REPORT DOCUMENTATION PAGE	FORM APPROVED OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302 and to the Office of Management and Budget, Paperwork Reduction Project (0704-01880), Washington, DC 20503.

1. AGENCY USE ONLY	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE Field Demonstration of Slurry Reactor Biotreatment of Explosives-Contaminated Soils	5. FUNDING NUMBERS
6. AUTHOR(S)	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Argonne National Laboratory Environmental Research Division, Bioremediation Group 9700 South Cass Avenue	8. PERFORMING ORGANIZATION REPORT NUMBER None
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Environmental Center (USAEC) Environmental Technology Division	10. SPONSORING/ MONITORING AGENCY REPORT NUMBER SFIM-AEC-ET-CR-96178
11. SUPPLEMENTARY NOTES USAEC Project Officer: Mr. Mark Hampton (410) 612-6852	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Distribution Unlimited	12b. DISTRIBUTION CODE

13. ABSTRACT (MAXIMUM 200 WORDS)

Bioslurry technology requires excavation and screening of soil to remove rocks, mixing soil with water to form a slurry, mixing the slurry in a reactor, and removal of the slurry from the reactor. Biodegradation of explosives also requires a co-substrate (e.g., molasses), pH > 6, and aerobic-anoxic operation. In this study, the native microbial population degraded explosives in soil. Four reactors (350-380 gal) were operated at the Joliet Army Ammunition Plant: a control with no co-substrate, 20% and 10% weekly replacement (by volume) reactors, and a 5% daily replacement reactor. This design allowed investigation of different soil (and therefore TNT [2,4,6-trinitrotoluene]) loading rates. The target soil slurry was 15% (weight/weight). Explosives concentrations in soil were 2,000-8,000 mg/kg. Environmental conditions were identical for all reactors, and temperature, pH, and dissolved oxygen were similar. This demonstration showed that the important process parameters for successful (> 99%) removal of TNT are an organic co-substrate (molasses), operation in an aerobic-anoxic sequence, and temperature. Cold temperatures slowed the rate of microbial metabolism. The demonstration successfully removed explosives and microbial intermediates from the soil. In summary, the bioslurry system has a real potential to degrade explosives, particularly TNT, from soil.

14. SUBJECT TERMS Contaminated Soil, Explosives, Slurry Reactor, Soil Treatment, 2,4,6-Trinitrotoluene	15. NUMBER OF PAGES 180
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS REPORT	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

Field Demonstration of Slurry Reactor Biotreatment of Explosives-Contaminated Soils

Report No. SFIM-AEC-ET-CR-96178

by J.F. Manning, Jr., R. Boopathy,
and E.R. Breyfogle

Bioremediation Group, Environmental Research Division
Argonne National Laboratory, 9700 South Cass Avenue,
Argonne, Illinois 60439-4843

December 1996

Work sponsored by the U.S. Army Environmental Center, SFIM-AEC-ETD,
Aberdeen Proving Ground, Aberdeen, Maryland 21010-5401

NOTICE

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision unless so designated by other documentation.

The use of trade names in this report does not constitute an official endorsement or approval of the use of such commercial products. This report may not be cited for purposes of advertisement.

Distribution unlimited. Approved for public release.

Requests for this document must be referred to:
Commander
U.S. Army Environmental Center
Aberdeen Proving Ground, Maryland 21010-5401

Contents

Notation xi

1 Summary 1

2 Background Information 4

2.1 Nature of the Problem 4
2.2 Bioslurry Reactors 4
2.3 Bioremediation of Explosives-Contaminated Soil 5
2.4 Joliet Army Ammunition Plant 5
2.5 Site Description and History (Group 61, Site L1) 7

3 Test Objective and Approach 9

3.1 Objective 9
3.2 Technical Issues Requiring Investigation 9
3.3 Approach 10

4 Materials and Methods 12

4.1 Overview of Test System 12
4.2 Location and Site Layout 12
4.3 Bioslurry Reactors 12
4.4 Test Soil 16
4.5 Materials Handling and Slurry Preparation 16
4.6 Water Piping and Discharge 17
4.7 Gas Supply System 19
4.8 Dewatering System for Treated Slurry 19
4.9 Description of Bioslurry Reactor Operation 21
4.10 Operational Monitoring 23
4.10.1 Purpose 23
4.10.2 Sampling Procedures 23
4.10.3 Analytical Procedures 24
4.11 Short-Term Laboratory Biodegradation Studies 27
4.11.1 Laboratory Soil Slurry Reactors 27
4.11.2 Carbon-14 Mineralization Studies in the Slurry Reactor 27
4.11.3 Identification of the Unknown Intermediate Generated in the Reactor Radiolabeling Study Described in Section 4.11.2 28
4.11.4 Plant Growth Studies 28
4.11.5 Studies of the Fate of Total Organic Carbon 28
4.12 Chemicals 28

5 Results 29

5.1 Soil Characteristics 29
5.2 Phase I — Reactor Characteristics 29
5.2.1 Soil Suspension 29
5.2.2 Oxygen Transfer 32

Contents (Cont.)

5.3 Phase II and Phase III — Biological Degradation Studies..... 33
5.3.1 Control Reactor 33
5.3.2 20% Replacement Reactor 35
5.3.3 10% Replacement Reactor 46
5.3.4 5% Daily Replacement Reactor..... 56
5.4 Degradation of 2,4- and 2,6-Dinitrotoluene..... 67
5.4.1 DNT in Soil in the Control Reactor..... 67
5.4.2 DNT in Soil in the 20% Replacement Reactor..... 67
5.4.3 DNT in Soil in the 10% Replacement Reactor..... 67
5.4.4 DNT in Soil in the 5% Replacement Reactor..... 69
5.4.5 DNT in Liquid in the Control Reactor..... 69
5.4.6 DNT in Liquid in the 20% Replacement Reactor..... 71
5.4.7 DNT in Liquid in the 10% Replacement Reactor..... 71
5.4.8 DNT in Liquid in the 5% Replacement Reactor..... 71
5.5 Separation of Solids 73
5.6 Laboratory (Bench-Scale) Studies 75
5.6.1 Laboratory (Bench-Scale) Reactor Studies..... 75
5.6.2 Radiolabeling Studies 77
5.6.3 Soil Disposition Studies 80

6 Conclusions..... 84

7 Lessons Learned..... 86

8 References..... 89

Appendix A: Drawings Relevant to the Field Demonstration..... A-1

Appendix B: On-Site Analytical Procedures..... B-1

Appendix C: Daily Operating Data..... C-1

Figures

1 Location Map for JAAP..... 6

2 Overview of Functional Areas at JAAP..... 6

3 Bioremediation Flow Diagram..... 13

4 Wet-Screening and Mixing Operation..... 14

5 Bioslurry Reactor Tank with Anchor-Type Impeller..... 14

6 Bioslurry Reactor Tank with Dual-Turbine Impeller..... 15

7 Schematic Diagram of Piping for the Bioslurry Reactor 18

Figures (Cont.)

8 Gas Supply System 19

9 Wedgewater Filter Bed..... 20

10 Explosives Concentrations in Soil in the Control Reactor 34

11 Explosives Concentrations in Liquid in the Control Reactor 34

12 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 20% Replacement Reactor 36

13 Explosives Concentrations in Soil in the 20% Replacement Reactor 36

14 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 20% Replacement Reactor during Adaptation..... 37

15 Explosives Concentrations in Soil in the 20% Replacement Reactor during Adaptation..... 37

16 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 20% Replacement Reactor during Cold Weather 39

17 Explosives Concentrations in Soil in the 20% Replacement Reactor during Cold Weather..... 39

18 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 20% Replacement Reactor during Warm Weather..... 40

19 Explosives Concentrations in Soil in the 20% Replacement Reactor during Warm Weather 40

20 Explosives Concentrations in Liquid in the 20% Replacement Reactor 42

21 Solids Concentration in the 20% Replacement Reactor..... 42

22 Ammonia Concentration in Slurry in the 20% Replacement Reactor 43

23 Nitrite Concentration in Slurry in the 20% Replacement Reactor 43

24 Phosphorus Concentration in Slurry in the 20% Replacement Reactor..... 45

25 Bacterial Count in Solids in the 20% Replacement Reactor..... 45

26 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 10% Replacement Reactor 47

27 Explosives Concentrations in Soil in the 10% Replacement Reactor 47

28 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 10% Replacement Reactor during Adaptation..... 48

Figures (Cont.)

29 Explosives Concentrations in Soil in the 10% Replacement Reactor during Adaptation 48

30 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 10% Replacement Reactor during Cold Weather 50

31 Explosives Concentrations in Soil in the 10% Replacement Reactor during Cold Weather 50

32 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 10% Replacement Reactor during Warm Weather 51

33 Explosives Concentrations in Soil in the 10% Replacement Reactor during Warm Weather 51

34 Explosives Concentrations in Liquid in the 10% Replacement Reactor 53

35 Solids Concentration in the 10% Replacement Reactor 53

36 Ammonia Concentration in Slurry in the 10% Replacement Reactor 54

37 Nitrite Concentration in Slurry in the 10% Replacement Reactor 54

38 Phosphorus Concentration in Slurry in the 10% Replacement Reactor 55

39 Bacterial Count in Solids in the 10% Replacement Reactor 56

40 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 5% Replacement Reactor 58

41 Explosives Concentrations in Soil in the 5% Replacement Reactor 58

42 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 5% Replacement Reactor during Adaptation 59

43 Explosives Concentrations in Soil in the 5% Replacement Reactor during Adaptation 59

44 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 5% Replacement Reactor during Cold Weather 60

45 Explosives Concentrations in Soil in the 5% Replacement Reactor during Cold Weather 60

46 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 5% Replacement Reactor during Warm Weather 62

47 Explosives Concentrations in Soil in the 5% Replacement Reactor during Warm Weather 62

Figures (Cont.)

48 Explosives Concentrations in Liquid in the 5% Replacement Reactor..... 63

49 Solids Concentration in the 5% Replacement Reactor..... 63

50 Ammonia Concentration in Slurry in the 5% Replacement Reactor..... 65

51 Nitrite Concentration in Slurry in the 5% Replacement Reactor..... 65

52 Phosphorus Concentration in Slurry in the 5% Replacement Reactor..... 66

53 Bacterial Count in Solids in the 5% Replacement Reactor 66

54 Dinitrotoluene Concentrations in Soil in the Control Reactor..... 68

55 Dinitrotoluene Concentrations in Soil in the 20% Replacement Reactor..... 68

56 Dinitrotoluene Concentrations in Soil in the 10% Replacement Reactor..... 69

57 Dinitrotoluene Concentrations in Soil in the 5% Replacement Reactor 70

58 Dinitrotoluene Concentrations in Liquid in the Control Reactor..... 70

59 Dinitrotoluene Concentrations in Liquid in the 20% Replacement Reactor..... 71

60 Dinitrotoluene Concentrations in Liquid in the 10% Replacement Reactor..... 72

61 Dinitrotoluene Concentrations in Liquid in the 5% Replacement Reactor 72

62 Concentrations of TNT and 4-Amino-2,6-Dinitrotoluene versus Time in the Laboratory 20% Replacement Reactor..... 75

63 Concentrations of TNT and 4-Amino-2,6-Dinitrotoluene versus Time in the Laboratory 10% Replacement Reactor..... 76

64 Concentrations of TNT and 4-Amino-2,6-Dinitrotoluene versus Time in the Laboratory 5% Replacement Reactor 77

65 Concentrations of TNT and 4-Amino-2,6-Dinitrotoluene versus Time in the Laboratory Control Reactor..... 78

66 Distribution of Radiolabeled TNT in a Sample Taken from the Field Control Reactor 78

67 Distribution of Radiolabeled TNT in a Sample Taken from the Field 20% Weekly Replacement Reactor..... 79

68 Distribution of Radiolabeled TNT in a Sample Taken from the Field 5% Daily Replacement Reactor 79

69 Effect of Treated Soil Slurry on the Growth of Corn Plants 81

Figures (Cont.)

70 Effect of Treated Soil Slurry on the Growth of Bluestem Grass..... 81

71 Degradation of Total Organic Carbon in Mixtures of Slurry and Clean Soil..... 83

72 Carbon Dioxide Generation in Mixtures of Slurry and Clean Soil 83

Tables

1 Summary of Analytical Results for Explosives in Soil..... 30

2 Soil Suspension Data..... 31

3 Results of Reaeration Test 32

4 Soil Size Distribution before Treatment 73

5 Soil Size Distribution for Samples A and B after Treatment 74

Notation

APHA	American Public Health Association
2A46DNT	2-amino-4,6-dinitrotoluene
4A26DNT	4-amino-2,6-dinitrotoluene
Btu	British thermal unit(s)
°C	degree(s) Celsius
CDM	Camp Dresser and McKee, Inc.
cfm	cubic foot (feet) per minute
CFU	colony-forming unit
cm	centimeter(s)
cpm	count(s) per minute
DNB	1,3-dinitrobenzene
DNT	dinitrotoluene
DO	dissolved oxygen
EPA	Environmental Protection Agency
°F	degree(s) Fahrenheit
ft	foot (feet)
g	gram(s)
gal	gallon(s)
GC/MS	gas chromatography/mass spectrometry
gpm	gallon(s) per minute
h	hour(s)
HMX	octahydro-1,3,5,7-tetranitro-1,3,5,7-tetraazocine
hp	horsepower
HPLC	high-performance liquid chromatograph(y)
HRS	Hazard Ranking System
i.d.	inner diameter
in.	inch(es)
JAAP	Joliet Army Ammunition Plant
kg	kilogram(s)
L	liter(s)
LAP	Load-Assemble-Package (Area)
lb	pound(s)
m	meter(s)
M	molar
mol	mole(s)
mCi	millicurie(s)
mg	milligram(s)
min	minute(s)
mL	milliliter(s)
m*M*	millimolar

mm	millimeter(s)
µg	microgram(s)
µL	microliter(s)
µm	micrometer(s)
N	normal
NB	nitrobenzene
nm	nanometer(s)
NPL	National Priority List
NT	nitrotoluene
psig	pound(s) per square inch gauge
QA/QC	quality assurance/quality control
RCRA	Resource Conservation and Recovery Act
RDX	hexahydro-1,3,5-trinitro-1,3,5-triazine
RF	response factor
rpm	revolution(s) per minute
s	second(s)
SARM	standard analytical reference material
tetryl	N-methyl-N,2,4,6-tetranitroaniline
TNB	1,3,5-trinitrobenzene
TNT	2,4,6-trinitrotoluene
TOC	total organic carbon
USACHPPM	U.S. Army Center for Health Promotion and Preventive Medicine
USAEC	U.S. Army Environmental Center (formerly USATHAMA)
USAEHA	U.S. Army Environmental Hygiene Agency (now USACHPPM)
USATHAMA	U.S. Army Toxic and Hazardous Materials Agency (now USAEC)
UV	ultraviolet
V	volt(s)
V/V	volume/volume
W/V	weight/volume
W/W	weight/weight
yd	yard(s)

Field Demonstration of Slurry Reactor Biotreatment of Explosives-Contaminated Soils

1 Summary

The U.S. Army Environmental Center (USAEC) has conducted field demonstration studies at the Joliet Army Ammunition Plant (JAAP), located at Joliet, Illinois, on a bioslurry soil treatment system. These studies were conducted between July 1994 and August 1995. The overall goal was to determine the effectiveness and cost of bioslurry systems for degrading explosives in soil. The bioslurry system is another biological treatment technology (in addition to composting) that could represent an acceptable, cost-effective alternative to incineration for the treatment of explosives-contaminated soils. The bioslurry system removed more than 99% of explosives from the input soil and demonstrated mineralization of 2,4,6-trinitrotoluene (TNT). We estimate that bioslurry technology could be implemented for $290-350/yd^3.

Bioslurry technology requires excavation of soil, screening of the soil to remove large rocks (larger than 0.25 in.) and plant roots, mixing of the soil with water to form a slurry, mixing of the slurry in a reactor, and, finally, removal of the slurry from the reactor. In addition, biodegradation of explosives requires a co-substrate (molasses in this case), pH adjustment (to pH > 6), and an aerobic-anoxic operating strategy. The bioslurry system can be operated as a batch or semibatch process, depending on site-specific conditions. The operation described in this report relied on the native microbial population to degrade explosives in soil.

Four reactors were operated at JAAP: a control with no co-substrate, a 20% weekly replacement (by volume) reactor, a 10% weekly replacement (by volume) reactor, and a 5% daily (four days per week) replacement (by volume) reactor. This design allowed investigation of different soil loading rates and therefore different TNT mass loading rates. All reactors had a target soil slurry of 15% (weight/weight [W/W]); in reality, the reactors operated with a 10-16% W/W soil slurry. The reactors were subjected to identical environmental conditions, and the temperature, pH, and dissolved oxygen level were approximately the same in all systems. The composition of molasses was consistent throughout the field demonstration. Explosives concentrations in soil were 2,000-8,000 mg/kg. The reactors had working volumes of 350-380 gal.

The results from the study indicated that the control reactor did not have the conditions necessary to achieve degradation of explosives. No co-substrate was added to this system. Over the period of the study, no explosives (TNT, RDX [hexahydro-1,3,5-trinitro-1,3,5-triazine], or TNB [1,3,5-trinitrobenzene]) were removed from the soil. In addition, none of the intermediates associated with TNT degradation was observed. These results confirmed that added co-substrate is needed for degradation of TNT.

The 20% weekly replacement reactor (with a soil retention time of five weeks) demonstrated the capability to degrade TNT effectively. When the temperature was above 25°C, the residual TNT concentration in the soil was less than 50 mg/kg, and the 4-amino-2,6-dinitrotoluene (4A26DNT) concentration was less than 100 mg/kg. In addition, RDX and TNB levels were below 10 mg/kg. When the temperature was below 25°C, the biological system could not maintain this high rate of TNT degradation, and significant accumulation of the 4A26DNT intermediate occurred.

The 10% weekly replacement reactor (with a soil retention time of ten weeks) had a large capability to degrade TNT. In addition, RDX and TNB were effectively removed to residual concentrations in soil of less than 10 mg/kg. When the temperature was above 25°C, the residual TNT in the soil was less than 20 mg/kg, and the 4A26DNT level was below 10 mg/kg. When the temperature was below 25°C, TNT removal continued with very little change in soil concentrations, but 4A26DNT accumulated to concentrations of 100 mg/kg.

The 5% daily replacement reactor (with a soil retention time of five weeks) had a large capability to degrade TNT. On the basis of mass, this reactor was similar to the 20% weekly replacement reactor, but the concentrations of explosives surrounding the microorganisms at any particular time were significantly less. In this system, TNT was removed to levels below 20 mg/kg, and the 4A26DNT concentration was less than 50 mg/kg. When temperatures were below 25°C, the TNT concentration was less than 200 mg/kg, and 4A26DNT accumulated significantly in the system.

A laboratory study with radiolabeled TNT was conducted on samples from the control reactor, the 20% weekly replacement reactor, and the 5% daily replacement reactor. The purpose of this study was to measure the mineralization of TNT by the reactors. The sample from the control reactor generated essentially no radiolabeled carbon dioxide; in samples from the active reactors, approximately 20-23% radiolabeled carbon dioxide was generated from the radiolabeled TNT, indicating that ring cleavage had occurred. Most of the remainder of the radiolabel was distributed in water-soluble biomass and fatty acid intermediates. A very small fraction was incorporated into 4A26DNT.

Overall, the important process parameters, as determined in this field demonstration, are the need for an organic co-substrate (molasses), the operation of the reactors in an aerobic-anoxic sequence, and temperature. In warm temperatures, operation of the system at 20% (or higher) replacement will achieve removal of explosives. Cold temperatures did not destroy the microbial activity, but they slowed the rate of microbial metabolism. In particular, degradation of TNT continued with the accumulation of 4A26DNT. The reactors were operated successfully at lower replacement rates ≤ 10%) in cold weather. The treated soil (bioslurry) can be applied directly to land and will not affect plant growth. In summary, the bioslurry system has a real potential to remove explosives, particularly TNT, from soil.

The purpose of this report is to summarize all procedures and activities associated with the bioslurry field demonstration. The results of the field activities are presented, along with a discussion.

Previous studies supporting the field demonstration described here were reported in the following documents:

- Montemagno, C.D., and Irvine, R.L., 1990, *Feasibility of Biodegrading TNT-Contaminated Soils in a Slurry Reactor*, Technical Report CETHA-TE-CR-90062, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, prepared by Argonne National Laboratory, Argonne, Illinois, June.

- Montemagno, C.D., 1991, *Evaluation of the Feasibility of Biodegrading Explosives-Contaminated Soils and Groundwater at the Newport Army Ammunition Plant (NAAP)*, Technical Report CETHA-TS-CR-92000, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, prepared by Argonne National Laboratory, Argonne, Illinois, June.

- Manning, Jr., J.F., Boopathy, R., and Kulpa, C.F., 1995, *A Laboratory Study in Support of the Pilot Demonstration of a Biological Soil Slurry Reactor*, Technical Report SFIM-AEC-TS-CR-94038, U.S. Army Environmental Center, Aberdeen Proving Ground, Maryland, prepared by Argonne National Laboratory, Argonne, Illinois, July (available in print and on CD-ROM).

2 Background Information

2.1 Nature of the Problem

The manufacturing and handling of explosives and propellants at Army industrial facilities have resulted in contamination of soils and sediments. Contamination has often resulted from disposal practices that were common and acceptable at the time of discharge.

Because of the potential for groundwater contamination and the migration of hazardous substances, treatment of the contaminated source may be necessary to safeguard the environment, to protect the public, and to avoid costly groundwater remediation in the future. Treatment of soil can be labor intensive and expensive when large quantities are handled. Incineration is one method that has been used to treat explosives-contaminated soil. Unfortunately, incineration is costly and often is not favored for other reasons. Composting is a biological method of remediating explosives-contaminated soil. The USAEC (formerly the U.S Army Toxic and Hazardous Materials Agency [USATHAMA]) has conducted extensive work on composting explosives-contaminated soil. Successful demonstrations of this work have led to full-scale application of composting to biologically degrade explosives-contaminated soil (Weston 1993).

Composting may not be useful at all facilities with explosives contamination. This report describes the field demonstration of a bioslurry system to treat explosives-contaminated material.

2.2 Bioslurry Reactors

Bioslurry reactors operate by a process in which organic materials are biodegraded by microorganisms, and organic and inorganic by-products result. Contaminated soil is loaded into a reactor or tank to produce a water-based slurry (typically 1-20% soil W/W). Appropriate electron acceptors (oxygen, nitrate, nitrite, or sulfate) and nutrients are supplied. The bioslurry reactor provides an optimal environment allowing microorganisms, nutrients, and contaminants to be in contact. Microorganisms that can degrade the contaminants of interest by a co-metabolic process occur naturally. Generally, enhancing the indigenous microbial numbers in the contaminated soil at the site is sufficient. No supplemental organisms are typically required.

The bioslurry reactors used in this study were designed to be operated in a sequencing batch mode. In this system, each cycle of bioslurry operation involved three discrete periods: FILL, REACT, and DRAW. During FILL, a contaminated soil slurry and any water needed to achieve the proper solids concentration (typically 12-17% W/W) were added to a tank that was being mixed. This took approximately 15-30 min. The volume of slurry added depended on the percent replacement established for the given tank. For example, a total of 17.5 gal (i.e., 5% of

350 gal, the usable volume of each tank) was added to a tank during each cycle if the reactor was being operated as a 5% replacement system. After FILL, co-substrate and pH-adjusting chemicals were delivered to the reactor. The REACT period followed FILL. During REACT, the mixers remained on, and the reactions necessary to degrade the explosives took place. When oxygen was serving as the exogenous electron acceptor, the aeration system was activated. When nitrate, nitrite, or sulfate was serving as the exogenous electron acceptor, only the mixing system was used to suspend the slurry. In either case, the co-substrate served as the primary carbon and energy source, and the soil contaminants (the explosives) were co-metabolized.

2.3 Bioremediation of Explosives-Contaminated Soil

Previous studies (Montemagno and Irvine 1990; Manning et al. 1995) showed that indigenous microbes at JAAP can biodegrade TNT. Soil samples collected at the site contained a bacterial consortium capable of degrading TNT. Shake flask experiments indicated that succinate or malate used as co-metabolites enhanced TNT biodegradation. In addition, laboratory reactor studies demonstrated that the addition of molasses and the use of varying electron acceptor conditions (aerobic-anoxic) could achieve mineralization of TNT.

The advantage of the bioslurry reactor in treating contaminated soil is its inherent flexibility. Co-substrate, nutrients, oxygen, and mixing can be altered to achieve the desired treatment. The reactor can naturally select populations with increased degradation rates and the ability to degrade metabolic intermediates. Only naturally occurring microorganisms were used in this study.

2.4 Joliet Army Ammunition Plant

The USAEC selected JAAP as the site of the pilot-scale demonstration field study. An initial site visit by the USAEC (then USATHAMA) and Argonne personnel occurred in early 1991. Personnel from the U.S. Environmental Protection Agency (U.S. EPA), the Illinois EPA, and the command and staff at JAAP supported the proposed bioslurry pilot demonstration study.

In the early 1940s, JAAP was constructed in Will County, Illinois, approximately 17 miles south of Joliet (Figure 1). As Figure 2 shows, JAAP is divided into two major functional areas. The section west of U.S. Highway 53, referred to as the Manufacturing Area, covers 14 square miles. The principal operations in this area were the production of constituent chemicals and explosive materials. The section east of U.S. Highway 53, referred to as the Load-Assemble-Package (LAP) Area, covers approximately 27 square miles. This area contains munitions filling and assembly lines, storage magazines, and a demilitarization area. Items such as bombs, projectiles, fuses, and supplementary charges were produced almost continuously from World War II through 1975 in the LAP Area.

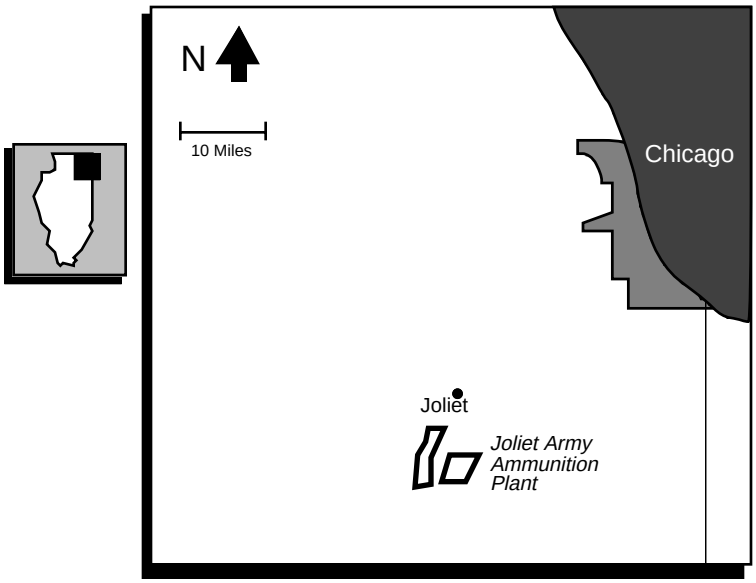


FIGURE 1 Location Map for JAAP

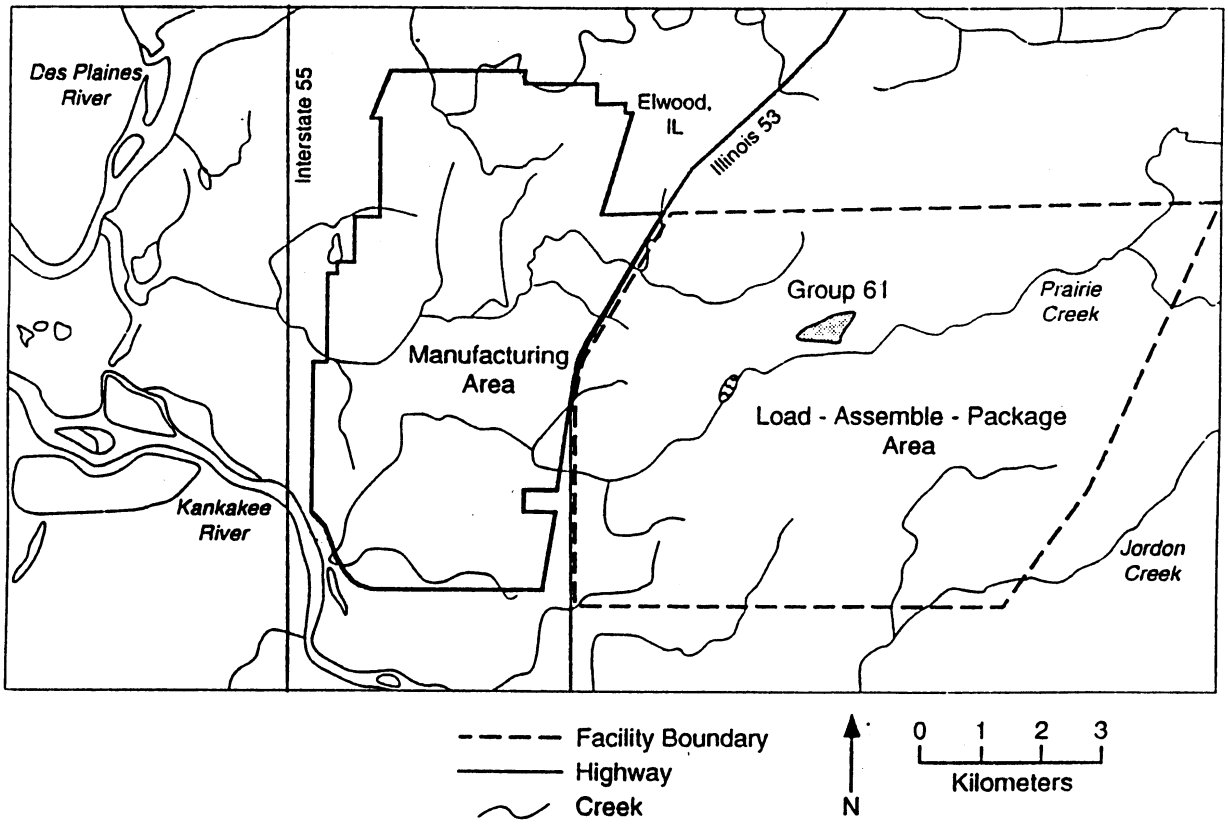


FIGURE 2 Overview of Functional Areas at JAAP

During the installation assessment (U.S. Army 1978) and the installation restoration surveys (Batzner et al. 1982) conducted by USATHAMA in 1978 and 1982, respectively, site conditions indicated the potential for contamination from past and present operations. A number of additional investigations were conducted at various production, waste management, and spill areas throughout JAAP. Past studies at the LAP Area included Phase II contamination surveys (Underwood et al. 1983a,b,c), a surface water sampling investigation (Hazelton Laboratories 1982), an historic aerial photointerpretation (Stout and Sitton 1986), a Midwest Confirmation Survey (Dames and Moore 1986), soil sampling and baseline studies (Dames and Moore 1988a,b; CDM 1989, 1990; Health Effects Group, Inc., 1990a,b), an investigation of underground storage tanks (U.S. Army Corps of Engineers 1989), outfall monitoring (USAEHA 1990), and sampling for polychlorinated biphenyls in soil (Uniroyal, Inc., 1990).

As evaluations of the LAP Area proceeded, they revealed several areas of contamination. The LAP Area was proposed for placement on the National Priority List (NPL) and designated a Superfund site on the basis of its Hazard Ranking System (HRS) score of 35.23 for the overall potential for contaminant migration. In April 1989 the LAP Area was, in fact, placed on the final NPL.

2.5 Site Description and History (Group 61, Site L1)

Group 61, constructed in 1941 as part of the initial operations of the JAAP installation to support Word War II efforts, is centrally located in the northern portion of the LAP Area. The LAP Area, covering approximately 80 acres, has been the site of demilitarization and reclamation efforts for various munitions, including the defusing of munitions, the removal of explosives, and the recycling of various munitions. Originally used for crystallizing ammonium nitrate, the area was extensively modified and functioned as a shell renovation and TNT recovery plant until 1945. In April 1946, the facility was reactivated to reclaim TNT from 75-mm, 90-mm, and 3-in. high-explosive shells (U.S. Army Corps of Engineers 1950). Washout operations involving the larger munitions were performed outside the main building on a concrete pad. During recycling of the removed explosives as part of JAAP operations, process water was collected in a large concrete sump south of the main building. The solids that settled out in the sump were sent to Site L2 (Explosive Burning Grounds), while the overflow water from the sump (pink water) was discharged for infiltration into a 10-acre ridge-and-furrow system (or evaporating bed) adjacent to the sump. Historical aerial photos revealed that by 1952, two rectangular pits or lagoons were constructed southeast of the ridge-and-furrow system on either side of the drainage ditch. Water flowing in the drainage ditch would occasionally accumulate in the lagoons. The lagoons are no longer identifiable features of the area. Ponding also apparently occurred in a low area east of the sump and washout area. During the July 1990 site reconnaissance, red water was observed within the sump located southeast of Building 4, which collected runoff from the washout operations before it was discharged to the ridge-and-furrow system. The water was presumably rainwater, probably contaminated by residual contamination still in the sump. Red soil was observed around

the drainage ditch and evaporating bed, both of which are currently fenced to keep out grazing cattle. All soils used in the field-scale demonstration were obtained from Group 61, Site L1 (the ridge-and-furrow area).

Previous environmental sampling indicated that surface TNT concentrations in the ridge-and-furrow area of Group 61, Site L1, were 20-14,400 mg/kg. The primary risk associated with explosives-contaminated soil is a reactivity hazard. Soils with a concentration of explosives greater than 12% can propagate detonation. This generalization does not preclude an explosion if the explosives content is below 12%, but it describes a limit below which propagation will not occur. The USAEC uses a 10% safety limit on the explosives concentration in soil. Argonne added a further safety margin by limiting the explosives content to 8% (Manning and Montemagno 1992b).

3 Test Objective and Approach

3.1 Objective

The overall objective of the bioslurry field-scale demonstration was to examine the technical viability and cost of bioremediating explosives-contaminated soil in a slurry reactor. The specific objective was to evaluate a field-scale system for its mechanical integrity and its ability to enrich for a microbial consortium capable of degrading explosives and to analyze system performance over an extended operating period.

To determine the ability of the bioslurry system to degrade explosives, testing was conducted in four phases: (1) determination of mechanical and physical information about the reactors, (2) adaptation and the development of operating characteristics, (3) long-term operation with a variety of weather conditions and explosives input concentrations, and (4) optimization of physical operating conditions. During the last three phases, four reactors were operated to investigate several different soil-processing rates. In addition to explosives concentrations, extensive information was collected on nutrient and dissolved oxygen (DO) concentrations and on pH. This information allowed the operational process to be characterized extensively.

3.2 Technical Issues Requiring Investigation

The goal of this bioslurry field demonstration was to prove that bioremediation of explosives-contaminated soil in a slurry reactor could achieve cleanup standards and be operated cost-effectively. Concentrations of TNT below 20 mg/kg were assumed as the target, because cleanup goals for JAAP had not been established at the time of this study. To achieve this goal, equipment had to be evaluated for its ability to mix a soil slurry and provide oxygen. Microorganisms capable of degrading explosives had to be present in sufficient numbers, and the ability of the system to degrade explosives biologically had to be validated over an extended period of time. Because TNT is the major contaminant in the JAAP soils selected for this demonstration, TNT was used as the target compound to monitor the degradation of explosives. Influent and effluents were analyzed for all explosives and TNT metabolites. Particular attention was given to the 2-amino-4,6-dinitrotoluene (2A46DNT) and 4-amino-2,6-dinitrotoluene (4A26DNT) intermediates.

In practice, operation of the bioslurry reactor depended on three constraints: (1) enhancement of the appropriate native microbial consortia, (2) operation under appropriate conditions with a suitable electron acceptor, and (3) replacement of a volume of soil to provide new, contaminated soil for microbial processing. If more soil can be replaced during each period, the overall remediation will be faster. This last constraint will determine the overall efficiency of the

bioremediation process. The demonstration at JAAP tested whether field-scale bioslurry degradation of explosives-contaminated soil is feasible.

Previous laboratory studies showed that TNT can be degraded by microbes under both aerobic and anoxic electron acceptor conditions (in the presence or absence of oxygen) with molasses as a co-substrate. Both aerobic and anoxic conditions require a co-substrate to promote TNT degradation. For this field demonstration, molasses was chosen as the co-substrate.

The key technical issue in the JAAP field demonstration was selection of the appropriate equipment and operating conditions to degrade explosives under three distinct operating systems. All of the operating systems investigated the effect of soil residence time on aerobic-anoxic biodegradation of explosives.

Overall, the key technical issues examined in the present study were the following:

- Evaluating anchor and impeller mixers, to determine the optimal soil-mixing regime
- Determining the oxygen transfer characteristics of the reactors in the presence of uncontaminated soil
- Monitoring the development of a microbial consortium capable of degrading explosives
- Testing the ability of the microbes to degrade explosives under aerobic-anoxic reactor conditions
- Evaluating operation of the bioslurry reactor with a variety of soil replacement volumes on both a daily basis and a weekly basis
- Investigating the effectiveness and degradation rates of explosives under various reactor operating conditions, including temperature and input explosives concentration

3.3 Approach

The field demonstration study was divided into three phases. The first two phases each had several experiments. In Phase I, two tanks were constructed. For Phases II and III, two

additional tanks were constructed. Phase I studies examined the mechanical integrity of the tanks and the oxygen transfer characteristics of the mixers and aeration devices in clean water and in uncontaminated soil. In Phase II work, enrichment was provided to enhance a native microbial consortium appropriate to degrade TNT. In Phase III, four tanks were used to investigate long-term operation at different replacement rates, including 5% slurry replacement per day, four days per week; 10% slurry replacement per week; and 20% slurry replacement per week. The fourth tank was a control containing contaminated soil that was mixed and aerated; however, this control tank received no nutrient or co-substrate additions or soil replacements.

4 Materials and Methods

4.1 Overview of Test System

A process flow diagram is presented in Figure 3. The field bioslurry system included the following units: a soil-screening operation to remove oversized particles (Figure 4) and initially mix the slurry; four 420-gal bioslurry reactor tanks (Figures 5 and 6) tested and operated in parallel; a 2,000-gal tank for storage and delivery of recycled process water; a 2,000-gal tank for storage and delivery of clean water; a chemical delivery system for adding nutrients, co-substrate, and pH-adjusting chemicals; two slurry dewatering beds; and a 2,000-gal storage tank for treated process water. Initially, only two reactors were operated. One was equipped with a variable-speed-drive mixer and a large anchor-type impeller for mixing (Figure 5). The other also had a variable-speed-drive mixer but was equipped with a double-turbine impeller (Figure 6). Phase I activities evaluated the tanks and the mixing equipment and assessed oxygen transfer capabilities. During Phases II and III, all four tanks were outfitted with a dual-turbine impeller system. Four reactors were operated: a control reactor, a reactor receiving 20% replacement per week, a reactor receiving 10% replacement per week, and a reactor receiving a 5% replacement per day (four days a week).

4.2 Location and Site Layout

The field bioslurry system was housed in a warehouse in the area designated as Group 70, Building 47. This building has a concrete floor. The reactor location was maintained at a minimum of 55°F with the aid of a boiler-hot air heating system. The electrical distribution system in the building was retrofitted to provide 208-V (three-phase) and 100-V (single-phase) power as needed. All electrical service in the reactor and soil-processing area was explosion proof for dust. Schematic diagrams of the building layout are in Appendix A, Figures A.1 and A.2.

4.3 Bioslurry Reactors

Four bioslurry reactor units were operated in the field study. All of the units had a variable-speed-drive mixer equipped with a double-turbine impeller (Figure 6). All reactors had the following specifications:

1. The 420-gal reactor tank was made of 304 stainless steel plate. Side walls were 3/16 in. thick, and the tank top and bottom were 1/4 in. thick. The interior tank diameter was 4 ft. The total height was 4 ft, 5 in. (not including leg

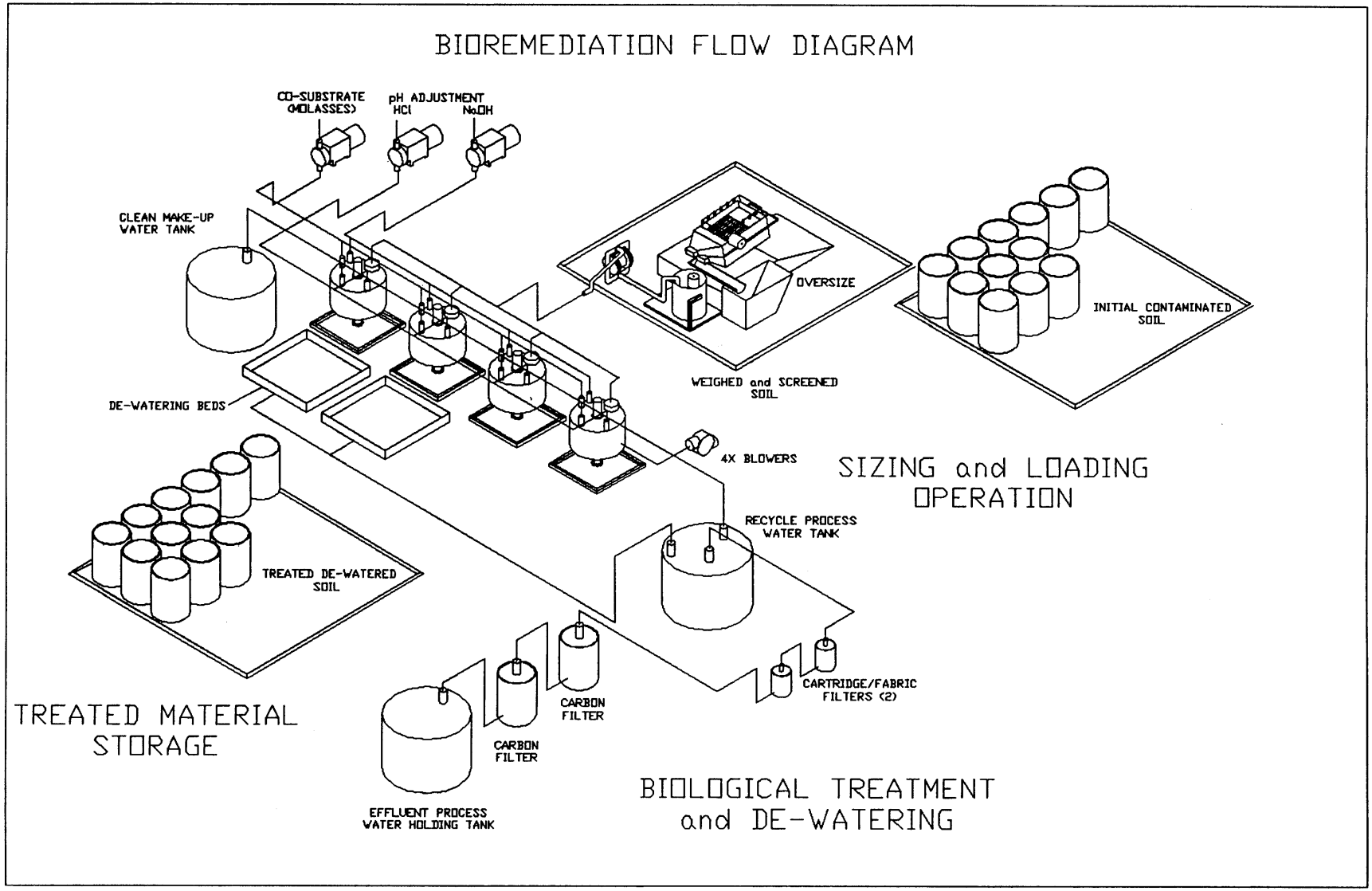


FIGURE 3 Bioremediation Flow Diagram

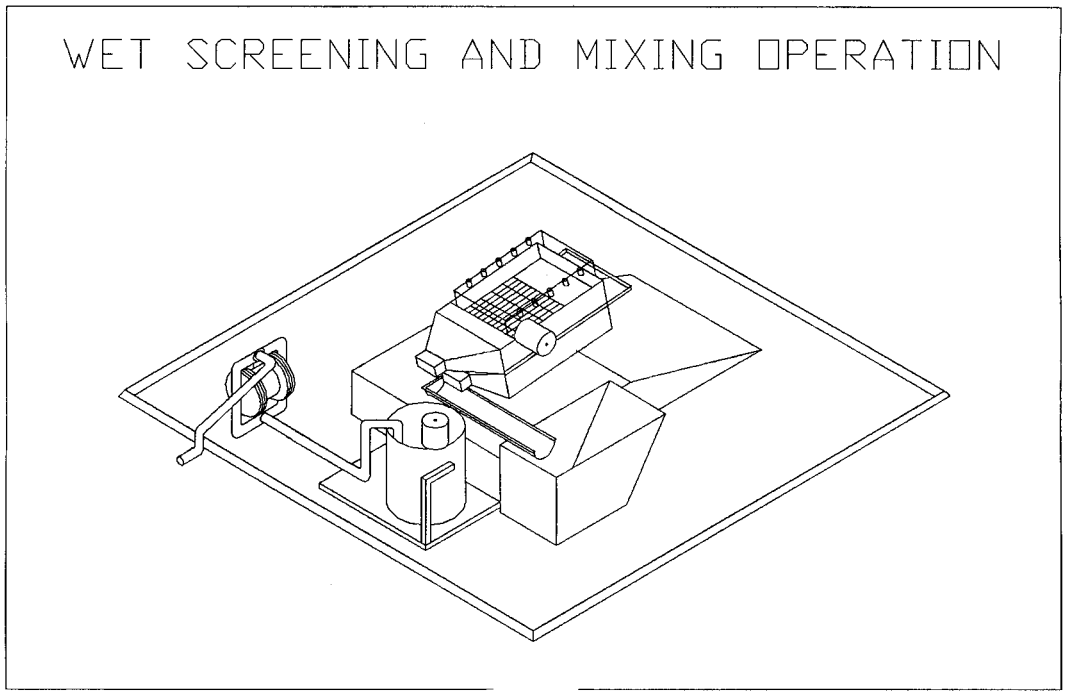


FIGURE 4 Wet-Screening and Mixing Operation

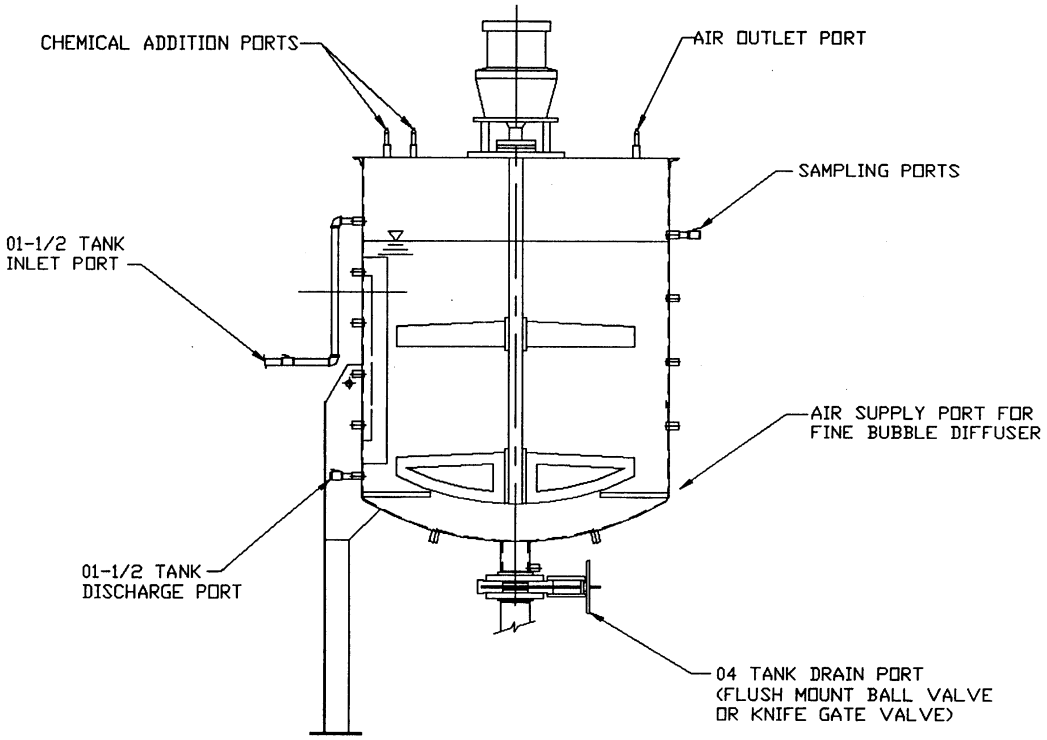


FIGURE 5 Bioslurry Reactor Tank with Anchor-Type Impeller

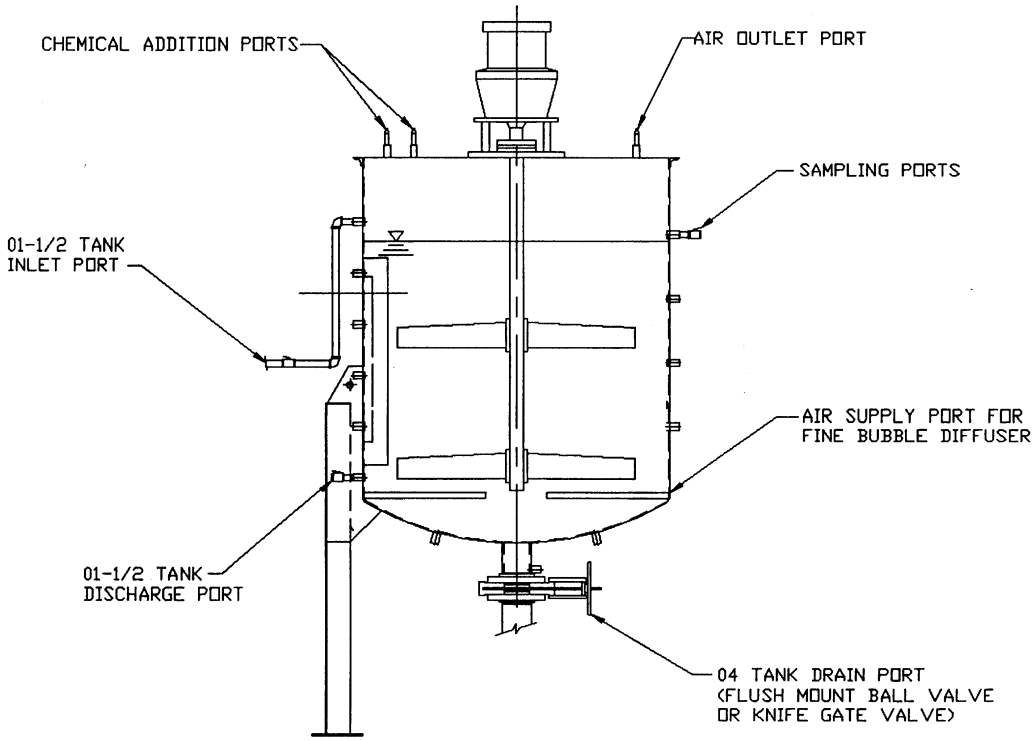


FIGURE 6 Bioslurry Reactor Tank with Dual-Turbine Impeller

height), with 8 in. of free board. The usable volume was approximately 350 gal. The tank top was sealed with a flange-gasket arrangement. (Construction drawings are in Appendix A, Figures A.3 and A.4.)

2. The 1-hp, explosion-proof-drive motor (three-phase, 208 V) for the impeller had a variable motor speed controller (30-100 rpm). The motor was obtained from JWI, Inc., Holland, Michigan.

3. Four fine-bubble diffusers (Eimco Equipment Corporation, Salt Lake City, Utah) were mounted along the reactor bottoms. The mountings of these diffusers are shown in Appendix A, Figure A.4.

4. The air delivery system included a blower, hoses, connectors, and valves.

5. A 10-gallon-per-minute (gpm) air-operated diaphragm pump transferred treated slurry from the reactor to the slurry dewatering bed. The pumps were obtained from Wilden, Inc., Grand Terrace, California, and were of three diameters (2 in., 1.5 in., and 1 in.).

6. The 4-in. bottom drain valve was operated manually. This was a knife-type valve.

7. The flow meters for the diffusers had a capacity of 10 cubic feet per minute (cfm).

8. All necessary valves and fittings were provided for slurry discharge, chemical feed lines, gas lines, and sample ports. The sampling ports on the reactors were Teflon-on-Teflon ball valves.

