2003030516 4

AD-A285 577

NTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE 06/00/79

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
BASIN F INVESTIGATIVE STUDIES, REPORT 2, HISTORICAL REVIEW (MISCELLANEOUS PAPER EL-79)

5. FUNDING NUMBERS

6. AUTHOR(S)
BUHTS, R.; FRANCINGUES, N.; GREEN, A.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
ARMY ENGINEER WATERWAYS EXPERIMENT STATION. ENVIRONMENTAL LABORATORY
VICKSBURG, MS

8. PERFORMING ORGANIZATION REPORT NUMBER
81266R18

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MD

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
THIS REPORT PRESENTS A HISTORY OF CHEMICAL WASTE DISPOSAL AT RMA AS COMPILED FROM THE FILES OF VARIOUS GOVERNMENT AGENCIES AND OTHER SOURCES. AREAS ADDRESSED INCLUDE THE INTEGRITY OF THE ASPHALT MEMBRANE, EVAPORATION RATES ASSOCIATED WITH BASIN F LIQUID, DEEP-WELL DISPOSAL, OF BASIN F LIQUID AND SLUDGE, AND MIGRATION OF CONTAMINANTS VIA GROUND WATER WHICH MIGHT BE ATTRIBUTED TO BASIN F. A LARGE BODY OF EVIDENCE IS PRESENTED TESTIFYING THAT THE ASPHALT MEMBRANE NO LONGER PROVIDES AN IMPERVIOUS LINING IN THE BASIN. SUCH EVIDENCE INCLUDE PHOTOGRAPHS OF THE DETERIORATED LINER, A CLOSE CORRELATION BETWEEN CHLORIDE LEVELS IN THE MONITORING WELLS SURROUNDING THE BASIN AND THE LIQUID LEVELS IN BASIN F, AND THE FINDING OF SIGNIFICANT COPPER CONTAMINATION IN THE SOIL SURROUNDING THE BASIN PERIPHERY.

94 10

14. SUBJECT TERMS
TREATMENT, GROUNDWATER, DISPOSAL, SPILLS, LINERS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

7.

81266R18
Historical Review

81266R18
original

MISCELLANEOUS PAPER EL-79-

BASIN F INVESTIGATIVE STUDIES

Report 2

HISTORICAL REVIEW

by

Robert E. Buhts, Norman R. Francingues, Andrew J. Green

Environmental Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

June 1979

Report 2 of a Series

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

DRAFT

Prepared for U. S. Army Toxic and Hazardous Materials Agency
Aberdeen Proving Ground, Maryland 21010

'iscellaneous Paper EL-79-	
4. TITLE (and Subtitle) BASIN F INVESTIGATIVE STUDIES; Report 2, HISTORICAL REVIEW	5. TYPE OF REPORT & PERIOD COVERED Report 2 of a series 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert E. Buhts, Norman R. Francingues, Andrew J. Green	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Environmental Laboratory P. O. Box 631, Vicksburg, Miss. 39180	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Toxic and Hazardous Materials Agency Aberdeen Proving Ground, Md. 21010	12. REPORT DATE June 1979 13. NUMBER OF PAGES 53
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

ABSTRACT - REPORT 2

Rocky Mountain Arsenal (RMA) has been a chemical manufacturing and chemical demilitarization facility since 1942. Originally, the waste products resulting from military and industrial operations were discharged into various unlined evaporation ponds. In 1956, a new earthen basin (Basin F) was constructed and lined with an asphalt membrane; subsequently, the majority of all wastes were discharged into this basin. During the 21 years since Basin F became operational, numerous investigations have been conducted to define the chemical make-up of the basin and ascertain the extent of its contribution to existing groundwater contamination at RMA.

This report presents a history of chemical waste disposal at RMA as compiled from the files of various Government Agencies and other sources. Areas addressed include the integrity of the asphalt membrane, evaporation rates associated with Basin F liquid, deep-well disposal of Basin F fluid, characterization and treatment studies of Basin F liquid and sludge, and migration of contaminants via groundwater which might be attributed to Basin F. A large body of evidence is presented testifying that the asphalt membrane no longer provides an impervious lining in the basin. Such evidence includes photographs of the deteriorated liner, a close correlation between chloride levels in the monitoring wells surrounding the basin and the liquid levels in Basin F, and the finding of significant copper contamination in the soil surrounding the basin periphery.

PREFACE

This literature search was conducted by the Environmental Laboratory (EL) of the U. S. Army Engineer Waterways Experiment Station (WES) for the U. S. Army Toxic and Hazardous Materials Agency (USATHAMA), (formerly Project Manager for Chemical Demilitarization and Installation Restoration (PM-CDIR)). The s. .y was authorized by Intra-Army Order for Reimbursable Services No. RM 60-77, dated 3 May 1977, Rocky Mountain Arsenal (RMA), Commerce City, Colorado 80022.

Principal contributors to this effort were CPT Robert E. Buhts, CE, Norman R. Francingues, Treatment Processes Research Branch, and Mr. Andrew J. Green, Chief of the Environmental Engineering Division (EED), EL, WES. Dr. John Harrison was Chief, EL.

Special acknowledgement is extended to the following individuals for their special assistance during the course of this work: Messrs. Carl Loven, Ed Berry, and Irwin Glassman, and Drs. Nicolay Timofeeff, Roland Grabbe, and Michael Witt, RMA; personnel of the Material Analysis Laboratory Division of the RMA for their work on sample analysis; CPT Joe Kolmer and Messrs. Dennis Wynne and Donald Campbell of USATHAMA; Mr. Michael Asselin, Chemical Systems Laboratory, Edgewood Arsenal; LTC Charles H. Coates and Mr. Jack Dildine, WES; and Dr. O. Rendon (WES consultant).

COL John L. Cannon, CE, was Commander and Director of the WES during the preparation of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.856	square metres
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
gallons (U. S. liquid)	3.785412	cubic decimetres
inches	25.4	millimetres
miles (U. S. statute)	1.609344	kilometres
square yards	0.8361274	square metres
tons (2000 lb, mass)	907.1847	kilograms

ABBREVIATIONS

AEHA	Army Environmental Hygiene Agency
EWA	Edgewood Arsenal
MUCOM	U. S. Army Munitions Command
OCE	Office, Chief of Engineers
PM-CDIR	Project Manager for Chemical Demilitarization and Installation Restoration
RMA	Rocky Mountain Arsenal
USGS	U. S. Geological Survey
WES	U. S. Army Engineer Waterways Experiment Station

BASIN F INVESTIGATIVE STUDIES

HISTORICAL REVIEW

PART I: INTRODUCTION

Background

1. The investigative studies of activities related to design, use, and subsequent environmental concerns about Basin F at Rocky Mountain Arsenal (RMA), Commerce City, Colorado, are an integral part of the mission assigned to the Department of the Army's Project Manager for Chemical Demilitarization and Installation Restoration (PM-CDIR). The U. S. Army Engineer Waterways Experiment Station (WES) was requested by RMA on 3 May 1977 to participate in these investigative studies. One objective assigned to the WES was to assemble historical information concerning the Basin.

Purpose and Scope

2. The specific purposes of this report are to present the findings of a 5-month literature search on the history of Basin F that was compiled from the files of various Government Agencies and other sources. The remainder of this report is organized as follows:

Part II:	Chemical Waste Disposal from 1942 to 1977
Part III:	Integrity of the Asphalt Membrane
Part IV:	Evaporation Studies
Part V:	Contaminant Migration Attributed to Basin F
Part VI:	Summary of Findings from Literature Review

PART II: CHEMICAL WASTE DISPOSAL FROM 1942 TO 1977

Disposal Prior to Construction of Basin F

3. Rocky Mountain Arsenal was established in 1942 to manufacture chemical warfare agents. Military operations have included production of nerve agents, lewisite, mustard, arsenic trichloride, chlorine gas, and white phosphorus munitions. Demilitarization of select chemical materiel and blending of hydrazine fuel have been additional missions of RMA. Portions of the industrial plants area have also been leased since 1946 to private companies for the manufacture of insecticides and other chemicals.

4. Waste disposal at RMA has been a matter of concern since the beginning of operations at RMA. A survey of waste disposal alternatives in 1943 recommended that evaporation ponds for chemical manufacturing waste be located in Sections 26 and 36 (Figure 1). These ponds were to be kept highly alkaline so that lime reaction with the soil would ~~in~~de-crease the permeability of the bottoms. An increase in chemical waste production generated wastewater in excess of the capacity of the evaporation ponds and this overflow was diverted into the area known as Basin A, which received all arsenal wastes until 1951.

5. Upon construction of a GB-manufacturing plant at RMA, the waste disposal requirements of this facility were examined by the Vitro Corporation of New York and the U. S. Army Engineer District, Omaha (Ralph M. Parsons Company 1955). They concluded that the existing waste disposal system was appropriate for the RMA but required additional capacity. As a result, the dike around Basin A was raised. As GB production continued, however, Basin A proved too small to accept the large quantities of wastewater and brine. This led to the design of Basins C, D, and E patterned after Basin A. From 1953 to October of 1956, virtually all of RMA industrial waste, an estimated 60,000 tons* of material, was

---

* A table of factors for converting U. S. customary units of measurement to metric (SI) can be found on page 4.

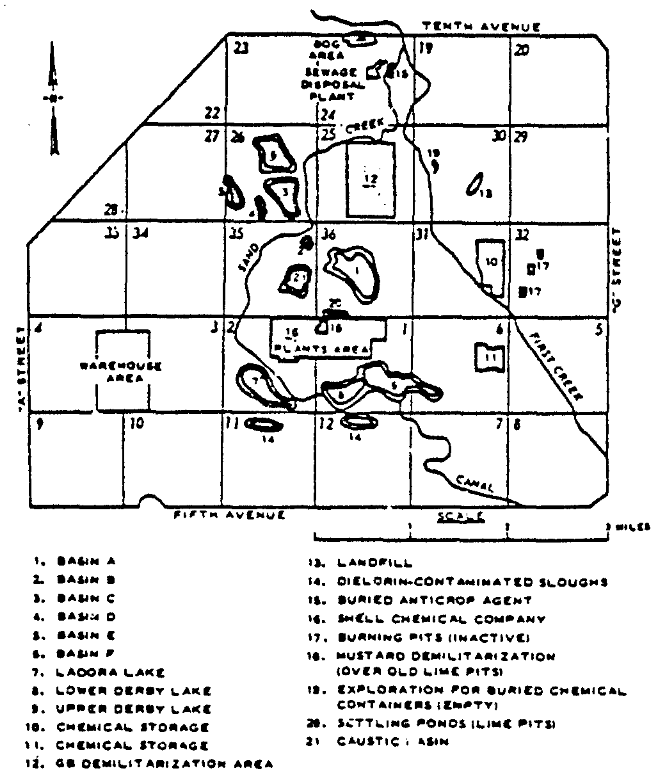

Figure 1. Locations of areas of interest, Rocky Mountain Arsenal, Denver, Colorado

deposited in these evaporation basins.

6. In June 1954, RMA received complaints of groundwater contamination from farmers located northwest of the arsenal. Meetings were held that were attended by representatives of cognizant Federal and State agencies. As a result, the Army Chemical Corps began to investigate crop damage allegedly caused by using contaminated groundwater for irrigation. Vegetative uptake studies were initiated by Fort Detrick, Maryland, to determine what substances made the irrigation water detrimental to plant growth. Simultaneously, the U. S. Geological Survey (USGS) conducted a study of groundwater flow into and out of the arsenal. Findings from both studies indicated that the groundwater in the area did contain abnormally high concentrations of chloride and chlorate ions, both traceable to earlier manufacturing processes at the arsenal.

7. The Omaha District recommended that a study of arsenal waste

operations be conducted by an engineering firm and contracted with the Ralph M. Parsons Company for that purpose. The Ralph M. Parsons report (1955), submitted in October 1955, contained the following recommendations:

a. Reduce to a minimum the volume of industrial wastes discharged by all plants (Table 1).

b. Immediately install an asphalt membrane seal in the existing 142 acres of waste disposal basins.

Table 1

RMA Waste in 1955*

	Tons/Month			
	Chemical Corps		Shell	
	Plant No. 1	Plant No. 2	Chemical Company	Total
Present				
Sodium chloride, NaCl	400	None	None	400
Sodium fluoride, NaF	40	None	None	40
Sodium hydroxide, NaOH (100%)	140*	None	None	140
Sodium methyl phosphonate $CH_3PL(ONa)_2$	110	None	None	110
Sodium acetate and sulfate	None	None	130	130
Total	690	None	130	820
Future Expected				
Sodium chloride, NaCl	1630	1349	None	2979
Sodium fluoride, NaF	163	None	None	163
Sodium hydroxide, NaOH	570**	None	None	570
Sodium methyl phosphonate	475	125	None	600
Sodium acetate and sulfate	None	None	130	130
Aluminum hydroxide	None	391	None	391
Total	2838	1865	130	4833

* Ralph M. Parsons Company 1955.

