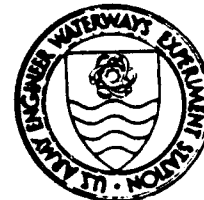
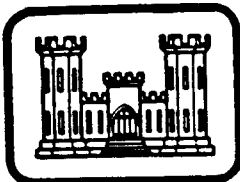


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LABORATORY-SCALE SOLIDIFICATION OF BASIN F CONCENTRATE

ROCKY MOUNTAIN ARSENAL

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

by

Tommy E. Myers and Douglas W. Thompson

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July 1983

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LABORATORY-SCALE SOLIDIFICATION

OF

BASIN F CONCENTRATE

ROCKY MOUNTAIN ARSENAL

by

Tommy E. Myers and Douglas W. Thompson

Environmental Engineering Division

Environmental Laboratory

USAE Waterways Experiment Station

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## PREFACE

This laboratory study of solidification techniques for Basin F liquid was conducted during the period May 1981 to December 1982 by the Environmental Laboratory (EL) of the U.S. Army Engineer Waterways Experiment Station (WES) for the U.S. Army Toxic and Hazardous Materials Agency (THAMA). The principal contributors to this effort were Mr. Tommy Myers and Mr. Douglas Thompson, Water Supply and Waste Treatment Group, WES.

The authors would like to thank Mr. Carl Loven, Solidification Task Manager, RMA, Mr. Edwin Berry, Contamination Control Systems Coordinator, RMA, and Mr. Donald Cambell, Program Manager, THAMA, for their direction and support during all stages of the study and Mr. Rudy Sweder and Mr. Dennis Prusinski, RMA, for their cooperation and helpful advice. Special thanks are extended to Mr. Johnnie Lee and Mr. Larry Caviness for their assistance with sample preparation and testing. The authors on behalf of the Army would like to thank the vendors for participating in this study at no cost to the Government; without their support and cooperation this study would not have been possible.

This work was performed under the direct supervision of Mr. Norman Francingues, Chief, Water Supply and Waste Treatment Group, WES, and under the general supervision of Mr. Andrew Green, Chief, Environmental Engineering Division, WES, and Dr. John Harrison, Chief, Environmental Laboratory, WES. COL Tilford C. Creel was Commander and Director of the WES during preparation of this report. Mr. Fred R. Brown was Technical Director.

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## PART I: INTRODUCTION

### Background

1. Rocky Mountain Arsenal (RMA) was established in 1942 for the production of chemical agents and chemical filled munitions. After World War II, a portion of the manufacturing facilities was leased to private industry for the production of herbicides and insecticides. Present military activities on the arsenal are limited to demilitarization (incineration) of obsolete chemical munitions. Figure 1 is a vicinity map that shows the location of the Rocky Mountain Arsenal.

2. Over the years wastes from the military and industrial operations have been disposed of in accordance with standard engineering practice. Although acceptable at the time, some of these practices have since proven to be inadequate. Originally, wastes were discharged to unlined, earthen evaporation ponds. Beginning in 1955 waste discharges were diverted to an asphalt-lined evaporation lake known as Basin F (1). The 93-acre (37.7-hectare) lake is located in the northern half of the Arsenal property in Section 26 (Figure 2). Design capacity for Basin F is 240 million gallons. In early 1957 waste flow into Basin F was halted due to the discovery of a break in the liner. As a result of this discovery the contents of Basin F were pumped into a nearby unlined basin so that the liner could be repaired. By the end of 1957, Basin F was again accepting all chemical waste discharges on the Arsenal. The physical integrity of the asphaltic membrane has been the subject of discussion and inquiry ever since the 1957 leak/repair episode (2).

3. From 1962 through 1965 approximately 175 million gallons ( $663,000 \text{ m}^3$ ) of Basin F fluid were injected through a deep well into the bedrock at a depth

of 12,045 feet (3671 m). Due to a marked increase in the number and intensity of earth tremors in the metropolitan Denver area during the deep well injection activity, the well was closed. Following the closing of the deep well disposal facility Basin F was again used for chemical waste disposal on the Arsenal and functioned as the primary repository of military and industrial waste discharges. In 1978 wastewater flows to Basin F were eliminated when military discharges were stopped and volume reduction of the industrial waste by inplant conservation and recovery made offsite disposal of the RMA industrial waste feasible. From then until 1982 the primary source of flow into the basin was groundwater infiltration into the chemical sewers leading to the basin. In early 1982, discharge of wastes to Basin F was made physically impossible by excavation of the chemical sewers leading to the basin. The basin is esti-

ated to contain 30 million gallons (144,000 m<sup>3</sup>) of liquid waste at this time. A summary of the chemical characteristics of Basin F liquid is given in Table 1. Basin F liquid is in contact with precipitated solids in the bottom sludge and theoretically should be approaching equilibrium. The actual contaminant concentrations at any given time depend, however, on meteorological influences such as evaporation, precipitation, and temperature.

4. Basin F materials present a potential environmental hazard through at least three pathways, as follows: 1) the migration of contaminants to the groundwater due to the liquid head in the basin, 2) the migration of contaminants to the air due to volatilization, and 3) the hazard to wildlife that come in contact with the liquid. A notice of hazardous waste activity and Part A of the permit application required under the Resource Conservation and Recovery Act (RCRA) of 1976 was filed with EPA in 1980 listing Basin F as a hazardous waste surface impoundment. The RCRA interim status standards as set forth in 40 CFR Part 265 are applicable to Basin F and require a written closure plan

including a description of how and when the facility will be closed. The closure actions currently being proposed include: 1) solidification of Basin F waste insitu followed by capping of the basin using natural and/or synthetic material, and 2) solidification followed by disposal of the solidified material in a secure landfill constructed on RMA.

5. With respect to the proposed remedial action, solidification is defined as the conversion of liquid or semi-solid waste to solid form with no free liquid remaining on the surface or as weep water within the solid. Solidification is accomplished by the admixing of absorption materials with liquid waste and the incorporation of the resulting slurry into a solid, crystalline, or polymeric matrix. The objective is to produce a solid that can be safely handled and landfilled. Commercial solidification processes usually produce a dry, monolithic solid with some degree of structural strength; (however, it is not necessary in this case that a monolithic mass be produced in order to be considered an acceptable solidification process.) The most important factors for evaluating the applicability of solidification techniques to Basin F liquid are: 1) elimination of free liquid, 2) suitable bearing capacity to support a final cover and construction equipment, 3) volume increase due to solidification and 4) chemical leaching potential.

6. In order to properly address the proposed Basin F closure action, information on the technical and economic feasibility of solidifying Basin F liquid is needed. The U.S. Army Engineer Waterways Experiment Station (WES) was tasked by the U.S. Army Toxic and Hazardous Materials Agency (THAMA) to study the feasibility of solidifying Basin F liquid. The purpose of this report is to document the results of this feasibility study.

## Objectives and Approach

7. The primary purposes of this study were to identify solidification techniques that may be applied to the liquid contents of Basin F, to conduct a series of tests in order to characterize samples of solidified materials from the basin, and to determine the feasibility of solidifying the liquid contents of Basin F. The specific objectives were as follows:

- a. Evaluate the ability of various treatments to absorb and solidify Basin F concentrate, including proprietary commercial processes and non-proprietary processes that use materials available onsite or in the vicinity of RMA.
- b. Perform laboratory physical tests and laboratory chemical leaching tests on solidified specimens of Basin F concentrate.
- c. Evaluate the durability and trafficability of solidified material.
- d. Develop procedures for comparing various solidification techniques.

8. The study was performed in two separate phases identified as Phase I and Phase II. In Phase I commercial vendors of proprietary solidification techniques were invited to participate in the study under a gift agreement, i.e., at no cost to the Government. Those who chose to participate under the terms of the gift agreement were given a sample of Basin F concentrate for process development and testing in their laboratories. The commercial processes included in Phase I are described in Table 2. Vendors and their processes are referred to anonymously throughout this report. Each participating vendor, upon completion of their in-house testing, reported to the Government their findings, and based on these results indicated their desire to either continue to participate in the study or to drop out.

9. In Phase II the WES performed selected physical and chemical tests on solidified specimens supplied by the vendors. These samples were prepared at the RMA by the vendors and in the presence of a WES representative who took custody of the samples and certified their authenticity. In addition to the vendor preparations the WES investigated the solidification properties of a limited number of absorbent, non-proprietary materials. Government preparations were made in order to establish a benchmark for comparison of the physical/chemical properties of proprietary products to products developed using known additives and processes, and to evaluate the ability of these materials to absorb and solidify Basin F waste.

## PART II: MATERIALS AND METHODS

### Solidification Procedures

#### Identification and Preparation of Basin F Liquid Concentrate

10. Under an FY 82 MCA program, the chemical sewer leading to Basin F was physically removed. This action eliminated inflow to Basin F except for precipitation falling directly on the basin. As anticipated, the volume of liquid contained in Basin F has been decreasing. Theoretical calculations estimate the evaporation rate for Basin F to be 1.5 gpm per acre (2). Field studies indicate that the evaporation rate for Basin F is not constant, but progressively declines with increasing salt concentration until it becomes essentially zero (3). Ideally the liquid used in this bench scale study should be evaporated to a concentration that is representative of the basin condition at the time of closure of Basin F. Predicting the character of Basin F liquid with time is a problem compounded by uncertainty about the rate at which the evaporation rate diminishes, by uncertainty about when a full-scale solidification project would begin, by uncertainty about meteorological influences, and by uncertainty about the effect evaporation has on composition and character of Basin F liquid. For these reasons it was necessary to make an estimate of what degree of evaporation is reasonable and probable. A 70 percent volume reduction by evaporation was selected for this study on the basis of the following reasons and assumptions:

- 1) A 70 percent volume reduction of Basin F is achievable in 1-2 years if the assumption of an average evaporation rate of 1.5 gpm/acre is correct. A 1-2 year projection for reaching equilibrium is a reasonable waiting period.

- 2) A 70 percent volume reduction is achievable using accelerated evaporation in a reasonable length of time (7-14 days) in sufficient volumes to conduct a bench scale study.
- 3) 70 percent volume reduction is consistent with the diminishing rate rule, i.e., the liquid is difficult to concentrate beyond 70 percent volume reduction.

Approximately 217 gallons (821 liters) of Basin F liquid were evaporated to 65 gallons (246 liters) by a solar enhanced/thin-film evaporation technique. The thin-film equipment consisted of a 4 x 16 ft (1.24 x 4.97 m) evaporation platform, a 4 ft (1.24 m) diameter catch-pan, and a pump (Figure 3). Basin F liquid was pumped from the catch-pan to the top of an inclined evaporation platform where the liquid was allowed to flow by gravity as a thin-film back into the catch-pan. The liquid was recirculated until the original volume in the catch-pan had been reduced by 70 percent. The concentrated liquid was removed from the catch-pan and stored in plastic drums. Five (5) gallons (18.9 liters) of Basin F concentrate was shipped to each Phase I participant for testing and process evaluations. A second batch of Basin F concentrate was similarly produced for the solidification work carried out in Phase II.

#### Onsite Solidification of Basin F Concentrate

11. Samples of solidified Basin F concentrate were prepared at the RMA by a representative(s) from each participating vendor. A WES representative was on site to take custody of the solidified material after the vendor certified the material as acceptable for testing. Vendor activities at RMA began in June 1982 and were completed in September 1982. During this time-frame WES personnel solidified aliquots of the Basin F concentrate using conventional, i.e., non-proprietary materials that were either available onsite at RMA or were locally available.

12. Additives were blended with Basin F concentrate in 0.5-1.0 liter batches in a Hobart laboratory grout mixer. Mix-time was 3-4 minutes per additive. The weight-to-weight ratio of additive-to-Basin F concentrate for each process is listed in Table 3. Following reagent addition and mixing, the admixture was transferred and compacted by hand into various sample containers as listed in Table 4. In preparing the samples no attempt was made to simulate any specific field compaction effort. The treated material was compacted into the sample containers in a series of lifts and in such a fashion as to minimize voids.

13. Non-proprietary process development was conducted by the WES in parallel with the opportunities for process development offered to the vendors in Phase I. Various materials were screened by the WES for their ability to absorb and solidify Basin F liquid. These materials are listed in Table 5. The material list includes commercial absorbents and bentonites, cement, pozzolans, soil, and others. Onsite soil samples were obtained from a location near the intersection of "E" Street and 9th Avenue at RMA from 2-3 feet (0.6 - 0.9 meters) below the surface. The particle size distribution for the soil is shown in Figure 4. This clay/fine-sand soil had a natural moisture content of 4.13 percent when used. Flyash was supplied by the Public Service Co., Denver, CO. A sample of Hazorb,<sup>®</sup> containing inert sodium borosilicate, was provided by Diamond Shamrock Corporation. Kiln dust was provided by Radian Corp. of Austin, TX. Other commercially available absorbents were purchased from local distributors. The screening tests showed that combinations of 1) soil and kiln dust, 2) soil and lime, and 3) soil, lime, and flyash were

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<sup>®</sup> Registered Trademark, Diamond Shamrock Corporation.

the most suitable materials for solidifying Basin F waste. This determination was based on comparison of the materials costs for producing a solidified product with no free, residual liquid.

#### Physical/Chemical Test Procedures

14. There are many physical properties tests that can provide information on the suitability of the solidified waste for a particular purpose (4). The test procedures described in this section were selected to provide information on criteria of importance in evaluating the performance of solidification techniques in Basin F liquid. The criteria used were as follows:

- Residual free liquid after solidification processing.
- Bearing capacity to support a cover material and the construction equipment needed to spread the material and place the cover.
- Handling characteristics (Bulk Weight and Volume Increase).
- Durability (wet/dry cycling).
- Potential contaminant migration through leaching (Permeability and Chemical Leaching Characteristics).

Details of the standard test procedures applied to the solidified product samples are presented below with the exception of the free liquid determination. There is no standard procedure for quantifying the "free liquid" in a material. A simple gravity filtration test was developed by WES personnel and used in the Phase I screening program.

## Bearing Capacity

15. Bearing capacity is normally defined as the allowable bearing pressure of the soil, or the load or pressure that can be applied to the soil without introducing damaging movement or settling. The product produced from solidifying Basin F liquid must have sufficient strength to support a cover (which can be classified as a "dead" load) and the construction equipment used to spread the solidified product and construct the cover (which can be classified as a "live" load). In comparing these two types of loads, it was determined that the bearing capacity needed to support the "live" load could greatly exceed that required for the "dead" load. The cover would probably exert a pressure of approximately 4 psi ( $2.76 \text{ N/cm}^2$ ) on the solidified material whereas the construction equipment would probably exert a pressure of at least several times that value. In addition, the equipment would be moving, possibly making multiple passes over the same material and thereby potentially requiring a higher bearing capacity for needed mobility. As a result, testing of the solidified products was directed toward evaluating their trafficability properties since trafficability would be the limiting factor with respect to bearing capacity.

16. Therefore, for purposes of this study, bearing capacity is defined as the ability of a material to support a vehicle without undue sinkage of the vehicle, and, as such is a measure of the material's trafficability or ability to support vehicular traffic. Bearing capacity was determined using a cone penetrometer and reported in terms of the cone index (CI) in pounds per square inch (psi). The CI is actually a number representing resistance to penetration of a 30-degree cone with 1/2-square-inch ( $3.2 \text{ cm}^2$ ) base area. Procedures for using the cone index to predict trafficability have been developed by the Mobility Systems Division at the WES (5, 6). CI's were measured by pushing

cone penetrometer into solidified Basin F material contained in 800 ml glass jars. The dial reading from the penetrometer was recorded as the base of the cone became flush with the surface of the material.

#### Wet/Dry Cycling

17. The purpose of this test is to determine if a material or product tends to deteriorate with respect to time and environmental cycling. A modification of the wet/dry durability test in ASTM Method D559-57 was used in this study; solidified samples were placed in a 100 percent relative humidity room at 70°F (21°C) for 24 hours, and then removed to dry for 24 hours at 120°F (49°C). This process was repeated for five (5) cycles. At the end of each cycle, the cone index was measured. These data provide information on the physical durability and stability of the solidified product with respect to potential wet/dry cycling that may be encountered in the field.

#### Bulk Weight

18. Bulk weight was determined by weighing a known volume of solidified material. Samples were compacted by hand into glass jars of 800 ml capacity using the same technique and at the same time the other specimens listed in Table 4 were prepared. A regression analysis was performed to relate height to jar volume. For each sample the compacted height was measured and converted to jar volume. The jars were weighed before and after filling so that the sample weight could be taken by difference. Results are expressed as weight per unit volume in pounds per cubic foot (lb/ft<sup>3</sup>).

### Volumetric Increase

19. The increase in volume of waste material resulting from solidification is expressed as the ratio of the final volume of solidified material to the initial volume of Basin F concentrate, that is,

$$\text{Vol. Increase Ratio} = (\text{Final Vol.})/(\text{Initial Vol. BF})$$

*How about units?*  
The result is dimensionless. Final volumes were determined from the volume of sample compacted into a jar using the height-volume regression referred to above. Initial volumes were calculated for given weights of untreated Basin F concentrate using a density for Basin F concentrate of 1.25 g/ml.

### Permeability

20. Permeability, also referred to as the coefficient of permeability, is defined as the rate of discharge of water under conditions of laminar flow through a unit cross-section under a unit hydraulic gradient. This is the velocity at which water will flow through a porous medium under laminar flow conditions and complete saturation. Permeability has the units of velocity and is expressed in cm/sec. Triaxial, upflow permeability of the solidified products was determined by standard Corps of Engineers procedures (7). Information developed through permeability testing is used in conjunction with leaching tests to assess the potential of water infiltrating the solidified material to migrate through the material and to leach contaminants from the material.

## Chemical Leach Procedures

21. Leaching tests have been adopted by the scientific community as a means of estimating the contaminants likely to be released by a waste through contact with aqueous media (8). Leaching tests are generally assumed to indicate the maximum release of contaminants because they provide a more rigorous leaching environment than that normally found in a landfill. Regulatory agencies use leach tests to classify wastes and to set disposal requirements accordingly. Leaching tests were conducted using both the USEPA EP Toxicity Test Procedure (9) and the Solid Waste Leaching Procedure (SWLP) developed by Battelle Columbus Laboratories for the USEPA (10). Leach tests were performed in triplicate; prior to chemical analysis the replicate leachates were composited into a single leachate sample representing either the EP leach or the SWLP leach for a given waste material. As prescribed in the EP and SWLP protocols, solidified samples were subjected to the structural integrity test prior to the EP leach and the SWLP leach. EP leachates and SWLP leachates were analyzed by the Analytical Laboratory Group (ALG) at the WES for the parameters listed in Table 6 in addition to the parameters specified in the EP protocol (Table 7). The organic analyses were conducted using standard GC/MS techniques while metal analyses were conducted using plasma-arc emission spectrophotometry and flameless atomic absorption spectrophotometry. Mercury and arsenic were analyzed using cold vapor and hydride generation atomic absorption spectrophotometry techniques, respectively. Total organic carbon (TOC) was determined by oxidative destruction/non-dispersive infrared spectrophotometry. Chloride and pH were determined by specific ion analysis. Conductivity was measured on a laboratory conductivity meter. References for the methods used are cited in Table 8. The ALG carries out a quality assurance and quality control program involving replicate analyses, internal standards, equipment calibration,

quality control samples, and reagent control as is appropriate to each specific analysis. The ALG also participates in a laboratory quality assurance program used by the EPA to monitor EPA contractors.

### PART III: RESULTS AND DISCUSSION

#### Phase I

22. Seven (7) of the eight (8) vendors receiving Basin F concentrate reported successful in-house process development tests. Process descriptions for the Phase I participants have been previously summarized in Table 2. The processes employed by these vendors fall into two basic categories: cement processes and pozzolanic processes, the latter being silicate processes without cement.

23. Malone, Jones, and Larson (11) categorize current solidification technologies as follows:

- a. Cement-based processes
- b. Pozzolanic processes (silicate processes that do not use cement)
- c. Thermoplastic techniques
- d. Organic polymer techniques
- e. Self-cementing techniques
- f. Glassification and production of synthetic minerals or ceramics.

The cost and effectiveness of the processes vary widely depending upon the nature of the waste to be treated. Cement processes are mixtures of slurried wastes and portland cement, and produce a rigid, hardened solid. Pozzolanic techniques in their most basic application simply replace the cement with a less costly material that contains silicates. The most common pozzolanic materials are flyash, ground blast-furnace slag, and kiln dust from cement kilns. These are by-products with limited commercial value that in some situations are viewed as waste materials themselves. In thermoplastic techniques the waste is dried, heated, dispersed through a heated plastic matrix (bitumen,

paraffin, or polyethylene), and then cooled. The process requires expensive, complicated equipment and large amounts of energy. Organic polymer techniques utilize polymerization properties of organic chemicals such as urea-formaldehyde to form a spongy mass that typically produces a "weep" water as it ages. Normally self-cementing techniques are limited to high calcium sulfate sludges generated by flue-gas cleaning scrubbers at coal fired power plants. Glassification and synthetic mineralization are not cost effective, but for the most highly hazardous materials (e.g. radioactive wastes).

24. Although cement and pozzolanic processes may be the least sophisticated of the technologies listed above, they are, for the same reason, the most widely applied and least expensive of the available solidification technologies. The advantages of cement and pozzolanic processes are several: cement and pozzolans with the right amount of water will give a good set at reasonable cost, do not require complex reactors or similar equipment, are not as sensitive to temperature as are the other technologies, can be applied to a wide variety of wastes, and in the case of pozzolans use other waste materials as solidification reagents. The vendor supplied information in Table 2 shows that most of the Phase I participants are either strictly pozzolanic technologies or are primarily pozzolanic technologies that offer a high performance version of their process which uses cement. It will be shown in the next section that Basin F liquid can be solidified using pozzolans. Thus, other waste materials and industrial by-products of limited commercial value can be used to solidify Basin F wastes.

## Phase II

25. Of the seven participants in Phase I, five were willing to participate in Phase II at no cost to the Government. These five are referred to

anonymously throughout the remainder of this report as processes 100, 200, 300, 400, and 500. The non-proprietary process formulated by WES is referred to as process 600. Two of the Phase II participants actually began participation very late in the program so that for them Phases I and II were not distinct phases but really just one accelerated involvement. Two vendors prepared multiple samples using variations of their proprietary solidification techniques. One of these, process 300, offered four versions of their basic process. Three (processes 300, 301, and 302) are discussed in this report but only two of the three were carried through the full test program. Process 300 is a low cost, no ammonia control process.<sup>1</sup> Process 301 is a high cost (high performance), no ammonia control process, and process 302 is a low cost, ammonia control process. The 300 and 302 processes were carried through the full test program so that an assessment could be made of how changes made in the process formulation for ammonia control affects other aspects of process performance. The 301 process was subjected to chemical leach testing so that an assessment could be made of any benefits (in terms of environmental protection) to be obtained from a more expensive process. Process 500 also offered low cost and high performance options, 500 and 501, respectively. Only the 500 process was carried through the complete test program, although some information obtained on 501 is provided in Table 3. The results of the physical and chemical tests for the five commercially available processes evaluated and the non-proprietary process are discussed below.

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<sup>1</sup> A significant amount of ammonia gas is released from Basin F liquid when alkaline solidification reagents are added. Two vendors developed special solidification formulations on their own initiative aimed at minimizing ammonia evolution. This subject is further discussed later in this section.