9. The 2-ton-capacity adjustable gantry had a 15-ft span and 10 ft, 8 in. maximum height, with a 2-ton-capacity hoist and trolley for lifting the reactor tops during maintenance.

10. An explosives safety review was conducted for all components in contact with explosives. The final design was based on the information obtained in that review.

4.4 Test Soil

Explosives-contaminated soil was obtained from the Group 61, Site L1, ridge-and-furrow area. The intention in this study was to have soils in the field demonstration area contain no more than 8% TNT.

Only soils with a TNT content below 80,000 mg/kg (on the basis of dry weight) were used for the field study. Soils containing large crystal aggregates of TNT were excluded from use. Soil was excavated by hand with shovels and scoops. Soil was screened in the area of excavation within the area of contamination. The material passing through the screen was contained in a 55-gal storage drum. The screen had 1/4-in. openings and was agitated by hand. Material not passing through the screen was returned to the area of excavation in the area of contamination. The storage drums were decontaminated by wiping them with a dry cloth. After decontamination, the drums were transported by truck to the building containing the field-scale demonstration system.

4.5 Materials Handling and Slurry Preparation

The drummed contaminated soil was stored in a portable berm containment pad in the warehouse housing the bioslurry system. This soil was subjected to additional mechanical screening to remove rocks, stones, very coarse sand, and other debris with nominal diameters

greater than 0.0165 in. (#40 mesh). This screening required shoveling the contaminated soil out of the drums and onto a multiple-deck vibrating-screen system equipped with water spray bars and screens with openings of 0.187 in. (#4 mesh) and 0.0165 in. (#40 mesh) (Figure 4). The contaminated, screened soil slurry passing through the bottom screen was deposited directly in a stainless steel mixing tank placed on a 2,000-lb-capacity floor scale. When the mixing tank reached its operating volume (200 gal), the screens and spray water were turned off manually. The weight of the slurry was used to estimate and control the solids content of the slurry before it was pumped to the bioslurry reactors. This mechanical screening system tended to produce a very dilute slurry (with about 5% solids). Use of this system was discontinued for this reason.

Slurry for the field demonstration was prepared in the following manner. Soil excavated and screened in the field was removed from its storage drum. A known volume of water was placed in a drum on the 2,000-lb scale. Soil was added to the water until a 15% slurry (W/W) was achieved. This slurry was mixed with a high-torque pneumatic mixer to maintain the suspension. After the appropriate slurry was prepared, it was pumped with a 2-in. air-operated diaphragm pump to one of the four reactors. The volume of replacement slurry varied with the replacement strategy. The target slurry was 15% W/W, but the slurry in the reactors generally ranged from 12% to 16% W/W. The range was due to settling and inaccuracies in material preparation (including the initial soil moisture content).

Oversized material from the slurry preparation in Building 70-47 was stored in a 55-gal drum.

4.6 Water Piping and Discharge

A detailed schematic diagram of the piping for the bioslurry reactor is in Figure 7. The original assumption was that the fabric filters, granular activated carbon, and ion exchange system shown in Figure 7 would be needed to remove particles, soluble carbon, and salts prior to discharge of water, but this treatment was not necessary for the demonstration. All piping shown in Figure 7 was made of reinforced Viton tubing. To reduce the volume of water used, discharged process water from the soil dewatering was held in the tank for recycled process water.

Pump sizes and hose sizes were chosen with ease of operation as the primary consideration. Generally, it was easier to pump slurry through the 2-in. pump, because settling in the pump and pump failures were minimized. Fresh water and recycled water from the dewatering process were pumped through a 1-in. or 1.5-in. pump. Because these process streams contained very few discrete solid particles, clogging of these pumps was not a problem.

Water from the dewatering operation was recycled into the slurry preparation system to reduce the need for fresh makeup water.

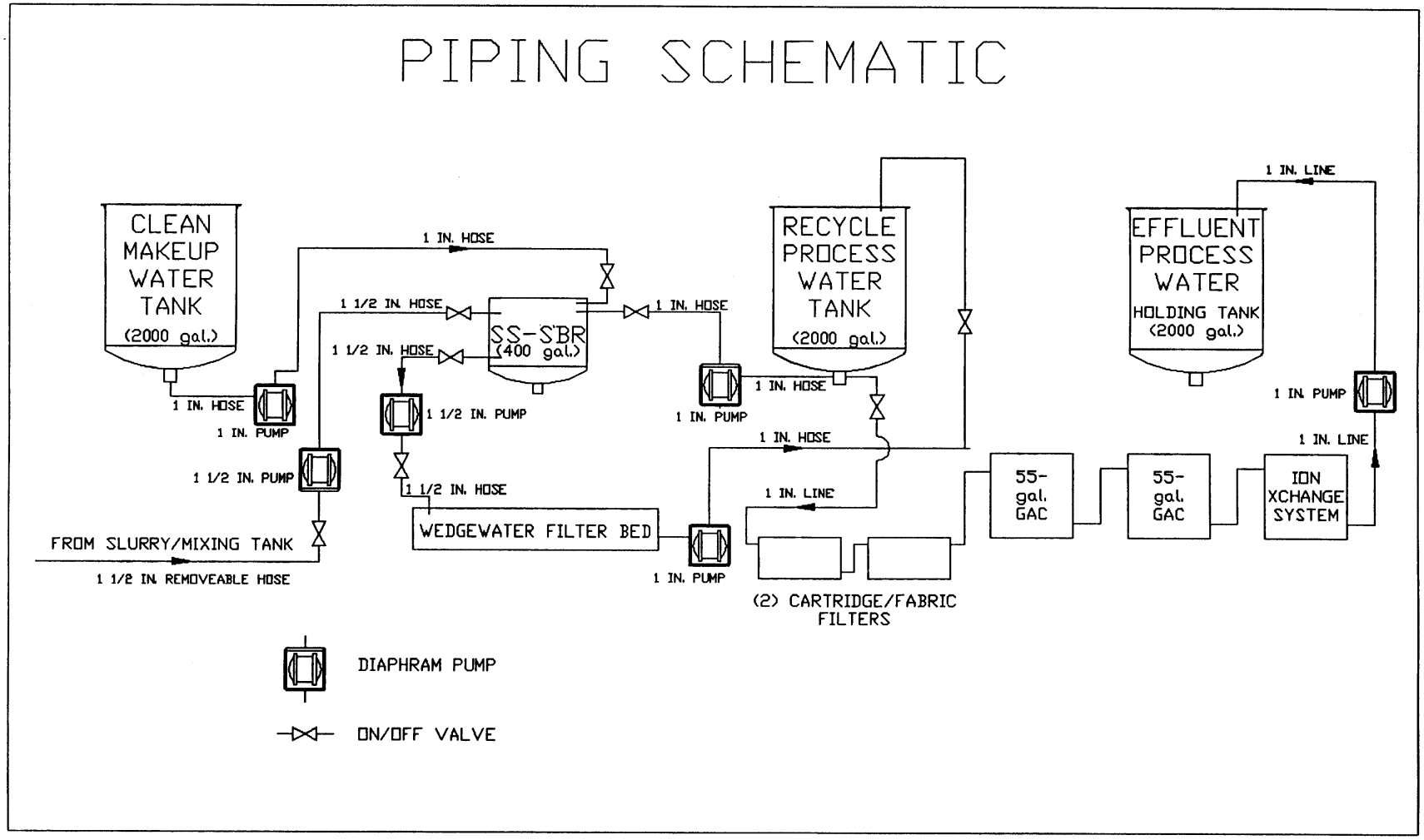


FIGURE 7 Schematic Diagram of Piping for the Bioslurry Reactor

4.7 Gas Supply System

A schematic diagram of the aeration system is shown in Figure 8. Air was supplied at 4.2 pounds per square inch gauge (psig) to the fine-bubble diffusers in each bioslurry reactor by a ring compressor/blower (maximum capacity 60 cfm) at a rate of 5 cfm per reactor. During anoxic operation, the air supply was turned off, but the mixer was left on at 80% of maximum speed.

4.8 Dewatering System for Treated Slurry

Treated slurry was pumped from the bioslurry reactors through a 1.5-in.-i.d. Viton discharge hose to slurry dewatering beds. Two sand filter beds with a wedgewater-type underdrain system (Figure 9) were used to dewater treated slurry. Each bed had a total surface area of 72 ft^2 and was constructed from shallow, square carbon steel tanks with a baffle system (8 ft by 9 ft by 24 in. deep). The drainage surface was a geotextile fabric. The geotextile was supported by a wedgewater polyurethane plate underdrain system. Each wedgewater plate was 2 in. by 12 in. by 12 in. (for a total of 64 plates per bed) with 0.015-in. slot openings. Drain lines and risers were made of 2-in.-diameter steel pipe. Inlet ports were made of 1.5-in.-i.d. steel pipe with 1.5-in. steel ball valves.

This original design for the dewatering system did not work. Because of the size reduction of particles during the bioslurry processing, approximately 50% of the particles passed through the fine-mesh geotextile fabric. Finer-mesh fabrics were not available to allow water to pass through the material but retain the treated soil particles.

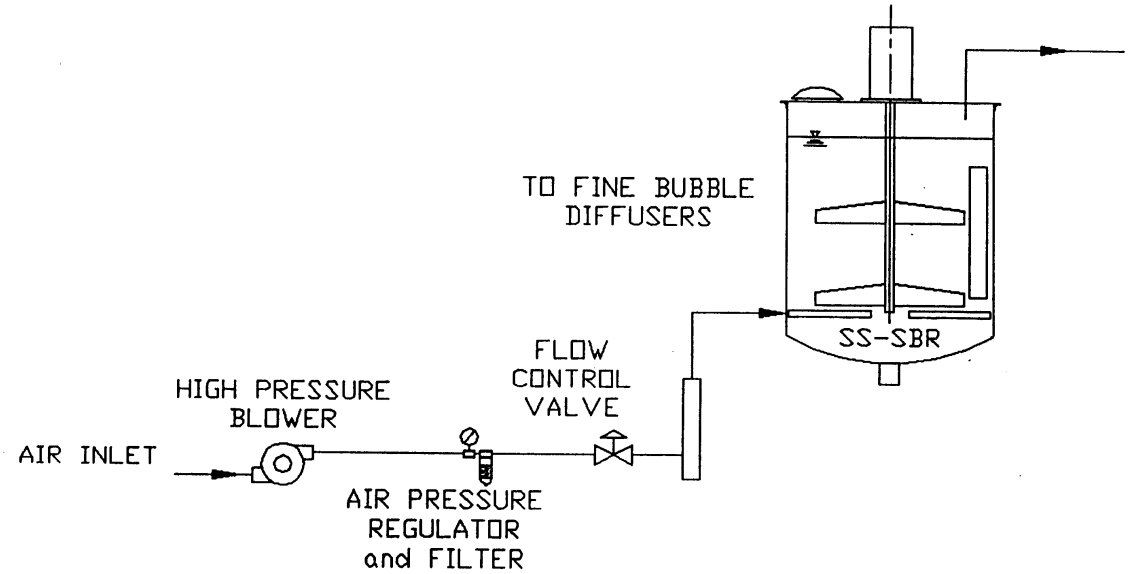
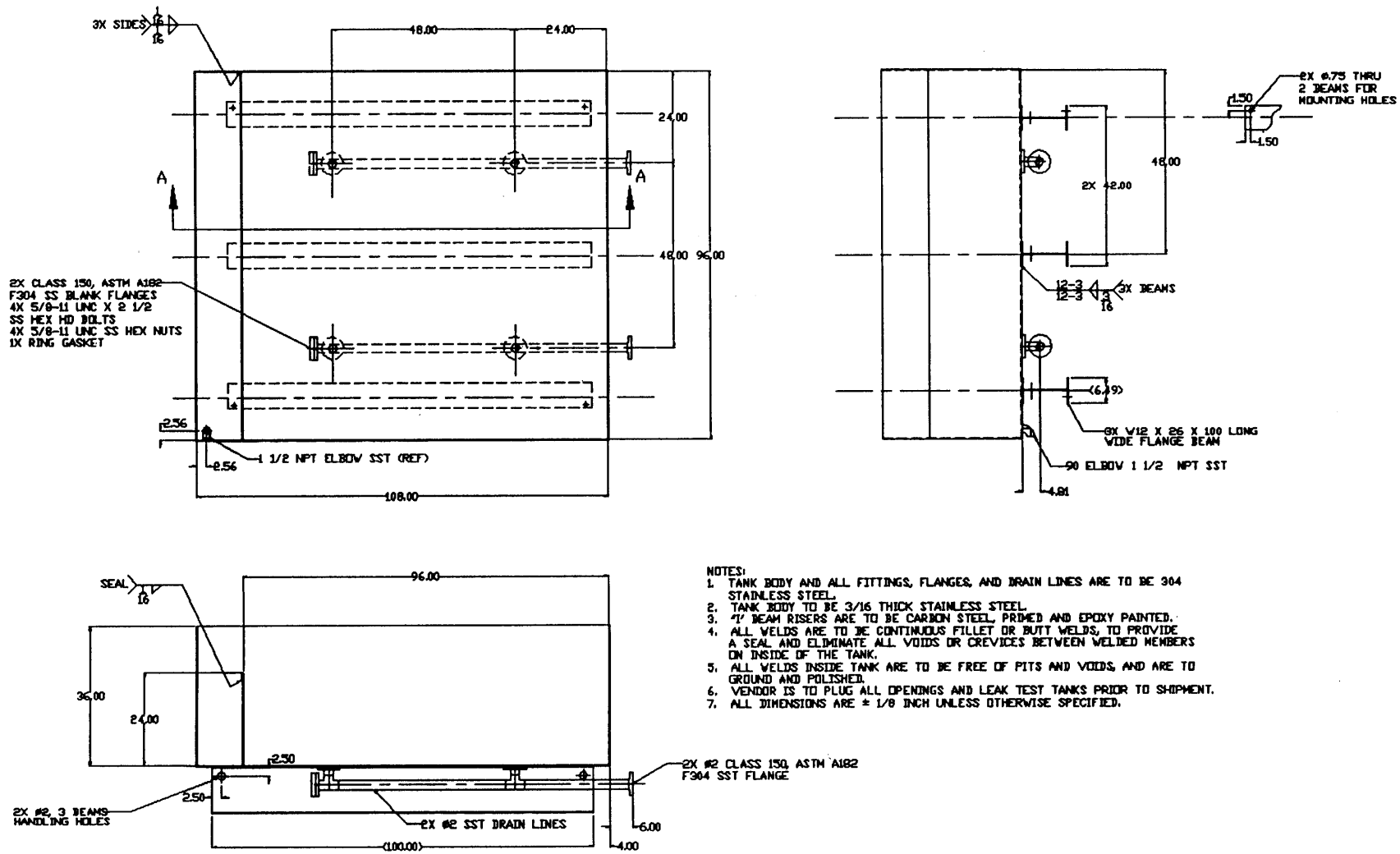


FIGURE 8 Gas Supply System



NOTES:
1. TANK BODY AND ALL FITTINGS, FLANGES, AND DRAIN LINES ARE TO BE 304 STAINLESS STEEL.
2. TANK BODY TO BE 3/16 THICK STAINLESS STEEL.
3. "I" BEAM RISERS ARE TO BE CARBON STEEL, PRIMED AND EPOXY PAINTED.
4. ALL WELDS ARE TO BE CONTINUOUS FILLET OR BUTT WELDS, TO PROVIDE A SEAL AND ELIMINATE ALL VOIDS OR CREVICES BETWEEN WELDED MEMBERS ON INSIDE OF THE TANK.
5. ALL WELDS INSIDE TANK ARE TO BE FREE OF PITS AND VOIDS, AND ARE TO GROUND AND POLISHED.
6. VENDOR IS TO PLUG ALL OPENINGS AND LEAK TEST TANKS PRIOR TO SHIPMENT.
7. ALL DIMENSIONS ARE ± 1/8 INCH UNLESS OTHERWISE SPECIFIED.

FIGURE 9 Wedgewater Filter Bed

To accomplish dewatering, several systems were investigated with equipment manufacturers, primarily press-type systems. Because of the fine particle size, no press-type system examined could separate the solids and water without chemical additions. This point is discussed further in Section 5.6.3.

Finally, a 500-gal conical-bottom tank was obtained to accomplish a preliminary separation of solids and water. This system removed most of the solids and allowed the decanted water to be used in the recycling system.

The solids from the bottom of the conical-bottom tank were temporarily stored in 55-gal drums. Analytical data for explosives were obtained for each drum. This information showed that levels of TNT, RDX, and HMX (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetraazocine) were below 20 mg/kg. After this information was presented to the regulators, the slurry was applied to uncontaminated areas of Group 61. The treated slurry, which acted as a soil amendment, was tilled into the top 4-6 in. of soil, and the soil was seeded.

4.9 Description of Bioslurry Reactor Operation

Each tank was operated in the general manner described here.

To fill each reactor, the discharge hose from a 2.0-in. air-operated diaphragm pump (40 gpm maximum capacity) was used to pump the slurry from the slurry mixing tank (Section 4.5) to the inlet port of any tank in the bioslurry reactor system. The suction and discharge lines were made of Viton rubber. The discharge line was placed in one of the open ports on the top of the reactor, and the air to the diaphragm pump was actuated to begin pumping at a rate of approximately 10 gpm. If the slurry in the reactor was too concentrated (> 15% W/W), recycled process water was pumped to the reactor for dilution.

While the reactor was being filled with the appropriate amount of slurry and makeup water, the mixer was turned on and operated at approximately 90 rpm. Twice a week, generally on Tuesday after slurry replacement and on Friday, 1.0-2.5 gal of a concentrated solution of co-substrate (molasses) was added to the reactor. The molasses (44-46% sugar) was obtained from Quality Liquid Feeds, LaSalle, Illinois, and was rated at 85-89 brix.

After the co-substrate was added, a grab sample was taken from one of the sample ports on the side of the reactor, and the pH was measured. If the pH was outside the desired operating range (< 6.0), the amount of base required to adjust the pH in the reactor to the desired value was delivered to the reactor. The pH in the reactor was always on the acidic side, requiring the addition of NaOH (50% caustic soda), obtained from Seeler Industries, Joliet, Illinois.

After the co-substrate was added and the pH adjusted, additional recycled process water was pumped into the reactor to bring the operating volume up to 350 gal. When the maximum operating volume was reached, the recycled-water pump was turned off manually. Analysis for explosives occurred after the reactor was full.

Molasses provides a variety of organic compounds for enhancing microbial metabolism, including sugars and fatty acids. In addition, molasses provides organic and inorganic nutrients such as nitrogen and phosphorus. The nitrogen is present in organic (proteins, amino acids) and inorganic forms. Phosphorus is present as organic phosphorus and inorganic orthophosphate. We chose to measure the inorganic forms (ammonia, nitrate, and orthophosphate) to ensure that concentrations were adequate for microbial metabolism. Measurable concentrations of ammonia and orthophosphate in liquid slurry samples were considered "adequate." Measurable concentrations indicated that some amount of these compounds had not been used by the bacteria in the system. The ammonia, nitrite, nitrate, and phosphorus in the system came primarily from molasses, although small amounts were present in the contaminated soil.

When the aeration and blower systems were turned on, air flow rates were adjusted to meet a target DO level of 1-2 mg/L. After sufficient aeration, the blowers were turned off, and mixing continued for the rest of the cycle. The air was turned on for 15-30 min each day. This aeration increased the DO values from very low levels of approximately 0.1 mg/L to 1-2 mg/L. Such a pattern of intermittent aeration is referred to as aerobic-anoxic cycling.

The two primary benefits of the aerobic-anoxic cycling were decreased foaming due to aeration and decreased formation of intermediates during the aerobic period. In particular, the cycling between aerobic and anoxic conditions is believed to select for a wider diversity of bacteria capable of rapidly reducing TNT and subsequently oxidizing the ring backbone of the parent TNT molecule.

Upon completion of a reactor batch cycle, a portion of the treated slurry (typically 5-20% of the reactor's operating volume or 17.5-70 gal of treated slurry) was discharged directly to the slurry dewatering beds. Discharge was accomplished by connecting a 1.5-in.-diameter Viton flex hose to a valved (ball valve) discharge port on the side of the reactor. The hose was connected to an air-operated diaphragm pump that pumped the treated slurry to the dewatering beds at a rate of 10 gpm. After the appropriate volume of slurry was discharged and the pump was turned off, the ball valve on the discharge line at the reactor was closed. The reactor was then refilled with an equal volume of contaminated slurry to begin a new cycle. After the failure of the slurry dewatering beds, slurry was discharged to the conical-bottom tank for separation.

During most of the field demonstration, the schedule described here was followed. On Tuesdays, treated slurry was removed from the 20% replacement reactor and the 10% replacement reactor. Prepared slurry containing contaminated soil was added to each reactor in the appropriate

volume. The system was continually mixed at 90 rpm, and the pH was adjusted as necessary. Molasses (0.3% volume/volume [V/V], on the basis of the laboratory studies) was added to the system, and the system was aerated. On Wednesdays, Thursdays, and Mondays, the system was monitored for pH and DO levels. The pH was adjusted if necessary, and the system was aerated for 15-30 min. On Fridays, pH adjustment and DO monitoring occurred, and molasses was added. Although some variations in this operational procedure occurred because of holidays, vacations, and illnesses, for most of the field demonstration this procedure was routinely followed. The system was unattended on weekends and holidays.

The treated slurry was applied directly to an uncontaminated area of Group 61. The slurry (soil and water) was tilled to a depth of 6 in.

Because of the extreme winter temperatures at JAAP, a heating system was needed to prevent the bioslurry system and ancillary components from freezing. An electric hot-water boiler system (Weil-McLain Model CE-112; two units of 300,000 Btu each) and seven hot-air diffusers were installed. The purpose was only to prevent the bioslurry system from freezing, not to provide optimal temperatures for microbial growth.

4.10 Operational Monitoring

4.10.1 Purpose

The objectives of the operational monitoring at the on-site laboratory were

- To provide up-to-date information on both the extent and rate of removal of the target compound (TNT) from the soil slurry during treatment; and

- To routinely monitor other process parameters such as pH, DO levels, nutrient levels (ammonia, phosphorus, and nitrite concentrations), and total dissolved solids to ensure that the proper operating conditions were maintained in each reactor.

4.10.2 Sampling Procedures

Slurry samples for chemical characterization were obtained from three 1-in. sampling ports located at different depths along the side of each reactor (Figures 5 and 6). Composite samples consisted of equal volumes of slurry taken from each sampling port. Soil samples were obtained from the pile of homogenized soil used to load the reactors. Sample location and type (i.e., single

port or composite) were recorded in a data logbook. All samples were stored in amber bottles with Teflon-lined screw caps. Samples to be analyzed on-site were either tested immediately after sample collection or stored in a refrigerator at 4°C for analysis later.

4.10.3 Analytical Procedures

4.10.3.1 Explosives

The analytical procedures used for TNT are described in detail in Appendix B. At the beginning of the study, the USATHAMA-recommended method was used to analyze for explosives; approximately halfway through the study, EPA Method 8330 became the official method for explosives. This change in analytical procedure did not affect the results in any observable way. Samples collected on Tuesdays, before soil replacement, were composite samples from three reactor ports. These Tuesday samples represent the soil concentrations expected in treated or discharged soil. Samples for explosives analysis obtained on Fridays were single-port samples. These samples were *not* representative of the treated soil. The Friday samples were process-control samples, taken to monitor the degradation process.

4.10.3.2 Field Determination of pH, Temperature, and Dissolved Oxygen

Samples were taken daily for the determination of pH, temperature, and DO levels. Samples obtained from a single port were subjected to immediate analysis for these parameters.

Dissolved Oxygen

The DO level was measured by obtaining a daily sample from one of the sample ports. The sample was collected in a standard biological oxygen demand bottle, filled to the top to minimize diffusion of air into the system. For the DO measurement, a DO probe with attached mixer was inserted into the top of the bottle. All equipment used for DO measurements was calibrated according to the manufacturers' instructions.

pH Determination

The pH was monitored daily in slurry samples removed from the reactors. The slurry sample (100 mL) was placed in a 150-mL beaker and mixed. All equipment used for pH measurements was calibrated according to the manufacturers' instructions.

Temperature Monitoring

The temperature of the slurry in each reactor was measured on the grab sample taken for DO measurement. A simple thermometer was used for this purpose. Ambient air temperatures were also recorded.

4.10.3.3 Laboratory Determination of Ammonia, Nitrite, Phosphorus, and Total Dissolved Solids and Microbial Enumeration

Samples were taken occasionally from a single port to conduct analyses for important operating parameters.

Analysis of Ammonia

The ammonia concentration in soil slurry samples was analyzed by a colorimetric method with a Hach water analysis reagent kit (Hach Company, Loveland, Colorado). The 5-mL slurry sample was prepared for analysis by centrifugation (Dynac II centrifuge, Becton Dickinson, Cockeysville, Maryland) for 10 min at 4,000 rpm. The supernatant was filtered through a 0.45-µm filter (Millipore Corporation, Bradford, Massachusetts). The filtrate used for the ammonia analysis was diluted 25 times with water. Three drops each of mineral stabilizer and polyvinyl alcohol were added to the diluted sample. Then 1 mL of Nessler reagent was added. After vigorous mixing, the yellow color developed was read at 425 nm with a Spectronic 20 spectrophotometer. The mineral stabilizer complexes the calcium and magnesium salts in the sample. The polyvinyl alcohol dispersing agent aids color formation in reactions of Nessler reagent with ammonium ions. Reagent-grade ammonium chloride (Fisher Scientific, Fair Lawn, New Jersey) was used as a standard for calculating the concentrations of ammonia in the samples.

Analysis of Nitrite

The nitrite concentration in aqueous solution was determined by a colorimetric method through the formation of a reddish-purple azo dye produced at pH 2.0-2.5 by coupling diazotized sulfanilic acid with N-(1-naphthyl)ethylenediamine dihydrochloride (APHA 1988). This method is suitable for determination of nitrogen as nitrite down to 1 µg/L. Reagent-grade sodium nitrite (Fisher Scientific, Fair Lawn, New Jersey) was used as the standard for calculating the nitrite concentrations in the samples.

Analysis of Phosphorus

The phosphorus concentration in soil slurry samples was analyzed by a colorimetric method with a Hach water analysis reagent kit (Hach Company). A 10-mL slurry sample was prepared for analysis by centrifugation (Dynac II centrifuge, Becton Dickinson) for 10 min at 4,000 rpm. The supernatant was filtered through a 0.45-µm filter (Millipore). The filtrate was diluted 25 times with deionized water and used for the analysis. Diluted sample (25 mL) was mixed with the PhosVer 3 phosphate reagent (powder pillows supplied by Hach). After a 2-min reaction time, the color developed was read at 890 nm with a Hach spectrometer. The result was expressed as milligrams of phosphorus per liter of soil slurry.

Analysis of Total Solids

The total solids concentration in recycled slurry process water was expected to increase with time because of the leaching of salts from the soil and the addition of nutrients, co-substrate, and pH-adjusting chemicals to the reactors. Exceedingly high concentrations of total dissolved solids could inhibit TNT-degrading microorganisms. The total dissolved solids concentration was measured on filtered (0.45-µm Teflon) recycled process water by using Method 2540 C of *Standard Methods* (APHA 1988).

Microbial Enumeration

To evaluate the overall microbial health of the system, the number of heterotrophic microorganisms in the system was monitored. The population density of heterotrophic microorganisms was determined at approximately one-month intervals for selected contaminated soils and treated slurries. One gram of soil or slurry was transferred aseptically into 90 mL of sterile 0.1 *M* phosphate buffer and agitated by hand for several minutes. Large particles were allowed to settle after agitation. The soil (or slurry) extract was diluted serially into sterile phosphate buffer (1 mL of extract into 9 mL of buffer) to a dilution of 10^{-9}. Each dilution was spread-plated or pour-plated onto nutrient agar (Difco Laboratories, Detroit, Michigan). Plates were incubated at 55°F for 5 days. Total colony counts were made after days 2 and 5 of incubation. The total number of microbial colonies on each plate was used to calculate the number of colony-forming units (CFUs) per gram of dry soil.

Microbial enumeration was performed on contaminated soil, on slurry samples from the reactor units, and on dewatered slurry samples.

4.11 Short-Term Laboratory Biodegradation Studies

Several short-term studies were conducted to investigate at the bench scale the effect of cold weather on the microbial degradation process and to determine the fate of radiolabeled TNT.

4.11.1 Laboratory Soil Slurry Reactors

With the information gained in the previous experiments, we used four 2-L aerobic-anoxic soil slurry reactors to determine in the laboratory whether the microbial biomass could degrade explosives after being subjected to extreme cold at JAAP. TNT-contaminated slurry was collected from the reactors at JAAP. The laboratory-scale reactors were operated semicontinuously and were started with 15% (weight/volume [W/V]) of explosives-contaminated slurry. Air was provided through a diffuser for 15-30 min each day. The soil slurry was mixed continuously at the rate of 90 rpm by using a magnetic stirrer.

4.11.2 Carbon-14 Mineralization Studies in the Slurry Reactor

After seven months of operation, 100 mL of soil slurry was taken from each field reactor. The soil slurry was incubated in the laboratory with [^{14}C]TNT (uniformly ring labeled) to establish mass balance and follow the production of metabolites, including $^{14}CO_2$. The [^{14}C]TNT was added to the soil slurry in respirometer flasks at a level of 20,000 cpm/mL (Bartha and Pramer 1965). The control flask contained autoclaved soil slurry. Samples were withdrawn periodically, and the quantity of TNT converted to biomass was determined as material precipitable by trichloroacetic acid (Mans and Novelli 1961) by using a liquid scintillation spectrometer (Beckman Model LS 5000 TD, Beckman Instruments, Inc., Palo Alto, California). The CO_2 evolved from degradation of [^{14}C]TNT by the soil bacteria was monitored according to the method described by Bartha and Pramer (1965). KOH (0.5 *N*) was added to the side arms of the respiratory flasks. The flasks were incubated at ambient temperature in a shaker set at 50 rpm. The resipirometer was sampled periodically by withdrawing KOH. The percentage of [^{14}C]TNT mineralized as $^{14}CO_2$ was calculated. The analyses were conducted in duplicate.

The TNT metabolites were analyzed by collecting fractions every 30 s after passage through a high-performance liquid chromatography (HPLC) column. The radioactivity in each fraction was measured by using a liquid scintillation counter. Soil-bound radioactive TNT was analyzed by using the soil extraction procedure described in Section 4.10.3, and the radioactivity in the soil was measured by using a liquid scintillation counter.

4.11.3 Identification of the Unknown Intermediate Generated in the Reactor Radiolabeling Study Described in Section 4.11.2

The intermediate that eluted at 2.2 min during the EPA Method 8330 HPLC analysis was collected (by passage through the HPLC column), concentrated, and resuspended in acetonitrile. The concentrated sample was analyzed by gas chromatography/mass spectrometry (GC/MS) in the electron ionization mode on a Hewlett Packard Model 5970 system (Hewlett Packard Co., Palo Alto, California). The samples were chromatographed with a gradient temperature program. The initial temperature of 100°C was held for 2 min, and then the temperature was increased to 280°C at 10°C/min and held at 280°C for 20 min. An SPB-5 (30 m × 0.25 mm, 0.25-μm film) column was used (Supelco, Inc., Bellefonte, Pennsylvania). The injection temperature was 280°C, and the transport line was kept at 220°C. The helium flow was 10 cm/s, and injections volumes were 1 μL.

4.11.4 Plant Growth Studies

After treatment, the slurry was mixed with clean, uncontaminated soil from Group 61 to evaluate the ability of the mixture to support the growth of plant species commonly found in the midwestern United States. The plant species used were corn and bluestem grass. Slurry was mixed with clean soil in ratios of 0:100, 5:95, 10:90, 25:75, and 50:50 (treated slurry to uncontaminated Group 61 soil). The plants were cultivated for seven weeks in a growth chamber providing constant temperature and humidity. Biomass was measured as emergent growth above the soil line. Five replicates of each slurry-soil mixture were tested.

4.11.5 Studies of the Fate of Total Organic Carbon

Soluble total organic carbon (TOC) was determined by using small laboratory pans containing the specified composition of slurry and native, uncontaminated soil from JAAP, Group 61. Samples were removed periodically for TOC measurements, with a Dohermann Model 418 TOC analyzer, of the soluble material removed by washing 5 g of soil with 10 mL of distilled water. Carbon dioxide generation studies were conducted by mixing 10 g of soil and 10 mL of distilled water in a sealed vial. Gas samples removed with an air-tight syringe were injected into an Illinois Instruments carbon dioxide-oxygen analyzer.

4.12 Chemicals

Radiolabeled TNT (uniformly ring labeled; specific activity 21.58 mCi/mmol, 98.5% pure) was purchased from Chemsyn Science Laboratories, Lenexa, Kansas. The nonradioactive TNT (98% pure) was obtained from Chem Service, Inc., Westchester, Pennsylvania. The TNB, dinitrotoluene (DNT), RDX, and HMX were obtained from the Naval Surface Warfare Center, Indian Head, Maryland, through the USAEC's Standard Analytical Reference Material Program. All other chemicals were of reagent grade.

5 Results

The results of this field demonstration are presented in six sections. These sections report on the soil characteristics, the physical characteristics of the reactors (corresponding to the first phase of the study), the biological soil slurry process (corresponding to the second and third phases of the study [adaptation and operation]), the degradation of dinitrotoluenes, the separation of solids, and small-scale laboratory studies conducted in support of the field demonstration.

5.1 Soil Characteristics

Previous sampling of the Group 61 soils at JAAP had indicated various levels of explosives contamination. We excavated soil from the southwest corner of Group 61, from areas containing significant red discoloration and lacking vegetation (indicating rather high concentrations of TNT). Excavation in this area minimized the amount of screening required, because vegetation and associated roots were largely absent. Excavation of soil in this way provided the study with a natural gradient of TNT concentrations for treatment. As the study progressed, the TNT concentrations in the soil generally increased to a maximum of approximately 6,500 mg/kg. Large, oversized rocks that did not pass through the 1/4-in. field screen remained behind in Group 61. For ease of screening, soil was excavated only after any rainwater or precipitation had drained.

The concentrations of TNT, DNT, TNB, RDX, and HMX in excavated soils are summarized in Table 1. At no time did analysis reveal any of the 4A26DNT and 2A46DNT intermediates, indicating that no biodegradation had occurred. Although DNT, TNB, RDX, and HMX were present in the soil, the TNT concentration dominated as the contaminant of concern.

5.2 Phase I — Reactor Characteristics

Before operations began, two studies were conducted to determine whether the reactors could mix the soil and keep it in suspension and to establish the oxygen transfer characteristics of the reactors. These are described as the Phase I studies in the *Test Plan* (Manning and Montemagno 1992a).

5.2.1 Soil Suspension

Uncontaminated soil of a composition similar to that of JAAP soil (i.e., a silty, clayey loam) was prepared and added to the reactors to determine the theoretical weight of soil/weight of

TABLE 1 Summary of Analytical Results for Explosives in Soil

Date	Concentration (mg/kg of soil)				
	TNT	DNT	TNB	RDX	HMX
Initial (Reactors 1 and 2)	1,000	ND[a]	70	20	ND
Initial (Reactors 3 and 4)	2,100	ND	75	18	ND
8/94-9/94	4,176	136	148	ND	52
8/94-9/94	3,898	120	144	60	140
8/94-9/94	3,179	260	137	80	ND
8/94-9/94	2,962	320	135	120	96
8/94-9/94	4,113	140	150	256	88
8/94-9/94	3,897	ND	98	80	112
10/4/94	3,478	140	216	55	96
10/10/94	3,873	310	260	166	215
1/5/95	3,644	78	48	ND	ND
1/31/95	4,888	340	257	111	150
2/7/95	4,487	106	77	216	ND
3/2/95	5,911	190	144	116	175
3/21/95	4,639	ND	88	66	104
4/11/95	4,707	ND	288	ND	ND
4/25/95	3,814	166	211	310	ND
5/2/95	3,057	224	360	109	96
5/9/95	3,311	180	120	206	200
5/16/95	3,688	198	76	154	66
6/20/95	6,226	210	212	222	98
7/18/95	6,140	360	148	270	126
7/25/95	5,426	215	166	ND	66
8/1/95	3,683	200	190	88	ND
8/8/95	6,110	ND	220	110	214
9/7/95	4,697	66	211	90	86

[a] ND indicates that no detectable concentration was observed after soil extraction.

slurry required for the suspension. The tests were started with the mixer set at 100 rpm. Over time, the mixer speed was reduced to 50 rpm, and the effect on the percent of solids in suspension was examined. A simple suspended-solids analysis was conducted to determine the percent of solids in suspension. The results are in Table 2.

The results in Table 2 reveal two significant trends in this clean-soil test. The first trend is that the speed (rpm) of the mixer affects the ability of the mixing system to keep the soil in suspension. Soil concentrations were similar at 80 and 100 rpm, but when the mixer speed was reduced to 60 or 50 rpm, a significant portion of the soil fell to the bottom of the reactor, outside the mixing zone.

TABLE 2 Soil Suspension Data

Target Soil in Suspension (%)	Measured Soil in Suspension (%)	Mixer Motor Speed (rpm)	Type of Impeller
10	9.0	100	Anchor
10	9.5	80	Anchor
10	8.0	60	Anchor
10	8.0	50	Anchor
10	9.0	100	Turbine
10	9.0	80	Turbine
10	9.0	60	Turbine
10	8.0	50	Turbine
15	14.0	100	Anchor
15	11.0	80	Anchor
15	10.0	60	Anchor
15	6.0	50	Anchor
15	14.0	100	Turbine
15	14.0	80	Turbine
15	13.0	60	Turbine
15	12.0	50	Turbine
20	15.0	100	Anchor
20	13.0	80	Anchor
20	12.0	60	Anchor
20	10.0	50	Anchor
20	17.0	100	Turbine
20	16.0	80	Turbine
20	15.0	60	Turbine
20	15.0	50	Turbine

A second factor in maintaining soil in suspension is the type of impeller. Anchor-type (Figure 5) and turbine-type (Figure 6) impellers were tested. Across soil concentrations, the turbine-type impeller kept a higher soil concentration in suspension than the anchor-type impeller.

Degradation occurs in the bioslurry reactor only when the soil remains in contact with the bulk water, which contains microorganisms, along with co-substrate and nutrients to enhance biological activity. For this reason, turbine-type impellers, operating at 80 rpm in a 15% (W/W) soil slurry, were selected for the demonstration. Although unpublished laboratory data indicate that constant mixing is not required, operational concerns precluded stopping of mixing for long

periods. The concern was that once the slurry settled in the reactor, resuspension might be very difficult with the size of motors available at the site.

5.2.2 Oxygen Transfer

Another study determined the oxygen concentrations achieved in the reactor by using the aeration system or by reaeration with the mixing system. The operation system was tested with clean water, with 5 cfm of air delivered to each reactor at 5 psig, or with the water deaerated (i.e., reading 0 mg/L on a DO probe). Within 2-4 min after the aeration system was started, saturation levels of oxygen in the water were reached. It was not possible to reduce the volume of air or the pressure at which the air was delivered to study the rate of reaeration.

The second part of this study examined reaeration with the mixing system alone (without air added through the aeration system). With deaerated water in the tank, the dual-turbine mixer was operated at 80 rpm to indicate the amount of reaeration achieved by mixing alone. Table 3 summarizes these results. Although some differences exist between the three trials, significant reaeration consistently occurred with mixing alone. No aeration system was required to incorporate some oxygen into the water. Microbial consumption of oxygen precluded measurement of this kind of reaeration in systems with microbial activity.

TABLE 3 Results of Reaeration Test

Time (h)	Dissolved Oxygen Concentration[a] (mg/L)		
	Trial 1	Trial 2	Trial 3
0.0	0.0	0.0	0.1
0.5	0.1	0.0	0.1
1.0	0.6	0.2	0.2
2.0	1.1	0.8	0.7
3.0	2.4	2.0	1.8
5.0	3.0	4.2	3.9
8.0	5.2	5.1	4.8
12.0	7.6	6.9	7.3
15.0	7.5	7.4	7.3
18.0	7.3	7.6	7.2
21.0	7.4	7.4	7.3
24.0	7.4	7.5	7.2

[a] Measured 2.5 ft below the water surface.

5.3 Phase II and Phase III — Biological Degradation Studies

After completion of the Phase I studies to investigate the physical and mechanical characteristics of the reactors, they were loaded with a 15% (W/W) slurry. Contaminated soil from Group 61 with a TNT concentration of 1,200-2,000 mg/kg was used for this initial loading. Adaptation and early operation occurred from late August 1994 until December 1994.

5.3.1 Control Reactor

The control reactor was loaded with slurry on July 8, 1994. The initial TNT concentration was about 1,100 mg/kg. Over the next three months, the TNT concentration in soil in this reactor showed significant variability, from a low of 1,037 mg/kg to a high of 3,561 mg/kg, although no new soil was added. Eventually, the TNT concentration in soil remained at 2,000-2,500 mg/kg (Figure 10). The variation in TNT concentration in the control reactor was due to homogenization of the soil and any particulate TNT in the soil. This homogenization decreased the soil particle size and increased the amount of TNT recovered by the analytical procedure.

No intermediates were identified in the control reactor (Figure 10), indicating that TNT was not used as a sole source of carbon and nitrogen. Trinitrobenzene was present in the soil at approximately 100-150 mg/kg, and HMX was present at approximately 80-110 mg/kg. As with TNT, TNB and HMX showed some initial variability in concentration, followed by a longer-term leveling of the concentration at a more stable value.

Figure 11 shows the TNT, TNB, and RDX concentrations in the liquid portion of the slurry. These concentrations resulted from an equilibrium between each contaminant adsorbed to the solid particles and the contaminant in the liquid phase.

Other parameters of importance in the control reactor stayed fairly constant, with a pH of approximately 7.5-8.5, a DO concentration near saturation at all times (without continuous aeration), and a temperature profile that closely followed the ambient temperature profile. The bacterial enumeration studies on this reactor consistently indicated 10^3-10^5 microorganisms per gram of soil.

These data confirmed the previous laboratory work indicating that TNT, TNB, and RDX are not degraded unless a co-substrate is present. This control reactor had no co-substrate added. Some natural co-substrate in the form of humic and fulvic acids might have been present, but these were not sufficient to enhance the biodegradation of the explosives.

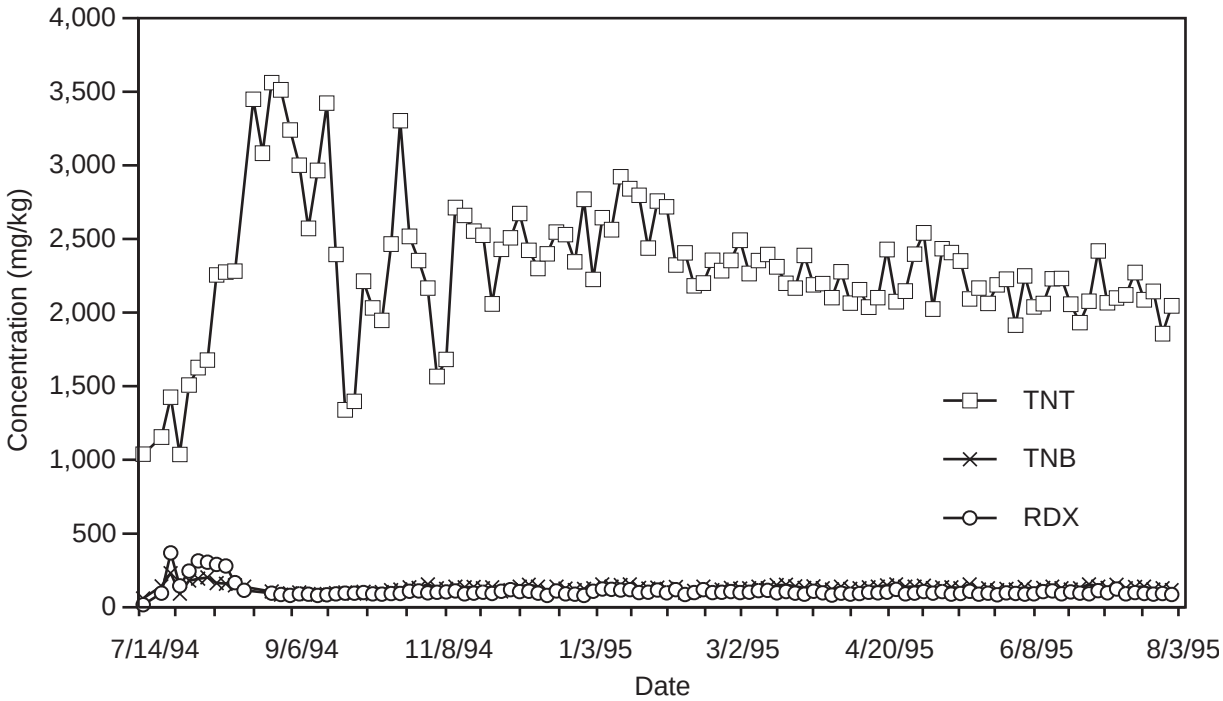


FIGURE 10 Explosives Concentrations in Soil in the Control Reactor

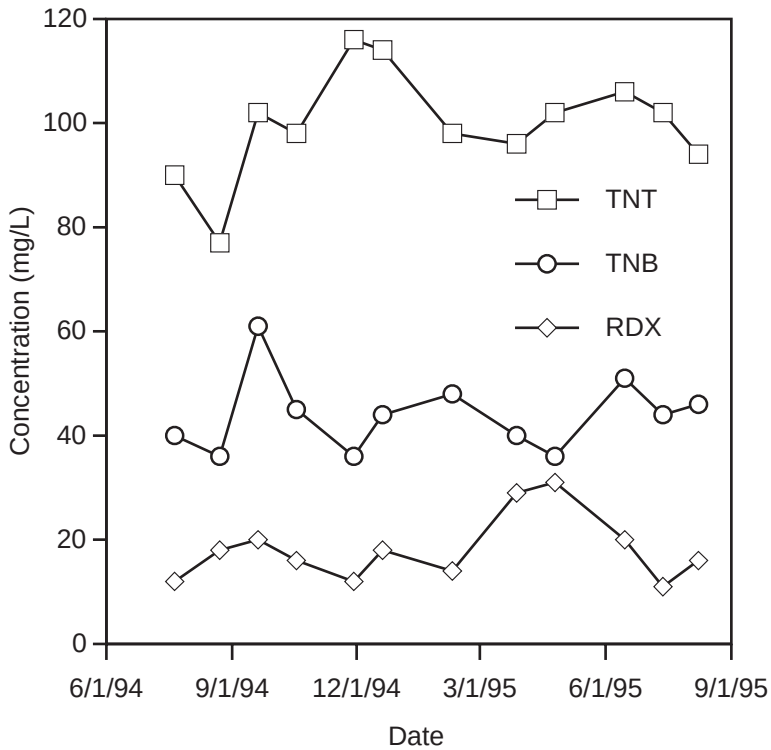


FIGURE 11 Explosives Concentrations in Liquid in the Control Reactor

5.3.2 20% Replacement Reactor

The reactor with 20% weekly replacement was operated from July until August 9, 1994, with the soil slurry mixed and aerated once per day but without molasses (co-substrate) added. On August 9, 1994, 0.5 gal of molasses was added to the reactor. On August 22, 1994, 1 gal of molasses was added, and thereafter molasses was added once or twice a week at 1-3 gal per week to enhance biological degradation of explosives. On September 20, 1994, weekly replacement of 20% of the reactor volume (with a 15% [W/W] slurry) began. This replacement continued until December 13, 1994, when replacements were suspended because of cold weather. On January 17, 1995, replacements resumed after the building heater system was installed. Replacements continued until August 6, 1995. The concentration of TNT in the soil increased from approximately 1,100 mg/kg in the initial replacements to approximately 6,000 mg/kg in the later replacements.

5.3.2.1 Overview

Figures 12 and 13 provide an overview of the data obtained for the 20% replacement reactor. The temperature profile shows that in November, the temperature fell below 20°C. In December, the temperature was below 12°C. In mid January the heater system installed to warm the building became operational, and the temperature subsequently rose above 20°C. The data in Figures 12 and 13 include results for samples collected on Tuesdays (before replacement) and Thursdays (two days after the beginning of a cycle). The Tuesday data are relevant for determining removal potential. The Thursday data are relevant for determining process efficiency. As expected, Tuesday data have lower concentrations of explosives, 4A26DNT, and 2A46DNT. Thursday data tend to have higher explosives, 4A26DNT, and 2A46DNT concentrations.