** This quantity of free caustic dumped into the lake resulted from the practice of using 140 percent of the theoretical requirements. This excess quantity fluctuated according to variations in operational procedures.

c. Provide additional facilities for disposal of chemical wastes by means other than open storage and evaporation.

8. As a result of this study, RMA reviewed its waste-handling procedures and made changes in plant layout and operating requirements that substantially reduced the volume of liquid waste effluent. The Chemical Corps also initiated a program of groundwater surveillance by drilling observation wells in areas suspected to be contaminated on and off the arsenal. Based mainly on the recommendations of the Parsons report, a decision was made to construct a new chemical waste disposal basin, later designated as Basin F.

9. Numerous investigations have been conducted on Basin F since its construction. Many of the decisions concerning the operation and disposition of Basin F were, in part, based on the results of these studies. Many of the reports reviewed are referenced throughout the remainder of this report.

Construction of Basin F

Description of basin and dikes

10. In early 1956, the Omaha District received a directive to proceed with construction of a sealed basin capable of receiving chemical waste from the arsenal operations. The area finally sealed (Basin F, Figure 1) consisted of 93 acres with a capacity for holding 243,090,000 gal.

11. The basin, roughly oval in shape, was created in a natural depression (Figure 2). It measured approximately 2900 ft across at the north end and 1600 ft across at the south end. The average depth of the basin was reported to be 10 ft (Engineering News Record 1956). Relatively little grading work was performed in the construction of Basin F (Figures 2 and 3). The major part of the grading operations consisted of two cuts (about 500,000 yd^3) located on the west side of the 93-acre basin. The maximum height of cut in those particular areas varied from 6 to about 13 ft. Relatively minor cutting and filling (about 70,000 yd^3) of less than 1.0 ft in depth was performed in a few

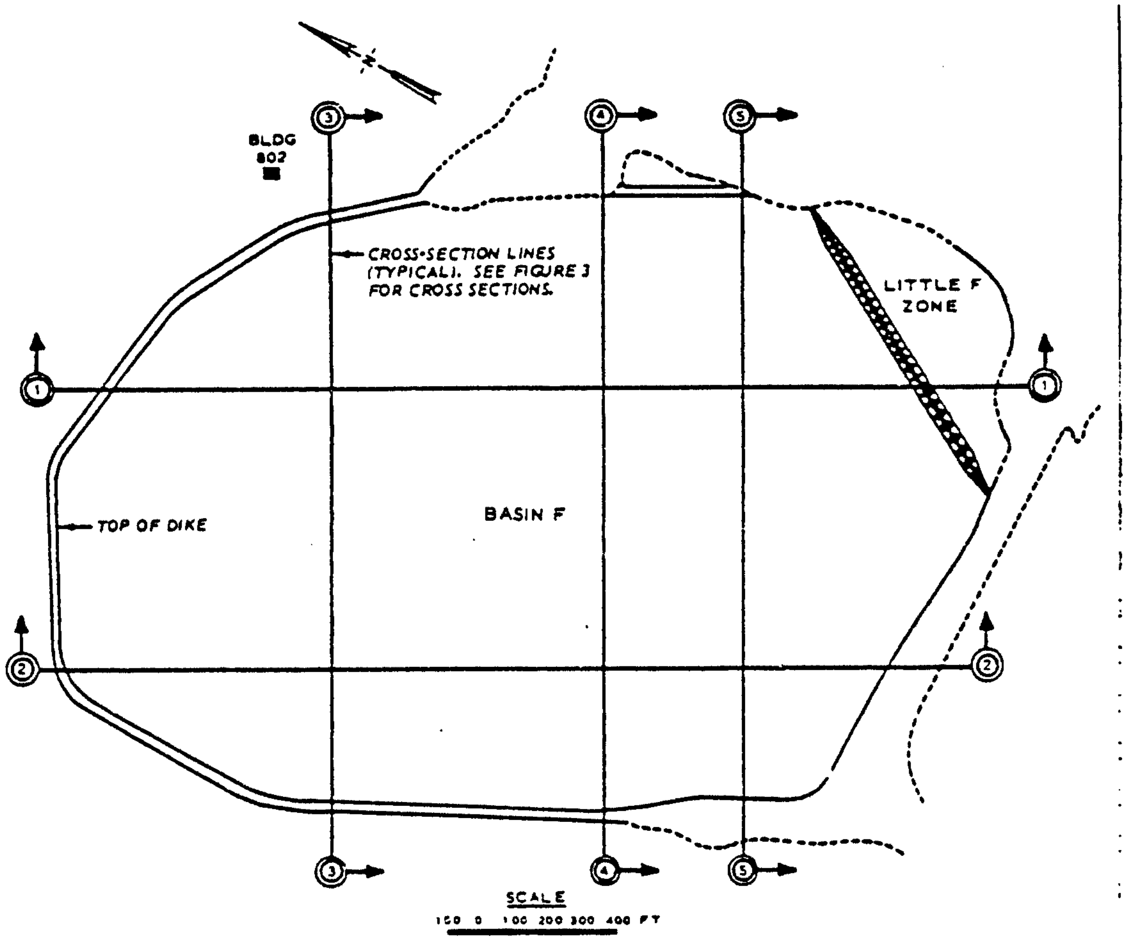

Figure 2. Plan view of Basin F

areas in the northern side of the basin (Rendon 1977). Based on the geotechnical information available at the time on soils near the location of the cuts, it was surmised that the excavations were contained within the relatively impervious upper layer.

12. The main reservoir dike (crown elevation 5202 ft msl*) extends from the vicinity of Building No. 802 (Figure 2), where the ground surface elevation is 5205$\pm$ ft msl, counterclockwise (plan view) around the basin to the westernmost side of the existing earth-filled dike for Basin C. (The ground surface elevation at this point is approximately 5200 ft msl.) The new earth-fill dike that was built in Basin F in the

* Elevations cited herein are in feet referenced to mean sea level (msl).

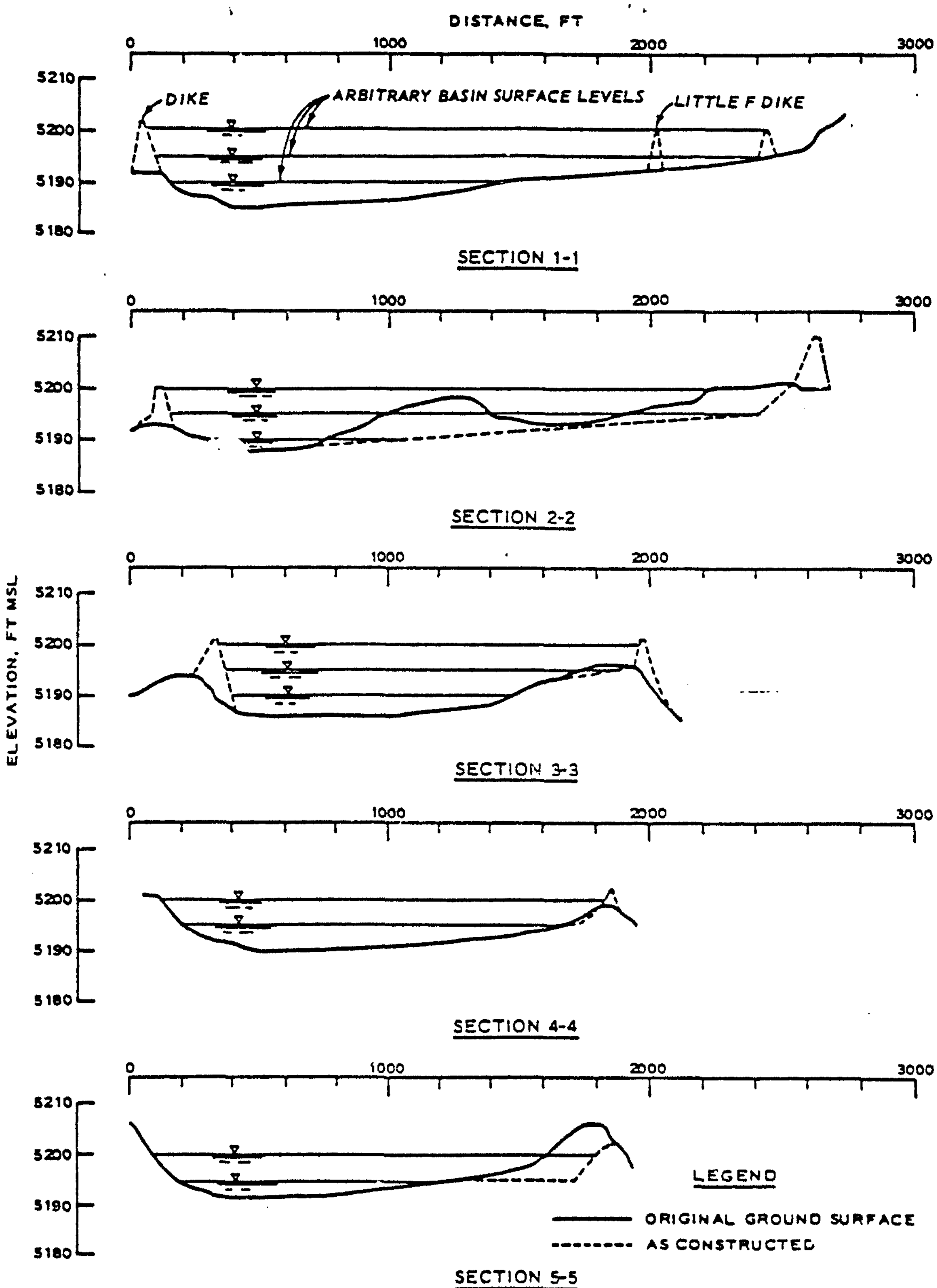

Figure 3. Cross sections, Basin F

southeastern end of the reservoir sections off a zone (known as Little F) within the limits of the basin. Detailed cross sections of the main dike are not available. Figure 4 shows a typical cross section (approximate) of the dike (Rendon 1977).

Asphaltic membrane

13. A number of sealants were investigated by the Omaha District (ca 1956). These included Portland cement, asphalt, asphalt planks, impervious compacted earth, grouting with chemicals, and an asphaltic membrane. The choice was the asphaltic membrane (Engineering News Record 1956).

14. The use of asphalt for membrane barriers was pioneered by the Bureau of Reclamation and Michigan State University scientists to make irrigation ditches impervious. The asphaltic membrane barrier covered with 1 ft of soil was considered to have a design life of 15 years.

15. The asphaltic membrane (approximately 3/8 in. thick) was placed (ca 1956) on the basin bottom extending to a projected high water elevation at the edge of the seal area (see Figure 4). The following is quoted from the Engineering News Record (1956):

> First, a wide strip was excavated to grade and then compacted with a roller to give a smooth surface. Preheated asphalt was brought to the site in insulated tanker trucks and then transferred to a distributor which was modified especially for this job.... Asphalt was then sprayed in a strip about 1000 ft long and 12 ft wide at a rate of 1.35 to 1.50 gallons per square yard. The various strips overlapped from 4 to 6 in. Because application of the hot material at the total specified rate would have caused it to run, the membrane was built up in three successive applications. After the asphalt had been placed, an earth blanket, 1 ft thick, was placed on top of the completed asphalt membrane.

The asphalt used for the membrane material was reported to be a "very tough, rubbery membrane, and one that adapts itself to contours of the surface to which it is applied" (Engineering News Record 1956).

16. The sealing of Basin F and the placement of vitrified clay pipes with chemically resistant sealed joints to carry industrial waste to the reservoir was completed in 1956 at a cost of $673,000.