### Residual Free Liquid

26. Regulations promulgated by the EPA under the Resource Conservation and Recovery Act (RCRA) prohibit the landfilling of free flowing liquids (12). Thus the elimination of free liquid is an absolute requirement for solidification processes to be acceptable in this study. Even though solids with free liquids are prohibited from landfills, no standard free liquid test has been adopted by EPA. During the screening program conducted by WES under Phase I, a test procedure was needed to determine the relative additive dosage rates below which processed samples contained free liquid. For this purpose, WES developed a gravity filtration procedure using a Buchner funnel, filter paper, and a graduated cylinder for measuring the amount of liquid which drained from the sample over a 24-hour period. A sample was considered to have no free liquid if no liquid appeared in the cylinder at the end of 24 hours. In Phase II, only additive dosage rates above the minimum rates established in Phase I were used. Likewise, the vendors used additive dosage rates in the Phase II work that produced samples with no free liquid. Since water is a reactant in cementation and pozzolanic processes, the free water or liquid content of the processed material decreases with time as the product cures. Visual inspection of the solidified materials prepared in Phase II of this study indicated that within 1-2 minutes of additive addition and mixing, no free, flowable liquid remained in the Basin F concentrate. This was true for all of the processes evaluated. Therefore, a free liquid test was not conducted on the samples produced in Phase II.

### Bulk Weight

27. Bulk weight is the wet weight of solidified waste per unit volume. (Bulk weight is not to be confused with specific weight which is the weight of

the dry solids per unit volume.) Bulk weight data are used in this study to indicate the compaction that was achieved during the preparation of samples used for physical-chemical testing. The bulk weight for each process is listed in Table 9. These data range from a low of 79.4 lb/ft<sup>3</sup> to a high of 105 lb/ft<sup>3</sup>. The 26 lb/ft<sup>3</sup> spread between the minimum and maximum values is 29 percent of the average value. The spread is indicative of the combined variation in the density of the various additives used by the vendors and the variation in the compactive effort applied during sample preparation.

28. Laboratory compaction tests have been developed by highway engineers in order to predict the results of compaction equipment actually deployed in the field. As is the case with most tests designed for testing specifically either soil or concrete, the applicability of standard soil compaction tests to solidified wastes for the purpose of predicting field conditions has not been demonstrated. One vendor does use the standard Proctor test to prepare samples for chemical leaching and as a quick means of indicating the acceptability of the solidified material, i.e., the Proctor for a given laboratory formulation is compared with results found by the vendor to be acceptable in prior field applications. Most vendors, however, do not run compaction tests as part of their formulation development routine. Some processes, especially those that use cement cannot be compacted. Until they are given sufficient set time, they will flow.

#### Additive Requirements

29. Total additive to Basin F concentrate ratios for each process are presented in Table 3. These ratios range from 1.05/1 for Process 300 to 3.9/1 for the Process 200. Even though most of the processes fall in the pozzolanic category, the amount of solidifying reagents does vary considerably among the

vendors. It should be noted that all of these processes could be further optimized in order to achieve a specific result. For a given specification for physical strength, some vendors would probably use more additive than shown in Table 3 in order to meet the specification while others might be able to reduce their additive requirement. Modification of additive amounts directly translates into material costs increases or possibly cost savings for a solidification project.

30. The formulations developed by the vendors and by the WES were achieved without the benefit of a set of design specifications, other than that a process could leave no free, flowable liquid and still be considered a viable solidification process. This specification originates in EPA's rules for landfilling wastes, as previously discussed, that prohibit the landfilling of free-flowing material. The solidification industry itself has not developed an industry-wide accepted, standard code of specifications for solidified waste for the user community. Furthermore, the Department of Army, the user in this instance, was not in a position to provide detailed specifications for a treatment concept that traditionally has relied heavily on proprietary know-how. Consequently, the guidelines provided were of necessity very general in nature. The guidelines used are described below.

31. Beginning with the assumption that the logistics of landfilling will require that the in-place solidified material be able to support heavy equipment during the landfilling phase of the disposal activity, the vendors were advised that processes which tend to set-up as solid blocks with sufficient physical strength to support heavy equipment will be favored over those processes that produce less trafficable end-products. The vendors were also advised that although Basin F waste may still be presumed to be a hazardous waste after solidification, hazard reduction remains a desirable feature for

candidate solidification processes, since hazard reduction will impact the final land disposal design and the permitting process in a significant way. The vendors were also reminded that to be competitive, a process formulation should minimize costs by minimizing the amount of additives used. The above guidelines are only guidelines and not specifications. Without detailed performance criteria in terms of a set of specifications it was not possible for the vendors to truly optimize their process formulations. Since only guidelines were available when this study was initiated, none of the formulations presented in Table 3 should be taken as necessarily the best a vendor can deliver.

#### Volume Increase

32. Ratios for the final volume of solidified waste to the initial volume of Basin F concentrate range from 1.2/1 for Process 300 to 4.1/1 for the Process 200 (Table 9). On the average the ratio is 2.3/1. The cost of disposing of the solidified waste is dependent on the final volume after solidification processing. Therefore, it is important to minimize the volume increase since the cost of disposing of the solidified waste is a major part of the overall cost of the proposed Basin F closure action.

#### Trafficability

33. Trafficability, that is, vehicular mobility, on a given soil is related to the bearing capacity of the soil. In this study bearing capacity was measured using a cone penetrometer and is reported as the cone index (CI) in pounds per square inch (psi). When the CI of a given material is equal to or greater than that required for a given vehicle, then sufficient strength will be available in the material to withstand passage of that vehicle. As

previously discussed, the Mobility Division, Geotechnical Laboratory, WES, has developed information on soils trafficability and the use of the CI to predict trafficability for specific vehicles (5, 6). This technology was used to predict the ability of a solidified Basin F material to support earthmoving equipment.

34. The vehicle cone index (VCI) is the cone index assigned to a given vehicle that indicates the minimum bearing capacity required for passage of the vehicle. The VCI is related to a critical depth (layer) in the supporting material. The critical depth is the depth at which the cone index is considered a significant measure of trafficability for that vehicle. The critical depth varies primarily with vehicle weight and type, and generally ranges from zero to nine inches (23 cm) for earthmoving equipment. Critical depth is an important consideration when an abnormal soil strength profile is encountered. An abnormal profile is one in which at least one CI reading is lower than the one taken above it. In such cases, only the cone index reading at the critical depth for the vehicle of interest should be used to evaluate trafficability. For properly landfilled solidified hazardous waste, the CI profile should be monotonically increasing, i.e., CI readings either increase or remain constant with depth. In this case, the surface CI suffices for predicting trafficability and critical depth is therefore of no concern. Only surface CI's were measured in this study. Single pass VCI's ( $VCI_1$ ) and VCI's for 50 passes ( $VCI_{50}$ ) for a wide range of earthmoving equipment have been empirically determined at the USAE WES.  $VCI_1$ 's and  $VCI_{50}$ 's for various pieces of earthmoving equipment are listed in Table 10. By way of example, the  $VCI_{50}$  for a Caterpillar D-8 tracked bulldozer is 41 psi while  $VCI_{50}$  for a dump truck is about 73 psi.

35. A modification of the cone index termed the rating cone index (RCI) is used in conjunction with the VCI to predict the trafficability of a given

vehicle over a given terrain. When the RCI is greater than or equal to the VCI, then sufficient strength will be available in the material to withstand passage of the vehicle. The RCI is the measured CI multiplied by the remolding index. The working of a soil by traffic may result in a beneficial, neutral, or detrimental change in soil strength. This effect is quantitated in a test known as the remolding index (RI) which is the ratio of the remolded cone index to the original cone index of undisturbed material. The remolding test as developed for soils, however, does not lend itself to the testing of solidified material. For the purposes of this study, it is adequate to assume the remolding index to be unity for all of the materials examined. For this assumption the RCI simply reduces to the CI.

36. Five (5) CI measurements were taken for each process for cure times of 1, 3, 5, 7, 14, 21, and 28 days. Graphs of CI versus time for the various processes are presented in Figures 5 through 11. These graphs show that CI generally increases slightly or remains constant with time. Other notable features are as follows: 1) the shape of the CI versus time curve is similar for all the processes, 2) the data are scattered, 3) linear least squares regression yields straight lines with small, but positive slopes and large intercepts, and 4) curvilinear least squares regression yields better fit than linear fit over the entire range of possible values. Straight line or linear representation of CI over time is good for the data shown in Figures 5-11 between day 1 and 28 because the change in CI after an initial set time is small. This is true for all the processes. Linear representation is not, however, a satisfactory theoretical model of what happens; when taken to the limits for time,  $t = 0$  and time,  $t = \infty$ , linear models predict a measurable CI at  $t = 0$  and an infinitely large CI at  $t = \infty$ . The first condition is

inconsistent with field observations that at  $t = 0$ ,  $CI = 0$  and that  $CI$  does not become instantaneously measurable upon the addition of solidification reagents.  $CI$  increases with time in a mathematically well behaved fashion, albeit at a very rapid rate initially. The linear model prediction that  $CI$  will increase for all time is also untenable. A more reasonable condition is that  $CI$  will eventually reach some maximum value beyond which there is no increase. Although linear models may not be theoretically satisfying, they do represent the data well over 28 days beginning at day one, and they are attractive because the coefficients can easily be computed using built-in statistical functions on many of the hand-held calculators available today.

37. A general  $CI$  versus time curve is shown in Figure 12 which has the following important characteristics: 1) the curve goes through the point  $t = 0$ ,  $CI = 0$ , and 2) there is an increase in  $CI$  with time that is initially very rapid but soon begins to slow down yielding a relatively flat region that eventually becomes asymptotic to some maximum  $CI$  value. A mathematical model of this curve is derived as follows:

Word statement: The change in  $CI$  at any time  $t$  is proportional to the increase in  $CI$  that remains to be achieved before the maximum value is reached.

Mathematical statement:

$$\frac{d(CI)}{d(t)} = -k (CI_{\max} - CI) \quad \text{Eq 37-1}$$

where

k is the proportionality constant; a negative sign is included because the rate of change decreases from some positive value toward zero

CI = Cone Index; psi

CI<sub>max</sub> = maximum CI value attainable

$\frac{d(CI)}{d(t)}$  = time rate of change in CI

Rearranging we have

$$-kd(t) = \frac{d(CI)}{(CI_{max} - CI)}$$

Integration yields

$$-kt = -\ln(CI_{max} - CI) + C$$

where C is the constant of integration.

Rearranging, we have

$$\ln(CI_{max} - CI) = kt + C$$

Exponentating, we obtain

$$CI_{max} - CI = e^{(kt + C)} = e^C e^{kt}$$

Eq 37-2

now we impose the boundary condition that at

$t = 0$ ,  $CI = 0$  which yields

$$e^C = CI_{\max}$$

carrying this result into Eq (37-2) we have

$$CI_{\max} - CI = CI_{\max} e^{kt}$$

or

$$CI = CI_{\max} (1 - e^{kt}) \quad \text{Eq 37-3}$$

which is the desired result. Using Eq 37-3, CI is regressed onto time for each process by least squares analysis. The coefficients  $k$  and  $CI_{\max}$  are determined in this regression analysis and are indicated for each process in Figures 5 through 11. Equation 37-3 is the mathematical model of the generalized curve shown in Figure 12. It satisfactorily represents both the available data and the boundary conditions.

38. In terms of the theoretical curve discussed above, the CI versus time graphs presented in Figures 5 through 11 indicate that the interval of rapid change in CI with time (the steep rise in Figure 12) occurs within one day and that after a one-day cure the CI versus time curve begins an asymptotic approach to some maximum value. This information has important practical application. It means that a 1-day CI can be used as an indicator of present and future (near-term) trafficability. For example, an inadequate CI at day

one is not going to significantly improve in the next 7 or even 28 days. Thus, the 24-hour CI should be a very useful tool for assessing the suitability of a particular solidification formulation in the laboratory and in the field. Also, since the CI for solidified Basin F concentrate increases very rapidly toward a plateau, it may be possible to develop a test that can be used within minutes of having added the solidification reagents to predict the 24-hour CI. The ability to reliably predict a 24-hour CI from test results obtained within minutes of having mixed in the additives would provide an extremely valuable feedback mechanism for monitoring solidification processing.

39. The data scatter shown in these plots is not a characteristic of the cone penetrometer itself. For homogeneous soils, precision on the order of  $\pm 10$  psi has been demonstrated for the instrument (6). The most significant variance occurs between average values for different days for a given process. It should be noted that the scatter is not process dependent but is related to conditions common to the preparation and testing of all the solidified samples regardless of the process type. Some of the scatter is due to the manner in which the samples were tested. CI's were read for days 1 and 3 from one specimen, days 5 and 7 from a second, days 14 and 21 from a third, and day 28 from a fourth. Significant difference in individual samples is apparent in the graphs where older samples measure lower in CI than do earlier samples. One possible source of variation in individual samples is differences in compaction. A single technician manually compacted all the specimens in a consistent fashion and at the time of sample preparation, noticeable differences were not evident. However, some variation is to be expected. Another possible source of variation is localized sulfate inhibition of the setting reactions. High sulfate waters are known to be detrimental to concrete (13). Inadequate mixing resulting in localized regions of high concentrations of Basin F waste in which

sulfate inhibition is significant could account for some of the variation for the CI's taken from a single sample. Thus, differences in compaction and random sulfate inhibition are probable mechanisms for the variation in the CI data observed in this study. Sources of scatter in the laboratory data do not necessarily have parallel significance for a full-scale operation. In a full-scale operation, compaction should be relatively easy to control using standard field procedures. Adequate mixing, on the other hand, may be more difficult to achieve at full-scale than in a laboratory study. *Waffers, waffers!*

40. The temperature at which materials are cured can affect the strength achieved. Some materials are affected more than others. Since the temperature sensitivity of the various proprietary processes included in this study was unknown to the investigators and to the vendors with regard to Basin F, it was determined that cure temperatures should be allowed to range over a typical range of temperatures as might be encountered in a closure action for Basin F. Had an arbitrary laboratory controlled temperature been imposed in the study design, the feasibility of solidifying Basin F liquid at a different temperature would be uncertain since interpretation of the results would be limited to a specific temperature. Consequently, temperature was not controlled during the development of the solidified materials in this study. Solidified materials were cured in a trailer adjacent to building 802 at the Rocky Mountain Arsenal in which the temperature tracked the ambient temperature rather closely. For the purposes of this study it is assumed that the temperature extremes recorded by the National Weather Service at Stapleton International Airport, which is immediately adjacent to the Arsenal, are representative of the temperature extremes over which the solidified materials were cured. Solidified materials were tested for bearing capacity beginning in June 1982 and ending in September 1982. The temperature extremes over this period were

91°F (33°C) as the high and 49°F (9.4°C) as the low. Since the temperature was allowed to vary, the CI results are more general in their applicability and interpretation. Relative comparison of CI data from one process to another has, however, been somewhat compromised since the samples were not cured under exactly the same conditions, some being cured in June and some in September. The significance of temperature variation on the setting of concrete is not important for small samples until the temperature drops below freezing. The same can probably be said for the samples in this study.

41. A review of the cone index requirements for landfill construction equipment listed in Table 10 shows that a 24-hour CI greater than or equal to 75 psi will permit 50 passes of tracked vehicles and most all-wheel-drive trucks. If traffic is limited to tracked bulldozers and loaders, then a minimum CI of 50 psi should be satisfactory. From Table 9 it can be seen that 5 of the processes in this study provide a 24-hour CI greater than 50 psi and that only 3 provide a 24-hour CI greater than 75 psi. In considering a CI specification a conservative approach is recommended due to the lack of information on remolding index and because lower CI's are often indicative of a wet, sticky material. Under extreme conditions, sticky material can accumulate in the running gear of a vehicle to the point where travel and steering are difficult. Further, field application of CI technology has not been demonstrated.

42. The use of CI as an indicator of trafficability has been described in preceding paragraphs. In addition to being an index of trafficability, CI is used in this study to monitor changes in solidified wastes as they undergo wet/dry cycling, which is discussed in the next paragraph. Hence, CI can be used as a specific test method for characteristics which have been empirically

*correlated*

to CI, e.g., trafficability, and CI can be used as a relative test method for evaluation of solidified wastes under various experimental conditions, e.g., resistance to degradation brought on by wet/dry cycling.

#### Wet Dry Cycling

43. Results of the wet/dry durability testing are presented in Figures 13 through 19. In these figures, relative CI with respect to the initial CI taken before the cycling began is plotted against the cycle number. (A cycle consists of 24 hours at 100% relative humidity at 70°F followed by 24 hours of drying at 120°F.) Most of the processes did not deteriorate under the conditions of the wet/dry cycling but instead tended to gain strength indicating that wet/dry cycling strengthens rather than weakens solidified waste. Process 302, Figure 16, does show some indication of a solid that is weakening. Process 302, a modification of Process 300, was formulated to eliminate the ammonia gas evolution problem discussed later in this report. The wet/dry cycling for Process 300 shown in Figure 15 does not show signs of weakening under the conditions of the test as did the formulation which contained ammonia control reagents.

44. For cements and pozzolanic solidification processes hydration of the binder (cement or some pozzolanic substitute) is responsible for the hardening process. The hydration process stops when no more water is available for reaction or when no more unhydrated binder is available. For the instances in which the curing process is apparently assisted by cyclic wetting and drying, the 100% humidity environment provides an external source of water which forms new hydration products with unreacted binder or with incompletely hydrated binder. Then in the dry step of the wet/dry cycle, the new products harden

and add strength to the material. For the products that tended to weaken under the conditions of the wet/dry test, a simple explanation is not readily at hand. If the externally supplied moisture is the problem, then the material may have initially undergone a "false set." A false set is operationally defined as one that can be overcome by an external source of water. The factors that may produce false set in solidified waste are not well understood at this point. It is also possible that the material is undergoing a thermal degradation process during the dry step of the wet/dry cycle, or that in the case of Process 302 the ammonia control reagents are interfering with the hardening process.

#### Permeability

45. Permeability is an important parameter because it partly determines the rate at which contaminants will be released. A low permeability, by limiting the passage of water through a waste, reduces the rate at which contaminants migrate. Permeabilities of natural materials range from  $10^{-1}$  cm/sec for sand to  $10^{-4}$  cm/sec for sandy silt to  $10^{-8}$  cm/sec for clay. Permeabilities equal to or less than  $10^{-7}$  cm/sec, in certain circumstances, are sufficiently low to be considered adequate for natural liner systems at waste disposal sites (Draft RCRA Guidance Document Landfill Design Liner Systems, and Final Cover, for use with RCRA Regulations Part 264 301(a) and 264.310(a)). Permeabilities were determined in triplicate on two test specimens from each solidified waste type according to the procedures referenced in the Materials and Methods section of this report. The average permeabilities for six determinations on each solidified waste type are presented in Table 9. The results range from  $10^{-4}$  to  $10^{-8}$  cm/sec. All but one of the solidified Basin F wastes

had permeabilities in the range of  $10^{-4}$  to  $10^{-6}$  cm/sec. The Process 100 product had a permeability of  $10^{-8}$  cm/sec. The variation in the permeabilities measured in this study is strongly process dependent indicating that the permeability of solidified Basin F waste is more dependent upon the solidification reagents used than on the amount used. For a given process the additive ratio controls permeability and probably other physical parameters of the solidified waste as well. The within process effect of additive ratio on permeability is indicated by the Process 300 and 302 process modifications which resulted in a two orders of magnitude change in permeability. Process manipulation to provide a solidified product with given physical properties such as low permeability is discussed later in this report.

#### Chemical Leaching

46. Two chemical leaching procedures, the USEPA EP Toxicity Procedure (EP) and the Battelle Solid Waste Leaching Procedure (SWLP), were used to assess contaminant migration potential from solidified Basin F liquid. The EP is part of the EPA's official protocol for classifying a waste as hazardous or non-hazardous under the Resource Conservation and Recovery Act regulatory system. In this study, the EP is used to indicate whether or not solidified Basin F wastes would be considered a hazardous waste with respect to EP toxicity. In Battelle's SWLP, the leach medium is selected to simulate in situ conditions so that a determination can be made of a material's ability to leach contaminants at levels requiring control strategies. For example, an acid medium would be chosen to simulate leaching by infiltration derived from acid rain. The default medium in the SWLP, distilled water, was chosen for this study instead of a more aggressive leach medium because the standard EP which uses

an acetic acid buffered leach medium probably adequately represents a worst case situation. In this study, the SWLP is used to estimate the leachate quality that would result should rainwater infiltrate solidified Basin F waste.

47. The SWLP was designed to simulate repeated leaching events through the use of sequential extraction steps. A single extraction step was determined to be adequate for the purposes of this study because 1) the first leach will probably show the highest concentrations of contaminants and 2) additional extraction steps with respect to the type of material being leached are normally used to determine diffusivity constants, something beyond the scope of this study.

48. The data for each leachate parameter is discussed in the following paragraphs. The pH, conductivity, and chloride data are presented in Table 11, metals data in Table 12, organics in Table 13, and a summary of leachable contaminate densities (leachable contaminant mass per unit volume of Basin F liquid concentrate solidified) in Table 14. Although the parameter list is not exhaustive, it does include, in addition to the parameters specifically listed in the EPA EP Toxicity Test, three parameters that are highly concentrated in Basin F liquid (copper, TOC, and chloride). Contaminant concentrations in the EP and SWLP leachates were used to assess the potential of leachates from solidified Basin F liquid to pollute receiving waters. Leachable contaminant densities for arsenic, copper, mercury, TOC, sulfone, and chloride were used to compare the relative abilities of the solidification processes investigated in this study to immobilized two general classes of contaminants: metals and organics.

49. pH. pH is the negative logarithm to the base 10 of the hydrogen ion concentration. The practical pH scale begins at 0, very acidic, and extends to 14, very alkaline. pH 7 corresponds to exact neutrality. Most natural

waters fall in the range of pH 4-9. The EP leachates all have a pH of approximately 5 since in a properly run EP, pH control to a pH of 5 is required. The SWLP leachates all have a pH in the range of 8-11. These data show that in an unbuffered leach medium, the pH of the leachate will vary from slightly to strongly basic reflecting the alkaline nature of the additives used in a particular solidification process. These data further suggest that neutralization should be included in any leachate treatment system designed to treat leachate from solidified Basin F waste.

50. Conductivity. Conductivity is a measure of a material's ability to convey an electrical current. Results are expressed in  $\mu$ mhos, the inverse of  $10^6$  ohms. In the case of a liquid, conductivity is a rough measure of the dissolved ionic species in the liquid. Most natural waters have conductivities in the range of 50 to 500  $\mu$ mhos. The conductivity of EP leachates varies from the EP blank by up to 3 orders of magnitude. The SWLP leachates are consistently 3 orders of magnitudes higher than the SWLP blank. Both the EP and SWLP leachates were on the order of  $10^4$   $\mu$ mho.

51. Chloride. Chloride is a ubiquitous ion occurring in practically all natural waters to some degree. An extreme example is the 21,000 mg/l chloride found in open ocean waters. By comparison, Basin F liquid contains about 50,000 mg/l chloride. Chloride is one of the most difficult chemical species for a solidification process to tie up because chloride salts are very soluble and very easily redissolved. The chloride concentrations in the EP and SWLP leachates were an order of magnitude lower than the chloride concentration in the Basin F liquid. Interpretation of the significance of this 10-fold dilution in chloride concentration is confounded by the likelihood of chloride being present in the proprietary additives of the vendors. In addition, the EP and SWLP tests provide significant dilution factors with respect to the

amount of solid used in each test. In any case, chloride is not an EP toxicity parameter. The actual impact of the leachable chloride concentrations observed in this study on a receiving water will depend primarily on the background quality of the receiving water. *PAD science*

52. Metals. The metals investigated in this study for their leaching potential were arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), selenium (Se), and silver (Ag). Because these metals occur naturally in the earth's crust they are present throughout the earth's soils, rivers, and oceans. Chromium, copper, and selenium are trace elements that in the proper amounts are essential and beneficial to biological function (14). These same elements are toxic when concentrations are too high. Barium is a non-essential element that has medicinal value when used in the proper dose (14). Otherwise it too can be toxic. The other metals (As, Cd, Pb, Hg, and Ag) have no known nutritional or beneficial value for life processes and are toxic even in very low concentration. Since these metals are neither biodegradable nor capable of being completely locked into sediments through natural processes, their occurrence in the environment has been a source of concern over the toxicity of these metals to aquatic organisms and about the effects of excessive human exposure to these metals.