5.3.2.2 Adaptation

Figures 14 and 15 describe data for Tuesday samples from the 20% replacement reactor for the adaptation period (Phase II in the *Test Plan* [Manning and Montemagno 1992a]). During adaptation, the first activity was developing confidence in the operation of the system. This activity occurred in July 1994, before the addition of molasses. The second activity, the adaptation of the native microbial consortium to degrade TNT, occurred when the molasses was added to the system. Almost immediately after the addition of molasses on August 9, 1994, the TNT concentration in the system decreased, and 4A26DNT appeared (Figure 14). In addition, TNB and RDX removal occurred (Figure 15). After approximately one month of operation, the TNT concentration fell below 20 mg/kg. After replacements began on September 20, 1994, the TNT concentration began to increase in the soil removed from the reactor, and the 4A26DNT

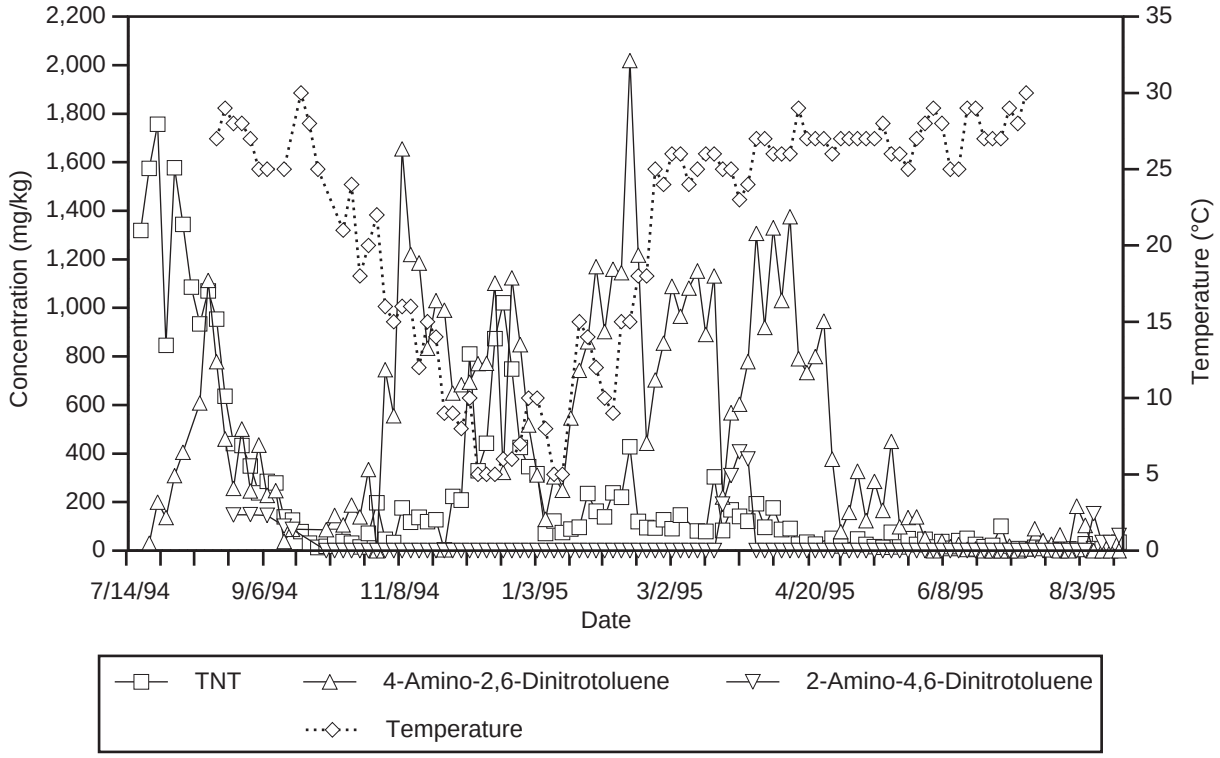


FIGURE 12 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 20% Replacement Reactor

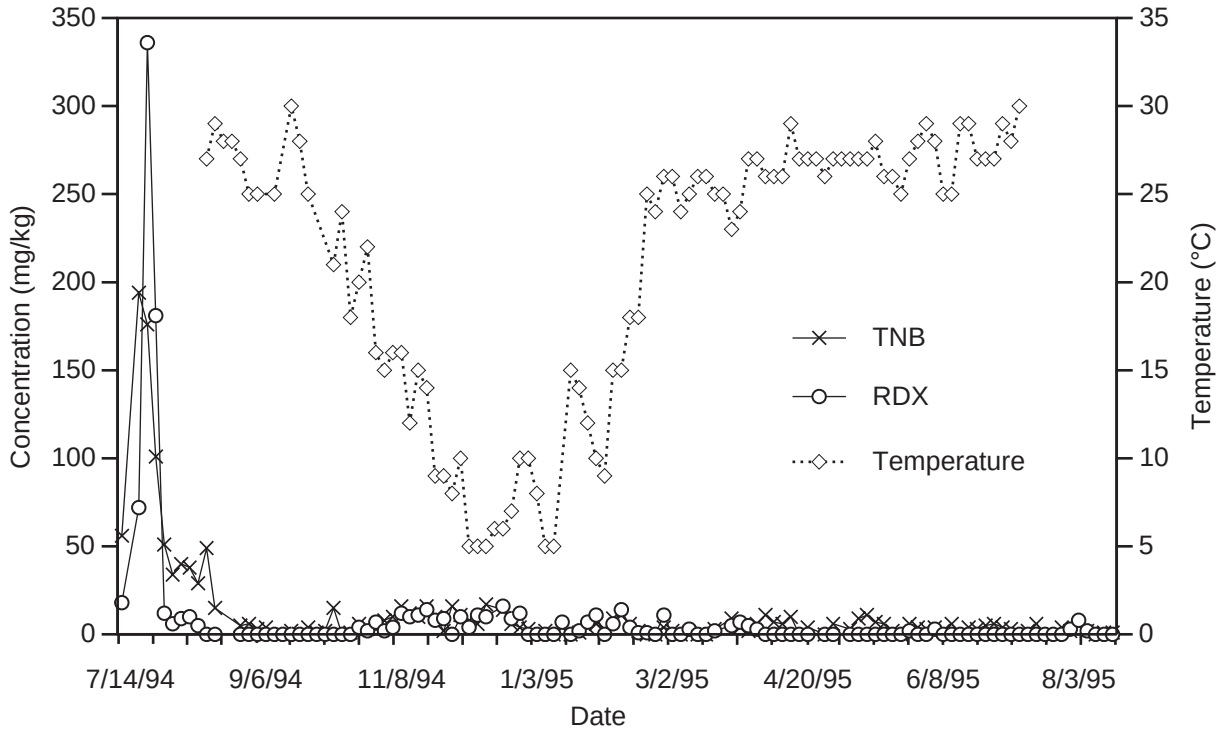


FIGURE 13 Explosives Concentrations in Soil in the 20% Replacement Reactor

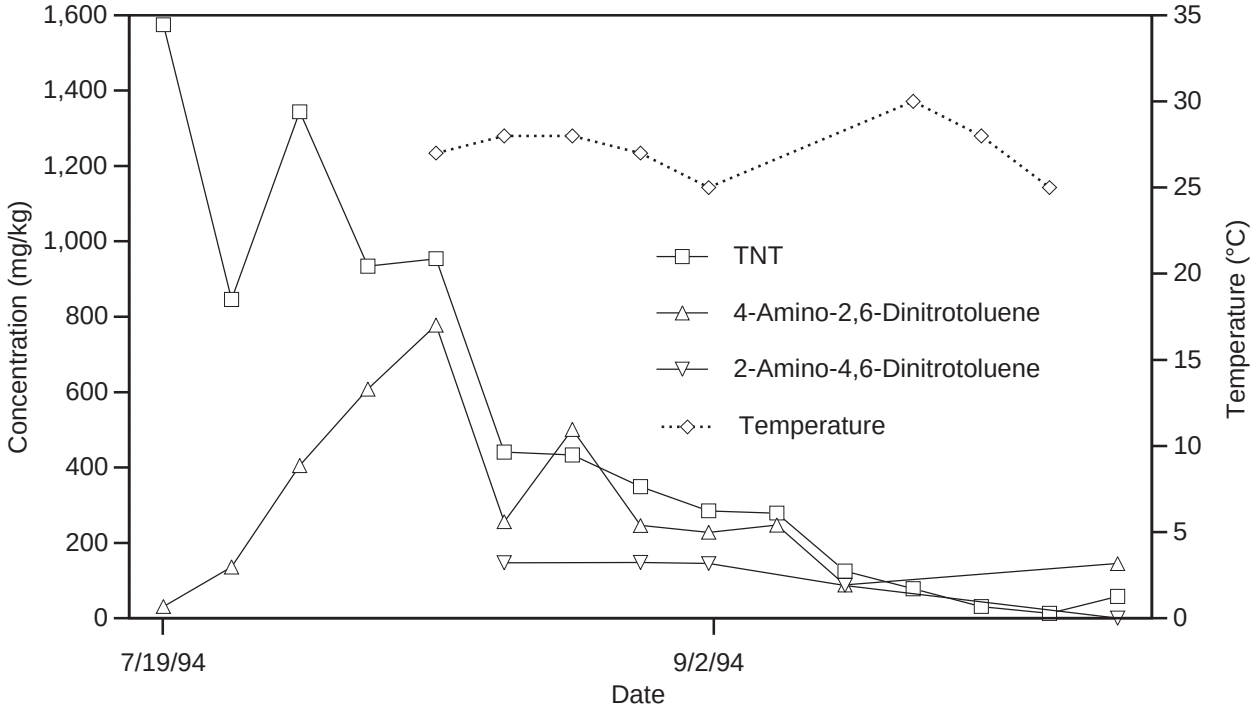


FIGURE 14 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 20% Replacement Reactor during Adaptation

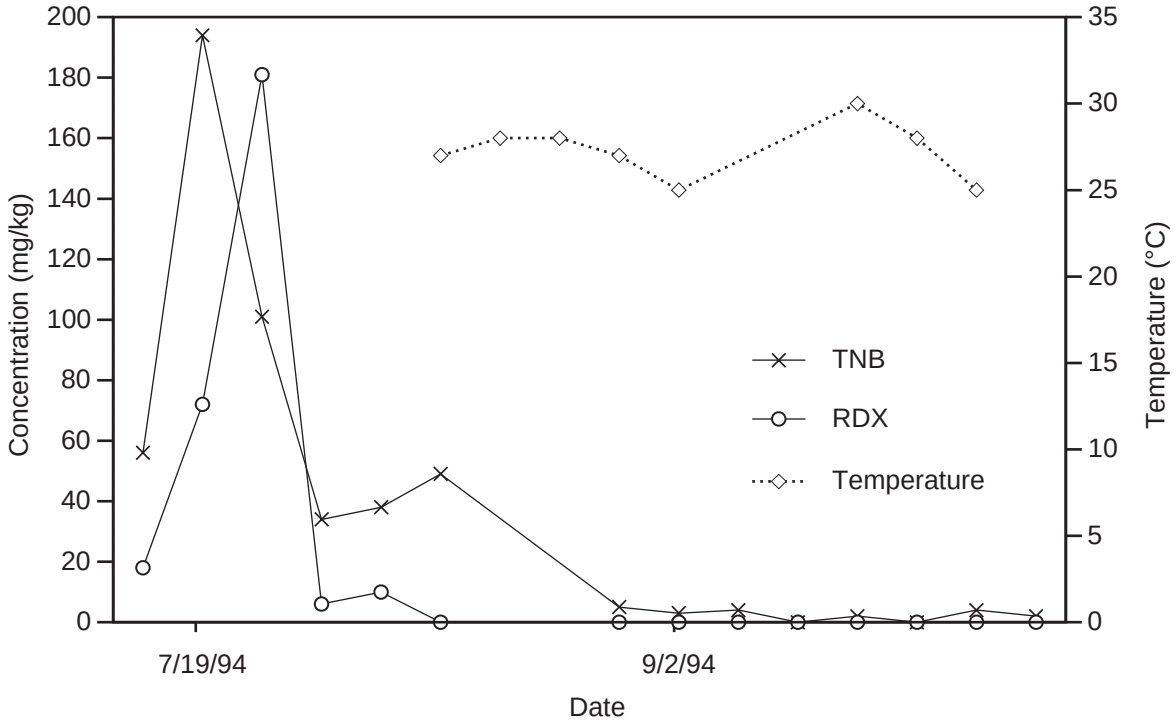


FIGURE 15 Explosives Concentrations in Soil in the 20% Replacement Reactor during Adaptation

concentration also began to increase. These trends were in direct response to the decrease in temperature from a high of 25-30°C in August and September to less than 15°C in December. The same pattern occurred for TNB and RDX, because the removal of TNB and RDX also decreased as the temperature decreased.

5.3.2.3 Cold-Weather Operation

Figures 16 and 17 describe the period of operation from January 1995 through mid April 1995. As the figures show, the 20% replacement reactor continued to have many of the characteristics observed during adaptation. As the temperature increased, the removal of TNT increased, although the concentration of TNT remained at about 100 mg/kg even when the temperature was above 25°C after March 1, 1995. Of more concern are the relatively high concentrations of the 4A26DNT intermediate, ranging from 500 to 1,000 mg/kg. The reactors were expected to remove TNT and 4A26DNT from the soil when the temperature was above 25°C. As Figure 16 shows, the temperature was about 25°C during most of this period, but removal of TNT and 4A26DNT was limited. One possible explanation is that cold water (about 10-12°C) used in the replacement process might have negatively affected the microorganisms.

The removal of TNB and RDX followed the same pattern of decreasing in cold weather (Figure 17).

5.3.2.4 Warm-Weather Operation

Figure 18 shows the soil concentrations of TNT, 4A26DNT, and 2A46DNT in the 20% replacement reactor during warm-weather operation. After May 1, 1995, the temperature in the reactor rose above 25°C. At that time, TNT concentrations were below 50 mg/kg, as were 4A26DNT concentrations. During this time the TNT concentration in the replacement soil was 4,000-6,000 mg/kg. This removal of TNT and 4A26DNT indicates that the biodegradation process is sensitive to temperature and that for high weekly mass loadings, the temperature needs to be maintained above 25°C. The temperatures in this reactor never were higher than 31-33°C. No reduction in performance or enhancement of performance was observed at these temperatures.

The removal of TNB and RDX (Figure 19) also increased in warm weather. Low concentrations (10 mg/kg) of each compound remained in the treated soil removed from the reactors.

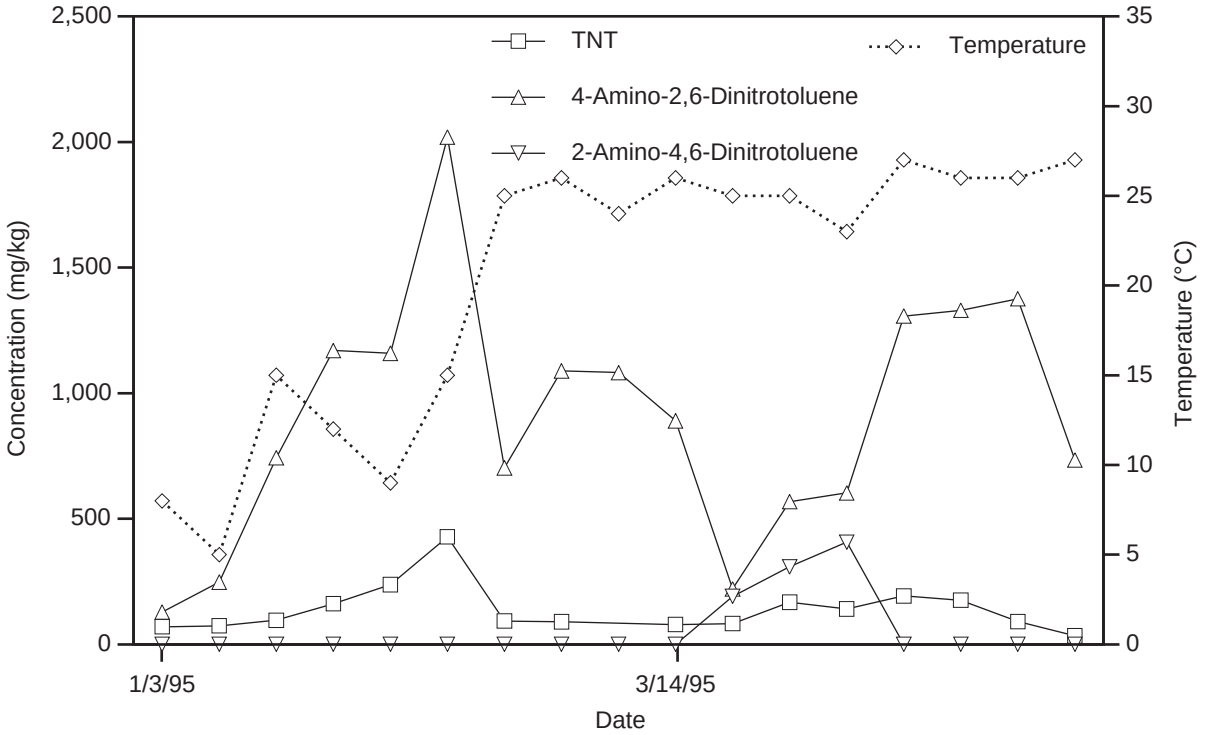


FIGURE 16 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 20% Replacement Reactor during Cold Weather

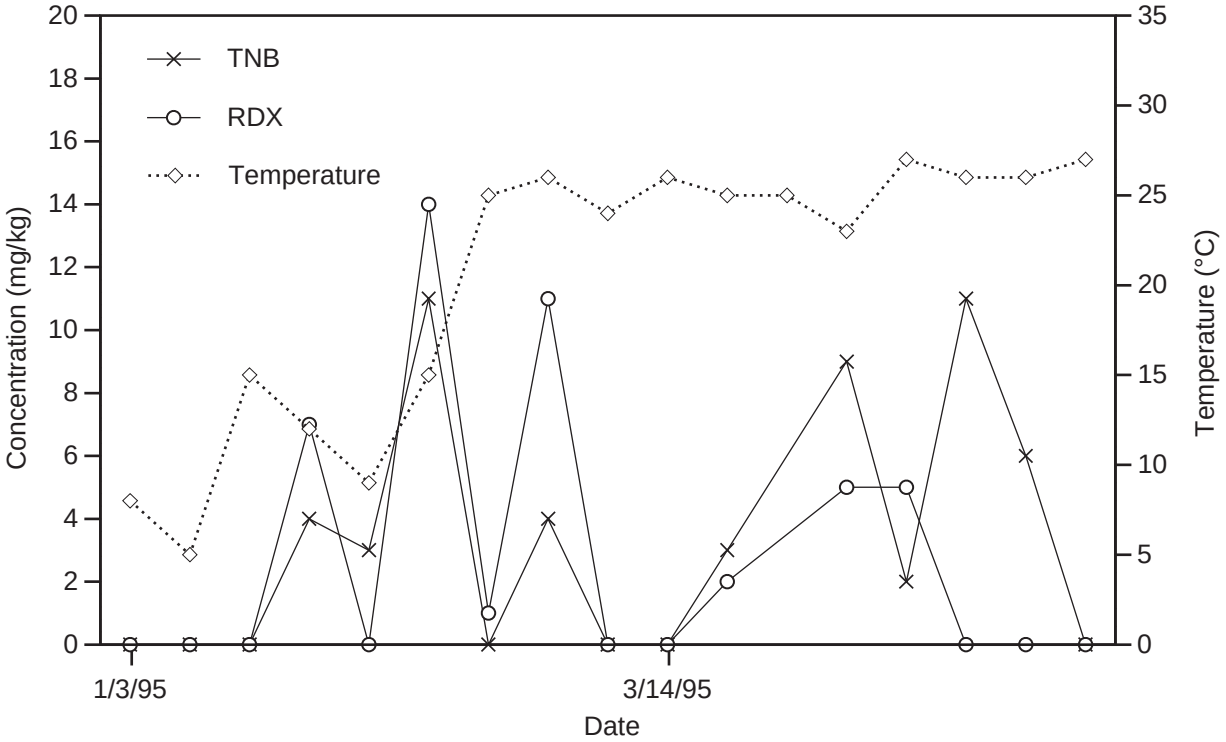


FIGURE 17 Explosives Concentrations in Soil in the 20% Replacement Reactor during Cold Weather

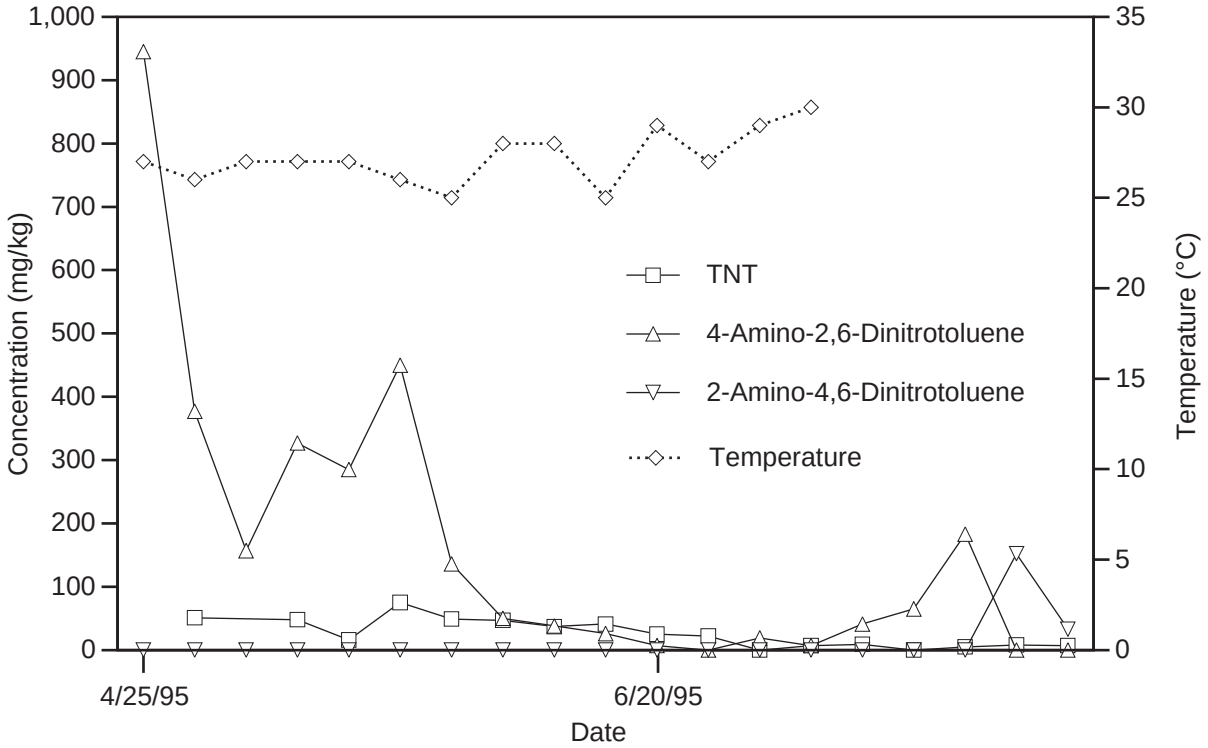


FIGURE 18 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 20% Replacement Reactor during Warm Weather

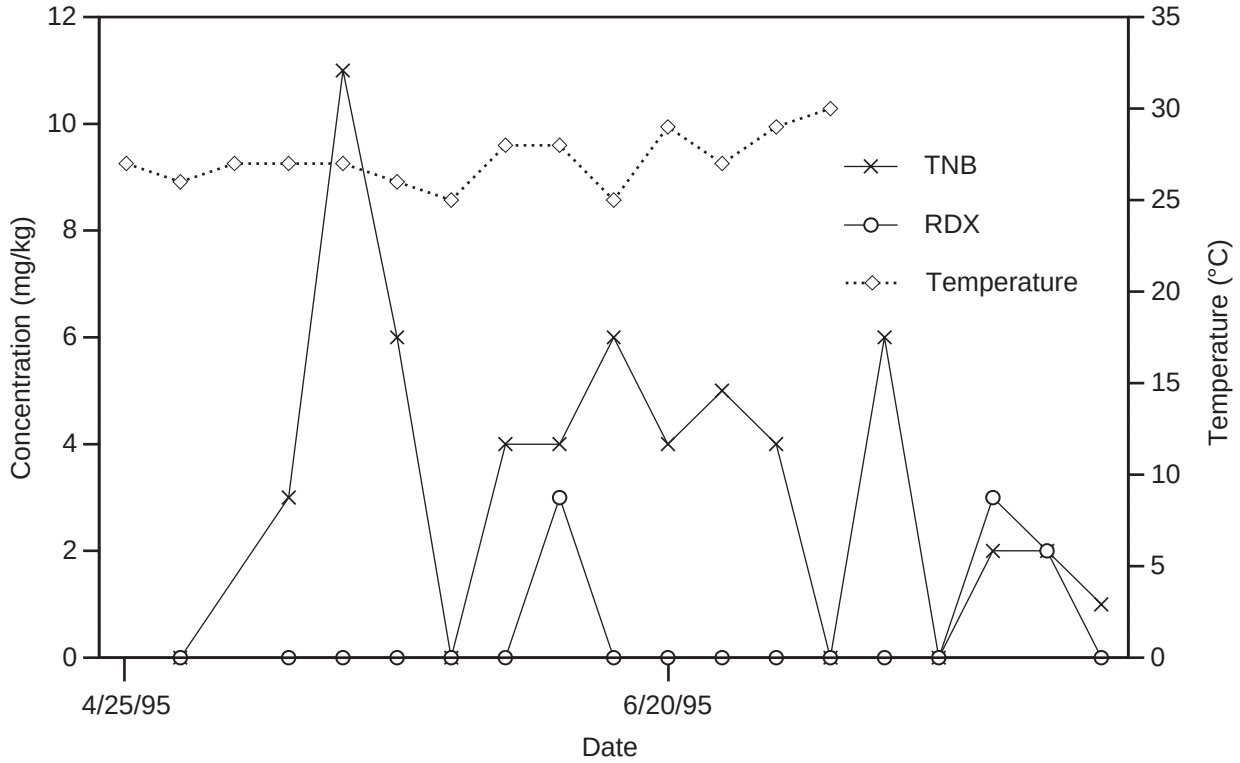


FIGURE 19 Explosives Concentrations in Soil in the 20% Replacement Reactor during Warm Weather

5.3.2.5 Liquid Concentrations

Figure 20 shows that for the 20% replacement reactor, the concentrations of TNT, TNB, and RDX in the water separated from the solid particles in the slurry followed the concentrations observed in the slurry. This result was expected, because the concentration in the liquid phase of the slurry is determined by the solid-phase concentration on the basis of thermodynamics.

5.3.2.6 Solids Concentration

The total solids concentration in the 20% replacement reactor is shown in Figure 21. This figure portrays the attempts to develop a 15% slurry in the reactor. Initially, the slurry was only 12%. As the field demonstration continued, the solids concentration was increased to about 14-16% by soil addition. The solids concentration achieved at the end of the study period closely matched the target concentration of 15%. The solids concentration was not affected by temperature.

5.3.2.7 Ammonia Concentration

Figure 22 shows the ammonia concentration in the slurry phase of the 20% replacement reactor. During the field demonstration, the ammonia level increased as more molasses was added to the system. The increase in ammonia concentration accompanying the mid February temperature drop was very dramatic. Two explanations are possible: (1) The temperature drop decreased microbial activity dramatically, causing the accumulation of ammonia in the system. (2) The ammonia concentration in the molasses increased dramatically, and the microorganisms could not process the additional ammonia. The first explanation is more probable than the second, because the same drum of molasses was used in late December, January, and February, and no other ammonia spikes occurred in this time frame.

5.3.2.8 Nitrite Concentration

The nitrite concentration profile in the 20% replacement reactor during the field demonstration (Figure 23) did not reflect a strong influence of temperature on measured concentrations. The nitrite fluctuations observed were probably due to process fluctuations.

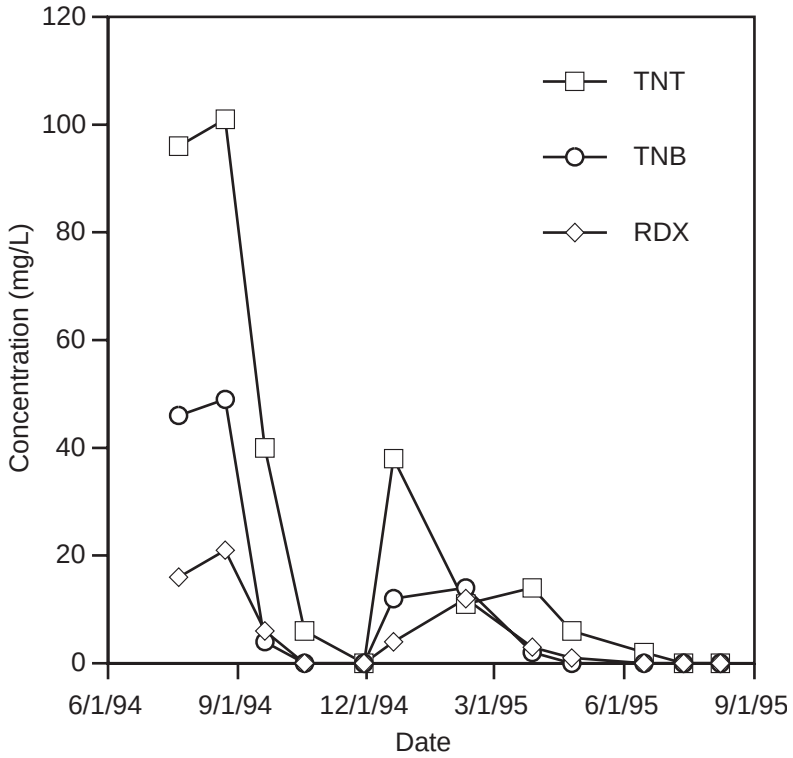


FIGURE 20 Explosives Concentrations in Liquid in the 20% Replacement Reactor

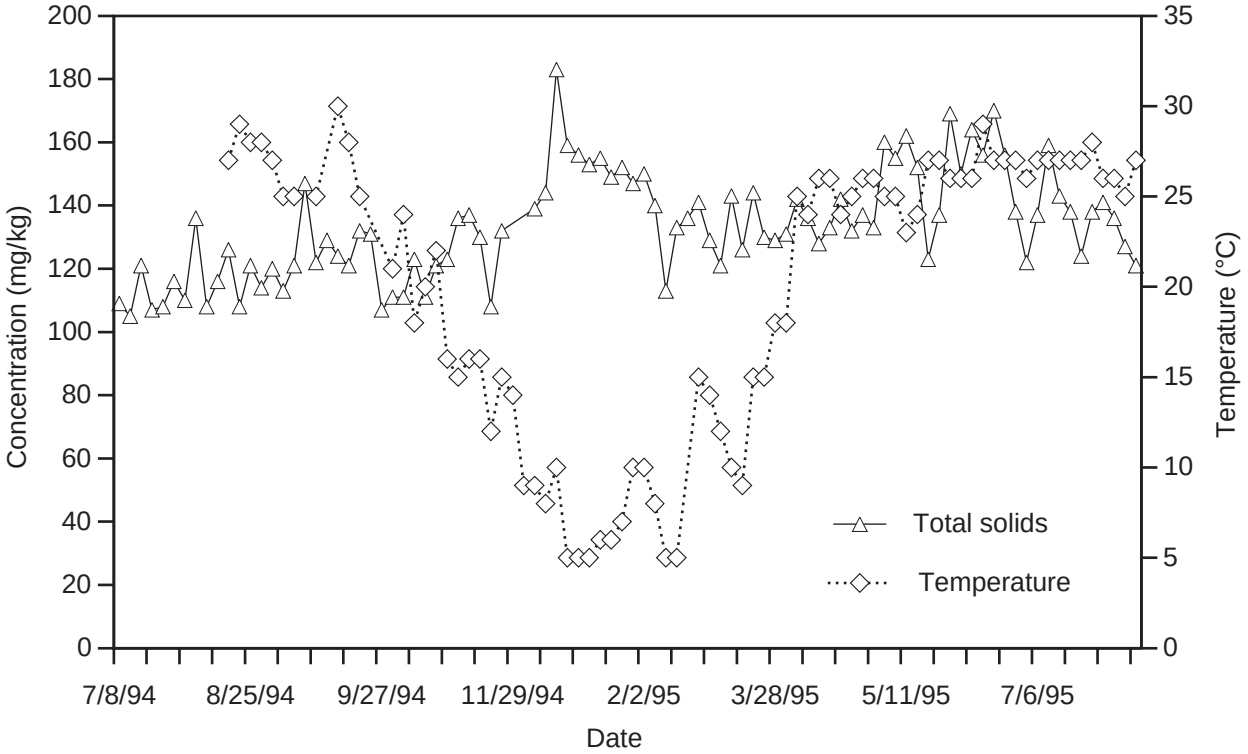


FIGURE 21 Solids Concentration in the 20% Replacement Reactor

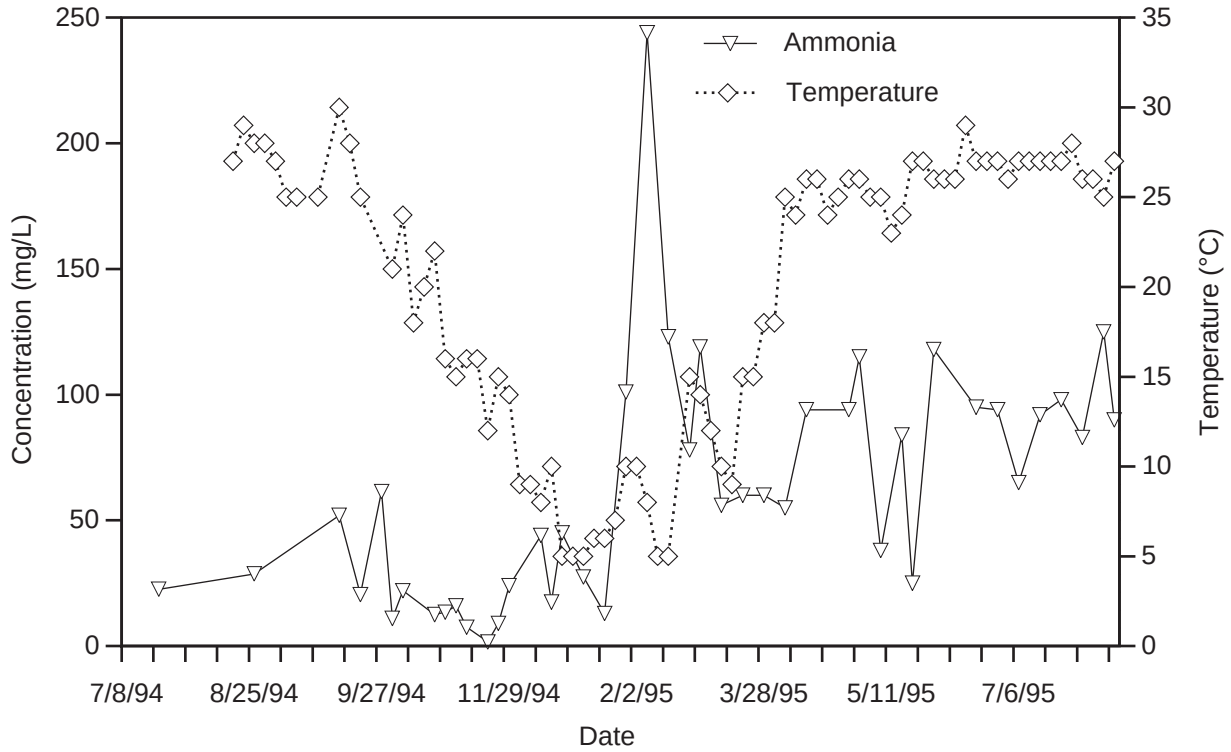


FIGURE 22 Ammonia Concentration in Slurry in the 20% Replacement Reactor

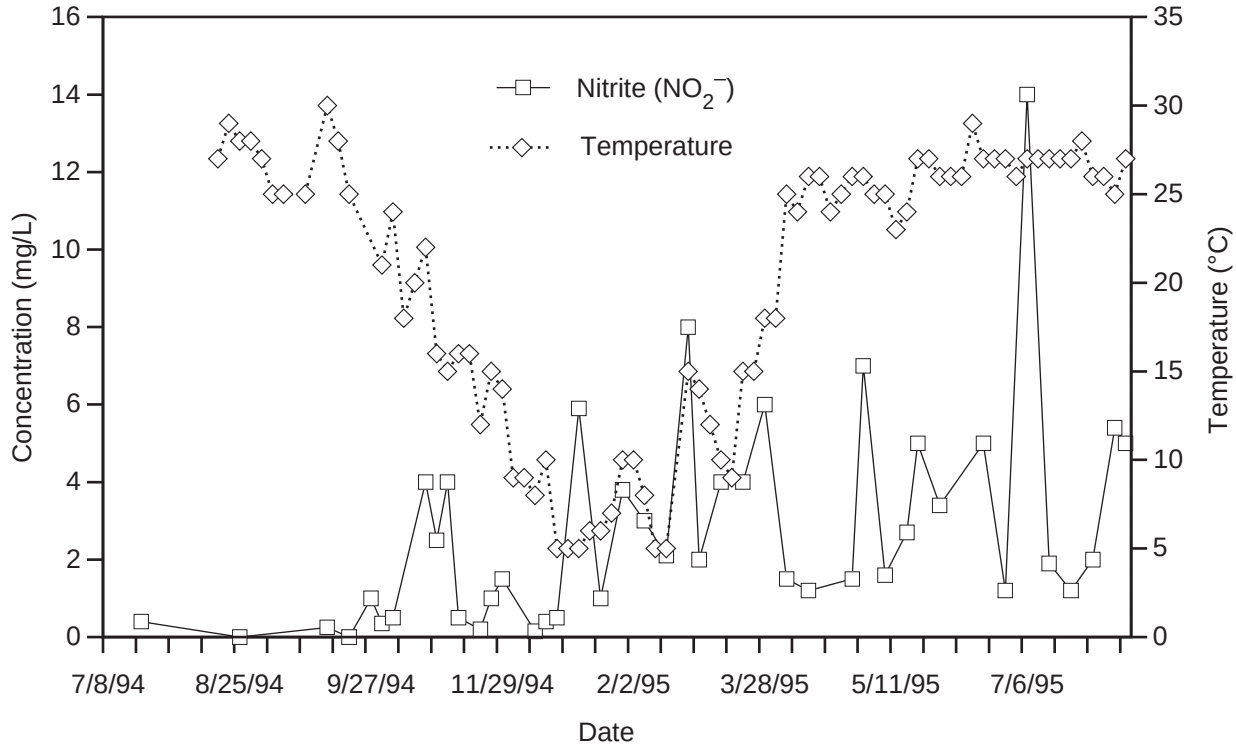


FIGURE 23 Nitrite Concentration in Slurry in the 20% Replacement Reactor

5.3.2.9 Phosphorus Concentration

The concentration of orthophosphate phosphorus in the 20% replacement reactor is shown in Figure 24. Some of the increase in phosphorus concentration was apparently related to decreased temperatures. In particular, the spike in mid February corresponds to a decrease in the temperature in the reactor. The remaining orthophosphate in solution indicates that the microorganisms had sufficient phosphorus for metabolic functions. The phosphorus (both inorganic and organic) was derived from the molasses.

5.3.2.10 Microbial Enumeration

Figure 25 shows that the microbial enumeration results (bacterial counts) obtained from the 20% replacement reactor demonstrated a strong temperature dependence. As the temperature decreased, the microbial numbers decreased from 10^{10} to 10^{7} microorganisms per gram of dry soil. As the temperature increased, the number of microorganisms increased. Figure 25 demonstrates that when the reactors were operating in warm weather and removing TNT efficiently, the microbial counts were very high (10^{9}-10^{10}). When TNT was not being removed, the microbial counts were reduced (10^{7}-10^{8}). This correlation with temperature is not unexpected and is probably the reason for reduced performance in cold weather. The changes in microbial counts in mid February, when a sharp temperature change occurred, probably accounted for the increase in ammonia and phosphorus in the liquid phase (Figures 22 and 24).

5.3.2.11 pH

Appendix C, Table C.2, contains the pH data for the 20% replacement reactor. After March 1995, the pH was controlled to maintain pH levels greater than 6.0. The first number of a pair of numbers in the pH column in Appendix C describes the pH at the beginning of the day. The second number in the column describes the adjusted pH after addition of NaOH. The system tended to have a pH value of 5.5-6.0 after anoxic mixing overnight. The pH was adjusted to a value greater than 6.0 to provide a traditional pH range for the microbial population.

5.3.2.12 Dissolved Oxygen

The DO concentrations presented in Appendix C, Table C.2, for the 20% replacement reactor were less than 0.5 mg/L but were measurable during the biologically active period. These measurements were obtained prior to aeration.

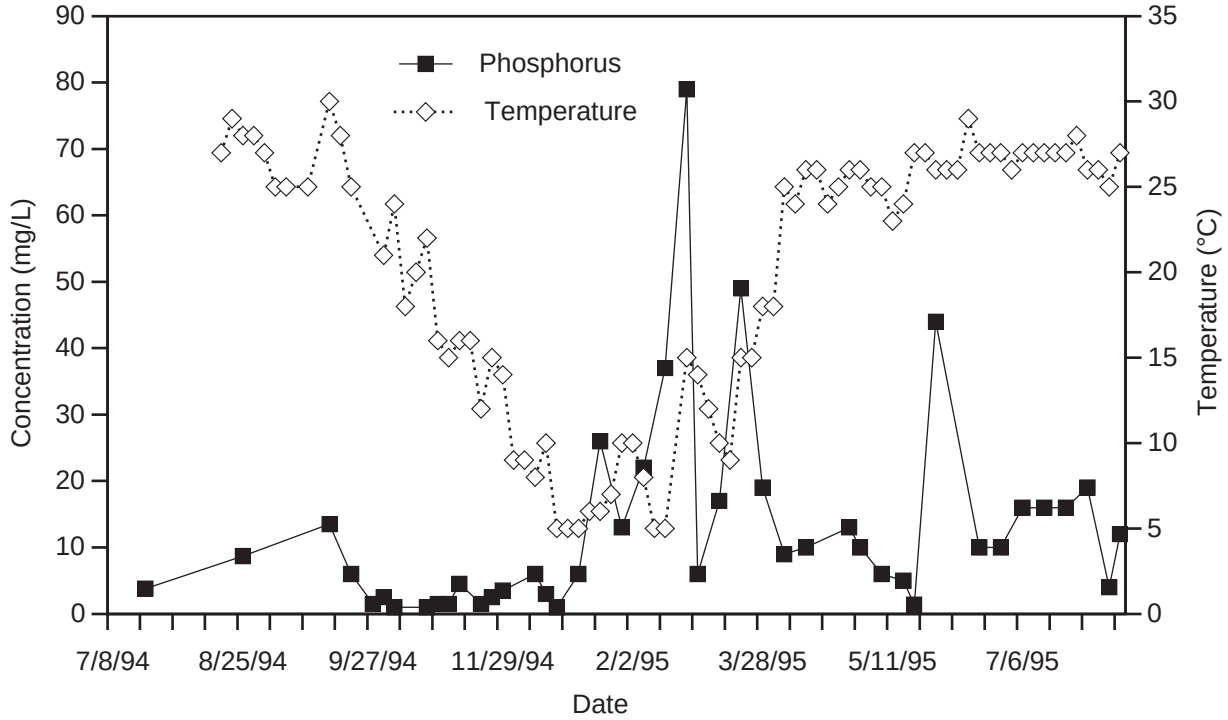


FIGURE 24 Phosphorus Concentration in Slurry in the 20% Replacement Reactor

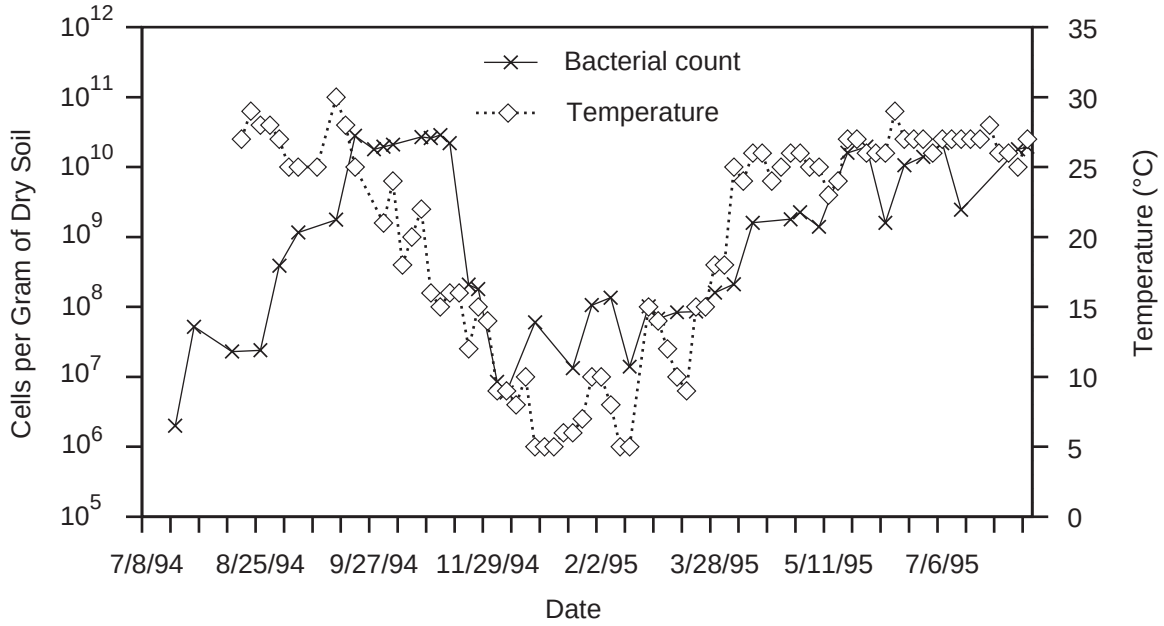


FIGURE 25 Bacterial Count in Solids in the 20% Replacement Reactor

5.3.3 10% Replacement Reactor

The reactor with 10% weekly replacement was operated from July 12, 1994, until August 8, 1994, with the soil slurry mixed and aerated once per day. Molasses (0.5 gal) was added on July 19, 1994. On August 9, 1994, another 0.5 gal of molasses was added to the system. On August 22, 1994, weekly additions of molasses began. Molasses was added once or twice a week at 1-3 gal per week to enhance the degradation of explosives. On September 20, 1994, weekly replacements of 10% of the reactor volume (at 15% W/W) began. Except for December 13, 1994, this weekly replacement continued until December 27, 1994. Replacement was resumed on January 16, 1995. The last replacement occurred on August 6, 1995. The TNT concentration in the soil replacements increased from approximately 2,000 mg/kg in the initial soil to approximately 6,000 mg/kg in the later replacements.

5.3.3.1 Overview

Figures 26 and 27 provide an overview of the data obtained with the 10% replacement reactor. The temperature profile shows that in November, the temperature fell below 20°C. In December, the temperature was below 12°C. In mid January, the heater system in the building became operational, and the temperature of the reactor contents was about 15°C. In February, the temperature of the reactor contents was above 20°C. Figures 26 and 27 contain data for both Tuesdays (before replacement) and Thursdays (two days after replacement). The Tuesday data are relevant for determining removal potential. The Thursday data are relevant for determining process efficiency. As expected, the Tuesday data have lower concentrations of explosives and the intermediates 4A26DNT and 2A46DNT. Thursday data tend to have higher explosives, 4A26DNT, and 2A46DNT concentrations.

5.3.3.2 Adaptation

Figures 28 and 29 show data for the Tuesday (end-of-cycle) samples from the 10% replacement reactor for the adaptation period (Phase II in the *Test Plan* [Manning and Montemagno 1992a]). During adaptation, the first activity was aimed at developing confidence in the operation of the system. The second activity, the adaptation of the microorganisms to degrade TNT, occurred almost immediately upon the addition of molasses to the system. With the aggressive addition of molasses in late August 1994, the TNT concentration immediately began to decrease, and the 4A26DNT concentration began to increase, indicating conversion of the TNT. As additional molasses was added to the system, the 4A26DNT concentrations were reduced. At the end of this adaptation period, TNT concentrations were below 20 mg/kg, and 4A26DNT concentrations were below 50 mg/kg. Replacement soil added through November of 1995 had

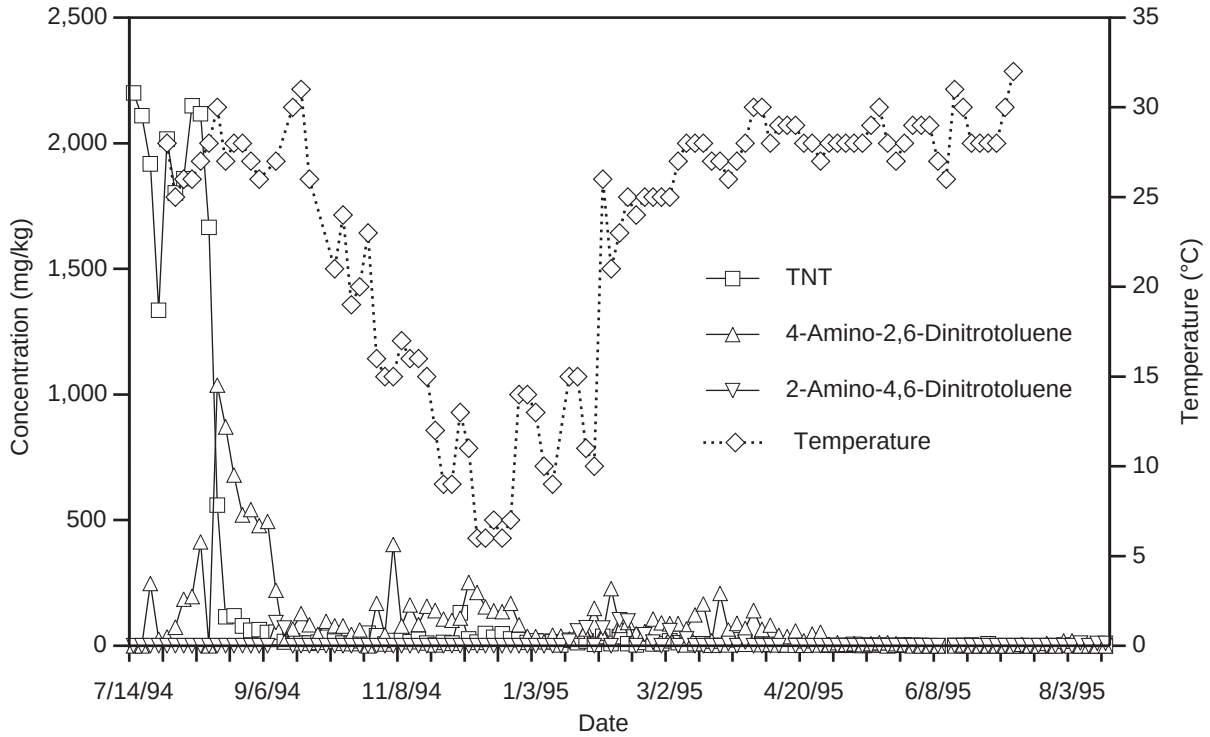


FIGURE 26 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 10% Replacement Reactor

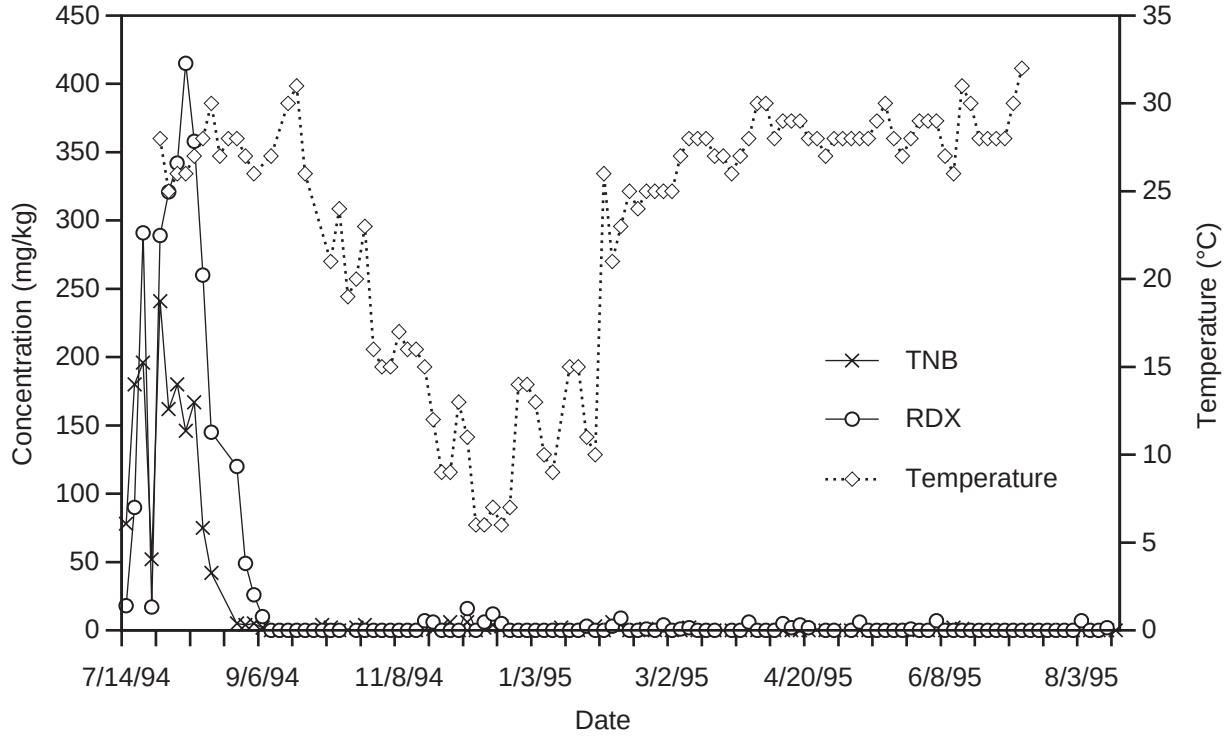


FIGURE 27 Explosives Concentrations in Soil in the 10% Replacement Reactor

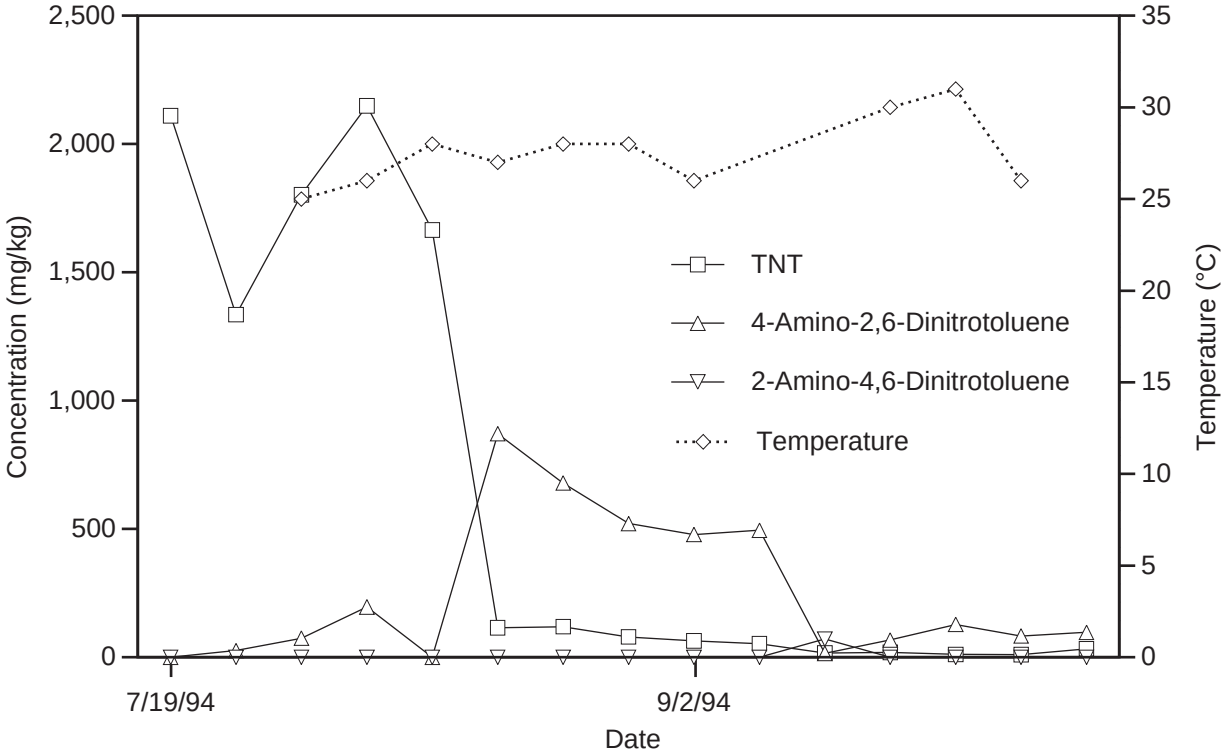


FIGURE 28 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 10% Replacement Reactor during Adaptation

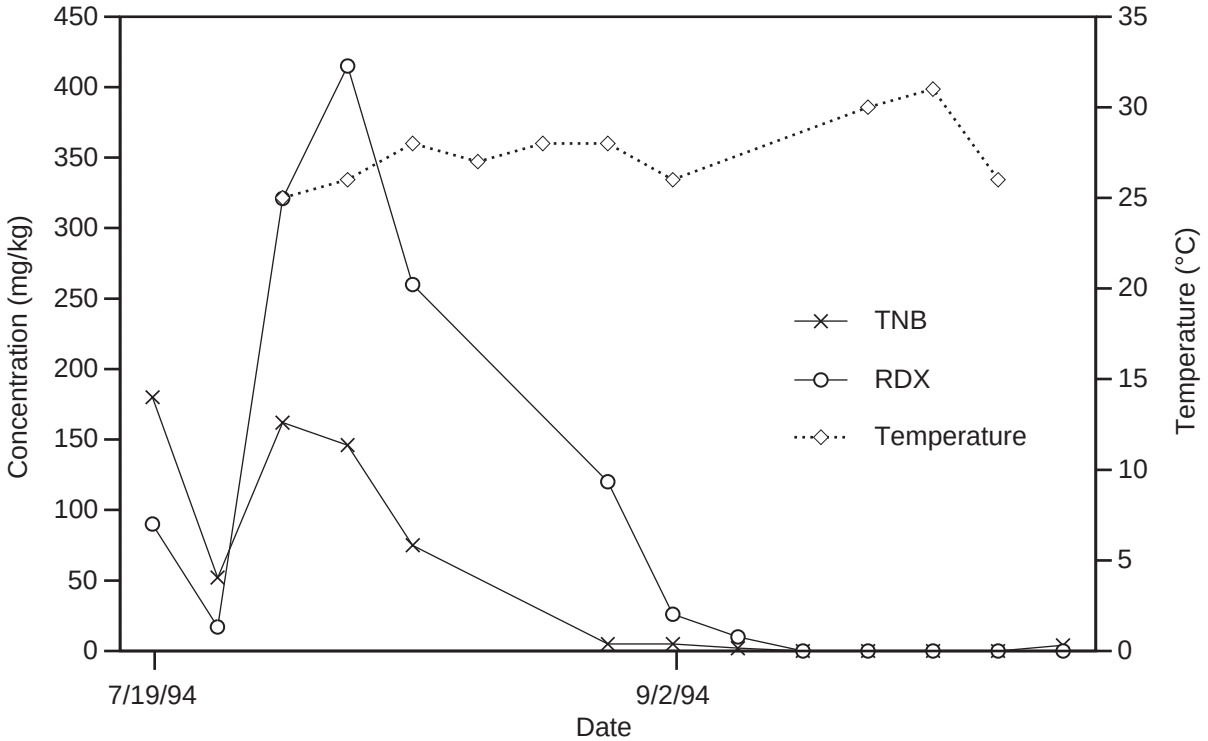


FIGURE 29 Explosives Concentrations in Soil in the 10% Replacement Reactor during Adaptation

TNT concentrations of less than 30 mg/kg and 4A26DNT concentrations below 150 mg/kg. This is significant, because the temperature dropped to 14-18°C during this period. In December, as the temperature fell below 15°C, the TNT concentration was less than 50 mg/kg, and the 4A26DNT concentration was less than 200 mg/kg.