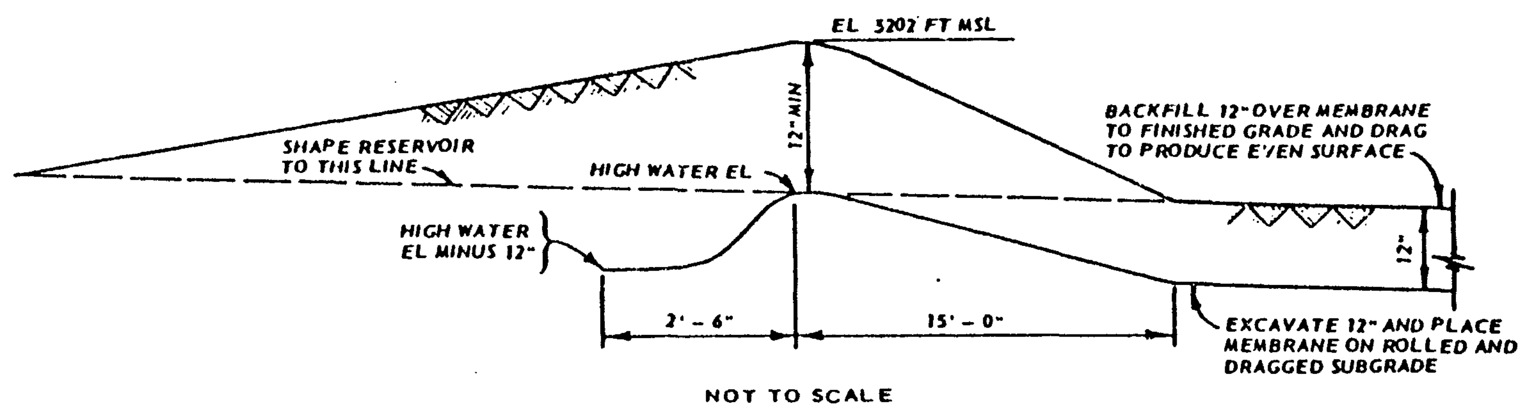

Figure 4. Detail of asphalt membrane at edge of seal area (as built)

Membrane-waste compatibility

17. The industrial waste effluent at RMA in 1955 consisted of soluble salts and organic chemicals as shown in Table 1. The Parsons report did not discuss the possibility of organic contaminants coming into contact with the liner, but a 28 Nov 1955 memo to the Chemical Corps from Chief, Army Projects Division, Military Construction, addressed the incompatibility of asphalt with certain types of waste. The memo stated:

> This type of construction should produce an impermeable and continuous seal for the reservoir. The membrane is flexible and tough and all seepage should be stopped unless the seal is perforated. No maintenance will be required for the portion of the membrane lying under the soil and continuously below the surface of the reservoir. Periodic examination and possibly repairs may be necessary in the membrane above the water line if erosion of the cover soil occurs or if fluctuation of the water level is so great and so rapid as to produce back pressures. The seal material is inert and will not be affected by waste of the type now present in the existing ponds. Resealing within the necessary life of the structure is very unlikely. The following compounds, if dissolved in the waste, will have a deleterious effect on the catalytically blown asphalt: (a) concentrated mineral acids, nitric and sulfuric and strong alkali such as sodium and potassium hydroxide. (b) Phosphorus or P_2O_5 at moderately high temperatures. (c) Halogens - chlorine, bromine, etc. (d) Organic solvents - hydrocarbons; chlorinated hydrocarbons; sulfur derivatives; and nitrogen derivatives. Alcohols, ether, esters, and aldehydes, even though only weak asphalt solvents may be deleterious....

Basin F Operational

18. With the construction and sealing of Basin F complete, draining of Basin A commenced on 14 Dec 1956 and an estimated 60 million gal of liquid was transferred into Basin F. The transfer operation continued until 23 April 1957, at which time the flow was stopped because the membrane liner in Basin F had developed a break at the waterline. At this time the basin contained an estimated 105 million gal (approximately

half full). Due to this break in the membrane lining, the contents above the break were pumped into the adjoining Basin C, lowering the contents of Basin F 20 in. The seal was repaired and riprap was placed on the banks to prevent further damage by wave action.

19. By September 1957 the contents of existing basins were drained into Basin F, and the persistent question was whether the membrane seal was holding. The option of obtaining resistivity measurements in the Basin F area was considered and rejected since a measurement would be meaningless because of anticipated technology problems.

20. Attempts were made to compute a complete water balance as a means of proving or disapproving that significant leakage was occurring. Meters were installed in influent lines, evaporation rates and precipitation meters were measured and/or computed, and historical climatological records were reviewed. The spread of the data available was sufficiently large to preclude the reaching of a conclusion based on overall water balance.

Deep-Well Disposal

Design and operation

21. It became obvious in late 1957 that Basin F was not large enough to handle the waste material generated by the Government and Shell Chemical Co. As a result, a meeting was held in New York City to discuss the continuing waste disposal problem at RMA. Several prominent consultants were requested to recommend alternatives to the Chief Chemical Officer. At the meeting it was stated that since the quantities and types of wastes varied, it was the recommendation of these consultants that a deep well be drilled at RMA. The well would be similar to one then used by DOW Chemical Co., Midland, Michigan, and DuPont Chemical Co., Orange, Texas. Both companies had reported good results with their deep-well disposal units but also emphasized the need to remove all solid material from the waste prior to injection.

22. The Chemical Corps considered deep disposal because at the time it was considered an environmentally safe permanent means of

disposal whereas the membrane seal was recognized to have a finite design life. Subsequently, the Omaha District commissioned the design and construction of a deep-well disposal system at RMA (E. A. Polumbus, Jr., and Associates 1960). The well was approximately 11,400 ft deep and was estimated to have an allowable injection rate of 800 gpm. Representatives of the Omaha District and its consultants advised that the waste to be disposed must be free of solids before injection because the solids would plug the formation and destroy the well in a very short period of time. The Corps of Engineers, recognizing this problem, contemplated modification of Basin F (e.g., construction of Little F or chemical addition) to permit its continued use as part of the treatment system.

23. Accordingly, A. J. Ryan and Associates of Denver conducted a detailed study of the various methods for treatment of the Basin F liquid (A. J. Ryan and Associates, Inc. 1960). DOW Industrial Service, a division of the DOW Chemical Company, served as consultant. The results of the analysis of Basin F material revealed the existence of an extremely fine colloidal material, which, unless taken out of solution prior to injection, would clog the formation pores and result in premature loss of the well. The firm of A. J. Ryan and Associates was then retained to design a waste treatment facility capable of creating a suspensoid-free liquid prior to injection.

24. During a 12 April 1960 conference, Chemical Corps personnel indicated a desire to reconsider retention of Basin F as a link in the deep-well disposal system with use of the pond as a depository for solids remaining after treatment. This procedure was considered in the Ryan report (A. J. Ryan and Associates, Inc. 1960). In view of this, the Omaha District made several recommendations regarding Basin F based upon advice from waste treatment consultants. The suggestions dealt mainly with introducing a biological cycle in Basin F aimed at reducing the solids content (DOW Industrial Service 1960). Basin F was treated with 100 tons of ammonium phosphate in the hope that this would induce microbial action and liquify solids. This and other attempts to clarify

the liquid waste failed and a settling basin was constructed within Basin F (i.e., Little F).

25. A contract for the design of the drilling portion of the work was negotiated by the Polumbus Co., and design of the first stage treatment facilities was completed in September 1960. A contract for construction was awarded to the Newstron-Davis Co. in December 1960. The contract for the drilling of the well was awarded to Loftlin Brothers Drilling Company in January 1961. Drilling of the well commenced in March 1961 and the final depth of 12,045 ft was reached in September 1961. The well head was installed, and the well was completed in November 1961.

26. The completed well was test operated from December 1961 to March 1962, at which time injection of liquid waste pumped from Little F was initiated. Approximately 175 million gallons of fluid was injected during the period of March 1962 to December 1965.

27. The treatment plant, consisting of a chemical addition followed by sedimentation, never operated successfully because the waste material would not flocculate. The liquid was transferred from Basin F to Little F and some filtration and sedimentation may have occurred. However, because of the presence of suspended solids and other problems, the injection rate was limited to 250 gpm.

28. In 1962, the metropolitan Denver area, particularly the Commerce City section, began to experience a marked increase in the number and the intensity of earth tremors. During the week of 22 Nov 65, a Denver television station reported that the number and intensity of earth tremors in the Denver area were directly related to the waste injection into the deep well.

Effluent problem

29. Within the publicity generated by the earthquakes, public concern was expressed about the chemical composition of the waste injected into the deep well. At the time, Shell Chemical Co. generated approximately 85 percent of all the waste being introduced to Basin F. It was general knowledge that the waste was phytotoxic and primarily contained organic and inorganic compounds of nitrogen, fluorine, phosphorus, and sulphur. However, no records were maintained by either RMA or Shell

Chemical Co. as to chemical analysis of the waste.

Operation suspension

30. On 12 December 1966, the Corps completed its investigation of the earthquake problem and together with RMA issued a press release stating that use of the deep well could continue without fear of initiating an earthquake of higher magnitude than already experienced. The possibility of contaminating the aquifer by deep-well operations was considered as unlikely. However, about the same time, the U. S. Army Munitions Command (MUCOM) received a request from Edgewood Arsenal (EWA) that it consider a $1.7 million project to design and construct a chemical waste disposal system at RMA. The transmittal letter stated that the deep well could no longer be used and that Basin F must be eliminated as soon as possible. In 1967, Denver experienced its largest earthquake on record (Evans 1967), and this successfully muted all discussion of reopening the deep well.

Disposal Alternatives

Plans to eliminate Basin F

31. Construction of the deep-well disposal system represented a major effort aimed at eliminating open waste storage, but the adverse effects associated with well operations resulted in the discontinuation of its use. Since 1965 several feasibility studies, design studies, construction funding requests, industrial waste treatment studies, etc., have been proposed or conducted with the objectives of eliminating industrial waste discharge into Basin F and accomplishing its final cleanup. As part of the $1.7 million project suggested in 1966, tentative funding of $811,883 was set for a feasibility study and design and construction of a treatment facility. In 1967, EWA began an investigation of the entire aqueous waste problem at RMA. This study was conducted on a $77,000 contract awarded to Struthers Scientific Corporation to recommend design criteria for an overall aqueous waste disposal system to include treatment of the waste impounded in Basin F (Struthers Scientific and International Corp. 1968). The study indicated that the

cost of the treatment facility could exceed $1.8 million. Regulations did not permit the construction of a facility that would provide a direct benefit to a private corporation, i.e., Shell Chemical Co.

32. In recoginition of this, a letter was sent to Shell Chemical Company stating that, effective 30 June 1968, no further waste generated as a result of Shell Chemical operations would be allowed in Basin F. The basin was in fact receiving large quantities of chemical waste material from Shell at that time. A 1967 RMA memo described the situation. The memo stated in part:

> ...The large quantity of waste in Basin F must ultimately be removed and processed and it looks as if the Army will be stuck with the job....The residual material will have to be processed to remove the threat of additional aquifer contamination....Since the Basin F membrane could quite conceivably be ruptured by a quake, there is the hazard of additional groundwater contamination and additional claims for damage....

33. Disposal of waste into Basin F by Shell Chemical Co. did not cease in 1968. At the time, the Chemical Corps wanted to rewrite its disposal contract with Shell Chemical Co. to include their participation in whatever final treatment system was required for Basin F waste.

34. On 30 September 1969, RMA requested the cooperation of Shell Chemical Co. in identifying, measuring, and reporting on the process waste generated by the Denver plant. Shell responded in November 1969 that the aqueous liquid effluent from the plant was collected from each of the process areas, flowed through two metering stations, and was discharged into Basin F. Since this waste came from many different process areas and was affected by intermittent operations (equipment washouts, etc.), the exact composition of the waste stream was both difficult to analyze and to calculate from known plant operations. Shell Chemical Co. said, however, that analytical methods could determine certain key waste components, i.e., organic extractables, pH, total dissolved solids, and various ionic species. It was stated that these analyses, coupled with average material balances on operating units, would yield an approximate composition of the effluent stream.

35. Because daily chemical analyses or daily calculations of effluent compositions would be impractical, Shell Chemical Co. proposed weekly reporting of waste composition on an approximate basis along with daily flow rates. Since 1969 Shell has filed a weekly report with the Director of Facilities, RMA, containing the following information: organic extractables on a percent-by-weight basis, pH, dissolved solids on a percent-by-weight basis, concentration of iron in parts per million, and concentrations of copper in parts per million. In addition, daily flow rates, as taken from the east and west meters of the effluent line, are reported.

36. In late 1970, Shell Chemical Co. was again notified by MUCOM that plans were being made to discontinue the use of Basin F. Shell responded by indicating a desire to construct their own waste disposal basin in the southwest corner of Section 31 and immediately began a study of methods and designs for construction of a leakproof pond.

37. On 17 October 1972, a meeting was held between Shell Chemical Co. and MUCOM where Shell Chemical Co. informally presented plans for future effluent disposal when Basin F was closed. Shell proposed to build solar evaporation ponds on the arsenal, but the Army stated that neither construction of a new basin nor a reconstruction of Basin F by Shell Chemical Co. would be acceptable. The MUCOM suggested construction of a new basin on land adjacent to the arsenal bought by Shell Chemical Co. The company agreed to reexamine its position and sent a letter to the Army discussing its revised waste disposal program. It was agreed that Shell Chemical Co. would be given a reasonable time to develop and implement a suitable waste disposal program. The time allowed for implementation would depend on the Army's judgment of the feasibility of the program. Following this meeting, Shell personnel met to discuss the available alternatives for their Denver plant and to define areas of responsibility. Primary emphasis was placed on solar evaporation on land adjacent to RMA, pretreatment, and minimization of effluent from the individual units. Additionally, feasibility studies on submerged combustion and incineration would also be carried out.

Shell's plan for separate disposal outside RMA

38. In December 1973, Shell Chemical Co. compiled a feasibility report for construction and operation of a subsurface disposal system, i.e., deep-well injection (Shell Chemical Company 1973). This was submitted with the application of Shell Chemical Co. for a permit to construct and operate a subsurface disposal system in Morgan County, Colorado. The report discussed the various factors considered for effecting subsurface disposal of dilute brine effluent (Table 2) from the Denver plant operations. The site of the subsurface disposal or deep well was to be approximately 80 miles northeast of Denver. The feasibility study concluded that it would have minimum impact on the ecology of the area. It was noted that the disposal system and associated activity were virtually identical to the oil field operation that had been common in the area for many years. The proposed system was conservatively designed to ensure environmental protection and was expected to have negligible effect on industry, agricultural operation, and wildlife in the area. It was also noted that the earthquake risk associated with the proposed waste disposal well was very low.