53. As has been discussed previously, if the EP extract of a solid waste contains contaminants in concentrations 100 times greater than that specified in the National Interium Primary Drinking Water Standards, then the waste is considered hazardous and must be managed and disposed of in accordance with RCRA regulations for hazardous wastes. The maximum permissible metal contaminant levels for materials passing the EP Toxicity Test are listed in Table 7. (Copper is not in the primary drinking water standards.) Metal concentrations in the EP leachates are listed in Table 12. None of the solidified materials

examined in this study failed the EP Toxicity Test for metals. The EP leachable metal concentrations were, in general, one order of magnitude below the EP toxicity limit, and in many instances were two orders of magnitude below the limit. The secondary drinking water standard for copper is 1 mg/L. None of the EP leachates were 100 times greater than this standard.

54. Leachate data from the SWLP is probably more representative of the leachate quality that results from rainwater or groundwater infiltrating a disposal site containing solidified Basin F waste than is leachate from the EP which is designed to simulate leaching in a sanitary landfill environment. The SWLP data obtained in this study is also more likely to overestimate contaminant concentrations than to underestimate them because the tumbling action prescribed by the procedure resulted in complete destruction of the initial physical geometry of the test specimens (as was also the case with the paddle system employed in the EP). In each SWLP conducted, the cylindrical test specimen was reduced to a slurry by the end of the test, thereby significantly increasing the surface area exposed to leaching action. Silver, cadmium, and chromium were below detection limits in all the SWLP extracts. Only two of the eight selenium values were above detection limits, and there were three SWLP leachates with detectable lead concentrations. Arsenic was detectable in all but one leachate. Mercury, copper, and barium were measured in all eight SWLP leachates. Based on these data, the leaching of silver, cadmium, and chromium from solidified Basin F liquid would not be a threat to groundwater quality. The data also suggest that lead and selenium do not appear to pose a problem. The concentrations of arsenic, barium, and mercury leached are in most instances only one order of magnitude higher than the Interim Primary Drinking Water Criteria. Although significant amounts of copper were leached in the SWLP ranging from 29-131 mg/L, only one was 100 times greater than the

secondary drinking water criteria of 1.0 mg/l. The 100 times factor is the EPA established attenuation factor for the EP Toxicity Test. Through the use of this factor the EP Toxicity Test Procedure takes into account attenuation of toxic contaminants by soils lying between a source of actual leachate generation and a groundwater aquifer. The choice and application of an attenuation factor and the general problem of interpreting metal data from laboratory leaching tests have been addressed by several investigators (8, 15). The consensus has been that there are no laboratory leaching tests available with proven ability to reliably give a realistic assessment of the environmental risks related to contaminant leaching from solid waste. Site-specific factors that are not adequately simulated in the leaching tests determine the actual hazard potential of metal contaminants observed in laboratory prepared leachates.

55. Selected Organics. The first EP and SWLP leachates generated in this study were leachates for Processes 100, 300, 301, and 400. EP leachates and selected SWLP leachates from these processes were analyzed for Total Organic Carbon (TOC), endrin, lindane, methoxychlor, toxaphene, 2,4-D, and 2,4,5-TP. A semi-quantitative GC/MS scan was also made on selected leachates. The results, listed in Table 13, show that all the leachates were below the limits specified in Table 6. The GC/MS scans on these leachates showed sulfone (p-chlorophenylmethylsulfone) to be the major organic contaminants in the leachates. Sulfone was the "apparent" major constituent in all the scans performed. Due to varying instrument sensitivity to different compounds, the largest peak in a scan is not necessarily the compound highest in concentration in the sample. Compounds detected in each leachate scanned are listed in order of "apparent" significance in Table 13. Sulfone, the "apparent" major

ES!

constituent in the GC/MS scans, actually contributes less than 0.1 percent of the TOC leached. As indicated in Table 1, only about 6 percent of the TOC in Basin F liquid is accounted for by the available information. The other 95 percent is comprised of very water soluble compounds which do not extract very well and of high molecular weight compounds which are held up on the clean-up columns that the base, neutral extracts prepared for the GC/MS scan were put through prior to GC/MS analysis.

56. The analyses performed on the EP and SWLP leachates generated after the 100, 300, 301, and 400 leachates had been analyzed were limited to TOC, endrin, and sulfone for the following reasons:

- a. With the exception of endrin none of the organics listed in Table 6 are known to exist in Basin F liquid in significant amounts (16).
- b. The concentrations of these contaminants in the first leachates analyzed were negligible.
- c. The GC/MS scans on the first leachates analyzed showed sulfone to be one of the major organic contaminants.
- d. By continuing to perform TOC analyses on all leachates, comparison of the relative abilities of the solidification processes to retain organics could still be made even though the number of specific organic compounds analyzed was reduced.

Leachates from Processes 200, 302, 500, and 600 were analyzed according to the above protocol. The results are presented in Table 13. Endrin is again below the limit of 0.02 mg/L specified in Table 6. Sulfone ranges from 0.32 mg/L in

the 600/EP to 2.0 mg/L in the 302/SWLP. TOC's range from 1530 mg/L for the 200/SWLP to 5400 mg/L for the 100/SWLP.

57. The lack of organic accountability in the data obtained in this study and in previous studies (16) indicates that the organic content of Basin F liquid is very heterogeneous and cannot be characterized as primarily any one compound or group of compounds. The available data on selected organics show the solidified wastes as satisfying the EP Toxicity Test criteria for the specific organics listed in Table 7. Primary drinking water criteria are not available for sulfone. The Department of Army, however, recommends 0.020 mg/L as a water quality standard (17). The EP leachates were all below 100 times the DA recommended standard. One of the SWLP leachates was at 100 times this recommended standard and two others were close to the recommended standard.

58. Total Organic Carbon. TOC is a gross measure of the organic carbon present in a sample and as such the test does not have the capability of distinguishing between toxic and non-toxic compounds nor can it distinguish between man-made and naturally occurring compounds. Its primary utility in environmental studies is 1) as an indicator of the gross organic load placed on a receiving water and 2) to monitor treatment plant efficiency. The EP and SWLP leachates (1530-5400 mg/L TOC) are comparable in TOC to medium strength industrial waste. Untreated domestic sewage usually contains no more than 300 mg/L TOC (18) and high strength, chemical manufacturing wastewaters usually range from 10,000 to 50,000 mg/L TOC (19). The TOC data on the EP and SWLP leachates indicate the leachate from solidified Basin F liquid concentrate could pose a serious problem for a receiving water due to the organic load that will be placed on the assimilative capacity of a receiving water and due to the potentially detrimental biological effects of the specific constituents identified by the GC/MS scan. The TOC's observed in the EP and SWLP leachates

indicate that control strategies, possibly including treatment for TOC removal, for leachate generated by solidified Basin F wastes will probably be necessary unless the leachate generation rate is negligible. *which is not the case.*

59. Leachable Contaminant Density. The concentrations of selected EP and SWLP leachable contaminants were normalized with respect to the volume of Basin F liquid concentrate processed for solidification. These data are expressed as contaminant mass leached per unit volume of Basin F liquid concentrate that was solidified (milligrams/liter) and are presented in Table 14. Assuming that all other factors affecting the leach test are constant, the amount of contaminant leached is a function of only two variables. First is the amount and leachability of the contaminants in the solidification additives. This variable is an unknown quantity because the process additives were proprietary materials. It is known that vendors utilize other waste materials in the manufacture of their solidification reagents which can contribute to the overall level of leachable contaminants in the solidified product. Thus, the leachable contaminant densities reported in Table 14 include any leachable contaminants added by the solidification reagents during the solidification processing. The second variable is the ability of the process to immobilize the contaminants contributed by Basin F liquid. Since the same batch of Basin F liquid concentrate was used to prepare all the processed materials for leach testing, variation in contaminant concentration in Basin F does not contribute to the variation in the leachable contaminant densities listed in Table 14. The data in Table 14 show that the metals leached from the various processed wastes vary considerably. In the case of arsenic and copper the data range over an entire order of magnitude. There is less variability in the leach data for organics, and the chloride data are the most consistent of all the leach data. *which is not the case.*

Not valid - one cannot compare the RSD because processes are different & only a single sample run on each process. BS!

60. One way to compare variabilities in different sets of data is to compare the relative standard deviation (RSD) for each data set. In the present case one data set, for example, consists of the EP-arsenic data and another is the SWLP-mercury data. The relative standard deviation is the standard deviation of the data expressed as a percentage of the mean value for the data and as such is a convenient way of making comparisons because it is independent of units. Relative standard deviations, standard deviations, and sample means for the EP and SWLP leachable contaminant densities are listed in the last six rows of Table 14. Standard deviations were N-1 weighted not N weighted because the data represent one experimental trial (this study) out of an infinite population of duplicate trials that could be conducted. If this study were repeated the test results would be similar but not exactly the same. Thus, the data as a sample taken from a larger population of possible results were used to make statistical inferences about the entire population that would result from repeating the study an infinite number of times. RSD data are interpreted as follows: The greater the RSD the greater the variance in the data, and within the context that the RSD is used in this study, large RSD's indicate parameters for which there are substantial differences in the leachable contaminant densities which in turn is interpreted as meaning that there are real and substantial differences in the ability of the various processes to immobilize contaminants. A RSD of 50 percent means (assuming a normal distribution) that the mean value plus or minus 50 percent of the mean value encompasses about 68 percent of the total range of data. Similarly a RSD of 100 percent means that mean value plus or minus itself covers only 68 percent of the range in data. The larger the RSD the greater the spread in the data or in terms of a normal bell shaped curve, the flatter the curve. The large RSD for the arsenic-EP data of 138.5 percent suggests that some processes

were much better (or worse) than others in their ability to immobilize arsenic under the conditions of the EP. An alternate explanation is that some processes do add and some processes do not add significant amounts of leachable arsenic to the solidified product by way of the solidification reagents. The copper-EP RSD of 98.8 percent is less than that for arsenic, and the mercury-EP RSD of 83.8 percent is slightly less than that for copper, indicating the relative order of variability in the leaching of these metals under the conditions of the EP.

61. The chloride RSD is a convenient point of reference from which to analyze and interpret the variability in the leaching data. Ideally, a reference parameter used to measure the relative significance of RSD data should reflect only the random experimental error and should not reflect any true variability in the solidification processing techniques' abilities to immobilize the reference parameter. The variation in leaching of chloride, a geochemically conservative element, was assumed to be primarily a measure of the combined normal chance variation inherent in solidification processing, chemical leaching, and chemical analysis that occurred in this study. The chloride EP and SWLP RSD's were 23.0 percent and 15.0 percent, respectively. The arsenic, copper, and mercury EP-RSD's were 6.0, 4.3, and 3.6 times that observed for chloride. These data confirm the inference in paragraph 60 that there are substantial differences in the ability of the various processes to immobilize metals under the conditions of the EP. The SWLP RSD's, with the exception of copper, do not show differences as substantial in resistance to metal leaching under conditions of the SWLP as in the EP. The copper-SWLP RSD was 5.2 times that for chloride and the arsenic and mercury leaching was less variable under the SWLP than under the EP dropping to 2.6 and 2.0 times the chloride RSD, respectively. Thus, the variability in metal leaching was less

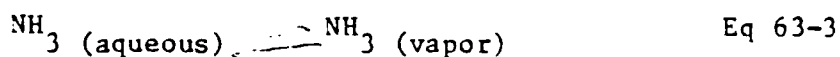
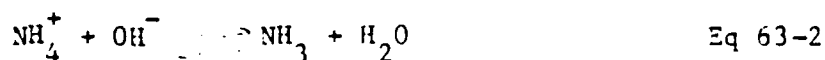
under the conditions of the SWLP than under the EP. (This is true for all the parameters investigated.) Less variability in the SWLP than in the EP is not unexpected since the distilled water leach of the SWLP is a more constant leaching environment than the EP protocol which proscribes varying amounts of acid addition depending on the buffering capacity of the solidified waste. The TOC RSD's were 1.8 and 0.61 times the chloride RSD for the EP and SWLP, respectively. The sulfone data are limited to half the number of leachates analyzed for the other parameters and cannot be compared directly with the chloride or other data. How much larger than the chloride RSD a parameter's RSD should be in order to be significant is a question that cannot be answered from the available data. It would be necessary to repeat the study several times in order to establish a confidence interval for the chloride RSD. Without replication a statistical answer is not possible. It was necessary, therefore, to apply an arbitrary safety factor (factor of ignorance) in order to assign significance. An arbitrary safety factor of 2 was assumed. Thus if a contaminant's RSD is twice that of chloride, it was interpreted as meaning that the variability in the leaching data was significant and due to real differences in the ability of the various processes to immobilize the contaminant. From the foregoing discussion it follows that the data on TOC leachability is much more consistent than the metal data, and that there is little if any real difference in the processes' abilities to immobilize Basin F organics, especially under the conditions of the SWLP which as previously alluded to is probably more representative of the leaching environment that solidified Basin F will be in than is the EP. There do appear to be substantial differences in the leachable metal densities among the solidified products. Thus, two general observations can be made concerning the RSD data for leachable contaminant density:

- a. If metal leaching is the only important criterion for selecting a solidification process, then it is important to select the right process (avoid the inferior processes).
- b. If TOC leaching is the only important criterion for selecting a solidification process, then it makes little or no difference which process is selected.

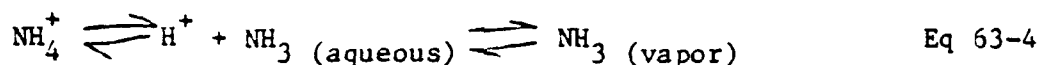
#### Ammonia Evolution

62. During the preparation of solidified material by the vendors and by the WES, the evolution of large quantities of ammonia gas were noted by the workers preparing the solidified samples. During the mixing of 2 liter batches of Basin F liquid concentrate with solidification additives, which was done outdoors, the amount of ammonia gas released was occasionally overwhelming, forcing workers to leave the immediate area. In several instances, it was virtually impossible to stand downwind or in the immediate vicinity of the mixer for several minutes following the addition of solidification reagents to Basin F liquid concentrate without the protection of gas masks. Even after a month of curing, objectionable ammonia odors continued to be released from some of the samples of solidified waste.

63. At room temperature, ammonia is a gas which compared to other gases is very soluble in water. In an aqueous system such as Basin F, liquid ammonia exists in ionized form ( $\text{NH}_4^+$ ) and unionized form ( $\text{NH}_3$ ). The controlling reactions are shown below:



The first two equations describe the aqueous phase and the third equation represents transport of ammonia from the aqueous phase to the vapor phase. All of these reactions are reversible. Combining the three equations yields,



Temperature, pH, and other dissolved ionic species affect the equilibrium point of this system. The fraction of the total dissolved ammonia that is present in the ionized form ( $\text{NH}_4^+$ ) and in the unionized form ( $\text{NH}_3$ ) is primarily a function of temperature and pH. Increasing temperature shifts equation 63-2 to the left, and 63-3 to the right. Increasing pH (increasing the  $\text{OH}^-$  ion) will shift equation 63-2 to the right. At 25°C and neutral pH approximately 95% of the ammonia present in the aqueous phase exists in ionized form, while for a pH of 10 at the same temperature only 2% is in the ionized form, the remainder existing as unionized ammonia. This means that at neutral and lower pH, relatively large concentrations of ammonia can be held in solution due to the fact that practically all of the ammonia is in the highly soluble ionized form. If the pH is raised, the equilibrium shifts toward the right in equation 63-4. The net result is a transfer of ammonia from the aqueous phase to vapor phase, i.e., to the atmosphere in the present case. An increase in temperature increases the transfer rate.

64. When alkaline solidification reagents are added to Basin F liquid, the pH increases, the unionized ammonia fraction increases, the exothermic hydration reactions cause the temperature to increase, and ammonia gas is evolved at a rapid rate and in large quantities from the mix. There is also another consequence with regard to ammonia evolution that takes place when solidification reagents are added. The free water decreases to or near to

zero leaving behind a residual of ammonium salts within the matrix of the solidified waste. Under the alkaline conditions present, these salts continue the release of ammonia gas initiated when the solidification additives were first mixed with Basin F liquid.

65. Ammonia occurs in Basin F liquid in concentrations in excess of 40,000 mg/l. In one gallon of Basin F liquid, there may be as much as 0.5 lbs of ammonium ion available for conversion to ammonia gas as a result of the addition of alkaline solidification reagents. For a large scale solidification project, the evolution of ammonia gas will pose a very serious occupational hazard and a potentially difficult air pollution problem. Preliminary results indicate that the problem will not be eliminated, even when the solidified material is placed and covered, unless the formation of ammonia gas is somehow prevented. The release of ammonia gas from a large buried mass could be difficult and costly to contain. It would certainly impact groundwater resources and possibly escape to the atmosphere, poisoning vegetation on the cover in the process.

66. Fortunately two approaches to the solution of this problem appear technically feasible. In order to prevent the release of ammonia during the solidification of Basin F waste, either reagents with no or very low alkalinity may be used or the ammonium ion may be tied-up through complex ion formation and precipitation before alkaline reagents are added. Both mechanisms appear to have been demonstrated, the former in the application of Processes 500 and 501 and the latter in the application of Process 302. The chemistries involved are proprietary and the specifics are unknown to the authors although the vendors involved do acknowledge the general approaches that they took to the problem. The vendors referred to above began work on the ammonia evolution problem at their own initiative during the course of their process development under the Phase I work.

67. The ammonia evolution problem associated with each process is indicated in Table 15. In this table subjective, qualitative descriptions are used since no quantitative measurements were made. With the exception of Processes 302, 500, and 501, solidification processes applied to Basin F liquid result in a significant evolution of ammonia gas, both during the mixing of additives with Basin F liquid and later during the curing process.

#### Process Formulation and Evaluation

68. Process Formulation. The problem of developing a solidification formulation to meet a given specification can be approached in two ways. First the additive-to-waste ratios can be adjusted, or secondly different additives can be substituted into the formulation. As an example of how both methods work, consider the problem of improving the 24-hour CI for a soil/flyash/kiln dust/waste (0.8/0.8/0.8/1) formulation that has a 24-hour CI of 25 psi. This particular formulation was included in the list of materials screened under Phase I by the WES. First by increasing the additive-to-Basin F ratios in the formulation to 1/1/1/1 the 24-hour CI is improved to 100 psi. This is an increase of 300% in bearing capacity for an additive increase of 25%. Then, if lime is substituted for kiln dust in the 1/1/1/1 formulation, the 24-hour CI is improved to 400 psi, another 300% increase. The CI versus time curves for the original and improved processes are shown in Figure 20. The process manipulation demonstrated in the foregoing example is in no way restricted to non-proprietary formulations. This type of manipulation is at the heart of formulation development and optimization by process vendors, and by using this approach, any of the processes included in this study can be optimized with respect to a given specification. The real challenge, however, is to develop a process formulation that meets a set of specifications with conflicting

goals, such as the maximization of physical properties while minimizing additive requirements.

69. Process Selection. There are two general approaches to the process selection problem. One is to minimize the expenditure of funds (select the least costly alternative). In this approach minimum performance criteria in terms of physical-chemical properties of the solidified product are established to meet specific disposal requirements. Then the lowest cost process that meets the minimum performance criteria is selected. This approach does not necessarily select the optimum process. As a general rule the desired process formulation is one that meets minimum specifications while providing maximum performance for important criteria, and, of course, that minimizes cost. The process that delivers maximum performance, typically, does not also minimize cost relative to alternative processes that also meet or exceed the minimum performance requirements. A second approach to process selection is an optimization approach that maximizes economic efficiency by determining which of a group of alternative processes delivers the maximum performance (over and above the minimum acceptable performance) per unit cost. A selection procedure based on optimization can be made more or less sensitive to different types of performance benefits through the use of weighting factors applied to the various criteria used in the procedure.

70. Worked Example. The physical, chemical, and cost data collected in Phase II of this study were used to work through an illustrative example of a selection procedure based on the optimization approach. The selection procedure involved six major steps as follows:

1. Laboratory testing.
2. Development of specific performance criteria and establishment of weighting factors.

3. Scoring the processes using a relative performance index (RPI).
4. Estimation of total cost for each process to solidify and landfill.
5. Graphical or mathematical determination of process with maximum RPI/dollar.

The process selected in this example cannot be regarded as the best process of those tested because the specific criteria used in the example were not available to the vendors prior to the preparation of solidification samples for testing and because incomplete cost data were used in the example. In order for future application of the selection procedure described here to be truly objective, it is important that the parameters and weighting factors which will be used are established before the vendors are asked to prepare solidified samples for testing.

71. The following simplifying assumptions were made for the purpose of providing a backdrop of site-specific factors about which to pose the example problem.

- a. Compliance with applicable laws and regulations is a primary objective.
- b. Isolation and containment of contaminants is a primary objective.
- c. Solidified waste will be disposed in a secure landfill with sufficient capacity and consisting of an impermeable liner system and cap.
- d. Compaction of the solidified waste although important is not critical to landfill construction.
- e. Different measures of performance should carry different weight.
- f. Arsenic and copper are the only contaminants of concern.

- g. Parameters of interest are residual free liquid, trafficability, bulk weight, volume increase, permeability, and chemical leaching characteristics.

72. Weighting Factors. In general the choice of parameters and weighting factors should be based on site-specific factors such as waste characteristics, hydrogeology, climate, and landfill design. One of the assumptions listed above which had to be made in order to arrive at weighting factors, is the a priori assumption that different measures of performance should carry different weight. For example, once the minimum trafficability requirements are met there is little to be gained by producing a product with superior trafficability if that trafficability is to be buried and never used. The ability to immobilize contaminants, on the other hand, provides benefits over the entire life of the landfill and therefore should carry more weight than trafficability. Since isolation and containment of contaminants is a primary objective of disposal by solidification processing/landfilling, the ability to immobilize contaminants was used as a reference point (weighting = 1.0) for assigning weighting factors to the other parameters of interest. The weighting factors chosen are listed in Table 16. The rationale behind each weighting factor is presented with the rationale developed for minimum performance criteria presented below for the parameters listed in assumption (g).

73. Example Residual Free Liquid Performance Criterion and Weighting Factor. As previously alluded to, landfilling of free flowing liquids is regulatorily prohibited (12). Since no standard test is available for determining residual free liquid, a weighting factor could not be assigned because a quantitative test is not available. Because the release of any flowable liquid is to be avoided at practically all cost the residual liquid criterion is basically a GO/NO-GO criterion, and a process either passes or fails whatever test is used.

74. Example Trafficability Performance Criterion and Weighting Factor.

A 24-hour  $CI \geq 50$  psi is specified so that a D-8 Caterpillar (tracked) bulldozer will be able to place and compact fresh waste over waste that has been in place for only 24 hours. The  $VCI_{50}$  for the D-8 caterpillar is 41 psi (6). It is assumed that vehicles with a  $VCI > 50$  psi will not be operated on the landfill. Once buried there is no additional benefit to be derived from exceeding the minimum trafficability specification. Thus, a low weighting factor of 0.2 is assigned to trafficability.

75. Example Permeability Performance Criterion and Weighting Factor. A

permeability of less than  $5 \times 10^{-4}$  cm/sec is specified. A relatively high permeability is permitted because the landfill design was assumed to include an impermeable cap, and a liner. Since infiltration and groundwater seepage are assumed to be controlled by the landfill design, the permeability specifications is relatively lenient. However, should infiltration and seepage control fail, then it will be beneficial to have in place a material with as low a permeability as possible. Thus, a relatively high weighting factor of 0.85 is assigned to permeability. This is an example of a situation in which a lenient specification and a heavy weighting factor can complement one another and are not necessarily contradictory. When such a situation arises the lenient performance specification implies that control strategies external to the performance of the solidified waste are operative, and the heavy weighting factor implies that performance beyond the minimum specification has significant potential benefit should external controls fail.

76. Example Bulk Weight and Volume Increase. Minimum performance cri-

teria and weighting factors for these two parameters are not required because they are included in the cost estimate as part of haul cost and landfill cost, respectively.

77. Example Immobilization of Contaminants Performance Criteria and Weighting Factors. Even though a secure landfill for the solidified waste is assumed to be available, passing the EP Toxicity Test procedure is specified as the minimum level of acceptable performance due to the character of the waste. Arsenic and copper are assumed to be the principal contaminants of concern and the leachability of these contaminants were the only two included in the analysis in order simplify the example. Immobilization of arsenic and copper are assigned weighting factors of 1.0 and 1.3 respectively. These weighting factors reflect relative waste concentrations of these contaminants. Even though arsenic is much more toxic than copper, immobilization of copper was more heavily weighted because its concentration in the waste is on the order of one thousand times that of arsenic.

78. Scoring. Samples of processed waste were tested for the selected parameters discussed above, and the processes were then scored according to how each ranked with respect to the best performer for a given criterion. For each criterion, the best performer received a score of 100 and the rest received a score that was a fraction of 100 depending on how close their performance was to the best performer. The computation of scores for most criteria were based on performance above the minimum criteria relative to the best performer. For example, for a minimum performance specification of 24-hour CI > 20 psi, if the best performer, Process A, produces a product with a 24-hour CI of 100 psi and another process, Process B, produces a product with a 24-hour CI of 50 psi, then Process A is assigned a score of 100 for trafficability and Process B is assigned a score of

$$(100) \frac{(50 - 20)}{(100 - 20)} = 37.5$$

The computation of scores for permeability and for chemical leaching characteristics are exceptions to this rule as discussed in following paragraphs. Weighting factors were applied to the various criteria before the total score for each process was tallied and recorded as the relative performance index (RPI). The general scoring equation for physical properties criteria (except permeability) is as follows:

$$S(i,j) = WF(j) \left[ \frac{P(i,j) - MP(j)}{P(b,j) - MP(j)} \right] (100) \quad \text{Eq 78-1}$$

$S(i,j)$  = Score for  $i^{\text{th}}$  process,  $j^{\text{th}}$  criterion

$WF(j)$  = Weighting factor for  $j^{\text{th}}$  criterion

$P(i,j)$  = Performance of  $i^{\text{th}}$  process,  $j^{\text{th}}$  criterion

$P(b,j)$  = Performance of best performer,  $j^{\text{th}}$  criterion

$MP(j)$  = Minimum performance specification for  $j^{\text{th}}$  criterion

(100) = Score for best performer

Since any migration of contaminants away from the disposal site is undesirable, the computation of scores for immobilization of contaminants was not based on performance above the minimum performance criteria. It was based on absolute EP contaminant leachability, computed as follows for each contaminant of interest:

$$S(i,k) = WF(k) \frac{LCD(b,k)}{LCD(i,k)} (100) \quad \text{Eq 78-2}$$

where

$S(i,k)$  = Immobilization score for the  $i^{\text{th}}$  process,  $k^{\text{th}}$  contaminant

$LCD(i,k)$  = EP Leachable Contaminant Density of the  $i^{\text{th}}$  process for  $k^{\text{th}}$  contaminant (mg/L)

$LCD(b,k)$  = EP Leachable Contaminant Density of the best performer for a  $k^{\text{th}}$  contaminant

$WF(k)$  = Weighting factor for  $k^{\text{th}}$  contaminant

100 = Score for best performer.

Permeability scores were calculated for the  $\text{LOG}_{10}$  transform of the permeability data using Equation 78-1. Without a log transform of the permeability data, practical differences in the rates at which water moves through the solidified waste are not distinguished by the scoring. Performance scores computed as discussed above for each category and weighting factors are summarized in Table 16. Example calculation of the scores for process 200 are presented below.

$$24\text{-hr CI} = (0.2) \left( \frac{210 - 50}{412 - 50} \right) (100) = 9$$

$$\text{Permeability} = (0.85) \left( \frac{\text{LOG}_{10} (1.7 \times 10^{-4}) - \text{LOG}_{10} (5 \times 10^{-4})}{\text{LOG}_{10} (1.2 \times 10^{-6}) - \text{LOG}_{10} (5 \times 10^{-4})} \right) (100) = 15$$

$$\text{Arsenic} = (1.0) (2.48/69.8) (100) = 4$$

$$\text{Copper} = (1.3) (723/3122) (100) = 30$$

$$\text{RPI} = 9 + 15 + 4 + 30 = 58$$

79. Cost Estimation. The total cost function used in this example included three types of costs: cost of additive materials, haul cost from solidification site to landfill site, and landfill costs. Vendor supplied estimates of material costs for the formulations in Table 3 are listed in Table 17. These cost estimates are based on processing 10 to 20 million gallons of Basin F concentrate. Material costs for the various processes range over an order of magnitude beginning at about \$0.10/gallon. Cost estimates for the non-proprietary processes in Tables 3 and 17 were based on the following: soil cost = \$0, flyash cost = \$0, kiln dust cost = \$25.00 per ton, lime cost = \$31.00 per ton as CaO. Material costs do not include transportation, materials handling at the site, or mixing costs. Haul costs were computed from Final volume/Initial volume ratios, initial volume of liquid waste, bulk unit weight, an estimated haul cost of \$.13/ton-mile, and a haul distance of 3 miles using the following equation:

$$HC = (BW) (FV/IV) (LV) ($.39/\text{ton})$$

where

HC = haul cost

BW = Bulk unit weight (tons/cu yd)

FV/IV = Final volume of solidified product to initial volume of waste  
before solidification (dimensionless)

LV = Total volume of liquid to be disposed of (cu yd)

= 49500 cu yd

Landfill costs were based on an estimated unit costs of \$25/cu yd of landfill space. Landfill costs were computed using the following equation:

$$LC = (LV) (FV/IV) (\$25/yd)$$

The total cost function is the sum of the materials cost, haul cost, and land-fill cost. Total cost for each process is presented in Table 18. No data were available for labor costs.

80. After the RPI scores and total costs were computed, a scattergram of relative performance (RPI) vs total cost was plotted (Figure 21). The scattergram is a helpful tool in the selection process because it depicts the trade-offs between the incremental costs of increased performance. Although performance is expected to increase with cost for a given process, this is not necessarily true for a heterogeneous plot of different processes. The final step is to determine which process delivers the greatest return in performance per unit cost. This is graphically determined by connecting each point on the scattergram with a straight-line to the origin. The point with the lowest cost and highest RPI, i.e., the uppermost left-hand point on the scattergram, is the best choice. The straight lines in Figure 21 which connect the various points to the origin indicate the slope of the returned benefit per unit cost of procuring a product exceeding minimum performance criteria. The steeper the slope the greater the return on the investment. Process 600 is the obvious choice in this example. The solution can be found mathematically as the follows:

- a) Calculate  $SL(i) = RPI(i)/\$ (i)$  for each process(i)
- b) Sort  $SL(i)$  data from highest to lowest
- c) Select process with highest  $SL(i)$ .

81. Summary. The formulations investigated in this study and included in the above example probably do not represent the best formulations that the solidification process vendors could produce had more specific guidance been available. It does appear that most, if not all, of the processes investigated in this study are applicable to Basin F liquid and that solidification is a feasible technique with regard to the disposal of Basin F liquid. No particular process appears capable of exceptional, superior solidification processing relative to its competitors. Nor is there evidence that any process should be eliminated as a candidate for solidification processing of Basin F liquid.

## PART IV: CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

82. Solidification is a feasible technique for converting liquid Basin F waste to a solid form which can be landfilled and which is capable of supporting landfill construction equipment. Release of ammonia gas during solidification is the major technical obstacle to full scale implementation of solidification technology to Basin F liquid. Specific conclusions drawn from evaluation of the data obtained in this study are as follows:

- a. Five commercial solidification processes and a non-proprietary solidification process satisfactorily converted concentrated Basin F liquid to solid form.
- b. Additive requirements for solidification range from 1.01/l to 3.9/l weight-by-weight ratio of total additives to concentrated Basin F liquid.
- c. Material costs for solidification additives range from \$.10/gal to \$1.00/gallon of Basin F liquid concentrate.
- d. Volume increase resulting from solidification expressed as the ratio of the final volume of solidified waste to the original volume of concentrated Basin F liquid ranges from 1.2/l to 4.1/l. Seven of ten variations on the six basic processes had volume increase ratios of 2.5/l or less.
- e. Cone index as measured with the cone penetrometer is a useful tool for judging the performance of solidification processes and products.

- f. A simple equation for predicting cone index as a function of cure time was derived.
- g. Most of the solidified materials prepared in this study do not deteriorate with repeated wet/dry cycles, but, in fact, increase in strength.
- h. The ammonia gas released during the solidification process could present technical difficulties in a full-scale solidification project unless the process chemistry for sequestering ammonia gas release is further developed.
- i. All solidified waste tested passed the EP Toxicity Test Procedure.
- j. Chemical leach data indicate an order of magnitude reduction of contaminant levels in samples prepared by leaching of solidified Basin F liquid concentrate compared to the untreated liquid.
- k. Limited statistical analysis data indicate that there are no substantial differences in the ability of the processes investigated in this study to immobilize gross organic contamination (TOC) in Basin F liquid.
- l. Limited statistical analysis data indicate that there are real and substantial differences in the ability of the processes investigated in this study to immobilize arsenic, copper, and mercury in Basin F liquid.
- m. An objective procedure for selecting the solidification process that yields maximum performance per unit cost was developed and illustrated by example.

### Recommendations

81. The following recommendations are made with regard to the application of solidification processing technology to Basin F wastes.

- a. A field verification study should be conducted in order to relate laboratory results to actual field performance, to provide correlation data between rapid tests when employed in the field, and to reduce the dependence of design guidance on proprietary know-how.
- b. Rapid test procedures for determining the quality of solidified materials as they come out of a mixer should be investigated. Correlation with 24-hour cone index and other appropriate parameters should be established.
- c. If solidification is used as a treatment process in the closure of Basin F, a set of minimum performance criteria should be established.
- d. Application of solidification processing to Basin F overburden should be investigated.

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Table 1  
Chemical Characterization of Basin F Liquid

| <u>Parameter</u>   | <u>Units</u> | <u>Historical Record<br/>on Basin F (6)</u> | <u>Basin F CONC.<br/>This Study</u> |
|--------------------|--------------|---------------------------------------------|-------------------------------------|
| pH                 | -            | 6.9 - 7.2                                   | -                                   |
| Aldrin             | ppm          | 50 - 400                                    | -                                   |
| Isodrin            | ppb          | 2 - 15                                      | -                                   |
| Dieldrin           | ppb          | 5 - 110                                     | -                                   |
| Endrin             | ppb          | 5 - 40                                      | -                                   |
| Dithiane           | ppb          | 30 - 100                                    | -                                   |
| DIMP               | ppm          | 10 - 20                                     | -                                   |
| DMMP               | ppm          | 500 - 2,000                                 | -                                   |
| Sulfoxide          | ppm          | 4 - 10                                      | -                                   |
| Sulfone            | ppm          | 25 - 60                                     | 200                                 |
| Chloride           | ppm          | 48,000 - 56,000                             | 123,700                             |
| Sulfate            | ppm          | 21,000 - 25,000                             | -                                   |
| Copper             | ppm          | 700 - 750                                   | 6,600                               |
| Iron               | ppm          | 5 - 6                                       | -                                   |
| Nitrogen           | ppm          | 20,000 - 50,000                             | -                                   |
| Phosphorus (total) | ppm          | 2,050 - 2,150                               | -                                   |
| Hardness           | ppm          | 2,100 - 2,800                               | -                                   |
| Fluoride           | ppm          | 110 - 117                                   | -                                   |
| Arsenic            | ppm          | 1.0 - 1.3                                   | 7.25                                |
| Magnesium          | ppm          | 35 - 40                                     | -                                   |
| Mercury            | ppb          | 26 - 29                                     | 97.1                                |
| Cyanide            | ppm          | 1.45 - 1.55                                 | -                                   |
| COD                | ppm          | 24,500 - 26,000                             | -                                   |
| TOC                | ppm          | 20,500 - 22,500                             | 98,200                              |

20  
 101 is not 690  
 44

Table 2  
Process Descriptions - Phase I

| Process                                              | Phase II<br>Code | Examples of Past Applications                                                                                                                                            |
|------------------------------------------------------|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Pozzolonic, uses kiln dust                           | 100              | Has been applied to chemical, petroleum, and metal finishing wastes                                                                                                      |
| Pozzolonic, uses fly-ash and other additives         | 200              | Has contracts to solidify SO <sub>2</sub> scrubber sludge at 11 electric power plants. Also has contract to treat sludge generated by a battery manufacturer             |
| Cement based plus other additives.                   | --               | Has been applied primarily to contaminated turbine oil and lube oil generated at nuclear power stations.                                                                 |
| Cement or Pozzolonic, plus other additives           | 300              | Proprietary absorbent has been used on a commercial basis to remove oil and grease from industrial waste water. No large scale solidification to date.                   |
| Cement or Pozzolonic, uses lime plus other additives | --               | A R&D firm specializing in hazardous waste consulting. Provides solidification process development services.                                                             |
| Pozzolonic, uses lime plus other additives           | 400              | Has been utilized on petroleum waste, municipal waste water treatment sludges, plating waste, PCB's, paint waste. In the process of testing process on uranium tailings. |
| Pozzolonic, uses fly-ash plus other additives        | 500              | Operates regional treatment plants handling a variety of wastes from different sources.                                                                                  |

Table 3  
Additive Requirements for Solidification

| Process                | Additive              | Additive-To-Basin F Conc. Ratio (wt/wt) | Total Additive-To-Basin F Conc. Ratio (wt/wt) |
|------------------------|-----------------------|-----------------------------------------|-----------------------------------------------|
| 100                    | Kiln Dust             | 0.7/1                                   | 0.7/1                                         |
| 200                    | 1                     | 3.7/1                                   |                                               |
|                        | 2                     | 0.2/1                                   | 3.9/1                                         |
| 300                    | Sorbant               | 0.02/1                                  |                                               |
|                        | Water Demanding Agent | 0.23/1                                  |                                               |
|                        | Kiln Dust             | 0.80/1                                  | 1.05/1                                        |
| 301                    | Sorbant               | 0.04/1                                  |                                               |
|                        | Water Demanding Agent | 0.23/1                                  |                                               |
|                        | Cement                | 0.80/1                                  | 1.07/1                                        |
| 302                    | Sorbant               | 0.05/1                                  |                                               |
|                        | 1                     | 0.03/1                                  |                                               |
|                        | 2                     | 0.08/1                                  |                                               |
|                        | Water Demanding Agent | 0.30/1                                  |                                               |
|                        | Kiln Dust             | 0.80/1                                  | 1.26/1                                        |
| 400                    | G                     | 0.02/1                                  |                                               |
|                        | V                     | 0.70/1                                  |                                               |
|                        | S                     | 0.77/1                                  |                                               |
|                        | C                     | 0.41/1                                  | 1.9/1                                         |
| 500                    | A                     | 2.25/1                                  | 2.25                                          |
| 501                    | B                     | 2.05/1                                  | 2.05                                          |
| 600 Series             |                       |                                         |                                               |
| Soil/Kiln Dust         | Soil                  | 1.7/1                                   |                                               |
|                        | Kiln Dust             | 1.3/1                                   | 3.0/1                                         |
| Soil/Lime              | Soil                  | 1.7/1                                   |                                               |
|                        | Lime*                 | 1.0/1                                   | 2.7/1                                         |
| Soil/Flyash/Lime (600) | Soil                  | 0.8/1                                   |                                               |
|                        | Flyash                | 0.8/1                                   |                                               |
|                        | Lime                  | 0.8/1                                   | 2.4/1                                         |

\* Lime as Calcium Hydroxide

Table 4  
Field Prepared Samples

| <u>Test</u>      | <u>Container</u> | <u>No. Filled</u> |
|------------------|------------------|-------------------|
| Bulk wt.         | 800 ml Glass Jar | 3                 |
| Bearing Capacity | 800 ml Glass Jar | 6                 |
| Wet/dry          | 800 ml Glass Jar | 6                 |
| Permeability     | 2.8" x 4" PVC    | 3                 |
| EP/SWLP          | 1.3" x 4" PVC    | 6                 |

*Note: NOT a  
fixative,  
merely a means of absorbing it.*

Table 5

Absorbent Combinations Screened by the WES in Phase I

---

Soil

Fly Ash

Bentonite - Zeogel, Polygel, Quickgel

Diatomaceous Earth

Hazorb®

Fly Ash/Cement

Fly Ash/Zeogel

Soil/Zeogel

Soil/Fly Ash

Soil/Lime

Soil/Kiln Dust

Soil/Hazorb/Fly Ash

Soil/Fly Ash/Zeogel

Soil/Fly Ash/Lime

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Table 6  
Additional Chemical Leach Parameters Analyzed

---

pH

Conductivity

Chloride

Copper

TOC

Sulfone

---

Note: Above analyses are in addition to the parameters analyzed in the EP Test

Table 7  
EP Toxicity Parameters

| <u>EPA Hazardous<br/>Waste Number</u> | <u>Contaminant</u>                                                                                                                         | <u>Maximum<br/>Concentration<br/>(milligrams<br/>per liter)</u> |
|---------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|
| D004.....                             | Arsenic.....                                                                                                                               | 5.0                                                             |
| D005.....                             | Barium.....                                                                                                                                | 100.0                                                           |
| D006.....                             | Cadmium.....                                                                                                                               | 1.0                                                             |
| D007.....                             | Chromium.....                                                                                                                              | 5.0                                                             |
| D008.....                             | Lead.....                                                                                                                                  | 5.0                                                             |
| D009.....                             | Mercury.....                                                                                                                               | 0.2                                                             |
| D010.....                             | Selenium.....                                                                                                                              | 1.0                                                             |
| D011.....                             | Silver.....                                                                                                                                | 5.0                                                             |
| D012.....                             | Endrin (1, 2, 3, 4, 10, 10-hexa-<br>chloro-1,7-epoxy-1, 4, 4a, 5, 6,<br>7, 8, 8a-octahydro-1, 4-endo,<br>endo-5, 8-dimethano naphtahalene. | 0.02                                                            |
| D013.....                             | Lindane (1, 2, 3, 4, 5, 6-hexachloro-<br>cyclohexane--gamma isomer.                                                                        | 0.4                                                             |
| D014.....                             | Methoxychlor (1, 1, 1-Trichloro-<br>2, 2-bis [p-methoxyphenyl]<br>ethane).                                                                 | 10.0                                                            |
| D015.....                             | Toxaphene (C <sub>10</sub> H <sub>10</sub> Cl <sub>10</sub> Technical<br>chlorinated camphene, 67-69<br>percent chlorine).                 | 0.5                                                             |
| D016.....                             | 2,4-D (2,4-Dichlorophenoxyacetic<br>acid)                                                                                                  | 10.0                                                            |
| D017.....                             | 2, 4, 5-TP Silvex (2, 4, 5-<br>Trichlorophenoxypropionic<br>acid).                                                                         | 1.0                                                             |

Table 8  
Methods of Analysis

| <u>Analysis</u>     | <u>Method</u>                                                                                                    | <u>Reference</u> |
|---------------------|------------------------------------------------------------------------------------------------------------------|------------------|
| <b>Metals</b>       |                                                                                                                  |                  |
| Ba                  | Argon Plasma Emission<br>Spectrophotometry Screen,<br>finish by Flameless Atomic<br>Absorption Spectrophotometry | (20, 21)         |
| Cd                  |                                                                                                                  |                  |
| Cr                  |                                                                                                                  |                  |
| Cu                  |                                                                                                                  |                  |
| Pb                  |                                                                                                                  |                  |
| Se                  |                                                                                                                  |                  |
| Ag                  |                                                                                                                  |                  |
| Ag                  | Hydride Generation, Atomic<br>Absorption Spectrophotometry                                                       | (20, 21)         |
| Hg                  | Cold Vapor Atomic Absorption                                                                                     | (20, 21)         |
| <b>Organics</b>     |                                                                                                                  |                  |
| Endrin              | As per EPA Protocol                                                                                              | (22)             |
| Lindane             |                                                                                                                  |                  |
| Methoxychlor        |                                                                                                                  |                  |
| Toxaphene           |                                                                                                                  |                  |
| 2,4, - D            | As per EPA Protocol                                                                                              | (22)             |
| 2, 4, 5 - TP Silvex |                                                                                                                  |                  |
| DIMP                | As per Army Protocol                                                                                             | (23)             |
| Sulfone             |                                                                                                                  |                  |
| GC/MS Scan          | Base, neutral extract                                                                                            |                  |
| <b>Other</b>        |                                                                                                                  |                  |
| pH                  | Ion Selective Electrode                                                                                          | (20)             |
| Chloride            |                                                                                                                  |                  |

Table 9  
Physical Properties of solidified Basin F Waste

| <u>Process</u>                                | <u>Bulk Wt.<br/>(lb/ft<sup>3</sup>)</u> | <u>Volume Increase<br/>(Vol. solid/vol<br/>BF conc.)</u> | <u>24-hour<br/>Cone Index<br/>(psi)</u> | <u>Permeability<br/>(cm/sec)</u> |
|-----------------------------------------------|-----------------------------------------|----------------------------------------------------------|-----------------------------------------|----------------------------------|
| 100                                           | 101                                     | 1.5/1                                                    | 35                                      | $6.9 \times 10^{-8}$             |
| 200                                           | 90.4                                    | 4.1/1                                                    | 210                                     | $1.7 \times 10^{-4}$             |
| 300 Series                                    |                                         |                                                          |                                         |                                  |
| 300                                           | 105                                     | 1.2                                                      | 75                                      | $3.2 \times 10^{-4}$             |
| 301                                           | 83.7                                    | --                                                       | --                                      | --                               |
| 302                                           | 82.0                                    | 1.8                                                      | 412                                     | $7.0 \times 10^{-6}$             |
| 400                                           | 94.0                                    | 2/1                                                      | 168                                     | $1.2 \times 10^{-6}$             |
| 500 Series                                    |                                         |                                                          |                                         |                                  |
| 500                                           | 79.4                                    | 2.3                                                      | 37                                      | $1.0 \times 10^{-4}$             |
| 501                                           | 80.6                                    | 2.1                                                      | --                                      | --                               |
| 600 Series                                    |                                         |                                                          |                                         |                                  |
| Soil/Kiln Dust                                | 89.1                                    | 3.0                                                      | 60                                      | --                               |
| Soil/Lime                                     | 96.6                                    | 2.6                                                      | 52                                      | --                               |
| Soil/Flyash/<br>Lime - 600<br>(0.8/0.8/0.8/1) | 83.5                                    | 2.5                                                      | 60                                      | $1.4 \times 10^{-6}$             |

Table 10

Cone Index Requirements for Landfill Construction Equipment<sup>1</sup>

| <u>Vehicle Description</u>                                                                                                     | <u>Vehicle Weight (kips)</u> | <u>VCI<sub>1</sub></u> | <u>VCI<sub>50</sub></u> |
|--------------------------------------------------------------------------------------------------------------------------------|------------------------------|------------------------|-------------------------|
| <u>Trucks</u>                                                                                                                  |                              |                        |                         |
| Truck, cargo: 3/4 ton,<br>4 x 4, M37                                                                                           | 7.4                          | 27                     | 61                      |
| Truck, dump: 2 1/2 ton,<br>6 x 6, M47                                                                                          | 19.2                         | 28                     | 64                      |
| Truck, dump: 5 ton<br>6 x 6, M51                                                                                               | 32.7                         | 32                     | 72                      |
| Truck, tractor, wrecker:<br>medium, 5 ton, 6 x 6,<br>M246 (w/payload)                                                          | 44.8                         | 32                     | 73                      |
| <u>Earthmoving Tractors</u>                                                                                                    |                              |                        |                         |
| Tractor, full tracked, low<br>speed: DED, heavy dbp,<br>w/bulldozer, w/scarifier<br>IH Model TD-24-241<br>FSN 2410-542-2388    | 54.2                         | 18                     | 43                      |
| Caterpillar Model D-8<br>FSN 2410-542-4882                                                                                     | 51.0                         | 17                     | 41                      |
| Tractor, full tracked, low<br>speed: DED, medium dbp,<br>w/bulldozer, cable PCU<br>Caterpillar Model D-7<br>FSN 2410-277-1280  | 35.8                         | 16                     | 38                      |
| Tractor, full tracked, low<br>speed: DED, medium dbp,<br>w/angledozer, w/scarifier,<br>IH Model TD-18-182<br>FSN 2410-541-7655 | 39.8                         | 14                     | 34                      |
| Tractor, full tracked, low<br>speed: DED, medium dbp,<br>w/angledozer, w/scarifier,<br>IH Model TD20-200<br>FSN 2410-542-2498  | 40.2                         | 15                     | 36                      |
| Tractor, full tracked low<br>speed: DED, light dbp,<br>w/bulldozer, w/scarifier,<br>Caterpillar Model D-6<br>FSN 2410-542-4206 | 16.0                         | 17                     | 40                      |

(Continued)

<sup>1</sup> MXX designations are Army vehicle codes

Table 10

| <u>Vehicle Description</u>                                                                                                  | <u>Vehicle Weight (kips)</u> | <u>VCI<sub>1</sub></u> | <u>VCI<sub>50</sub></u> |
|-----------------------------------------------------------------------------------------------------------------------------|------------------------------|------------------------|-------------------------|
| Tractor, full tracked, low speed: DED, light dbp w/bulldozer, w/scarifier w/wn, Caterpillar Model D-4 FSN 2410-843-6374     | 17.3                         | 21                     | 49                      |
| Tractor, full tracked, low speed: DED, light dbp, w/bulldozer, PCU Hydraulic crane; Caterpillar Model 933 FSN 2410-555-1756 | 16.0                         | 20                     | 48                      |
| Tractor, full tracked, low speed, DED, medium dbp, w/bulldozer, w/scarifier, Allis Chalmers HD-16M FSN 2410-078-6483        | 48.5                         | 16                     | 38                      |
| Caterpillar Model D-7 FSN 2410-782-1130                                                                                     | 48.5                         | 16                     | 38                      |
| Tractor, full tracked, 5 ton universal ballastable, (Universal Engineer Tractor)                                            | 36.0                         | 16                     | 39                      |
| Tractor, wheeled, industrial: DED, medium dbp, w/bulldozer front, Clark Model 290M FSN 2420-088-9384                        | 54.2                         | 34                     | 77                      |
| Caterpillar Model 830M FSN 2420-806-0031                                                                                    | 54.2                         | 28                     | 65                      |
| <u>Cranes and Loaders</u>                                                                                                   |                              |                        |                         |
| Crane shovel, basic unit, crawler mtd; 2 cu yd 40 ton Baldwin-Lima-Hamilton FSN 3810-230-3821                               | 132.6                        | 21                     | 50                      |
| Crane shovel, basic unit crawler mtd: Baldwin-Lima-Hamilton FSN 3810-221-2327                                               | 38.2                         | 14                     | 33                      |
| Crane shovel basic unit, crawler mtd: 10 ton 3/4 cu yd, "UNIT" Model 1020 yd FSN 3810-255-7593                              | 35.0                         | 9                      | 21                      |
| Crane shovel, crawler w/catwalk: 2 cu yd, 40 ton, Bucyrus-Erie FSN 3810-263-3068                                            | 132.6                        | 21                     | 50                      |

(Continued)

Table 10 (Concluded)

| <u>Vehicle Description</u>                                                                                                           | <u>Vehicle<br/>Weight<br/>(kips)</u> | <u>VCI<sub>1</sub></u> | <u>VCI<sub>50</sub></u> |
|--------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|------------------------|-------------------------|
| Crane, revolving, crawler mtd:<br>30-40 ton,<br>Thew Shovel L-82                                                                     | 103.0                                | 22                     | 52                      |
| Crane, wheel mounted: 3/8 cu yd<br>5 ton, DED, 4 x 4, rough<br>terrain, air transportable,<br>Koehring Model M7<br>FSN 3810-828-4457 | 16.0                                 | 40                     | 89                      |
| Crane, wheel mounted<br>20 ton, 3/4 cu yd,<br>rough terrain, 4 x 4<br>FSN 3810-060-2735                                              | 60.5                                 | 42                     | 93                      |
| Loader, bucket type:<br>full tracked, DED<br>3 cu yd per min,<br>Haiss Model 77-PC                                                   | 23.0                                 | 20                     | 47                      |

How about Sodium values  
They probably are very high!

Table 11

pH, Conductivity, and Chlorides in EP and SWLP Leachates

| <u>Sample</u> | <u>pH</u> | <u>Conductivity</u><br>(umhos) | <u>Chloride</u><br>(mg/l) |
|---------------|-----------|--------------------------------|---------------------------|
| 100           |           |                                |                           |
| EP            | 4.95      | †                              | 2602                      |
| SWLP          | 8.5       | $2.3 \times 10^4$<br>23,000    | 5869                      |
| 200           |           |                                |                           |
| EP            | 5.0       | $2.0 \times 10^4$              | 1193                      |
| SWLP          | 11.5      | $1.15 \times 10^4$<br>11,500   | 1988                      |
| 300           |           |                                |                           |
| EP            | 5.30      | †                              | 2772                      |
| SWLP          | 10.4      | $1.7 \times 10^4$<br>17,000    | 4796                      |
| 301           |           |                                |                           |
| EP            | 5.20      | †                              | 1790                      |
| SWLP          | 11.4      | $1.2 \times 10^4$<br>12,000    | 4628                      |
| 302           |           |                                |                           |
| EP            | 5.0       | $1.7 \times 10^4$              | 2993                      |
| SWLP          | 11.7      | $2.0 \times 10^4$<br>20,000    | 6285                      |
| 400           |           |                                |                           |
| EP            | 5.1       | †                              | 1760                      |
| SWLP          | 11.4      | $0.9 \times 10^4$<br>9,000     | 4179                      |
| 500           |           |                                |                           |
| EP            | 5.0       | $1.5 \times 10^4$              | 1496                      |
| SWLP          | 8.75      | $1.2 \times 10^4$              | 3037                      |
| 600           |           |                                |                           |
| EP            | 5.3       | $1.7 \times 10^4$              | 1129                      |
| SWLP          | 11.6      | $1.5 \times 10^4$              | 3247                      |
| EP Blank      | 5.0       | $2.6 \times 10^1$              | 5                         |
| EP Blank      | 7.2       | $2.9 \times 10^1$              | 5                         |

† Data unavailable

Table 12  
Metals in EP and SWLP Leachates (mg/L)

| Process  | Ag   | As    | Ba   | Cd   | Cr   | Cu   | Hg     | Pb   | Se    |
|----------|------|-------|------|------|------|------|--------|------|-------|
| 100 EP   | <.05 | .092  | .76  | <.05 | <.05 | 53.6 | .0006  | .04  | .012  |
| 100 SWLP | <.05 | .255  | 2.30 | <.05 | <.05 | 81.2 | .0023  | .12  | .011  |
| 200 EP   | <.05 | .492  | .59  | <.05 | <.05 | 22.0 | .0008  | <.01 | <.03  |
| 200 SWLP | <.05 | .062  | 1.31 | <.05 | <.05 | 24.0 | .0011  | <.01 | <.04  |
| 300 EP   | <.05 | .130  | .64  | <.05 | <.05 | 58.0 | .0024  | .02  | .024  |
| 300 SWLP | <.05 | .200  | 1.02 | <.05 | <.05 | 86.8 | .0047  | .01  | .01   |
| 301 EP   | <.05 | .045  | .18  | <.05 | <.05 | 3.7  | .0007  | <.01 | <.05  |
| 301 SWLP | <.05 | .150  | 1.46 | <.05 | <.05 | 9.1  | .0022  | <.01 | <.005 |
| 302 EP   | <.05 | .077  | <.01 | <.05 | <.05 | 24.0 | .0012  | <.01 | <.04  |
| 302 SWLP | <.05 | .127  | .46  | <.05 | <.05 | 53.0 | .0029  | .01  | <.09  |
| 400 EP   | <.05 | .370  | .194 | <.05 | <.05 | 8.6  | <.0002 | .02  | <.005 |
| 400 SWLP | <.05 | .140  | .93  | <.05 | <.05 | 41.0 | .0012  | .17  | <.005 |
| 500 EP   | <.05 | .124  | .76  | <.05 | <.05 | 85.0 | .0019  | <.01 | <.03  |
| 500 SWLP | <.05 | <.020 | 1.02 | <.05 | <.05 | 131  | .0029  | <.01 | <.04  |
| 600 EP   | <.05 | .029  | .48  | <.05 | <.05 | 11.0 | .0004  | <.01 | <.02  |
| 600 SWLP | <.05 | .075  | 2.30 | <.05 | <.05 | 29.0 | .0012  | <.01 | <.04  |

Table 13

## Organics in EP and SWLP Leachates (mg/l)

| Process  | TOC  | Endrin | Lindane | Methoxychlor | Toxaphene | 2,4-D | 2,4,5-TP | Sulfone | Qualitative GC/MS Scan                     |
|----------|------|--------|---------|--------------|-----------|-------|----------|---------|--------------------------------------------|
| 100 EP   | 4050 | <.01   | <.02    | <.02         | <.5       | .13   | .021     | NA      | Sulfone, Sulfoxide, TMP                    |
| 100 SWLP | 5400 | <.01   | <.02    | <.02         | <.5       | .30   | <.037    | NA      |                                            |
| 200 EP   | 2260 | <.01   | NA      | NA           | NA        | NA    | NA       | .53     |                                            |
| 200 SWLP | 1530 | <.01   | NA      | NA           | NA        | NA    | NA       | .80     |                                            |
| 300 EP   | 4490 | <.01   | <.02    | <.02         | <.5       | .15   | .015     | NA      | Sulfone, Sulfoxide, TMP                    |
| 300 SWLP | 4350 | <.01   | <.02    | <.02         | <.5       | .20   | <.035    | NA      | Sulfone, Sulfoxide, MSR, EDP, DP, Dithiane |
| 301 EP   | 1650 | <.01   | <.02    | <.02         | <.5       | NA    | NA       | NA      | Sulfone, Sulfoxide, MSR, TNB, DP           |
| 301 SWLP | 3420 | <.01   | NA      | NA           | NA        | NA    | NA       | NA      |                                            |
| 302 EP   | 2020 | <.01   | NA      | NA           | NA        | NA    | NA       | .98     |                                            |
| 302 SWLP | 3830 | <.01   | NA      | NA           | NA        | NA    | NA       | 2.0     |                                            |
| 400 EP   | 1640 | <.01   | <.02    | <.02         | <.5       | .075  | .012     | NA      |                                            |
| 400 SWLP | 2840 | <.01   | <.02    | <.02         | <.5       | .14   | <.045    | NA      | Sulfone, Sulfoxide, DP                     |
| 500 EP   | 1730 | <.01   | NA      | NA           | NA        | NA    | NA       | 1.1     |                                            |
| 500 SWLP | 2620 | <.01   | NA      | NA           | NA        | NA    | NA       | 1.7     |                                            |
| 600 EP   | 2980 | <.01   | NA      | NA           | NA        | NA    | NA       | .32     |                                            |
| 600 SWLP | 2230 | <.01   | NA      | NA           | NA        | NA    | NA       | 1.5     |                                            |

DP: Dimethyl-2(III)-pyridone

Sulfone: P-chlorophenylmethylsulfone

TMP: 1,3,6-trimethyl-2,4(1H,3H)pyrimidinone

MSB: Methylsulfonybenzene

Sulfoxide: P-chlorophenylmethylsulfoxide

EDP: Ethyldiisopropylamine

TNB: 1,4-dimethoxy-2,3,5,6-tetramethyl benzene

NA: Not analyzed

Table 14  
Leachable Contaminant Density\* (mg/l)

| Process                 | Arsenic | Copper | Mercury | TOC     | Sulfone | Chloride |
|-------------------------|---------|--------|---------|---------|---------|----------|
| 100 EP                  | 3.78    | 2207   | .02     | 166,000 | NA      | 107,000  |
| 100 SWLP                | 5.41    | 1725   | .04     | 114,000 | NA      | 124,300  |
| 200 EP                  | 69.83   | 3122   | .11     | 320,000 | 75.23   | 169,000  |
| 200 SWLP                | 3.79    | 1469   | .06     | 93,000  | 48.99   | 122,000  |
| 300 EP                  | 8.19    | 3656   | .15     | 283,000 | NA      | 175,000  |
| 300 SWLP                | 5.12    | 2224   | .12     | 111,000 | NA      | 123,000  |
| 301 EP                  | 2.94    | 242    | .04     | 108,000 | NA      | 117,000  |
| 301 SWLP                | 3.88    | 235    | .05     | 88,000  | NA      | 120,000  |
| 302 EP                  | 4.74    | 1478   | .07     | 124,000 | 60.38   | 184,000  |
| 302 SWLP                | 3.58    | 1497   | .08     | 108,000 | 56.5    | 178,000  |
| 400 EP                  | 31.33   | 728    | <.01    | 138,000 | NA      | 149,000  |
| 400 SWLP                | 5.07    | 1486   | .04     | 102,000 | NA      | 151,000  |
| 500 EP                  | 11.79   | 8086   | .18     | 164,000 | 104.65  | 142,000  |
| 500 SWLP                | <.81    | 5321   | .11     | 106,000 | 69.06   | 123,000  |
| 600 EP                  | 2.48    | 941    | <.03    | 255,000 | 27.39   | 96,600   |
| 600 SWLP                | 3.18    | 1232   | .05     | 94,000  | 63.75   | 138,000  |
| Mean EP                 | 16.89   | 2557   | 0.076   | 195,000 | 66.91   | 143,000  |
| Mean SWLP               | 3.86    | 1899   | 0.069   | 102,000 | 59.57   | 135,000  |
| Std. Dev. EP            | 23.4    | 2527   | 0.0637  | 180,000 | --      | 32,800   |
| Std. Dev. SWLP          | 1.49    | 1491   | 0.0314  | 94,000  | --      | 20,300   |
| Rel. Std. Dev. EP (%)   | 138.5   | 98.8   | 83.8    | 41.0    | --      | 23.0     |
| Rel. Std. Dev. SWLP (%) | 38.6    | 78.5   | 45.5    | 9.2     | --      | 15.0     |

\* Milligrams contaminant leached per liter of Basin F concentrate  
NA: Not analyzed

Table 15

Qualitative Assessment of Ammonia Gas Release by Solidification Processes

| <u>Process</u> | <u>Ammonia</u> |             |
|----------------|----------------|-------------|
|                | <u>Strong</u>  | <u>None</u> |
| 100            | +              |             |
| 200            | +              |             |
| 300            | +              |             |
| 301            | +              |             |
| 302            |                | +           |
| 400            | +              |             |
| 500            |                | +           |
| 501            |                | +           |
| 600            | +              |             |

Table 16  
Relative Performance Index for Five Solidification  
Processes Applied to Basin F Concentrate

| Weighting Factors | Parameter                  |                   |                                   |                               |     | RPI |
|-------------------|----------------------------|-------------------|-----------------------------------|-------------------------------|-----|-----|
|                   | Residual<br>Free<br>Liquid | 24-Hour CI        | LOG <sub>10</sub><br>Permeability | Contaminant<br>Immobilization |     |     |
|                   |                            |                   |                                   | As                            | Cu  |     |
| Process           |                            | 0.2               | 0.85                              | 1.0                           | 1.3 |     |
| 100               | pass                       | <del>f</del> fail | --                                | --                            | --  | --  |
| 200               | pass                       | 9                 | 15                                | 4                             | 30  | 58  |
| 300               | pass                       | 1                 | 6                                 | 30                            | 26  | 63  |
| 302               | pass                       | 20                | 60                                | 52                            | 64  | 196 |
| 400               | pass                       | <del>f</del> 6    | 85                                | 8                             | 130 | 229 |
| 500               | pass                       | <del>f</del> fail | --                                | --                            | --  | --  |
| 600               | pass                       | 1                 | 83                                | 100                           | 101 | 285 |

Table 17  
Material Cost for Solidifying Basin F Concentrate

| <u>Process</u>           | <u>\$ /gal</u> |
|--------------------------|----------------|
| 100                      | \$0.07         |
| 200                      | \$0.80-\$1.00  |
| 300                      | \$0.59         |
| 301                      | \$0.99         |
| 302                      | \$0.59         |
| 400                      | \$0.54         |
| 500                      | \$0.21-\$0.34  |
| 600 Series               |                |
| Soil/Kiln Dust           | \$0.17         |
| Soil/Lime                | \$0.12         |
| Soil/Flyash/Lime - (600) | \$0.10         |

Table 18  
Example Cost Estimates for Solidification/Landfilling  
of Basin F Concentrate\*

| <u>Process</u> | <u>Materials<br/>Cost (<math>10^6</math> \$)</u> | <u>Haul Cost<br/>(<math>10^6</math> \$)</u> | <u>Landfill<br/>Cost (<math>10^6</math> \$)</u> | <u>Total Cost<br/>(<math>10^6</math> \$)</u> |
|----------------|--------------------------------------------------|---------------------------------------------|-------------------------------------------------|----------------------------------------------|
| 200            | 8.00                                             | 0.10                                        | 5.07                                            | 13.17                                        |
| 300            | 5.90                                             | 0.03                                        | 1.43                                            | 7.41                                         |
| 302            | 5.90                                             | 0.04                                        | 2.23                                            | 8.17                                         |
| 400            | 5.40                                             | 0.05                                        | 2.48                                            | 7.93                                         |
| 600            | 1.00                                             | 0.05                                        | 3.09                                            | 4.14                                         |

\* Costs do not include labor, equipment, or materials transportation to the site. Based on processing  $10^7$  gallons.

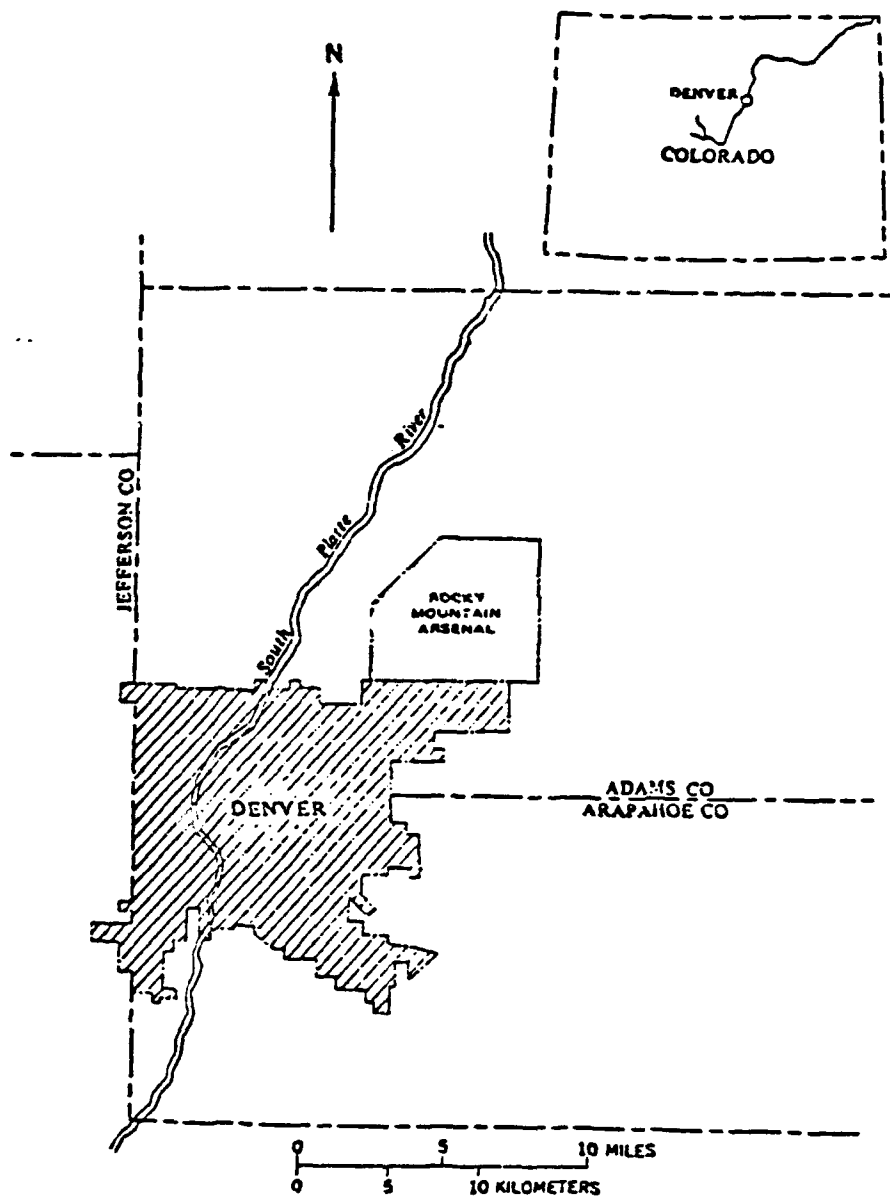


Figure 1. Vicinity Map

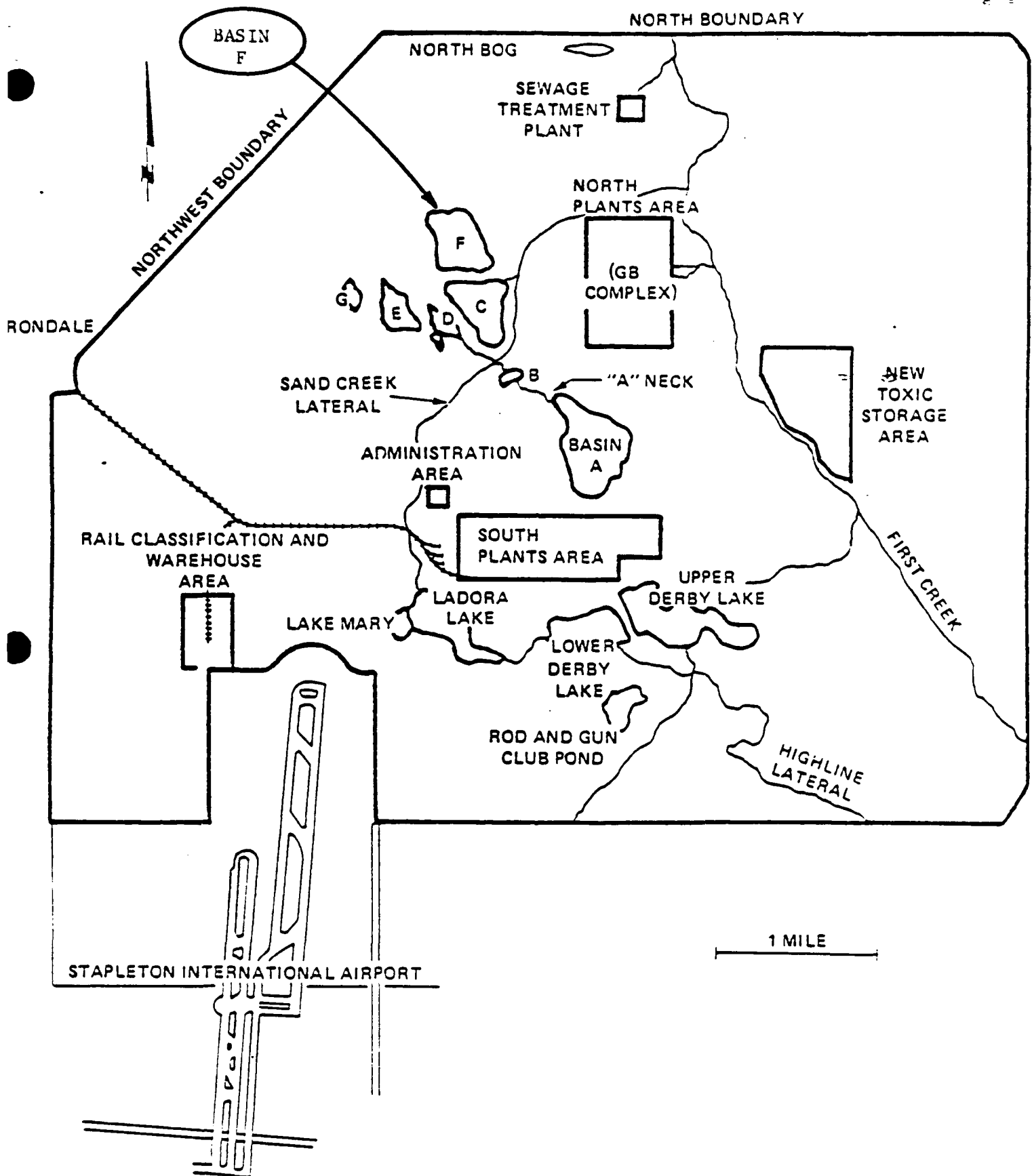


Figure 2. General Map of RMA

# EVAPORATION PLATFORMS (Top View)

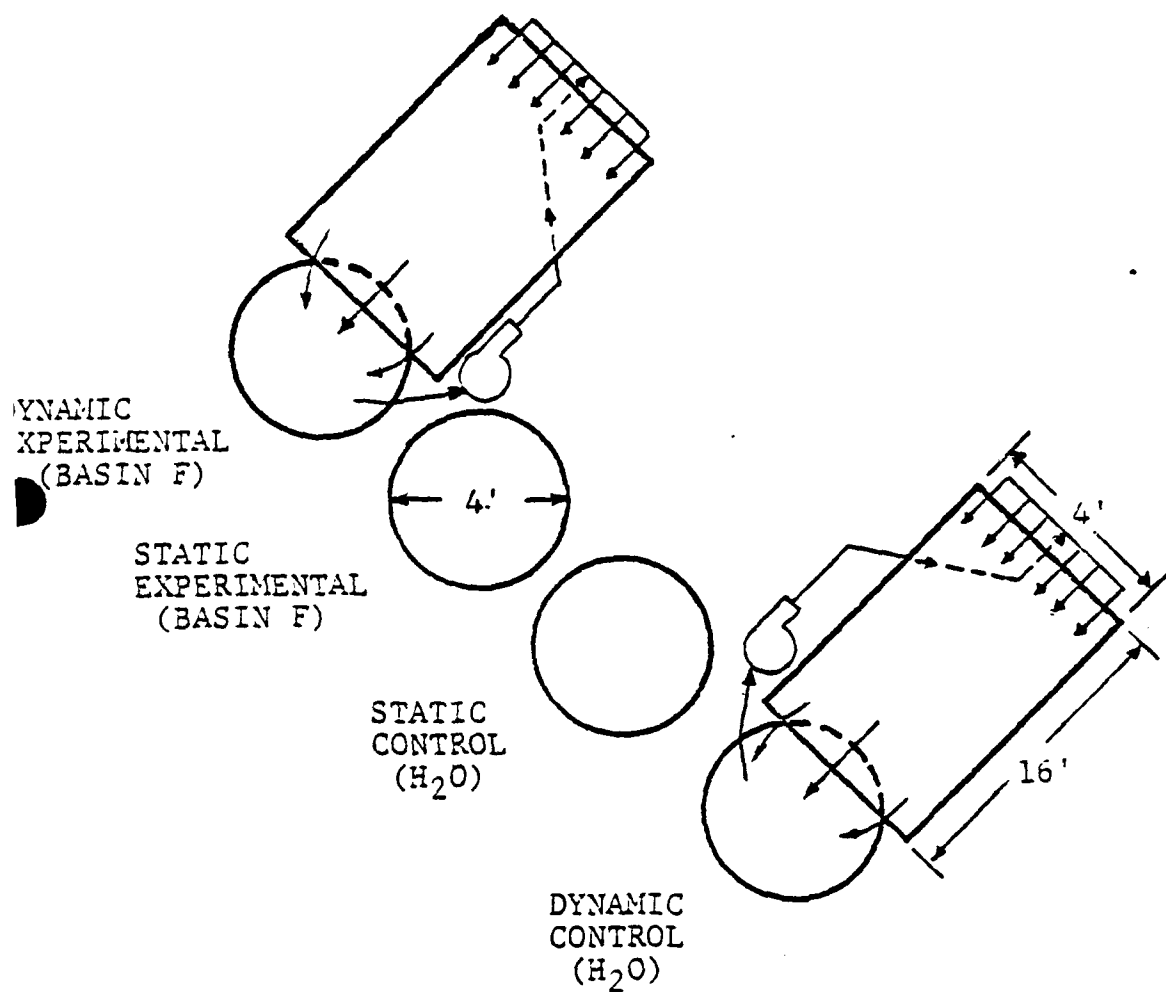


Figure 3. Solar Enhanced, Thin-Film Evaporation Equipment

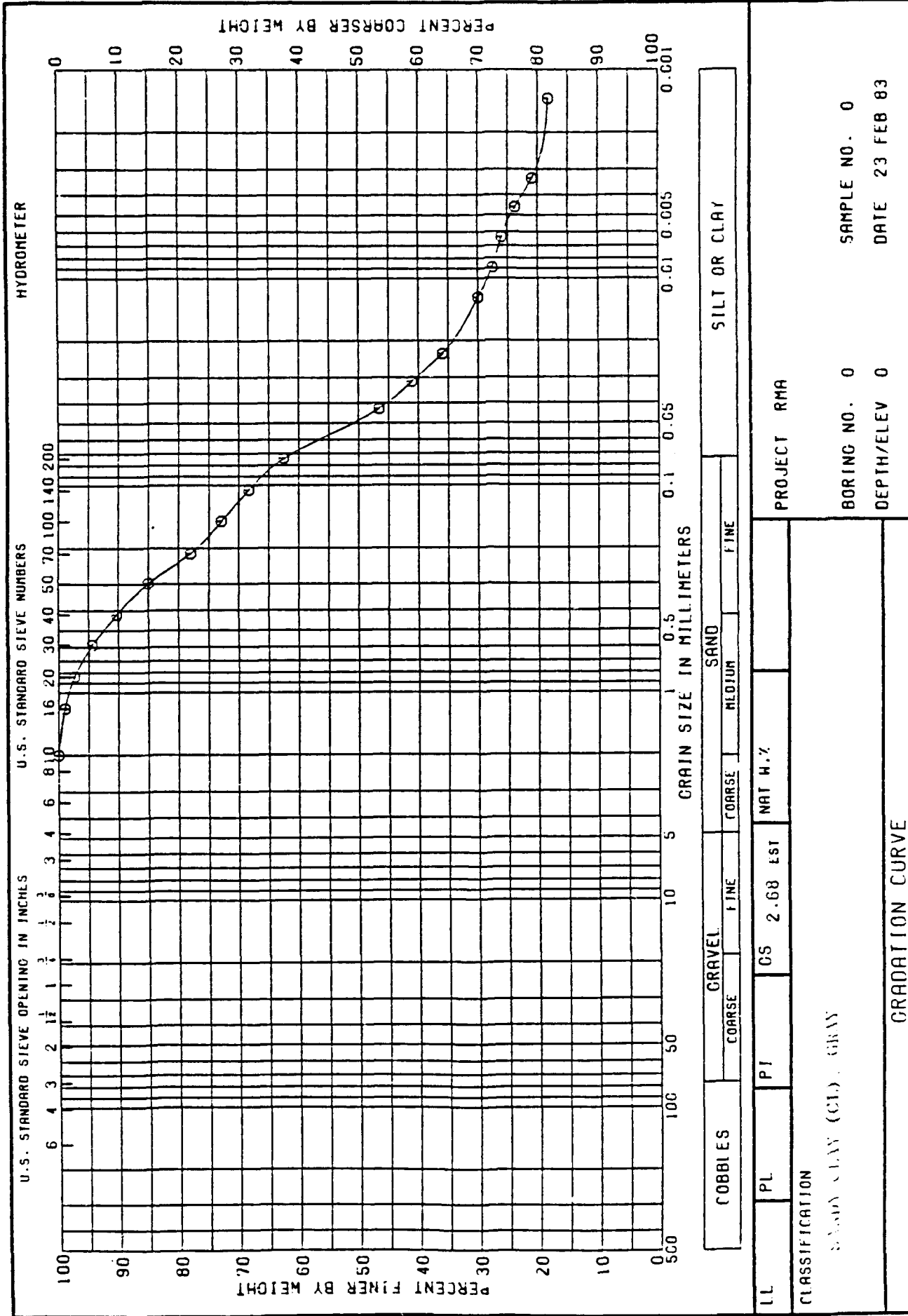


Figure 4. Grain Size Distribution of RNA Soil Used as an Absorbant

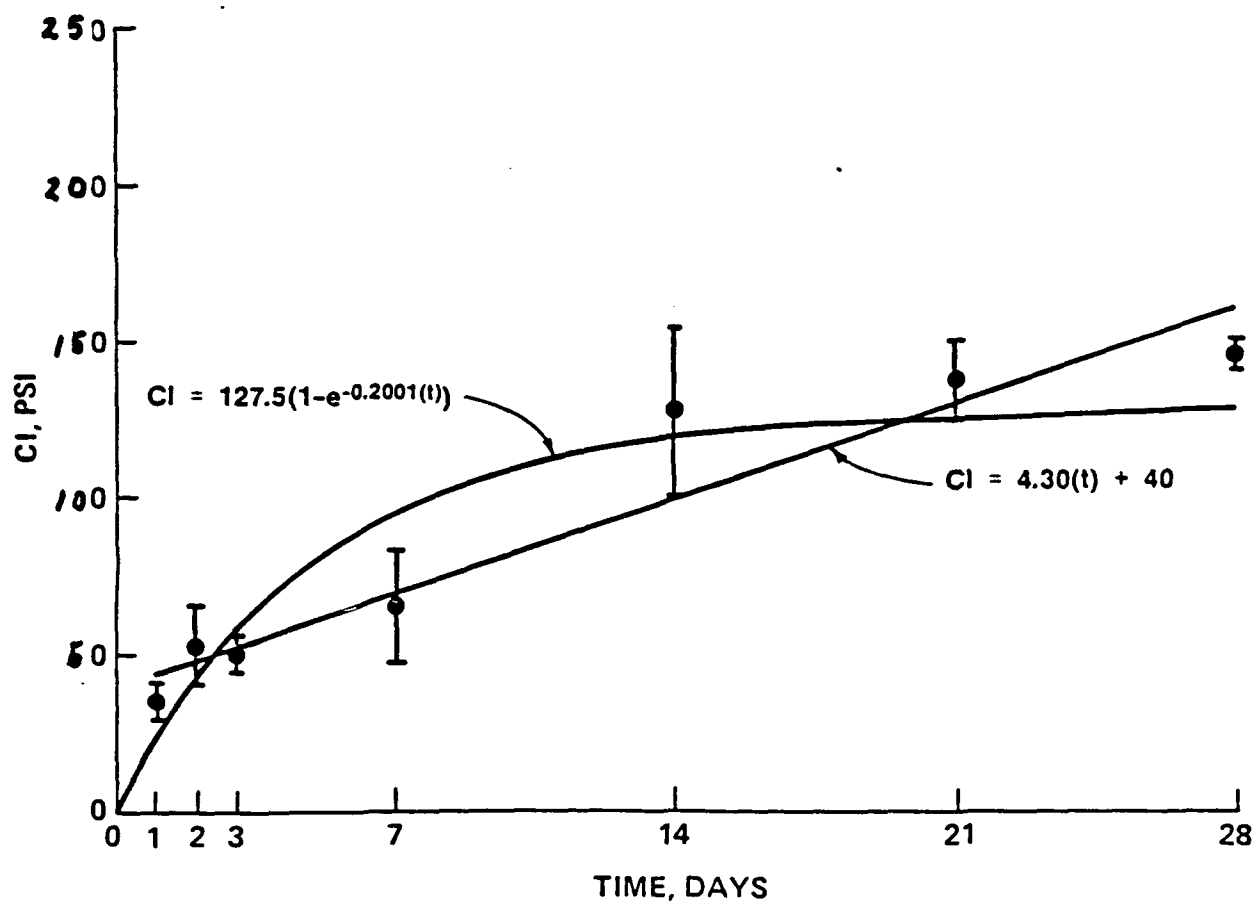


Figure 5. CI versus time, Process 100

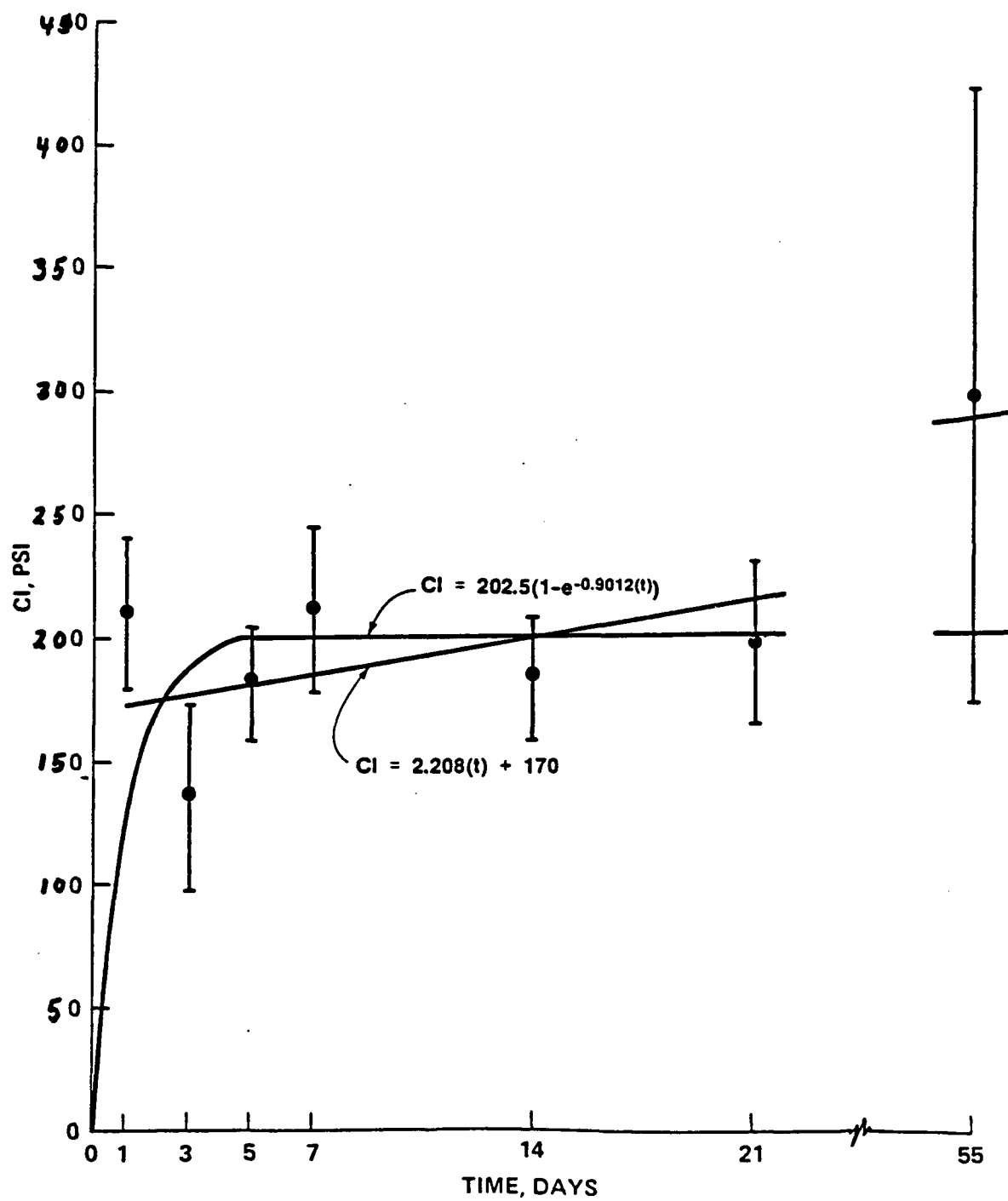


Figure 6. CI versus time, Process 200

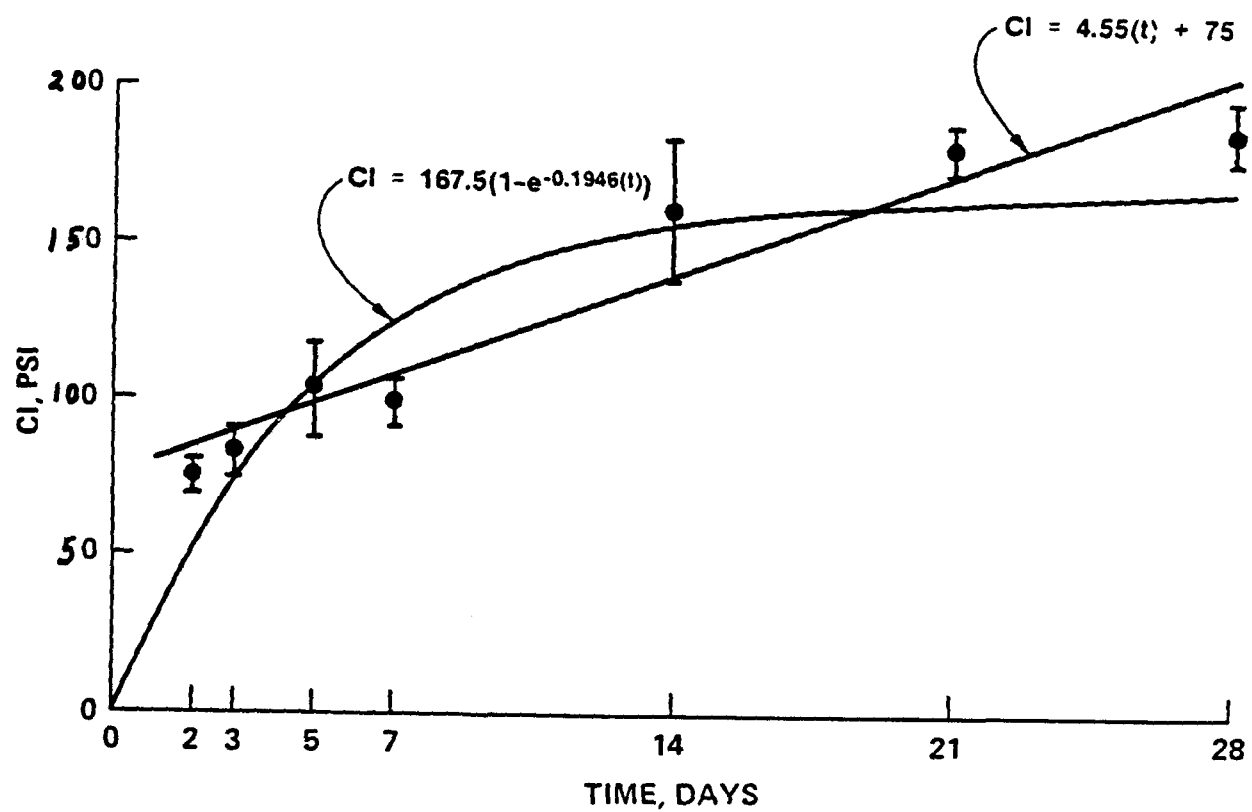


Figure 7. CI versus time, Process 300

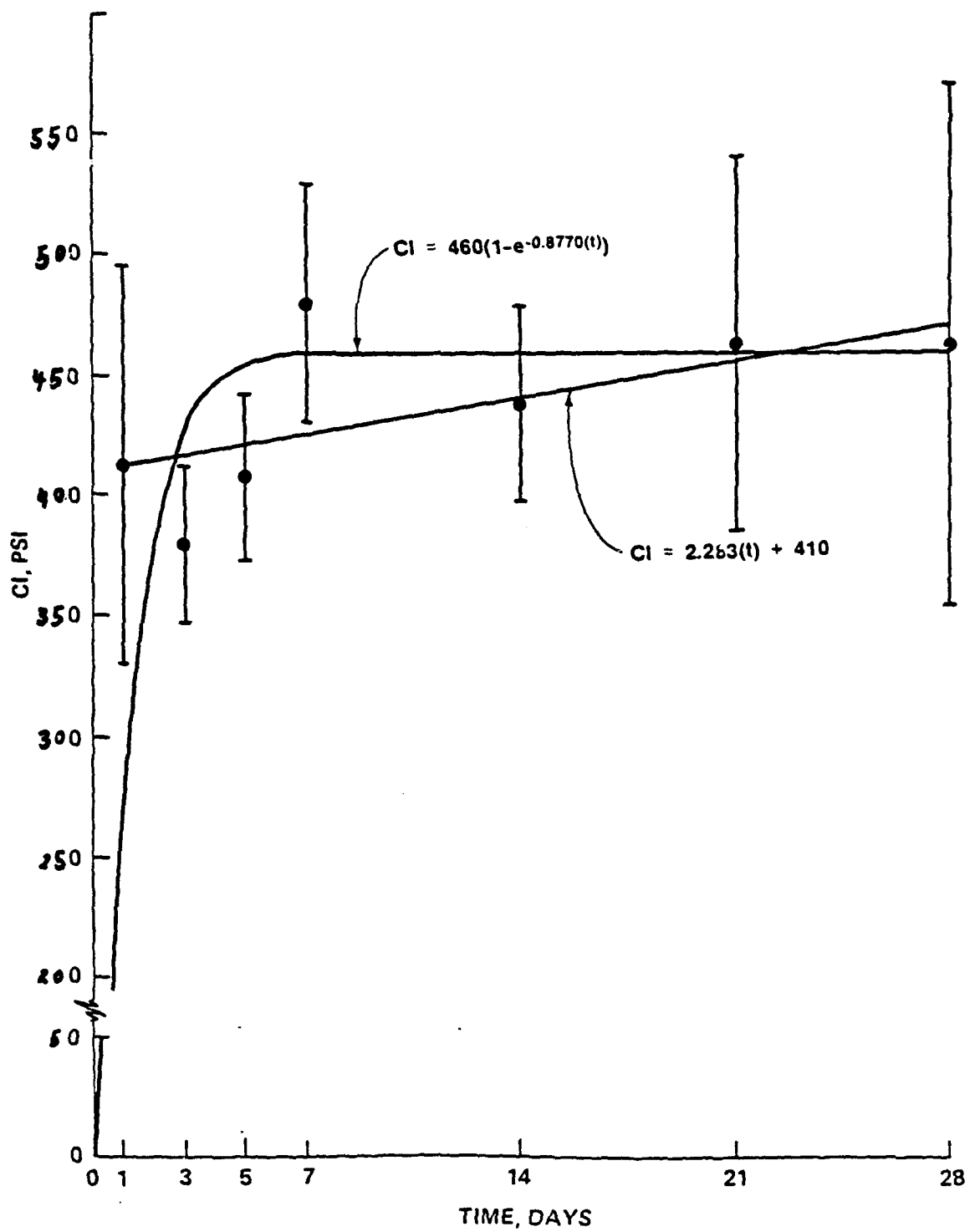


Figure 8. CI versus time, Process 302

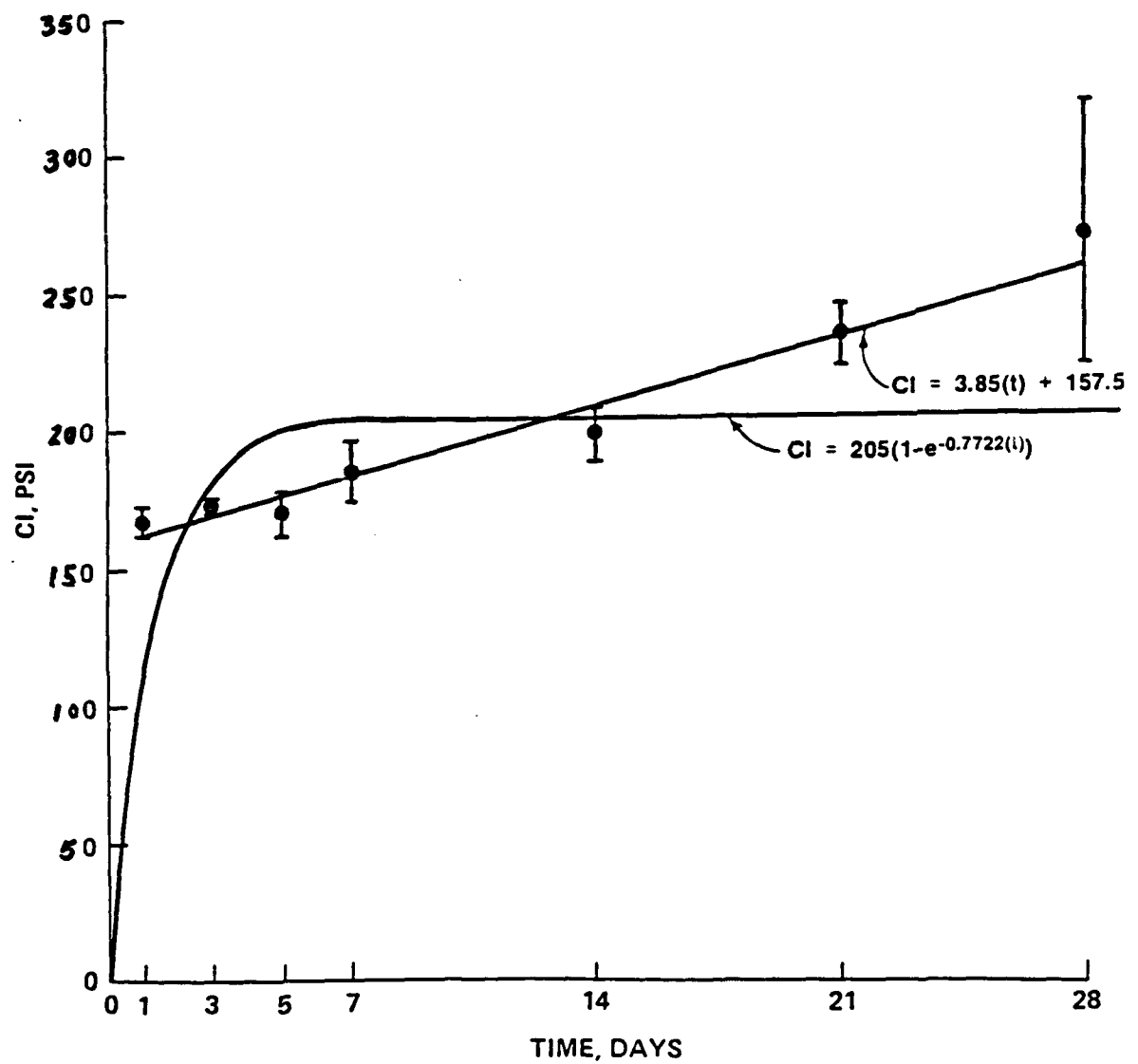


Figure 9. CI versus time, Process 400

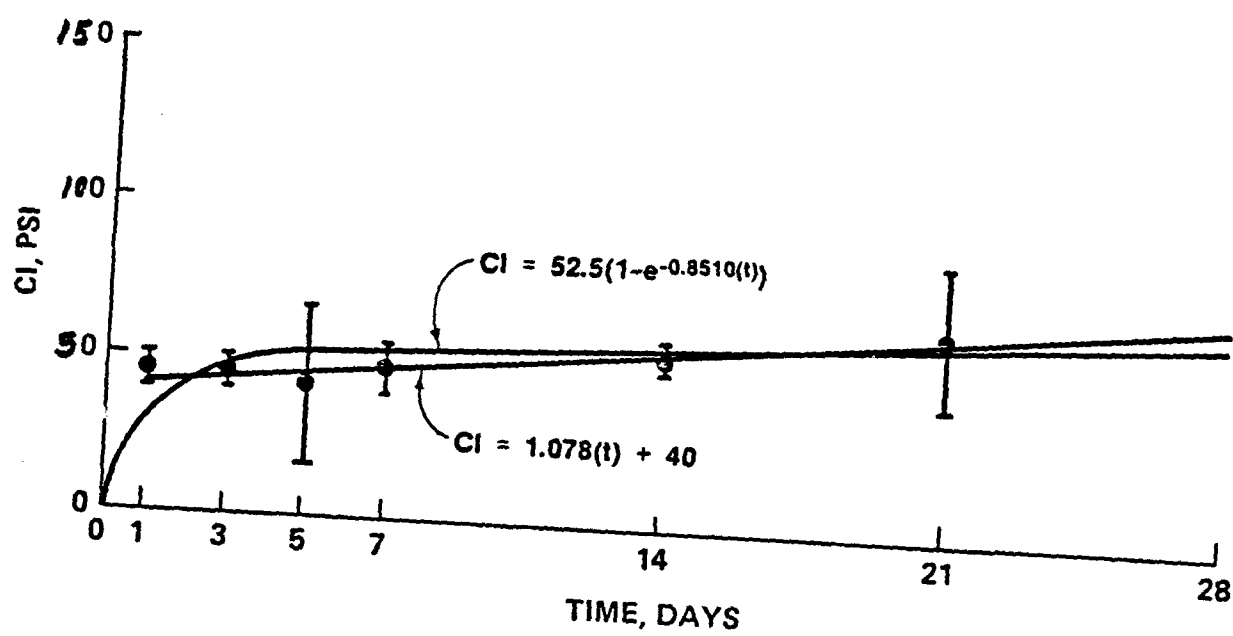


Figure 10. CI versus time, Process 500

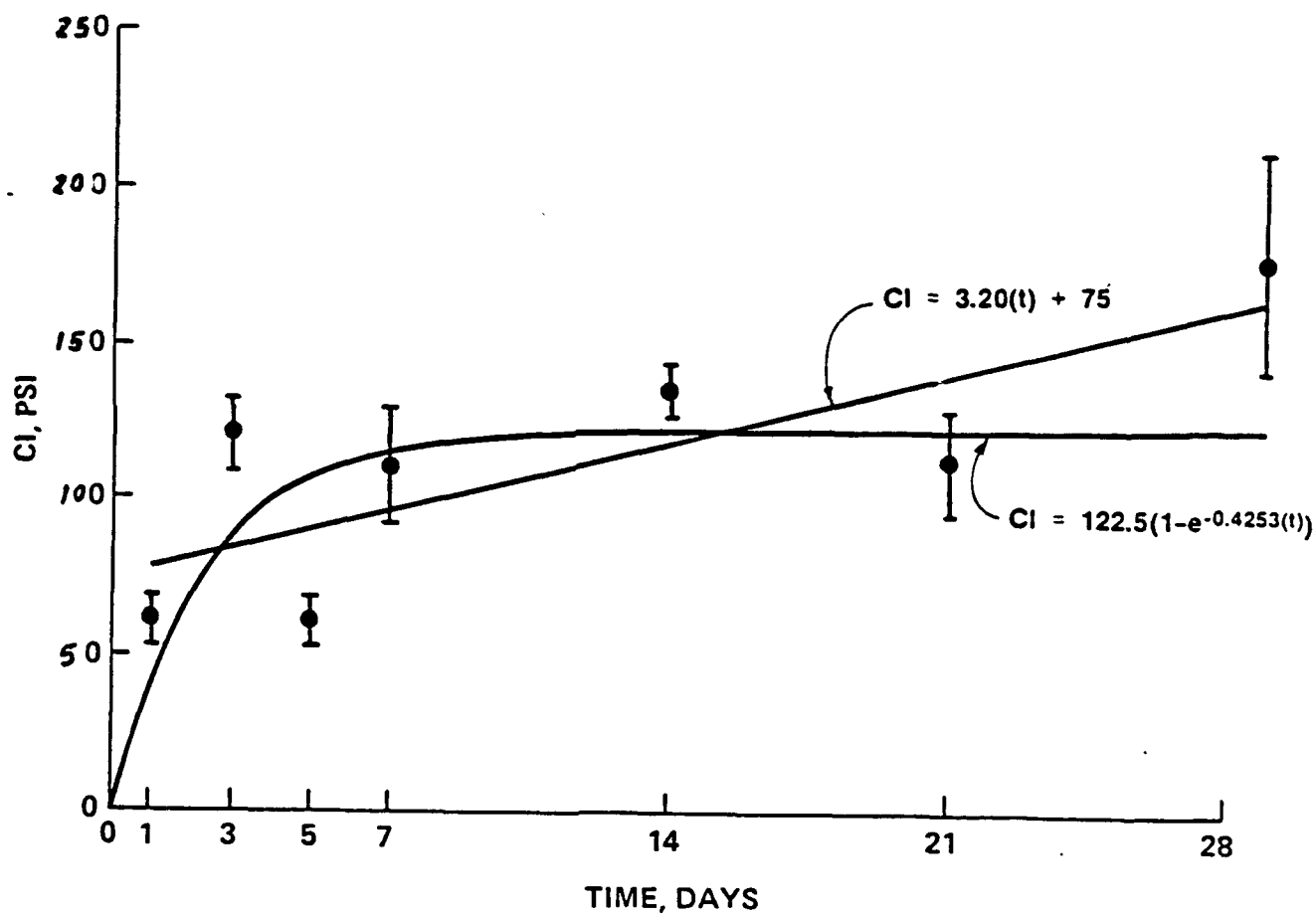


Figure 11. CI versus time, Process 600

PERFORMANCE VS CURE TIME

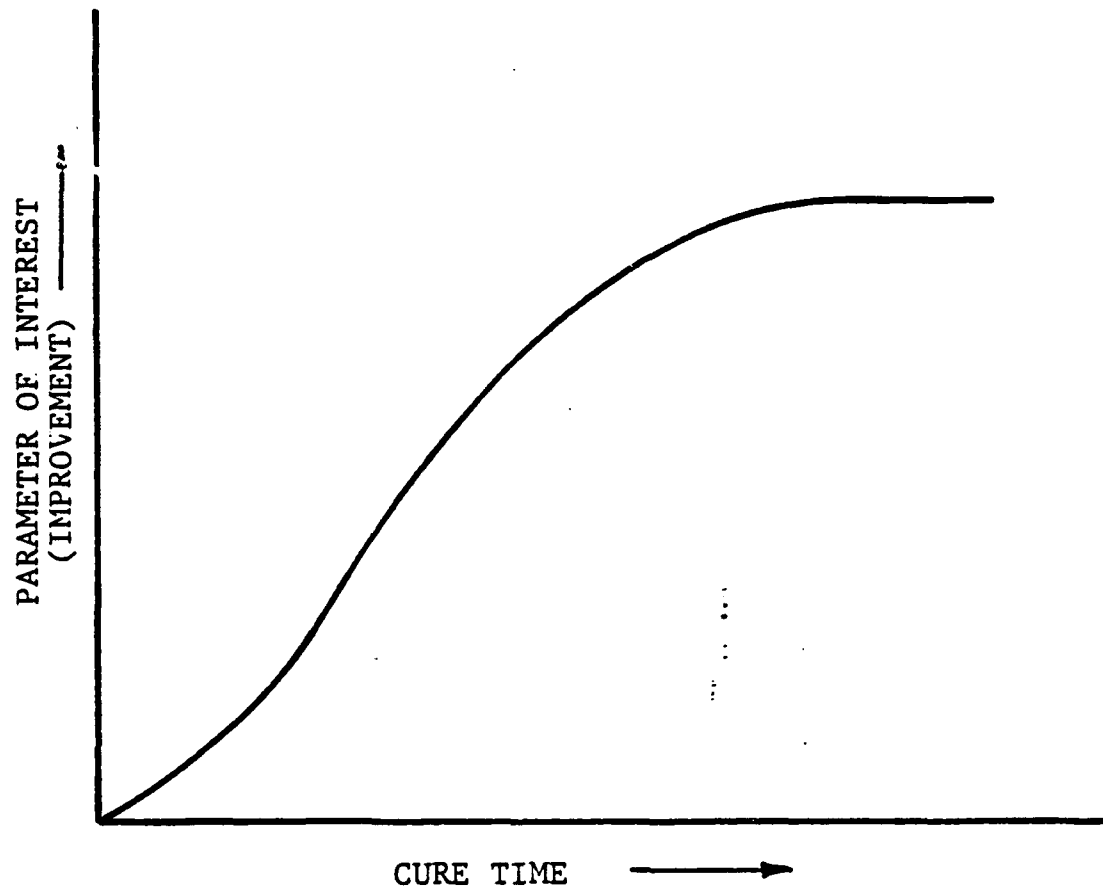


Figure 12. Generalized CI Versus Time Curve

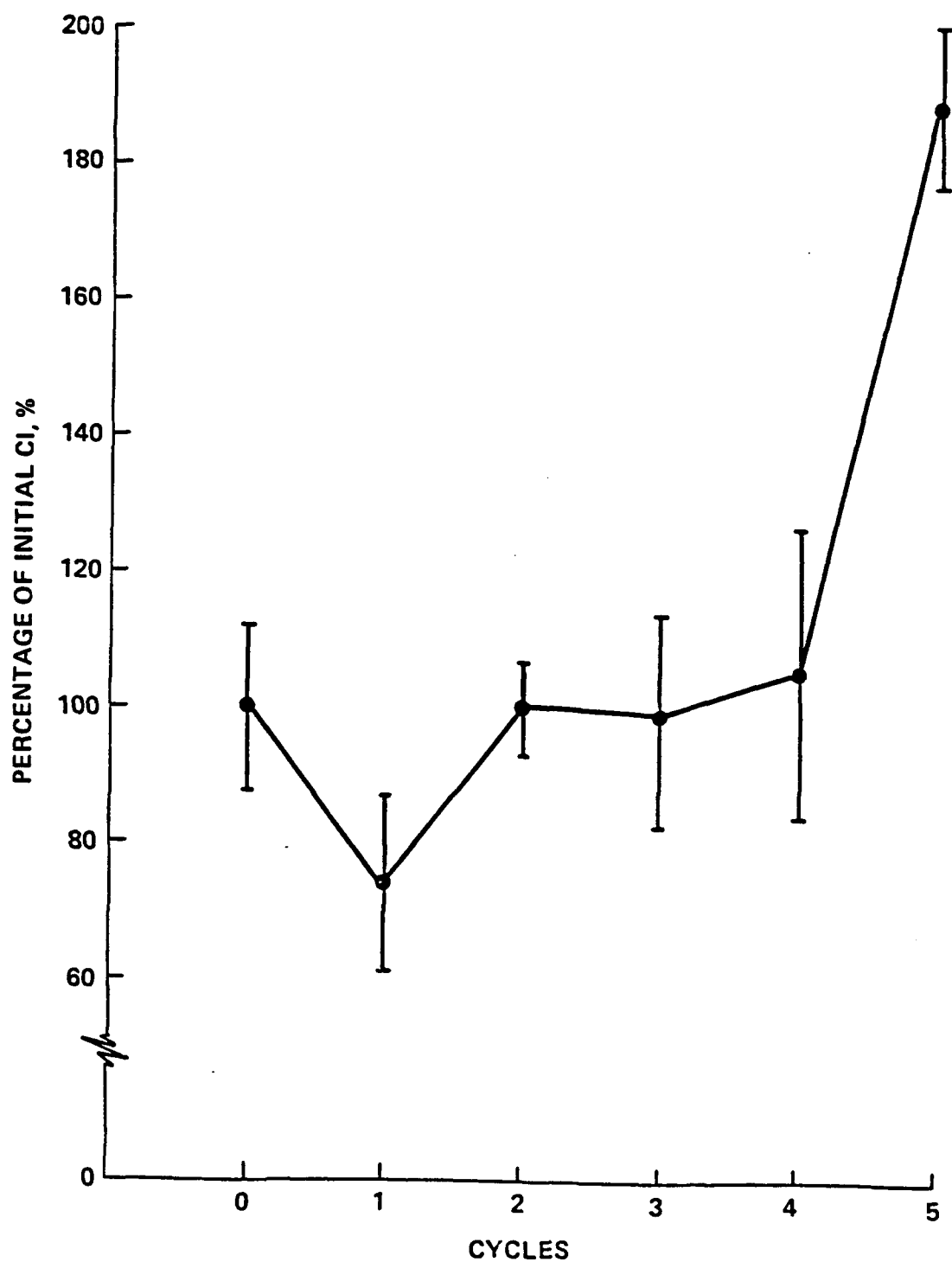


Figure 13. CI versus wet/dry cycling, Process 100

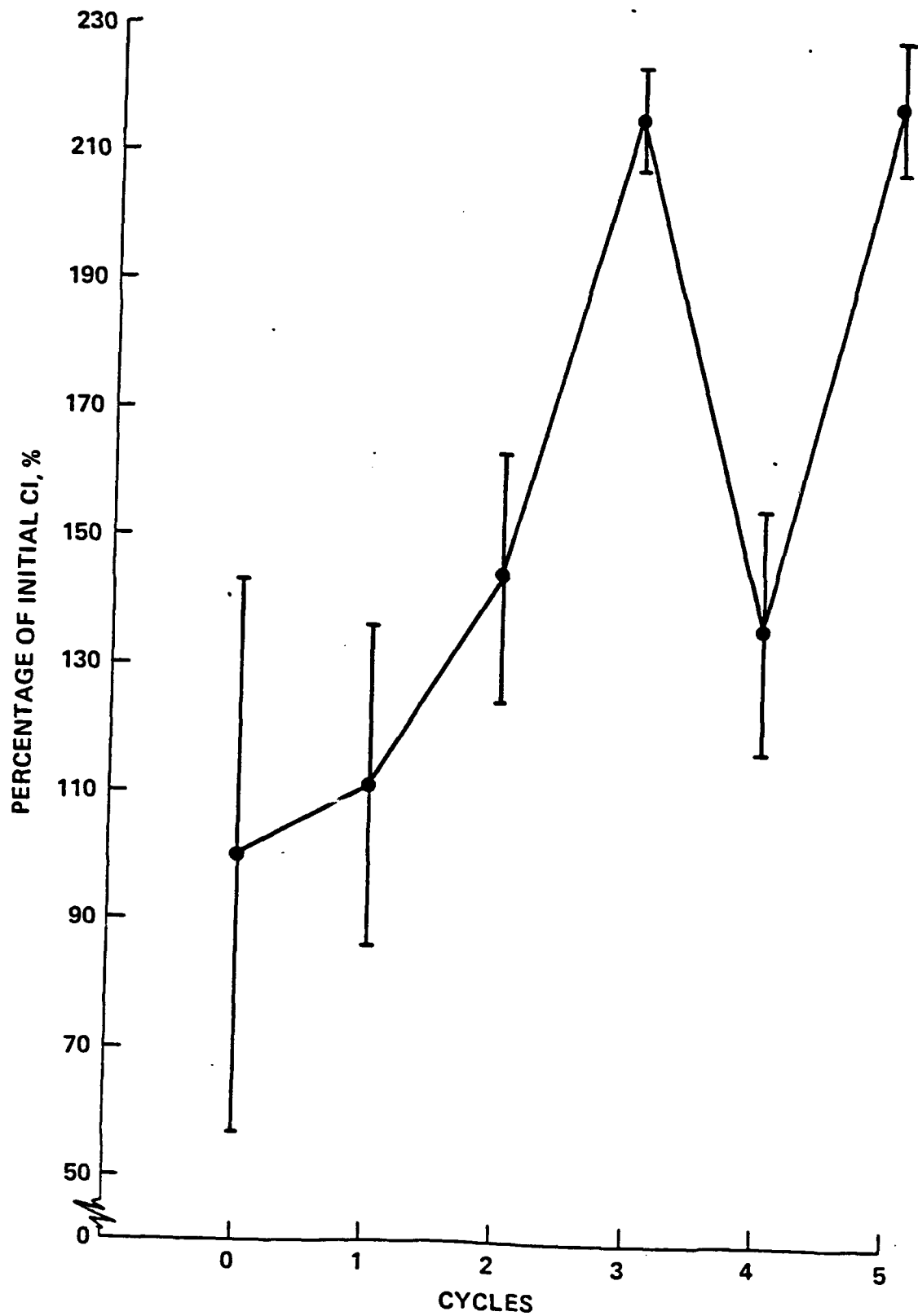


Figure 14. CI versus wet/dry cycling, Process 200

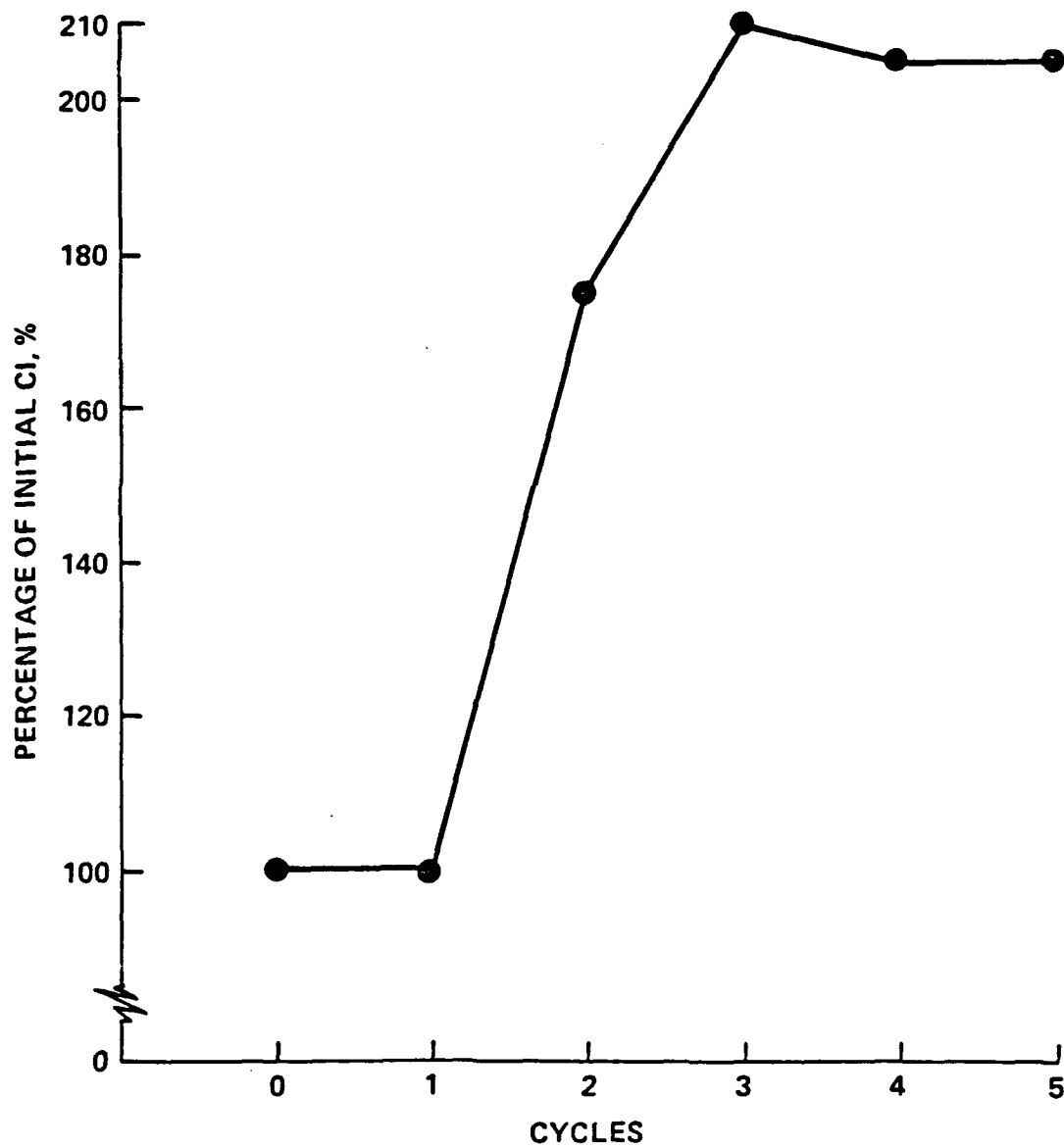


Figure 15. CI versus wet/dry cycling, Process 300

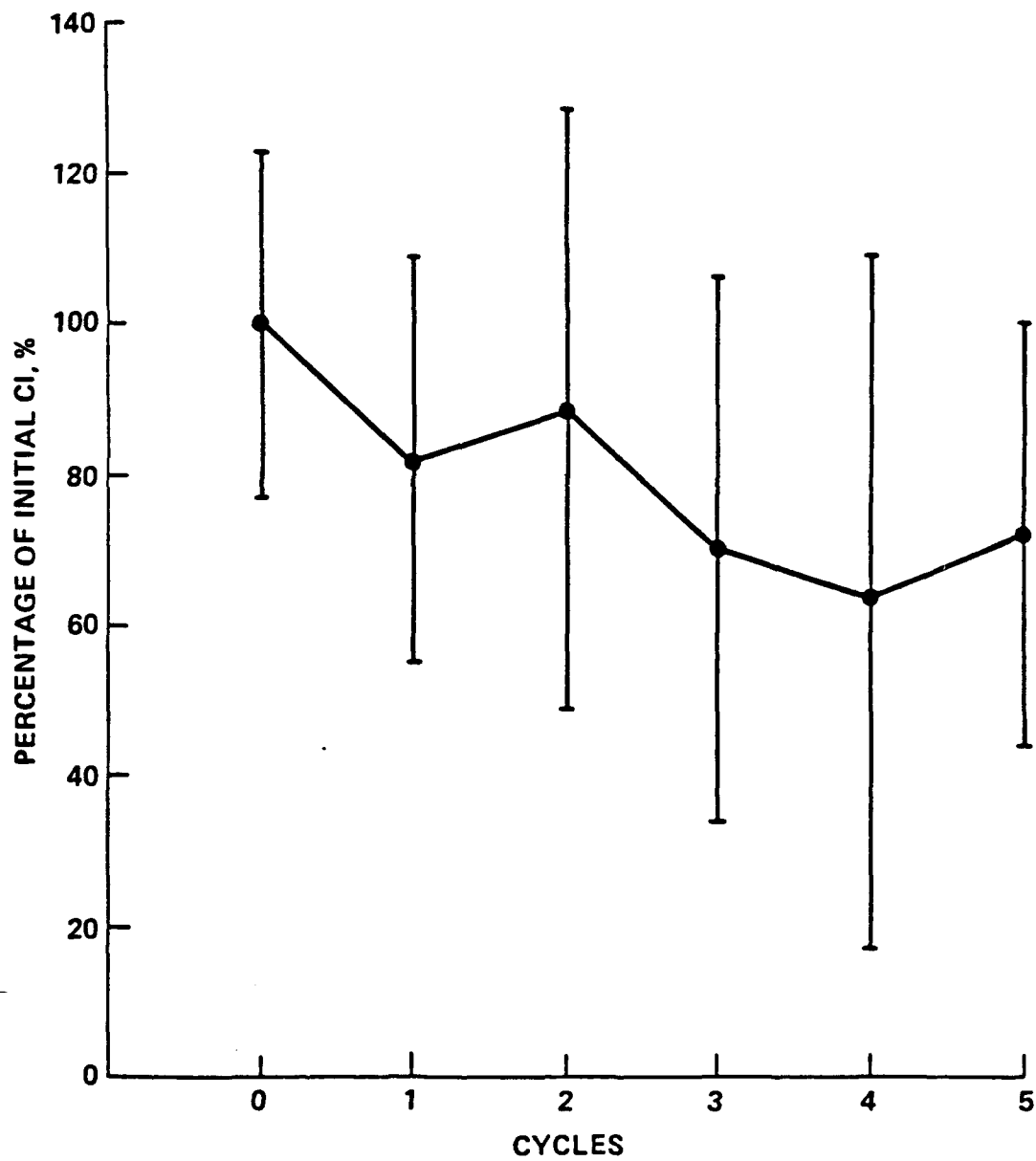


Figure 16. CI versus wet/dry cycling, Process 302

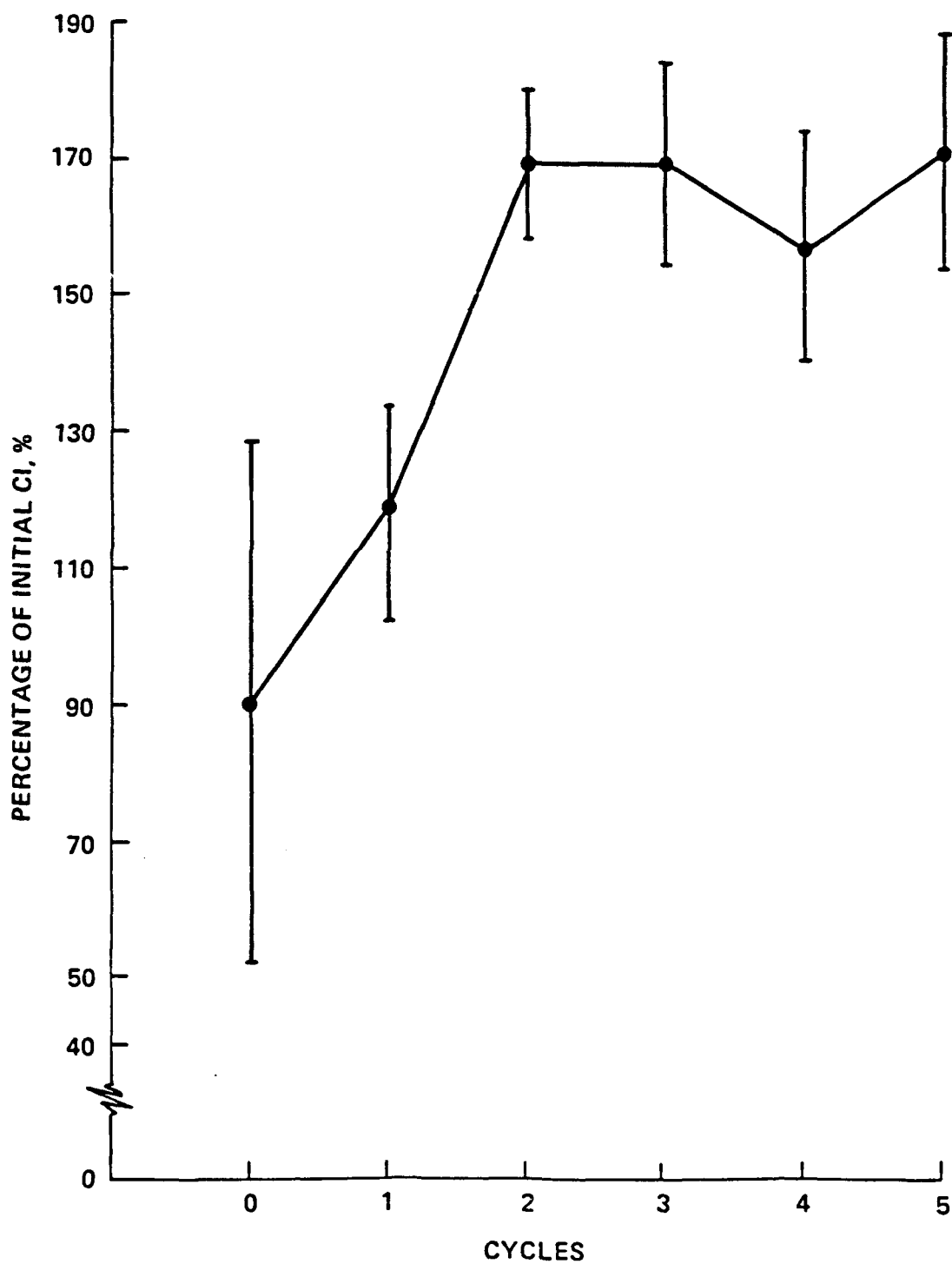


Figure 17. CI versus wet/dry cycling, Process 400

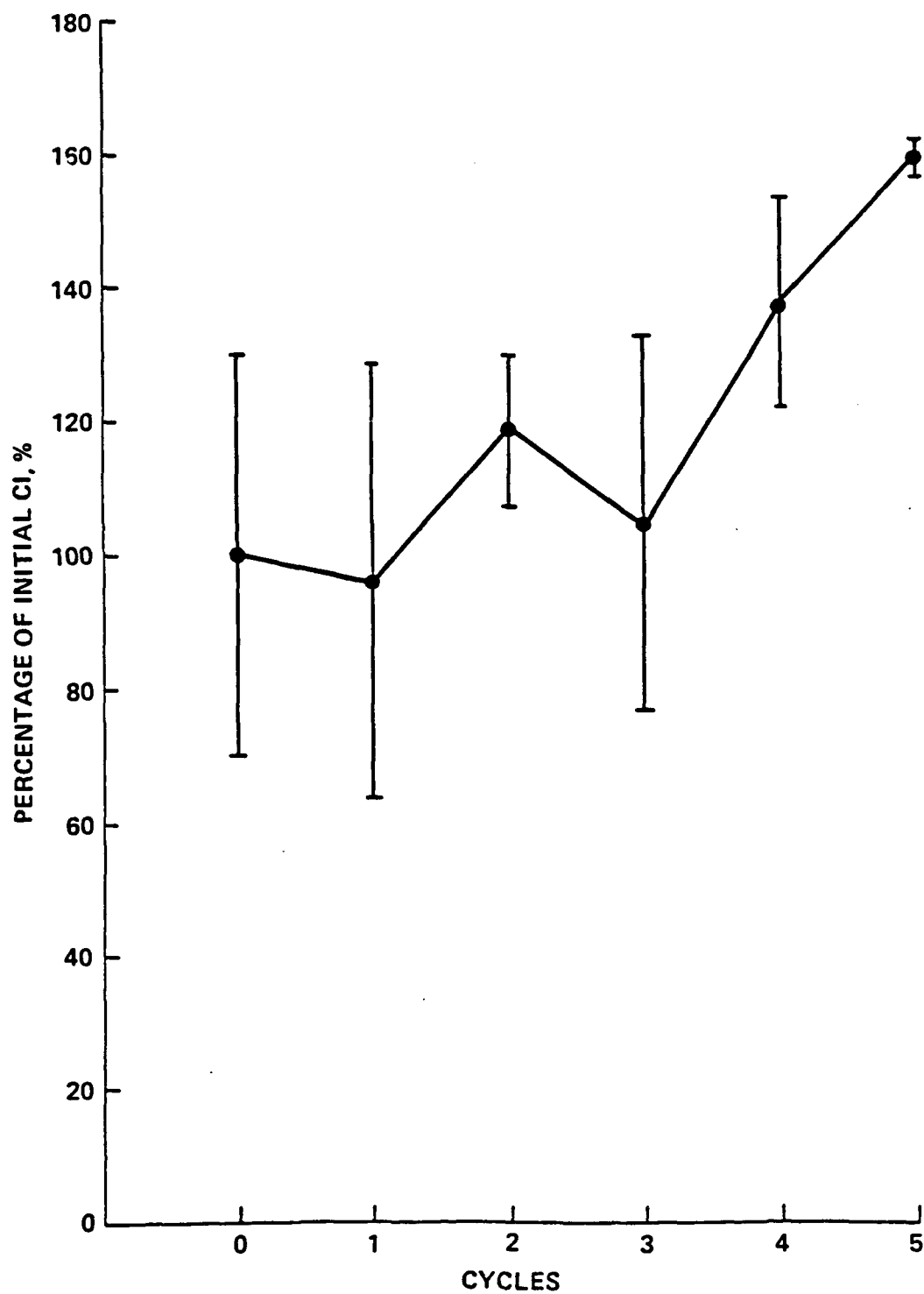


Figure 18. CI versus wet/dry cycling, Process 500

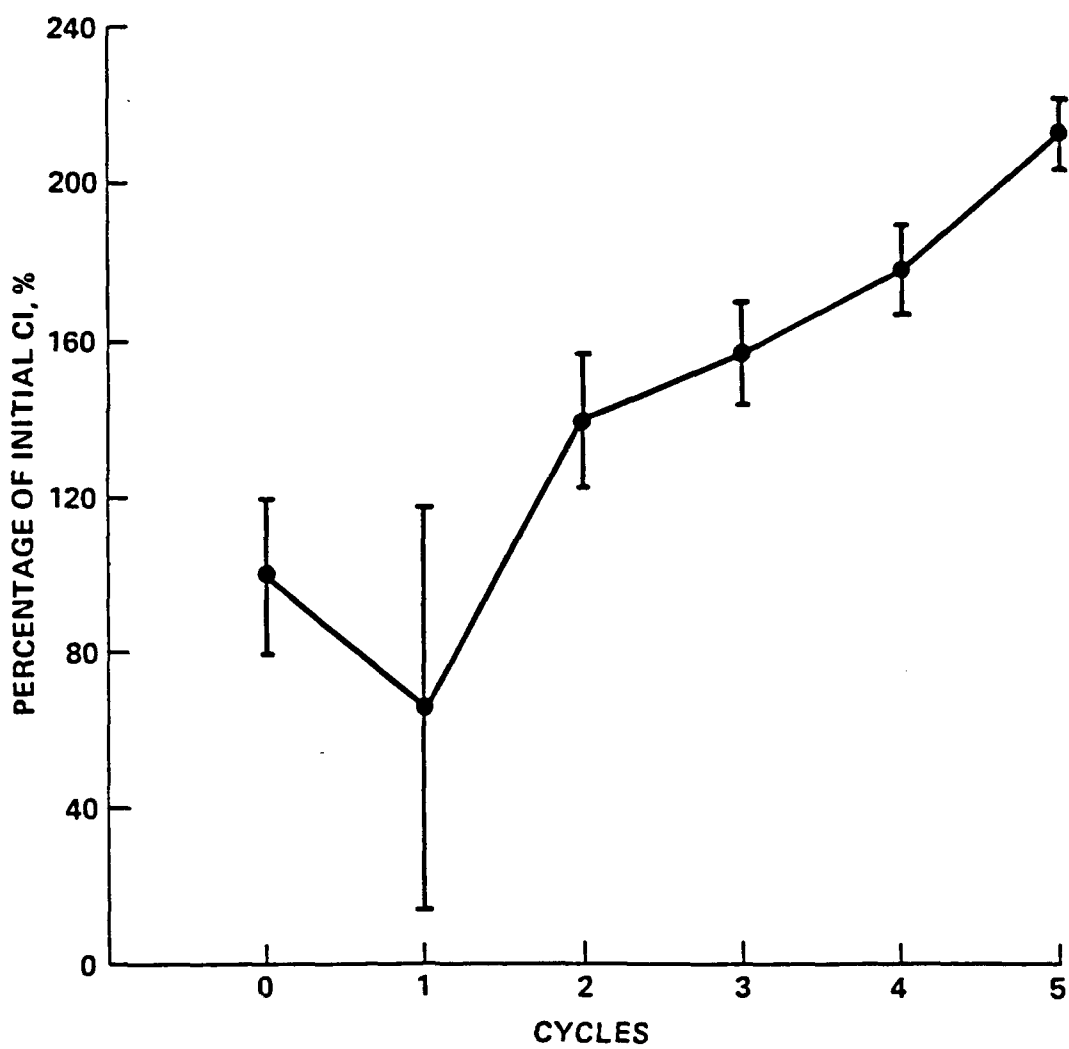


Figure 19. CI versus wet/dry cycling, Process 600

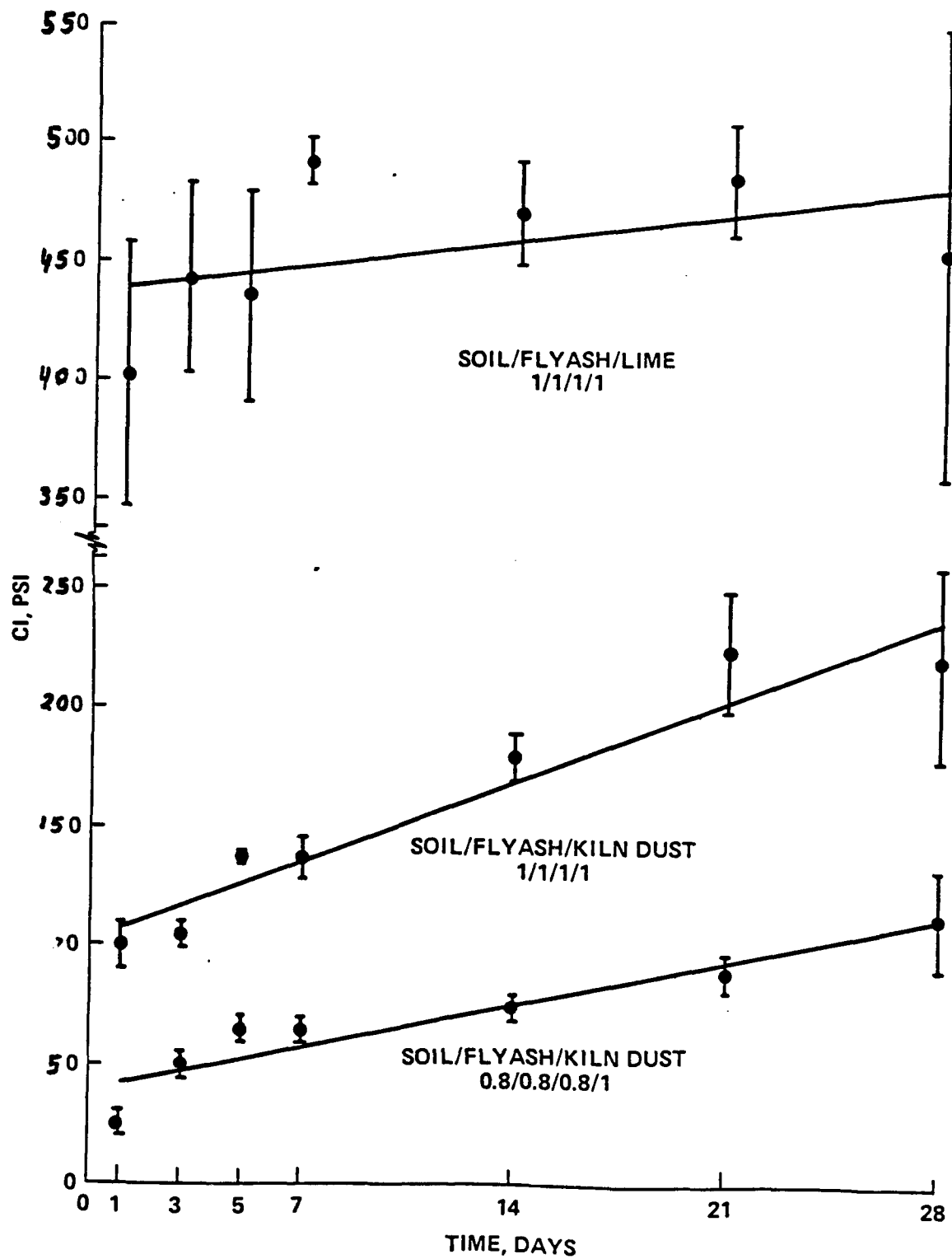
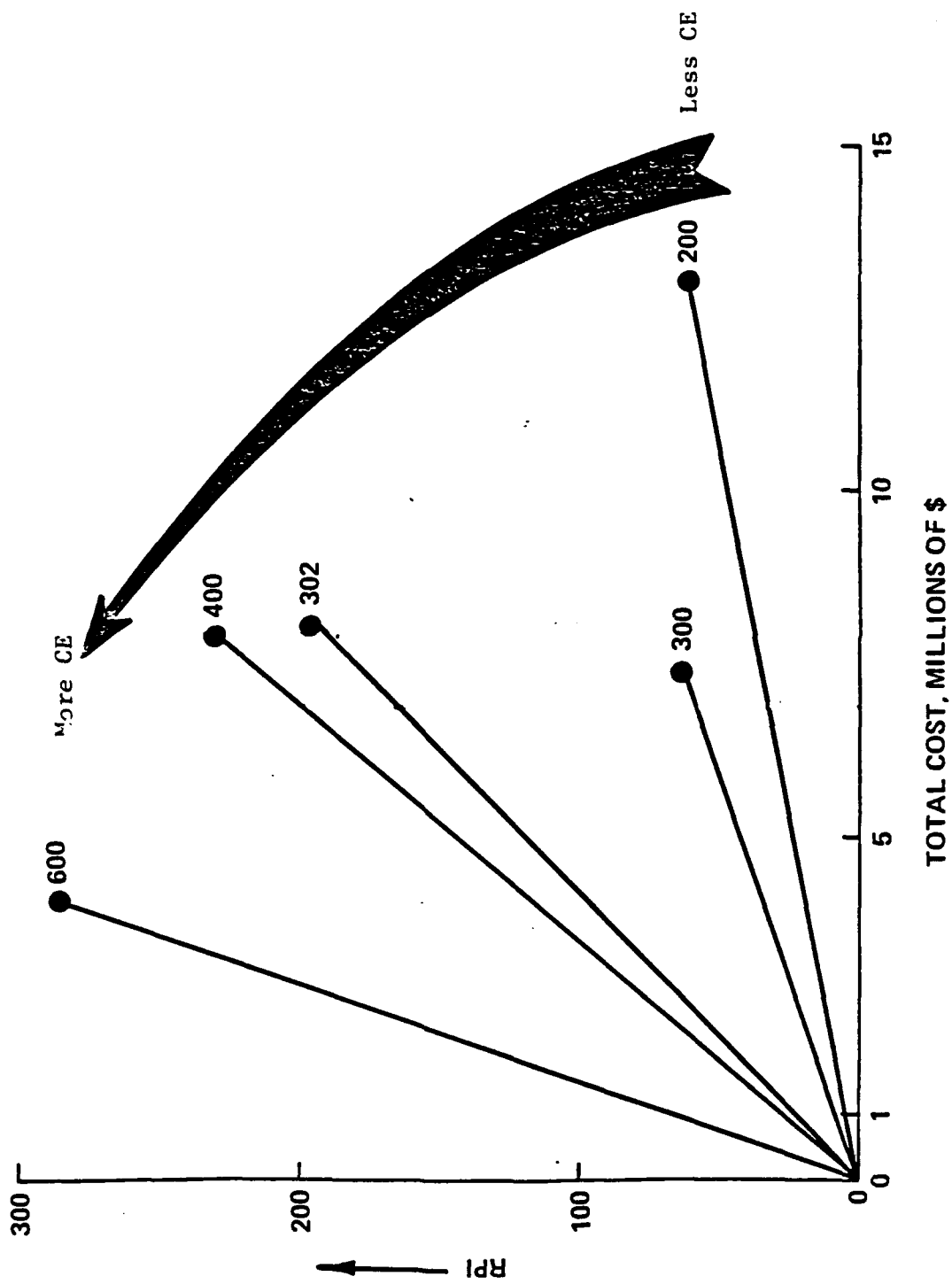


Figure 20. Comparative CI versus time curves for three process formulations



CE: COST EFFECTIVE

Figure 21. Scattergram for selecting optimum process