The TNB concentrations (Figure 29) remained below 5 mg/kg after replacements began, regardless of the temperature. The RDX concentrations were less than 20 mg/kg after replacements began, regardless of the temperature.

5.3.3.3 Cold-Weather Operation

Figures 30 and 31 cover the period of operation from January 1995 through mid April 1995. As the figures show, the 10% replacement reactor continued to have many of the characteristics observed during adaptation. As the temperature increased in mid February, the TNT concentration fell below 20 mg/kg, and the 4A26DNT concentration remained below 100 mg/kg (Figure 30). As the system readapted to temperatures above 25°C, the TNT concentration stayed below 10 mg/kg, and the 4A26DNT concentration was generally less than 75 mg/kg. The cold water used to make the replacement slurry could have affected the microbial activity. The removal of TNB and RDX (Figure 31) continued during the cold weather. The soil contained less than 5 mg/kg of TNB or RDX.

The fact that biodegradation of explosives and intermediates continued during cold weather shows that the system did not fail or cease to function, although it operated at a lower rate of microbial activity.

5.3.3.4 Warm-Weather Operation

Figures 32 and 33 summarize the operation of the 10% replacement reactor in warm weather. During this period, TNT and 4A26DNT concentrations were below 20 mg/kg, and the concentrations of RDX and TNB were below 5 mg/kg. In addition, the Thursday data during this period show TNT concentrations of less than 15 mg/kg and 4A26DNT concentrations of less than 20 mg/kg. These results indicate that at this mass loading and during warm weather (> 27°C), the bioslurry process was operating at a very high rate of metabolism. No negative effect on performance was observed at temperatures of 29-32°C.

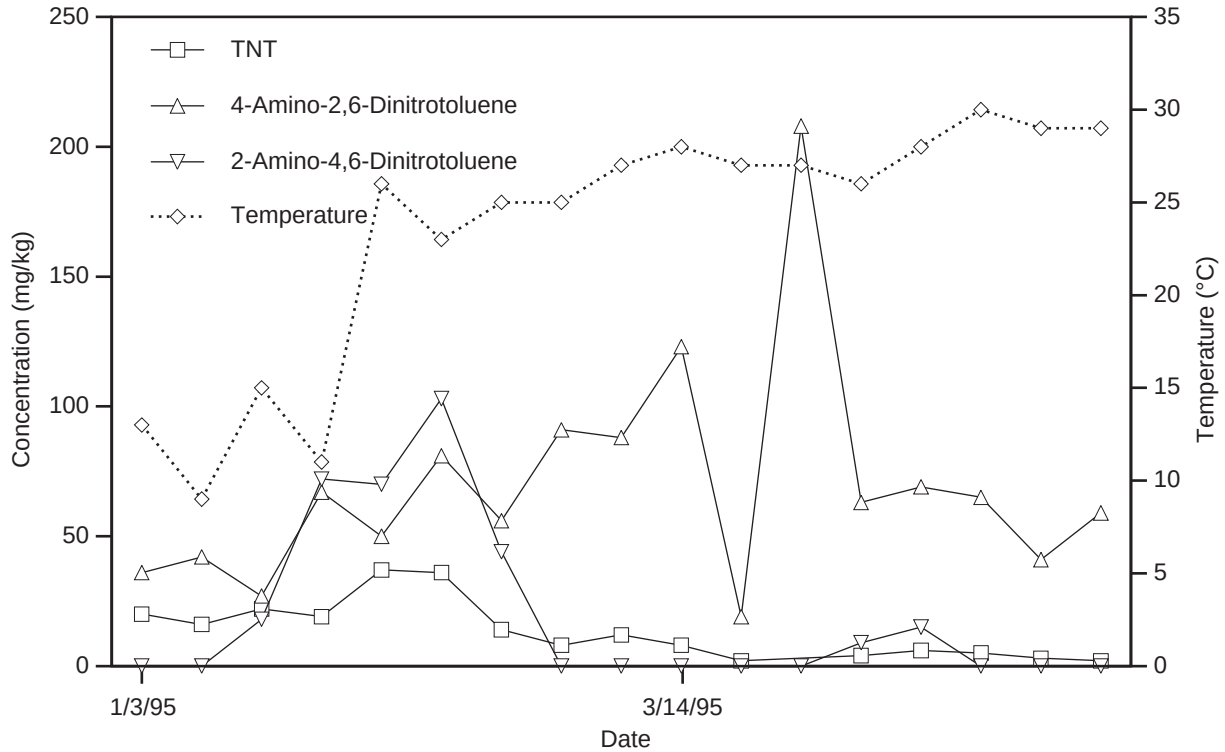


FIGURE 30 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 10% Replacement Reactor during Cold Weather

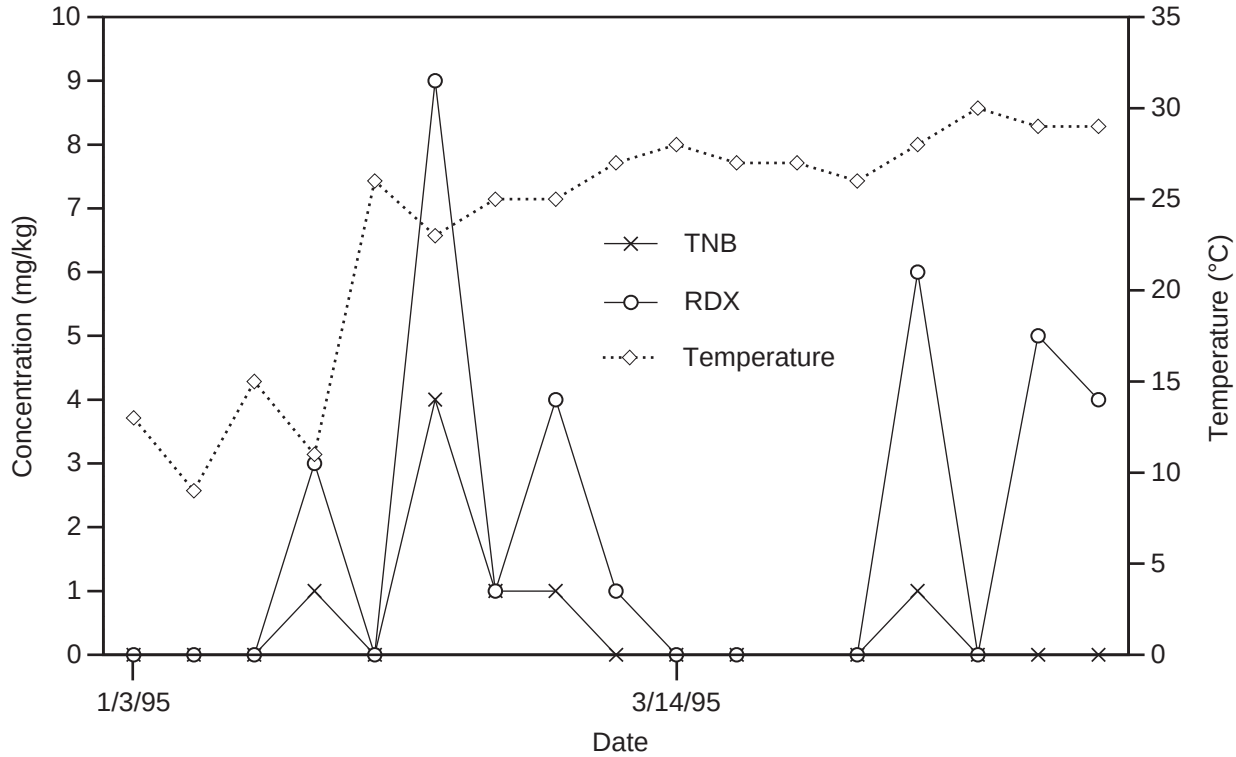


FIGURE 31 Explosives Concentrations in Soil in the 10% Replacement Reactor during Cold Weather

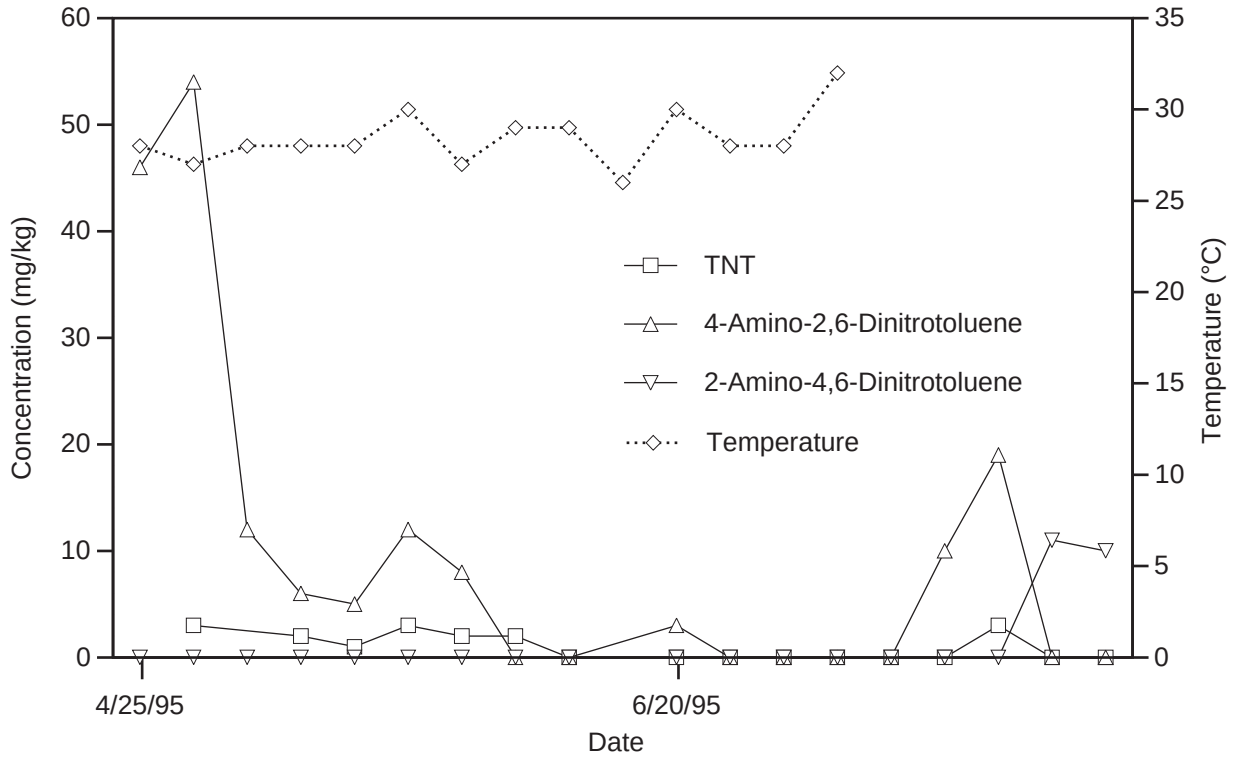


FIGURE 32 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 10% Replacement Reactor during Warm Weather

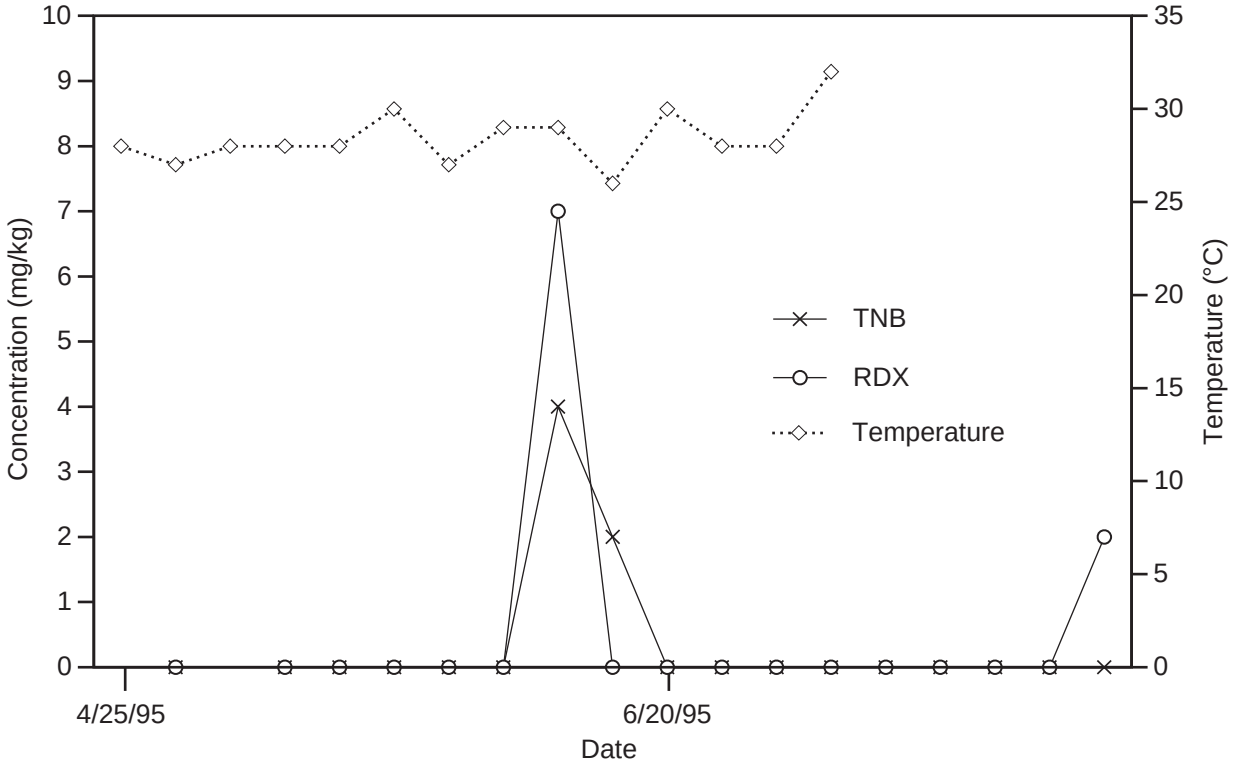


FIGURE 33 Explosives Concentrations in Soil in the 10% Replacement Reactor during Warm Weather

5.3.3.5 Liquid Concentrations

Figure 34 shows that the concentrations of TNT, TNB, and RDX in the water separated from the solid particles in the slurry in the 10% replacement reactor followed the observed concentrations in the soil slurry. This result was expected, because the concentration in the liquid phase of the slurry is determined by the solid-phase concentration on the basis of thermodynamics. Although the liquid concentrations were only about 1 mg/L, this level would violate some discharge standards, possibly making activated-carbon polishing necessary.

5.3.3.6 Solids Concentration

The total solids level in the 10% replacement reactor is shown in Figure 35. The results demonstrate that the slurry was closer to a 10-12% slurry than a 15% slurry, although at times the slurry was 13-14%. The solids concentration was not affected by temperature.

5.3.3.7 Ammonia Concentration

Figure 36 shows the ammonia concentration in the slurry phase of the 10% replacement reactor. During the field demonstration, the ammonia level increased as more molasses was added to the system during adaptation. After replacements began, the ammonia concentration decreased. During cold weather in December and January, the ammonia concentration increased. This trend closely followed the decrease in temperature to about 10°C. After the system returned to temperatures above 25°C, the ammonia concentration was relatively constant.

5.3.3.8 Nitrite Concentration

Figure 37 shows that the nitrite concentration profile in the 10% replacement reactor during the field demonstration was not strongly influenced by temperature. The nitrite fluctuations probably reflect process fluctuations. The increase in nitrite during warm-weather operation was probably due to the increase in molasses additions.

5.3.3.9 Phosphorus Concentration

The phosphorus concentration profile (Figure 38) for the 10% replacement reactor shows some influence of temperature in the peak concentrations occurring when the temperature was less than 15°C. In addition, small peaks accompanied temperature drops at other times. The general

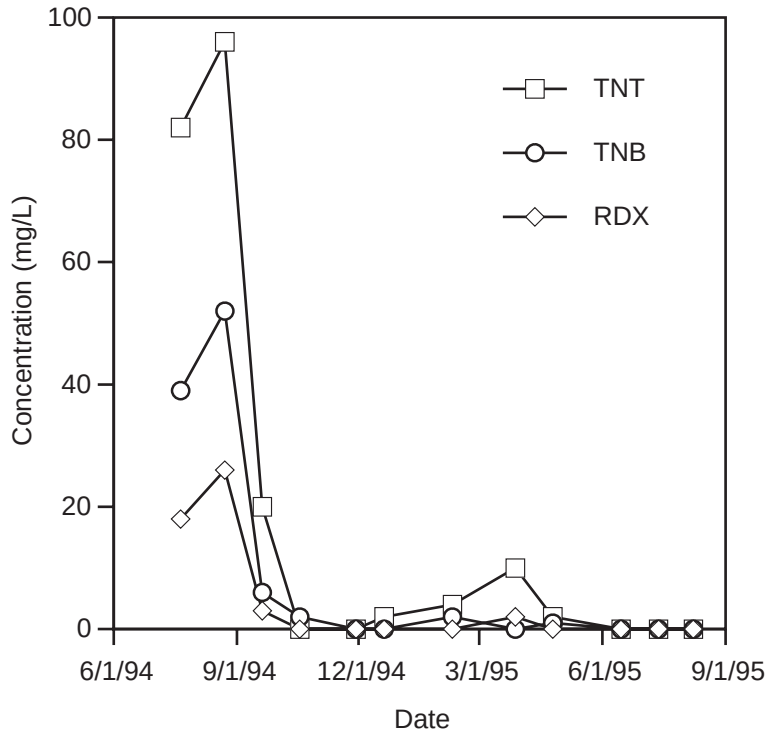


FIGURE 34 Explosives Concentrations in Liquid in the 10% Replacement Reactor

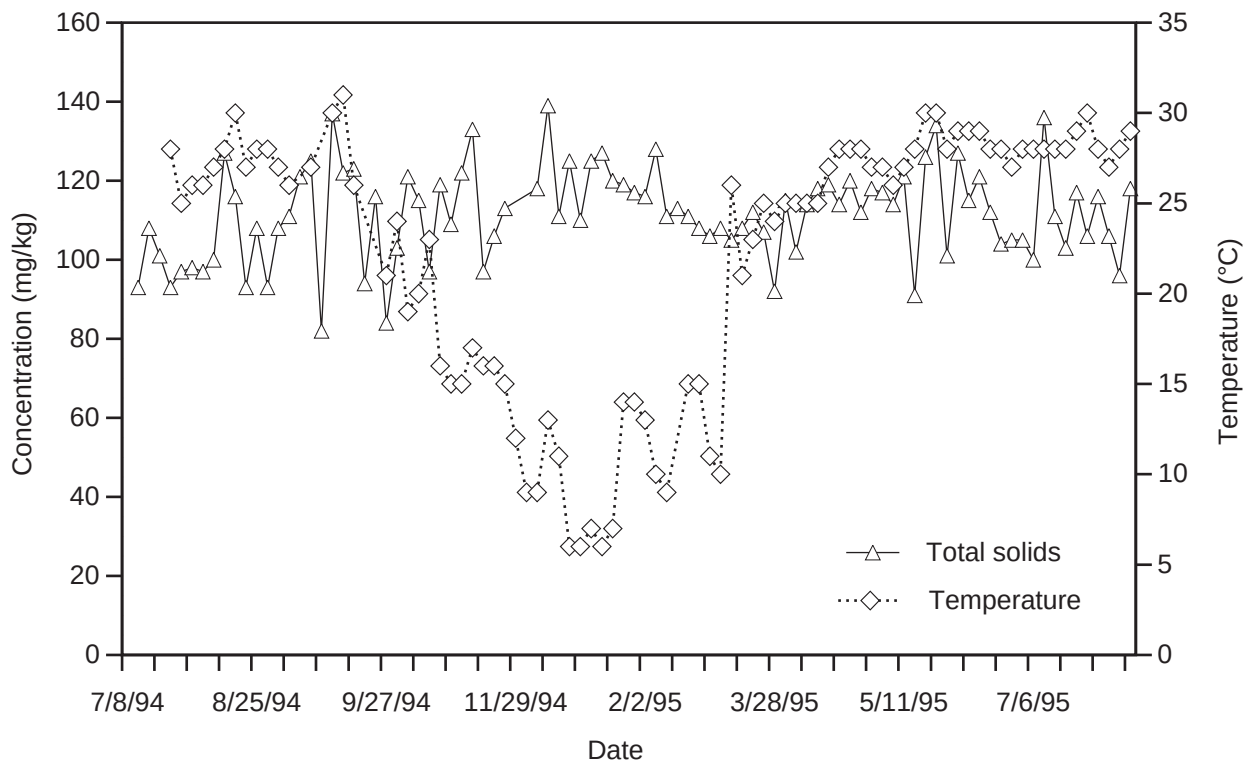


FIGURE 35 Solids Concentration in the 10% Replacement Reactor

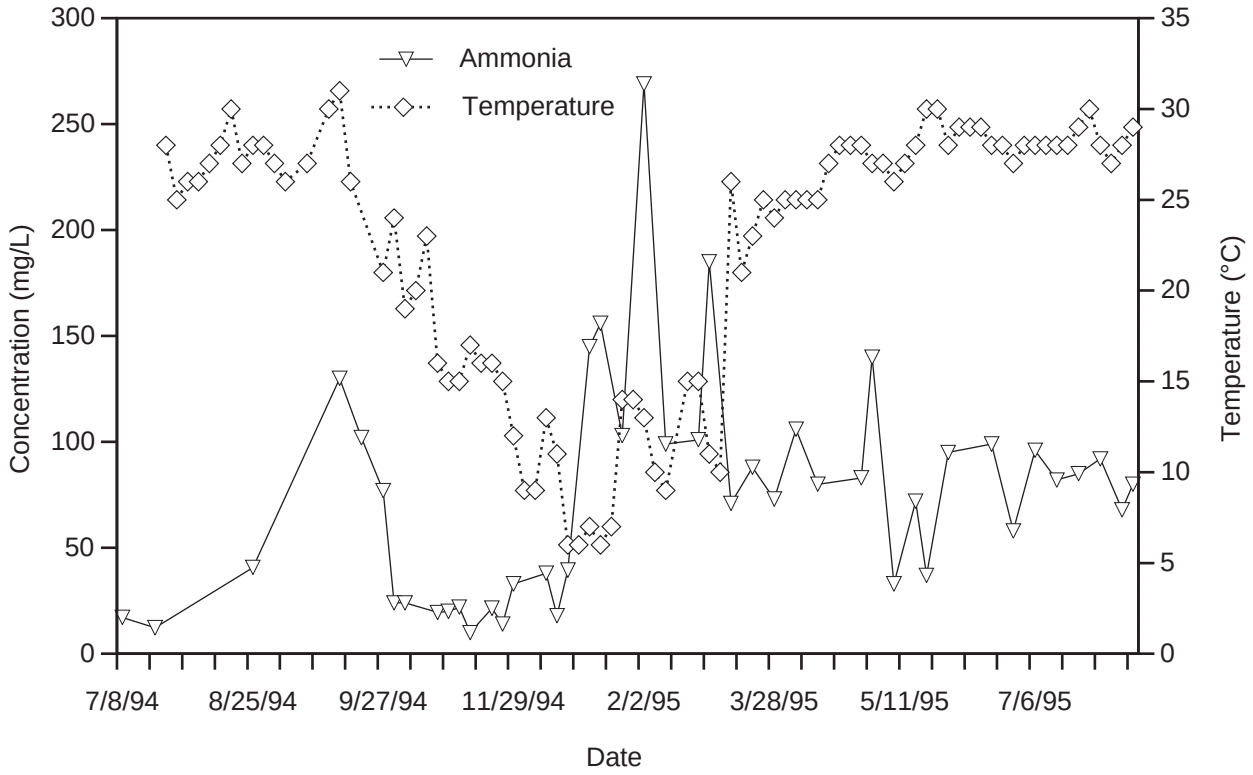


FIGURE 36 Ammonia Concentration in Slurry in the 10% Replacement Reactor

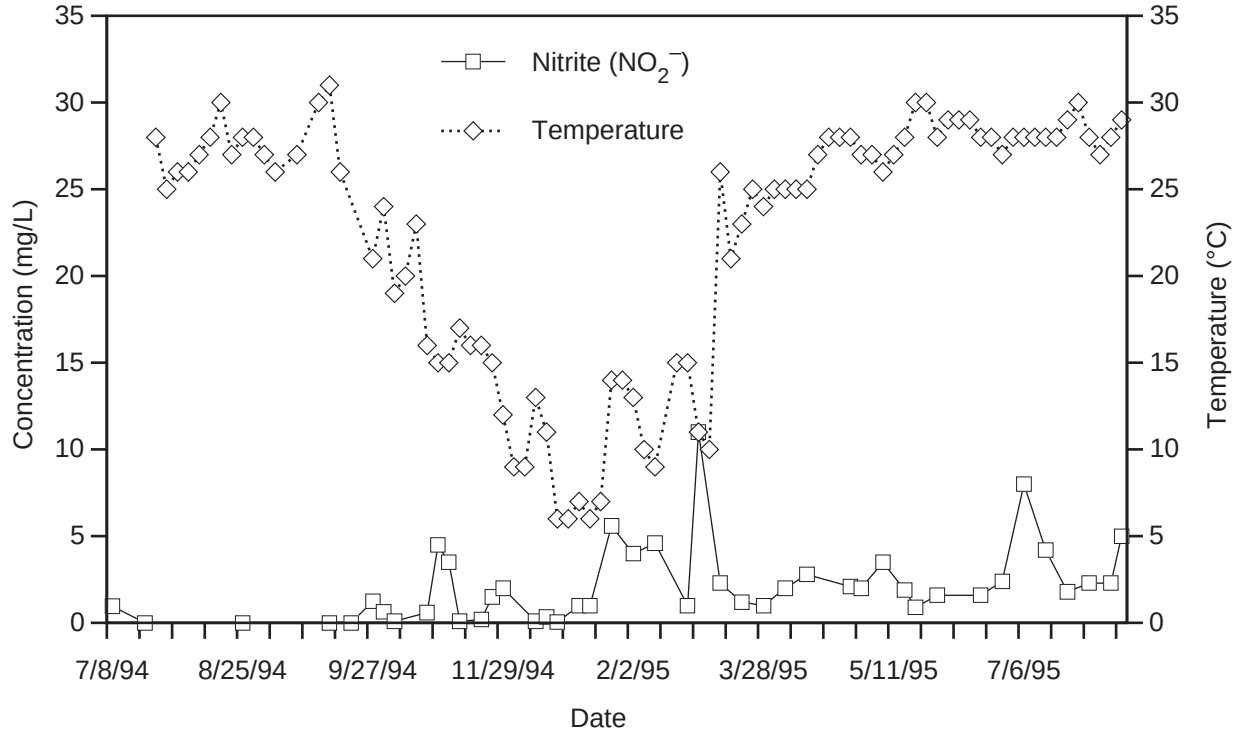


FIGURE 37 Nitrite Concentration in Slurry in the 10% Replacement Reactor

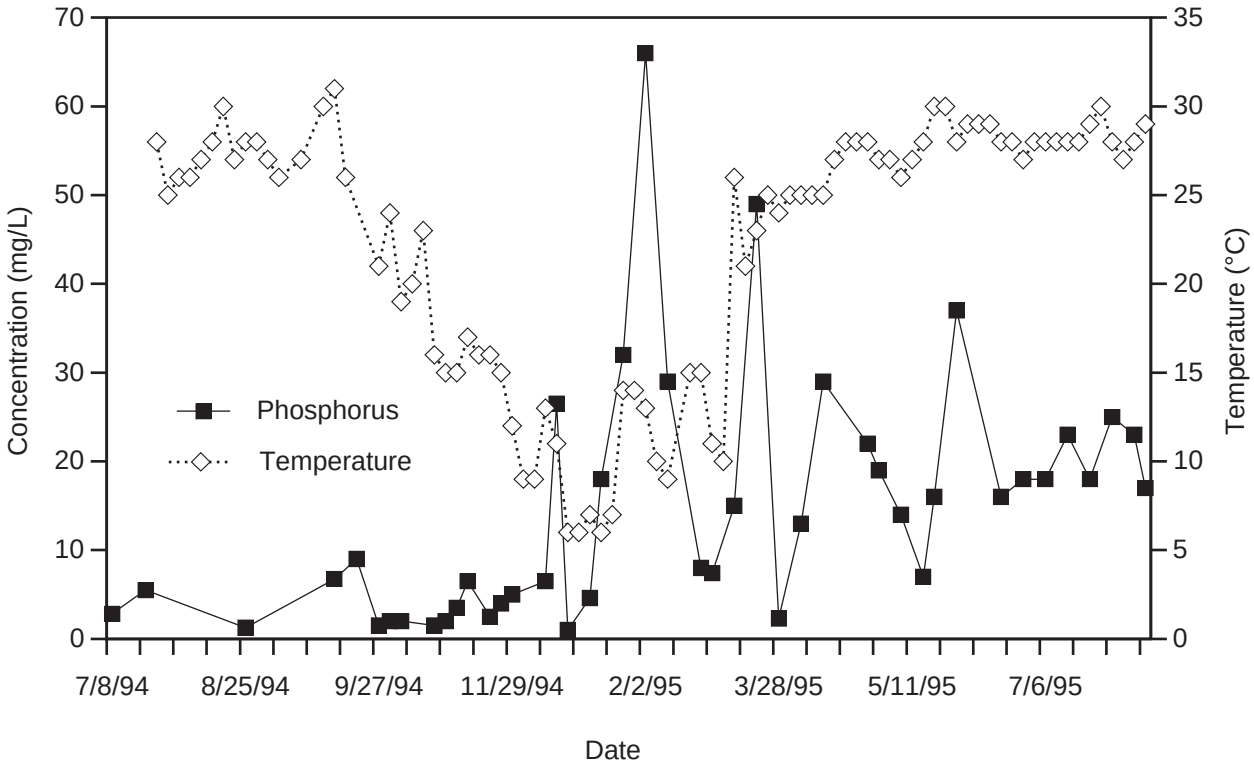


FIGURE 38 Phosphorus Concentration in Slurry in the 10% Replacement Reactor

overall increase in phosphorus during warm weather was probably due to the increase in molasses additions to the system.

5.3.3.10 Microbial Enumeration

Figure 39 shows that the microbial enumeration results (bacterial counts) obtained from the 10% replacement reactor were strongly influenced by the December-January temperature decrease. The microbial numbers decreased from 10^{10} to 10^{8} microorganisms per gram of dry soil. The microbial numbers, in general, never recovered to their previous level after the temperature rose above 25°C.

5.3.3.11 pH

Appendix C, Table C.3, contains the pH data for the 10% replacement reactor. The pH of the system varied in the range 5.5-6.0 in December 1994-March 1995. After March 1995, the pH was controlled to maintain a minimum value of 6.0.

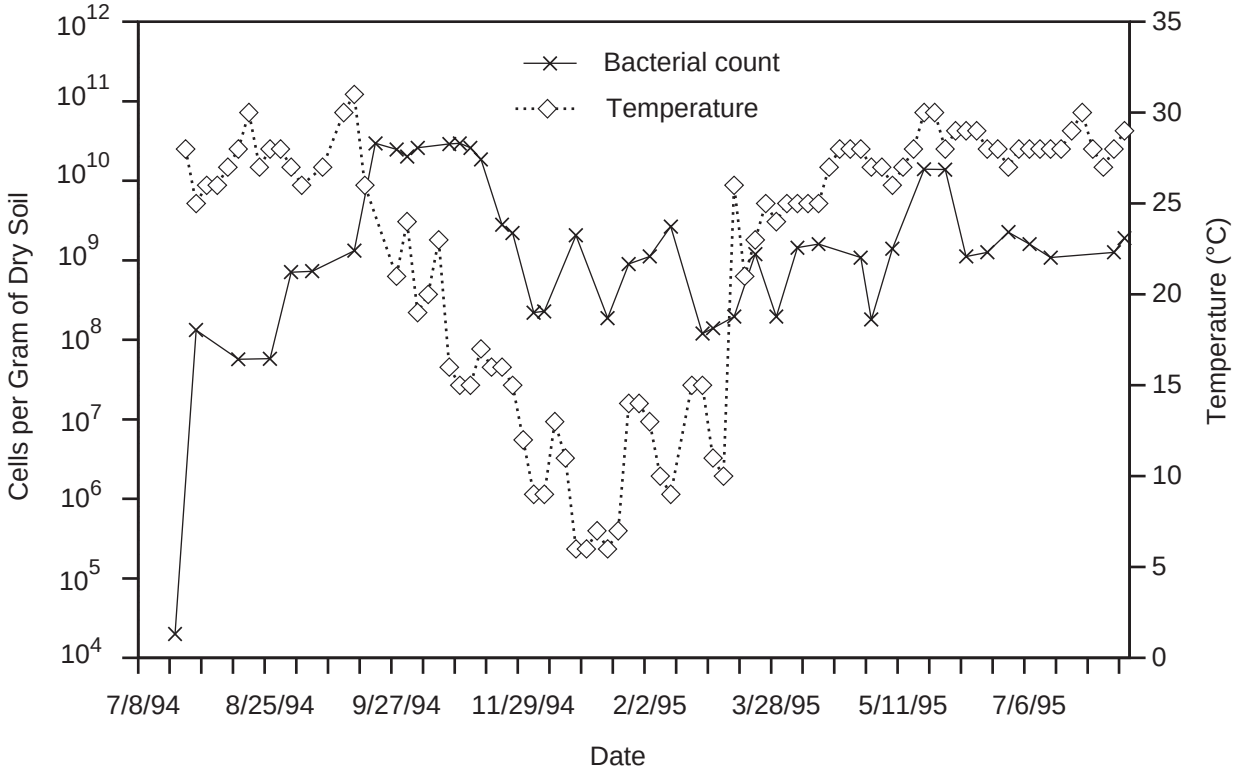


FIGURE 39 Bacterial Count in Solids in the 10% Replacement Reactor

5.3.3.12 Dissolved Oxygen

Appendix C, Table C.3, contains the DO data. The DO levels measured in the 10% replacement reactor before aeration were less than 0.5 mg/L during the biologically active period. The DO levels decreased soon after molasses was added to the system.

5.3.4 5% Daily Replacement Reactor

The 5% daily (four-day work week) replacement reactor was operated from July 10, 1994, until August 9, 1994, with the soil slurry mixed and aerated once daily. Molasses (0.5 gal) was added to the system on July 19, 1994. On August 9, 1994, another 0.5 gal of molasses was added. On August 22, 1994, weekly addition of molasses began. On September 19, 1994, the replacement strategy was initiated. This replacement strategy was designed to mimic the operation of the 20% weekly replacement reactor in terms of mass loading. The smaller replacement volumes in the 5% replacement reactor were designed to determine whether smaller daily loadings would provide any microbial advantage. The replacements continued until December 26, 1994, then resumed on January 16, 1995, and continued until August 3, 1995.

5.3.4.1 Overview

Figures 40 and 41 provide an overview of the data obtained for the 5% replacement reactor. The temperature profile shows that in November, the temperature fell below 20°C. In December, the temperature dropped to less than 12°C. In mid January, the heater system became operational in the building, and the temperature of the reactor contents rose above 15°C. In February, the reactor contents reached temperatures above 20°C. Figures 40 and 41 contain data for both Tuesdays and Thursdays. For this reactor, the Thursday data are most meaningful, because replacement occurred on four consecutive days. The data show acceptable removal of TNT (to less than 20 mg/kg) and 4A26DNT concentrations below 100 mg/kg during adaptation (Figure 40), although the TNT level varied significantly. Removal of TNT was diminished most during December and January. The TNT concentrations increased to around 1,000 mg/kg in early December; when replacement stopped in late December and early January, the TNT concentration fell again, indicating that microbial activity was maintained but that the rate of TNT conversion to intermediates decreased. The 4A26DNT concentration continued to be affected by temperatures below 25°C. In March and April, when TNT concentrations were below 20 mg/kg, 4A26DNT concentrations were still highly variable at 250-1,000 mg/kg.

The removal of TNB and RDX was very consistent in this reactor at all temperatures. Both compounds were removed to levels below 5 mg/kg (Figure 41).

5.3.4.2 Adaptation

Figures 42 and 43 show the Tuesday data for samples collected from the 5% replacement reactor during adaptation (Phase II). During adaptation, molasses was added weekly after August 22, 1994. After this weekly addition began, TNT concentrations quickly fell below 20 mg/kg (Figure 42). As the temperature decreased during October, November, and December from 30°C to 10°C, the TNT concentration increased, as did the 4A26DNT concentration. During December, TNT concentrations were 200-900 mg/kg, and 4A26DNT concentrations were 250-900 mg/kg. Only small differences were observed between Tuesday and Thursday samples.

Concentrations of TNB and RDX were below 20 mg/kg after replacement began. No effect of temperature on removal of TNB and RDX was observed (Figure 43).

5.3.4.3 Cold-Weather Operation

Figures 44 and 45 describe the operation of the 5% replacement reactor in January-April 1995. As Figure 44 shows, TNT concentrations were below 40 mg/kg, with most results below

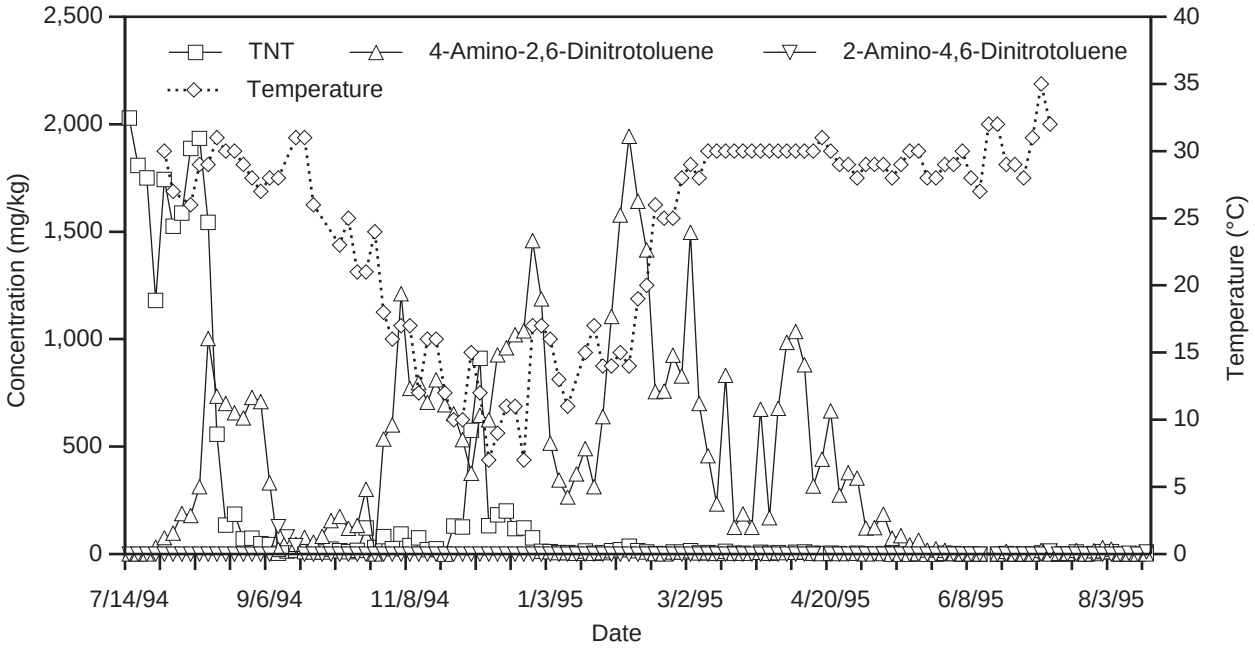


FIGURE 40 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 5% Replacement Reactor

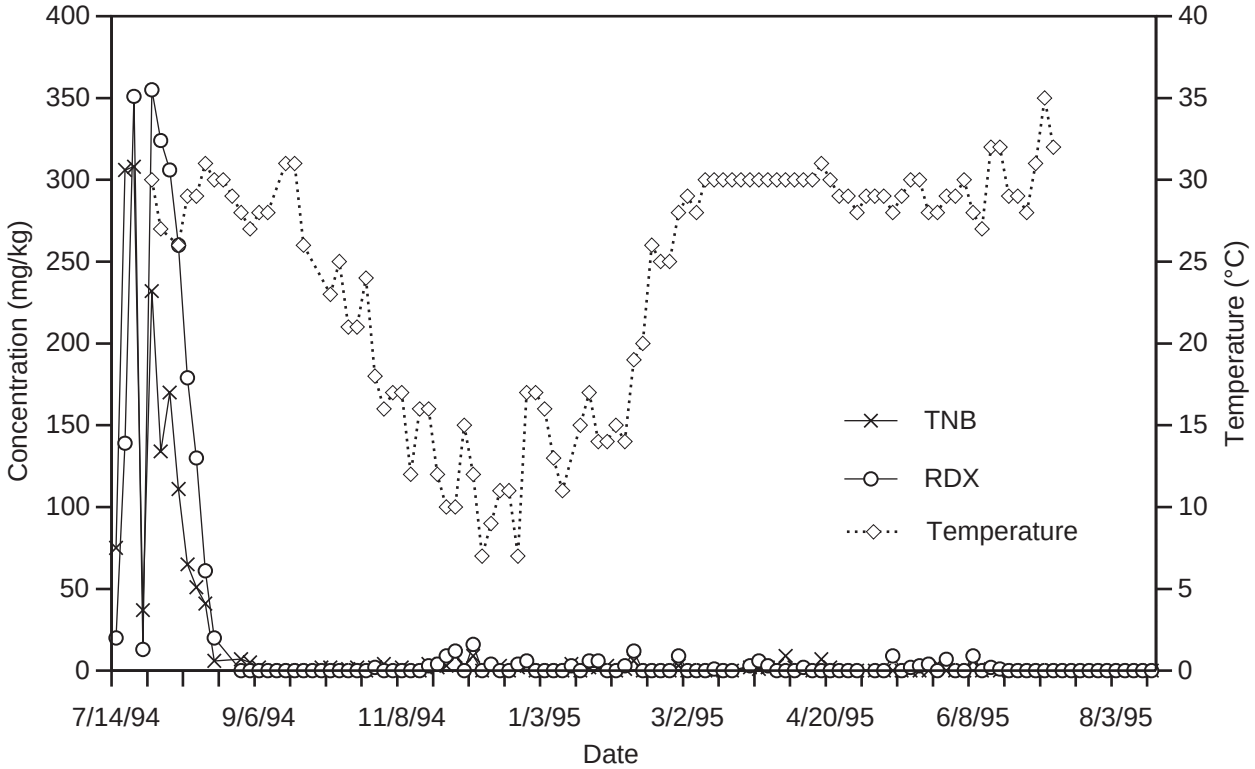


FIGURE 41 Explosives Concentrations in Soil in the 5% Replacement Reactor

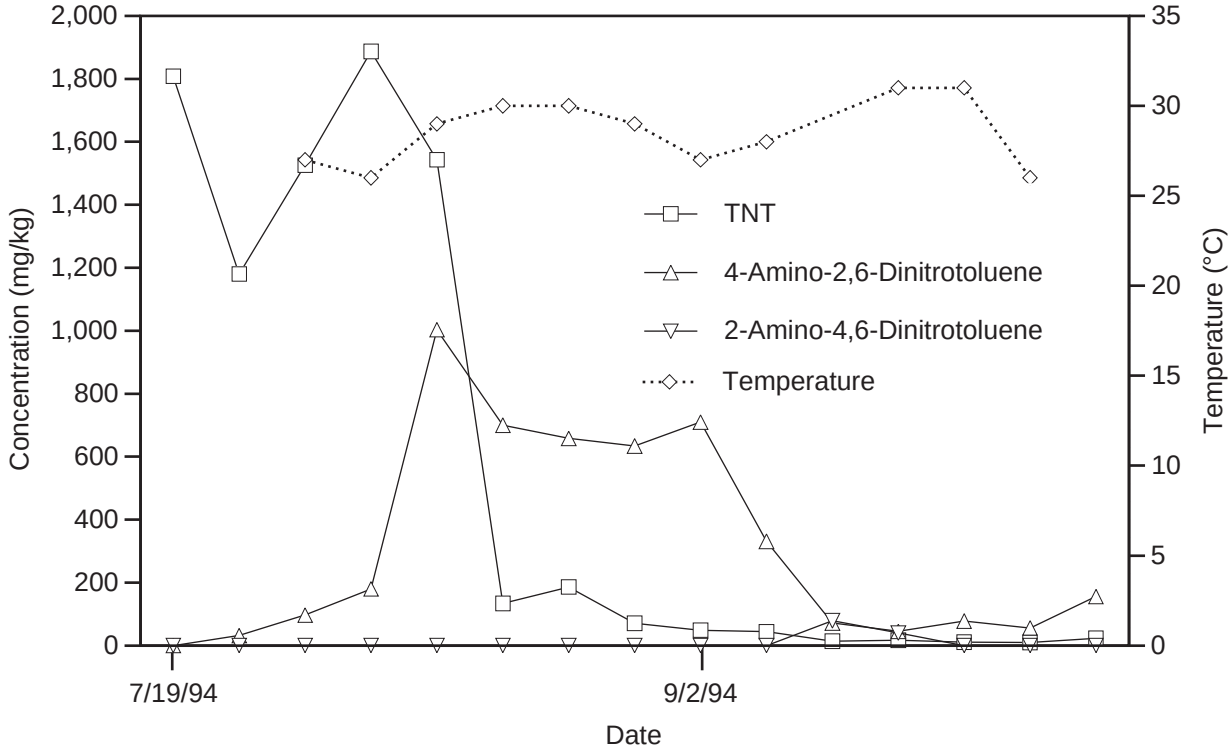


FIGURE 42 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 5% Replacement Reactor during Adaptation

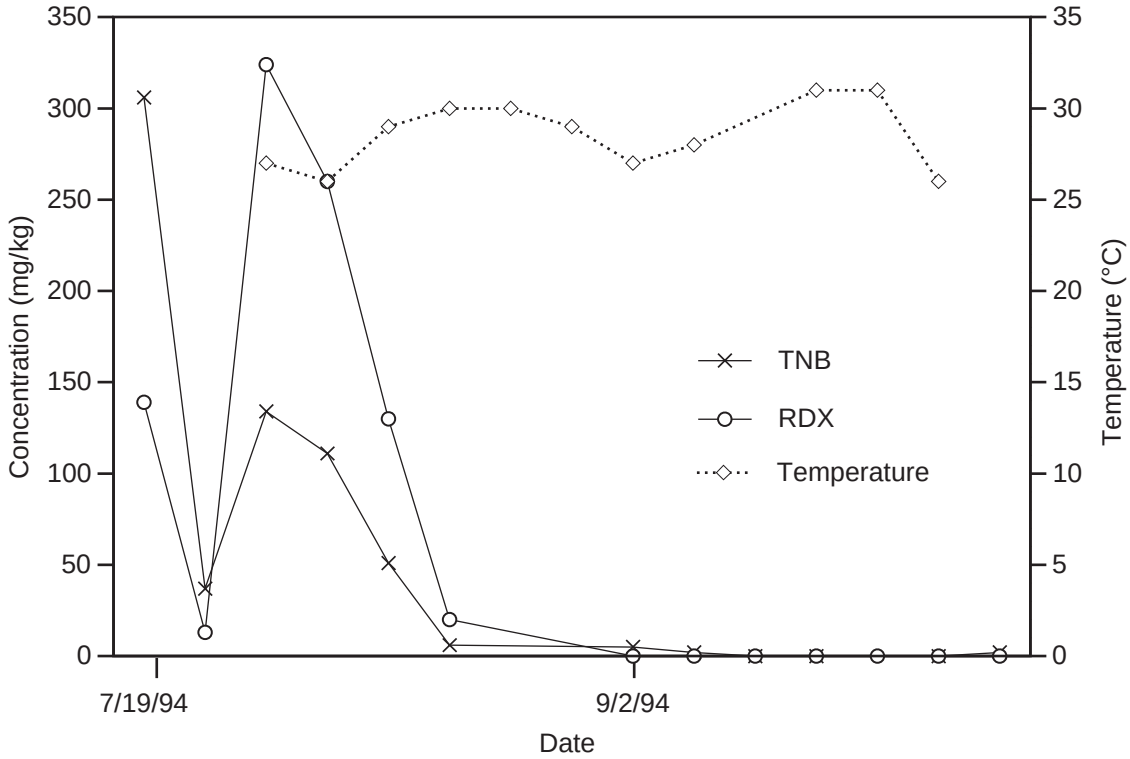


FIGURE 43 Explosives Concentrations in Soil in the 5% Replacement Reactor during Adaptation

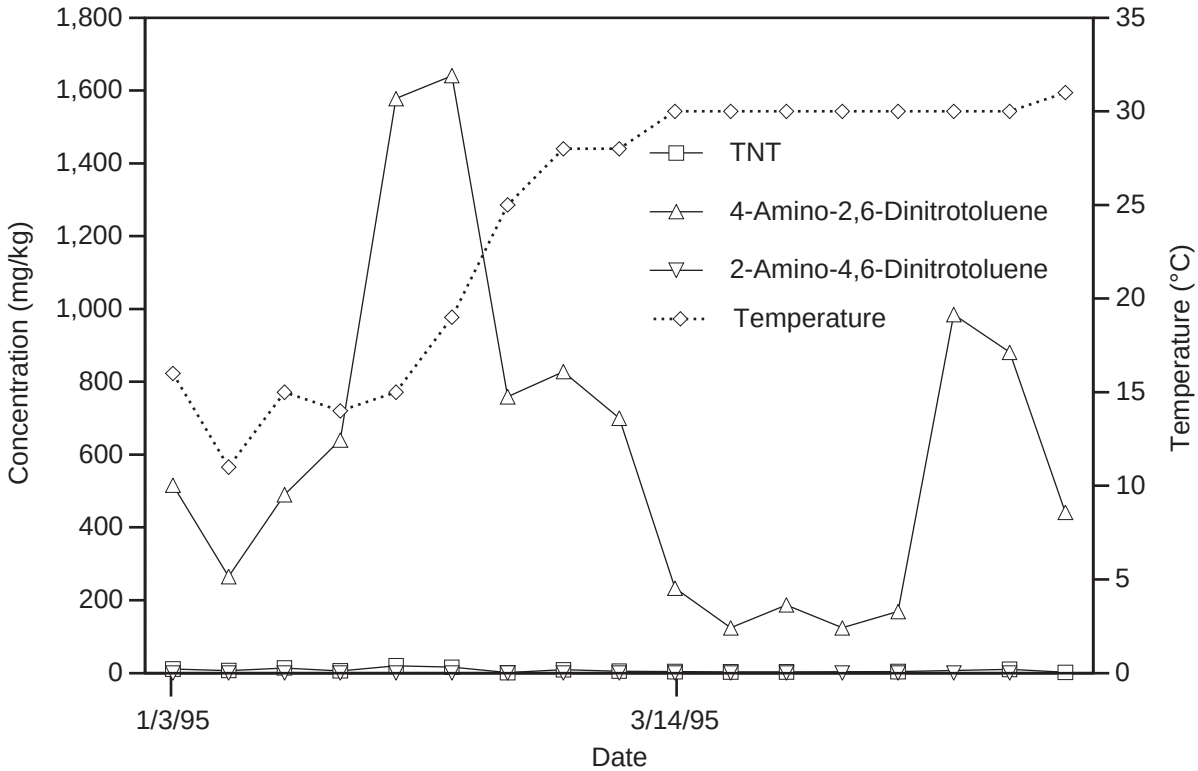


FIGURE 44 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 5% Replacement Reactor during Cold Weather

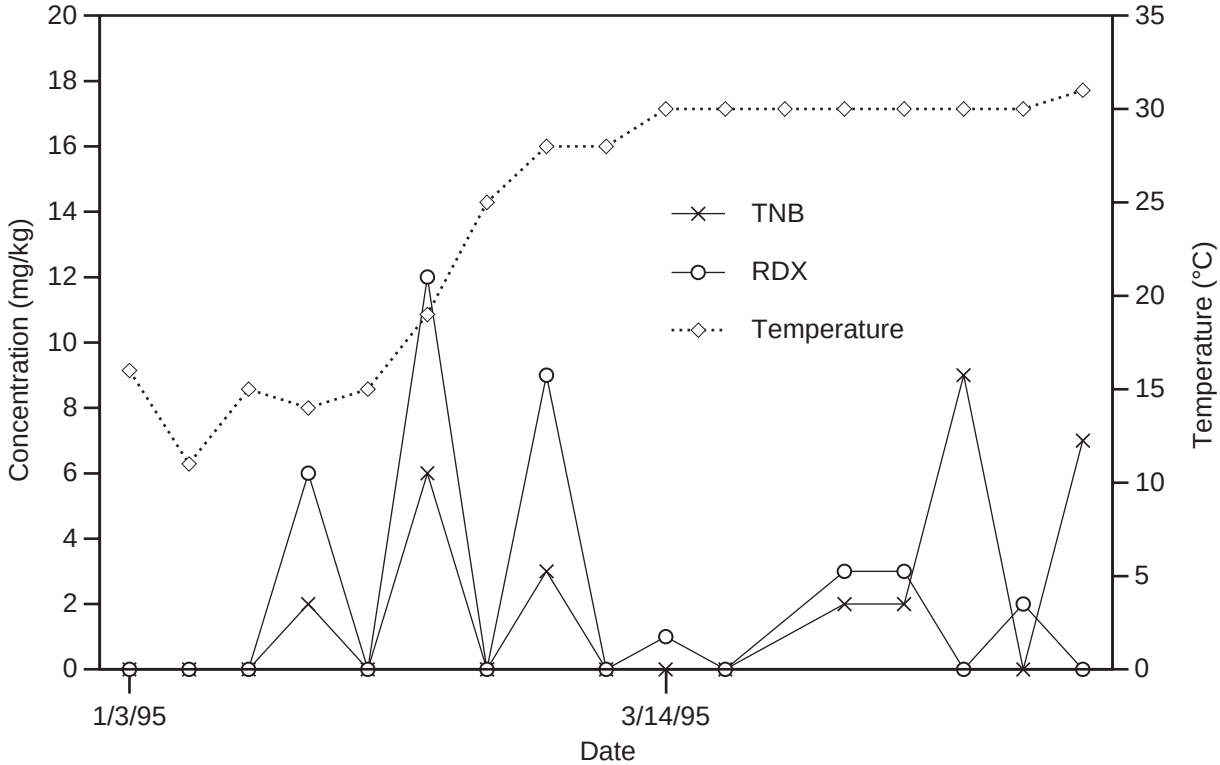


FIGURE 45 Explosives Concentrations in Soil in the 5% Replacement Reactor during Cold Weather

20 mg/kg. The TNT concentration did not appear to be affected by temperature. The 4A26DNT concentration was below 2,000 mg/kg. When the temperature of the slurry increased, the concentration of 2A46DNT remained at 100-1,000 mg/kg.