Plans for new storage basin at RMA

39. Just prior to the October 1972 discussions between MUCOM and Shell Chemical Co., RMA decided to propose construction of a new storage basin. The new basin was to contain all industrial wastes at RMA for a period of 5 years, and the influent would consist of approximately 100 gpm from Shell and 30 gpm from the Chemical Corps' operations scheduled to begin on 1 April 1971 (GB demilitarization program). The proposed appropriation for this project was $4,888,200.

40. Several interesting design features were suggested:

a. The basin would have a double liner separated by a layer of approximately 1 ft of loose material and would contain a network of drain tile. The drain tile would extend to the edges of the basin where visual inspection for leaks could be performed.

b. The basin was to be constructed in sections so that the location of any leaks could be identified and the waste pumped from the leaking section to another so that the leak could be repaired.

Table 2

Estimated Shell Chemical Co. Plant Effluent Flow and Composition*

Components	Annual Averages lb/hr	Annual Averages Concentration
Water	29,859	91%
Sodium chloride	1,259	3.8%
Sodium sulfate	650	2%
Sodium sulfite	29	890 ppm
Sodium bicarbonate	80	2,440 ppm
Sodium carbonate	4	120 ppm
Sodium nitrite	4	120 ppm
Sodium bromide	1	30 ppm
Sodium hydroxide	2	60 ppm
Urea	672	2%
Chloroform	45	1,380 ppm
Methyl isobutyl ketone	6	180 ppm
Aldrin	Trace	Less than 0.001 ppm
AZODRIN[R] insecticide	0.25	8 ppm
NUDRIN[R] insecticide	0.02	0.6 ppm
Other organics	186	0.57%
Totals	32,797	
(gallons per minute)	(65)	

* Based on the projected 1975 production schedule.

c. The annular space created by separating the double liner with 1 ft of loose material such as pea gravel and a network of tile could be drained. Drainage would be collected in a sump and pumped back into the basin, thus intercepting leaks prior to their escape to the groundwater.

41. Eighty acres had been selected as the optimum size for the area with a depth of approximately 6 ft. With average conditions it was expected that over a 1-year period more than 130 gpm/acre would evaporate from 80 acres. The 6-ft depth would allow containment of waste regardless of the fluctuations in depth due to seasonal evaporation and would also provide storage capacity sufficient to permit emergency repairs to a section. After construction, the basin was to be surrounded by an arrangement of monitoring and pumping wells. The USGS was requested to recommend a suitable site on RMA, and the U. S. Bureau

of Reclamation was requested to study and evaluate available liners and make a recommendation as to the material to be used. A construction cost estimate was prepared by the Omaha District.

42. None of these plans were implemented; i.e., neither Shell nor the Chemical Corps ever constructed an alternative to Basin F. However, in response to the problems identified by the Army, the Shell Chemical Co. concentrated its efforts on recycling and on reducing effluent volume. Shell also began reclaiming chemicals and metals from the waste stream prior to discharge into Basin F. A recent (1977) addition to Shell's waste disposal effort is an incinerator currently undergoing trial operation.

43. The Chemical Corps continued to allow Shell Chemical Co. to dispose of its waste into Basin F until March 1978. It assessed a per-gallon charge for this service based on weekly reports filed by Shell Chemical Co. Wastewater from RMA plant operations continued to be discharged into Basin F during the period from 1973 to 1976.

Physical Integrity

44. No historical review of Basin F can be written without mentioning the almost continuous 20-year debate on the integrity of the asphalt membrane. During the initial filling, Basin F wave action caused a break in the asphalt that required extensive repairs and there is evidence that suggests that the asphalt liner is not providing an impervious seal.

45. As stated, groundwater contamination was reported by farmers near the northwest boundary in 1954 and in 1957 crop damage was observed north of the RMA boundary. The crop damage observed suggested the presence of 2,4-D. There is no evidence that 2,4-D was ever manufactured at RMA, yet the material has been found in Basin F in amounts too great to have accumulated from use of herbicides in the area. It is possible that the 2,4-D may have been synthesized within Basin F.

46. A U. S. Public Health Service report (Walton 1961) written in 1959 said "...although there is no evidence of leakage from the asphalt-lined waste evaporation pond, this waste is highly concentrated and even small amounts of leakage may contribute to substantial amounts of groundwater contamination...."

47. In 1966 the liquid level in Basin F was extremely low. Extensive areas of the bottom were exposed on the east and south sides and in several places the soil placed to protect the lining had eroded away. An examination revealed extensive breaks in the asphalt lining on the east side. The reported length of the ruptured membrane was approximately 100 ft running parallel to the shore. A more thorough survey was suggested to determine the exact extent of the damage. It was also recommended that Basin F be maintained at a lower level to prevent further leakage into the aquifer. There is no record of repairs being made subsequent to this report, but it is known that the volume of chemical waste being pumped into Basin F increased significantly in later years and that the liquid level was above the rupture.

48. Up through 1966, it was the practice of Shell Chemical Co. to dump semisolid waste known as "still bottoms" into Basin F. This material consisted of organic compounds such as product precursors, side-reaction products, high-boiling solvents, etc. It was known that the effect of this material on the asphalt liner would be deleterious.

49. A 1969 MUCOM report on the structural soundness of Basin F stated that there was a scouring in the area of the weir measuring box and a suspected scouring where the chemical waste enters the basin. This scouring action may have exposed the liner and the asphaltic membrane in this area was thought to be a potential or actual point of leakage. The placement of an earthen dam across the membrane also caused concern. It was felt that the pressures placed on the membrane by truck operations during construction of the dam and by its subsequent weight could have easily damaged the liner. The report concluded that

> ...the present monitoring system cannot positively identify a leak or no leak condition and since certain well tests indicate the strong possibility of a leak and since the soundness of the membrane is questionable in at least two areas, it cannot be positively assumed that Basin F is tight. On the contrary, a substantial quantity of waste could be lost without detection. On the basis of this rationale, it is prudent to assume that a leak condition exists.

50. As a result of the MUCOM report, discussions were held on using tracer technology to determine the leak condition of Basin F; however, no field applications of this technology were attempted and the MUCOM gave instructions to RMA to pursue the possibilities of constructing a new basin.

51. In November 1969, the question was raised with representatives of the USGS as to whether the organic chemicals in Basin F would penetrate or deteriorate the membrane. The USGS stated that they had a laboratory capable of testing the compatability of the asphalt membrane with chlorinated hydrocarbons. The MUCOM was advised that action was being taken on this aspect of the problem; no test results from USGS relating to this matter were found.

52. Also in November 1969, several individuals detected an odor

in well 118 (located 50 ft northeast of Basin F) similar to that coming from Basin F. This well is the external sampling point most proximate to the deepest contour of the basin. Conjecture at the time revolved around the possibility of hydrocarbon permeation of the membrane with subsequent transfer through the aquifer to well 118. Analysis of water samples showed the presence of chlorinated hydrocarbons and other substances denser than water.

Onsite Inspections and Observations

53. In December 1969, a visual inspection of the membrane was conducted; 14 color photographs and a written report of the inspection still exist. The level of the basin was very low at the time of the inspection, and the pictures clearly show the exposed liner. The following descriptions were taken from the back of each photograph:

> ...Photo #1 is taken from the southeast corner of Lake F looking west/northwest across the lake.
> Photo #2 is taken from the southeast corner of Lake F looking north/northwest across the lake, again the low level of the lake is evident.
> Photo #3 shows the location of hole 3 on a sand bar near the southwest corner of Lake F.
> Photo #4 is of hole 3. The asphaltic liner was still intact at approximately 1.5 ft below the ground level. Liquid at the bottom of the photo is from saturated sand around the hole and above the liner.
> Photo #5 is of hole 3A dug about 10 ft west of hole 3. Seepage from side walls was so great in hole 3 that samples of the liner could not be taken safely. This photo shows the liner still intact and not as much penetration of the liquid into the soil overburden as in photo #4.
> Photo #6 is also of hole 3A showing a section of the asphaltic liner which has been removed and stood on edge beside the hole. Clean, natural-looking sand is clearly evident under the liner.
> Photo #7 is a closer shot of the same material and hole.
> Photo #8 is of the location of hole 4 which is on the west side of the lake approximately 650 ft north of hole 3. The liner was intact and a square

foot section sample of the liner was taken. The soil underneath it was its natural color.

Photo #9 is a trench dug to expose the liner and also two holes dug to expose the liner. The liner was intact at the end near the camera. There were occasional soft spots near the center, and the liner was in a state of liquefication at the end away from the camera. In hole 1 the liner was completely liquified but not completely dissolved.

Photo #10 is a view looking down into the trench. This trench is approximately two ft wide. At this location the liner was intact except for two spots--one below the board and one showing a dark, liquid pool in the left center. The liner at these points was liquified.

Photo #11 was taken midway through the trench. At this point the asphalt liner was still intact. The liner is approximately 14 in. below the soil overburden and there is approximately six inches of foreign material which has been deposited by the effluent on top of that.

Photo #12 shows the location in the trench where the liner changes from a solid state to a liquified state. This point is approximately 30 ft north of the south end of the trench. The liner is approximately 3/8 in. thick at this point; although the liner is liquified it was not completely dissolved.

Photo #13 is at the north end of the trench which shows approximately eight inches of foreign material deposited on top of the original soil overburden.

Photo #14 is of hole 1. The liner at this point had liquified and can be seen oozing out along with other liquids at a point two ft below the surface. Liquid in the bottom of the hole is material that has seeped out from above the liner location.

54. Photographs 6 and 14 are reproduced in this report as Figures 5 and 6, respectively. These photographs were selected to illustrate two extremely different conditions of the membrane liner: intact (Figure 5) and severely compromised (Figure 6). These photos show that sections of the asphalt membrane had little or no integrity as early as 1969.

55. On 17 December 1969, it was decided that the Director of the

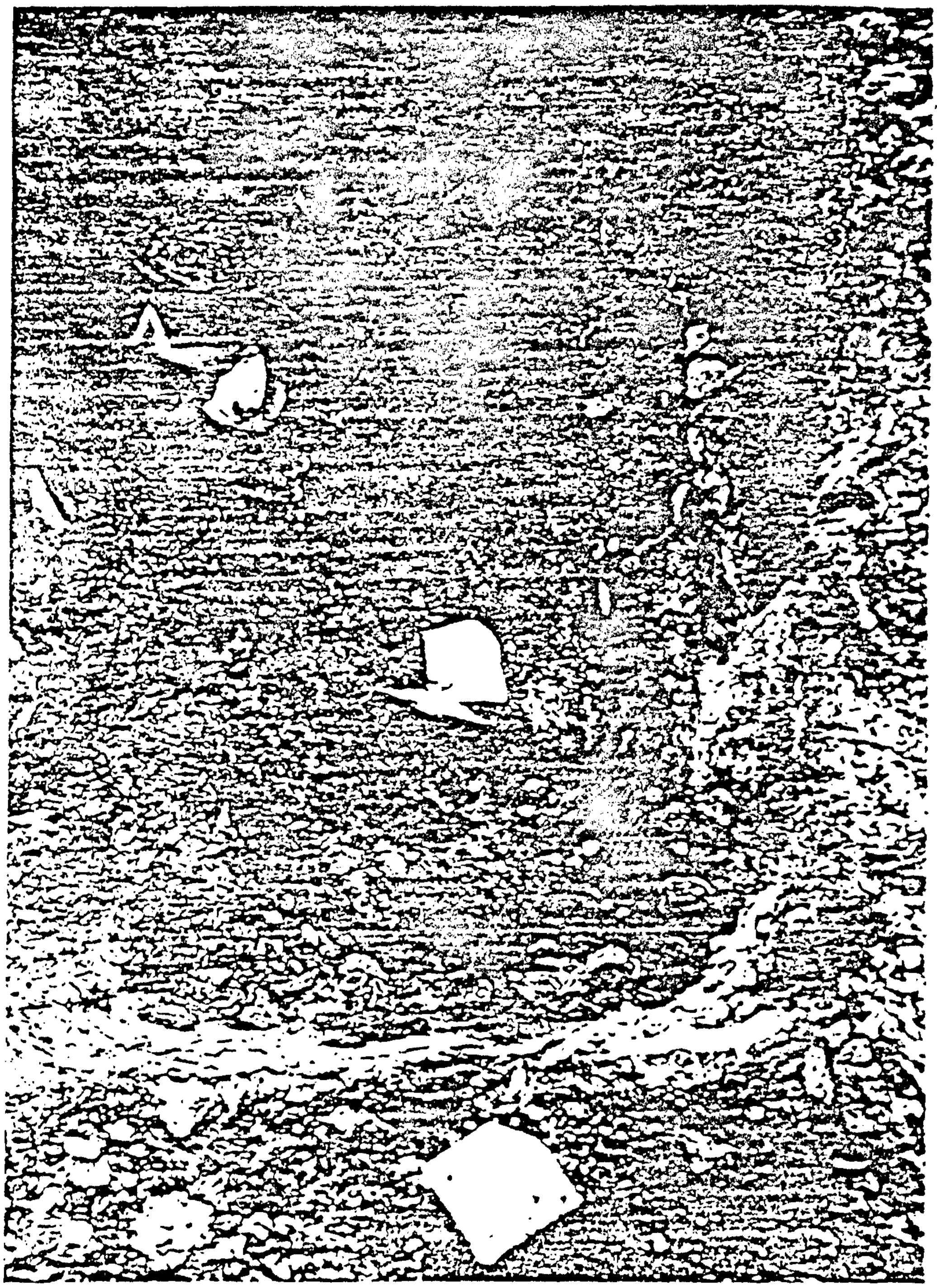

Figure 5. Hole 3a dug in an area of structural membrane integrity. Note the clean sandy soil exposed under the liner

