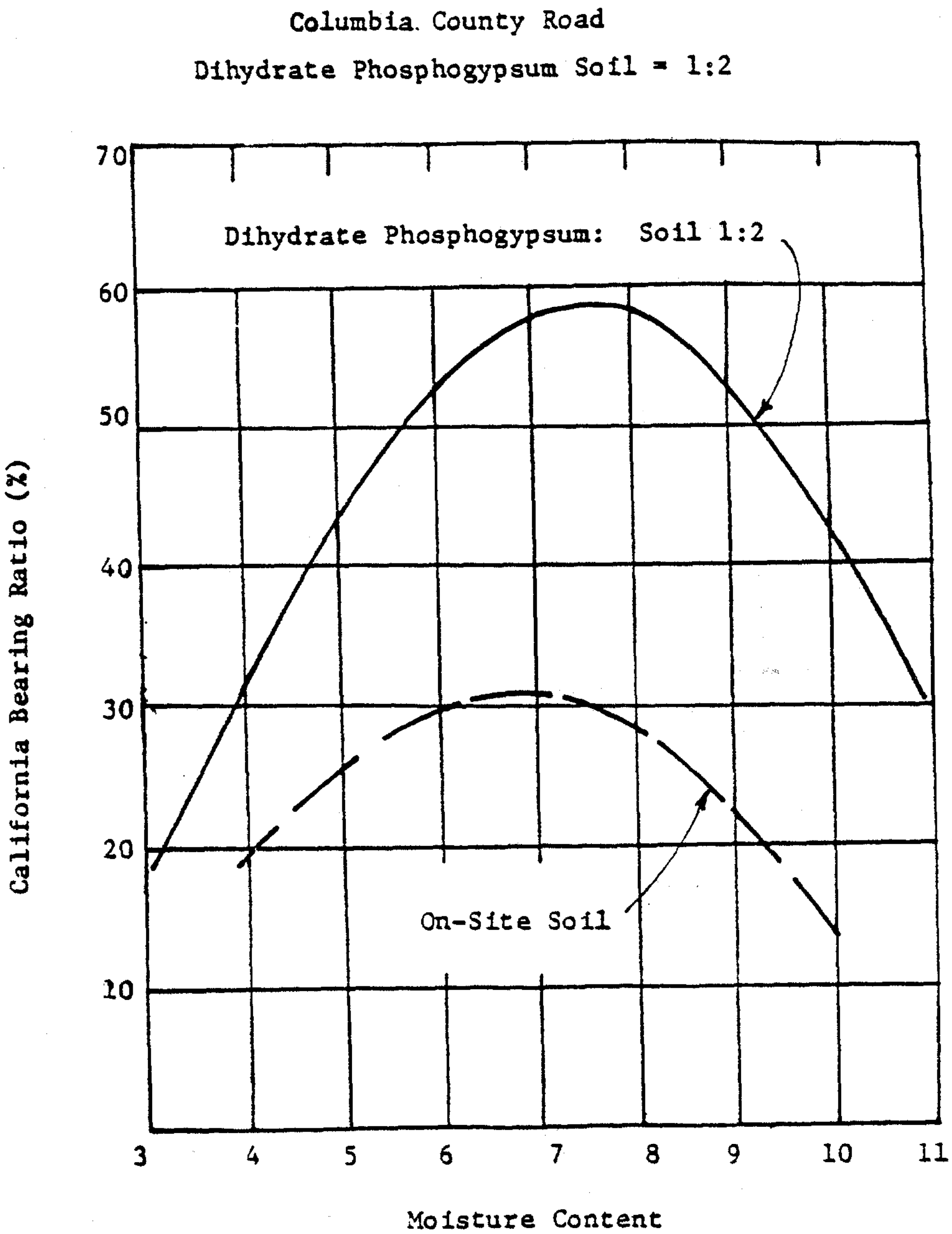


Figure 4.4 Moisture and CBR Relationships

uniform mixing operation on-site.

Nuclear density and speedy moisture tests were conducted at various locations along the completed roadway base section to verify compliance with the established density requirements. Tables 4.1 and 4.2 show the values of field density and moisture obtained at the completion of the compaction operation for the Polk County and Columbia County projects, respectively.

4.2.2 California Bearing Ratio Tests

The bearing capacity of the road base at the Polk County road was measured in accordance with the California Bearing Ratio Test. Test results, as shown in Table 4.3, indicated that the bearing capacity of the compacted on-site soil can be greatly improved by stabilizing the soil with phosphogypsum. Phosphogypsum-soil mixtures are sensitive to moisture content resulting in the decrease of CBR value with the increase of moisture content.

4.2.3 Clegg Impact Tests

The Clegg Impact Tester was designed and developed by Dr. B. Clegg of the University of Western Australia. It consists primarily of a modified AASHTO compaction hammer weighing 10 lbs. (4.5 kg), with a piezoelectric accelerometer attached to the hammer. The hammer is dropped manually from a height of approximately 18 inches through a guide tube. Upon impact with the soil, output from the accelerometer is fed into a hand held peak level meter. Clegg's Impact Values (CIV) of the fourth Impact are recorded for analysis.

Testing with the Clegg Impact device was conducted at each of the nuclear density test locations at the Columbia County Project. The CIV were obtained at the centerline and at 6 feet and 9 feet offsets from the centerline, both left and right. Table 4.4 is a numerical summary of the CIV data.

Figure 4.5 shows the transverse variation of the CIV. Longitudinal variation of CIV for the centerline and 6 feet and 9 feet offsets from the centerline are shown in Figures 4.6 and 4.7. The data indicates that the CIV further away from the centerline are lower than those close to the center of the pavement.

The CIV had been correlated with laboratory LBR (limerock bearing ratio) for some Florida soils such as limerock, sand-clay and clayey and silty sand at the Bureau of Materials Research, Florida Department of Transportation, but not for phosphogypsum and sand mixtures. Generally, the higher values of the CIV correspond to the higher values of the LBR.

Table 4.1

FIELD DENSITY AND MOISTURE - POLK COUNTY

	Location	γd	% w	% Compaction
1	54+00	114.8	5.8	92.5
2	62+00	114.6	5.6	92.3
3	68+00	117.6	4.3	92.3
4	78+00	121.6	2.5	95.4
5	90+00	122.9	3.3	96.4
6	93+00	124.0	6.1	97.3

Table 4.2

FIELD DENSITY AND MOISTURE - COLUMBIA COUNTY

	Location	Yd	%w	%compaction
1	10+97, 9'LT	110.6	11.0	92
2	14+72, 7'RT	115.9	7.2	97
3	18+63, 6'RT	114.7	8.3	96
4	23+06,	117.1	8.3	98
5	27+50, 6'LT	119.9	7.1	100
6	31+29, 10'RT	116.9	6.7	97
7	36+59, 9'LT	114.9	7.5	96
8	41+50,	117.6	8.3	98
9	46+76, 8'RT	115.3	7.8	96
10	52+10, 6'LT	114.8	9.1	96
11	56+78,	115.9	8.2	97
	60+55	END GYPSUM BLEND		

Table 4.3

ON SITE MEASUREMENT OF CBR VALUES - POLK COUNTY ROAD

Date	Station	PPG/Soil	Moisture Content	CBR (%) Readings	Average CBR Value	Remarks
9/10/86	90 to 100	0:1	L	12 21	17	Fine sand with organic compound
9/17/86	90 to 100	1:3	L	110 135 115 109 198	133	
10/9/86	90 to 100	1:3	L	103 148	126	
	66 to 90	1:4	L	55 53 85	64	PPG/sandy clay
	50 to 66	1:2	H	47 42 45	43	PPG/fine sand with organic compound
11/13/86	90 to 100	1:1	H	45 49 53	49	Small areas of asphalt tack coat were removed for CBR tests
	66 to 90	1:4	H	62 48 67 40	54	
	50 to 66	1:2	H	45 40 42 45	46	

Table 4.4

CLEGG IMPACT TESTS

Location	9'LT	6'LT	C. L.	6'RT	9'RT
10+97	25	31	31	31	18
14+72	26	41	32	22	19
18+63	15	23	27	25	18
23+06	24	27	27	35	22
27+50	14	20	23	22	23
31+29	16	24	25	24	18
36+59	20	30	26	24	22
41+50	16	18	23	20	16
46+76	24	38	33	21	16
52+10	34	29	27	26	27
56+78	19	29	31	24	17
Mean	21.2	28.2	27.7	24.9	19.6
Standard Deviation	6.1	7.0	3.5	4.5	3.4

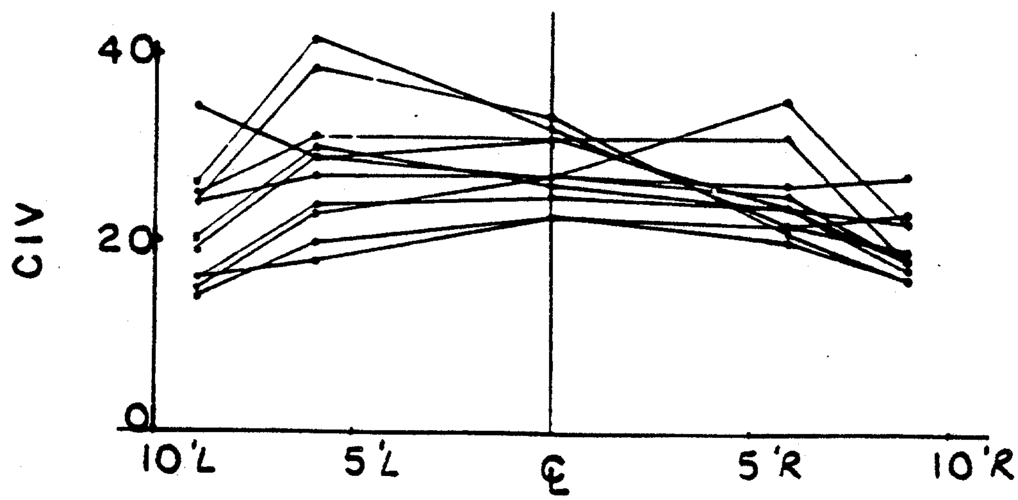


Figure 4.5 Transverse CIV Profile

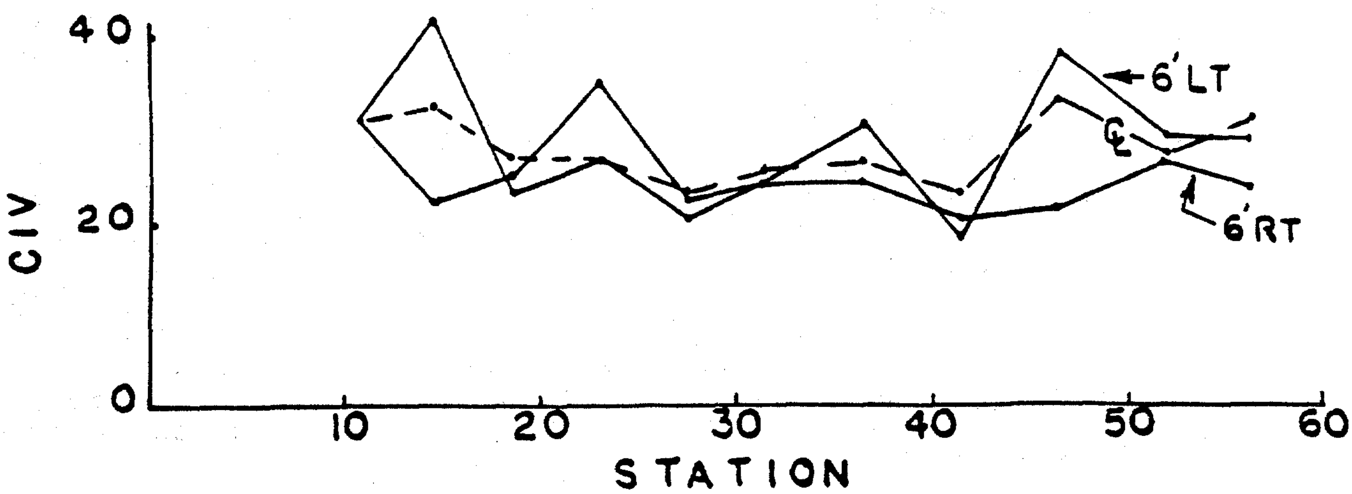


Figure 4.6 Longitudinal CIV Profile

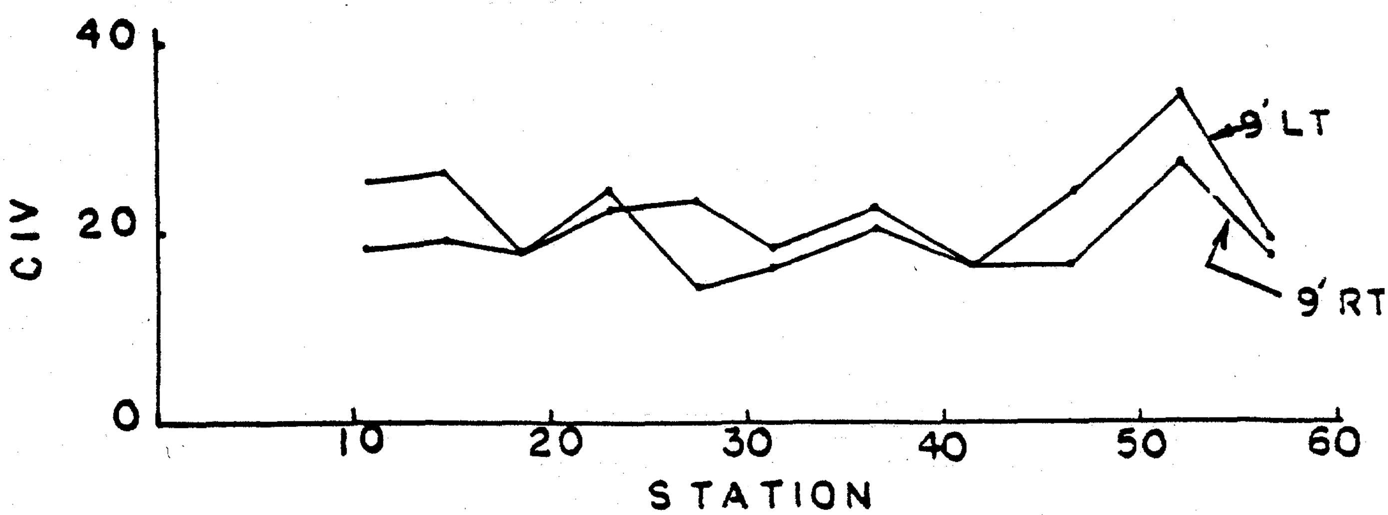


Figure 4.7 Longitudinal CIV Profile

4.2.4 Dynaflect Testing

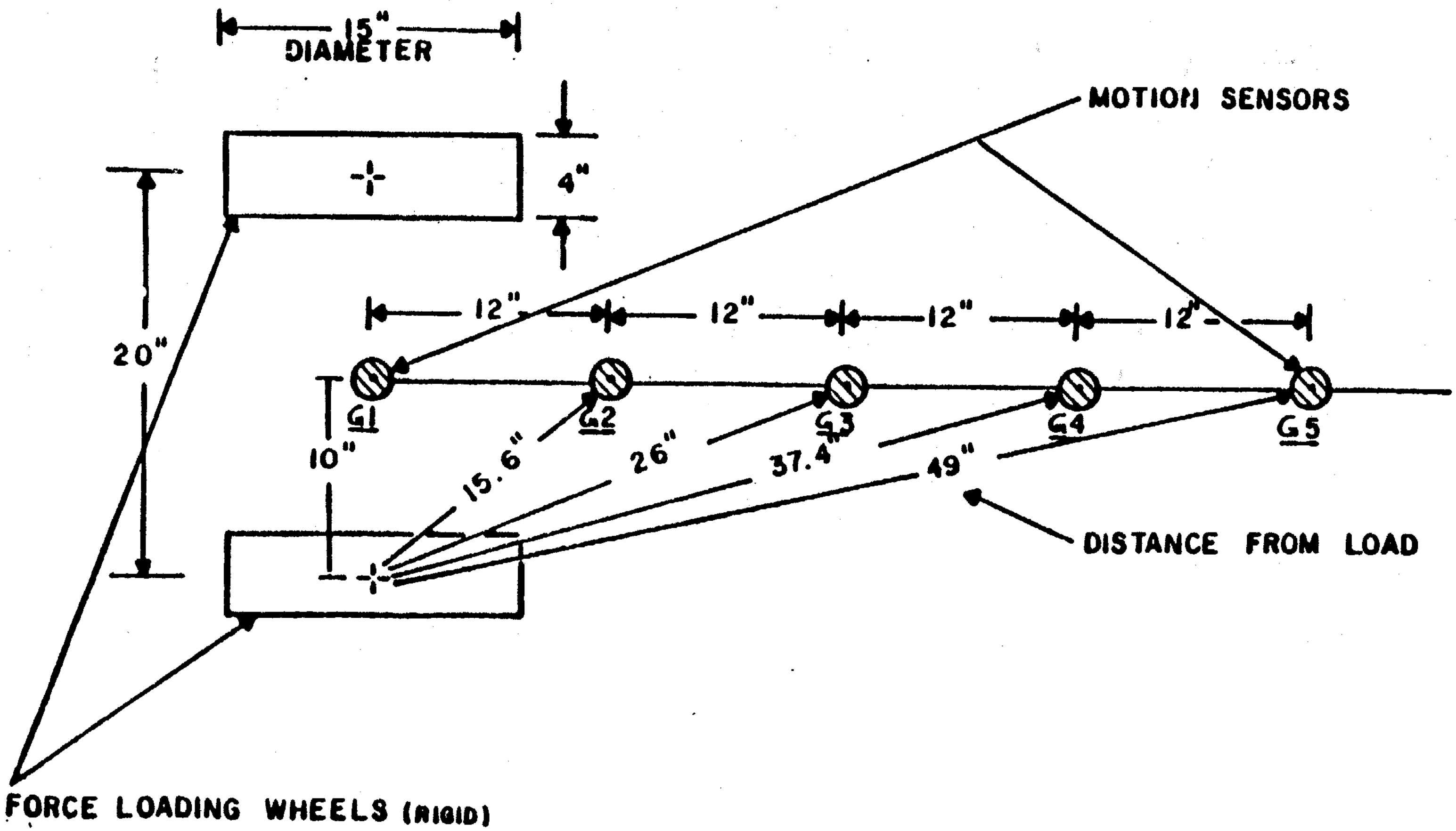
1. Columbia County Road.

Following the paving of the 5000-foot test section at the Columbia County Project, the dynaflect was used for the non-destructive measurement of dynamic deflections. It consists of a dynamic force generator, sensor assembly and digital control device mounted on a relatively lightweight (2,000 pound) two-wheel trailer. Two counter-rotating steel weights provide a 1,000 pound dynamic force to the pavement surface through a pair of rigid wheels. Deflections along the pavement surface away from the rigid wheels are measured by five geophones spaced at one foot intervals as shown in Figure 4.8. Electric signals from each geophone are amplified and recorded as deflections in milli-inches. The deflections of sensor G2 are then used to estimate soil modulus E of the base using equations developed from field research studies conducted by the Florida Department of Transportation.

Dynaflect testing performed on the Columbia County project consisted of 29 test sites in each traffic lane along the outside wheel path (OWP) plus 29 test sites in the northbound traffic lane along the inside wheel path (IWP). Figures 4.9, 4.10, and 4.11 show the measured deflections at the five geophone locations for northbound inner wheel path (NBTL - IWP), northbound outer wheel path (NBTL - OWP) and southbound outer wheel path (SBTL-OWP), respectively, with the nearest geophone (Gl) measuring the maximum deflection. The IWP deflection data are lower than the OWP measurements indicating better compaction and confirmed by the CIV data in the previous section. Table 4.5 gives a comparison of the computed E values for the phosphogypsum and sand mixture and the Clegg Impact Values (CIV) at approximate corresponding locations.

2. Polk County Road.

Dynaflect testing was conducted by the Florida Department of Transportation on July 13, 1988. The paved portion of the road was divided into three sections as shown in Figure 4.12. The tests as conducted, consisted of 17 test sites in Section 1, 16 test sites in Section 2 and 20 test sites in Section 3 and in each traffic lane along the outside wheel path (OWP) plus the same number of test sites in the northbound traffic lane along the inside wheel path (IWP). Figures 4.13, 4.14 and 4.15 show the measured deflections at the five geophone locations for northbound outer wheel path (NCBTL - OWP) at Sections 1, 2, and 3, respectively. Figures 4.16, 4.17 and 4.18 show the measured deflections for northbound inner wheelpath (NBTL - IWP) at Sections 1, 2 and 3, respectively. Figures 4.19, 4.20 and 4.21 show the measured deflection for southbound outer wheelpath (SBTL - OWP) at Sections 1, 2 and 3, respectively. The deflection measurements taken at Parrish Road in Polk County project are generally less than those taken at White Springs Road in Columbia



DYNAFLECT MEASURING ARRAY

Figure 4.8

FLORIDA DOT BUREAU OF MATERIALS & RESEARCH
DYNAFLECT DEFLECTIONS ALL SENSORS

State Route: 0 Date Tested: 03-04-87
Lane: NBTL Date Printed: 03-18-87
A: 28000NT1.D01 IWP Scale: 1 Mi/Page

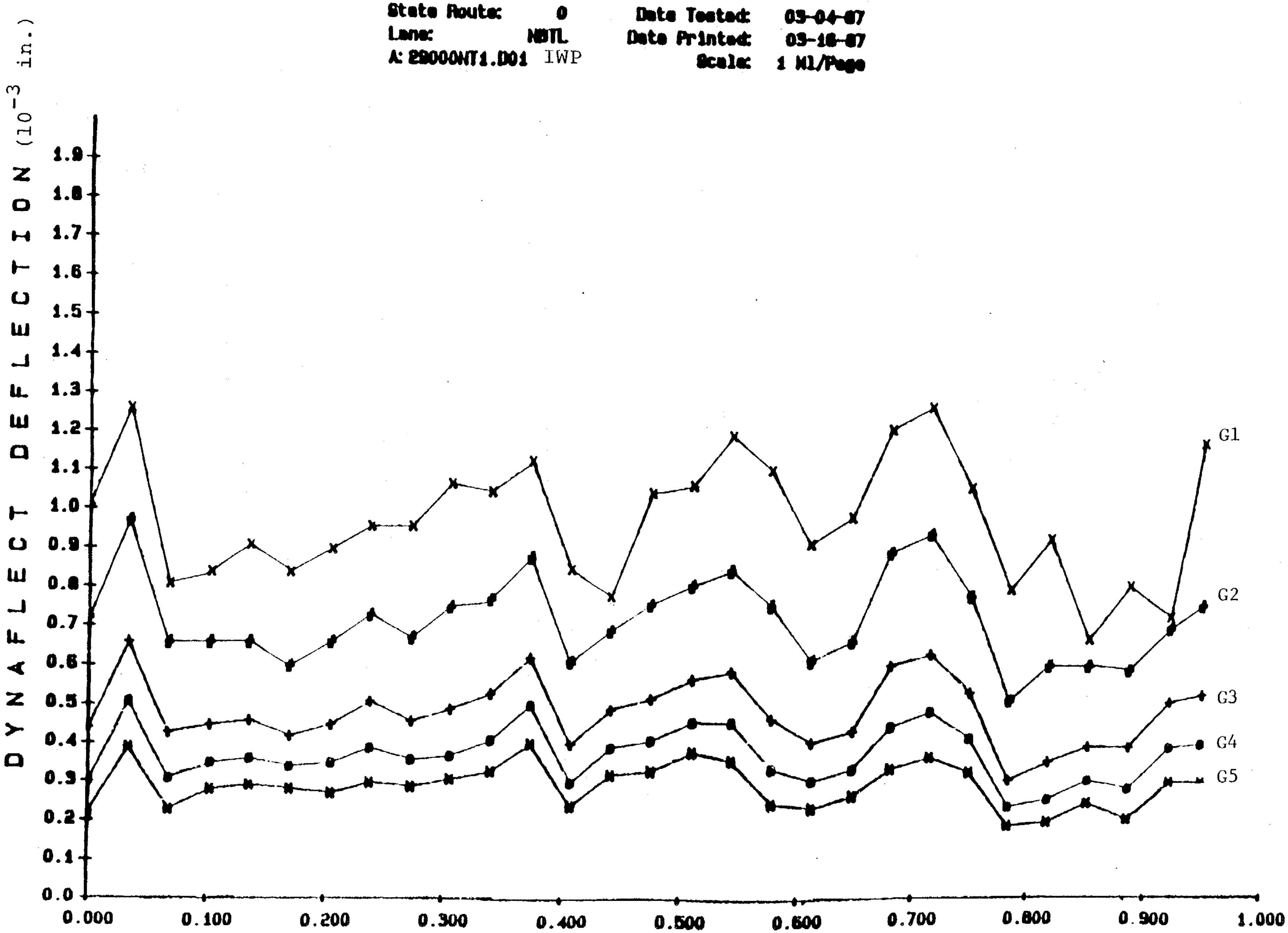


Figure 4.9 Mile Post

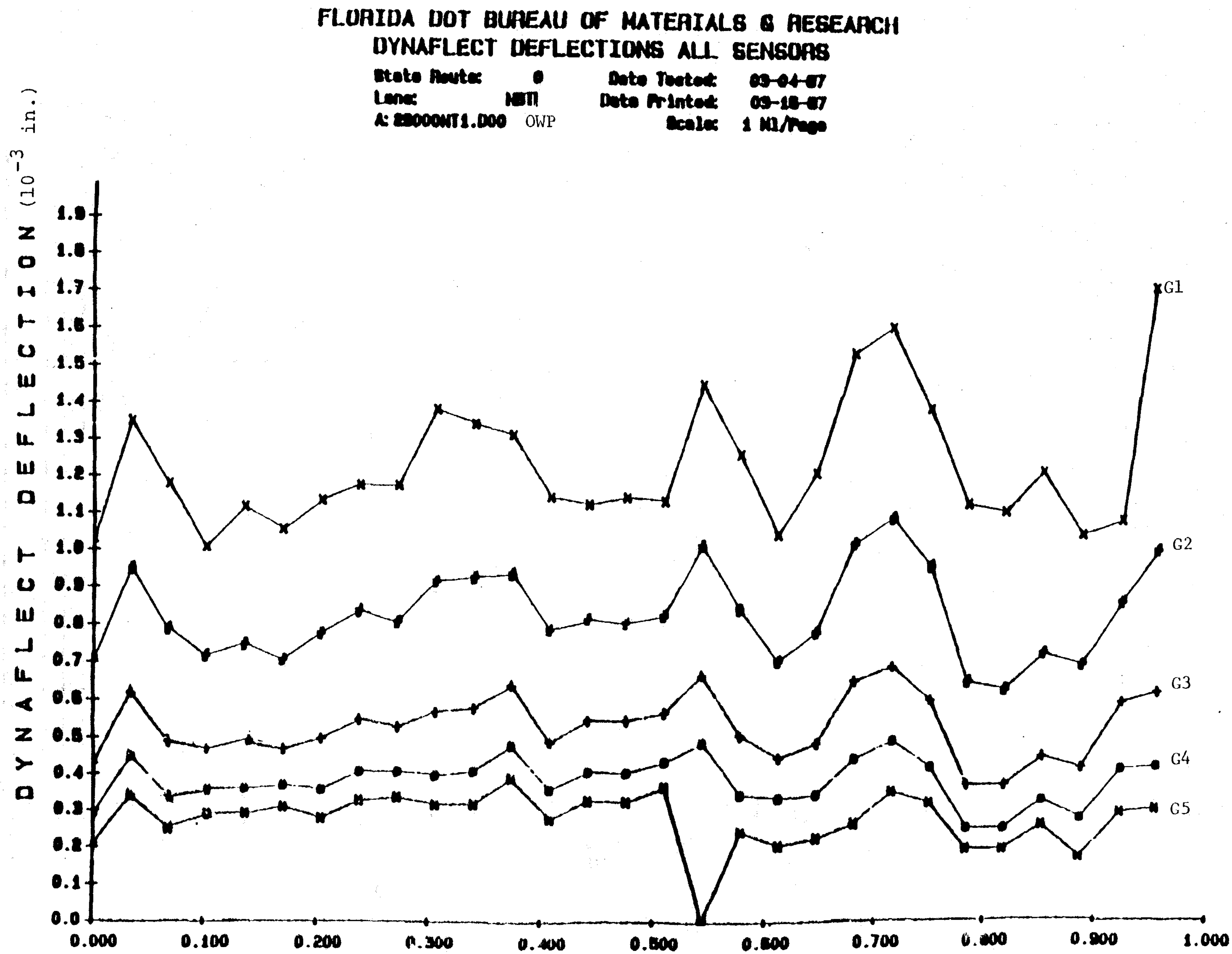


Figure 4,10 Mile Post

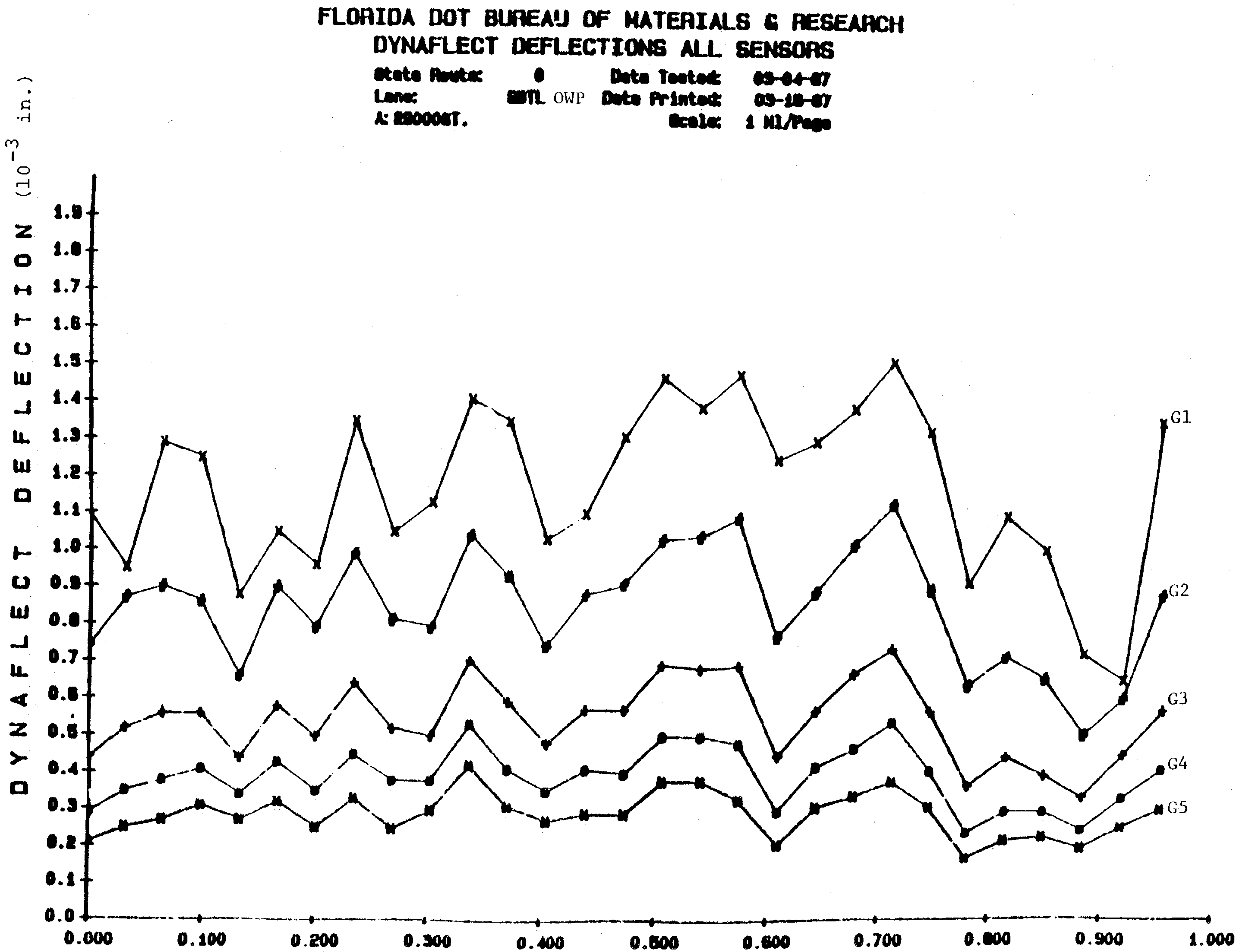


Figure 4.11 Mile Post

Table 4.5

CLEGG VS DYNAFLECT "E "VALUES

Location	M.P.	MODULUS E FROM DYNAFLECT			CLEGG IMPACT TEST		
		NBOWP	SBOWP	NBIWP	9'RT	C.L.	9'LT
10+97	0.018	29,458	33,215	33,657	25	31	18
14+72	0.089	32,189	30,902	35,095	26	32	19
18+63	0.163	33,884	30,234	36,740	15	27	18
23+06	0.247	31,253	28,880	33,435	24	27	22
27+50	0.331	29,761	28,204	32,588	14	23	23
31+29	0.403	32,189	33,217	36,450	16	25	18
36+59	0.504	31,433	28,335	32,288	20	26	22
41+50	0.597	31,076	27,575	34,353	16	23	16
46+76	0.696	27,454	28,469	29,838	24	33	16
52+10	0.797	35,095	35,618	37,817	34	27	27
56+78	0.886	33,884	39,725	36,740	19	31	16
60+10	0.949	END PAVEMENT					

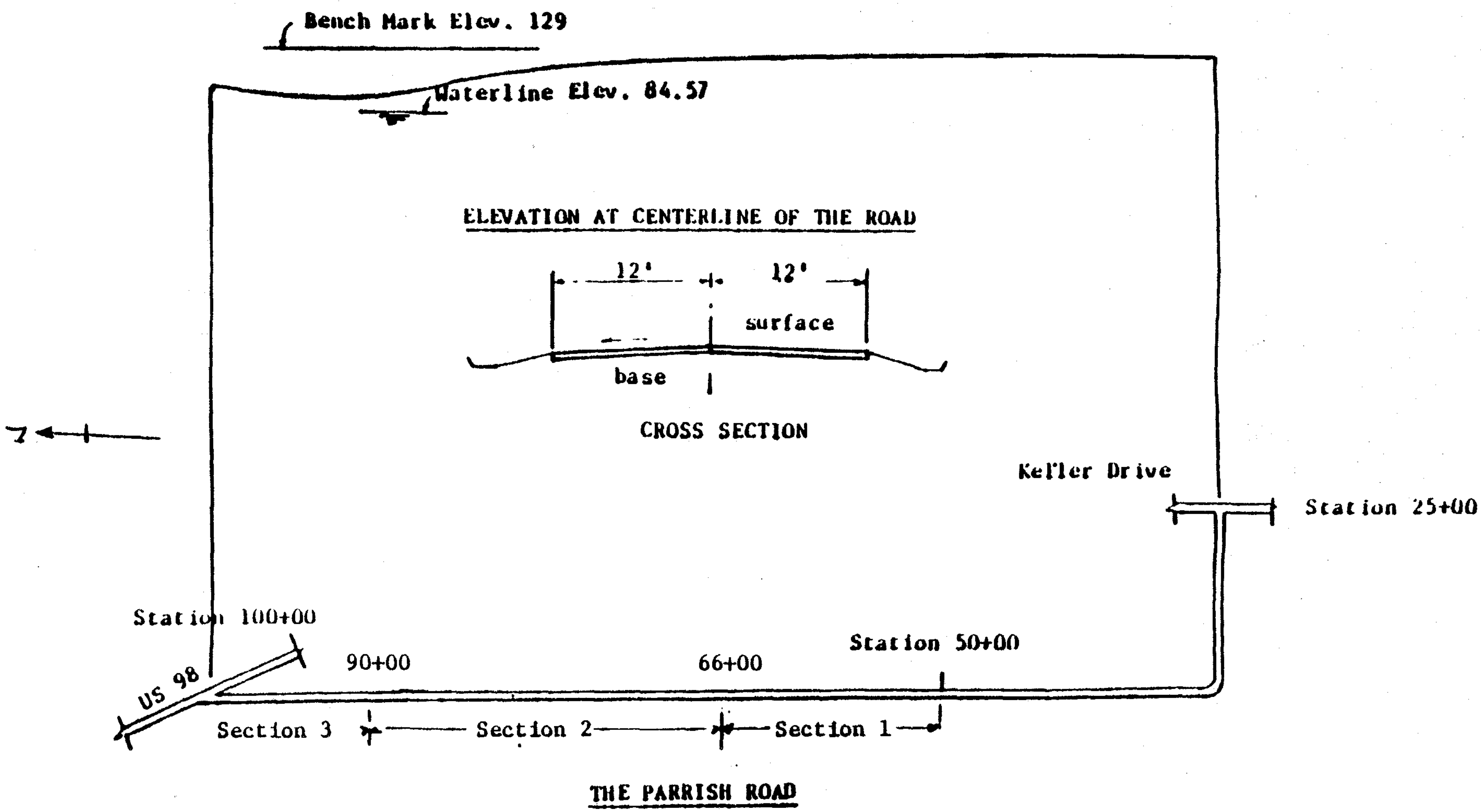

Bench Mark Elev. 129
Waterline Elev. 84.57
ELEVATION AT CENTERLINE OF THE ROAD
12'
12'
surface
base
CROSS SECTION
Keller Drive
Station 25+00
Station 100+00
US 98
90+00
66+00
Station 50+00
Section 3
Section 2
Section 1
THE PARRISH ROAD