Figure 45 shows that TNB and RDX were removed in this system to concentrations below 10 mg/kg.

5.3.4.4 Warm-Weather Operation

Figure 46 shows the soil concentrations of TNT, 4A26DNT, and 2A46DNT in the 5% replacement reactor during warm-weather operation. After April 20, 1995, the TNT concentration was below 10 mg/kg. The 4A26DNT concentration remained at about 500 mg/kg. The 4A26DNT concentration continued to decrease. In mid May, the 4A26DNT concentration was below 10 mg/kg. This reactor was capable of effectively removing TNT and the 4A26DNT intermediate to concentrations of less than 10 mg/kg.

Figure 47 summarizes TNB and RDX levels during warm-weather operation. During this period, both TNB and RDX were removed to levels below 10 mg/kg.

5.3.4.5 Liquid Concentrations

Figure 48 shows that the concentrations of TNT, TNB, and RDX in the water separated from the solid particles in the slurry of the 5% replacement reactor followed the concentrations in soil. As the soil concentrations decreased, the concentrations in water decreased. These concentrations in water are above water discharge standards, making polishing with granular activated carbon necessary.

5.3.4.6 Solids Concentration

The total solids level in the 5% replacement reactor is shown in Figure 49. The results indicate that after January 1995, the reactor was operated at a slurry concentration of 12-16%. At the beginning of the operation, the slurry concentration was approximately 10-12%. Adjustments were made to increase the slurry concentration to 12-16%.

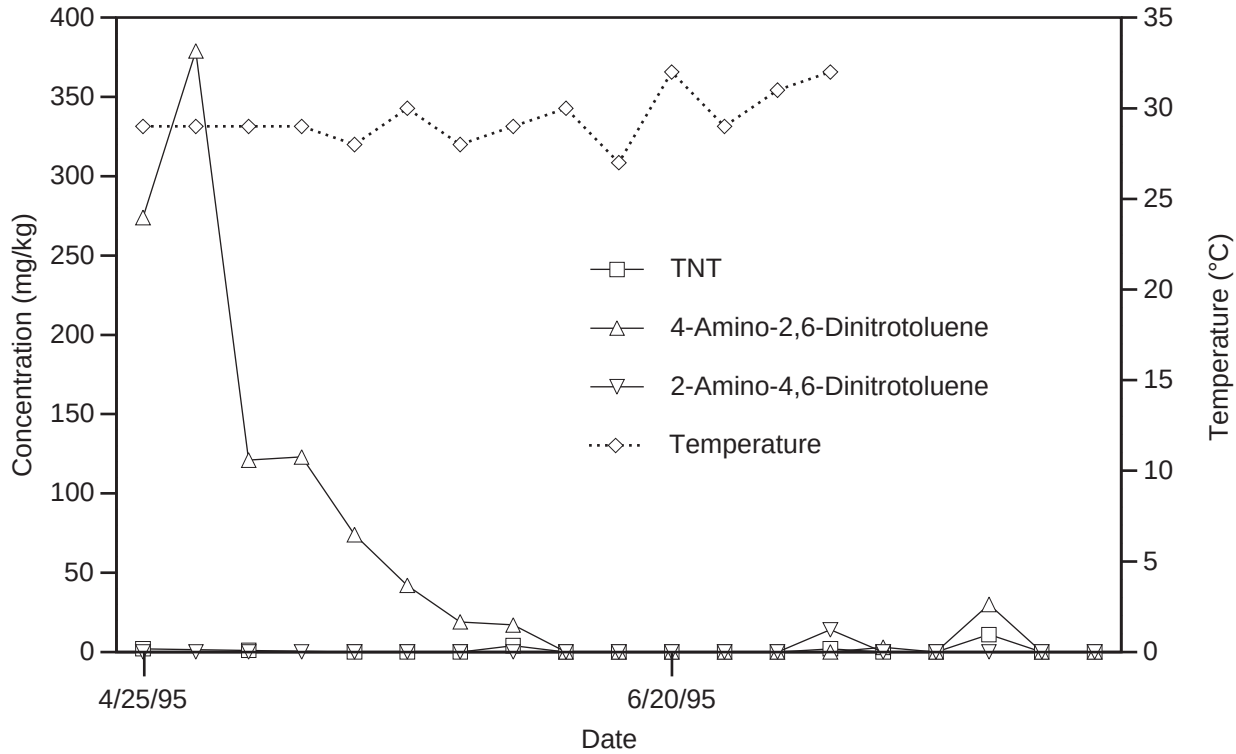


FIGURE 46 Concentrations of TNT and Aminodinitrotoluenes in Soil in the 5% Replacement Reactor during Warm Weather

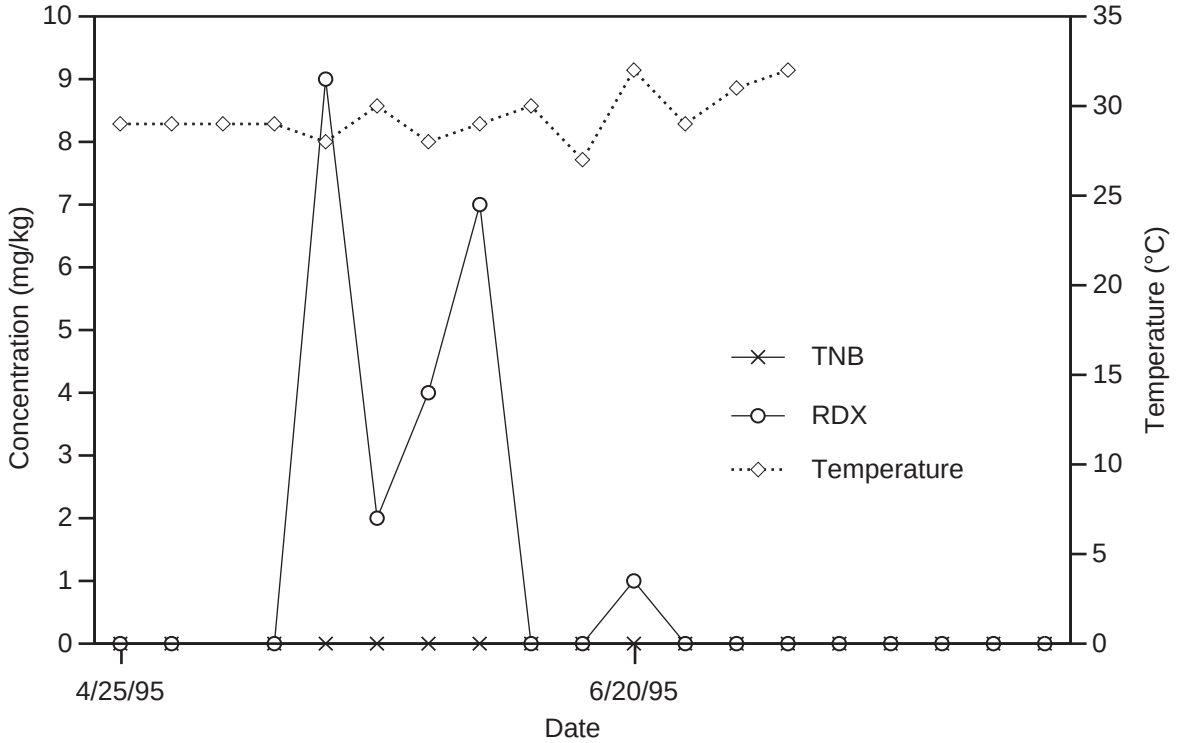


FIGURE 47 Explosives Concentrations in Soil in the 5% Replacement Reactor during Warm Weather

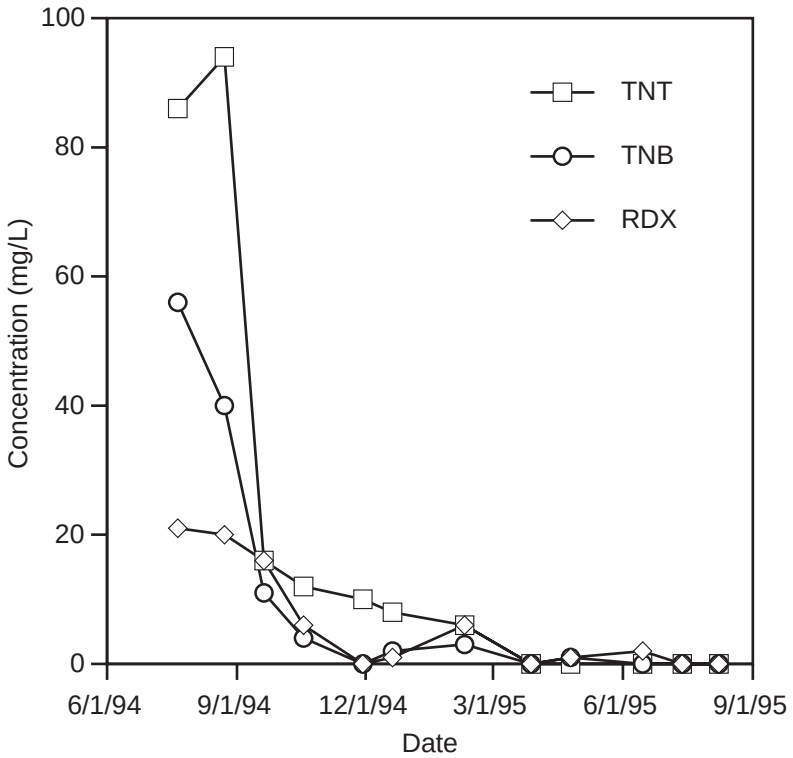


FIGURE 48 Explosives Concentrations in Liquid in the 5% Replacement Reactor

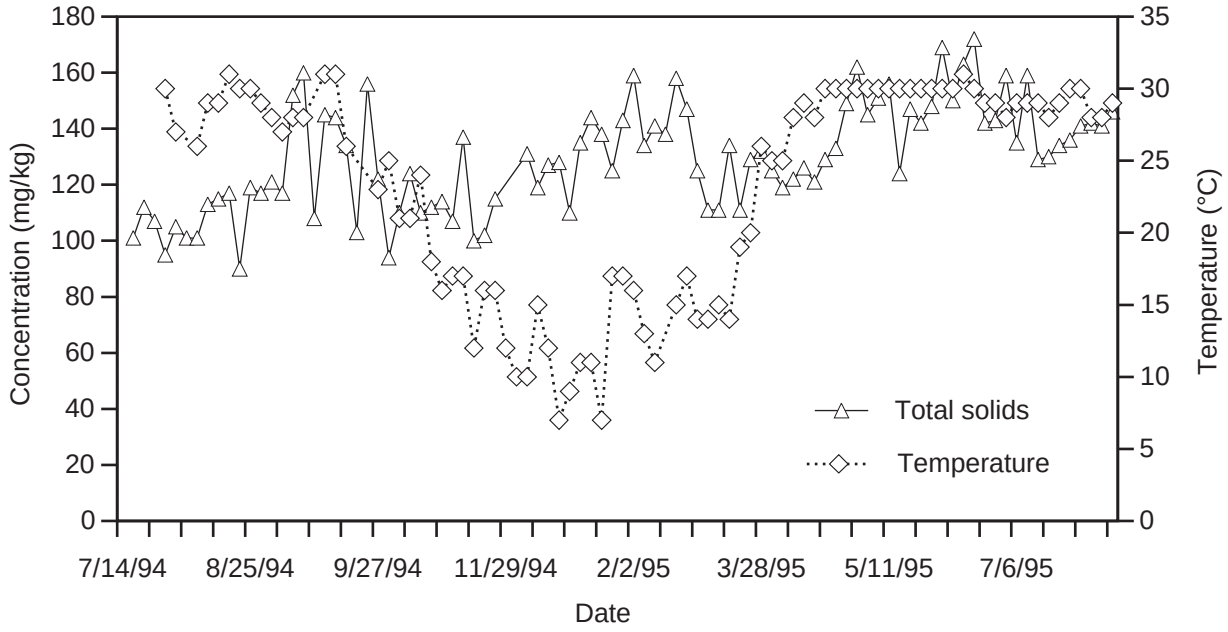


FIGURE 49 Solids Concentration in the 5% Replacement Reactor

5.3.4.7 Ammonia Concentration

Figure 50 shows the ammonia concentration in the slurry phase in the 5% replacement reactor. As in the other reactors, a spike of ammonia appeared as the temperature decreased in January. As the temperature decreased further, another spike occurred. The overall higher concentration of ammonia in February-July was probably due to the increase in molasses added as a co-substrate.

5.3.4.8 Nitrite Concentration

The nitrite concentration in the 5% replacement reactor is shown in Figure 51. This nitrite profile does not demonstrate a strong correlation with temperature. The fluctuations were probably due to process fluctuations.

5.3.4.9 Phosphorus Concentration

The concentration of orthophosphate phosphorus is shown in Figure 52. The phosphorus concentration in the 5% replacement reactor was highly variable and distinctly different from that in the other reactors. Because the same molasses stock was used in all of the reactors at a given time, the only apparent reason for this difference is process related. The cause of these large fluctuations in phosphorus levels is not known.

5.3.4.10 Microbial Enumeration

Figure 53 shows the microbial enumeration results (bacterial counts) for the 5% replacement reactor. Initially, the microbial numbers reached 10^{10} microorganisms per gram of soil. During the cold weather, the microbial numbers decreased to 10^{7}-10^{8} microorganisms per gram of soil. After the temperature returned to about 30°C, the microbial population increased to 10^{9}, but it never reached the previous range of 10^{10}-10^{11}. This permanent drop of one or two orders of magnitude is interesting, because TNT removal continued at an excellent rate during this period, and the quantity of molasses delivered to the reactor increased.

5.3.4.11 pH

Appendix C, Table C.4, contains the pH data. After March 1995, the pH was controlled daily to maintain a minimum value of 6.0.

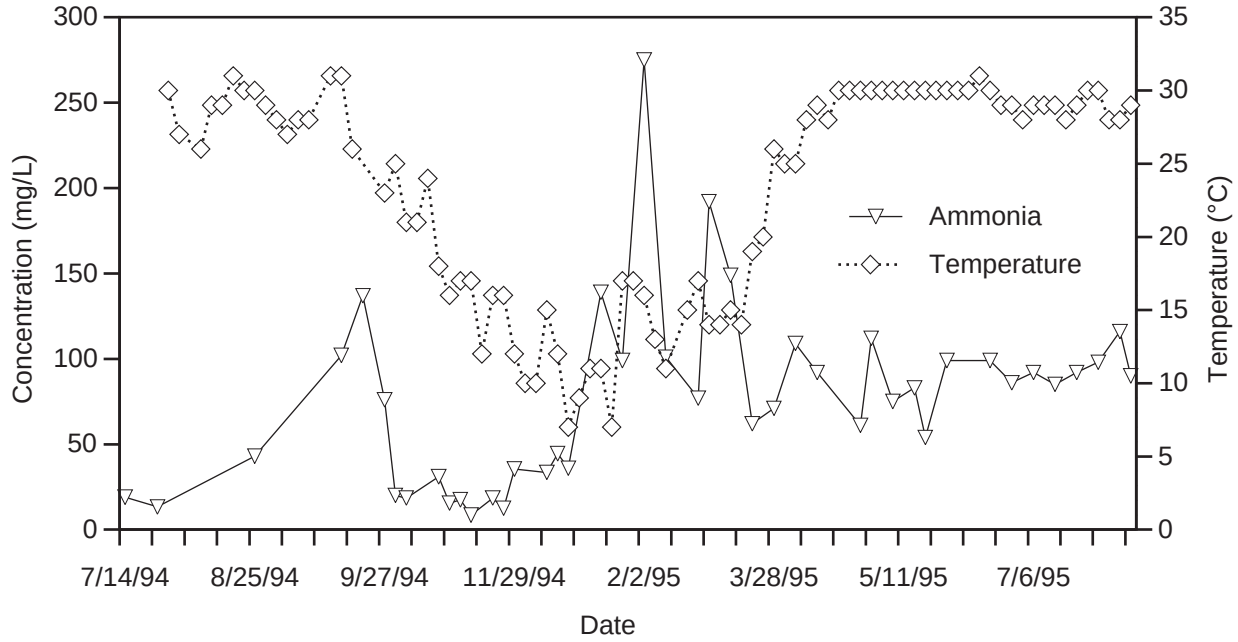


FIGURE 50 Ammonia Concentration in Slurry in the 5% Replacement Reactor

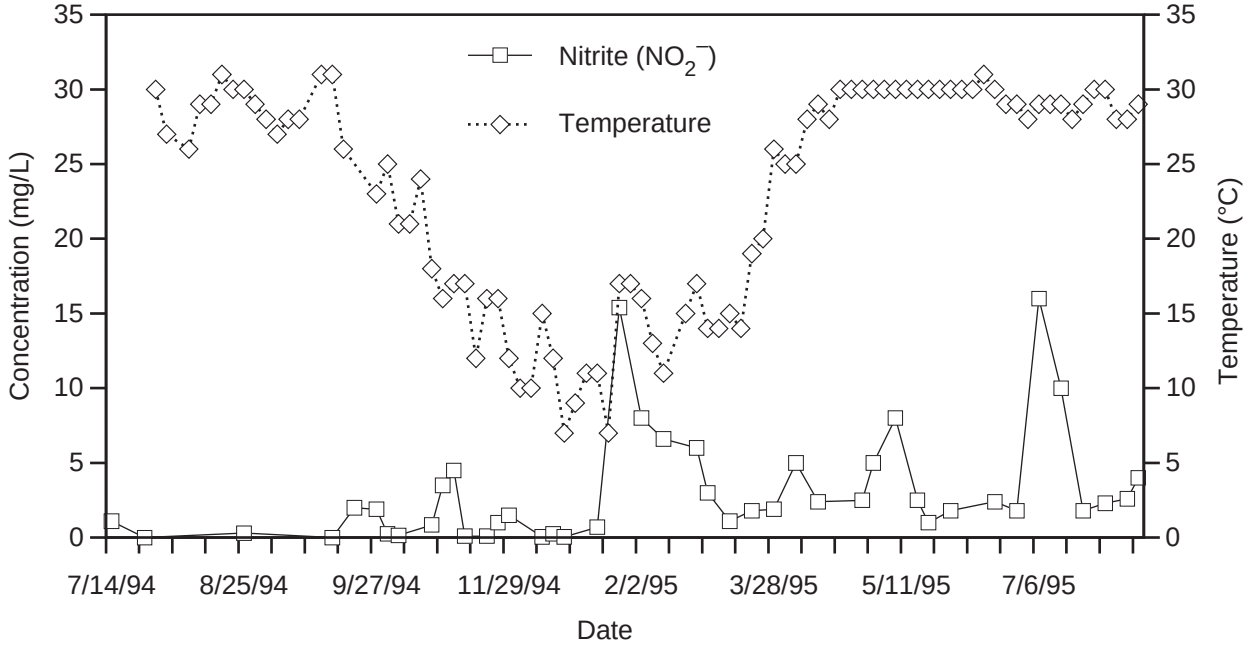


FIGURE 51 Nitrite Concentration in Slurry in the 5% Replacement Reactor

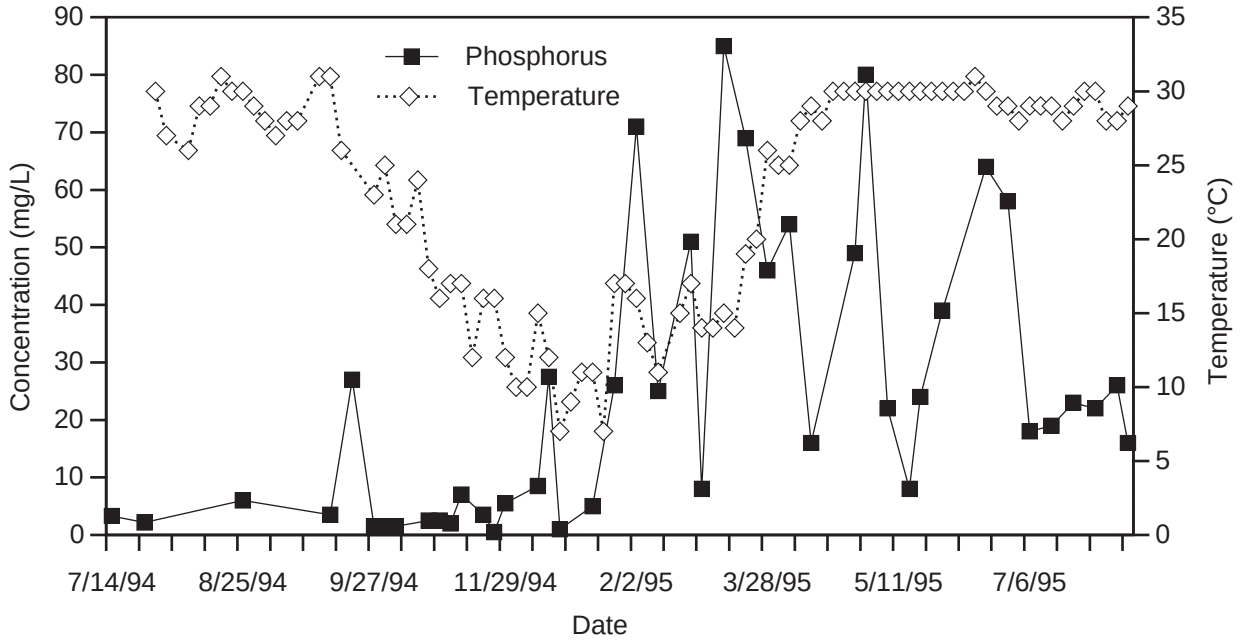


FIGURE 52 Phosphorus Concentration in Slurry in the 5% Replacement Reactor

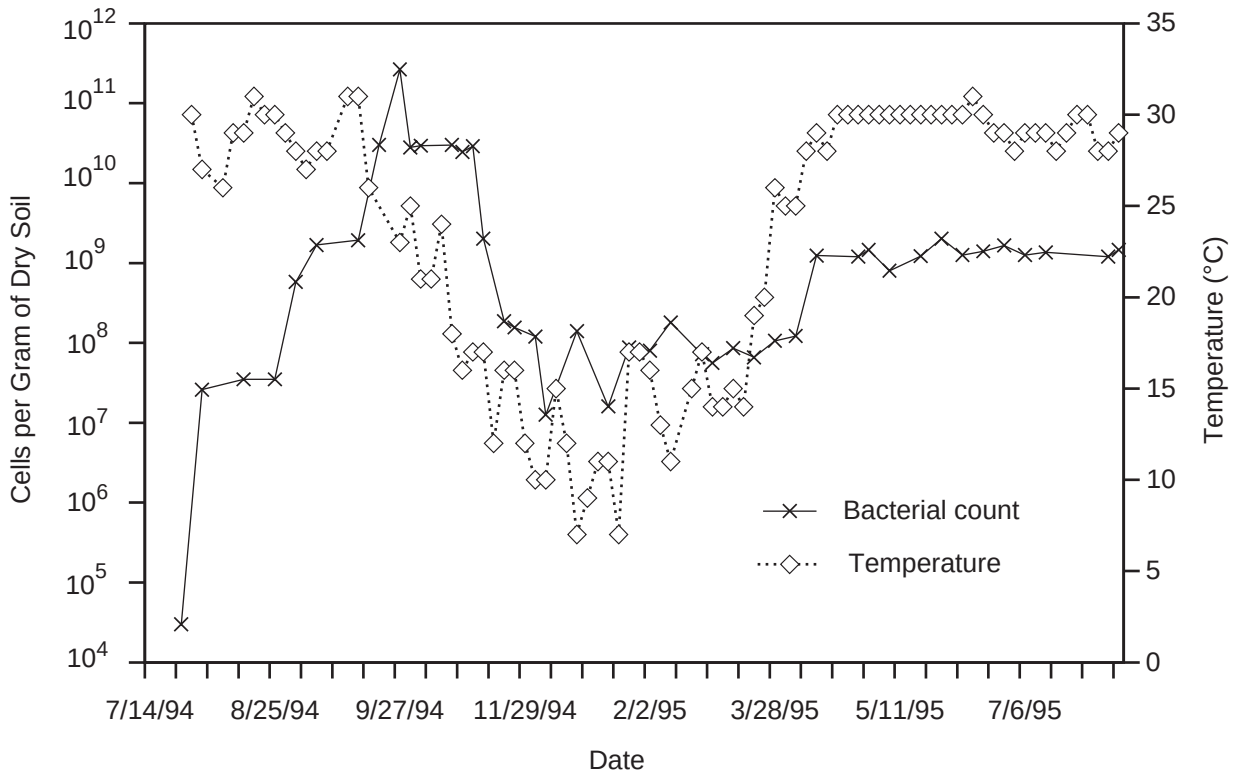


FIGURE 53 Bacterial Count in Solids in the 5% Replacement Reactor

5.3.4.12 Dissolved Oxygen

The DO concentration results are in Appendix C, Table C.4. The DO levels were always less than 0.5 mg/L, but they were measurable. The DO measurements were made prior to aeration.

5.4 Degradation of 2,4- and 2,6-Dinitrotoluene

As can be seen in Table 1, the soil in Group 61 had DNT concentrations of 66-360 mg/kg. (We have combined results for 2,4-DNT and 2,6-DNT, because our HPLC system could not distinguish the two compounds.) Dinitrotoluene is an important system component, because it could be of regulatory interest. The data presented here are from the field demonstration reactors described previously. Degradation of DNT was very similar to degradation of explosives in the bioslurry system. We did not determine whether a co-metabolic process is necessary for removal of DNT. Increasing the number of bacteria in the system might be sufficient for DNT degradation, and co-metabolism might not be required.

5.4.1 DNT in Soil in the Control Reactor

Figure 54 shows the DNT concentrations in soil in the control reactor. Because of sampling variability, the DNT concentration ranged from 70 to 120 mg/kg in the control reactor. The results demonstrate that without co-substrate (molasses), DNT was not removed from the soil.

5.4.2 DNT in Soil in the 20% Replacement Reactor

Figure 55 shows the DNT concentrations in soil in the 20% replacement reactor. The microbial biomass adapted to degrading DNT after the addition of molasses. Removal of DNT occurred throughout the operational period. When the temperature fell below 15°C, some process fluctuations occurred, but DNT concentrations remained at 2-3 mg/kg. When the temperature was above 15°C, the DNT concentrations were below 1 mg/kg.

5.4.3 DNT in Soil in the 10% Replacement Reactor

Figure 56 shows the DNT concentrations in soil in the 10% replacement reactor. The microbial biomass adapted to degrading DNT after the addition of molasses. Removal of DNT occurred throughout the operational period. Slight increases in DNT levels accompanied the first

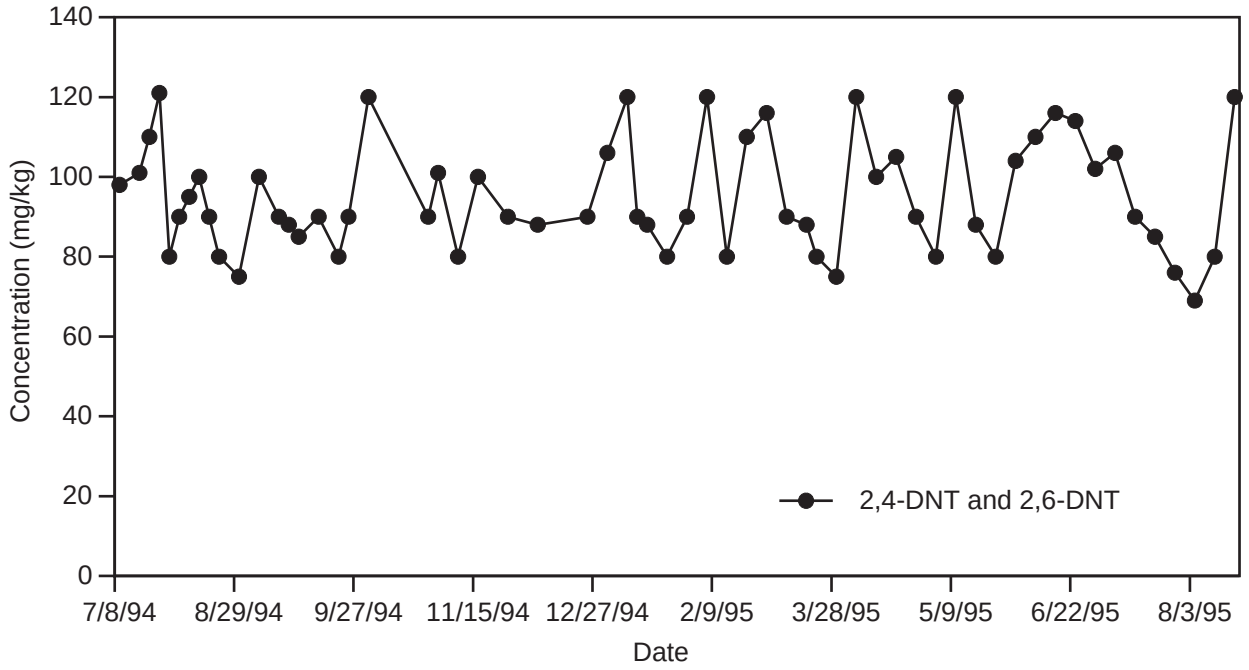


FIGURE 54 Dinitrotoluene Concentrations in Soil in the Control Reactor

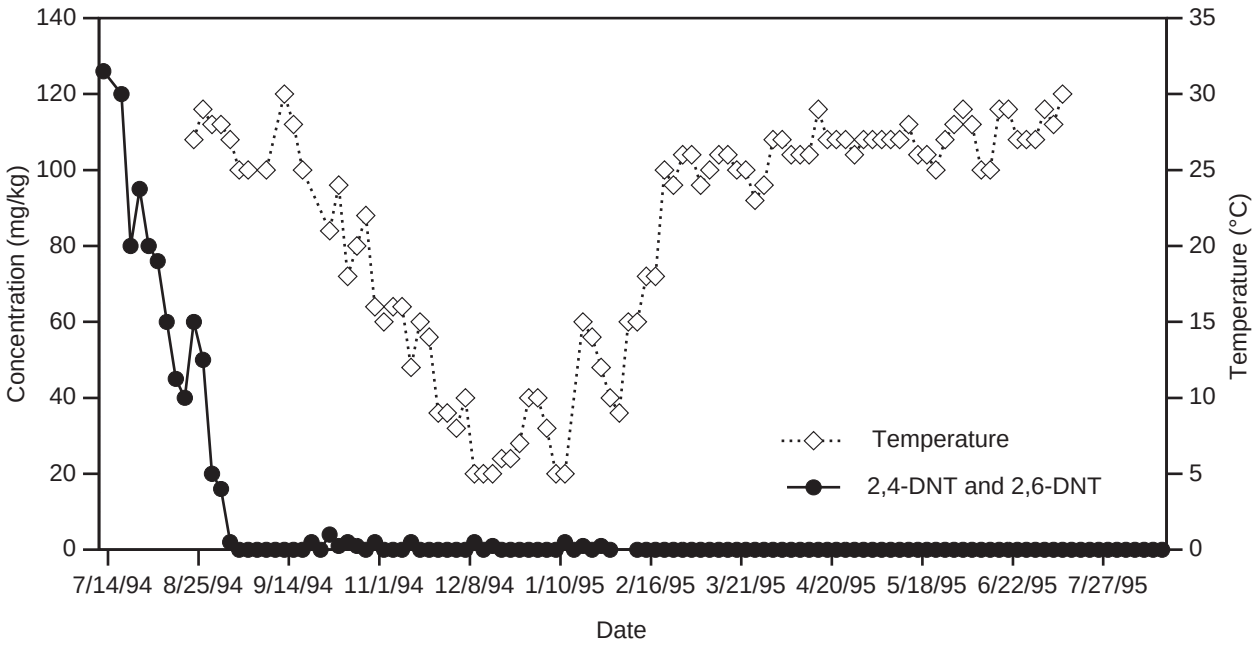


FIGURE 55 Dinitrotoluene Concentrations in Soil in the 20% Replacement Reactor

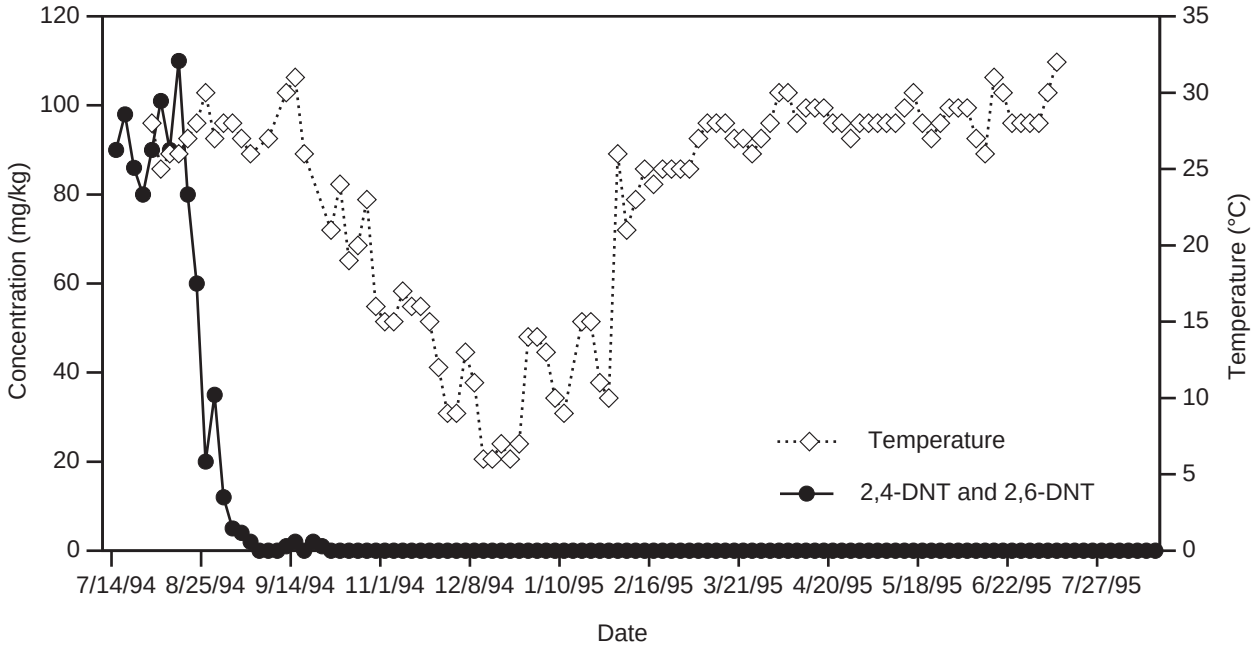


FIGURE 56 Dinitrotoluene Concentrations in Soil in the 10% Replacement Reactor

replacements in September 1994. After that adjustment, the bioslurry process kept DNT levels below 1 mg/kg throughout the study period.

5.4.4 DNT in Soil in the 5% Replacement Reactor

Figure 57 shows the DNT concentrations in soil in the 5% daily (four days per week) replacement reactor. The microbial biomass adapted to degrading DNT after the addition of molasses. Removal of DNT occurred throughout the operational period. During October 1994, as replacements began and the temperature dropped, a small increase in the DNT levels occurred, but the DNT concentrations remained below 5 mg/kg. After this episode, DNT levels were below 1 mg/kg for the remainder of the study period.

5.4.5 DNT in Liquid in the Control Reactor

Figure 58 shows that the DNT concentrations in liquid in the control reactor were 9-18 mg/L, averaging about 12-13 mg/L. DNT was not removed in this reactor with no molasses co-substrate.

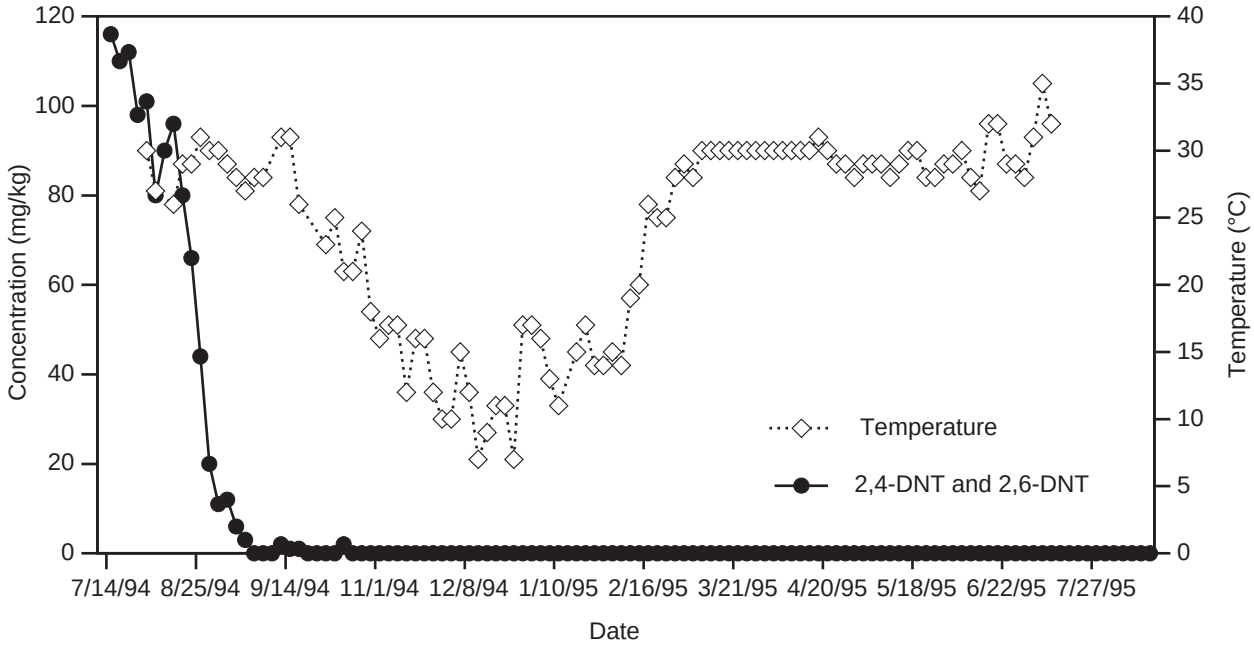


FIGURE 57 Dinitrotoluene Concentrations in Soil in the 5% Replacement Reactor

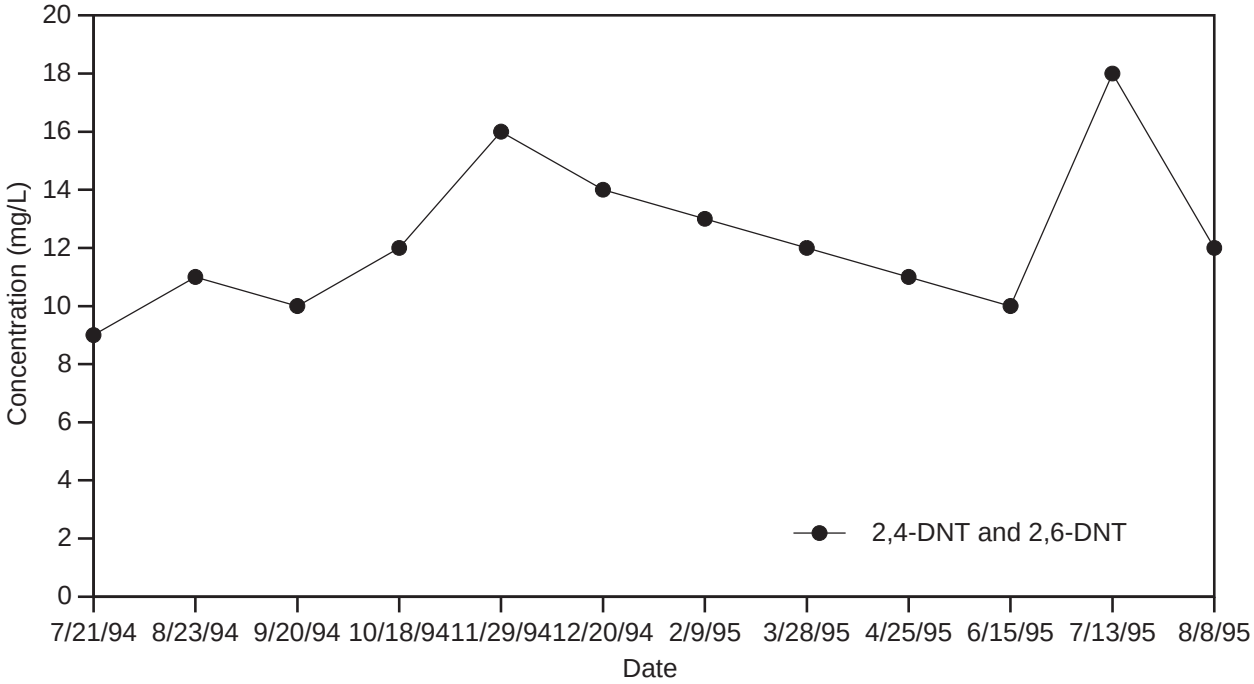


FIGURE 58 Dinitrotoluene Concentrations in Liquid in the Control Reactor

5.4.6 DNT in Liquid in the 20% Replacement Reactor

Figure 59 shows that the DNT concentrations in liquid in the 20% replacement reactor slowly fell to less than 1 mg/L. The DNT concentrations fell below 2 mg/L quickly, but then several months were required to reach levels below 1 mg/L.

5.4.7 DNT in Liquid in the 10% Replacement Reactor

Figure 60 shows that the DNT concentrations in liquid in the 10% replacement reactor fell below 2 mg/L during adaptation. A longer period of adjustment was needed before the concentrations fell below 1 mg/L.

5.4.8 DNT in Liquid in the 5% Replacement Reactor

Figure 61 shows that the DNT concentrations in liquid in the 5% daily (four-day work week) replacement reactor fell below 1 mg/L more slowly than in the 20% and 10% replacement reactors. Adaptation in this system took longer, and more time was required to reach a discharge concentration of less than 1 mg/L.