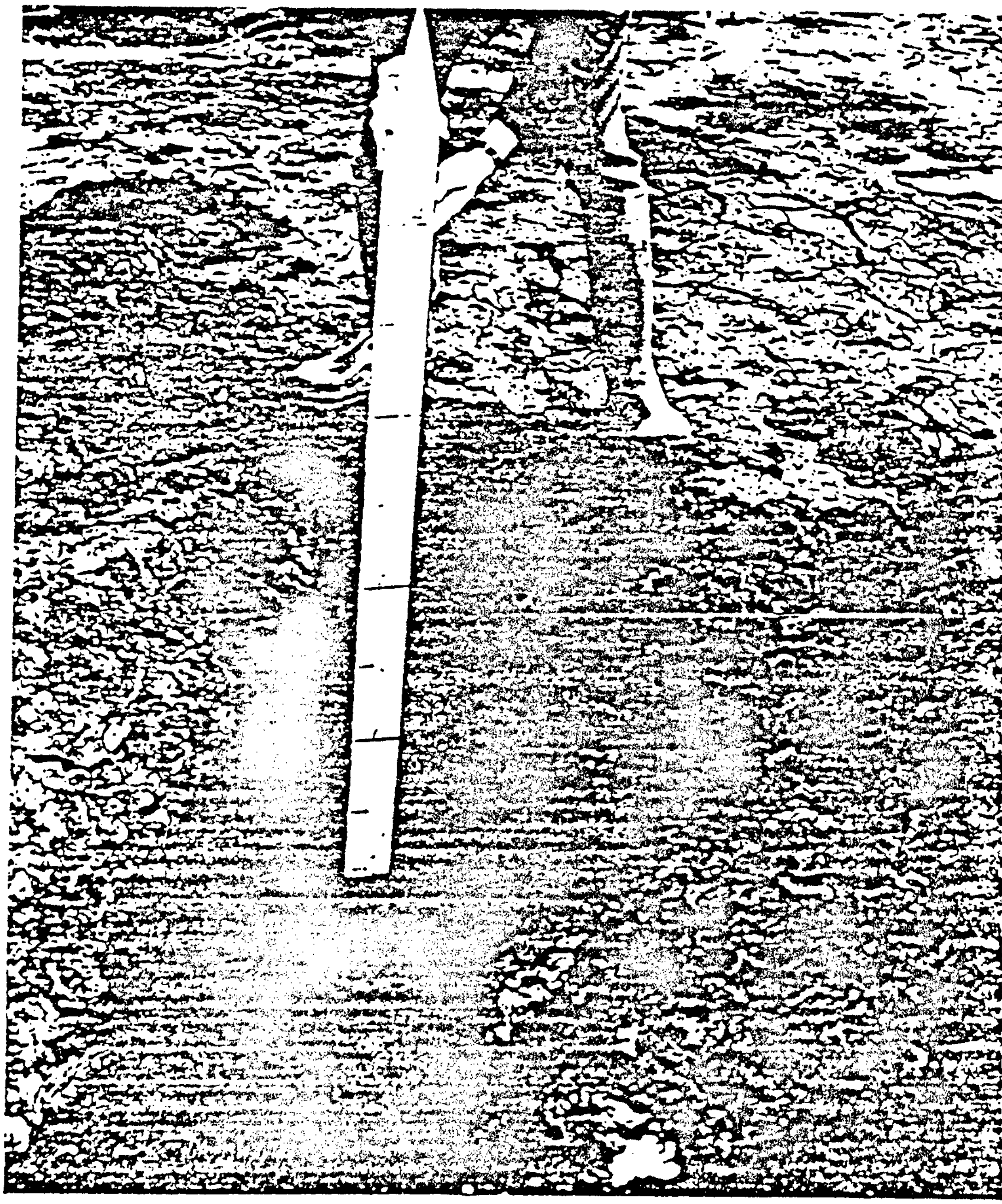

Figure 6. Hole 1 dug in an area where membrane liner had been severely compromised. Liquid at the bottom of the hole was dissolved liner and other material that had seeped out from above the liner

Chemical Demilitarization Project would recommend to MUCOM the use of Basin F as the best means of disposing of M34 waste. In February 1970, a program review on the proposed demilitarization project (Project Eagle) indicated that all neutralized agent GB wastes from demilitarization operations would be disposed of by other means and would not be discharged into Basin F. At about the same time, Shell Chemical Co. began to make plans for alternate disposal systems.

56. During June 1970, holes drilled in areas of F-1 (Little F) where the membrane was no longer intact showed that there were considerable soluble organics in the ground with the upper level samples generally showing more than the samples taken in deeper strata. These data are consistent with what could be expected where no liner exists. The reduction in concentration of organic and inorganic compounds with depth demonstrates the soils natural ability to attenuate these substances. In addition to the information on organic extractables, data were obtained on nickel, copper, fluoride, and chloride. A letter from the EWA to RMA noted that the expected report from USGS covering their study of historical documents and their recommended further actions was still required. The same letter also requested that a construction project request be submitted to provide an industrial waste storage basin at RMA designed to accommodate Government wastes, including wastes resulting from M34 demilitarization.

Membrane Compatibility Study

57. In September 1970 the Bureau of Reclamation evaluated butyl, neoprene, hypalon, rubber, polyvinyl chloride, and polyethylene plastic as potential liner material for a new waste basin at RMA (Bureau of Reclamation Engineering and Research Center 1970). Performance of each substance was evaluated using a C-rated industrial waste and existing wastes from Basin F. The report of this test program mentioned that catalytically blown asphalt lining (hot spray application), which has been used extensively in irrigation canals and some water storage reservoirs, can be used for pond waste of acid or saltwater solutions.

The report noted, however, that petroleum and its derivatives are solvents of asphalt and cannot be stored in asphalt-lined structures:

> Hydrocarbons and hydrocarbon derivatives such as toluene, chloroform, trichloroethylene, and acetone are detrimental to asphalt in varying degrees. Variable amounts of these hydrocarbon materials may be expected in the waste to be stored in the new RMA basin. Thus, asphalt lining would not be suitable for this installation.
>
> Tests with catalytically blown asphalt membrane, 1/4 inch thick, immersed 30 days in RMA simulated waste with 1.0 percent chloroform, by weight added, indicated only a slight softening effect on the asphalt. With a significant volume (approximately 10 percent) of chloroform or trichloroethylene added to the RMA simulated waste, the asphalt membrane was dissolved within 24 hours. The catalytically blown asphalt membrane had disadvantages because of its incompatibility with hydrocarbons and hydrocarbon derivatives. The nylon-reinforced neoprene membrane appears questionable because of high absorption and volume swell. The best candidate liners appear to be the standard PVC, Hypalon, and nylon-reinforced butyl.

58. In 1971 and 1972, Basin F contained approximately 85 million gal of waste effluent. This was much less than that present in 1966 or in December 1969. The low liquid level exposed additional areas of the bottom. Erosion and weathering may have occurred if there were gaps in the soil blanket covering the liner. This would cause the underlying asphalt to become brittle and develop fractures or cracks. Beginning in late 1972, the liquid level increased steadily reaching 200 million gallons in 1976.

59. An investigation in January 1977 showed that asphalt liner samples absorbed approximately equal amounts of Basin F fluid or distilled water and become soft when exposed to either liquid.

Infrared Spectroscopic Examination

60. A March 1976 infrared spectrum, performed by Hauser Laboratories, Boulder, Colorado, on material thought to be the original

catalytically blown asphalt seal showed major absorptions due to nitrogen-hydrogen bonding and other heteroatoms. The spectrum had no similarity to virgin asphalt. The report said:

> The material may have been the original asphalt layer, but chemical change has apparently occurred. Contamination would have to exceed 50 to 70 percent in order to account for the observed spectrum. The physical properties of the material are dissimilar to asphalt by inspection especially the ductility and penetration. It is probable that this layer has none of the properties which made it valuable as a water barrier.

It should be remembered that the liquid in Basin F is dissimilar to water. The molecules are larger and have different properties and this would affect their ability to penetrate the membrane.

PART IV: EVAPORATION STUDIES

Material-Balance Calculations

61. Material-balance calculations on Basin F have been attempted since 1957. The Basin F liquid level is recorded monthly and the volume of chemical waste discharged into the basin is obtained from meters placed in the influent lines. It should be remembered that these meters are placed near the plant and cannot account for the exfiltration and infiltration from the chemical sewer line which is known to leak (Figure 7) and which may extend below the water table in some places. Other data, such as wind velocity, precipitation, humidity, etc., are available from weather bureau records. In conducting a material-balance study on Basin F, it is necessary to make the following assumptions: accuracy of measurements; no liquid loss other than evaporation; and a standard evaporation rate with which to compare the calculated value. At its best this represents only a gross measurement and the number derived each month lacks the precision to be of value by itself.

62. Despite the problems inherent in the Basin F evaporation and inflow measurements, almost 16 years of evaporation data on Basin F exist and are of collective importance. Table 3 shows calculated monthly evaporation rates for Basin F from 1957 to 1977. Complete data on the years 1959 through 1964 were not available. An examination of the data shows many inconsistencies and several anomalously high or low monthly values. The yearly averages are more interesting and qualitatively yield more information about Basin F. From 1958 through 1961, the rate of evaporation decreased approximately 13 percent each year. This was noticed at the time and was used as partial justification for construction of the deep-well disposal system. When data again became available, a significant increase in the yearly evaporation rate was noticed. This increase puts the rate above the generally accepted upper limit of 2.0 gpm per acre quoted in numerous memoranda and studies on Basin F. "The yearly evaporation from Basin F is approximately 75 million gallons (MG). This volume is based on an average rainfall of