Figure 4.12

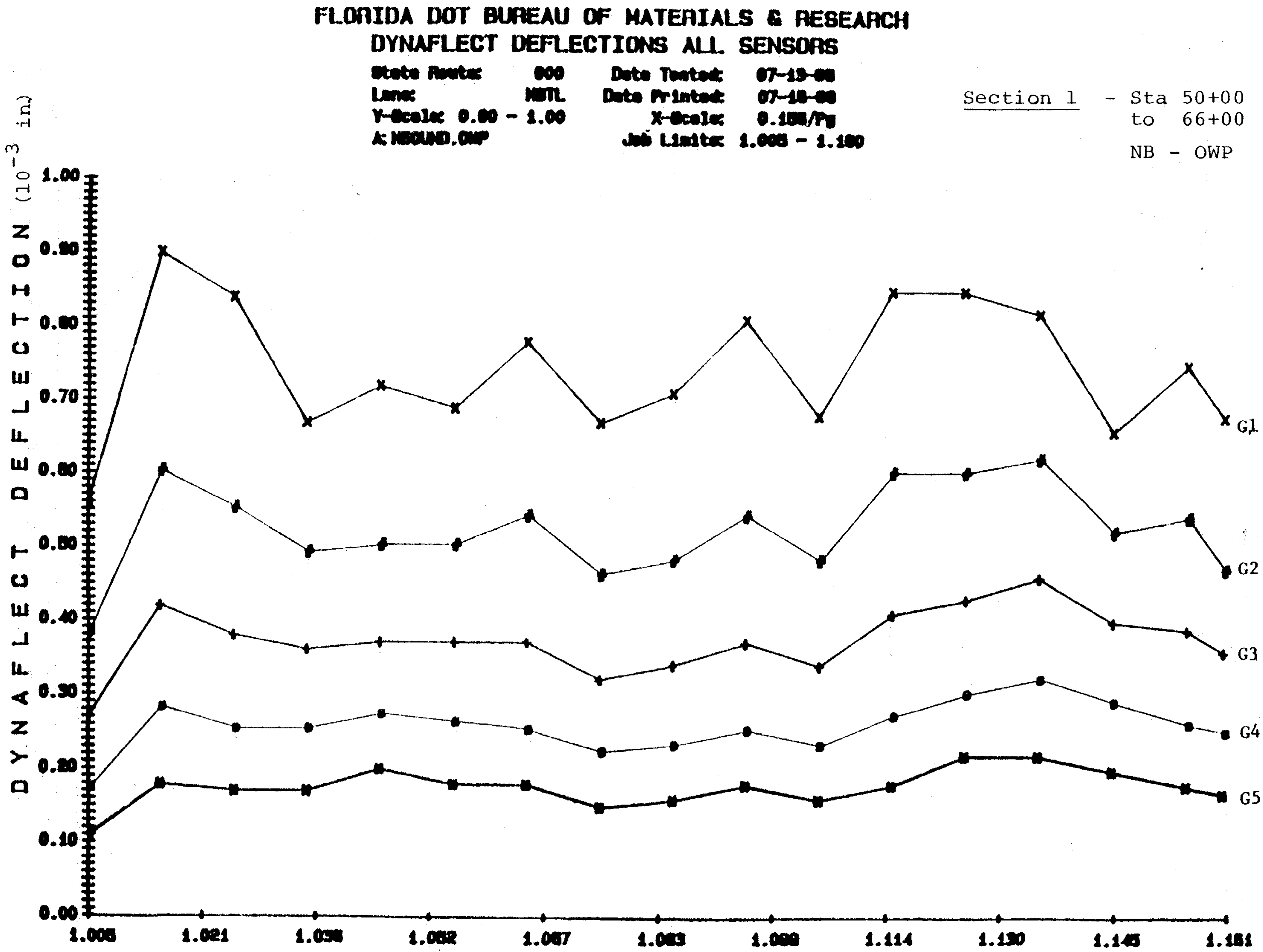


Figure 4.13 Mile Post

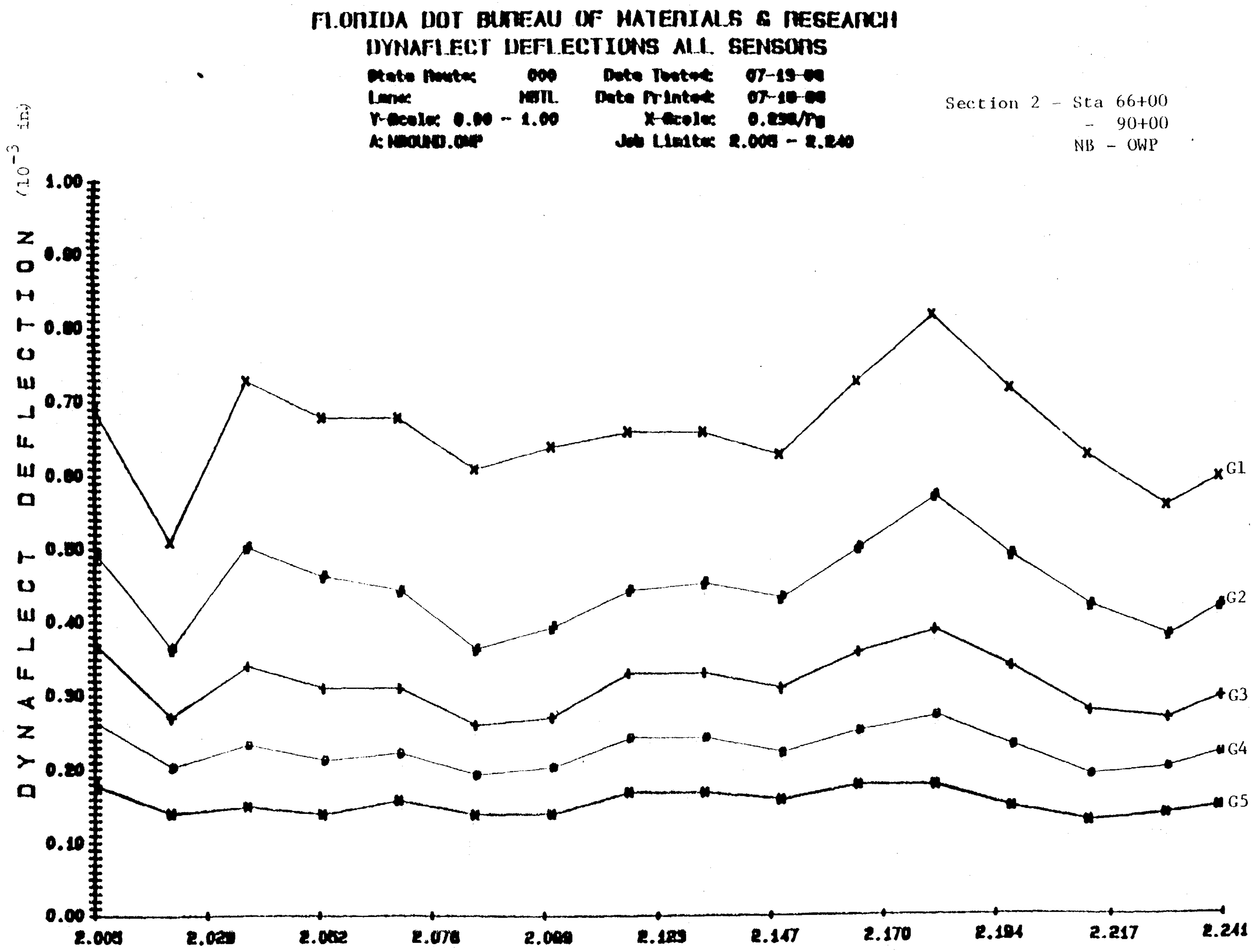


Figure 4.14 Mile Post

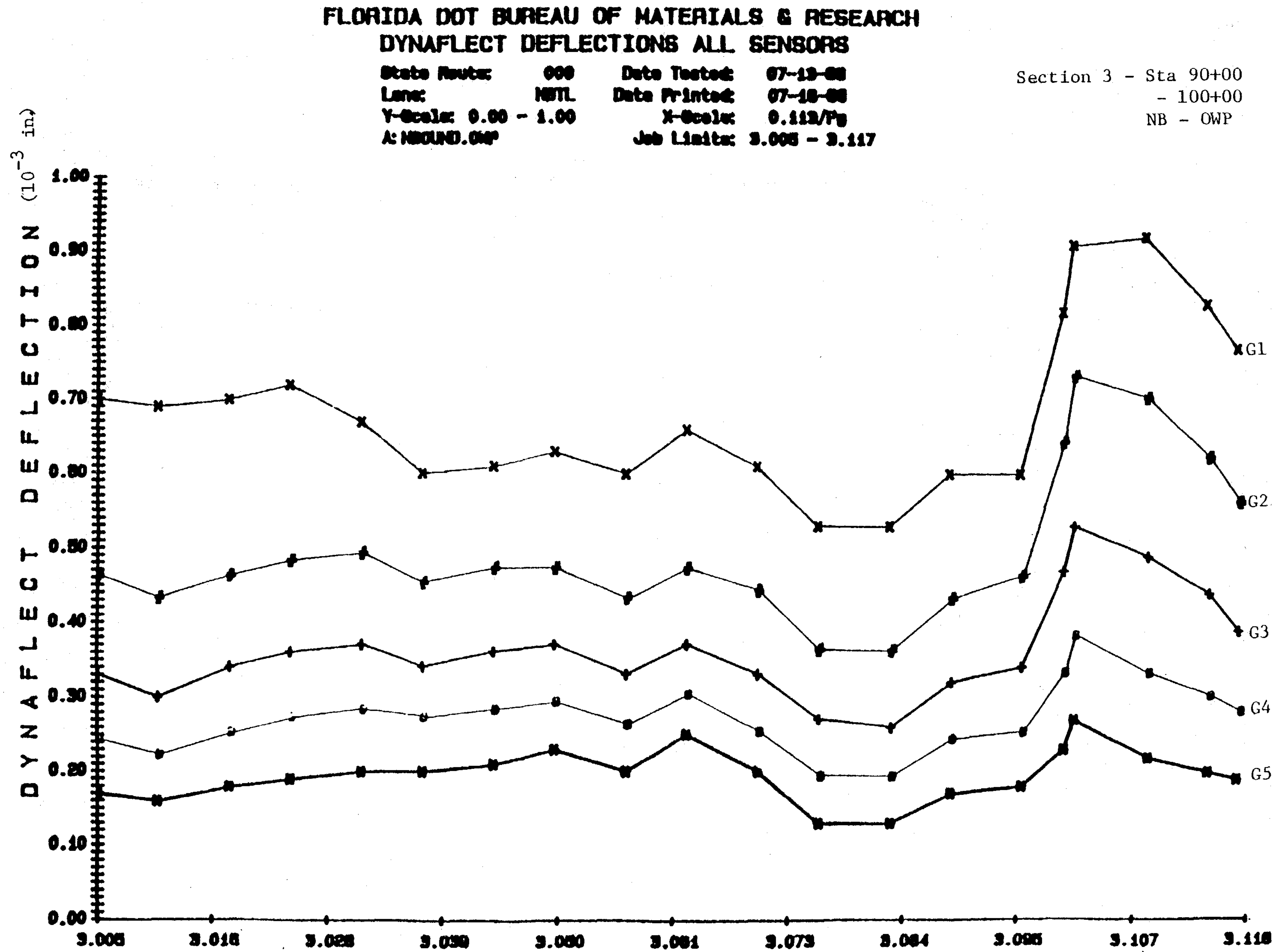


Figure 4.15 Mile Post

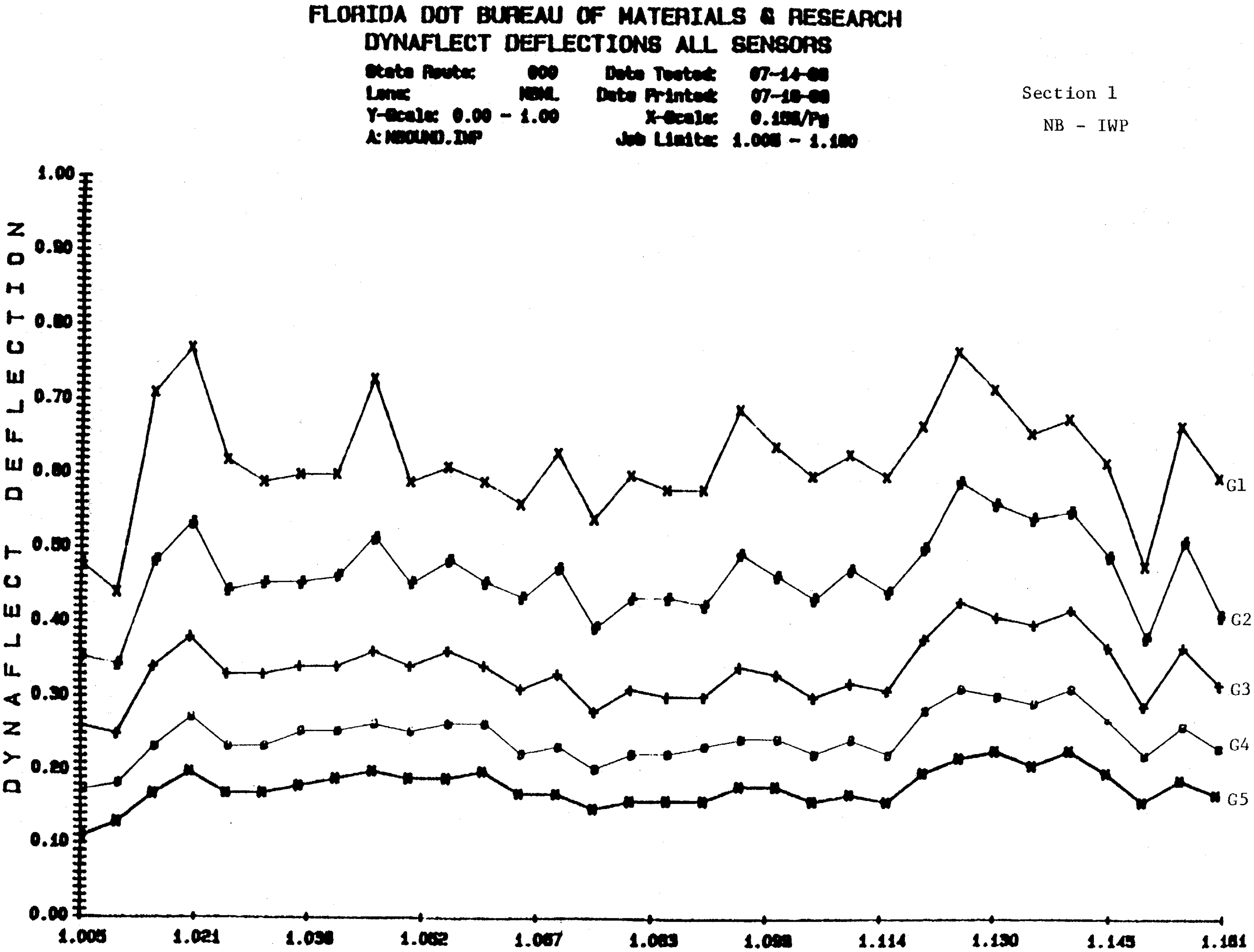


Figure 4.16 Mile Post

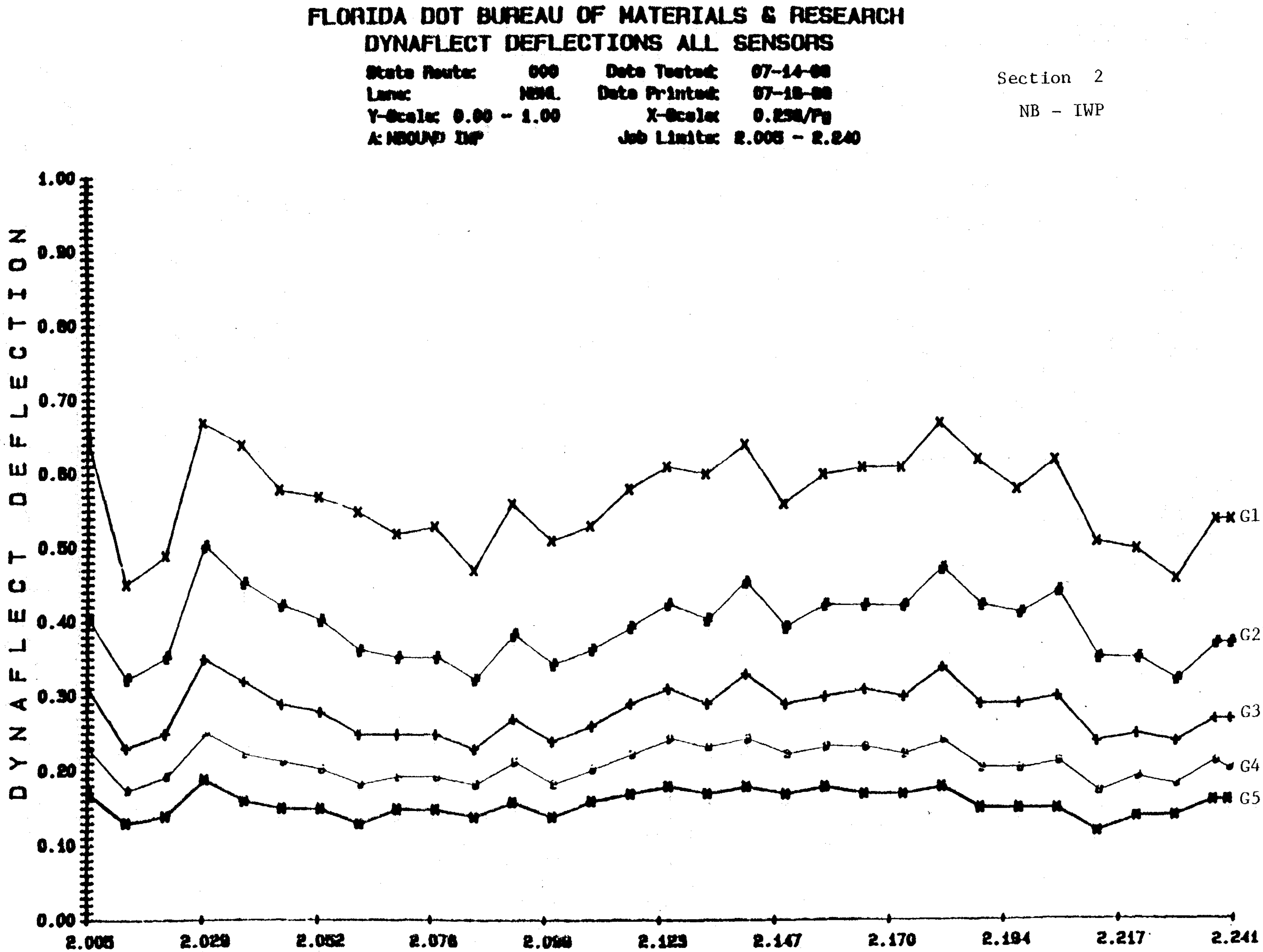


Figure 4.17 Mile Post

FLORIDA DOT BUREAU OF MATERIALS & RESEARCH
DYNAFLECT DEFLECTIONS ALL SENSORS

State Route: 000 Date Tested: 07-14-88
Lane: NBNL Date Printed: 07-18-88
Y-Scale: 0.00 - 1.00 X-Scale: 0.112/Pg
A:NBOUND.IMP Job Limits: 3.005 - 3.117

Section 3
NB = IWP

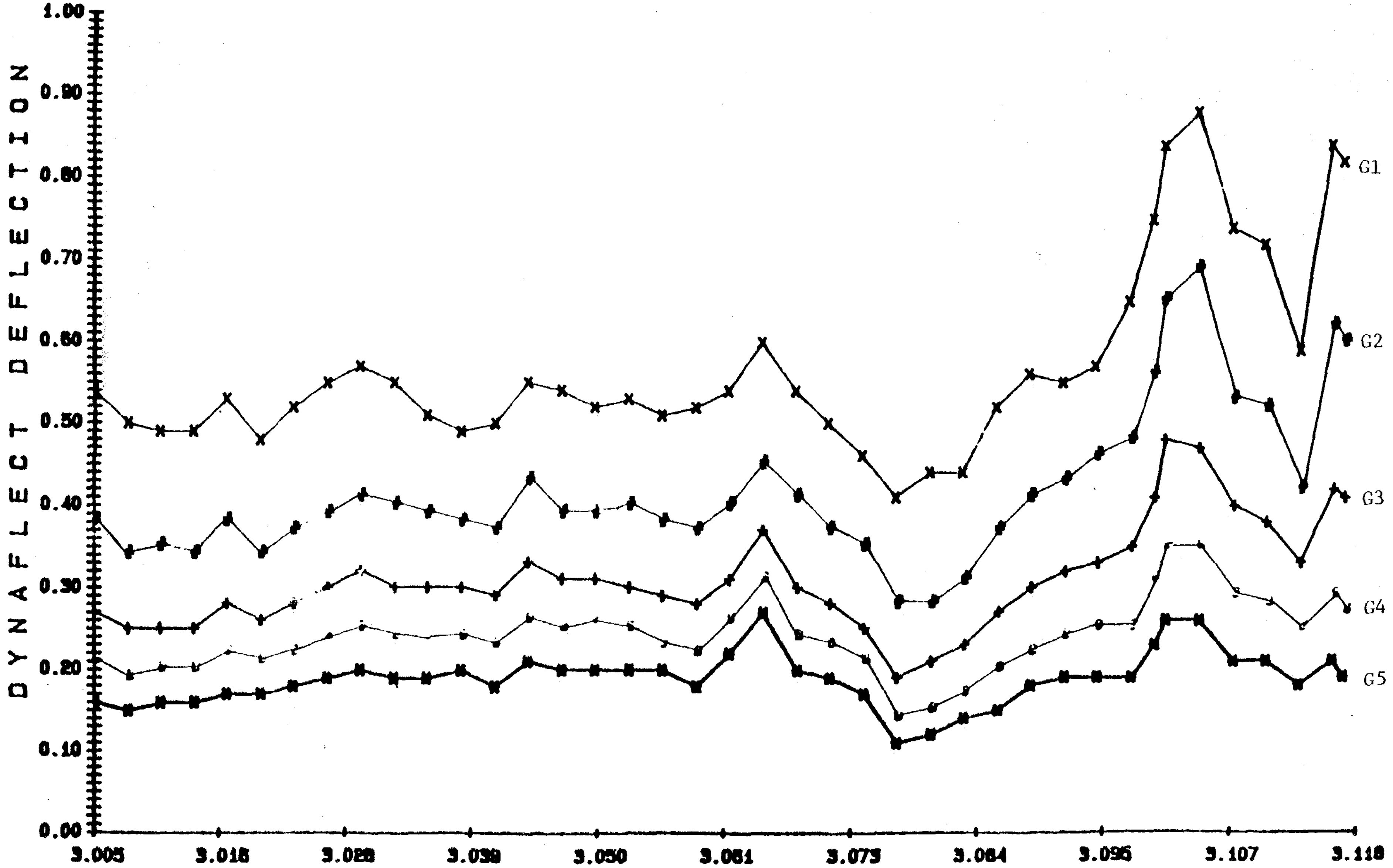


Figure 4.18 Mile Post

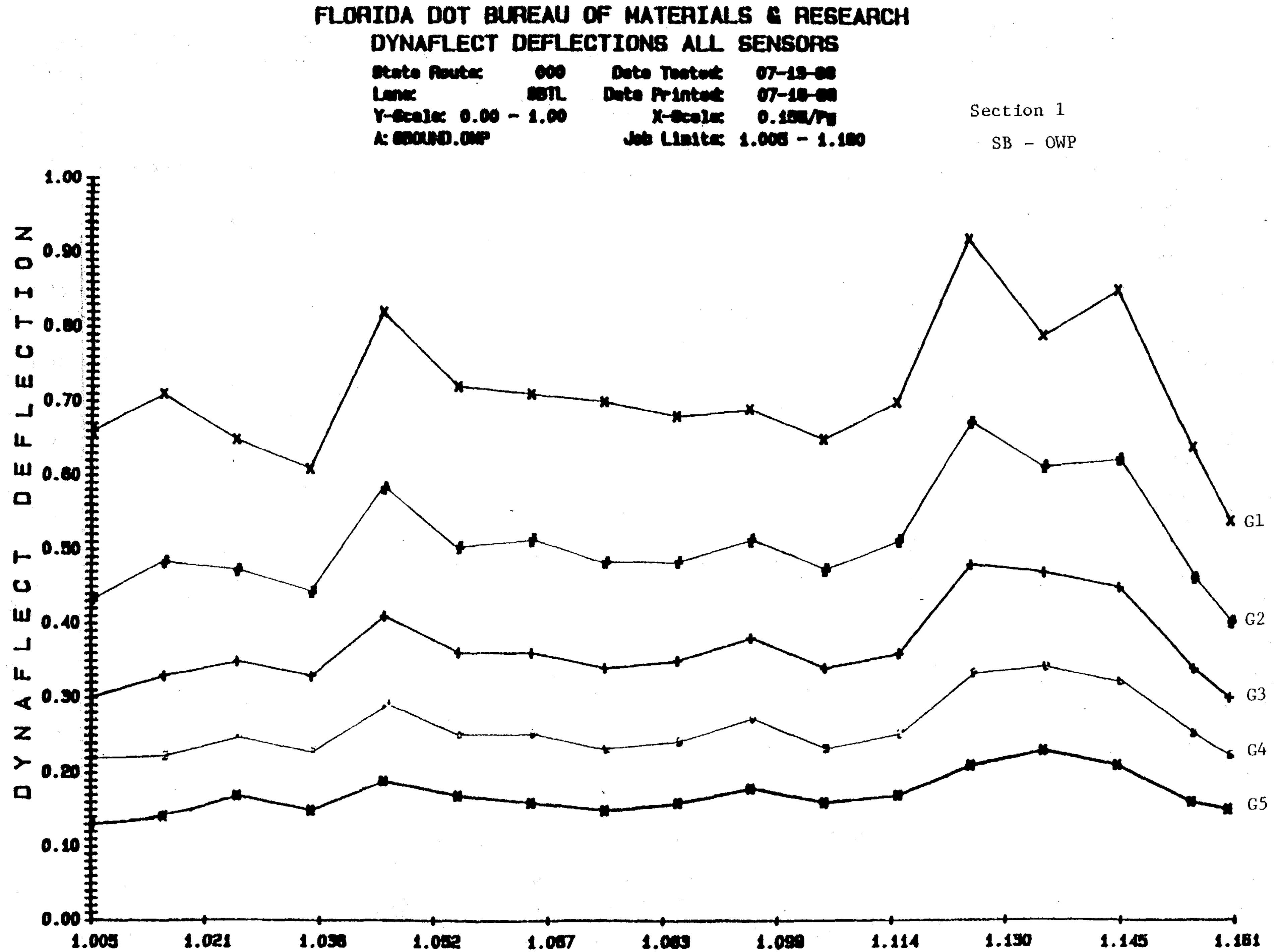


Figure 4.19 Mile Post

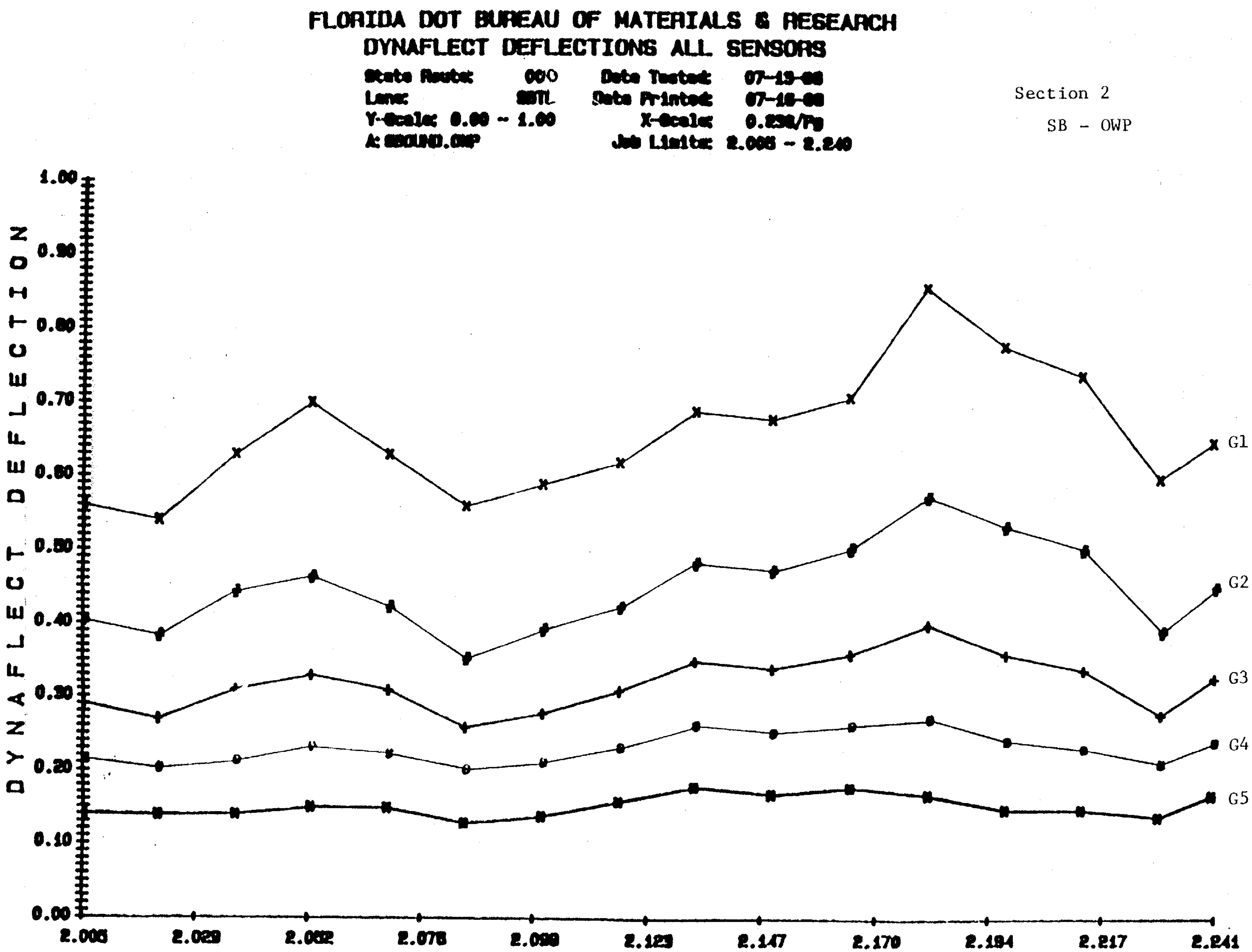


Figure 4.20 Mile Post

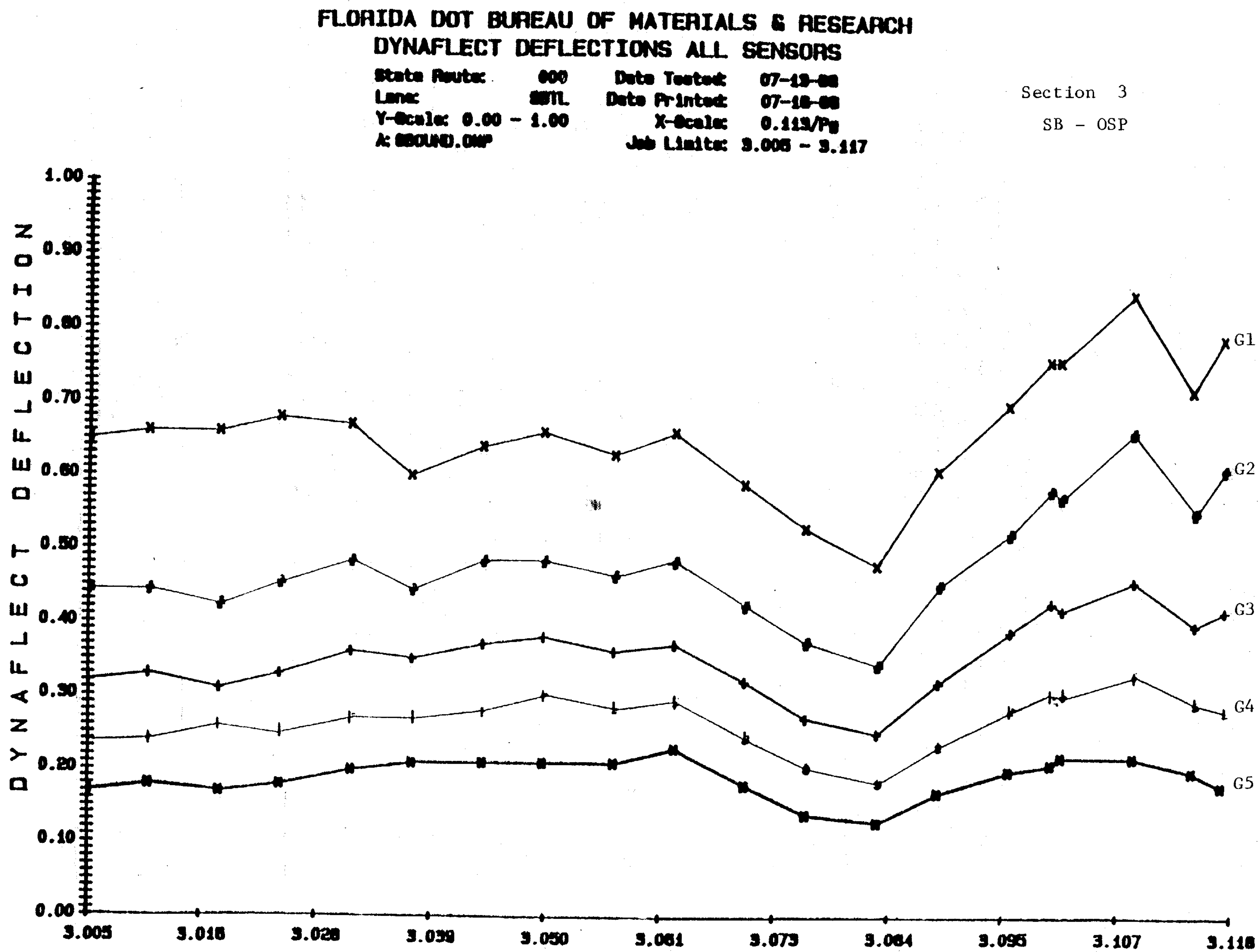


Figure 4.21 Mile Post

V. GROUNDWATER MONITORING STUDY

5.1 INTRODUCTION

This chapter describes the groundwater monitoring program, and addresses the question of whether construction of the experimental roads has had any impact on the quality of the groundwater adjacent to the roads. Although the experimental design and sampling protocol have been the same at both sites, significant hydrogeological and geochemical differences exist between the sites. In this chapter, the results of the investigation at each site will be discussed individually. These results will then be contrasted to determine the role of site differences and how they affect the final conclusions of the study.

5.2 POLK COUNTY STUDY

5.2.1 Hydrogeology

Parrish Road is located in Central Polk County and within the Southwest Florida Water Management District (SWFWMD). The road is bounded on both sides by reclaimed land, which consists primarily of sand with some phosphate. The land to the west of the road was reclaimed in 1964, while the land to the east was reclaimed in 1972. The land immediately beneath Parrish Road has not been mined. The length of the roadway containing phosphogypsum is bounded by large lakes on both sides. The lake on the east side of the roadway has a larger surface area than that on the west, indicating that rainfall will induce a flow of groundwater from west to east. The closest rain gauge to the Parrish Road is operated by the SWFWMD in the city of Pembroke. Rainfall measurements collected during the course of this study are shown in Fig. 5.1. These data show that rainfall amounts vary considerably throughout the year, with highest rainfalls expected during the summer months. Rapid infiltration rates are expected through the sandy fill material. The surface elevation of the road increases in a southerly direction such that wells 1 and 2, Fig. 5.2, are located approximately 11 ft above the average water table, while wells 9 and 10 are approximately 20 ft above the water table.

5.2.2 Design of Monitoring Well Array

The site was surveyed in October 1985 by a team from the University of Miami. At this time the ground elevations and lake levels on both sides of the roadway were determined. Within the accuracy of the survey, the lake elevations were found to be the same and hence no predominant flow direction could be determined. Based on this result, it was decided to place the

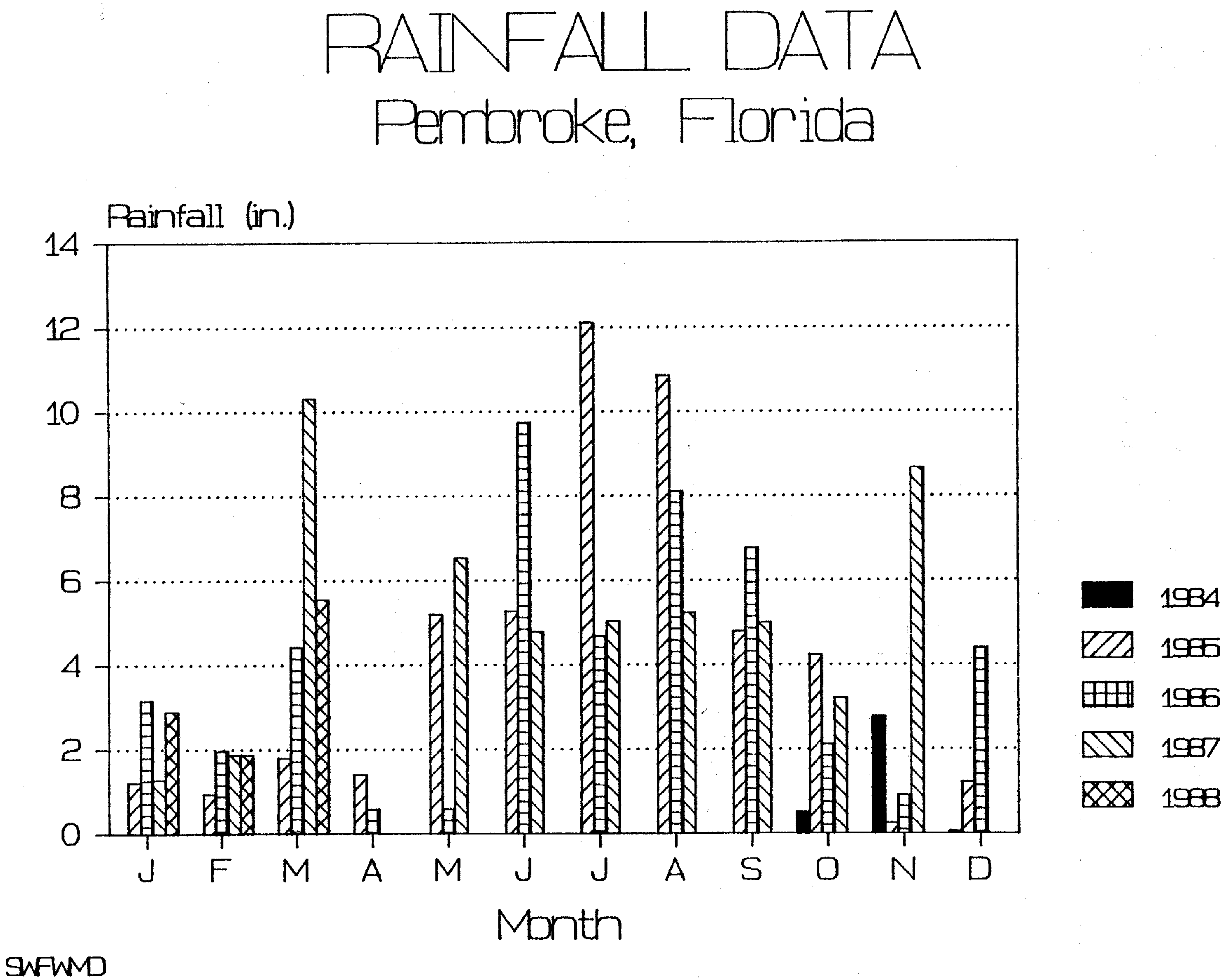


Figure 5.1 Rainfall at Pembroke, Florida.

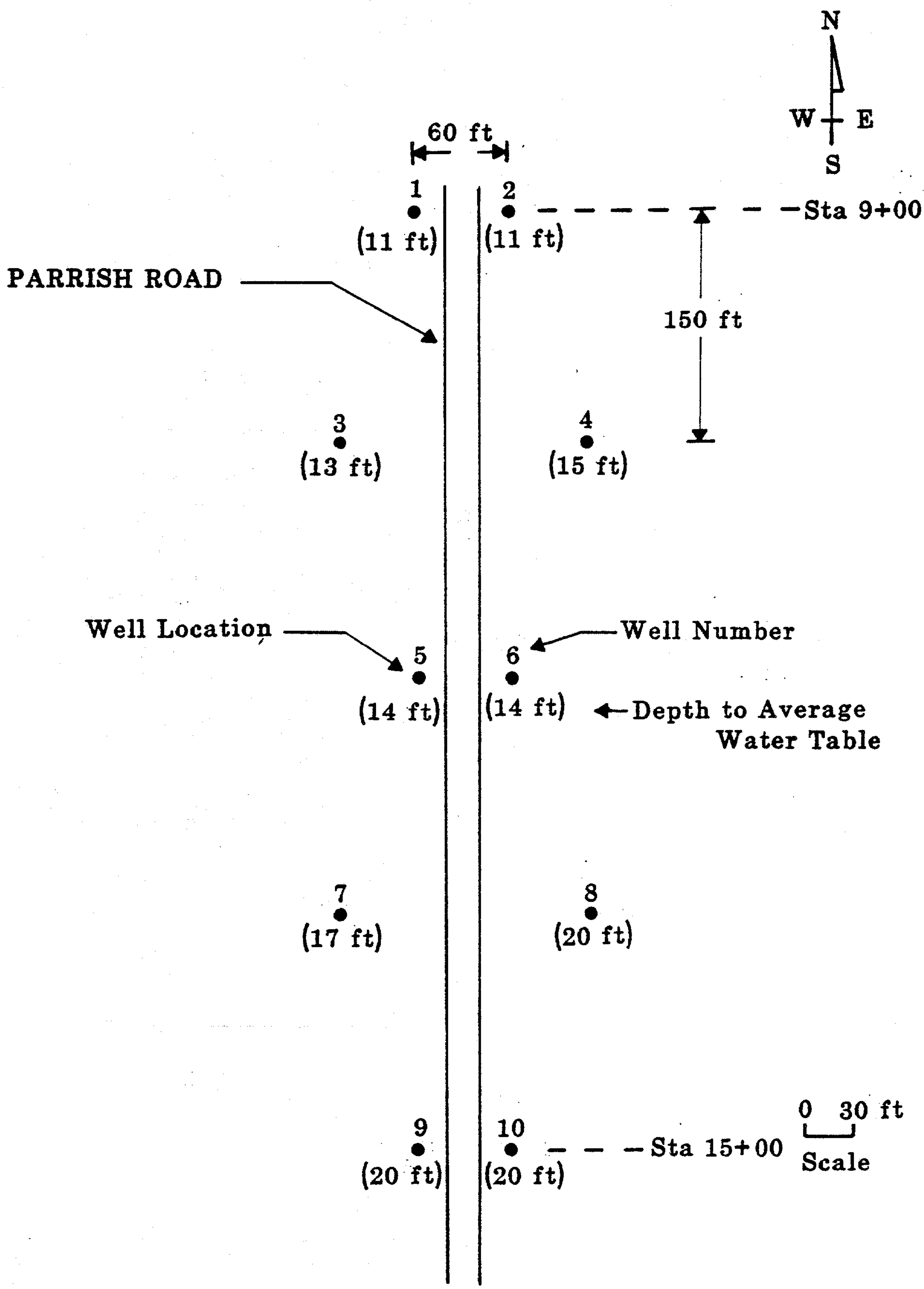


Figure 5.2 Layout of Monitoring Wells, Parrish Road.

the monitoring wells is shown in Fig. 5.2. In order to identify any contamination moving from the roadway outward, two lines of wells were used on each side. The outer line is 50 ft further away from the road than the inner line. There are 3 wells on the inner line and 2 on the outer line, and the wells in each line are placed 300 ft apart. The inner line of wells was placed 20 ft from the edge of the road which is approximately equal to the maximum distance from the road surface to the groundwater. This approach is consistent with the fact that leachate tends to move vertically through the unsaturated zone.

Monitoring Well Design: The monitoring wells were designed in accordance with generally accepted criteria (Todd, 1980). The typical monitoring well specifications are shown in Fig. 5.3. An aquifer particle size distribution was assumed for typical sand used as fill material. These sand characteristics indicated that a screen with a slot size of 0.01 inches surrounded by 6/20 silica sand would be adequate. The screen length was designed to be 10 ft long. The top of the screen was placed at the mean wet season water table level. Above the well screen a 6 inch bentonite layer was placed to restrict vertical flow. Above the bentonite, the hole was backfilled to 3 ft below the ground surface which was grouted in with cement. A 4 inch diameter protective steel casing was placed within the cement grout. Well development was done by the contractor who installed the wells. Installation was completed in January 1986.

5.2.3 Sampling Protocol

Sampling of the wells was initiated in February 1986 and continued at irregular intervals until October 1986, after which sampling was done at regular monthly intervals until the conclusion of the project in August 1988.

An ISCO Model 2600 submersible well pump was used throughout the study. This pump delivered approximately 3.5 liters/min from each well. The number of well volumes to be pumped before a representative groundwater sample is obtained has been studied by several investigators (eg. Papadopulos and Cooper, 1967; Barber and Davis, 1987). According to Papadopulos and Cooper (1967) the pumping time, tp at each well before a representative sample of ground water is obtained is given by

$$t_p = 250 \frac{r_c^2}{T} \quad (5.1)$$

where r_c is the radius of the well casing and T is the transmissivity of aquifer which, in the case of a partially penetrating monitoring well, is equal to the hydraulic conductivity of the aquifer times the screen length. Assuming a typical hydraulic conductivity of the sandy fill of 23 ft/day, and with a casing radius of 1 inch and a screen length of 10 ft, Eq. 5.1 yields a pumping time of 11 minutes. A recent study by

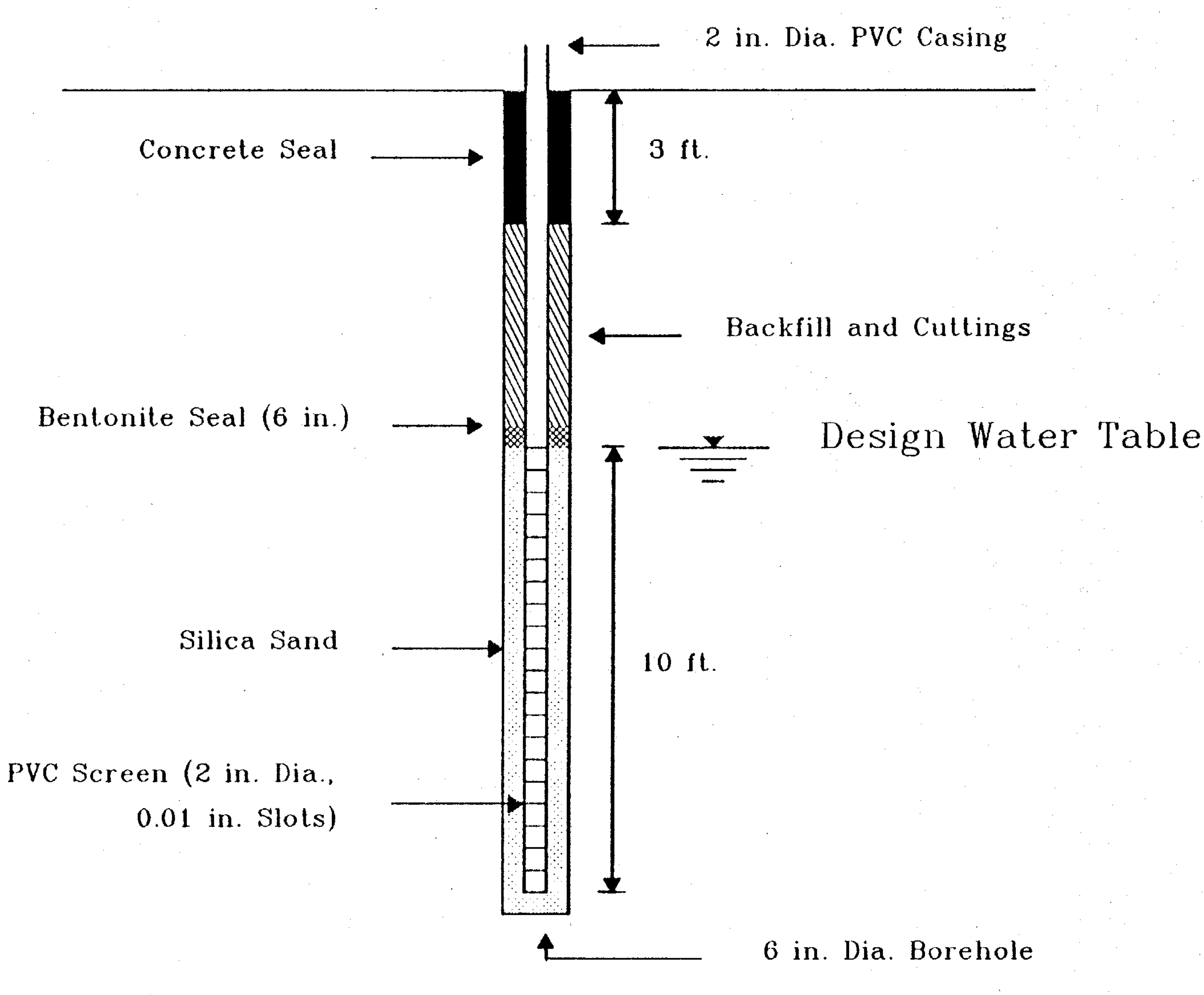


Figure 5.3 Typical Monitoring Well

Barber and Davis (1987) considered the effect of mixing within the well casing on the pumping time required to obtain a representative groundwater sample. In aquifers with high transmissivities and the pump intake within the screened interval, then the groundwater tends to move directly through the screen and into the pump intake. This results in limited mixing between groundwater and water stored within the casing and relatively small pumping times for representative sampling. The pumping time, t_p , was given by Barber and Davis (1987) as

$$t_p > 25 \frac{r_e^2}{T} \qquad (5.2)$$

where r_e is the effective radius of the well and T is the transmissivity. In this study r_e is equal to 0.95 inches and T is again equal to the hydraulic conductivity times the casing length. Using these values we obtain a pumping time of 1 minute. It is interesting to note that the pumping time given by Eq. 5.2 is approximately one tenth of that given by Eq. 5.1. This difference is due to the exponential nature of the governing equations since Eq. 5.1 should yield 99.9% pure groundwater while Eq. 5.2 yields 98.8%. If the case exists where the transmissivity is low compared with the pumping rate, then significant mixing takes place between groundwater and water stored within the casing; This leads to an estimated pumping time, t_p for a representative sample given by

$$t_p > 3.2 \frac{V}{Q} - 0.9 \frac{r_e^2}{T} \qquad (5.3)$$

where V is the volume of water in the casing, and Q is the pumping rate. For the monitoring wells used in this study, Eq. 5.3 yields a pumping time of 5 minutes. The results of using the various formulations in estimating pumping time are shown in Table 5.1. The average estimated pumping time is approximately 6 minutes and, given the uncertainty of the hydraulic conductivity estimate, a pumping time of 10 minutes was used throughout this study.

Water was pumped directly from the well into a 4 liter reservoir containing a probe which was connected to an instrument reading conductivity and temperature. After pumping for 10 minutes, the odor as well as the temperature and conductivity of the sample were recorded. Four sample bottles, 3 polyethylene and 1 glass, were then rinsed and filled with groundwater. The samples were immediately transferred to the sampling van for pH and turbidity measurement, preservation and storage. Turbidity measurements were estimated qualitatively by observing the sample within the glass bottle. The categories used were: very cloudy, cloudy, slightly cloudy, and clear. Bias was somewhat removed by having the same person provide estimates during each sampling event. Preservation of the samples was done according to which analyses were to be performed. The

Table 5.1. Pumping Times for Representative Sampling (Parrish Road)

Equation	t_p (mins)	Reference
$t_p > 250 \frac{r_c^2}{T}$	11	Papadopulos and Cooper (1967)
$t_p > 25 \frac{r_e^2}{T}$	1	Barber and Davis (1987)
$t_p > 3.2 \frac{V}{Q} - 0.9 \frac{r_e^2}{T}$	5	Barber and Davis (1987)

sample to be analysed for phosphorous (dissolved and total) was contained in the glass bottle and was simply refrigerated. All other samples were contained in polyethylene bottles. The sample to be analysed for metals was preserved with HNO_3 to pH < 2, and refrigerated, the sample to be analysed for nitrate and ammonia was preserved with H_2SO_4 to pH < 2 and refrigerated, a third sample to be analysed for dissolved solids, sulfate, fluoride, chloride, and alkalinity was simply refrigerated. Field refrigeration consisted of placing the samples in a cooler of ice. After collecting samples at all 10 monitoring wells, the samples were transported to the Environmental Engineering Laboratory at the University of Miami for immediate analysis. The analytical protocol is described in the next section.

5.2.4 Analytical Protocol

The parameters to be measured and the analytical techniques used are shown in Table 5.2. All parameters were measured within the recommended maximum holding times given by Standard Methods (1985). The internal quality control program used in this study, and approved by the Department of Environmental Regulation (DER), consisted of using replicate analysis and quality control standards to measure the accuracy of the laboratory analyses. In replicate analysis, every tenth sample was analysed again. Quality control standards were measured after every tenth field sample and compared with known values. The results of the replicate analyses are shown in Table 5.3, while the results of quality control analyses are shown in Table 5.4. The results of the replicate analyses, Table 5.3, indicate that the root-mean-square (rms) differences between replicate analyses was on the order of ten percent or less for all parameters except total phosphorous (unfiltered), nitrate, and lead. The variability in total phosphorous was a result of the large variability in the suspended solids content of replicate samples, and variability in the lead measurements was a result of the lead levels being on the order of the detection limit of the atomic absorption spectrophotometer (AAS). The variability in the nitrate levels is probably reflective of the difficulty inherent in using the cadmium reduction column. The accuracy and precision of the analytical techniques used in the study are determined based on the measurements of the control samples. These results are shown in Table 5.4, where they are also contrasted with the accuracies and precisions reported by EPA (1979). These results indicate that the analytical accuracies obtained in this study are certainly comparable to results reported by EPA as being representative of analytical laboratories in the United States.

The precision and accuracy data reported in this section are an extremely important reference when interpreting the measured data. Only fluctuations in the water quality data that significantly exceed measurement errors can be detected with any certainty. The measured data are analysed in the next section.

Table 5.2. Methods Used in Chemical Analyses

Parameter	Measurement Technique
Sodium (Na)	AASM[1]
Potassium (K)	AASM
Calcium (Ca)	AASM
Magnesium (Mg)	AASM
Iron (Fe)	AASM
Copper (Cu)	AASM
Lead (Pb)	AASM
Chromium (Cr)	AASM
Manganese (Mn)	AASM
Cadmium (Cd)	AASM
Alkalinity	Titrimetry
Sulfate (SO_4)	Turbidimetry
Chloride (Cl)	Electrode
Nitrate (NO_3)	CRM[2]
Fluoride (F)	Electrode
Ammonia (NH_3)	Electrode
Phosphorous (P)	SCM[3]
Dissolved Solids (TDS)	Gravimetry

[1] Atomic Absorption Spectrophotometer
[2] Cadmium Reduction Method
[3] Stannous Chloride Method

Table 5.3. Results of Replicate Analyses

Constituent	Mean Difference (%)	RMS Difference (%)
Na	-0.96	3.92
K	-0.27	2.43
Ca	0.13	1.96
Mg	-0.51	2.75
Alkalinity	0.25	2.43
SO_4	-0.23	11.96
Cl	0.26	2.97
F	2.31	8.26
NO_3	4.74	41.19
Fe	0.50	3.42
NH_3	1.12	3.98
P	-1.57	7.71
Cu	2.74	3.90
Pb	6.49	35.11
Cr	0.02	4.28
Mn	-0.46	7.37
Cd	-0.34	4.34
TDS	0.92	11.40

Table 5.4. Results of Quality Control Analyses

Constituent	Accuracy (%)		Precision (%)	
	This Study	EPA (1979)	This Study	EPA (1979)
Na	2.09	±2	4.91	4.4
K	-0.84	±2	5.07	4.4
Ca	3.40	±2	6.24	4.4
Mg	5.65	±2	7.02	4.4
Alkalinity	0.11	10.6	1.63	15.9
SO_4	-4.46	-8.26	19.49	19.3
Cl	6.21	2.2	8.51	9.1
F	4.37	–	8.14	–
NO_3	-2.84	8.3	12.85	43.7
Fe	1.45	±3	4.73	27.8
NH_3	11.97	–	26.10	–
P	-6.65	–	20.80	–
Cu	7.77	–	12.63	–
Pb	1.30	–	18.77	–
Cr	-5.60	–	13.45	–
Mn	-0.06	–	6.83	–
Cd	5.58	–	11.11	–
TDS	-2.55	–	8.78	–

5.2.5 Results

The monitoring study has resulted in the collection of a large quantity of data from which we may extract both the temporal and spatial variability in the water quality beneath the roadway. Based on these data, the impact of the experimental roadway on the water quality may be inferred. The mean and standard deviation of each parameter at each of the wells is shown in Table 5.5. The temporal variability at each well may be quantified by the coefficient variation, which is defined as the standard deviation divided by the mean. The average coefficient of variation for each parameter measured, expressed as a percentage, are shown in Table 5.6. The results, when compared with the accuracy and precision of the measurement techniques, show that the measured variability in all cases exceed analytical errors. This indicates that significant fluctuations may be detected with the measurement techniques used. It is interesting to note the relatively low variations in temperature and pH, which indicates that these parameters are not very sensitive to the chemical changes in the groundwater. The results shown in Table 5.5 clearly indicate that there is significant variation in water quality between wells. This variability is vividly illustrated in Table 5.7, where the range of mean measurements at the wells are shown. In several cases, there are order of magnitude variations in the mean values. These relatively large variations over distances on the order of 100 ft provide a vivid illustration of the inherent limitations of characterizing the water quality over a large area based on measurments at a single monitoring well location.

Methods used in Statistical Analyses: A statistical package developed by Chin (1988) was used to analyze the measured data. The statistical techniques commonly applied to water quality data are tests for trend, normality, log-normality, seasonality, serial correlation, and cross-correlation. Because such tests are applied in many areas of study, a generic analysis spreadsheet (Chin, 1988) is used. Segments from the geochemical data spreadsheet are transferred into the analysis package using LOTUS l-2-3 commands/FILE and /COMBINE. The transferred segments are stored in designated areas of the spreadsheet which are analysed by the statistical package. This section describes statistical methods that are applied to each well in the monitoring network. For each water quality parameter, a statistical method either confirms or denies that the data have a particular characteristic, within a certain confidence interval. Several of these methods have been utilized by other researchers in studying the characteristics of groundwater qualify variables (Montgomery et al., 1987) and particular attention is given to methods which are applicable in cases where the amount of data is limited (Harris et al., 1987).

Trend Analysis.- This test determines whether the data has a significant trend. The method consists of fitting a straight line to the data using least squares analysis, and then

Table 5.5. Means and Standard Deviations of Measured Constituents (Parrish Road)[1]

Well No.	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Alkalinity (mg/l)	SO_4 (mg/l)
1	(3.0,0.6)	(0.69,0.47)	(41.5,24.3)	(2.0,0.7)	(29, 6)	(36.2,13.4)
2	(4.7,0.9)	(0.77,0.64)	(42.3,23.9)	(3.0,0.6)	(41, 8)	(12.3, 4.2)
3	(3.4,0.5)	(0.72,0.24)	(17.2,17.3)	(3.8,0.8)	(45, 9)	(3.8, 1.4)
4	(7.1,1.2)	(0.37,0.27)	(33.3,16.9)	(10.3,2.6)	(88, 9)	(3.8, 2.4)
5	(5.4,1.8)	(1.16,1.19)	(65.4,37.6)	(6.0,1.3)	(43, 9)	(6.1, 3.4)
6	(4.1,0.8)	(0.58,0.44)	(29.6,18.1)	(1.6,0.6)	(23, 6)	(8.7, 3.2)
7	(5.1,2.6)	(0.66,0.32)	(28.8,13.4)	(9.0,3.2)	(78,18)	(10.1, 6.1)
8	(2.8,0.7)	(0.31,0.20)	(18.2, 9.4)	(1.9,0.4)	(23, 4)	(7.2, 0.9)
9	(3.5,0.8)	(0.38,0.30)	(29.8,15.4)	(5.8,1.0)	(47, 4)	(3.0, 0.7)
10	(3.0,0.7)	(0.26,0.17)	(20.9, 7.2)	(5.7,1.6)	(49, 7)	(5.4, 1.0)

Well No.	Cl (mg/l)	F (mg/l)	NO_3 (mg/l)	Fe (mg/l)	NH_3 (mg/l)	P (mg/l)
1	(4.8,0.7)	(0.58,0.15)	(0.9,0.6)	(3.3,1.2)	-	(1.1,0.4)
2	(11.0,1.3)	(0.66,0.34)	(0.4,0.5)	(3.1,1.0)	-	(1.6,0.8)
3	(7.5,1.2)	(0.49,0.07)	(0.5,0.7)	(3.3,0.7)	(2.4,0.6)	(2.3,0.7)
4	(18.7,2.9)	(0.81,0.10)	(0.4,0.5)	(2.2,0.4)	(0.5,0.3)	(0.9,0.2)
5	(5.2,0.7)	(0.76,0.34)	(2.3,1.0)	(2.6,1.9)	-	(1.6,2.0)
6	(7.8,1.6)	(0.70,0.15)	(1.1,0.9)	(0.8,0.5)	-	(1.5,0.8)
7	(7.5,1.4)	(0.41,0.07)	(0.6,0.8)	(9.4,1.5)	(1.3,0.5)	(0.8,0.4)
8	(7.0,1.3)	(0.25,0.03)	(0.9,0.6)	(1.6,1.2)	-	(0.4,0.2)
9	(5.4,0.8)	(0.52,0.20)	(1.5,0.6)	(0.9,0.7)	-	(0.9,0.3)
10	(7.3,1.2)	(0.53,0.17)	(0.6,0.3)	(0.7,0.4)	-	(1.0,0.1)

Well No.	Pb (mg/l)	Mn (mg/l)	TDS (mg/l)	Temp (^oC)	pH	Ω^{-1} (μmho/cm)
1	(0.03,0.01)	(0.02,0.01)	(118,33)	(23.4,1.0)	(5.65,0.31)	(168,36)
2	(0.03,0.01)	(0.07,0.16)	(110,41)	(23.9,0.7)	(5.82,0.29)	(162,18)
3	(0.03,0.02)	(0.04,0.02)	(116,38)	(23.2,0.8)	(5.58,0.35)	(157,30)
4	(0.03,0.02)	(0.10,0.03)	(160,29)	(23.4,1.0)	(6.30,0.24)	(289,22)
5	(0.04,0.02)	(0.10,0.06)	(115,59)	(23.5,0.8)	(6.12,0.33)	(147,38)
6	(0.03,0.01)	(0.03,0.03)	(86,34)	(23.9,0.8)	(5.79,0.38)	(119,13)
7	(0.04,0.02)	(0.11,0.03)	(150,43)	(23.6,0.8)	(6.01,0.21)	(274,54)
8	(0.03,0.01)	(0.03,0.03)	(75,34)	(23.7,0.6)	(5.89,0.34)	(113,12)
9	(0.03,0.02)	(0.03,0.04)	(93,33)	(23.9,0.7)	(6.38,0.23)	(152,13)
10	(0.03,0.01)	(0.03,0.05)	(99,30)	(23.6,0.8)	(6.22,0.23)	(155,18)

Well No.	Ra-226 (pCi/l)
1	(12.6,12.1)
2	(16.3,14.9)
3	(4.1, 2.9)
4	(7.2, 7.5)
5	(18.7,15.7)
6	(5.2, 5.3)
7	(3.1, 2.4)
8	(4.8, 5.5)
9	(4.0, 2.8)
10	(1.9, 1.3)

[1] **The results are given as an ordered pair (mean, standard deviation).**

Table 5.6. Coefficients of Variation of Measured Data (Parrish Road)

Constituent	Ave. Coef. of Variation (%)
Na	24
K	70
Ca	51
Mg	26
Alkalinity	18
SO_4	38
Cl	16
F	27
NO_3	87
Fe	48
P	49
Pb	46
TDS	35
Temp	3
pH	5
Ω^{-1}	15
Ra-226	88

Table 5.7. Spatial Variability in Measured Data (Parrish Road)

Constituent	Units	Range of Means
Na	mg/l	2.8 - 7.1
K	mg/l	0.26 - 1.16
Ca	mg/l	17.2 - 65.4
Mg	mg/l	1.6 - 10.3
Alkalinity	mg/l	23 - 88
SO_4	mg/l	3.0 - 36.2
Cl	mg/l	4.8 - 18.7
F	mg/l	0.25 - 0.81
NO_3	mg/l	0.36 - 2.31
Fe	mg/l	0.7 - 9.4
P	mg/l	0.4 - 2.3
Pb	mg/l	0.03 - 0.04
Mn	mg/l	0.02 - 0.11
TDS	mg/l	75 - 160
Temp.	oC	23.2 - 23.9
pH	-	5.65 - 6.38
Ω^{-1}	µmho/cm	113 - 289
Ra-226	pCi/l	1.9 - 18.7

determining whether the slope of the best fit line is significantly different from zero. The best fit line is defined by the equation

$$y = mt + c \qquad (5.4)$$

where y is the value of the water quality parameter, t is the time in days from the some reference date, and m and c are the slope and intercept of the best fit line. These values are obtained from the measured data by the equations

$$m = \frac{N \sum_{i=1}^{N} y_i t_i - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} y_i\right)}{N \sum_{i=1}^{N} t_i^2 - \left(\sum_{i=1}^{N} t_i\right)^2} \qquad (5.5)$$

$$c = \bar{y} - m\bar{t} \qquad (5.6)$$

where N is the number of measurement points, y_i and t_i are measured values of y and t respectively, and $\bar{y}$ and $\bar{t}$ are mean values of y_i. and t_i. In order to test the null hypothesis that the slope is not sufficiently different from zero, we calculate the value of the t statistic given by

$$t = \frac{m (S_{tt})^{1/2}}{s} \qquad (5.7)$$

where

$$S_{tt} = \sum_{i=1}^{N} t_i^2 - \frac{\left(\sum_{i=1}^{N} t_i\right)^2}{N} \qquad (5.8)$$

$$s^2 = \frac{S_{yy} - m\, S_{ty}}{N - 2} \qquad (5.9)$$

$$S_{yy} = \sum_{i=1}^{N} y_i^2 - \frac{(\sum_{i=1}^{N} y_i)^2}{N} \quad (5.10)$$

$$S_{ty} = \sum_{i=1}^{N} t_i y_i - \frac{(\sum_{i=1}^{N} t_i)(\sum_{i=1}^{N} y_i)}{N} \quad (5.11)$$

Choosing a confidence interval of 95%, the next step is to look up in statistical tables the value of the t statistic with N-2 degrees of freedom and a significance level of 0.025. Referring to this value as $t_{0.025}$, then if the following inequality is satisfied

$$|t| < t_{0.025} \quad (5.12)$$

then the slope of the trend line does not significantly differ from zero with 95% confidence (Walpole and Myers, 1978). If there is found to be a significant trend, then this trend must be removed before subsequent statistical tests are performed.

Normality Analysis.- This test determines whether the measured data, or detrended data, is normally distributed. A normal distribution of the data is a fundamental assumption in many of the tests commonly applied to measured data. Normality of data generally indicates symmetric random variations about some mean value. To test for normality we must determine the skewness coefficient, γ , where

$$\gamma = (N)^{1/2} \frac{\sum_{i=1} (y_i - \bar{y})^3}{\left[\sum_{i=1}^{N} (y_i - \bar{y})^2\right]^{3/2}} \quad (5.13)$$

If the absolute value of the skewness coefficient exceeds the tabulated value (Harris et al., 1987), then the alternate hypothesis that the data are significantly skewed and not normal is accepted.

Test for Seasonality.- This test determines whether there are any periodic variations in the data. To apply this test, measurements at regular intervals must be available. The first step in this method is to determine the periodogram, $I(\omega_j)$, of data at the Fourier frequencies, ω_j . The periodogram is defined by the equation

$$I(\omega_j) = \frac{1}{N\,q} \left\{ \left(\sum_{n=1}^{N} y_n \cos \omega_j n \right)^2 + \left(\sum_{n=1}^{N} y_n \sin \omega_j n \right)^2 \right\} \quad \ldots\ldots (5.14)$$

where q is the number of Fourier frequencies, equal to the integer part of N/2, and ω_j is defined by

$$\omega_j = \frac{2\Pi j}{N}, \quad j=1,q \quad \ldots\ldots (5.15)$$

After the periodogram has been determined, the next step is to calculate Fischer's c statistic by the equation

$$c = \frac{\max I(\omega_j)}{1/q \sum_{j=1}^{q} I(\omega_j)} \quad \ldots\ldots (5.16)$$

The null hypothesis that the data has a periodic fluctuation, with a frequency corresponding to the maximum value on the periodogram, is rejected at the α significance level if $\alpha > P$ where

$$P = 1 - \sum_{j=0}^{q} \left[(-1)^j \; q_j \; (1 - \frac{j\,c}{q})^{q-1}{}_{+} \right] \quad \ldots\ldots (5.17)$$

where the "+" indicates that only the positive parts of (1 - jc/q) are included, and q_j is given by the equation

$$q_j = \frac{q!}{j\;(q-j)!} \quad \ldots\ldots (5.18)$$

The detection of significant seasonality may require many years of data since annual cycles in the data are generally expected.

Serial Correlation.- This test determines whether lagged measurements are correlated. This test is important because it measures whether the data collected each month is correlated with that collected in previous months. If significant serial correlation exists, this gives an indication that the sampling interval may need to be increased. The serial correlation coefficient with lag-k, r_k, is defined by (Salas et al., 1980)

$$r_k = \frac{\sum_{i=1}^{N-k} (y_i - \bar{y}_i)(y_{i+k} - \bar{y}_{i+k})}{\left[\sum_{i=1}^{N-k} (y_i - \bar{y}_i)^2 \sum_{i=1}^{N-k} (y_{i+k} - \bar{y}_{i+k})^2\right]^{1/2}} \quad \ldots\ldots (5.19)$$

where $\bar{y}_i$ is the mean of the first N-k values, and $\bar{y}_{i+k}$ is the mean of the last N-k values. The null hypothesis that there is no correlation between measurements lagged by k is accepted with 95% confidence if r_k is within the interval defined by

$$\frac{-1-1.96(N - k - 1)^{1/2}}{N - k} < r_k < \frac{-1+1.96(N - k - 1)^{1/2}}{N - k} \quad \ldots\ldots (5.20)$$

Test for Independence in Space.- This test determines whether the measurements at two different wells are significantly correlated. This test is useful in determining the scale over which water quality fluctuations are significantly coherent. The lag-zero cross-correlation coefficient, *r,* is defined by

$$r = \frac{\sum_{i=1}^{N} (y_i - \bar{y})(z_i - \bar{z})}{\left[\sum_{i=1}^{N} (y_i - \bar{y})^2 \sum_{i=1}^{N} (z_i - \bar{z})^2\right]^{1/2}} \quad \ldots\ldots (5.21)$$

where y_i and z_i are synoptic measurements at different wells, and $\bar{y}$ and $\bar{z}$ are the means of y_i and z_i respectively. The null hypothesis that there, is no correlation between. the fluctuations measured at the two wells is accepted with 95% confidence if r is within the interval defined by (Salas et al., 1980).

$$\frac{1 - \exp\left[\frac{3.92}{(N - 3)^{1/2}}\right]}{1 + \exp\left[\frac{3.92}{(N - 3)^{1/2}}\right]} < r < \frac{1 - \exp\left[\frac{- 3.92}{(N - 3)^{1/2}}\right]}{1 + \exp\left[\frac{- 3.92}{(N - 3)^{1/2}}\right]} \quad \ldots (5.22)$$

Results of Statistical Analyses: The number of wells having various statistical properties are shown in Table 5.8. Each statistical test was applied to all 10 wells at the site, and the number of wells having each stated property are shown. To illustrate, consider the case of Sodium (Na) where measurements at 4 wells show significant downward trend and 6 wells showed no significant trend. At the 4 wells showing significant trend, the least-squares best fit straight line was calculated and subtracted from the measurements. Testing the residuals for normality showed that at 3 wells the residuals were normally distributed and 1 well was not normally distributed. Of the 6 wells not having any trend, 4 were normally distributed and 2 were not normally distributed. The raw data was analysed for log-normality and 8 wells were log-normally distributed, with 2 wells not demonstrating log-normality. The seasonality and autocorrelation tests were applied to the data with any mean trend removed if the data had no trend, these tests were applied directly to the measured data. For the Na measurements, 2 wells showed significant seasonality, while 8 wells did not demonstrate any significant seasonality. The data at 4 wells were significantly autocorrelated while that at 6 wells was not. In viewing the overall results shown in Table 5.8, one result is immediately apparent: the data are not statistically homogeneous. It is instructive to identify some important characteristics of the data. The major cations predominantly either show a downward trend or no trend at all. Of the major anions, alkalinity shows a predominant downward trend, while the sulfate and chloride data are divided between an upward trend and no trend at all. The overall quality of the groundwater is measured by the electrical conductivity (Ω^{-1}) which has no trend at 8 of the 10 wells.

Since the primary objective of this study is to identify whether the phosphogypsum roadway has had any effect on the groundwater quality, we will look in detail at the primary constituents of phosphogypsum in the groundwater, Ca, SO_4 and Ra-226, and see how they have changed since the construction of the roadway. The primary statistical property of interest is the trend. The trend data for Ca, SO_4 and Ra-226 at each of the wells are shown in Table 5.9. The trends of each parameter are best described individually.

The variation of Ca levels in the groundwater adjacent to the roadway are shown in Figs. 5.4 to 5.8. In each of the figures, measurement at wells that are symmetrical about the roadway (Fig. 5.2) are compared, and only measurements taken since the construction of the roadway, in October 1986, are shown. A trend analysis of these data, Table 5.9, show that Ca levels have a predominant downward trend at most wells. This is a direct result of collecting unfiltered samples, and the fact that significant decreases in turbidity were experienced. There is a consensus among groundwater monitoring specialists that samples collected should be filtred in the field before preservation and analysis for the constituents of interest in this study (eg. Barcelona, 1985, EPA 1985). Although the original proposal for this study recommended that the samples be filtered, the Florida Department of Environmental Regulation (DER) required that all samples collected for analyses should not be filtered. To determine the quantitative effect of not filtering, three experiments were conducted. In each of these experiments one

Table 5.8. Statistical Properties of Measured Data (Parrish Road)[1]

Constituent	Trend			Normal				Log-Normal		Seasonal		Auto-Correlated	
				Residual		No Trend							
	Y+	Y−	N	Y	N	Y	N	Y	N	Y	N	Y	N
Na	0	4	6	3	1	4	2	8	2	2	8	4	6
K	0	3	7	3	0	2	5	9	1	3	7	9	1
Ca	0	6	4	5	1	3	1	9	1	3	7	2	8
Mg	1	5	4	5	1	3	1	6	4	1	9	4	6
Alkalinity	0	9	1	9	0	1	0	8	2	0	10	0	10
SO_4	5	1	4	6	0	4	0	7	3	4	6	3	7
Cl	7	0	3	7	0	3	0	10	0	0	10	1	9
F	0	1	9	1	0	2	7	7	3	1	9	1	9
NO_3	0	2	8	2	0	7	1	6	4	4	6	5	5
Fe	0	6	4	4	2	3	1	10	0	0	10	0	10
P	1	2	7	3	0	2	5	5	5	3	7	5	5
Pb	0	5	5	5	0	4	1	10	0	2	8	2	8
TDS	0	6	4	6	0	4	0	9	1	7	3	7	3
Temp.	0	0	10	0	0	7	3	7	3	4	6	3	7
pH	0	0	10	0	0	6	4	9	1	2	8	1	9
Ω^{-1}	1	1	8	1	1	3	5	6	4	2	8	6	4
Ra-226	0	1	9	0	1	9	0	10	0	–		–	

[1] The numbers in the table indicate the number of wells having the stated property: Y and N indicate whether the data do/do not have the stated property; and Y^+ and Y^- indicate positive and negative trend respectively.

Table 5.9. Trend Data for Phosphogypsum Constituents (Parrish Road)

Well No.	Ca	SO4	Ra-226
1	N	Y^+	N
2	Y^-	Y^+	N
3	Y^-	Y^+	Y^-
4	N	Y^-	N
5	Y^-	Y^+	N
6	N	Y^+	N
7	Y^-	N	N
8	N	N	N
9	Y^-	N	N
10	Y^-	N	N

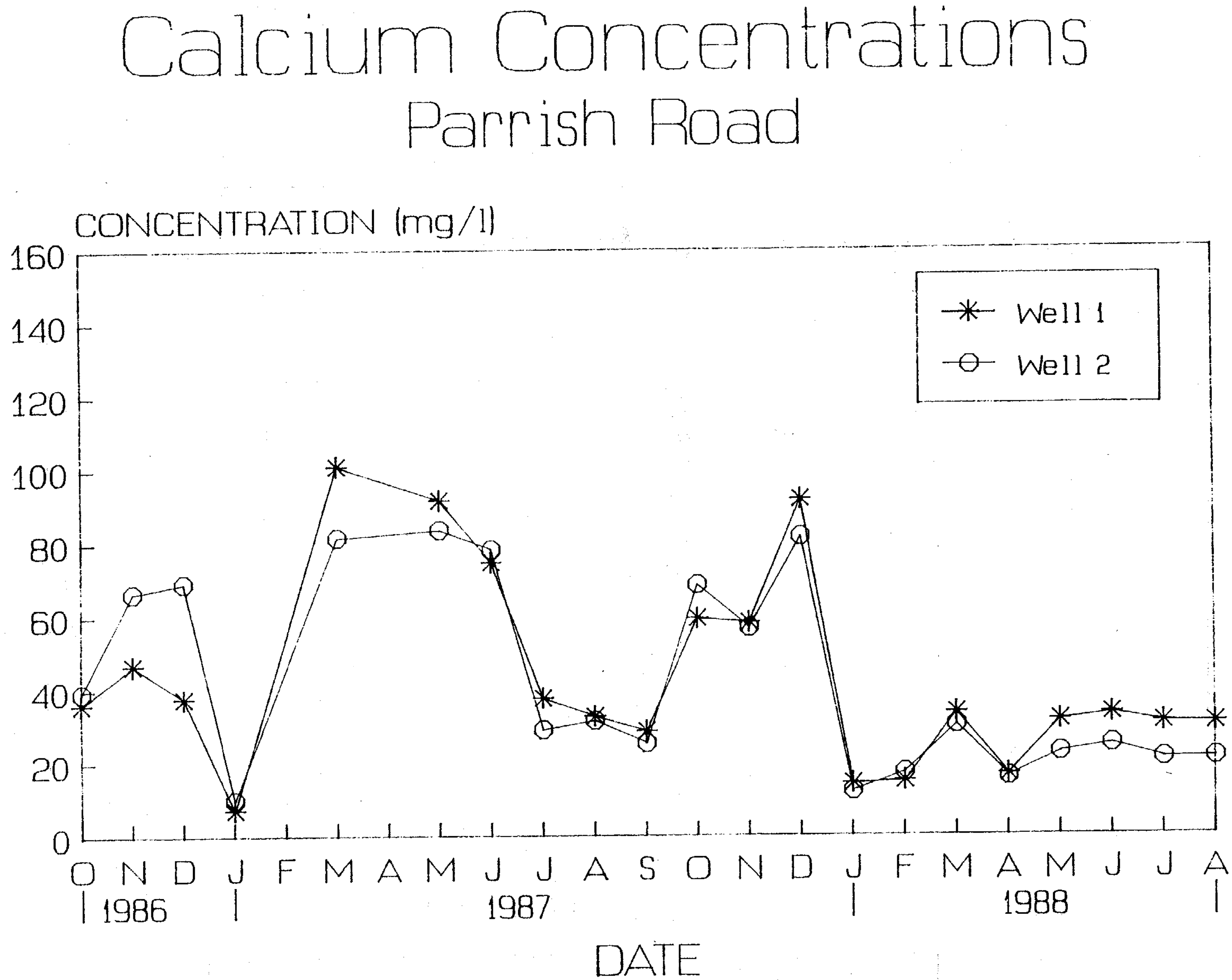


Figure 5.4 Calcium Levels at Wells 1 and 2, Parrish Road.

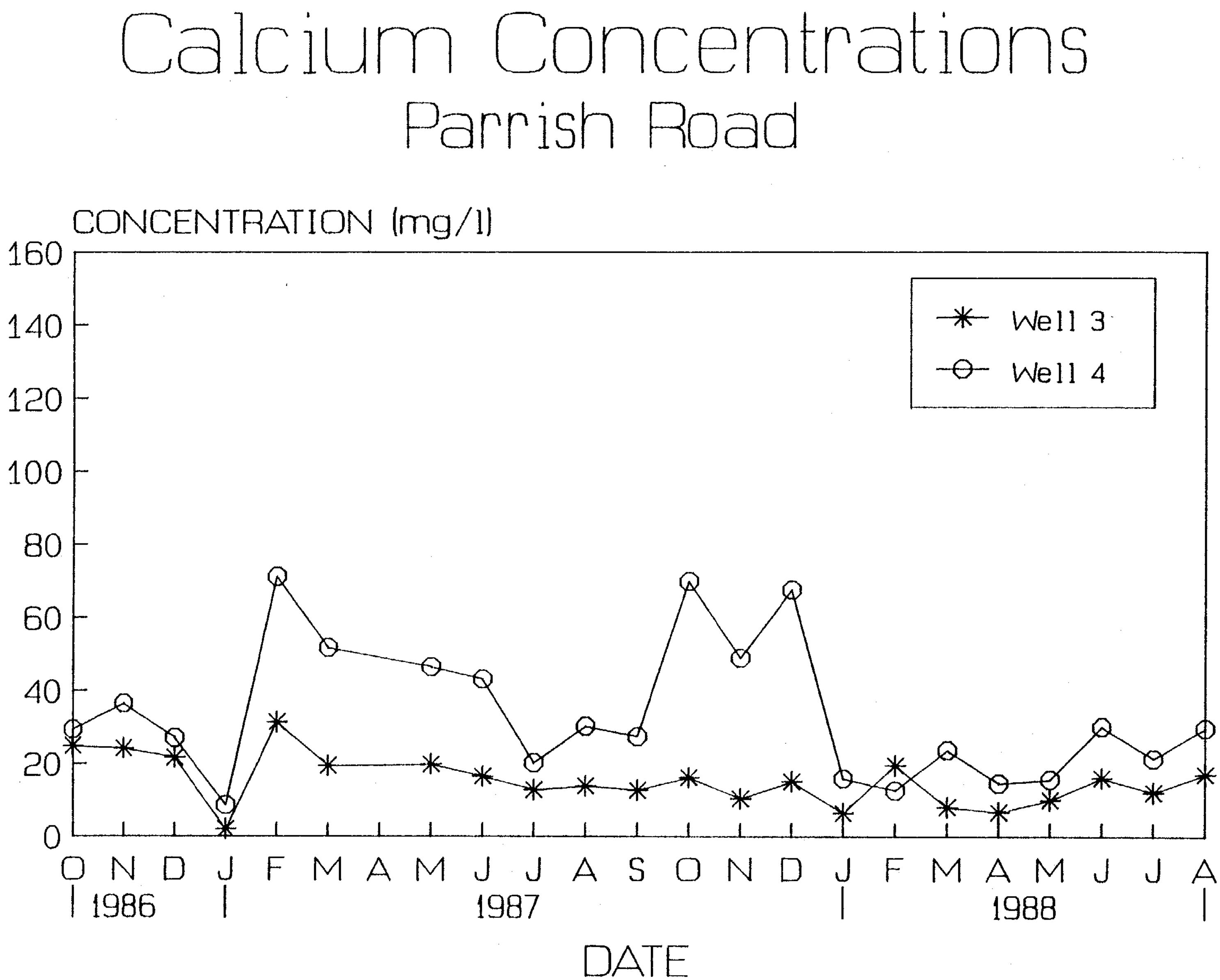


Figure 5.5 Calcium Levels at Wells 3 and 4, Parrish Road.

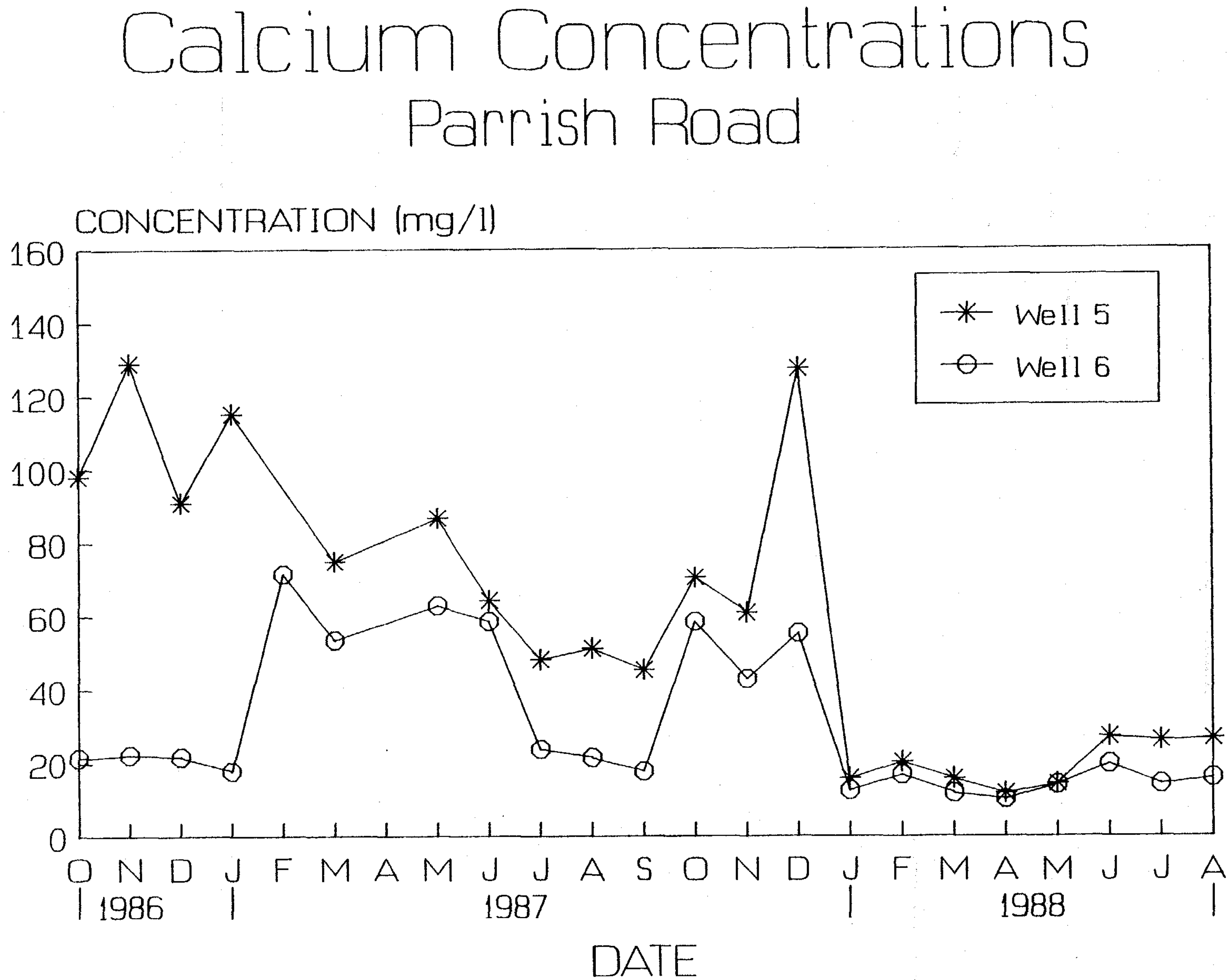


Figure 5.6 Calcium Levels at Wells 5 and 6, Parrish Road.

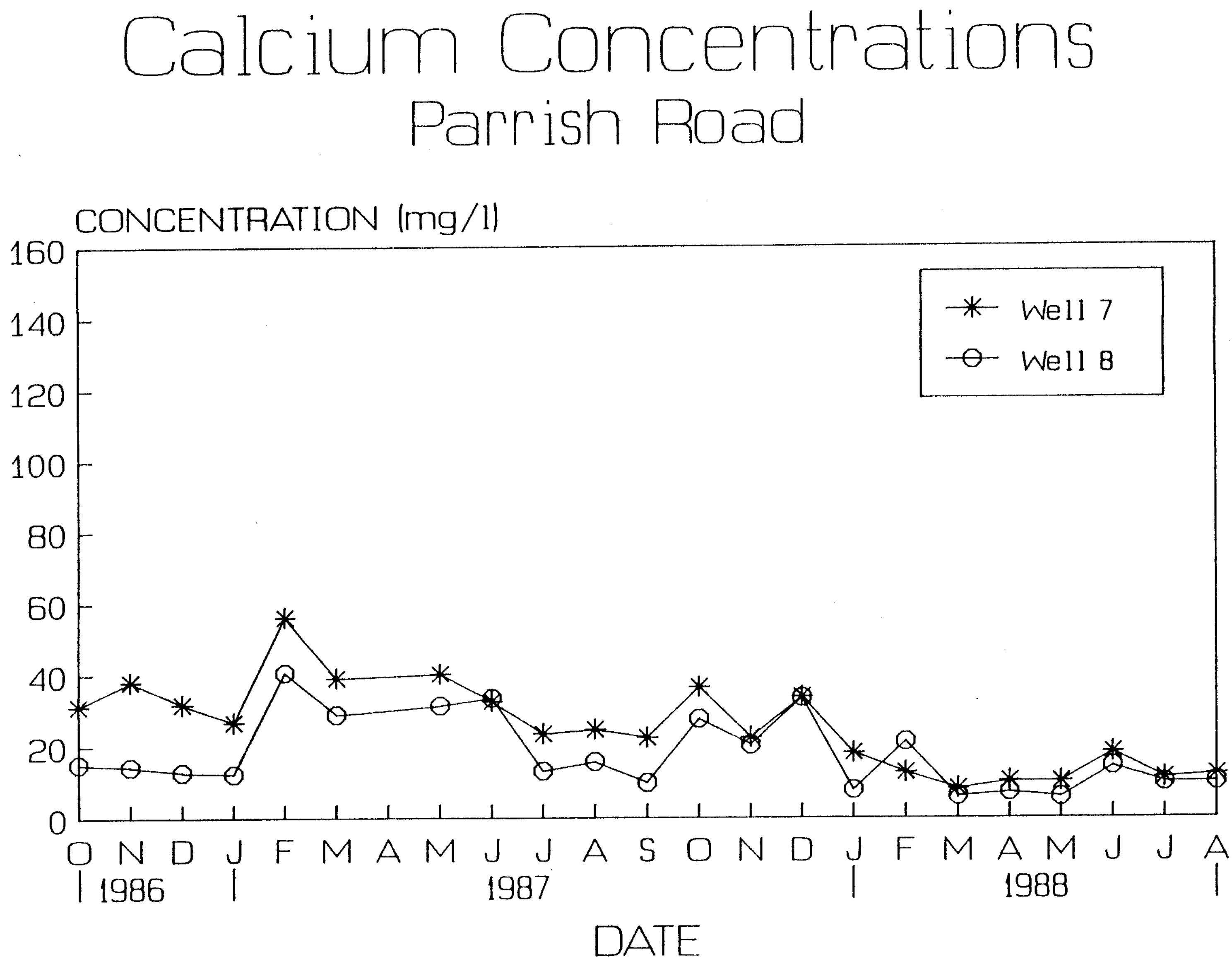


Figure 5.7 Calcium Levels at Wells 7 and 8, Parrish Road.

Calcium Concentrations
Parrish Road

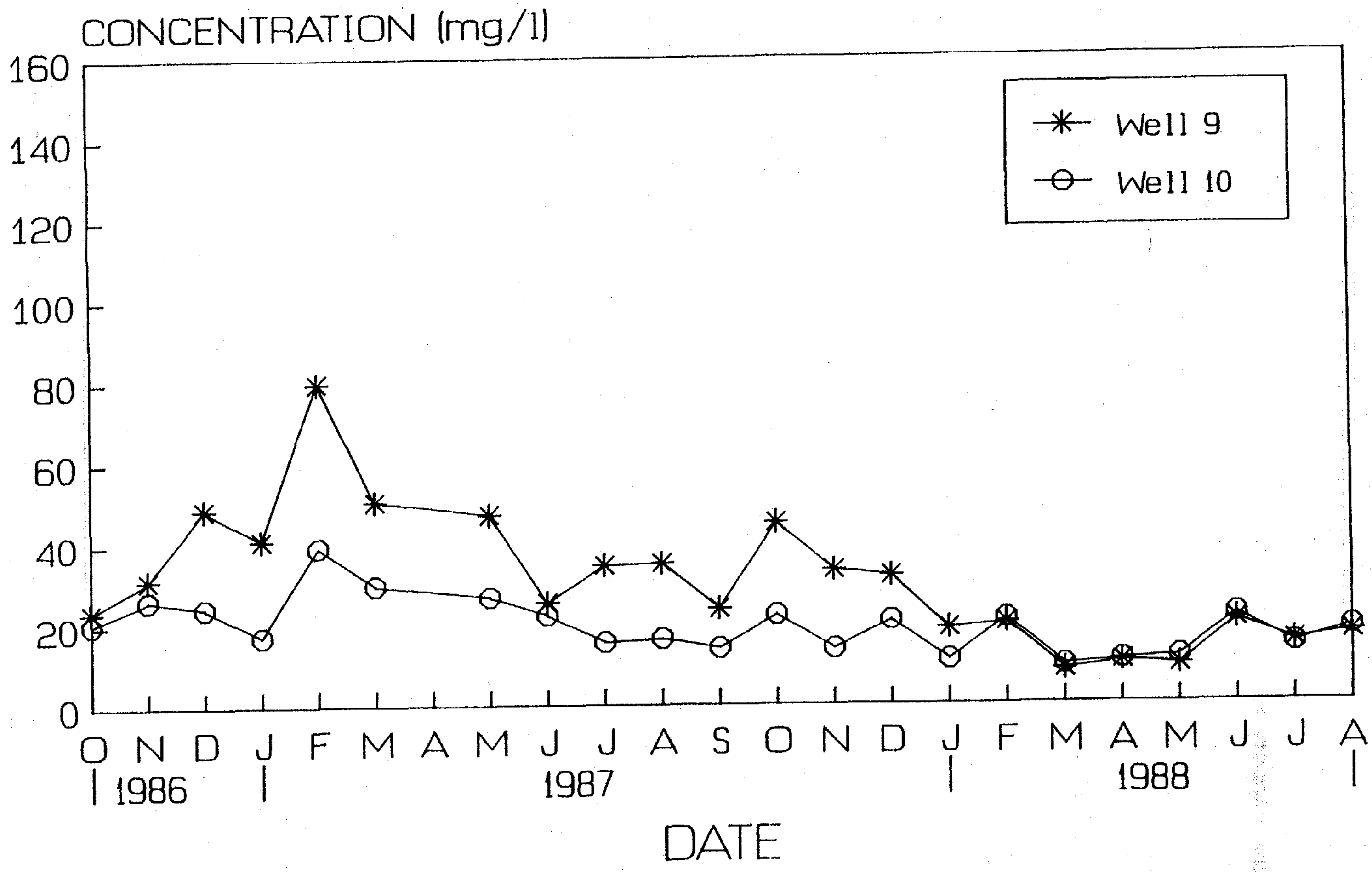


Figure 5.8 Calcium Levels at Wells 9 and 10, Parrish Road.

sample set was filtered in the field, preserved, and then analysed. A second sample set was not filtered but otherwise handled in a manner identical to the first sample. The results of these experiments are shown in Table 5.10. These results show that filtration tends to reduce the measured levels of most constituents. The most significantly affected parameter is Ca, with sulfate only moderately affected. Since filtration primarily removes suspended solids, these results clearly indicate that measured Ca levels are sensitive to the suspended solids, and hence turbidity content, of the groundwater. The primary force behind this relationship is the addition of acid preservative which partially dissolves the suspended solids. To identify the correlation between turbidity and measured Ca levels, the qualitative turbidity measurements were given numerical values, according to Table 5.11, and a correlation analysis was conducted between Ca and turbidity. The results are shown in Fig. 5.9. Significant correlation between Ca levels and turbidity at all wells is immediately apparent. Since a significant decrease in turbidity was observed at all wells, it is obvious that any possible leaching of Ca from the roadway is secondary compared to the Ca fluctuations associated with turbidity variations.

The variation in sulfate levels are shown in Figs. 5.10 to 5.14. Performing trend analyses on these data, Table 5.9, showed that the sulfate levels at wells 1, 2, 3, 5 and 6 have statistically significant upward trend. This trend is most noticable at wells 1, 5, and 6, Figs. 5.10 and 5.12. Since wells 1, 2, 5 and 6 are all immediately adjacent to the roadway, phosphogypsum used in roadway construction could be a possible source of sulfate. The correlation between sulfate and turbidity are shown in Fig. 5.15, which reflects a significant negative correlation at the wells that show upward trends in sulfate. This means that as the turbidity decreased increases in sulfate levels were measured. This increase in sulfate levels is probably due to sources other than turbidity changes, since the filtration experiments showed that removal of suspended solids also caused reductions in sulfate levels.

The variation in measurements of Ra-226 are shown in Figs. 5.16 to 5.20. These results show peaks in May 1987, 7 months after road construction. The most noteworthy characteristic of these peaks is that the highest peaks were recorded at wells 1, 2, and 5, which are all immediately adjacent to the roadway indicating that leaching from the roadway may have contributed to these peaks. However, since data from all wells show some peaking characteristics, it is probable more than one phenomenon may have influenced these results. The correlation between Ra-226 and turbidity is shown in Fig. 5.21. It is clear that, at almost all wells, there is a significant positive correlation between turbidity and Ra-226. This is a similar result to that between Ca and turbidity and further reinforces the need to filter samples before analysis. On re-examining the turbidity data, it is observed that the peaks in Ra-226 during May 1987

Table 5.10. Effect of Filtration on Measured Groundwater Quality

Parameter	Ave. Change Due to Filtration (%)
Na	14.1
K	-5.1
Ca	-36.4
Mg	4.2
Alkalinity	-4.3
SO_4	-18.4
Cl	-4.8
F	-16.7
NO_3	-23.7
Fe	-30.8
Pb	8.3
Mn	1.1
TDS	-12.4

Table 5.11. Numerical Equivalents of Turbidity

Qualitative Measure	Numerical Equivalent
clear	1
slightly cloudy	2
cloudy	3
very cloudy	4

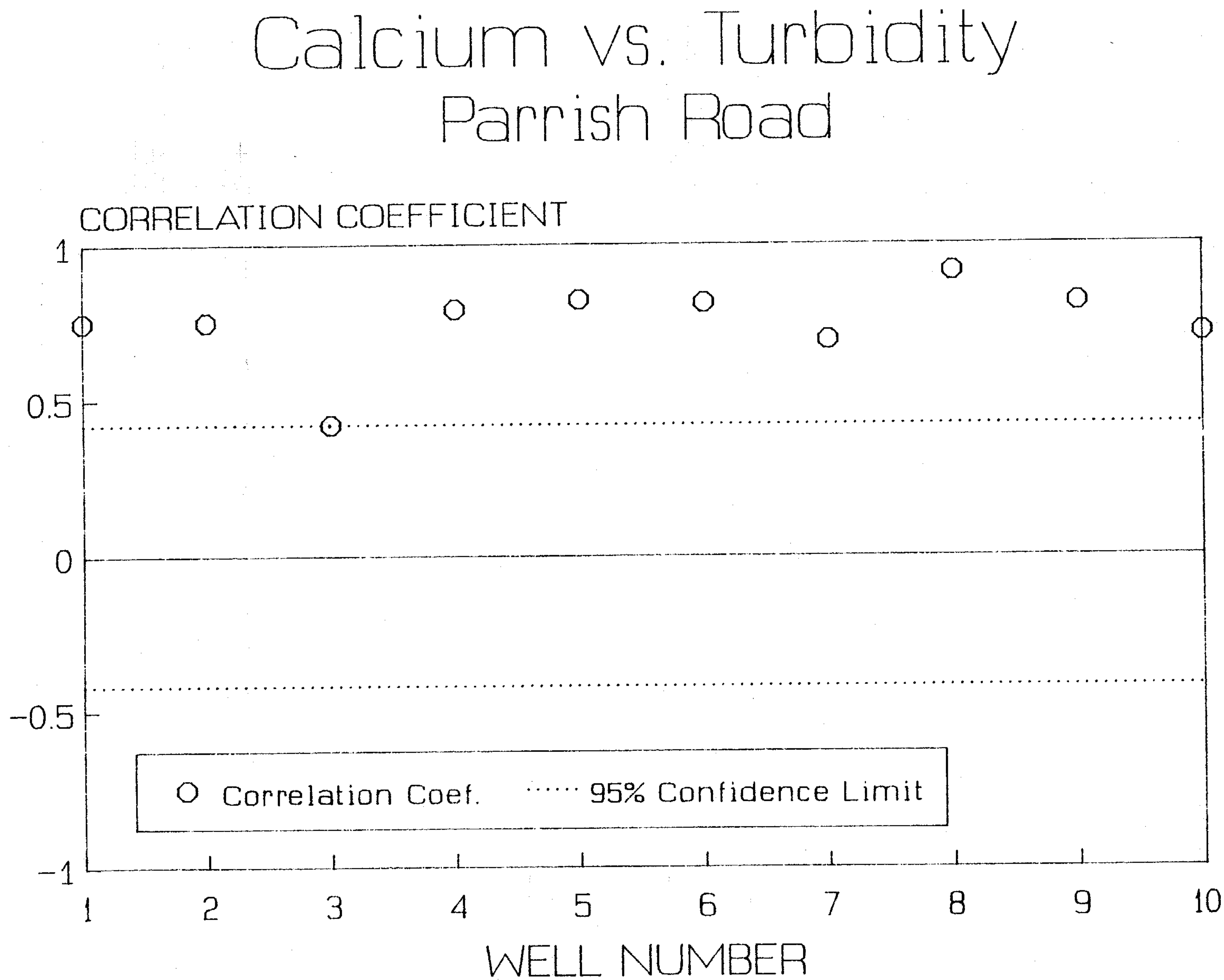


Figure 5.9 Correlation Between Calcium and Turbidity, Parrish Road.

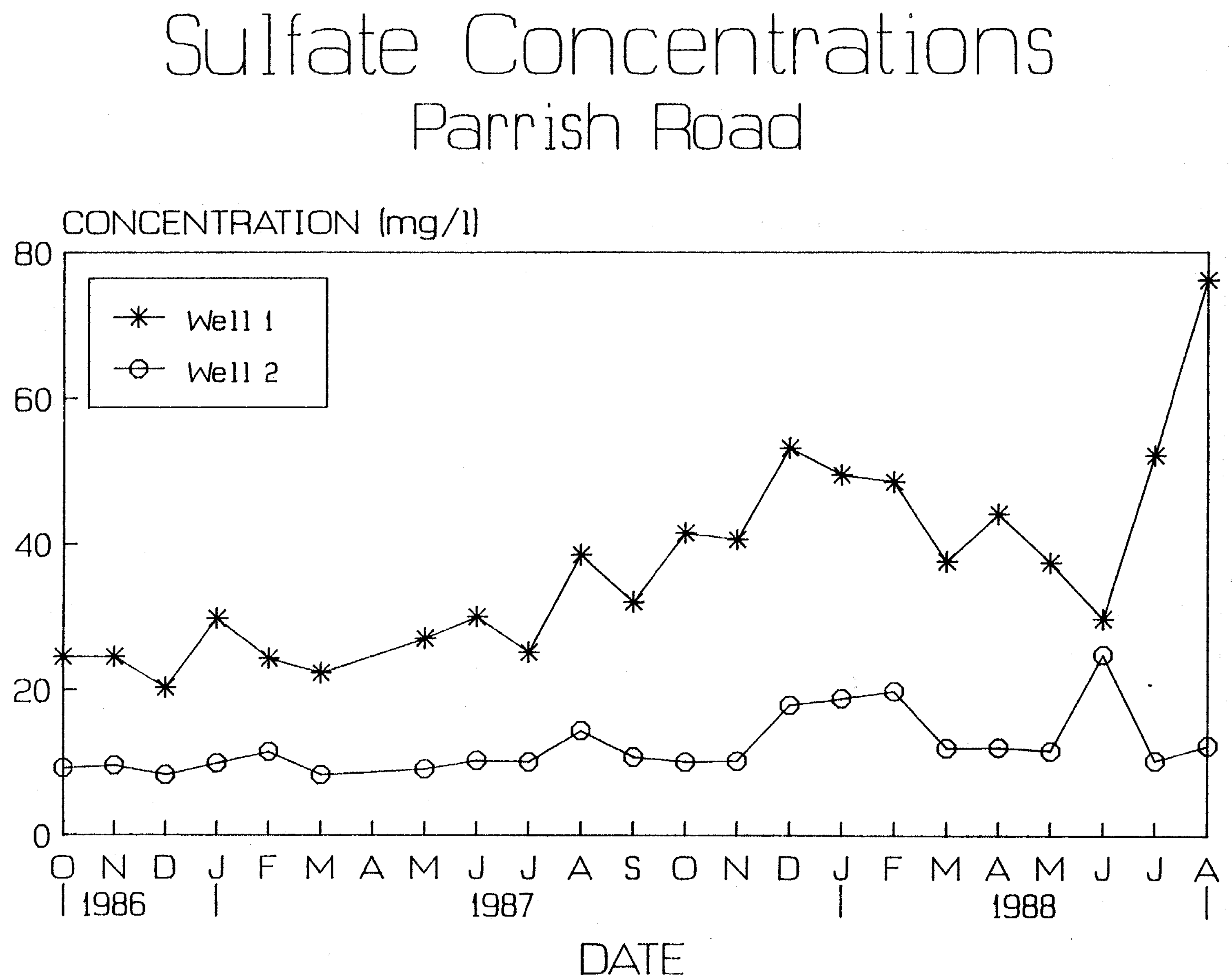


Figure 5.10 Sulfate Levels at Wells 1 and 2, Parrish Road.

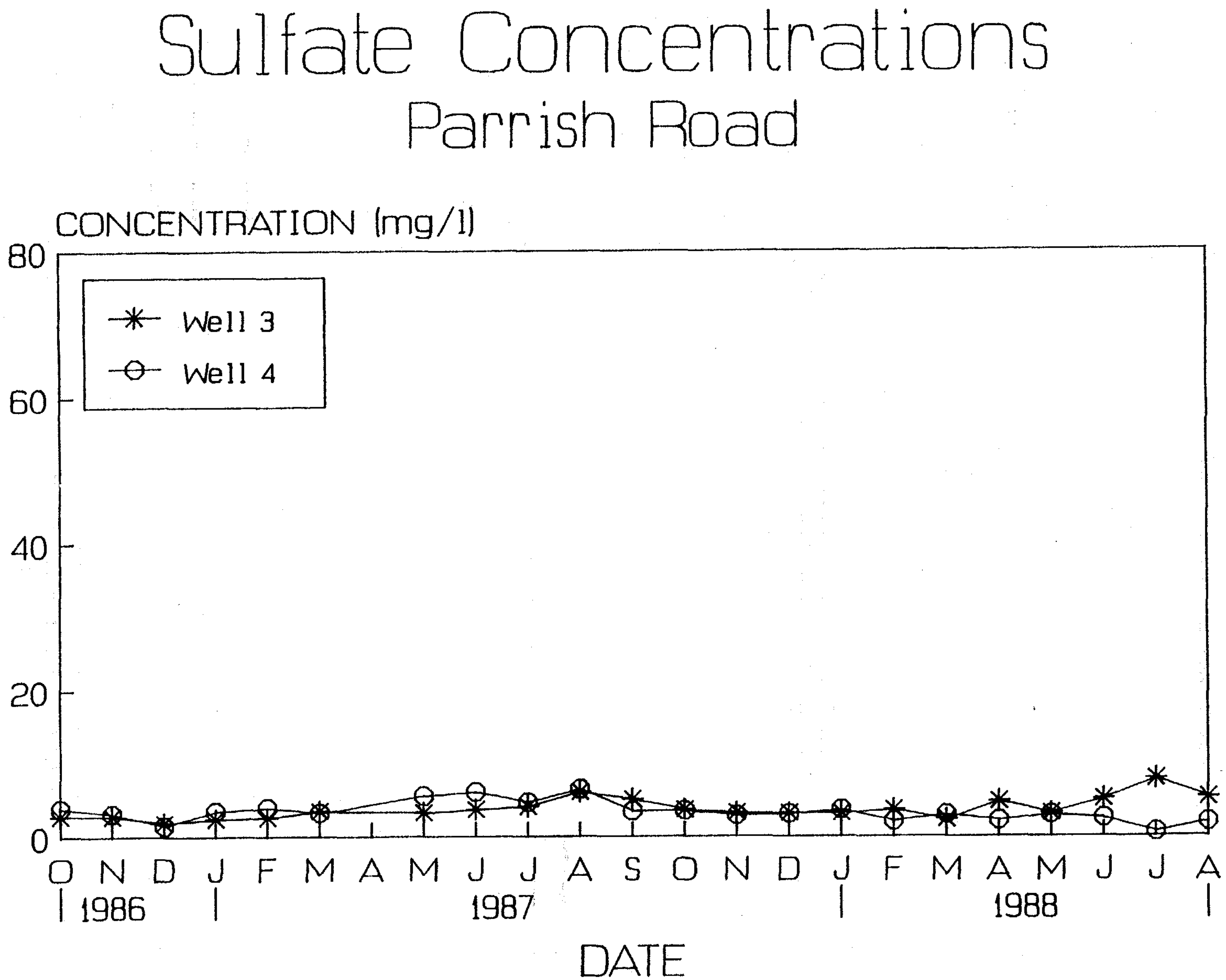


Figure 5.11 Sulfate Levels at Wells 3 and 4, Parrish Road.

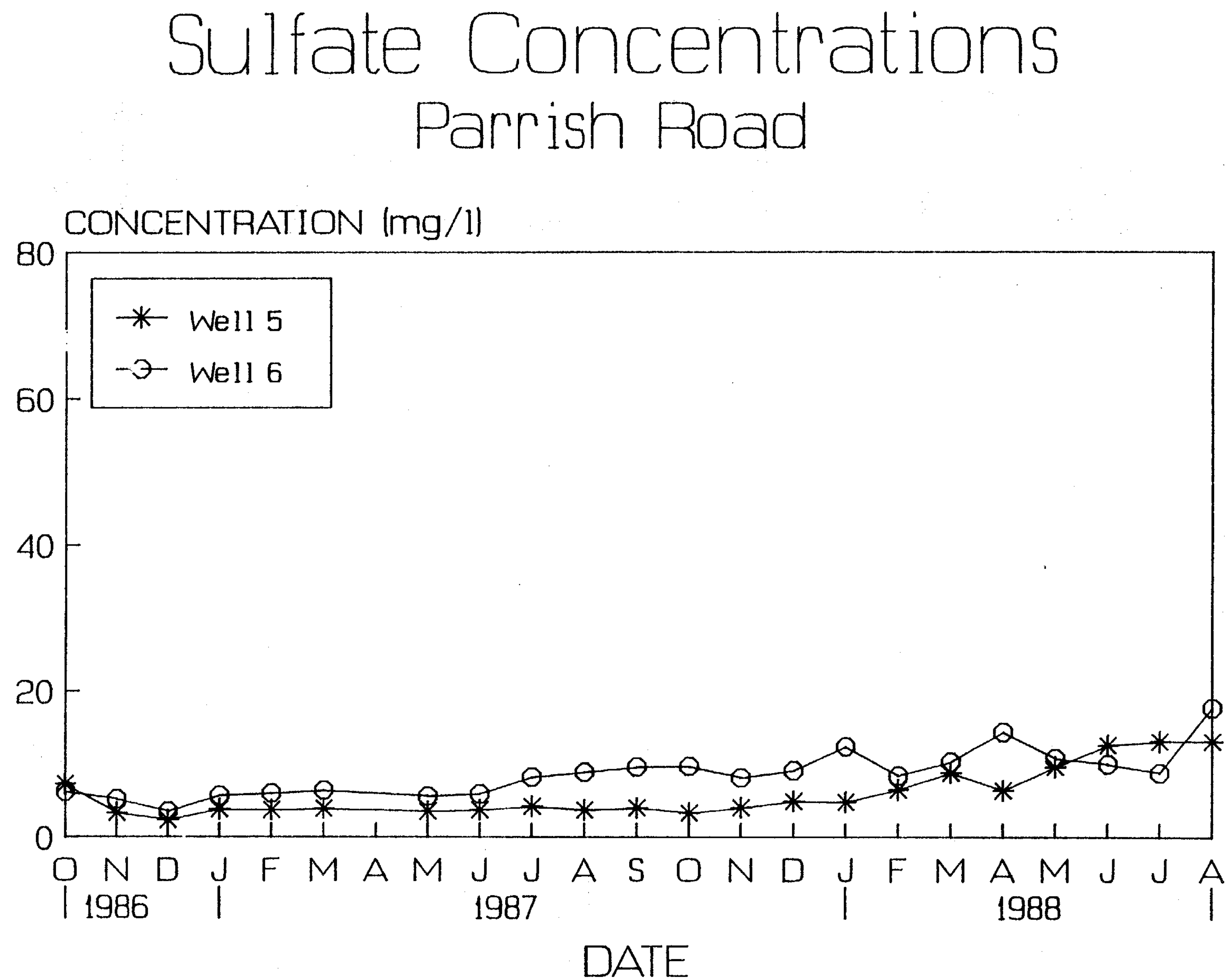


Figure 5.12 Sulfate Levels at Wells 5 and 6, Parrish Road.

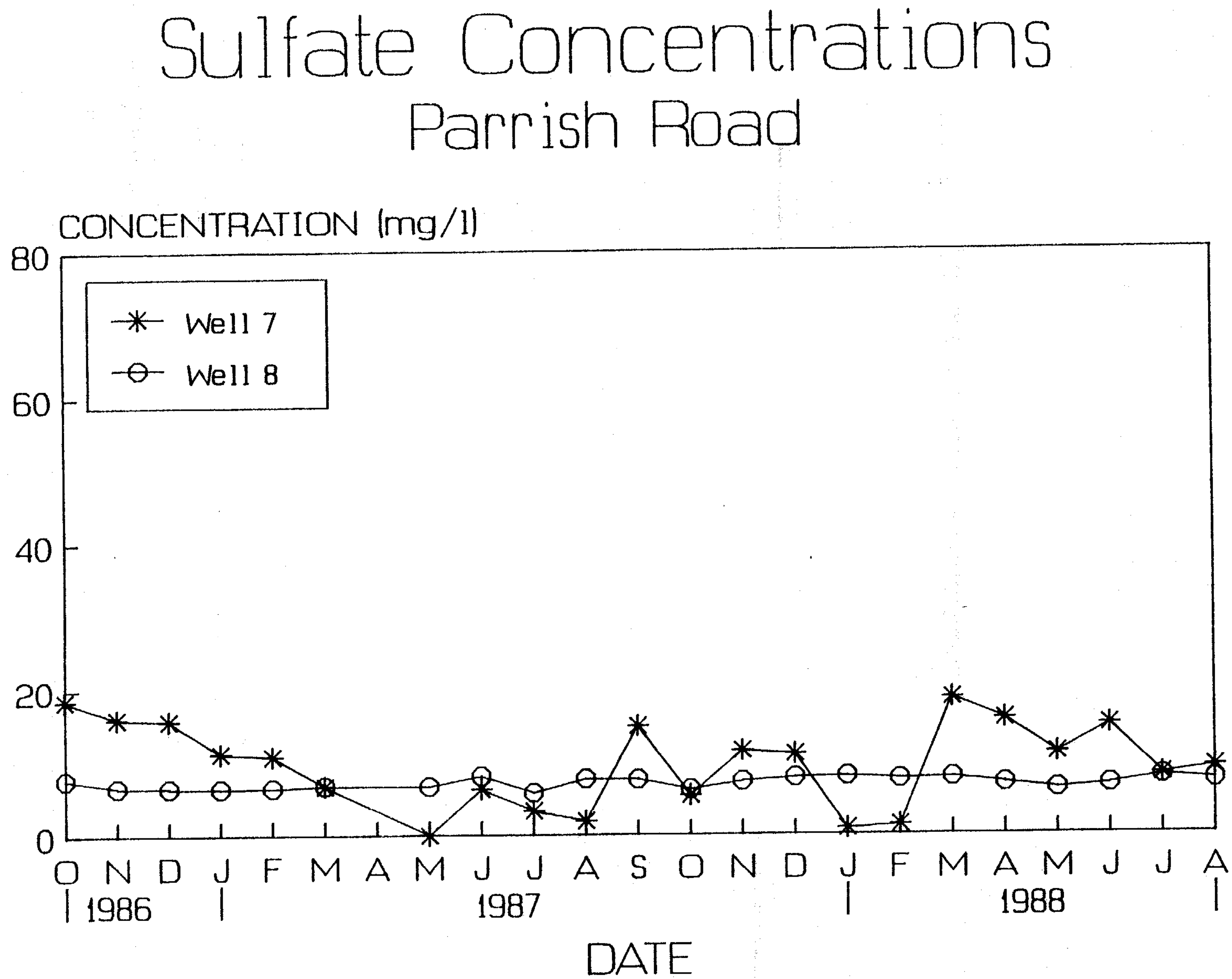


Figure 5.13 Sulfate Levels at Wells 7 and 8, Parrish Road.

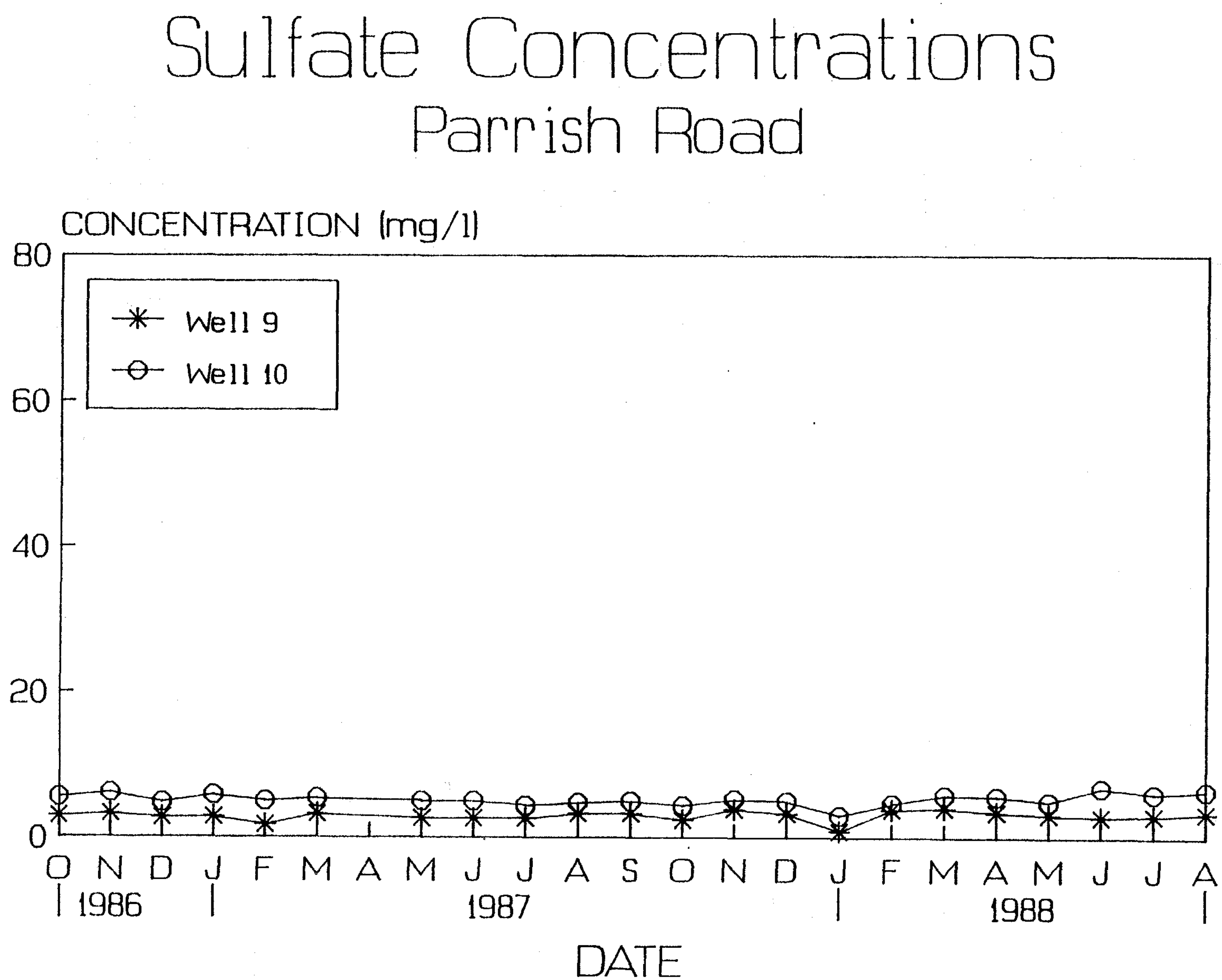


Figure 5.14 Sulfate Levels at Wells 9 and 10, Parrish Road.

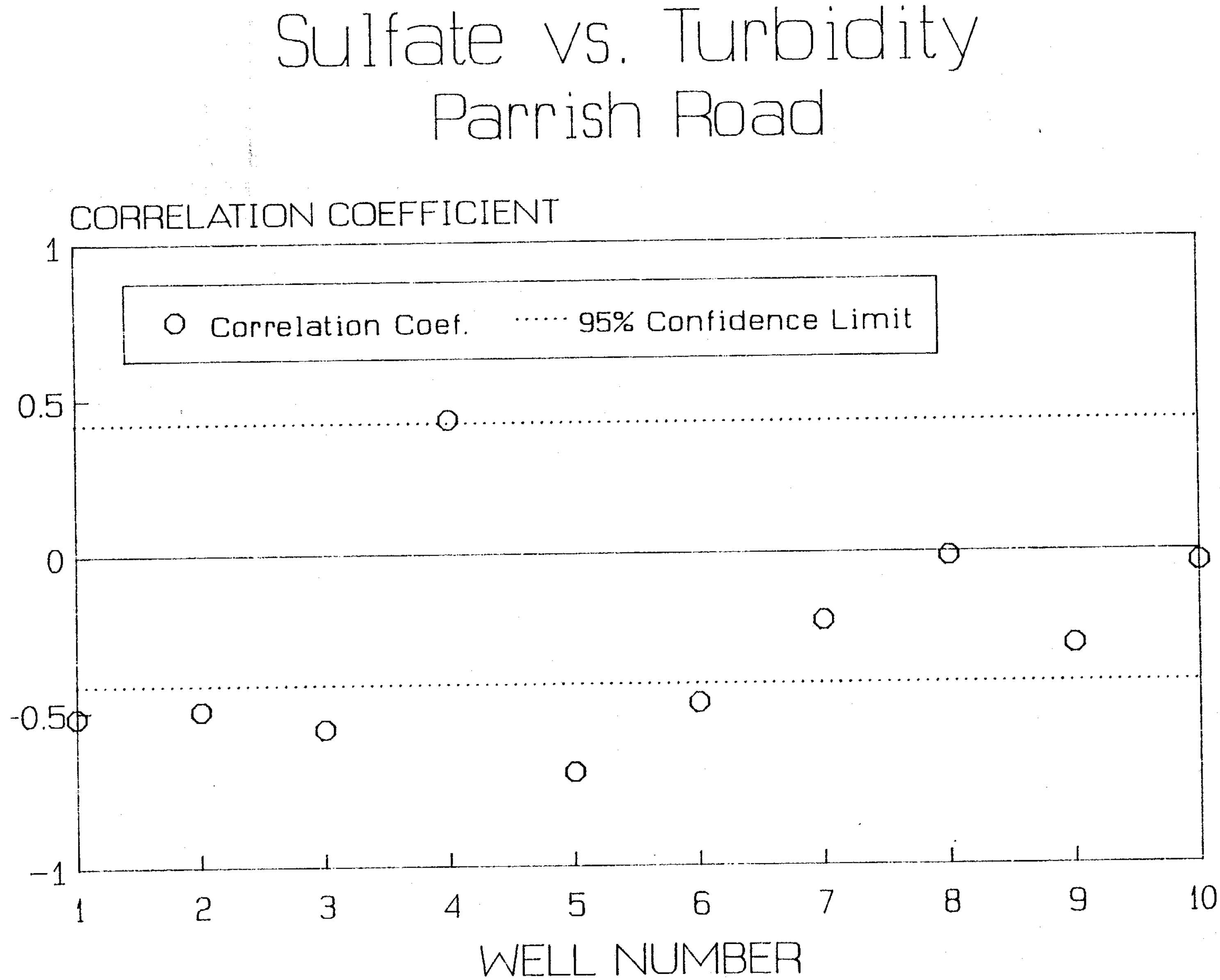


Figure 5.15 Correlation Between Sulfate and Turbidity, Parrish Road

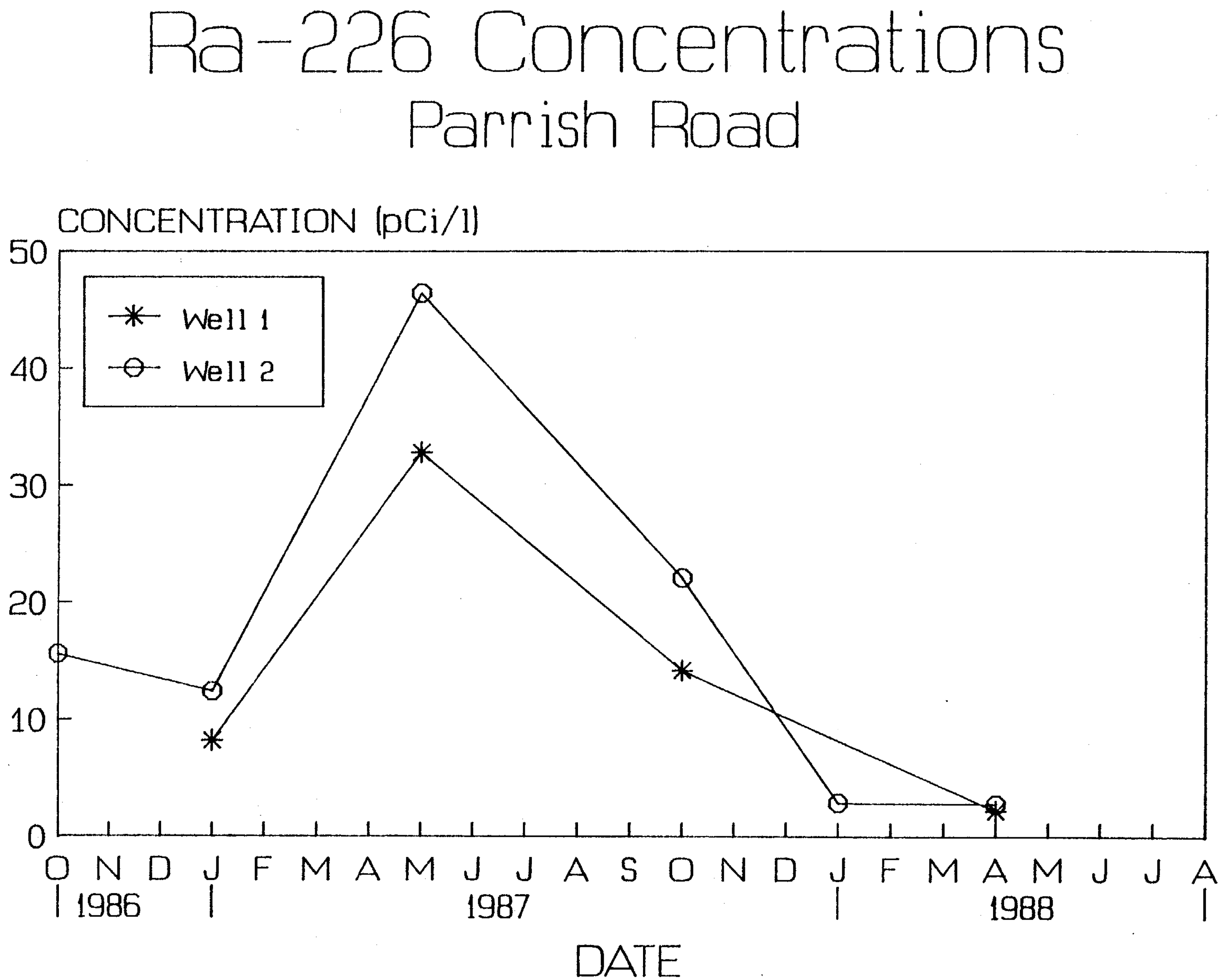


Figure 5.16 Ra-226 Levels at Wells 1 and 2, Parrish Road.

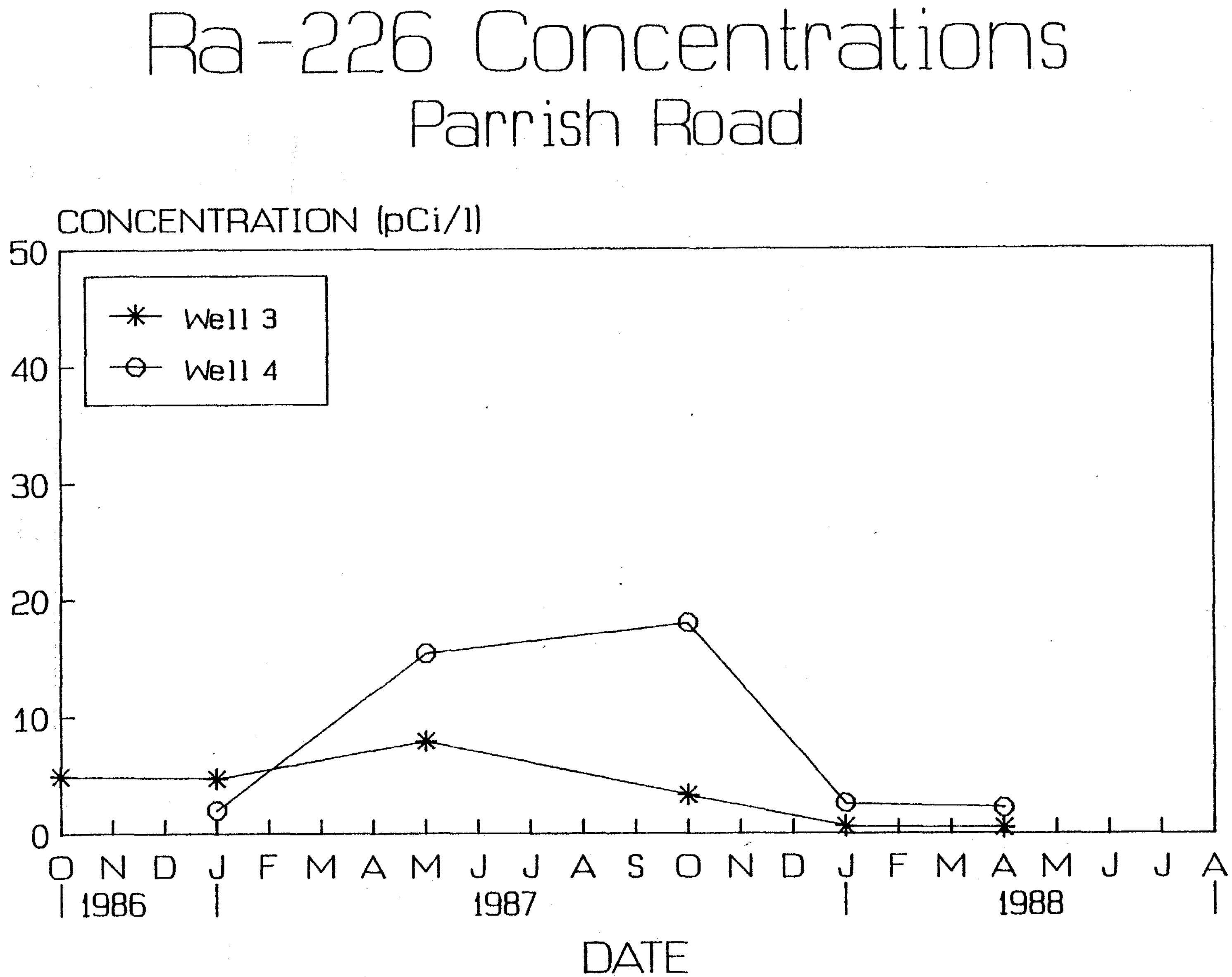


Figure 5.17 Ra-226 Levels at Wells 3 and 4, Parrish Road.

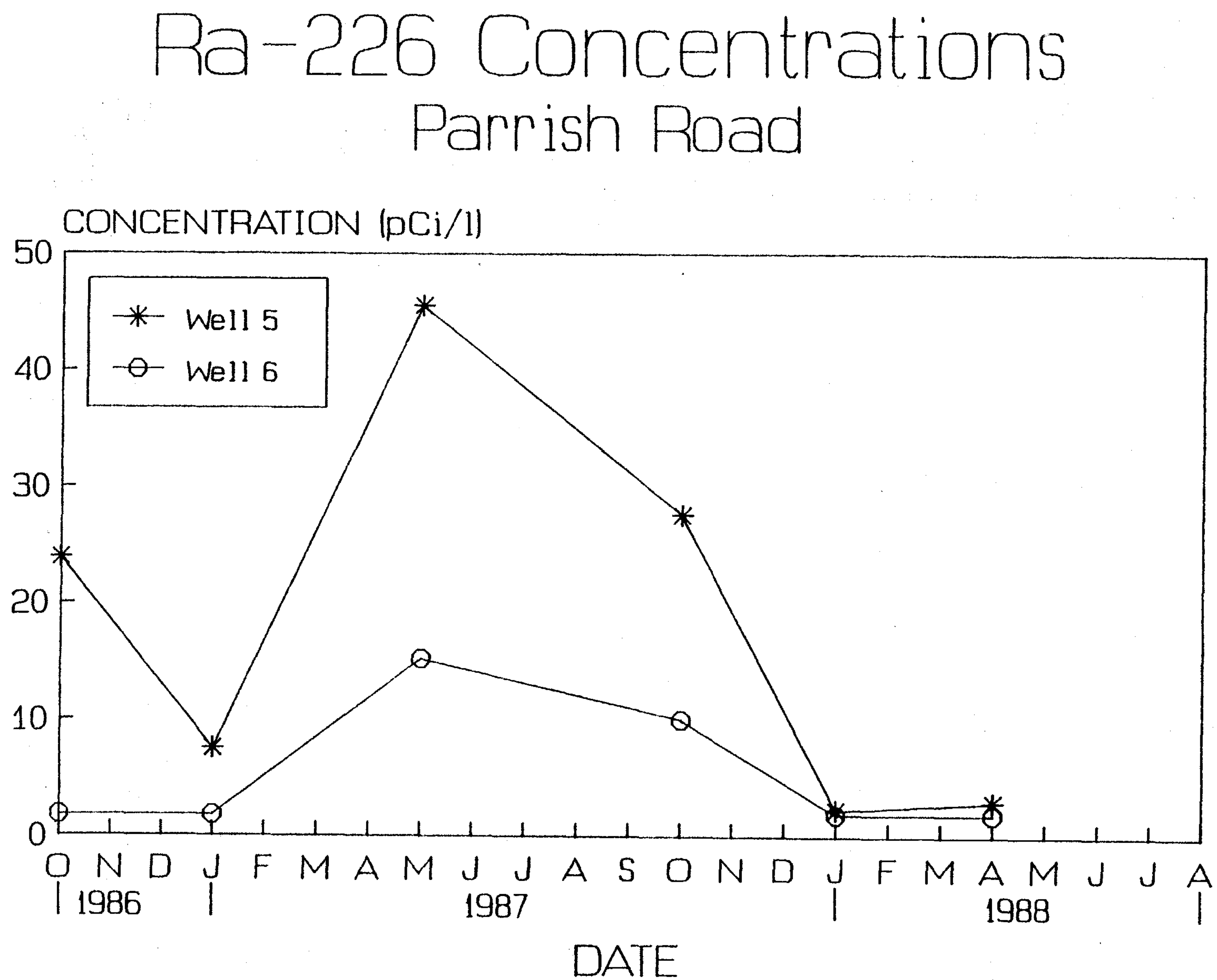


Figure 5.18 Ra-226 Levels at Wells 5 and 6, Parrish Road.

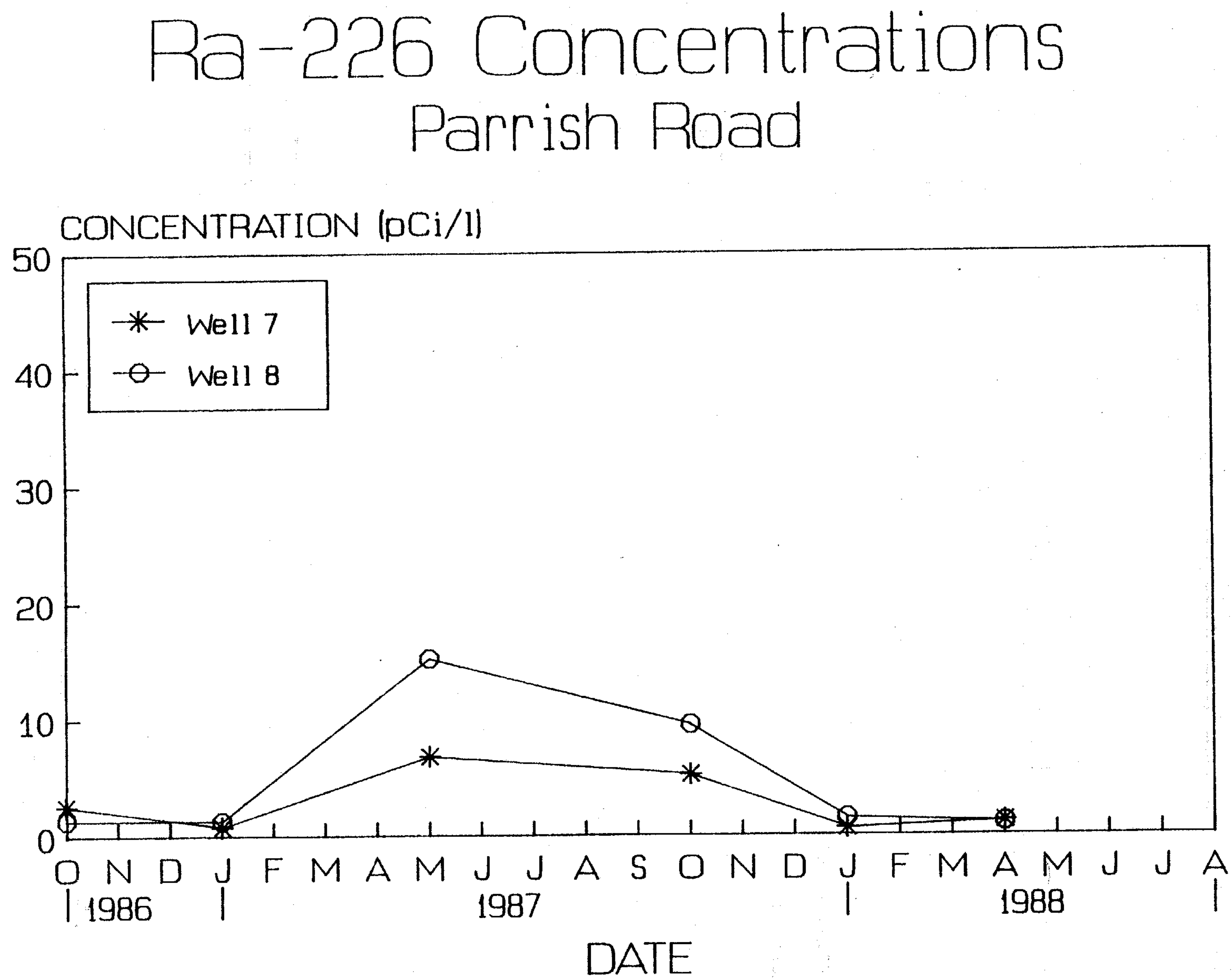


Figure 5.19 Ra-226 Levels at Wells 7 and 8, Parrish Road.

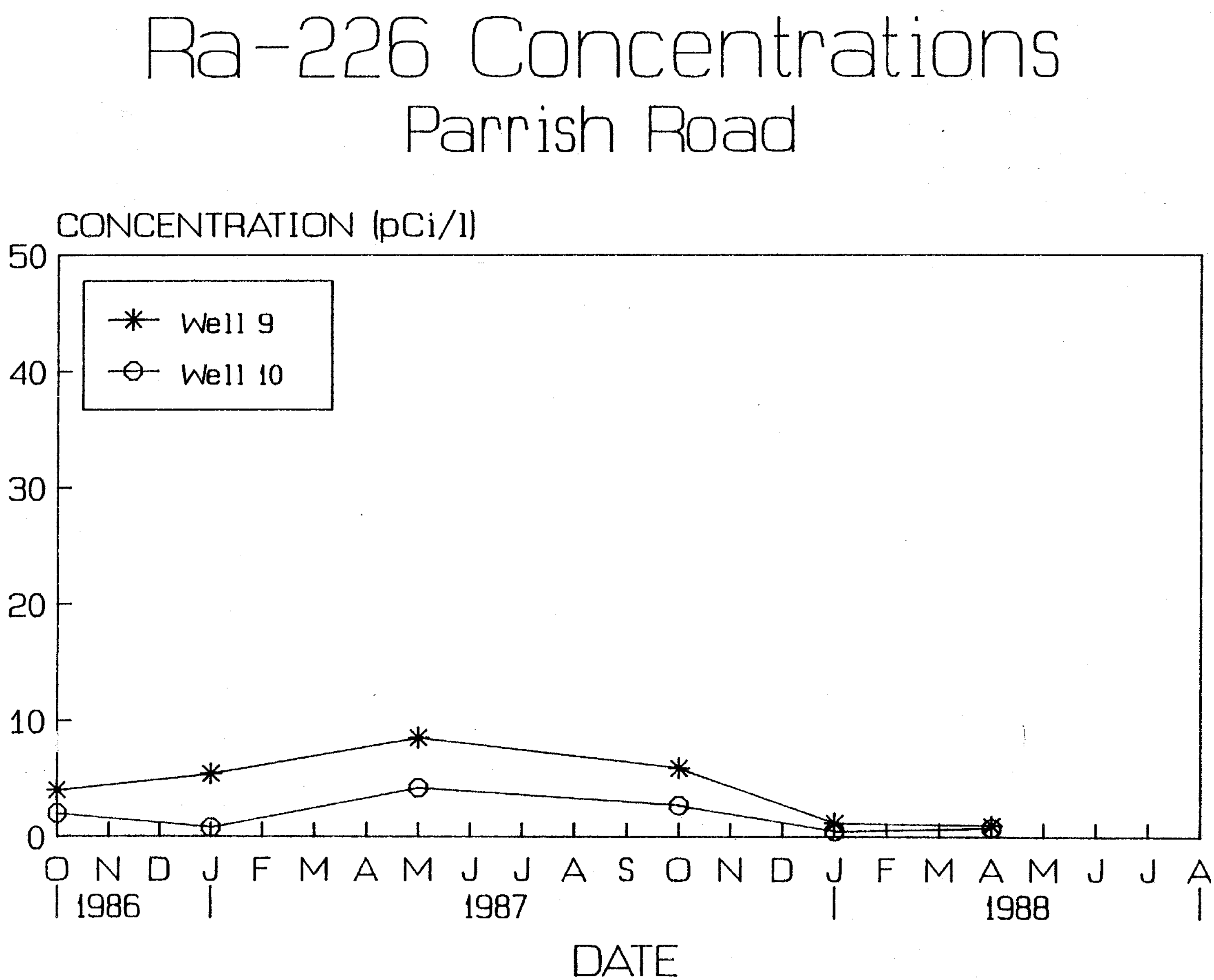


Figure 5.20 Ra-226 Levels at Wells 9 and 10 Parrish Road.

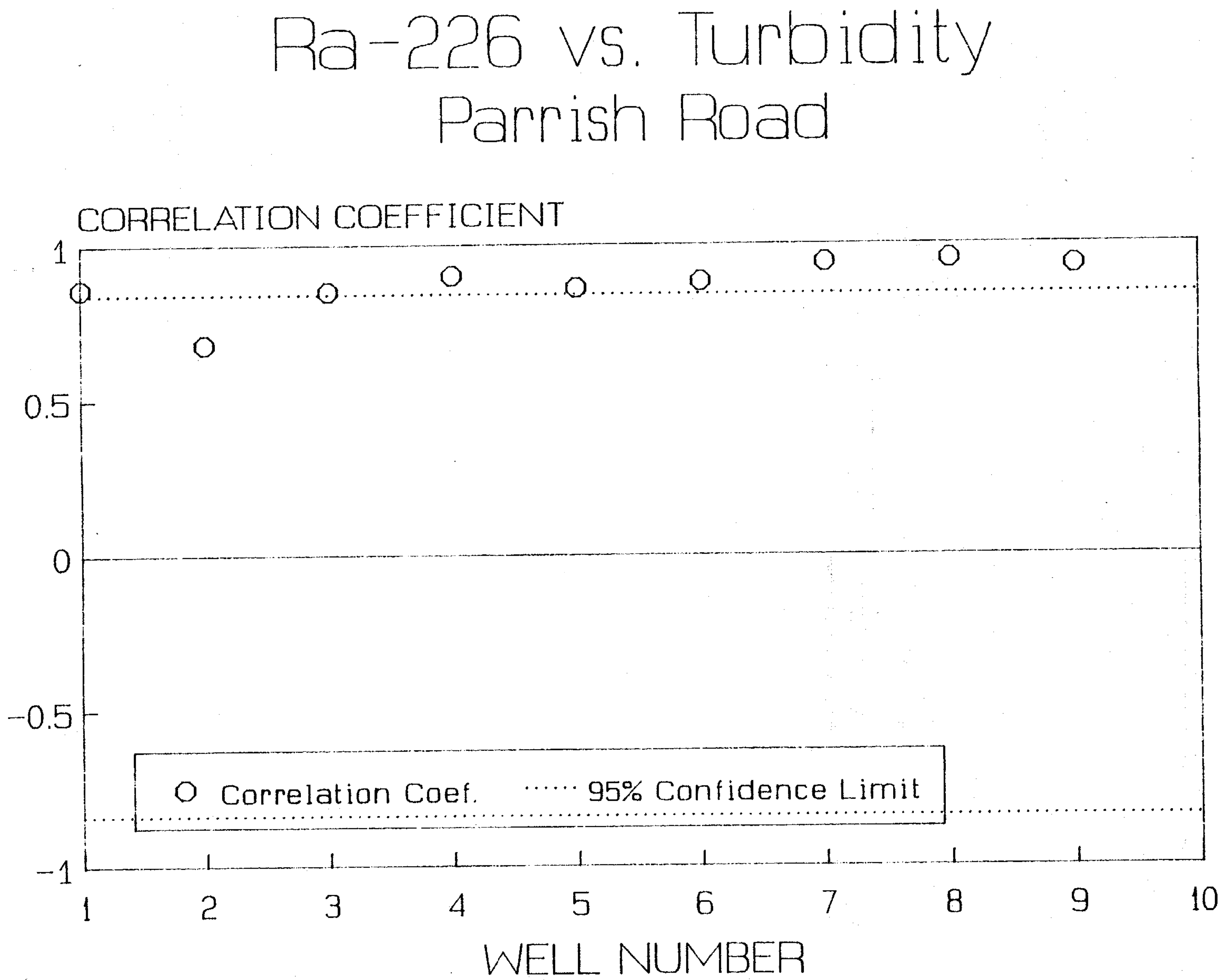


Figure 5.21 Correlation Between Ra-226 and Turbidity, Parrish Road

corresponded to increased turbidity levels. This is illustrated clearly in Fig. 5.22, which shows the results of Ra-226 and turbidity measurements at well 1.

5.2.6 Impact of the Roadway on Groundwater Quality

Based on the results presented in the previous section, we may conclude that: (a) Construction of the roadway is probably responsible for statistically significant elevations in sulfate levels in the groundwater immediately adjacent to the roadway: (b) The effect of roadway construction on Ca and Ra-226 levels could not be identified due to significant variations in sample turbidity, which are highly correlated with measured Ca and Ra-226 levels. In using the above results to assess the feasibility of road construction using phosphogypsum, the following points should be noted: (a) The elevated sulfate levels do not threaten the potability of the groundwater; and (b) The leaching of sulfate is probably from excess gypsum on the side of the road, and not from gypsum in the main roadway which is bound and covered with asphalt.

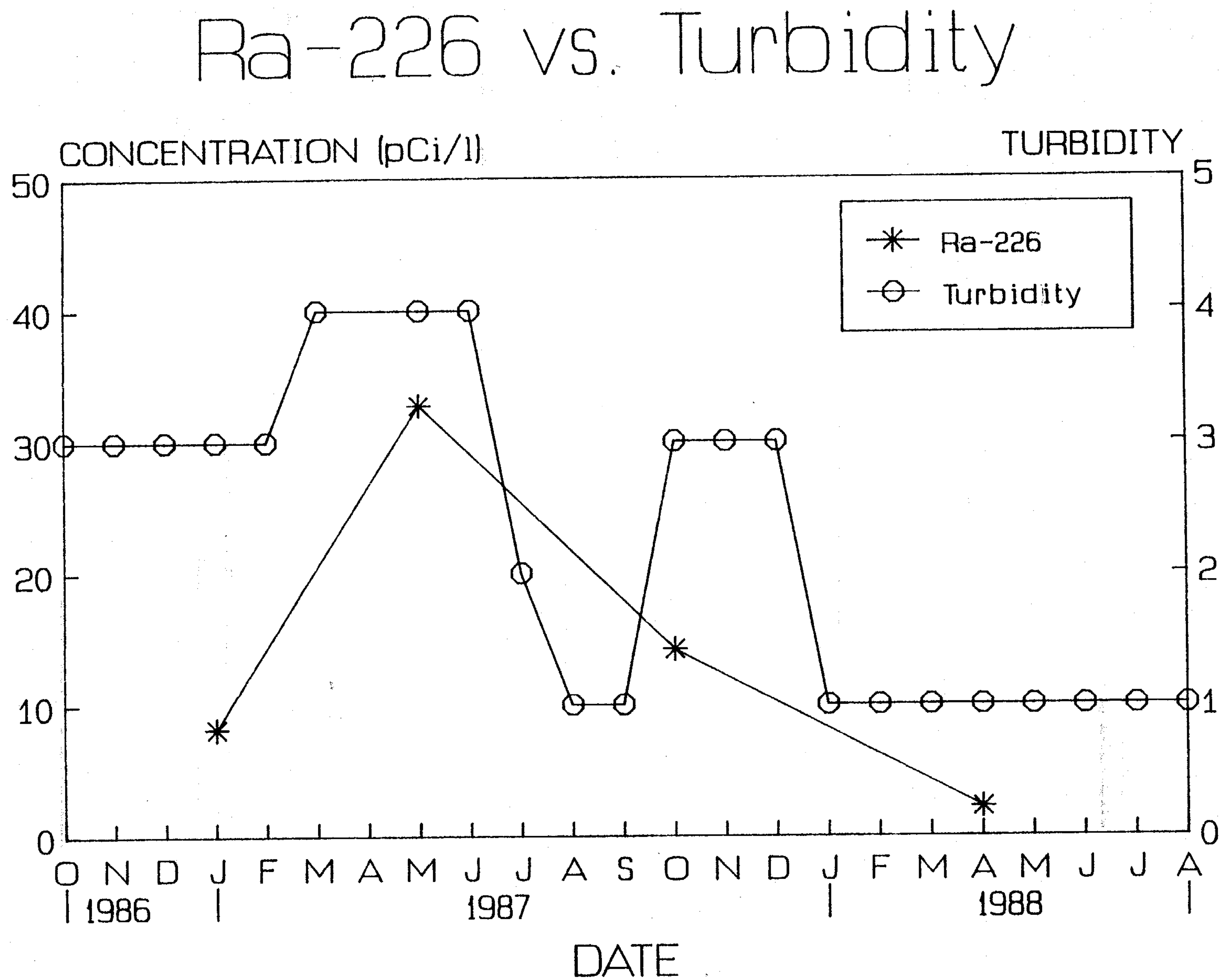


Figure 5.22 Turbidity and Ra-226 Levels at Well 1, Parrish Road.

5.3 Columbia County Study

5.3.1 Hydrogeology

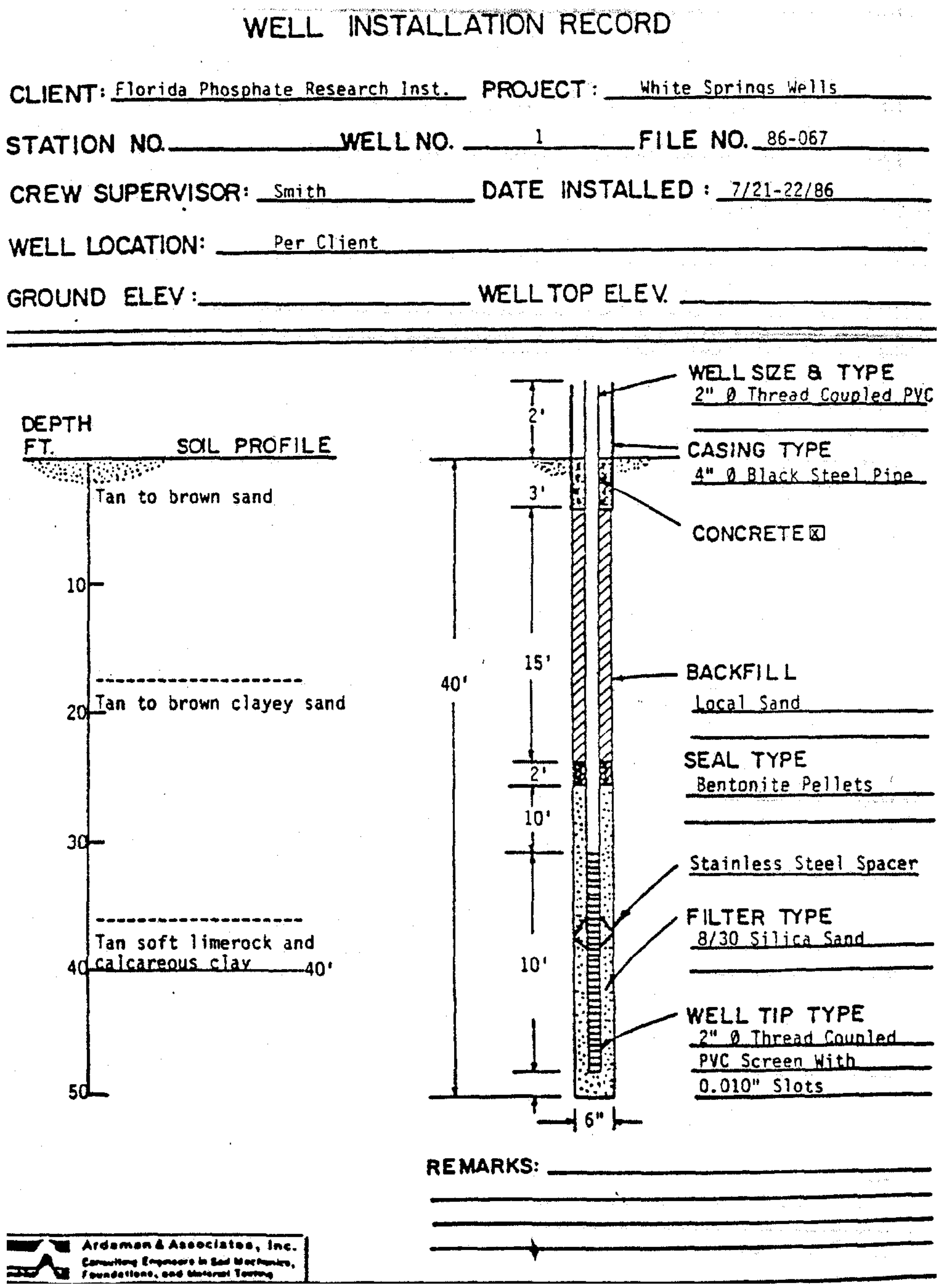
White Springs Road is located in northern Columbia County and within the Suwannee River Water Management District (SRWMD). The geology and hydrology of this area has been extensively documented by Ceryak et al, 1983. In this area, the Floridan aquifer is the only aquifer beneath the site. It is unconfined and the water is under atmospheric pressure. The water table normally fluctuates between elevation 50 ft. and elevation 65 ft. However, when the Suwannee River floods, the water table is above ground level at the site. The experimental roadway is between elevations 87 and 89 ft. The geology immediately beneath the roadway was determined during well installation and found to be predominantly clay with scattered amounts of sand and limestone. The well installation records, showing the soil profile at each well, are shown in Figs. 5.23 to 5.30. The rainfall amounts experienced at the site during this project are shown in Fig. 5.31. These data show that most of the rainfall occurred during the summer months with moderate amounts of rainfall during other times.

5.3.2 Design of Monitoring Well Array

The monitoring well array, Fig. 5.32, was placed in approximately the same alignment, relative to the roadway, as the monitoring wells at Parrish Road. Using this approach, we are able to isolate the effect of leaching, if any, at fixed distances from the roadway for different hydrogeologies. An identical well design to that used at Parrish Road was installed. Since the minimum historical piezometric elevation at the site is 50 ft, the wells were screened to elevation 45 ft, with the top of the screen at elevation 55 ft. Since the length of open land adjacent to the roadway was limited, and it was desirable to use the same well spacing as Parrish Road, only 4 symmetric pairs of wells were used, instead of the 5 pairs that were used at Parrish Road.

5.3.3 Sampling Protocol

The same equipment used at the Parrish Road site was employed at this site, however, because of the tendency of many of the wells to go dry, a modified sample collection scheme was utilized. The clay, sand, and limestone geology found at this site is significantly less permeable than that found at the Parrish Road site. The hydraulic conductivity at the site was given a value of 1.6 ft/day in order to determine the required pumping time for sample collection. Using the equations developed by Barber and Davis (1987), discussed in detail earlier in this chapter, pumping times of 14 minutes for the non-mixing case, Eq. 5.2, and 2 minutes for the mixing case Eq. 5.3 obtained. These estimates are based on an average, zero drawdown, water depth in the wells of 20.5 ft, and a screen length of 10 ft. Based on



WELL INSTALLATION RECORD

CLIENT: Florida Phosphate Research Inst. PROJECT: White Springs Wells

STATION NO. ________ WELL NO. 1 FILE NO. 86-067

CREW SUPERVISOR: Smith DATE INSTALLED: 7/21-22/86

WELL LOCATION: Per Client

GROUND ELEV: ________ WELL TOP ELEV. ________

REMARKS: ________

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Figure 5.23 Well Installation Record at Well 1, White Springs Road.

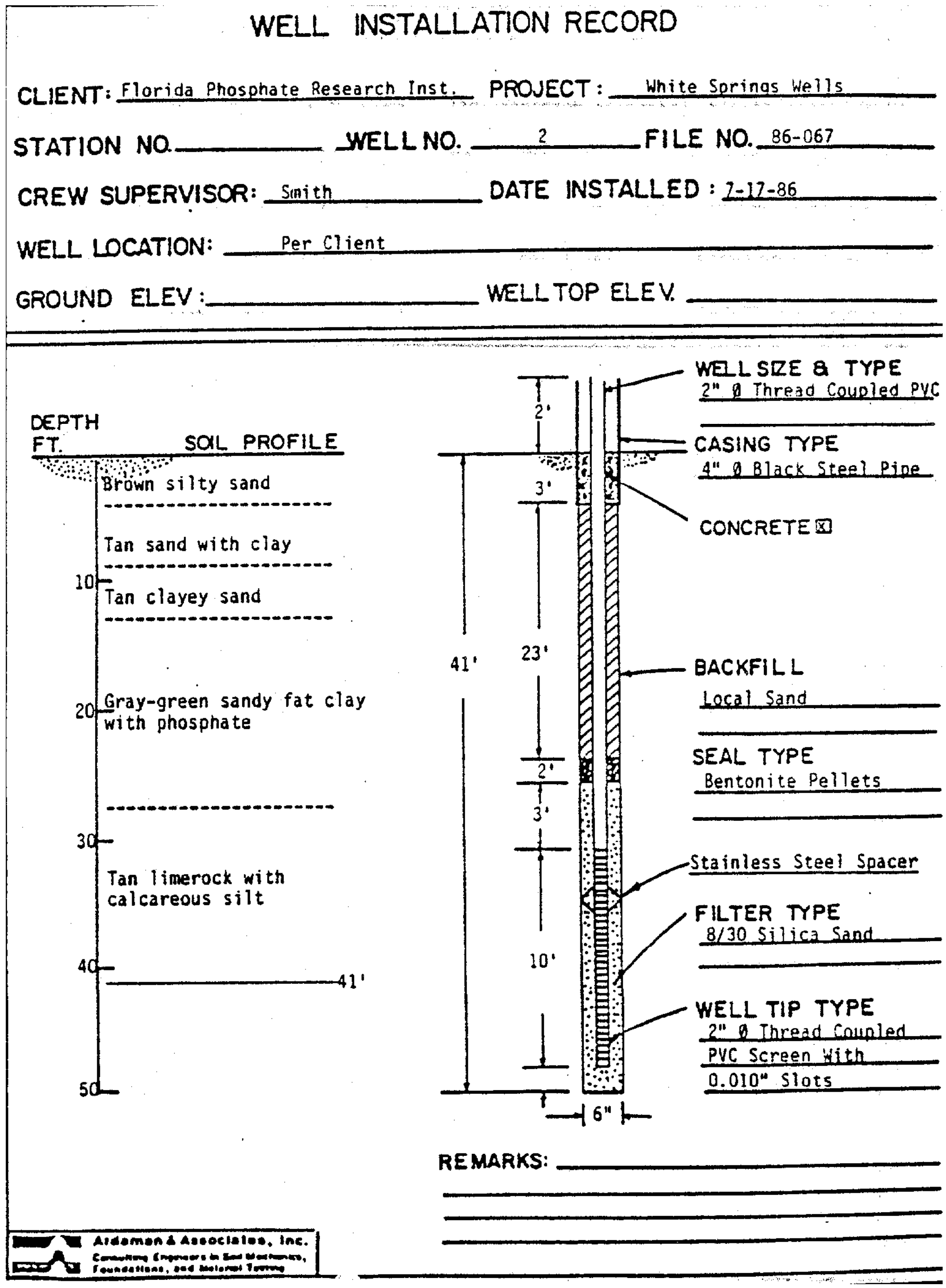


Figure 5.24 Well Installation Record at Well 2, White Springs Road.

WELL INSTALLATION RECORD

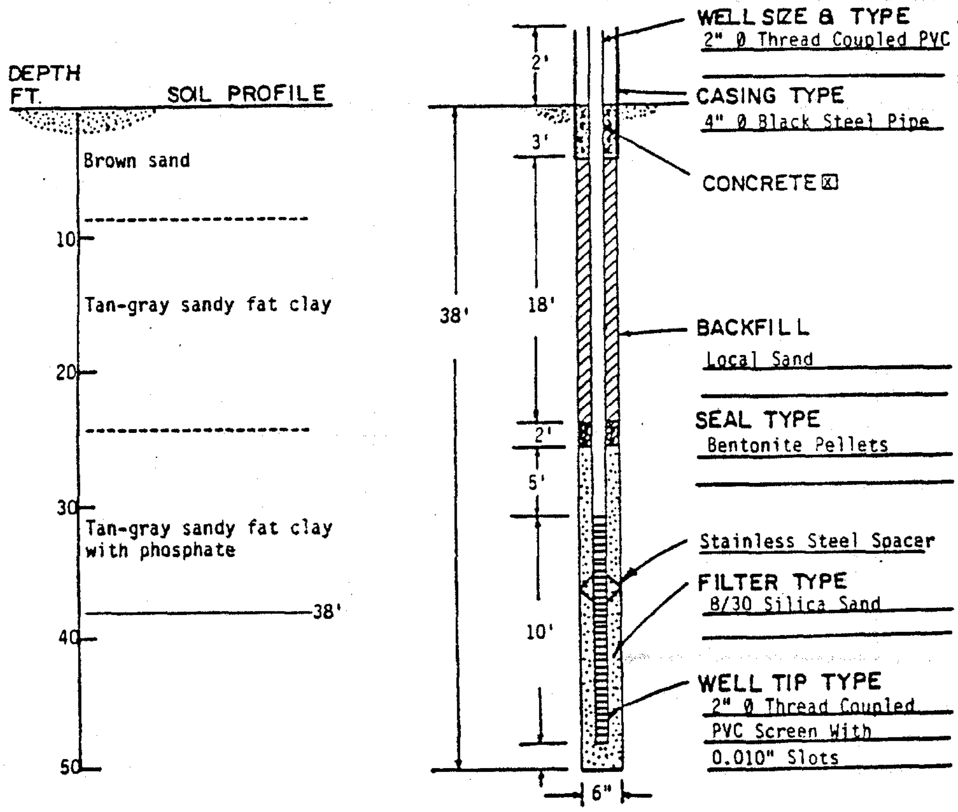
CLIENT: Florida Phosphate Research Inst. PROJECT: White Springs Wells

STATION NO. ______ WELL NO. 3 FILE NO. 86-067

CREW SUPERVISOR: Smith DATE INSTALLED: 7-22-86

WELL LOCATION: Per Client

GROUND ELEV: ______ WELLTOP ELEV. ______



REMARKS: ______

Ardaman & Associates, Inc.
Consulting Engineers in Soil Mechanics, Foundations, and Material Testing

Figure 5.25 Well Installation Record at Well 3, White Springs Road.

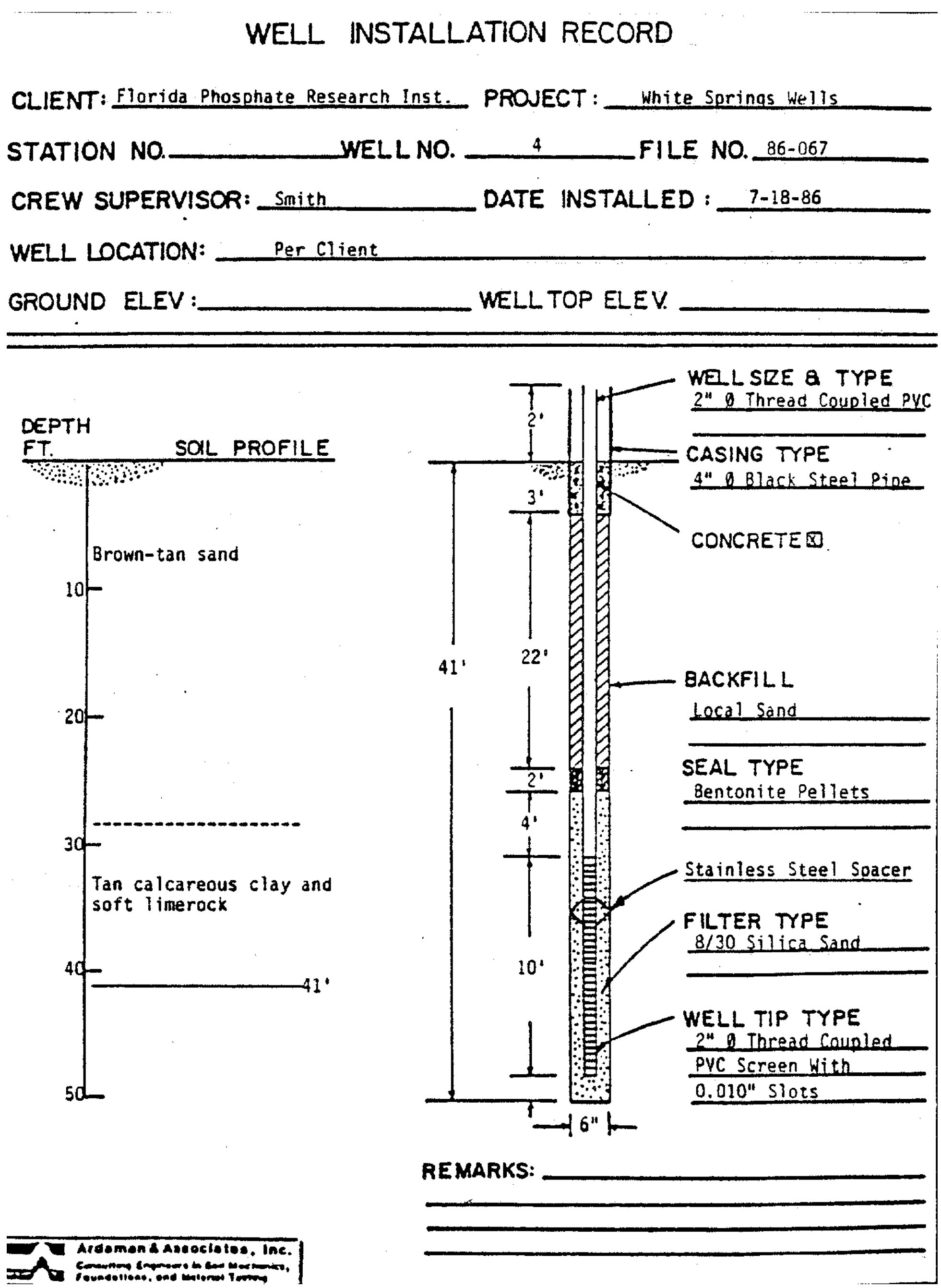


Figure 5.26 Well Installation Record at Well 4, White Springs Road.

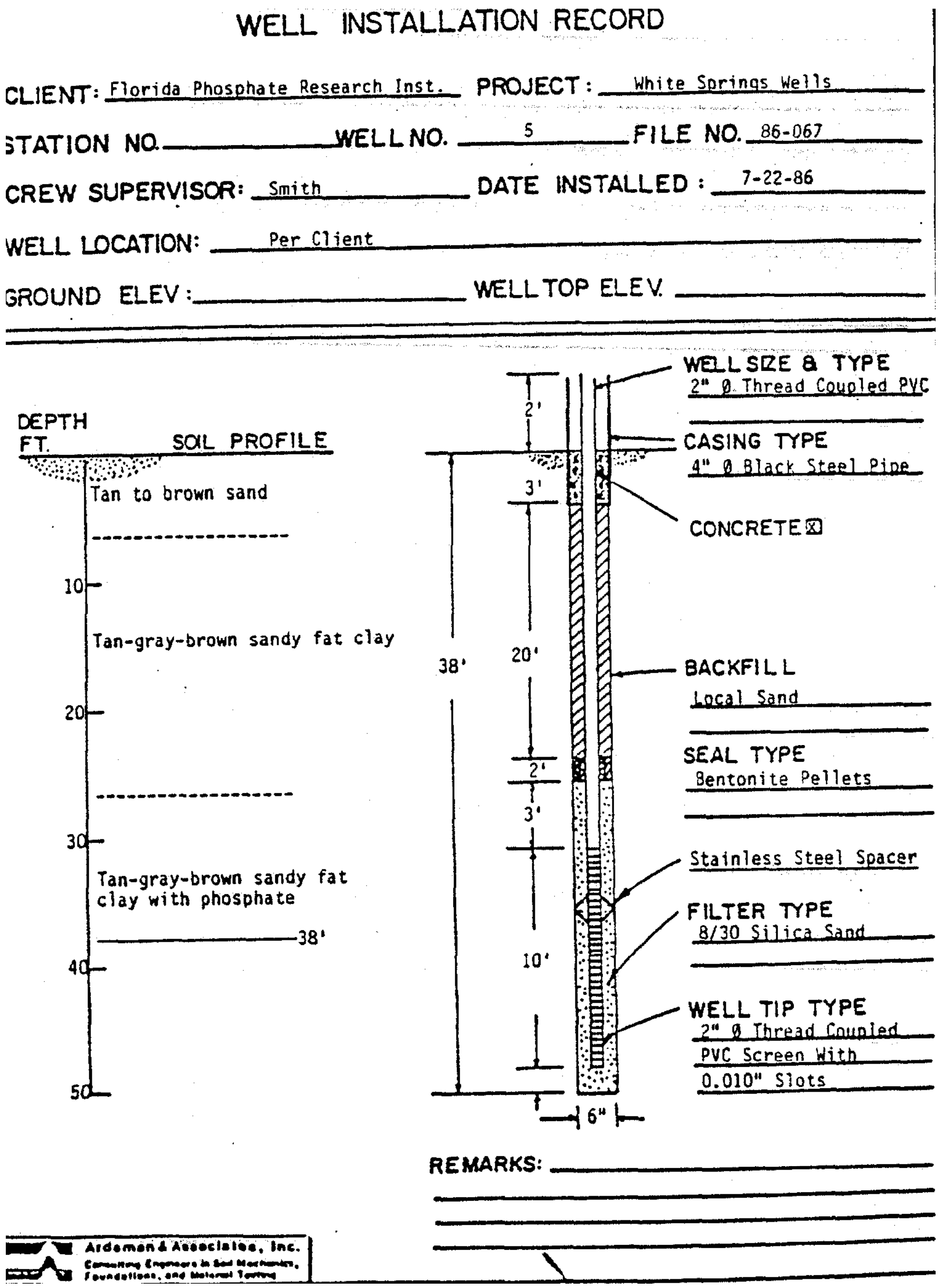
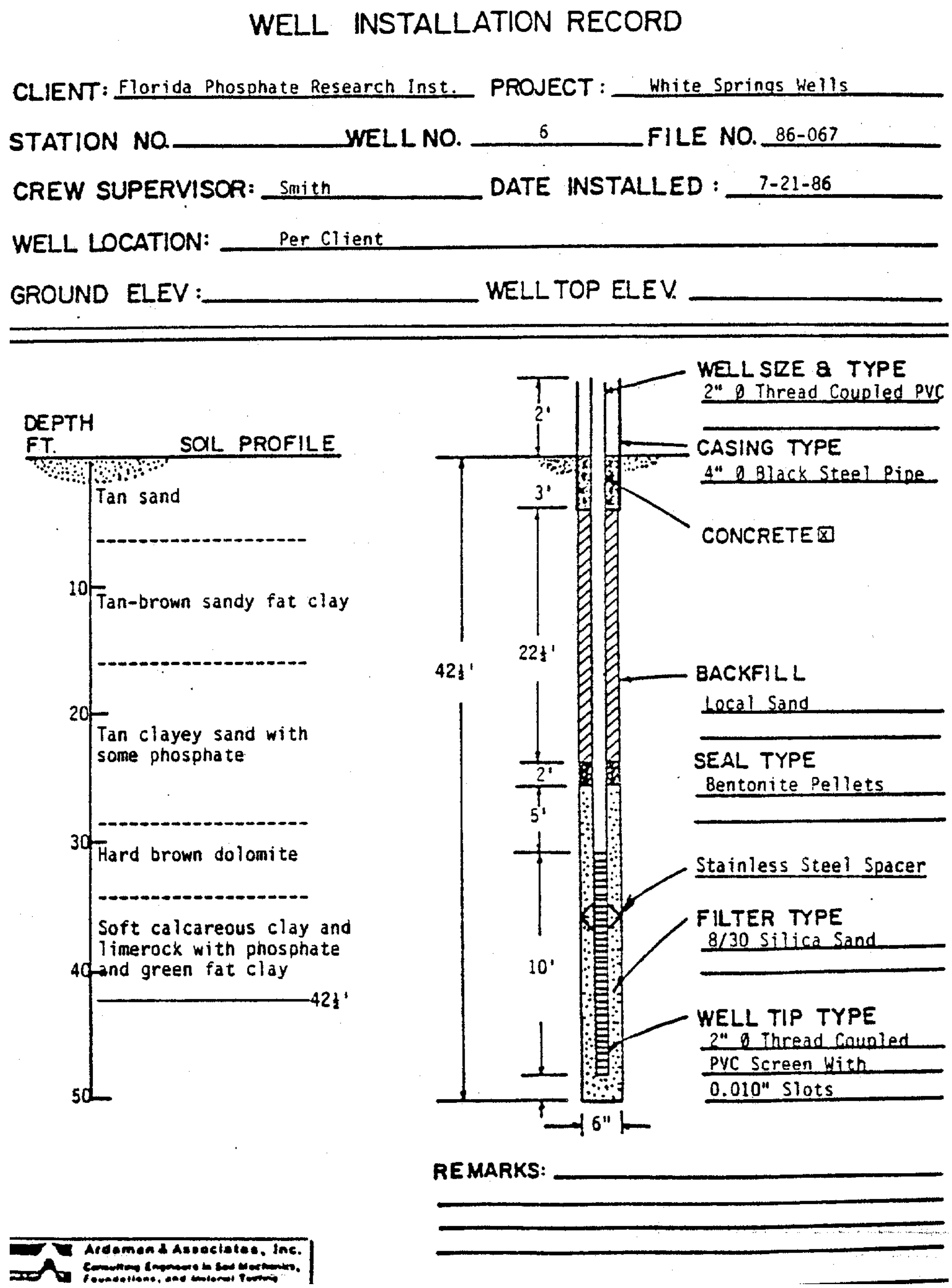


Figure 5.27 Well Installation Record at Well 5, White Springs Road.



WELL INSTALLATION RECORD

CLIENT: Florida Phosphate Research Inst. PROJECT: White Springs Wells

STATION NO. ______ WELL NO. 6 FILE NO. 86-067

CREW SUPERVISOR: Smith DATE INSTALLED: 7-21-86

WELL LOCATION: Per Client

GROUND ELEV: ______ WELL TOP ELEV. ______

DEPTH FT. SOIL PROFILE

Tan sand

10 Tan-brown sandy fat clay

20 Tan clayey sand with some phosphate

30 Hard brown dolomite

Soft calcareous clay and limerock with phosphate
40 and green fat clay

42½'

50

2'
3'
22½'
42½'
2'
5'
10'
6"

WELL SIZE & TYPE: 2" Ø Thread Coupled PVC

CASING TYPE: 4" Ø Black Steel Pipe

CONCRETE ⊠

BACKFILL: Local Sand

SEAL TYPE: Bentonite Pellets

Stainless Steel Spacer

FILTER TYPE: 8/30 Silica Sand

WELL TIP TYPE: 2" Ø Thread Coupled PVC Screen With 0.010" Slots

REMARKS:

Ardaman & Associates, Inc. Consulting Engineers in Soil Mechanics, Foundations, and Material Testing

Figure 5.28 Well Installation Record at Well 6, White Springs Road.

WELL INSTALLATION RECORD

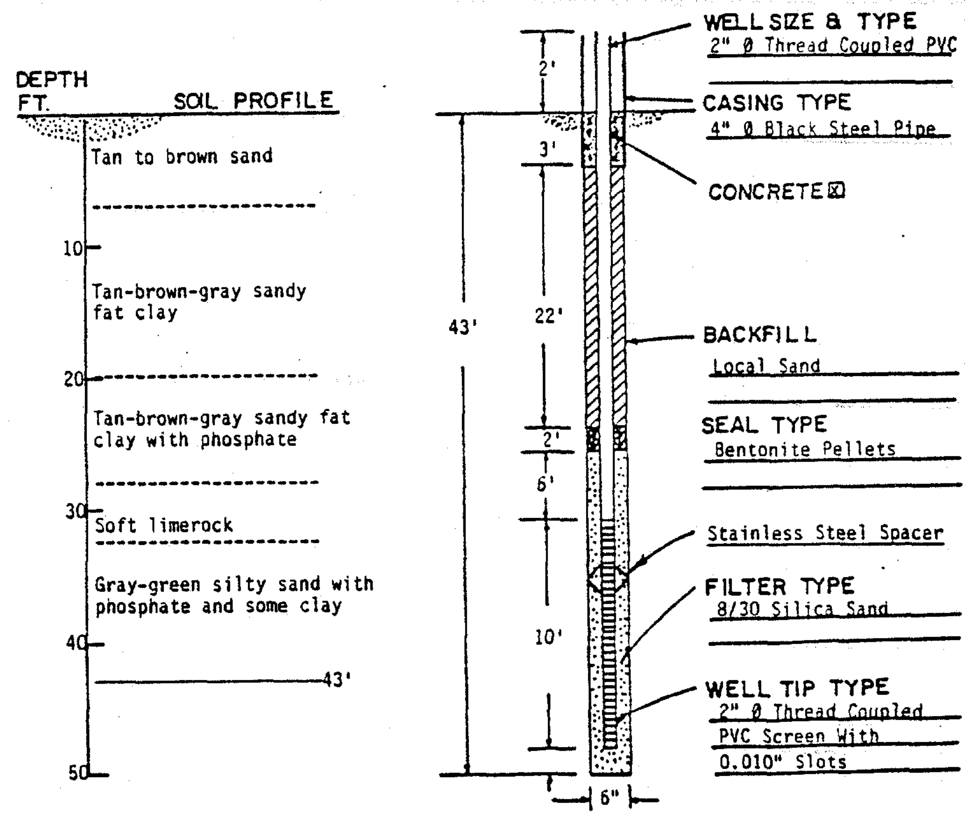
CLIENT: Florida Phosphate Research Inst. PROJECT: White Springs Wells

STATION NO. ______ WELL NO. 7 FILE NO. 86-067

CREW SUPERVISOR: Smith DATE INSTALLED: 7-22-86

WELL LOCATION: Per Client

GROUND ELEV: ______ WELL TOP ELEV. ______



REMARKS: ______

Ardaman & Associates, Inc.

Figure 5.29 Well Installation Record at Well 7, White Springs Road.

WELL INSTALLATION RECORD

CLIENT: Florida Phosphate Research Inst. PROJECT: White Springs Wells

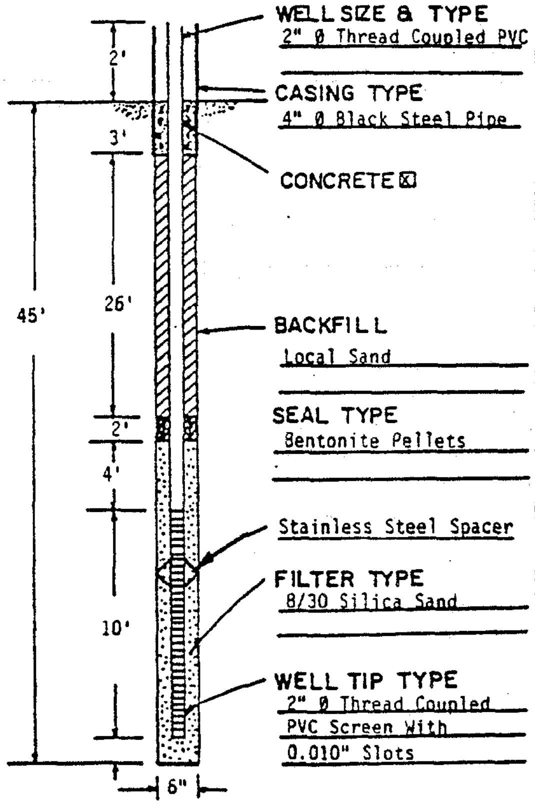
STATION NO. ______ WELL NO. 8 FILE NO. 86-067

CREW SUPERVISOR: Smith DATE INSTALLED: 7-21-86

WELL LOCATION: Per Client

GROUND ELEV: ______ WELL TOP ELEV. ______

DEPTH FT.	SOIL PROFILE
0–10	Tan to brown sand
20	Tan-brown sandy fat clay
30	Tan clayey sand
40	Tan calcareous clay and limerock
45'	
50	



REMARKS: ______

Ardaman & Associates, Inc.
Consulting Engineers in Soil Mechanics, Foundations, and Material Testing

Figure 5.30 Well Installation Record at Well 8, White Springs Road.

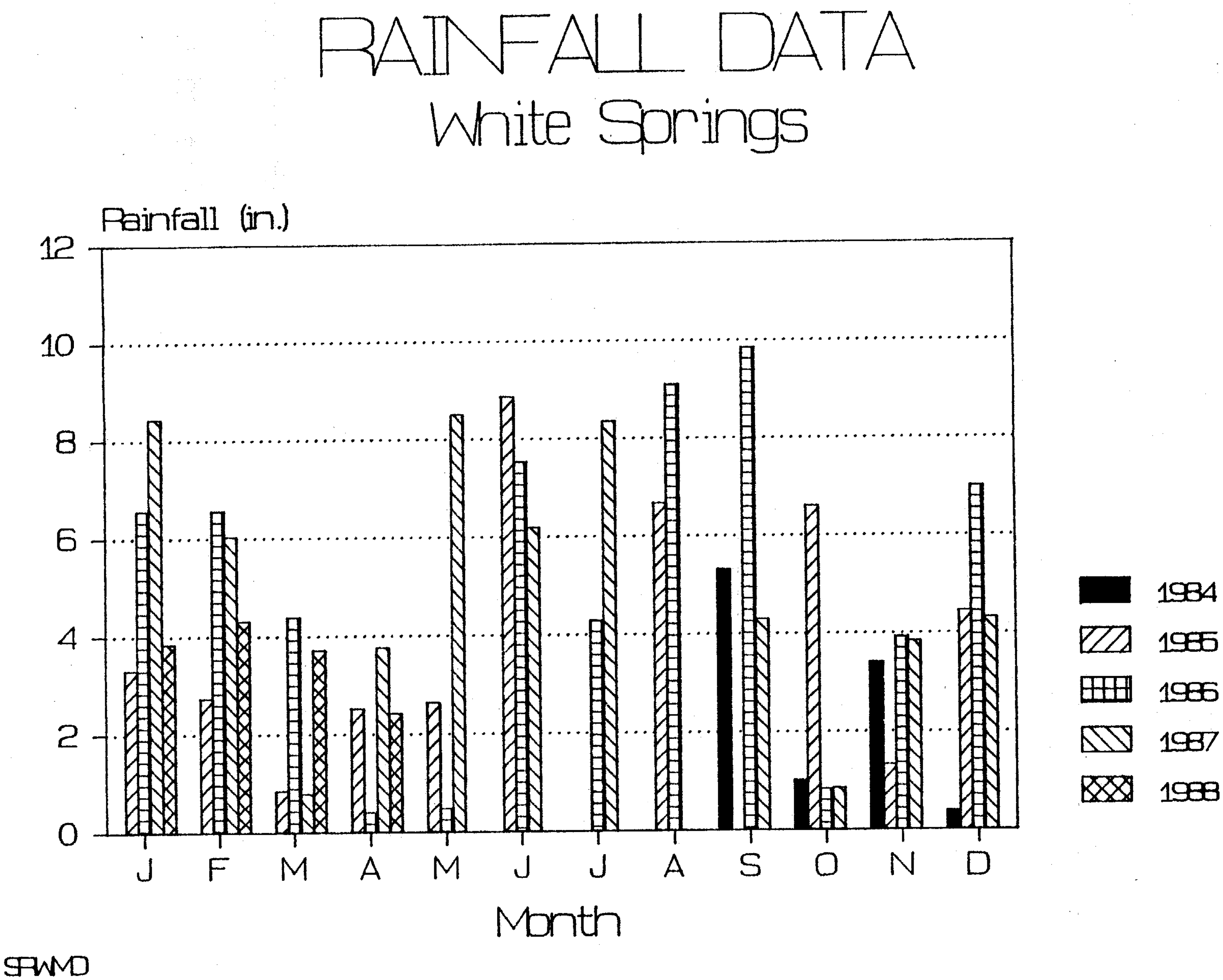


Figure 5.31 Rainfall at White Springs, Florida.

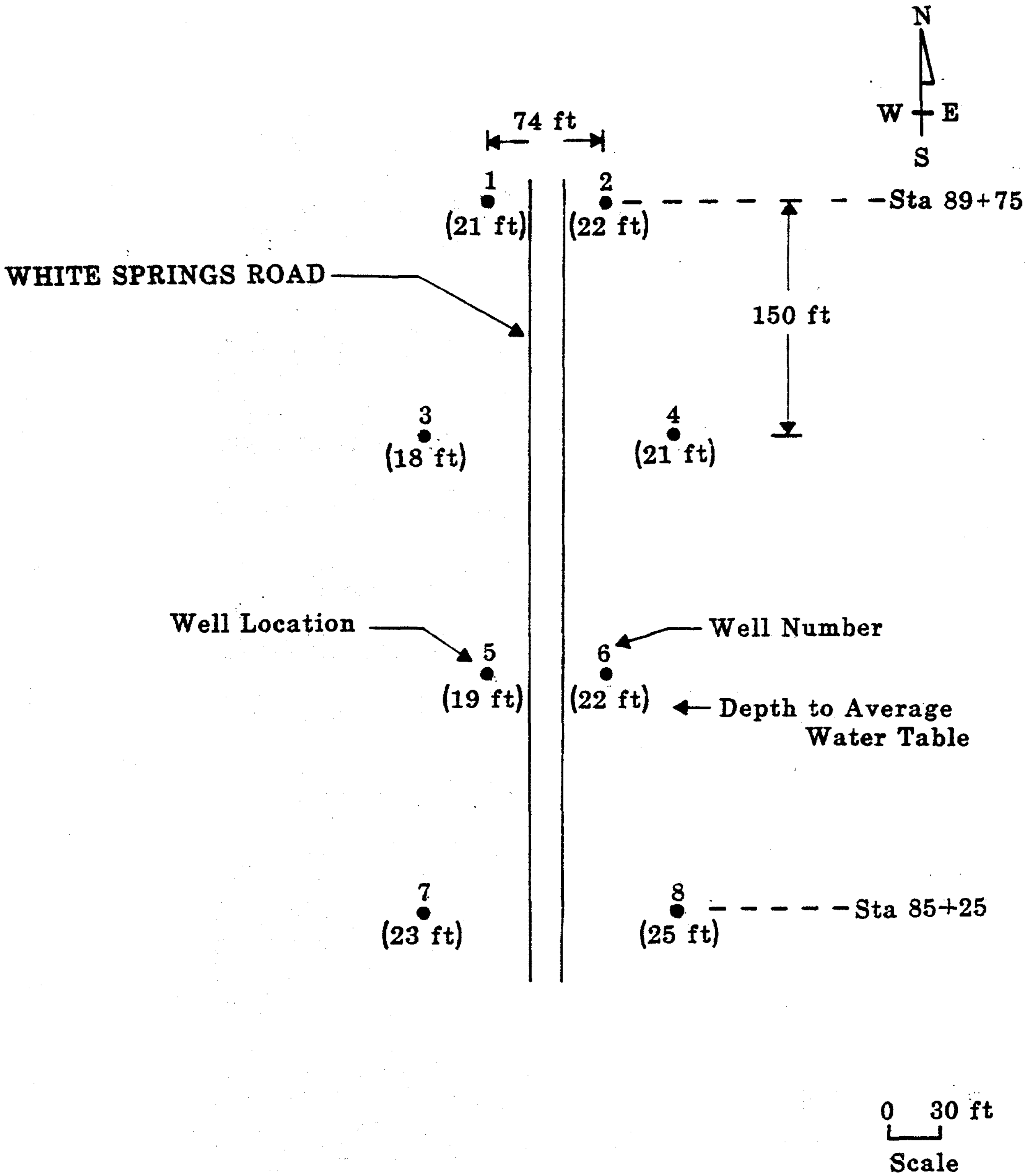


Figure 5.32 Layout of Monitoring Wells, White Springs Road.

the estimated pumping times, a minimum pumping time of 10 minutes was required before sample collection. At the wells that went dry after less than 10 minutes of pumping, the pump was turned off and the well allowed 5 minutes to refill. Pumping was then resumed and samples collected. In cases where the well did not go dry after 10 minutes of pumping, samples were collected after a 10 minute pumping time. Electrical conductivity, temperature, pH, turbidity and odor were measured in the field, and then the samples were preserved by methods identical to those used at Parrish Road.

5.3.4 Analytical Protocol

These analytical protocol used to measure the water quality this site was identical to that used at Parrish Road. Since January 1987, the analyses for both sites were processed in the same batch.

5.3.5 Results

The overall results of the study are summarized in Table 5.12 which shows the mean and standard deviation of the measurements at each well. The temporal variability in the measurements at each well is measured by the coefficient of variation of the data, defined as the standard deviation divided by the mean. The average coefficient of variation for each of the parameters is shown in Table 5.13. These results show that the measured parameters typically vary by about 50% from their mean value. The lowest variability is associated with temperature and pH. Contrasting the variability in measurements at White Springs Road and Parrish Road, Table 5.6, it is apparent that the variability in the parameters are quite similar. Comparing the variability in the major ionic constituents, shows that for Na, Mg, and Alkalinity, significantly higher variability is encountered at White Springs Road. These variations significantly exceed experimental errors documented by the quality control results, Table 5.4. The spatial variability in the measured data is illustrated in Table 5.14, which shows the range of mean values for each parameter. These results show that for all the major ionic constituents, order of magnitude variations in the mean were measured. Order of magnitude variations are also found for Ra-226. The least amount of spatial variability was found in temperature. Comparing the White Springs Road results with those at Parrish Road, Table 5.7 show that while the range of variability at both sites are similar, Ca, Alkalinity, and pH do show much wider ranges of means at White Springs Road.

Results of Statistical Analyses: The results of statistical analysis of the measured data are summarized in Table 5.15. These data show that: (a) The major ionic constituents have either a downward trend or no trend at all; (b) In cases of trend, the residuals tend to be normally distributed: (c) The measured data shows a predominantly log-normal distribution, and tends not to be seasonal. In determining whether construction of the phosphogypsum roadway has had any effect on the ambient

Table 5.12. Means and Standard Deviations of Measured Constituents (White Springs Road)[1]

Well No.	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Alkalinity (mg/l)	SO_4 (mg/l)
1	(1.9, 1.8)	(2.3,1.4)	(6.7, 2.9)	(3.9, 0.9)	(5, 4)	(25.4, 7.2)
2	(2.4, 0.4)	(1.1,0.9)	(31.8,24.3)	(13.8, 6.6)	(47, 7)	(3.4, 1.1)
3	(3.1, 2.1)	(1.7,1.3)	(3.5, 2.8)	(2.3, 2.0)	(11, 5)	(4.9, 2.1)
4	(15.5,14.6)	(2.5,1.6)	(14.7,11.2)	(4.2, 1.4)	(65,66)	(23.4,14.5)
5	(2.3, 0.5)	(0.8,0.3)	(31.2,10.9)	(3.4, 1.9)	(78,18)	(4.8, 2.0)
6	(2.8, 0.7)	(1.9,0.8)	(45.1,19.7)	(13.7, 6.0)	(66,19)	(3.6, 1.7)
7	(12.3, 6.2)	(3.4,1.5)	(93.6,28.6)	(12.5, 5.6)	(135,43)	(3.6, 1.6)
8	(4.0, 2.8)	(2.3,1.8)	(47.2,27.7)	(19.3,13.5)	(65,25)	(3.5, 1.1)

Well No.	Cl (mg/l)	F (mg/l)	NO_3 (mg/l)	Fe (mg/l)	P (mg/l)
1	(3.7,0.8)	(0.07,0.09)	(2.1, 1.2)	(4.7,2.1)	(0.02,0.03)
2	(5.5,0.6)	(0.47,0.08)	(5.5, 2.6)	(3.0,1.8)	(0.08,0.05)
3	(6.4,3.1)	(0.03,0.06)	(0.7, 0.7)	(5.1,2.7)	(0.05,0.07)
4	(3.3,1.2)	(0.02,0.05)	(3.4, 1.7)	(1.8,1.3)	(0.07,0.04)
5	(3.8,0.5)	(0.24,0.14)	(0.6, 0.6)	(2.4,1.8)	(0.07,0.03)
6	(7.3,1.1)	(0.48,0.31)	(8.2, 3.2)	(1.6,0.7)	(0.14,0.05)
7	(24.2,5.4)	(0.37,0.14)	(21.1,17.3)	(4.2,2.3)	(0.19,0.10)
8	(8.6,1.1)	(1.24,1.43)	(9.2, 3.3)	(5.6,3.1)	(0.16,0.08)

Well No.	Pb (mg/l)	Mn (mg/l)	TDS (mg/l)	Temp (^oC)	pH	Ω^{-1} (μmho/cm)
1	(0.02,0.01)	(0.07,0.04)	(64, 28)	(21.3,2.0)	(4.52,0.38)	(101, 12)
2	(0.03,0.01)	(0.06,0.04)	(127, 37)	(21.4,2.3)	(7.65,0.37)	(170, 9)
3	(0.03,0.01)	(0.10,0.05)	(87,183)	(21.3,2.0)	(4.88,0.50)	(31, 9)
4	(0.03,0.01)	(0.15,0.12)	(125,106)	(21.4,2.2)	(6.74,0.40)	(181,133)
5	(0.03,0.01)	(0.03,0.02)	(118, 45)	(21.2,2.0)	(6.81,0.42)	(177, 19)
6	(0.03,0.01)	(0.06,0.03)	(165, 33)	(21.5,1.9)	(7.28,0.35)	(222, 12)
7	(0.04,0.02)	(0.12,0.08)	(398, 80)	(21.8,2.3)	(7.14,0.26)	(603, 32)
8	(0.04,0.02)	(0.18,0.13)	(184, 67)	(21.2,2.0)	(7.40,0.38)	(253, 98)

Well No.	Ra-226 (pCi/l)
1	(3.4, 1.1)
2	(10.1,11.0)
3	(1.1, 1.2)
4	(1.4, 0.5)
5	(2.1, 1.8)
6	(2.5, 1.7)
7	(2.8, 1.0)
8	(4.3, 2.6)

[1] **The results are given as an ordered pair (mean, standard deviation).**

Table 5.13. Coefficients of Variation of Measured Data (White Springs Road)

Constituent	Ave. Coef. of Variation (%)
Na	55
K	61
Ca	55
Mg	50
Alkalinity	46
SO_4	41
Cl	22
F	111
NO_3	64
Fe	57
P	73
Pb	43
TDS	60
Temp	10
pH	6
Ω^{-1}	22
Ra-226	67

Table 5.14. Spatial Variability in Measured Data (White Springs Road)

Constituent	Units	Range of Means
Na	mg/l	1.9 - 15.5
K	mg/l	0.8 - 3.4
Ca	mg/l	3.5 - 93.6
Mg	mg/l	2.3 - 19.3
Alkalinity	mg/l	4.5 - 135.2
SO_4	mg/l	3.4 - 25.4
Cl	mg/l	3.3 - 24.2
F	mg/l	0.02 - 1.24
NO_3	mg/l	0.6 - 21.1
Fe	mg/l	1.6 - 5.6
P	mg/l	0.02 - 0.19
Pb	mg/l	0.02 - 0.04
Mn	mg/l	0.03 - 0.18
TDS	mg/l	64 - 398
Temp.	oC	21.2 - 21.8
pH	-	4.52 - 7.65
Ω^{-1}	µmho/cm	31 - 603
Ra-226	pCi/l	1.1 - 10.1

Table 5.15. Statistical Properties of Measured Data (White Springs Road)[1]

Constituent	Trend			Normal				Log-Normal		Seasonal		Auto-Correlated	
				Residual		No Trend							
	Y+	Y−	N	Y	N	Y	N	Y	N	Y	N	Y	N
Na	0	5	3	4	1	2	1	7	1	2	6	2	6
K	0	7	1	4	3	1	0	4	4	3	5	6	2
Ca	0	4	4	3	1	1	3	7	1	1	7	2	6
Mg	0	5	3	4	1	0	3	7	1	1	7	4	4
Alkalinity	0	6	2	5	1	0	2	6	2	2	6	2	6
SO_4	1	1	6	1	1	4	2	6	2	1	7	1	7
Cl	2	2	4	3	1	1	3	4	4	0	8	2	6
F[2]	2	0	3	1	1	1	2	5	0	0	5	1	4
NO_3	0	1	7	1	0	4	3	2	6	2	6	2	6
Fe	0	6	2	6	0	1	1	6	2	3	5	6	2
P[2]	1	1	3	2	0	3	0	4	1	1	4	3	2
Pb	1	0	7	0	1	5	2	7	1	0	8	0	8
TDS	1	2	5	1	2	4	1	6	2	0	8	2	6
Temp.	0	0	8	0	0	8	0	8	0	4	4	7	1
pH	3	1	4	3	1	4	1	8	0	0	8	2	6
Ω[1]	0	4	4	2	2	3	1	6	2	6	2	5	3
Ra-226	0	2	6	2	0	6	0	8	0	–		–	

[1] The numbers in the table indicate the number of wells having the stated property; Y and N indicate whether the data do/do not have the stated property; and Y^+ and Y^- indicate positive and negative trend respectively.

[2] The measurements at 3 wells were consistently below the detection limit.

groundwater quality, it is instructive to investigate in detail the temporal behavior of Ca, and Ra-226 in the groundwater.

The measured variations in Ca at all the wells are shown in Figs. 5.33 to 5.36. These data were analysed to see if any significant trends existed. The results of these analyses are given in Table 5.16. The results show that a significant downward trend exists at wells 1, 2, 3, and 7, with other wells showing no significant trend. Recalling that the Parrish Road results showed a significant correlation between Ca levels and turbidity, the correlation between these two parameters at White Springs Road were calculated and are shown in Fig. 5.37. These results indicate that there is not any widespread correlation between these quantities. A possible reason for this is that turbidity variations were in a fairly narrow range at White Springs Road, while Ca levels in the groundwater show a large natural variability.

The variation in sulfate levels are shown in Figs. 5.38 to 5.41. The results of a trend analysis of this data are shown in Table 5.16, which indicates that well 4 has a statistically significant upward trend, well 8 a statistically significant downward trend, and no significant trend at all other wells. The reason for the upward trend at well 4 is probably not related to the construction of the roadway since this trend was not detected at any other well and well 4 is within the outer line of wells, not immediately adjacent to the roadway. The results of a correlation analysis between sulfate and turbidity is shown in Fig. 5.42, which illustrates that there is no significant correlation between these quantities. This is the same result found at Parrish Road.

The Ra-226 concentrations measured during this study are shown in Figs. 5.43 to 5.45, and the results of a trend analysis on these data is given in Table 5.16. Significant downward trends are detected at wells 2 and 3, with measurements at all other wells showing no trend. The downward trend at well 2 is quite noticable, Fig. 5.43, more so than that at well 3. Since Ra-226 was found to be significantly correlated with turbidity at Parrish Road, a correlation analysis between these two quantities was conducted on the White Springs Road data. This is shown in Fig. 5.47, which indicates that turbidity is significantly correlated with Ra-226 at well 2, but no significant correlations exist at other wells. Since the largest changes in turbidity was experienced at well 2, this result is probably expected since at other wells variations in measured wells variations in measured Ra-226 due to turbidity changes were probably on the same order as background fluctuations. Based on the results presented here, it is apparent that there has been no measurable leaching of Ra-226 from the phosphogypsum roadway.

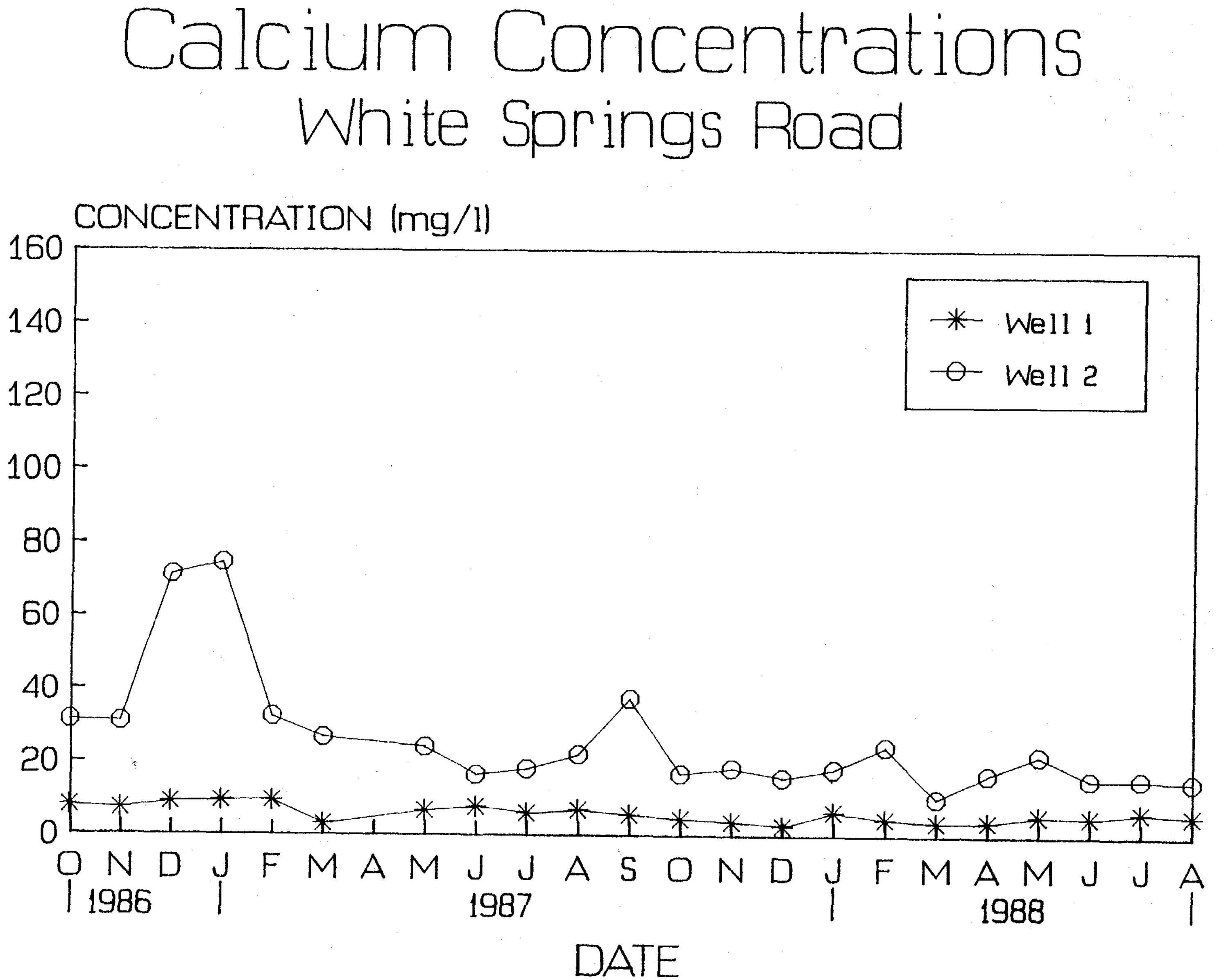


Figure 5.33 Calcium Levels at Wells 1 and 2, White Springs Road.

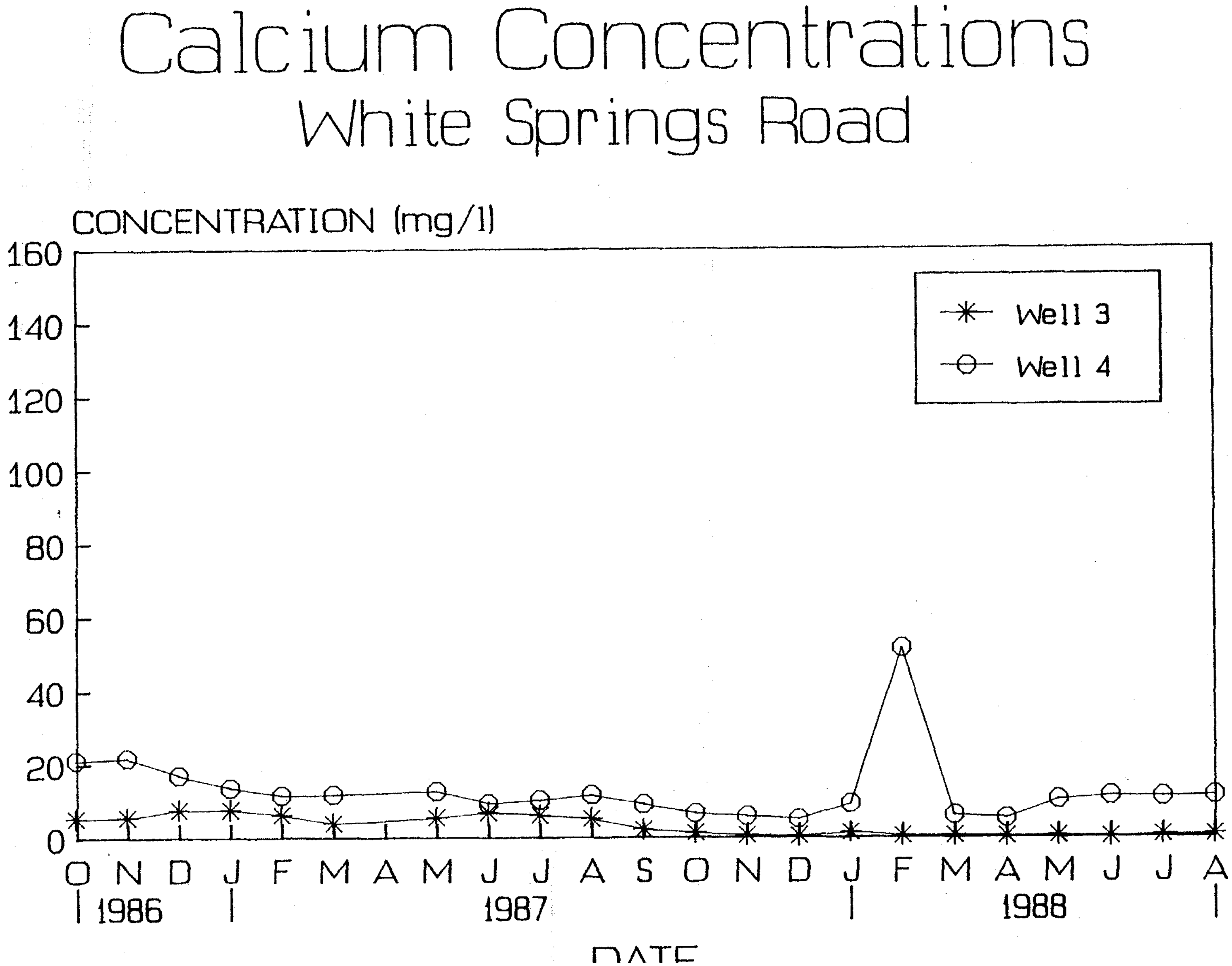


Figure 5.34 Calcium Levels at Wells 3 and 4, White Springs Road.

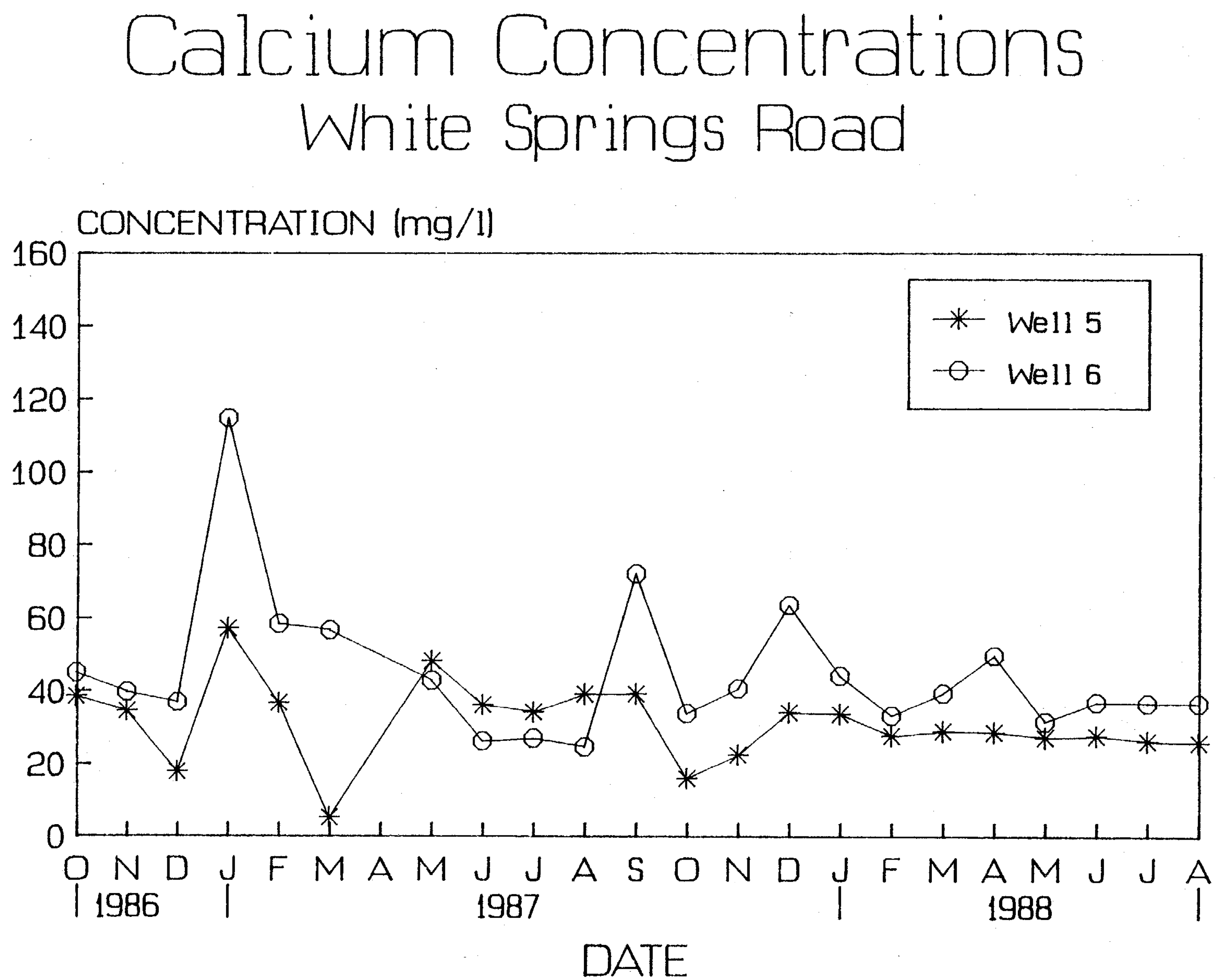


Figure 5.35 Calcium Levels at Wells 5 and 6, White Springs Road.

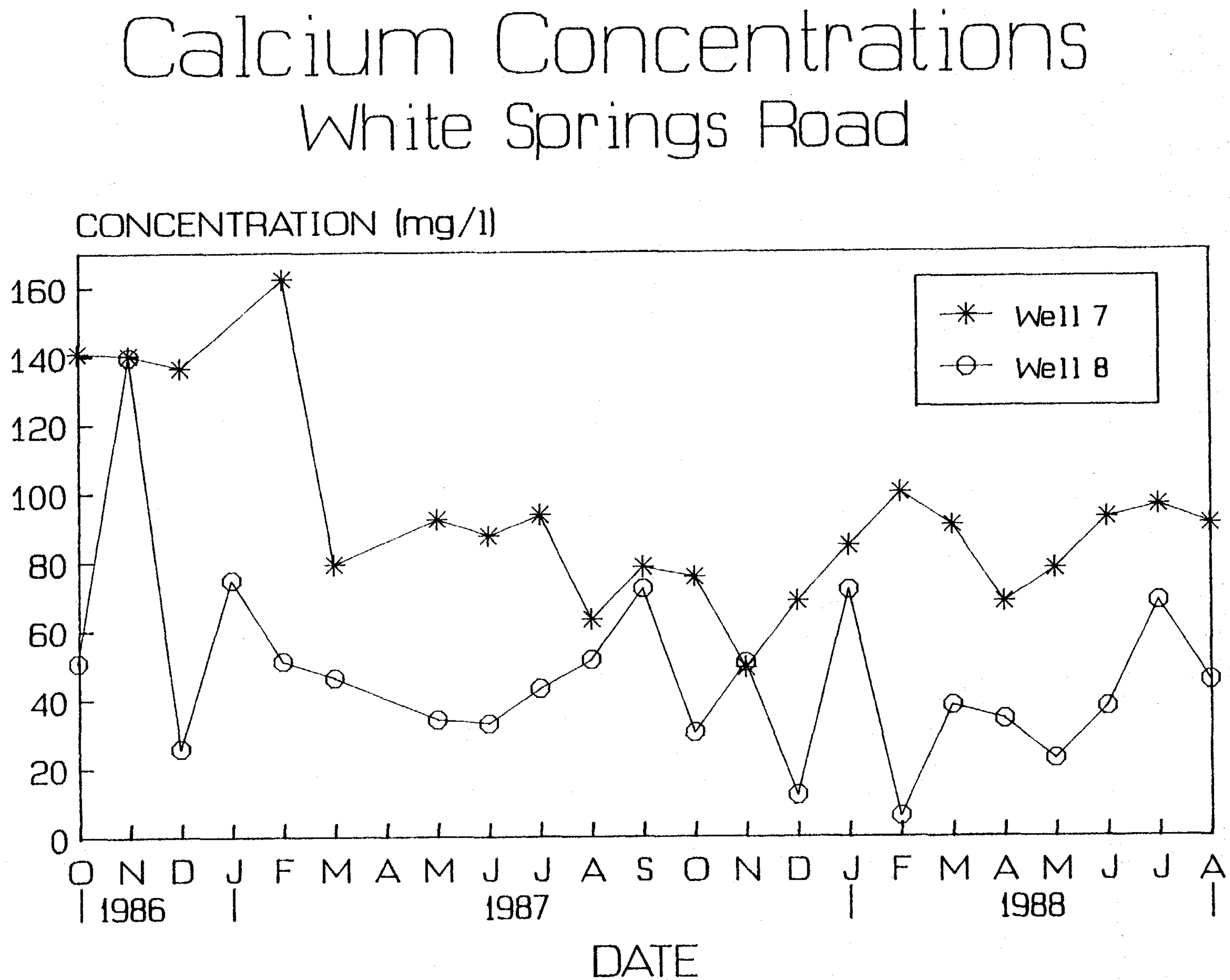


Figure 5.36 Calcium Levels at Wells 7 and 8, White Springs Road.

Table 5.16. Trend Data for Phosphogypsum Constituents (White Springs Road)

Well No.	Ca	SO4	Ra-226
1	Y^-	N	N
2	Y^-	N	Y^-
3	Y^-	N	Y^-
4	N	Y^+	N
5	N	N	N
6	N	N	N
7	Y^-	N	N
8	N	Y^-	N

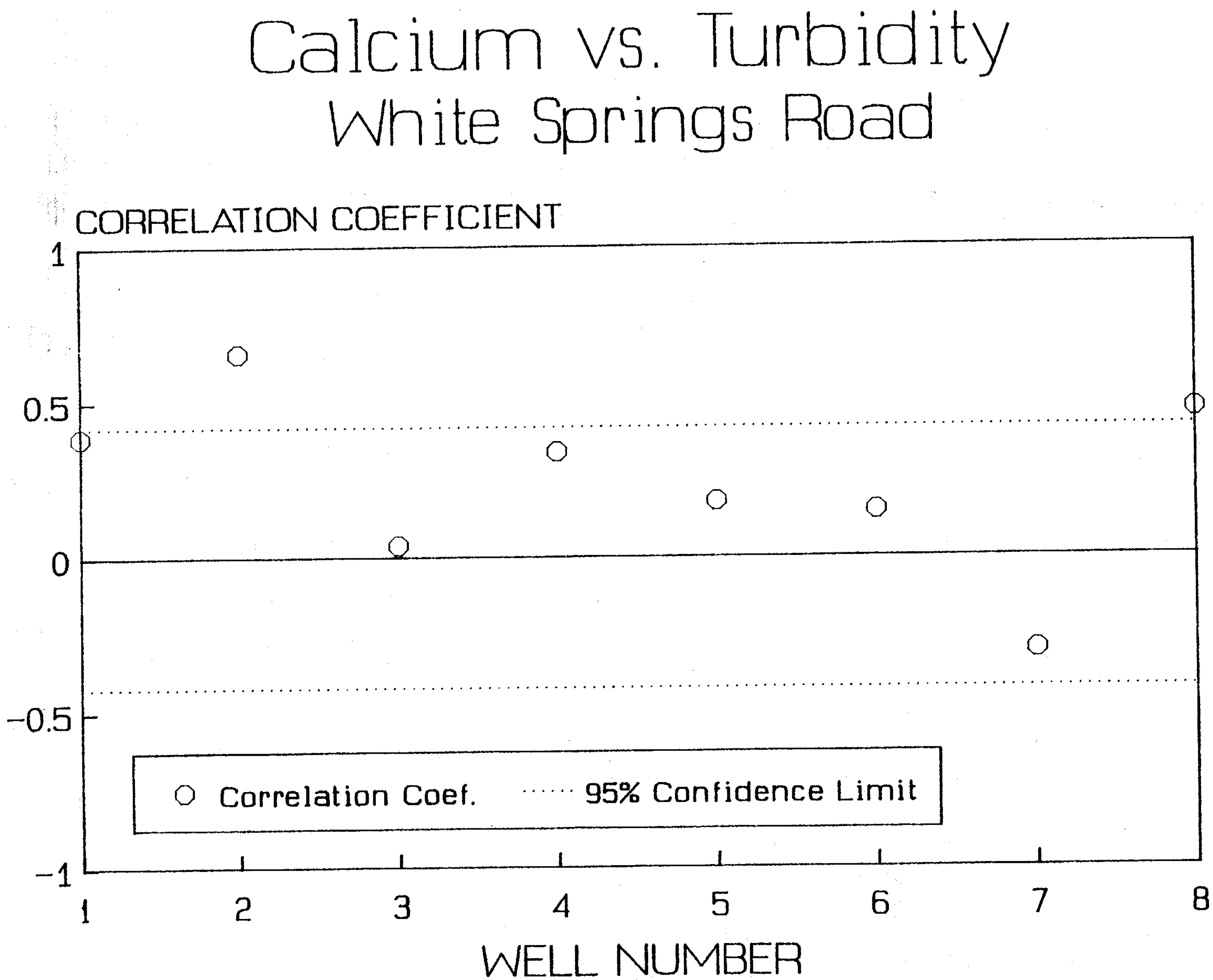


Figure 5.37 Correlation Between Calcium and Turbidity, White Springs Road.

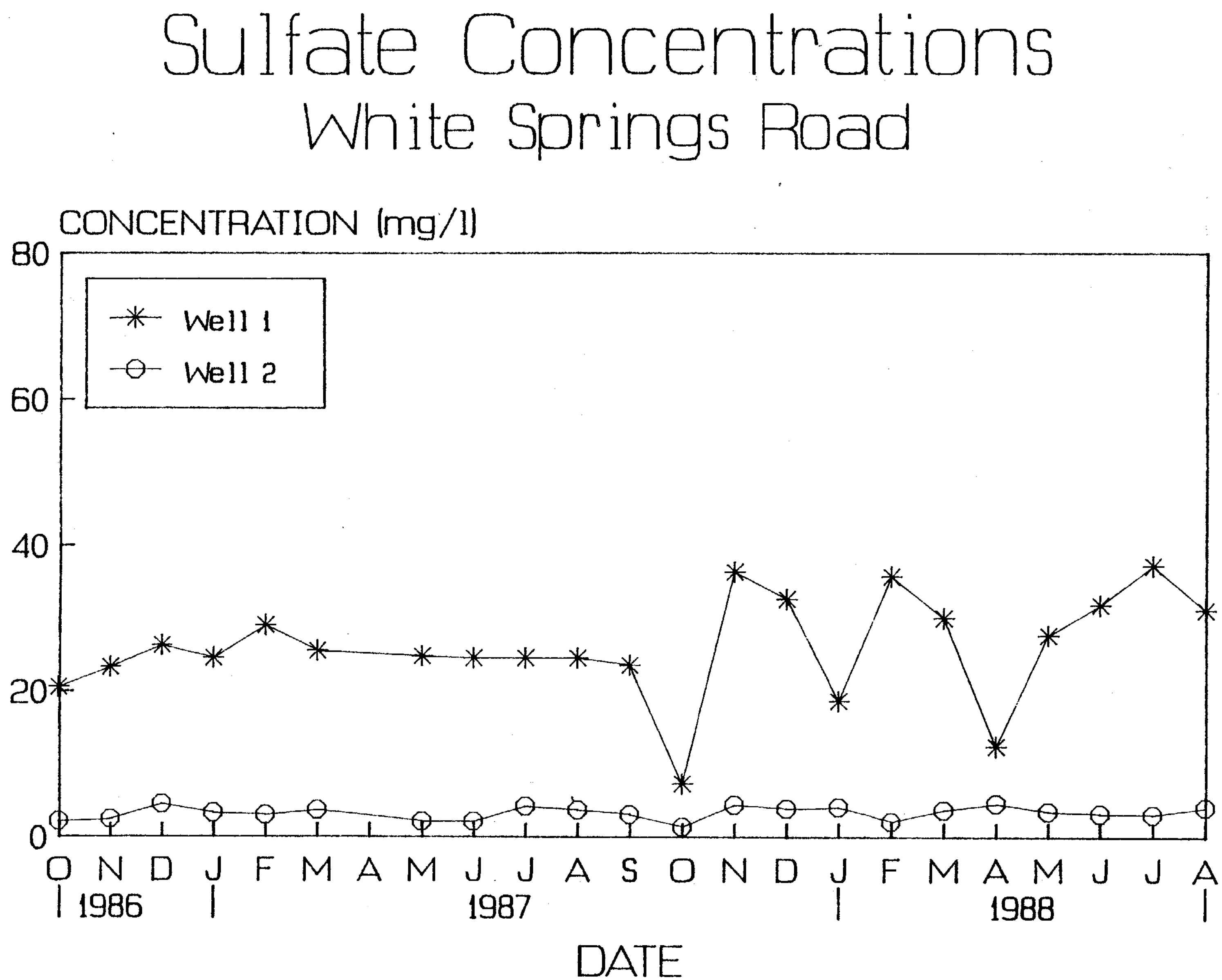


Figure 5.38 Sulfate Levels at Wells 1 and 2, White Springs Road.

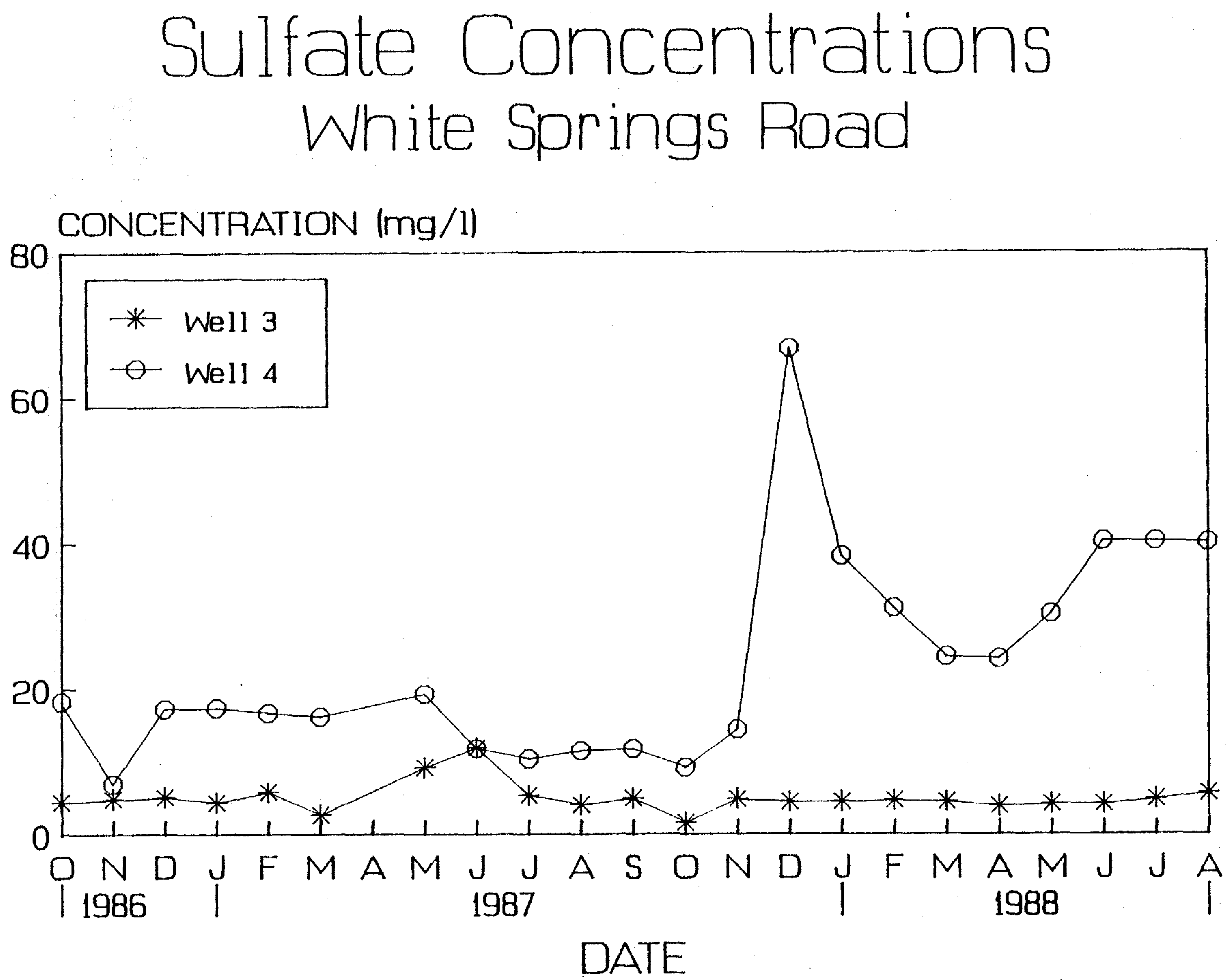


Figure 5.39 Sulfate Levels at Wells 3 and 4, White Springs Road.

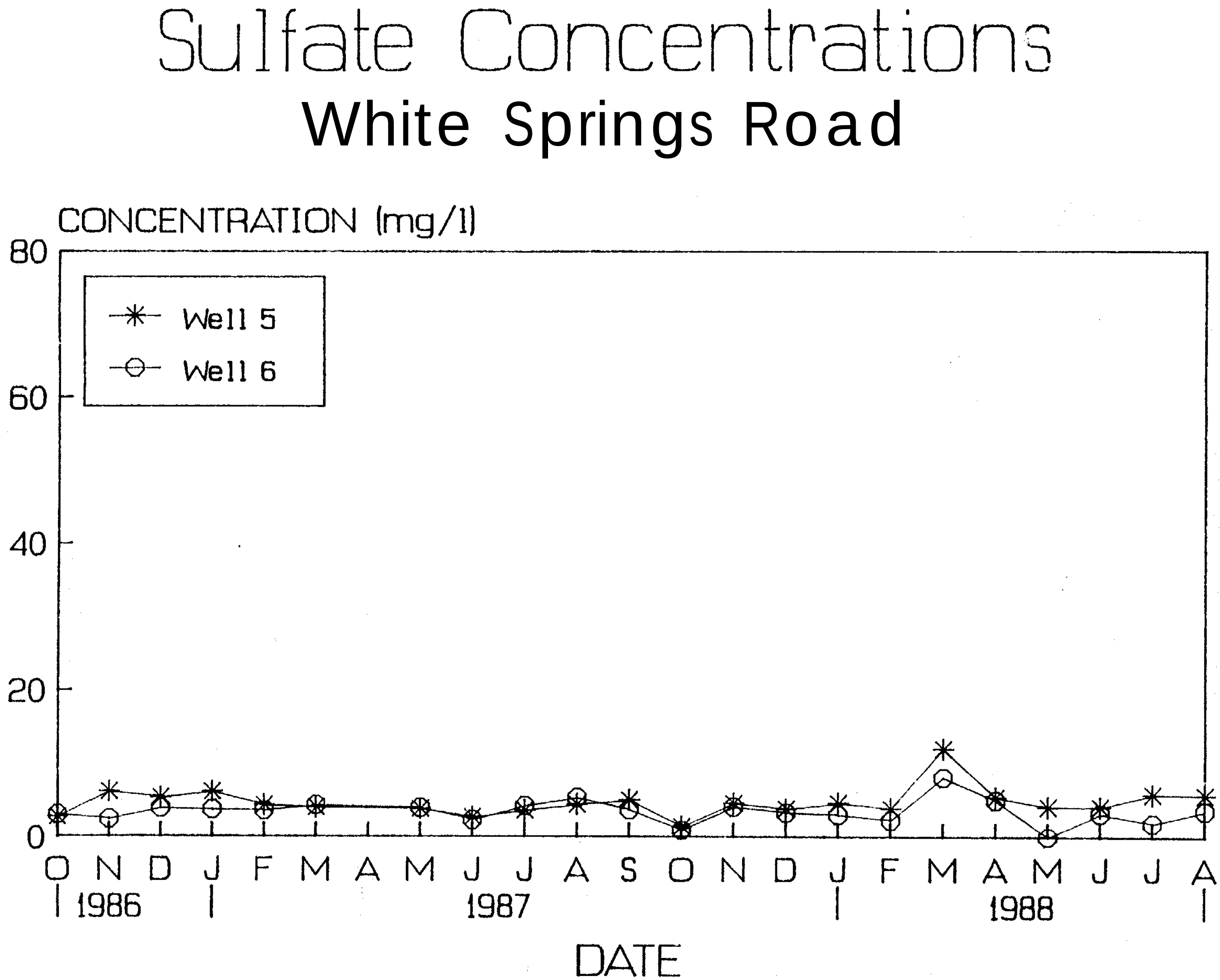


Figure 5.40 Sulfate Levels at Wells 5 and 6, White Springs Road.

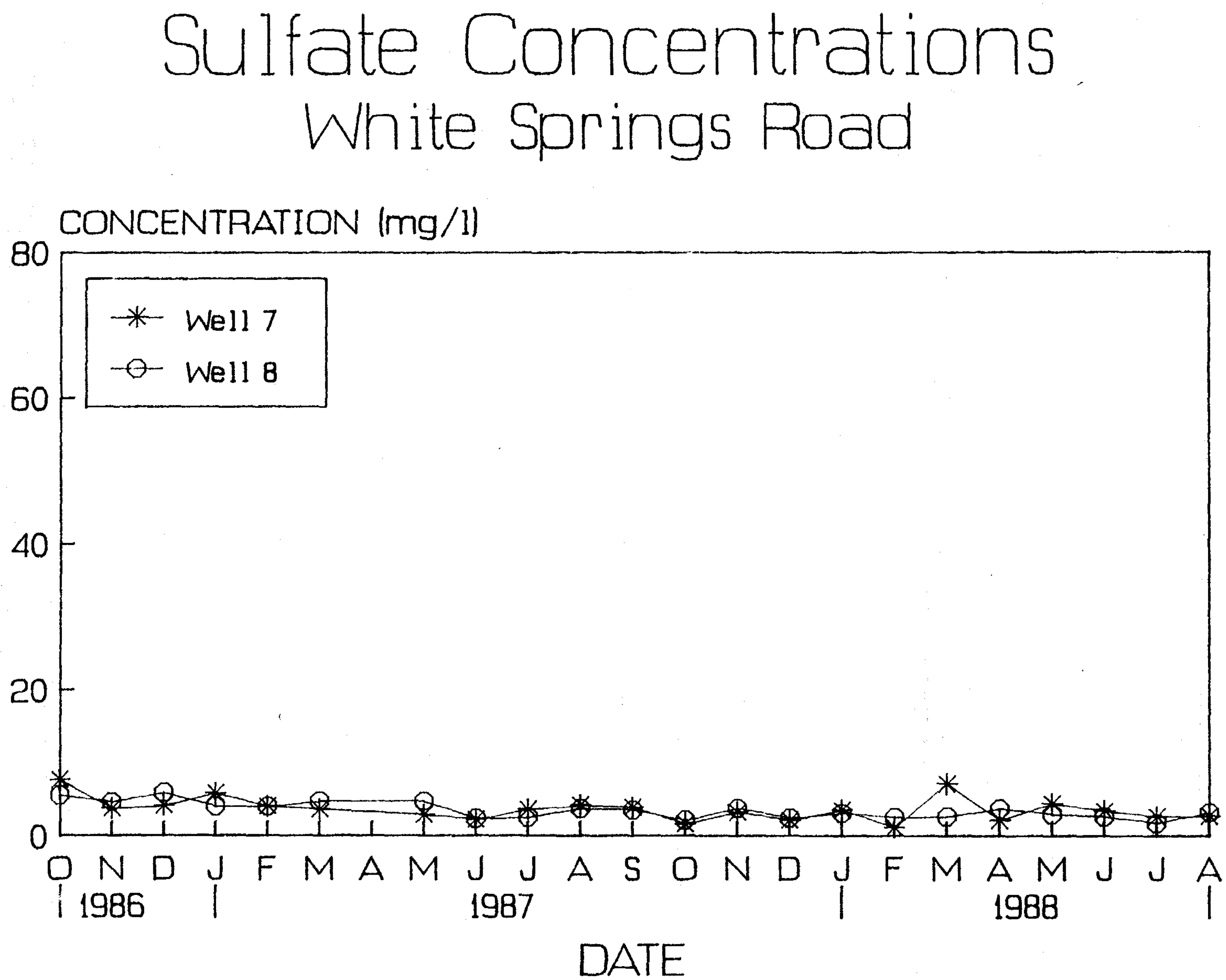


Figure 5.41 Sulfate Levels at Wells 7 and 8, White Springs Road.

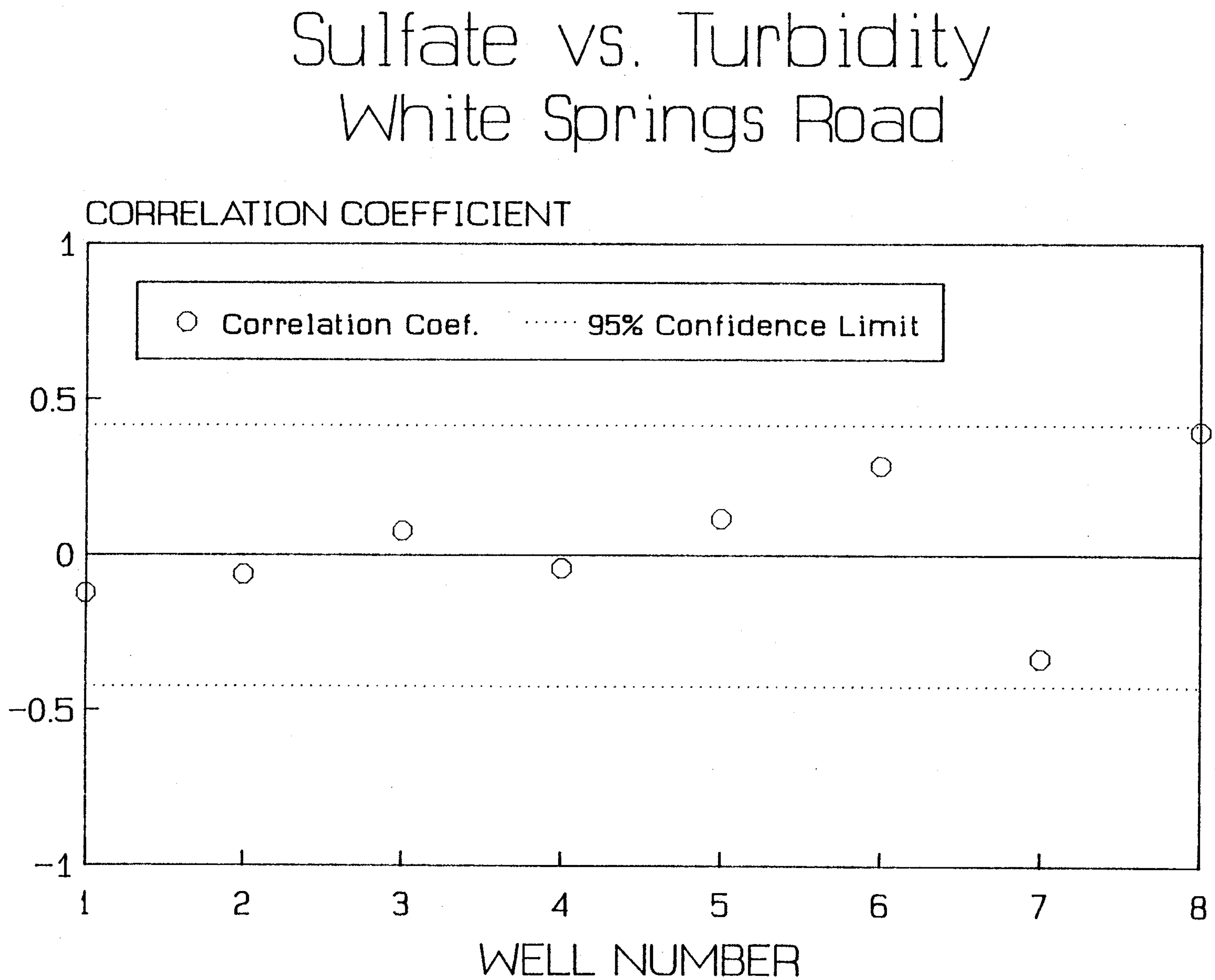


Figure 5.42 Correlation Between Sulfate and Turbidity, White Springs Road

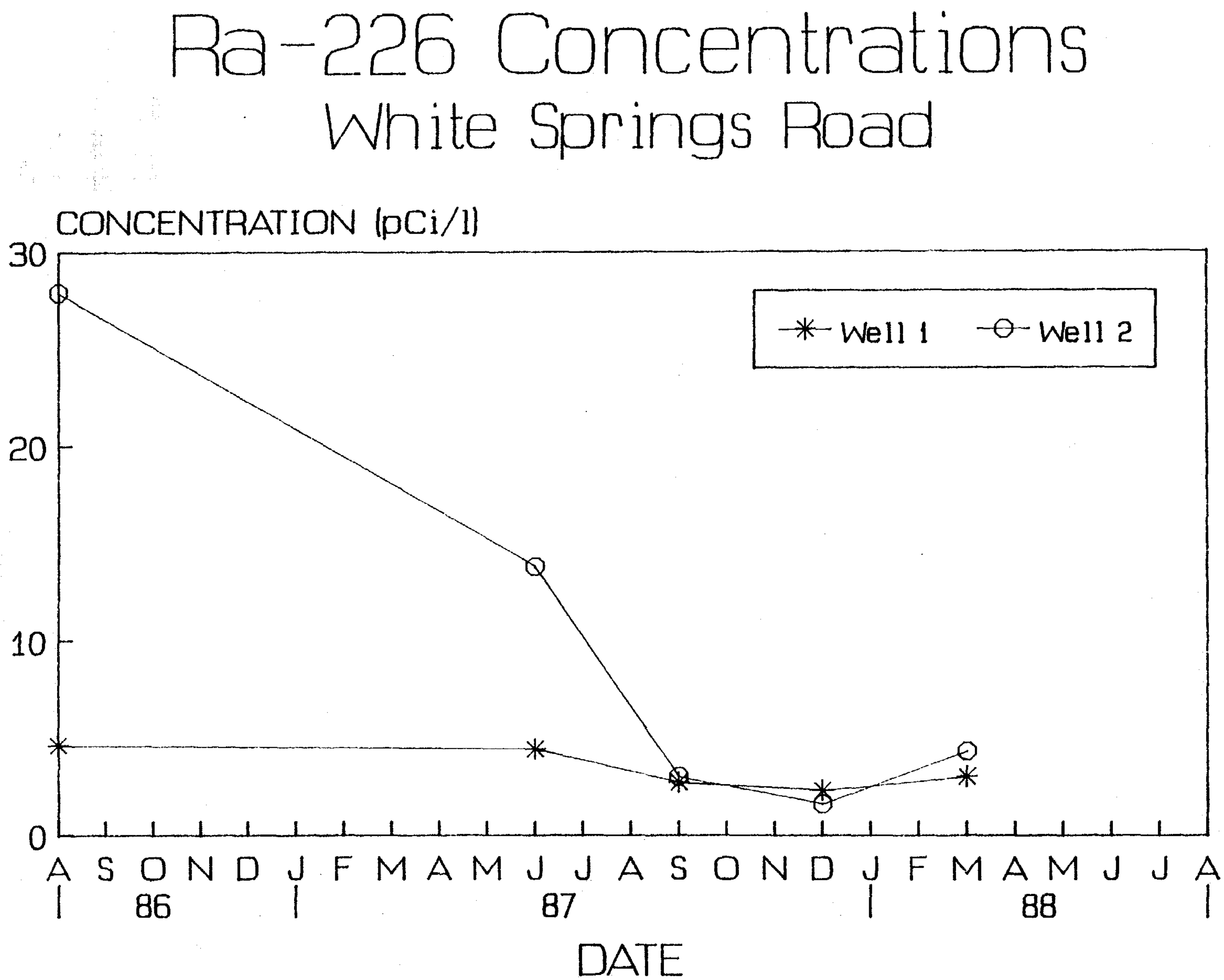


Figure 5.43 Ra-226 Levels at Wells 1 and 2, White Springs Road.

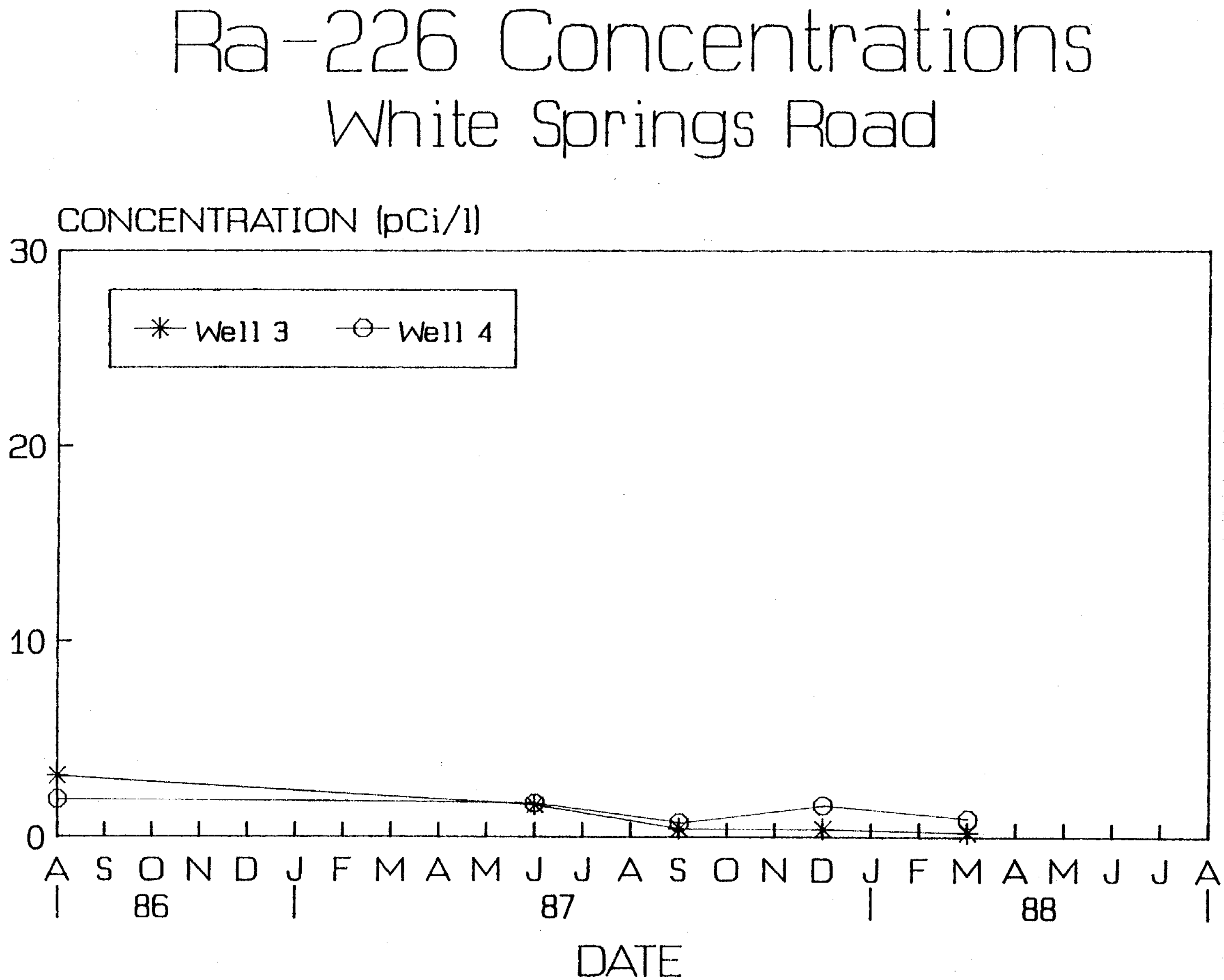


Figure 5.44 Ra-226 Levels at Wells 3 and 4, White Springs Road.

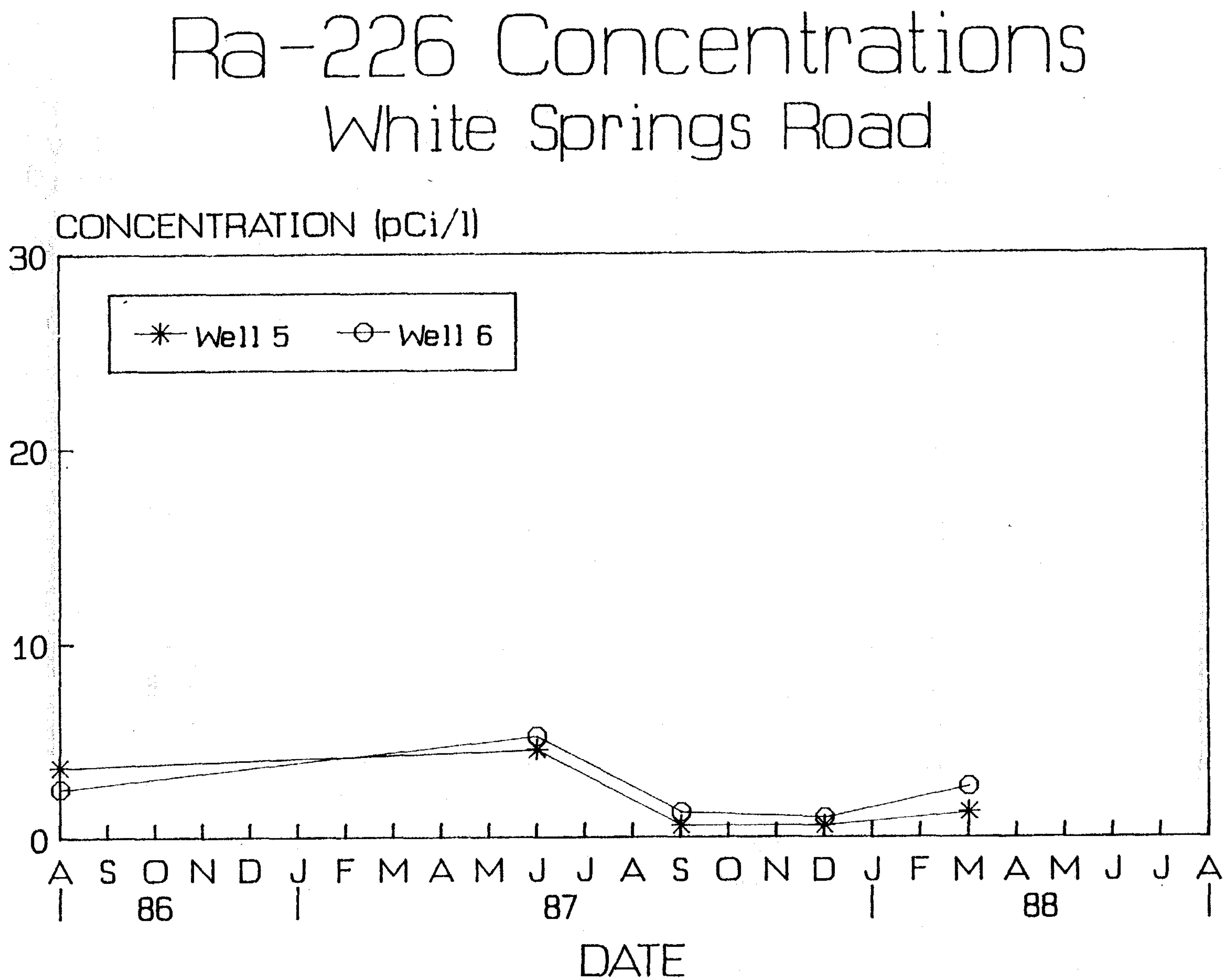


Figure 5.45 Ra-226 Levels at Wells 5 and 6, White Springs Road.

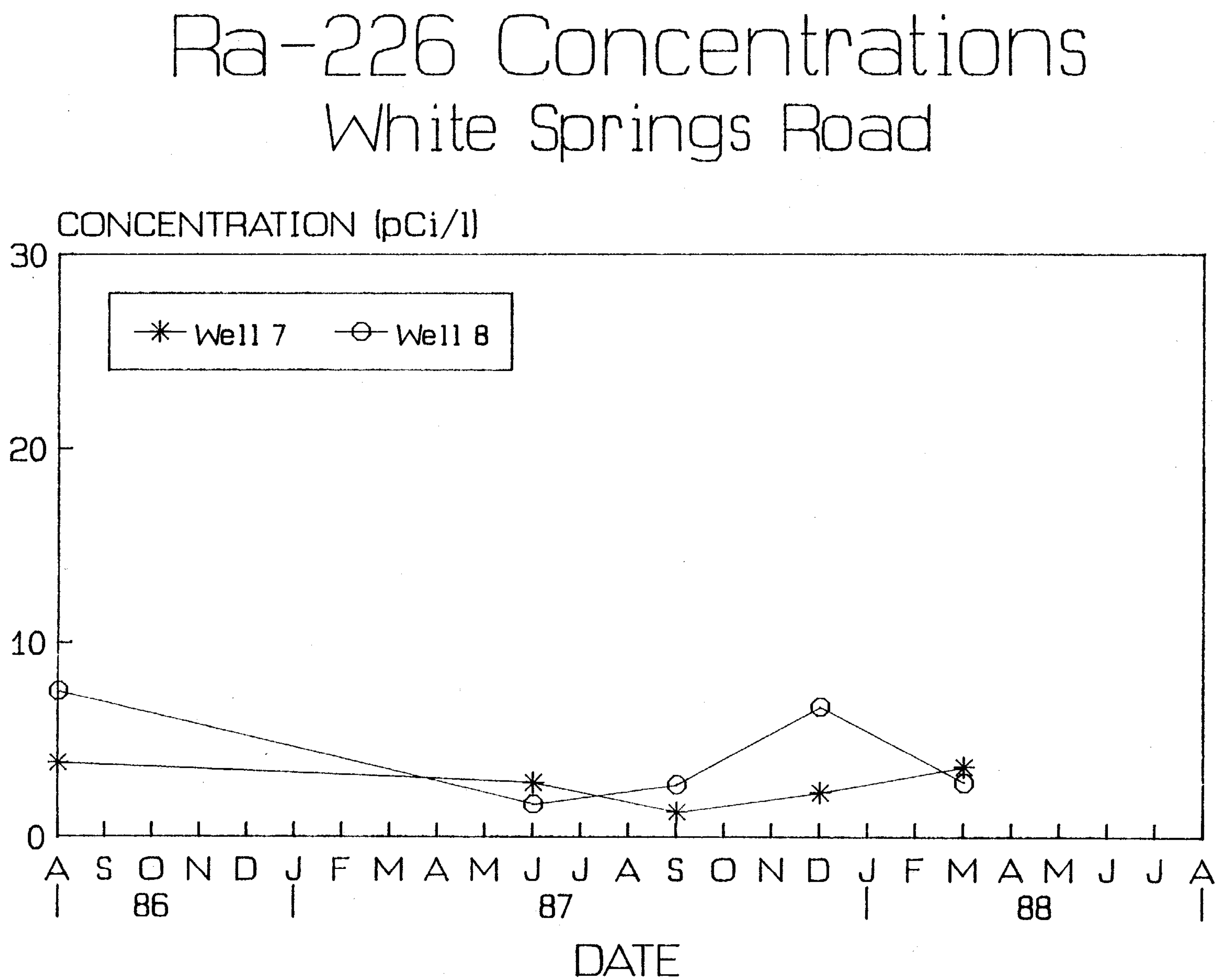


Figure 5.46 Ra-226 Levels at Wells 7 and 8, White Springs Road.

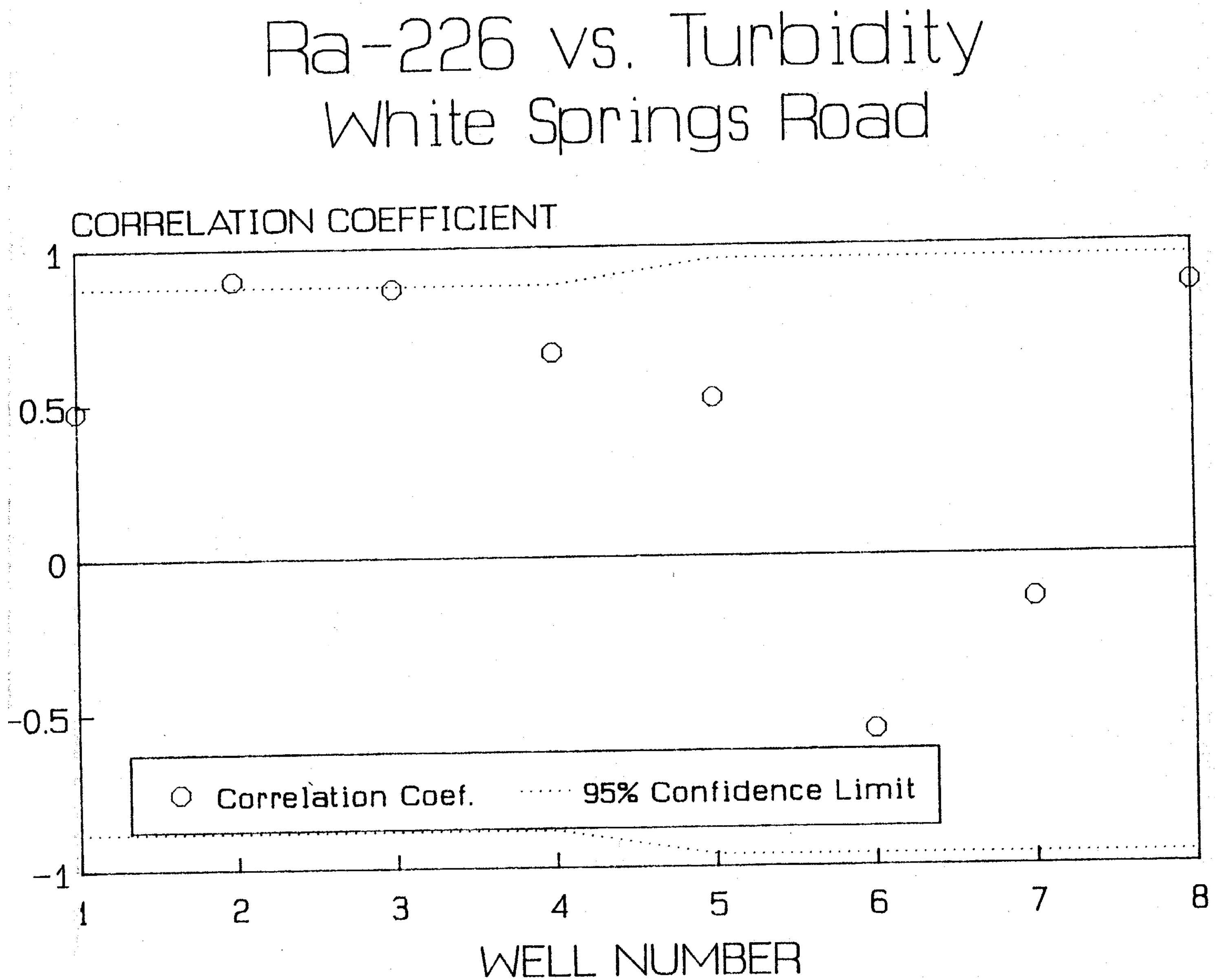


Figure 5.47 Correlation Between Ra-226 and Turbidity, White Springs Road

5.4 Conclusions

The groundwater monitoring study has addressed the question of whether construction of a phosphogypsum roadway has any measurable impact on the ambient groundwater. The two sites selected have significantly different hydrogeological characteristics and have been analysed separately. At Parrish road, the results show that Ca and Ra-226 measurements were highly correlated with the turbidity of the samples, which were not filtered according to DER requirements. Any variations in Ca and Ra-226 due to leaching were significantly less than variations associated with turbidity fluctuations. At several wells immediately adjacent to the roadway, statistically significant upward trends in SO_4 were detected. Since these trends were not found at outlying wells, leaching of phosphogypsum is suspected. It should be noted, however, that the magnitude of these increases were not sufficient to cause the ambient levels of SO_4 to exceed drinking water standards. At White Springs Road, significant trends in Ca, Ra-226 and SO_4 were not found, and it is apparent that the phosphogypsum roadway has had no measurable effect on the quality of the ambient groundwater.

5.5 References

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VI. RADIATION MONITORING

The Environmental Radiation Survey plan for the experimental roads includes gamma radiation monitoring, outdoor radon measurements in soil and the atmosphere, and radium-226 analyses in water and soil samples. In order to evaluate radioactive contamination, if any, from the use of phosphogypsum in road construction, environmental monitoring of air, soil and groundwater before and after construction was conducted.

6.1 GAMMA RADIATION

Gamma radiation levels were monitored along the roads at a height of 1 meter above the road surface using an ESP-1 survey meter with a calibrated 1" x 1" Na I (T1) scintillation detector. Figures 6.1 and 6.2 show the locations at which gamma radiation levels were monitored for the Parrish Road and White Springs Road, respectively.

Due to the radium-226 contained in the phosphogypsum which was used to stabilize on-site soil for the road base, there is an enhancement in the gamma radiation levels. Tables 6.1 and 6.2 show the gamma radiation levels of these two experimental roads before and after construction.

On the Parrish Road, the average post-construction gamma radiation levels were 14 uR/hr. and 12 uR/hr. on the crown of the road surface and off the edge of the road respectively, while average pre-construction gamma radiation levels were 11.0 uR/hr. and 11.5 uR/hr., respectively.

On the White Springs Road, the average post-construction gamma radiation level was about 7 uR/hr. on the road surface and the edge of the road, while the average pre-construction value was about 4 uR/hr.

Figures 6.3 through 6.6 show graphically the observed changes in gamma radiation levels on the roads during the period of study. Linear and linear-quadratic regressions on the post-construction data show no significant difference in gamma radiation levels over time.

Because there was no significant trend over time in radiation levels, the repeated (over time) measurements after construction can be pooled for the purpose of analyzing the pre- versus post-construction radiation levels. A two-way (time and location) Analysis of Variance was used to compare the gamma radiation levels as measured on the road surface before and after construction and at different locations. The following diagram gives the sketch of the statistical design.

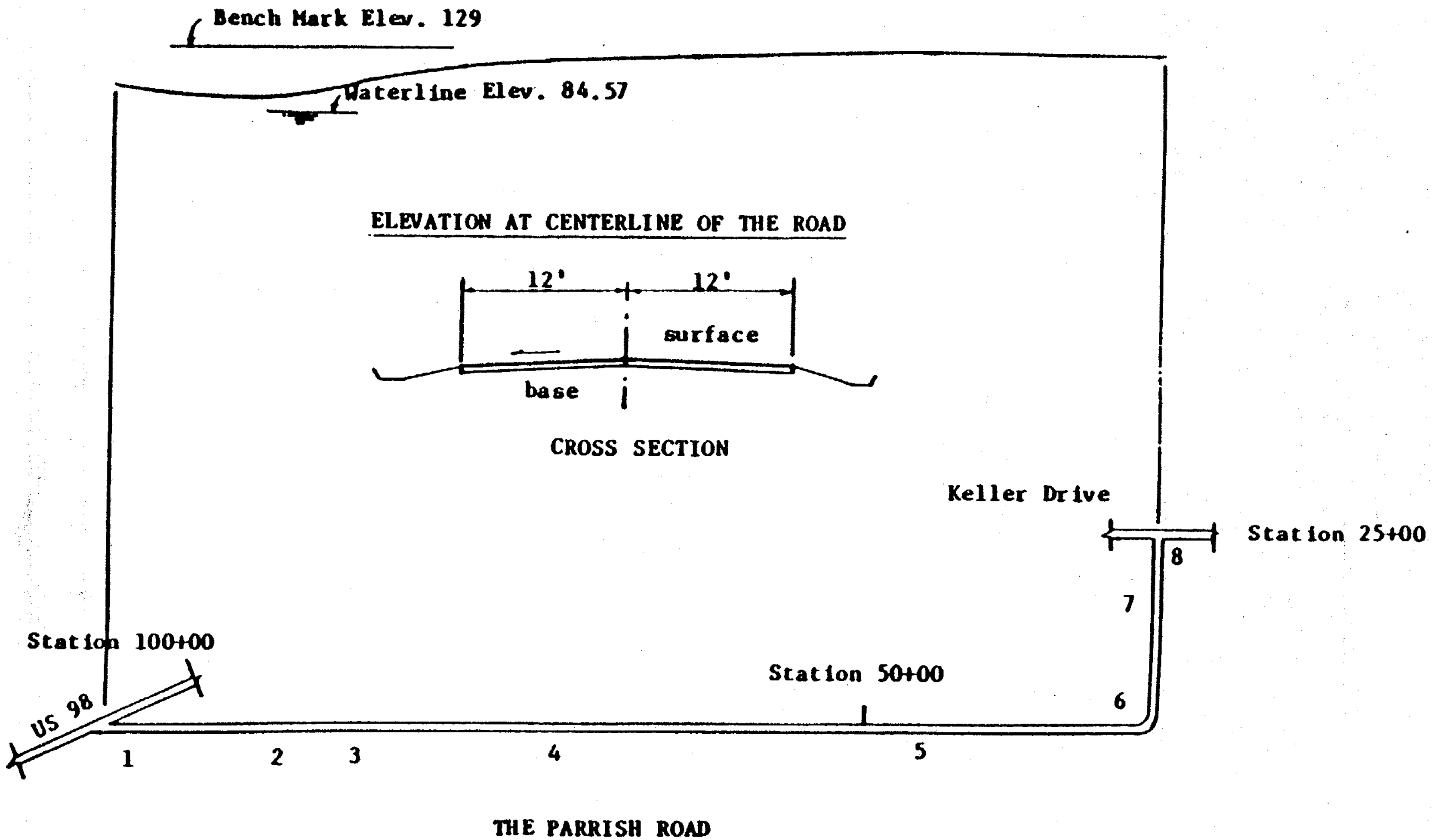
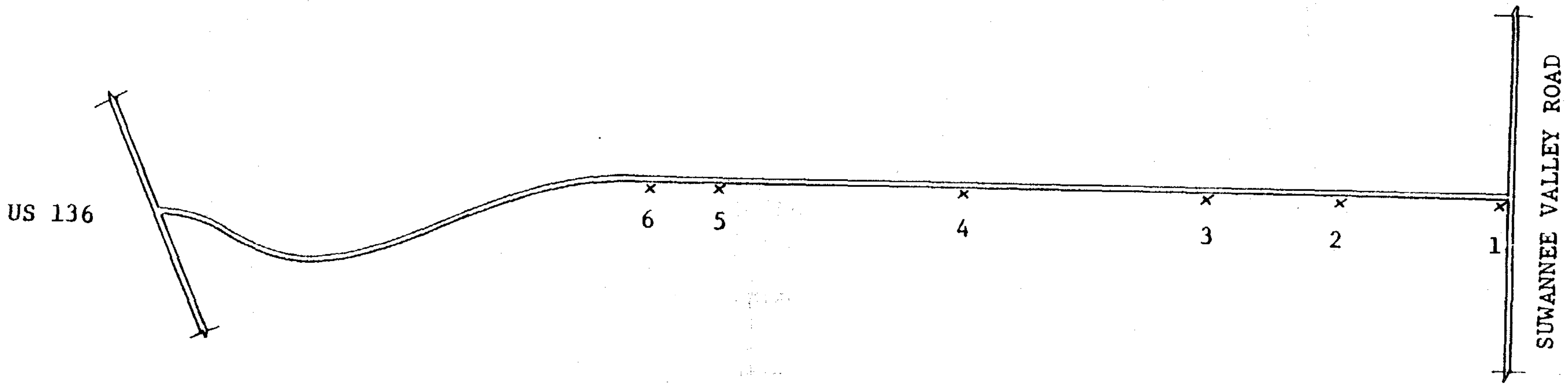


FIGURE 6.1 LOCATIONS OF GAMMA RADIATION MEASUREMENT



THE WHITE SPRINGS ROAD

FIGURE 6.2 LOCATIONS OF GAMMA RADIATION MEASUREMENT

Table 6.1

GAMMA RADIATION LEVELS (uR/hr) - PARRISH ROAD

ON THE ROAD

Sample Number	Pre-Construction	Post-Construction						
	1/13/86	10/16/86	12/30/86	1/31/87	5/15/87	7/17/87	10/16/87	1/15/88
1	--	--	--	--	--	--	--	--
2	13	16	19	19	16	15	16	16
3	11	14	15	14	13	12	13	13
4	11	13	14	13	12	12	12	12
5	8	12	11	11	10	10	10	10
6	11	14	15	15	13	14	14	15
7	--	15	15	15	14	14	14	14
8	11	14	13	13	14	12	12	12
AVG	11	14	15	14	13	13	13	13

ADJACENT TO THE ROAD

Sample Number	1/13/86	10/16/86	12/30/86	1/31/87	5/15/87	7/17/87	10/16/87	1/15/88
1	14	12	13	13	12	12	12	12
2	15	16	16	16	13	13	13	13
3	11	12	12	13	12	12	12	12
4	11	12	13	13	12	12	12	12
5	8	8	9	10	9	9	9	9
6	13	10	13	14	15	14	17	16
7	11	13	13	13	12	13	13	11
8	9	10	11	11	10	10	10	9
AVG	12	12	13	13	12	12	12	12

Location: 1. 500 ft. from US 98 2. Pole 5123129 3. Pole 5123126 4. Pole 5123122 5. Pole 51237 6. Road bend 7. Pole 51231 8. 100 ft. from Keller Dr.

TABLE 6.2

GAMMA RADIATION LEVELS (uR/hr.) - WHITE SPRINGS ROAD

ON THE ROAD

Sample Number	Pre-Construction	Post-Construction				
	8/12/86	5/14/87	7/16/87	10/15/87	1/14/88	4/14/88
1	4	7	7	7	7	7
2	4	7	7	7	7	7
3	4	6	7	7	7	7
4	4	8	7	7	7	7
5	4	8	7	7	8	7
6	4	8	7	7	7	7
AVG	4	7	7	7	7	7

ADJACENT TO THE ROAD

1	4	4	7	7	6	6
2	4	4	6	6	6	6
3	4	5	6	6	6	6
4	3	4	6	6	6	6
5	3	6	6	7	7	6
6	4	7	6	7	7	6
AVG	4	5	6	6	7	6

Location: 1. Junction of WSP Rd. & SWA Rd.
2. Pole E-6-24-10-99
3. 0.5 Mile from Suwannee Valley Rd.
4. Intersection of WSP Rd & Nova1 Rd.
5. Near Well #7
6. Near Well #1

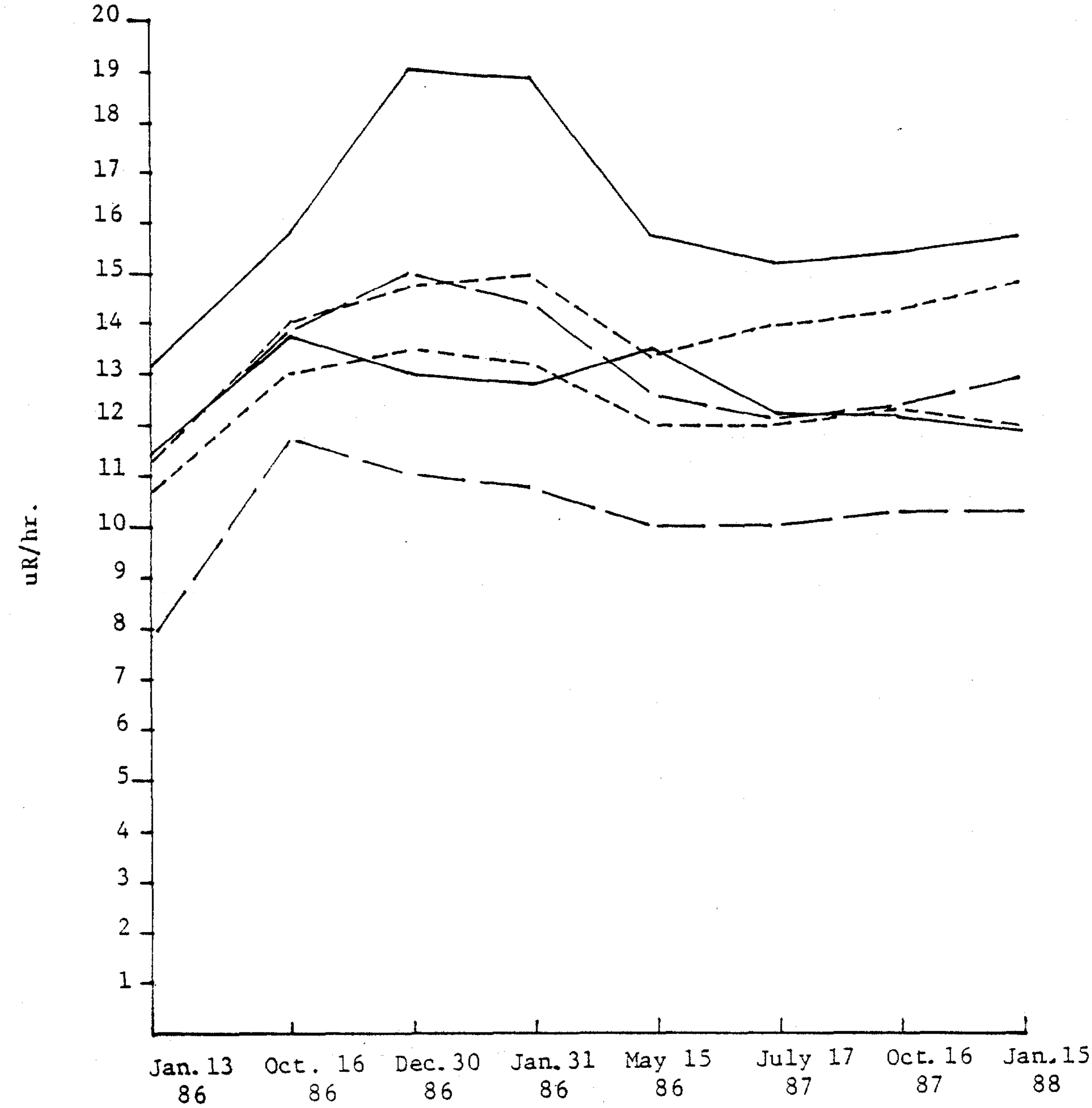


Figure 6.3 Gamma Radiation Levels, Parrish Road
(Road Surface)

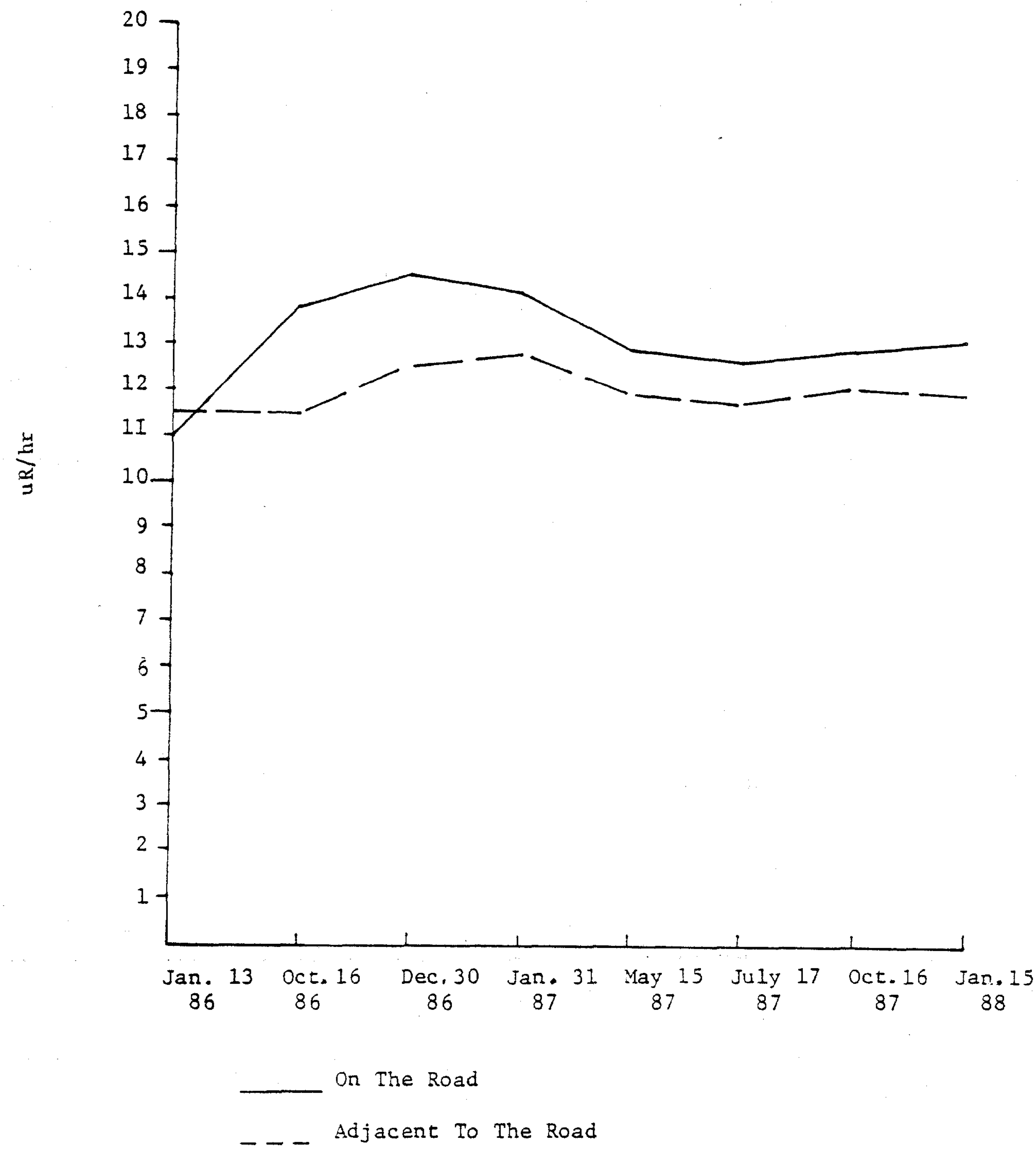


Figure 6.4 Gamma Radiation Levels (Averaged) Parrish Road

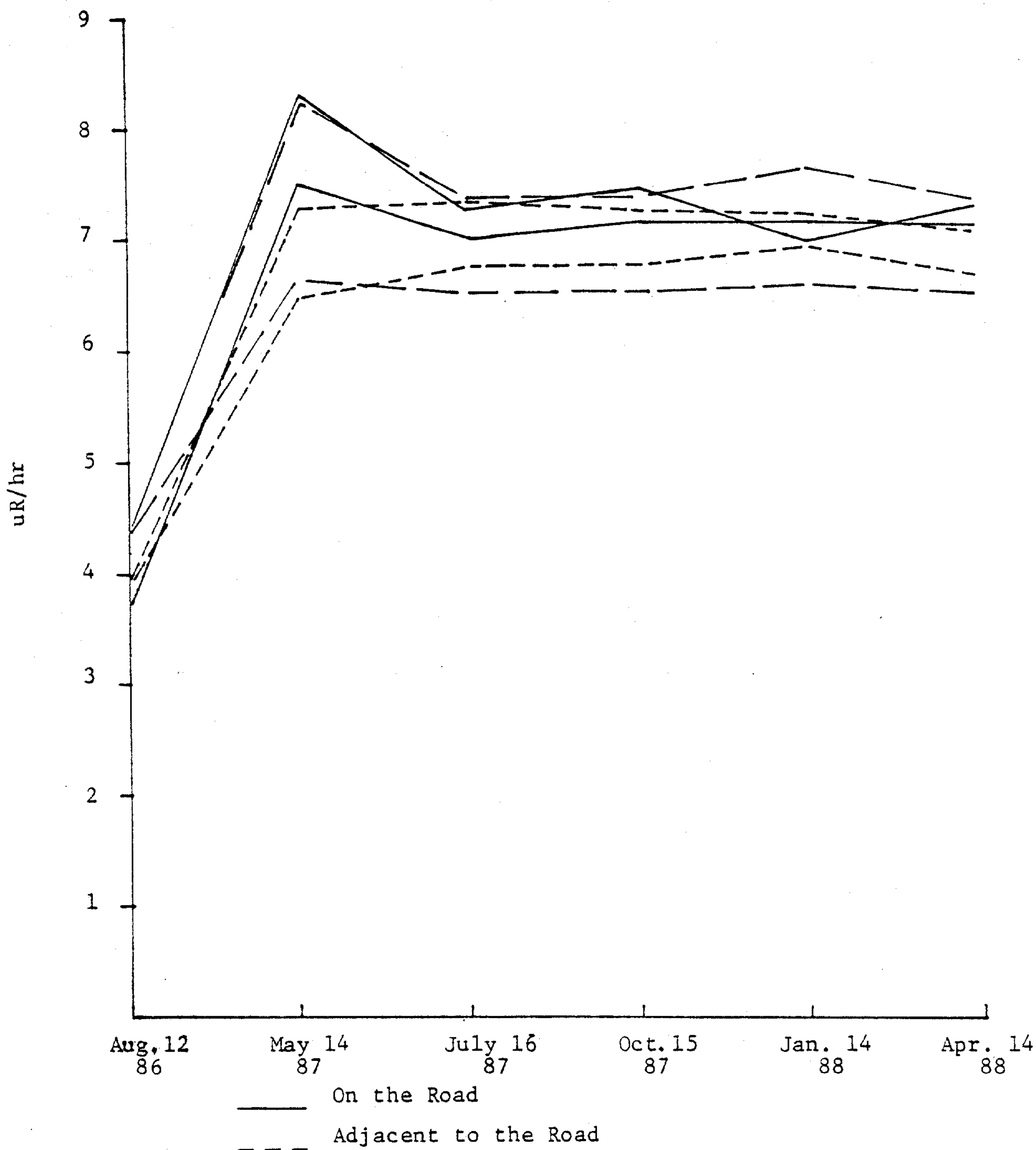


Figure 6.5 Gamma Radiation Levels White-Springs Road
(Road Surface)

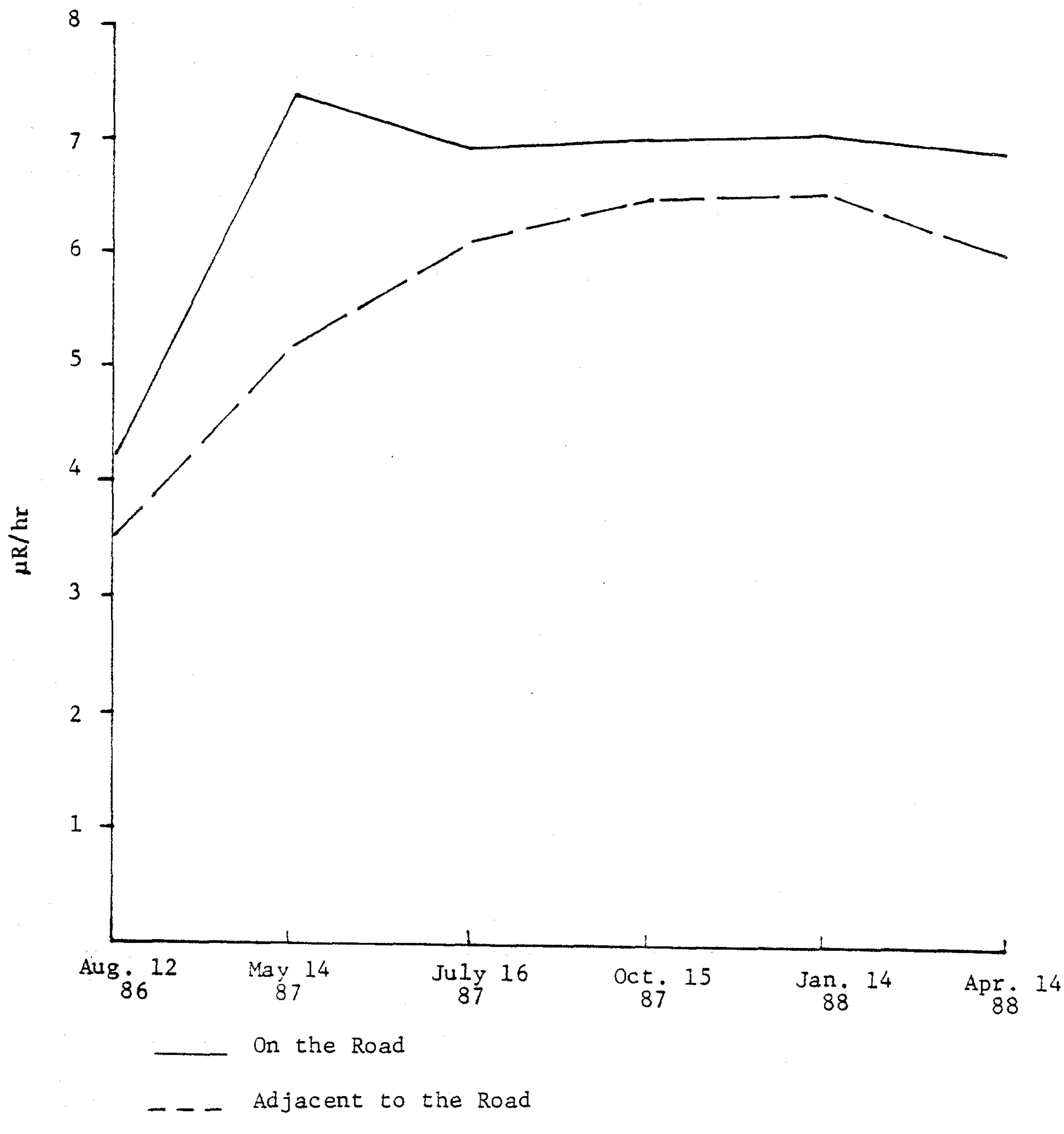


Figure 6.6 Gamma Radiation Levels (Averaged) White Springs Road

A (time factor)

		a1 (pre-con.)	a2 (post-con.)
B (locations)	1	x11	x121, x122, --- x12k
	2	x21	x221, x222, --- x22k
	3		
	:		
	n	xn1	xn21, --- xn2k

Factor A stands for the time effects, i.e. al stands for the pre-construction data, a2 stands for all the post-construction data, the period covered by the post-construction measurements is about one year. The values of k for the Parrish Road and the White Springs Road are 7 and 5, respectively. In the hypothesis testing process the pooled variance is approximated as the variance from the post-construction data only.

Tables 6.3 and 6.4 give the results of statistical analysis for the Parrish Road and White Springs Road, respectively. The results for the Parrish Road indicate a significant (P 0.001) increase in gamma radiation levels after the construction and significant (P 0.001) changes with location. For the White Spring Road, a significant (P 0.001) increase in gamma radiation levels after the construction was also observed. Variation in gamma radiation levels with location were not significant.

The results indicate an enhancement of gamma radiation levels, averaging about 2-4 uR/hr. along the two experimental roads. Although measurable, the increased background levels do not constitute a hazard to people. An increase of 4 uR/hr will mean an increase of about 35 mrem dose to the yearly total exposure, but only to someone who would spend 100% of his time all year at the road. In the content of the dose limitation to the general population used in radiation protection (500 mrem/year), and the generally observed background radiation levels in the United States, the gamma radiation levels around the experimental roads cannot be considered as abnormal.

The gamma radiation levels decreased rapidly with the distance from the center of the road, as shown in Figure 6.7.

TABLE 6.3

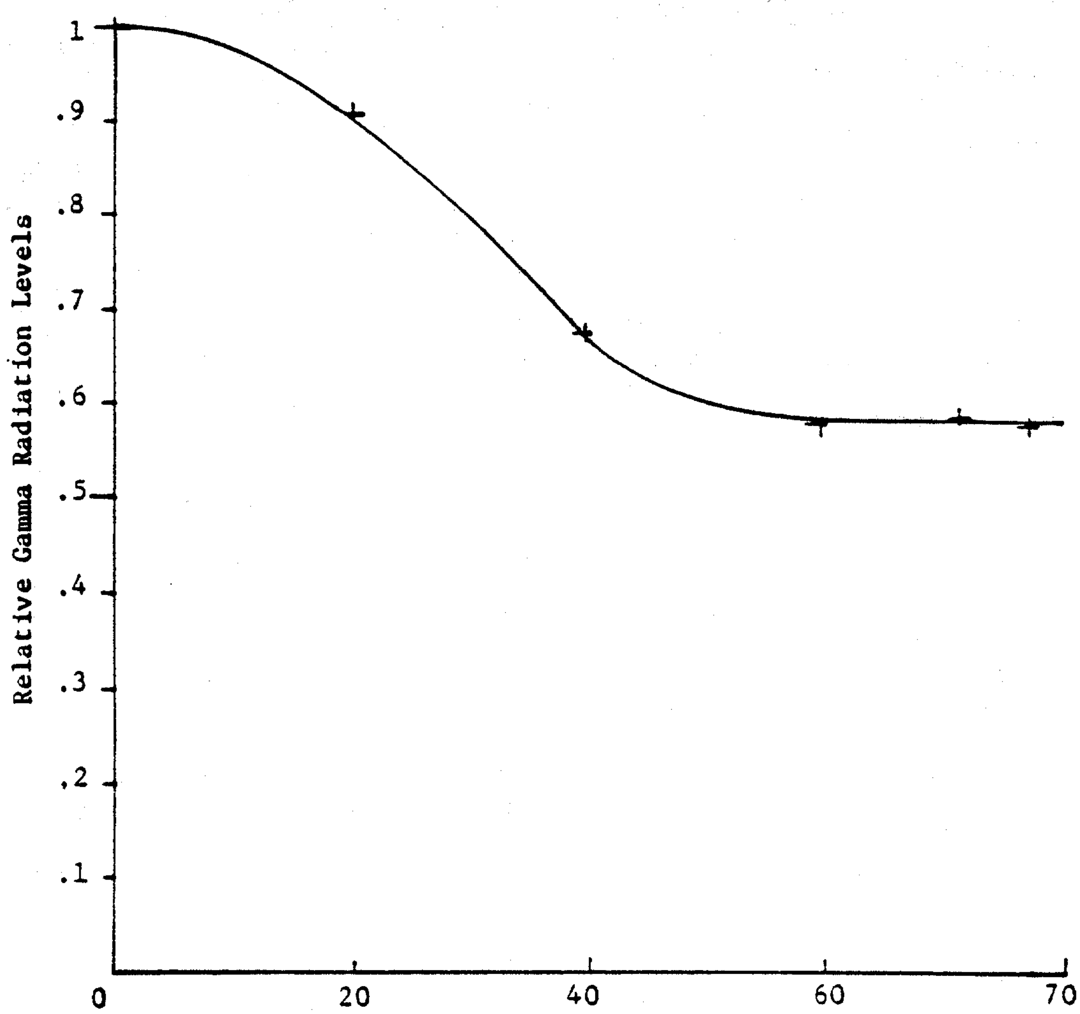
F-TEST ON γ RADIATION LEVELS, PARRISH ROAD

SOURCE	SUM-OF-SQUARE	DF	MEAN-SS	F-RATIO	P
A	30.198	1	30.198	33.039	<0.001
B	59.525	5	11.905	13.025	<0.001
AXB	2.628	5	0.526	0.575	0.718
ERROR	32.905	36	0.514		

TABLE 6.4

F-TEST ON γ RADIATION LEVELS, WHITE SPRINGS RD.

SOURCE	SUM-OF-SQUARE	DF	MEAN-SS	F-RATIO	P
A	45.975	1	45.975	594.815	<0.001
B	1.314	5	0.263	3.400	0.018
AXB	0.848	5	0.170	2.194	0.088
ERROR	1.855	24	0.077		



Distance (ft.)

Figure 6.7 Gamma Radiation Levels Vs. Distance from Center of Road.

6.2 RADON MEASUREMENT ALONG THE ROADS

Since the phosphogypsum used in the road base construction contains radium-226, there is concern-about changes in the radon-222 concentration in the environment. Track Etch detectors (Type F) manufactured by Terradex Corporation were used to measure the radon levels in the soil and the air along the roads.

For the measurement of radon levels in the air, the Track Etch detectors are inserted into a special container to protect them against the weather, then suspended from trees or utility poles at a height of about six to seven feet. After an exposure period of two to four months, the detectors were sent back to the company to be read.

For the measurement of radon levels in the soil, the Track Etch detectors are buried in the soil beside the roads to a depth of six to eight inches. The exposure period is also two to four months.

The purpose of measuring radon concentration in the soil is that the radon concentration in the air depends primarily on the radon flux from the ground and the convection situation in the air. The radon concentration in the soil together with the radon levels in the air reflect the radon level in the environment.

Tables 6.5 and 6.6 show the radon-222 levels in the air and soil, respectively, before and after the construction at the Parrish Road. Tables 6.7 and 6.8 show the radon-222 levels in the air and soil, respectively, before and after the construction at the White Springs Road. Because of damages to the detectors, some data were missing as shown in the Tables.

Table 6.9 shows the statistical results, using a linear regression model, from some selected locations along the experimental roads. The results show no significant effects of radon levels on the environment from the use of phosphogypsum in road construction.

6.3 RADIUM-226 ANALYSIS IN THE SOIL SAMPLES

The water samples were collected from the monitoring wells which had been placed symmetrically on both sides of the experimental roads as described in Chapter V. The soil samples were collected with an auger from a depth of about 1-2 ft. at the edge of the roads. The water and soil samples were sent to the Radiochemical Laboratory of the HRS, Orlando, Florida for the radium-226 analysis. Results of radium-226 in the groundwater are presented in Chapter V, in order to indicate the variations of Ra-226 measurement which may be due to turbidity changes as related to the background fluctuations.

Table 6.5

RADON-222 OUTDOOR AIR (pCi/ℓ), PARRISH ROAD

Location	Exposure Period				
	Pre-con.	Post-construction			
	1/13/86- 3/7/86	5/15/87- 7/17/87	7/17/87- 10/16/87	10/16/87- 1/15/88	4/14/88- 8/17/88
Pole - 51236	0.97	0.6	1.1	NA	0.6
Pole - 51231	NA	0.9	1.4	NA	1.5
Pole - 5123124	NA	NA	NA	0.3	NA

Table 6.6

RADON-222 IN SOIL (pCi/ℓ), PARRISH ROAD

Location	Exposure Period				
	Pre-con.	Post-construction			
	1/13/86- 3/7/86	5/15/87- 7/17/87	7/17/87- 10/16/87	10/16/87- 1/15/88	4/14/88- 8/17/88
Pole - 51236	497	957	367	653	441
Pole - 51231	271	293	205	296	NA
Pole - 5123124	2818	2997	NA	NA	NA

Table 6.7

RADON-222 OUTDOOR AIR (pCi/ℓ), WHITE SPRINGS RD.

Location	Exposure Period				
	Pre-con.	Post-construction			
	7/17/86-9/17/87	5/14/87-7/16/87	7/16/87-10/15/87	10/15/87-1/14/88	4/15/88-8/18/88
Near well 1	1.0	NA	NA	NA	0.4
E-60241099 (pole)	NA	1.4	1.2	1.1	-

Table 6.8

RADON-222 IN SOIL (pCi/ℓ), WHITE SPRINGS RD.

Location	Exposure Period				
	Pre-con.	Post-construction			
	7/17/86-9/17/86	5/14/87-7/16/87	7/16/87-10/15/87	10/15/87-1/14/88	4/15/88-8/18/88
Near well 1	236	NA	NA	NA	NA
Near well 7	106	56	NA	18	38
E60241099	NA	145	60	33	58
0.5 mile - SWA*	286	60	74	25	NA

* SWA: junction of White Spring Rd. and Suwannee Valley Rd.

Table 6.9

LINEAR REGRESSION ON RADON-222 OVER TIME

Location	Coefficient of time	t	Prob>|t|	R-Square
Parrish Rd.				
Pole-51236 (air)	-0.06	-0.612	0.603	0.157
Pole-51236 (soil)	-41.6	-0.507	0.647	0.079
Pole-51231 (soil)	- 1.3	0.056	0.960	0.002
White Spring Rd.				
0.5 mile-SWA (soil)	-76.9	2.182	0.161	0.704

Radium-226 analysis in soil samples, carried out by the Florida HRS Orlando Laboratory, are presented in Tables 6.10 and 6.11 for the Parrish Road and the White Springs Road, respectively.

Results shown in the tables can be summarized as follows:

1. No significant difference was found in radium-226 levels in the soil around the road before and after the construction. construction.

2. No significant difference was found in radium-226 levels in the soil from different sampling locations along the road.

Table 6.10

Ra-226 IN SOIL SAMPLES - PARRISH ROAD

Sample * Number	Pre-Construction	Post-Construction			
	Mar. 86	Oct. 86	Jan. 87	Oct. 87	Jan. 88
1	4.5	1.9	0.8	1.8	0.9
2	3.6	7.8	1.5	-	1.2
3	3.8	1.6	2.0	1.2	0.8
4	2.3	1.0	2.4	4.1	1.0
5	2.5	2.1	6.2	2.5	1.6
6	2.4	1.4	8.4	2.3	0.8
7	1.5	4.6	1.1	-	1.7
8	1.6	3.6	3.3	4.0	0.8
9	1.5	2.7	2.5	1.7	1.5
10	1.3	1.7	-	2.0	1.9

*Sample Location

1. next to pole 5-123
2. across from pole 5-123
3. edge of the road at pole 5-123-2
4. road border at pole 5-123-2
5. edge of the road opposite side of pole 5-123-4
6. road border at pole 5-123-4
7. road border opposite of pole 5-123-10
8. next to pole 5-123-10
9. next to pole 5-123-12-7
10. edge of the road opposite side of pole 5-123-12-7

Table 6.11

Ra-226 IN SOIL SAMPLES - WHITE SPRINGS ROAD

Sample Number *	Pre-Construction July, 86	Post-Construction July, 87
1	0.5	0.5
2	0.2	0.5
3	0.3	0.5
4	0.4	0.4
5	0.4	0.8
6	0.5	0.5
7	0.3	- -

* Sample Location

1. Intersection White Springs and S. W. Valley
2. Near well 7, Trailer house (red)
3. Intersection of Nova and White Springs
4. Phone E6-24-10-99
5. 1/2 mile from Suwanne Valley Jr.
6. 1/4 mile from State Road 136
7. Near Environmental Detailer

VII. ECONOMIC ANALYSIS

The purpose of the economic analysis conducted by Dr. David J. Sumanth, is to analyze the economic justification aspects with phosphogypsum vs. traditional materials in an experimental road construction project. The standard costing method used is provided by the Total Productivity Model as described in the entitled, Productivity Engineering and Management, by Dr. D. J. Sumanth. The cost of building the Parrish road is then compared to that of Tanner road and Windy Hill road, located in Polk County. The findings indicate the definite economic advantage in using phosphogypsum as a base material in comparison with clay, a traditional material used in road construction.

7.1 METHODOLOGY

A System-Flow chart, shown in Figure 7.1, shows at a glance, the approach used in conducting the economic and productivity analysis. The entire sequence of expected tasks in the road construction, Operation Process chart, is shown in Figure 7.2. Field observations were made and the actual tasks list was prepared as shown in Table 7.1. Then, using a data sheet as shown in Table 7.2, field data was collected in a systematic manner through the joint efforts of a graduate student assistant, the Construction Supervisor, and his personnel. A Computer program was developed for economic evaluation based on the logic shown in Figure 7.3. The field data was then processed with this computer program. A sample calculation on spreading gypsum is shown in Table 7.3.

7.2 RESULTS AND CONCLUSIONS

The findings indicate the definite economic advantage in using phosphogypsum as a base material in highway construction The construction cost of the Parrish Road was compared to that of two recently completed Polk County roads, Tanner and Windy Hill, as shown in Figure 7.4. A tremendous cost saving per mile was achieved by the use of phosphogypsum in road construction.

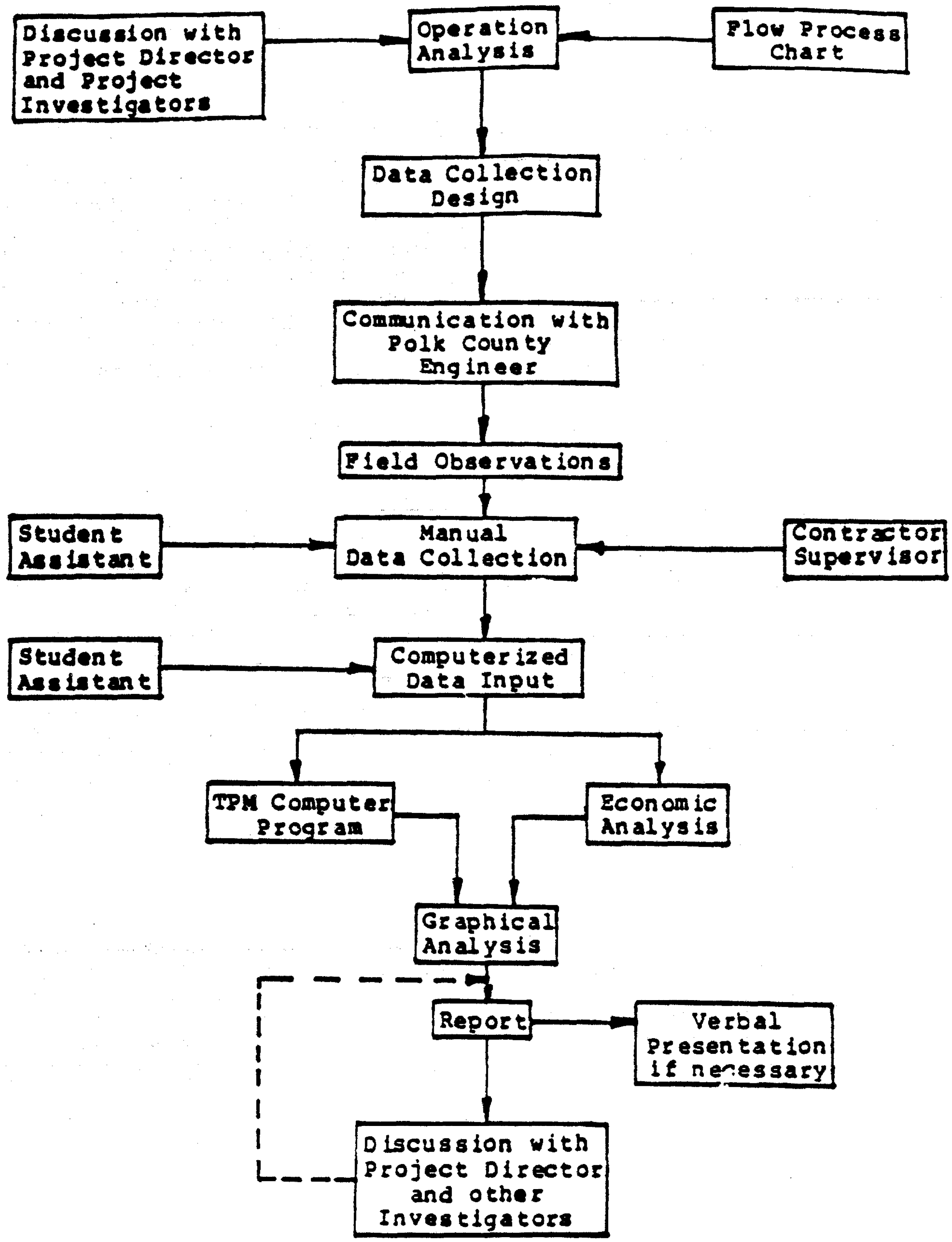


Figure 7.1 SYSTEM-FLOW CHART

PHOSPHOGYPSUM PROJECT

OPERATION PROCESS CHART

SUBJECT CHARTED: Construction of a secondary 1-mile rural road.

DEPARTMENT: Productivity Research Group, Department of Industrial Engineering, University of Miami.

PROCESS DESCRIPTION	CHART SYMBOL
EXCAVATE THE GYPSUM FROM THE STACK.	1
LOAD GYPSUM ON DUMP TRUCKS TO TRANSPORT TO SITE.	2
TRANSPORT THE GYPSUM TO THE SITE.	1
UNLOAD THE TRUCKS ON SITE.	3
LEVEL THE GROUND.	4
SPREAD GYPSUM WITH A LOADER AND BULLDOZER. (MOVE THE BULLDOZER BACK AND FORTH OVER THE GYPSUM TO BREAK THE HARD LUMPS.)	5
LEVEL THE GYPSUM TO 10" THICKNESS WITH A MOTOR GRADER.	6
MIX SOIL SAND WITH THE GYPSUM, USING A ROTOMIXER.	7
CHECK THE MATERIAL THICKNESS AFTER THE MIXING HAS TAKEN PLACE.	1
COMPACT INITIALLY WITH THE BULLDOZER.	8
GRADE THE SURFACE SMOOTH WITH A MOTOR GRADER.	9
COMPACT FINALLY WITH A 15-TON STEEL WHEELED ROLLER.	10
	A

Figure 7.2

SPRAY THE TACK COAT (1/4" THICK).

SPRAY THE ASPHALT (1" THICK).

APPLY PAINT AND MARKINGS ON THE ROAD.

POST THE TRAFFIC SIGNS IN PLANNED POSITIONS.

Figure 7.2 Cont'd.

Table 7.1 Tasks List of the road construction with phosphogypsum

1. Setting stakes and Grading
2. Hauling Gypsum
3. Spreading Gypsum
4. Boxing out and Shaping up
5. Mixing subgrade and Gypsum
6. Watering
7. Final blade
8. Compaction
9. Foreman's work (Considered as a separate task)

PHOSPHATE GYPSUM PROJECT

Data Sheet

A. Task Number: 008

B. Task Description: COMPACTION

C. Crew Engaged (including Supervisors)

Station No	Name	Start Date	Start Time	End Date	End Time	Hourly Rate
68-60	WANDA BLAIR	10-7-86	1:00 PM	10-7-86	2:30PM	$9.15
68-50	WAYNE COMBEE	10-8-86	8:30 AM	10-8-86	10:30AM	$9.15
68-50	WANDA BLAIR	10-8-86	8:30 AM	10-8-86	10:30AM	$9.15
68-60	WANDA BLAIR	10-09-86	8:30 AM	10-9-86	10:00AM	$9.15
68-50	WAYNE COMBEE	10-14-86	10:20 AM	10-14-86	11:45AM	$9.15
68-60	WANDA BLAIR	10-14-86	10:20AM	10-14-86	11:45AM	$9.15

D. Equipment Used

	Equipment Name	Model	Purchased Price	Useful Life (Years)	Approximate Hours Used in this Task
	STEEL WHEEL ROLLER	FB204-116	-	-	5 HOURS
	RUBBER TIRE ROLLER	FB204-122	-	-	5 HOURS

Table 7.2 Data collection form

Table 7.2 Data collection form Cont'd.

E. Materials Consumed

	Material Name	Quantity Used	Units (tons pounds, etc.)	Price/ Unit	
	PHOSPHOGYPSUM				

F. Other Items Consumed (e.g., Utilities, Transportation Expenses, etc.)

	Item Description	$ Expense
	ENERGY	
	NUMBER OF GALLONS: 634	459
	MACHINE RATE	
	S.W & R.T ROLLER - $/12/HOUR	
	SHEEPFOOT ROLLER - $20/HOUR	
	MACHINE EXPENSE	4544

G. Special Notes, if any

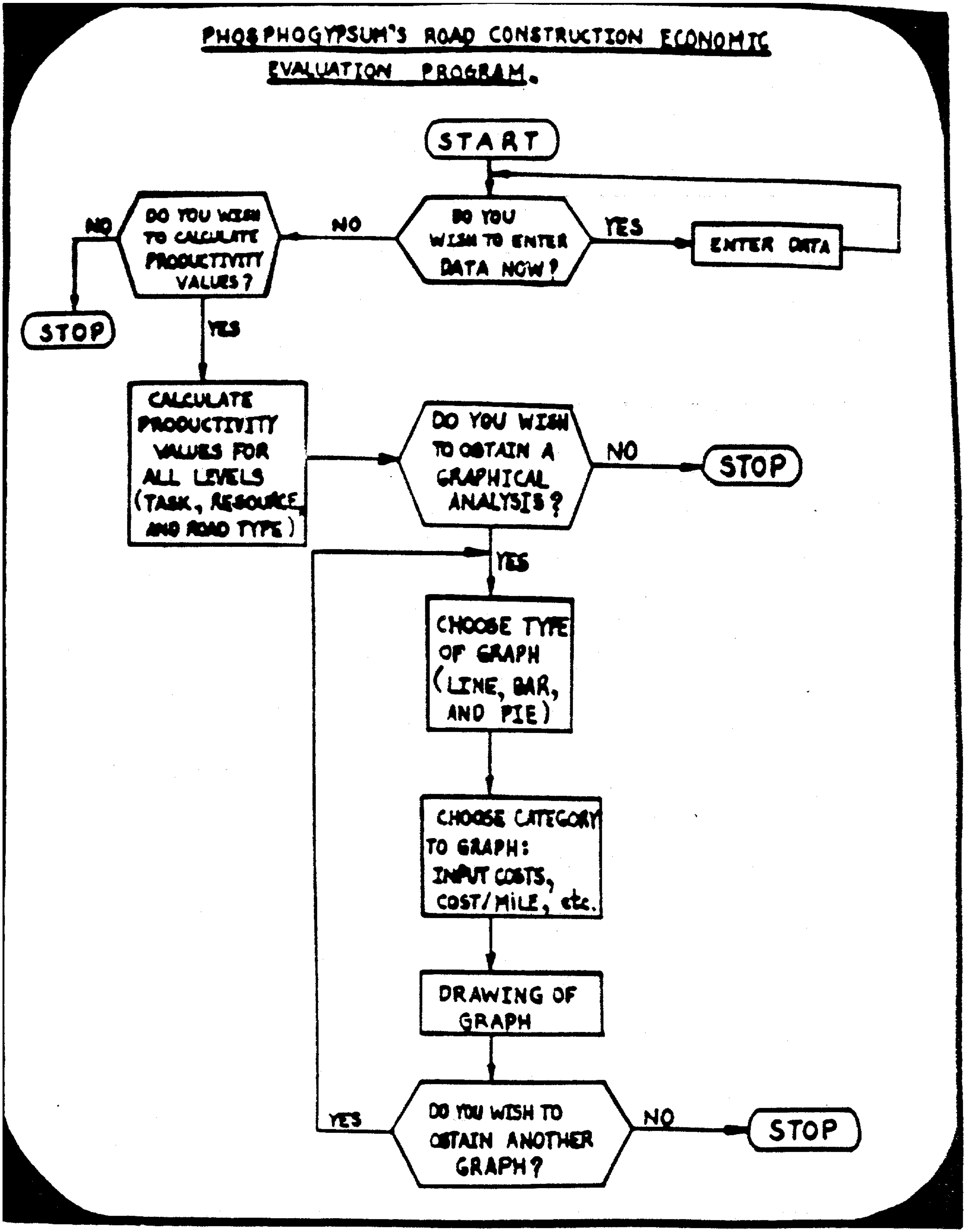


Figure 7.3 Flowchart of the computerized economic evaluation program

Table 7.3 Sample calculations

Task #3. Spreading Gypsum

Labor expenses:

Man-hours= Persons x Days x Hours= 1 x 11 x 8= 88 man-hours
Hourly-labor rate= $ 11.60 / hr
Total labor expense= I_h = 88 hrs x $ 11.60 / hr= $ 1,020.80

Capital expenses:

Bulldozer used for 11 days at 8 hrs / day
Hourly bulldozer's rate= $ 18.00
Total capital (Equipment) expense=
I_c = 11 days x 8 hrs / day x $ 18.00 / hr= $ 1,584.00

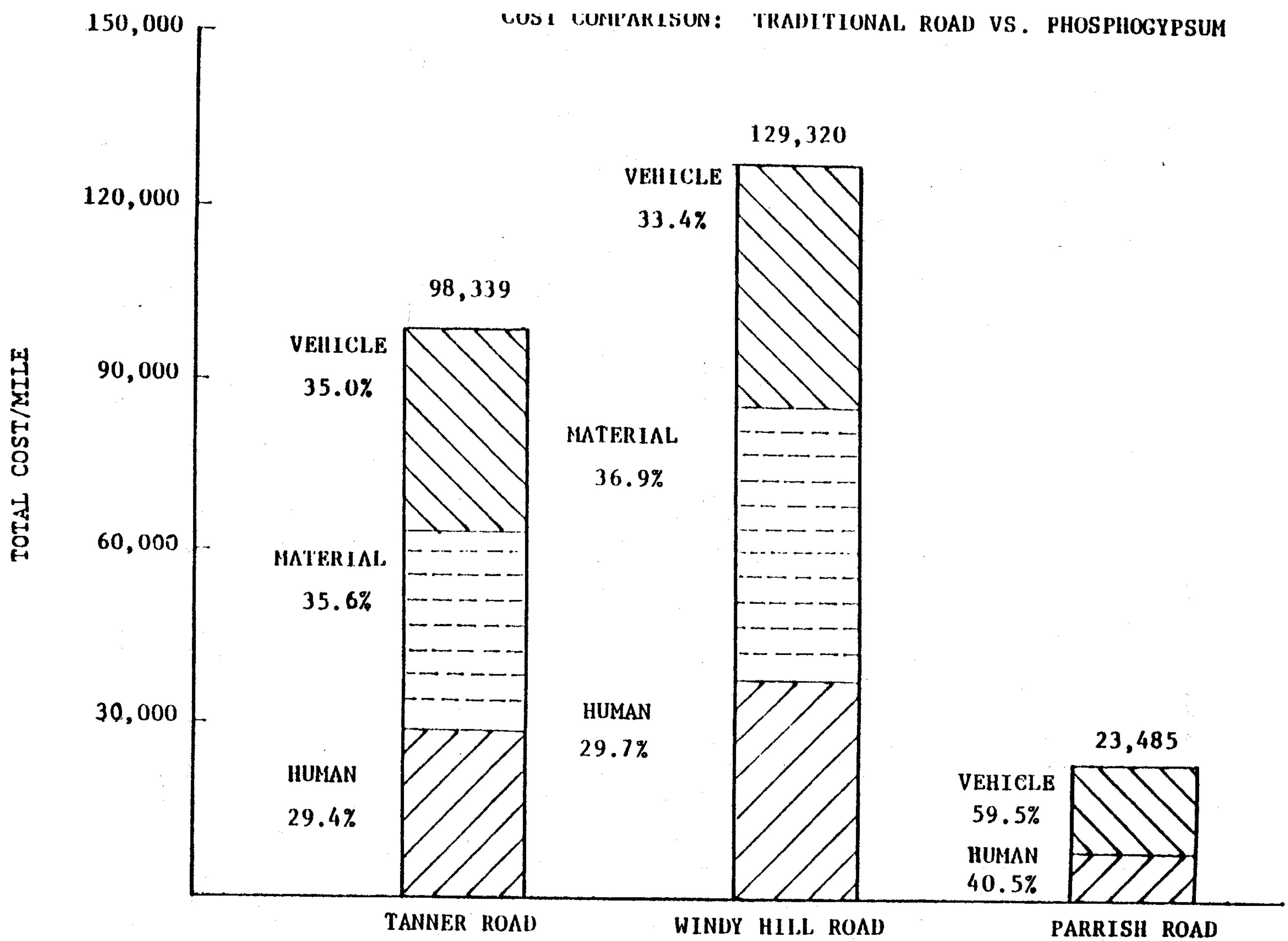
Energy expenses:

Speed= 10 miles / hr. Time of use= 35.67 hrs.
Distance travelled: 356.7 miles.
Miles / gallon= 2 miles / gal. No. gal.= 356.7 / 2= 178.35
Fuel cost / gal.= $ 0.86 / gal.
Energy cost= I_e = 178.35 x 0.86= $ 153.38

Costs per mile of construction:

Distance constructed= 0.95 miles= 5,000 ft.
Labor cost / mile= $ 1,020.80 / 0.95= $ 1,074.53
Capital cost / mile= $ 1,584.00 / 0.95= $ 1,667.37
Energy cost / mile= $ 153.38 / 0.95= $ 161.45

Total cost / mile for task #3= $ 2,903.35


COST COMPARISON: TRADITIONAL ROAD VS. PHOSPHOGYPSUM
TOTAL COST/MILE
150,000
120,000
90,000
60,000
30,000
98,339
VEHICLE
35.0%
MATERIAL
35.6%
HUMAN
29.4%
129,320
VEHICLE
33.4%
MATERIAL
36.9%
HUMAN
29.7%
23,485
VEHICLE
59.5%
HUMAN
40.5%
TANNER ROAD
WINDY HILL ROAD
PARRISH ROAD

VIII. CONCLUSIONS

Two experimental roads were built in Polk County and Columbia county in 1986 and 1987, respectively, utilizing phosphogypsum. The design, construction, supervision and testing of the road projects were conducted by a collective effort of the University of Miami, the respective County Divisions of Public Works and the Florida Department of Transportation.

The projects call for a thorough environmental impact investigation which includes the pre and post-construction sampling of air, soil and groundwater. Environmental monitoring as described were conducted by the University of Miami, in cooperation with the Florida Department of Environmental Regulation and the Florida Department of Health and Rehabilitative Services. Findings from the projects are summarized as follows:

1. Tremendous Cost Savings of Using Phosphogypsum in Road Construction

   The construction cost of the Parrish Road was compared to that of two recently completed Polk county roads, Tanner and Windy Hill as described in Chapter VII. A tremendous cost saving per mile was achieved by the use of phosphogypsum inroad construction.

2. Ease of the Shortage in Road Construction Materials in Florida

   The population increase in Florida is one of the highest in the country. Each year many new roads have to be built and many existing roads upgraded. However, traditional highway construction materials, such as limerock, shellrock, shell and clay, are in short supply in many parts of Florida. Significant tonnages of aggregates used in road construction are now imported from foreign countries. The U. S. Bureau of Mines has forcasted that Florida will have to import all its aggregate by the year 2000. The lack of adequate sources of locally available road materials is a major concern to road builders in the State. The use of phosphogypsum in road construction will certainly ease the shortage of road materials in Florida.

3. By-Product Utilization

   According to recent statistics, the phosphate industry in Florida annually produces 33 million tons of phosphogypsum, and has over 500 million tons stockpiled. It is estimated that by the year 2000, Florida could accumulate over one billion tons of phosphogypsum. The continued accumulation of phosphogypsum has created urgent pressure to find useful applications for this by-product.

4. Adequate Strength for Road Building

Phosphogypsum, when subjected to compaction, can be transformed into a valuable solid of high strength. It can then be used effectively as a binder to stabilize on-site soil as demonstrated by the experimental projects.

Laboratory studies conducted in 1982 by the Bureau of Materials and Research, Florida Department of Transportation, indicated a potential use of phosphogypsum as embankment material above the water table in highway construction.

Phosphogypsum and sand mixtures, stabilized with a smell amount of cement, possess a bearing strength higher than that of limerock and are suitable for use as base courses for highway construction. Mobil Mining & Minerals has a successful commercial operation of manufacturing phosphogypsum mixtures stabilized with cement in Houston, Texas.

Phosphogypsum can also be incorporated in a cement-based mixture for Roller Compacted Concrete (RCC)- The use of proper amounts of phosphogypsum in RCC leads to superior compaction and improves pavement strength properties. A demonstration project of RCC containing phosphogypsum. was built at the Florida Institute Of Phosphate Research in the Spring of 1988.

5. No Adverse Environmental Impact

The groundwater monitoring studies of the Parrish Road and White Springs Road indicate that there is no measurable impact on the ambient groundwater due to the construction of the phosphogypsum roadways. At the Parrish Road, the results showed that Ca and Ra-226 measurements were highly correlated with the turbidity of the samples collected. At several wells immediately adjacent to the roadway, significant upward trends in SO_4 were detected. It should be noted, that the magnitude of increases were not sufficient to cause the ambient levels of SO_4 to exceed drinking water standards.

Gamma radiation level measurements along the roadways indicate an average enhancement of about 2-4 uR/hr. after the construction of the roads. The maximum post-construction gamma radiation levels as measured, are all considered to be within the normal range for background.

The radon levels, measured in the soil and air, as well as Ra-226 analysis in soil around the experimental roads, do not show any significant changes after the completion of phosphogypsum roadways.