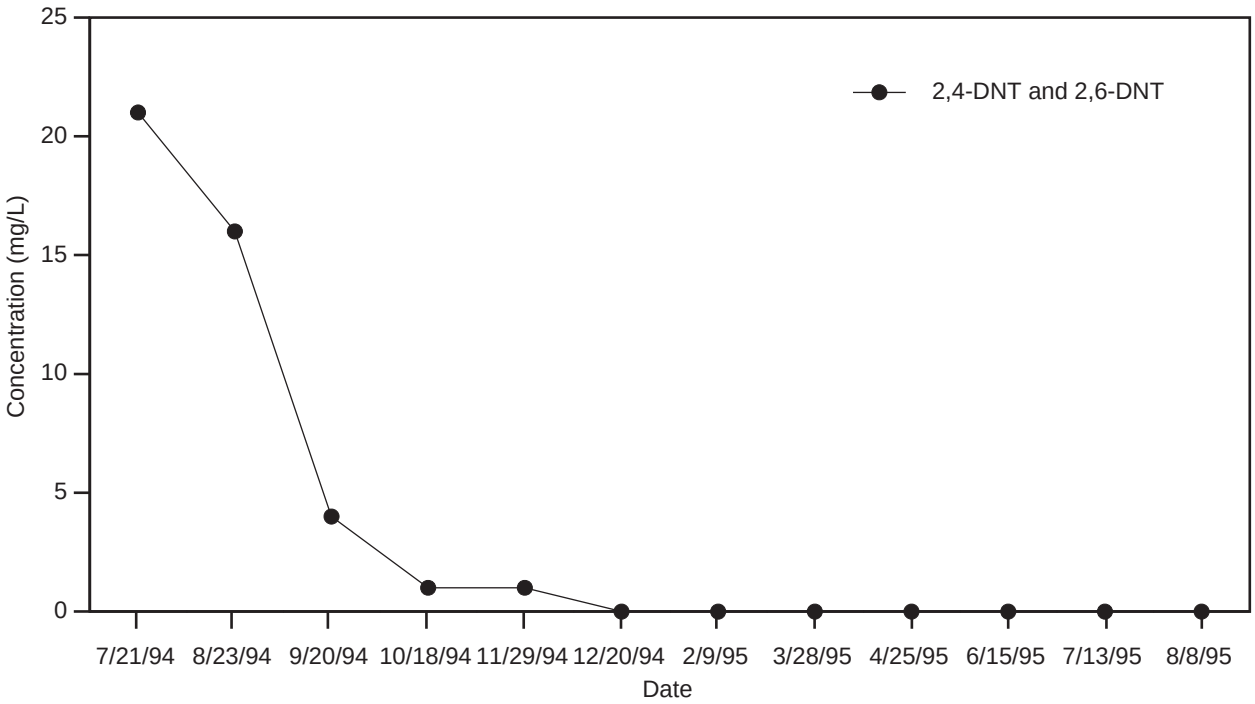


FIGURE 59 Dinitrotoluene Concentrations in Liquid in the 20% Replacement Reactor

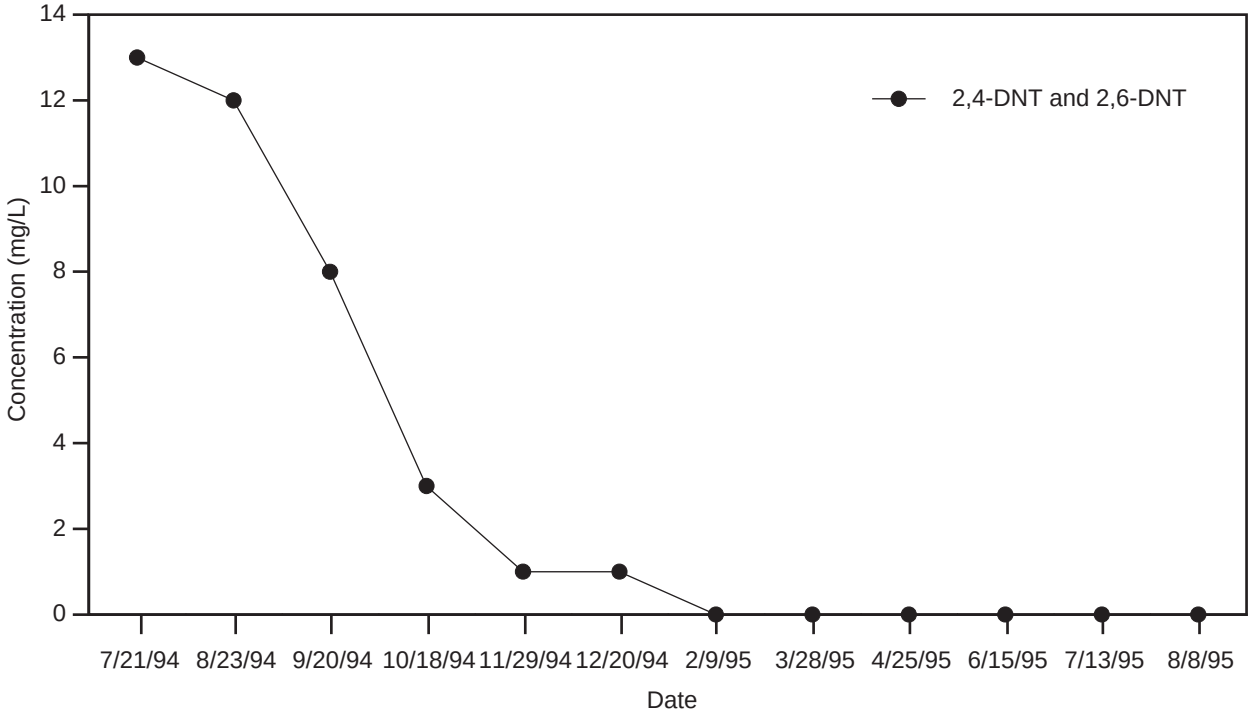


FIGURE 60 Dinitrotoluene Concentrations in Liquid in the 10% Replacement Reactor

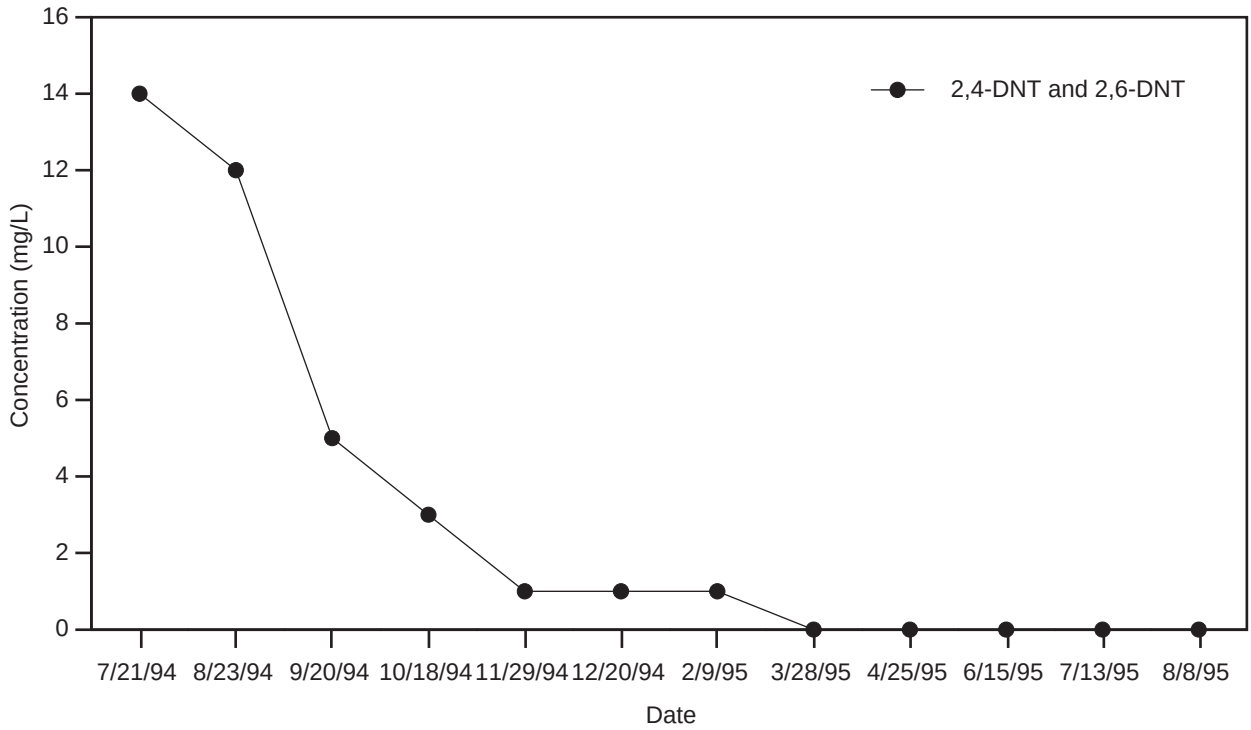


FIGURE 61 Dinitrotoluene Concentrations in Liquid in the 5% Replacement Reactor

5.5 Separation of Solids

The original filter bed system for separation of solids did not work as planned because of the significant reduction in particle size that occurred in the reactors. Passing the particles through a sand or fabric filter or both provided no separation. Results of a wet-sieve analysis of the soil before treatment are in Table 4. Results of a wet-sieve analysis of two samples after treatment in the control reactor are in Table 5. The results show that soil particle sizes were decreased significantly in the biological system. This explains the difficulty in using filter fabric to dewater the soil. The decrease in particle size could be expected because of the aggressive mixing that occurred in the system.

The soil was gravity-separated in drums to provide recycled water for preparing new slurry and to decrease the volume of material requiring disposal after treatment. The gravity settling of the slurry achieved a volume reduction of approximately 50%.

The ultimate disposal of the soil occurred in the fall of 1996, after the U.S. EPA Region 5, the Illinois EPA, and the Army approved a request to apply the slurry to uncontaminated land in the Group 61 area. All material land-applied had a TNT concentration below 20 mg/kg. In addition, concentrations of all other explosives and intermediates were below regulatory levels of concern. The land-applied material acts as a soil amendment because of its high organic material content and residual nitrogen and phosphorus.

TABLE 4 Soil Size Distribution before Treatment

Opening (mm)	Sieve Number	Retained[a] (%)	TNT (mg/kg)
2.0	10	8	2,524
1.7	12	23	3,330
1.4	14	12	3,228
1.0	18	12	3,516
0.425[b]	40	30	4,235
0.180	80	13	4,330
0.106	140	< 1	4,667
-	PAN[c]	< 1	6,225

[a] May not total 100 because of rounding.

[b] Box indicates the predominant size.

[c] PAN indicates that the material passed through all of the sieves listed.

TABLE 5 Soil Size Distribution for Samples A and B after Treatment

Opening (mm)	Sieve Number	Retained[a] (%)	TNT (mg/kg)
Sample A			
1.0	18	4	246
0.420	40	5	356
0.177	80	14	2,907
0.149	100	2	3,498
0.106	140	1	3,425
0.074	200	2	3,501
0.053	270	4	4,414
0.044	325	2	4,384
0.033	400	< 1	5,202
-	PAN[b,c]	64	5,624
Sample B			
1.0	18	3	316
0.420	40	6	387
0.177	80	5	3,101
0.149	100	1	3,546
0.106	140	16	3,625
0.074	200	2	4,626
0.053	270	4	4,455
0.044	325	7	4,625
0.033	400	2	5,416
-	PAN	53	5,948

[a] May not total 100 because of rounding.

[b] PAN indicates that the material passed through all of the sieves listed.

[c] Boxes indicate the predominant size.

5.6 Laboratory (Bench-Scale) Studies

Several laboratory studies conducted during the field demonstration influenced the field demonstration. The first was a short-run batch experiment on slurry removed from the operational reactors in early January 1995. The purpose of this experiment was to determine whether the slurry could still degrade explosives-contaminated soil after suffering the effects of cold weather. The second study involved removing a small quantity of slurry (200-500 mL) from each field reactor and conducting metabolic analyses in the laboratory with radiolabeled TNT to determine the metabolic fate of the TNT. Section 4.11 describes how these studies were conducted. Other studies investigated the fate of organic material after land application and the ability of land-applied material to support the growth of common plant species.

5.6.1 Laboratory (Bench-Scale) Reactor Studies

Figures 62-64 demonstrate the removal of TNT and 4A26DNT in the laboratory (29-35°C) from slurry removed from the field reactors during January 1995. This slurry had been maintained at 5-10°C for several weeks. For the laboratory 20% weekly replacement reactor, as many as 25 days were needed to achieve TNT and 4A26DNT concentrations of less than 20 mg/kg

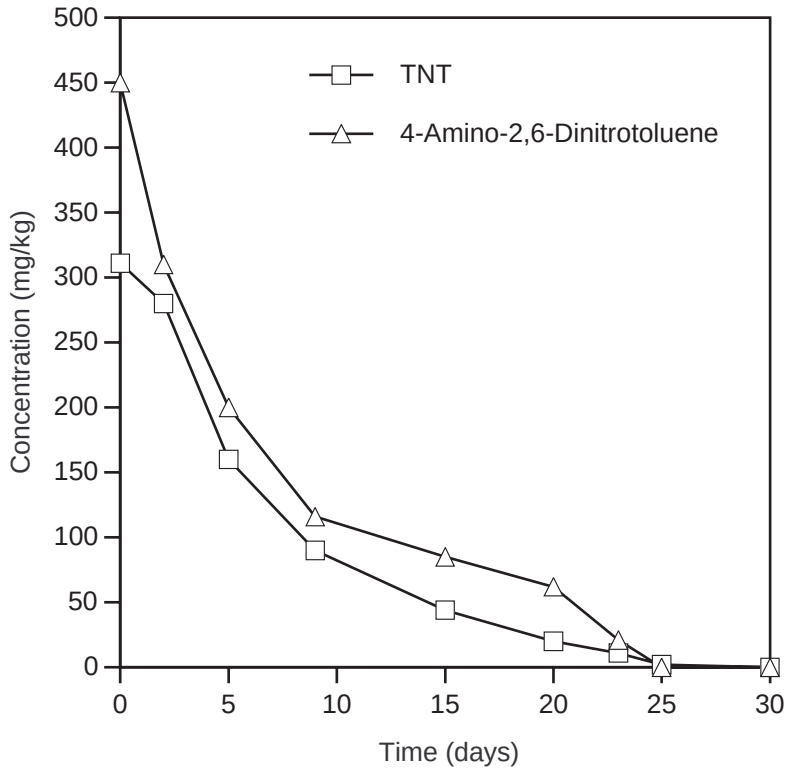


FIGURE 62 Concentrations of TNT and 4-Amino-2,6-Dinitrotoluene versus Time in the Laboratory 20% Replacement Reactor

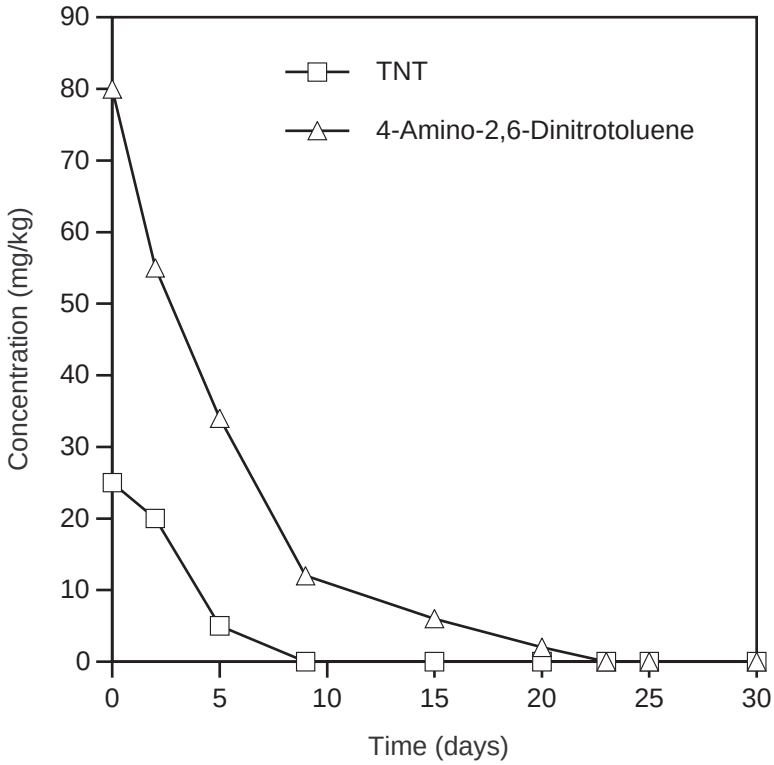


FIGURE 63 Concentrations of TNT and 4-Amino-2,6-Dinitrotoluene versus Time in the Laboratory 10% Replacement Reactor

(Figure 62). In the laboratory 10% weekly replacement reactor (starting from much lower initial concentrations), TNT removal recovered quickly, but 4A26DNT removal took much longer. In the laboratory 5% daily replacement reactor, recovery of TNT and 4A26DNT removal took as many as 25 days after the cold weather, as compared with more than 2 months in the field system. Although these were static tests with no replacements and molasses added only once per week, the results clearly demonstrate that significant recovery times were needed after the microbial population was disturbed by cold weather. Figure 65 shows the TNT and 4A26DNT levels in the laboratory control reactor. These results suggest that the recovery of microbial consortia is greatly influenced by the consistency of temperature exposure. The laboratory system was operated under extremely consistent temperatures. The field system, by its nature, was exposed to some temperature fluctuations. Members of the consortium degrading the amino intermediates are apparently particularly temperature sensitive.

These results imply that during cold weather, soil replacements should be stopped or minimized until the level of amino compounds drops. The microbial population survives cold weather, but its rate of metabolism is greatly decreased. Operation with lower-volume replacements under these conditions will give the microbial population time to remove the amino compounds.

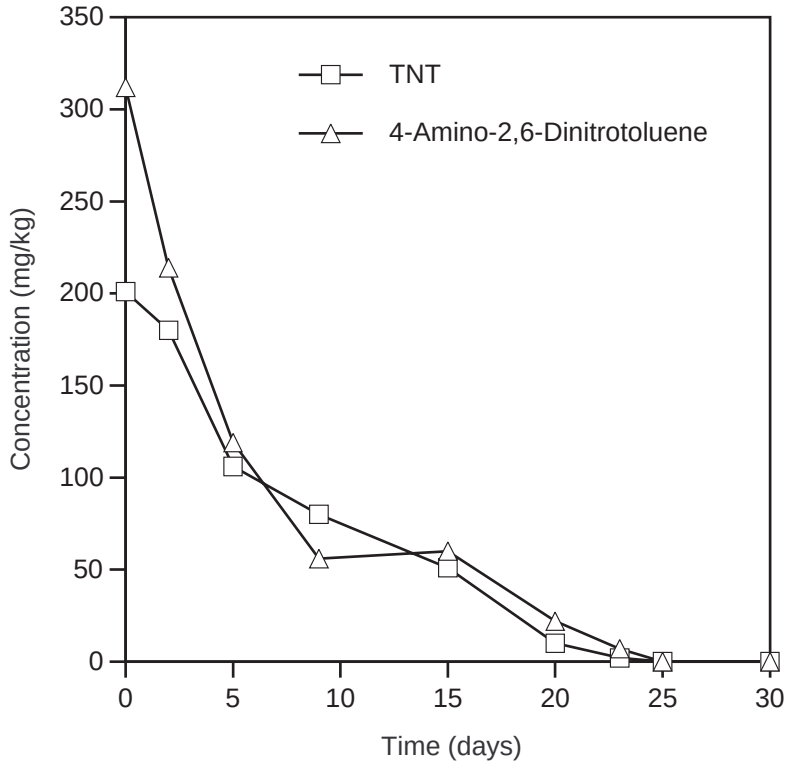


FIGURE 64 Concentrations of TNT and 4-Amino-2,6-Dinitrotoluene versus Time in the Laboratory 5% Replacement Reactor

5.6.2 Radiolabeling Studies

Figures 66-68 show the distribution of radiolabel after 22 days of incubation of the samples from field bioslurry reactors with radiolabeled TNT. Figure 66 shows that in the sample from the control reactor, little TNT (9%) was transformed to intermediates or end products. The small percentage of label converted to other compounds probably reflects laboratory contamination with a small amount of a material that acted as a co-substrate. This analysis of the radiolabeling studies is based on the assumption that 100% of the radiolabel was recovered. In reality, about 83-85% of the original radiolabel was recovered, and 15-17% was not recovered or accounted for.

The mass balance for the sample from the field 20% replacement reactor indicates that approximately 23% of the radiolabel was converted to carbon dioxide (Figure 67). Approximately 25% was converted to microbial biomass, and about 25% was converted to two by-products. One by-product was 2,3-butanediol, and the second was an unidentified compound eluting at 3.2 min with EPA Method 8330. Although this 3.2-min compound was not characterized by GC/MS, it eluted very near 2,3-butanediol and could be a fatty acid. Small fractions of the radiolabel were converted to other compounds and were not accounted for in the analysis.

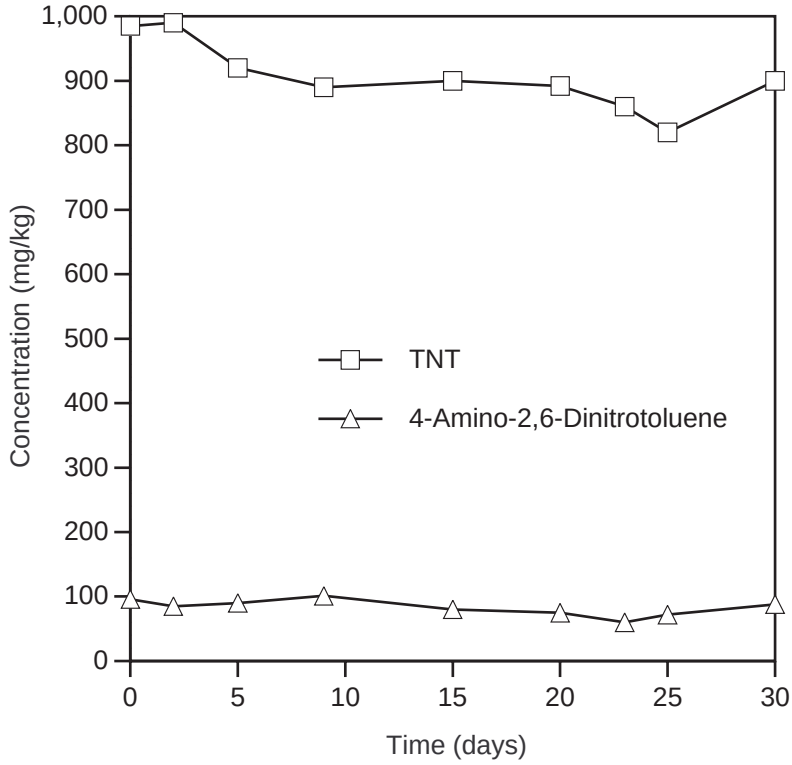


FIGURE 65 Concentrations of TNT and 4-Amino-2,6-Dinitrotoluene versus Time in the Laboratory Control Reactor

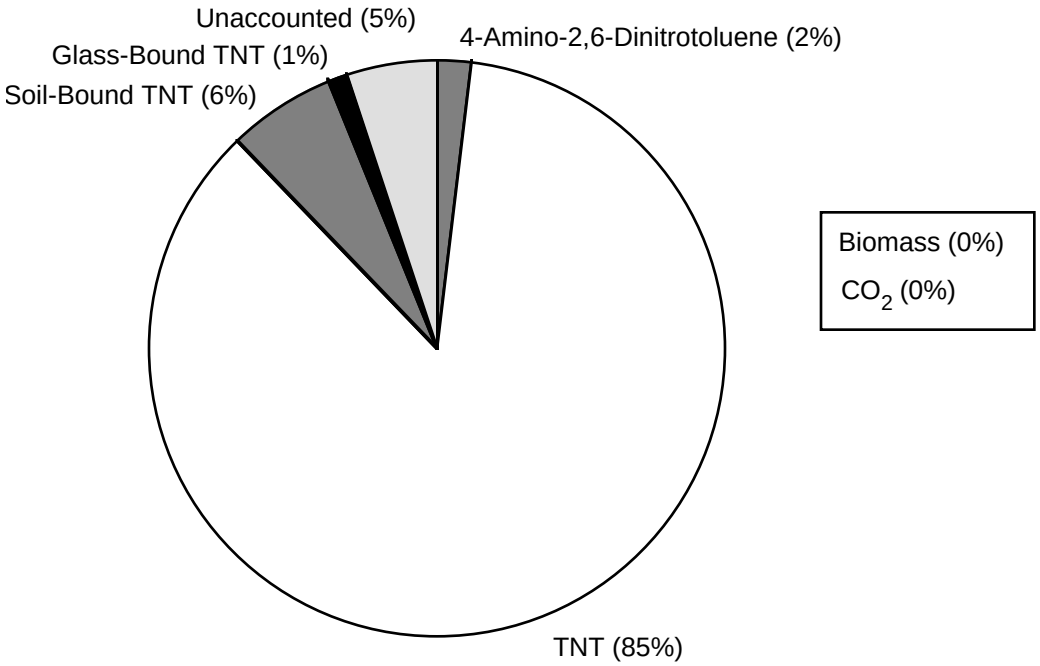


FIGURE 66 Distribution of Radiolabeled TNT in a Sample Taken from the Field Control Reactor

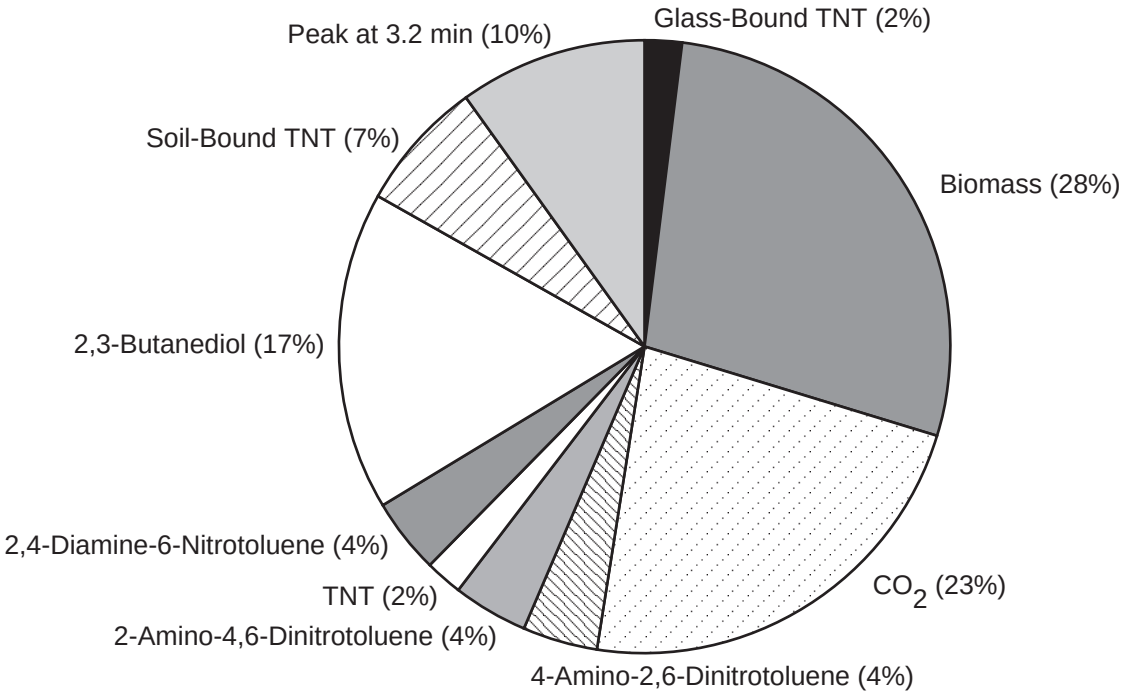


FIGURE 67 Distribution of Radiolabeled TNT in a Sample Taken from the Field 20% Weekly Replacement Reactor

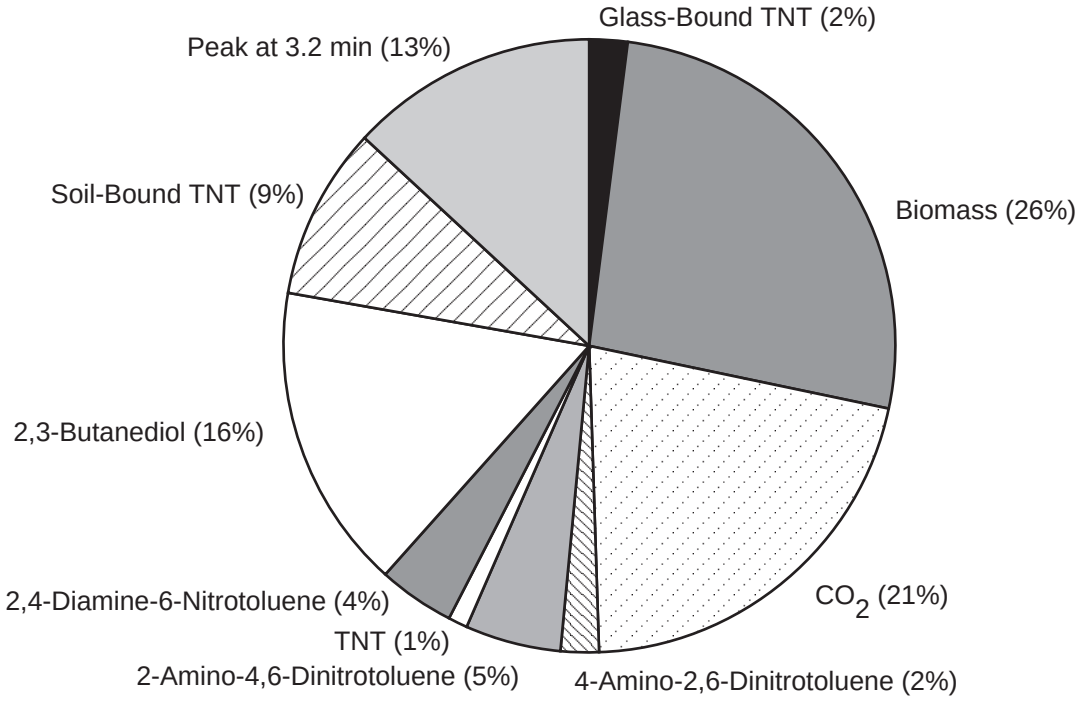


FIGURE 68 Distribution of Radiolabeled TNT in a Sample Taken from the Field 5% Daily Replacement Reactor

The results for the sample from the field 5% daily replacement reactor (Figure 68) were almost identical to the results for the 20% replacement reactor (Figure 67).

The radiolabeling studies demonstrated that significant ring cleavage of TNT occurred. The 21% of the TNT that was converted to carbon dioxide represents complete mineralization. The amount converted to 2,3-butanediol and other intermediates represents ring cleavage but not complete mineralization. One of the potential benefits of slurry treatment is this demonstrated ring cleavage and mineralization, rather than adsorption of TNT onto solid material.

5.6.3 Soil Disposition Studies

After operation of the field demonstration ended, studies were conducted to evaluate two methods for soil disposition. The two methods investigated were (1) mechanical and chemical separation of soil and water and (2) direct application of the slurry to land.

5.6.3.1 Mechanical-Chemical Systems

Various mechanical systems were investigated, including a filter press, fabric filters, and centrifugation at the laboratory scale. All of these systems had the potential to dewater the slurry, but all suffered because of the small particle sizes described in Section 5.5. These systems were not investigated further after preliminary laboratory studies indicated either long treatment times (for centrifugation) or the requirement to add polymers or coagulants to improve filterability. (Such systems generally can achieve filter cakes with approximately 30-70% moisture content.) The added costs of such systems were of concern when full-scale implementation was considered.

5.6.3.2 Direct Application of Slurry to Land

The two studies conducted to determine whether the treated soil could be applied to land focused on plant growth and removal of the residual TOC from the slurry.

Plant Growth Studies

Figures 69 and 70 show the dry weights of aboveground biomass of corn and a bluestem grass growing on various mixtures of slurry with uncontaminated Group 61 soil. Higher concentrations of slurry had no negative effect on the growth of corn and might have had a slight

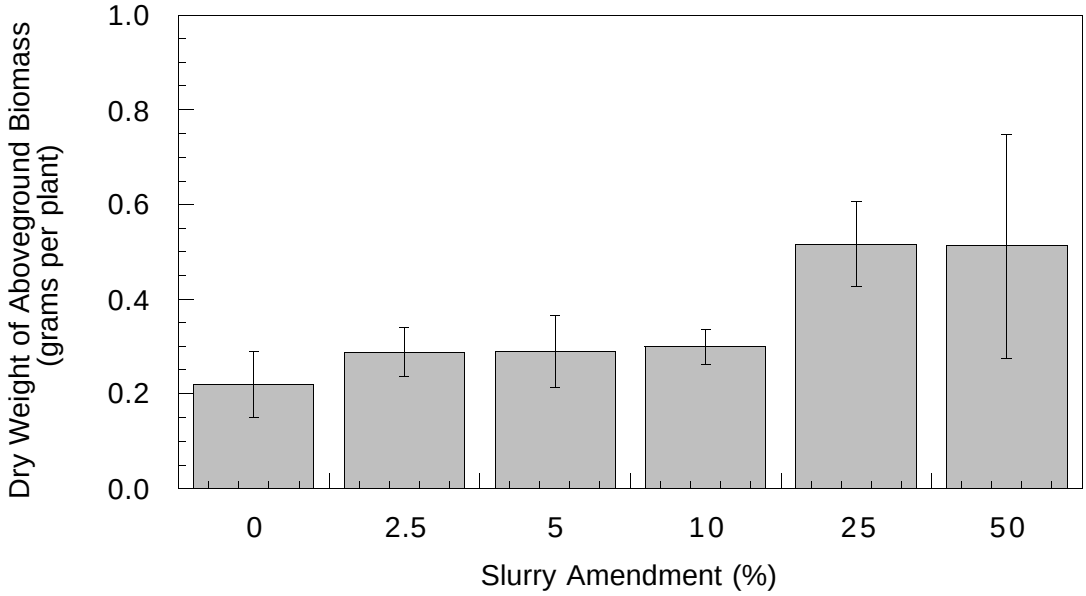


FIGURE 69 Effect of Treated Soil Slurry on the Growth of Corn Plants

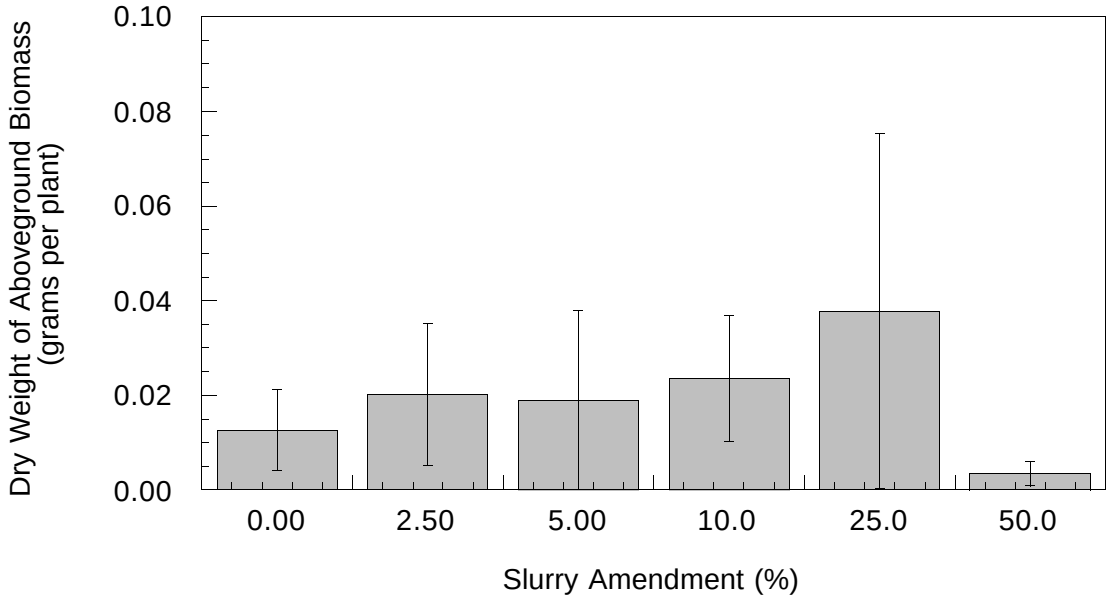


FIGURE 70 Effect of Treated Soil Slurry on the Growth of Bluestem Grass

benefit (Figure 69). Bluestem grass showed no negative effects of slurry up to the 50% level; however, the 50% slurry mixture caused some surface hardening that could have affected the emergence of the stem.

Removal of Total Organic Carbon

Figures 71 and 72 show the results of studies to determine whether direct application to soil of a slurry with a high TOC load might have harmful effects. The results showed that the TOC was removed quickly from a mixture of slurry with clean Group 61 soil, in many cases leaving no detectable soluble TOC in the system (Figure 71). In addition, carbon dioxide production was enhanced by addition of the slurry (Figure 72), indicating that the soluble TOC was mineralized by the native microorganisms.

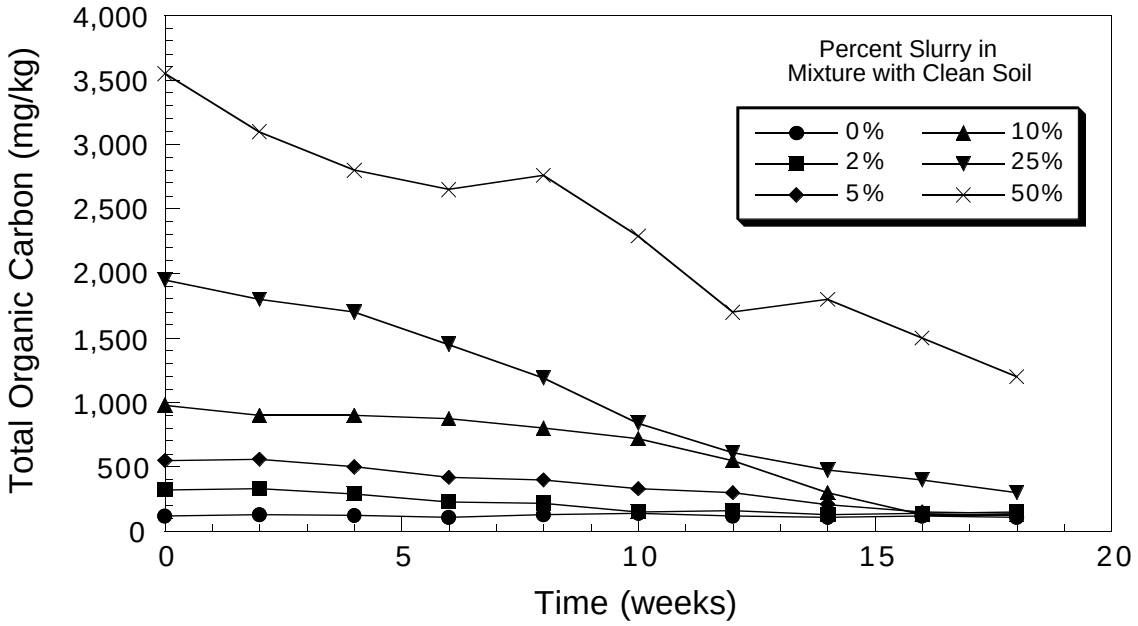


FIGURE 71 Degradation of Total Organic Carbon in Mixtures of Slurry and Clean Soil

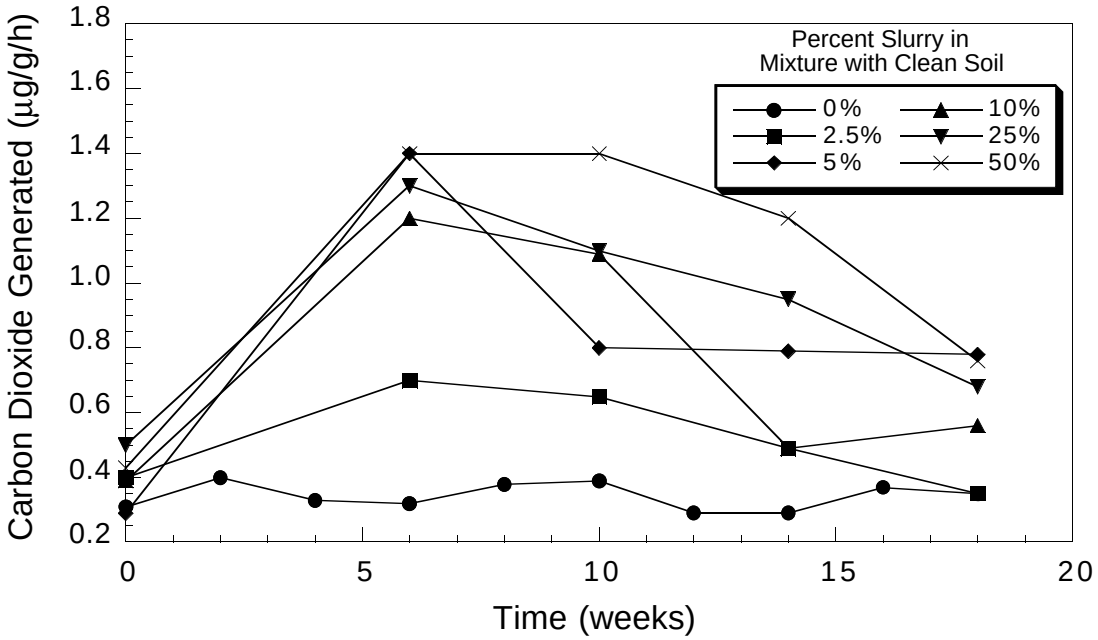


FIGURE 72 Carbon Dioxide Generation in Mixtures of Slurry and Clean Soil

6 Conclusions

On the basis of the data presented in Section 5, the following major conclusions are drawn from the bioslurry field demonstration:

- Bioslurry systems can be used effectively to bioremediate soils contaminated with TNT, RDX, TNB, and DNT to a variety of treatment goals. This study demonstrated that TNT can be removed to levels below 20 mg/kg. In warm weather, the 20% replacement strategy will meet all treatment goals.

- Aerobic-anoxic operation and co-substrate are necessary for removal of explosives from soil.

- The treated material is suitable for land application, as demonstrated by removal and mineralization of explosives and by the plant growth studies. Residual carbon is removed by natural soil degradation.

- The systems achieved different removal levels of TNT from soil, depending on the mass of soil replaced each week and the temperature. Under similar conditions, the 10% replacement reactor performed slightly better than the others.

- Temperature plays a major role in determining the amount of TNT degraded and the subsequent degradation of the 4A26DNT intermediate. Degradation of intermediates is affected at temperatures below 25˚C, and accumulation of intermediates becomes a significant operational concern at temperatures below 15˚C.

- Readaptation after temperatures fell below 25°C took longer than adaptation at start-up. The biological mechanism for this phenomenon is unknown, but it might have to do with changes in the microbial population.

- Recycled process water after dewatering is an acceptable source of water for slurry preparation. The crucial factors affecting the use of recycled process water seem to be accumulated salts (Na^+, Mg^{2+}, and Ca^{2+}). In addition, K^+ and HCO_3^- were found in the process water and soil (Griest et al. 1997).

- Significant reaeration by the mixing equipment occurred in these systems, resulting in conditions where oxygen was added to the system constantly in

small quantities, in addition to the aeration accomplished by the forced-air diffusers.

- Approximately 20-23% mineralization was achieved in a laboratory study on samples removed from the reactors. Approximately 55% of the remaining radiolabel was converted to biomass and fatty acids, representing ring cleavage but not mineralization.

- The bioslurry system is relatively simple to operate and can be implemented with commercially available equipment. A safety review addressing explosives should be conducted before any equipment is used in areas where explosives can concentrate and become a hazard to human health or equipment.

7 Lessons Learned

In addition to the specific technical data and discussion already presented, a variety of observations were made that might prove valuable in implementing a bioslurry process at a large scale. These lessons relate to the specific conditions of the JAAP field demonstration and are not directly quantifiable; however, they do result from extensive operating experience. Actions taken in response to these observations should not directly affect the bioslurry process but could enhance operation of a bioslurry system. The following are the general observations:

- The major lesson learned concerns the adaptability of the bioslurry treatment process to a variety of different cleanup standards. The frequency of replacements and the volume of replacements could be increased greatly, depending on the amount of explosives that could remain in the soil. For example, with a risk-based cleanup standard for TNT of 150 mg/kg, a 10% reactor could be operated all winter, and then in the summer, replacements could be increased to 50%. This strategy would greatly increase the throughput of soil and reduce the cleanup time and cost. In some cases, the determining factor in reactor operations will be DNT, which often has a risk-based cleanup concentration below that of any other explosive. DNT can be removed from soil by microorganisms.

- Process monitoring could be reduced from the intensive sampling regime implemented in this field demonstration. Daily sampling for pH and DO is not necessary, particularly after the operating characteristics of the reactors have been determined. Automatic recording of pH and DO levels might be suitable.

- Foaming of the reactor contents upon the addition of air through the diffusers needs to be monitored and controlled. No foam control was attempted in this demonstration, but additives are available for that purpose. Foam control is difficult and expensive. The addition of a foam warning system or an antifoam addition system would be a cost consideration. Foam can be controlled by careful monitoring of air addition.

- The reduction in soil particle size needs to be monitored, because the size of the particles after bioslurry treatment directly affects dewatering or ultimate land disposal. It might be possible to operate reactors with different mixing configurations or strategies to diminish the particle size reduction. It might also be possible to operate the reactors with intermittent mixing if the motors used can resuspend the slurry. The ability of a mixing system to suspend the material to be treated must be investigated. The torque, horsepower, and shape of the mixer are significant considerations.

- Water supply requirements for a full-scale facility need to be examined. The source of water and its constituents (particularly heavy metals) must be evaluated for potential negative effects on the biological process.

- EPA Method 8330 should be used to analyze the initial soil and the treated slurry at the end of processing. EPA Method 8330 is the method of choice for determining accurately when intermediates have been removed.

- Field test kits should be evaluated for use in monitoring TNT concentrations approximately weekly during adaptation and operation.

- Adaptation might proceed faster than indicated in this report. The operators in this study allowed the system to adapt very slowly to develop operating experience. Molasses could be added aggressively on a weekly basis during adaptation. This strategy would shorten the adaptation period.

- Adaptation after temperatures fall below 25°C needs to be examined carefully. Operation as a batch process to remove intermediates might improve throughput. This procedure could reduce the operating problems encountered at temperatures below 25°C and could alleviate accumulation of 4A26DNT.

- pH control is required if the pH drops to below 6.0. The process can operate at a wide range of pH values between 6.0 and 8.0. The process tended to operate naturally at pH 6.0.

- Final soil disposition should be considered as part of the feasibility study process. Depending on how the soil is ultimately disposed, significant cost savings could result. After this demonstration, direct land application was used for disposal of the soil.

- The steps in operating a full-scale system are excavation, soil screening, slurry preparation, molasses addition, air addition, mixing, chemical analysis (particularly for explosives and pH), and soil disposition.

- Sampling is designed to maximize process efficiency. Field test kits can identify when TNT and other explosives have been removed from the system. Test kits can also estimate when EPA Method 8330 should be used. This determination will be based in part on site-specific operational experience, but the analyses should begin approximately five days after molasses addition. An appropriate pH level is required to operate the microbial process efficiently; pH should be measured every other day. Dissolved oxygen levels should be measured every day after air addition.

- The bioslurry process is extremely flexible and resilient in its operation. In this demonstration, the performance of the 20% replacement reactor in warm weather was equivalent to that of the 10% replacement reactor. In cold weather, a 10% replacement reactor can be operated to achieve desired cleanup standards. This observation supports the *potential* for year-round operation. The decision to operate year-round is an economic consideration, not a performance issue.

- The complete removal of explosives in the 20% replacement reactor during warm weather indicates that higher replacement volumes could potentially be accommodated.

- A potential problem with operating a bioslurry system to more stringent cleanup levels (i.e., TNT levels of 150 mg/kg) is the accumulation of intermediates in the slurry.

- The amount of soil in the slurry (15% in this study) was limited by mixer design. Other mixing systems might allow operation with a 20-40% slurry.

- Heating methods investigated included wrapping heat tape around the reactors, adding steam to the slurry, and heating the input water. These methods were not implemented because of safety concerns or cost. Insulation and area heating were used in this demonstration. Insulation of a full-scale system would probably be cost-effective and would take advantage of heat generation by the microbes during metabolism. Area heating systems are not cost-efficient.

8 References

APHA, 1988, *Standard Methods for the Examination of Water and Wastewater*, 15th ed., American Public Health Association, New York.

Bartha, R., and D. Pramer, 1965, "Features of a Flash Method for Measuring the Persistence and Biological Effects of Pesticides in Soil," *Soil Science* 100:68-70.

Batzner, et al., 1982, *Installation Restoration Surveys: Joliet Army Ammunition Plant (JAAP), Final Technical Report*, Volumes 1 and 2, prepared for U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, by Donohue and Associates, Inc., November 10.

CDM, 1989, *JAAP Environmental Baseline Study for Talley Defense Systems*, prepared for Talley Defense Systems, Inc., Mesa, Arizona, by Camp Dresser and McKee, Inc., Cambridge, Massachusetts.

CDM, 1990, *Addendum to JAAP Environmental Baseline Study for Talley Defense Systems*, prepared for Talley Defense Systems, Inc., Mesa, Arizona, by Camp Dresser and McKee, Inc., Cambridge, Massachusetts.

Dames and Moore, 1986, *Midwest Confirmatory Survey Assessment Report for Joliet Army Ammunition Plant*, prepared for U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, November.

Dames and Moore, 1988a, *Draft Assessment Report: Task Order No. 10, PCB Spill Area, Group 70, Load-Assemble-Package (LAP) Area, Joliet Army Ammunition Plant, Illinois*, prepared for U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, August.

Dames and Moore, 1988b, *Final Report: Honeywell LAP Facility, Group 3A and AT4-PVC, Environmental Baseline Study, Joliet, Illinois*, prepared for Honeywell Joliet LAP Facility, Joliet, Illinois, May 6.

Griest, W.H., A.A. Vass, A.J. Stewart, and C.-H. Ho, 1997, *Chemical and Toxicological Characterization of Bioslurry Reactor Biotreatment of Explosives-Contaminated Soils*, ORNL/TM-13384, prepared for the U.S. Army Environmental Center, Aberdeen Proving Ground, Maryland, by Oak Ridge National Laboratory, Oak Ridge, Tennessee, March.

Hazelton Laboratories, 1982, *Chemical Analysis Data for Surface Water Sampling at Joliet Army Ammunition Plant*, prepared for Uniroyal, Inc., Joliet, Illinois.

Health Effects Group, Inc., 1990a, *Industrial Hygiene Survey: Joliet Army Ammunition Plant, Groups 3 and 64: Nitroaromatics and Metals*.

Health Effects Group, Inc., 1990b, *Talley Defense Systems Joliet Army Ammunition Plant Group 64 Soil Sampling for Lead and Chromium*, prepared for Talley Defense Systems, Inc., Mesa, Arizona.

Manning, Jr., J.F., and C.D. Montemagno, 1992a, *Test Plan for a Soil Slurry-Sequencing Batch Reactor Pilot Scale Demonstration at Joliet Army Ammunition Plant*, prepared for U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, by Argonne National Laboratory, Argonne, Illinois, April.

Manning, Jr., J.F., and C.D. Montemagno, 1992b, *Final Health and Safety Plan for a Soil Slurry-Sequencing Batch Reactor Pilot Scale Demonstration at Joliet Army Ammunition Plant*, report prepared for U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, by Argonne National Laboratory, Argonne, Illinois, December.

Manning, Jr., J.F., R. Boopathy, and C.F. Kulpa, 1995, *A Laboratory Study in Support of the Pilot Demonstration of a Biological Soil Slurry Reactor*, Technical Report SFIM-AEC-TS-CR-94038, U.S. Army Environmental Center, Aberdeen Proving Ground, Maryland, prepared by Argonne National Laboratory, Argonne, Illinois, July.

Mans, R.J., and G.D. Novelli, 1961, "Measurement of the Incorporation of Radioactive Amino Acids into Protein by a Filter Paper Method," *Archives of Biochemistry and Biophysics* 94:48-53.

Montemagno, C.D., 1991, *Evaluation of the Feasibility of Biodegrading Explosives-Contaminated Soils and Groundwater at the Newport Army Ammunition Plant (NAAP)*, Technical Report CETHA-TS-CR-92000, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, prepared by Argonne National Laboratory, Argonne, Illinois, June.

Montemagno, C.D., and R.L. Irvine, 1990, *Feasibility of Biodegrading TNT-Contaminated Soils in a Slurry Reactor*, CETHA-TE-CR-90062, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, prepared by Argonne National Laboratory, Argonne, Illinois.

Stout, K.K., and M.D. Sitton, 1986, *Comprehensive Summary Report: Joliet Army Ammunition Plant, Joliet, Illinois,* Volumes 1 and 2, Contract 68-03-3161, Environmental Photo Interpretation Center, September.

Underwood, et al., 1983a, *Joliet Army Ammunition Plant — Phase II: Technical Report — TNT Ditch Complex, Red Water Area, Explosive Burning Grounds, and Group 61*, prepared for U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, by Donohue and Associates, Inc., August.

Underwood, et al., 1983b, *Joliet Army Ammunition Plant — Phase II: Geotechnical, Chemical, and Survey Data*, prepared for U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, by Donohue and Associates, Inc., August.

Underwood, et al., 1983c, *Joliet Army Ammunition Plant — Phase II: Technical Report — Excessing Parcels,* prepared for U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland, by Donohue and Associates, Inc., August.

Uniroyal, Inc., 1990, *Analysis Report on PCBs in Soil, Joliet, Illinois: Investigation and Evaluation of Underground Storage Tanks*, prepared for Department of the Army, Corps of Engineers, Huntsville, Alabama, August 22.

USAEHA, 1990, *Storm Water Outfall Evaluations: Joliet Army Ammunition Plant, Joliet, Illinois,* Wastewater Management Consultation 32-24-0029-90, U.S. Army Environmental Hygiene Agency, Aberdeen Proving Ground, Maryland.

U.S. Army, 1978, *Installation Assessment of Joliet Army Ammunition Plant*, Record Evaluation Report No. 128, Office of the Project Manager for Chemical Demilitarization and Installation Restoration, Aberdeen Proving Ground, Maryland, September.

U.S. Army Corps of Engineers, 1950, *Master Plan, Phase II: Analysis of Existing Facilities, Joliet Arsenal, Joliet, Illinois.*

U.S. Army Corps of Engineers, 1989, *Investigation and Evaluation of Underground Storage Tanks, Joliet Army Ammunition Plant, Joliet, Ill.*, prepared for Department of the Army Corps of Engineers, Huntsville Division, Huntsville, Alabama, September.

USATHAMA, 1990, *Quality Assurance Program*, USATHAMA PAM 11-41, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland.

Weston, 1993, *Window Composting Demonstration for Explosives-Contaminated Soils at the Umatilla Depot Activity, Hermiston, Oregon*, CETHA-TS-CR-93043, prepared for U.S. Army Environmental Center, Aberdeen Proving Ground, Maryland, by Roy F. Weston, Inc., Westchester, Pennsylvania, August.