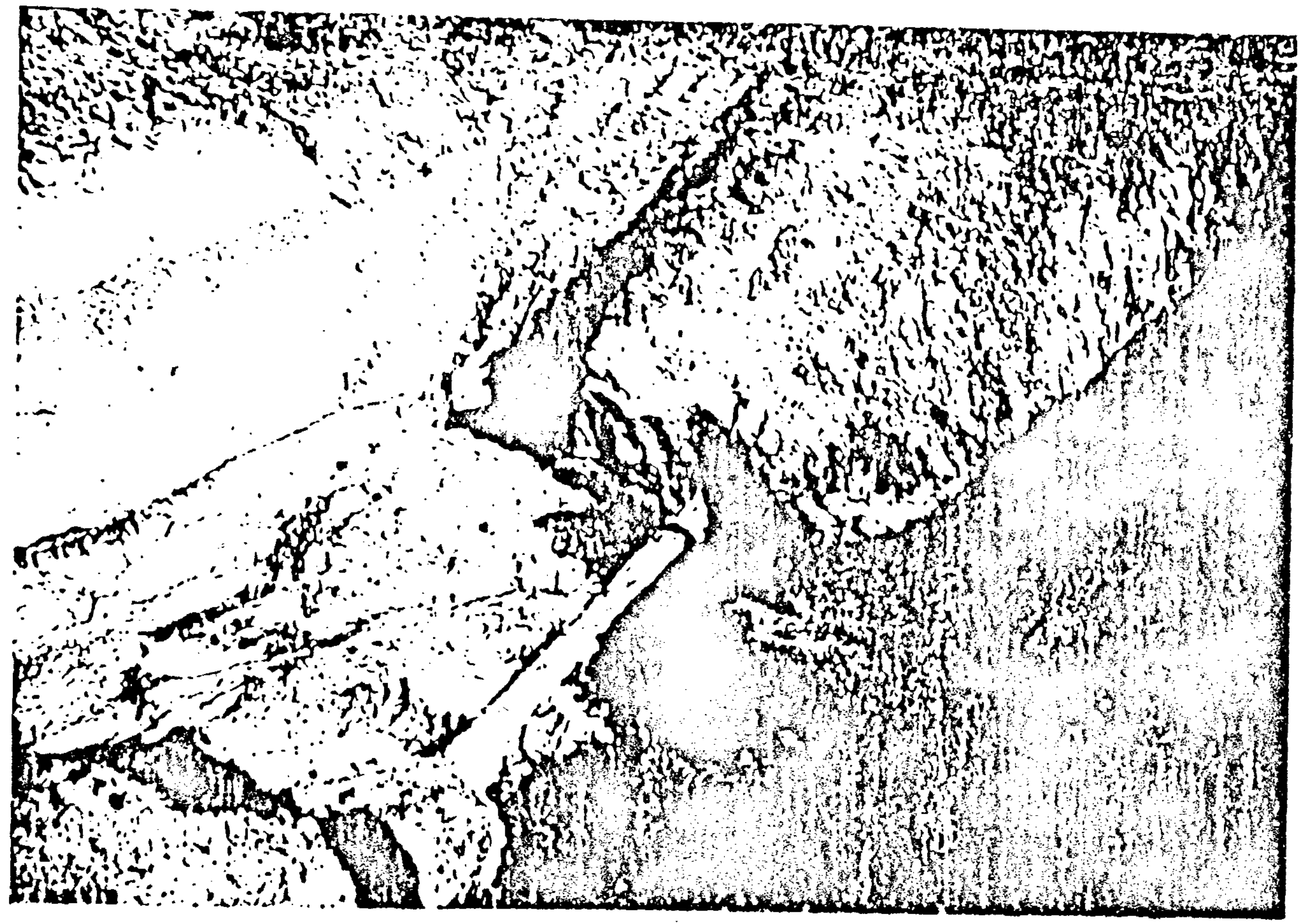

Figure 7. Excavated leaking chemical sewer

Table 3

Monthly Evaporation Rates for Basin F*

	Year of Measurement - gpm/acre																				
Month	1977	1976	1975	1974	1973	1972	1971	1970	1969	1968	1967	1966	1965	1964	1963	1962	1961	1960	1959	1958	195-
Dec		0.80	2.72	0.37	0.51	0.37	0.54	0.88	1.04	1.25	0.94	0.49	0.44	0.24							0.18
Nov		1.65	0.76	1.23	0.94	0.05	0.74	1.45	1.01	1.24	1.22	1.17	1.47	0.95							1.87
Oct		1.45	2.09	1.56	2.04	1.78	2.24	1.65	0.10	2.46	2.48	2.16	1.76	2.08						0.35	1.57
Sep		2.27	2.82	2.88	2.81	2.59	2.84	2.76	3.20	3.28	3.26	2.60	2.75							1.69	
Aug		5.69	3.34	3.48	4.42	3.39	4.86	5.02	4.94	3.76	3.42	4.52	3.96							1.85	
Jul			3.20	4.44	4.06	4.66	3.66	4.24	4.38	4.74	3.80	4.68	3.89							3.44	
Jun	3.80	3.15	2.38	4.20	4.84	4.06	5.37	4.03	3.46	4.63	2.94	4.01	2.76							2.83	
May	3.26	2.86		4.04	2.03	2.76	3.06	3.82	2.47	3.18	1.92	3.72	2.66						1.07	0.67	
Apr	1.02	1.73	1.48	1.50	1.24	2.41	2.59	2.75	2.88	2.21	3.20	2.74	2.98						1.16		
Mar	1.13	1.31	2.38	1.86	0.93	1.22	1.04	1.28	1.49	1.62	2.33	1.08	0.47						0.56		
Feb	1.20	0.95	0.86	0.55	0.96	1.19	1.08	1.22	1.28	2.04	1.52	1.40	0.15								
Jan	0.17		0.74	0.21	0.06	0.29	0.79	0.56	0.36	0.07	0.45	0.72	0.06								
Yearly Average		2.18	2.07	2.19	2.07	2.10	2.40	2.47	2.22	2.54	2.28	2.44	1.94				1.23**	1.42**	1.63†	1.87†	

* Monthly evaporation rates calculated from RMA Engineering Division Reports. Averages were calculated from tabulated data except as indicated.

** Chemical Corps estimate.

† From Chemical Corps memo on Basin F evaporation.

15 inches per year, with an evaporation rate of 42 inches per year, for a net evaporative loss of 27 inches per year or approximately 1.5 gpm/acre" (McNeil 1975). The holding capacity of Basin F at various liquid level elevations and surface areas is shown in Table 4.

Spray Raft Operation

63. In an attempt to reduce the volume of liquid in Basin F and ultimately dispose of all its liquid in a cost-effective means, a spray raft was constructed and operated during 1965 and 1966. The spray raft operated on an intermittent basis, but eventually had to be shutdown because of air pollution problems, i.e., odors and wind dispersion of dried salt. Two Army Environmental Hygiene Agency (AEHA) reports of 1965 state that the combined evaporation rate from the surface of Basin F and the spray raft averaged approximately 140 gpm during the 8 months

Table 4

Basin F Capacity

Elevation, msl	Area, acres	Holding Capacity gal × 10^3
5185	1.4	
5186	5.1	1,050
5187	14.7	4,280
5188	21.3	10,150
5189	26.1	17,890
5190	29.1	26,890
5191	35.2	37,360
5192	43.3	50,150
5193	51.6	65,600
5194	60.6	83,890
5195.55	75.6	106,090
5196	80.6	131,690
5197	82.9	158,390
5198.1	85.3	185,790
5199	87.7	214,090
5200	90.1	243,090

of the year when conditions were most favorable for its use (Reuter and Milbury 1965, Milbury 1965). With an average surface area of 83 acres during that time, the evaporation rate is calculated to be 1.68 gpm/acre.

Evaporation or Leakage

64. Using best records available and considering long-term averages in computing a water balance, the data suggest that leakage may have begun as early as 1965. However, the lack of information on the condition of the sewers and variations in other available data preclude the forming of any statement confirming leakage (and quantities of leakage) based on water balance alone.

PART V: CONTAMINANT MIGRATION ATTRIBUTED TO BASIN F

Monitoring Wells

65. Because of environmental concerns and the need to confirm (or disaffirm) leakage from the basin to justify the expense of developing alternate disposal systems, the monitoring wells around Basin F (shown in Figure 8) were installed in 1969 and 1975 to ensure that any increase in groundwater contamination (attributable to Basin F leakage) would be

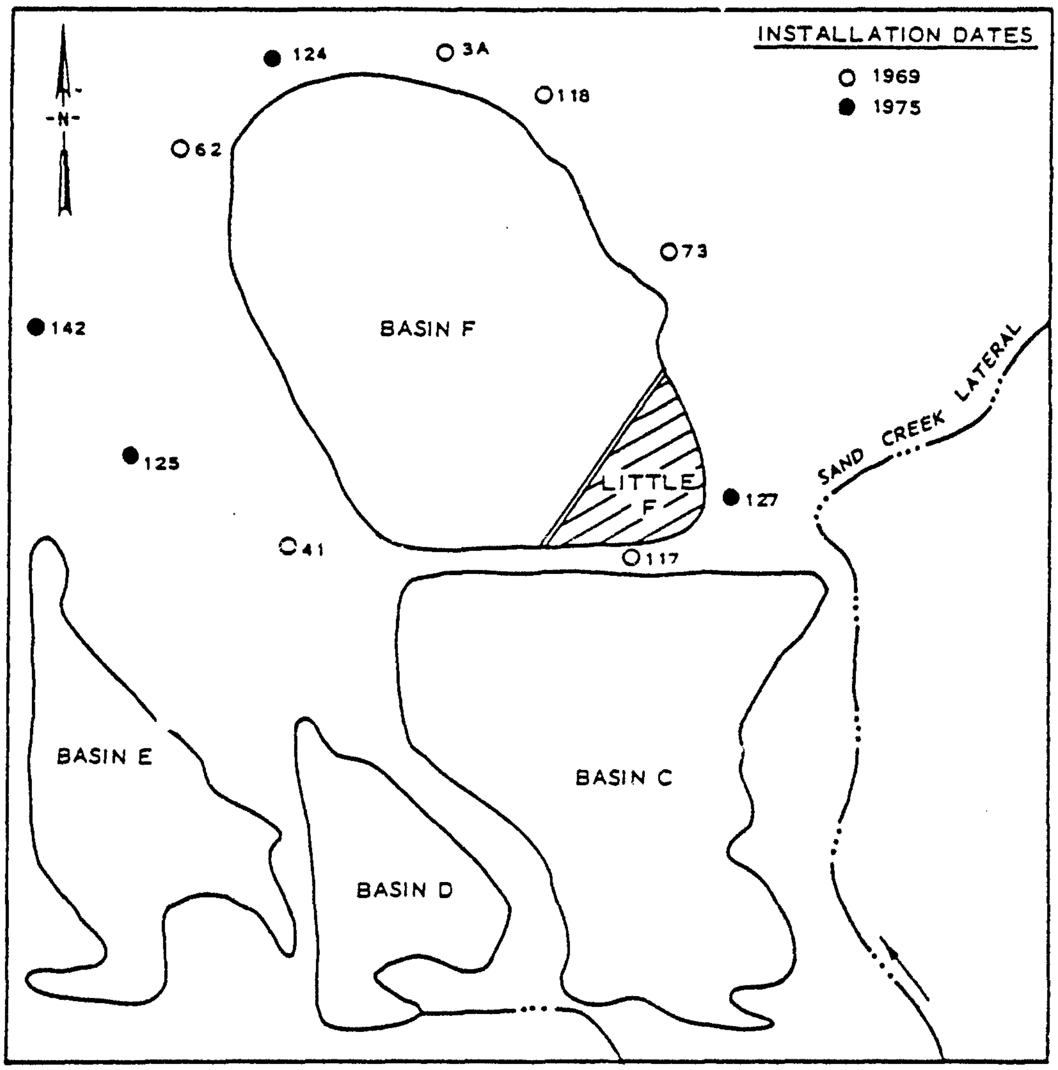

Figure 8. Basin F monitoring wells

detected. In 1969, six of these wells were recorded as being in the basin area at distances varying from 50 to 300 ft from the dike. Since 1969 the number of monitoring wells has been increased from six to ten.

Chemicals Suggested as Indicators of Contaminant Migration

Chloride ion

66. From 1969 through 1974, water samples were taken from the monitoring wells on a regular basis and analyzed for chloride ion. A compilation of yearly averages of these data is given in Table 5. A review of the data reveals that two distinct periods exist where the chloride concentration was either decreasing or increasing. From 1969 to 1970, there is a substantial decrease in chloride concentration; whereas, following relatively stable concentrations, a general increase in chloride levels is evidenced from 1974 to 1975. This increase in chloride concentrations continued through 1977. The decrease in chloride levels in the wells surrounding Basin F from 1969 to 1974 has been attributed to a general flushing of the aquifer by new and relatively

Table 5

Annual Average Chloride Ion Concentrations Measured in Basin F Monitoring Wells

	Year-Average Chloride Ion Concentrations, ppm								
Well No.*	1969	1970	1971	1972	1973	1974	1975	1976	1977
125							130	932	
41	450	114	156	170	100	82	739	632	524
117	694	218	230	356	210	578	698	803	
127							765		
73	281	198	112	110	150	252	271	549	1286
118	736	206	182	122	125	144	338	1010	1960
3A	329	190	117	110	129	117	136	211	
124							167	150	
62	249	107	99	104	63	94	138	138	292
142							134	282	805

* Wells are tabulated in counterclockwise sequence as they were located around Basin F.

unpolluted groundwater (Konikow 1977). This theory assumed that the basin was not leaking and that observable chloride levels were due to contamination originating from sewer leakage or other waste disposal areas on RMA.

67. With the increase in chloride levels during 1974 clearly evident, a new theory was needed. Since well 117 registered the earliest and most significant increase in chloride concentration, leakage from the southeast corner of Basin F (Little F) became the focus of attention. A functioning hypothesis surfaced, "...the source of groundwater contamination exists in the southeast corner of Basin F... it does not appear to be the main body of Basin F" (Colorado Department of Health 1975).

68. Virtually all investigations of Basin F have reached the conclusion that Basin F was not leaking; however, ample evidence exists to support an opposite view. Supporting evidence has been accumulating since measurements of chloride levels began around Basin F. Chloride data (1969-1976) for wells 41, 117, 73, 118, 3A, and 62 are presented in Table 6. A close correlation exists between the chloride concentration found in wells 117, 118, and 73 and the level of waste in Basin F. Figure 9 shows a plot of monthly chloride levels for wells 117 and 118 superimposed upon monthly liquid level fluctuations of Basin F. It can be noted that an increase in the liquid level of Basin F was accompanied by an increase in chloride levels of the monitoring wells.

