Conceptual Hydrogeologic Model of the Kerr-McGee Corporation Cushing Remediation Site

July 2001

KERR-McGEE CORPORATION

Cushing, Oklahoma

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CONCEPTUAL HYDROGEOLOGIC MODEL OF THE KERR-McGEE CORPORATION CUSHING REMEDIATION SITE

Cushing, Oklahoma

Prepared by:

Steven R. Lower
(Project Hydrogeologist)
Kerr-McGee Corporation Safety and Environmental Affairs Division
Hydrology, Geology, and Remediation Department
Hydrology Services Group
and
Burns & McDonnell Engineering Company, Inc.
Engineers-Geologists-Scientists
Kansas City, Missouri

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TABLE OF CONTENTS

EXECUTIVE SUMMARY v
1.0 INTRODUCTION 1
1.1 DESCRIPTION OF THE SITE 1
2.0 OVERVIEW OF REGIONAL GEOLOGY 3
2.1 DESIGNATION OF GEOLOGIC PROVINCES IN OKLAHOMA 3
2.2 ORIGINS OF BEDROCK UNDERLYING PAYNE COUNTY 3
2.3 CONCLUSIONS REGARDING REGIONAL GEOLOGY 4
3.0 GEOLOGY OF THE CUSHING REMEDIATION SITE AND VICINITY 5
3.1 DESCRIPTIONS OF SOIL AND BEDROCK UNITS 5
3.1.1 Unconsolidated Soil 5
3.1.2 Stream Terrace Deposits 6
3.1.3 Vanoss Group 6
3.1.3.1 Pony Creek Shale 7
3.1.3.2 Grayhorse Limestone 7
3.1.3.3 Gano Shale 7
3.1.3.4 Reading Limestone 7
3.1.4 Vamoosa-Ada Aquifer 7
3.1.5 Vanoss Group Shale versus Mudstone 7
3.1.6 Cushing Site Vanoss Group "Type Sequence" 8
3.2 LATE PENNSYLVANIAN DEPOSITIONAL ENVIRONMENTS 8
3.3 GEOLOGIC STRUCTURE 9
3.3.1 Small-Scale Localized Fracturing 9
3.3.2 Large-Scale Regional Fracturing 10
3.4 CONCLUSIONS REGARDING THE GEOLOGY OF THE CUSHING REMEDIATION SITE AND VICINITY 11
4.0 CONCEPTUAL HYDROGEOLOGIC MODEL OF THE SITE 12
4.1 SURFACE WATER 12
4.2 GROUNDWATER 12
4.2.1 Occurrence of Groundwater 12
4.2.2 Groundwater Regimes 13
4.2.2.1 Unconsolidated Soil Regime 14
4.2.2.2 Stream Terrace Regime 14
4.2.2.3 Upper Vanoss Regime 15
4.2.2.4 Lower Vanoss Regime 15

TABLE OF CONTENTS (continued)

4.2.2.5 Vamoosa-Ada Aquifer Regime 16
4.2.3 Seasonal Water-Level Fluctuations 16
4.2.4 Transmissive Properties of the Bedrock 17
4.2.4.1 Slug Test Permeabilities 17
4.2.4.2 Pumping Test Permeabilities 17
4.2.4.3 Laboratory Tests of Core Permeabilities 17
4.2.4.4 Permeabilities Calculated from Analysis of Long-Term Water-Level Recovery 18
4.2.5 Groundwater Chemistry and Quality 18
4.2.6 Groundwater Circulation 21
4.2.6.1 Potentiometric Surface 21
4.2.6.2 Hydrogeologic Cross Sections through the Site 21
4.2.6.3 Vanoss Group-Vamoosa Ada Aquifer Cross Section 23
4.3 CONCLUSIONS REGARDING THE CONCEPTUAL HYDROGEOLOGIC MODEL 24
5.0 REFERENCES CITED 26

TABLES

Table 1: Compilation of Permeability Values
Table 2: Comparison of Selected Groundwater Quality Parameters to Secondary Drinking Water Standards

PHOTOGRAPHS

Photograph 1: Stream terrace material overlying red mudstone of the Lower Vanoss Regime
Photograph 2: The Cushing "Type Sequence" Exposed in the rerouted channel of Skull Creek.
Photograph 3: Another view of the Cushing "Type Sequence" Showing the Grayhorse Limestone and the underlying sequence of gray to tan thinly laminated silty and sandy "shale" and the gray mudstone.
Photograph 4: Close-up view of the Grayhorse Limestone where exposed in Skull Creek showing the fossils weathering out of the friable material.

TABLE OF CONTENTS (continued)

Photograph 5: Close-up view of a more cemented portion of the Grayhorse Limestone fossils where exposed in the East Tributary.

PLATES

Plate 1: Site Location Map
Plate 2: Site Map
Plate 3: Geologic Map of the Cushing Area Showing Profile Line for Cross Sections A-A' And H-H'
Plate 4: Area Hydrogeologic Cross Section A-A'
Plate 5: Potentiometric Surface Map
Plate 6: Cross Section Index Map
Plate 7: Site Hydrogeologic Cross Section B-B'
Plate 8: Site Hydrogeologic Cross Section C-C'
Plate 9: Site Hydrogeologic Cross Section D-D'
Plate 10: Site Hydrogeologic Cross Section E-E'
Plate 11: Site Hydrogeologic Cross Section F-F'
Plate 12: Site Hydrogeologic Cross Section G-G'
Plate 13: Area Hydrogeologic Cross Section H-H'

FIGURES

Figure 1: Hydrogeologic Column of the Cushing Site and Vicinity
Figure 2: Historical Groundwater Elevations and Completion Interval Unconsolidated Soil Monitor Well USMW-6
Figure 3: Historical Groundwater Elevations and Completion Interval Terrace Monitor Well QTMW-48
Figure 4: Historical Groundwater Elevations and Completion Interval Unconsolidated Soil Monitor Well USMW-11
Figure 5: Historical Groundwater Elevations and Completion Interval Upper Vanoss Monitor Well UVMW-11
Figure 6: Comparison of Historical Groundwater Elevations and Completion Intervals Unconsolidated Soil (USMW-6) and Upper Vanoss (UVMW-6)

TABLE OF CONTENTS (continued)

Figure 7: Comparison of Historical Groundwater Elevations and Completion Intervals Upper Vanoss (UVMW-2), Lower Vanoss (LVMW-2.1) and Deep Lower Vanoss (LVMW-2)

Figure 8: Comparison of Historical Groundwater Elevations and Completion Intervals Upper Vanoss (UVMW-12), Lower Vanoss (LVMW-12.2) and Deep Lower Vanoss (LVMW-12.3)

Figure 9: Historical Groundwater Elevations and Completion Interval Vamoosa-Ada Aquifer Monitor Well VAMW-29

APPENDICES

APPENDIX A: Tabulation of Cushing Monitor Well Completions and Water-Level Elevations

APPENDIX B: Estimation of Mudstone Permeabilities from Analysis of Monitor Well Water-Level Recovery Data and Laboratory Tests of Core Samples

APPENDIX C: Data for Stiff and Radar Diagram Analyses

APPENDIX D: Stiff Diagrams

APPENDIX E: Radar Diagrams

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EXECUTIVE SUMMARY

The following report has been prepared in conjunction with of the Phase II Remedial Investigation Work Plan. The report provides the reader with a description of the geology and hydrology of the Kerr-McGee Cushing Remediation Site (Site) as it is understood at this time (2001). Work proposed for the Phase II Remedial Investigation will fill gaps in our knowledge of the Site. The following conclusions regarding the hydrogeology of the Site based upon our knowledge at this time:

Regarding the geology of the Site:

- Payne County in central Oklahoma is directly underlain by bedrock of Pennsylvanian and Permian age, which range in age from 280 to 310 million years and 230 to 280 million years, respectively.

- Bedrock immediately underlying the Kerr-McGee Cushing site consists of mudstones, lenticular sandstones, and thin limestones of the Upper Pennsylvanian Vanoss Group. The Vanoss Group is in turn underlain in sequence by the sandstones and shales of the Ada Group and Vamoosa Formation, collectively known as the Vamoosa-Ada Aquifer, also of Upper Pennsylvanian age. The lithology of this bedrock represents cyclic sedimentation during multiple transgressions and regressions of shallow seas in the fringe area between deltaic and shallow marine environments.

- A persistent sequence of limestone underlain by gray fossiliferous mudstone, gray non-fossiliferous mudstone, and hard, red mudstone has been recognized in lithologic logs for borings and in surface exposures in Skull Creek. Where exposed in Skull Creek this is considered to be the "type sequence" for the Site for correlation purposes.

- Water-bearing sandstones are present in the Vanoss Group and the underlying Vamoosa-Ada Aquifer. The predominant mudstones and the limited thickness and areal extent of the lenticular sandstones limit the availability of potable groundwater from the Vanoss Group. The deeper sandstones of the Vamoosa-Ada Aquifer are more prolific sources of groundwater.

Regarding the hydrology of the Site:

- The Site is drained by Skull Creek, a tributary to the Cimarron River, a major tributary to the Arkansas River. The Arkansas River is in turn a tributary to the Mississippi River.

- Most of the Cushing Remediation Site is located within a groundwater discharge area. Skull Creek is the discharge point for most groundwater originating within its large drainage basin. With the exception of the unconsolidated soil, groundwater in the

uppermost 100 feet or more of bedrock is moving through the Site on its way to discharge to Skull Creek. Deeper groundwater is discharging to the Cimarron River.

- Soils and bedrock beneath the Site have been divided into five groundwater flow regimes, the Unconsolidated Soil Regime, Stream Terrace Deposit Regime, Upper and Lower Vanoss Regimes, and the Vamoosa-Ada Aquifer Regime.

- Permeabilities of the mudstones underlying the Site range from 10^{-6} to 10^{-9} cm/sec, with the majority of the values falling within the 10^{-7} to 10^{-8} cm/sec range. These values are consistent with the observed very slow groundwater movement through the mudstones and published permeabilities typical for clay. A permeability of 3.2×10^{-4} cm/sec has been determined for the Vamoosa-Ada Aquifer beneath the Site, which is consistent with published permeability values for the Vamoosa-Ada Aquifer.

- With the exception of the unconsolidated soil and the uppermost weathered bedrock, in which the groundwater is typically unconfined, groundwater beneath the Site is under confined conditions, with water levels rising above the zones of completion.

- Significant shallow groundwater circulation is limited to the sandstones of the Upper Vanoss Regime. Precipitation and overland flow recharge most groundwater in these sandstones across off-site outcrops. Groundwater is discharged through evapotranspiration at seeps and as base flow to tributary streams that ultimately flow into Skull Creek.

- Significant deep groundwater circulation is limited to the deeper sandstones of the Lower Vanoss Regime. Groundwater in these sandstones is recharged at off-site outcrops. Groundwater is discharged as base flow to Skull Creek either directly or through its tributary streams.

- Recharge to the Vamoosa-Ada Aquifer is through infiltration of precipitation and runoff on outcroppings, which start about 3.5 miles east of the Site and continue eastward from there. Discharge is to the Cimarron River.

- Groundwater quality data indicate that there is a distinct difference between groundwater in the Upper Vanoss Regime and that in the Lower Vanoss Regime. Groundwater in the Upper Vanoss Regime is typically high in alkalinity and low in sulfates. Groundwater in the Lower Vanoss Regime is typically low in alkalinity and high in sulfates.

- Most of the groundwater in the Upper and Lower Vanoss Regimes exceeds Secondary Drinking Water Standards for total dissolved solids. Groundwater in the Lower Vanoss Regime also exceeds Secondary Drinking Water Standards for sulfates.

- The three main hydrogeologic units present at the Site, the Upper Vanoss, the Lower Vanoss, and the Vamoosa-Ada Aquifer regimes, are, for the most part, mutually

exclusive of one another. Potentiometric surface and water quality data indicate that these units are hydrologically isolated from one another. The rate of any significant movement of groundwater from the surface downward would be measured in terms of geologic time, not in human terms.

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CONCEPTUAL HYDROGEOLOGIC MODEL OF THE KERR-McGEE CORPORATION CUSHING REMEDIATION SITE
Cushing, Oklahoma

1.0 INTRODUCTION

This report has been prepared as part of the Phase II Remedial Investigation Work Plan to provide the reader with an understanding of the geology and hydrology of the Kerr-McGee Corporation Cushing Remediation Site (Site). The report is separated into four parts. The first part provides a description of the Site. The second part provides an overview of the regional geology. The third part discusses the geologic and hydrologic characteristics of the formations underlying the Cushing remediation site.

The fourth part of this report presents the conceptual hydrogeologic model itself. The report will discuss the groundwater recharge and discharge characteristics of the various formations underlying the Site. Work proposed under the Phase II Remedial Investigation Work Plan is intended to increase the knowledge of Site hydrogeology.

1.1 DESCRIPTION OF THE SITE

The Site is located approximately two miles north of the city of Cushing, in the southeastern corner of Payne County. Payne County is located in north-central Oklahoma. The site occupies approximately 440 acres in Section 22 and Section 27, Township 18 North, Range 5 East (see Plate 1 at the back of this report).

The topography of the Site is typical for Payne County, characterized by rolling plains and broad hills and valleys. Land surface elevations on the Site vary from a high of about 910 feet mean sea level at the southeast corner to a low of about 825 feet where Skull Creek exits the Site. The differential erosion of soft mudstones and shales and hard resistant sandstones has created much of the topography on the Site.

Most of Payne County, including the Site, lies within the drainage basin of the Cimarron River, a major tributary to the Arkansas River. The Arkansas River is in turn a tributary to the Mississippi River. The region is well drained with a dendritic drainage pattern that shows an overall southeastern trend north of the Cimarron River and a northeasterly trend south of the river.

Topographically the Site lies entirely within the drainage basin of Skull Creek, a tributary to the Cimarron River. Skull Creek originates about 1.5 miles southwest of the Site, cuts diagonally through the site from south to east, and joins the Cimarron River about four miles northeast of the Site. All surface runoff from the Site is to Skull Creek either directly or via tributaries.

Geologically the Site can be described as a series of highlands overlooking a broad stream valley. Resistant sandstones and limestones underlie the highlands, while the valley floor is cut through unconsolidated terrace deposits and underlying mudstones.

Hydrologically the Site can be described as lying within a groundwater discharge area. Review of groundwater circulation patterns suggests that most of the shallow groundwater discharges directly to Skull Creek. The exceptions to this pattern are very shallow groundwater that discharges to surface seeps or to tributaries of Skull Creek, or deeper groundwater that discharges to the Cimarron River.

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2.0 OVERVIEW OF REGIONAL GEOLOGY

2.1 DESIGNATION OF GEOLOGIC PROVINCES IN OKLAHOMA

Oklahoma has been divided into several geologic provinces based upon the specific major structural features described above. Rocks underlying the central and northern parts of the state are structurally part of the relatively flat lying Northern Shelf Area geologic province. This area, of which Payne County is part, is bounded on the east by the Ozark Uplift province, to the southeast by the Arkoma Basin and Ouachita Mountain Uplift provinces, to the south by the Arbuckle Mountain Uplift and the Ardmore Basin provinces, and to the west and southwest by the Anadarko Basin, Wichita Mountain Uplift, and the Hollis Basin provinces (Johnson, 1971).

Corresponding to the Northern Shelf Area geologic province, structurally the rocks underlying Payne County are part of the Central Oklahoma Platform, the southern part of the Prairie Plains Homocline, a regional feature of gently westward-dipping strata. On a regional scale these rocks are dipping to the west-southwest from the shallow Ozark Uplift in northeastern Oklahoma towards the axis of the deep (35,000 feet) Anadarko Basin in southwestern Oklahoma.

2.2 ORIGINS OF THE BEDROCK UNDERLYING PAYNE COUNTY

Payne County is directly underlain by bedrock of Pennsylvanian and Permian age, the last two periods of the Paleozoic Era, ranging in age from 280 to 310 million years and 230 to 280 million years, respectively. What is now North America was located on the equator during the Pennsylvanian period. The climate in North America at that time is believed to have been arid or semi-arid.

The bedrock underlying Payne County consists primarily of thick sequences of mudstones and shales containing thin interbeds of siltstone, sandstone, and limestone. Because of the typically gentle dip of these rocks, the older Pennsylvanian rocks are exposed at the surface in the eastern part of the county, while the younger Permian rocks are exposed in the western part (Shelton, et. al., 1985).

The crust of the North American continent, including Oklahoma, was subjected to more severe deformation during the Pennsylvanian period than at any other time in earth history. This deformation resulted in the formation of the Appalachian mountain belt, which runs from the far northeastern corner of the United States through the southern states, the ancestral Rocky Mountains to the west, as well as other smaller mountain-building events.

Crustal deformation in Oklahoma during this time resulted in both mountain building and the development of deep basins. Formation of the Wichita Mountains and Criner Hills south of Ardmore, Oklahoma, occurred during the early Pennsylvanian period. The broad uplift of the Oklahoma Arch, which raised the land surface of central Oklahoma above the surrounding shallow seas, also occurred during this time. The principal feature of this uplift was the Nemaha Ridge, a series of fault-block mountains that extended in a northerly direction through central Oklahoma. By the middle of the Pennsylvanian period this uplift had been removed by erosion,

and replaced by shallow seas. Mountain building continued in the middle of the Pennsylvanian period with the uplift of the Ouachita Mountains in southeast Oklahoma (Levin, 1978).

The late Pennsylvanian period was a time of strong crustal compression and uplift that affected all of the mountain ranges in eastern and southern Oklahoma and caused prominent folding in the Ardmore, Marietta, and Anadarko basins. Sources of the clastic sandstone and shale seen in Payne County were the Ozark Mountains to the east, the Ouachita Mountains to the southeast, and the Wichita Mountains to the southwest (Levin, 1978). Rivers carried sand, silt and clay eroded from these newly uplifted mountain ranges to shallow seas, depositing the sediment in massive river and shallow marine deltaic systems.

During the late Pennsylvanian period the depositional environment was alternately terrestrial and marine as shallow seas transgressed and regressed across the relatively flat continental interior. Small changes in sea level caused by either large-scale warping of the land surface itself or glaciation in other parts of the world caused shorelines to transgress and regress over distances measured in hundreds of miles.

Because of these oscillations in the depositional environment, the resulting Pennsylvanian bedrock seen in outcrops at the surface and in samples collected during subsurface investigations at the Site consists of a repetitious sequence of mudstones and lenticular sandstones. High concentrations of carbon dioxide in the atmosphere during this time in earth history also resulted in deposition of the chemical precipitate limestone in these warm, shallow seas. In some areas this environment resulted in the formation of thick coal deposits due to the accumulation of vast amounts of plant material in coastal areas and swamps. Together these rocks represent cyclic sedimentation during a series of recurring depositional environments of alternating tidal flat and shallow marine conditions (Dott and Batten, 1976).

2.3 CONCLUSIONS REGARDING REGIONAL GEOLOGY

From the discussions presented in this section of the report, the following conclusions can be made regarding the regional geology:

- Payne County in central Oklahoma is directly underlain by bedrock of Pennsylvanian and Permian age, the last two periods of the Paleozoic Era, which range in age from 230 to 310 million years ago. Because of the typically gentle dip of these rocks, the older Pennsylvanian rocks are exposed at the surface in the eastern part of the county, while the younger Permian rocks are exposed in the western part.

- The crust of the North American continent, including Oklahoma, was subjected to more severe deformation during the Pennsylvanian period than at any other time in earth history. This deformation resulted in the formation of mountains and deep basins in Oklahoma and elsewhere. Rivers originating in the mountain ranges carried sediment eroded from the uplifted areas to the coast, depositing sand and clay on an extensive delta and in shallow seas.

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3.0 GEOLOGY OF THE CUSHING REMEDIATION SITE AND VICINITY

Investigations of the geology and hydrology of the Cushing site began in 1985 and continue to this day. Hundreds of soil and bedrock borings have been drilled to gain understanding of the geology underlying the Site. Of these borings, a total of about 98 have been completed as groundwater monitoring wells to investigate the groundwater beneath the Site.

It should be noted that much of the Site has been disturbed by past refinery operations and more recent remediation activities, which have changed the nature of shallow subsurface materials in some areas. To provide convenient storage for tank bottom sludges and acidic wastes generated during operation of the refinery, the original channels of Skull Creek and some of its tributaries were dammed, and the stream flow rerouted around the resulting impoundments. Softer stream sediments and terrace deposits were removed from the impoundments down to firm bedrock, and replaced with waste. The channels of some of the streams have been rerouted again during more recent remediation or final reclamation activities.

3.1 DESCRIPTIONS OF SOIL AND BEDROCK UNITS

Soils, stream terrace deposits, and a series of relatively flat-lying bedrock formations of the Upper Pennsylvanian Vanoss Group directly underlie the Site. The Vanoss Group is in turn underlain in sequence by the Ada Group and Vamoosa Formation, also of Upper Pennsylvanian age. This bedrock is characterized by a cyclic or repetitious sequence of mudstones, lenticular sandstones, and thin limestones (Shelton, et. al., 1985).

3.1.1 Unconsolidated Soil

A total of five soil series have been identified on the Site. Most of these are residual soils, their physical composition reflecting the underlying mudstone and sandstone bedrock from which they were derived. A complete description of these soils, as well as a map showing their distribution across the Site, can be found in the report "Preliminary Assessment of Clay Availability/Kerr-McGee Cushing Refinery Site" (Kerr-McGee Corporation, 1994).

- Soils of the Agra Series directly overlie mudstone and shale containing thin sandstone lenses.
- Soils of the Steedman Series directly overlie mudstone.
- Soils of the Coyle Series are derived from the weathering of underlying sandstone.
- Soils of the Easpur and McClain Series are developed on alluvium and are found along the floodplains of Skull Creek and its tributaries.

These soils typically consist of sandy and/or silty clays, organic silts, and clayey silts that are dark brown, reddish brown, gray, and tan in color. The thickness of the soil profile varies from being absent where it has been removed and bedrock is exposed at the surface to locally several feet (Henley, et. al., 1987).

3.1.2 Stream Terrace Deposits

Quaternary stream terrace deposits consisting of varying amounts of unconsolidated clay, silt, sand, and gravel have been identified along the floodplains of the Cimarron River and some of its major tributary creeks (Shelton, et. al., 1985). Terrace deposits have been identified on the Site within the floodplain of Skull Creek. Recent drilling as well as observations of outcroppings along Skull Creek east of the Site have shown these unconsolidated sediments to consist of silty clay with thin layers of fine sand that lie directly on firm, red mudstone bedrock. A thin layer of coarse sand and gravel has been observed at the base of the terrace material in some borings. Photograph 1 at the back of this report shows the contact between terrace material and underlying mudstone bedrock.

Observations of the contact between the stream terrace deposits and the underlying bedrock indicates that the ancestral Skull Creek had eroded its channel down into the underlying red mudstone bedrock of the Gano Shale some time during the geologically recent past. This would have occurred at a time when the base level to which Skull Creek was flowing was lower than that at present. A later rise in the base level relative to the elevation of the Skull Creek channel caused the creek to start depositing sediment in its channel rather than erode downward. As a result, the floodplain was filled with sediment, raising the bed of the stream to a higher elevation. A subsequent drop in the base level caused Skull Creek to cut downward through the floodplain deposits of clay, silt, sand, and gravel. As a result, remnants of these terrace deposits were stranded on the edges of the floodplain as Skull Creek eroded its channel to the present depth.

In some areas, mainly along the floodplain of Skull Creek where it crosses the Site, in-place terrace deposits are difficult to distinguish from fill used to replace rerouted former channels. As noted earlier, portions of Skull Creek were rerouted during refinery operations to provide storage for waste in Pit 5 (see Plate 2). Review of vintage maps and aerial photographs and channel geometry suggests that other portions of Skull Creek may have also been rerouted to provide space for refinery facilities, with the old channel being backfilled. What appears to be terrace material may, in some areas, be fill.

3.1.3 Vanoss Group

Most of the Site is directly underlain by mudstone and sandstone bedrock of the Upper Pennsylvanian Vanoss Group. The sand and silt content of the mudstones vary locally both laterally and vertically. The lenticular sandstones are generally fine- to medium-grained, and are typically highly cemented, which makes them hard and resistant to erosion. A thin, fossiliferous limestone unit is prevalent across the Site.

The Vanoss Group in the Cushing area has been divided into, in descending order, the Long Creek Limestone, the Admiral Shale, the Pony Creek Shale, the Grayhorse Limestone, the Gano Shale, and the Reading Limestone. The Long Creek Limestone and Admiral Shale are not

present on the Site itself. Plate 3 shows a line of cross section across a geologic map of the area. Plate 4 has been developed to show the relationship between the bedrock formations as reported by Shelton (1985).

3.1.3.1 Pony Creek Shale - The Pony Creek Shale consists of thinly interbedded mudstones, highly cemented lenticular sandstones, and thin limestone sequences seen in numerous shallow boreholes. This unit directly underlies the highlands that border the Skull Creek Valley. Sandstones outcropping at the Site are in the Pony Creek Shale.

3.1.3.2 Grayhorse Limestone - The Grayhorse Limestone marks the contact between the Pony Creek Shale and the underlying Gano Shale, separating the two units. This is a thin, gray-colored, very fossiliferous, sandy limestone unit typically one to two feet in thickness. Fossils include crinoids, oysters, bryozoans, and brachiopods. Because it often appears to have more fossils than carbonate cement, it is highly friable and weathers readily where exposed.

3.1.3.3 Gano Shale - The Gano Shale consists primarily of massive gray and red mudstones, the individual units often exceeding 50 feet in thickness. Surface exposure of these mudstones on the Site are limited to the channel of the rerouted Skull Creek. Samples of these materials have also been collected from boreholes drilled into the Gano Shale. The hard, dense, red mudstones of the Gano Shale also directly underlie Pits 4 and 5. Sandstones in the upper portion of the unit are thin and infrequent, becoming thicker and more frequent at depth.

3.1.3.4 Reading Limestone - The Reading Limestone underlies the Gano Shale, marking the base of the Vanoss Group. In the Cushing area the Reading Limestone is typically two feet or less in thickness.

3.1.4 Vamoosa-Ada Aquifer

Shales and sandstones of the Ada Group directly underlie the Vanoss Group. The thin Reading Limestone Member described above is continuous across the Site, marking the contact between the Ada Group and the overlying Vanoss Group.

Shales and sandstones of the Vamoosa Formation underlie the Ada Group. Since the Oklahoma Geological Survey has combined the Ada Group and the Vamoosa Formation into one hydrogeologic unit, the two units will herein be referred to by the accepted name of the Vamoosa-Ada Aquifer. Outcroppings of the Vamoosa-Ada Aquifer begin about 3.5 miles to the east of the Site at an elevation of about 850 feet MSL, continuing eastward for several miles. Deep sandstones of the Vamoosa-Ada Aquifer are a source of groundwater for the City of Cushing.

3.1.5 Vanoss Group Shale versus Mudstone

The shales implied by the names of the Pony Creek Shale and Gano Shale are more claystones or mudstones than true shales. While the mudstones have the high clay content of

shale, the absence of the definitive parting typical of true shales is missing in most of these shallow units. What appears to be shale in some exposures is finely laminated silt and sand.

No significant parting or fracturing is typically seen in fresh samples of mudstone. These structures do not generally appear until the mudstones are allowed to dry out in either exposures or core samples. Given the depositional history of this area and the lack of compressional deformation of shell fossils, it is thought that sediment loading never became sufficient to generate the bearing pressures necessary to transform the mudstones into true shales.

3.1.6 Cushing Site Vanoss Group "Type Sequence"

The Grayhorse Limestone provides a good marker unit on the Site. This limestone and an underlying sequence of Gano Shale bedrock consisting of finely laminated brown- to gray-colored shaley silt, gray fossiliferous mudstone, gray non-fossiliferous mudstone, and hard, red mudstone have been recognized in lithologic logs for borings across the Site and in surface exposures in Skull Creek. On the west side of the Site the top of the Grayhorse limestone is found 20 to 30 feet below the surface at an elevation of about 835 to 840 feet MSL. The fossiliferous limestone is exposed in the East Tributary west of Pit 4 at an elevation of about 843 feet MSL. It is exposed in the banks of Skull Creek west of Pit 5 at an elevation of about 840 feet MSL. Fossils are weathering out of the friable unit where exposed at both the East Tributary and Skull Creek locations.

For correlation purposes the persistent sequence of limestone and underlying gray fossiliferous mudstone, gray non-fossiliferous mudstone, and red mudstone is considered to be the "type sequence" for the Site. Photograph 2 shows this type sequence where it is exposed in Skull Creek. Photograph 3 shows a fossil assemblage weathering from the friable Grayhorse Limestone in Skull Creek. Photograph 4 shows a fossil assemblage in a more cemented sample of the Grayhorse Limestone where exposed in the East Tributary.

3.2 LATE PENNSYLVANIAN DEPOSITIONAL ENVIRONMENTS

All of the late Pennsylvanian sediments were deposited during multiple transgressions and regressions of shallow seas in the fringe area between deltaic and shallow marine environments. The sandstones were deposited in distributary channels as part of sand-rich, tide-dominated river delta system in an arid or semi-arid environment. Given that depositional environment, these channel deposits are typically sinuous and of limited lateral extent. Paleocurrent data suggest that the Ouachita Mountains in southeastern Oklahoma are the probable predominant source area for the sediment deposited on the late Pennsylvanian delta (Johnson, 1971).

In those areas between distributary channels where little sand was being deposited, tidal-flat conditions consisting of extensive mud flats were predominant. This prodelta-type of deposition is thought to be the origin of the mudstones underlying the Site. The red color of some mudstones may be indicative of oxidation on mud flats or in shallow water under arid or

semiarid climatic conditions. As noted above, North America was located at the equator during the late Pennsylvanian. Thin limestones were deposited during transgressions of the warm, shallow seas across the mud flats.

Transgression of the shallow sea across the expansive delta can be seen in the "type sequence" described above in Section 3.1.6. The thick sequence of non-fossiliferous red mudstone and overlying non-fossiliferous gray mudstone exposed in the bottom of Skull Creek probably originated on the late Pennsylvanian mud flats. The fact that the gray mudstone becomes fossiliferous and shaley in the upper few feet, indicates transition to a shallow marine environment where clay and silt were still being deposited. The presence of the overlying fossiliferous Grayhorse Limestone suggests the transition to a deeper marine environment where clay deposition was absent and a limey bottom supported a rich assemblage of oysters, crinoids, and brachiopods (Shelton, et. al., 1985).

3.3 GEOLOGIC STRUCTURE

On a regional scale the rocks underlying Payne County are dipping to the west-southwest from the shallow Ozark Uplift in northeastern Oklahoma towards the axis of the deep (35,000 feet) Anadarko Basin in southwestern Oklahoma (Johnson, 1971). The rocks of the Upper Pennsylvanian Vanoss Group and Vamoosa-Ada Aquifer described above dip to the west at an average of 40 to 50 feet per mile in Payne County, although locally the dip can range from less than 20 to as much as 200 feet per mile (Shelton, et.al.,1985). The overall dip of the Vanoss group across the Site is about 5 feet or less.

Folds, faults, and joints comprise the local geologic structures in the Payne County area. Shelton (1985) reports some minor faulting in the Cushing area, but nothing of significance in the immediate vicinity of the Site. Shelton also reports minor folding in the area, the trends of which may be responsible for the courses of some streams.

3.3.1 Small-Scale Localized Fracturing

Closely spaced vertical fractures related to the expansion of bedrock as overlying rocks are removed by erosion over geologic time, known as "unloading fractures" or "joints," have been noted in some outcroppings of Vanoss Group sandstones and mudstones. Interconnections between these types of fractures are typically very localized. Unloading fractures in the Vanoss Group sandstones were most notable in the bed of the West Tributary opposite Pit 1 prior to tributary rerouting following final remediation of that area.

Observations of bedding plane fractures, small fissures parallel to approximate original bedding, as well as micro-fractures perpendicular to the bedding plane, have been noted in excavations made into these same sandstones. While the appearance of groundwater moving through inter-granular spaces on exposed vertical sandstone surfaces (wetting surfaces) may take some time to become apparent, groundwater has been noted discharging from both bedding plane fractures and micro-fractures immediately after exposure of the sandstone in excavations.

Groundwater movement through inter-granular spaces in the highly cemented sandstones appears to be limited, while movement through bedding plane fractures and micro-fractures may be more significant at some locations.

Noticeable fracturing is typically not seen in fresh (moist) core samples of Vanoss Group mudstones. Vertical unloading fractures have, however, been observed in outcroppings of the Vanoss Group mudstones where exposed in the bottoms and banks of Skull Creek and some of its tributaries.

3.3.2 Large-Scale Regional Fracturing

A recurring pattern of parallel bedrock fracturing on a regional scale has been recognized by Shelton (1985). These fractures, which occur on a much larger spacing then the typical jointing described above, trend in the northwest by southeast and east-northeast by west-southwest directions.

Review of maps of major Oklahoma drainage patterns shows that the courses of the major rivers follow a predominant northwest by southeast linear trend (Johnson, 1971). This trend parallels the axis of the deep Anadarko structural basin in the southwestern part of the state. A second, less predominant drainage pattern follows an east-northeast by west-southwest linear trend paralleling the axis of the Arkoma structural basin in the southeastern part of the state. These drainage patterns apply to the North Canadian River and the South Canadian River in western and central Oklahoma, as well as to the Cimarron River in Payne County and the Arkansas River to the north and east.

These drainage pattern trends may represent preferential erosion along major intersecting tectonic fracture systems created during crustal deformation. The existence of these fracture systems may have major significance in the movement of groundwater from deeper formations to the surface.

3.4 CONCLUSIONS REGARDING THE GEOLOGY OF THE CUSHING REMEDIATION SITE AND VICINITY

From the discussions presented in this section of the report, the following conclusions can be made regarding the geology of the Site and vicinity:

- The Site is directly underlain by soils that overlie bedrock in many areas. Alluvium and associated terrace deposits may be found along some of the tributary creeks.

- Bedrock immediately underlying the Site consists of mudstones, lenticular sandstones, and thin limestones of the Upper Pennsylvanian Vanoss Group. The Vanoss Group is in turn underlain in sequence by the sandstones and sandstones of the Ada Group and Vamoosa Formation, collectively known as the Vamoosa-Ada Aquifer, also of Upper Pennsylvanian age.

- The lithology of this bedrock represents cyclic sedimentation during multiple transgressions and regressions of shallow seas in the fringe area between deltaic and shallow marine environments. These recurring depositional environments resulted in the deposition of a repetitious sequence of mudstones, lenticular sandstones, and thin limestones deposited during alternating tidal flat and shallow marine environments.

- The Grayhorse Limestone, the lowermost part of the Upper Vanoss Regime, provides a good marker bed across the Site. The limestone and an underlying sequence of gray fossiliferous mudstone, gray non-fossiliferous mudstone, and hard, red mudstone in the Lower Vanoss Regime have been recognized in lithologic logs for borings across the Site and in surface exposures in Skull Creek. Where exposed in Skull Creek the persistent sequence is considered to be the "type sequence" for the Site for correlation purposes.

- Closely spaced vertical fractures related to the expansion of bedrock as overlying rocks are removed by erosion over geologic time, known as "unloading fractures" or "joints," have been noted in some outcroppings of Vanoss Group sandstones and mudstones. Interconnections between these types of fractures are typically very localized.

- A recurring pattern of parallel bedrock fracturing on a regional scale has been recognized. These fractures, which occur on a much larger spacing then the typical jointing described above, trend in the northwest by southeast and east-northeast by west-southwest directions and appear to control surface drainages and rivers.

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4.0 CONCEPTUAL HYDROGEOLOGIC MODEL OF THE SITE

4.1 SURFACE WATER

The Site is drained by Skull Creek, a tributary to the Cimarron River, a major tributary to the Arkansas River. The Arkansas River is in turn a tributary to the Mississippi River.

Prior to 1991 the quality of water in Skull Creek where it flows across the Site was very poor. This was due largely to contamination by acidic groundwater and hydrocarbon waste leaking from Pit 5, the largest of the acid waste pits on the Site (see Plate 2), as well as oil seeping into the creek from contaminated sediments. In 1991 the course of Skull Creek was moved to the west away from the direct influence of Pit 5. A French drain was installed in the old Skull Creek channel between Pit 5 and the rerouted Skull Creek to eliminate impact by acidic groundwater. An additional groundwater interception trench was subsequently installed between the southwest end of Pit 5 and the rerouted Skull Creek to further eliminate the discharge of acidic groundwater into the creek. Additional trenches were installed down stream from Pit 5 to intercept oil before it could enter the creek. As a result of this work, the quality of water in Skull Creek has increased dramatically as demonstrated by both chemical analyses and the return of aquatic flora and fauna.

4.2 GROUNDWATER

As noted earlier, hydrogeologic investigations of the Site began in 1985 and continue to this day. An important aspect of these hydrogeologic investigations has been the long-term monitoring of groundwater levels. This groundwater monitoring began with the installation of 38 monitoring wells around four of the five large acid waste pits, Pits 1, 2, 3, and 4 (see Plate 2). Monitor wells were placed around the largest of the acid waste pits, Pit 5, in 1990 and 1991. Additional wells have been installed since in response to specific informational needs, the most recent being constructed in April 2000 to monitor groundwater upgradient and downgradient from Radioactive Materials Areas RMA-10 and RMA-11 (see Plate 2). As of May 2001a total of 98 monitor wells have been installed to investigate the groundwater beneath the Site, of which 78 were still in use. Table A-1 in Appendix A lists the wells currently being monitored as well as January 2001 water-level elevations.

Studies done to date show that the Site is located in an area of groundwater discharge. Skull Creek represents the local base level, and is thus the receiving stream for discharging groundwater as well as surface runoff. Groundwater recharged to the shallow bedrock underlying the highlands surrounding the Site is moving down-gradient through the Site to discharge to the creek.

4.2.1 Occurrence of Groundwater

Although its presence may not be notable, or even detected in many instances, groundwater occurs in all of the lithologic units underlying the Site. Through investigations

involving borings, installation of monitor wells, and excavations into shallow bedrock, the hydrologic characteristics of the geologic units can be summarized as follows:

- Unconsolidated soils are generally too thin and limited in area to be viable sources of potable groundwater.

- Extensive stream terrace deposits along the floodplains of major rivers in Payne County, such as the Cimarron River, can be prolific sources of groundwater. While they may contain groundwater, terrace deposits found along some of the tributary creeks are too limited in extent to be viable sources of groundwater.

- The predominant mudstones and the limited thickness and areal extent of the lenticular sandstones limit the availability of potable groundwater from the Vanoss Group. The mudstones typically have high clay contents, which impede the lateral and vertical movement of groundwater through the rock. It is not unusual for a new monitor well constructed in the mudstones to be completely dry following completion. Groundwater will typically accumulate in the monitor well given adequate time.

- Groundwater movement through inter-granular spaces in the highly cemented, lenticular sandstones of the Vanoss Group appears to be limited; movement through bedding plane fractures and micro-fractures may be more significant at some locations. This has been substantiated by observations of groundwater discharging from bedding plane fractures, small fissures parallel to approximate original bedding, as well as small micro-fractures perpendicular to the bedding plane, in excavations made into the shallow sandstones. While the appearance of groundwater moving through inter-granular spaces on exposed vertical sandstone surfaces may take some time to become noticeable, groundwater has been noted discharging from both bedding plane fractures and vertical micro-fractures immediately after exposure of the sandstone in excavations.

- The deeper sandstones of the Vamoosa-Ada Aquifer are more prolific sources of groundwater. The aggregate thickness of these water-bearing sandstones ranges from about 100 feet to a maximum thickness of 550 feet. The City of Cushing has several municipal water-supply wells in the Vamoosa-Ada Aquifer. Completions of these wells vary from depths of nearly 400 feet to as deep as 700 feet or more. There is a water-supply well on the Site which is completed to a depth of about 510 feet in the Vamoosa-Ada Aquifer.

4.2.2 Groundwater Regimes

To facilitate development of this conceptual hydrogeologic model, the rocks underlying the Site have been divided into five groundwater flow regimes. The Unconsolidated Soil Regime consists of soil and uppermost weathered bedrock. The Stream Terrace Regime consists of remnant terrace sediments found along the floodplain of Skull Creek. The Vanoss Group is

divided into the Upper Vanoss Regime and the Lower Vanoss Regime. The fifth regime consists of the Vamoosa-Ada Aquifer. These regimes are shown on Figure 1at the back of this report.

The resistant sandstones and limestones of the Upper Vanoss Regime directly underlie the highlands surrounding the Site. Since the elevation of the Skull Creek valley floor is approximately the same as the contact between the Upper and Lower Vanoss Regimes, the Upper Vanoss Regime is missing altogether in that area. Stream terrace deposits directly underlie the Skull Creek valley floor, underlain in turn by the mudstones of the Lower Vanoss regime. Surface exposures of the Lower Vanoss regime on the Site occur only in the rerouted channel of Skull Creek. The red mudstone of the Lower Vanoss regime was also seen during final remediation of Pit 5. Because this sequence of bedrock units is relatively flat-lying, at higher elevations on the Site some intermediate (30 feet) wells are completed in the Upper Vanoss Regime, while in the lower elevations shallow wells (20 feet deep or less) may be completed in the Lower Vanoss Regime.

Potentiometric surface elevations vary across the Site. Groundwater in the Unconsolidated Soil and Stream Terrace regimes is typically under water-table conditions, reflecting localized groundwater recharge and discharge characteristics. The potentiometric surfaces in these materials typically follow the topography. Groundwater in the bedrock regimes, the Upper and Lower Vanoss regimes and the Vamoosa-Ada Aquifer, occurs under artesian conditions with generally significant hydraulic heads. Each of these five regimes exhibits different recharge-discharge characteristics.

4.2.2.1 Unconsolidated Soil Regime - The Unconsolidated Soil Regime is represented by soils and weathered bedrock, the lowest horizon of the soil profile, extending to a depth of only a few feet. As of March 2001 only six wells were completed in the Unconsolidated Soil Regime, five of which are located on the west side of the Site near the West Tributary around an area once occupied by acid sludge Pits 1, 2, and 3 (see Plate 2).

As typified by the hydrograph for Monitor Well USMW-6 shown in Figure 2 at the back of this report, water levels in the shallow wells show rapid fluctuations in immediate response to individual precipitation events. This reflects localized groundwater recharge-discharge characteristics. Groundwater completed by these wells is typically under water-table conditions, indicating connection to the surface. During the dry summer months these wells may go dry as evapotranspiration or discharges to nearby drainages consume the shallow groundwater.

4.2.2.2 Stream Terrace Regime - The Stream Terrace Regime is represented by unconsolidated clays, silts, sands, and thin gravels that occur in remnants of terrace deposits along the Skull Creek floodplain. These deposits are known to extend to a maximum depth of about 20 feet. Eight wells are completed in the Stream Terrace Deposit Regime, five of which are located around RMA-10 (see Plate 2).

Outcroppings of terrace deposits and underlying mudstone bedrock exposed in the banks of Skull Creek down stream from the Site show the relationship between the two units. The basal sequence of coarse sand and gravel seen in the terrace deposits underlying RMA-10 is also seen on Skull Creek (see Photograph 1). Groundwater has been observed discharging from the

exposed contact between the basal terrace sequence and the underlying mudstone bedrock, as the clay content of the mudstone prevents the downward movement of the groundwater.

Groundwater in the stream terrace deposits in RMA-10 discharges to Skull Creek. Since these wells were installed in April 2000, There is insufficient data as yet to describe long-term water-level fluctuations in the terrace deposits. The hydrograph for Terrace regime monitor well QTMW-48, shown on Figure 3, shows an apparent response to seasonal precipitation.

4.2.2.3 Upper Vanoss Regime - Thinly bedded sandstones and mudstones of the Vanoss Group, which as noted earlier correlates with the Pony Creek Shale, represent the Upper Vanoss Regime. The Grayhorse Limestone, which separates the Pony Creek Shale from the underlying Gano Shale, is included in this regime.

The shallow weathered Upper Vanoss Regime bedrock is exposed at the surface at many locations. As shown on the hydrograph for Monitor Well USMW-11 (Figure 4), water levels show responses similar to the Unconsolidated Soils Regime to individual precipitation events. Groundwater in this weathered bedrock is typically unconfined.

As typified by the hydrograph for Monitor Well UVMW-11 shown on Figure 5, water levels in the Upper Vanoss Regime beneath the weathered zone can also show some fluctuations in response to precipitation events. These fluctuations are less than those in wells completed in the Unconsolidated Soil Regime. Groundwater completed by these wells is typically confined, with some rise of the static water level (potentiometric surface) above the completion zone, indicating some isolation from the surface. In the case of well UVMW-11, the static water level is at or slightly above the zone of completion.

As shown on Figure 6, which compares the hydrograph for Upper Vanoss monitor well UVMW-6 to Unconsolidated Soil monitor well USMW-6, water levels in even deeper portions of the Upper Vanoss Regime typically show smaller fluctuations in response to seasonal precipitation. These fluctuations are less than those in wells completed in the Unconsolidated Soil Regime and the more shallow portions of the Upper Vanoss Regime. Groundwater completed by these wells is typically confined with potentiometric surfaces rising above the completion intervals. In the case of well UVMW-6, the static water level is five to ten feet above the zone of completion.

4.2.2.4 Lower Vanoss Regime - The Lower Vanoss Regime is represented by the thick mudstones and interbedded lenticular sandstones that are typical of the deeper portions of the Vanoss Group. This unit correlates with the Gano Shale.

Hydrographs for a cluster of monitor wells completed at different depths on the west side of the Site (UVMW-2, LVMW-2, and LVMW-2.1) show a progression of water-level responses to precipitation events from the weathered bedrock to the deeper portions of the Lower Vanoss Regime mudstones. As shown on Figure 7, water levels in the deeper portions of the Lower Vanoss Regime typically take months or years to equilibrate following well construction and development. In addition, the deeper groundwater typically exhibits long-period fluctuations, as compared to the shallow portion of the Lower Vanoss regime and the Upper Vanoss regime,

showing the delayed effects of recharge. Groundwater completed by these wells is typically highly confined with potentiometric surfaces rising above the completion intervals.

Hydrographs for a cluster of wells completed to different depths at the north end of Pit 4 on the east side of the Site (see Plate 2) show the transition through the shallow Upper Vanoss regime to the deeper part of the Lower Vanoss Regime (see Figure 8). Water levels in the Lower Vanoss regime do not respond to individual precipitation events. Responses to seasonal precipitation in the deeper portions of the Lower Vanoss regime are again more subdued than those in the more shallow materials.

4.2.2.5 Vamoosa-Ada Aquifer Regime - The Vamoosa-Ada Aquifer Regime is represented by thick sandstones and interbedded mudstones. As typified by the hydrograph for Monitor Well VAMW-29 shown on Figure 9, water levels in these wells typically exhibit very slight fluctuations showing the delayed effects of recharge. The period and magnitude of these fluctuations are similar to, or less than, those in wells completed in the Lower Vanoss Regime. Groundwater intercepted by these wells is confined with water levels rising well above the completion zone. The water level in Monitor Well VAMW-29 rises to a point about 65 feet above the top of the completion zone.

A comparison of tritium values in groundwater from Vamoosa-Ada Aquifer monitor well VAMW-29 to (then) recent surface water was performed in 1991. The difference in the tritium/hydrogen ratios was in excess of eight half-lives. Since the half-life of tritium is over 12 years, the groundwater in the Vamoosa-Ada Aquifer was determined to be at least 100 years older than the surface water.

This tritium analysis indicates that the Vamoosa-Ada Aquifer is in poor hydraulic communication with the overlying Vanoss Group. This supports the conclusion that recharge to the Vamoosa-Ada Aquifer occurs primarily by infiltration of precipitation and overland recharge on outcrops located miles to the east of the Site (Burns & McDonnell, 1993).

4.2.3 Seasonal Water-Level Fluctuations

As was described in the previous sections, hydrographs show a repetitious pattern of water-level fluctuations, the magnitudes of which decrease with increasing depth. Water levels in the shallowest wells show rapid responses to individual precipitation events. Water levels in wells completed in deeper formations show smooth responses to seasonal precipitation, seasonal highs and lows that can be characterized as "sine curves."

An obvious offset is seen in seasonal highs and lows in some hydrographs comparing water levels in multiple well clusters. This is due to the lag time between groundwater recharge to the shallow formations and that to the deeper formations. The shallow bedrock typically receives its recharge from sources on or near the Site, while the deeper formations are most likely recharged at outcrops east of the Site.

Because the seasonal variations are consistent over the long term, there is no way to tell if the seasonal highs and lows shown on a deep-well hydrograph correspond to the same seasonal response seen in a shallow well, or if there is a delay of months or even years. For instance, the above discussion of tritium values showed that the groundwater in the Vamoosa-Ada Aquifer was determined to be at least 100 years older than surface water. For that reason, the seasonal highs and lows seen in the hydrograph for monitor well VAMW-29 are not related to recent recharge events. Seasonal responses seen in wells completed in the Lower Vanoss Regime may likewise be delayed by months or years.

4.2.4 Transmissive Properties of the Bedrock

Groundwater can move through sandstone and mudstone bedrock two basic ways. The first is through primary porosity consisting of inter-granular spaces in clastic materials such as sandstone and mudstone and shale. The second is through secondary porosity consisting of fractures through the bedrock.

Permeability is a measure of the ability of a material to transmit fluid, in this case groundwater. Several tests of bedrock permeabilities have been performed on the Site. These tests include instantaneous recharge and discharge (slug) tests of monitor wells, one pumping test, laboratory tests of core samples from boreholes, and analyses of long-term recovery of monitor well water levels following initial development or groundwater sampling events. These tests are described below. A compilation of permeabilities is shown in Table 1.

4.2.4.1 Slug Test Permeabilities - Several slug tests have been performed on shallow wells completed in the unconsolidated soil and bedrock of the Vanoss Group. Permeabilities determined from these tests range from 10^{-4} to 10^{-5} cm/sec for the both the unconsolidated soil and underlying Vanoss Group bedrock. This range of permeability values is typically representative of silt and fine silty sand.

4.2.4.2 Pumping Test Permeabilities - Pumping tests are generally impossible to conduct due to the very low yields and low permeabilities of the cemented sandstones and mudstones underlying the Site. However, one pumping test has been performed on Vamoosa-Ada Aquifer Monitor Well VAMW-29. The results of this test show an aquifer permeability of 3.2×10^{-4} cm/sec, which compares well with reported Vamoosa-Ada Aquifer permeabilities ranging from 7.1×10^{-4} cm/sec to 1.4×10^{-3} cm/sec. These permeabilities are typical of fine sand.

4.2.4.3 Laboratory Tests of Core Permeabilities - Laboratory tests determine the vertical permeability of a material as compared to the horizontal permeability as determined from pumping and slug tests. Laboratory tests of permeability have been run on cores from several borings. Of the 22 laboratory permeability values reported, 16 were performed on mudstones of the Vanoss Group, with the remaining six tests being performed on mudstones and shales of the underlying Ada Group of the Vamoosa-Ada Aquifer. Of the 16 Vanoss Group tests, two have values of 10^{-6} cm/sec, which is consistent with silt. Six additional tests have values of 10^{-7} cm/sec, with the remaining eight having values of 10^{-8} cm/sec, which are representative of clay, the predominant component of the mudstones underlying the Site. Of the six Ada Group tests,

one has a value of 10^{-6} cm/sec, with two having values of 10^{-7} cm/sec and three having values of 10^{-8} cm/sec.

4.2.4.4 Permeabilities Calculated from Analysis of Long-Term Water-Level Recovery - Hydrographs of monitor wells completed in the deeper mudstones of the Lower Vanoss Regime typically show very slow recovery of water levels following completion and development and following groundwater sampling events. Time periods of recovery are measured in months or years. The slow recovery reflects the low permeability imparted to the mudstone by the high clay content.

To quantify the apparent low permeabilities of the mudstones underlying the Site, estimates of the permeabilities of the deeper mudstones were made from analyses of water-level recovery plots in five monitor wells. The two methods used to analyze the water-level recovery data were Cooper, Bredehoeft, and Papadopulos (1967) and Skibitzke (1958), as described in Lohman (1972). A report of these analyses is presented in Appendix B. The results of these analyses show mudstone permeabilities of 10^{-8} and 10^{-9} cm/sec, which are consistent with the high clay contents of the mudstones.

4.2.5 Groundwater Chemistry and Quality

An assessment of background groundwater quality at the Cushing Site was performed in 2000. This assessment included the characterization of basic groundwater quality parameters in several wells across the Site. Pertinent groundwater quality parameters were analyzed to determine if there were any differences in groundwater quality between the various regimes.

Review of data from the background groundwater quality assessment shows that the shallow groundwater at the Site is highly mineralized. Table 2 below presents a comparison of selected groundwater quality parameters for 16 monitor wells to the EPA Secondary Drinking Water Standards. The seven Upper Vanoss regime and seven Lower Vanoss regime wells are all background wells located at sites hydraulically upgradient from the past refinery operation.

Review of Table 2 below shows that the quality of the groundwater generally decreases with depth as indicated by increasing total dissolved solids (TDS) and sulfate parameters. It also shows that there is a definite and consistent distinction in the chemistry of the groundwater between the Stream Terrace, Upper Vanoss, Lower Vanoss, and Vamoosa-Ada groundwater regimes. This is in large part due to the fact that the Upper Vanoss regime consists of thinly bedded mudstones, sandstones, and limestones, while the underlying Lower Vanoss regime consists primarily of mudstones with thinly bedded sandstones.

The naturally poor quality of the shallow groundwater can also be demonstrated graphically by the use of Stiff and "radar" diagrams. A tabulation of sodium+potassium, calcium, magnesium, chloride, and sulfate concentrations in the groundwater is presented in Appendix C. A total of 17 Stiff diagrams comparing these groundwater quality parameters are included in Appendix D. Three radar diagrams showing pH, alkalinity, and sulfate data for the 17 wells are included in Appendix E.

TABLE 1
COMPILATION OF PERMEABILITY VALUES
Cushing Remediation Site

Site	Depth Interval Tested (ft)	Tested Lithology	Maximum Permeability From Analysis of Slug Test Data (cm/sec)	Maximum Permeability from Analysis of Water-Level Recovery Data (cm/sec)	Maximum Permeability from Analysis of Pump Test Data (cm/sec)	Laboratory Permeability (cm/sec)
Permeability Data Reported in the Phase I Remedial Investigation Report						
Well USMW-6	1.8 - 6.8	Unconsolidated soil	$5.2x10^{-5}$			
Well USMW-7	3.5 - 6.5	Unconsolidated soil	$3.4x10^{-4}$			
Well UVMW-5	10 - 15	Vanoss mudstone	$9.3x10^{-5}$			
Well LVMW-9	24 - 44	Vanoss Mudstone	$1.5x10^{-4}$			
Well LVMW-24	9 - 29	Vanoss mudstone	$5.9x10^{-4}$			
Borehole P5-1A	50 - 53.5	Vanoss Silty mudstone				$1.0x10^{-7}$
Borehole P5-2	53 - 53.5	Vanoss mudstone w/gravel				$9.9x10^{-7}$
Borehole P5-3	40 - 44.5	Vanoss Silty mudstone				$1.8x10^{-6}$
Borehole P5-4	33.5 - 34	Vanoss sandy, shaley mudstone				$9.9x10^{-8}$
Well VAMW-29	124	Ada mudstone				$5.3x10^{-8}$
Well VAMW-29	129	Ada mudstone				$1.1x10^{-7}$
Well VAMW-29	134	Ada shale				$2.2x10^{-6}$
Well VAMW-29	156	Ada mudstone				$5.8x10^{-7}$
Well VAMW-29	164	Ada shale				$4.3x10^{-8}$
Well VAMW-29	166	Ada shale				$7.1x10^{-6}$
Well VAMW-29	174 - 244	Vamoosa-Ada Aquifer			$3.2x10^{-4}$	
Permeability Data Collected Since the Phase I Remedial Investigation Report						
Borehole B-120-2	15 - 16	Vanoss mudstone				$1.2x10^{-8}$
Borehole B-120-2	35 - 37	Vanoss mudstone				$5.8x10^{-8}$
Borehole B-120-2	43 - 44	Vanoss mudstone				$6.1x10^{-7}$
Borehole B-120-2	58 - 59	Vanoss mudstone				$1.7x10^{-8}$
Borehole B-120-2	63 - 65	Vanoss mudstone				$8.8x10^{-8}$
Borehole B-120-2	77 - 78	Vanoss mudstone				$3.1x10^{-7}$
Borehole B-127-2	26 - 27	Vanoss mudstone				$3.2x10^{-7}$
Borehole B-127-2	39 - 40	Vanoss mudstone				$5.8x10^{-8}$
Borehole B-127-2	47 - 48	Vanoss mudstone				$1.9x10^{-8}$
Borehole B-127-2	63 - 64	Vanoss mudstone				$1.6x10^{-7}$
Borehole B-127-2	70 - 71	Vanoss mudstone				$1.8x10^{-6}$
Borehole B-127-2	77 - 78	Vanoss mudstone				$3.4x10^{-8}$
Well LVMW-2	40.5 - 70	Vanoss mudstone		$2.4x10^{-9}$		
Well LVMW-30.2	88 - 103	Vanoss mudstone		$7.0x10^{-8}$		
Well LVMW-30.2	88 - 103	Vanoss mudstone		$1.0x10^{-9}$		
Well LVMW-32.1	58 - 73	Vanoss mudstone		$2.4x10^{-9}$		
Well LVMW-38	50 - 72	Vanoss mudstone		$2.1x10^{-9}$		
Well LVMW-39	37 - 62	Vanoss mudstone		$1.0x10^{-9}$		

Review of the information presented in Table 2 and the Stiff diagrams and Radar diagrams presented in the appendices shows that there is a definite and consistent difference in the chemistry of the groundwater between the Stream Terrace, Upper Vanoss, Lower Vanoss, and Vamoosa-Ada groundwater regimes.

- Groundwater in all but one of the Upper Vanoss Regime wells exceeds Secondary Drinking Water Standards for total dissolved solids.

- Groundwater in the shallow Stream Terrace and Upper Vanoss regimes, the latter consisting mainly of thinly interbedded mudstones, sandstones, and limestones, typically has high alkalinity and low sulfate.

- Groundwater in the Lower Vanoss regime, consisting mainly of thick mudstones and interbedded sandstones and thin limestones, typically has low alkalinity and high sulfates. Groundwater in all of the Lower Vanoss regime wells exceeds the Secondary Drinking Water Standards for sulfates.

- Groundwater in the Vamoosa-Ada regime, consisting mainly of thick sandstones with thinly bedded mudstones, typically has low alkalinity and low sulfate.

Review of the Stiff diagrams presented in Appendix D supports this distinction in groundwater chemistry between the Upper Vanoss and Lower Vanoss Regimes. This distinction in groundwater chemistry is due primarily to differences in mineral composition, depositional history, and post-depositional flushing by fresh groundwater recharge. The chemistry of groundwater in the Upper Vanoss regime reflects the impact of limestone (calcium carbonate) and dolomite (calcium-magnesium carbonate). Groundwater in the Lower Vanoss regime reflects the impact of salt (sodium chloride) and anhydrite (calcium sulfate).

Sulfate concentrations in mudstones completed by shallow Upper Vanoss wells, such as that in UVMW-50.1, are comparable to those of other Upper Vanoss wells rather than the mudstones of the Lower Vanoss regime.

The salt most likely originated as connate water trapped in the mudstone since original deposition. The anhydrite could have originated as post-depositional fracture filling, or, given original deposition under arid conditions, in the connate water. Regardless as the origin, the presence of the salt and anhydrite suggest the lack of significant flushing of the low permeability mudstones by fresh water derived from geologically recent groundwater recharge. Conversely, the lack of salt and anhydrite impact in the Upper Vanoss regime suggests sufficient freshwater flushing to eliminate much of the connate water.

The chemistry of groundwater in Vamoosa-Ada regime, as shown by the Stiff diagram for well VAMW-29 in Appendix D, also shows some impact from salt and anhydrite, but at concentrations much lower than those of the mudstones in the overlying Lower Vanoss regime. This difference in groundwater chemistry suggests significant flushing of the higher permeability sandstones in the Vamoosa-Ada Aquifer.

TABLE 2
COMPARISON OF SELECTED GROUNDWATER QUALITY PARAMETERS TO SECONDARY DRINKING WATER STANDARDS

Groundwater Quality Parameter (mg/l, October 2000 Data)		PH	Total Dissolved Solids	Chloride	Sulfate	Iron
Secondary Drinking Water Standard (mg/l)		6.8 - 8.5	500	250	250	0.3
Well Number	Completed Unit					
QTMW-46	Terrace	6.79	668	44.9	1.0	23.600
QTMW-49	Terrace	6.43	882	112	0.0	5.610
UVMW-50.1	Upper Vanoss	7.55	488	46	61	1.1
UVMW-43	Upper Vanoss	7.3	1680	237	6.43	1.060
UVMW-52.2	Upper Vanoss	7.31	1440	360	218	0.132
UVMW-41	Upper Vanoss	6.95	1060	40.2	136	0.075
UVMW-11	Upper Vanoss	7.55	452	75.3	27.8	0.029
UVMW-18	Upper Vanoss	6.96	678	5.85	133	0.312
UVMW-23	Upper Vanoss	7.51	788	92.7	53.4	0.052
LVMW-30.1	Lower Vanoss	7.23	2400	75.1	1290	1.170
LVMW-40	Lower Vanoss	7.99	4330	21.1	2490	0.352
LVMW-31	Lower Vanoss	7.64	3890	61.7	2180	0.022
LVMW-38	Lower Vanoss	7.26	4520	46.0	2220	22.0
LVMW-31.1	Lower Vanoss	8.80	4520	26.4	2790	0.020
LVMW-18	Lower Vanoss	7.82	3770	12.1	2120	0.085
LVMW-20.1	Lower Vanoss	7.40	2840	40.9	1730	0.042
VAMW-29	Vamoosa-Ada	7.97	1620	114	743	0.039
	Shading indicates a value exceeding Secondary Drinking Water Standard					

4.2.6 Groundwater Circulation

4.2.6.1 Potentiometric Surface - Plate 5 shows the shallow potentiometric surface as of January 2001. This map shows that the shallow groundwater is following the topography, moving from the higher elevations around the Site towards the lower elevations along Skull Creek. The channel of Skull Creek represents the point of discharge for this shallow groundwater.

The potentiometric surface map shown on Plate 5 confirms the fact that the Site is located in a groundwater discharge area. Groundwater is moving onto the Site from off-site sources on its way to discharge to Skull Creek. Skull Creek is thus the local base level, and is the receiving stream for discharging groundwater as well as surface runoff.

4.2.6.2 Hydrogeologic Cross Sections Through the Site - Plate 6 is an index map for the hydrogeologic cross sections constructed through the Site. Hydrogeologic cross sections B-B' through G-G' are shown on Plates 7 through 13, respectively.

Cross sections C-C', D-D', and E-E' shown on Plates 8, 9, and 10 are drawn in west-to-east directions through the Vanoss Group approximately parallel to the direction of dip. North to south cross sections B-B' and F-F' shown on Plates 7 and 11 were constructed along the strike of the Vanoss Group formation, perpendicular to the dip. Review of these cross sections confirm the typical Vanoss Group sequence of mudstones and generally discontinuous, lenticular sandstones. They also show that the mudstones and sandstones of the Vanoss Group control the topography of the Site and immediate vicinity. Cross section G-G' shown on Plate 12 helps visualize the relationship between the Vanoss Group and the underlying Vamoosa-Ada Aquifer.

- Cross Section B-B' runs north to south along the east property line. This cross section clearly shows how the sandstones of the Upper Vanoss Regime form the cap of the highlands to the north and south of the Site, protecting the upland surfaces from erosion. Based upon comparison of water-level elevations to ground surface elevations, it also shows that groundwater in the Upper Vanoss Regime is discharging as seeps to the surface or to local tributaries, and that groundwater in the Lower Vanoss Regime is discharging to Skull Creek.

- Cross Section C-C' runs west to east along the south property line, then turns northwest to tie in monitor wells located at the south end of the North Disposal Cell. It shows both the thinning of the resistant sandstones of the Upper Vanoss Regime towards the west and the increased sand content in the lower portion of the Lower Vanoss Regime. Based upon comparison of water-level elevations to ground surface elevations, this cross section also shows that groundwater in the Lower Vanoss Regime is discharging to Skull Creek.

- Cross Section D-D' runs west to east through the northern portion of the Site. Based upon comparison of water-level elevations to ground surface elevations, this cross section again shows that groundwater in the Upper Vanoss Regime is discharging as seeps to the surface or to local tributaries, and that groundwater in the Lower Vanoss Regime is discharging to Skull Creek.

- Cross Section E-E' runs west to east through the central part of the Site. Based upon comparison of water-level elevations to ground surface elevations, this cross section again shows that groundwater in the Upper Vanoss Regime is discharging as seeps to the surface or to local tributaries, and that groundwater in the Lower Vanoss Regime is discharging to Skull Creek.

- Cross Section F-F' runs north to south along the western side of the Site. This cross section again shows the sandstones of the Upper Vanoss Regime. Based upon comparison of water-level elevations to ground surface elevations, it also shows that groundwater in the Upper Vanoss Regime is discharging as seeps to the surface or to local tributaries, and that groundwater in the Lower Vanoss Regime is discharging to Skull Creek.

- Cross Section G-G' runs northwest to southeast through the central part of the Site and shows the relationship of the Vanoss Group and the underlying Vamoosa-Ada

Aquifer. This cross section shows that the top of the Vamoosa-Ada Aquifer was found in borehole CC-6 (Monitor Well VAMW-29), located at the northwest corner of the Site, at a depth of about 175 feet below ground surface, at an elevation of about 719 feet MSL. On the east side of the Site, the top of the Vamoosa-Ada Aquifer was found in borehole CMW-32 (Monitor Well LVMW-32.1) at a depth of about 124 feet below ground surface, at an elevation of about 726 feet MSL.

4.2.6.3 Vanoss Group - Vamoosa-Ada Aquifer Cross Section - This cross section (H-H') follows the section line shown on Plate 3. It runs northwest to southeast through the central part of the Site and shows the relationship of the Vanoss Group and the underlying Vamoosa-Ada Aquifer.

A comparison of water-level elevations to ground surface elevations again shows that groundwater in the Lower Vanoss Regime is discharging to Skull Creek. It also shows that groundwater in the Vamoosa-Ada Aquifer is discharging to the Cimarron River unless intercepted by pumping.

Work done by the U. S. Geological Survey (Wood and Burton, 1968) and the Oklahoma Geological Survey (D'lugosz, et. al., 1986) in Oklahoma and Logan Counties indicates that the Cimarron River is a major point of discharge for groundwater in the Garber-Wellington Aquifer. The Garber-Wellington Aquifer overlies the Vanoss Group and is a major source of potable groundwater in those counties. The USGS and OGS also report that the interface between shallow fresh water originating from geologically recent surface recharge and brackish or salty groundwater originating as connate water trapped since deposition in the deeper formations also rises to discharge to the Cimarron River in Logan County. Discharge of the brackish or salty groundwater to the Cimarron River makes the water unsuitable for many uses.

The saltwater interface reported by Shelton (1985) for Payne County suggests a similar scenario in the vicinity of the Site. Water-level elevation data for the Vamoosa-Ada Aquifer indicate groundwater historically discharged to the Cimarron River. Cross section H-H' also shows that the saltwater interface is rising sharply from a depth of 800 feet below ground surface beneath the City of Cushing and vicinity to 100 feet or less a half mile east of the Cimarron River (Shelton, 1985). As with the Logan County scenario, this shows that the natural discharge of fresh water from the Vamoosa-Ada Aquifer to the river over geologic time has released hydraulic pressure on the formation. This has allowed brackish or salty connate water to rise from the deeper portions of the Vamoosa-Ada Aquifer and/or deeper formations to discharge to the surface at the Cimarron River. The result of this rise in the saltwater interface means that the availability of fresh, potable groundwater becomes limited near the Cimarron River.

4.3 CONCLUSIONS REGARDING THE CONCEPTUAL HYDROGEOLOGIC MODEL

From the discussions presented in this section of the report, the following conclusions can be made regarding the conceptual hydrogeologic model:

- The Site is drained by Skull Creek, a tributary to the Cimarron River, a major tributary to the Arkansas River. The Arkansas River is in turn a tributary to the Mississippi River.

- Water-bearing sandstones are present in the Vanoss Group and the underlying Vamoosa-Ada Aquifer. The predominant mudstones and the limited thickness and areal extent of the lenticular sandstones limit the availability of potable groundwater from the Vanoss Group. The deeper sandstones of the Vamoosa-Ada Aquifer are more prolific sources of groundwater. The City of Cushing has several municipal water-supply wells completed in the Vamoosa-Ada Aquifer.

- Soils and bedrock beneath the Site have been divided into five groundwater flow regimes, the Unconsolidated Soil Regime, Stream Terrace Deposit Regime, Upper and Lower Vanoss Regimes, and the Vamoosa-Ada Aquifer Regime.

- Permeabilities of the mudstones underlying the Site range from 10^{-6} to 10^{-9} cm/sec, with the majority of the values falling within the 10^{-7} to 10^{-8} cm/sec range. These values are consistent with the observed very slow groundwater movement through the mudstones and published permeabilities typical for clay. A permeability of 3.2×10^{-4} cm/sec has been determined for the Vamoosa-Ada Aquifer beneath the Site, which is consistent with published permeability values for the aquifer.

- With the exception of the unconsolidated soil and the uppermost weathered bedrock of the shallow Vanoss, in which the groundwater is typically unconfined, groundwater beneath the Site is under confined conditions, with water levels rising above the zones of completion.

- Groundwater quality data indicate that there is a distinct difference between naturally occurring groundwater in the Upper Vanoss regime and that in the Lower Vanoss regimes. Groundwater in the Upper Vanoss Regime is typically high in alkalinity and low in sulfates. Groundwater in the Lower Vanoss Regime is typically low in alkalinity and high in sulfates.

- Most of the naturally occurring groundwater in the Upper and Lower Vanoss Regimes exceeds Secondary Drinking Water Standards for total dissolved solids. Groundwater in the Lower Vanoss Regime also exceeds Secondary Drinking Water Standards for sulfates.

- Most of the Cushing Remediation Site is located within a groundwater discharge area. Skull Creek is the discharge point for most groundwater originating within its large drainage basin. With the exception of the unconsolidated soil, groundwater in the

uppermost 100 feet or more of bedrock is moving onto the Site on its way to discharge to Skull Creek. Deeper groundwater is discharging to the Cimarron River.

- Water-level data for shallow wells completed on the west side of the Site show that the groundwater in the Upper Vanoss Regime is discharging to the West Tributary. These data also show that groundwater in the Upper Vanoss Regime on the east side of the Site around Pit 4 is discharging to the East Tributary and its tributary streams. Groundwater in the Upper Vanoss Regime on the far south end of the Site is discharging to Skull Creek through its tributary streams.

- Significant shallow groundwater circulation is limited to the shallow sandstones of the Upper Vanoss Regime. Most groundwater in these sandstones is recharged by precipitation and overland flow across off-site outcrops. Groundwater is discharged through evapotranspiration at seeps and as base flow to tributary streams that ultimately flow into Skull Creek.

- Significant deep groundwater circulation is limited to the deeper sandstones of the Lower Vanoss Regime. Groundwater in these sandstones is recharged at off-site outcrops. Groundwater is discharged as base flow to Skull Creek either directly or through its tributary streams.

- Recharge to the Vamoosa-Ada Aquifer is through infiltration of precipitation and runoff on outcroppings, which start about 3.5 miles east of the Site and continue eastward from there. Discharge is to the Cimarron River.

- The three main hydrogeologic units present at the Site, the Upper Vanoss, the Lower Vanoss, and the Vamoosa-Ada Aquifer regimes, are, for the most part, hydrologically separated. Potentiometric surface and water quality data indicate that these units are hydrologically isolated from one another. The rate of any significant movement of groundwater from the surface downward would be measured in terms of geologic time, not in human terms.

******

5.0 REFERENCES CITED

Copper, H. H., Jr., J. D. Bredeheoft, and I. S. Papadopulos, 1967, Response of a finite-diameter to an instantaneous charge of water: Water Resources Research, V. 3, no. 1, p. 263-269.

D'lugosz, J. J., R. G. McClaflin, M. V. Marcher, 1986, Geohydrology of the Vamoosa-Ada Aquifer/East Central Oklahoma: Oklahoma Geological Survey Circular 87

Dott, R.H., Jr., and R. L. Batten, 1976, Evolution of the Earth: McGraw-Hill Book Company, Second Edition, 504p.

Henley, J., R. D. Gelnar, and R. E. Mayhugh, 1987, Soil survey of Payne County, Oklahoma: U. S. Department of Agriculture, Soil Conservation Service, 268p.

Johnson, K. S., 1971, Guidebook of geologic field trips in Oklahoma Book I: Introduction, Guidelines, and Geologic History of Oklahoma: Oklahoma Geological Survey, educational Publication 2, 15p.

Burns & McDonnell, 1993, Phase I Remedial Investigation Report: Document.

Kerr-McGee Corporation, 1994, Preliminary Assessment of Clay Availability, Kerr-McGee Cushing Refinery Site: Document.

Levin, H.L., 1978, The earth through time: W.B. Saunders Company, 530p.

Lohman, S.W., 1972, Ground-water hydraulics: U. S. geological Survey Professional Paper 708, 70p.

Shelton, J. W., J. S. Ross, A. J. Garden, and J. L. Franks, 1985, Geology and mineral resources of Payne County, Oklahoma: Oklahoma Geological Survey Bulletin 137, 85p.

Skibitzke, H. E., 1958, An equation for potential distribution about a well being bailed: U. S. Geological Survey Ground Water Note 35.

Wood, P. R., and L. C. Burton, 1968, Ground-water resources in Cleveland and Oklahoma Counties, Oklahoma: Oklahoma Geological Survey Circular 71, 59p.

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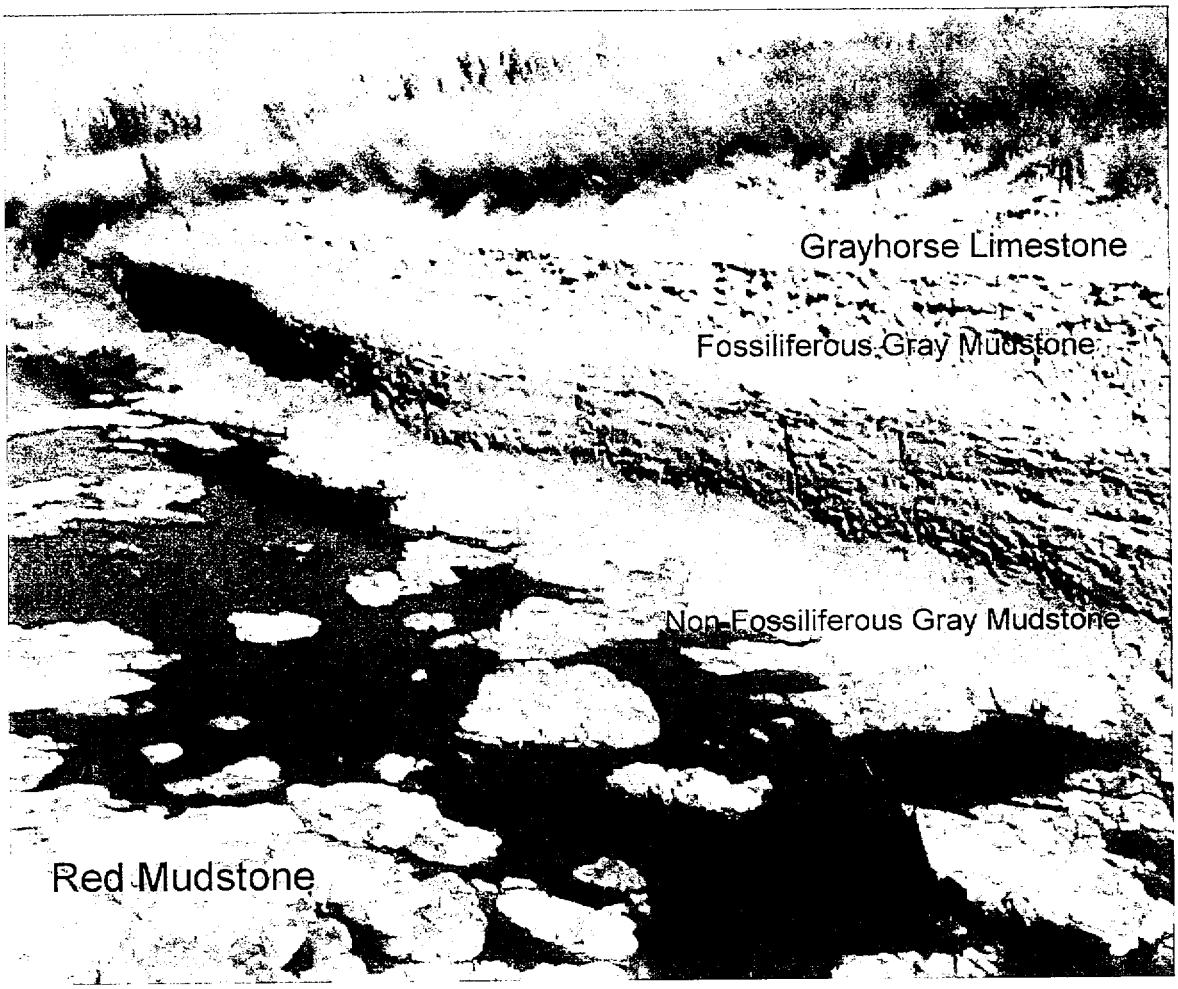
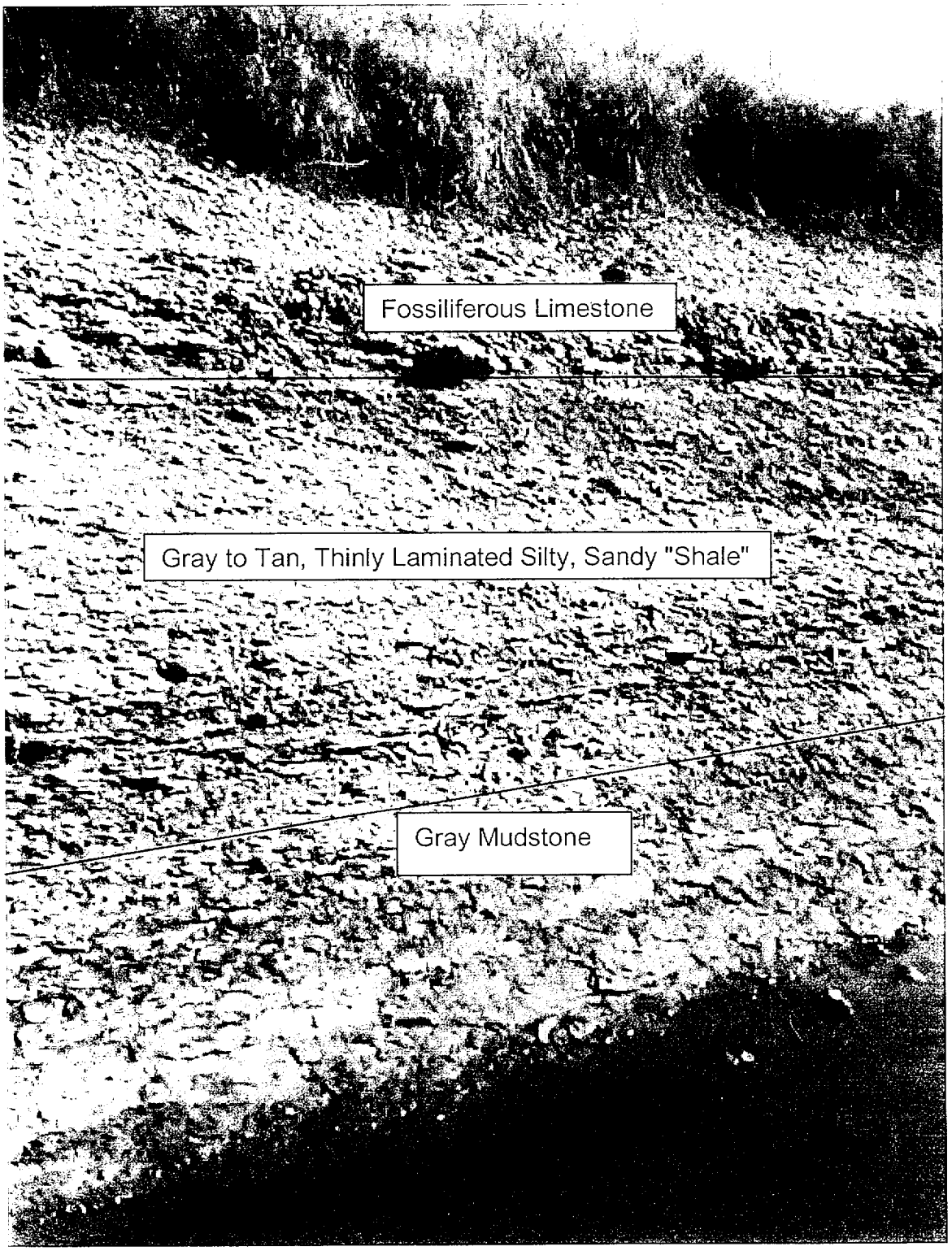
PHOTOGRAPHS

PHOTOGRAPH 1: Stream terrace material overlying red mudstone of the Lower Vanoss regime. Note the large gravel and cobbles in the terrace material.

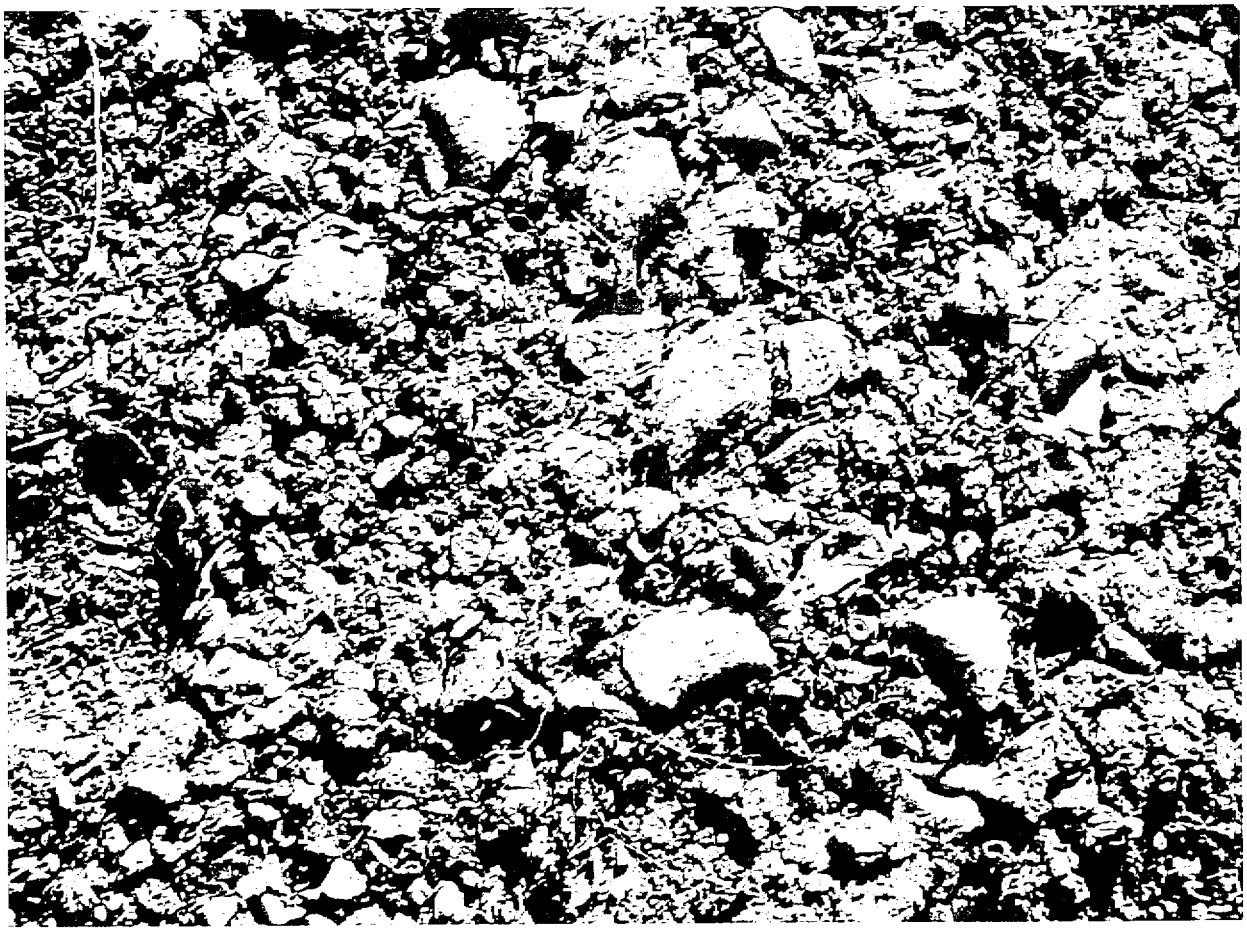
PHOTOGRAPH 2: The Cushing "Type Sequence" exposed in the rerouted channel of Skull Creek. The sequence consists of the Grayhorse Limestone, which is very friable at this location, underlain in sequence by a fossiliferous gray mudstone, a non-fossiliferous gray mudstone, and a hard, red mudstone. The Grayhorse Limestone represents the base of the Upper Vanoss Regime. The mudstone sequence underlying the limestone represents the uppermost lithologic units of the Gano Shale, which is equivalent to the top of the Lower Vanoss Regime.



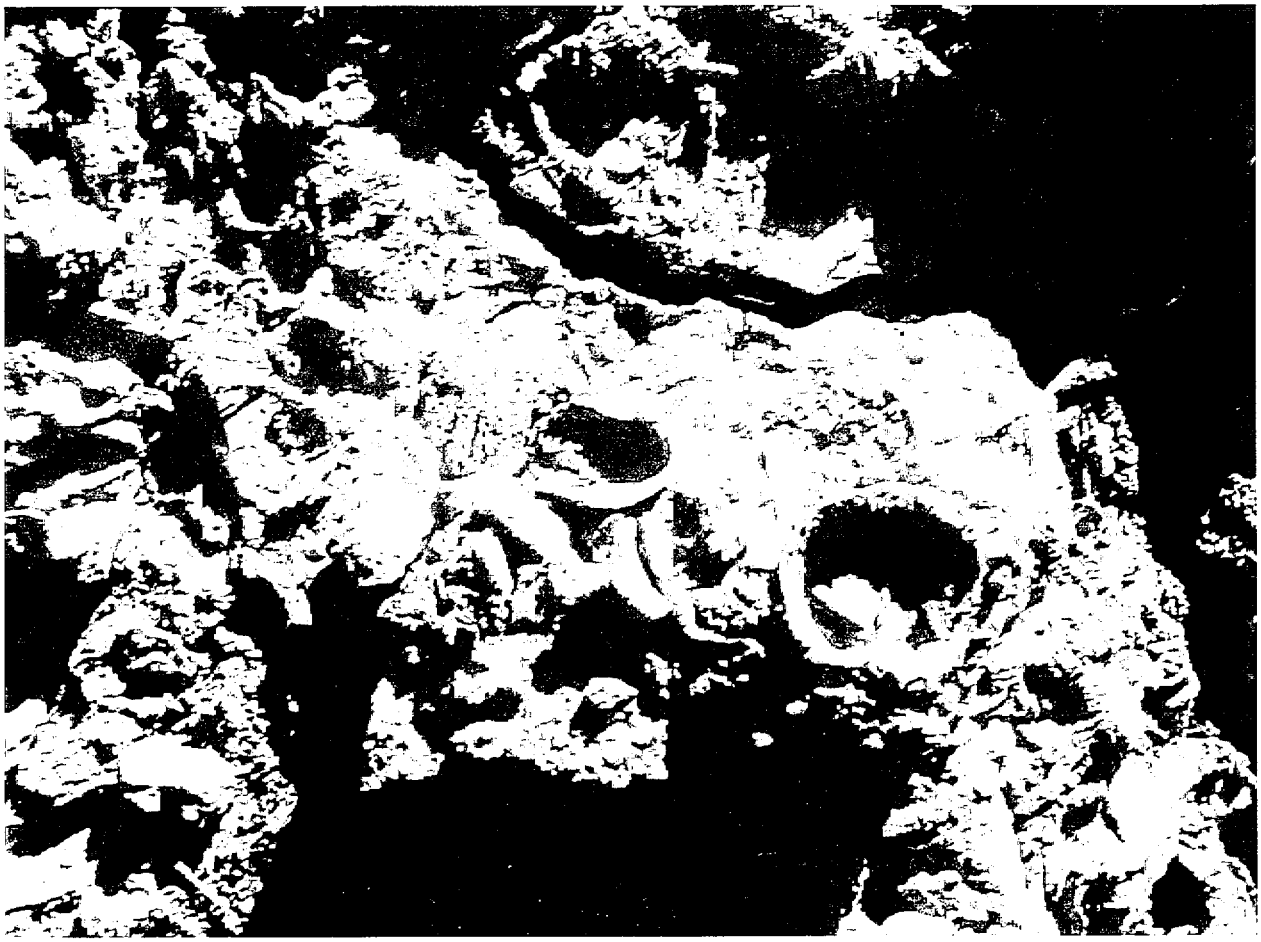
PHOTOGRAPH 3: Another view of the Cushing "Type Sequence" exposed in the rerouted bed of Skull Creek. The photo shows the Grayhorse Limestone and the underlying sequence of gray to tan thinly laminated silty and sandy "shale" and the gray mudstone.



PHOTOGRAPH 4: Close-up view of the Grayhorse Limestone where exposed in Skull Creek showing the fossils weathering out of the friable material. The larger shells are oysters. Small circular objects are crinoid (sea lily) stem plates.



PHOTOGRAPH 5: Close-up view of a more cemented portion of the Grayhorse Limestone. Fossils where exposed in the East Tributary. Fossils shown here include oysters and smaller pelcypods, crinoids, and bryozoans.



PLATES

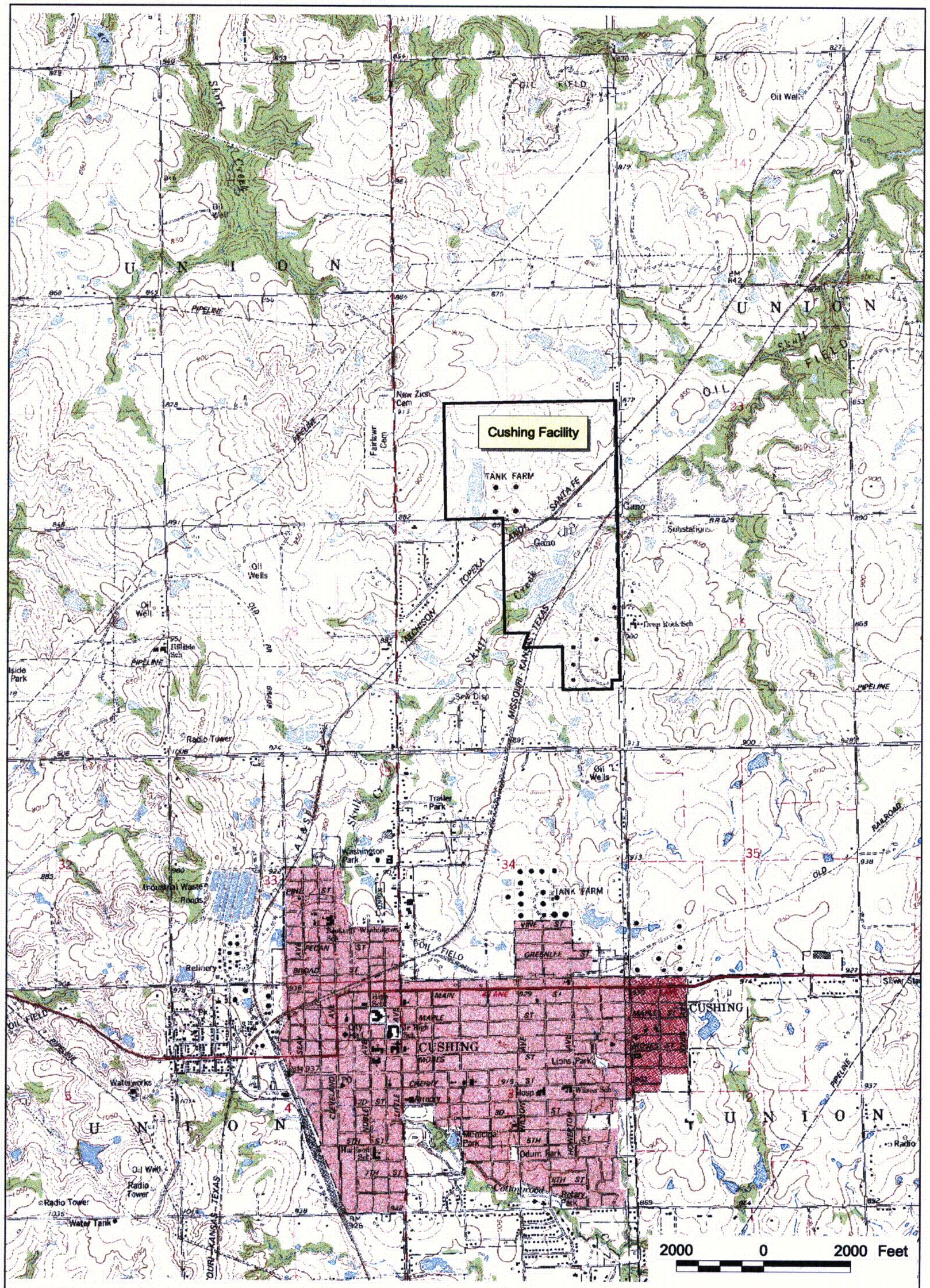

Cushing Facility
TANK FARM
SANTA FE
MISSOURI KANSAS TEXAS
TOPEKA
CUSHING
UNION
OIL FIELD
PIPELINE
Oil Wells
Oil Well
Radio Tower
Water Tank
Waterworks
Refinery
Industrial Waste Ponds
Trailer Park
Washington Park
Lions Park
Odum Park
Rotary Park
Municipal Park
Hosp
Substation
Drop Rock Sch
New Zion Cem
Fairlawn Cem
Sewer Disp
Silver Sta
2000 0 2000 Feet
Payne County
Stillwater
Tulsa
Cushing Facility
Oklahoma City
N
Burns & McDonnell
SINCE 1898
Plate 1
Site Location Map
Kerr-McGee Cushing Facility
Conceptual Hydrogeologic Model
Requested By: jb
Date: 07/10/01
Drawn By: cgb
Project: pb_house.apr
C01

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PLATE 2
Site Map
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PLATE 2

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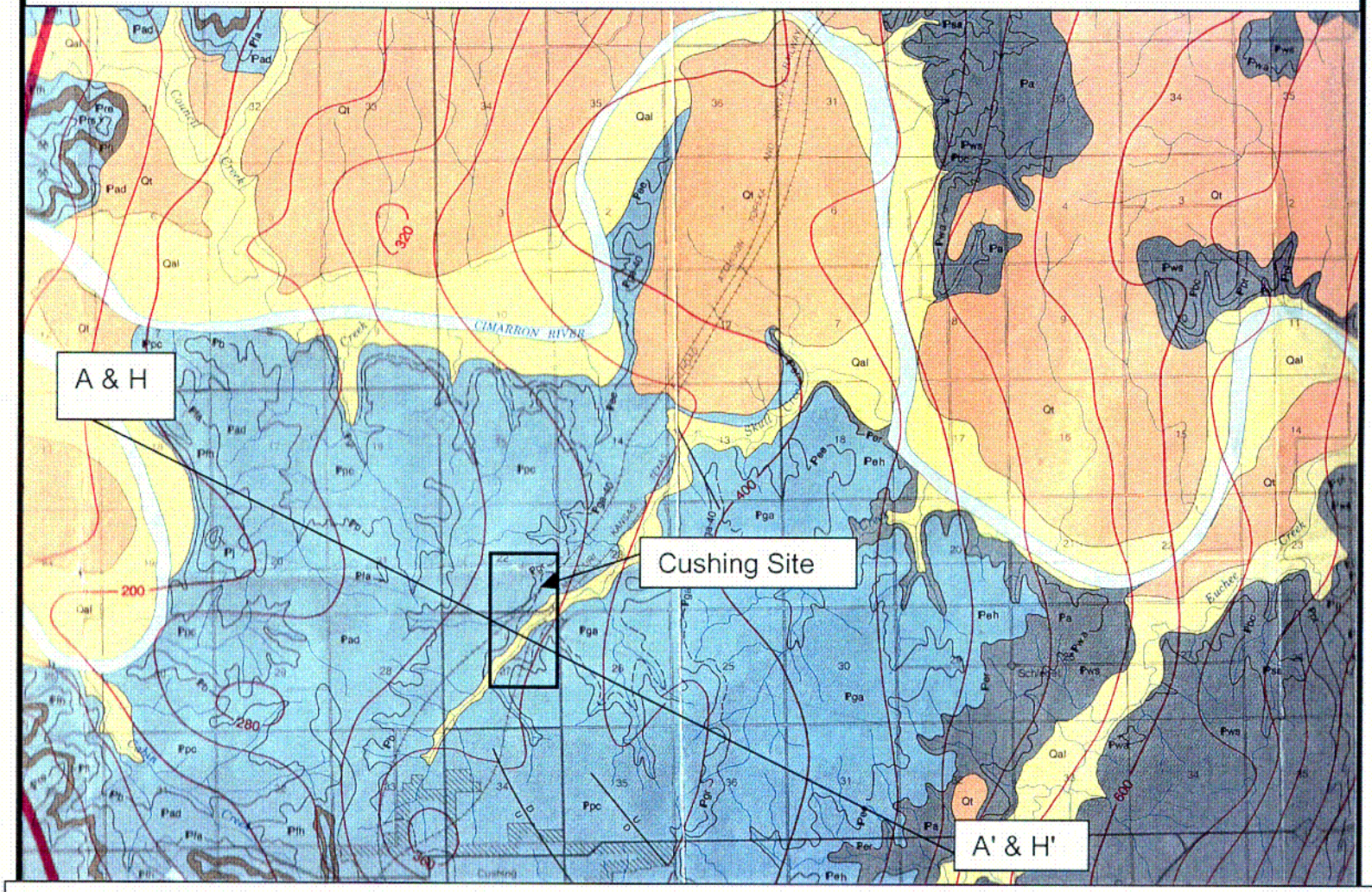
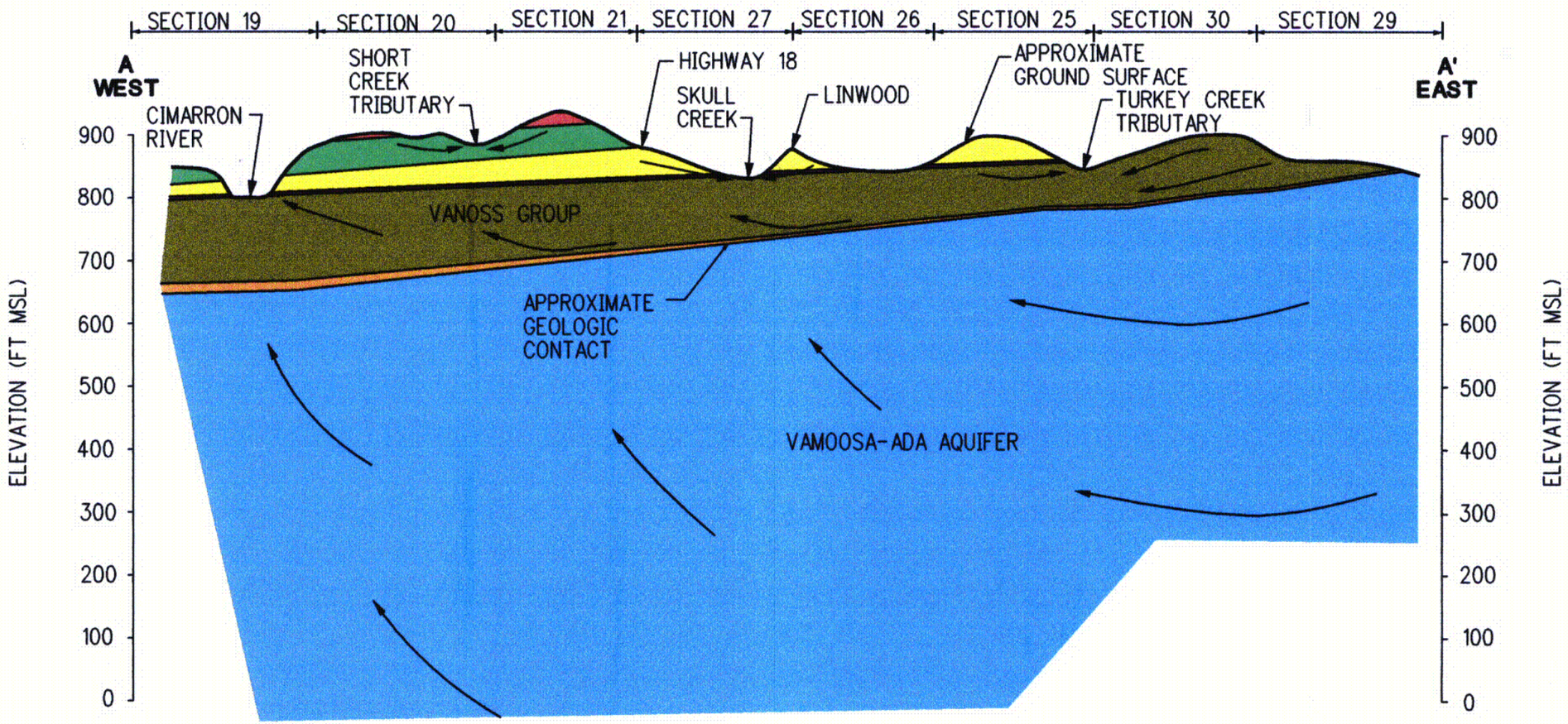
PLATE 3: GEOLOGIC MAP OF THE CUSHING AREA
SHOWING PROFILE LINE FOR CROSS-SECTIONS A-A' AND H-H'



Pfa = Americus Limestone (Vanoss Group)
Pad = Admire Shale (Vanoss Group)
Ppc = Pony Creek Shale (Vanoss Group)
Pgr = GrayHorse Limestone (Vanoss Group)
Pga = Gano Shale (Vanoss Group)
Per = Reading Limestone (Vanoss Group)
Pa = Auburn Shale (Vamoosa-Ada Aquifer)

C02

HYDROGEOLOGY OF THE VANOSS GROUP AND THE VAMOOSA-ADA AQUIFER CUSHING, OKLAHOMA



NOTES:

1. VERTICAL EXAGGERATION - 18 X.
2. BASED UPON SHELTON, et.al, 1985.

LEGEND

- GROUNDWATER FLOW DIRECTION
- LONG CREEK LIMESTONE
- ADMIRAL SHALE
- PONY CREEK SHALE
- GRAYHORSE LIMESTONE
- GANO SHALE
- READING LIMESTONE

(LONG CREEK LIMESTONE through READING LIMESTONE: VANOSS GROUP)

- ADA GROUP (VAMOOSA-ADA AQUIFER)

VERTICAL: 200' 0' 200' 400' SCALE IN FEET

HORIZONTAL: 3566' 0' 3566' 7132' SCALE IN FEET

C03

Burns & McDonnell SINCE 1898

PLATE 4

AREA HYDROGEOLOGIC CROSS SECTION A-A'
KERR-MCGEE CORP
CUSHING FACILITY

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PLATE 5
Potentiometric Surface Map

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PLATE 6
Cross Section Index Map

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PLATE 6

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PLATE 7

Site Hydrogeologic Cross Section B-B'

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PLATE 7

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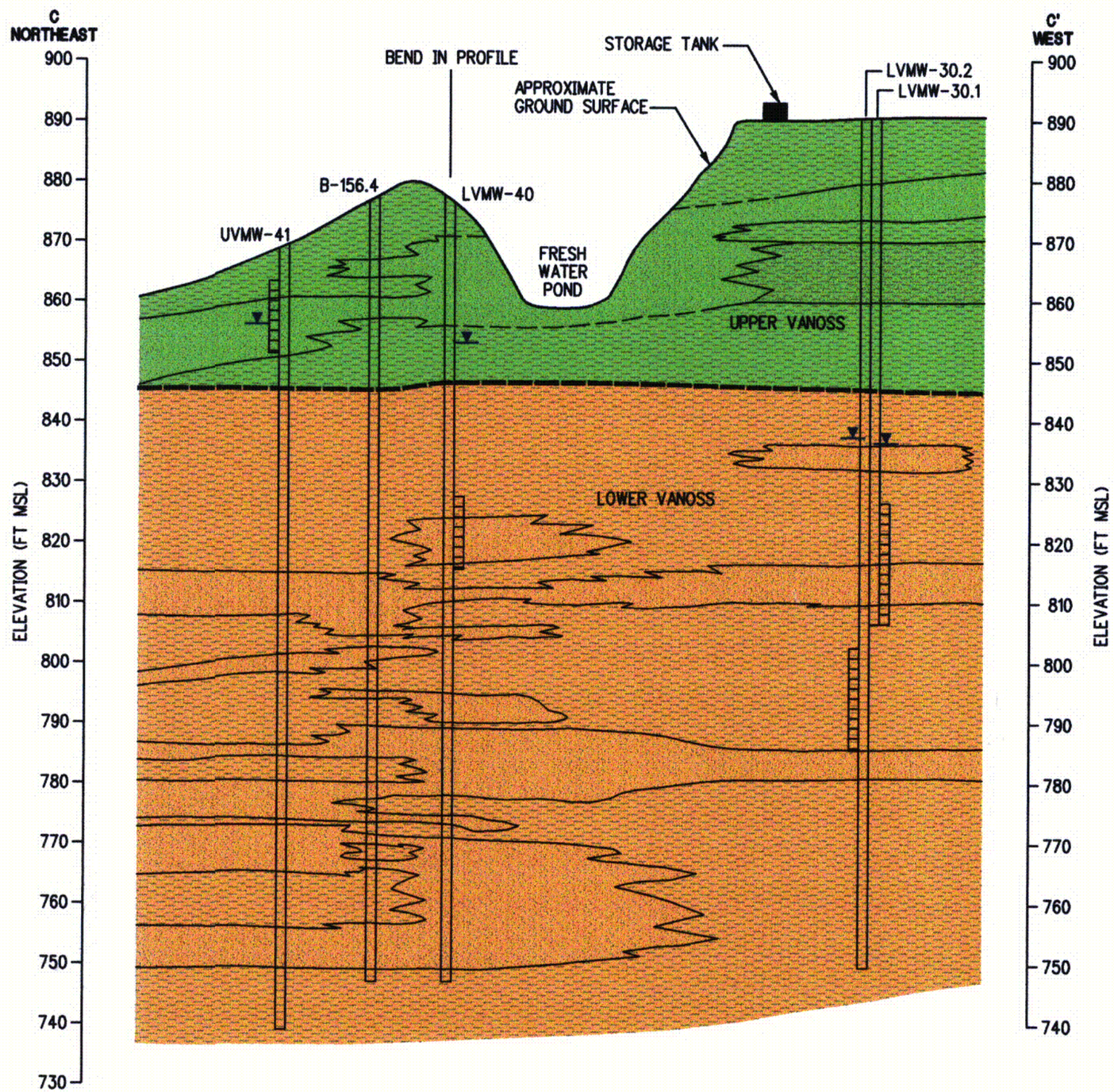

LEGEND

- UPPER VANOSS
- LOWER VANOSS
- MUDSTONE VARIABLE GRAY TO RED
- SANDSTONE TYPICALLY FINE-GRAINED
- SILTY/SANDY SHALE
- WATER LEVEL

NOTE

1. VERTICAL EXAGGERATION - 10 X

VERTICAL SCALE: 20' 0' 20' 40' — SCALE IN FEET

HORIZONTAL SCALE: 200' 0' 200' 400' — SCALE IN FEET

C04

Burns & McDonnell SINCE 1898

Plate 8

SITE HYDROGEOLOGIC CROSS SECTION C-C'
KERR-MCGEE CORP
CUSHING FACILITY

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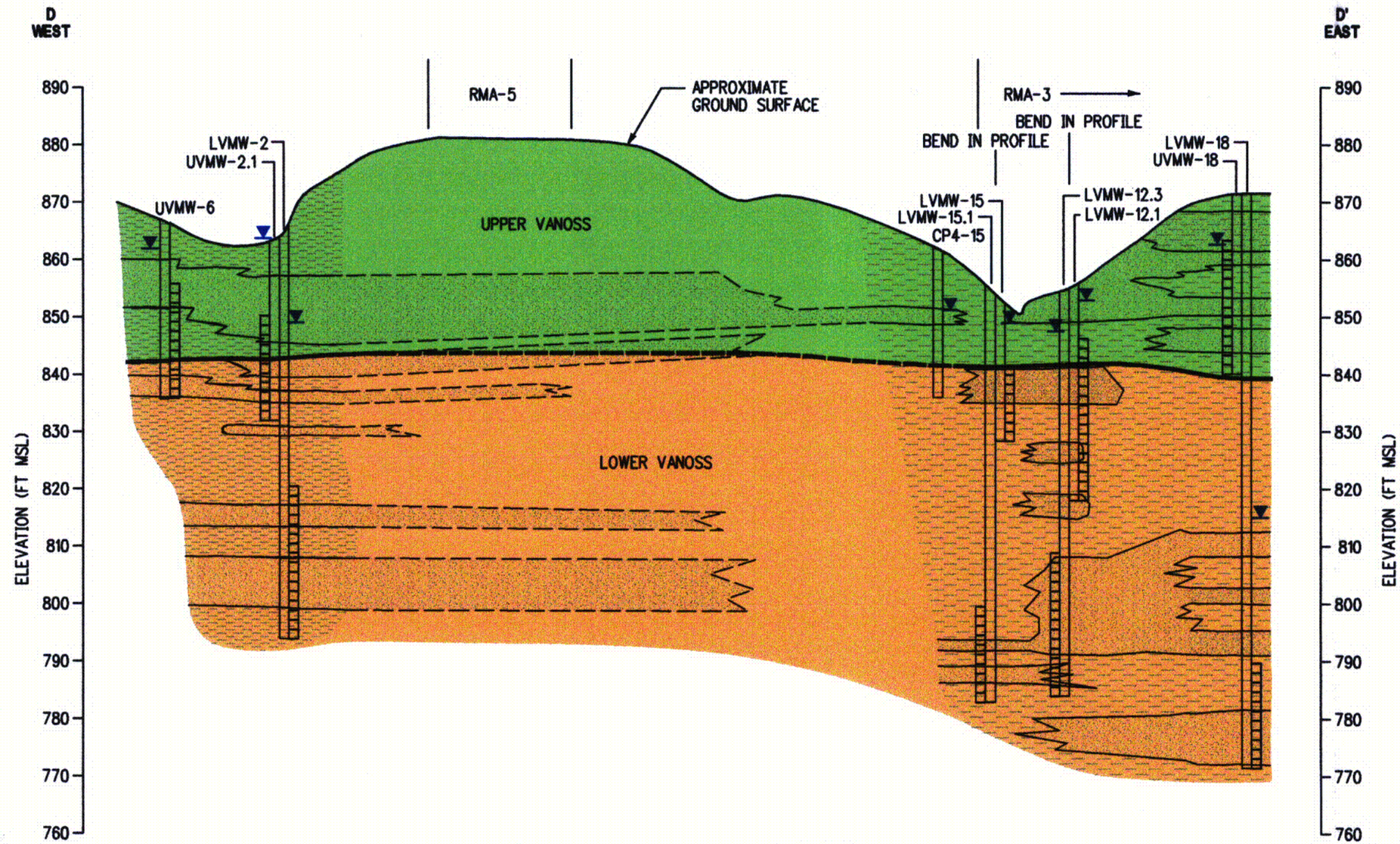

LEGEND

- UPPER VANOSS
- LOWER VANOSS
- MUDSTONE VARIABLE GRAY TO RED
- SANDSTONE TYPICALLY FINE-GRAINED
- SILTY/SANDY SHALE
- WATER LEVEL

NOTE

1. VERTICAL EXAGGERATION - 10 X

VERTICAL SCALE 20' 0' 20' 40'
SCALE IN FEET

HORIZONTAL SCALE 200' 0' 200' 400'
SCALE IN FEET

C05

Burns & McDonnell
SINCE 1898

Plate 9

SITE HYDROGEOLOGIC
CROSS SECTION D-D'
KERR-MCGEE CORP
CUSHING FACILITY

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PLATE 10

Site Hydrologic Cross Section E-E'

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PLATE 10

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PLATE 11

Site Hydrologic Cross Section F-F'

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PLATE 11

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PLATE 12
Site Hydrologic Cross Section G-G'
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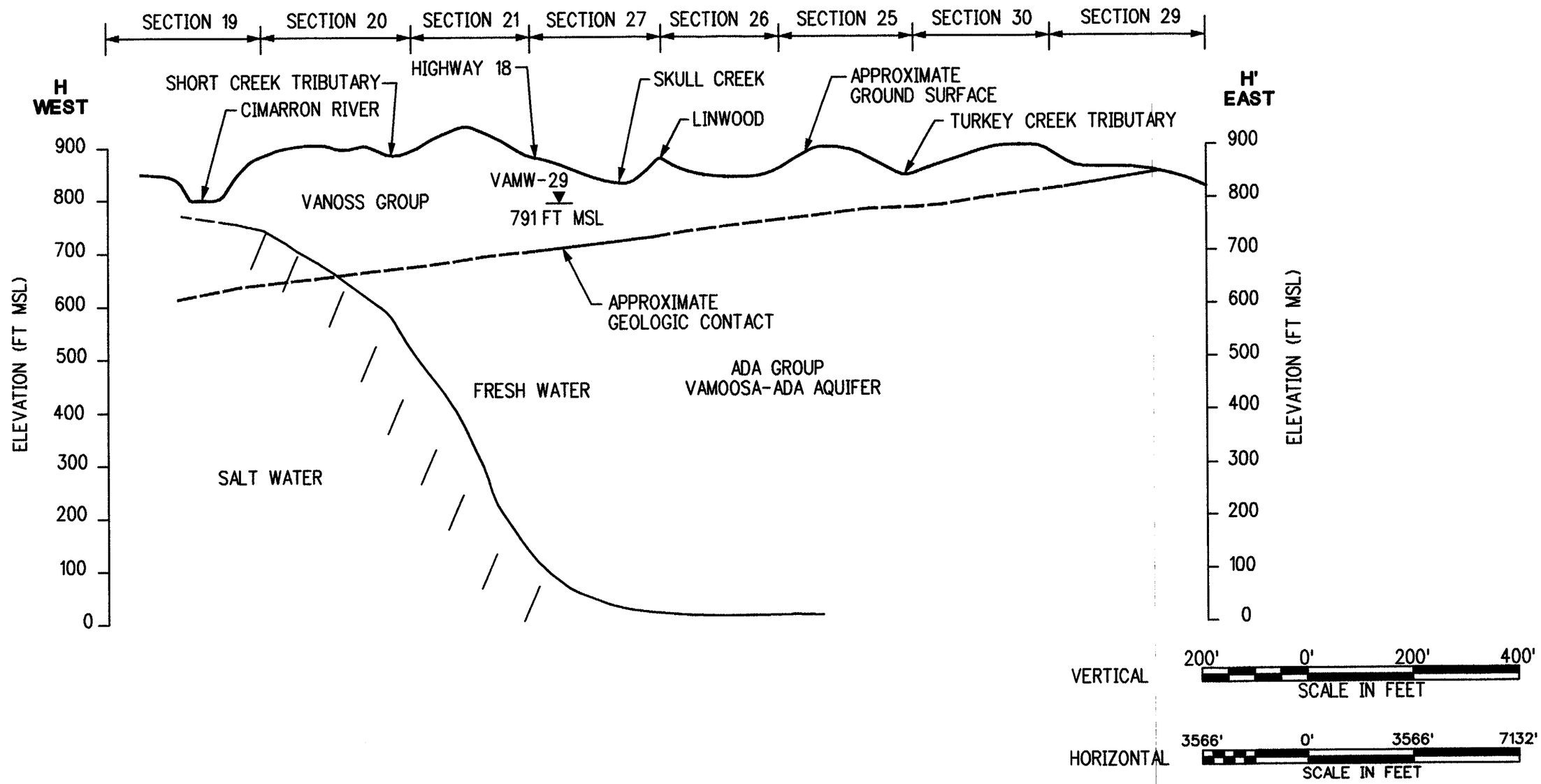
GROUNDWATER RECHARGE-DISCHARGE RELATIONSHIPS IN THE VAMOOSA-ADA AQUIFER
KM CUSHING FACILITY AND VICINITY



NOTES:

1. VERTICAL SCALE EXAGGERATION 18X.
2. BASED UPON SHELTON, ET. AL, 1985.

Burns & McDonnell
SINCE 1898

Plate 13

AREA HYDROGEOLOGIC
CROSS SECTION H-H'
KERR-MCGEE CORP
CUSHING FACILITY

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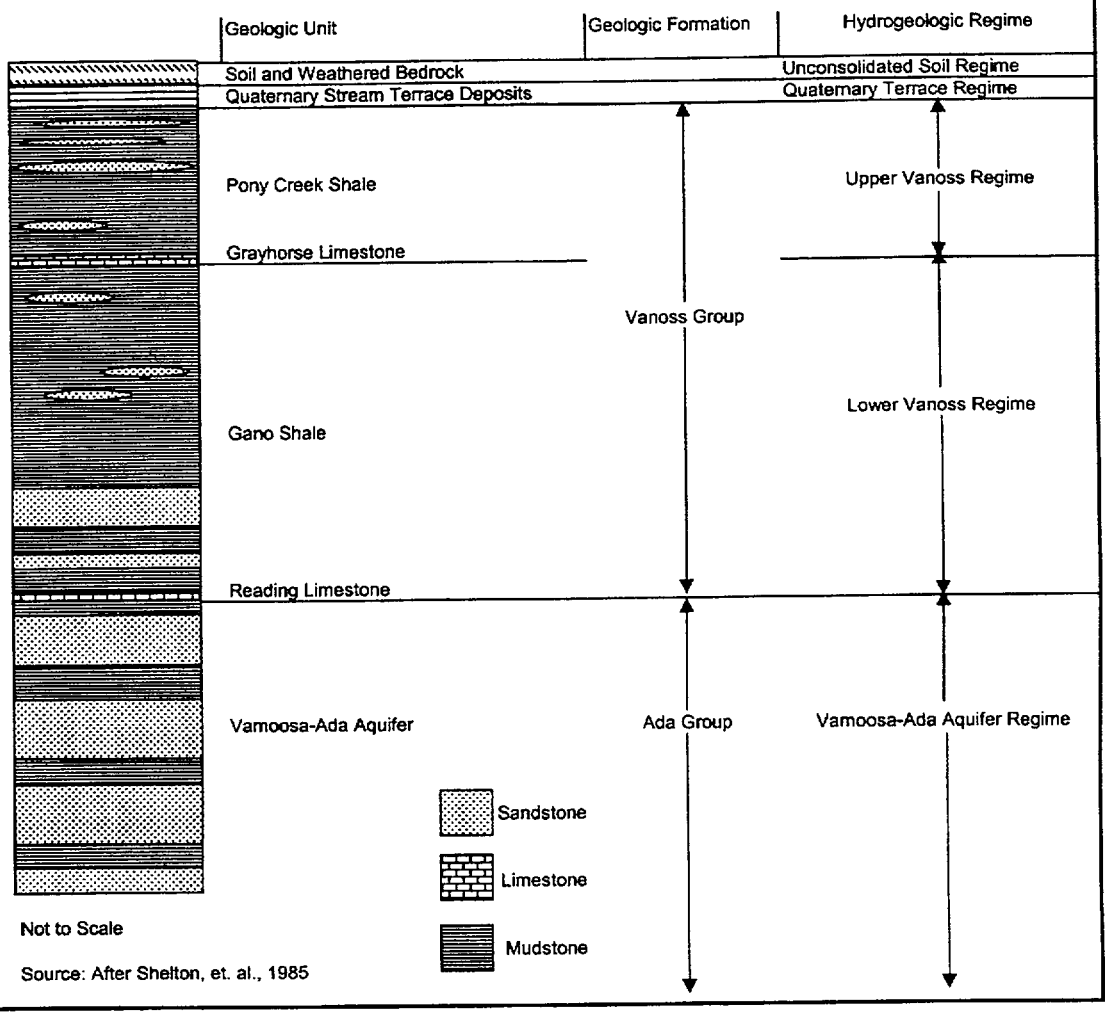
FIGURES

FIGURE 1
HYDROGEOLOGIC COLUMN OF THE CUSHING SITE AND VICINITY
Kerr-McGee Cushing Site



Not to Scale

Source: After Shelton, et. al., 1985

FIGURE 2
Historical Groundwater Elevations and Completion Interval
Unconsolidated Soil Monitor Well USMW-6
Kerr-McGee Cushing, OK Facility

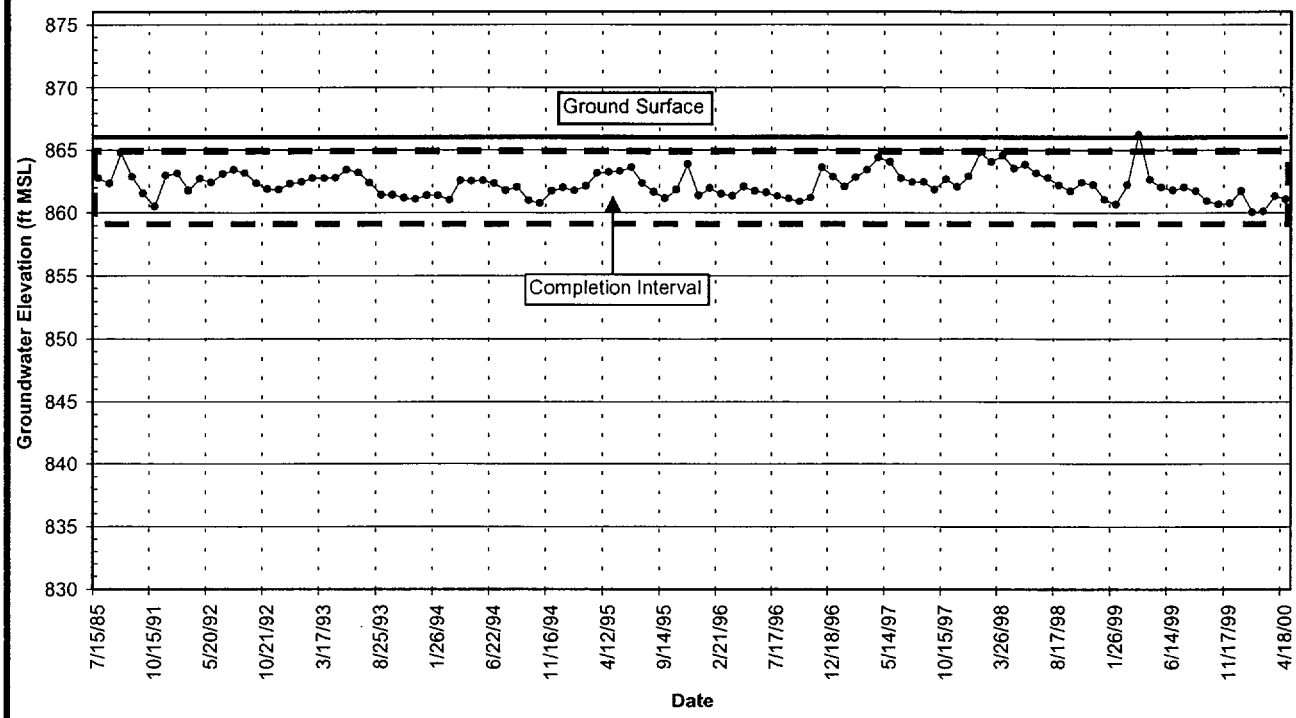


FIGURE 3
Historical Groundwater Elevations and Completion Interval
Quaternary Terrace Monitor Well QTMW-48
Kerr-McGee Cushing, OK Facility

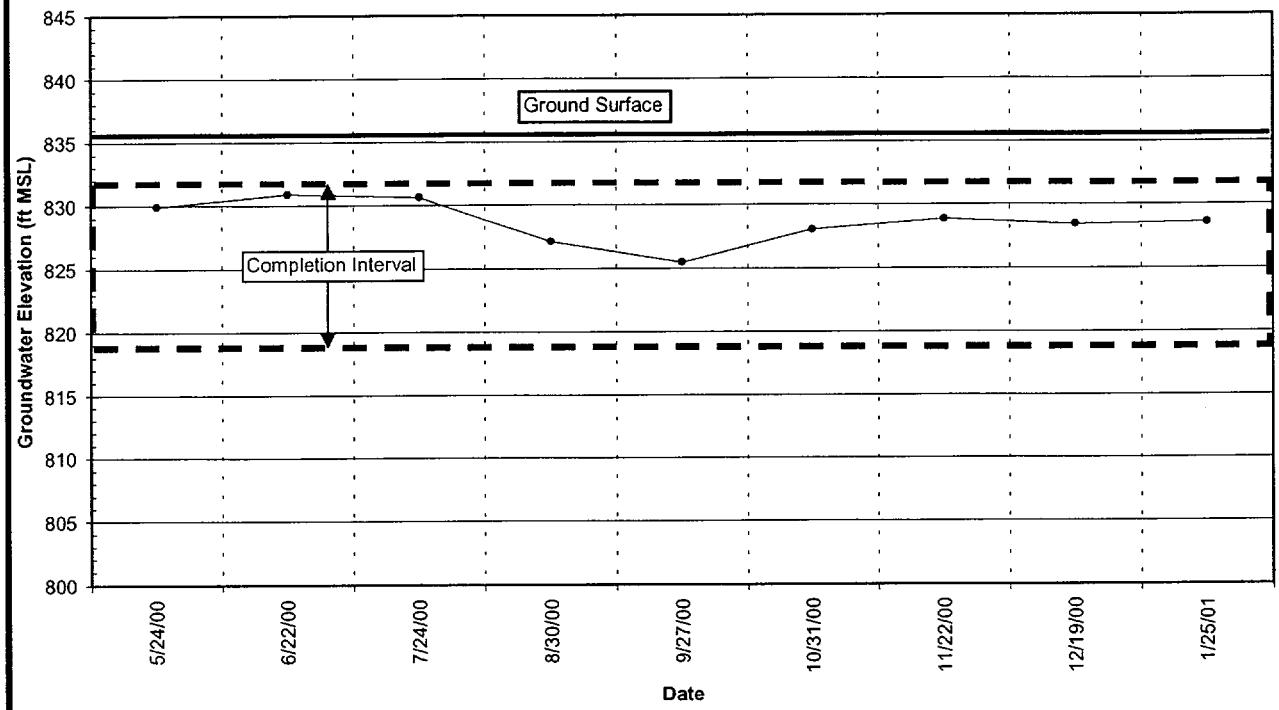


FIGURE 4
Historical Groundwater Elevations and Completion Interval
Unconsolidated Soil Monitor Well USMW-11
Kerr-McGee Cushing, OK Facility

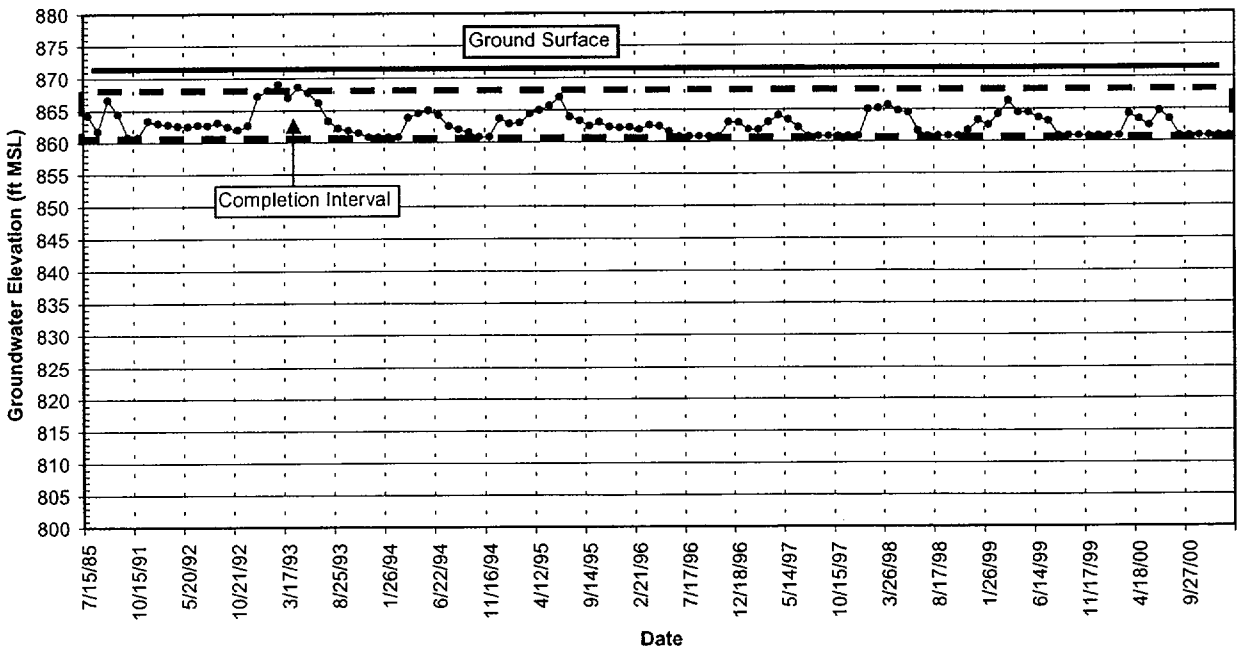


FIGURE 5
Historical Groundwater Elevations and Completion Interval
Upper Vanoss Monitor Well UVMW-11
Kerr-McGee Cushing, OK Facility

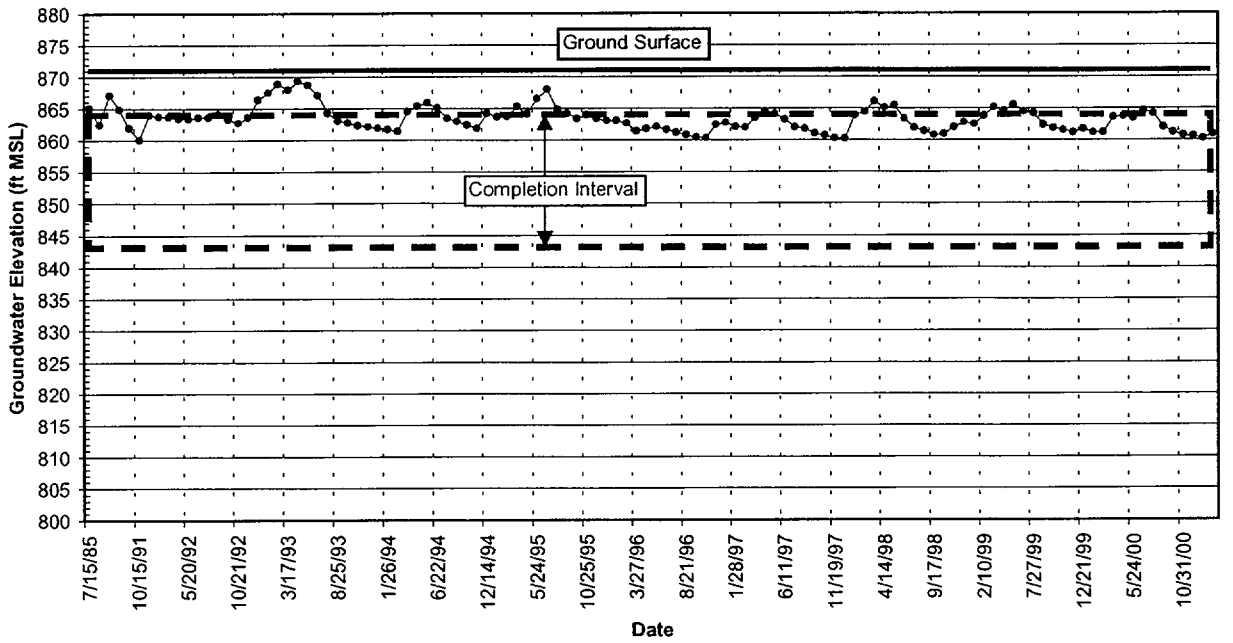
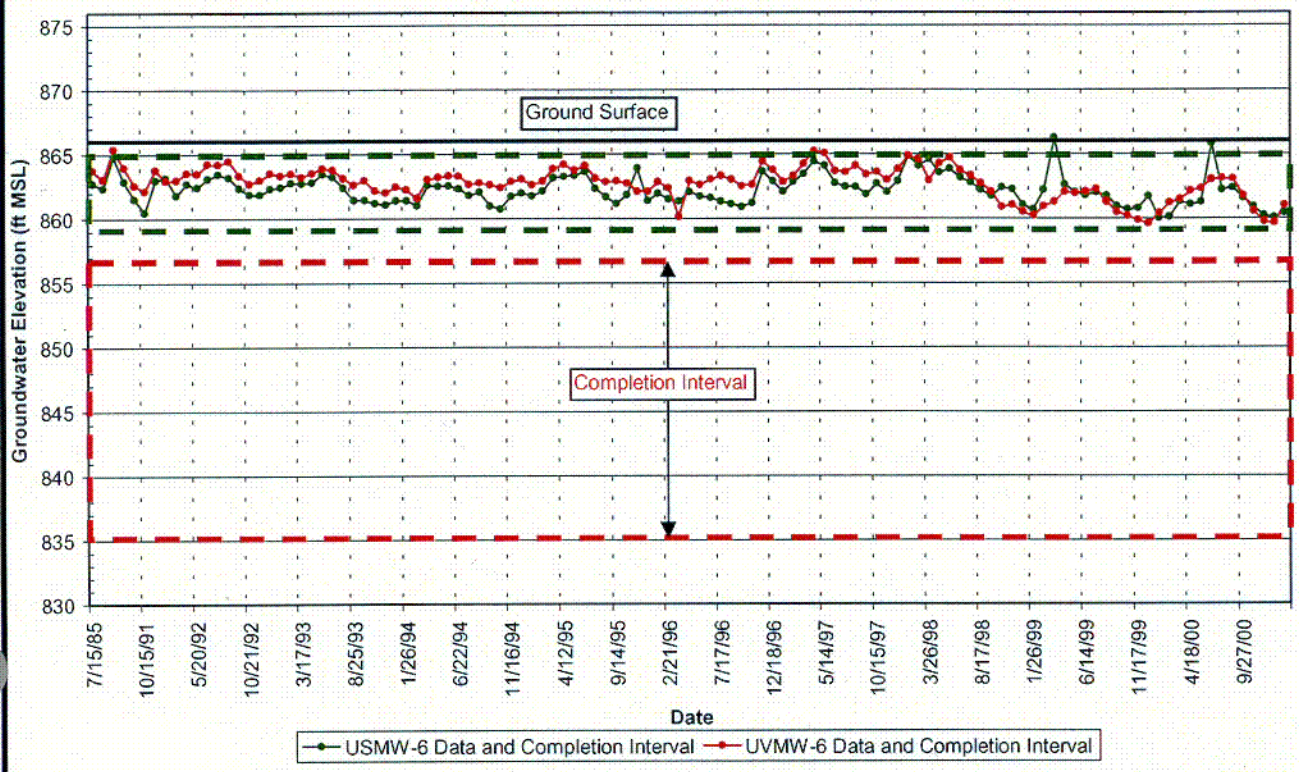
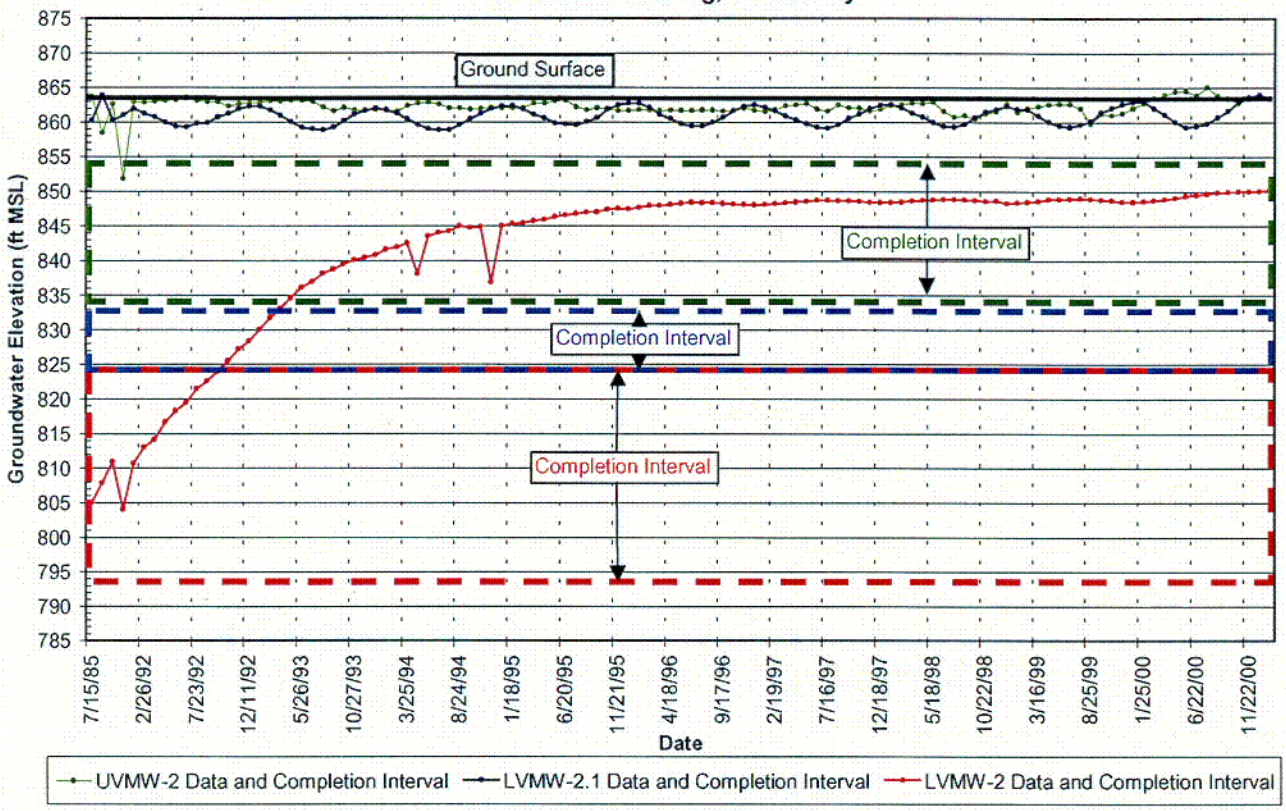


FIGURE 6
Comparison of Historical Groundwater Elevations and Completion Intervals
Unconsolidated Soil (USMW-6) and Upper Vanoss (UVMW-6)
Kerr-McGee Cushing, OK Facility



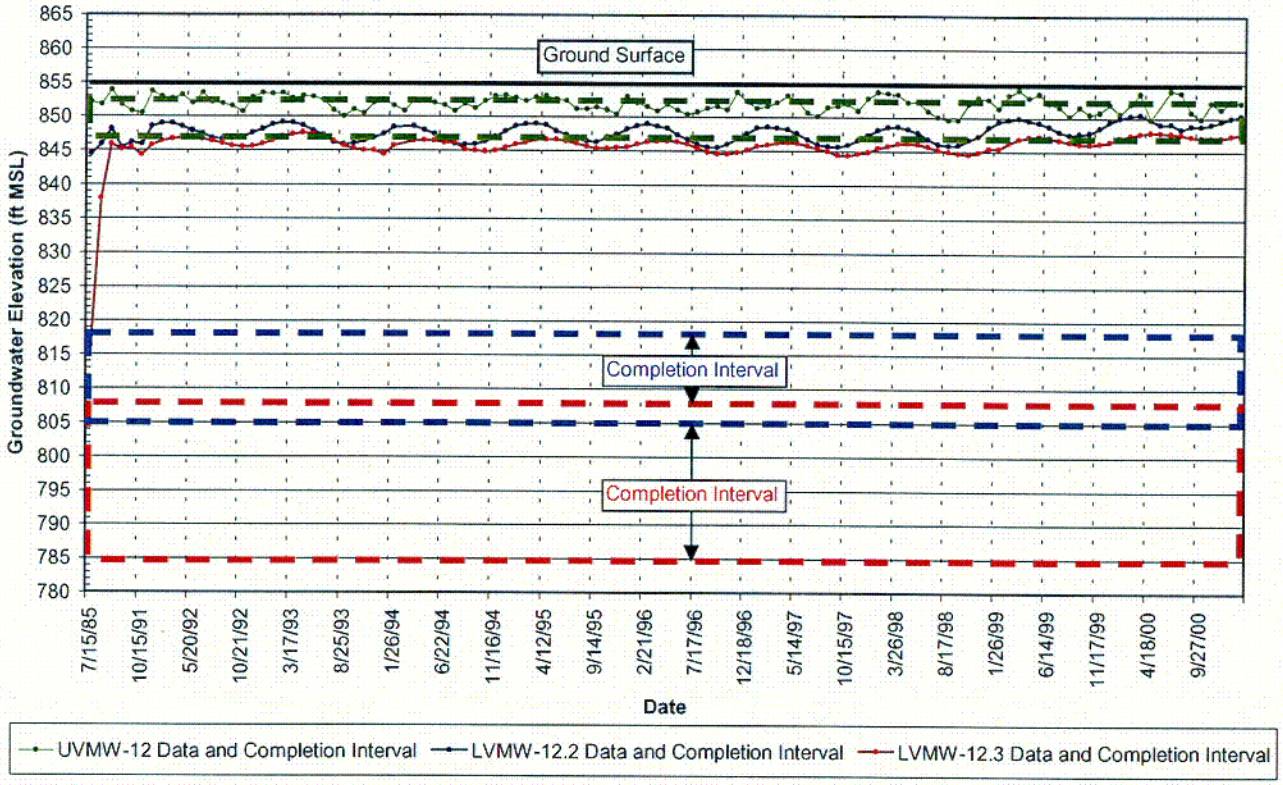
C06

FIGURE 7
Comparison of Historical Groundwater Elevations and Completion Intervals
Upper Vanoss (UVMW-2), Lower Vanoss (LVMW-2.1), and Deep Lower Vanoss (LVMW-2)
Kerr-McGee Cushing, OK Facility



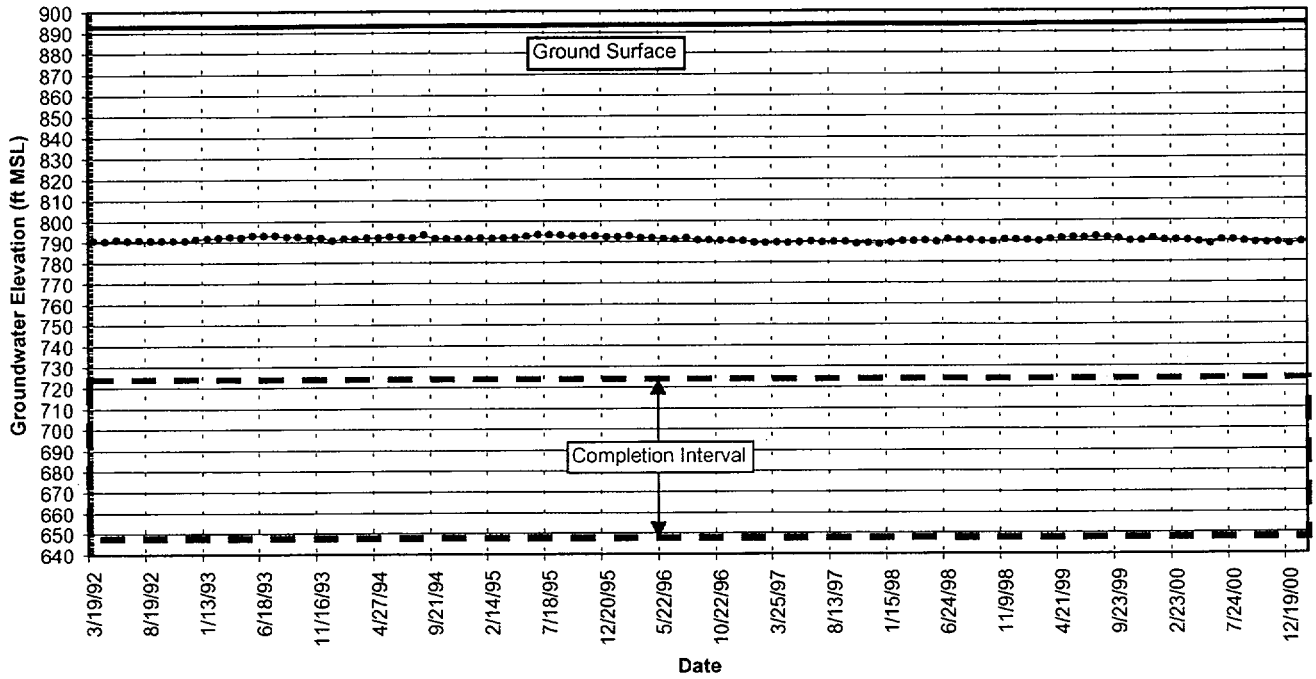
C07

FIGURE 8
Comparison of Historical Groundwater Elevations and Completion Intervals
Upper Vanoss (UVMW-12), Lower Vanoss (LVMW-12.2), and Deep Lower Vanoss (LVMW-12.3)
Kerr-McGee Cushing, OK Facility



C08

FIGURE 9
Historical Groundwater Elevations and Completion Interval
Vamoosa-Ada Aquifer Monitor Well VAMW-29
Kerr-McGee Cushing, OK Facility



APPENDIX A

TABULATION OF CUSHING MONITOR WELL COMPLETIONS AND WATER-LEVEL ELEVATIONS

TABLE A-1
Monitor Well Completions and Water Level Elevations for March 22, 2001
Kerr-McGee Cushing Remediation Facility
Cushing, Oklahoma

New Well Designation	Old Well Designation	Date Installed	Top of Casing Elevation (feet MSL)	Completion Interval (feet)	Groundwater Regime Completed	Original Purpose of Well	Depth to Water on 3-22-2001 (feet BTOC)	Water-Level Elevation (feet MSL)
UVMW-1	CMW-1.1	5-10-1985	866.96	10-33.5	Upper Vanoss	Upgradient Pit 1 Groundwater Assessment Monitoring	3.66	863.30
UVMW-2	CMW-2.1	5-20-1985	865.11	9.5-19	Upper Vanoss	Pit 1 Groundwater Assessment Monitoring	2.71	862.40
UVMW-2.1	CMW-2.2	5-20-1985	865.15	10.5-30	Upper Vanoss	Pit 1 Groundwater Assessment Monitoring	2.99	862.16
LVMW-2.1	CMW-2.3	6-19-1985	865.20	19.7-40	Lower Vanoss	Pit 1 Groundwater Assessment Monitoring	1.95	863.25
LVMW-2.2	CMW-2.4	5-17-1985	865.46	31-40	Lower Vanoss	Pit 1 Groundwater Assessment Monitoring	1.50	863.96
LVMW-2	CMW-2.5	5-17-1985	865.54	40.5-70	Lower Vanoss	Pit 1 Groundwater Assessment Monitoring	15.47	850.07
LVMW-3	CMW-3.1	5-7-1985	864.68	12-32.5	Lower Vanoss	Pit 2 Groundwater Assessment Monitoring	8.17	856.51
USMW-5	CMW-5.1	5-6-1985	856.78	3-7	Unconsolidated Soil	Downgradient Pit 3 Groundwater Assessment Monitoring	4.68	852.10
UVMW-5	CMW-5.2	6-20-1985	857.15	8.5-15	Upper Vanoss	Downgradient Pit 3 Groundwater Assessment Monitoring	4.90	852.25
LVMW-5	CMW-5.3	6-20-1985	856.92	16-24	Lower Vanoss	Downgradient Pit 3 Groundwater Assessment Monitoring	7.31	849.61
USMW-6	CMW-6.1	5-10-1985	867.95	1-6.8	Unconsolidated Soil	Upgradient Pit 1 Groundwater Assessment Monitoring	7.89	860.06
UVMW-6	CMW-6.2	5-13-1985	868.94	9.5-30.5	Upper Vanoss	Upgradient Pit 1 Groundwater Assessment Monitoring	9.29	859.65
USMW-7	CMW-7.1	5-15-1985	861.89	2-6.5	Unconsolidated Soil	Upgradient Pit 2 Groundwater Assessment Monitoring	5.98	855.91
UVMW-7	CMW-7.2	5-15-1985	862.12	11-30	Upper Vanoss	Upgradient Pit 2 Groundwater Assessment Monitoring	6.48	855.64
USMW-9	CMW-9.1	5-5-1985	853.91	2-5	Unconsolidated Soil	Downgradient Pit 3 Groundwater Assessment Monitoring	3.75	850.16
LVMW-9	CMW-9.2	6-19-1985	853.51	11-44	Lower Vanoss	Downgradient Pit 3 Groundwater Assessment Monitoring	5.65	847.86
USMW-10	CMW-10.1	6-10-1985	857.21	2-6.5	Unconsolidated Soil	Downgradient Pit 3 Groundwater Assessment Monitoring	2.57	854.64
LVMW-10	CMW-10.2	6-20-1985	857.32	12-26	Lower Vanoss	Downgradient Pit 3 Groundwater Assessment Monitoring	3.40	853.92
LVMW-10.1	CMW-10.3	6-10-1985	857.30	28-36.5	Lower Vanoss	Downgradient Pit 3 Groundwater Assessment Monitoring	5.19	852.11
USMW-11	CMW-11.1	5-8-1985	874.02	4-10.5	Unconsolidated Soil	Upgradient Site Groundwater Monitoring	Dry	Dry
UVMW-11	CMW-11.2	6-9-1985	872.99	7.5-29	Upper Vanoss	Upgradient Site Groundwater Monitoring	13.83	859.16
LVMW-11	CMW-11.3	6-18-1985	872.67	38-70	Lower Vanoss	Upgradient Site Groundwater Monitoring	41.64	831.03
UVMW-12	CMW-12.1	5-24-1985	855.91	3-8	Upper Vanoss	Upgradient Pit 4 Groundwater Assessment Monitoring	3.45	852.46
LVMW-12.1	CMW-12.2	5-24-1985	856.33	10.2-36	Lower Vanoss	Upgradient Pit 4 Groundwater Assessment Monitoring	3.85	852.48
LVMW-12.2	CMW-12.3	5-24-1985	856.29	37.5-50	Lower Vanoss	Upgradient Pit 4 Groundwater Assessment Monitoring	6.29	850.00
LVMW-12.3	CMW-12.4	5-23-1985	856.30	47-70	Lower Vanoss	Upgradient Pit 4 Groundwater Assessment Monitoring	8.93	847.37
UVMW-13	CMW-13.1	5-23-1985	853.15	4-12	Upper Vanoss	Upgradient Pit 4 Groundwater Assessment Monitoring	6.07	847.08
LVMW-13	CMW-13.2	5-22-1985	852.78	53.4-76	Lower Vanoss	Upgradient Pit 4 Groundwater Assessment Monitoring	5.19	847.59
LVMW-15	CMW-15.1	5-30-1985	855.25	10.5-26	Lower Vanoss	Upgradient Pit 4 Groundwater Assessment Monitoring	9.20	846.05
LVMW-15.1	CMW-15.2	5-29-1985	855.14	54.5-70	Lower Vanoss	Upgradient Pit 4 Groundwater Assessment Monitoring	10.80	844.34
UVMW-18	CMW-18.1	1-3-1990	872.86	8.7-30	Upper Vanoss	Upgradient Site Groundwater Monitoring	16.00	856.86
LVMW-18	CMW-18.2	1-8-1990	872.86	81.3-100	Lower Vanoss	Upgradient Site Groundwater Monitoring	58.80	814.06
LVMW-19	CMW-19.1	1-15-1990	836.24	7-29	Lower Vanoss	Downgradient Pit 4 Groundwater Monitoring	6.6	829.64
LVMW-20	CMW-20.1	1-12-1990	848.03	19-42.4	Lower Vanoss	Phase I Groundwater Monitoring	33.89	814.14
LVMW-20.1	CMW-20.2	1-11-1990	847.26	65.2-87.4	Lower Vanoss	Phase I Groundwater Monitoring	32.59	814.67
LVMW-21	CMW-21.1	1-12-1990	841.67	6.5-27.5	Lower Vanoss	Downgradient Pit 5 Groundwater Monitoring	13.32	828.35
LVMW-22	CMW-22.1	1-16-1990	842.75	5.5-27.5	Lower Vanoss	Phase I Groundwater Monitoring	7.35	835.40
UVMW-23	CMW-23.1	1-16-1990	863.78	5.4-27	Upper Vanoss	Upgradient Pit 3 Groundwater Assessment Monitoring	6.60	857.18
LVMW-23	CMW-23.2	1-10-1990	864.50	63.9-99	Lower Vanoss	Upgradient Pit 3 Groundwater Assessment Monitoring	42.68	821.82
VAMW-29	CMW-29.1	8-17-1991	897.20	168-245	Vamoosa-Ada Aquifer	Vamoosa-Ada Groundwater Monitoring	108.90	788.30
UVMW-30	CMW-30.1	7-20-1993	892.83	5-22	Upper Vanoss	North Disposal Cell Upgradient Groundwater Characterization	18.03	874.80
LVMW-30.1	CMW-30.2	7-20-1993	894.22	64.5-82	Lower Vanoss	North Disposal Cell Upgradient Groundwater Characterization	57.89	836.33
LVMW-30.2	CMW-30.3	7-15-1993	894.17	88-105	Lower Vanoss	North Disposal Cell Upgradient Groundwater Characterization	87.71	806.46
LVMW-31	CMW-31.1	7-20-1993	848.29	28-43	Lower Vanoss	North Disposal Cell Upgradient Groundwater Characterization	15.90	832.39
LVMW-31.1	CMW-31.2	7-15-1993	849.52	55-75	Lower Vanoss	North Disposal Cell Upgradient Groundwater Characterization	28.70	820.82
LVMW-32	CMW-32.1	7-16-1993	853.30	37-53	Lower Vanoss	North Disposal Cell Upgradient Groundwater Characterization	24.60	828.70
LVMW-32.1	CMW-32.2	7-17-1993	853.00	58-75	Lower Vanoss	North Disposal Cell Upgradient Groundwater Characterization	62.00	791.00
UVMW-33	CMW-33.1	1-11-1994	897.47	8-17	Upper Vanoss	Northwest Disposal Cell Site Groundwater Characterization	9.05	888.42
QTMW-34	CMW-34.1	10-15-1996	831.75	9-21	Terrace Deposits	East Site Boundary-ARCO Groundwater Characterization	10.24	821.51
QTMW-35	CMW-35.1	10-15-1996	830.57	9-21	Terrace Deposits	East Site Boundary-ARCO Groundwater Characterization	9.03	821.54
QTMW-36	CMW-36.1	10-16-1996	832.88	9-21	Terrace Deposits	East Site Boundary-ARCO Groundwater Characterization	13.00	819.88
LVMW-37	CMW-37.1	6-1-1999	846.47	8-27	Lower Vanoss	South Disposal Cell Down-Gradient Groundwater Characterization	11.95	834.52
LVMW-37.1	CMW-37.2	6-1-1999	846.39	37-52	Lower Vanoss	South Disposal Cell Down-Gradient Groundwater Characterization	8.35	838.04
LVMW-38	CMW-38.1	6-1-1999	862.77	50-72	Lower Vanoss	South Disposal Cell Upgradient Groundwater Characterization	22.44	840.33
LVMW-40	CMW-40.1	6-4-1999	881.47	52-72	Lower Vanoss	South Disposal Cell Upgradient Groundwater Characterization	27.86	853.61
UVMW-41	CMW-41.1	5-5-1999	870.56	6-22	Upper Vanoss	South Disposal Cell Upgradient Groundwater Characterization	12.73	857.83
UVMW-42	CMW-42.1	10-8-1999	881.80	10-24	Upper Vanoss	Upgradient RMA-6 RAD Groundwater Characterization	12.80	869.00
UVMW-43	CMW-43.1	10-8-1999	880.89	10-25	Upper Vanoss	Upgradient RMA-6 RAD Groundwater Characterization	12.83	868.06

TABLE A-1
Monitor Well Completions and Water Level Elevations for March 22, 2001
Kerr-McGee Cushing Remediation Facility
Cushing, Oklahoma

New Well Designation	Old Well Designation	Date Installed	Top of Casing Elevation (feet MSL)	Completion Interval (feet)	Groundwater Regime Completed	Original Purpose of Well	Depth to Water on 3-22-2001 (feet BTOC)	Water-Level Elevation (feet MSL)
UVMW-44	CMW-44.1	10-8-1999	873.83	12-25.5	Upper Vanoss	Upgradient RMA-6 RAD Groundwater Characterization	13.80	860.03
QTMW-45	CMW-45.1	4-3-2000	838.44	5-19.5	Terrace Deposits	Down-Gradient RMA-10 RAD Groundwater Characterization	10.15	828.29
QTMW-46	CMW-46.1	4-4-2000	841.61	6-20	Terrace Deposits	Upgradient RMA-10 RAD Groundwater Characterization	10.32	831.29
QTMW-47	CMW-47.1	4-4-2000	844.76	6-20	Terrace Deposits	Upgradient RMA-10 RAD Groundwater Characterization	11.42	833.34
QTMW-48	CMW-48.1	4-4-2000	838.28	4-17	Terrace Deposits	Down-Gradient RMA-10 RAD Groundwater Characterization	9.83	828.45
QTMW-49	CMW-49.1	4-5-2000	840.18	5-19	Terrace Deposits	Down-Gradient RMA-10 RAD Groundwater Characterization	11.55	828.63
UVMW-50.1	CMW-50.1	4-5-2000	893.65	6-15	Upper Vanoss	Upgradient RMA-11 RAD Groundwater Characterization	15.72	877.93
UVMW-50.2	CMW-50.2	4-5-2000	893.79	18-27	Upper Vanoss	Upgradient RMA-11 RAD Groundwater Characterization	14.58	879.21
UVMW-51	CMW-51.1	4-6-2000	881.92	6-22	Upper Vanoss	Down-Gradient RMA-11 RAD Groundwater Characterization	6.20	875.72
UVMW-52.1	MW-2	11-19-1991	891.75	2-11	Upper Vanoss	Northwest Disposal Cell Site & Side-Gradient RMA-11 Groundwater Characterizations	9.26	882.49
UVMW-52.2	MW 8	11-25-1991	892.28	18-31	Upper Vanoss	Northwest Disposal Cell Site & Side-Gradient RMA-11 Groundwater Characterizations	13.95	878.33
UVMW-52.3	MW 7	11-22-1991	891.48	40.5-52.5	Upper Vanoss	Northwest Disposal Cell Site Groundwater Characterization	13.06	878.42
UVMW-53.1	MW 3	11-20-1991	879.55	2.5-10.5	Upper Vanoss	Northwest Disposal Cell Site & Down-Gradient RMA-11 Groundwater Characterizations	10.30	869.25
UVMW-53.2	MW-9	11-25-1991	880.24	19-36	Upper Vanoss	Northwest Disposal Cell Site & Down-Gradient RMA-11 Groundwater Characterizations	36.44	843.80
UVMW-53.3	MW 10	11-25-1991	880.64	8-26	Upper Vanoss	Northwest Disposal Cell Site Groundwater Characterization	9.59	871.05
UVMW-54	MW-4	11-20-1991	881.16	3-11	Upper Vanoss	Northwest Disposal Cell Site Groundwater Characterization	22.17	858.99
UVMW-54.1	MW-11	11-26-1991	881.32	8-31	Upper Vanoss	Northwest Disposal Cell Site Groundwater Characterization	14.87	866.45
UVMW-55.1	MW-1	11-19-1991	895.64	1-9	Upper Vanoss	Northwest Disposal Cell Site Groundwater Characterization	12.02	883.62
UVMW-55.2	MW 6	11-21-1991	897.23	17-30	Upper Vanoss	Northwest Disposal Cell Site Groundwater Characterization	12.61	884.62
UVMW-55.3	MW 5	11-21-1991	897.04	38-61	Upper Vanoss	Northwest Disposal Cell Site Groundwater Characterization	14.58	882.46

Key to New Well Designations Indicating Completed Units: USMW = Unconsolidated Weathered Bedrock and Soil; QTMW = Quaternary Stream Terrace; UVMW = Upper Vanoss; LV MW = Lower Vanoss; VAMW = Vamoosa-Ada Aquifer.

APPENDIX B

ESTIMATION OF MUDSTONE PERMEABILITIES FROM ANALYSES OF MONITOR WELL WATER-LEVEL RECOVERY DATA AND LABORATORY TESTS OF CORE SAMPLES

ESTIMATION OF MUDSTONE PERMEABILITIES FROM ANALYSES OF MONITOR WELL WATER-LEVEL RECOVERY DATA AND LABORATORY TESTS OF CORE SAMPLES

Cushing Remediation Facility

1.0 INTRODUCTION

Investigation of the hydrogeology at the former Kerr-McGee refinery site and vicinity, located north of Cushing, Oklahoma, began in 1985 and continues to this day. The geology underlying the refinery site typically consists of a series of sandstones and siltstones underlain by a thick sequence of mudstones. As the name suggests, the mudstones typically have high clay contents that impede the lateral and vertical movement of groundwater.

One important aspect of the hydrogeologic investigations has been the long-term monitoring of groundwater levels. Groundwater monitoring began with the installation of the first wells in 1985, which were placed around acid waste Pits 1, 2, 3, and 4. Additional wells have been installed since then in response to specific informational needs, the most recent being constructed in April 2000. As of May 2001 a total of 78 wells are actively being monitored as part of the Cushing Facility Groundwater Monitoring Program.

Since 1991 water levels have been measured on a monthly basis. Water-level data are reviewed as they become available, and are analyzed quarterly as part of a quarterly site hydrology report.

Review of plotted data show several interesting features:

- Water levels in the most shallow wells, which are typically completed in soil and weathered bedrock, show rapid, large-magnitude fluctuations in immediate response to seasonal precipitation.

- Water levels in wells completed in shallow bedrock also show seasonal fluctuations, but of less magnitude and with slower responses.

- The deeper the well, the smaller the seasonal fluctuation magnitude becomes, reflecting greater isolation from overland recharge sources.

- Hydrographs of the deeper wells completed in mudstones show very slow recovery of water levels following completion and development and groundwater sampling events. The slow recovery reflects the low permeability of the mudstone resulting from the high clay content. The slow recovery also suggests a lack of interconnecting fractures that reach through the mudstones to near-surface sources of groundwater recharge.

To quantify the apparent low mudstone permeabilities, this report estimates the permeability of the deeper mudstones based upon analyses of water-level recovery plots in five monitor wells. These permeability estimates are also compared to laboratory permeabilities of mudstone core samples.

2.0 DESCRIPTION OF THE WATER-LEVEL RECOVERYANALYSIS METHODOLOGIES

Two methods were used to analyze water-level recovery data for five wells. The methodologies of Cooper, Bredehoeft, and Papadopulos (1967) and Skibitzke (1958), as described in Lohman (1972), are described below.

2.1 Cooper, Bredehoeft, and Papadopulos Methodology

Cooper, Bredehoeft, and Papadopulos is essentially a "slug test" method used to analyze the change in water level after a known volume or "slug" of water has been injected into or removed from the well (Copper, H. H., Jr., J. D. Bredeheoft, and I. S. Papadopulos, 1967; Lohman, 1972). The resulting rise or fall in water level is measured over a period typically lasting minutes. In this case, however, the rise in water level after removal of water by well development or sampling was measured for a period lasting months.

This is a graphical analysis method. The ratio of the water level at time "t" (H) to the water level at time zero following the removal of water (H_0) are plotted against the elapsed time. This plot is then compared to a set of "type" curves presented on Lohman (1972) Plate 2. A match point is selected, from which a time "t" is derived for use in the calculation. The mathematics of this method are shown on Table A-1 in Addendum A.

2.2 Skibitzke Methodology

Skibitzke, also called the "bailer" method, is a procedure used to estimate transmissivity from the recovery of the water level in a well after the well has been bailed (Ferris, J. G., D. B. Knowles, R. H. Brown, and R. W. Stallman, 1962; Lohman, 1972; Skibitzke, 1972). This is a mathematical analysis method that relates the rise in water level over time to the volume of water removed from the casing. It is applied to water-level observations after the time since bailing stopped becomes large. The mathematics of this method are shown on Table A-2 in Addendum A.

3.0 DESCRIPTIONS OF THE WELLS

The five wells used in these analyses are LVMW-2, LVMW-30.2, LVMW-32.1, LVMW-38, and CMW-39.1, the latter of which has been abandoned. Water-level data for these five wells were chosen for analysis because:

- The wells are completed in the deeper mudstones.
- Water-level recoveries following well development and/or groundwater sampling events occurred over months or years, attesting to the low permeability of the mudstones.
- Hydrographs for these deeper completions show minimal influence from seasonal groundwater recharge, suggesting that any rise in water level shown on the recovery curve is due to water-level recovery in the well, and not seasonal recharge.

Monitor well LVMW-2 was installed in May 1985 during the initial investigation of acid sludge Pit 1. It is completed to a depth of 70 feet, and screened in mudstone in the interval 60 to 70 feet. A graph of historical water-level data is shown on Figure B-1 in Addendum B.

Monitor wells LVMW-30.2 and LVMW-32.1 were installed in July 1993 during the hydrogeologic investigation of the North Disposal Cell site (Kerr-McGee Corporation, 1993). Well LVMW-30.2 is completed to a depth of 103 feet, and screened in mudstone in the interval 91 to 101 feet. Water-level recoveries following both development and a sampling event were analyzed. Well LVMW-32.1 is completed to a depth of 73 feet, and screened in mudstone in the interval 61 to 71 feet. Graphs of historical water-level data for these two wells are shown on Figures B-2 and B-3, respectively, in Addendum B.

Monitor wells LVMW-38 and CMW-39.1 were installed in June 1999 during the hydrogeologic investigation of the South Disposal Cell site (Kerr-McGee Corporation, 1999). Well LVMW-38 is completed to a depth of 72 feet, and screened in mudstone in the interval 60 to 70 feet. Well CMW-39.1 is completed to a depth of 62 feet, and screened in mudstone in the interval 40 to 60 feet. Well CMW-39.1 was abandoned in October 1999 to make way for construction of the disposal cell. Graphs of historical water-level data for these two wells are shown on Figures B-4 and B-5, respectively, in Addendum B.

4.0 RESULTS OF WATER-LEVEL RECOVERY ANALYSES OF PERMEABILITY

Table 1 below summarizes permeability data for the six analyses of water-level recovery data for the five wells calculated using the Cooper, Bredehoeft, and Papadopulos and the Skibitzke methodologies. Results of these analyses show mudstone permeabilities in the 10^{-8} to 10^{-9} centimeters per second range.

TABLE 1
COMPILATION OF WATER-LEVEL RECOVERY CURVEY PERMEABILITY ANALYSES
CUSHING CONCEPTUAL HYDROGEOLOGIC MODEL
Cushing Remediation Site

Monitor Well No.	Completed Interval (feet)	Completed Interval (elevation, feet MSL)	Completed Lithology	Permeability (cm/sec)	
				Cooper, et al. (1967) Method	Skibitzke (1958) Method
LVMW-2 Post-Sampling Data	40.5 - 70	823.5 - 794	Dark gray mudstone to 55 ft. Red mudstone and red sandy mudstone to 70 feet	2.4×10^{-9}	10^{-9}
LVW-30.2 Post-Development Data	88 - 103	804 - 789	Red mudstone with some gray mudstone	7.0×10^{-8}	10^{-8}
LVW-30.2 Post-Sampling Data	88 - 103	804 - 789	Red mudstone with some gray mudstone	1.0×10^{-8}	10^{-9}
LVMW-32.1 Post-Sampling Data	58 - 73	793 - 778	Red mudstone with some gray mudstone	2.4×10^{-8}	10^{-9}
LVMW-38 Post-Development Data	50 - 72	810 - 788	Red mudstone to 62 ft. Interbedded hard, cemented, red sandstones and mudstones to 72 ft.	2.1×10^{-8}	10^{-8}
CMW-39.1 Post-Development Data	37 - 62	810 - 788	Red mudstone to 47 ft. Red mudstone with some fine sand to 62 ft.	1.0×10^{-8}	10^{-9}

4.1 Descriptions of Water-Level Recovery Analyses

Following are descriptions of the water-level recovery analyses.

4.1.1 LVMW-2 - Post-sampling water-level recovery during the period October 1991 to February 1996 were analyzed. A tabulation of water-level data, showing results of the Skibitzke analyses, is presented in Table C-1 in Addendum C. An arithmetic plot of the analyzed data is presented on Figure D-1 in Addendum D. A plot of H/H_0 versus time, showing the type curve and match point, is presented on Figure E-1 in Addendum E. The Cooper, Bredehoeft, and Papadopulos analysis of these data, which show a permeability of 2.4×10^{-9} cm/second, is presented in Table F-1 in Addendum F. The Skibitzke analyses also show a permeability of 10^{-9} cm/second.

4.1.2 LVMW-30.2 - Both post-development and post-sampling water-level recoveries were analyzed for this well. A tabulation of the post-development water-level data for the period July 1993 to February 1994, showing results of the Skibitzke analyses, is presented in Table C-2. An arithmetic plot of the analyzed data is presented on Figure D-2. A plot of H/H_0 versus time, showing the type curve and match point, is presented on Figure E-2. The Cooper, Bredehoeft, and Papadopulos analysis of these data, which show a permeability of 7.8×10^{-8}

cm/second, is presented in Table F-2. The Skibitzke analyses also show a permeability of 10^{-8} cm/second.

A tabulation of the post-sampling water-level data for well LVMW-30.2, showing results of the Skibitzke analyses, is presented in Table C-3. An arithmetic plot of the analyzed data is presented on Figure D-3. A plot of H/H_0 versus time, showing the type curve and match point, is presented on Figure E-3. The Cooper, Bredehoeft, and Papadopulos analysis of these data, which show a permeability of 1.0×10^{-8} cm/second, is presented in Table F-3. The Skibitzke analyses show a permeability of 10^{-9} cm/second.

4.1.3 LVMW-32.1 - Post-sampling water-level recovery during the period March 1994 to September 1995 were analyzed. A tabulation of water-level data, showing results of the Skibitzke analyses, is presented in Table C-4. An arithmetic plot of the analyzed data is presented on Figure D-4. A plot of H/H_0 versus time, showing the type curve and match point, is presented on Figure E-4. The Cooper, Bredehoeft, and Papadopulos analysis of these data, which show a permeability of 2.4×10^{-8} cm/second, is presented in Table F-4. The Skibitzke analyses show a permeability of 10^{-9} cm/second.

4.1.4 LVMW-38 - Post-development water-level recovery during the period June to November 1999 were analyzed. A tabulation of water-level data, showing results of the Skibitzke analyses, is presented in C-5. An arithmetic plot of the analyzed data is presented on Figure D-5. A plot of H/H_0 versus time, showing the type curve and match point, is presented on Figure E-5. The Cooper, Bredehoeft, and Papadopulos analysis of these data, which show a permeability of 2.1×10^{-8} cm/second, is presented in Table F-5. The Skibitzke analyses also show a permeability of 10^{-8} cm/second.

4.1.5 CMW-39.1 - Post-development water-level recovery during the period July to October 1999 were analyzed. A tabulation of water-level data, showing results of the Skibitzke analyses, is presented in Table C-6. An arithmetic plot of the analyzed data is presented on Figure D-6. A plot of H/H_0 versus time, showing the type curve and match point, is presented on Figure E-6. The Cooper, Bredehoeft, and Papadopulos analysis of these data, which show a permeability of 1.0×10^{-8} cm/second, is presented in Table F-6. The Skibitzke analyses also show a permeability of 10^{-9} cm/second.

Comparison of Water-Level Recovery Permeability Values to Laboratory Values

Permeabilities calculated from the six recovery curves for the five wells completed in mudstone are all in the 10^{-8} to 10^{-9} centimeters per second range. These values compare well with laboratory permeability tests run on core samples collected during the 1993 investigation of the first disposal cell. As shown on Table 2, permeabilities for the mudstone core samples ranged between 10^{-7} and 10^{-8} centimeters per second.

TABLE 2
COMPILATION OF LABORATORY TESTS OF BEDROCK CORE PERMEABILITIES
NORTH DISPOSAL CELL INVESTIGATION
Cushing Remediation Site

Borehole No.	Sample Interval (feet below grade)	Sample Interval (elevation, feet MSL)	Lithologic Description	Core Permeability (cm/sec)
B-120-2	15 - 16	858 - 857	Dark gray shaly mudstone	$1.2x10^{-8}$
B-120-2	35 - 37	838 - 836	Red shaly mudstone	$7.1x10^{-8}$
B-120-2	43 - 44	830 - 829	Red mudstone	$6.1x10^{-7}$
B-120-2	58 - 59	815 - 814	Red/gray silty mudstone	$1.7x10^{-8}$
B-120-2	63 - 65	810 808	Dark gray shaly mudstone	$8.8x10^{-8}$
B-120-2	77 - 78	796 - 795	Dark gray mudstone	$3.1x10^{-7}$
B-127-2	26 - 27	856 - 855	Dark gray mudstone	$3.2x10^{-7}$
B-127-2	39 - 40	843 - 842	Red shaly mudstone	$5.8x10^{-8}$
B-127-2	47 - 48	835 - 834	Red shaly mudstone	$1.9x10^{-8}$
B-127-2	77 - 78	805 - 804	Dark gray shaly mudstone	$3.4x10^{-8}$

5.0 CONCLUSIONS

This report has presented the results of six analyses of water-level recovery data for five wells using two analytical methods. These analyses show mudstone permeabilities in the range of the 10^{-8} to 10^{-9} centimeters per second. While the mudstone permeabilities of 10^{-9} centimeters per second as calculated by the Skibitzke method may appear to be low, they are consistent with the observed long periods of water-level recovery following development and/or groundwater sampling.

The values shown in Table 1 above are consistent with published clay permeability values. Davis and DeWiest (1966) report permeability values typically ranging from 10^{-6} to 10^{-8} centimeters per second for native clays. Similarly, Todd (1959) reports permeability values typically ranging from 10^{-7} to 10^{-8} centimeters per second for unweathered clays.

Heath (1983) reports permeability values for shales and clays that are similar or even lower. Permeabilities for shale range from 10^{-7} centimeters per second for fractures shales to 10^{-11} centimeters per second for unfractured shales. Heath (1983) reports permeabilities for clay in the range of 10^{-6} to 10^{-10} centimeters per second.

Based upon the favorable comparisons of water-level recovery analyses and laboratory analyses of core permeabilities, it can be concluded that the mudstones underlying the site are essentially impermeable to the vertical migration of contaminants.

6.0 REFERNCES CITED

Copper, H. H., Jr., J. D. Bredeheoft, and I. S. Papadopulos, 1967, Response of a finite-diameter to an instantaneous charge of water: Water Resources Research, V. 3, no. 1, p. 263-269.

Davis, S. N., and R. J. M. DeWiest, 1966, Hydrogeology: John Wiley and Sons, Inc., 463p.

Ferris, J. G., D. B. Knowles, R. H. Brown, and R. W. Stallman, 1962, Theory of aquifer tests: U. S. Geological Survey Water-Supply Paper 1536-E, p. 69-174.

Heath, R. C., 1983, Basic Ground-Water Hydrology: U. S. Geological Survey Water-Supply Paper 2220, 84p.

Kerr-McGee Corporation, 1993, Other industrial waste disposal cell site characterization, Kerr-McGee Cushing Refinery Site: Document.

Kerr-McGee Corporation, 1999, Pit 5 disposal cell design and site Characterization report, Kerr-McGee Cushing Refinery Site: Document.

Lohman, S.W., 1972, Ground-water hydraulics: U. S. Geological Survey Professional Paper 708, 70p.

Skibitzke, H. E., 1958, An equation for potential distribution about a well being bailed: U. S. Geological Survey ground Water Note 35.

Todd, D. K., 1959, Groundwater water hydrology: John Wiley and Sons, Inc., 336p.

APPENDIX B
ADDENDUM A
WATER-LEVEL RECOVERY ANALYSIS METHODOLOGIES

APPENDIX B ADDENDUM A
TABLE A-1
DESCRIPTION OF AQUIFER PERMEABILITY CALCULATION METHODOLOGY
Analysis of Long-Term Monitor Well Water-Level Recovery Data
Using the Data Analysis Methodology of Cooper, Bredehoeft, and Papadopulos (1967),
As Described in Lohman (1972):

$$T = \frac{(Tt/r_c^2)x(86400\text{seconds/day})x(r_c^2)}{t}$$

Where:
- T = Transmissivity, in square feet per day
- t = Time value of match point on semi-log plot of H/H_0 versus time equivalent to the point where $Tt/r_c^2 = 1.0$, in seconds
- r_c = Radius of the well casing, in feet

Definitions of other hydrologic parameters used in these calculations:

- H_0 = Maximum depth of water in well below the static water level at start of the recovery period.
- H = Depth of water in well below the static water level at time "t" during the recovery period.
- K = Hydraulic conductivity, in feet per day.
- P = Permeability, in centimeters per second

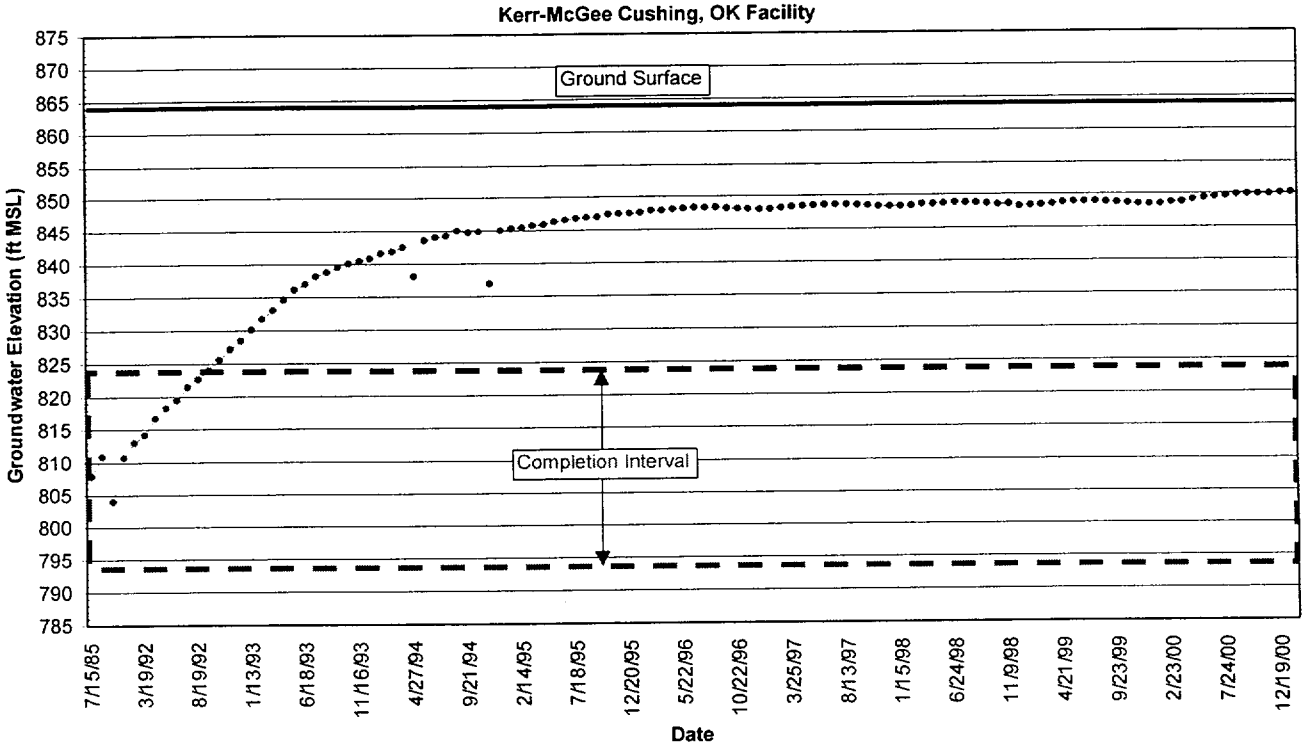
APPENDIX B ADDENDUM A
TABLE A-2
DESCRIPTION OF AQUIFER PERMEABILITY CALCULATION METHODOLOGY
Analysis of Long-Term Monitor Well Water-Level Recovery Data
Using the Data Analysis Methodology of Skibitzke (1958)
As Described in Lohman (1972):

$$T = \frac{V}{4\pi s't}$$

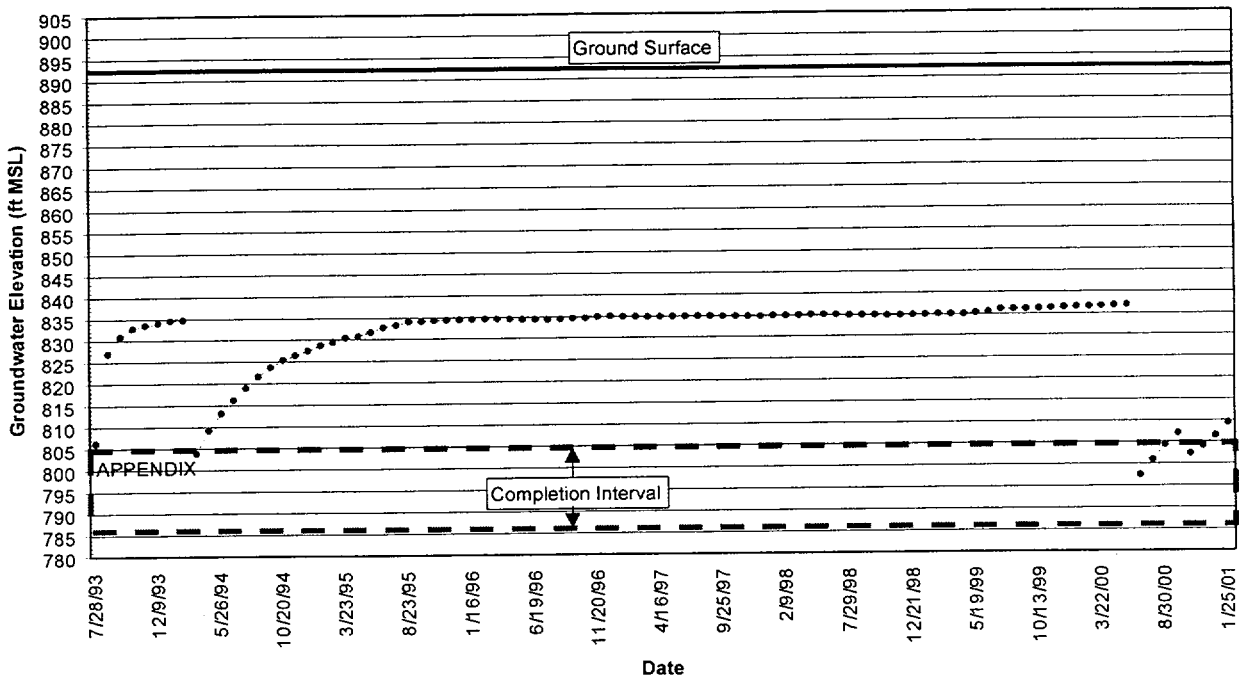
Where:
- T = Transmissivity, in square feet per day
- V = Volume of water removed from the well casing
- t = Length of time since the start of recovery, in days
- s' = Residual drawdown at time "t".

APPENDIX B
ADDENDUM B
GRAPHS OF HISTORICAL WATER-LEVEL DATA

APPENDIX B ADDENDUM B
FIGURE B-1
Historical Groundwater Elevations and Completion Intervals
Lower Vanoss Monitor Well LVMW-2
Kerr-McGee Cushing, OK Facility

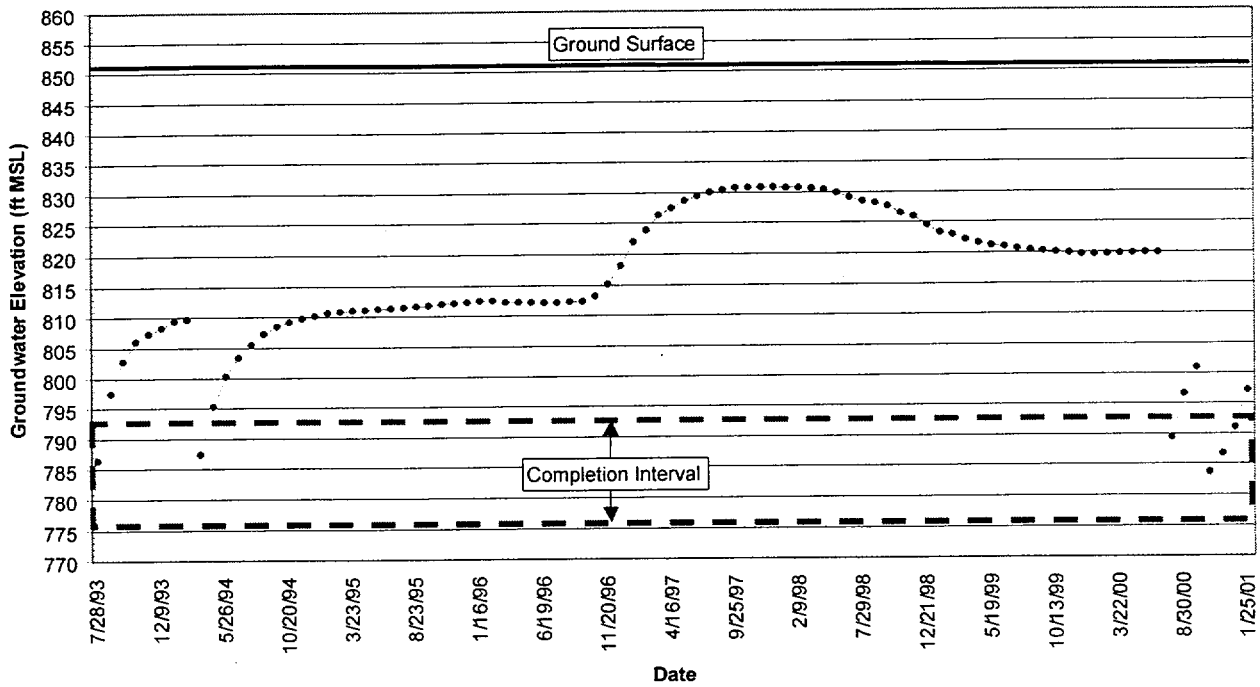


APPENDIX B ADDENDUM B
FIGURE B-2
Historical Groundwater Elevations and Completion Intervals
Lower Vanoss Monitor Well LVMW-30.2
Kerr-McGee Cushing, OK Facility

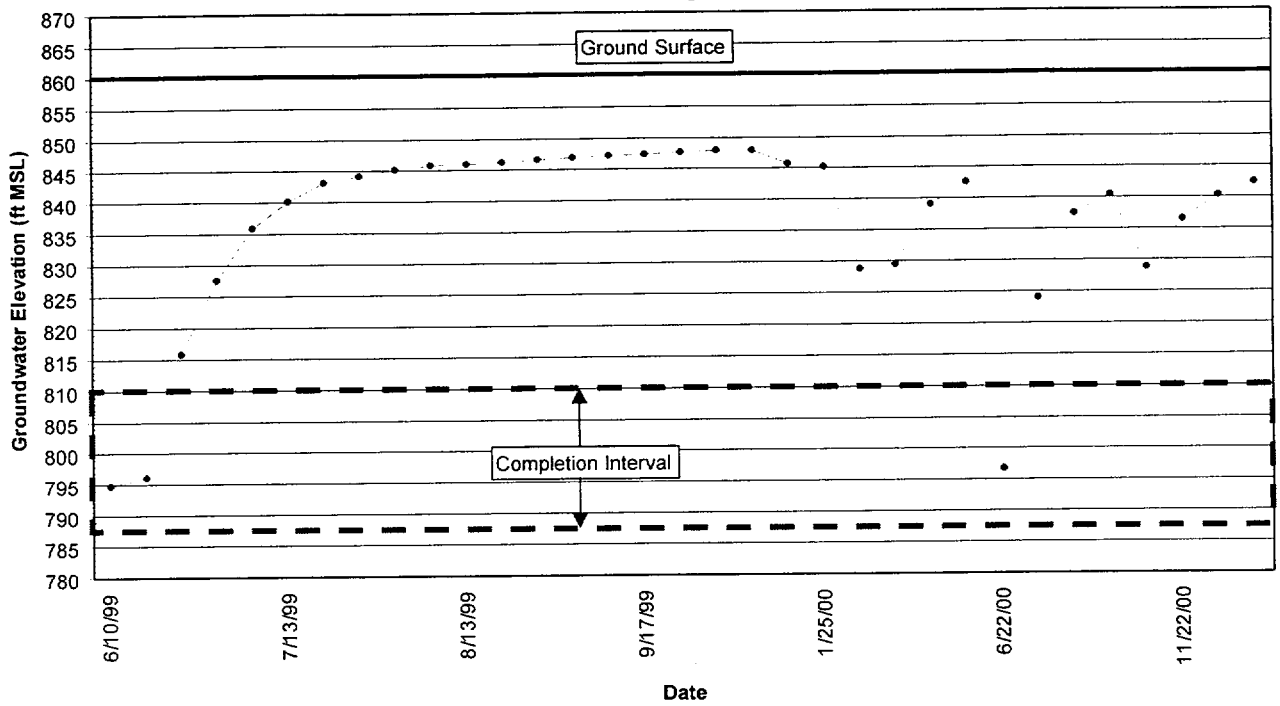


APPENDIX

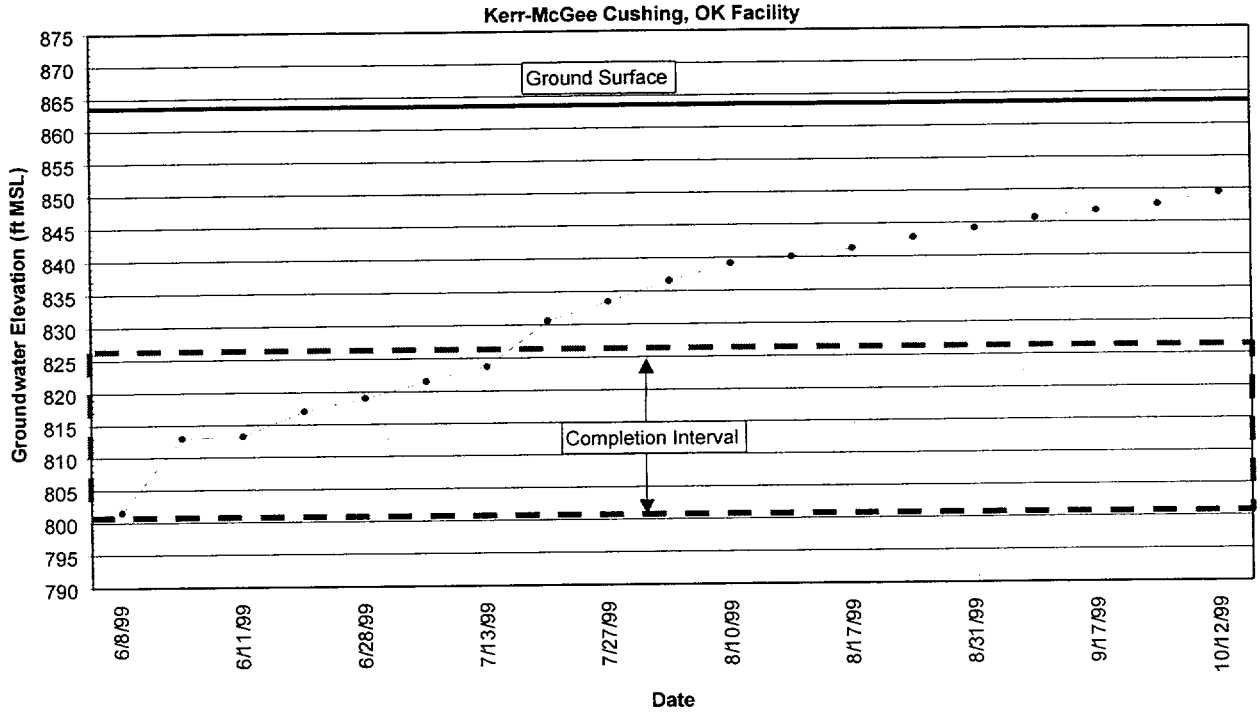
APPENDIX B ADDENDUM B
FIGURE B-3
Historical Groundwater Elevations and Completion Intervals
Lower Vanoss Monitor Well LVMW-32.1
Kerr-McGee Cushing, OK Facility



APPENDIX B ADDENDUM B
FIGURE B-4
Historical Groundwater Elevations and Completion Intervals
Lower Vanoss Monitor Well LVMW-38
Kerr-McGee Cushing, OK Facility



APPENDIX B ADDENDUM B
FIGURE B-5
Historical Groundwater Elevations and Completion Intervals
Lower Vanoss Monitor Well LVMW-39
Kerr-McGee Cushing, OK Facility



APPENDIX B
ADDENDUM C
TABULATIONS OF WATER-LEVEL DATA SHOWING SKIBITZKE ANALYSES

APPENDIX B ADDENDUM C
TABLE C-1
ANALYSIS OF POST-SAMPLING WATER-LEVEL RECOVERY DATA FOR LOWER VANOSS MONITOR WELL LVMW-2
Cushing Remediation Facility

Well Specifics

Date of Well Completion: 5-17-85
Casing Diameter: 4 inches (ID)
Screened Interval: 60 - 70 feet below grade (804 - 794 feet MSL
Time period of water-level recovery data: 10/15/91 - 2/21/96
Equivalent Volume of Water Removed: 28.6 gallons (3.8ft^3)

										Skibitzke (1958) Method		
Date	Time	Days	Hours	Minutes	Seconds	Water-Level Elevation (ft MSL)	Residual Drawdown (feet)	Water-Level Recovery (feet)	H/H_0	Transmissivty (ft^2/day)	Hydraulic Conductivity (ft^2/day)	Permeability (cm/sec)
10/15/91	0759.59					848.00	0.00	0.00				
10/15/91	0800	0.1	0	1	60	804.01	43.99	0.00	1.00			
1/22/92	0800	99	2376	142560	8553600	810.72	37.28	6.71	0.85	0.00008	0.000008	2.8E-09
2/26/92	0800	134	3216	192960	11577600	813.01	34.99	9.00	0.80	0.00006	0.000006	2.2E-09
3/19/92	0800	158	3744	224640	13478400	814.19	33.81	10.18	0.77	0.00006	0.000006	2.0E-09
4/21/92	0800	189	4536	272160	16329600	816.70	31.30	12.69	0.71	0.00005	0.000005	1.8E-09
5/20/92	0800	218	5232	313920	18835200	818.29	29.71	14.28	0.68	0.00005	0.000005	1.6E-09
6/17/92	0800	246	5904	354240	21254400	819.44	28.56	15.43	0.65	0.00004	0.000004	1.5E-09
7/23/92	0800	282	6768	406080	24364800	821.46	26.54	17.45	0.60	0.00004	0.000004	1.4E-09
8/19/92	0800	309	7416	444960	26697600	822.61	25.39	18.60	0.58	0.00004	0.000004	1.3E-09
9/23/92	0800	344	8256	495360	29721600	824.01	23.99	20.00	0.55	0.00004	0.000004	1.3E-09
10/21/92	0800	372	8928	535680	32140800	825.55	22.45	21.54	0.51	0.00004	0.000004	1.3E-09
11/18/92	0800	400	9600	576000	34560000	827.18	20.82	23.17	0.47	0.00004	0.000004	1.3E-09
12/11/92	0800	423	10152	609120	36547200	828.42	19.58	24.41	0.45	0.00004	0.000004	1.3E-09
1/13/93	0800	456	10944	656640	39398400	830.07	17.93	26.06	0.41	0.00004	0.000004	1.3E-09
2/17/93	0800	491	11784	707040	42422400	831.76	16.24	27.75	0.37	0.00004	0.000004	1.3E-09
3/17/93	0800	519	12456	747360	44841600	833.08	14.92	29.07	0.34	0.00004	0.000004	1.4E-09
4/21/93	0800	554	13296	797760	47865600	834.63	13.37	30.62	0.30	0.00004	0.000004	1.4E-09
5/26/93	0800	589	14136	848160	50889600	836.14	11.86	32.13	0.27	0.00004	0.000004	1.5E-09
6/18/93	0800	612	14688	881280	52876800	836.98	11.02	32.97	0.25	0.00004	0.000004	1.6E-09
7/28/93	0800	652	15648	938880	56332800	838.16	9.84	34.15	0.22	0.00005	0.000005	1.6E-09
8/25/93	0800	680	16320	979200	58752000	838.76	9.24	34.75	0.21	0.00005	0.000005	1.7E-09
9/24/93	0800	710	17040	1022400	61344000	839.53	8.47	35.52	0.19	0.00005	0.000005	1.7E-09
10/27/93	0800	743	17832	1069920	64195200	840.13	7.87	36.12	0.18	0.00005	0.000005	1.8E-09
11/16/93	0800	763	18312	1098720	65923200	840.45	7.55	36.44	0.17	0.00005	0.000005	1.8E-09
12/9/93	0800	786	18864	1131840	67910400	840.84	7.16	36.83	0.16	0.00005	0.000005	1.9E-09
1/26/94	0800	834	20016	1200960	72057600	841.63	6.37	37.62	0.14	0.00006	0.000006	2.0E-09
2/16/94	0800	855	20520	1231200	73872000	841.92	6.08	37.91	0.14	0.00006	0.000006	2.0E-09
3/25/94	0800	892	21408	1284480	77068800	842.53	5.47	38.52	0.12	0.00006	0.000006	2.2E-09
5/26/94	0800	954	22896	1373760	82425600	843.54	4.46	39.53	0.10	0.00007	0.000007	2.5E-09
6/22/94	0800	981	23544	1412640	84758400	844.04	3.96	40.03	0.09	0.00008	0.000008	2.7E-09
7/21/94	0800	1010	24240	1454400	87264000	844.23	3.77	40.22	0.09	0.00008	0.000008	2.8E-09
8/24/94	0800	1044	25056	1503360	90201600	845.00	3.00	40.99	0.07	0.00010	0.000010	3.4E-09
9/21/94	0800	1072	25728	1543680	92620800	844.72	3.28	40.71	0.07	0.00009	0.000009	3.0E-09
10/20/94	0800	1101	26424	1585440	95126400	844.86	3.14	40.85	0.07	0.00009	0.000009	3.0E-09
12/14/94	0800	1156	27744	1664640	99878400	845.03	2.97	41.02	0.07	0.00009	0.000009	3.1E-09
1/18/95	0800	1191	28584	1715040	102902400	845.34	2.66	41.33	0.06	0.00010	0.000010	3.3E-09
2/14/95	0800	1218	29232	1753920	105235200	845.44	2.56	41.43	0.06	0.00010	0.000010	3.4E-09
3/23/95	0800	1255	30120	1807200	108432000	845.77	2.23	41.76	0.05	0.00011	0.000011	3.8E-09
4/12/95	0800	1275	30600	1836000	110160000	845.90	2.10	41.89	0.05	0.00011	0.000011	3.9E-09
5/24/95	0800	1317	31608	1896480	113788800	846.33	1.67	42.32	0.04	0.00014	0.000014	4.8E-09
6/20/95	0800	1344	32256	1935360	116121600	846.57	1.43	42.56	0.03	0.00016	0.000016	5.5E-09
7/18/95	0800	1372	32928	1975680	118540800	846.78	1.22	42.77	0.03	0.00018	0.000018	6.3E-09
8/23/95	0800	1408	33792	2027520	121651200	846.97	1.03	42.96	0.02	0.00021	0.000021	7.2E-09
9/14/95	0800	1430	34320	2059200	123552000	847.02	0.98	43.01	0.02	0.00022	0.000022	7.5E-09
10/25/95	0800	1471	35304	2118240	127094400	847.41	0.59	43.40	0.01	0.00035	0.000035	1.2E-08
11/21/95	0800	1498	35952	2157120	129427200	847.51	0.49	43.50	0.01	0.00041	0.000041	1.4E-08
12/20/95	0800	1527	36648	2198880	131932800	847.49	0.51	43.48	0.01	0.00039	0.000039	1.3E-08
1/16/96	0800	1554	37296	2237760	134265600	847.69	0.31	43.68	0.01	0.00063	0.000063	2.2E-08
2/21/96	0800	1590	38160	2289600	137376000	848.00	0.00	43.99	0.00			

APPENDIX B ADDENDUM C
TABLE C-2
ANALYSIS OF POST-DEVELOPMENT WATER-LEVEL RECOVERY DATA FOR LOWER VANOSS MONITOR WELL LVMW-30.2
Cushing Remediation Facility

Well Specifics

Date of Well Completion: 7-15-93
Casing Diameter: 4 inches (ID)
Screened Interval: 91 - 101 feet below grade (801 - 791 feet MSL
Time period of water-level recovery data: 7/28/93 - 2/16/94
Equivalent Volume of Water Removed: 19.4 gallons (2.6ft^3)

										Skibitzke (1958) Method		
Date	Time	Days	Hours	Minutes	Seconds	Water-Level Elevation (ft MSL)	Residual Drawdown (feet)	Water-Level Recovery (feet)	H/H_o	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft^2/day)	Permeability (cm/sec)
7/28/93	0759.59					834.74	0.00	0.00				
7/28/93	0800	0.1	0	1	60	806.27	28.47	0.00	1.00			
8/25/93	0800	28	672	40320	2419200	826.99	7.75	20.72	0.27	0.0010	0.00010	3.3E-08
9/24/93	0800	58	1392	83520	5011200	830.82	3.92	24.55	0.14	0.0009	0.00009	3.2E-08
10/27/93	0800	91	2184	131040	7862400	832.83	1.91	26.56	0.07	0.0012	0.00012	4.1E-08
11/16/93	0800	111	2664	159840	9590400	833.53	1.21	27.26	0.04	0.0015	0.00015	5.3E-08
12/9/93	0800	134	3216	192960	11577600	833.97	0.77	27.70	0.03	0.0020	0.00020	7.0E-08
1/26/94	0800	182	4368	262080	15724800	834.54	0.20	28.27	0.01	0.0057	0.00057	2.0E-07
2/16/94	0800	203	4872	292320	17539200	834.74	0.00	28.47	0.00			

APPENDIX B ADDENDUM C
TABLE C-3
ANALYSIS OF POST-SAMPLING WATER-LEVEL RECOVERY DATA FOR LOWER VANOSS MONITOR WELL LVMW-30.2
Cushing Remediation Facility

Well Specifics

Date of Well Completion: 7-15-93
Casing Diameter: 4 inches (ID)
Screened Interval: 91 - 101 feet below grade (801 - 791 feet MSL
Time period of water-level recovery data: 3/25/94 - 1/16/96
Equivalent Volume of Water Removed: 20.6 gallons (2.8ft^3)

										Slubitzke (1958) Method		
Date	Time	Days	Hours	Minutes	Seconds	Water-Level Elevation (ft MSL)	Residual Drawdown (feet)	Water-Level Recovery (feet)	H/H_o	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft^2/day)	Permeability (cm/sec)
3/25/94	0759.59					834.40	0.00	0.00				
3/25/94	0800	0.1	0	1	60	803.82	30.58	0.00	1.00			
4/27/94	0800	33	792	47520	2851200	809.21	25.19	5.39	0.82	0.0003	0.00003	9.3E-09
5/26/94	0800	62	1488	88280	5356800	813.10	21.30	9.28	0.70	0.0002	0.00002	5.9E-09
6/22/94	0800	89	2136	128160	7689600	816.18	18.22	12.36	0.60	0.0001	0.00001	4.8E-09
7/21/94	0800	118	2832	169920	10195200	818.97	15.43	15.15	0.50	0.0001	0.00001	4.2E-09
8/24/94	0800	152	3648	218880	13132800	821.60	12.80	17.78	0.42	0.0001	0.00001	4.0E-09
9/21/94	0800	180	4320	259200	15552000	823.68	10.72	19.86	0.35	0.0001	0.00001	4.0E-09
10/20/94	0800	209	5016	300960	18057600	825.27	9.13	21.45	0.30	0.0001	0.00001	4.1E-09
11/16/94	0800	236	5664	339840	20390400	826.45	7.95	22.63	0.26	0.0001	0.00001	4.1E-09
12/14/94	0800	264	6336	380160	22809600	827.55	6.85	23.73	0.22	0.0001	0.00001	4.3E-09
1/18/95	0800	299	7176	430560	25833600	828.74	5.66	24.92	0.19	0.0001	0.00001	4.6E-09
2/14/95	0800	326	7824	469440	28166400	829.46	4.94	25.64	0.16	0.0001	0.00001	4.8E-09
3/23/95	0800	363	8712	522720	31363200	830.31	4.09	26.49	0.13	0.0002	0.00002	5.2E-09
4/12/95	0800	383	9192	551520	33091200	830.73	3.67	26.91	0.12	0.0002	0.00002	5.5E-09
5/24/95	0800	425	10200	612000	36720000	831.69	2.71	27.87	0.09	0.0002	0.00002	6.7E-09
6/20/95	0800	452	10848	650880	39052800	832.69	1.71	28.87	0.06	0.0003	0.00003	1.0E-08
7/18/95	0800	480	11520	691200	41472000	833.19	1.21	29.37	0.04	0.0004	0.00004	1.3E-08
8/23/95	0800	516	12384	743040	44582400	834.04	0.36	30.22	0.01	0.0012	0.00012	4.2E-08
9/14/95	0800	538	12912	774720	46483200	834.14	0.26	30.32	0.01	0.0016	0.00016	5.5E-08
10/25/95	0800	579	13896	833760	50025600	834.30	0.10	30.48	0.00	0.0038	0.00038	1.3E-07
11/21/95	0800	606	14544	872640	52358400	834.37	0.03	30.55	0.00	0.0123	0.00123	4.3E-07
12/20/95	0800	635	15240	914400	54864000	834.40	0.00	30.58	0.00			
1/16/96	0800	662	15888	953280	57196800	834.40	0.00	30.58	0.00			

APPENDIX B ADDENDUM C
TABLE C-4
ANALYSIS OF POST-SAMPLING WATER-LEVEL RECOVERY DATA FOR LOWER VANOSS MONITOR WELL LVMW-32.1
Cushing Remediation Facility

Well Specifics

Date of Well Completion: 7-17-93
Casing Diameter: 4 inches (ID)
Screened Interval: 61 - 71 feet below grade (790 - 780 feet MSL
Time period of water-level recovery data: 3/25/94 - 9/14/95
Equivalent Volume of Water Removed: 16.0 gallons (2.2ft^3)

										Skibitzke (1958) Method		
Date	Time	Days	Hours	Minutes	Seconds	Water-Level Elevation (ft MSL)	Residual Drawdown (feet)	Water-Level Recovery (feet)	H/H_0	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft^2/day)	Permeability (cm/sec)
3/25/94	0759.59					812.00	0.00	0.00				
3/25/94	0800	0.1	0	1	60	787.41	24.59	0.00	1.00			
4/27/94	0800	33	792	47520	2851200	795.22	16.78	7.81	0.68	0.0003	0.00003	1.1E-08
5/26/94	0800	62	1488	89280	5356800	800.25	11.75	12.84	0.48	0.0002	0.00002	8.3E-09
6/22/94	0800	89	2136	128160	7689600	803.37	8.63	15.96	0.35	0.0002	0.00002	7.9E-09
7/21/94	0800	118	2832	169920	10195200	805.50	6.50	18.09	0.26	0.0002	0.00002	7.9E-09
8/24/94	0800	152	3648	218880	13132800	807.31	4.69	19.90	0.19	0.0002	0.00002	8.5E-09
9/21/94	0800	180	4320	259200	15552000	808.47	3.53	21.06	0.14	0.0003	0.00003	9.6E-09
10/20/94	0800	209	5016	300960	18057600	809.20	2.80	21.79	0.11	0.0003	0.00003	1.0E-08
11/16/94	0800	236	5664	339840	20390400	809.73	2.27	22.32	0.09	0.0003	0.00003	1.1E-08
12/14/94	0800	264	6336	380160	22809600	810.20	1.80	22.79	0.07	0.0004	0.00004	1.3E-08
1/18/95	0800	299	7176	430560	25833600	810.65	1.35	23.24	0.05	0.0004	0.00004	1.5E-08
2/14/95	0800	326	7824	469440	28166400	810.83	1.17	23.42	0.05	0.0005	0.00005	1.6E-08
3/23/95	0800	363	8712	522720	31363200	811.01	0.99	23.60	0.04	0.0005	0.00005	1.7E-08
4/12/95	0800	383	9192	551520	33091200	811.07	0.93	23.66	0.04	0.0005	0.00005	1.7E-08
5/24/95	0800	425	10200	612000	36720000	811.21	0.79	23.80	0.03	0.0005	0.00005	1.8E-08
6/20/95	0800	452	10848	650880	39052800	811.32	0.68	23.91	0.03	0.0006	0.00006	2.0E-08
7/18/95	0800	480	11520	691200	41472000	811.45	0.55	24.04	0.02	0.0007	0.00007	2.3E-08
8/23/95	0800	516	12384	743040	44582400	811.63	0.37	24.22	0.02	0.0009	0.00009	3.2E-08
9/14/95	0800	538	12912	774720	46483200	811.75	0.25	24.34	0.01	0.0013	0.00013	4.5E-08

APPENDIX B ADDENDUM C
TABLE C-5
ANALYSIS OF POST-DEVELOPMENT WATER-LEVEL RECOVERY DATA FOR LOWER VANOSS MONITOR WELL LVMW-38
Cushing Remediation Facility

Well Specifics

Date of Well Completion: 6-2-99
Casing Diameter: 2 inches (ID)
Screened Interval: 60 - 70 feet below grade (800 - 790 feet MSL
Time period of water-level recovery data: 6/10/99 - 11/1/99
Equivalent Volume of Water Removed: 8.2 gallons (1.1ft^3)

Date	Time	Days	Hours	Minutes	Seconds	Water-Level Elevation (ft MSL)	Residual Drawdown (feet)	Water-Level Recovery (feet)	H/H_0	Skibitzke (1958) Method: Transmissivity (ft^2/day)	Hydraulic Conductivity (ft^2/day)	Permeability (cm/sec)
6/10/99	0759.59					847.92	0.00	0.00				
6/10/99	0800	0.1	0	1	60	794.77	53.15	0.00	1.00			
6/11/99	0800	1	24	1440	86400	796.17	51.75	1.40	0.97	0.0017	0.00017	5.9E-08
6/21/99	0800	11	264	15840	950400	815.77	32.15	21.00	0.60	0.0002	0.00002	8.6E-09
6/28/99	0800	18	432	25920	1555200	827.57	20.35	32.80	0.38	0.0002	0.00002	8.3E-09
7/6/99	0800	26	624	37440	2246400	835.92	12.00	41.15	0.23	0.0003	0.00003	9.7E-09
7/13/99	0800	33	792	47520	2851200	840.15	7.77	45.38	0.15	0.0003	0.00003	1.2E-08
7/22/99	0800	42	1008	60480	3628800	843.21	4.71	48.44	0.09	0.0004	0.00004	1.5E-08
7/27/99	0800	47	1128	67680	4060800	844.22	3.70	49.45	0.07	0.0005	0.00005	1.7E-08
8/3/99	0800	54	1296	77760	4665600	845.17	2.75	50.40	0.05	0.0006	0.00006	2.0E-08
8/10/99	0800	61	1464	87840	5270400	845.80	2.12	51.03	0.04	0.0007	0.00007	2.3E-08
8/13/99	0800	64	1536	92160	5529600	845.97	1.95	51.20	0.04	0.0007	0.00007	2.4E-08
8/17/99	0800	68	1632	97920	5875200	846.25	1.67	51.48	0.03	0.0008	0.00008	2.7E-08
8/24/99	0800	75	1800	108000	6480000	846.62	1.30	51.85	0.02	0.0009	0.00009	3.1E-08
8/31/99	0800	82	1968	118080	7084800	846.90	1.02	52.13	0.02	0.0010	0.00010	3.6E-08
9/9/99	0800	91	2184	131040	7862400	847.15	0.77	52.38	0.01	0.0012	0.00012	4.3E-08
9/17/99	0800	99	2376	142560	8553600	847.40	0.52	52.63	0.01	0.0017	0.00017	5.9E-08
9/24/99	0800	106	2544	152640	9158400	847.67	0.25	52.90	0.00	0.0033	0.00033	1.1E-07
10/12/99	0800	124	2976	178560	10713600	847.92	0.00	53.15	0.00			
11/1/99	0800	144	3456	207360	12441600	847.92	0.00	53.15	0.00			

APPENDIX B ADDENDUM C
TABLE C-6
ANALYSIS OF POST-DEVELOPMENT WATER-LEVEL RECOVERY DATA LOWER VANOSS FOR MONITOR WELL CMW-39.1 (abandoned)
Cushing Remediation Facility

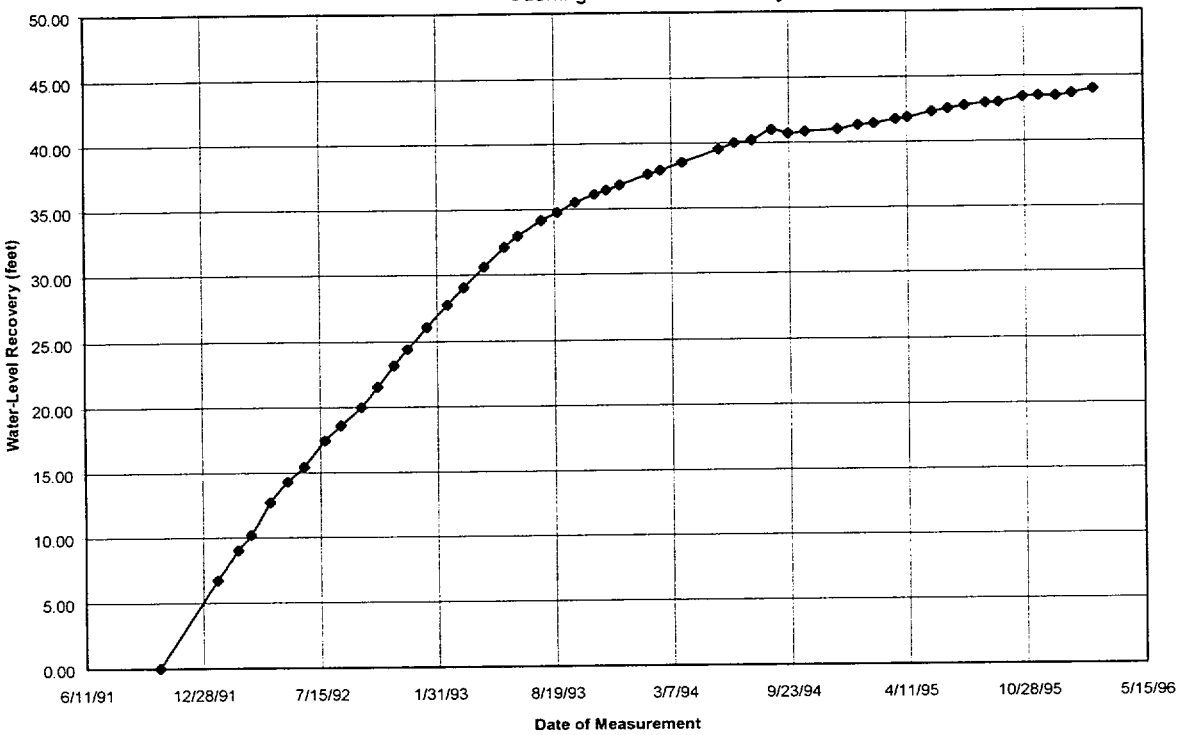
Well Specifics

Date of Well Completion: 6-8-99
Casing Diameter: 2 inches (ID)
Screened Interval: 40 - 60 feet below grade (826 - 806 feet MSL
Time period of water-level recovery data: 7/13/99 - 10/12/99
Equivalent Volume of Water Removed: 3.9 gallons (0.52ft^3)

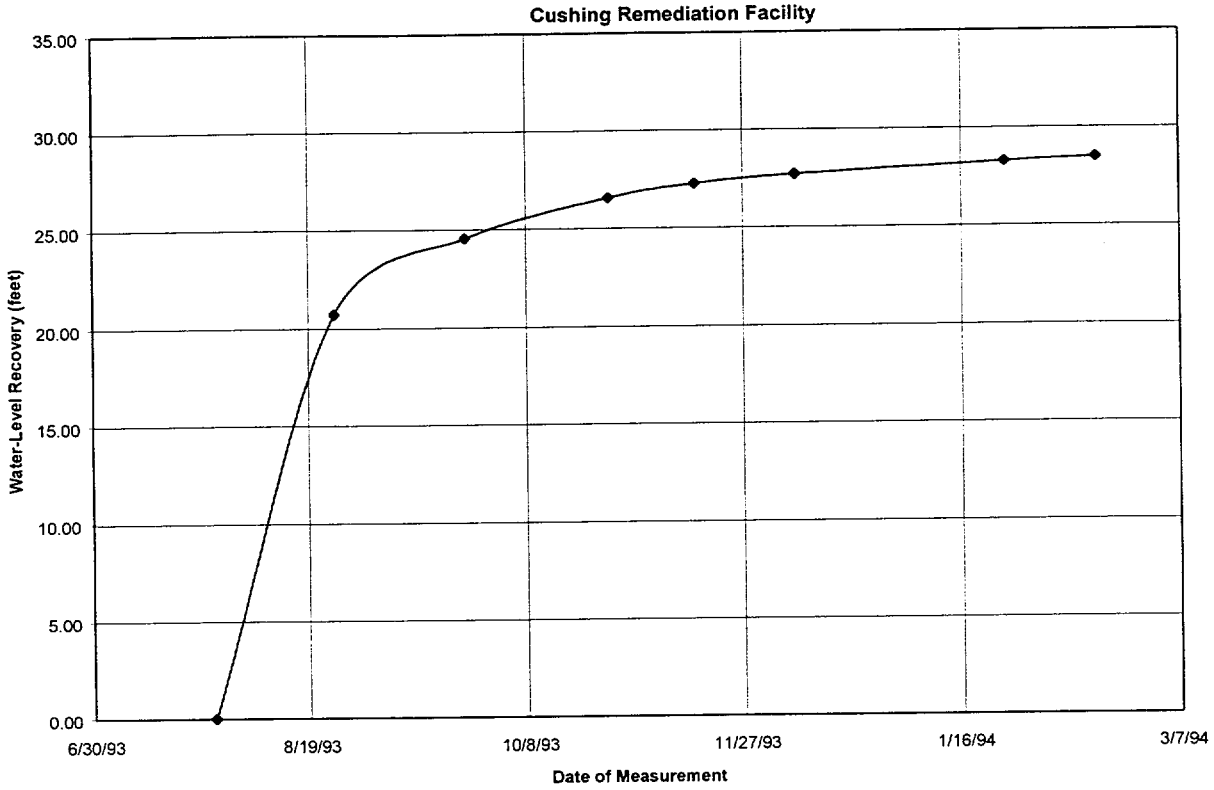
										Skibitzke (1958) Method		
Date	Time	Days	Hours	Minutes	Seconds	Water-Level Elevation (ft MSL)	Residual Drawdown (feet)	Water-Level Recovery (feet)	H/H_o	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft^2/day)	Permeability (cm/sec)
7/13/99	0759.59					849.51	0.00	0.00				
7/13/99	0800	0.1	0	144	8640	823.71	25.80	0.00	1.00			
7/22/99	0800	9	0	12960	777600	830.58	18.93	6.87	0.73	0.0002	0.00001	4.2E-09
7/27/99	0800	14	336	20160	1209600	833.30	16.21	9.59	0.63	0.0002	0.00001	3.2E-09
8/3/99	0800	21	504	30240	1814400	836.55	12.96	12.84	0.50	0.0002	0.00001	2.6E-09
8/10/99	0800	28	672	40320	2419200	839.13	10.38	15.42	0.40	0.0001	0.00001	2.5E-09
8/13/99	0800	31	744	44640	2678400	840.13	9.38	16.42	0.36	0.0001	0.00001	2.5E-09
8/17/99	0800	35	840	50400	3024000	841.28	8.23	17.57	0.32	0.0001	0.00001	2.5E-09
8/24/99	0800	42	1008	60480	3628800	842.88	6.63	19.17	0.26	0.0001	0.00001	2.6E-09
8/31/99	0800	49	1176	70560	4233600	844.26	5.25	20.55	0.20	0.0002	0.00001	2.8E-09
9/9/99	0800	58	1392	83520	5011200	845.70	3.81	21.99	0.15	0.0002	0.00001	3.3E-09
9/17/99	0800	66	1584	95040	5702400	846.79	2.72	23.08	0.11	0.0002	0.00001	4.0E-09
9/24/99	0800	73	1752	105120	6307200	847.75	1.76	24.04	0.07	0.0003	0.00002	5.6E-09
10/12/99	0800	91	2184	131040	7862400	849.51	0.00	25.80	0.00			

APPENDIX B
ADDENDUM D
ARITHMETIC PLOTS OF WATER-LEVEL DATA

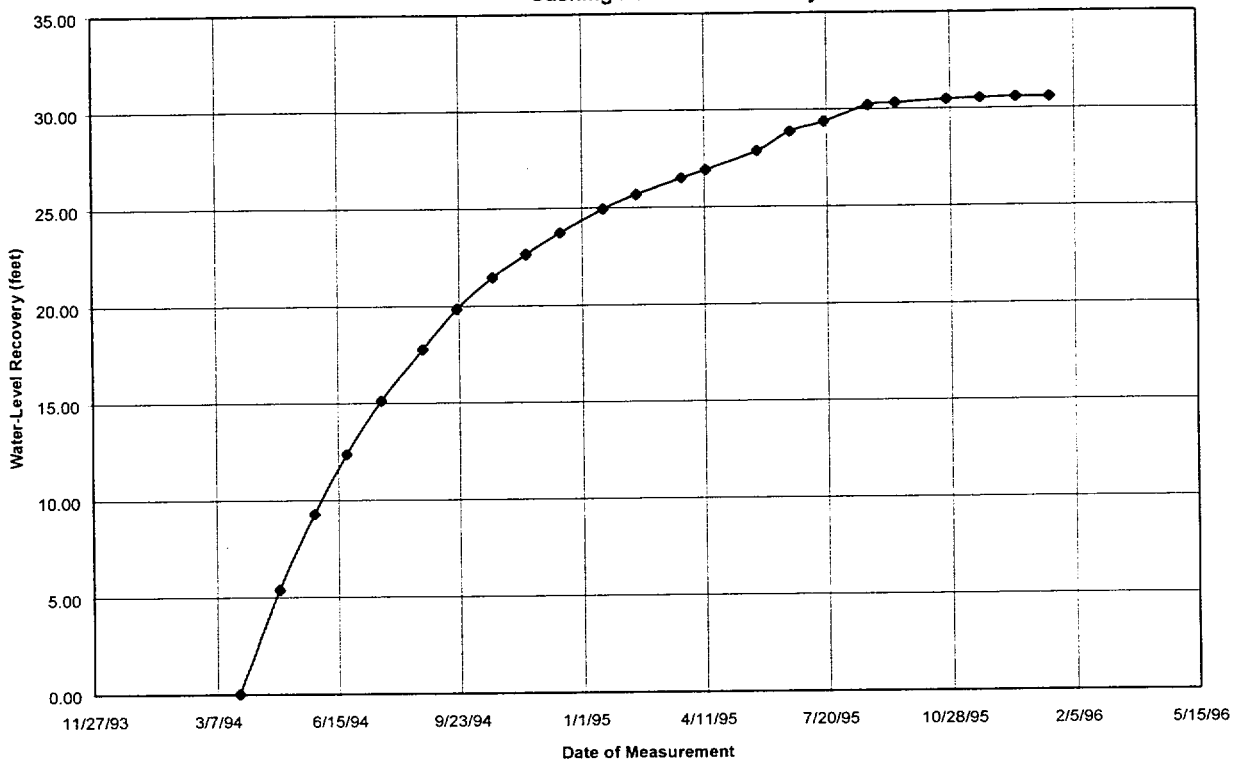
APPENDIX B ADDENDUM D
FIGURE D-1
ARITHMETIC PLOT OF POST-SAMPLING WATER-LEVEL RECOVERY DATA
MONITOR WELL LVMW-2
Cushing Remediation Facility



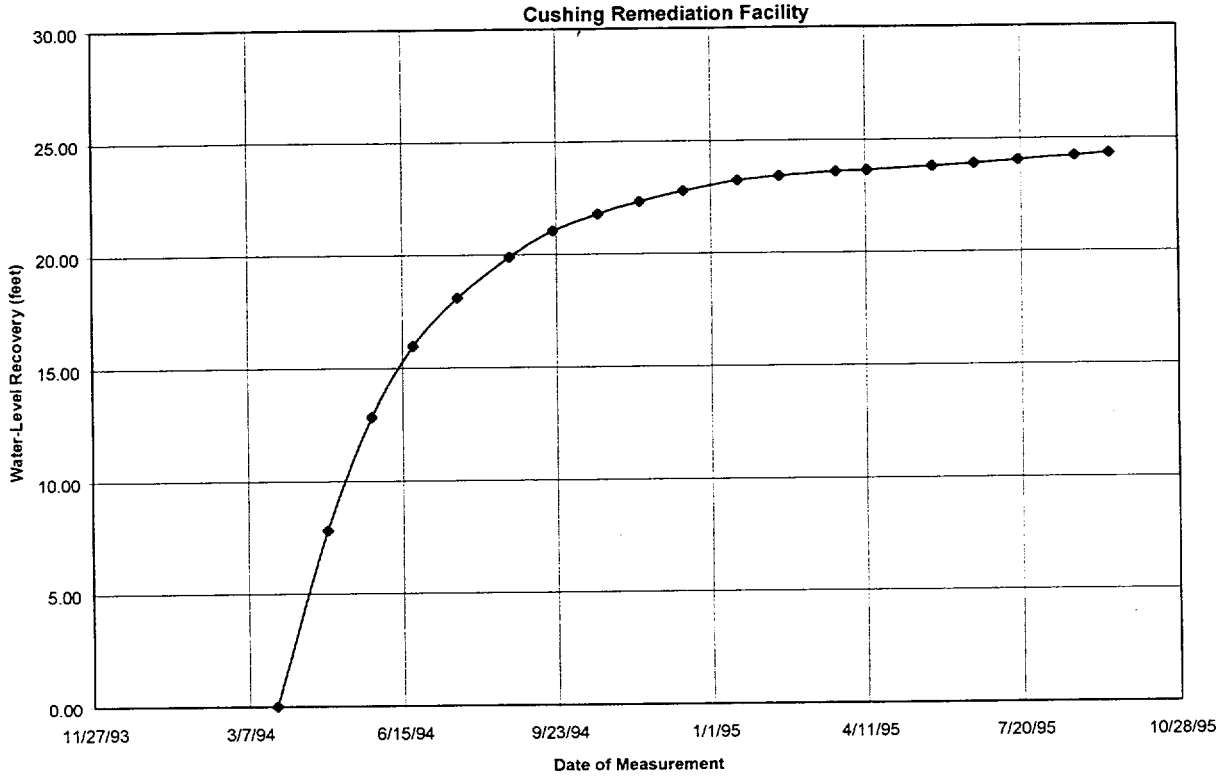
APPENDIX B ADDENDUM D
FIGURE D-2
ARITHMETIC PLOT OF POST-DEVELOPMENT WATER-LEVEL RECOVERY DATA
MONITOR WELL LVMW-30.2
Cushing Remediation Facility



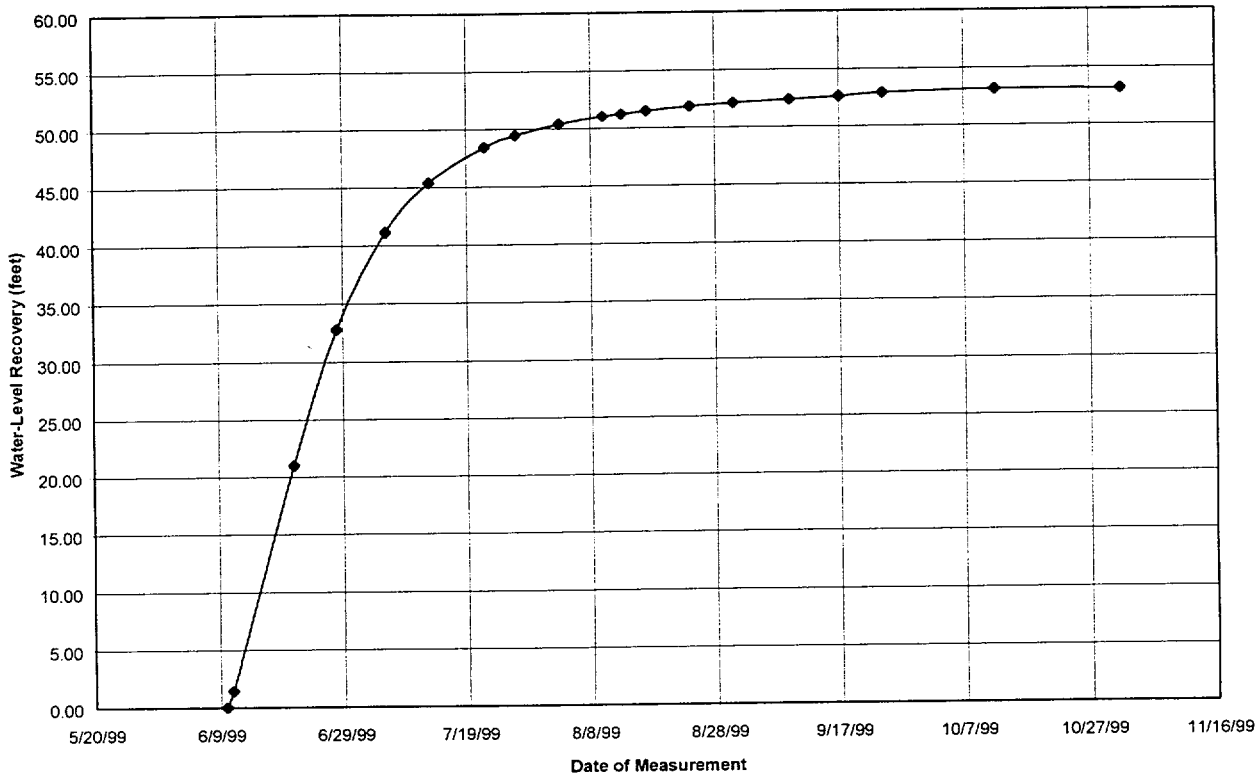
APPENDIX B ADDENDUM D
FIGURE D-3
ARITHMETIC PLOT OF POST-SAMPLING WATER-LEVEL RECOVERY DATA
MONITOR WELL LVMW-30.2
Cushing Remediation Facility



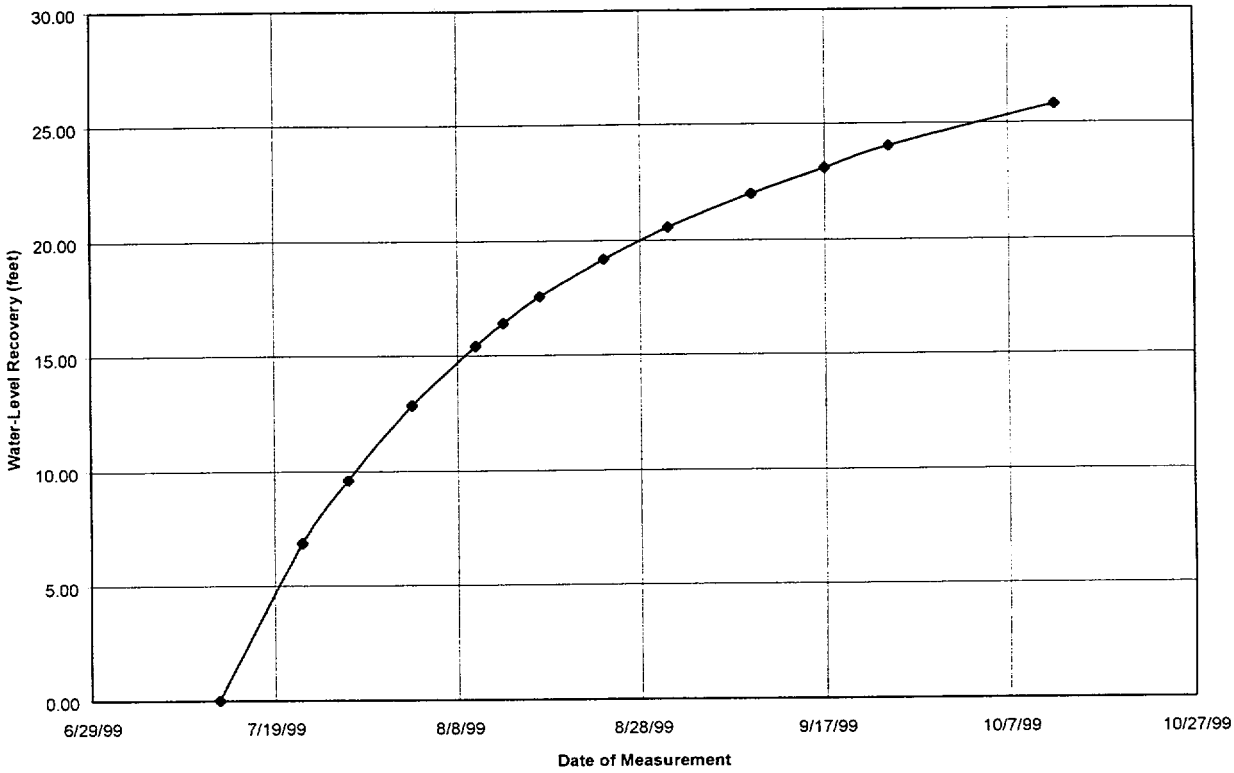
APPENDIX B ADDENDUM D
FIGURE D-4
ARITHMETIC PLOT OF POST-SAMPLING WATER-LEVEL RECOVERY DATA
MONITOR WELL LVMW-32.1
Cushing Remediation Facility



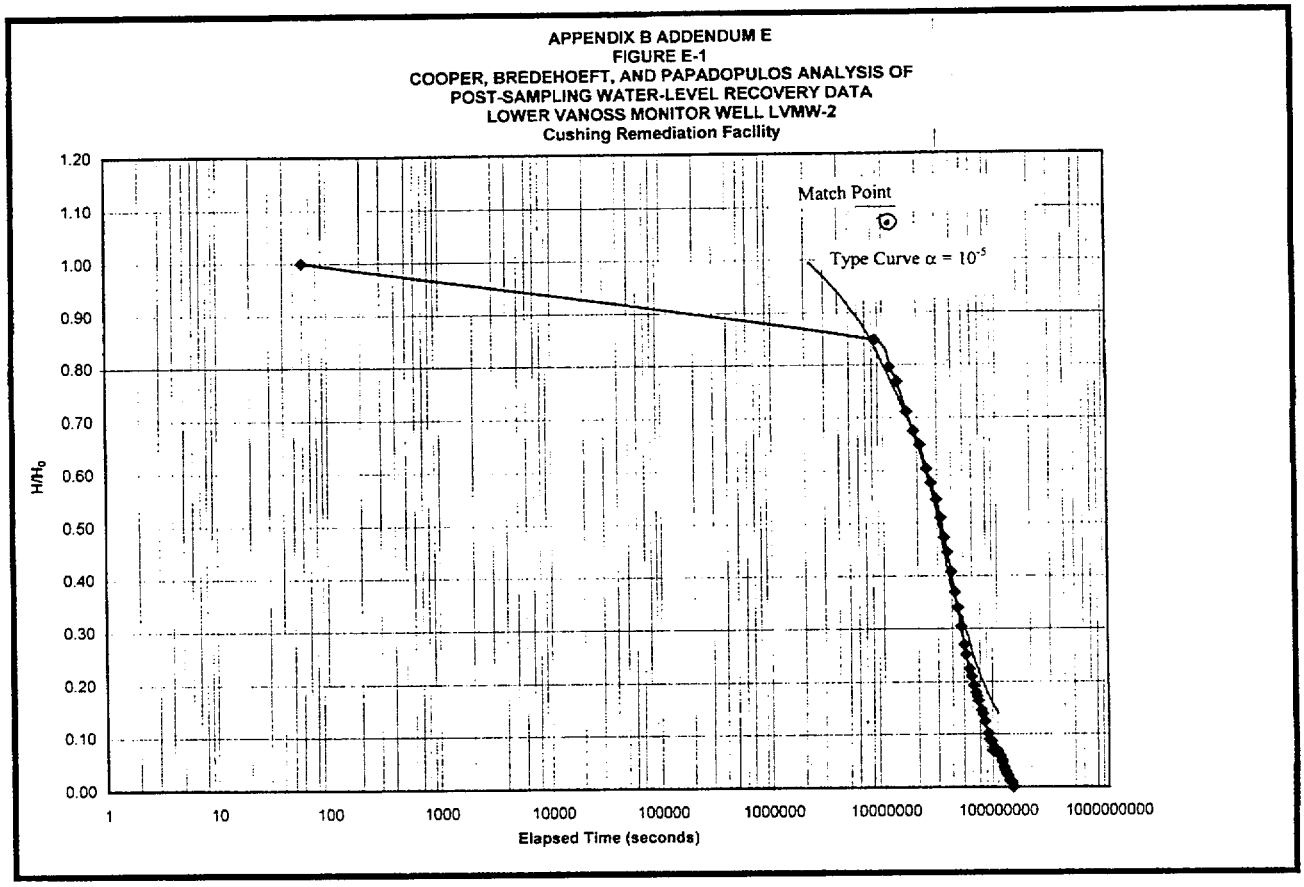
APPENDIX B ADDENDUM D
FIGURE D-5
ARITHMETIC PLOT OF POST-DEVELOPMENT WATER-LEVEL RECOVERY DATA
MONITOR WELL LVMW-38
Cushing Remediation Facility

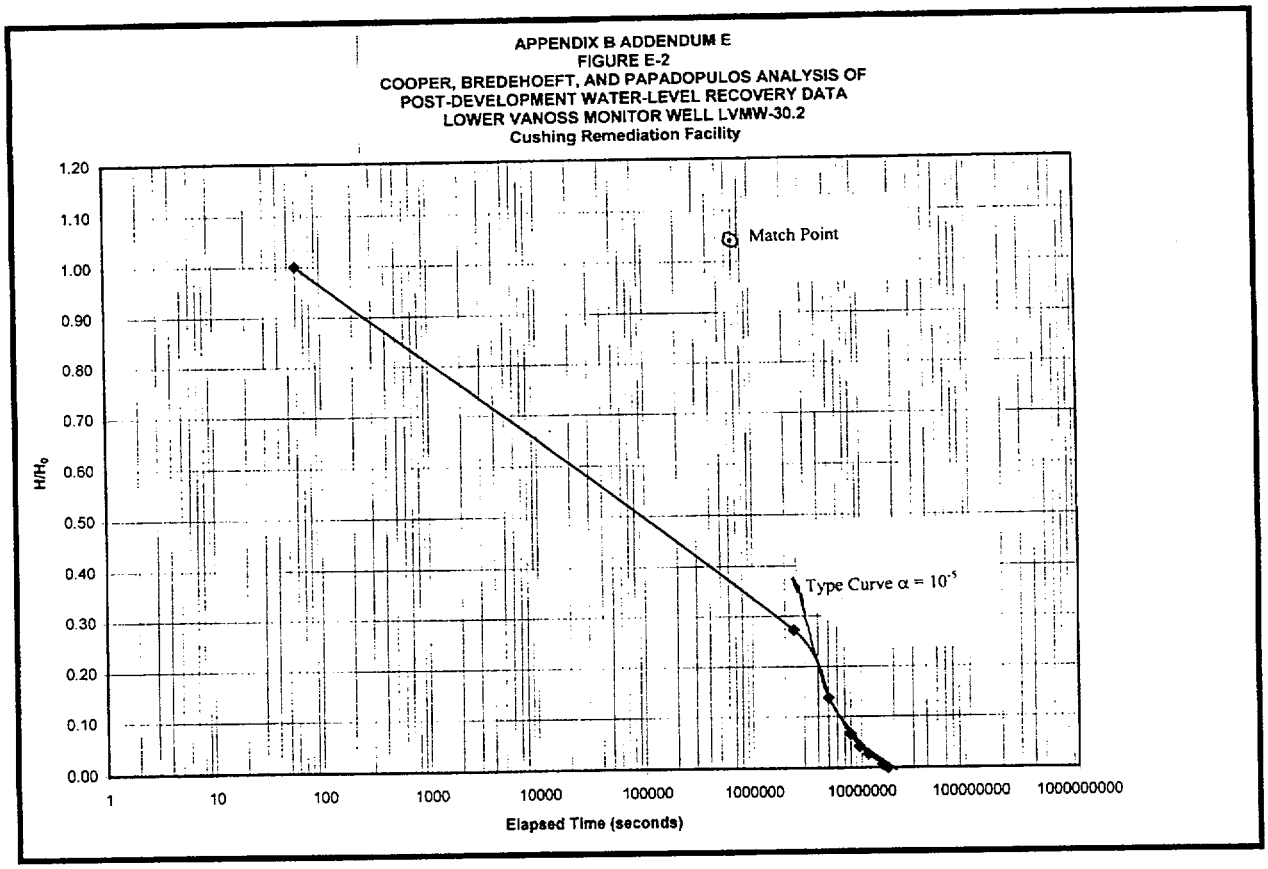


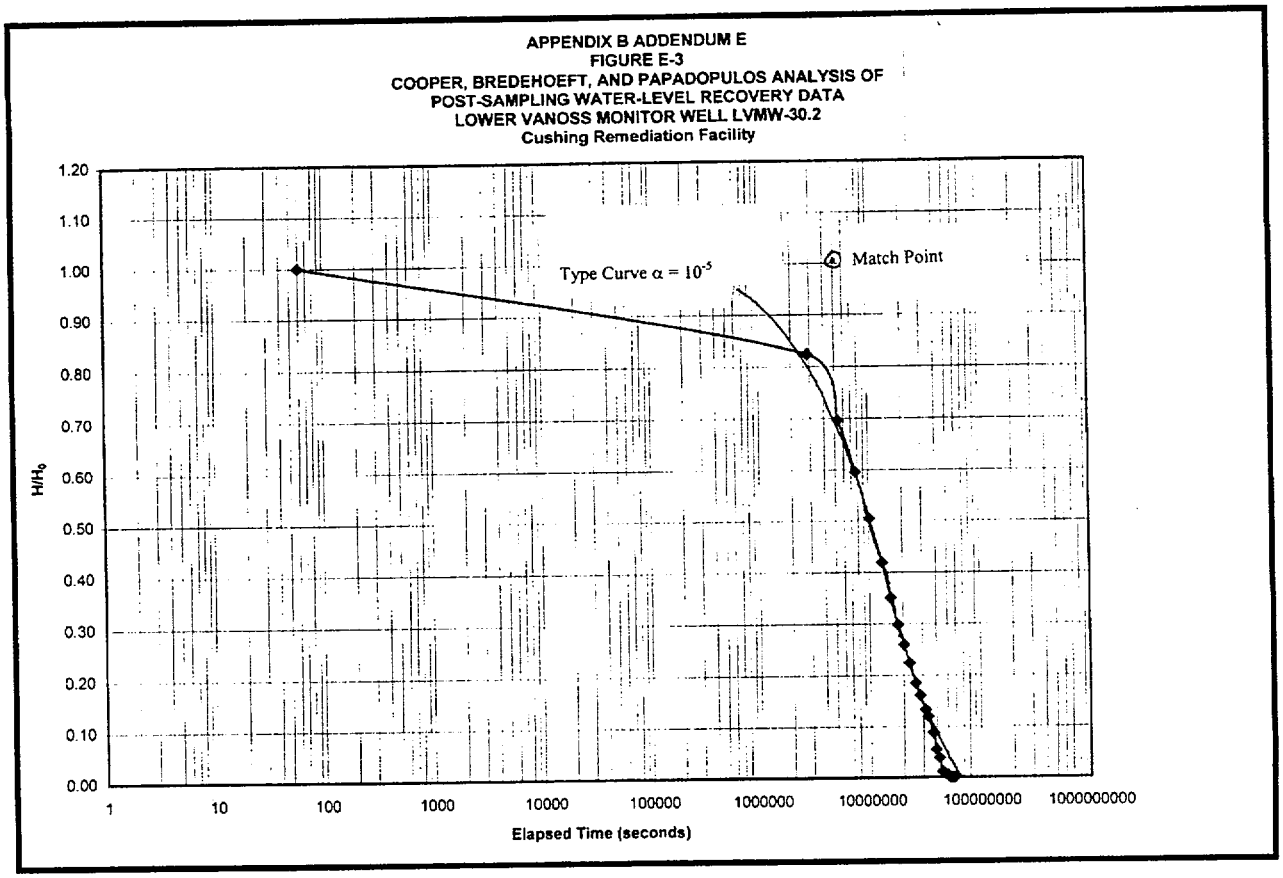
APPENDIX B ADDENDUM D
FIGURE D-6
ARITHMETIC PLOT OF POST-DEVELOPMENT WATER-LEVEL RECOVERY DATA
MONITOR WELL LVMW-39
Cushing Remediation Facility

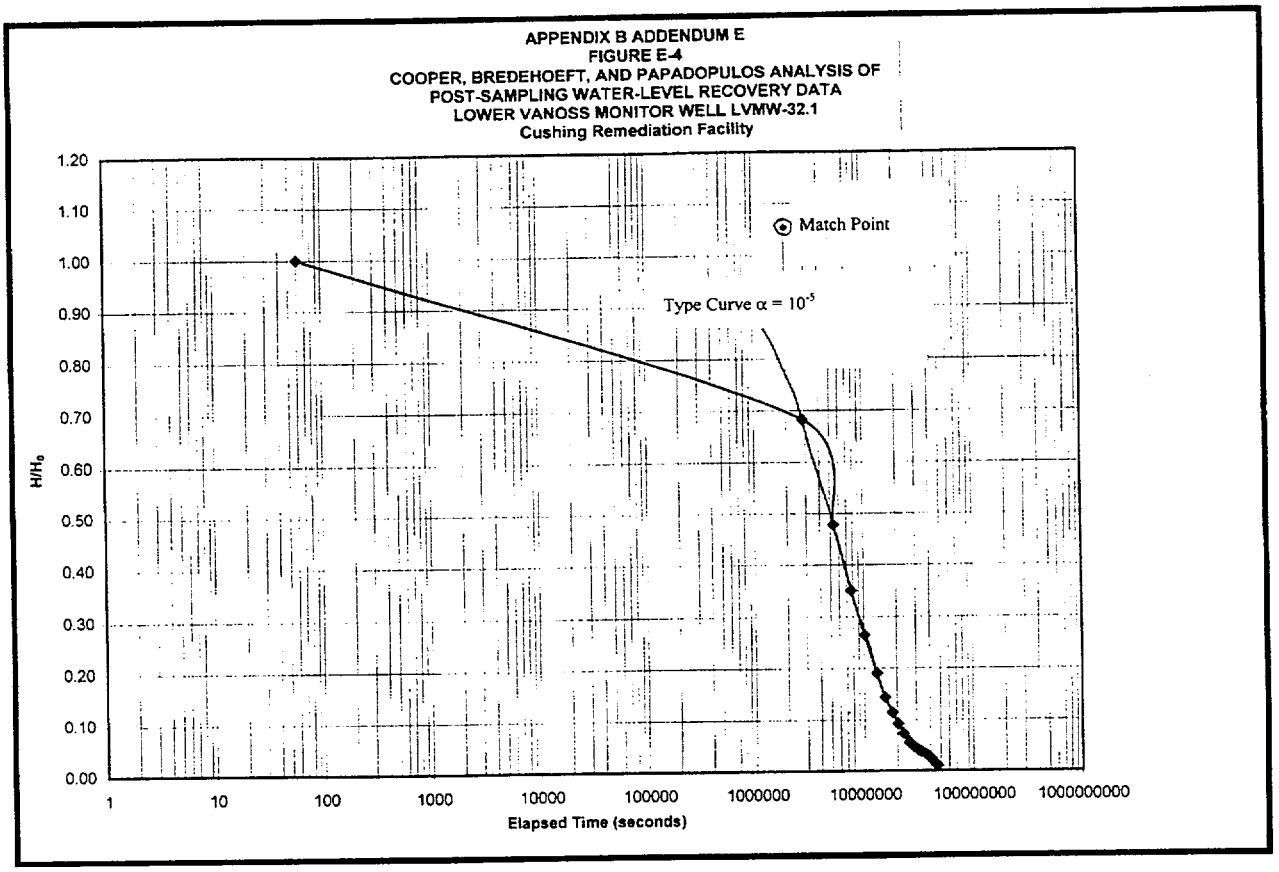


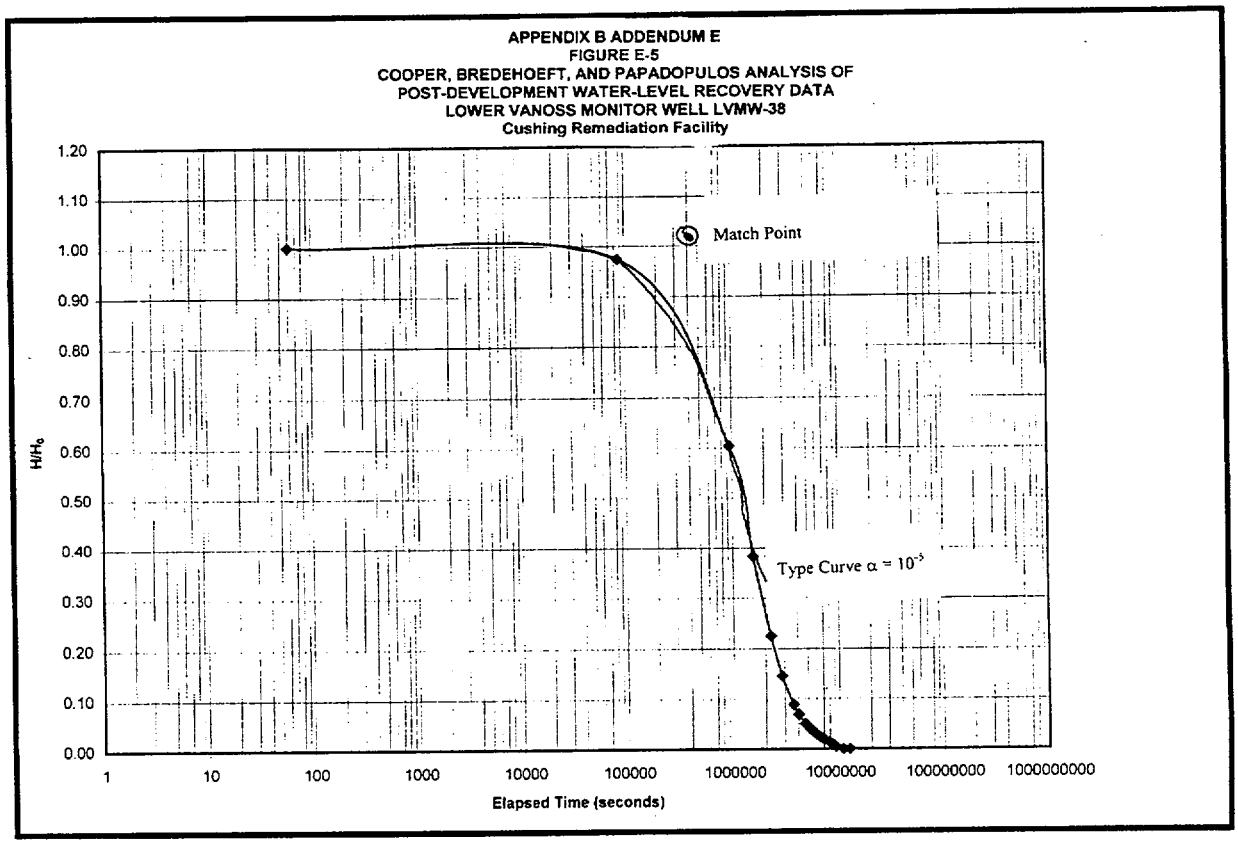
APPENDIX B
ADDENDUM E
SEMI-LOG PLOTS OF H/H_O VERSUS TIME

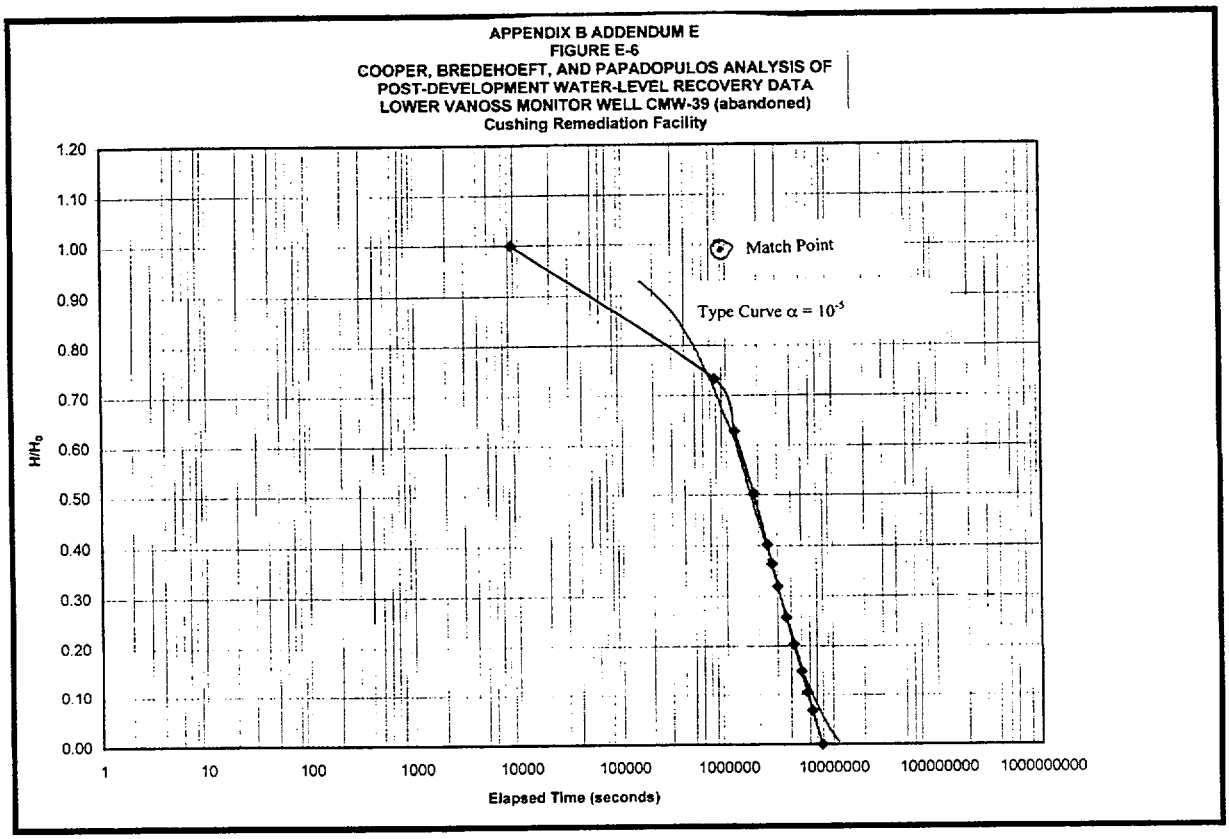

APPENDIX B ADDENDUM E
FIGURE E-1
COOPER, BREDEHOEFT, AND PAPADOPULOS ANALYSIS OF
POST-SAMPLING WATER-LEVEL RECOVERY DATA
LOWER VANOSS MONITOR WELL LVMW-2
Cushing Remediation Facility
Match Point
Type Curve α = 10^-5
H/H0
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
10
100
1000
10000
100000
1000000
10000000
100000000
1000000000
Elapsed Time (seconds)


APPENDIX B ADDENDUM E
FIGURE E-2
COOPER, BREDEHOEFT, AND PAPADOPULOS ANALYSIS OF
POST-DEVELOPMENT WATER-LEVEL RECOVERY DATA
LOWER VANOSS MONITOR WELL LVMW-30.2
Cushing Remediation Facility
Match Point
Type Curve α = 10⁻⁵
H/H₀
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
10
100
1000
10000
100000
1000000
10000000
100000000
1000000000
Elapsed Time (seconds)


APPENDIX B ADDENDUM E
FIGURE E-3
COOPER, BREDEHOEFT, AND PAPADOPULOS ANALYSIS OF
POST-SAMPLING WATER-LEVEL RECOVERY DATA
LOWER VANOSS MONITOR WELL LVMW-30.2
Cushing Remediation Facility
Type Curve α = 10^-5
Match Point
H/H0
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
10
100
1000
10000
100000
1000000
10000000
100000000
1000000000
Elapsed Time (seconds)


APPENDIX B ADDENDUM E
FIGURE E-4
COOPER, BREDEHOEFT, AND PAPADOPULOS ANALYSIS OF
POST-SAMPLING WATER-LEVEL RECOVERY DATA
LOWER VANOSS MONITOR WELL LVMW-32.1
Cushing Remediation Facility
Match Point
Type Curve α = 10^-5
H/H0
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
10
100
1000
10000
100000
1000000
10000000
100000000
1000000000
Elapsed Time (seconds)


APPENDIX B ADDENDUM E
FIGURE E-5
COOPER, BREDEHOEFT, AND PAPADOPULOS ANALYSIS OF
POST-DEVELOPMENT WATER-LEVEL RECOVERY DATA
LOWER VANOSS MONITOR WELL LVMW-38
Cushing Remediation Facility
Match Point
Type Curve α = 10^-5
H/H0
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
10
100
1000
10000
100000
1000000
10000000
100000000
1000000000
Elapsed Time (seconds)


APPENDIX B ADDENDUM E
FIGURE E-6
COOPER, BREDEHOEFT, AND PAPADOPULOS ANALYSIS OF
POST-DEVELOPMENT WATER-LEVEL RECOVERY DATA
LOWER VANOSS MONITOR WELL CMW-39 (abandoned)
Cushing Remediation Facility
Match Point
Type Curve α = 10^-5
H/H0
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
10
100
1000
10000
100000
1000000
10000000
100000000
1000000000
Elapsed Time (seconds)

APPENDIX B
ADDENDUM F
TABULATIONS OF COOPER, BREDEHOEFT, AND PAPADOPULOS ANALYSES

APPENDIX B ADDENDUM F
TABLE F-1
Cooper, Bredehoeft, and Papadopulos Analysis of Post-Sampling Water-Level Recovery Data Lower Vanoss Monitor Well LVMW-2

Date of well completion: 5-17-85
Casing Diameter: 4-inches (ID)
Screened interval: 60 - 70 feet below grade (804 - 794 feet MSL)
Completed interval: 40.5 - 70 feet below grade (823.5 - 794 feet MSL)
Time period of water-level recovery data: 10/15/91 - 2/21/96
Match Point Data: $H/H_0 = 1$; $Tt/r_c^2 = 1$; $t = 15{,}000{,}000$ seconds; Type Curve = 10^{-5}

$$T = \frac{(Tt/r_c^2)\text{x}(86400\text{seconds/day})\text{x}(r_c^2)}{t}$$

$$T = \frac{(1)\text{x}(86400\text{seconds/day})\text{x}(0.167\text{ft})^2}{15{,}000{,}000 \text{ seconds}} = \frac{2410}{15{,}000{,}000 \text{ seconds}} = 0.0002\text{ft}^2\text{/day}$$

$$K = \frac{0.0002\text{ft}^2\text{/day}}{29.5\text{-foot completion zone}} = 0.000007 \text{ ft/day}$$

$$P = \frac{0.000007 \text{ ft/day x } 30\text{cm/ft}}{86400\text{seconds/day} =} = 2.4\text{x}10^{-9}\text{cm/second}$$

APPENDIX B ADDENDUM F
TABLE F-2
Cooper, Bredehoeft, and Papadopulos Analysis of Post-Development Water-Level Recovery Data Lower Vanoss Monitor Well LVMW-30.2

Date of well completion: 7-15-93
Casing Diameter: 4-inches (ID)
Screened interval: 91 - 101 feet below grade (801 - 791 feet MSL)
Completed interval: 88 - 103 feet below grade (804 - 789 feet MSL)
Time period of water-level recovery data: 7/28/93 - 2/16/94
Match Point Data: $H/H_0 = 1$; $Tt/r_c^2 = 1$; t = 700,000 seconds; Type Curve = 10^{-5}

$$T = \frac{(Tt/r_c^2)x(86400\text{seconds/day})x(r_c^2)}{t}$$

$$T = \frac{(1)x(86400\text{seconds/day})x(0.167\text{ft})^2}{700{,}000\text{ seconds}} = \frac{2410}{700{,}000\text{ seconds}} = 0.0034\text{t}^2\text{/day}$$

$$K = \frac{0.0034\text{ft}^2\text{/day}}{15\text{-foot completion zone}} = 0.0002\text{ ft/day}$$

$$P = \frac{0.0002\text{ ft/day x 30cm/ft}}{86400\text{seconds/day} =} = 7.0x10^{-8}\text{cm/second}$$

APPENDIX B ADDENDUM F
TABLE F-3
Cooper, Bredehoeft, and Papadopulos Analysis of Post-Sampling Water-Level Recovery Data Lower Vanoss Monitor Well LVMW-30.2

Date of well completion: 7-15-93
Casing Diameter: 4-inches (ID)
Screened interval: 91 - 101 feet below grade (801 - 791 feet MSL)
Completed interval: 88 - 103 feet below grade (804 - 789 feet MSL)
Time period of water-level recovery data: 3/25/94 - 1/16/96
Match Point Data: $H/H_0 = 1$; $Tt/r_c^2 = 1$; $t = 5{,}000{,}000$ seconds; Type Curve = 10^{-5}

$$T = \frac{(Tt/r_c^2)x(86400\text{seconds/day})x(r_c^2)}{t}$$

$$T = \frac{(1)x(86400\text{seconds/day})x(0.167\text{ft})^2}{5{,}000{,}000 \text{ seconds}} = \frac{2410}{5{,}000{,}000 \text{ seconds}} = 0.0005\text{t}^2\text{/day}$$

$$K = \frac{0.0005\text{ft}^2\text{/day}}{15\text{-foot completion zone}} = 0.00003 \text{ ft/day}$$

$$P = \frac{0.00003 \text{ ft/day x } 30\text{cm/ft}}{86400\text{seconds/day} =} = 1.0x10^{-8}\text{cm/second}$$

APPENDIX B ADDENDUM F
TABLE F-4
Cooper, Bredehoeft, and Papadopulos Analysis of Post-Sampling Water-Level Recovery Data Lower Vanoss Monitor Well LVMW-32.1

Date of well completion: 7-17-93
Casing Diameter: 4-inches (ID)
Screened interval: 61 - 71 feet below grade (790 - 780 feet MSL)
Completed interval: 58 - 73 feet below grade (793 - 778 feet MSL)
Time period of water-level recovery data: 3/25/94 - 9/14/95
Match Point Data: $H/H_0 = 1$; $Tt/r_c^2 = 1$; $t = 2{,}000{,}000$ seconds; Type Curve = 10^{-5}

$$T = \frac{(Tt/r_c^2)\text{x}(86400\text{seconds/day})\text{x}(r_c^2)}{t}$$

$$T = \frac{(1)\text{x}(86400\text{seconds/day})\text{x}(0.167\text{ft})^2}{2{,}000{,}000 \text{ seconds}} = \frac{2410}{2{,}000{,}000 \text{ seconds}} = 0.001\text{ft}^2\text{/day}$$

$$K = \frac{0.001\text{ft}^2\text{/day}}{15\text{-foot completed zone}} = 0.00007 \text{ ft/day}$$

$$P = \frac{0.00007 \text{ ft/day x } 30\text{cm/ft}}{86400\text{seconds/day} =} = 2.4\text{x}10^{-8}\text{cm/second}$$

APPENDIX B ADDENDUM F
TABLE F-5
Cooper, Bredehoeft, and Papadopulos Analysis of Post-Development Water-Level Recovery Data Lower Vanoss Monitor Well LVMW-38

Date of well completion: 6-2-99
Casing Diameter: 2-inches (ID)
Screened interval: 60 - 70 feet below grade 800 - 790 feet MSL)
Completion interval: 50 - 72 feet below grade 810 - 788 feet MSL)
Time period of water-level recovery data: 6/10/99 - 11/1/99
Match Point Data: $H/H_0 = 1$; $Tt/r_c^2 = 1$; $t = 420{,}000$ seconds; Type Curve = 10^{-5}

$$T = \frac{(Tt/r_c^2)x(86400\text{seconds/day})x(r_c^2)}{t}$$

$$T = \frac{(1)x(86400\text{seconds/day})x(0.083\text{ft})^2}{420{,}000\text{ seconds}} = \frac{595}{420{,}000\text{ seconds}} = 0.0014\text{ft}^2\text{/day}$$

$$K = \frac{0.0014\text{ft}^2\text{/day}}{22\text{-foot completed zone}} = 0.00006\text{ ft/day}$$

$$P = \frac{0.00006\text{ ft/day x 30cm/ft}}{86400\text{seconds/day} =} = 2.1x10^{-8}\text{cm/second}$$

APPENDIX B ADDENDUM F
TABLE F-6
Cooper, Bredehoeft, and Papadopulos Analysis of Post-Development Water-Level Recovery Data
Lower Vanoss Monitor Well CMW-39.1 (abandoned)

Date of well completion: 6-8-99
Casing Diameter: 2-inches (ID)
Screened interval: 40 - 60 feet below grade 826 - 806 feet MSL)
Completion interval: 37 - 62 feet below grade 829 - 804 feet MSL)
Time period of water-level recovery data: 7/13/99 - 10/12/99
Match Point Data: $H/H_0 = 1$; $Tt/r_c^2 = 1$; t = 800,000 seconds; Type Curve = 10^{-5}

$$T = \frac{(Tt/r_c^2)x(86400\text{seconds/day})x(r_c^2)}{t}$$

$$T = \frac{(1)x(86400\text{seconds/day})x(0.083\text{ft})^2}{800{,}000\text{ seconds}} = \frac{595}{800{,}000\text{ seconds}} = 0.0007\text{ft}^2\text{/day}$$

$$K = \frac{0.0007\text{ft}^2\text{/day}}{25\text{-foot completed zone}} = 0.00003\text{ ft/day}$$

$$P = \frac{0.00003\text{ ft/day x 30cm/ft}}{86400\text{seconds/day} =} = 1.0x10^{-8}\text{cm/second}$$

APPENDIX C

DATA FOR STIFF AND RADAR DIAGRAM ANALYSES

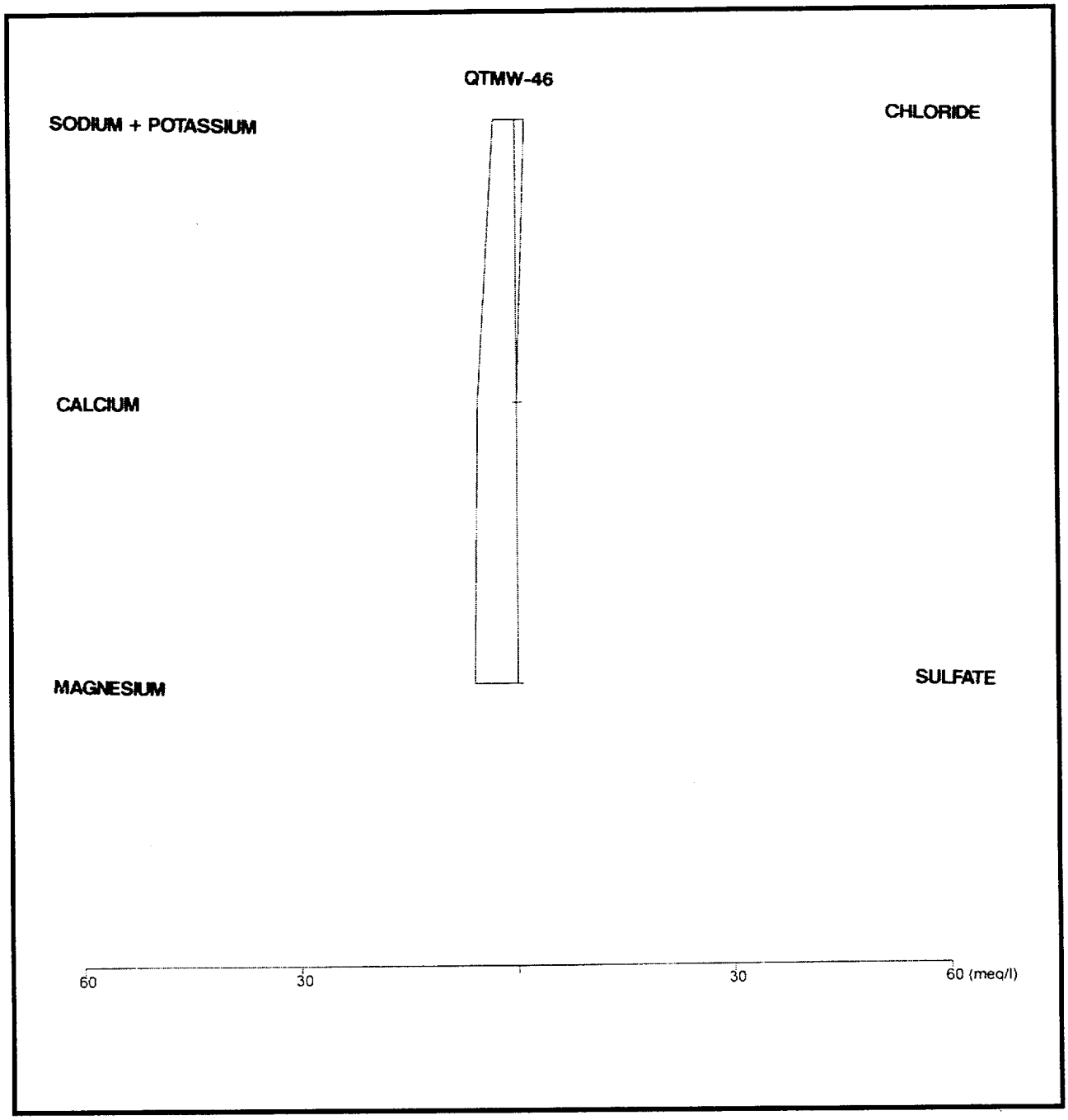
APPENDIX C
DATA FOR STIFF AND RADAR DIAGRAM ANALYSES OF CUSHING GROUNDWATER QUALITY PARAMETER DATA

Well	Field pH	Total Dissolved Solids (mg/l)	Sodium (mg/l)	Potassium (mg/l)	Sodium + Potassium (mg/l)	Calcium (mg/l)	Magnesium (mg/l)	Chloride mg/l	Sulfate mg/l	Radar Diagram Alkalinity mg/l	Radar Diagram Sulfate mg/l
QTMW-46 Stream Terrace Sediments (819-833ft MSL)	6.79	668	66.600	0.996	67.60	107.000	71.400	44.900	1.000	611	1
QTMW-49 Stream Terrace Sediments (819-833ft MSL)	6.43	882	243.000	0.307	243.31	44.100	26.900	112.000	0.000	584	0
UVMW-50.1 Mudstone (885-876ft MSL)	7.55	488	224.000	3.330	227.33	54.900	24.800	45.900	61.300	253	61
UVMW-43 Mudstone & Sandstone (868-853ft MSL)	7.30	1680	514.000	0.613	514.61	41.500	34.200	237.000	6.430	1030	6
UVMW-52.2 Sandstone (858-871ft MSL)	7.31	1440	272.000	3.340	275.34	99.200	90.200	360.000	218.000	445	218
UVMW-41 Sandstone w/Thin Mudstone (862-846ft MSL)	6.95	1060	102.000	5.940	107.94	183.000	60.400	40.200	136.000	356	136
UVMW-11 Mudstone w/Thin Sandstone (864-843ft MSL)	7.55	460	65.100	2.170	67.27	55.700	34.400	75.300	27.800	225	28
UVMW-18 Mudstone & Sandstone (862-841ft MSL)	6.96	678	77.500	0.773	78.27	111.000	42.900	5.850	133.000	442	133
UVMW-23 Sandstone w/Thin Mudstone (835-856ft MSL)	7.51	788	163.000	1.470	164.47	81.000	59.100	92.700	53.400	526	53
LVMW-30.1 Mudstone & Sandstone (828-810ft MSL)	7.23	2400	192.000	9.860	201.86	355.000	95.600	75.100	1290.000	309	1290
LVMW-40 Mudstone & Sandstone (826-806ft MSL)	7.99	4330	701.000	16.400	717.40	408.000	120.000	21.100	2490.000	179	2490
LVMW-31 Mudstone & Sandstone (819-804ft MSL)	7.64	3890	435.000	22.200	457.20	416.000	176.000	61.700	2180.000	206	2180
LVMW-38 Silty Mudstone (788-810ft MSL)	7.26	4520	794.000	16.000	810.00	378.000	120.000	46.000	2220.000	685	2220
LVMW-31.1 Mudstone & Siltstone (793-773ft MSL)	8.80	4520	852.000	38.700	890.70	413.000	82.000	26.400	2790.000	41	2790
LVMW-18 Mudstone & Sandstone (790-771ft MSL)	7.82	3770	464.000	13.300	477.30	442.000	135.000	12.100	2120.000	67	2120
LVMW-20.1 Mudstone & Sandstone (758-780ft MSL)	7.40	2840	529.000	10.300	539.30	234.000	78.100	40.900	1730.000	66	1730
VAMW-29 Mudstone & Sandstone (726-649ft MSL)	7.97	1620	433.000	5.090	438.09	52.900	33.500	114.000	743.000	252	743

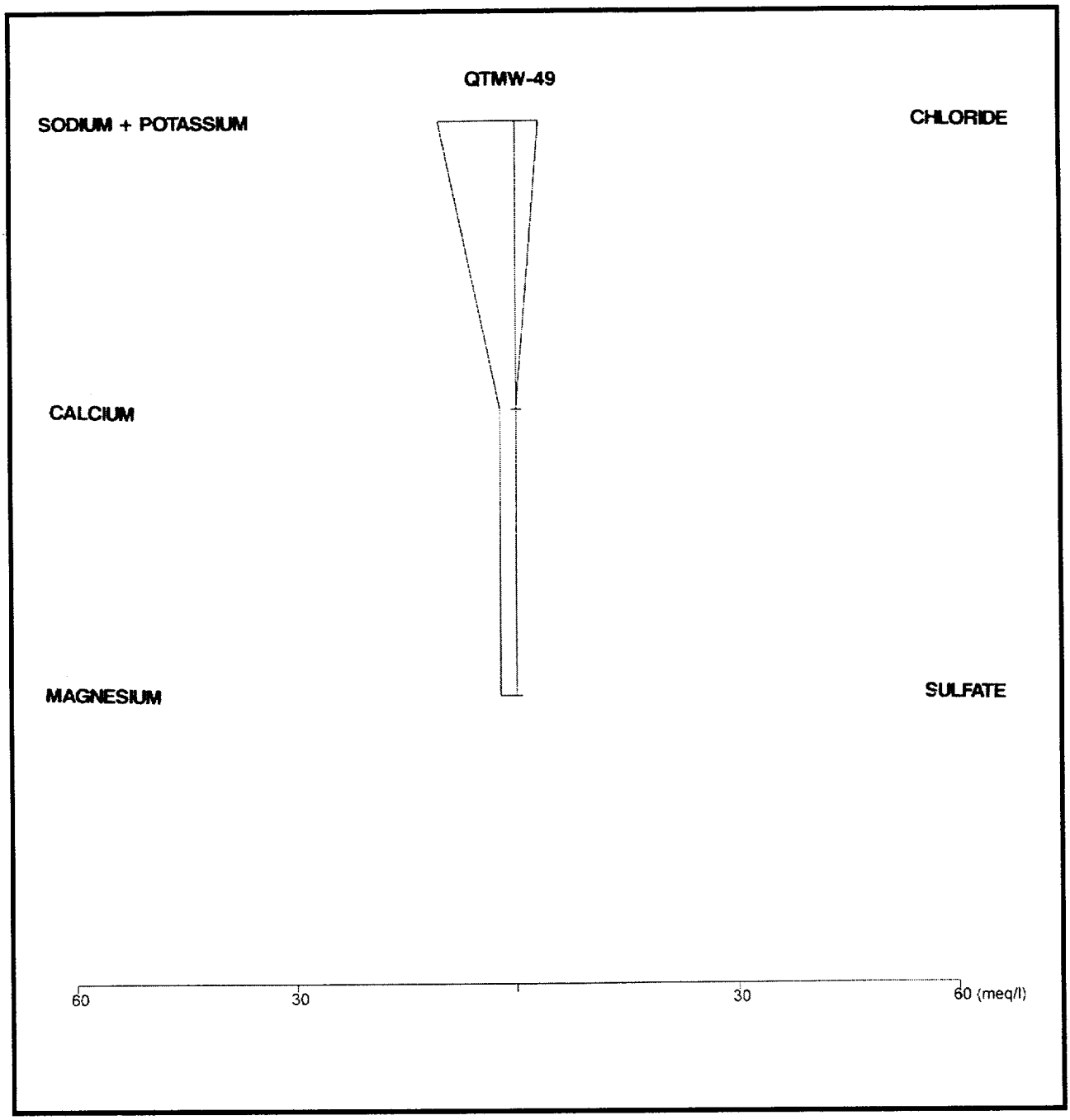
APPENDIX D

STIFF DIAGRAMS

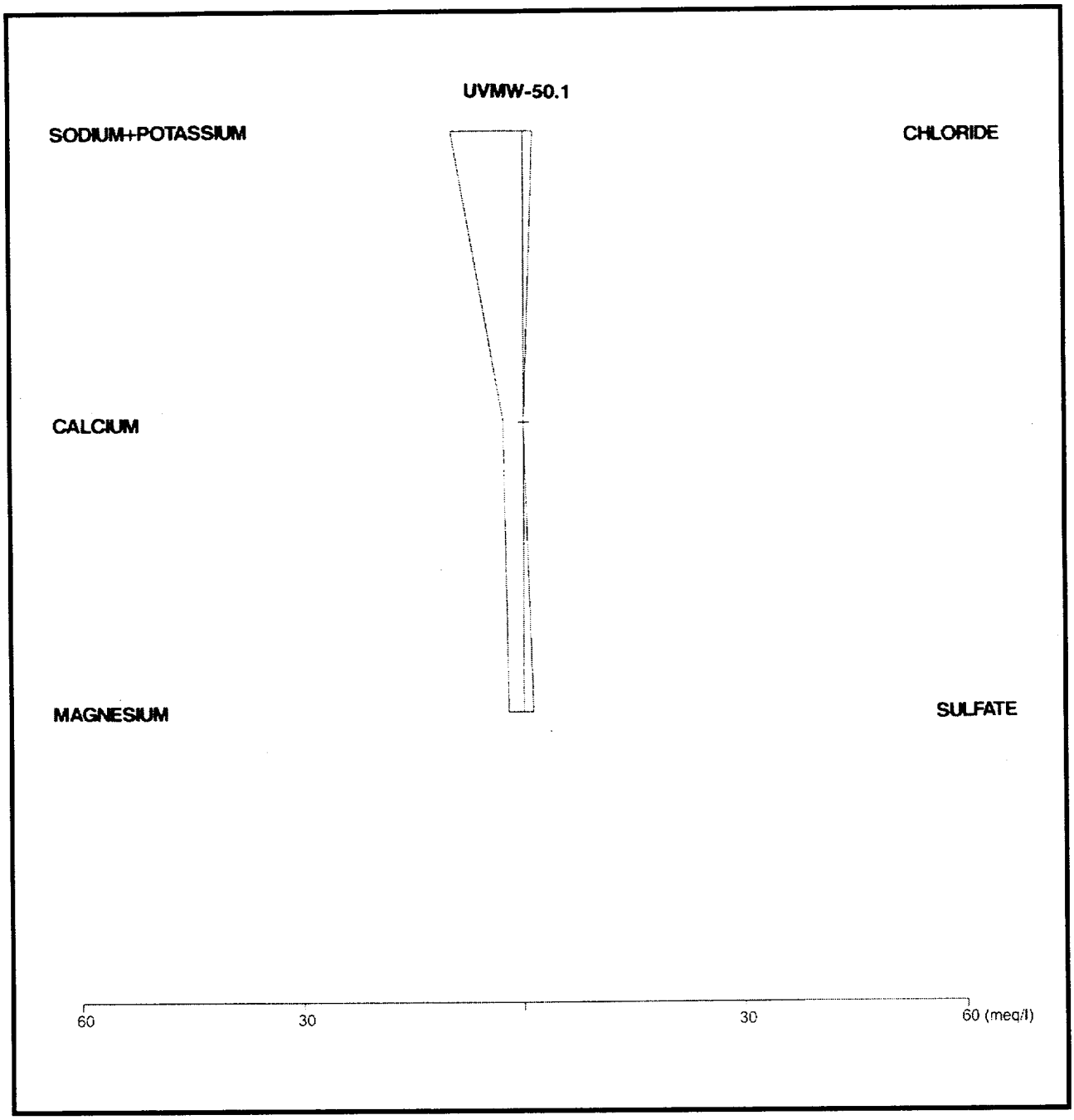
APPENDIX D
FIGURE D-1
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR QUATERNARY STREAM TERRACE REGIME MONITOR WELL UVMW-46



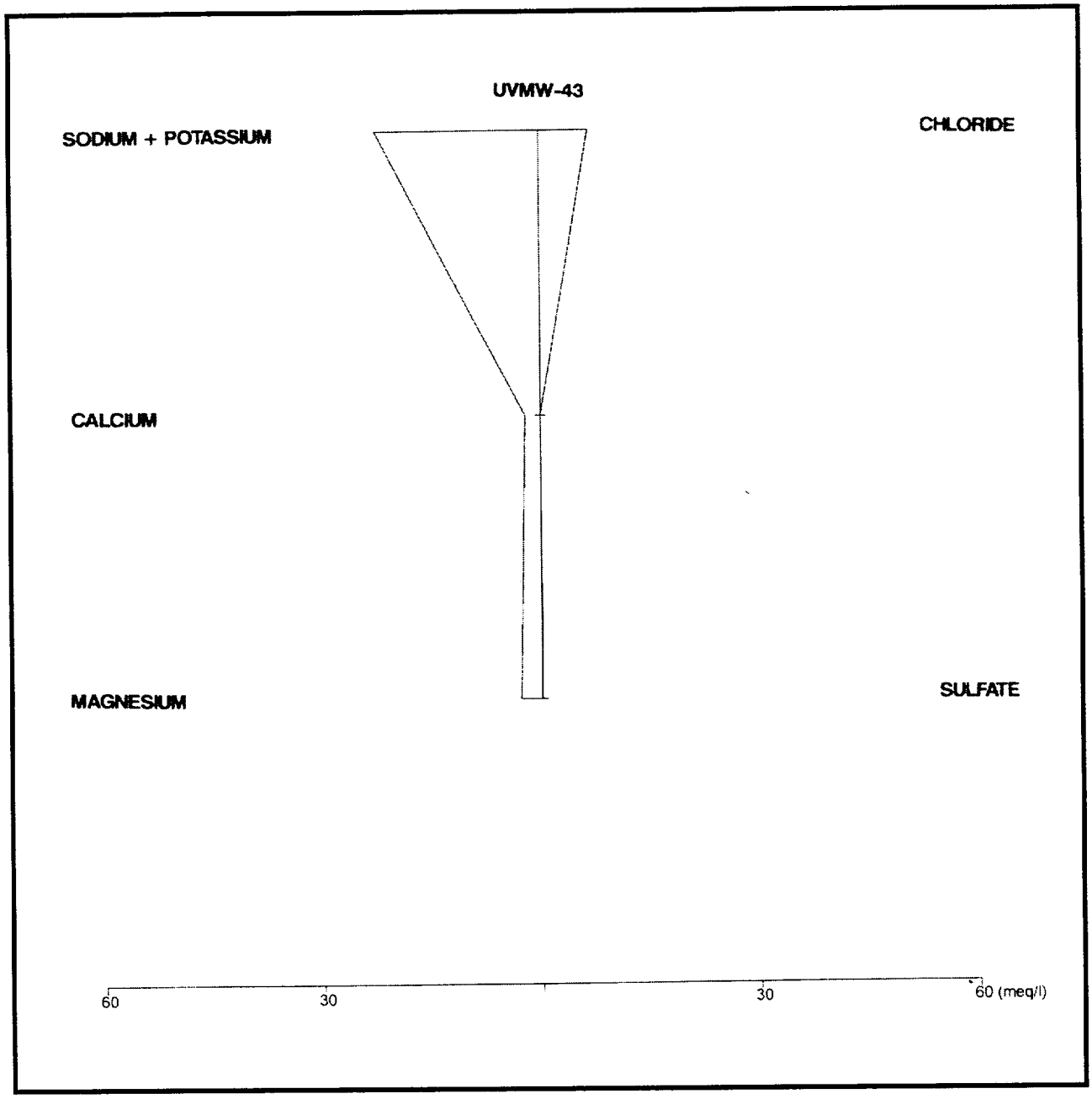
APPENDIX D
FIGURE D-2
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR QUATERNARY STREAM TERRACE REGIME MONITOR WELL UVMW-49



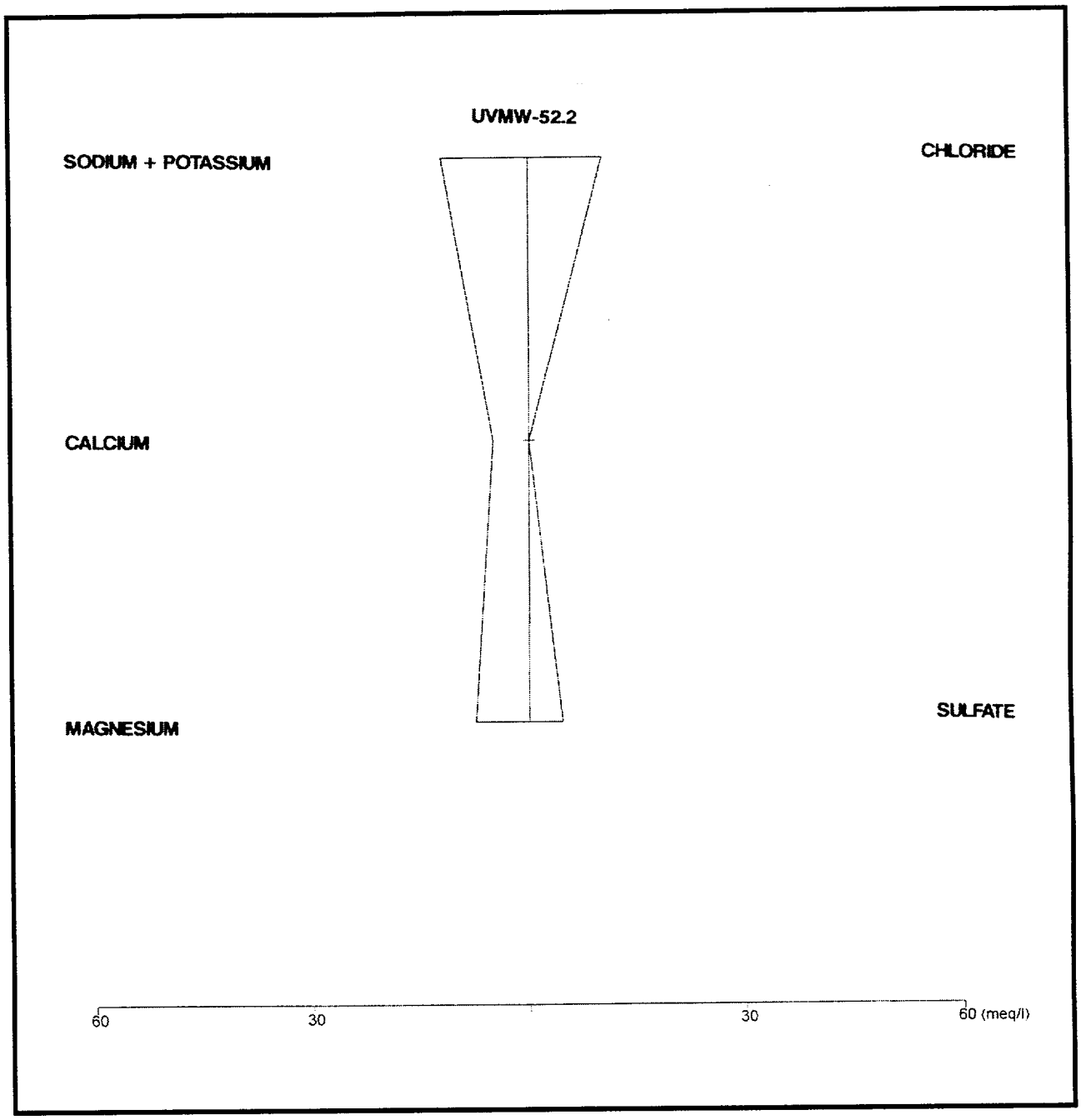
APPENDIX D
FIGURE D-3
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR UPPER VANOSS REGIME MONITOR WELL UVMW-50.1



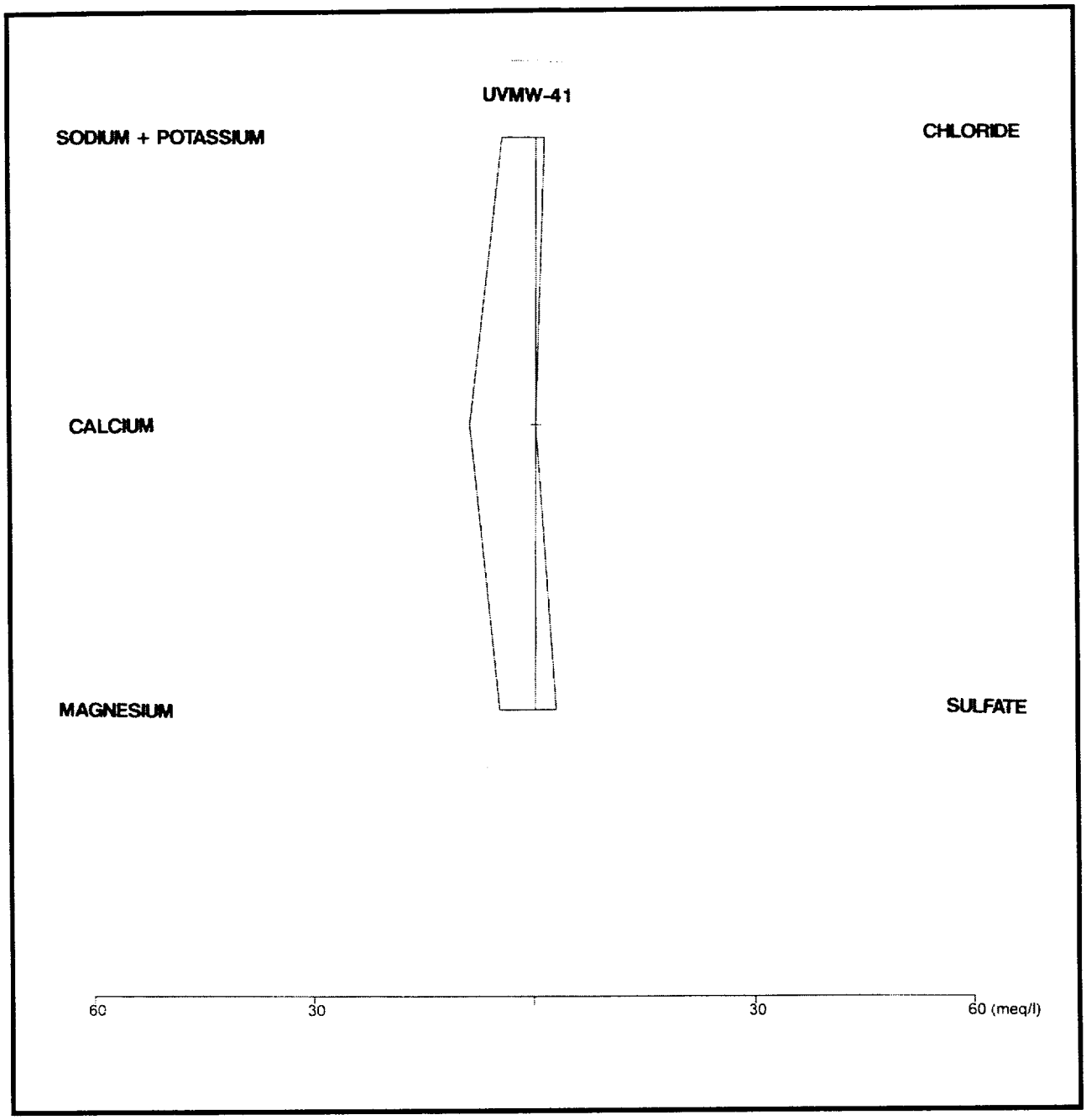
APPENDIX D
FIGURE D-4
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR UPPER VANOSS REGIME MONITOR WELL UVMW-43



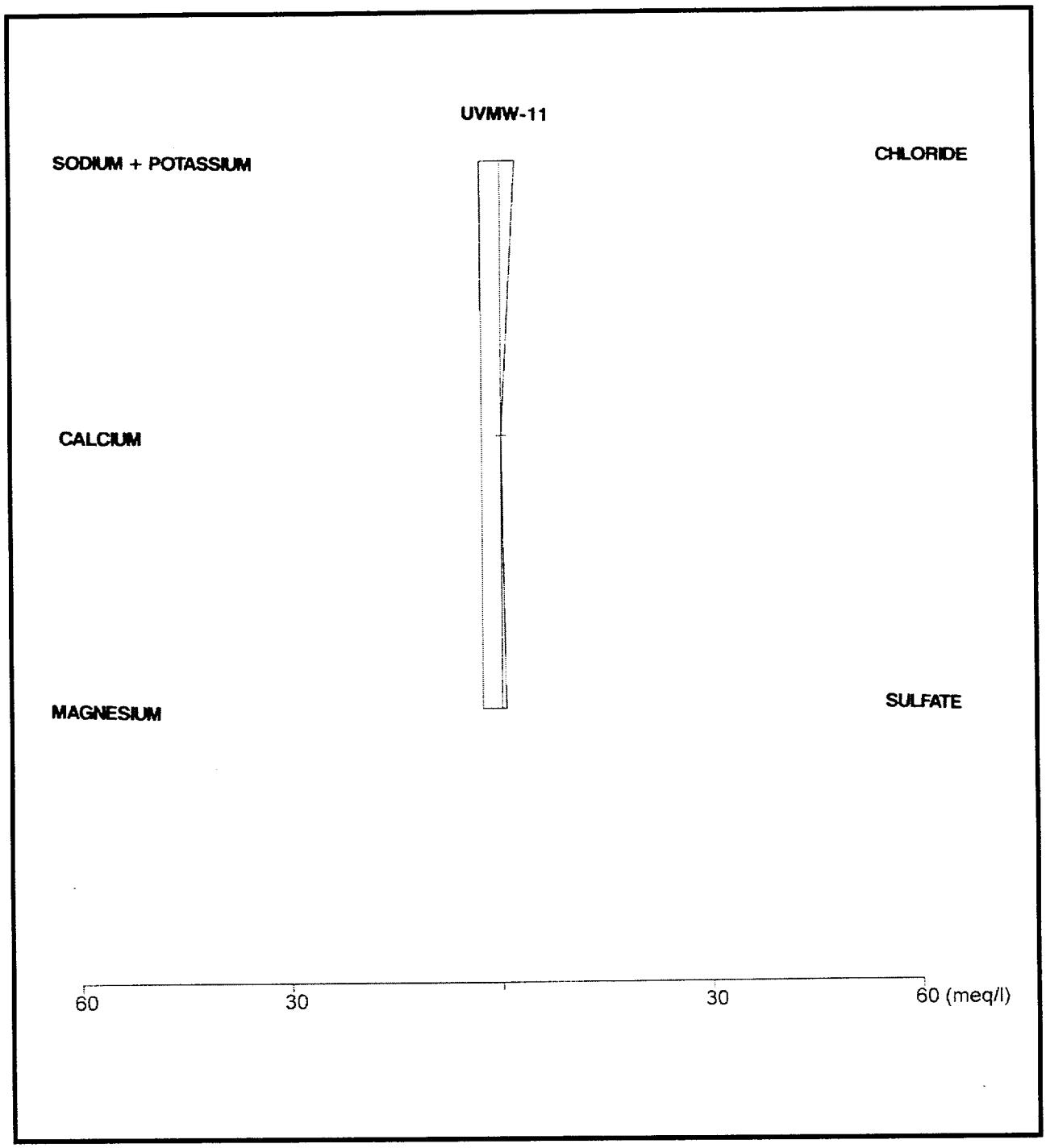
APPENDIX D
FIGURE D-5
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR UPPER VANOSS REGIME MONITOR WELL UVMW-52.2



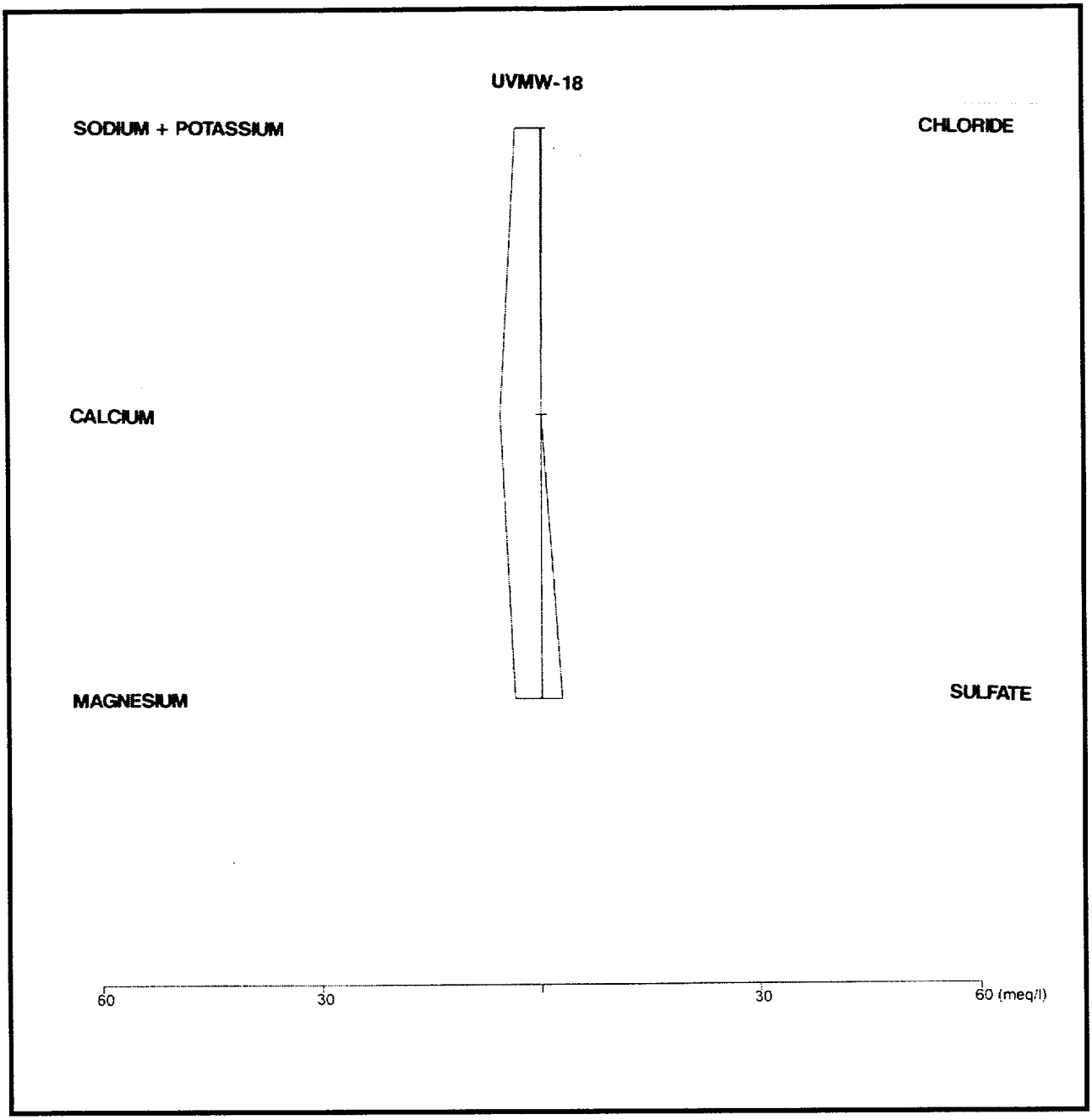
APPENDIX D
FIGURE D-6
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR UPPER VANOSS REGIME MONITOR WELL UVMW-41



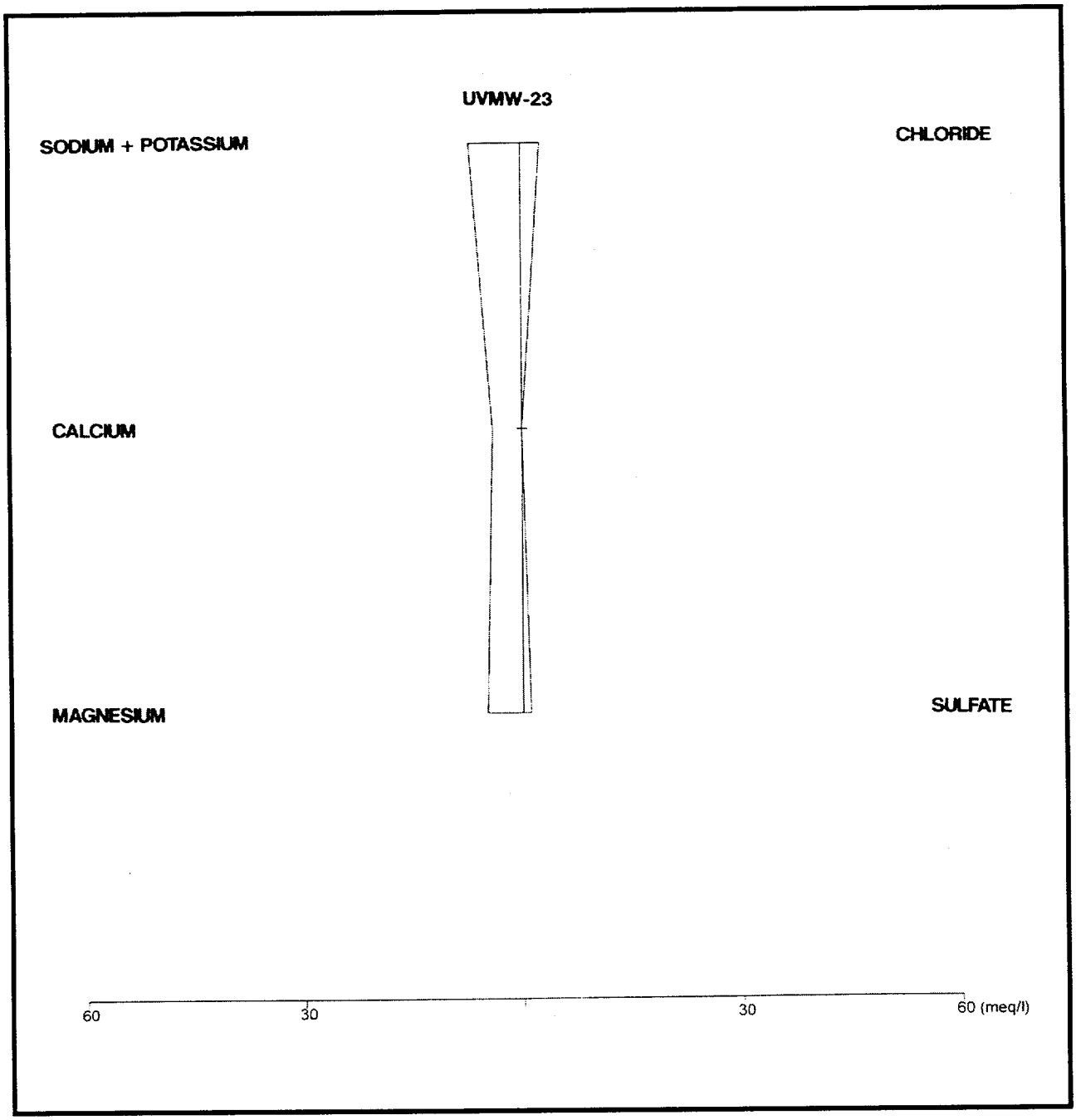
APPENDIX D
FIGURE D-7
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR UPPER VANOSS REGIME MONITOR WELL UVMW-11



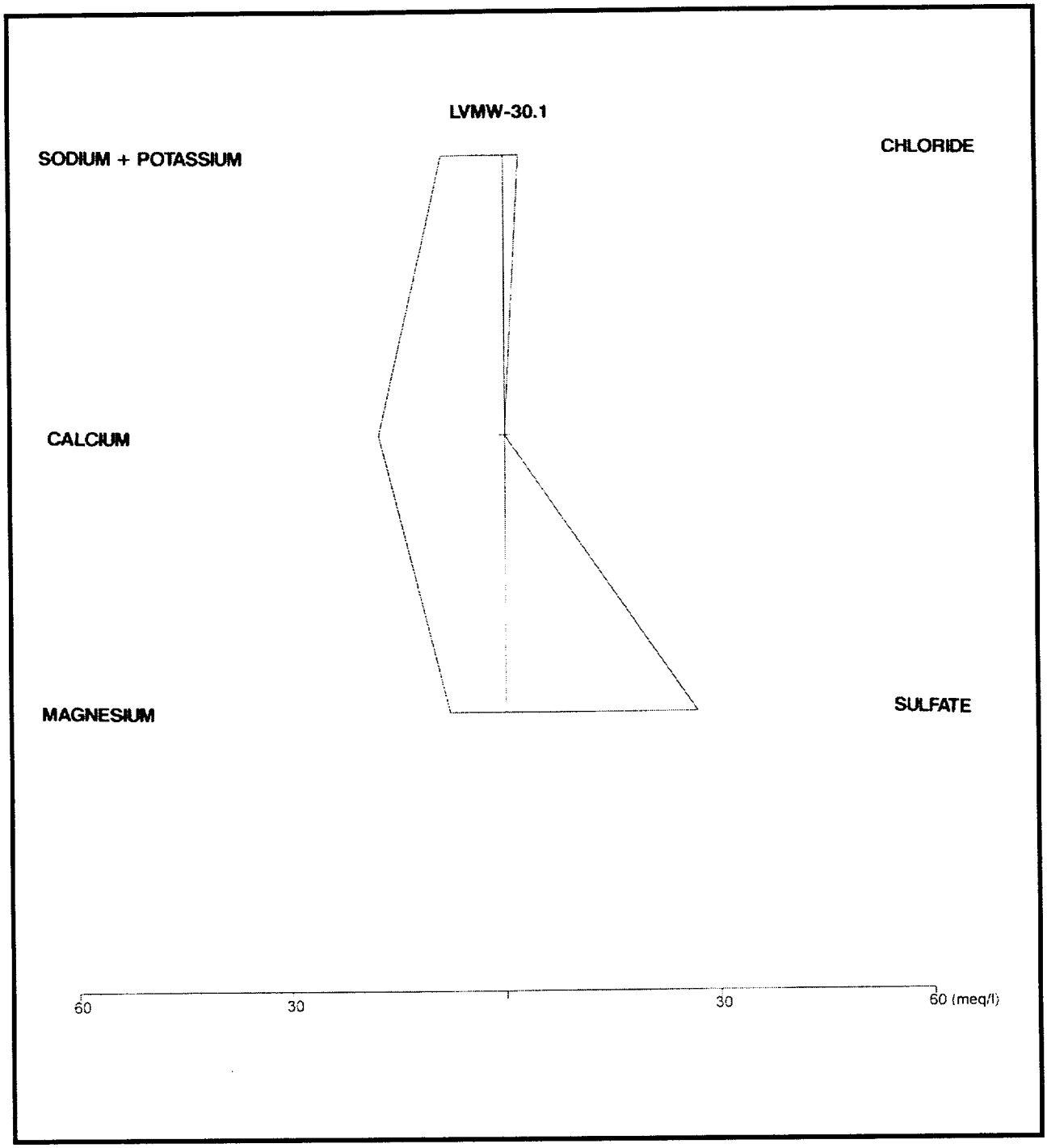
APPENDIX D
FIGURE D-8
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR UPPER VANOSS REGIME MONITOR WELL UVMW-18



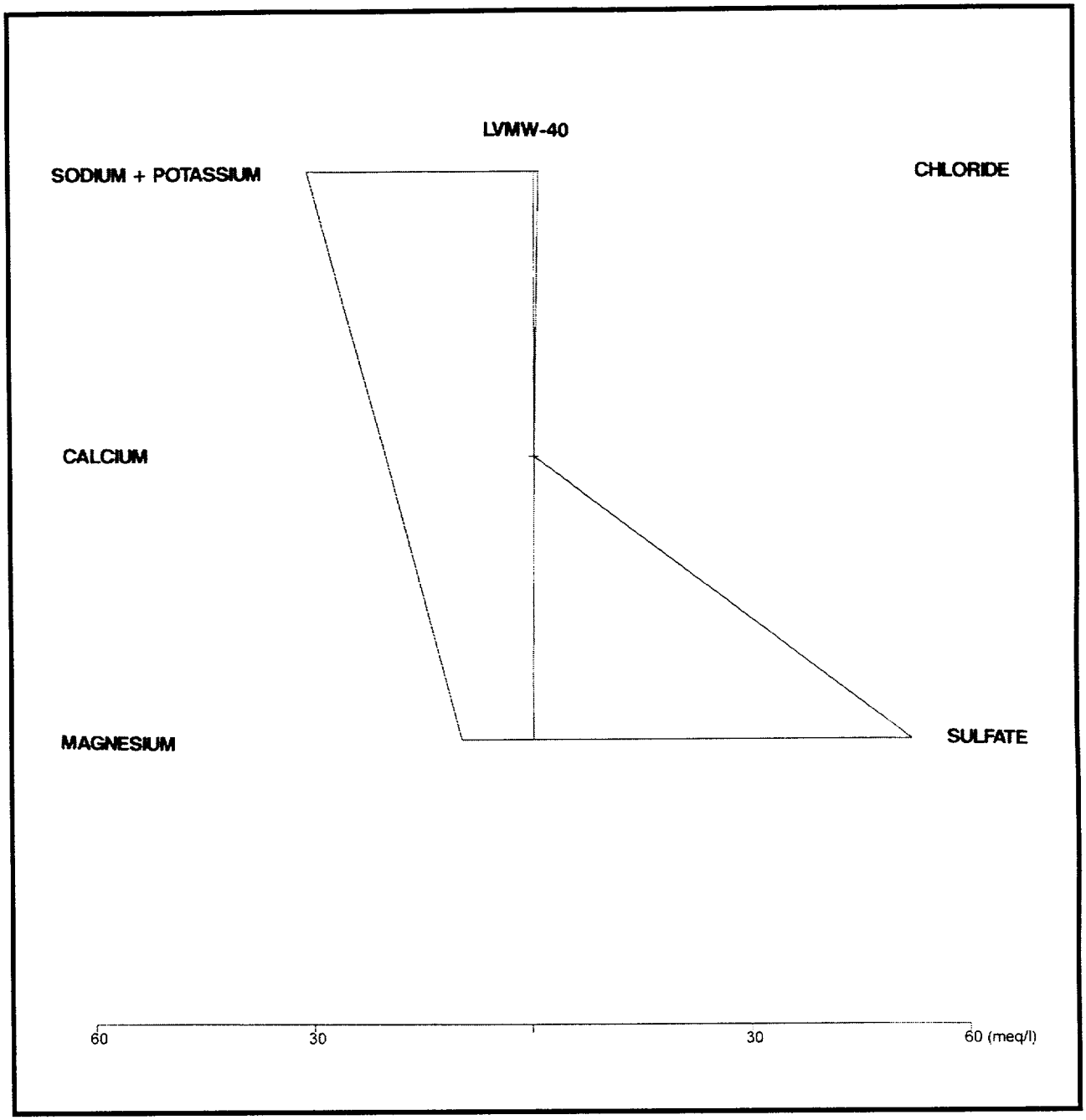
APPENDIX D
FIGURE D-9
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR UPPER VANOSS REGIME MONITOR WELL UVMW-23



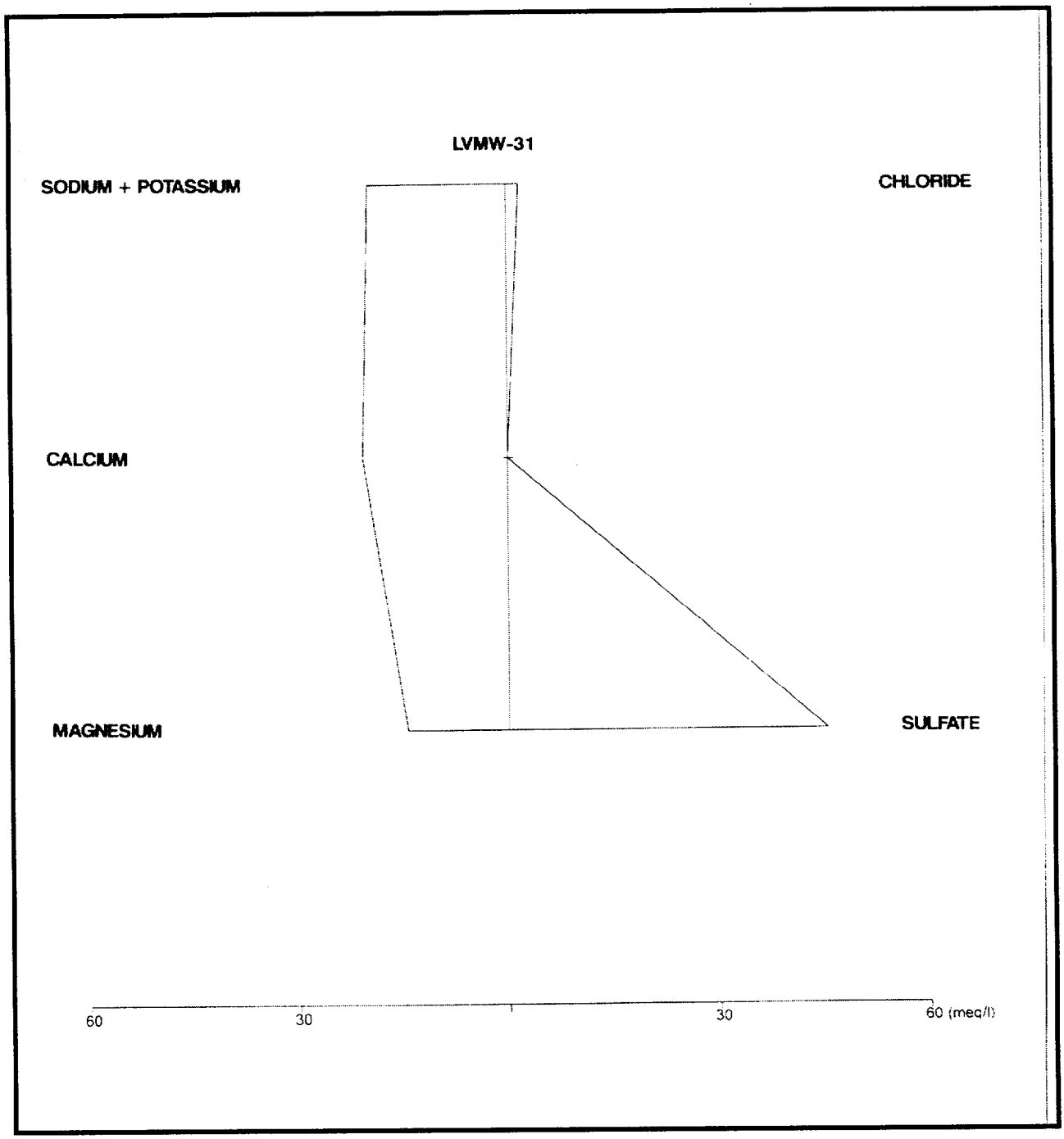
APPENDIX D
FIGURE D-10
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR LOWER VANOSS REGIME MONITOR WELL LVMW-30.1



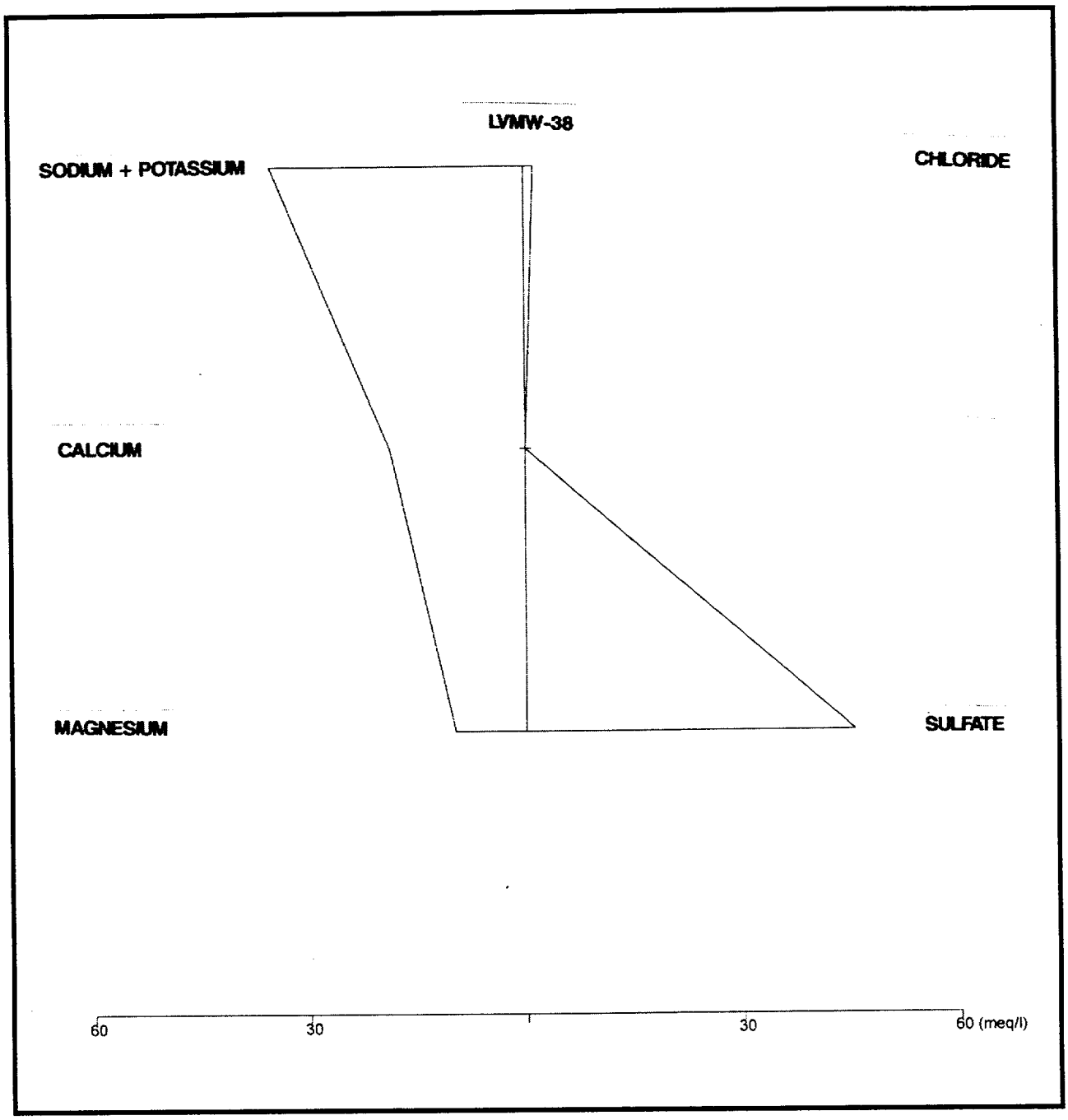
APPENDIX D
FIGURE D-11
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR LOWER VANOSS REGIME MONITOR WELL LVMW-40



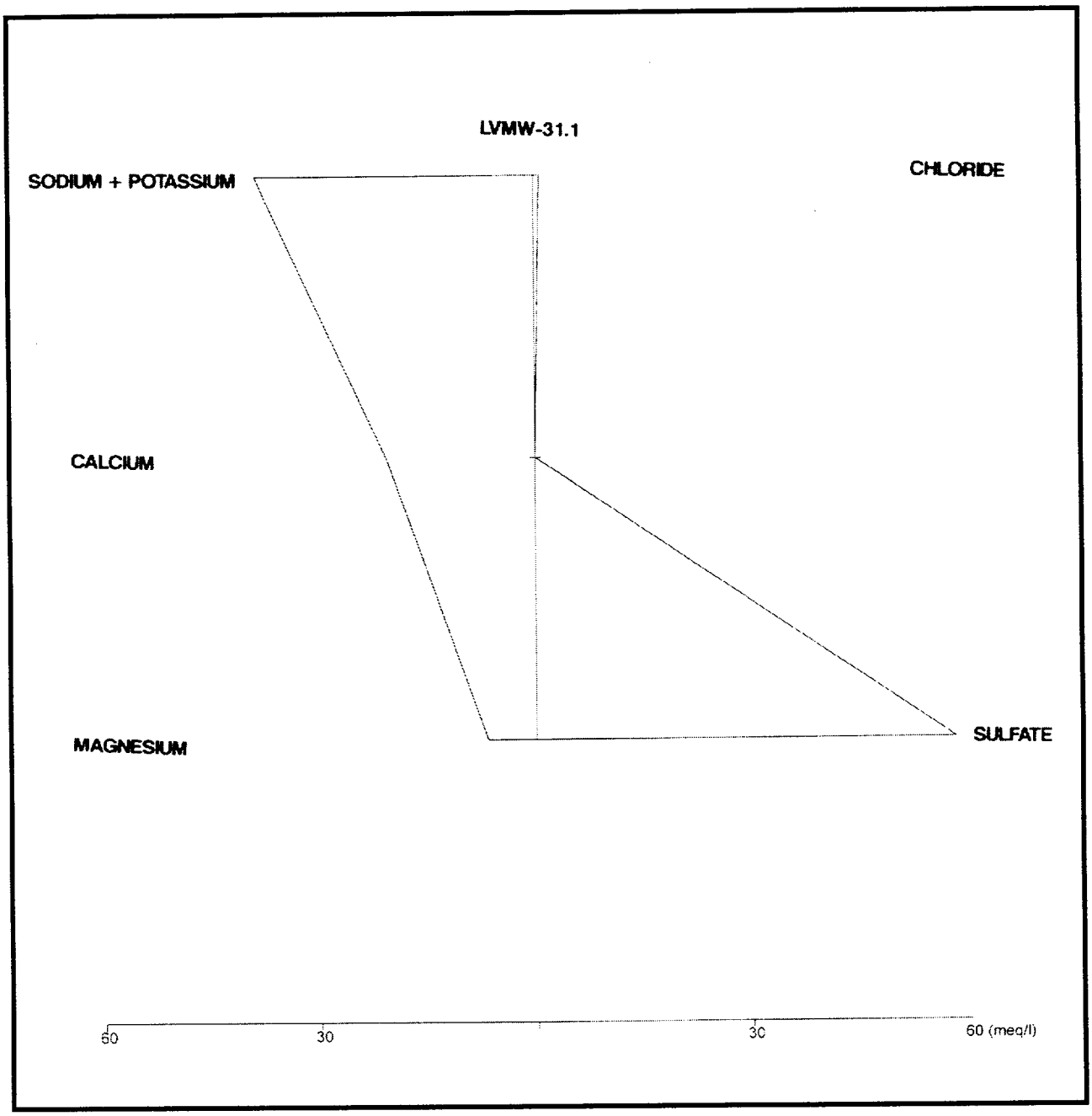
APPENDIX D
FIGURE D-12
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR LOWER VANOSS REGIME MONITOR WELL LVMW-31



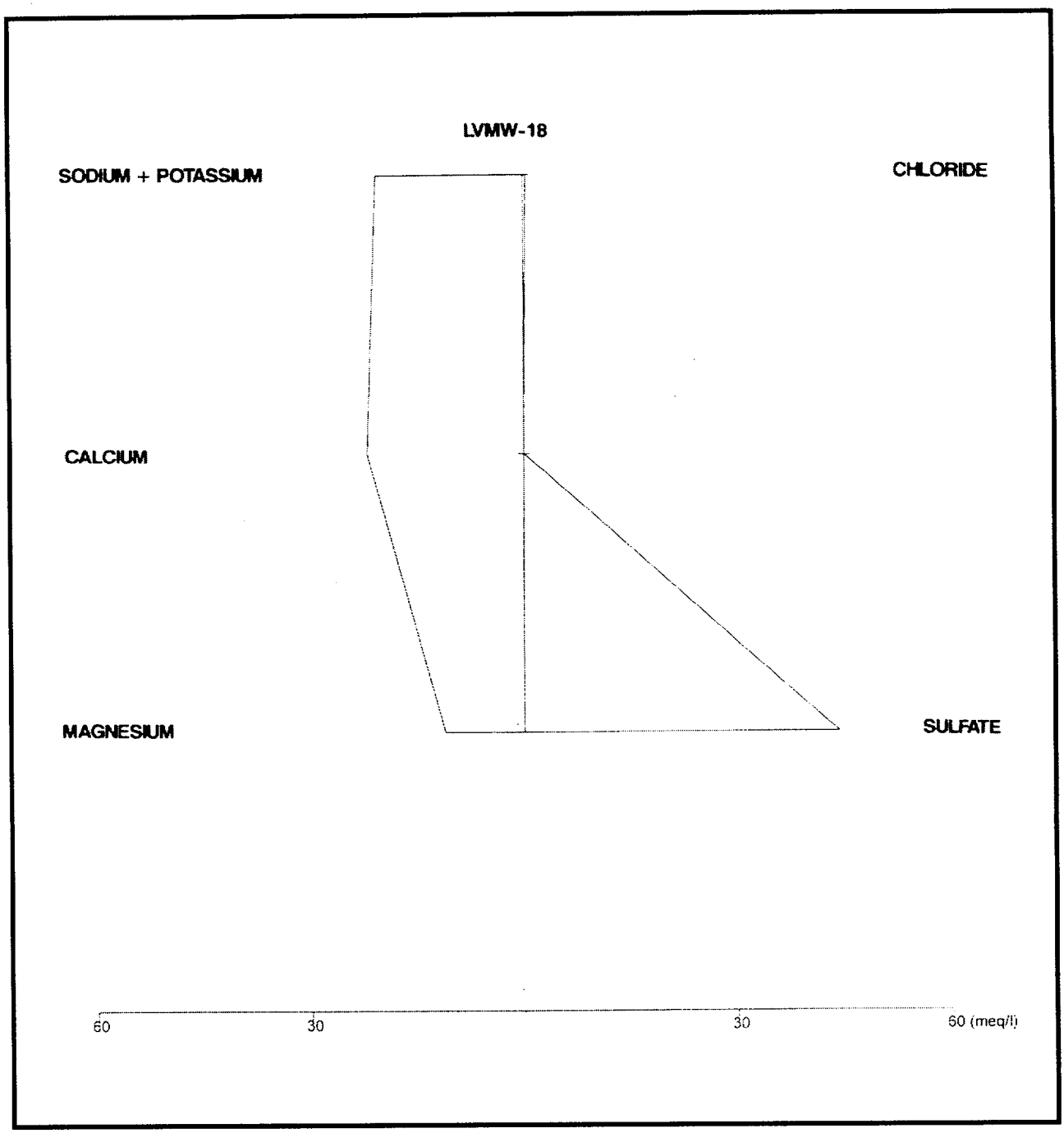
APPENDIX D
FIGURE D-13
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR LOWER VANOSS REGIME MONITOR WELL LVMW-38



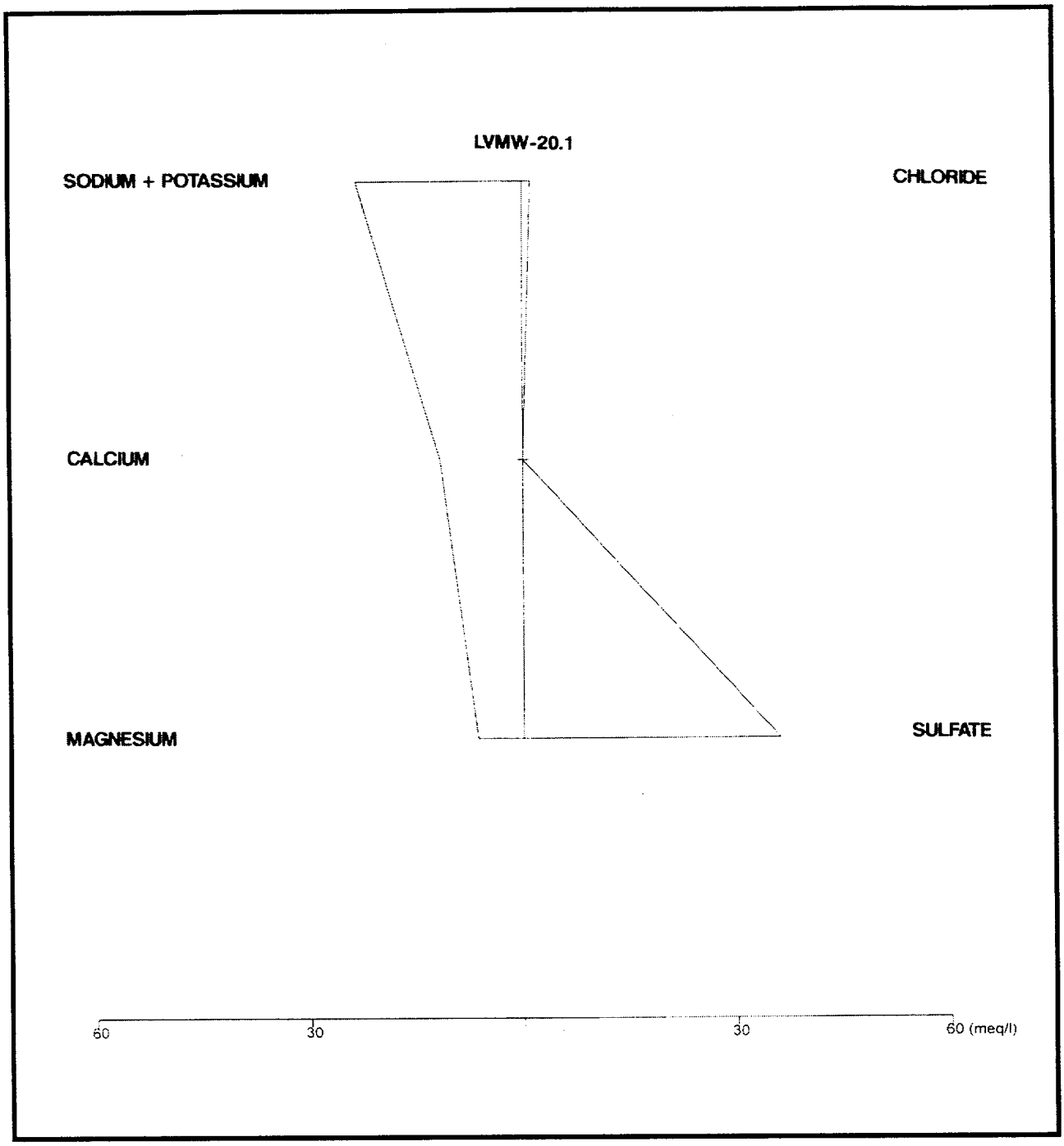
APPENDIX D
FIGURE D-14
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR LOWER VANOSS REGIME MONITOR WELL LVMW-31.1



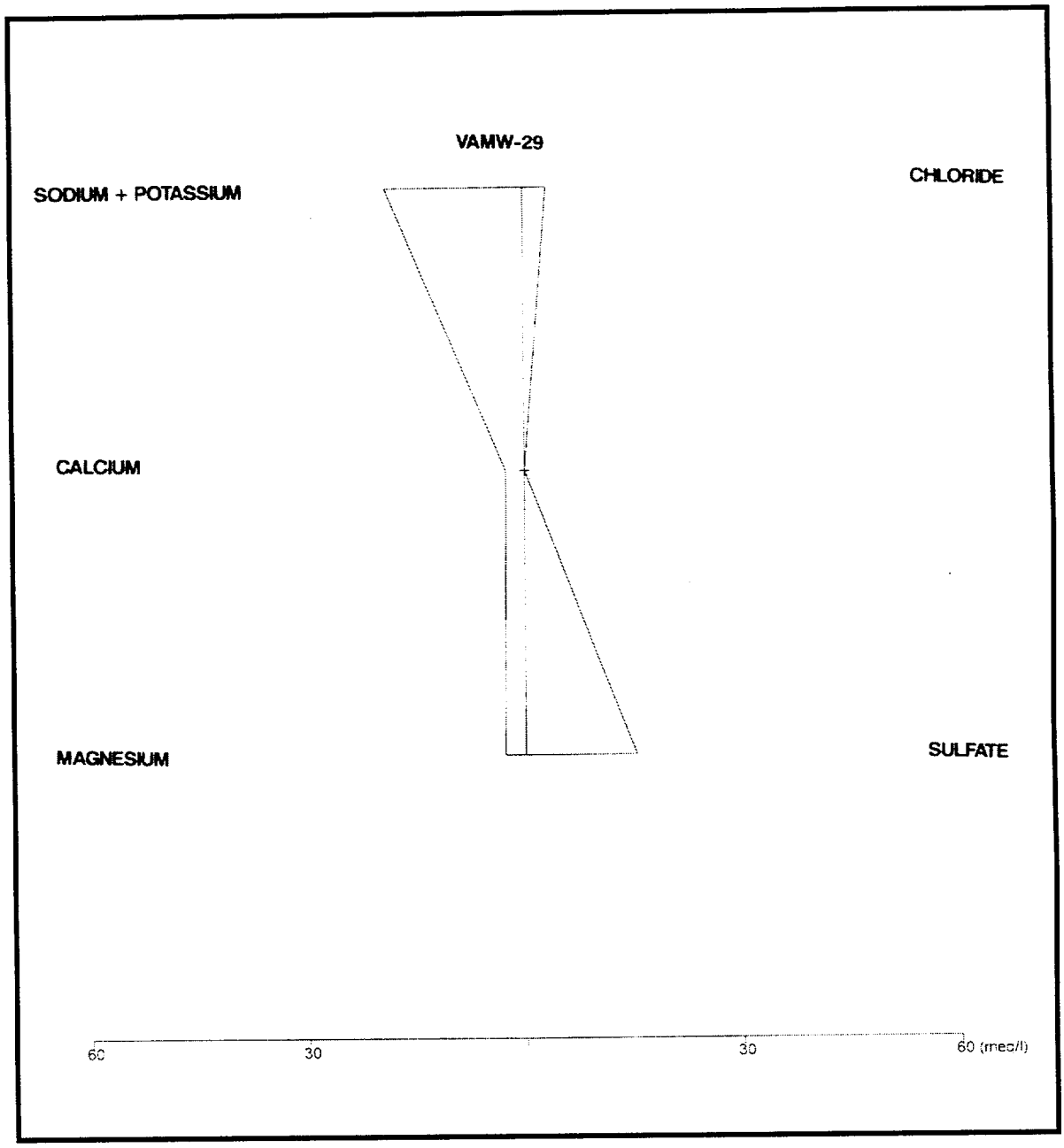
APPENDIX D
FIGURE D-15
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR LOWER VANOSS REGIME MONITOR WELL LVMW-18



APPENDIX D
FIGURE D-16
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR LOWER VANOSS REGIME MONITOR WELL LVMW-20.1



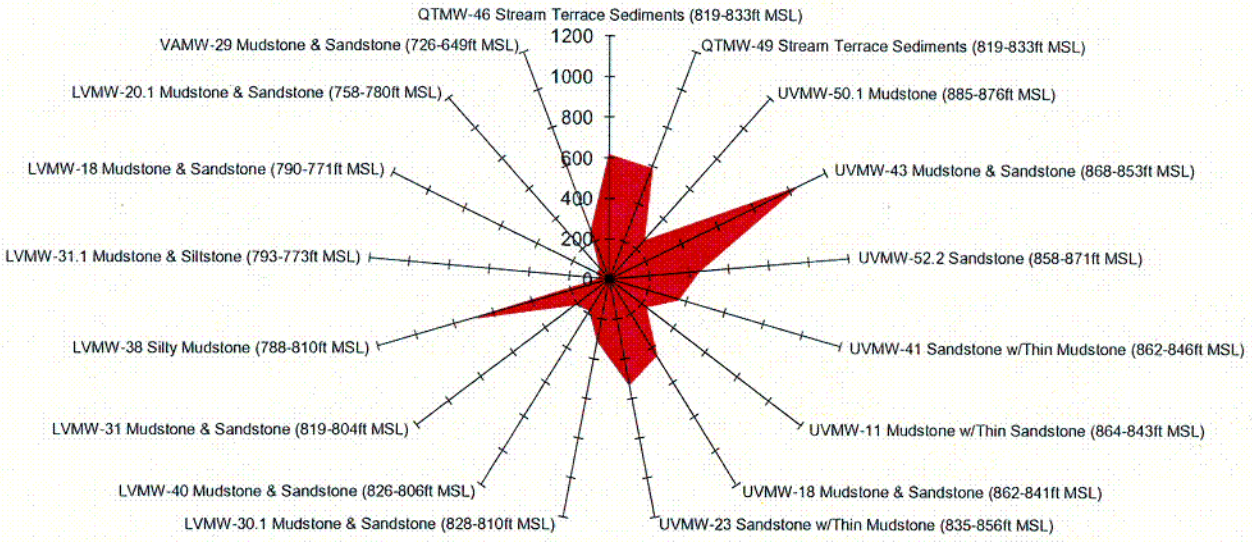
APPENDIX D
FIGURE D-17
STIFF DIAGRAM OF SELECTED GROUNDWATER QUALITY PARAMETERS FOR VAMOOSA-ADA AQUIFER REGIME MONITOR WELL VAMW-29



APPENDIX E

RADAR DIAGRAMS

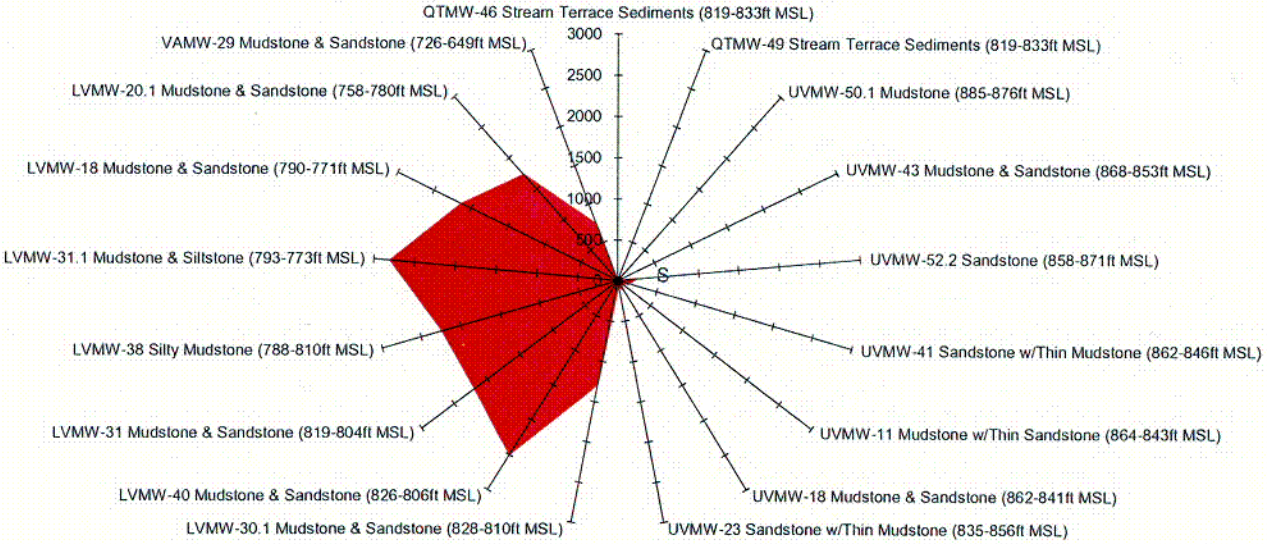
APPENDIX E
FIGIURE E-1
COMPARISON OF ALKALINITY CONCENTRATIONS
WITH LITHOLOGY AND ELEVATION IN SELECTED MONITOR WELLS
Cushing Facility



Key to Well Designations Indicating Hydrogeologic Regime Completed
QTMW=Quaternary Stream Terrace Deposits; UVMW=Upper Vanoss; LVMW=Lower Vanoss;
VAMW=Vamoosa-Ada Aquifer

C09

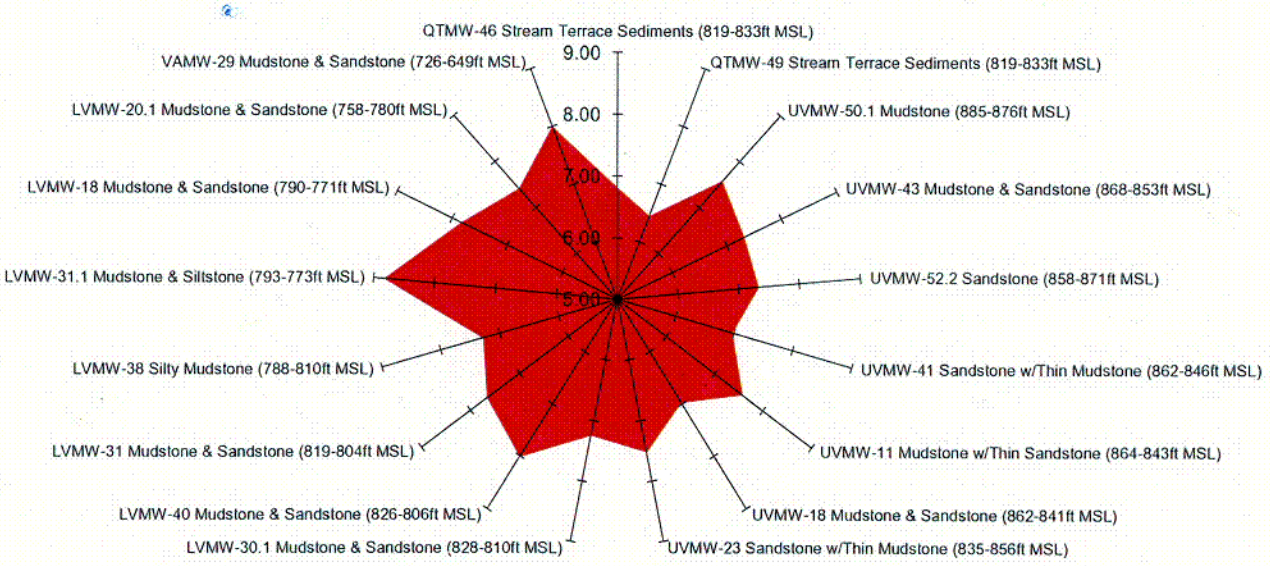
APPENDIX E
FIGIURE E-2
COMPARISON OF SULFATE CONCENTRATIONS
WITH LITHOLOGY AND ELEVATION IN SELECTED MONITOR WELLS
Cushing Facility



Key to Well Designations Indicating Hydrogeologic Regime Completed
QTMW=Quaternary Stream Terrace Deposits; UVMW=Upper Vanoss; LVMW=Lower Vanoss;
VAMW=Vamoosa-Ada Aquifer

C10

APPENDIX E
FIGIURE E-3
COMPARISON OF pH VALUES
WITH LITHOLOGY AND ELEVATION IN SELECTED MONITOR WELLS
Cushing Facility



Key to Well Designations Indicating Hydrogeologic Regime Completed
QTMW=Quaternary Stream Terrace Deposits; UVMW=Upper Vanoss; LVMW=Lower Vanoss;
VAMW=Vamoosa-Ada Aquifer

C11