Appendix A:

Drawings Relevant to the Field Demonstration

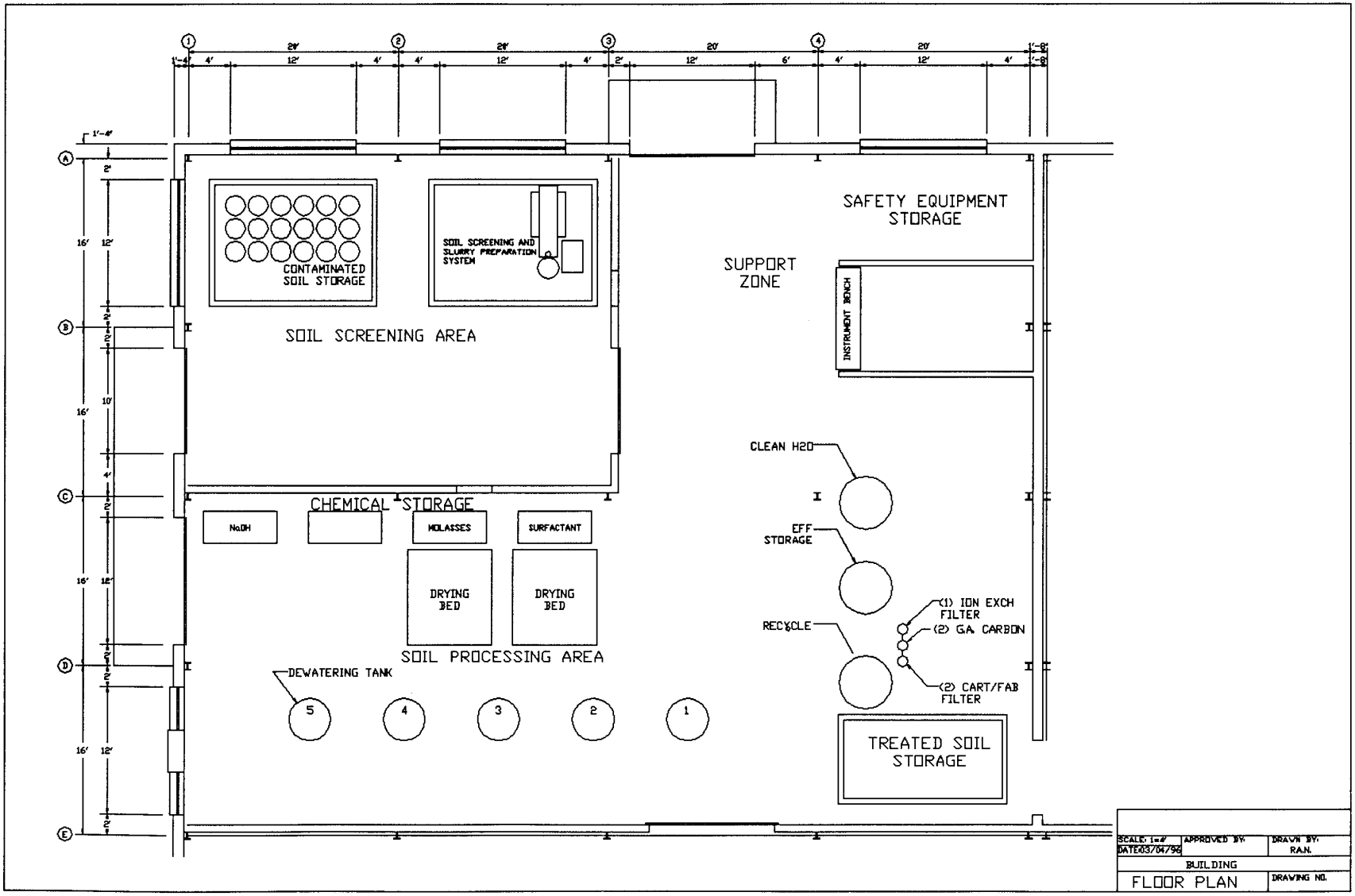


FIGURE A.1 Floor Plan, Part 1

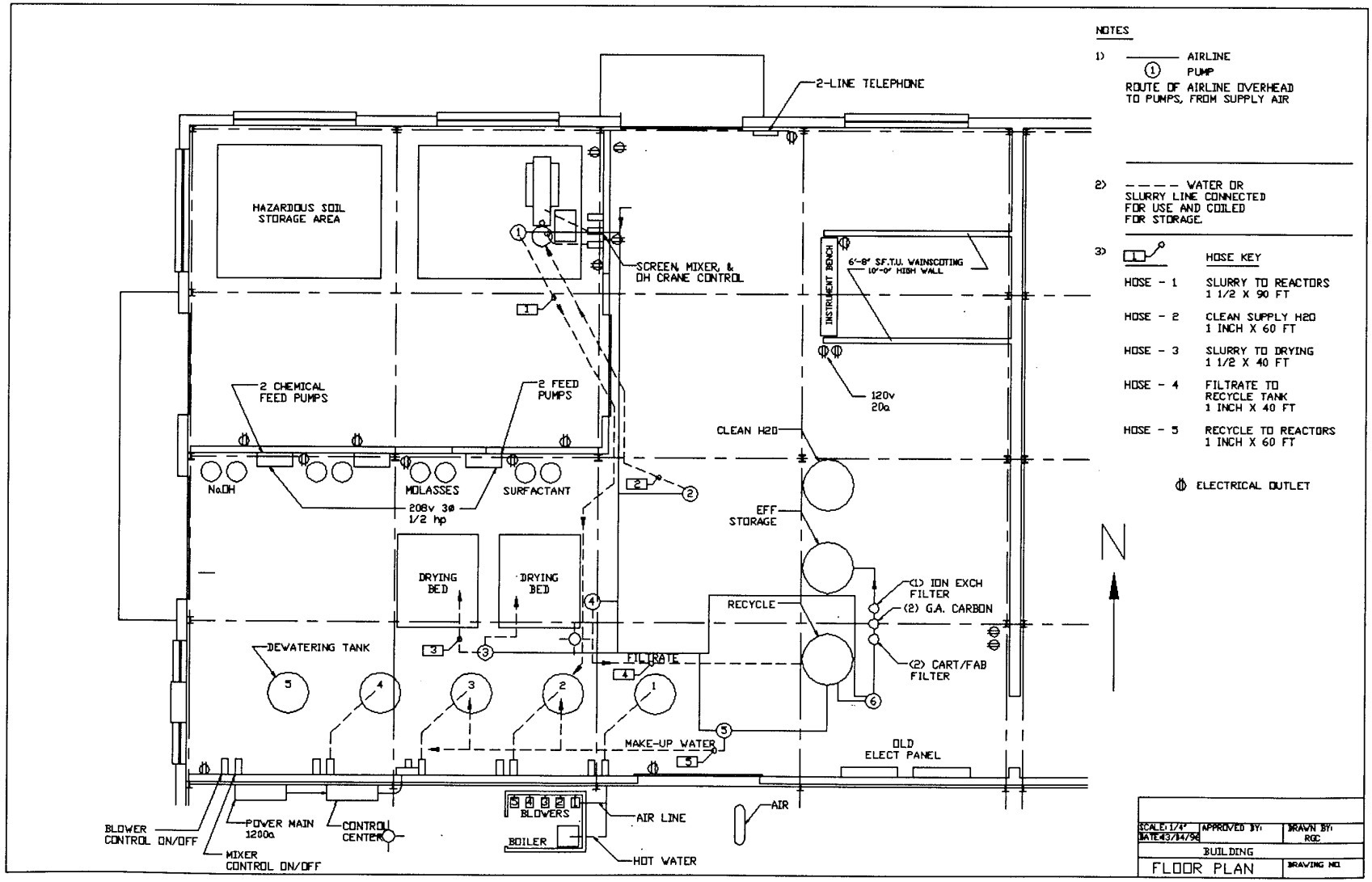


FIGURE A.2 Floor Plan, Part 2

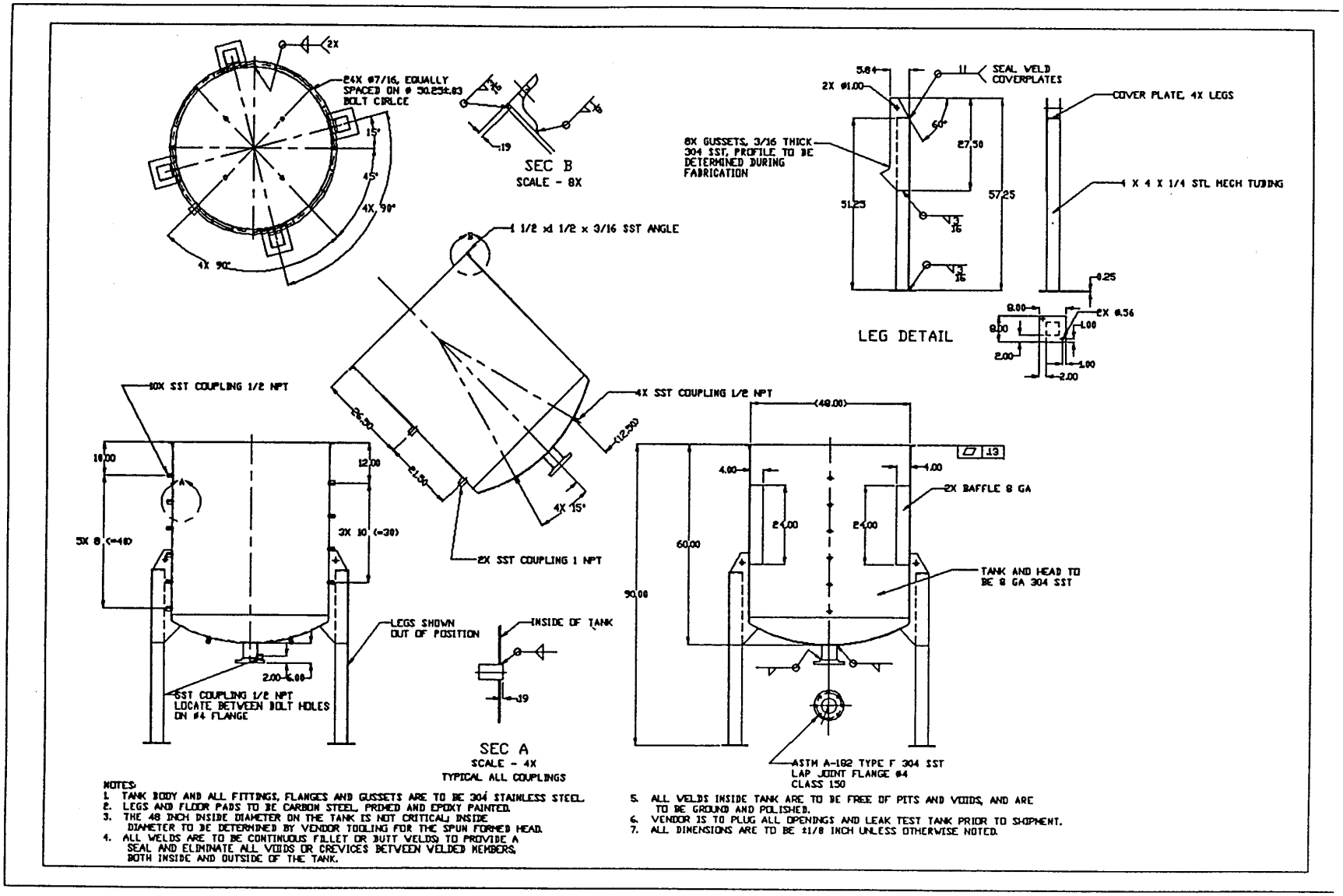


FIGURE A.3 Reactor Tanks

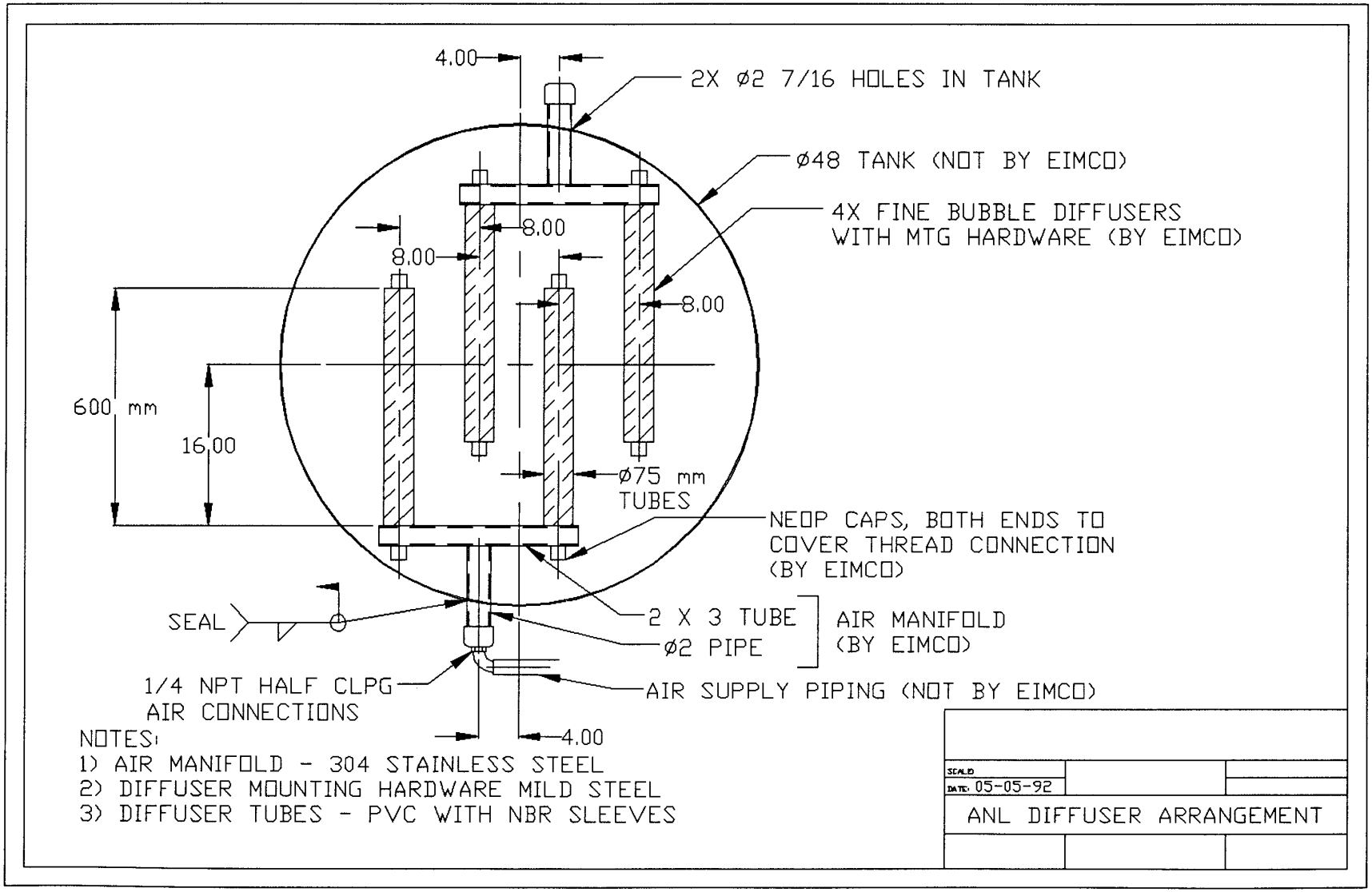


FIGURE A.4 Air Diffuser

Appendix B:

On-Site Analytical Procedures

Appendix B:

On-Site Analytical Procedures

Slurry samples were analyzed by the on-site laboratory primarily for TNT. However, the on-site laboratory had the capability to analyze for all explosive compounds. Slurry was separated into soil and water phases. The slurry was filtered through a 0.45-µm glass fiber filter to provide moist soil and filtrate (contaminated water) for TNT analysis.

B.1 Soil Analysis for Explosives

The following procedure was used to analyze soil samples:

1. Accurately weigh 2 g of moist soil into a 15-mL serum vial. Pipette 5 mL of acetonitrile onto the soil.

2. Place a Teflon-lined septum and cap on the vial. Subject the suspension to vortex mixing for 1 min, and place it in an ultrasonic bath for 18 h.

3. Remove samples from the ultrasonic bath and allow them to settle for 30 min. Remove 5.0 mL of supernatant. Combine it with 5.0 mL of aqueous $CaCl_2$ solution (5 g/L) in a glass scintillation vial. Shake the vial, and allow it to stand for 15 min.

4. Filter the extract as follows: Fit a 10-mL syringe with a needle. Draw the supernatant into the syringe barrel, and replace the needle with a Millex-SR 0.5-µm disposable filter. Force the sample slowly through the filter, and discard the first 2.0 mL. Collect the rest in a 5.0-mL Teflon-capped vial. Store the sample until the extract is analyzed by high-performance liquid chromatography (HPLC).

5. Use an HPLC with an ultraviolet (UV) light detector at 254 nm. Use LC-CN 4.6-mm-i.d. × 25-cm HPLC columns with a particle size of 5-6 µm. The mobile phase is 50% water and 50% methanol. The flow rate is 1.5 mL/min. Detection is at 254 nm, and the injection volume is 100 µL. The injection loop is flushed with 500 µL of sample. Retention times are shown in Table B.1.

TABLE B.1 HPLC Retention Times for Explosives in Soil Samples

Compound	Minutes
HMX	8.4
RDX	6.2
2,4-DNT	4.9
2,6-DNT	4.6
TNT	5.0
Tetryl[a]	7.4
TNB	5.1
2-NT[b]	12.3

[a] Tetryl is N-methyl-N,2,4,6-tetranitroaniline.
[b] NT is nitrotoluene.

6. Calculations

- Response Factors. Because a linear calibration curve with zero intercept is to be expected, calculate results daily by using response factors calculated for each analyte. Obtain the mean response $(\overline{R})$ for each analyte in repeated determinations of standards C-100 and D-100 in units of either peak area or peak height. Obtain the response factor (RF) for each analyte by dividing the mean response by the known solution concentration (C) in units of μg/L: $RF = \overline{R}/C$.

- Analytical Concentration. Obtain the concentration (μg/L) of the analyte (C_a) by dividing the response for each analyte (R_a) by the appropriate response factor (RF_a): $C_a = R_a/RF_a$.

- Concentration in Soil. Obtain the concentration in soil (X_a) in μg/g by multiplying the solution concentration by the volume of extraction solvent (0.01 L) and dividing by the actual mass of dry soil extracted (M): $X_a = C_a \cdot (0.01)/M$.

7. Calibration

- Initial Calibration

  - Preparation of Standards. Dry standards for each analyte to constant weight in a vacuum desiccator in the dark. Weight about 0.25 g of each dried standard analytical reference material (SARM) to the nearest 0.1 mg, transfer the SARMs to individual 250-mL volumetric flasks, and dilute the contents of each flask to volume with acetonitrile. Store stock solutions in a refrigerator at 4°C in the dark. Stock standards are good for periods up to a year after the date of preparation.

    Prepare two combined-analyte stock standards (A and B) as follows: For stock standard A, combine 5.0 mL each of HMX, RDX, TNB, 1,3-dinitrobenzene (DNB), tetryl (N-methyl-N,2,4,6-tetranitroaniline), TNT, and 2,4-DNT stock standards in a 250-mL volumetric flask and dilute to volume with acetonitrile. Stock standard B is prepared in an identical manner with NB (nitrobenzene), 2,4-DNT, 2,6-DNT, 2-NT (nitrotoluene), 4-NT, and 3-NT stock standards.

    To prepare the calibration standards, place 5.00 mL of stock standards A and B in separate 100-mL volumetric flasks and dilute to volume with acetonitrile. These standards, C-100 and D-100, contain each analyte at approximately 1,000 µg/L. Obtain further dilutions of C-100 as shown in Table B.2. Obtain dilutions for D-100 separately in an identical manner. Dilute all standards 1:1 with aqueous $CaCl_2$ (5 g/L) before injection.

  - Instrument Calibration. Sequentially inject duplicate aliquots of each standard over the concentration range of interest into the HPLC in random order. Obtain peak areas or peak heights for each analyte. Retention times for the various analytes are shown in Table B.1.

  - Analysis of Calibration Data. Assess the acceptability of a linear model with zero intercept by using the protocol specified by USATHAMA (1990). Experience indicates that a linear model with zero intercept is appropriate in all cases. Therefore, the slope of the best-fit regression line is equivalent to a response factor that can be compared with values obtained from replicate analyses of a single standard each day.

TABLE B.2 Preparation of Calibration Standards

Standard	Volume of Standard C (mL)	Size of Volumetric Flask (mL)	Approximate Concentration (µg/L)
C-100	Straight	-	1,000
C-50	25	50	500
C-20	10	50	200
C-10	10	100	100
C-5	5	100	50
C-2	2	100	20
C-1	1	100	10
C-0.5	0.5	100	5

- Daily Calibration

  Use standards C-100 and D-100, as described above, for daily calibration. These standards can be used for 30 days after preparation. Analyze each in triplicate at the beginning of the day, singly after the midpoint of the run, and singly after the last sample of the day. Calculate response factors for each analyte by comparing the mean peak areas or peak heights obtained over the course of the day with the response factor obtained for the initial calibration. The mean response factors for the first seven daily calibrations must be within 25% of the response factors obtained for the initial calibration. Subsequent response factors must be within two standard deviations of the initial calibration. If these criteria are not met, a new initial calibration must be performed.

- Preparation of Spiking Solutions

  Prepare individual stock analyte spiking solutions in a manner identical to that described for the stock calibration standards. Prepare two combined-analyte spiking standards as follows: for combined stock spiking solution A, combine 2.00 mL each of HMX, RDX, TNB, DNB, tetryl, TNT, and 2,4-DNT in a 200-mL volumetric flask. Dilute to volume with acetonitrile. The analyte concentrations in this solution (X-100) are about 10 µg/L. Prepare diluted spiking solutions as shown in Table B.3.

TABLE B.3 Preparation of Spiking Solutions

Standard	Volume of Combined Stock Spiking Solution (mL)	Size of Volumetric Flask (mL)	Approximate Concentration (µg/L)
X-100	Straight	-	100
X-50	50	100	5
X-20	20	100	2
X-10	10	100	1
X-5	5	100	0.5
X-2	2	100	0.2
X-1	1	100	0.1
X-0.5	1	200	0.05

- Preparation of Control Spikes

  Prepare spiked soil samples by placing a series of 2.00-g subsamples of USATHAMA standard soil in individual 15-mL glass vials. Spike each tube by adding 1.00 mL of one of the spiking standards described in Table B.3. Allow the tubes to stand uncapped for 18 h before the extraction solvent is added.

- Analysis of Soil Spikes

  Process and analyze soil spikes as described in points 1-5 of this procedure for unknown samples.

8. Use the following daily protocol for sample analysis:

   - Generate a full calibration curve and perform linear regression analysis for all analytes.

   - Run quality assurance/quality control (QA/QC) samples.

   - Run sample extracts.

- Run final calibration standards.

Dilute samples with the mobile phase as necessary to bring the target analytes into the calibration range.

9. Analyze the following QA/QC samples with each batch of soil samples:

- Method blank
- 2× standard soil spike
- 10× standard soil spike
- 10× standard soil spike duplicate

10. Sample Handling and Storage

- Storage. Store all soil samples in a refrigerator at 4°C in the dark until they are extracted. Air-dry and process samples as soon as possible after receipt, always within 7 days.
- Soil Drying/Homogenization. Air-dry soil samples to constant weight before extraction. Ensure that the soil is not exposed to direct sunlight during the drying period. Thoroughly grind and homogenize dried soil in a roller mill or by manual shaking in a closed container. Clean the mortar and pestle with solvent between samples.
- Containers. Clean all containers used to store wet or dried soil according to procedures specified by USATHAMA (1990). Rinse the containers with acetonitrile.

B.2 Water Analysis for Explosives

The following procedure was used to analyze water samples:

1. Analyze liquid samples for explosives by using a method that involves extraction and HPLC detection. Use the following procedure for sample extraction and preparation:

   - Filter slurry samples through a 0.45-µm glass fiber filter. The filtrate is used in the analysis.

   - Prepare samples and standard solutions for analysis by combining a 5.00-mL aliquot with an equal volume of methanol in a scintillation vial, shaking thoroughly, and filtering through a 0.5-µm Millex-SR filter. Discard the first 3 mL of solution, and collect the remainder in a clean scintillation vial. These filtered solutions will be referred to as sample solutions.

   - Determine the explosives concentrations by using reversed-phase HPLC with UV detection at 254 nm. Use a Supelco LC-18 RP-HPLC column, 4.6 mm i.d., 25 cm long, with a particle size of 5-6 µm. The mobile phase will be 50% methanol and 50% water (V/V). The flow rate will be 1.5 mL/min. The injection volume will be 100 µL. The sample loop will be flushed with 500 µL of sample. Retention times are as shown in Table B.4.

TABLE B.4 HPLC Retention Times for Explosives in Water Samples

Compound	Minutes
HMX	2.44
RDX	3.73
TNT	8.42
2,4-DNT	10.05
TNB	5.1
2-NT	12.3

2. Determine the sample concentration as follows:

   - Response Factors. Because a linear calibration curve with zero intercept is to be expected, calculate results daily by using response factors calculated for each analyte. Obtain the mean response $(\overline{R})$ for each analyte from repeated determinations of standards in units of either peak area or peak height. Obtain the response factor (RF) for each analyte by dividing the mean response by the known concentration (C) in units of µg/L: $RF = \overline{R}/C$.

   - Analytical Concentration. Obtain the concentration (µg/L) of each analyte (C_a) by dividing the response for each analyte (R_a) by the appropriate response factor (RF_a): $C_a = R_a/RF_a$.

3. Calibration

   - Preparation of Standards. Dry standards for each analyte to constant weight in a vacuum desiccator in the dark. Weigh about 0.1 g (100 mg) of each dried SARM to the nearest 0.1 mg, and transfer it to a 100-mL volumetric flask. Dilute to volume with HPLC-grade acetonitrile. Store stock standards in a refrigerator at 4°C in the dark. Stock standards are usable for periods up to a year after the date of preparation.

     If both 2,4-DNT and 2,6-DNT are to be determined, prepare two separate combined-analyte stock standards. For stock standard 1, combine 10.0 mL of the HMX and RDX stock standards and 5.0 mL of the TNB, DNB, NB, TNT, and 2,4-DNT stock standards in a 500-mL volumetric flask. Dilute to volume with methanol. This solution contains 20,000 µg/L of HMX and RDX and 10,000 µg/L of TNB, DNB, NB, TNT, and 2,4-DNT. Prepare stock solution 2 by combining 10.0 mL of the tetryl and 5.0 mL of the 2,6-DNT, 2-NT, 3-NT, and 4-NT stock solutions in a 500-mL volumetric flask. Dilute to volume with methanol. This solution contains 20,000 µg/L of tetryl and 10,000 µg/L of 2,6-DNT, 2-NT, 3-NT, and 4-NT.

     Pipette a 10.0-mL aliquot of combined stock standard 1 into a 100-mL volumetric flask. Dilute to volume with methanol, giving a concentration of approximately 2,000 µg/L of HMX and RDX, and approximately 1,000 µg/L of the remaining analytes. This solution will be referred to as solution A. Similarly, dilute a 10.0-mL aliquot of combined stock

standard 2 to 100 mL with methanol, giving a concentration of 2,000 µg/L of tetryl and 1,000 µg/L of 2,6-DNT, 2-NT, 3-NT, and 4-NT. This solution will be referred to as solution AA. From solutions A and AA, prepare two identical series of working standard as described in Tables B.5 and B.6.

TABLE B.5 Calibration Standards from Solution A

Standard	Aliquot of Solution A (mL)	Size of Volumetric Flask (mL)	Concentration (µg/L) HMX, RDX	Concentration (µg/L) TNB, DNB, NB, TNT, and 2,4-DNT
B	25.0	50	1,000	500
C	25.0	100	500	250
D	10.0	100	200	100
E	5.0	100	100	50
F	5.0	200	50	25
G	1.0	100	20	10
H	10.0 of E	100	10	5
I	5.00 of E	100	5	2.5

TABLE B.6 Calibration Standards from Solution AA

Standard	Aliquot of Solution AA (mL)	Size of Volumetric Flask (mL)	Concentration (µg/L) Tetryl	Concentration (µg/L) 2,6-DNT, 2-NT, 3-NT, and 4-NT
BB	25.0	50	1,000	500
CC	25.0	100	500	250
DD	10.0	100	200	100
EE	5.0	100	100	50
FF	5.0	200	50	25
GG	1.0	100	20	10
HH	10.0 of EE	100	10	5
II	5.00 of EE	100	5	2.5

- Initial Calibration. Dilute all of the standards 5/5 (V/V) with water in scintillation vials and shake well (by hand) before analyzing. Make duplicate injections of each standard over the concentration range of interest in random order. Obtain peak areas or peak heights for each analyte. Retention times for the analytes under these conditions are presented in Table B.4.

- Analysis of Calibration Data. Assess the acceptability of a linear model with zero intercept by using the protocol specified in the USATHAMA *Quality Assurance Program* (January 1990). Experience indicates that a linear model with a zero intercept is appropriate. Thus, the slope of the best-fit regression line is equivalent to a response factor that can be compared with values obtained from replicate analyses of a single standard each day.

- Daily Calibration. Use standards B and BB, described in Tables B.5 and B.6, for daily calibrations after each is diluted 5/5 (V/V) with water. Standards B and BB can be used for 28 days after preparation. Analyze standards in triplicate at the beginning of each day, singly after the last sample of the day, and singly at the midway point of the analyses of each day. Obtain response factors for each analyte over the course of the day and compare them with the response factors obtained for the initial calibration. The mean response factors for the first seven daily calibrations must be within 25% of the response factors obtained for the initial calibration. Subsequent response factors must be within two standard deviations of the initial calibration. If these criteria are not met, a new initial calibration must be performed.

4. Daily Quality Control

Control Spikes. Prepare spiked water samples as described for the Class 1 method in the USATHAMA *Quality Assurance Program* (January 1990). This procedure requires the use of a method blank, a single spike at two times the certified reporting limit, and duplicate spikes at ten times the certified reporting limit for each analytical lot. Prepare control spikes by using the appropriate spiking solution in the manner described in Tables B.5 and B.6.

Appendix C:

Daily Operating Data

TABLE C.1 Report of Operation for Control Reactor (Reactor 1) (mixer speed = 80%)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
7/1/94					Control	Control	Control	Not recorded	
7/2/94					reactor;	reactor;	reactor;	this month	
7/3/94					none added.	none added.	none added.		
7/4/94									
7/5/94									
7/6/94									
7/7/94									
7/8/94									
7/9/94									
7/10/94									
7/11/94									
7/12/94				6.0->8.6					
7/13/94									
7/14/94									
7/15/94									
7/16/94									
7/17/94									
7/18/94									
7/19/94									
7/20/94									
7/21/94									
7/22/94									
7/23/94									
7/24/94									
7/25/94									Mixed all weekend with
7/26/94									vents open.
7/27/94									
7/28/94									
7/29/94									
7/30/94									
7/31/94									

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
8/1/94					Control	Control	Control	Close to	
8/2/94					reactor;	reactor;	reactor;	Reactor 1	
8/3/94					none added.	none added.	none added.	temperature	
8/4/94	26.7	8.3	7.8					this month.	
8/5/94									
8/6/94									
8/7/94									
8/8/94									No foam.
8/9/94	25.4	8.3	6.8	8.4/9.2					
8/10/94	24.7		7.7						
8/11/94									
8/12/94									
8/13/94									
8/14/94									Electric power off 7 p.m., Sun.
8/15/94									8/14, due to storm; restart
8/16/94	24.0	8.4	7.9						mixers 2 p.m., 8/15/94.
8/17/94	24.2	8.3	7.8						8 a.m. VIP visit.
8/18/94									
8/19/94	26.3	8.3	7.6						
8/20/94									
8/21/94									
8/22/94	25.6	8.2	7.7	9.1					
8/23/94	25.8	8.2	7.2						
8/24/94	25.7	8.3	7.2	8.0					
8/25/94	26.9	8.4	7.5						
8/26/94									
8/27/94									
8/28/94									
8/29/94	26.7	8.4	7.4						
8/30/94	26.1	8.3	7.1	8.0					
8/31/94	24.5	8.4	7.7						

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
9/1/94	25.2	8.4	7.5	8.0	Control	Control	Control	22	
9/2/94	23.1	8.4	7.8		reactor;	reactor;	reactor;		
9/3/94					none added.	none added.	none added.		
9/4/94									
9/5/94									
9/6/94									
9/7/94	23.1	8.4	7.9	9.9					
9/8/94	23.3	8.4	8.0					20	
9/9/94									
9/10/94									
9/11/94	23.7	8.3	7.9					24	
9/12/94	26.1	8.4	7.4						
9/13/94	25.6	8.3	7.3						
9/14/94	26.5	8.3	7.4						
9/15/94									
9/16/94								30	
9/17/94									
9/18/94									
9/19/94	25.2	7.0	6.4						
9/20/94	24.8	6.9	5.8						
9/21/94	28.6	6.6	0.1(?)	10.2					
9/22/94									
9/23/94	24.0	6.9(?)	3.6(?)						
9/24/94									
9/25/94									
9/26/94	21.0	7.0	7.8					16	
9/27/94									
9/28/94	20.7	6.7	8.4	10.7				16	
9/29/94	19.0	8.2	8.9	9.0					
9/30/94	18.9	8.3	8.7						

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
10/1/94					Control	Control	Control		
10/2/94					reactor;	reactor;	reactor;		
10/3/94	20.4	8.4	8.3		none added.	none added.	none added.		
10/4/94	20.2	8.3	8.4						
10/5/94	20.0	8.3	8.4						
10/6/94	19.1	8.3	8.4					17	
10/7/94	20.0	8.3	8.5	10.0				18	
10/8/94									
10/9/94									
10/10/94	17.1	8.2	9.4					13	
10/11/94	17.0	8.3	9.1					14	
10/12/94	17.0	8.4	9.1						
10/13/94	17.7	8.3	9.1	9.4				16	
10/14/94	18.5	8.3	9.0						
10/15/94									
10/16/94									
10/17/94	20.1	8.3	8.5					18	
10/18/94	20.8	8.2	8.4						
10/19/94	20.7	8.2	8.4						
10/20/94	20.7	8.3	8.3	10.0				16	
10/21/94	19.9	8.3	8.4					15	
10/22/94								14	
10/23/94									
10/24/94	18.6	8.2	8.9					14	
10/25/94	16.8	8.3	9.0					12	
10/26/94	15.4	8.3	9.2					11	
10/27/94	14.5	8.3	9.7	9.6				11	
10/28/94	14.6	8.3	9.8					11	
10/29/94									
10/30/94									
10/31/94	15.9	8.3	9.3	9.7				8->13	

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
11/1/94	13.5	8.3	9.9		Control	Control	Control	8	
11/2/94	13.2	8.3	9.7	10.3	reactor;	reactor;	reactor;	10	
11/3/94	14.2	8.3	9.6		none added.	none added.	none added.	14	
11/4/94	16.0	8.3	9.3					17	
11/5/94									
11/6/94									
11/7/94	15.5	8.3	9.5					12	
11/8/94	14.7	8.4	9.4					13	
11/9/94	14.9	8.2	9.4	9.4				14	
11/10/94	14.1	8.4	9.5					10	
11/11/94	13.6	8.4	9.6					10	
11/12/94									
11/13/94									
11/14/94	15.0	8.4	9.4					15	
11/15/94	14.6	8.3	9.3	10.3				11	
11/16/94	14.0	8.3	9.4					9	
11/17/94	13.0	8.5	9.8					10	
11/18/94	13.8	8.4	9.8					10	
11/19/94									
11/20/94									
11/21/94	12.3	8.2	10.5					9	
11/22/94								3	
11/23/94	9.1	8.4	11.2					3	
11/24/94									
11/25/94									
11/26/94									
11/27/94									
11/28/94	9.3	8.3	11.1	9.7				4	
11/29/94	8.2	8.5	10.8					3	
11/30/94	7.4	8.3	11.3					3	

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
12/1/94	7.1	8.4	10.8		Control	Control	Control	4	
12/2/94	8.1	8.3	11.3		reactor;	reactor;	reactor;	6	
12/3/94					none added.	none added.	none added.		
12/4/94									
12/5/94	11.5	8.2	10.3					10	
12/6/94	11.2	8.3	10.4					7	
12/7/94	10.3	8.3	10.5					6	
12/8/94	9.2	8.2	10.8					5	
12/9/94	8.4	8.0	11.1					4	
12/10/94									
12/11/94									
12/12/94	4.4	8.4	12.5					1	
12/13/94	4.5	8.4	12.4					4	
12/14/94	5.0	8.5	12.2					2	
12/15/94	5.1	8.4	12.2					3	
12/16/94	5.9	8.4	11.8					4	
12/17/94									
12/18/94									
12/19/94	5.8	8.2	11.7	9.7				4	
12/20/94	5.8	8.2	11.2					4	
12/21/94	6.4	8.2	10.8					4	
12/22/94								4	
12/23/94								4	
12/24/94									
12/25/94									
12/26/94									
12/27/94	7.4	8.0	11.1	8.9				4	
12/28/94	7.8	8.0	11.0					4	
12/29/94	7.5	8.1	11.3					5	
12/30/94									
12/31/94									

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
1/1/95					Control	Control	Control		
1/2/95					reactor;	reactor;	reactor;		Holiday.
1/3/95	1.7		13.3		none added.	none added.	none added.	-5	Too cold for pH probe.
1/4/95	0.1		7.5					-11	Too cold for pH probe.
1/5/95	1.3		13.7					-9	Too cold for pH probe.
1/6/95	8.7	8.0	11.0					-4	
1/7/95									
1/8/95									
1/9/95	16.5	7.8	9.5					-3	
1/10/95	16.2	7.9	9.0	9.2				-1	
1/11/95	14.7	8.1	9.4					0	
1/12/95	14.1	8.1	9.7					4	
1/13/95	13.6	8.2	9.8					3	
1/14/95									
1/15/95									
1/16/95	12.6	8.1	10.0					3	
1/17/95	12.2	8.0	10.1					3	
1/18/95	12.0	8.0	10.1					3	
1/19/95	11.9	8.2	9.8					3	
1/20/95	11.8	8.2	9.9					0	
1/21/95									
1/22/95									
1/23/95	8.7	8.2	10.4					-5	
1/24/95	8.1	8.2	10.6					-5	
1/25/95								-3	
1/26/95	6.6	7.8	10.0					-3	
1/27/95	8.7	8.1	10.3					-1	
1/28/95									
1/29/95									
1/30/95	8.1	7.8	9.3					-2	
1/31/95	8.1	7.6	10.8					-1	

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
2/1/95	8.6	7.6	10.4		Control	Control	Control	2	
2/2/95	9.6	7.6	10.5		reactor;	reactor;	reactor;	7	
2/3/95	11.4	7.9	10.2		none added.	none added.	none added.	13	New heater on.
2/4/95									
2/5/95									
2/6/95	14.7	7.9	9.1					10	
2/7/95	15.5	7.9	9.7					13	
2/8/95	16.2	7.9	9.7					10	
2/9/95	16.4	8.4	9.3					12	
2/10/95	16.6	8.3	8.9					12	
2/11/95									
2/12/95									
2/13/95	17.3	8.5	9.4					10	
2/14/95	17.8	8.4	8.9					10	
2/15/95	17.7	8.5	9.1	9.3				12	
2/16/95	17.7	8.5	9.1					11	
2/17/95	18.4	8.2	8.0					13	
2/18/95									
2/19/95									
2/20/95	19.2	8.0	7.5					14	
2/21/95	20.4	8.0	7.6					17	
2/22/95	20.7	8.0	7.7					15	
2/23/95	20.9	7.9	7.9					17	
2/24/95	21.3	8.2	8.5					16	
2/25/95									
2/26/95									
2/27/95	21.7	8.3	8.1					15	
2/28/95	21.7	8.3	8.1					15	

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
3/1/95					Control	Control	Control	14	
3/2/95	21.5	8.2	7.8		reactor;	reactor;	reactor;	14	
3/3/95	21.7	8.2	7.8		none added.	none added.	none added.	14	
3/4/95									
3/5/95									
3/6/95	21.3	8.2	8.2					15	
3/7/95	22.1	8.2	8.2					17	
3/8/95	22.7	8.2	8.1					18	
3/9/95	22.9	8.2	7.9					17	
3/10/95								17	
3/11/95									
3/12/95									
3/13/95	24.7	8.3	7.8					18	
3/14/95	24.8	8.2	7.6					18	
3/15/95	24.5	8.2	7.5					16	
3/16/95	24.2	8.3	7.6					17	
3/17/95	24.1	8.2	7.5					17	
3/18/95									
3/19/95									
3/20/95	24.5	8.2	7.7						
3/21/95	24.4	8.2	7.8					16	
3/22/95	24.0	8.2	7.8					18	
3/23/95	23.7	8.1	8.0						
3/24/95								16	
3/25/95									
3/26/95									
3/27/95	23.8	8.2	7.9					16	
3/28/95	23.9	8.2	7.9					19	
3/29/95	24.4	8.0	7.7	8.6				20	
3/30/95	25.8	8.2	7.6					20	
3/31/95	25.0	8.2	7.6					21	

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
4/1/95					Control	Control	Control		
4/2/95					reactor;	reactor;	reactor;		
4/3/95	26.4	8.2	7.5		none added.	none added.	none added.	22	Light foam.
4/4/95	26.2	8.2	7.4					17	
4/5/95	25.2	8.2	7.4					17	
4/6/95	25.3	8.2	7.4					20	
4/7/95	25.9	8.1	7.6					20	
4/8/95									
4/9/95									
4/10/95	24.6	7.7	7.6	8.7					
4/11/95	24.8	8.0	7.8					19	
4/12/95	25.1	8.0	7.7					19	
4/13/95	25.4	8.1	7.6					18	
4/14/95								20	
4/15/95									
4/16/95									
4/17/95	27.5	8.1	7.3					23	
4/18/95								18	
4/19/95	24.9	8.2	7.7					19	
4/20/95								16	
4/21/95									
4/22/95									
4/23/95									
4/24/95	22.1	8.1	8.1					19	
4/25/95	21.8	8.1	8.0					18	
4/26/95	21.7	7.9->8.2	8.3					20	
4/27/95	21.5	8.2	8.3					19	
4/28/95	22.2	7.9	7.8					20	
4/29/95									
4/30/95									

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
5/1/95	20.1	8.1	7.9		Control	Control	Control	20	
5/2/95	20.8	8.1	8.5		reactor;	reactor;	reactor;	20	
5/3/95	21.2	8.0	8.3		none added.	none added.	none added.	20	
5/4/95	21.5	8.1	8.3	10.1				21	
5/5/95	21.6	8.2	8.1					20	
5/6/95									
5/7/95									
5/8/95	23.0	7.6	8.0					20	
5/9/95	21.8	7.8	8.3					20	
5/10/95	22.0	7.8	8.2					22	
5/11/95	22.1	8.3	8.3	8.8				21	
5/12/95	22.6	8.3	8.2					20	
5/13/95									
5/14/95									
5/15/95	23.5	7.7	8.1					22	
5/16/95	23.8	8.2	8.2					22	
5/17/95	24.1	7.9	7.8					22	
5/18/95	22.8	7.8	8.1					20	
5/19/95	20.5	8.2	8.6					16	
5/20/95									
5/21/95									
5/22/95	22.6	7.8	8.1					21	
5/23/95	21.9	8.1	8.1					21	
5/24/95	21.7	8.3	8.2					19	
5/25/95	20.4	8.2	8.6	9.3, 9.5, 8.3				16	
5/26/95	20.7	8.3	8.6					19	
5/27/95									
5/28/95									
5/29/95									Holiday.
5/30/95	22.6	8.3	8.2					21	
5/31/95	23.4	7.7	8.1					22	Boiler off for summer.

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
6/1/95	23.7	8.2	8.2		Control	Control	Control	22	
6/2/95	24.1	7.9	8.6		reactor;	reactor;	reactor;	22	
6/3/95					none added.	none added.	none added.		
6/4/95									
6/5/95	24.1	8.2	8.2					23	
6/6/95		8.2						22	
6/7/95	24.4	8.2	7.9					25	
6/8/95	24.2	8.1	8.1					22	
6/9/95	22.8	8.2	8.4					20	
6/10/95									
6/11/95									
6/12/95	23.5	8.2	7.9					21	
6/13/95	23.5	8.2	7.8					20	
6/14/95	23.2	8.1	8.2					22	
6/15/95	23.8	8.2	8.1					23	
6/16/95	25.1	8.1	7.9					23	
6/17/95									
6/18/95									
6/19/95	27.8	8.4	7.8					26	
6/20/95	28.5	8.1	7.6					27	
6/21/95	28.4	8.1	7.5	10.8				26	
6/22/95	28.4	8.0	7.2					25	
6/23/95	28.2	8.2	7.3					27	
6/24/95									
6/25/95									
6/26/95	28.5	7.9	7.3					26	
6/27/95	27.6	8.1	7.4					24	
6/28/95	27.1	8.2	7.4					24	
6/29/95	27.0	8.0	7.5					24	
6/30/95	26.5	8.1	7.5					23	

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
7/1/95					Control	Control	Control		
7/2/95					reactor;	reactor;	reactor;		
7/3/95	26.0	8.1			none added.	none added.	none added.		C. Leser.
7/4/95									Holiday.
7/5/95	27.1	8.0	7.8					27	
7/6/95	26.5	8.1	7.7	9.1				23	
7/7/95	26.4	8.2	7.8					22	
7/8/95									
7/9/95									
7/10/95	27.1	8.1	7.4					24	
7/11/95	27.4	8.2	7.3					26	
7/12/95	28.4	8.2	7.7					27	
7/13/95	28.9	8.1	7.6					28	
7/14/95								30	
7/15/95									
7/16/95									
7/17/95	31.5	8.0	6.9					27	
7/18/95	31.0	8.2						25	
7/19/95	28.5	8.3		8.6				26	No dissolved oxygen probe.
7/20/95	28.0	8.4						26	No dissolved oxygen probe.
7/21/95	27.5	8.4						25	No dissolved oxygen probe.
7/22/95									
7/23/95									
7/24/95	28.7	8.4	7.2					25	
7/25/95	28.9	8.4	6.9					26	
7/26/95	29.0	8.4	7.1					26	
7/27/95	28.5	8.3	7.3					26	
7/28/95	28.5	8.4	7.1					26	
7/29/95									
7/30/95									
7/31/95	29.4	8.4	7.1					28	

TABLE C.1 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
8/1/95	29.8	8.3	7.1		Control	Control	Control	28	
8/2/95	29.4	8.4	7.2		reactor;	reactor;	reactor;	28	
8/3/95	28.3	8.4	7.3		none added.	none added.	none added.	25	
8/4/95	27.7		7.1					26	
8/5/95									
8/6/95									
8/7/95	28.8	8.3	7.1					26	Aerate to test foam control.
8/8/95	28.6	8.3	7.1					27	
8/9/95	28.1	8.4	7.1					26	
8/10/95	27.4	7.7	7.2					25	Mixer off.
8/11/95	27.6	8.3	7.5					26	
8/12/95									
8/13/95									
8/14/95	30.4	8.3	7.2					32	
8/15/95	30.8	8.3	7.1					28	
8/16/95	30.3	8.3	7.1					29	
8/17/95	29.3	8.2	7.1					26	
8/18/95	29.0	8.3	7.2					27	
8/19/95									
8/20/95									
8/21/95	28.9	8.2	7.3					28	
8/22/95	28.7	8.3	7.4					25	
8/23/95	27.9	8.3	7.7					24	
8/24/95	27.8	8.3	7.3					26	
8/25/95	28.0	8.3	7.3					26	
8/26/95									
8/27/95									
8/28/95	28.8	8.3	7.2					27	
8/29/95	29.0	8.3	7.3					27	
8/30/95	29.0	8.3	7.2					27	
8/31/95	29.0	8.3	7.2					27	

TABLE C.2 Report of Operation for 20% Replacement Reactor (Reactor 2) (mixer speed = 80%)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
7/1/94					None this	None this	None this	No record	
7/2/94					month.	month.	month.	this month.	
7/3/94									
7/4/94									
7/5/94									
7/6/94									
7/7/94									
7/8/94									
7/9/94									
7/10/94									
7/11/94									
7/12/94				9.2					
7/13/94									
7/14/94									
7/15/94									
7/16/94									
7/17/94									
7/18/94									
7/19/94									
7/20/94									
7/21/94									
7/22/94									
7/23/94									
7/24/94									
7/25/94									Mix all weekend with vents open.
7/26/94									
7/27/94									
7/28/94									
7/29/94									
7/30/94									
7/31/94									

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
8/1/94					None this		None this	No record	
8/2/94					month.		month.	this month.	
8/3/94									
8/4/94	27.1	7.4	6.2						
8/5/94									
8/6/94									
8/7/94									
8/8/94									2 in. foam.
8/9/94	25.4	7.6	6.8	10.7/11.1		0.5			
8/10/94	25.3		5.9						12 in. foam.
8/11/94									
8/12/94									
8/13/94									
8/14/94									Electric power off 7 p.m., Sun.
8/15/94									8/14, due to storm; restart
8/16/94	24.8	7.5	6.1						mixers 2 p.m., 8/15/94.
8/17/94	25.5	7.4	5.7						8 a.m. VIP visit.
8/18/94									
8/19/94	26.5	7.8	7.0						
8/20/94									
8/21/94									
8/22/94	26.1	6.8	2.8	10.8		1			
8/23/94	26.8	6.6	0.0						
8/24/94	28.4	7.4	4.6	11.0					Began feeding 5 mL antifoam
8/25/94	29.0	6.9	0.1						today only.
8/26/94									
8/27/94									
8/28/94									
8/29/94	27.9	6.9	2.2			1			Added antifoam (25 mL concen-
8/30/94	27.6	6.7	0.1	11.0					trated silicone antifoam).
8/31/94	27.2	7.4	1.6						

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
9/1/94	25.6	6.9	0.1	11.0			None this	22	Added 10 mL antifoam.
9/2/94	24.9	7.0	0.9			1	month.		
9/3/94									
9/4/94									
9/5/94									
9/6/94									
9/7/94	24.0	6.5	0.2	11.6		1			Added 10 mL antifoam.
9/8/94	24.5	6.9	0.2					20	
9/9/94									
9/10/94									
9/11/94	25.3	6.5	0.2						
9/12/94	29.5	7.7	5.0					24	Added 20 mL antifoam.
9/13/94	29.2	7.7	4.9						
9/14/94	28.0	6.4	0.2						Added 25 mL antifoam.
9/15/94									
9/16/94						1		30	
9/17/94									
9/18/94									
9/19/94	26.0	6.8	0.3						
9/20/94	25.1	6.8	1.1		20				
9/21/94	28.2	6.5	0.2	10.7					
9/22/94									
9/23/94	24.4	6.8	0.2			1			
9/24/94									
9/25/94									
9/26/94	22.2	6.8	0.5					16	
9/27/94					0				No replacement slurry. Valves
9/28/94	23.2	6.9	5.5	9.9				16	blocked.
9/29/94	20.6	7.4	3.0	10.2					
9/30/94	20.3	7.3	6.0						

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
10/1/94							None this		
10/2/94							month.		
10/3/94	21.9	6.3	0.1						
10/4/94	23.9	7.7	0.2	10.5	20				
10/5/94	21.8	7.4	5.5						
10/6/94	20.8	7.4	2.3					17	
10/7/94	21.3	7.3	4.7	11.0		1		18	
10/8/94									
10/9/94									
10/10/94	18.4	6.2	0.3		20			13	
10/11/94	20.0	7.4	2.0					14	
10/12/94	19.7	7.2	0.3						
10/13/94	19.9	7.4	6.2	10.6				16	
10/14/94	20.2	7.2	3.9			1			
10/15/94									
10/16/94									
10/17/94	21.3	6.3	0.2					18	
10/18/94	21.8	6.7	0.6		20	0.5			
10/19/94	22.0	6.2	0.5						
10/20/94	21.6	6.4	0.2	11.0				16	
10/21/94	21.0	6.5	0.6->0.2			0.5		15	
10/22/94								14	
10/23/94									
10/24/94	19.3	6.4	0.2			0.5		14	Molasses to make up for
10/25/94	17.9	6.3	0.2		20	0.5		12	shortage on 10/21/94.
10/26/94	16.5	6.3	0.2					11	
10/27/94	15.7	6.4	0.1	11.7				11	
10/28/94	15.7	6.5	0.1			1		11	
10/29/94									
10/30/94									
10/31/94	19.5	6.9	0.1	11.5				8->13	

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
11/1/94	16.6	6.8	0.1		20	0.5	None this	8	Tracking study.
11/2/94	14.9	6.3	0.1	11.5			month.	10	
11/3/94	15.7	6.4	0.1					14	
11/4/94	18.3	7.1	0.5			1		17	
11/5/94									
11/6/94									
11/7/94	16.5	6.4	0.2					12	
11/8/94	16.3	6.4	0.2		20	0.5		13	
11/9/94	16.5	6.3	0.2	10.6				14	
11/10/94	15.4	6.3	0.3					10	
11/11/94	14.8	6.4	0.3			1		10	
11/12/94									
11/13/94									
11/14/94	15.8	6.2	0.2					15	
11/15/94	15.5	6.2	0.1	11.4	20	1		11	
11/16/94	15.0	6.2	0.2					9	
11/17/94	14.0	6.1	0.1					10	
11/18/94	14.2	6.4	4.1			1		10	Vented.
11/19/94									
11/20/94									
11/21/94	13.3	6.1	0.3					9	
11/22/94					20	1		3	
11/23/94	9.2	6.2	0.4					3	
11/24/94									
11/25/94						1			
11/26/94									
11/27/94									
11/28/94	10.6	6.4	0.3	13.1				4	
11/29/94	9.1	6.2	0.2		20	1		3	
11/30/94	8.1	6.1	0.2					3	

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
12/1/94	7.8	6.1	0.1				None this	4	
12/2/94	7.8	6.0	0.1			1	month.	6	
12/3/94									
12/4/94									
12/5/94	12.5	5.9	0.2					10	
12/6/94	11.7	5.9	0.4		20	1		7	
12/7/94	10.5	6.1	0.1					6	
12/8/94	9.6	6.2	0.1					5	
12/9/94	8.7	6.1	0.1			1		4	
12/10/94									
12/11/94									
12/12/94	4.6	6.0	0.1					1	
12/13/94	4.7	6.1	0.1		0	1		4	No replacement.
12/14/94	5.1	6.0	0.1					2	
12/15/94	5.3	6.0	0.1					3	
12/16/94	5.9	6.0	0.2			1		4	
12/17/94									
12/18/94									
12/19/94	5.5	6.0	0.2	12.9				4	
12/20/94	5.8	6.0	0.3		0	1		4	No replacement in #2 only.
12/21/94	6.7	6.1	0.4					4	Rebuild organism population.
12/22/94	7.4	6.0	0.1	14.2				4	
12/23/94	8.6		0.8			1		4	
12/24/94								4	
12/25/94									
12/26/94									
12/27/94	10.4	5.8	0.1	14.2	0	1		4	No replacement.
12/28/94	10.7	5.8	0.1					4	
12/29/94	10.9	5.8	0.0			1		5	
12/30/94									
12/31/94									

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
1/1/95							None this		Too cold to replace.
1/2/95							month.		Holiday.
1/3/95	8.2		0.1					-5	Too cold for pH probe.
1/4/95	6.8		0.3					-11	Too cold for pH probe.
1/5/95	5.2	6.1	0.2					-9	
1/6/95	4.8	5.7	0.1			1		-4	
1/7/95									
1/8/95									
1/9/95	4.9	5.6	0.2					-3	
1/10/95	5.3	5.6	0.3->7.5	14.7				-1	
1/11/95	8.4	5.7	1.7					0	No molasses.
1/12/95	11.5	5.6	0.1					4	
1/13/95	12.7	5.7	0.2					3	
1/14/95									
1/15/95									
1/16/95	14.4	5.6	0.2					3	
1/17/95	16.6	5.8	0.1		20	1		3	First soil replacement in 1995.
1/18/95	15.6	5.8	0.2					3	
1/19/95	14.4	6.0	0.2					3	
1/20/95	14.1	5.8	0.2					0	No molasses.
1/21/95									
1/22/95									
1/23/95	11.9	5.8	0.1					-5	
1/24/95	12.1	5.8	0.1		20	1		-5	
1/25/95	10.1	6.0	0.1					-3	
1/26/95	10.0	6.0	0.1					-3	
1/27/95	10.3	5.9	0.1					-1	No molasses.
1/28/95									
1/29/95									
1/30/95	8.1	6.0	0.1					-2	
1/31/95	8.6	6.0	0.0		20	1		-1	

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
2/1/95	11.1	6.2	0.1				None this	2	
2/2/95	15.1	6.0	0.1			1	month.	7	
2/3/95	16.2	6.0	0.2					13	New heater on.
2/4/95									
2/5/95									
2/6/95	17.5	5.9	0.1					10	
2/7/95	17.9	5.9	0.1		20	1		13	
2/8/95	17.5	6.1	0.1					10	
2/9/95	18.7	6.4	1.2			1		12	
2/10/95	19.1	6.1	0.1					12	
2/11/95									
2/12/95									
2/13/95	22.7	5.9	0.1					10	
2/14/95	22.4	5.8	0.1		20	1		10	
2/15/95	19.9	6.0	0.1	12.3				12	
2/16/95	19.5	5.9	0.1					11	
2/17/95	20.1	5.8	0.1			1		13	
2/18/95									
2/19/95									
2/20/95	21.8	5.5	0.2					14	
2/21/95	25.7	5.5	0.1		20	1		17	
2/22/95	23.3	5.7	0.1					15	
2/23/95	24.8	5.5	0.1			1		17	
2/24/95	25.3	5.5	0.1					16	
2/25/95									
2/26/95									
2/27/95	26.1	5.8	0.1					15	
2/28/95	25.4	5.8	0.1		20	1		15	

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
3/1/95								14	
3/2/95	25.8	6.0	0.1					14	
3/3/95	25.5	5.9	0.1			1		14	
3/4/95									
3/5/95									
3/6/95	23.4	5.6	0.1					15	
3/7/95	23.8	5.6	0.1			1		17	
3/8/95	24.8	5.9	0.1					18	
3/9/95	24.9	5.8	0.2			1		17	
3/10/95								17	
3/11/95									
3/12/95									
3/13/95	25.8	5.5->5.9	0.1					18	
3/14/95	26.2	5.8->5.9	0.1		20	1		18	
3/15/95	25.7	6.0	1.5					16	
3/16/95	25.7	6.0	0.1					17	
3/17/95	25.5	5.9->6.1	0.2			1	1.0	17	
3/18/95									
3/19/95									
3/20/95	25.9	5.8->6.1	0.1						
3/21/95	24.9	6.0->6.1	0.1		20	1		16	
3/22/95	23.9	6.0->6.2	0.1					18	
3/23/95	23.9	6.1	0.1	?					
3/24/95								16	
3/25/95									
3/26/95									
3/27/95	24.6	5.9->6.2	0.1					16	
3/28/95	25.2	6.0->6.2	0.1		20	1		19	
3/29/95	24.7	6.0->6.2	0.1	13.2				20	
3/30/95	25.3	6.0->6.2	0.1					20	
3/31/95	26.1	6.0->6.2	0.1			1	1.0	21	

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
4/1/95									
4/2/95									
4/3/95	27.4	5.8->6.2	0.1					22	
4/4/95	27.3	6.0->6.2	0.1		20	1		17	
4/5/95	25.7	6.5	5.7					17	Vented.
4/6/95	26.1	6.2	0.1					20	
4/7/95	26.8	6.1->6.3	0.1			1	0.6	20	
4/8/95									
4/9/95									
4/10/95	25.8	5.9->6.1	0.1	11.2				19	
4/11/95	26.3	5.9->6.2	0.1		20	1.5		19	
4/12/95	26.7	6.1->6.2	0.1					18	
4/13/95	27.4	5.9->6.1	0.1	11.2		1.5	0.5	20	
4/14/95									
4/15/95									
4/16/95									
4/17/95	29.3	5.5	0.1					23	
4/18/95	29.2	5.9->6.2	0.1		20	1.5		18	
4/19/95	27.9	5.8	0.1					19	
4/20/95						1.5		16	
4/21/95									
4/22/95									
4/23/95									
4/24/95	26.9	5.5->6.2	0.1					19	
4/25/95	26.8	6.2	0.1		20	1.5		18	
4/26/95	25.8	5.8->6.2	0.1					20	
4/27/95	25.9	6.1->6.2	0.1			1.5		19	
4/28/95	26.6	6.1->6.2	0.1					20	
4/29/95									
4/30/95									

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
5/1/95	25.9	5.6->6.3	0.1					20	
5/2/95	26.7	6.1	0.1		20	1.5		20	
5/3/95	26.3	5.8->6.2	0.1					20	
5/4/95	27.1	6.0->6.2	0.1	12.3				21	
5/5/95	26.8	6.1->6.2	0.1			1.5	1.8	20	
5/6/95									
5/7/95									
5/8/95	27.6	5.6->6.2	0.1					20	
5/9/95	27.3	6.0->6.2	0.1		20	1.5		20	
5/10/95	26.6	5.7->6.2	0.1					22	
5/11/95	26.6	5.9->6.2	0.1	12.7				21	
5/12/95	26.8	6.2->6.2	0.1			1.5	3.5	20	
5/13/95									
5/14/95									
5/15/95	27.7	5.6->6.2	0.1					22	
5/16/95	28.3	6.1->6.2	0.1		20	1.5		22	
5/17/95	27.5	5.8->6.2	0.1					22	
5/18/95	26.3	6.2	0.1					20	
5/19/95	24.5	6.1->6.3	0.1			1.5	2.9	16	
5/20/95									
5/21/95									
5/22/95	25.7	5.8->6.2	0.1					21	
5/23/95	25.6	6.2	0.1		20	1.5		21	
5/24/95	26.0	5.8->6.1	0.1					19	
5/25/95	25.2	6.1->6.2	0.1	14.7, 14.9, 16.1				16	
5/26/95	25.5	6.1->6.2	0.1			1.5	2.4	19	
5/27/95									
5/28/95									
5/29/95									Holiday.
5/30/95	26.6	5.7->6.2	0.1		20			21	
5/31/95	28.0	5.9->6.3	0.1			1.5		21	Boiler off for summer.

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
6/1/95	28.3	6.1->6.2	0.1					22	
6/2/95	29.1	6.2	0.1			1.5	2.4	22	
6/3/95									
6/4/95									
6/5/95	27.8	5.6->6.1	0.1					23	
6/6/95	28.7	6.1->6.2	0.1		20	1.5		22	
6/7/95	27.8	5.7->6.1	0.2					25	
6/8/95	27.9	6.2	0.1					22	
6/9/95	26.5	6.1->6.2	0.1			1.5	4.0	20	
6/10/95									
6/11/95									
6/12/95	25.8	5.6	0.1					21	
6/13/95	24.6	5.6->6.2	0.1		20	1.5		20	
6/14/95	24.4	5.8->6.2	0.1					22	
6/15/95	24.9	6.0->6.2	0.1					23	
6/16/95	25.8	6.1->6.2	0.1			1.5	4.4	23	
6/17/95									
6/18/95									
6/19/95	28.0	5.7->6.2	0.1					26	
6/20/95	29.1	6.2	0.1		20	1.5		27	
6/21/95	29.1	5.6->6.1	0.1	14.9				26	
6/22/95	29.3	6.2	0.1					25	
6/23/95	28.6	6.2	0.0			1.5	3.4	27	
6/24/95									
6/25/95									
6/26/95	28.5	5.9->6.2	0.1					26	
6/27/95	27.5	6.2	0.0		20	1		24	
6/28/95	27.7	5.7->6.2	0.1					24	
6/29/95	27.1	6.3	0.0					24	
6/30/95	27.2	6.3	0.0			1	2.4	23	

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
7/1/95									
7/2/95									
7/3/95	26.0	6.0							
7/4/95									Holiday.
7/5/95	27.5	6.1	0.1		20	1		27	
7/6/95	28.6	5.9->6.2	0.1	11.6				23	
7/7/95	27.5	6.1->6.2	0.1			1	0.8	22	
7/8/95									
7/9/95									
7/10/95	27.8	5.8	0.1					24	
7/11/95	28.0	5.8->6.2	0.1		20	1		26	
7/12/95	29.5	5.8->6.1	0.1					27	
7/13/95	30.2	6.2	0.1					28	
7/14/95						1		30	
7/15/95									
7/16/95									
7/17/95	32.3	5.7->6.2	0.0					27	
7/18/95	32.1	6.2	0.0		20	1		25	
7/19/95	30.0	5.9->6.2		11.6				26	
7/20/95	30.0	6.2						26	
7/21/95	29.0	6.3				1	2.2	25	
7/22/95									
7/23/95									
7/24/95	29.4	5.7	0.1					25	
7/25/95	30.5	5.8->6.2	0.0		20	1		26	
7/26/95	29.5	5.9->6.1	0.1					26	
7/27/95	29.2	6.2	0.1					26	
7/28/95	29.2	6.2	0.1			1	1.5	26	
7/29/95									
7/30/95									
7/31/95	31.1	5.8->6.3	0.1					28	

TABLE C.2 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
8/1/95	31.9	6.2	0.0		20	1		28	
8/2/95	31.1	6.2	0.1					28	
8/3/95	29.5	6.2	0.1					25	
8/4/95	28.9	6.1	0.0			1		26	
8/5/95									
8/6/95									
8/7/95	29.2	5.7->6.2	0.0					26	Aerate to test foam control.
8/8/95	29.3	6.2	0.1		20	1		27	
8/9/95	29.2	5.9->6.3	0.1					26	
8/10/95	28.1	6.3	0.0					25	Mixer off.
8/11/95	30.2	6.4	0.0			1	1.4	26	
8/12/95									
8/13/95									
8/14/95	31.8	5.8->6.1	0.0					32	
8/15/95	33.9	6.4	0.0		20	1		28	
8/16/95	31.9	5.9	0.0					29	
8/17/95	30.6	5.9->6.3	0.0				1.4	26	
8/18/95	30.2	6.3	0.0			1		27	
8/19/95									
8/20/95									
8/21/95	29.5	5.8	0.0					28	
8/22/95	29.2	5.8	0.1			1		25	
8/23/95	28.5	5.9	0.0					24	
8/24/95	29.1	5.9	0.0					26	
8/25/95	29.2	6.2	0.0			1	1.2	26	
8/26/95									
8/27/95									
8/28/95	29.5	5.9	0.1					27	
8/29/95	30.5	6.1	0.0		20	1		27	
8/30/95	30.3	5.9->6.2	0.0					27	
8/31/95	30.4	6.1	0.1				0.8	27	

TABLE C.3 Report of Operation for 10% Replacement Reactor (Reactor 3) (mixer speed = 80%)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
7/1/94					None this		None this	No record	
7/2/94					month.		month.	this month.	
7/3/94									
7/4/94									
7/5/94									
7/6/94									
7/7/94									
7/8/94									
7/9/94									
7/10/94									
7/11/94									
7/12/94				9.5					
7/13/94									
7/14/94									
7/15/94									
7/16/94									
7/17/94									
7/18/94									
7/19/94						0.5			
7/20/94									
7/21/94									
7/22/94									
7/23/94									
7/24/94									
7/25/94									Mix all weekend with vents open.
7/26/94									
7/27/94									
7/28/94									
7/29/94									
7/30/94									
7/31/94									

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
8/1/94			4.4	10.2	None this		None this	No record	
8/2/94					month.		month.	this month.	
8/3/94									
8/4/94	28.0	7.0	4.4						6 in. of foam on half of surface.
8/5/94									
8/6/94									
8/7/94									
8/8/94									4 in. of foam.
8/9/94	24.9	8.1	7.7	9.4/9.8		0.5			
8/10/94	25.6		6.6						Foamed over.
8/11/94									
8/12/94									
8/13/94									
8/14/94									Electric power off 7 p.m., Sun.
8/15/94									8/14, due to storm; restart
8/16/94	25.6	7.2	7.4						mixers 2 p.m., 8/15/94.
8/17/94	26.1	7.0	0.0->5.4						
8/18/94									
8/19/94	28.1	7.1	5.1						
8/20/94									
8/21/94									
8/22/94	27.2	6.5	0.1	10.2		1			
8/23/94	28.2	6.4	0.0						
8/24/94	29.9	7.0	3.6	10.0					
8/25/94	30.2	6.4	0.1						
8/26/94									
8/27/94									
8/28/94									
8/29/94	27.6	6.9	0.1			1			
8/30/94	27.8	6.3	0.3	10.9					
8/31/94	28.3	6.9	0.1						

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
9/1/94	26.9	7.0	0.1	11.1			None this	22	
9/2/94	26.2	6.9	0.1			1	month.		
9/3/94									
9/4/94									
9/5/94									
9/6/94									
9/7/94	25.4	6.3	0.1	10.5		1			
9/8/94	26.7	6.2	0.1					20	
9/9/94									
9/10/94									
9/11/94	29.7	7.1	0.2					24	
9/12/94	29.9	7.1	1.0						
9/13/94	31.7	7.3	0.3						
9/14/94	31.4	6.4	0.2						
9/15/94									
9/16/94						1		30	
9/17/94									
9/18/94									
9/19/94	27.2	6.8	0.2						
9/20/94	25.9	6.6	0.2		10				
9/21/94	26.2	6.9	0.1	11.0					
9/22/94									
9/23/94	24.8	6.5	0.2			1			
9/24/94									
9/25/94									
9/26/94	22.8	6.8	0.3					16	
9/27/94					0				No replacement slurry. Valves
9/28/94	24.9	6.6	3.5	10.8				16	blocked.
9/29/94	21.2	7.3	0.2	10.6					
9/30/94	20.8	7.4	6.2						

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
10/1/94							None this		
10/2/94							month.		
10/3/94	22.1	6.5	0.1						
10/4/94	23.8	7.3	0.1	10.1	10				
10/5/94	23.1	7.5	5.7						
10/6/94	21.9	7.2	0.1					17	
10/7/94	22.3	7.2	0.7	10.7		1		18	
10/8/94									
10/9/94									
10/10/94	19.2	6.2	0.3		10			13	
10/11/94	20.7	7.4	0.2					14	
10/12/94	20.1	7.0	0.4						
10/13/94	20.2	7.0	0.4	9.9				16	
10/14/94	20.8	7.0	0.4			1			
10/15/94									
10/16/94									
10/17/94	22.0	6.4	0.2					18	
10/18/94	22.6	6.6	0.3		10	0.5			
10/19/94	22.5	6.3	0.3						
10/20/94	22.1	6.4	0.2	11.0				16	
10/21/94	21.6	6.5	0.4->0.2			0.5		15	
10/22/94								14	
10/23/94									
10/24/94	19.5	6.3	0.2			0.5		14	
10/25/94	18.0	6.2	0.1		10	0.5		12	
10/26/94	16.9	6.3	0.2					11	
10/27/94	16.4	6.2	0.1	11.1				11	
10/28/94	16.5	6.3	0.2			1		11	
10/29/94									
10/30/94									
10/31/94	10.1	6.2	0.1	10.9				8->13	

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
11/1/94	15.5	6.3	0.1		10	0.5	None this	8	Tracking study.
11/2/94	15.3	6.2	0.1	11.2			month.	10	
11/3/94	15.3	6.2	0.1					14	
11/4/94	17.4	6.4	0.1			1		17	
11/5/94									
11/6/94									
11/7/94	17.0	6.1	0.1					12	
11/8/94	17.0	6.1	0.1		10	0.5		13	
11/9/94	17.6	6.1	0.2	10.1				14	
11/10/94	16.2	6.2	0.1					10	
11/11/94	15.5	6.2	0.1			1		10	
11/12/94									
11/13/94									
11/14/94	16.8	6.2	0.2					15	
11/15/94	16.0	6.1	0.1	11.2	10	1		11	
11/16/94	15.5	6.0	0.1					9	
11/17/94	14.8	6.0	0.1					10	
11/18/94	15.2	6.4	2.5			1		10	Vented.
11/19/94									
11/20/94									
11/21/94	14.1	6.0	0.3					9	
11/22/94					10	1		3	
11/23/94	10.0	6.0	0.1					3	
11/24/94									
11/25/94						1			
11/26/94									
11/27/94									
11/28/94	10.7	5.7	0.2	10.9				4	
11/29/94	9.2	5.8	0.2		10	1		3	
11/30/94	8.6	5.7	0.3					3	

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
12/1/94	8.7	5.7	0.1				None this	4	
12/2/94	9.8	5.6	0.1			1	month.	6	
12/3/94									
12/4/94									
12/5/94	14.6	5.4	0.5					10	
12/6/94	13.6	5.4	0.3		10	0.5		7	
12/7/94	12.3	5.5	0.3					6	
12/8/94	11.1	5.4	0.1					5	
12/9/94	9.7	5.5	0.4			0.5		4	
12/10/94									
12/11/94									
12/12/94	5.6	5.4	0.1					1	
12/13/94	5.8	5.4	0.1		0.0	0.5		4	No replacement.
12/14/94	6.4	5.4	0.1					2	
12/15/94	6.9	5.5	6.7					3	Vented.
12/16/94	7.7	5.6	0.1			1		4	
12/17/94									
12/18/94									
12/19/94	6.7	5.4	0.2	10.9				4	
12/20/94	7.4	5.5	0.3		10	0.5		4	
12/21/94	8.6	5.6	0.3					4	
12/22/94	9.9	5.5	0.2	11.3				4	
12/23/94	11.6		0.7			1		4	
12/24/94									
12/25/94									
12/26/94									
12/27/94	14.3	5.5	0.1	11.6	0	0.5		4	No replacement.
12/28/94	14.7	5.4	0.1					4	
12/29/94	14.5	5.5	0.1			0.5		5	
12/30/94									
12/31/94									

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
1/1/95							None this		
1/2/95							month.		Holiday.
1/3/95	12.7		0.1					-5	Too cold for pH probe.
1/4/95	11.3		0.1					-11	Too cold for pH probe.
1/5/95	9.5		0.1					-9	Too cold for pH probe.
1/6/95	8.9	5.3	0.1			0.5		-4	
1/7/95									
1/8/95									
1/9/95	8.1	5.2	0.1					-3	
1/10/95	8.5	5.2	0.1->0.3	11.4				-1	
1/11/95	9.5	5.3	0.2					0	
1/12/95	10.2	5.3	0.4					4	
1/13/95	11.4	5.3	0.2					3	
1/14/95									
1/15/95									
1/16/95	12.2	5.2	0.1					3	
1/17/95	14.3	5.4	0.1		10	1		3	First soil replacement in 1995.
1/18/95	14.9	5.3	0.1					3	
1/19/95	15.0	5.5	0.1					3	
1/20/95	14.9	5.5	0.4					0	No molasses.
1/21/95									
1/22/95									
1/23/95	11.6	5.5	0.1					-5	
1/24/95	11.1	5.6	0.1		10	1		-5	
1/25/95	10.6	5.6	0.1					-3	
1/26/95	10.4	5.6	0.1					-3	
1/27/95	11.0	5.6	0.0					-1	No molasses.
1/28/95									
1/29/95									
1/30/95	10.6	5.4	0.1					-2	
1/31/95	26.1	5.5	0.1		10	1		-1	

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
2/1/95	22.1	5.3	0.2				None this	2	
2/2/95	20.9	5.4	0.1			1	month.	7	
2/3/95	22.1	5.4	0.1					13	New heater on.
2/4/95									
2/5/95									
2/6/95	21.5	5.5	0.2					10	
2/7/95	22.8	5.6	0.1		10	1		13	
2/8/95	22.1	5.5	0.1					10	
2/9/95	25.1	6.2	0.1			1		12	
2/10/95	24.9	5.6	0.1					12	
2/11/95									
2/12/95									
2/13/95	31.5	6.3	0.1					10	
2/14/95	28.5	6.7	0.1		10	1		10	
2/15/95	25.6	6.0	0.1	10.7				12	
2/16/95	24.3	6.1	0.1					11	
2/17/95	24.7	5.7	0.1			1		13	
2/18/95									
2/19/95									
2/20/95	23.7	5.7	0.1					14	
2/21/95	25.1	5.7	0.1		10	1		17	
2/22/95	24.3	5.6	0.1					15	
2/23/95	25.2	5.6	0.1			1		17	
2/24/95	26.6	5.3	0.1					16	
2/25/95									
2/26/95									
2/27/95	26.5	5.6	0.1					15	
2/28/95	25.7	5.7	0.1		10	0.8		15	

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
3/1/95								14	
3/2/95	24.8	5.5	0.1					14	
3/3/95	25.3	5.6	0.1			0.8		14	
3/4/95									
3/5/95									
3/6/95	25.1	5.5	0.1					15	
3/7/95	26.6	5.5	0.1			0.8		17	
3/8/95	27.3	5.4	0.1					18	
3/9/95	28.1	5.5	0.1			0.8		17	
3/10/95								17	
3/11/95									
3/12/95									
3/13/95	27.4	5.4	0.1						
3/14/95	27.6	5.4	0.1		10	0.8		18	
3/15/95	27.4	5.4->5.8	0.1					18	
3/16/95	27.6	5.8	0.1					16	
3/17/95	27.5	5.8->6.1	0.1			0.8	1.7	17	
3/18/95								17	
3/19/95									
3/20/95	27.9	5.8->6.1	0.1						
3/21/95	27.4	6.1	0.1		10	0.8		16	
3/22/95	27.1	5.8->6.1	0.1					18	
3/23/95	27.2	6.1	0.1						
3/24/95								16	
3/25/95									
3/26/95									
3/27/95	26.4	6.0->6.2	0.1					16	
3/28/95	27.3	6.2->6.2	0.1		10	0.8		19	
3/29/95	26.8	6.0->6.2	0.1	9.9				20	
3/30/95	28.5	6.1->6.3	0.1					20	
3/31/95	29.6	6.2	0.1			0.8	1.1	21	

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
4/1/95									
4/2/95									
4/3/95	30.0	5.9->6.2	0.1					22	
4/4/95	29.6	6.1->6.2	0.1		10	0.8		17	
4/5/95	29.5	6.0->6.2	0.1					17	
4/6/95	29.8	6.1->6.3	0.1					20	
4/7/95	29.7	6.2	0.1			0.8	1.3	20	
4/8/95									
4/9/95									
4/10/95	27.9	6.9	0.1	9.5				19	
4/11/95	28.4	5.8->6.2	0.1		10	0.8		19	
4/12/95	28.7	5.9->6.2	0.1					18	
4/13/95	29.7	6.2->6.2	0.1			0.8	1.6	20	
4/14/95									
4/15/95									
4/16/95									
4/17/95	31.6	5.8	0.1					23	
4/18/95	31.1	6.2	0.1		10	0.8		18	
4/19/95	31.1	5.9	0.1					19	
4/20/95						0.8		16	
4/21/95									
4/22/95									
4/23/95									
4/24/95	28.6	5.9->6.2	0.1					19	
4/25/95	28.1	6.2	0.1		10	0.8		18	
4/26/95	27.3	5.9->6.1	0.1					20	
4/27/95	27.2	6.1->6.2	0.1					19	
4/28/95	28.5	6.2	0.1			0.8	1.2	20	
4/29/95									
4/30/95									

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
5/1/95	27.1	5.9->6.2	0.1					20	
5/2/95	27.6	6.2	0.1		10	0.8		20	
5/3/95	27.5	5.9->6.2	0.1					20	
5/4/95	27.7	6.2->6.2	0.1	10.7				21	
5/5/95	27.9	6.2	0.1			0.8	1.7	20	
5/6/95									
5/7/95									
5/8/95	28.8	5.9->6.2	0.1					20	
5/9/95	28.5	6.1->6.2	0.1		10	0.8		20	
5/10/95	28.3	5.9->6.2	0.1					22	
5/11/95	28.1	6.1->6.2	0.1	10.3				21	
5/12/95	28.5	6.2	0.1			0.8	1.7	20	
5/13/95									
5/14/95									
5/15/95	28.7	5.9->6.2	0.1					22	
5/16/95	29.5	6.2	0.1		10	0.8		22	
5/17/95	29.8	5.9->6.2	0.1					22	
5/18/95	29.2	6.2	0.1					20	
5/19/95	27.4	6.2->6.2	0.1			0.8	1.6	16	
5/20/95									
5/21/95									
5/22/95	28.5	5.9->6.2	0.1					21	
5/23/95	28.8	6.2	0.1		10	0.8		21	
5/24/95	28.6	5.9->6.1	0.1					19	
5/25/95	27.6	6.0->6.2	0.1	11.4, 12.0, 12.6				16	
5/26/95	27.5	6.1->6.2	0.1			0.8	1.6	19	
5/27/95									
5/28/95									
5/29/95									Holiday.
5/30/95	28.0	5.9->6.2	0.1		10	0.8		21	
5/31/95	28.5	6.0->6.1	0.1					22	Boiler off for summer.

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
6/1/95	28.7	6.1->6.2	0.1					22	
6/2/95	29.3	6.2	0.1			0.8	1.8	22	
6/3/95									
6/4/95									
6/5/95	29.3	5.9->6.2	0.1					23	
6/6/95	29.3	6.1->6.2	0.1		10	0.8		22	
6/7/95	29.1	5.9->6.2	0.2					25	
6/8/95	29.8	6.1	0.1					22	
6/9/95	28.6	6.1->6.2	0.1			0.8	1.7	20	
6/10/95									
6/11/95									
6/12/95	27.8	5.9	0.1					21	
6/13/95	26.5	5.9->6.2	0.1		10	0.8		20	
6/14/95	25.6	5.9->6.2	0.1					21	
6/15/95	25.8	6.2	0.2					23	
6/16/95	27.1	6.1->6.2	0.1			0.8	1.8	23	
6/17/95									
6/18/95									
6/19/95	30.0	5.9->6.2	0.1					26	
6/20/95	31.0	6.2	0.1		10	0.8		27	
6/21/95	30.3	5.9->6.1	0.1	13.6				26	
6/22/95	30.3	6.2	0.1					25	
6/23/95	29.3	6.1->6.2	0.1			0.8	1.7	27	
6/24/95									
6/25/95									
6/26/95	28.9	5.9->6.2	0.1					26	
6/27/95	28.2	6.1	0.1		10	0.8		24	
6/28/95	28.4	5.9->6.2	0.1					24	
6/29/95	28.2	6.2	0.0					24	
6/30/95	28.2	6.2	0.1			0.8	2.3	23	

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
7/1/95									
7/2/95									
7/3/95	28.0	5.9->6.0			10	0.8			
7/4/95									Holiday.
7/5/95	28.5	5.9	0.1					27	
7/6/95	28.1	6.0->6.1	0.8	11.9				23	
7/7/95	28.1	6.1->6.2	0.1			0.8	1.3	22	
7/8/95									
7/9/95									
7/10/95	30.1	6.2	0.1					24	Antifoam added.
7/11/95	30.3	6.3	0.1		10	0.8		26	
7/12/95	31.3	6.2->6.4	0.1					27	
7/13/95	32.1	6.5	0.1					28	
7/14/95						0.8		30	
7/15/95									
7/16/95									
7/17/95	33.8	6.0->6.2	0.0					27	Air added (no NaOH).
7/18/95	32.9	6.3	0.0		10	0.8		25	
7/19/95	31.0	6.1->6.3		11.4				26	
7/20/95	30.0	6.3						26	
7/21/95	29.5	6.4				0.8		25	No pH adjustment.
7/22/95									
7/23/95									
7/24/95	31.1	6.2	0.0					25	
7/25/95	30.9	6.3	0.0		10	0.8		26	No pH adjustment.
7/26/95	30.5	6.2	0.1					26	
7/27/95	29.8	6.3	4.1->0.7					26	
7/28/95	30.3	6.3	0.1			0.8		26	
7/29/95									
7/30/95									
7/31/95	33.5	6.2	0.1					28	

TABLE C.3 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
8/1/95	33.5	6.2	0.0		10	0.8		28	
8/2/95	32.1	6.3	0.0					28	
8/3/95	30.1	6.2	0.0					25	
8/4/95	29.3	6.2	0.0			0.8		26	No pH adjustment.
8/5/95									
8/6/95									
8/7/95	29.8	5.9->6.2	0.0					26	Aerate to test foam control.
8/8/95	29.6	6.2	0.0		10	0.8		27	
8/9/95	29.4	6.0->6.2	0.0					26	
8/10/95	28.1	6.2	0.0					25	Mixer off.
8/11/95	31.0	6.5	0.0			0.8	0.6	26	
8/12/95									
8/13/95									
8/14/95	33.3	6.2	0.1					32	End pH adjustment.
8/15/95	33.8	6.3	0.0		10	0.8		28	
8/16/95	33.5	6.3	0.0					29	
8/17/95	31.8	6.3	0.0					26	
8/18/95	32.2	6.6	0.0			1.8		27	
8/19/95									
8/20/95									
8/21/95	32.3	6.2	0.0					28	
8/22/95	31.4	6.3	0.1			0.8		25	
8/23/95	29.8	6.0	0.0					24	
8/24/95	31.2	6.2	0.0					26	
8/25/95	31.8	6.5	0.0			0.8		26	
8/26/95									
8/27/95									
8/28/95	31.1	6.2	0.0					27	
8/29/95	31.5	6.5	0.0		10	0.8		27	
8/30/95	31.5	6.3	0.0					27	
8/31/95	32.3	6.4	0.0					27	

TABLE C.4 Report of Operation for 5% Replacement Reactor (Reactor 4) (mixer speed = 80%)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
7/1/94					None this		None this	No record	
7/2/94					month.		month.	this month.	
7/3/94									
7/4/94									
7/5/94									
7/6/94									
7/7/94									
7/8/94									
7/9/94									
7/10/94									
7/11/94									
7/12/94				8.3					
7/13/94									
7/14/94									
7/15/94									
7/16/94									
7/17/94									
7/18/94									
7/19/94						0.5			
7/20/94									
7/21/94									
7/22/94									
7/23/94									
7/24/94									
7/25/94									Mix all weekend with vents open.
7/26/94									
7/27/94									
7/28/94									
7/29/94									
7/30/94									
7/31/94									

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
8/1/94					None this		None this	No record	
8/2/94					month.		month.	this month.	
8/3/94									
8/4/94	29.7	7.9	6.9						6 in. of foam on half of surface.
8/5/94									
8/6/94									
8/7/94									
8/8/94									8-10 in. of foam.
8/9/94	27.2	8.1	7.4	11.3/10.4		0.5			
8/10/94	27.3		6.6						Foam near top of reactor.
8/11/94									
8/12/94									
8/13/94									
8/14/94									Electric power off 7 p.m., Sun.
8/15/94									8/14, due to storm; restart
8/16/94	26.1	7.4	6.7						mixers 2 p.m., 8/15/94.
8/17/94	26.7	7.3	6.5						
8/18/94									
8/19/94	29.2	7.7	6.7						
8/20/94									
8/21/94									
8/22/94	27.9	6.8	3.6	11.2		1			
8/23/94	28.7	6.5	0.1						
8/24/94	30.1	7.3	4.1	9.0					
8/25/94	30.9	6.5	0.1						
8/26/94									
8/27/94									
8/28/94									
8/29/94	30.2	7.1	0.1			1			
8/30/94	30.0	6.6	0.1	11.0					
8/31/94	29.0	7.2	1.6						

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
9/1/94	27.9	6.8	0.1	11.0			None this	22	
9/2/94	27.4	6.8	0.1			1	month.		
9/3/94									
9/4/94									
9/5/94									
9/6/94									
9/7/94	27.1	6.6	0.5	10.4		1			
9/8/94	28.4	6.5	0.1					20	
9/9/94									
9/10/94									
9/11/94	28.7	6.4	0.2					24	
9/12/94	30.6	7.3	1.1						
9/13/94	29.5	7.1	1.1						
9/14/94	31.3	6.1	0.2						
9/15/94									
9/16/94						1		30	
9/17/94									
9/18/94									
9/19/94	27.1	6.6	0.4		5				17.5 lb of soil replaced.
9/20/94	26.0	6.7	0.3		5				
9/21/94	26.0	8.1(?)	6.5	9.8	5				
9/22/94					5				
9/23/94	25.1	6.5	0.2			1			
9/24/94									
9/25/94									
9/26/94	22.9	6.6	0.2					16	
9/27/94									
9/28/94	24.8	7.6	4.7	10.0				16	
9/29/94	22.9	7.2	3.4	9.5					
9/30/94	22.0	7.1	3.6	9.9					

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
10/1/94							None this		
10/2/94							month.		
10/3/94	23.9	6.5	0.1		5				
10/4/94	25.3	7.6	0.2	10.3	5				
10/5/94	23.8	7.5	6.2	10.7	5				
10/6/94	22.8	7.3	0.9		5			17	
10/7/94	22.9	7.3	2.9	11.0		1		18	
10/8/94									
10/9/94									
10/10/94	21.1	6.8	0.1		5			13	
10/11/94	21.6	7.4	5.2		5			14	
10/12/94	20.9	7.3	4.4		5				
10/13/94	20.9	7.5	6.2	10.9	5			16	
10/14/94	21.2	7.3	4.0			1			
10/15/94									
10/16/94									
10/17/94	23.8	6.7	0.2					18	
10/18/94	24.1	7.1	1.0		5	0.5			
10/19/94	24.0	6.7	0.2		5				
10/20/94	24.6	7.5	1.3	10.7	5			16	
10/21/94	23.3	7.3	2.6->0.2		5	0.5		15	
10/22/94								14	
10/23/94									
10/24/94	20.7	6.8	0.1		5	0.5		14	
10/25/94	19.4	6.6	0.1		5	0.5		12	
10/26/94	17.9	6.4	0.1		5			11	
10/27/94	18.4	6.6	0.1	10.7	5			11	
10/28/94	18.2	6.8	0.1			1		11	
10/29/94									
10/30/94									
10/31/94	18.9	6.5	0.1	10.5				8->13	

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
11/1/94	16.2	6.7	0.1		5	0.5	None this	8	Tracking study.
11/2/94	16.0	6.3	0.1	10.2	5		month.	10	
11/3/94	17.2	6.5	0.1					14	
11/4/94	18.6	6.8	0.1			1		17	
11/5/94									
11/6/94									
11/7/94	17.5	6.4	0.1		5			12	
11/8/94	17.4	6.5	0.1		5	0.5		13	
11/9/94	18.0	6.2	0.1	9.5	5			14	
11/10/94	16.7	6.4	0.1		5			10	Recycle water.
11/11/94	16.0	6.4	0.1			1		10	
11/12/94									
11/13/94									
11/14/94	17.4	6.3	0.1		5			15	
11/15/94	16.8	6.2	0.1	11.3	5	1		11	
11/16/94	16.0	6.3	0.1		5			9	
11/17/94	16.1	6.1	0.1		5			10	
11/18/94	15.3	6.1	0.1			1		10	Closed.
11/19/94									
11/20/94									
11/21/94	14.3	6.0	0.2		5			9	
11/22/94					5	1		3	
11/23/94	10.2	6.0	0.1		5			3	
11/24/94					0				
11/25/94						1			
11/26/94									
11/27/94									
11/28/94	11.1	5.9	0.2	10.6	5			4	
11/29/94	10.1	6.1	0.4		5	1		3	
11/30/94	9.5	6.0	1.6		5			3	

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
12/1/94	9.7	6.0	0.5		5		None this	4	
12/2/94	10.5	6.0	0.1			1	month.	6	
12/3/94									
12/4/94									
12/5/94	16.1	5.7	0.9		5			10	
12/6/94	14.6	5.8	0.3		5	1		7	
12/7/94	14.0	5.7	0.1		5			6	
12/8/94	12.2	5.8	0.3		5			5	
12/9/94	10.9	5.9	0.1			1		4	
12/10/94									
12/11/94									
12/12/94	6.6	5.8	0.1		0			1	
12/13/94	6.7	5.7	0.1		0	1		4	
12/14/94	8.6	5.7	0.1		0			2	
12/15/94	11.4	5.7	0.2		0			3	
12/16/94	12.9	5.7	0.1			1		4	
12/17/94									
12/18/94									
12/19/94	15.5	5.6	0.2	10.6	5			4	
12/20/94	16.0	5.7	0.3		5	1		4	
12/21/94	16.4	5.8	0.2		5			4	
12/22/94	17.1	5.8	0.2	13.0	5			4	
12/23/94	16.4		1.5			1		4	
12/24/94									
12/25/94									
12/26/94					0				
12/27/94	17.2	5.6	0.1	12.7	0	1		4	No replacement.
12/28/94	17.2	5.5	0.1		0			4	
12/29/94	17.3	5.6	0.2		0	1		5	
12/30/94									
12/31/94									

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
1/1/95							None this		
1/2/95							month.	-11	Holiday
1/3/95	16.1		0.1					-5	Too cold for pH probe.
1/4/95	14.8		0.2					-11	Too cold for pH probe.
1/5/95	12.8		0.1					-9	Too cold for pH probe.
1/6/95	12.1	5.2	0.1			1		-4	
1/7/95									
1/8/95									
1/9/95	11.4	5.1	0.1					-3	No molasses this week.
1/10/95	11.7	5.1	0.1->5.3	12.7				-1	
1/11/95	12.5	5.2	0.1					0	
1/12/95	13.1	5.3	0.1					4	
1/13/95	14.4	5.4	0.1					3	
1/14/95									
1/15/95									
1/16/95	15.2	5.3	0.1		5			2	First soil replacement in 1995.
1/17/95	15.3	5.4	0.1		5	1		3	
1/18/95	15.8	5.3	0.1		5			3	
1/19/95	17.5	5.5	0.0		5			3	
1/20/95	17.4	5.5	0.3					0	No molasses.
1/21/95									
1/22/95									
1/23/95	14.4	5.5	0.1		5			-5	
1/24/95	14.1	5.7	0.0		5	1		-5	
1/25/95	13.7	5.7	0.1		5			-2	
1/26/95	13.7	5.6	0.1		5			-2	
1/27/95	13.7	5.7	0.1					-1	No molasses.
1/28/95									
1/29/95									
1/30/95	13.6	5.6	0.1		5			-2	
1/31/95	15.1	5.8	0.1		5	1		-1	

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
2/1/95	15.1	5.5	0.1		5		None this	2	
2/2/95	14.4	5.8	0.1		5	1	month.	7	
2/3/95	16.5	5.7	0.1					13	New heater on.
2/4/95									
2/5/95									
2/6/95	18.4	5.6	0.1		5			10	
2/7/95	19.3	5.8	0.1		5	1		13	
2/8/95	19.5	5.7	0.1	12.2	5			10	
2/9/95	20.2	5.8	0.1		5	1		12	
2/10/95	22.1	5.6	0.1					12	
2/11/95									
2/12/95									
2/13/95	28.5	6.4	0.1		5			10	
2/14/95	27.7	6.2	0.1		5	1		10	
2/15/95	27.1	5.5	0.1	12.4	5			12	
2/16/95	26.1	5.7	0.1		5			11	
2/17/95	25.3	5.5	0.1			1		13	
2/18/95									
2/19/95									
2/20/95	24.2	5.6	0.1		5			14	
2/21/95	24.9	5.7	0.1		5	1		17	
2/22/95	24.7	5.4	0.1					15	
2/23/95	25.5	5.4	0.1			1		17	
2/24/95	26.6	5.4	0.3					16	
2/25/95									
2/26/95									
2/27/95	29.3	6.0	0.1		5			15	
2/28/95	28.9	6.1	0.1		5	1		15	

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
3/1/95								14	No replacement.
3/2/95	28.6	5.7	0.1		5			14	
3/3/95	27.9	5.8	0.1			1		14	
3/4/95									
3/5/95									
3/6/95	27.2	5.5	0.1					15	
3/7/95	27.6	5.7	0.1			1		17	
3/8/95	27.9	5.4	0.1					17	
3/9/95	29.9	5.9	0.1			1		16	
3/10/95								17	
3/11/95									
3/12/95									
3/13/95	29.6	5.6	0.1		5			18	
3/14/95	29.4	5.5	0.1		5	1		18	
3/15/95	28.9	5.4->5.9	0.1		5		0.7	17	
3/16/95	29.8	5.8	0.1		5			17	
3/17/95	29.5	5.8->6.1	0.1			1	0.3	17	
3/18/95									
3/19/95									
3/20/95	30.1	5.6->6.1	0.2		5		0.5	16	
3/21/95	29.5	6.0	0.1		5	1		16	
3/22/95	29.4	5.7->6.1	0.1		5		0.8	18	
3/23/95	28.7	6.0	0.1		5				
3/24/95		6.0->6.2					0.5	16	
3/25/95									
3/26/95									
3/27/95	27.8	5.9->6.2	0.1		5		0.5	16	
3/28/95	27.6	6.2->6.2	0.1		5	1		19	
3/29/95	28.2	5.8->6.2	0.1	12.3			0.7	20	
3/30/95	28.7	6.1->6.3	0.1		5		0.3	20	
3/31/95	28.8	6.2	0.1			1		21	

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
4/1/95									
4/2/95									
4/3/95	30.6	5.8->6.2	0.1		5		0.6	22	
4/4/95	30.5	6.2	0.1		5	1		17	pH not adjusted.
4/5/95	31.4	6.0->6.2	0.1		5		0.3	17	
4/6/95	30.5	6.0->6.2	0.1		5		0.3	20	
4/7/95	30.1	6.1	0.1			1	1.4	20	
4/8/95									
4/9/95									
4/10/95	28.1	5.8->5.9	0.1	10.8				19	
4/11/95	28.3	6.0->6.2	0.1		5	1		19	
4/12/95	28.4	5.8->6.2	0.1		5			18	
4/13/95	28.7	5.9->6.2	0.1		5	1	1.5	20	
4/14/95									
4/15/95									
4/16/95									
4/17/95	31.3	5.8	0.1		5			23	
4/18/95	30.8	6.2->6.2	0.1		5	1		18	
4/19/95	31.9	5.9	0.1		5			19	
4/20/95					5	1	1.0	17	
4/21/95									
4/22/95									
4/23/95									
4/24/95	29.3	5.7->6.2	0.1		5			19	
4/25/95	28.9	6.2	0.1		5	1		18	
4/26/95	28.5	5.8->6.2	0.1		5			20	
4/27/95	28.3	6.1->6.2	0.1		5	1		18	
4/28/95	30.4	6.2	0.1				1.5	20	
4/29/95									
4/30/95									

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
5/1/95	28.2	5.8->6.2	0.1		5			17	
5/2/95	28.8	6.2	0.1		5	1		20	
5/3/95	28.9	5.7->6.2	0.1		5			20	
5/4/95	28.8	6.1->6.2	0.1	12.3	5			20	
5/5/95	28.9	6.2	0.1			1	2.2	20	
5/6/95									
5/7/95									
5/8/95	28.5	5.8->6.2	0.1		5			20	
5/9/95	27.6	6.1->6.2	0.1		5	1		20	
5/10/95	28.5	5.8->6.2	0.1		5			22	
5/11/95	28.5	6.1->6.2	0.1	12.5	5			21	
5/12/95	28.5	6.2	0.1			1	2.1	20	
5/13/95									
5/14/95									
5/15/95	29.4	5.8->6.2	0.1		5			22	
5/16/95	30.2	6.1	0.1		5	1		22	
5/17/95	30.5	5.8->6.2	0.1		5			22	
5/18/95	30.1	6.2	0.1		5			20	
5/19/95	28.3	6.2->6.2	0.1			1	1.9	16	
5/20/95									
5/21/95									
5/22/95	29.9	5.8->6.2	0.1		5			21	
5/23/95	30.1	6.2	0.1		5	1		21	
5/24/95	29.3	5.8->6.2	0.1		5			19	
5/25/95	28.0	6.0->6.2	0.1	14.7, 14.9, 14.6	5			16	
5/26/95	27.3	6.2->6.2	0.1			1	2.3	19	
5/27/95									
5/28/95									
5/29/95									Holiday.
5/30/95	27.7	5.9->6.2	0.1		5	1		21	
5/31/95	28.2	5.8->6.2	0.1		5			21	

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
6/1/95	28.9	6.1->6.2	0.1		5			21	Boiler off for season.
6/2/95	30.3	6.2	0.1			1	1.9	21	
6/3/95									
6/4/95									
6/5/95	29.3	5.9->6.2	0.1		5			23	
6/6/95	29.4	6.2	0.1		5	1		22	
6/7/95	29.4	5.8->6.3	0.2		5			24	
6/8/95	30.1	6.2	0.1		5			22	
6/9/95	28.8	6.2	0.1			1	1.8	20	
6/10/95									
6/11/95									
6/12/95	28.5	5.9	0.1		5			21	
6/13/95	27.5	5.9->6.2	0.1		5	1		20	
6/14/95	26.6	5.8->6.2	0.1		5			21	
6/15/95	27.1	6.2	0.2		5			23	
6/16/95	28.2	6.2	0.1			1	2.2	23	
6/17/95									
6/18/95									
6/19/95	30.6	5.8->6.2	0.1		5			26	
6/20/95	31.9	6.2	0.1		5	1		27	
6/21/95	31.6	5.8->6.2	0.2	16.0	5			26	
6/22/95	31.5	6.2	0.1		5			25	
6/23/95	30.3	6.2	0.1			1	2.3	27	
6/24/95									
6/25/95									
6/26/95	30.0	5.8->6.2	0.1		5			26	
6/27/95	29.2	6.2	0.1		5	1		24	
6/28/95	29.2	5.9->6.2	0.1		5			24	
6/29/95	29.2	6.3	0.0		5			24	
6/30/95	29.3	6.4	0.0			1	2.4	23	

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
7/1/95									
7/2/95									
7/3/95	28.0	5.9->6.1			5	1			
7/4/95									Holiday.
7/5/95	31.4	6.1	0.1		5			27	
7/6/95	31.3	6.3	0.1	16.0	5			23	
7/7/95	29.5	6.3	0.1			1	0.5	22	
7/8/95									
7/9/95									
7/10/95	33.7	6.5	0.1					24	No replacement.
7/11/95	34.6	6.6	0.1		5	1		26	
7/12/95	32.5	5.9->6.1	0.0		5		0.6	27	
7/13/95	32.6	6.2	0.1		5			28	
7/14/95						1		30	
7/15/95									
7/16/95									
7/17/95	34.0	5.7->6.2	0.0		5			27	
7/18/95	32.5	6.3	0.0		5	1		25	
7/19/95	31.0	5.9->6.0		14.5	5			25	
7/20/95	31.0	6.2			5			26	
7/21/95	30.0	6.2				1	2.4	25	
7/22/95									
7/23/95									
7/24/95	33.8	6.4	0.0		5			30	
7/25/95	32.3	6.3	0.0		5	1		26	
7/26/95	30.7	6.0	0.0		5			26	
7/27/95	33.4	6.4	0.0		5			26	
7/28/95	33.0	6.3	0.1			1		26	No pH adjustment.
7/29/95									
7/30/95									
7/31/95	33.3	5.9->6.2	0.1		5			28	

TABLE C.4 (Cont.)

Date	Reactor Temperature (°C)	pH	Dissolved Oxygen (mg/L)	Solids (%)	Replacement Slurry (%)	Molasses Added (gal)	NaOH Added (L)	Ambient Temperature (°C)	Comment
8/1/95	33.6	6.2	0.0		5	1		28	
8/2/95	32.1	6.2	0.0		5			27	
8/3/95	30.0	6.1	0.0		5			25	
8/4/95	29.5	6.1	0.0			1		26	
8/5/95									
8/6/95									
8/7/95	30.5	5.9->6.2	0.0		5			26	Aerate to test foam control.
8/8/95	30.9	6.2	0.0		5	1		26	
8/9/95	30.4	5.9->6.2	0.1		5			26	
8/10/95	28.6	6.2	0.0		5			25	Mixer off.
8/11/95	32.4	6.3	0.1			1	1.2	26	
8/12/95									
8/13/95									
8/14/95	33.3	5.9->6.0	0.1					32	
8/15/95	35.0	6.2	0.0		5	1		28	
8/16/95	33.4	5.9	0.0		5			29	
8/17/95	31.7	5.9->6.2	0.0		5		1.1	26	
8/18/95	31.6	6.1	0.0			1		27	
8/19/95									
8/20/95									
8/21/95	31.2	5.8	0.0					28	
8/22/95	30.6	5.8	0.1			1		25	
8/23/95	29.8	5.9	0.0					25	
8/24/95	30.6	5.9	0.0					26	
8/25/95	30.7	6.2	0.0			1	2.0	26	
8/26/95									
8/27/95									
8/28/95	30.5	5.9	0.1		5			27	
8/29/95	31.1	6.2	0.0		5	1		27	
8/30/95	31.1	5.9->6.2	0.0		5			27	
8/31/95	31.6	6.1->6.1	0.0		5		0.9	27	