Copper

69. Trost report. A drilling program was conducted by Trost around Basin F in August 1976 (Trost 1976). Both soil and water samples were analyzed for elements known to be unique to the aqueous phase of Basin F: copper, arsenic, chloride, sulfate, phosphorus, and fluoride. It was felt that noticeable concentrations of these elements in the core samples would be indicative of either poor liner integrity or leakage through the dike around Basin F. High concentrations of copper, sulfate, arsenic, and chloride were noted around the southeast corner of Basin F. Holes dug by hand along the southeast shore showed a partially disintegrated liner. These holes rapidly filled with an aqueous

Table 6

Average Monthly Chloride Concentrations in Basin F Monitoring Wells

		Year-Chloride Concentration, ppm								
Well	Month	1969	1970	1971	1972	1973	1974	1975	1976	1977
41	January	332	65		150	89			335	351
	February	358	62	108	150	87	84		470	
	March	748	76	119	102	96	79		625	
	April	793	116	116	97	84				510
	May	875	120	131	130	130	84	1105	700	
	June	1029	138	165	126	104		1080		712
	July	439		98		86		1080	855	
	August	60	133	183	142			1040		
	September	61	181	180	146	128		718		
	October	72	144	192	156	124		350	810	
	November	62	157	217	137	106		300		
	December	80	152	212	110	88	117	240		
117	January	812	248		447	196			700	
	February	784	405	233	517	272	451		775	
	March	1269	408	391	567	326	499		770	
	April	1247	521	416	628	434	623			
	May	1235	304	428	778	352	794	650	800	
	June	986	94	106	328	69		755		
	July	214		65		66		740	880	
	August	45	81	71	107			800		
	September	43	88	64	82	78		610		
	October	43	76	72	88	86		642	895	
	November	48	79	130	87	108		720		
	December	88	81	286	94	247	524	670		
73	January	411	129		96	151			350	1150
	February	377	149	115	104	149	232		350	
	March		218	113	100	171	251		480	1460
	April	401	275	120	103		263			
	May	374	311	117	113	199	265	328	415	
	June		304	123				285		1250
	July	378						200	650	
	August	378			102			270		
	September	135	106		128	122		295		
	October	113	120			108		320	1050	
	November	108		100		118		122		
	December	118	58		136	182	224	348		

(Continued)

Well	Month	Year-Chloride Concentration, ppm								
		1969	1970	1971	1972	1973	1974	1975	1976	1977
118	January	440	173		106	148			535	2000
	February	540	178	110	98	128	111		760	
	March	975	193	106	98	130	118		800	
	April	1086	212	114	100	110	117		950	1920
	May	1113	228	119	159	106	124	240	1075	
	June	1131	207	140	146	110		226		
	July	1152		165		124		230	1350	
	August	1684	374	382	152			280		
	September	616	278	355	142	153		380		
	October	492	207	263	136	120		288	1600	
	November	221	187	208	148	112		540		
	December	195	174	139	156	128	252	520		
3A	January	240	254		108	116	No Data		150	
	February	230	208	112	107	124	115		185	
	March	330	206	116	105	114	106		190	
	April	364	222	113	100	137	115		204	
	May	376	216	120	104	136	107	135	220	
	June	385	239	122	98	129		142		
	July	396		118		115		126	320	
	August	419	285	134	119			130		
	September	352	174	134	120	151		120		
	October	341	143	133	122	132		135		
	November	378	136	113	108	122		136		
	December	324	119	104	118	118	144	165		
62	January	212	108		129	100			126	
	February	218	97	96	130	14	100		140	
	March	307	101	96	118	26	100		138	273
	April	313	104	81	106	58	99			
	May	298	111	76	108	11	79	149	133	310
	June	297	91	93	90	7		139		
	July	289		91		9		136	152	
	August	269	116	112	127			144		
	September	236	136	79	50	126		142		
	October	212	108	132	92	89		120	171	
	November	191	123	126	90	112		140	105	
	December	126	106	124	92	116	15	127		

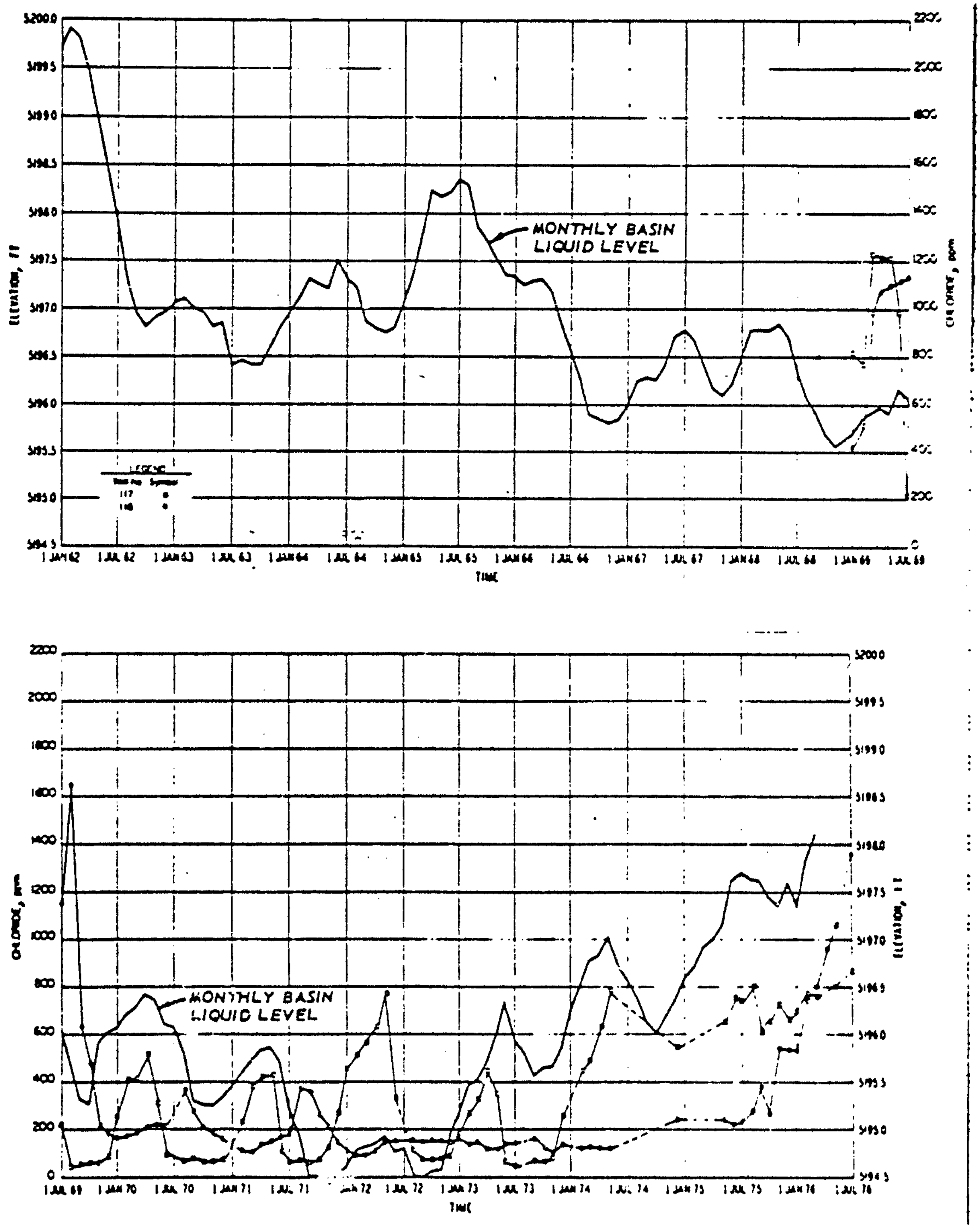

Figure 9. Comparison of liquid levels in Basin F with chloride concentration in wells 117 and 118

solution strongly resembling the liquid of Basin F. It was suggested that Basin F was leaking through the dike in the southeast corner (Little F) (Trost 1976). A correlation of sulfate and copper in the same core samples coupled with visual observation of caliche (calcium carbonate) suggested that malachite $Cu_2(CO_3)(OH)_2$ and/or azurite $Cu_3(CO)_3(OH)_2$ was forming. The highest concentration of copper was detected near the southeast corner.

70. Walden study. The November 1976 Walden report on coring data for compounds at RMA concluded that there was localized but significant copper contamination in Sections 36 and 26 (Figure 1) soils at mean depths to 19.5 ft (Cogley 1976). Figure 10 shows the copper distribution in Section 26. Of note are the high values from core samples taken north of Basin F.

71. Discussion. The finding of copper contamination in the periphery of Basin F is quite significant. Copper was first detected in Basin F in 1969. The concentration at that time was 100 ppm. Copper salts are present in waste generated during the Shell Chemical Co. production of Azodrin.

72. The observation that copper could not be detected in any of the monitoring wells adjacent to Basin F has been used to support the theory that the asphalt liner was intact. In 1969 the USGS, however, pointed out that copper was easily adsorbed by clays and it would be unlikely for researchers to find soluble copper in the groundwater. As recent as 1975 there were statements that still insisted that "if Basin F were leaking, a higher concentration of contaminants including copper would be expected in nearby wells" (McNeil 1975). The Walden report confirmed that copper had migrated from Basin F and had been located, not in the groundwater, but in the soil where it was predicated to be (Cogley 1976). This information indicates that Basin F is a source of groundwater contamination. This is corroborated by other evidence as discussed in the following paragraphs.

Stressed vegetation

73. Aerial color infrared photographs taken of the Basin F area showed a fringe or border of anomalously vigorous vegetation surrounding

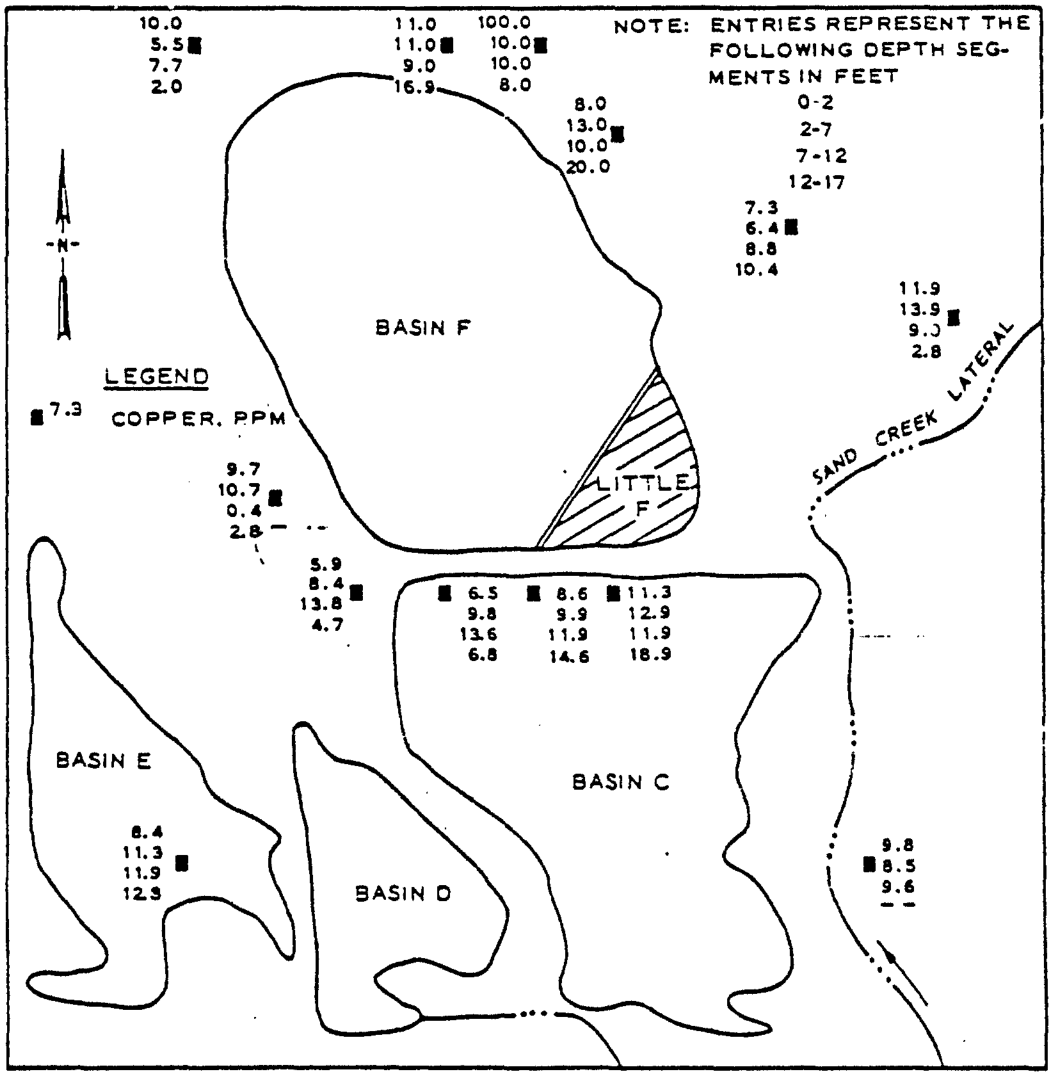

Figure 10. Copper distribution in Section 26
(Cogley 1976) (sheet 1 of 2)

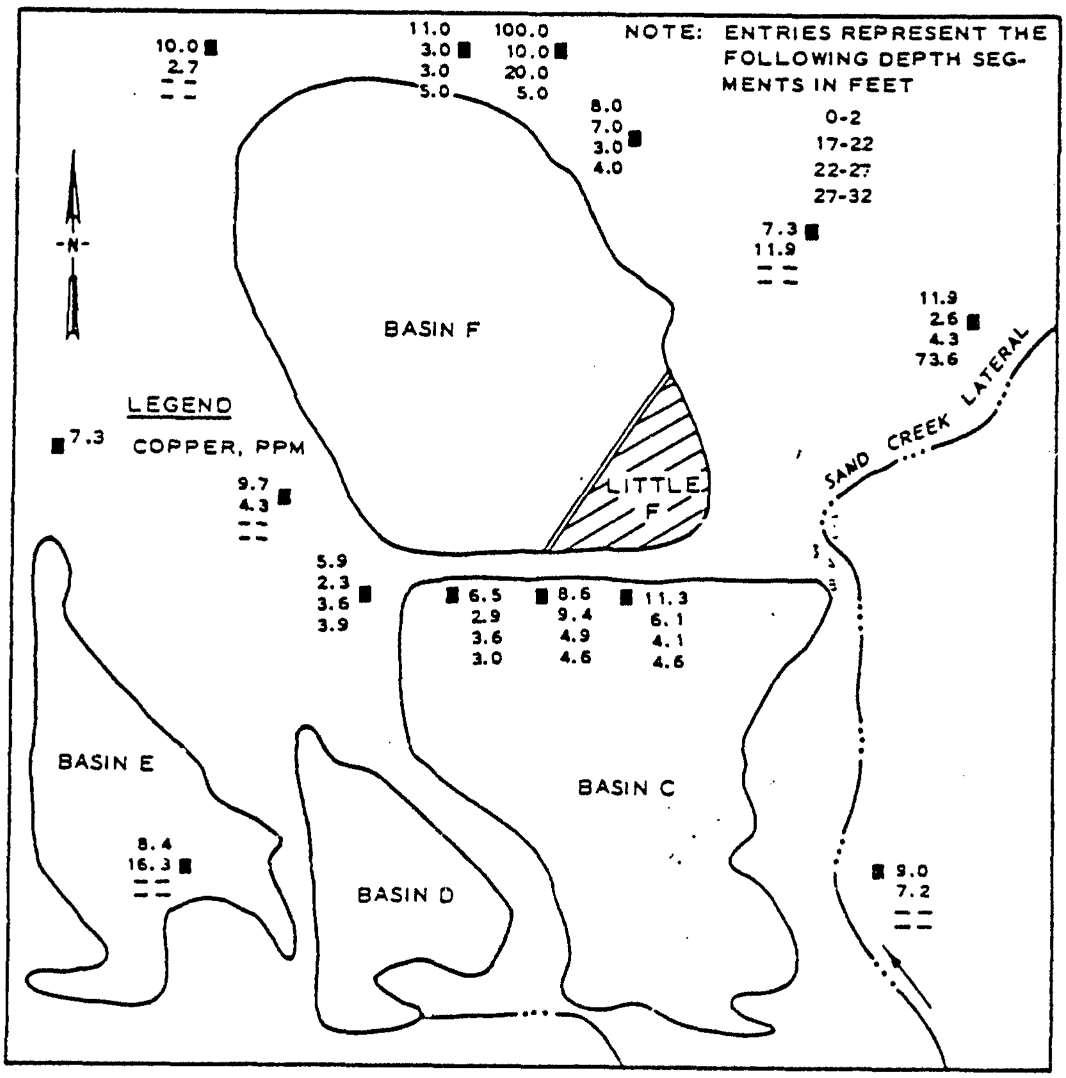

Figure 10. (sheet 2 of 2)

a large area of dead or dying vegetation (Muhm 1974). This pattern was predominant around Basin F and was most widespread on the north and east sides of the Basin. The aerial photographs were interpreted as indicating that water was escaping or was being discharged from at least three sides of Basin F (north, east, and west) that are all downgradient. As the water left the basin, its first effect was to nourish the early growth of water-seeking plants. The next effect was somewhat delayed with the vegetation exhibiting phytotoxicity after a period of exposure to the water from the basin.

Organo-sulfur compounds

74. Other compounds emanating from Basin F are p-chlorophenylmethylsulfide and p-chlorophenylmethylsulfone. These two compounds are process intermediates in the manufacture of Planavin. Shell Chemical Co. produced Planavin from 1966-1975 while all of the waste products were being discharged into Basin F. The chemical sewer leading to the basin has been suggested as a possible source from which these compounds enter the aquifer. Figure 7 (page 35) is an excavation showing that the sewer does, in fact, have some leaks. Several monitoring wells around Basin F contain significant concentrations of p-chlorophenylmethylsulfone (wells 118, 73, 41, and 62), suggesting that Basin F is also a source of groundwater contamination.

Summary

75. The evidence is substantial that Basin F is a principal source of groundwater contamination. It has often been stated that a major leak in Basin F would cause enormous increases in the concentrations of most chemical species found in wells downgradient to the basin. This reasoning envisions a massive movement of Basin F liquid to the soil below the liner. This scenario is unlikely to occur without the impetus of a natural phenomenon such as an earthquake.

76. The asphalt liner in Basin F is 21 years old and has not been immune to natural wear and aging. There is little doubt that the effectiveness of the liner has been seriously compromised by its contact with organic compounds and solvents.

77. The type of leakage occurring in Basin F is that of slow,

lation between chloride levels in the monitoring wells and the volume of waste contained in Basin F affirms this leakage. The volume of liquid contained in Basin F has varied considerably over the years (Figure 9). During extended periods of low liquid levels, the exposed shoreline could dehydrate and cause the underlying liner to become brittle and develop fractures or cracks. Any subsequent increase of the liquid level would allow seepage to occur.

78. Waste seepage through any portion of the deteriorated or chemically compromised liner would also be increased by the increase in head pressure resulting from added waste volume. Increasing the level of liquid in Basin F would increase the pressure exerted on each square foot of liner and add additional driving force to the liquid permeation of liner and soil.

79. It should also be remembered that the soil acts to attenuate the migration of contaminants (e.g., copper is seen in the soil, but not in the groundwater). This natural ability of the soil mass to reduce certain pollutant levels (by such processes as infiltration, adsorption, absorption, chelation, etc.), coupled with the dilution caused by constantly new and moving groundwater, would preclude ever measuring contaminant concentrations in the monitoring wells approximating those of Basin F itself.

PART VI: SUMMARY OF FINDINGS FROM LITERATURE REVIEW

80. Rocky Mountain Arsenal was established in 1942 to manufacture chemical warfare agents. Military operations at the facility have included the production of chemical agents, the fabrication of munitions containing these agents, and the demilitarization of such munitions. Portions of the industrial plant area have also been leased since 1946 to private companies for the manufacture of insecticides and other chemicals.

81. Prior to 1956, the waste products resulting from military and industrial operations were disposed of in various unlined evaporation ponds. In 1956, a new earthen basin (Basin F) was constructed and lined with an asphalt membrane; subsequently, the majority of all wastes have been discharged into this basin.

82. During the 21 years since Basin F became operational, numerous investigations of RMA waste disposal practices have been undertaken because of the Army's concern over its potential for causing environmental damage and because of their need for an adequate disposal system. These investigations addressed the adequacy of Basin F capacity, the integrity of the asphalt membrane, evaporation rates associated with Basin F liquid, deep-well disposal of Basin F fluid, characterization and treatment studies of Basin F liquid and sludge, and migration of contaminants via groundwater which might be attributed to Basin F. Many of the decisions concerning the operation and disposition of Basin F were, in part, based on the results of these studies.

83. There is one consistent finding derived from an intensive review of the literature concerning Basin F: it is a source of contamination and thus represents a potential environmental hazard. A large body of evidence exists testifying that the asphalt membrane no longer provides an impervious lining in the basin; photographs taken of the asphalt membrane clearly show that sections of the liner have been severely compromised. Further examinations of the asphalt membrane indicate that the properties that originally made it valuable as a water barrier no longer exist. Other evidence concerning migrating

contaminants attributed to Basin F includes a close correlation between chloride levels in the monitoring wells surrounding the basin and the liquid levels in Basin F and the finding of significant copper contamination in the soil surrounding the Basin periphery.

84. All of the evidence cited in the preceding paragraph indicates that the leakage and contamination attributed to Basin F are from the slow, persistent permeation of the waste through the membrane into underlying soils. The levels of contamination in the aquifer appear highly influenced by: the volume of waste in the Basin, the attenuation of pollutants by the soil, and the amount of dilution caused by constantly recharged groundwater in the vicinity of the Basin.

85. Based on the great amount of evidence concerning the existing and potential environmental hazard associated with Basin F, it is prudent to state that a decision should be made to begin containment, treatment, and/or disposal of the waste and contamination attributed to Basin F. Disposal of Basin F is such a complex undertaking, however, that simple and/or readily implementable schemes presently do not exist. Planning for a successful disposition study of Basin F requires obtaining answers to several questions:

- *a*. What is the nature of the waste in Basin F (e.g., chemical composition, physical properties)?
- *b*. What is the extent of contaminated material attributed to Basin F?
- *c*. What are the objectives of containment/treatment (e.g., is resource recovery desirable or realistic)?
- *d*. What treatment levels must be achieved?
- *e*. What treatment alternatives and cost-effective trade-offs exist?
- *f*. Is construction of a new waste disposal system for future use at RMA desirable or realistic?
- *g*. Is ultimate disposal intended?
- *h*. What priority and time frame for ultimate disposition of Basin F are intended?

REFERENCES

A. J. Ryan and Associates, Inc. 1960. "Comparative Methods of Treatment of Waste Effluents at Rocky Mountain Arsenal, Denver, CO," Prepared for U. S. Army Engineer District, Omaha.

"Asphaltic Membrane Is Used to Leakproof a Lake." 1956. Engineering News Record, pp 40-41.

Bureau of Reclamation Engineering and Research Center. 1970. "Results of Test Program for Candidate Liner Materials for New Rocky Mountain Arsenal Basin," Denver, Colo.

Cogley, D. R. 1976. "Report on OTSG Coring Data for Compounds at Rocky Mountain Arsenal," Walden Division of Abcor, Inc., Wilmington, Mass.

Colorado Department of Health, Water Quality Control Division. 1975. "Groundwater Study of the Rocky Mountain Arsenal and Some Surrounding Area," Denver, Colo.

DOW Industrial Service. 1960. "Report on the Chemical Characteristics of Deep Disposal Well Wastes, Rocky Mountain Arsenal, Denver, CO," Prepared for U. S. Army Engineer District, Omaha.

E. A. Polumbus, Jr. and Associates. 1960. "Design Study," Denver, Colo. Prepared for U. S. Army Engineer District, Omaha.

Evans, D. M. 1967. "Evans: Earthquake Theory Still Valid," Sunday Denver Post, Denver, Colo.

Konikow, L. F. 1977. "Modeling Chloride Movement in the Alluvial Aquifer at the Rocky Mountain Arsenal, Colorado," Geological Survey Water-Supply Paper 2044, Washington, D. C.

McNeil, W. 1975. "Condition and Utilization of Basin F at Rocky Mountain Arsenal," Memo to Program Manager for Demilitarization of Chemical Material, U. S. Army Materiel Command, Rocky Mountain Arsenal, Denver, Colo.

Milbury, W. F. 1965. USAEHA Report of Results of Laboratory Analyses on Lake F Industrial Wastes at Rocky Mountain Arsenal, Project No. 341E19-59/66, Rocky Mountain Arsenal, Denver, Colo.

Muhm, J. R. 1974. "An Evaluation of Hydrologic Conditions Influencing the Movement of Groundwater in an Area North of Rocky Mountain Arsenal," Geologics, Inc., Denver, Colo.

Ralph M. Parsons Company. 1955. "Disposal of Chemical Wastes at Rocky Mountain Arsenal," Los Angeles, Calif. Prepared for U. S. Army Engineer District, Omaha.

Rendon, O. 1977. "Containment/Engineered Storage of Basin F Contents, Rocky Mountain Arsenal, Denver, CO," Draft Report, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Reuter, L. H., and Milbury, W. F. 1965. USAEHA Report of Industrial

Waste Survey, Project No. 3471E19-59166, Rocky Mountain Arsenal, Denver Colo.

Shell Chemical Company. 1973. "Feasibility Report for Construction of a Subsurface Disposal System in Morgan County, CO," Denver, Colo.

Struthers Scientific and International Corporation. 1968. "Waste Treatment Facility for Rocky Mountain Arsenal," New York, N. Y.

Trost, P. 1976. "Report on Phase IIb Geochemical Dispersion of Elements in the Rocky Mountain Arsenal Area," Prepared for Department of the Army by Intrasearch, Inc., Denver, Colo.

Walton, G. 1961. "Public Health Aspects of the Contamination of Groundwater in the Vicinity of Derby, Colorado," Groundwater Contamination Symposium, Technical Report W61-5, pp 121-125 and references therein, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio.