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SYSTEMS AND MATERIALS TO PREVENT FLOODWATERS FROM ENTERING BUILDINGS

by

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Systems were tested that will protect homes and buildings from floodwaters up to a safe water height. There are many pitfalls which must be watched for and guarded against or leaks will develop in the flood-resistant system. A drainage system with a sump and pump is useful behind the water-resistant system to take care of any leaks which may occur.

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20. ABSTRACT (Continued).

An unreinforced brick-veneer or concrete-block building will support approximately 3 ft of water load without being damaged. A cementitious coating on a brick or block wall surface will strengthen the wall. Buildings must not be made resistant to water penetration above a safe design height or the building may be structurally damaged or collapsed.

Clear sealants do not make brick-veneer or block walls impermeable to a water head. Epoxies, polyurethanes, and asphalt coatings that were tested were not reliable in preventing water from penetrating a brick-veneer or block wall. Some cementitious coatings will make a brick-veneer or block wall impermeable against a water head. Cementitious coatings which can be brushed on walls are preferred.

A prototype test of a home was performed in Allenville, Arizona. Only 1 in. of water entered the house with a 4-ft head outside. The test did not involve underseepage and only tested a snap connection at the base of the building. The 4-ft water head structurally damaged the block wall house.

A prototype test performed on a home in Tulsa, Oklahoma, included the effects of underseepage and other factors associated with static water pressure. Only limited seepage occurred at exterior walls, and the cause of this seepage was determined and can be corrected. This test was a success, and it is now known that homes and buildings can be protected from approximately 3-ft-deep floodwaters without structural damage.

A snap seal at the base of a building with an impermeable membrane extending up the wall has been tested with partial success. These tests should be continued and completed. Promising materials and techniques for sealing block and brick walls should be tested for permeability and durability. Simple methods using on-site data should be developed to estimate underseepage. Uplift by the flow of water through various soils to the base of a building should be studied and defined. Drainage and sump systems should be studied and a simple, economical, and workable system found and presented in a homeowners's manual.

A loose-leaf homeowner's manual which can be continually updated should be written and published to present flood-resistant construction options and other pertinent information to the public.

An organized effort should be made among the public, contractors, material developers, and researchers so that the improvements in flood-resistant construction can be developed as quickly and efficiently as possible. Water-resistant protection systems can significantly reduce flood damages and save millions of dollars.

PREFACE

This investigation was performed in the Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES) for the US Army Engineer Division, Lower Mississippi Valley (LMVD).

The report was prepared by Dr. Carl E. Pace of the Research Group, Concrete Technology Division (CTD). The contract was monitored by Mr. Lawrence N. Flanagan of the LMVD. Mr. Flanagan worked closely with the project and was helpful in planning and coordinating the study.

The study was conducted under the general supervision of Messrs. Bryant Mather, Chief, SL; W. J. Flathau, formerly Assistant Chief, SL; James T. Ballard, present Assistant Chief, SL; and J. M. Scanlon, Chief, CTD, SL.

Commanders and Directors during the preparation and publication of this report were COL Tilford C. Creel, CE, and COL Robert C. Lee, CE. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
inches	0.0254	metres
feet	0.3048	metres
pounds (mass)	0.45359237	kilograms
pounds (force)	4.448222	newtons
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	6894.757	pascals
feet per second	0.3048	metres per second
gallons	3.785	litres

SYSTEMS AND MATERIALS TO PREVENT FLOODWATERS FROM ENTERING BUILDINGS

PART I: INTRODUCTION

Background

1\. Despite the construction of flood-control projects and the development of public programs to reduce flood losses, flood damage to homes and other buildings in the United States has increased dramatically. The growing exposure of structures to flooding is largely due to rising land costs and a reduction in the quantity of available land for building, producing an encroachment of building on floodplains.

2\. Flooding is not only expensive to the homeowner and the taxpayer, but also causes its victims despair and worry. To reduce the costs and hardships associated with flood damage to buildings, the Government should move rapidly to:

- a. Develop the expertise to advise homeowners and other property owners about flood-protection systems.
- b. Transfer technology for making homes and buildings resistant to floodwaters.

3\. Many US Army Engineer District offices are responsible for answering inquiries about flood protection and in many cases have responsibilities for protecting homes and buildings in areas subject to flooding. In correspondence with District offices, and others, the author has found widespread interest in, and a need for, materials and methods to protect homes and buildings from penetration by rain and floodwaters. Reduction of flood damage to homes and other buildings is desirable and should be part of a comprehensive flood-control plan.

4\. Because homeowners and the public have not had ready access to expert guidance for protecting their homes from floods, many individual and contractor attempts at flood protection have been inadequate. Contractors are now installing systems on homes to prevent damage due to floodwaters. This is a positive and very helpful service, but the Government needs to make faster advancements in flood-protection technology where private companies do not have the expertise or test facilities. This technology should then be transferred to other Government agencies and to the private sector. The Corps of Engineers needs to have expert advice for the homeowner because they are usually exasperated (especially after experiencing repeated flood losses) and are willing to attempt almost anything to protect their homes. They need an independent and nonpartial source of information to help them become knowledgeable about flood-protection systems.

5. Materials and methods for preventing the flow of water into homes should not be selected only on the basis of being logical systems which perform satisfactorily, but should be tested and used only after proven performance. A well-coordinated effort between the Districts, Divisions, and the research laboratory should be obtained through planning and technology transfer. Independent and piecemeal solutions are too expensive and time-consuming.

6. The tests and results described in this report are an effort to learn about materials and systems to protect houses from floods so the homeowner can benefit from the conclusions of the studies and better help himself prevent flood damages.

Purpose and Scope

7. This report presents the results of studies of methods and materials to protect homes and other buildings from flood damage. Studies are described that were conducted to (a) determine block-wall integrity, (b) test various sealing materials, (c) test protective systems installed on prototype dwellings, and (d) evaluate various systems currently being using to prevent flood damage to homes and buildings.

8. This study does not attempt to develop detailed solutions to the total problem of protecting homes from flooding. The author presents pertinent findings obtained during laboratory and prototype tests that should be useful to homeowners and contractors attempting to make buildings resistant to floodwaters.

PART II: BLOCK-WALL TESTS

Introduction

9. Houses or buildings should not be made resistant to the penetration of floodwaters above a safe water height; i.e., it is better to allow water to enter a building than subject it to a water load that will structurally damage or collapse the walls. After the floodwaters recede, the building may be reusable once it has been cleaned and the water damages repaired. Thus, before an attempt is made to make buildings in an area flood resistant, the flood risk must be carefully evaluated, and a flood-resistant design level established for various types of building construction. Conversely, houses or buildings which will experience floodwaters only to a height below that which would cause structural damage or collapse should be protected by materials or systems to prevent penetration of the floodwaters.

10. A previous study* conducted to evaluate the structural integrity of brick-veneer walls subjected to floodwaters demonstrated that, in general, brick-veneer test walls could safely withstand the load applied by a water height of approximately 2 ft.** However, with approximately 2.5 ft of water height, the brick-veneer test wall experienced structural damage. Prototype tests performed later demonstrated that the walls of a house are stronger than the test walls and can withstand about 3 ft of water head. Another study was also conducted to determine materials or systems that could be used to prevent floodwaters from penetrating the walls of a brick-veneer building.†

Objective

11. Since many homes and buildings are constructed of concrete block, it was decided that two concrete block test walls should be constructed and

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* C. E. Pace and R. L. Campbell. 1978. "Structural Integrity of Brick-Veneer Buildings," Technical Report C-78-3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

** A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

† C. E. Pace. 1978. "Tests of Brick-Veneer Walls and Closures for Resistance to Floodwaters," Miscellaneous Paper C-78-16, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

tested to determine their structural integrity and to evaluate some of the more promising materials and systems for preventing the penetration of floodwaters through such walls.

12. Various materials were to be troweled over the surface of one wall and the wall was to be tested to determine if the material made the wall resistant to water penetration and/or added structural integrity. Several systems for making a block wall resistant to water penetration were to be tested on another wall to determine their effectiveness.

Block-Wall Construction and Gage Locations

13. The plan and section for the two block walls used in the testing are as presented in Figure 1. The walls were constructed as block walls are normally constructed for homes or buildings.

14. Deflection gages (LVDT's) were installed against each of the two block walls to measure the deflected shape of the walls (Figure 2). An independent bracing system was constructed at the back of the wall to support the LVDT gages.

15. The first block wall before and after testing is shown in Figure 3. The front of the first wall was plastered, and a bulkhead was constructed in front of it to contain water to be supplied from a fire hydrant. The second block wall is shown in Figure 4. The second block wall was used to test several flood-resistant systems.

Block Wall 1

Experimental tests

16. An automatic data recording system (Figure 5) was used to record the response of the LVDT gages. The trough was slowly filled with water producing a water head on the block wall. Typical deflection data for block wall 1 are presented in Figures 6-8. As the water level was raised against the surfaced wall, the plaster was weakened and was penetrated by the water reducing its effectiveness in strengthening the wall against deflection. At a water depth of 3-1/2 ft the block wall was cracked and leaking so badly that the trough could not be kept filled with water from a fire hose connected to

the fire hydrant. Water flowed through the cracks faster than it could be put into the trough. Photographs of the leakage are shown in Figure 9.

Results

17. This test demonstrated that a plastered block wall will resist a higher head of water than the unplastered wall. This capability can be seen from a comparison of the test results from block wall 1 (Figures 6-8) with those from the tests of block wall 2 (Figures 10-18). The surfacing used on block wall 1 allowed it to resist a water head of between 3 and 3-1/2 ft. The particular surfacing material used in the test was inadequate for strengthening the block wall because it weakened, leaked, and began disintegrating before the trough was filled. A stronger surfacing of water-resistant material, such as coating 5 described in Table 1, will allow the block wall to withstand a water head of at least 3-1/2 ft of water. This test also demonstrated that the maximum deflection that will damage a block wall is very small.

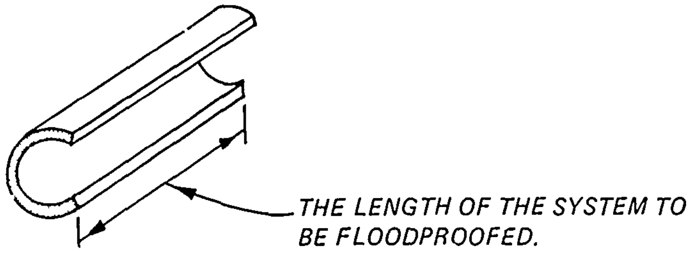
Block Wall 2

Experimental tests

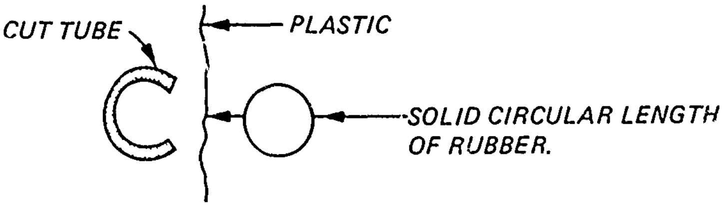
18. The first test performed on block wall 2 was to partially fill (approximately 1-1/2 ft) the trough to determine the leakage through the block wall (not treated or protected in any way). The leakage through the wall was severe and the test was stopped.

19. The second test evaluated vinyl sheeting attached with a tubular seal and also determined the deflected shape of the wall. The third test on block wall 2 was to again test the effectiveness of the tubular seal. The tubular seal (Figure 19) was constructed as follows:

a. About one-third of the tube was cut away. The tube was epoxied to the footing with the cut surface turned to the outside:



b. A solid circular length of rubber (an O-ring) was placed against the plastic and snapped into the cut tube, making a seal at the base of the building.



20. Deflection data for wall 2 are presented in Figures 10-18. It can be seen from these data that the safe water head on the block wall is approximately 2 ft, the same as that for the brick-veneer wall.

21. The tubular seal was judged to be inadequate since leaks occurred in tests 2 and 3. The reasons for this inadequacy were:

a. Even though the solid circular rubber O-ring component fit tightly into the cut tube, if started, it easily came out, failing the seal.

b. The cut tube became more flexible as it was used causing a greater possibility of the solid rubber cylinder pulling loose.

c. The solid O-ring was difficult to turn around 90° bends. The solid rubber cylinder had to be cut at 45° and fit together at the 90° bends. This left a small space at the intersection of the 45° cuts which had to be sealed.

22. An aluminum seal (Figure 20) was used in test 4. There was some leakage with the aluminum seal, and there was some difficulty in fitting the rubber O-ring against the plastic and into the L-shaped aluminum extrusion. The O-ring could be fitted into the aluminum extrusion, but the process was slow.

Results

23. In Figures 10-18, it can be seen that the safe water head on a block wall is approximately the same as that for a brick-veneer test wall; i.e., approximately 2 ft. By comparison, a house has more wall support and can withstand about 3 ft of water head. The tubular seal was inadequate; however, the aluminum L-shaped seal may be satisfactory if a faster method for snapping the seal can be developed.

PART III: SEALING MATERIALS

Introduction

24. Materials and systems which may be used to make homes and buildings more resistant to the penetration of floodwaters should be included in a homeowner's manual. Homeowners should be provided as many options as possible for making a house or building resistant to the penetration of floodwaters. A manual would permit the owner of a home or building to consider various methods and materials which have been proven to be satisfactory and to select a system which best meets his needs.

25. In many cases it is desirable to have a coating which will make a wall relatively impermeable to a head of water; therefore, it was decided to test available materials and determine their effectiveness. The materials were tested to determine if they made brick-veneer walls relatively impermeable to a water head and to determine their durability under environmental conditions over several years.

Test Specimens

26. Test walls were needed for the application of the coatings and to build prototype walls and bulkheads in order to test the coatings would have been very expensive. Brick cubes open at the top would be economical and expedient specimens on which to test the coatings. Therefore, eight 2- by 2- by 2-ft cubes and one 4- by 4- by 4-ft cube (Figure 21) were built for testing the coatings.

27. The cubes were used to test the coatings in several ways. Coatings were put on either the inside or outside of the cubes which were then filled with water to test the effectiveness of the coating against a direct or reverse water head. The larger cube was used to test materials and systems by placing water on the inside of the cube and also by building a bulkhead on the outside to have a water head acting from the outside inward.

Materials Test Results

28. A thorough search was made for coatings which manufacturers claimed could be used to seal a wall against a head of water.

Clear coatings

29. It was desirable to find a clear coating which would make a wall resistant to water penetration. Six proprietary coatings (Table 1) were found and tested. Three of the clear coatings will be discussed in this section, and the epoxy and polyurethane coatings will be discussed later. Each of coatings 1, 2, and 3 could be brushed or sprayed on the wall, and both techniques were used with each coating. The clear coatings depended on their ability to coat and penetrate the wall as they were applied by spray or brush. Penetration of the coatings was uncertain on a vertical wall, even when the wall was soaked and excess coatings allowed to run down the wall. All of the cubes with the clear coatings leaked when filled with water. The coated walls did not leak as much as an untreated wall, but did leak excessively. The clear coatings were very effective at beading and repelling rainwater, but they did not keep the cube from leaking even against a small head of water. In general, the results of the clear-coating tests were unsatisfactory.

Cementitious coatings

30. Six cementitious coatings (coatings 4-9) were obtained for testing. Five of these were proprietary products, and one was a formulation made by the author at the Waterways Experiment Station (WES). There are many cementitious coatings which would probably make brick-veneer walls resistant to water penetration; however, the above coatings were the ones initially found for testing. In no way is their use to be construed as indicating a preference for these coatings over others which were not tested. The cementitious coatings developed a good bond with the brick-veneer wall. In general, the cementitious material made the walls relatively impermeable to a water head for heights which are of interest in making homes resistant to floodwaters. Some were more successful than others.

Applications

31. There were two procedures by which the various materials could be applied to the surface of a brick-veneer wall. One of the six coatings had to be trowelled on the wall, while the others could be mixed to the consistency of paint and brushed on the wall. Trowelling on the coating was

time-consuming and thus increased the expense. It is highly desirable to use a material which can be brushed on the wall. The trowelled-on coating (coating 4) sealed the cube against a water head with only a small leak mainly at the cube-foundation interface (Figure 22). Coating 4 was not successful in terms of durability. It expanded, cracked, and began to come off the wall 3 months after it was applied (Figure 23).

32. Three years after application of the brush-on coatings, coatings 6 and 7 showed some cracking. Coating 7 lost its bond to the brick surface and peeled off in various places. After 4 years of service, coatings 5 and 8 showed no signs of cracking or loss of bond.

Mechanism of causing impermeability

33. One type of material (coatings 4, 5, and 7) was so impermeable that it kept water completely away from the wall. The other type of material (coatings 6 and 8) contained some agents which seeped into the voids of the mortar joints and reacted with the cement causing expansion and a filling of the spaces. One cementitious coating of each type (coatings 5 and 8) was found to be successful after 4 years in the climate at Vicksburg, Mississippi.

34. Material 5 (Figure 24) was a coating with excellent impermeability and bond characteristics. The darker material in this photo is coating 5. Pigment can be used to make the cementitious coating the desired color. For the maximum head of water tested (4 ft), coating 5 sealed the brick wall from both the positive and negative sides of the wall. This coating was less expensive than the proprietary products and would be excellent where a surface coating is required.

35. Coating 8 was as successful as coating 5 and also sealed the brick-veneer wall against 4 ft of water head from the negative and positive sides of the wall. Coating 8 seeped into the pore spaces of the mortar joints; it was observed to penetrate the joint and collect as a film on the opposite side of the wall. Initially, the brick-veneer wall leaked a small amount, but as the material seeped into the pore space, the leakage stopped.

36. The other three coatings initially caused the brick-veneer walls to be impermeable to water when applied to either the positive or negative side of the wall, but they were not durable and failed with the passage of time.

Epoxy coatings

37. Two epoxy coatings (coatings 9 and 10) were used to seal the brick-veneer walls. One epoxy coating was 100 percent solids. In each case, the wall with the epoxy coatings leaked excessively.

Polyurethane coatings

38. Polyurethane coatings were not effective in keeping the wall from leaking. If moisture collected between the polyurethane and the wall, the coating turned a milky color. After about a year of exposure to the elements, the polyurethane coating began to crack and peel off the wall.

Asphalt coatings

39. Asphalt coatings were not effective unless excellent workmanship was used and even then there were possibilities of leakage. An asphalt coating is adequate if an impermeable barrier such as roofing felt or sheet polyethylene is embedded in the coating. Good workmanship and correct application techniques must be used even when the impermeable barrier is used, or leaks may develop.

PART IV: PROTOTYPE HOUSE TEST, ALLENVILLE, ARIZONA

Background

40. Since tests had been performed to determine the structural integrity of brick and block walls and since materials and systems had been tested for effectiveness in keeping floodwaters out of houses, the next step was to test the best waterproofing system on a prototype house. The Corps of Engineers' Los Angeles District was involved in relocating a previously flooded subdivision in Allenville, Arizona, a few miles west of Phoenix, Arizona. All of the houses in the subdivision were vacated, and the homeowners were being relocated to another site. This situation presented a prime opportunity to select a suitable house on which to test flood-resistant systems.

41. The Los Angeles District was very helpful in acquiring the best available house and in helping with the test setup. Representatives of WES, the Lower Mississippi Valley Division (LMVD), and the Los Angeles District met at Allenville and finished test setup preparations and tested the house.

42. The objective of the prototype test was to (a) determine the practicality of using vinyl sheeting mechanically attached to the house slab, as a flood-resistant system, and (b) substantiate earlier tests which determined acceptable design levels for such systems. Water penetration and uplift under the house, sewer closure systems, etc., were not studied in this test.

Test Setup

House

43. The floor plan of the house is presented in Figure 25. The garage of the house (Figure 26) was not included in the testing. A plywood bulkhead was constructed across the garage along the side of the house, as shown in Figure 27. An earth berm was constructed around the rest of the house and tied into the plywood bulkhead (Figure 28). The earth berm and plywood bulkhead were used to retain a slowly increased water level. A plastic sheet was placed over the earth embankment and plywood bulkhead and extended downward and under an aluminum channel (Figures 20 and 29) which was to act as a bottom seal for the flood-resistant system (Figure 30). The aluminum channel was attached to the house with screws and plastic inserts. The rest of the

floodproofing system consisted of a reinforced plastic sheeting which had its top reinforced with gray duct tape and secured to hooks which had been placed in the outside wall every 2 ft (Figure 31). A properly sized O-ring was then pushed against the bottom of the reinforced plastic sheeting and into the aluminum channel. The O-ring was fitted against the reinforced plastic and into the aluminum to make a water-resistant seal (Figure 20). The total flood-resistant system consisted of this aluminum channel, plastic sheeting, and the O-ring insert around the base of the entire area of the house. Plywood reinforcement was used over door and window openings.

44. General problems were encountered while constructing this system on the house:

a. It was difficult to find a material to bond plastic to plastic. A waterproof construction cement was used to bond plastic to plastic at places where plastic was lapped.

b. Seating the O-ring into the aluminum channel was very difficult. Because of this difficulty, installation was time-consuming.

Gage system

45. Gages were placed on the walls inside the house to measure the wall deflection. The gage locations and numbering are shown in Table 2. Figure 32 shows some typical photographs of the gage placements. The wires from the gages were run cut windows to an automatic data recording system which was located in a van.

Test Results

46. The deflections of the walls were recorded during both the loading and unloading of the house. These data are presented in Figures 33-47.

47. Water was obtained from a well and pumped to the test site (Figure 48). The water level was raised slowly on the outside of the house. As the water level increased, some seepage did occur inside the house. About 1 in. of water leaked into the house during the test in which 4 ft of water flooded the outside.

48. The results demonstrated that house walls are stronger than individual test walls and that a prototype house can withstand approximately 3 ft of water head without damage.

49. The walls of the house were damaged by a 4-ft water head. This damage is indicated by the test data in Figures 33-47. The unloading curves show permanent deformation in the walls. An inspection the next morning after the water load had been removed revealed that the brick wall had visual cracks in the mortar joints.

50. Plastic was placed over the earth berm and under the aluminum strip to prevent water loss through the highly pervious soil during the test. Some of the leakage problems occurred because of this installation. It was discovered that a weatherstripping material did not stick to the plastic where it was placed at the intersection of the plastic and aluminum strip. However, it should be noted that the plastic under the aluminum strip would not be present in an actual flood-resistant construction.

Conclusions

51. A block or brick-veneer house will not support more than about 3 ft of water without damage. The system was considered valid; however, the sealing snap used in the test is not recommended because of the difficulty in attaching the sheeting.

PART V: SYSTEMS TESTS ON A BRICK CUBE

Background

52. The structural integrity tests of brick and block walls indicated that house walls will not withstand more than about 3 ft of water without structural damage, particularly if subjected to flowing water and debris loading. This result provided a baseline for systems tests to determine methods which would keep shallow-depth floodwaters out of houses and buildings.

53. Houses and other buildings can be strengthened in various ways; however, systems tests were performed for normally constructed homes in which the walls had not been strengthened. The systems tested would be used primarily for protecting homes in high-risk, shallow-depth, flood-prone areas.

54. Systems tests which were performed using the block wall and the walls of the test house at Allenville, Arizona, indicated that details are critically important. In particular, a better sealing strip must be obtained which will permit expedient and effective sealing against the passage of floodwaters.

55. The systems tests on the brick cube had several advantages:

- a. Tests would be less costly and time-consuming.
- b. The four corners of the cube would allow adequate testing of seal strips at corners.
- c. Outside and inside corners could be tested.
- d. Sealing of vertical seams in the waterproof membrane could be tested.
- e. Systems set up on the inside of the cube could not require a bulkhead to retain the water head.

Test Setup

Inside corners

56. The system which was tested was an expedient sealing snap at the base of the wall and a plastic sheet which would be pulled up the wall to the desired height of protection. As mentioned above, a better seal strip should be obtained. Commercial extrusions which could be used as a seal strip were

difficult to locate; therefore, a seal strip was designed and a manufacturer paid to extrude it (Figure 49).

57. Five tests were made with the system using the specially designed seal strip. Photos of the tests are shown in Figures 50 and 51. It was found that care must be taken in attaching the permanent part of the seal strip to the house. If any adhesive material adheres and stays in the snap area, it will hold the expedient snap open and allow water to enter behind the plastic.

58. It was thought that the corners (Figures 50 and 51) could be easily sealed. The one small place where there was a possibility of water entry was at the corner where the snap comes together. This was to be sealed by placing silicone caulk under the snap and at the intersection of the plastic and snap on the under side of the plastic. This solution seemed entirely logical, but in practice it turned out to be extremely difficult to keep the corners from leaking.

59. As the plastic sheet was pulled along the walls and around the corners, it was difficult to keep it from wrinkling. The vertical sections tended to pull crooked and wrinkle. Any wrinkles in the plastic under the expedient snaps would allow water to enter to the side of the wrinkles and make the system ineffective.

60. In general, the system can be made to work; however, careful attention must be paid to details or the system will leak. Because there is a possibility of leaks with any flood-resistant system, a sump and pump should be used in case there is a leak. A drainage system can be constructed inside the perimeter of the system which leads to a sump and pump. The pump can remove any water which might leak through the system. The drainage system and sump can also collect and remove any seepage water before it gets into and damages any of the house.

61. After several failures, this system was finally successfully tested.

Outside corners

62. A bulkhead was constructed to hold water for four tests performed on the outside of the cube. The same problems were encountered in working with the system as described above, although the outside corners were easier to work with and the plastic was not as easily wrinkled.

63. A second seal strip was found and tested (Figure 52). Again, there were leaks at the corners, and even though the system allowed very little leakage, all four tests leaked. The leakage could have been handled by a pumping system. Dye (a very effective indicator) was used (Figure 53) to determine where the leaks occurred, and it was determined that the corners were the weak part of the system. It appears that a better way to manage the corners of the system would be through fabrication of a one-piece molded corner strip.

Test Results

64. The snap-type flood-resistant system can be effective in keeping floodwaters from entering a house or building if great care is taken in its installation. To ensure a watertight system, a back-up drainage system with a sump and a pump should be used to collect any water which may get behind the vinyl sheeting. The two seal strips tested are shown in Figures 49 and 52. Leaks can develop in the snap-type waterproofing system if irregularities on the snap hold it open, if the plastic is wrinkled under the snap, or if the corners are not handled with care. Many minor details, depending on the particular situation, must be cared for adequately or leaks can develop.

PART VI: PROTOTYPE TEST, TULSA, OKLAHOMA

Introduction

65. Since the structural integrity of brick-veneer and block-wall buildings and the effectiveness of closures, sealants, and snap connections had been established, tests were planned for prototype houses of flood-resistant systems to protect a home or a building from floodwaters. Previous tests had not included the effects of underseepage; therefore, this factor was included in the tests along with other factors associated with static water pressure.

66. A request for contractor interest was published in the *Commerce Business Daily* on 6 February 1984, and one contractor responded. This test was conceived with the knowledge that contractors are developing systems and are experimenting with materials which, when properly applied, can keep floodwaters out of homes and buildings. The test was, in effect, a demonstration project that provided commercial flood-resistant construction contractors an opportunity to test their products in a controlled environment. The contractor was responsible for the installation of his system, and the Tulsa District coordinated the work, built a dike around the house, and supplied the water for testing the system. Personnel from WES inspected the test setup, observed and documented the test, and reported the results. LMVD provided the overall supervision of the project.

Objective and Scope

67. The objective of the test was to work with contractors to test a prototype house (Figure 54) under realistic flood conditions.

Experimental Test

Introduction

68. Private concerns were invited to participate in the testing of the prototype house because a few contractors have shown a great interest in protecting homes and buildings from floods and are beginning to perform these tasks on a continuing basis. The Corps of Engineers recognizes the expertise

and practical skills which will be developed by the private concerns and intends to work with them, as well as with home and building owners, to develop the most practical and economical method to protect homes and buildings from floodwaters.

Test setup

69. The contractor had a simple, but logical, protective system composed of a fabric (Figure 55) (vinyl-coated nylon with special fungus inhibitors) embedded to some depth in the ground (Figure 56, schematic of embedded system) next to the house to reduce underseepage by creating a longer seepage path. The fabric was extended out of the ground and up the side of the house (Figure 55) to form a continuous water-resistant barrier. A trough-like container at ground level (Figure 57) was used to store the fabric. The permanent storage system for the fabric was very efficient because the lid to the container could be opened (Figure 58) and the fabric rapidly pulled up on the house and connected to permanently installed snaps (Figure 59). A drainage system was installed at the base of the cutoff barrier (Figure 56) to intercept and drain any underseepage into a sump (Figure 60). It was then pumped outside the protected area (Figure 61).

70. The prototype house (Figure 54) was located in Tulsa County, Oklahoma. It was in a Corps of Engineers project area and was subject to removal and salvage. To facilitate testing, the shrubbery and debris were removed from the perimeter. Installation of the system required a trench to be dug beside the footing to a depth of about 2 ft (Figure 56). After the digging was completed, the drain system was installed, as shown in Figure 56. A 4-in. perforated drainpipe was placed at the base behind the protective fabric. A filter system of rocks was placed over the 4-in. drainpipe. An adhesive was spread on the house wall at ground level to seal a 2 by 4 board to the house. The 2 by 4 was then attached to the house by drilled holes, inserts, and screws.

71. The protective fabric was positioned in the trench and on the house. A 1 by 4 board was placed against the fabric and attached to the 2 by 4. The storage compartment for the fabric was attached to the 1 by 4. Once the storage compartment had been attached to the fabric and to the house, the backfilling of the trench was begun. The fabric was tightly positioned against the foundation at all times as the backfilling and tamping was accomplished. The backfill was compacted in 6-in. layers to achieve a density

which would minimize the seepage of the floodwaters. Since the test was performed about 2 days after compaction of the backfill, the fill did not have time to settle and reduce permeability. It is believed that the early testing of the system caused the seepage to be more severe than would have occurred with a better-compacted backfill.

72. The upper snaps (Figure 59) for attaching the protective fabric to the house at the desired elevation were installed. The top elevation of the protective sheathing should be the depth of flood protection plus 6 in. to 1 ft of freeboard to protect the house from waves caused by boats, wind, etc. (As stated earlier, the maximum depth to which a house or a building should be made resistant to floodwaters is approximately 3 ft.)

73. A backwater valve was installed in the sewage drain line to keep the floodwaters from backing up into the house through the toilet and bathtub by cutting the 4-in. pipe which drained water from the house and placing the valve in the line. The valve was enclosed in a plastic standpipe with a screw-on lid to provide easy access.

74. For the purpose of this test, plywood sheathing and wooden braces were used to provide support for the protective fabric around the patio and porch. These areas could be equipped with decorative railings of the desired height which can serve as permanent support for the fabric. A temporary brace can be installed at the time the system is to be used. Temporary bracing can also be prepared for garage doors (which have excessive span) to support them when a water load is acting on the door.

75. The fabric was raised from the permanent storage compartment and attached to the house by permanently installed snaps. A levee had been built around the house, and with the fabric in place the house was ready for testing.

Testing

76. Water was pumped into the area between the house and the dike (Figure 62). The water level was raised to a 1-ft head on 23 May 1984 and was held overnight. On 24 May 1984, the water level was raised to produce a 3-ft head on the walls of the house which was held for approximately 24 hr.

Test Results

77. As the water level was being raised to the 1-ft head, underseepage developed rapidly but stabilized in about 2-1/2 hr to 10 gal/min. There was some movement of fines into the sump, but the water cleared up during the night of 23 May 1984. The pump which was being used (Figure 63) ran for about 40 sec and then cut off for about 50 to 55 sec after the water level in the sump had been pumped down to a set level. This cycle continued until the raising of the water level around the house resumed at approximately 9:50 am on 24 May 1984.

78. As the water level was being raised toward the 3-ft level, the underseepage increased. At 11:00 am on 23 May 1984, the seepage level became too high in the sump (the level setting for the pump cuton and cutoff was too high). This development allowed the seepage water to rise excessively and caused some water to seep under the garage door (Figure 64) which was the lowest level of the house. The limits on the sump pump were changed, and the water was kept at a lower elevation in the sump which decreased the rate of seepage under the garage door.

79. There was a little seepage around the baseboards of some rooms (Figure 65). After the test, the cause of this seepage was found to be a leak at the lap of the fabric. The lap of the fabric was heat-treated but was not sealed adequately, and a small leak at the lap caused water leakage behind the seal and into the house.

80. In general, there was too much underseepage during this test. A larger pump had to be put into the sump with the smaller pump. The large pump pumped continuously and the smaller pump ran intermittently.

81. Also, the fabric was not placed deep enough in the ground to lower underseepage to an acceptable level. The fabric was placed about 2 ft below the ground without any knowledge of how this embedment would decrease the underseepage. Onsite tests and tabular or graphical data should be used to determine the depth of cutoff to control underseepage. For example, percolation tests could be performed onsite, and the values could be used in graphical charts to determine the underseepage for various depths of fabric embedment. From this analysis, a depth of fabric could be determined which would control underseepage to a tolerable level. Such an analysis would also allow the selection of a sump pump which could handle the underseepage.

82. Construction details must be considered carefully if any floodproofing system is to work properly. For example, fabric laps must be very carefully sealed, drains properly installed, and all construction adequately braced. Merely sealing to the extent that it is believed the barrier will work is not sufficient when attempting to make a barrier impermeable to a head of water. If attention is not paid to these details and the possibility of a leak is present, it is highly probable that a leak will occur.

83. The backwater valve worked well. It was found that it is important to embed the pipe in the filter material such that fines are not leached away and the filter will pass clear water easily. An appropriate filter cloth should be used to cover the filter material to help in stopping the movement of fines and to produce an effective filter.

84. No holes should be placed in the fabric by screws, nails, etc. when connecting the system to the house, since doing so produces a possibility for leaks.

Conclusions

85. With a few improvements, the test system would be satisfactory for protecting existing homes in floodplains from up to 3 ft of floodwaters. During the prototype test, only a small amount of water got into the house, and the cause of leaks was determined and can be corrected. The house stayed essentially dry and no damage occurred. In a real flooding situation, the limited dampness could have been removed and the house would have been back to normal. A permanently installed system, such as the one used in this test, is very desirable because of its speed and ease of implementation and because of decreased possibilities of water leaks.

Recommendations

86. Onsite tests should be performed, and the results should be used in graphical charts to determine the depth of fabric cutoff barrier for manageable underseepage. The sump pump can then be selected based on the expected underseepage. A safety factor of two should be used in sump-pump selection.

87. Standard bracing for specific water heads should be designed and presented in a homeowner's manual so that the homeowner and contractors can select adequate backing to support garage doors, etc. Also, effective drainage systems and filters should be described in the manual to allow the homeowner and contractors to install effective drainage for the underseepage.

88. No holes should be made in the fabric by screws, nails, etc. because doing so produces a possibility for leaks. All details must be considered carefully and the system made as foolproof as possible in its construction and operation.

PART VII: SYSTEMS NOW BEING USED TO PROTECT HOUSES FROM FLOODWATERS

Introduction

89. Over the years, homeowners have attempted many methods of reducing flood damage to homes. Probably the most popular and successful of these has been to raise the structure above the flood hazard. This method is, however, rarely applicable to the slab-on-grade construction which is popular today. Levees and low walls have also been common, but they often fail during the flood event. The poor success rate demonstrates that individuals often attempt flood-resistant systems naively and lack necessary technical knowledge and skills to successfully complete the complex job.

90. Because of the potentially large demand for flood-resistant systems, private firms are becoming interested in exploiting this market. This interest by the private sector is a very important development in that their work should rapidly expand flood-resistant technology. There are, however, areas of technology in which many contractors do not have the time, money, or expertise to research and develop. Also, there is little or no incentive for contractors to transfer learned technology to the homeowner.

91. The government can be and should be a key figure in making the environment of flood-resistant construction trustworthy and dependable. The government can do this as follows:

a. The Corps of Engineers can develop a homeowner's manual which presents up-to-date information about protecting homes and buildings from floodwaters. There are many pitfalls to watch for when making a building resistant to floodwaters. The homeowner's manual can bring these pitfalls, as well as materials and systems, for flood-resistant construction to the attention of the public.

b. The homeowner's manual should be a loose-leaf publication so that it can be updated as new developments are made.

c. Getting the public actively involved could be an invaluable asset, because this communication can generate new ideas about materials and systems which are effective.

d. Technology transfer and the education of the private sector by the Corps of Engineers will be invaluable to ensure that the public is protected. The technology transfer will help the public to be more knowledgeable about flood protection systems and will help to prevent any unscrupulous contractor from taking advantage of homeowners.

92. During the time when contractors are actively striving to develop and to implement better techniques, the Corps of Engineers can play an important role through transfer to both the contractor and homeowner its continued research and technology.

Flood-Resistant Systems

93. In addition to the more common raising of structures and constructing levees and walls, several other types of flood-resistant systems are being installed to prevent flood damage to homes and buildings. The author believes that a drainage, sump, and pump system is essential for any of the flood-resistant systems.

94. One system being installed uses the following procedure:

- a. Dig around the perimeter of the building to expose its foundation, then seal any cracks in the exposed foundation.
- b. Apply a cementitious waterproofing material to seal the foundation and wall of the house to the desired flood-resistant elevation.
- c. Place waterproof closures over openings such as doors and windows.
- d. Construct a curtain wall below the level of the foundation to such a depth that the building will be protected from uplift. The seepage path will have to be of such length, considering the given characteristics and conditions of foundation soil, that for the length of time of the flooding the seepage obtained under the building will not be harmful.

95. A second system to make houses and buildings resistant to floodwaters involves extending an impermeable membrane several feet into the ground and up the wall of the building to the desired floodproofing elevation (Figure 66). A trough or container is attached to the outside of the impermeable membrane and to the house at the ground level. The upper part of the membrane can be dropped down into the trough, and a lid can be put on the trough for the storage of the membrane. When floodwaters are rising, the lid of the trough can be removed and the membrane pulled upward and attached to the house. There are problems with this system still to be solved; i.e., the membrane has to pass doorways, pipes which extend from under the house, etc. All of these passageways or penetrations (such as by pipes) must be cared for to ensure that leaks can be eliminated and a pleasing appearance maintained.

96. There will probably be more contractors installing flood-resistant systems in the future, and it is critical that the Corps of Engineers move ahead in its studies and technology transfer efforts to help the public obtain effective systems to reduce or prevent floodwater damage.

Cooperative Flood-Resistant Construction Effort

97. It will be mutually beneficial for the Corps of Engineers and the private sector to work together to determine materials and systems that will prevent buildings from being damaged by floodwaters. The contractors who work daily in making buildings resistant to floodwaters will learn many useful ideas, techniques, concerns, etc., which are beneficial to flood-resistant construction. In the same manner, the Corps will learn many things that will help the contractor and building owner. The Corp of Engineers can determine areas, or needs, whereas, perhaps, the contractor does not have the time, money, or expertise to develop and research solutions to these needs. The Corps of Engineers could then provide this information not only to the contractors but also to the total private sector.

98. A homeowner's manual can be used to transmit the concerns, materials, techniques, suggestions, etc., which will help the homeowner to make his home resistant to floodwaters either in hiring a contractor or doing the work himself.

PART VIII: SUMMARY, RESULTS, AND RECOMMENDATIONS

Summary and Results

99. Buildings must not be made water resistant above safe-design water heights, or the building can be damaged or collapsed. An unprotected brick-veneer or block wall will safely support approximately 3 ft of water head without being damaged. A coating of the brick or block surface will strengthen the wall; however, the degree of strengthening depends on the coating, its thickness, its impermeability, and its durability.

100. Clear sealants do not make brick-veneer or block wall impermeable against a water head. Epoxies, polyurethanes, and asphalt coatings that were tested were not reliable in preventing a water head from penetrating a brick-veneer or block wall. Some cementitious coatings will make a brick-veneer or block wall nearly impermeable against a head of water. Coatings 5 and 8 have now performed successfully for 4 years in the climate at Vicksburg, Mississippi. Cementitious coatings which can be brushed on the walls are preferred, and they should be tested adequately for the environment in which they will be used.

101. Systems can be developed which will protect homes and buildings from floodwaters. The system tested at WES requires that a relatively impermeable barrier be used to a sufficient depth below the building foundation and around its perimeter to prevent undesirable uplift and underseepage. A snap connection around the building base was used to seal the sheeting which extended up the walls of the building. The openings, such as doors and windows at levels subject to water pressure, were reinforced to withstand the water pressure. The sheeting and one-half of the snap can be stored and put in place when needed. This type of system will work, but good workmanship is required. Construction details requiring special attention are as follows:

- a. A cementitious water-resistant coating (material) should be used to seal behind and below the permanent part of the seal strip before it is attached to the base of the building.
- b. The permanent part of the seal strip must be attached to the house with a strong durable adhesive and screws. It must also be cut to fit together well.
- c. The seal strip must not have any obstruction, such as trash or adhesive, which will prevent the plastic and nonpermanent part of the strip from sealing tightly.

d. When the sheeting is put around and snapped to the building, techniques must be used which will not pull the sheeting tight or pull it at angles so as to cause wrinkles under the seal strip.

e. Any laps of the sheeting should be sealed with a pliable adhesive bonding or a thermal sealing device. A water-resistant tape should be used to seal the edge of the lap. Several strips of tape should be used to seal the lapped edge.

f. All corners must be smoothed so that if reasonable care is taken, the sheeting will not be punctured at the corners during installation.

g. The intersection of the underside of the sheeting and the seal strip must be sealed at joints of the various pieces of the nonpermanent part of the seal strip.

h. Corners of the seal strip must be fit together easily, and sealing material must be used or leaks will occur.

i. A drainage system with a sump and pump must be used behind the water-resistant system to take care of any leaks which may occur.

102. Another system involves extending a continuous and relatively impermeable membrane into the ground a sufficient depth to prevent detrimental underseepage and continuously from in the ground up on the walls of the house. A trough is located at ground level for storage of the membrane when it is not in use. A drainage, sump, and pump system should be located behind the flood-resistant construction to collect any underseepage or water leaks.

103. A homeowner's manual should be written to transfer technology to the public. As many options of flood-resistant construction as possible should be presented to the public for consideration and use. The systems must not only be logical; they must have been tested and proven.

104. A prototype house of block-wall construction was tested, and 4 ft of water damaged the walls of the house. If a building owner allows a brick or block-wall building to experience greater than about 3 ft of water head, it is highly likely that the building will be structurally damaged. The test of the prototype house was partially successful, although some details of the flood-resistant system must be improved.

105. A prototype test was performed on a house in Tulsa, Oklahoma, with the fabric extending continuously from in the ground up the side of the house. This system with few improvements is considered satisfactory to protect existing building in floodplains from at least 3 ft of floodwaters. A permanently installed system such as the one used in this test is very desirable because

of the speed and ease of implementing and because of decreased possibilities of water leaks.

106. An active combined effort of researchers, contractors, material developers, and building owners is necessary for efficient and cost-effective improvements in decreasing the flood damage to buildings. The government should follow and learn from the private sector and should lead developments in areas where the private sector does not have the expertise or profit potential to prompt it to make such developments.

Recommendations

107. It is recommended that tests of promising cementitious coatings be performed to determine their effectiveness in preventing water penetration when subjected to various environmental conditions.

108. The snap connection for sealing an impermeable membrane at the base of the building should be perfected. There are only a few details which must be studied, improved, and tested to complete this system of water-resistant construction.

109. The penetration or flow of water with time through various foundation soils should be defined. The depth of impermeable barriers to reduce underseepage and uplift for specific time intervals for the various foundation soils should be determined.

110. A loose-leaf homeowner's manual should be written presenting the pitfalls of flood-resistant construction, options for making buildings resistant to floodwaters, and any other information which will be helpful to building owners or contractors. The manual should be organized so that it can be easily updated as pertinent information becomes available.

111. The homeowner's manual should present the following four systems for making buildings resistant to floodwaters:

a. System 1 (Figure 29):

(1) A relatively impermeable sheeting below the building base and to a sufficient depth to eliminate undesirable underseepage and uplift.

(2) A snap at the base of the building sealing against a relatively impermeable membrane which extends up the walls of the building.

(3) Reinforcements over windows and doors to withstand any water pressure.

(4) A drainage, sump, and pump system should be behind the flood-resistant construction to collect any water leaks.

b. System 2 (Figure 56):

(1) A relatively impermeable membrane which extends into the ground a sufficient depth to prevent detrimental uplift and underseepage and is continuous from in the ground up the walls of the house.

(2) A trough at ground level and against the membrane for storage of the membrane when it is not in use.

(3) At places where the membrane passes walkways or other passageways and at the locations of pipes or other extrusions from under the building, construction techniques should be developed which are adequate and result in a pleasing appearance.

(4) A drainage, sump, and pump system should be behind the flood-resistant construction to collect any underseepage or water leaks.

c. System 3:

(1) A relatively impermeable membrane placed at and below the foundation to prevent any detrimental underseepage and uplift.

(2) The foundation and walls sealed by relatively impermeable coatings.

(3) Relatively impermeable closures used over door and windows.

(4) A drainage, sump, and pump system should be behind the flood-resistant construction to collect any water leaks.

This system is probably most effective when installed by contractors who have become efficient in its construction.

d. System 4. This system involves the use of low flood walls located at some distance from and around the building.

112. A prototype house should be tested using each of the four systems to give a clear demonstration that they are workable.

113. Cooperative efforts should be made with the public, contractors, material developers, and researchers to improve water-resistant construction as quickly and as efficiently as possible.

Table 1

Coatings

Material	Coating No.	Comments
Clear water-repellents	1	Repelled rainwater well. Sealed some small openings against 1 to 2 ft of water head, but did not seal brick or block walls against 1 to 2 ft of water head.
Clear water-repellents	2	
Clear water-repellents	3	
Cementitious materials	4	Expansive, hard to apply. Sealed a brick-veneer wall against 2 ft of water head but cracked and failed after 3 months.
Cementitious materials	5	Relatively inexpensive, good bond, good crack resistance, and was still effective after 4 years of use.
Cementitious materials	6	Good bond but cracked after 3 years of use.
Cementitious materials	7	Cracked and peeled from brick surface after 3 years of use.
Cementitious materials	8	Good bond and was still effective after 4 years of use.
Epoxy	9	Not effective in sealing a brick wall against 1 to 2 ft of water head.
Epoxy	10	
Polyurethane	11	Not effective in sealing a brick wall against 1 to 2 ft of water head.
Asphalt	12	Only reliable if good workmanship is used and an impermeable barrier is embedded in the asphalt.

Table 2

Gage Designation and Location

		X, Y Coordinate	
Room	Gage*	Reference Corner Location in House	Coordinates
Kitchen	1-ES	NE	86-1/2 in., 24 in.
Kitchen	2-NW	NE	60-1/2 in., 29 in.
Br 4	3-NW	NW	60 in., 24 in.
Bath	4-NE	NW	26 in., 24 in.
Br 3	5-NE	NW	65 in., 24 in.
Br 3	6-WS	NW	83 in., 24 in.
Living Room	7-EN	SE	86 in., 24 in.
Living Room	8-SW	SE	84 in., 24 in.
Br 1	9-SW	SE	61 in., 24 in.
Br 2	10-SE	SW	77 in., 24 in.
Br 2	11-SE	SW	24 in., 24 in.
Br 2	12-WN	SW	24 in., 24 in.
Br 2	13-WN	SW	77 in., 84 in.
Br 2	14-WN	SW	77 in., 48 in.
Br 2	15-WN	SW	77 in., 24 in.

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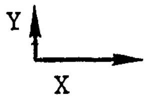
* Example of gage numbering:

First letter of gage designation is the direction of the wall in the room.
Second letter is the direction from reference corner.
Letter designations are: E - east; W - west; N - north; S - south;
Br - bedroom.



coordinate system

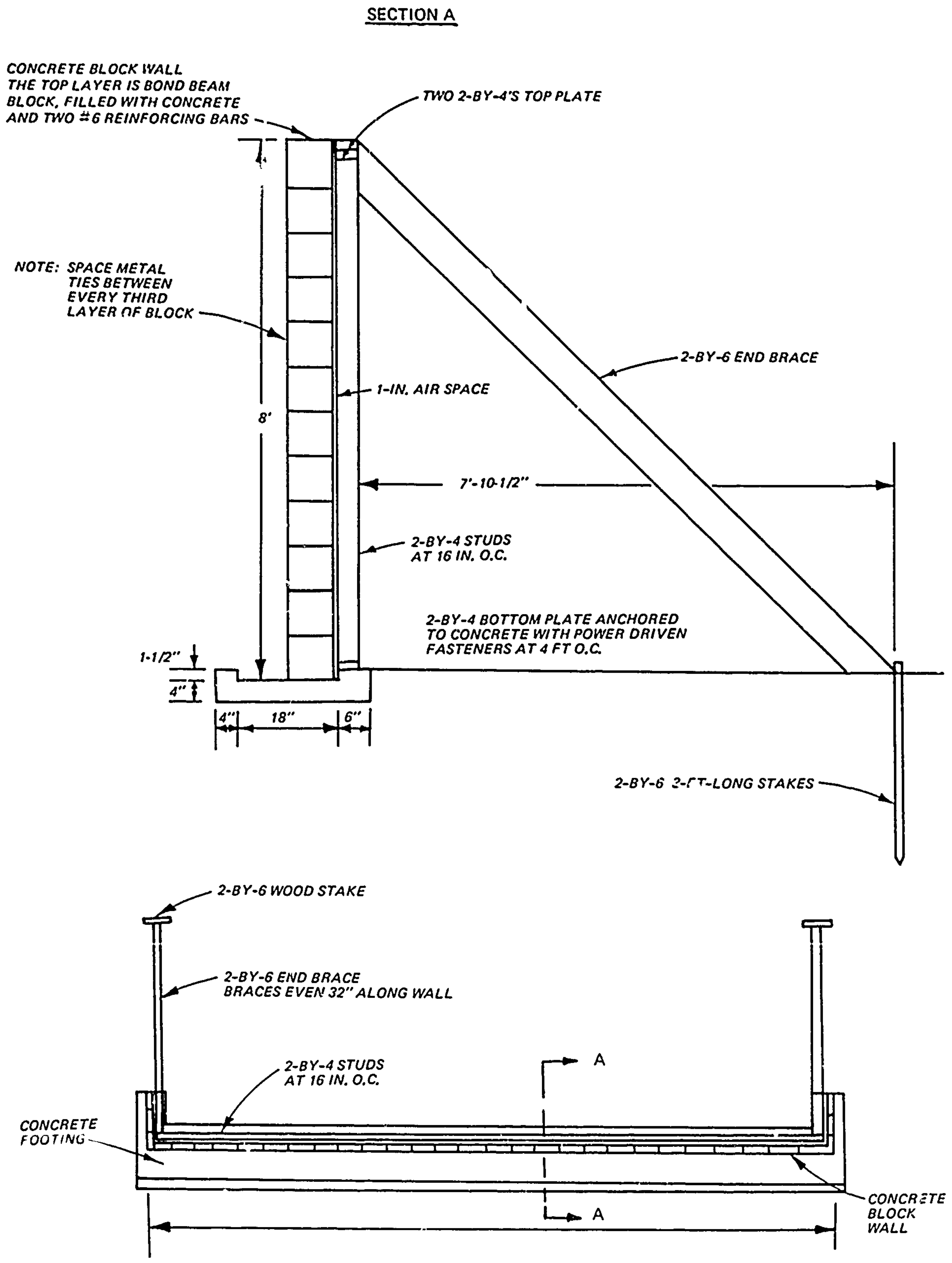


Figure 1. Concrete block wall plan and section

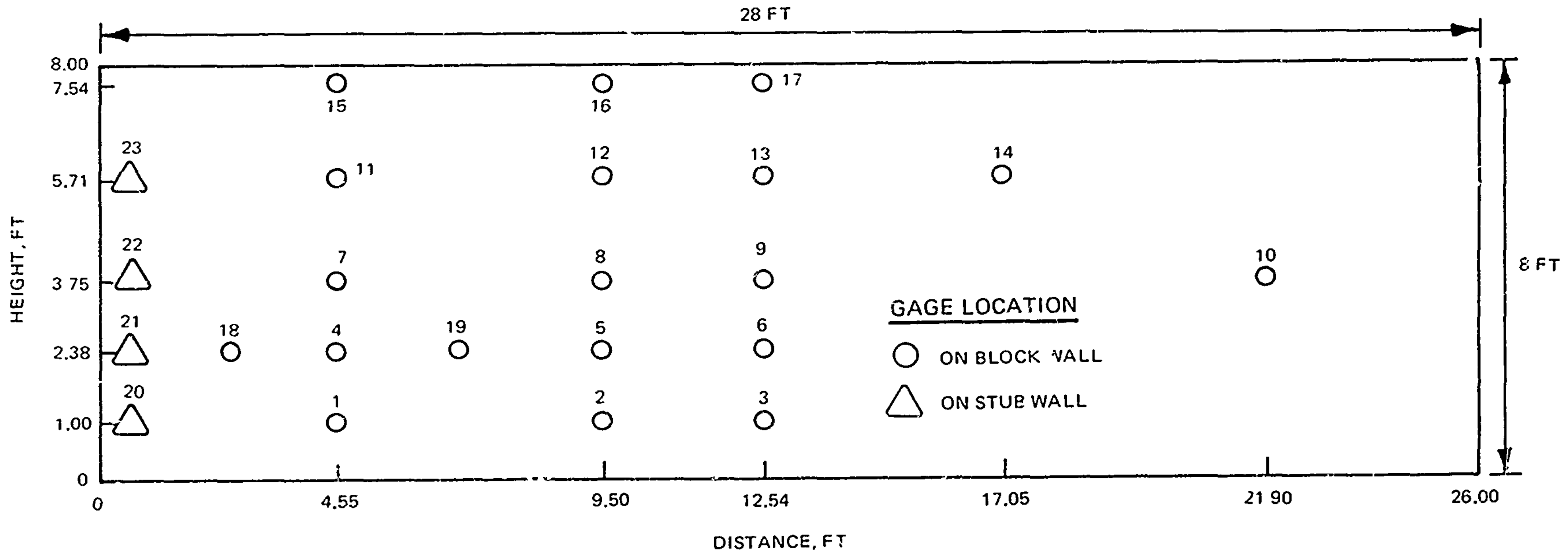
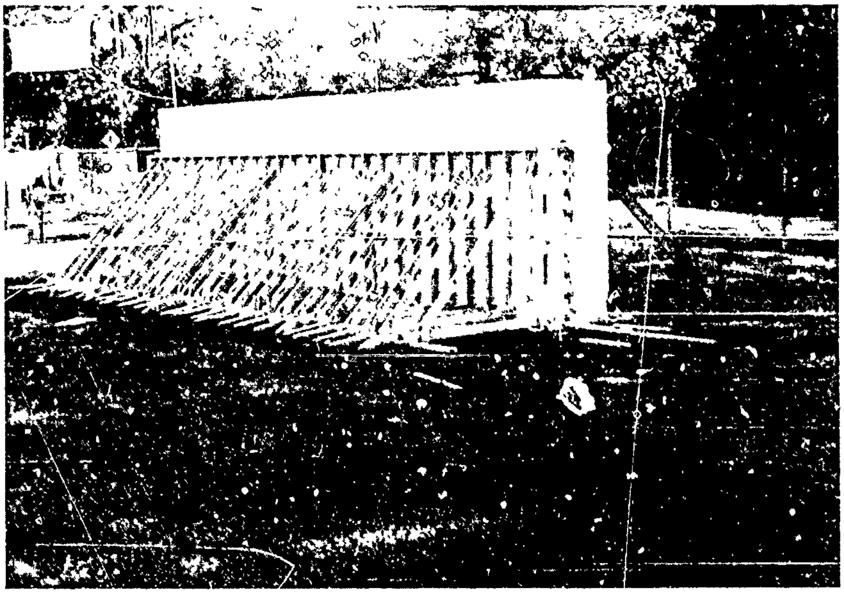
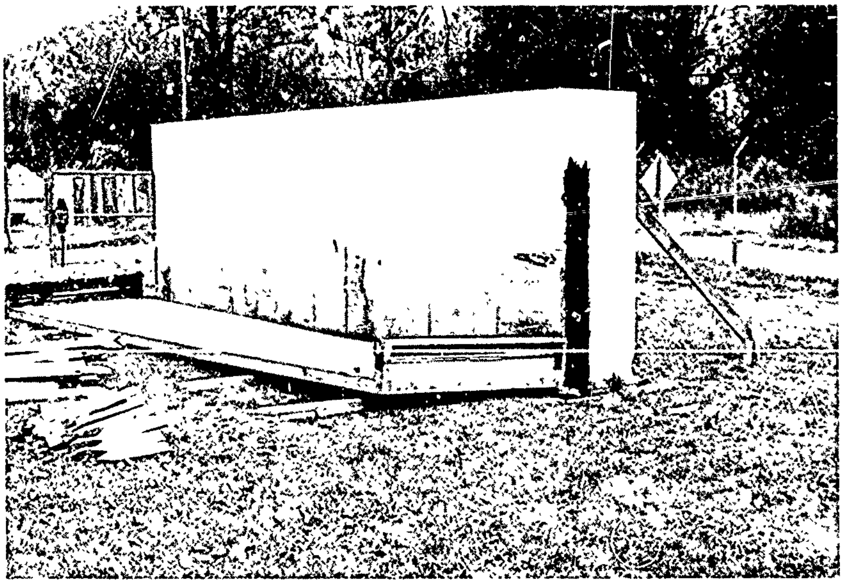


Figure 2. LVDT deflection gage locations

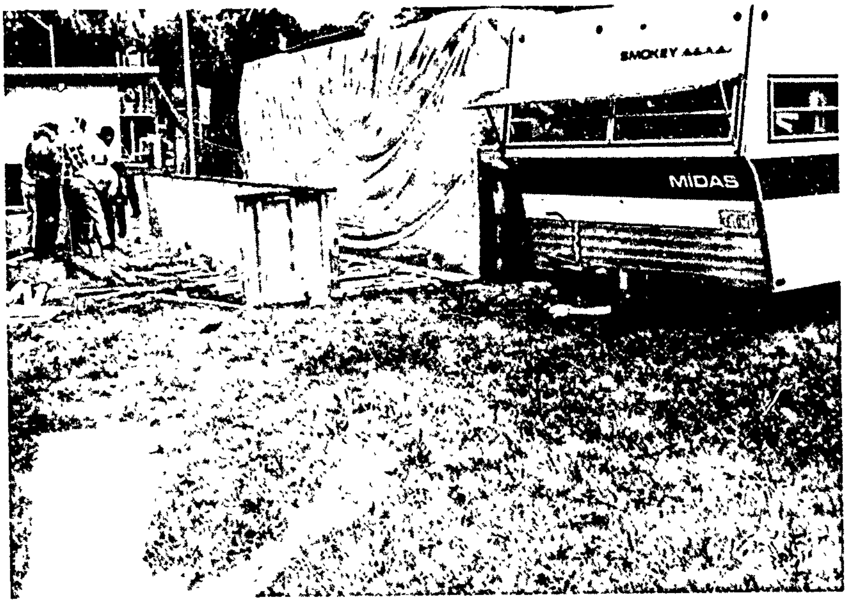


a. Before testing

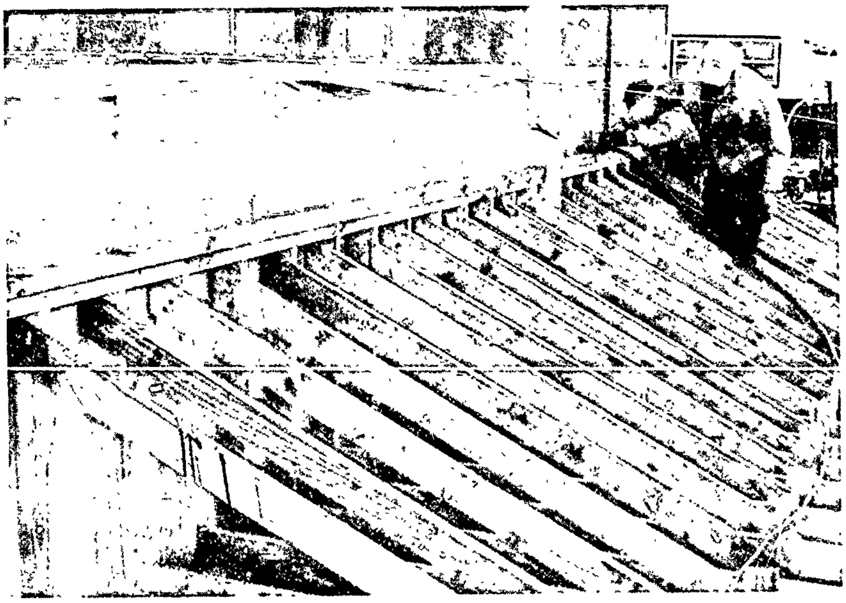


b. After testing

Figure 3. Block wall 1



a. Being prepared for testing



b. Being tested

Figure 4. Block wall 2

Figure 5. Automatic data recording equipment

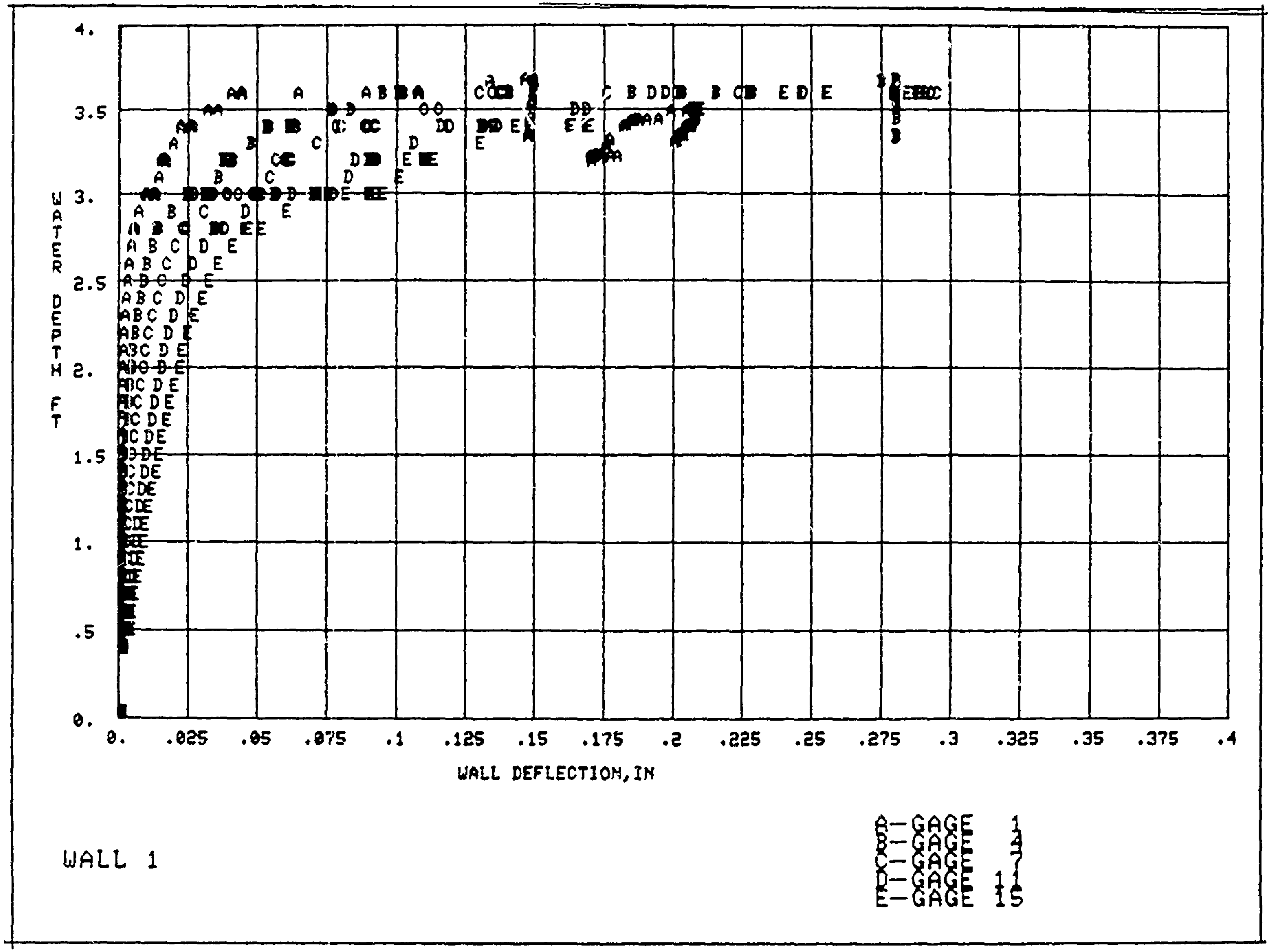


Figure 6. Water depth versus deflection, gages 1, 4, 7, 11, and 15

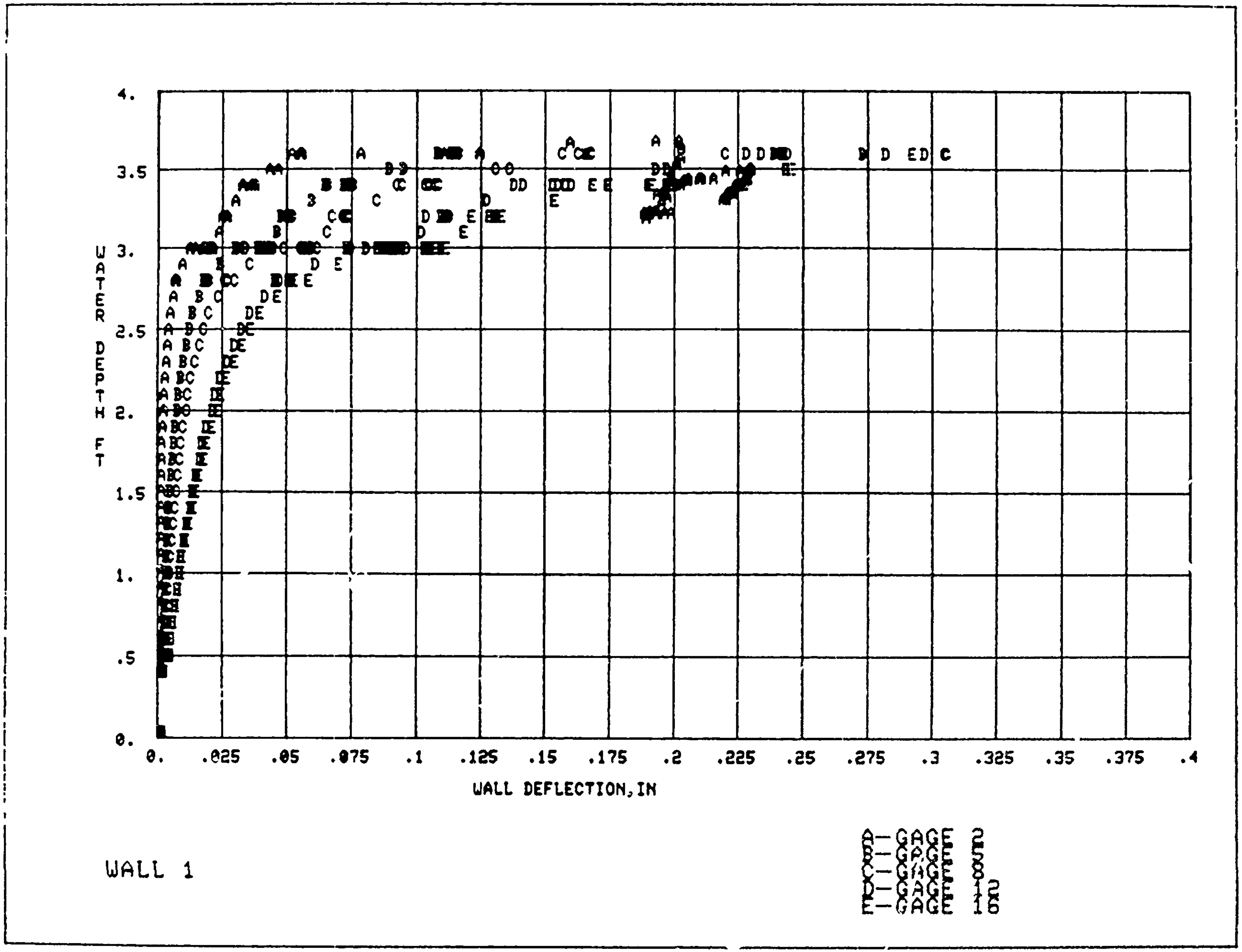


Figure 7. Water depth versus deflection, gages 2, 5, 8, 12, and 16

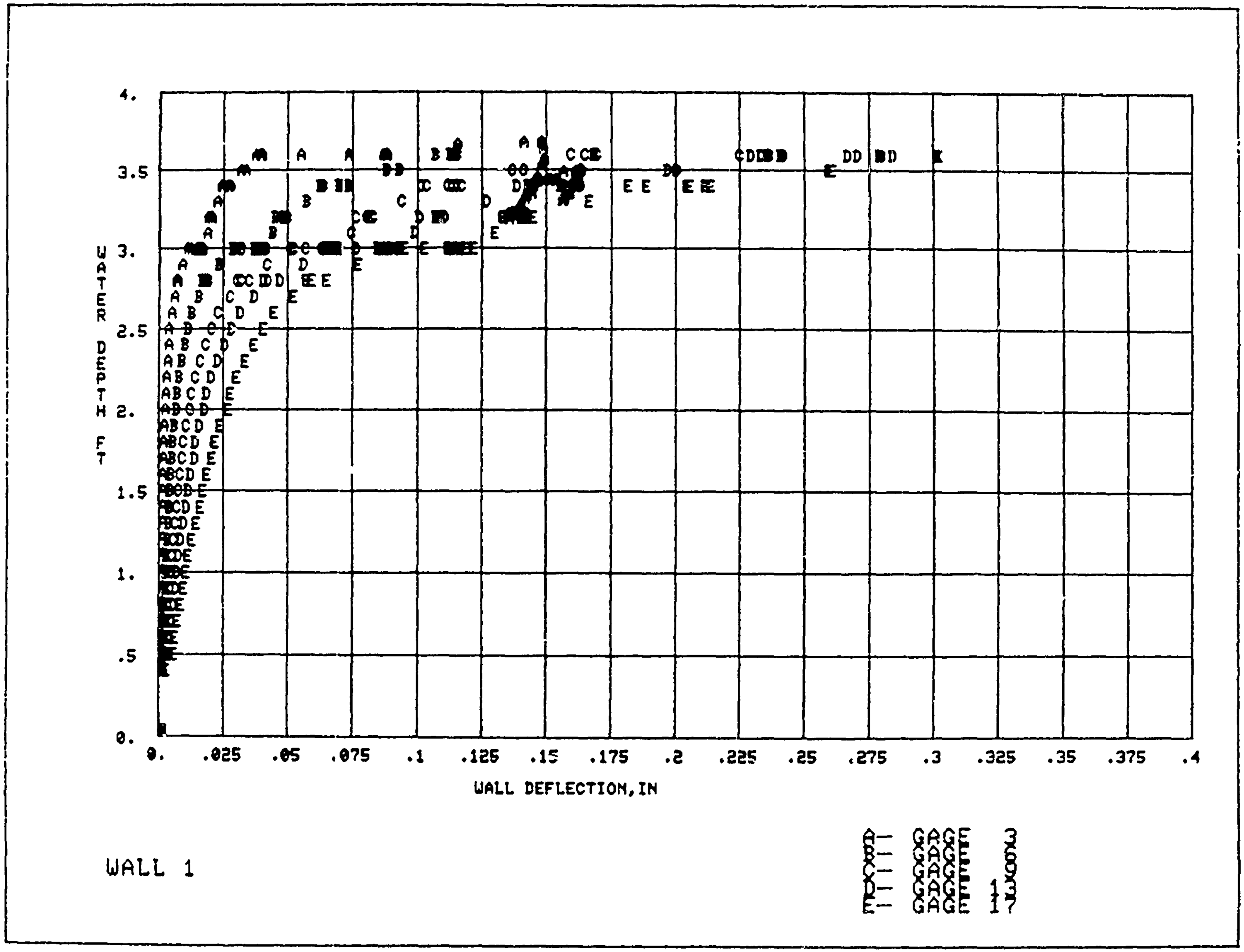
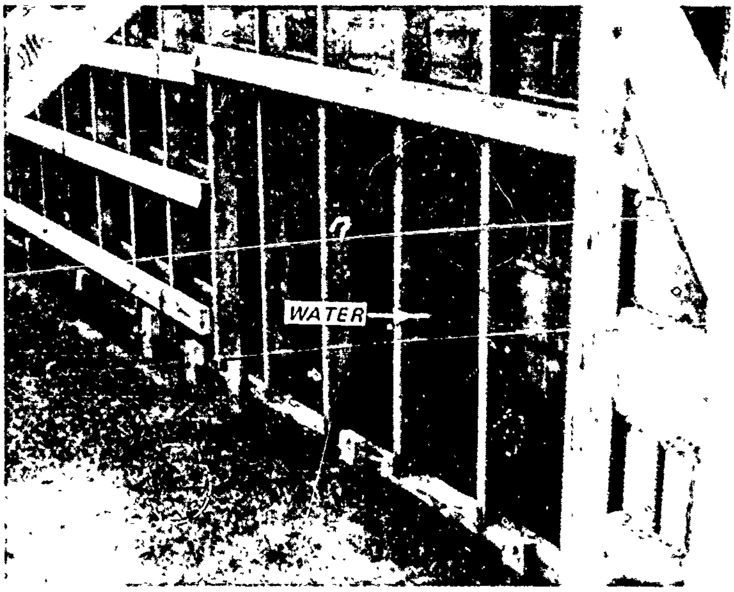
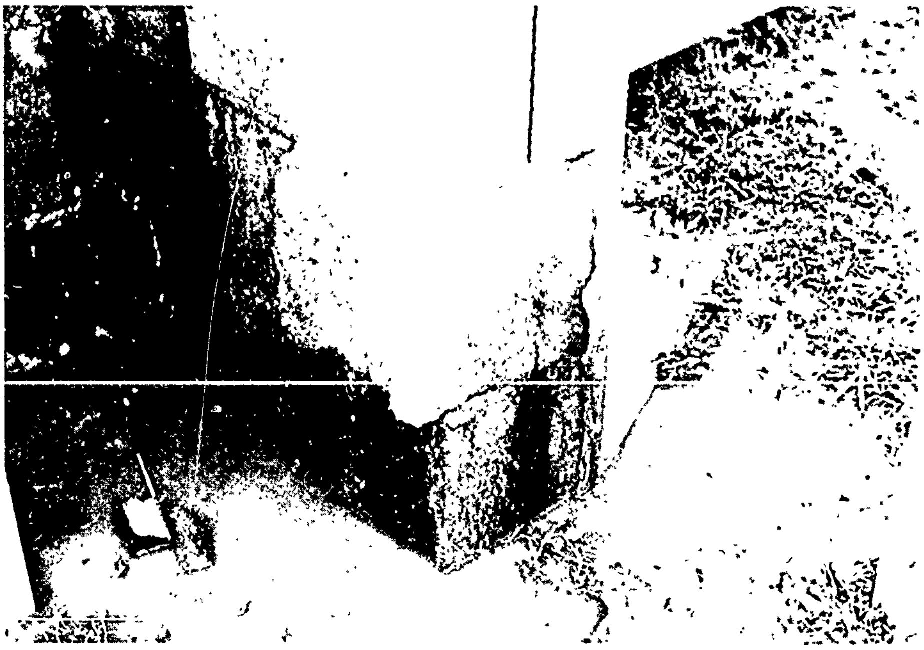


Figure 8. Water depth versus deflection, gages 3, 6, 9, 13, and 17



a. Stream of water coming through wall



b. Base of wall

Figure 9. Leakage through block wall

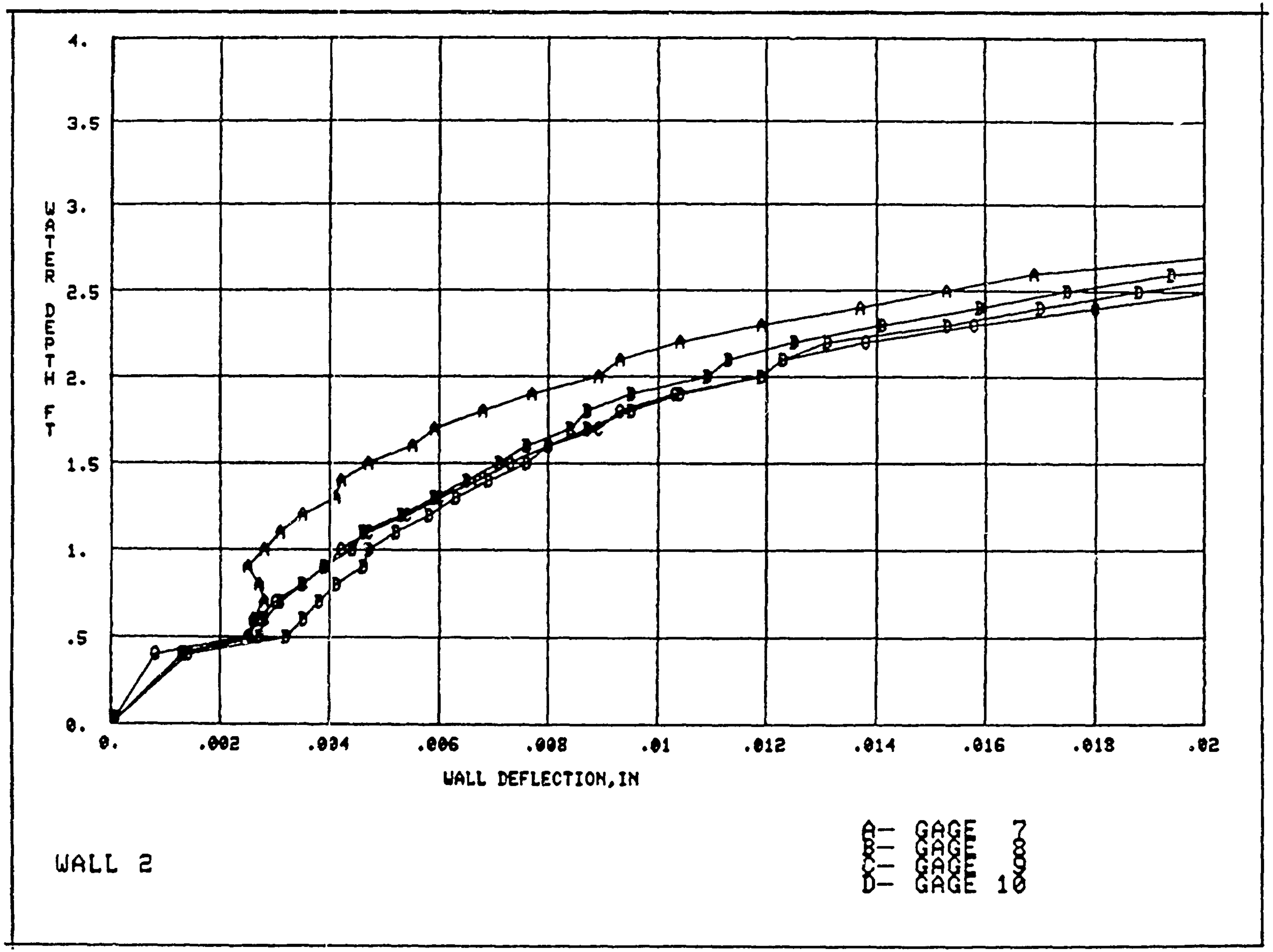


Figure 10. Wall deflections, gages 7, 8, 9, and 10.

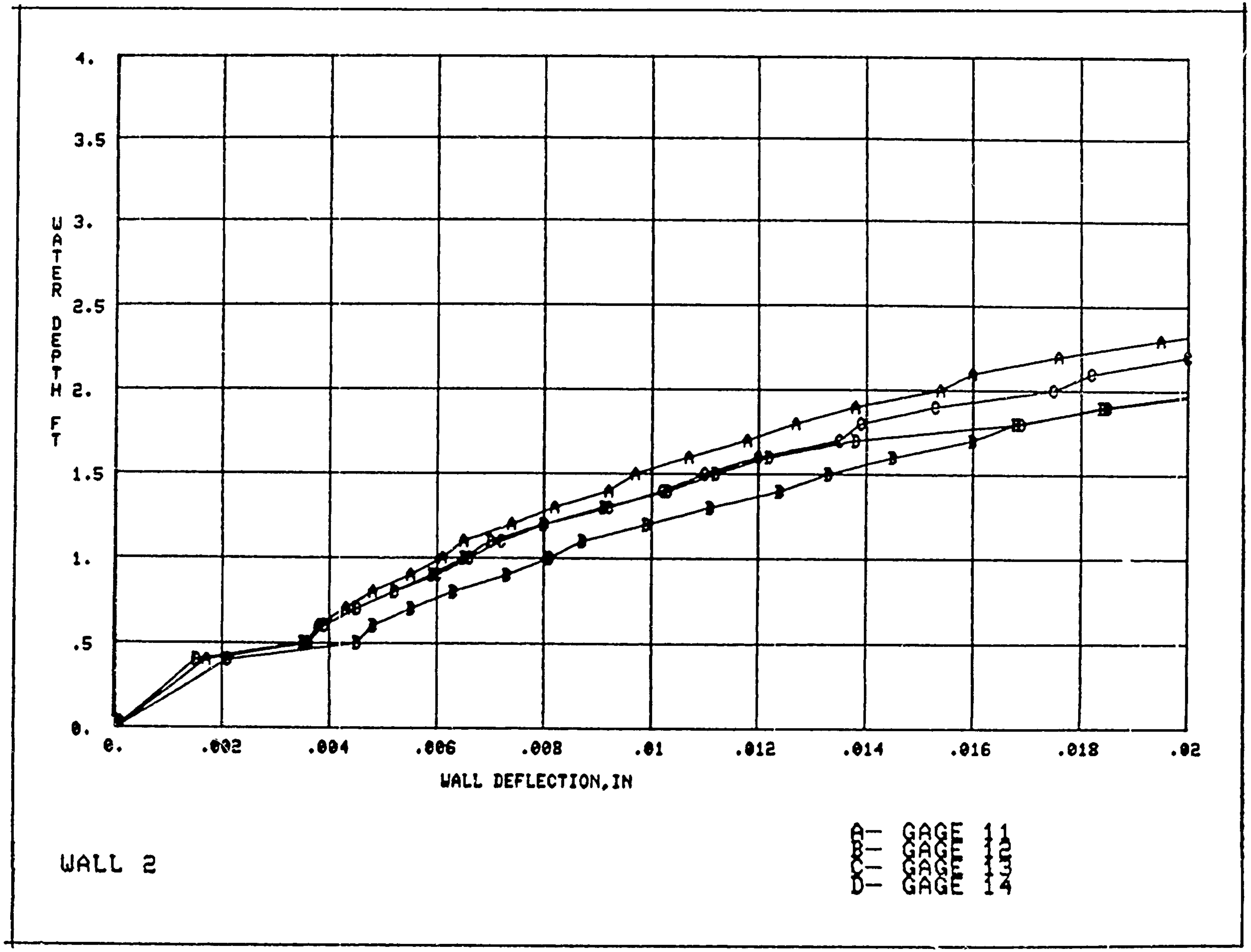


Figure 11. Wall deflections, gages 11, 12, 13, and 14

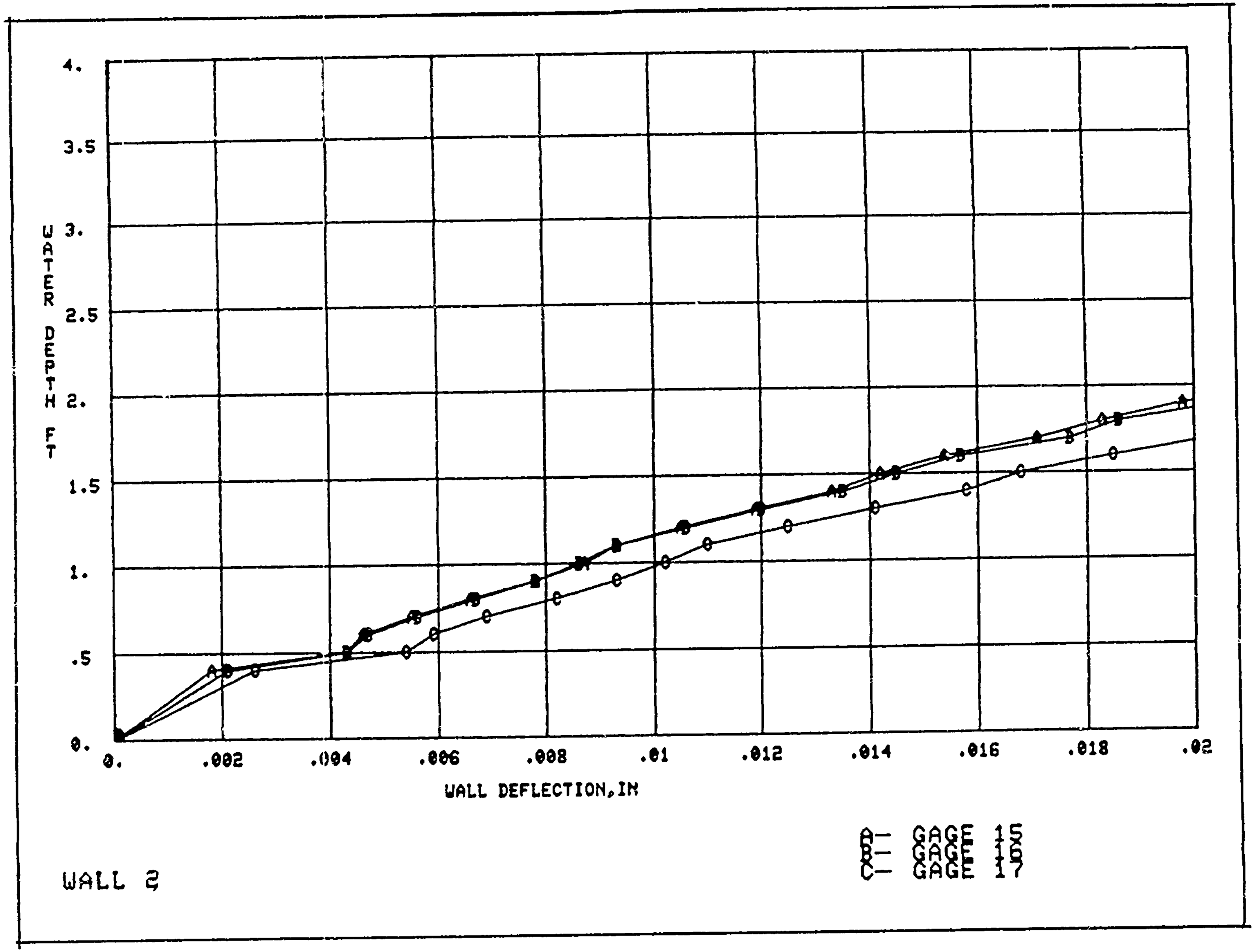


Figure 12. Wall deflections, gages 15, 16, and 17

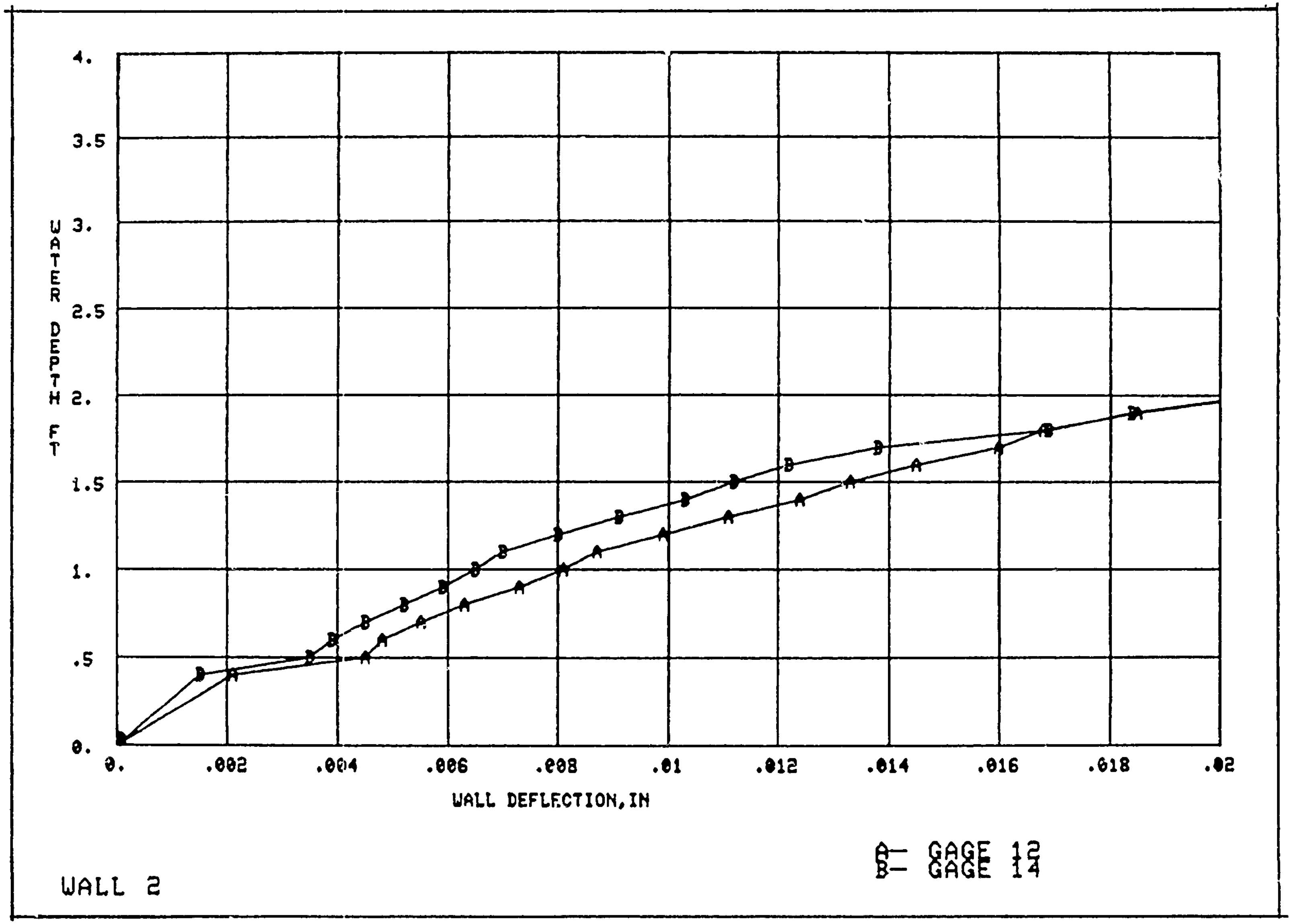


Figure 13. Wall deflections, gages 12 and 14

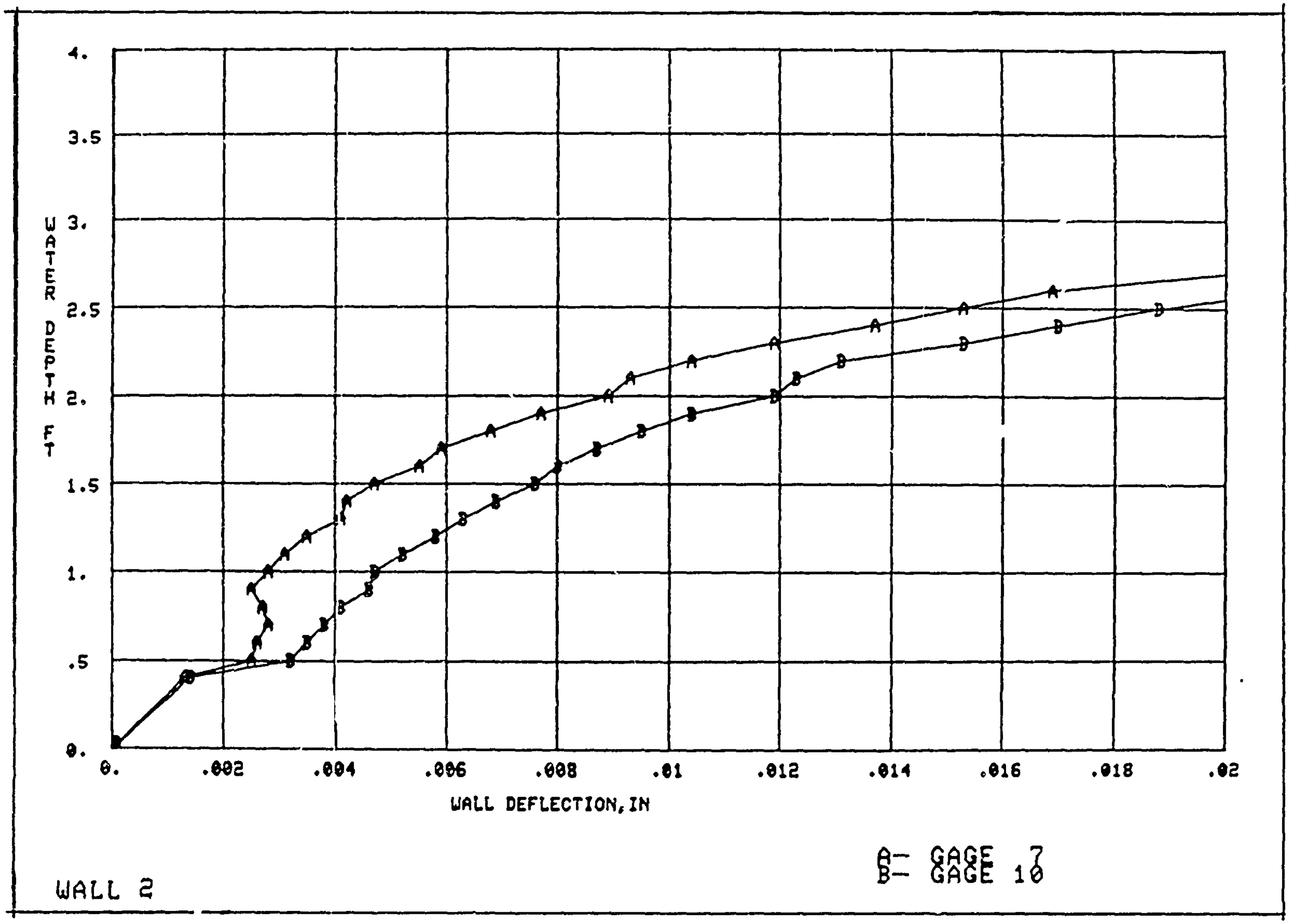


Figure 14. Wall deflections, gages 7 and 10

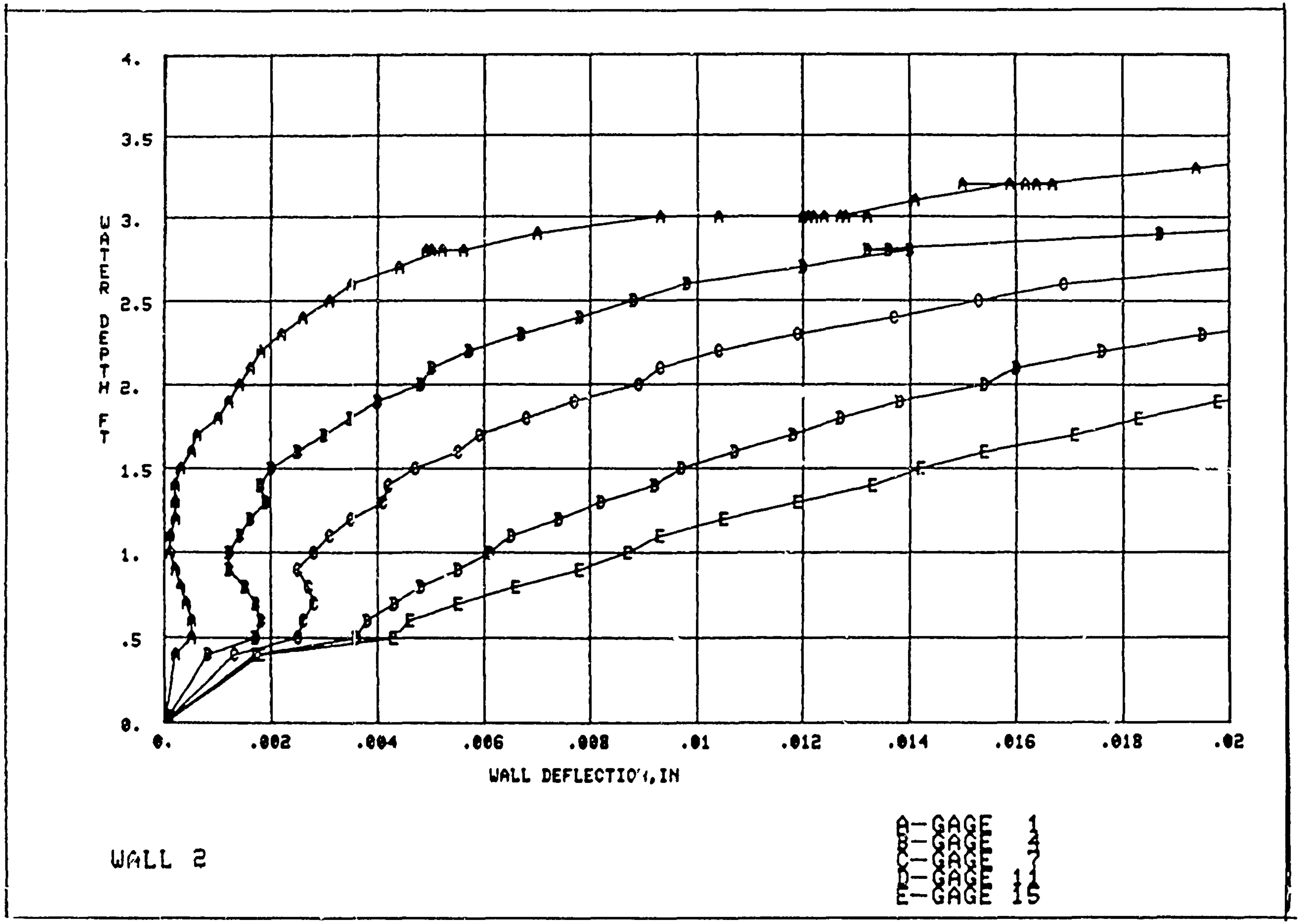


Figure 15. Wall deflections, gages 1, 4, 7, 11, and 15

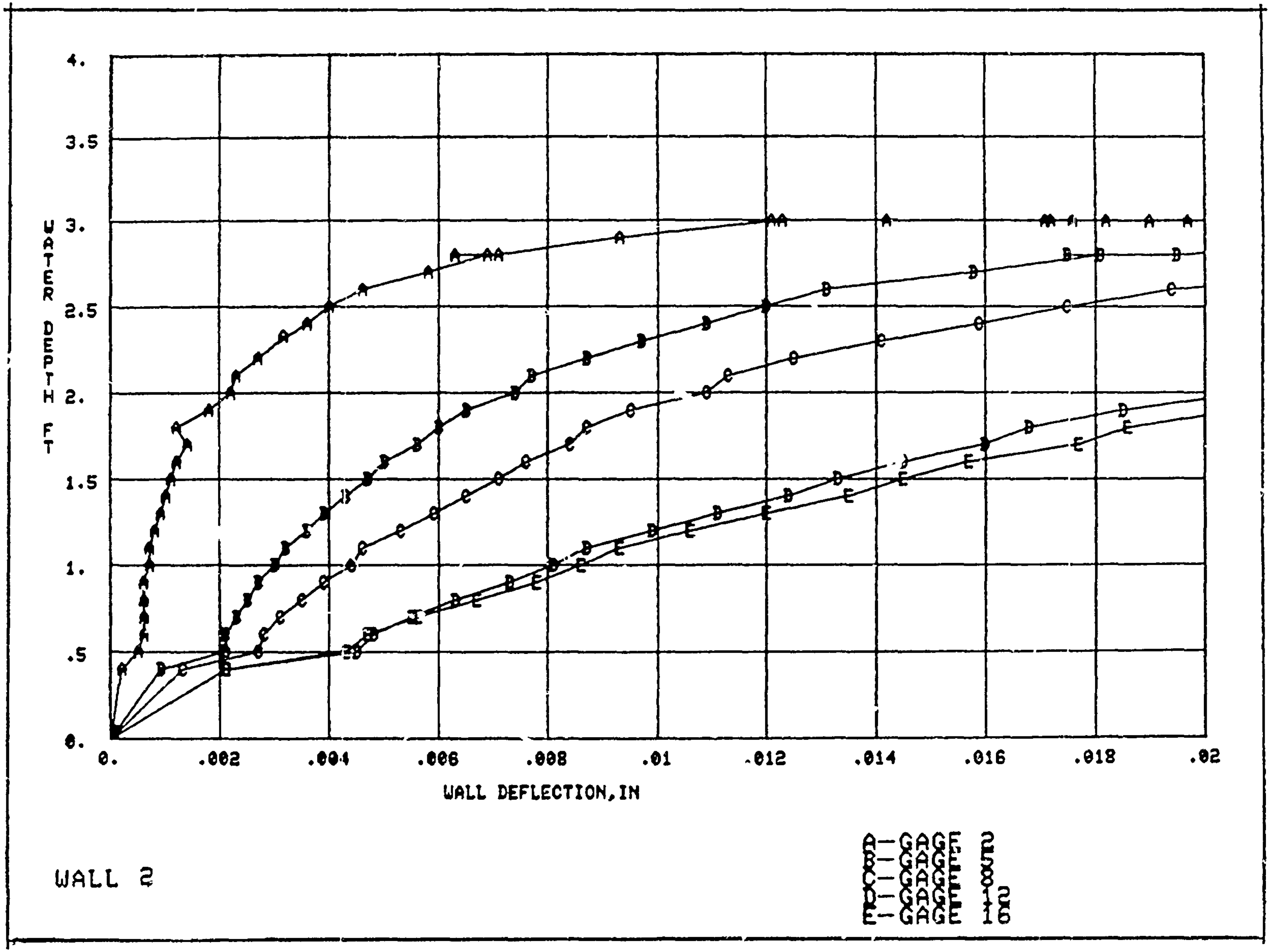


Figure 16. Wall deflections, gages 2, 5, 8, 12, and 16

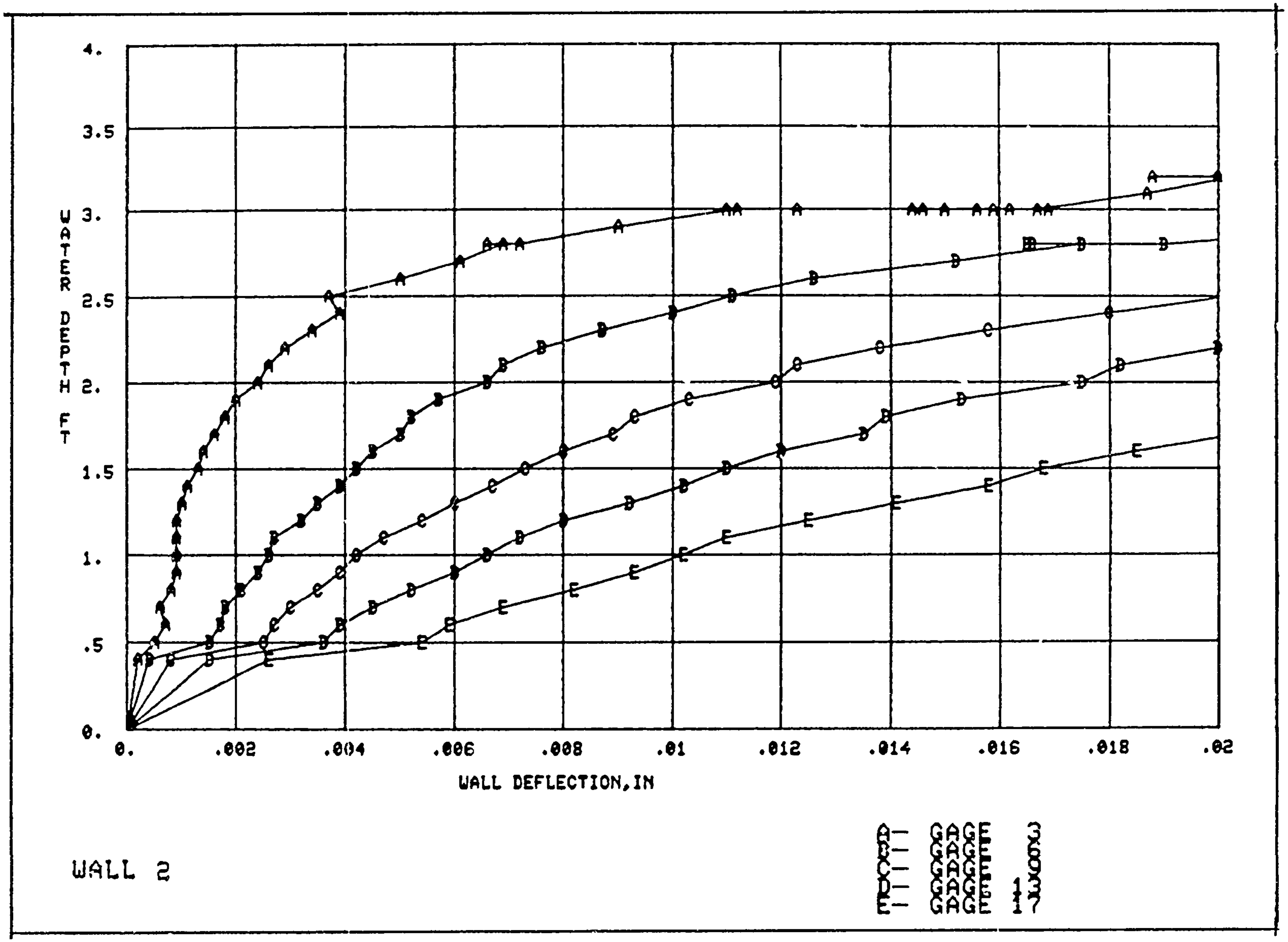


Figure 17. Wall deflections, gages 3, 6, 9, 13, and 17

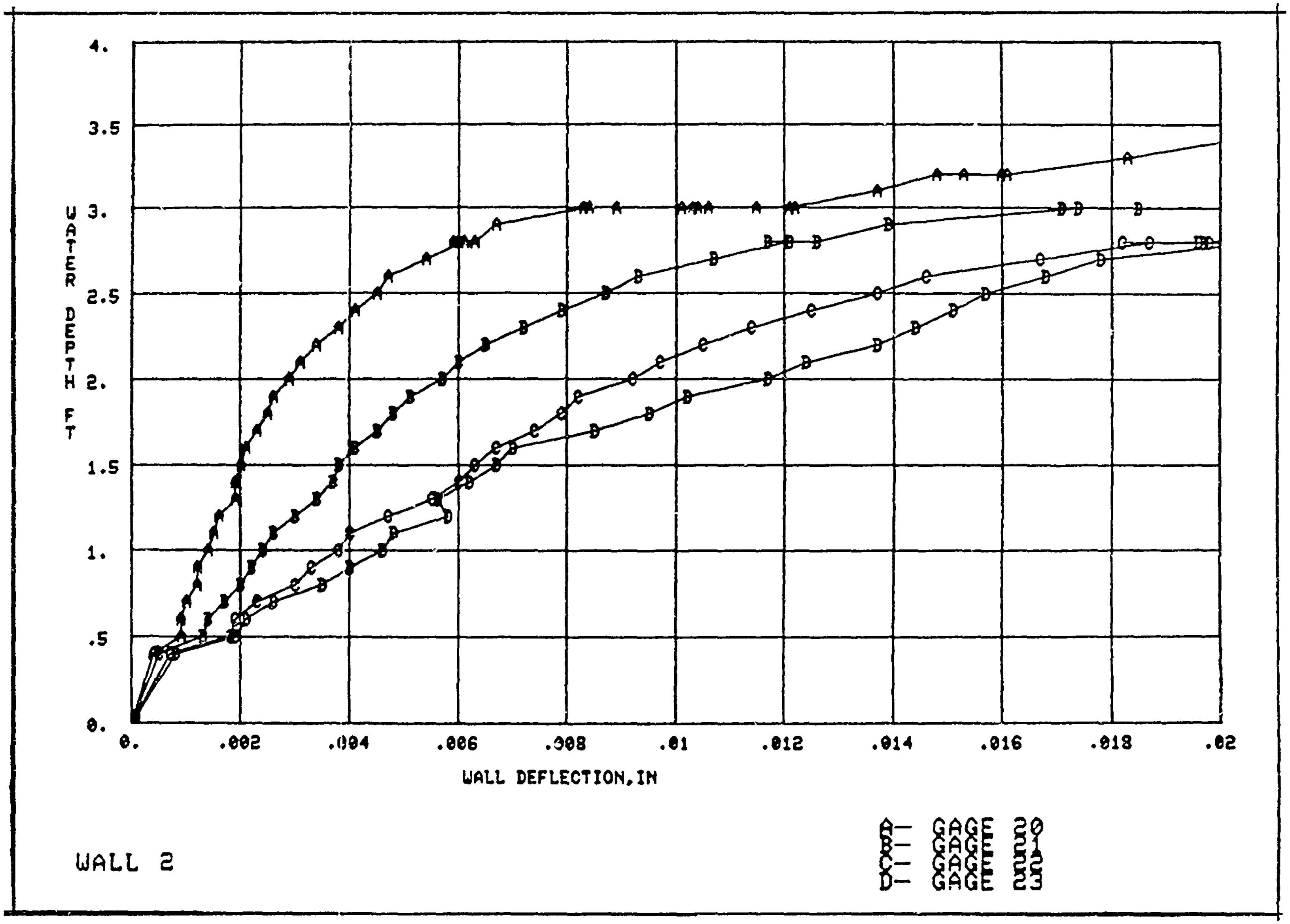


Figure 18. Wall deflections, gages 20, 21, 22, and 23

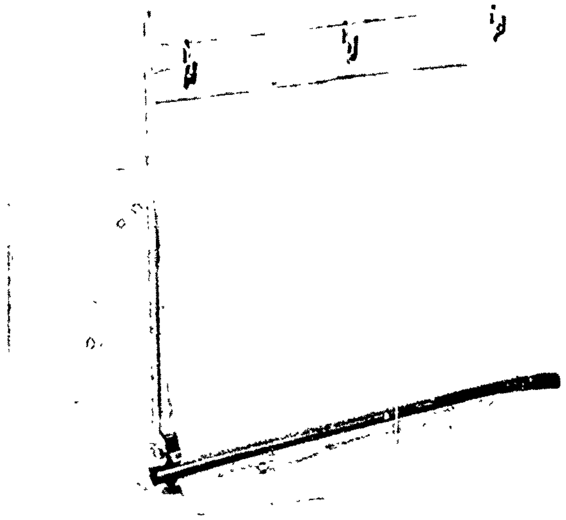


Figure 19. Tubular seal

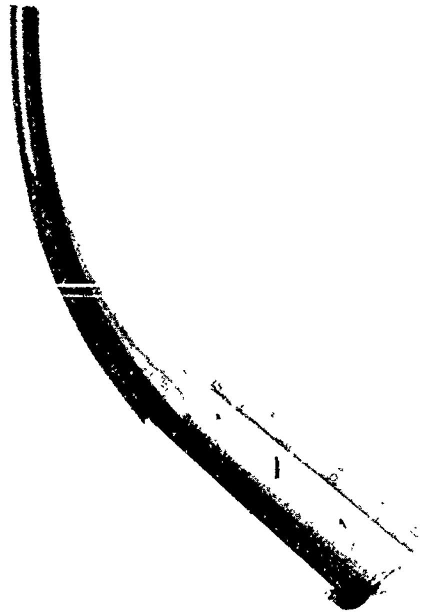


Figure 20. Aluminum seal

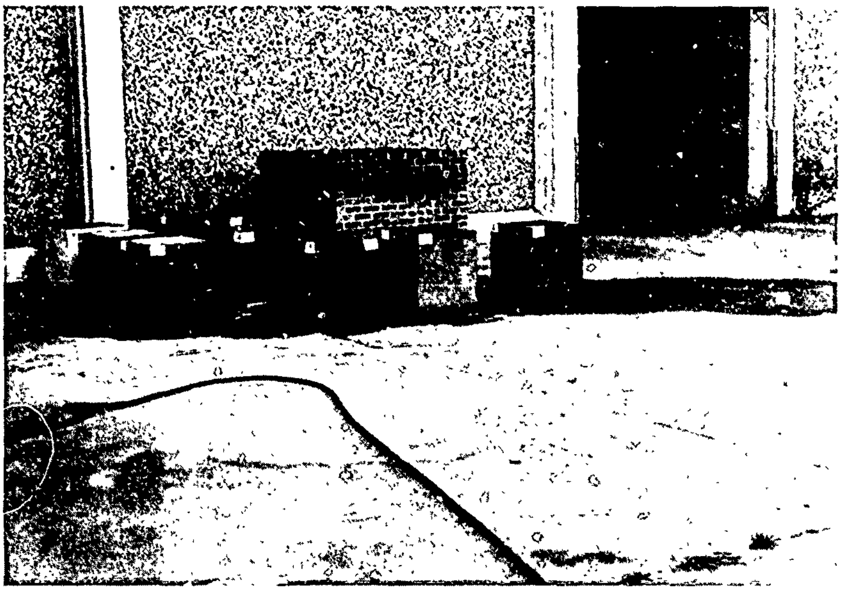
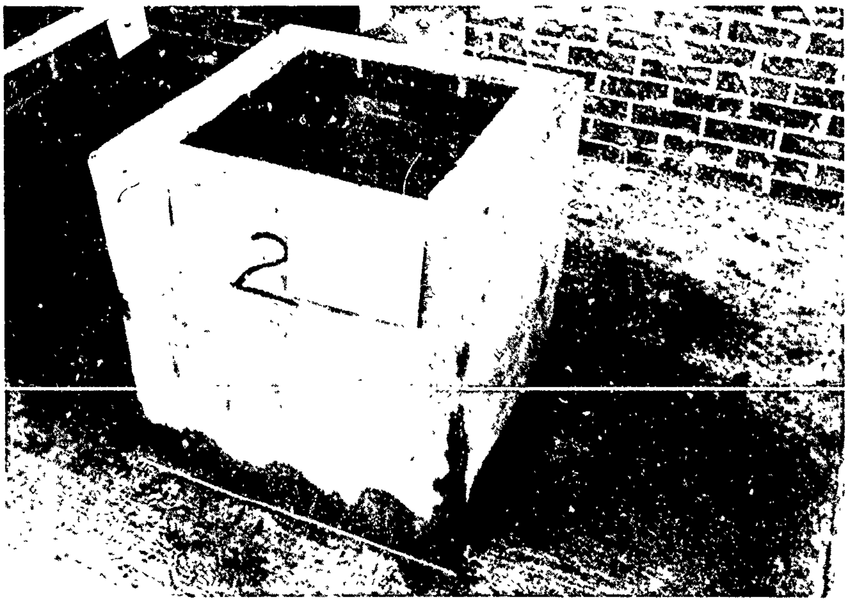


Figure 21. Brick cubes to test sealants and systems for preventing flood damage

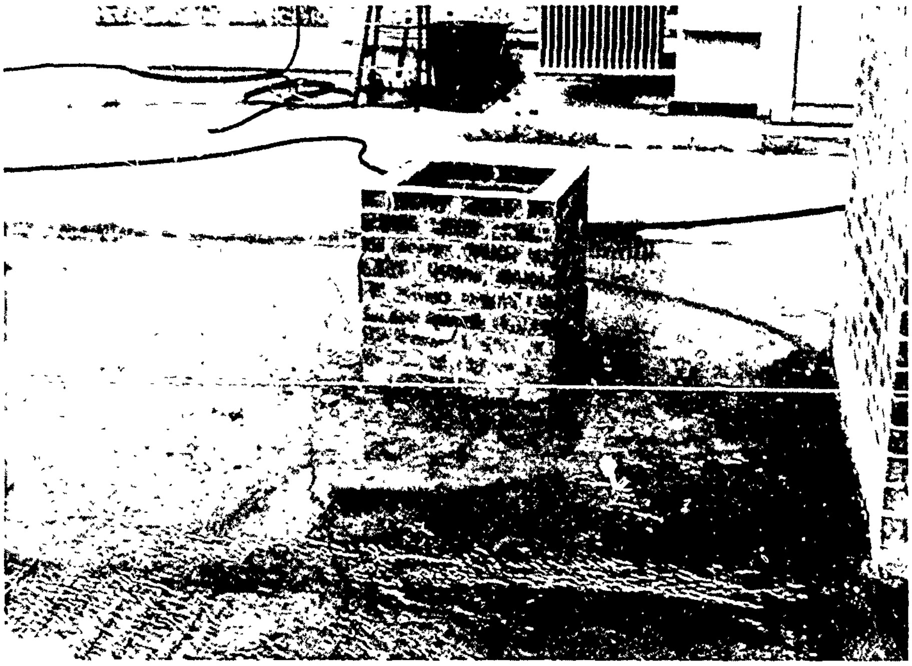
a. Two hours after cube was filled with water



b. One day after cube was filled with water

Figure 22. Initial testing of coating 4

a. Front view



b. Side view

Figure 23. Failure of coating 4

Figure 24. Coating 5

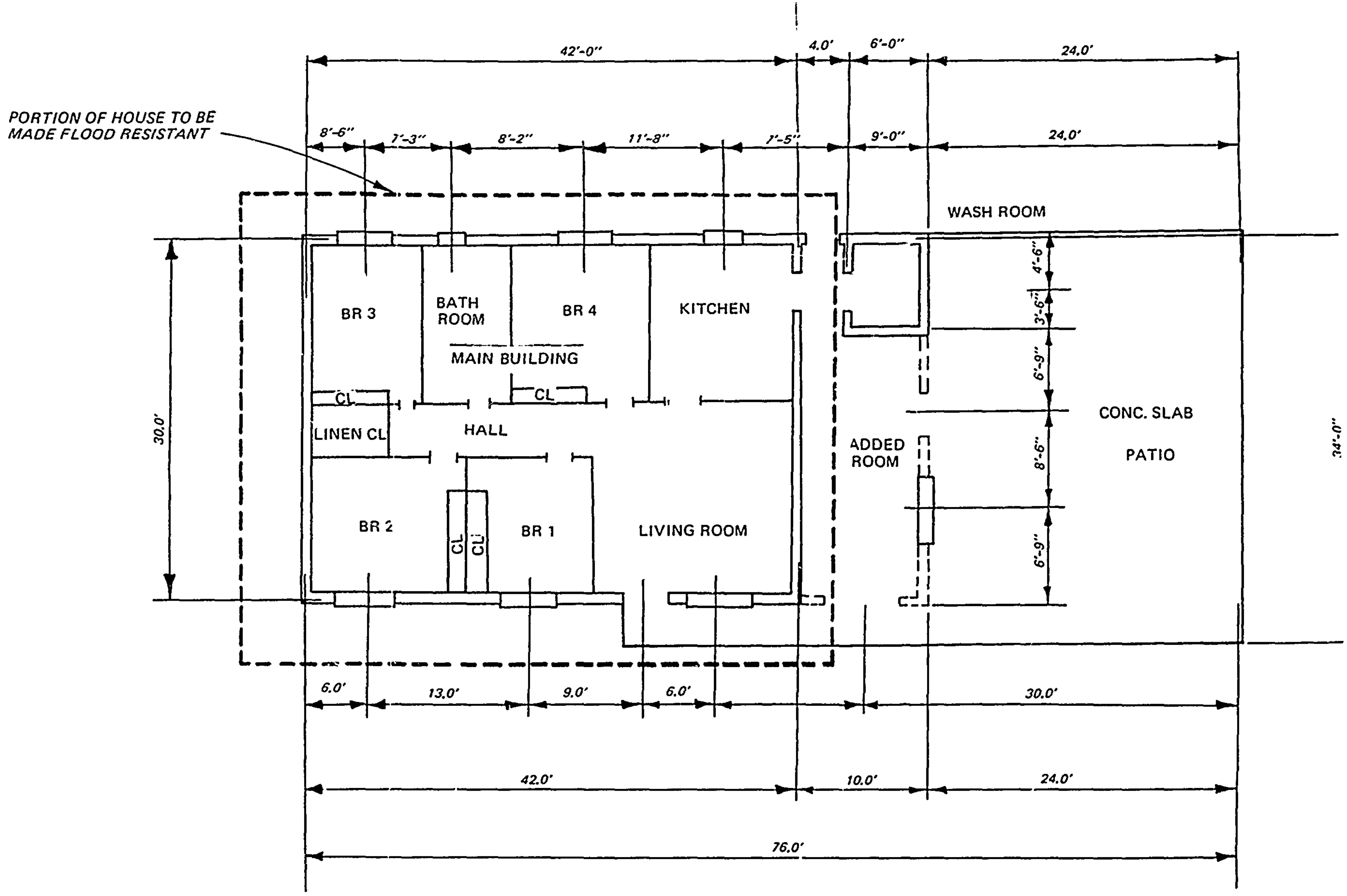


Figure 25. Floor plan of test house

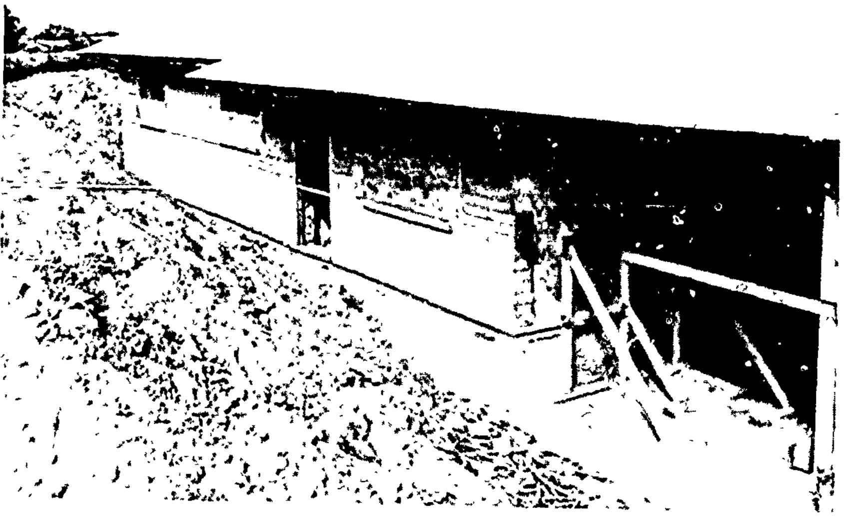
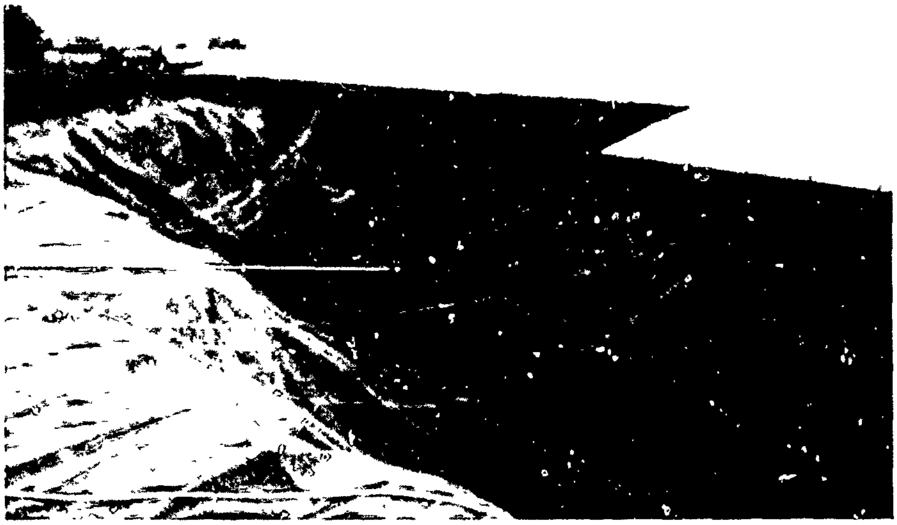


Figure 26. Front view of house to be made resistant to floodwaters

Figure 27. Plywood bulkhead

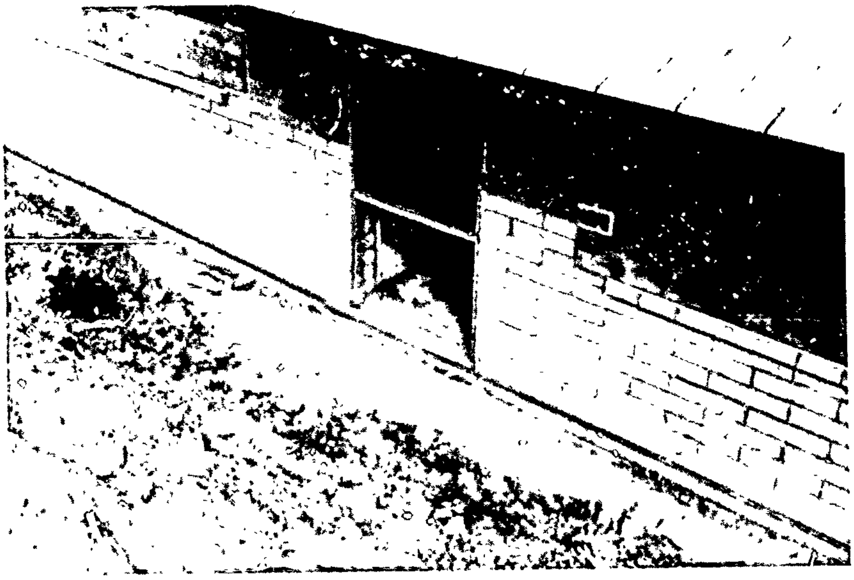


a. Earth berm

b. Plywood bulkhead

Figure 28. Earth berm and plywood bulkhead

Figure 29. Plastic-over-earth berm extending down and under aluminum sealing strip



a. General view

b. Close-up

Figure 30. Aluminum strip around base of house

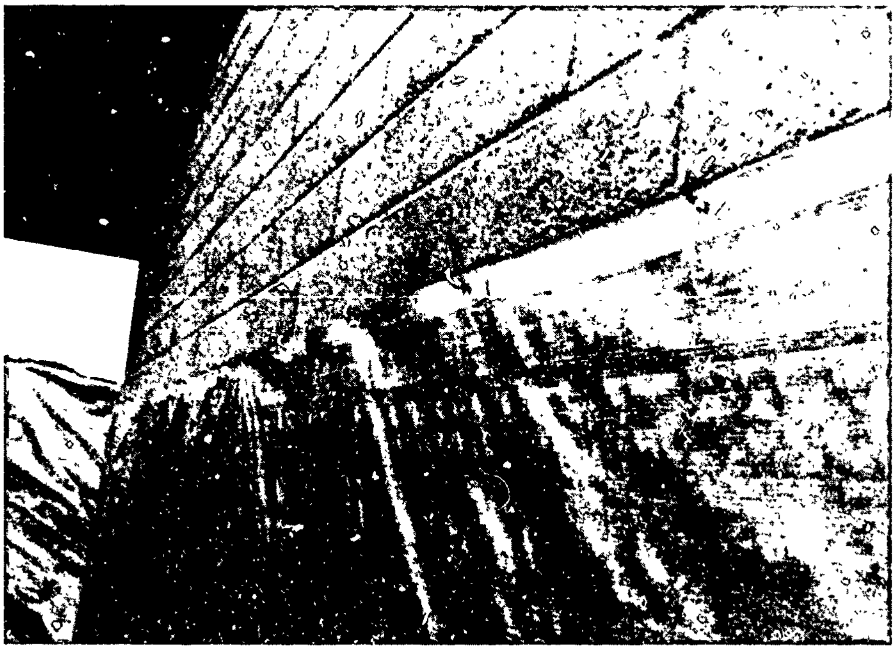
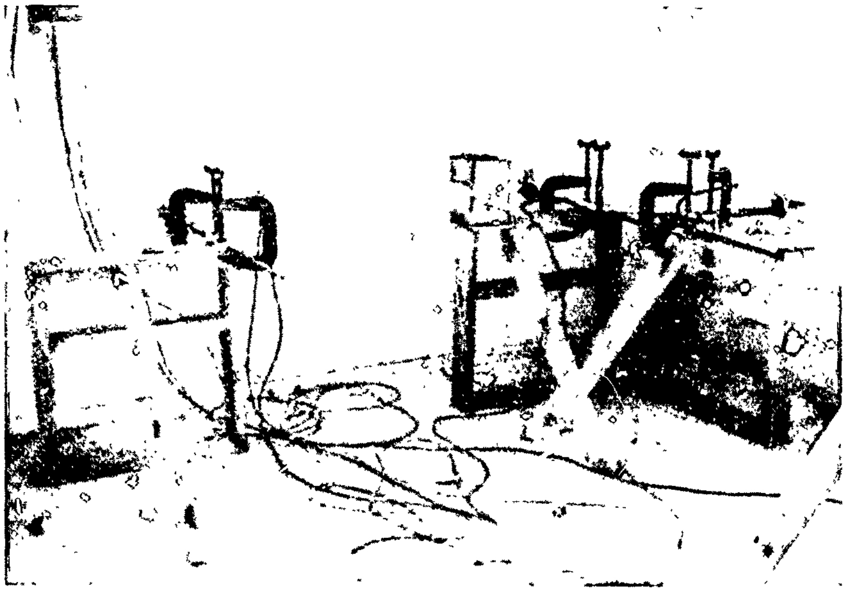
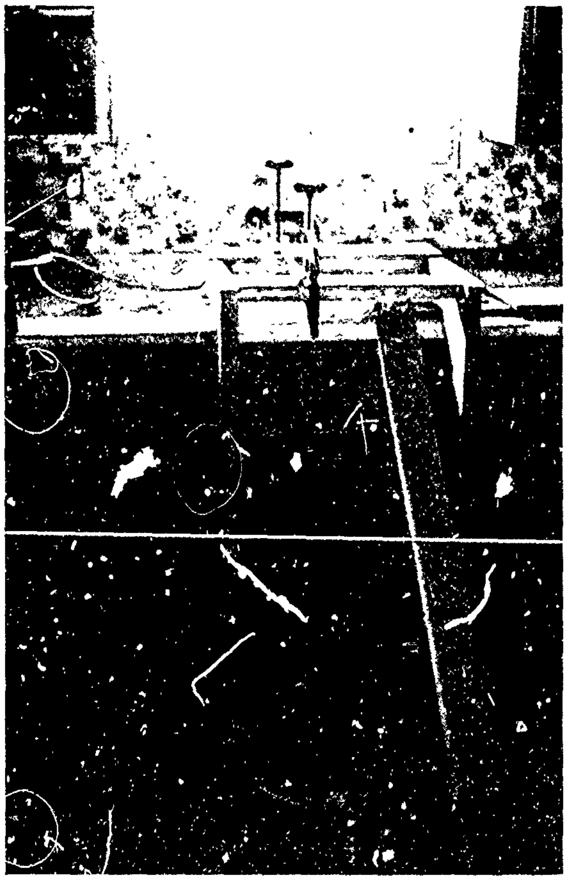


Figure 31. Hooks holding reinforced plastic sheeting



a. Gage placement in bedroom 2



b. Gage placement in kitchen

Figure 32. Gage placement

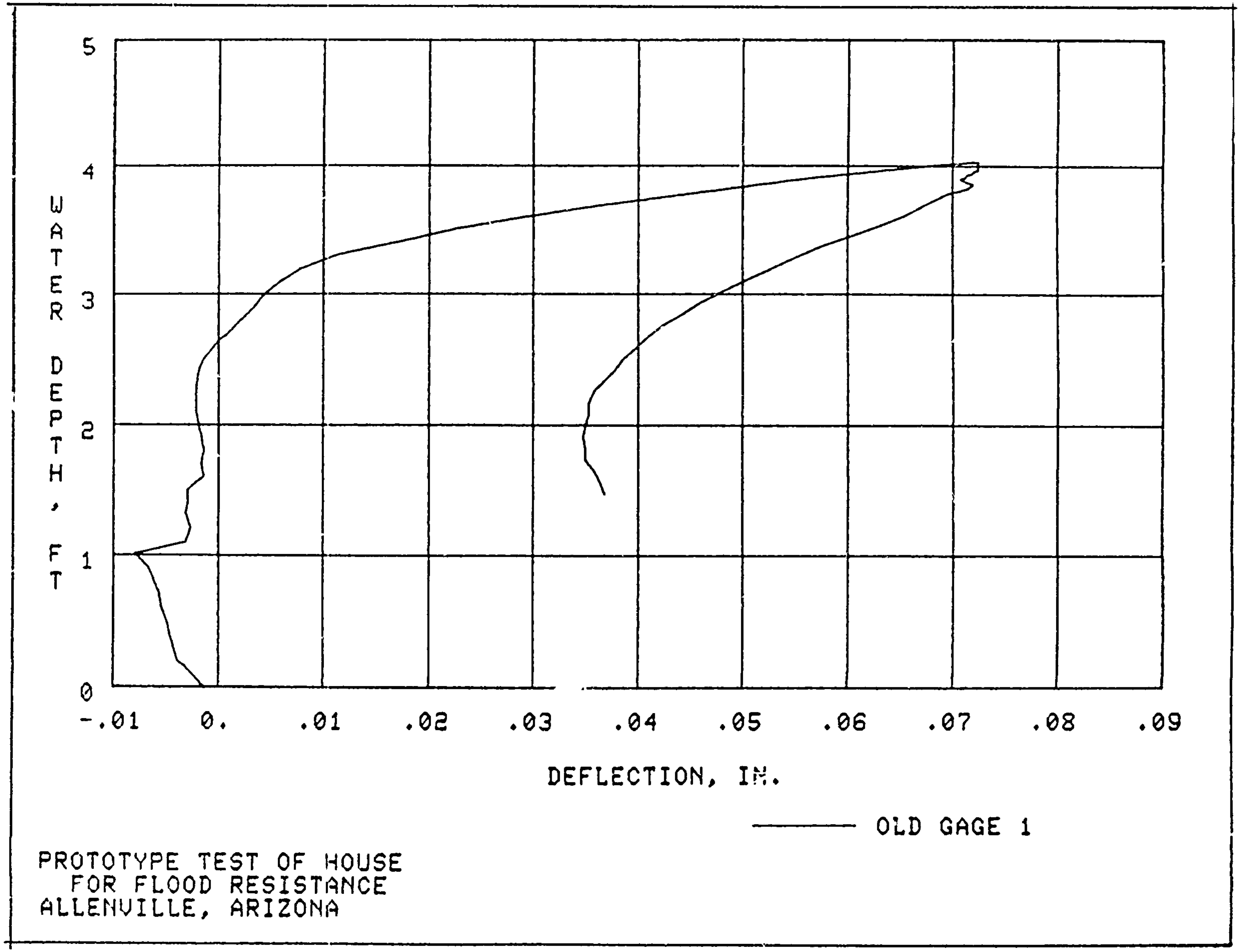


Figure 33. Prototype house test results, gage 1

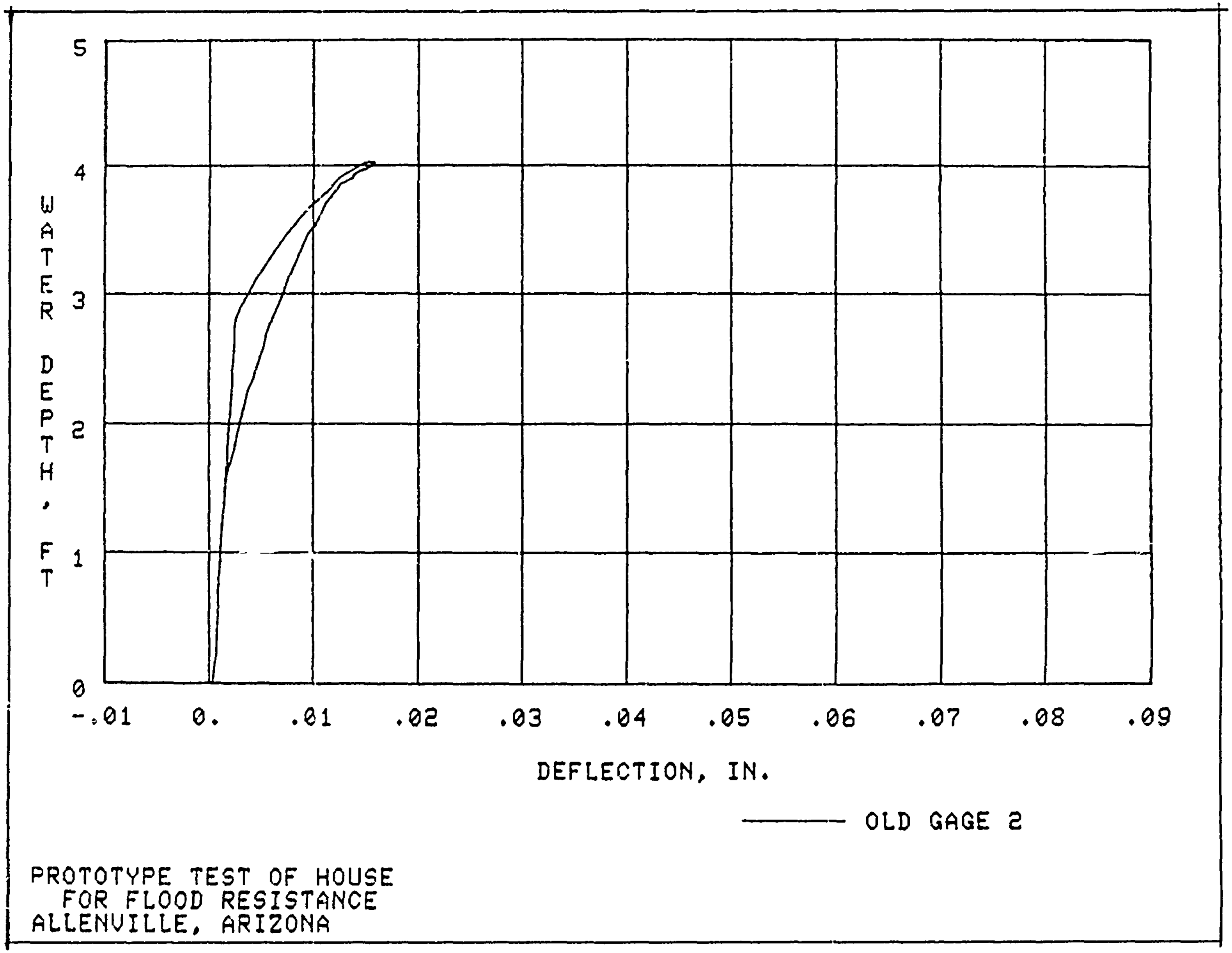


Figure 34. Prototype house test results, gage 2

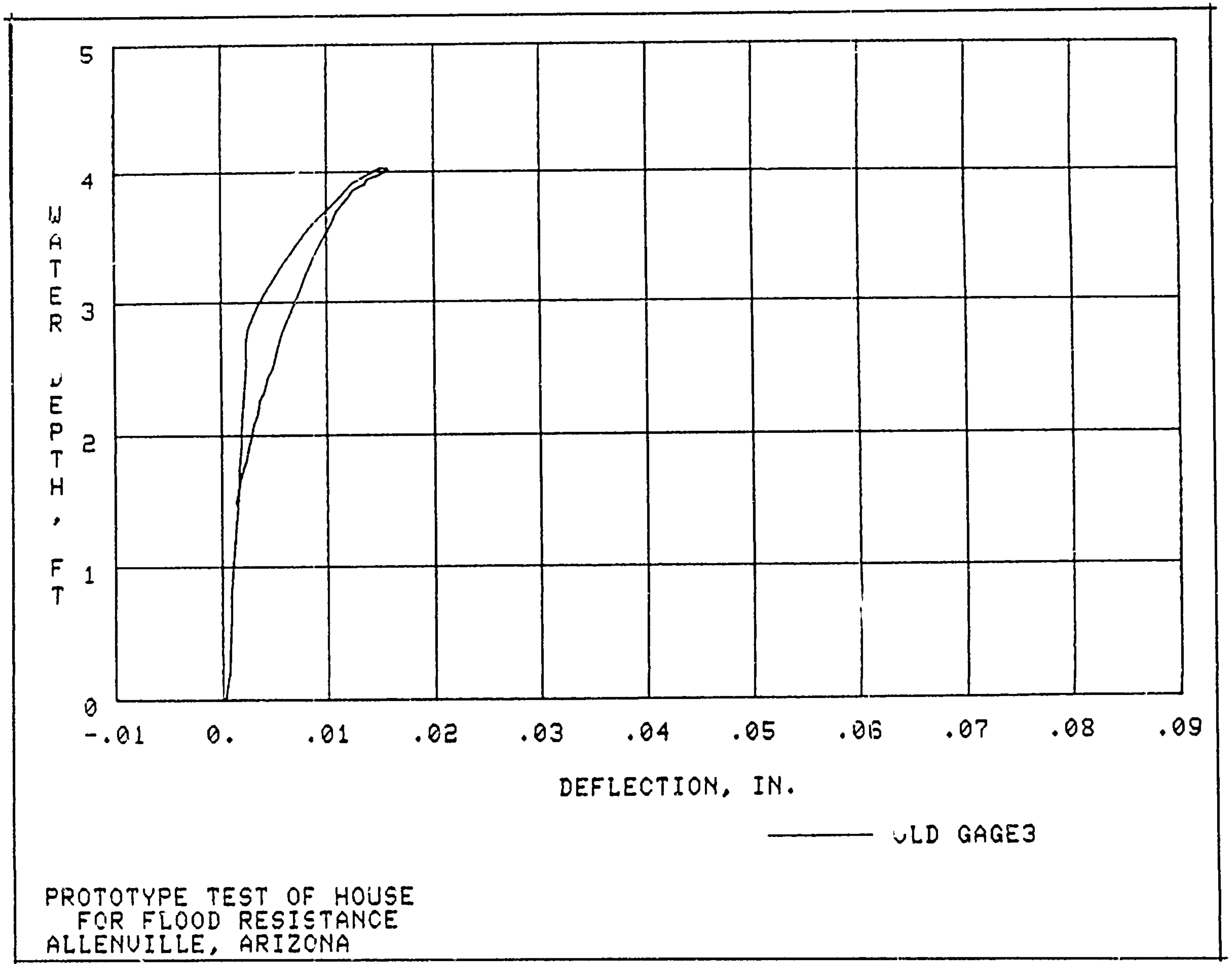


Figure 35. Prototype house test results, gage 3

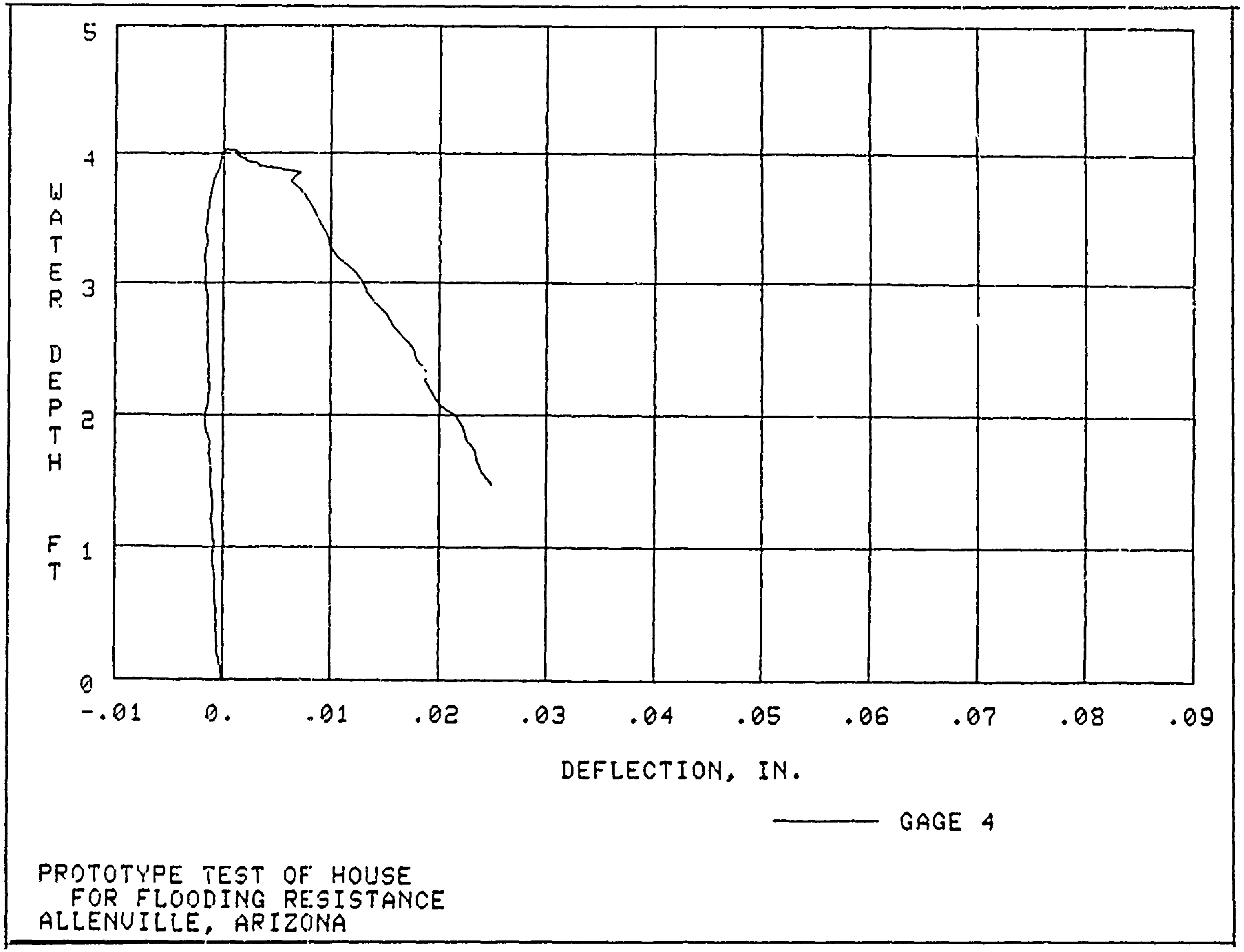


Figure 36. Prototype house test results, gage 4

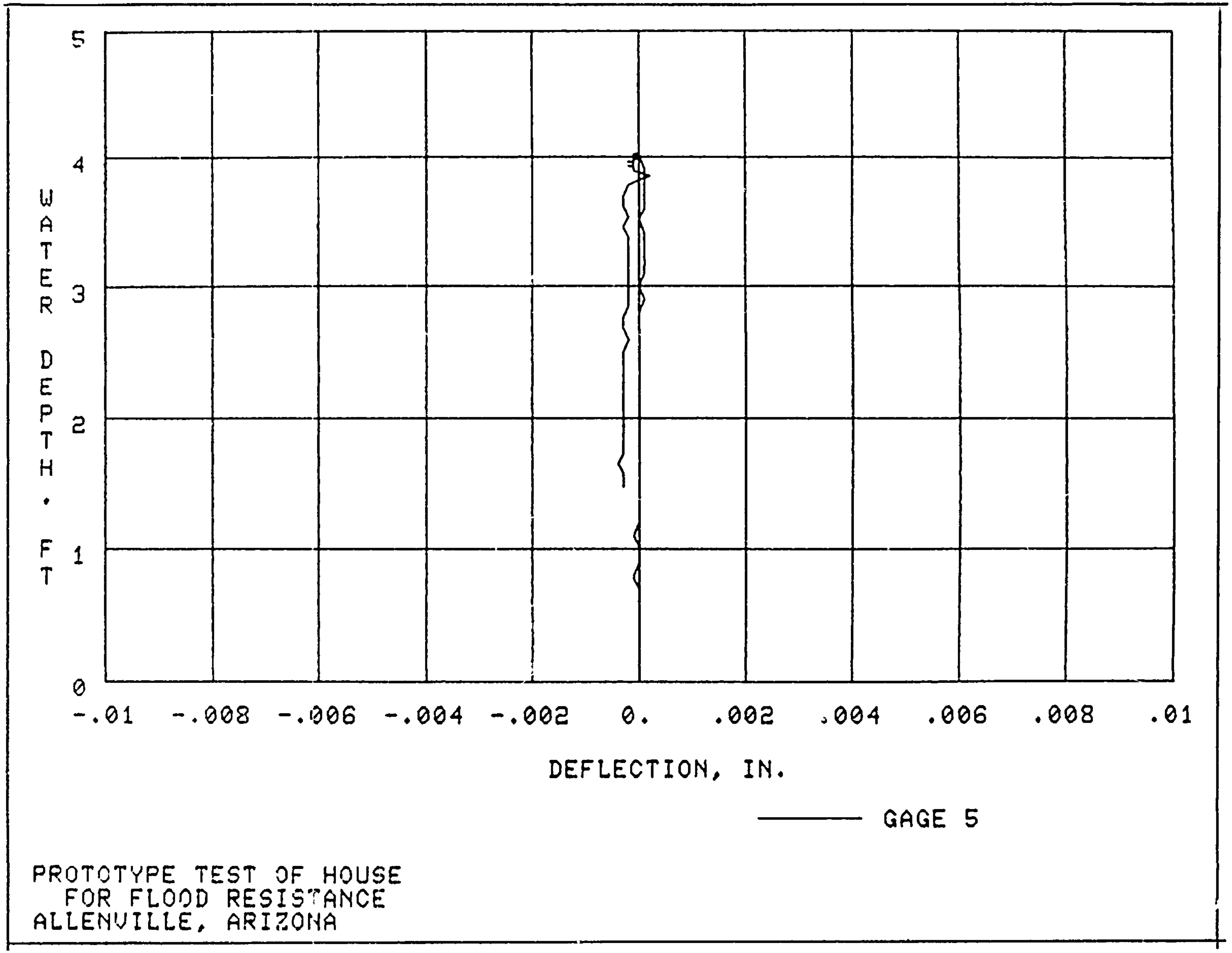


Figure 37. Prototype house test results, gage 5

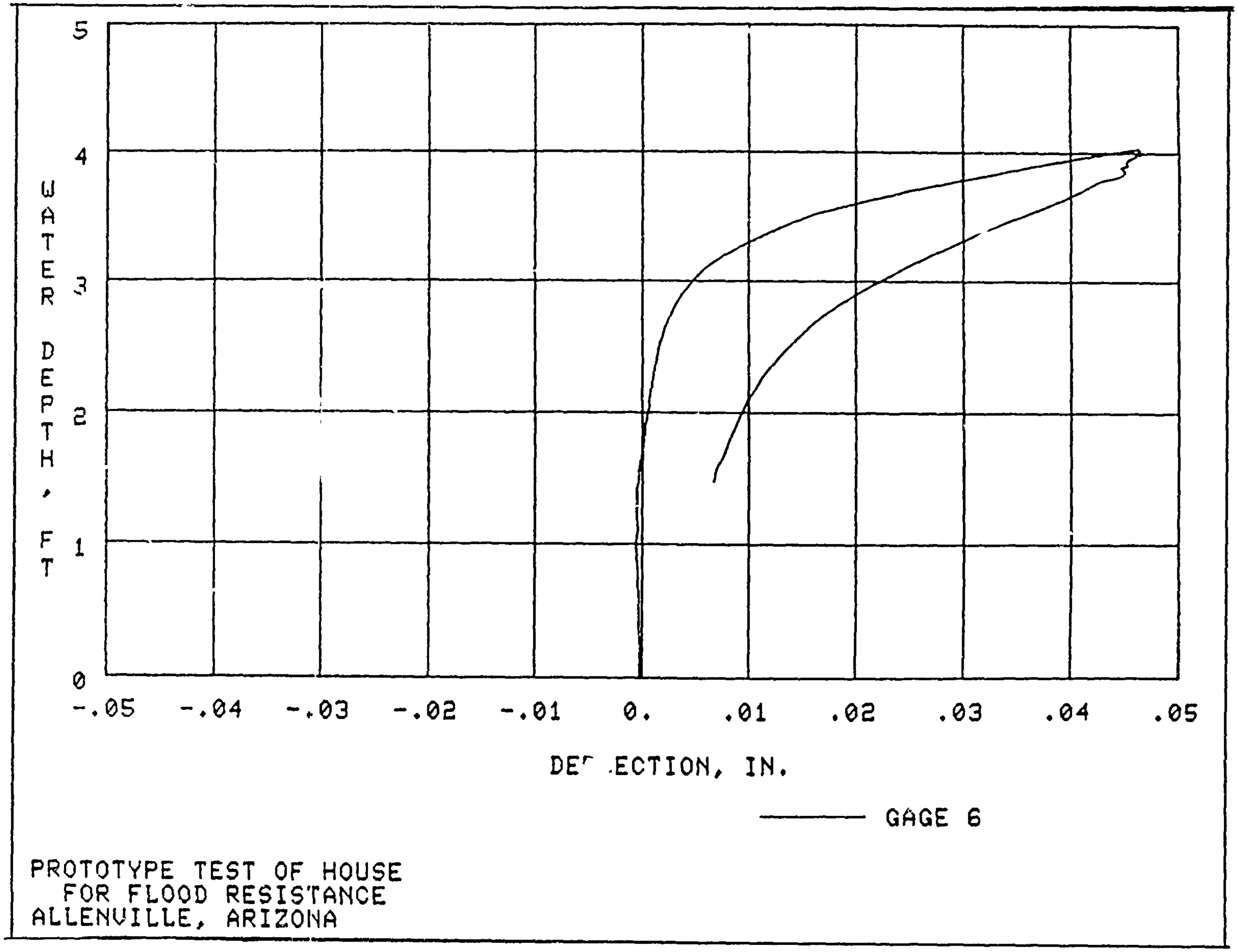


Figure 38. Prototype house test results, gage 6

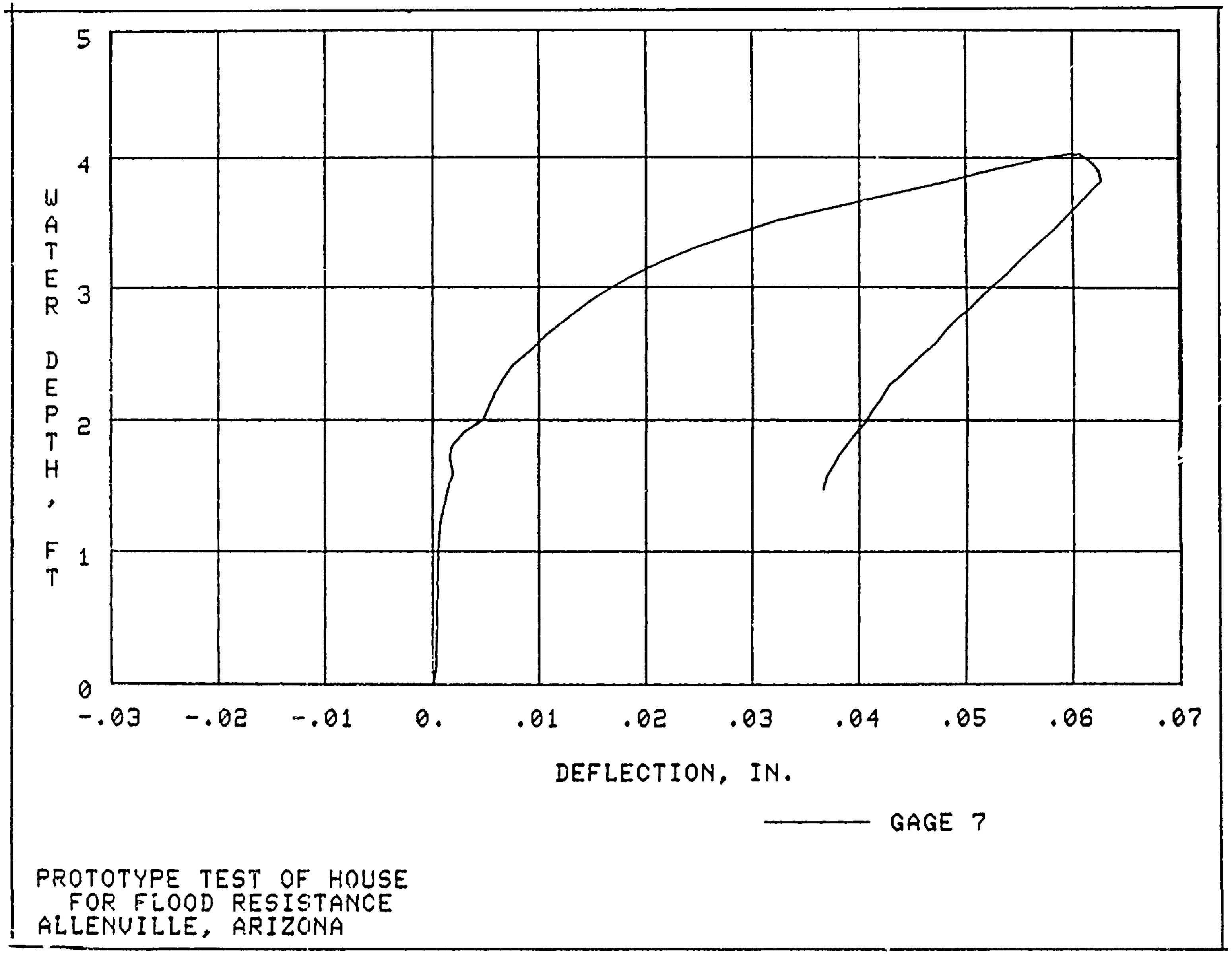


Figure 39. Prototype house test results, gage 7

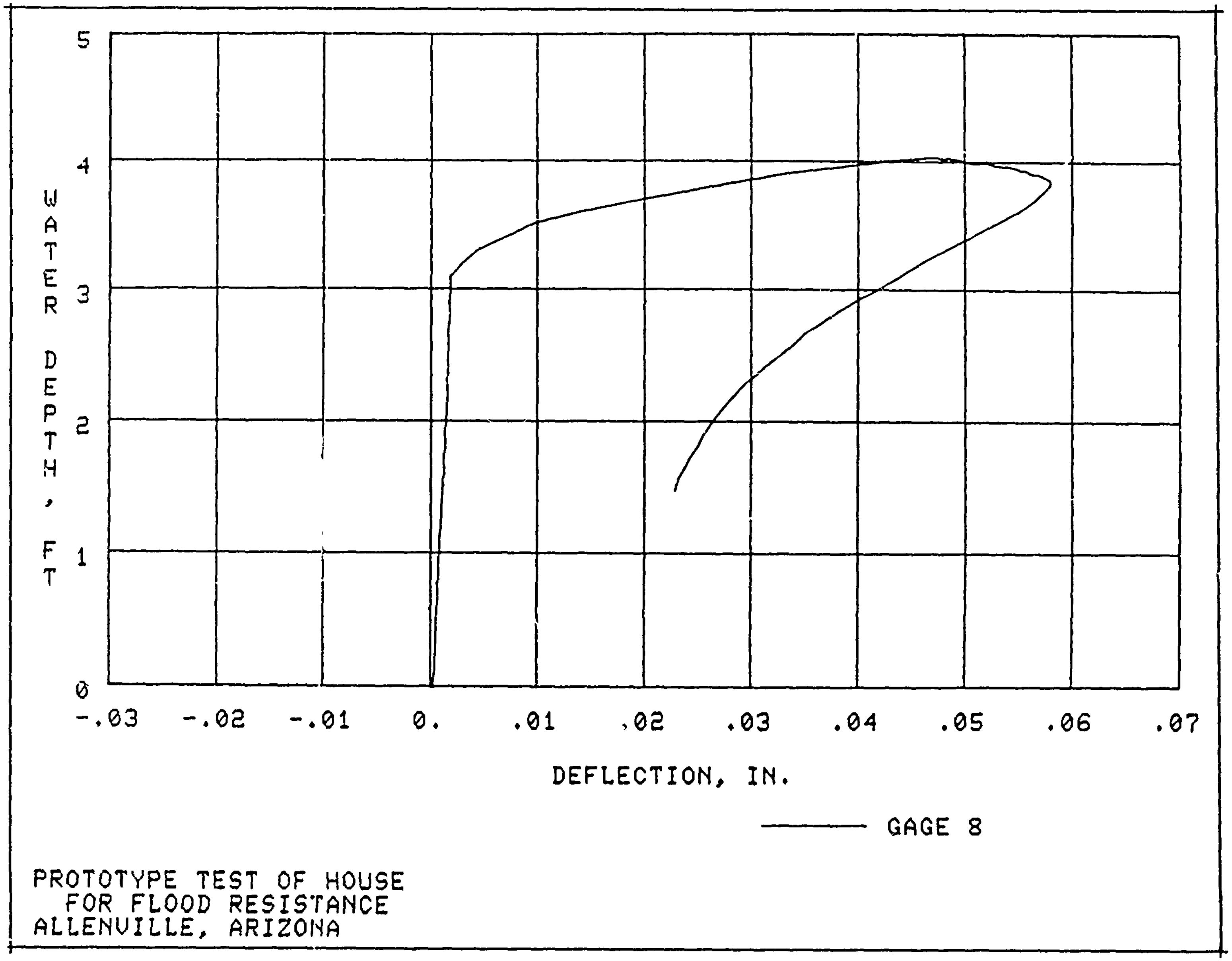


Figure 40. Prototype house test results, gage 8

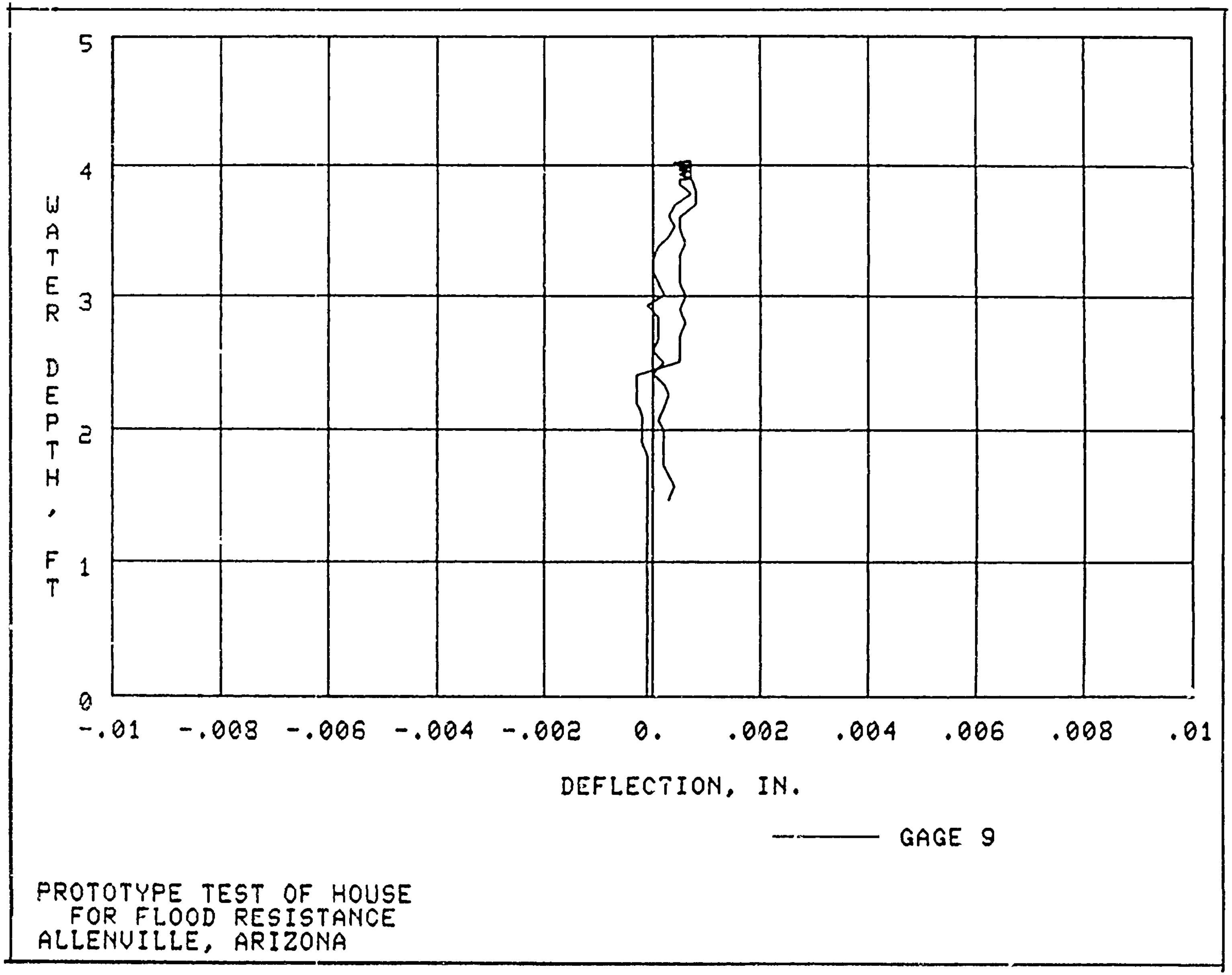


Figure 41. Prototype house test results, gage 9

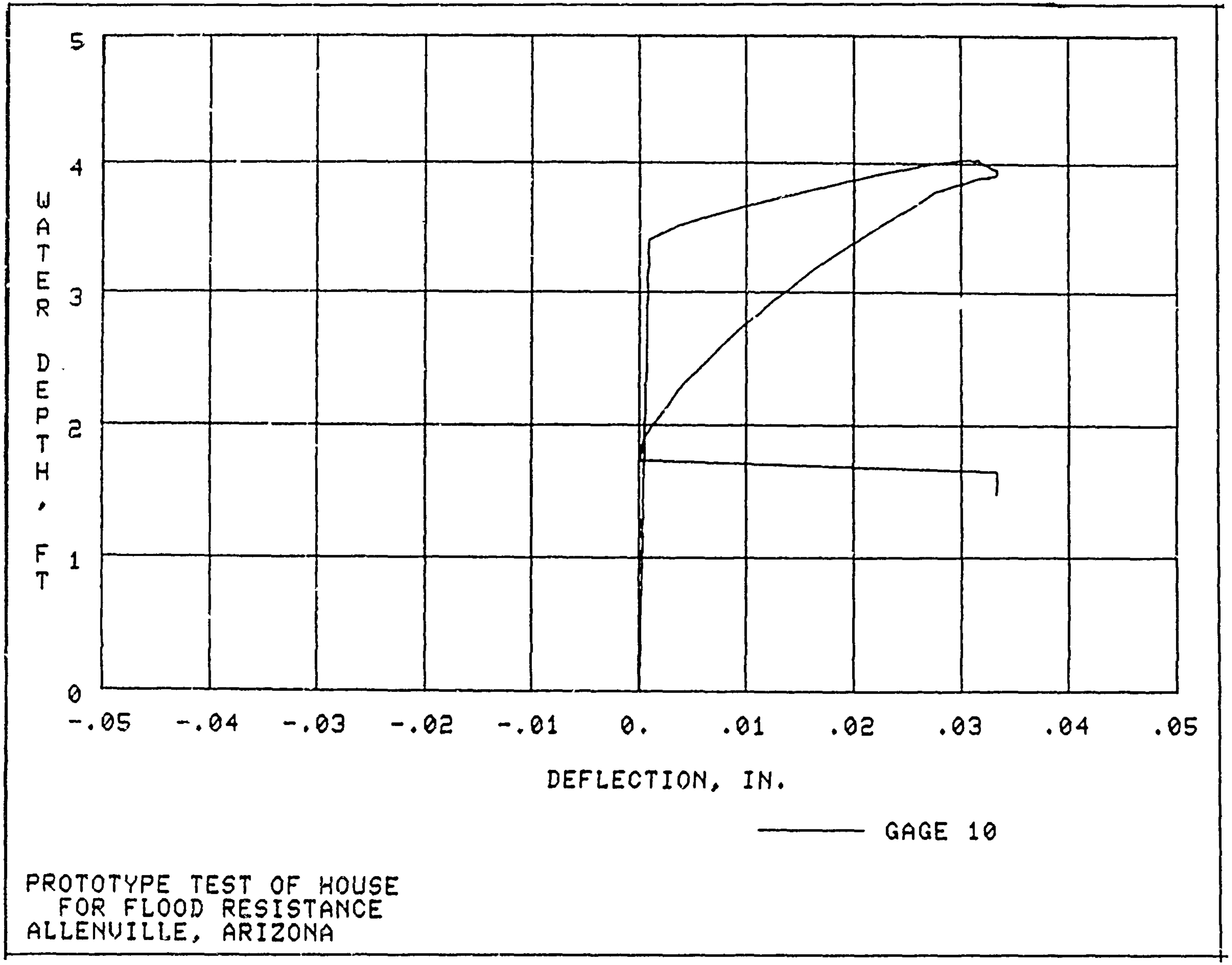


Figure 42. Prototype house test results, gage 10

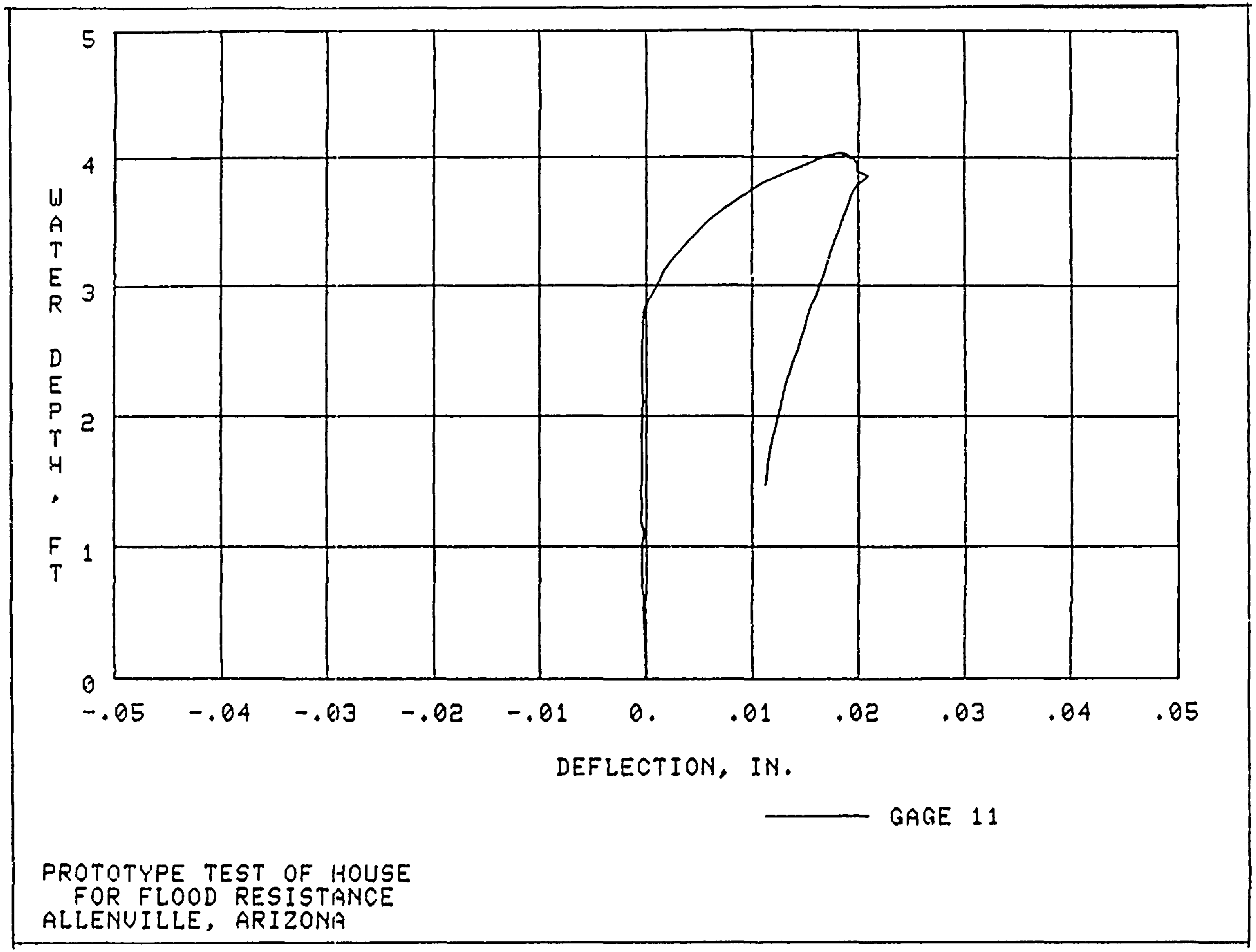


Figure 43. Prototype house test results, gage 11

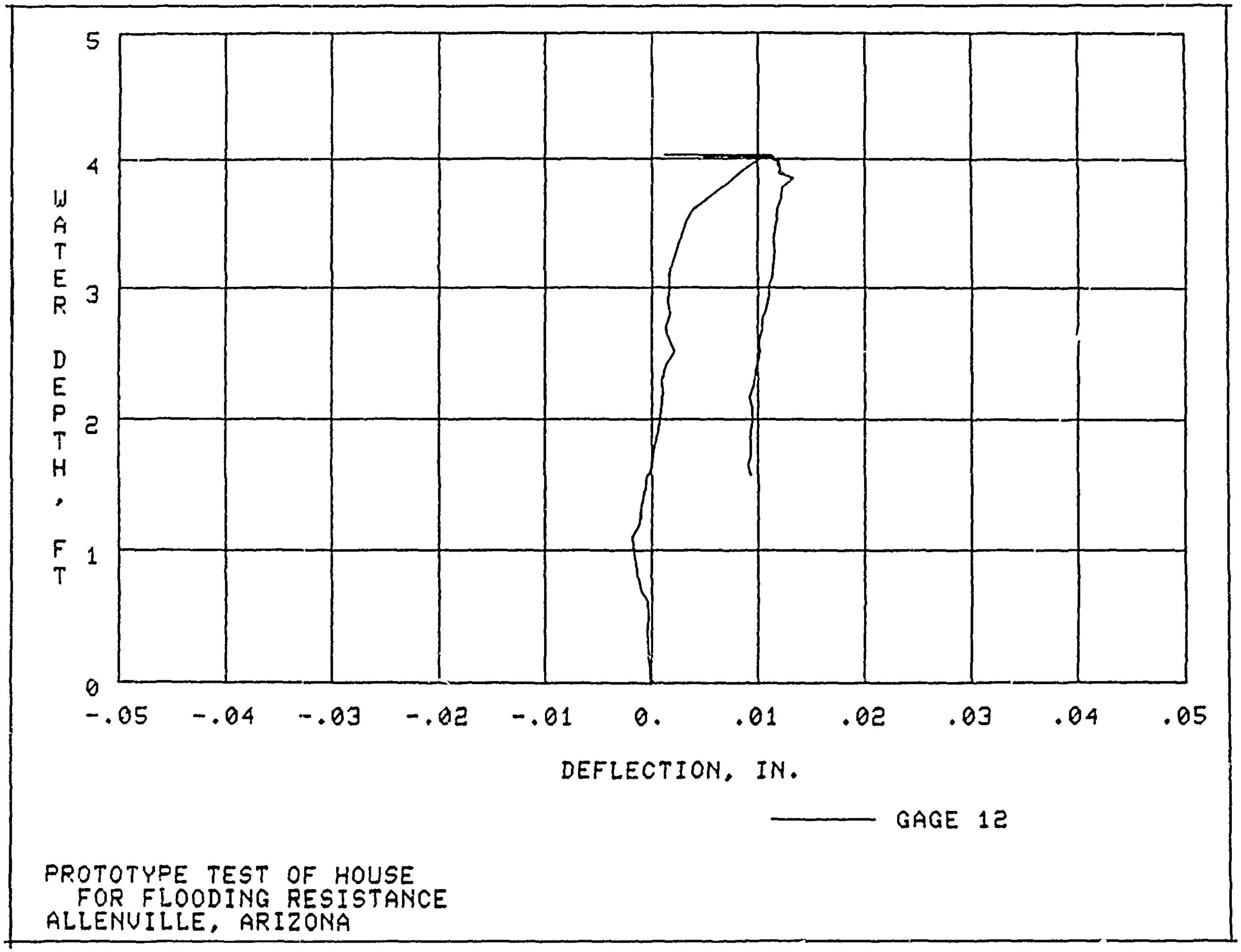


Figure 44. Prototype house test results, gage 12

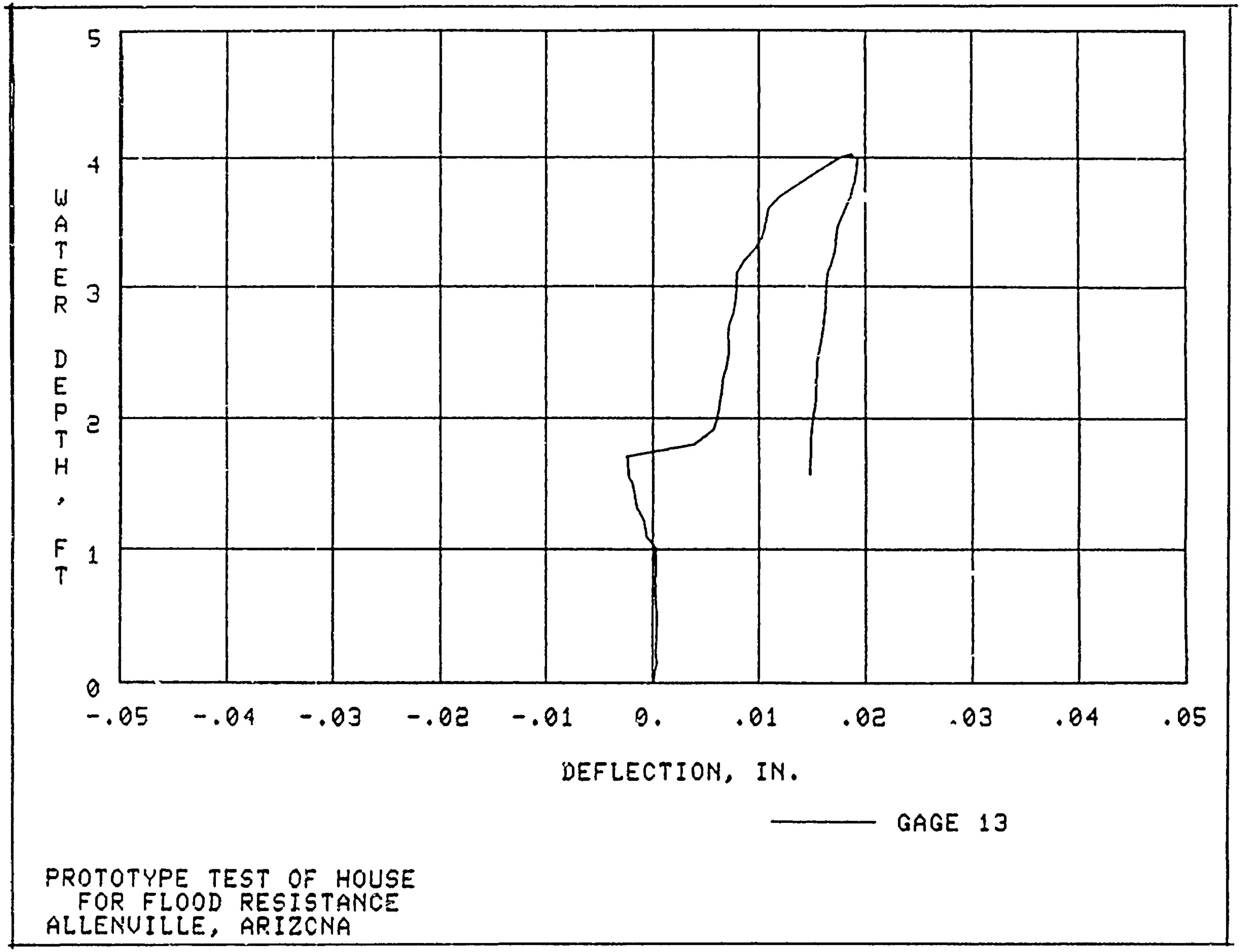


Figure 45. Prototype house test results, gage 13

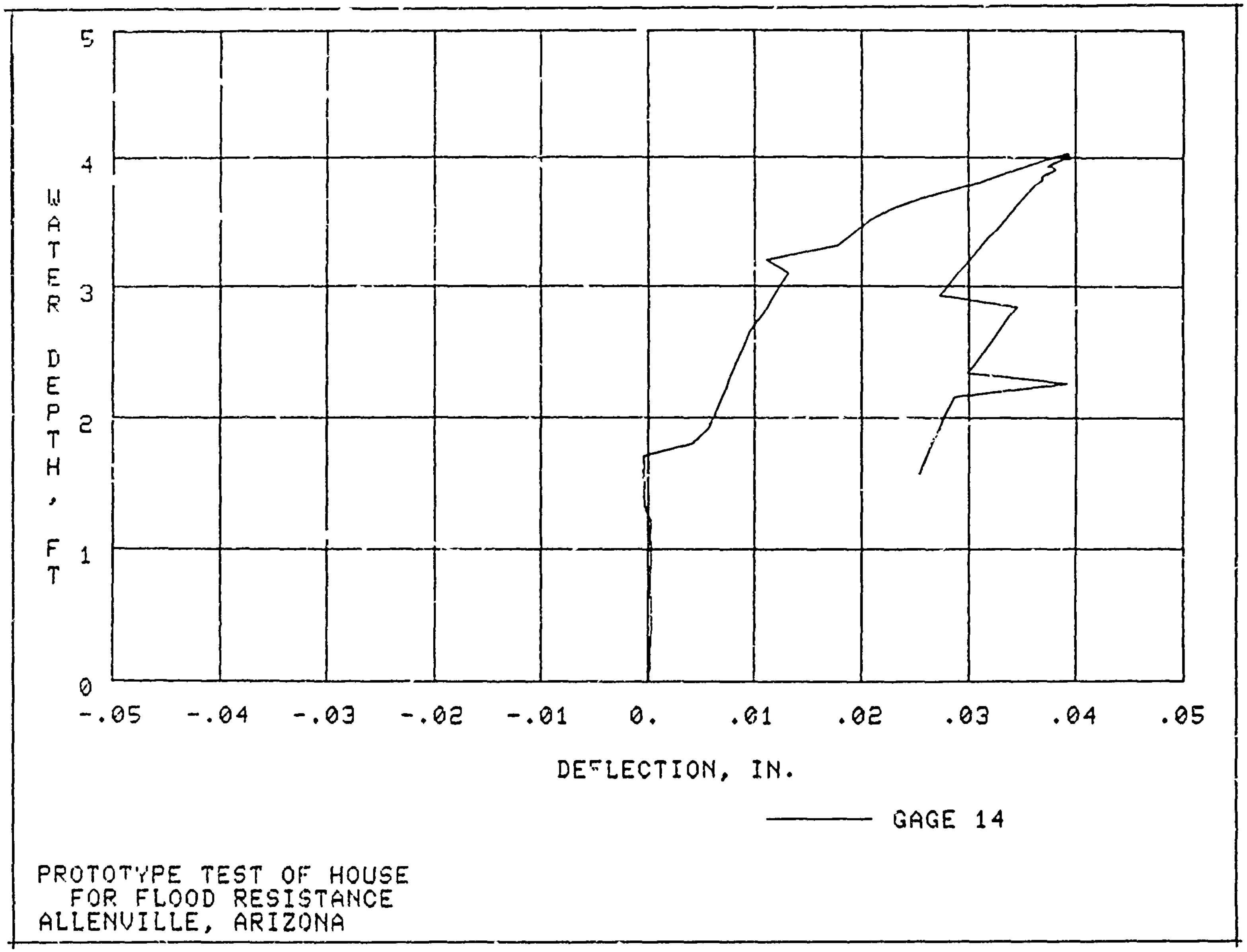


Figure 46. Prototype house test results, gage 14

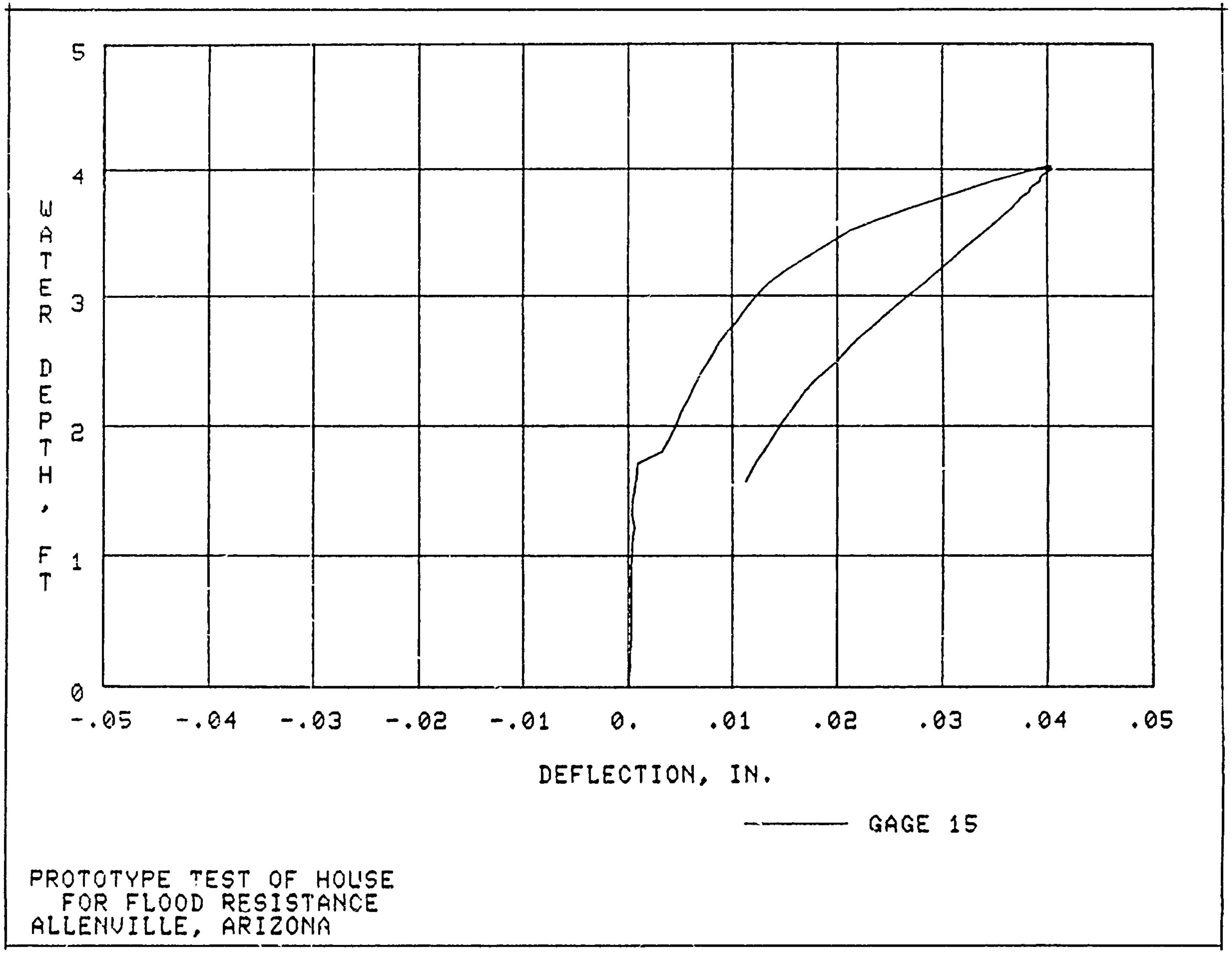


Figure 47. Prototype house test results, gage 15

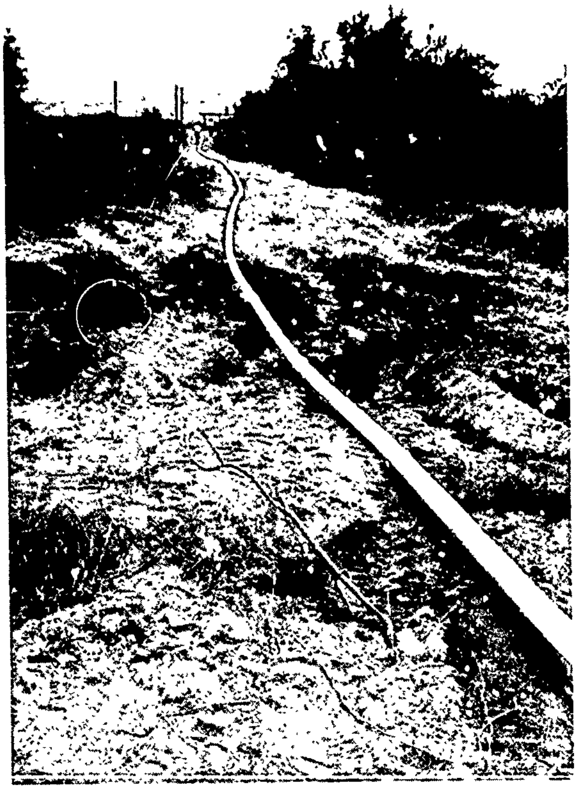


Figure 48. Pipe through which water was pumped to test house

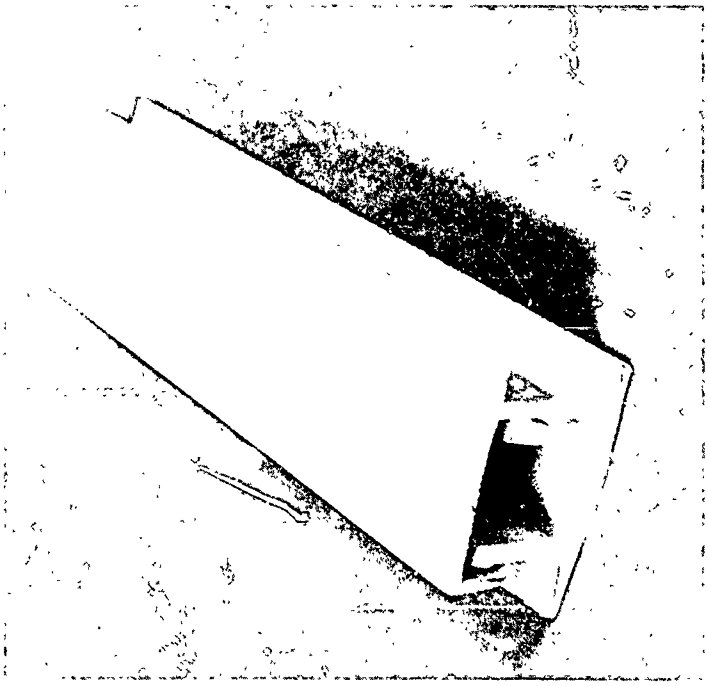


Figure 49. Designed sealing strip

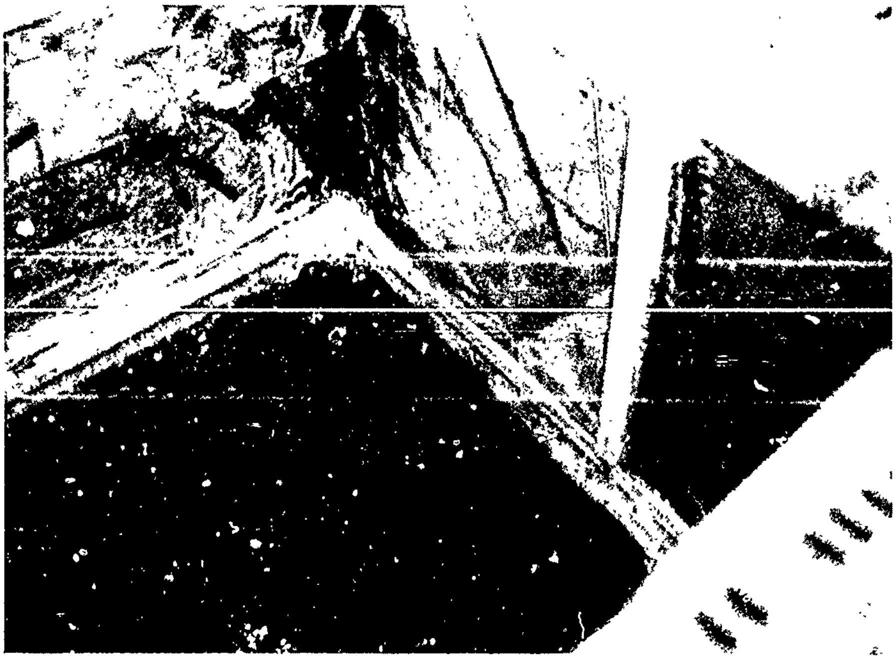
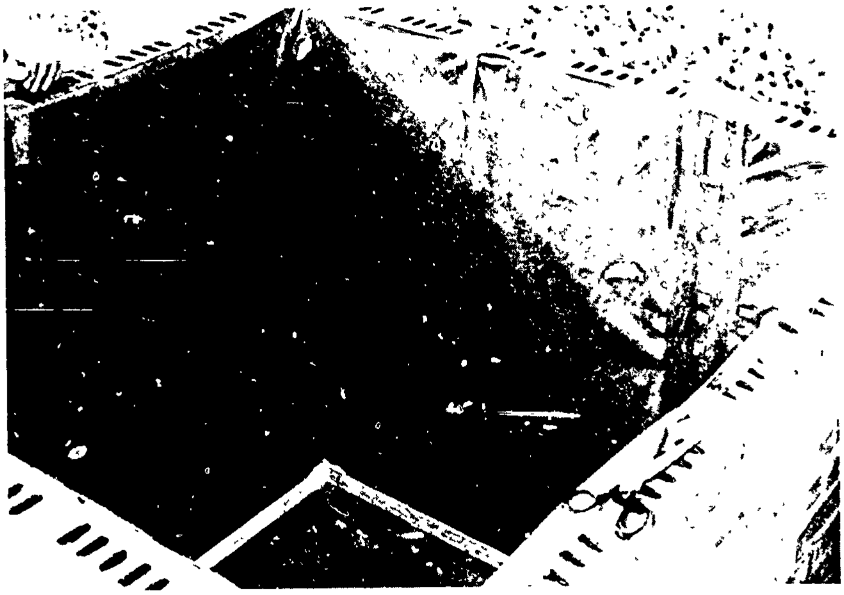
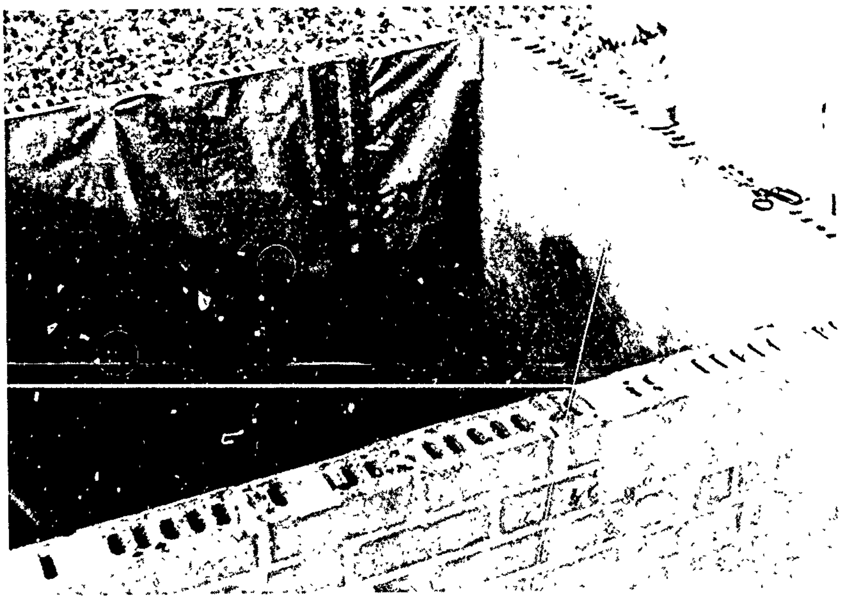


Figure 50. Seal strip snapped against plastic to form a seal



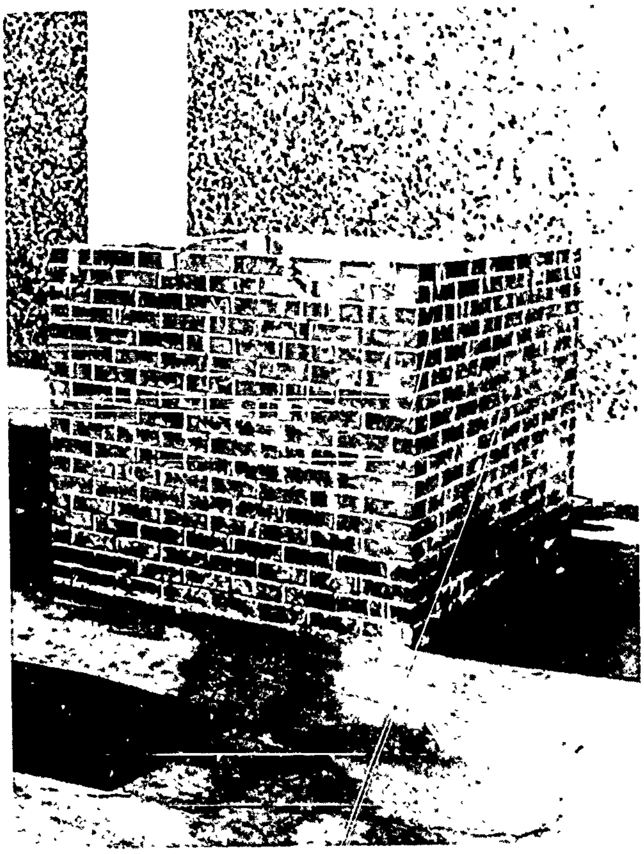
a. Seal strip corner



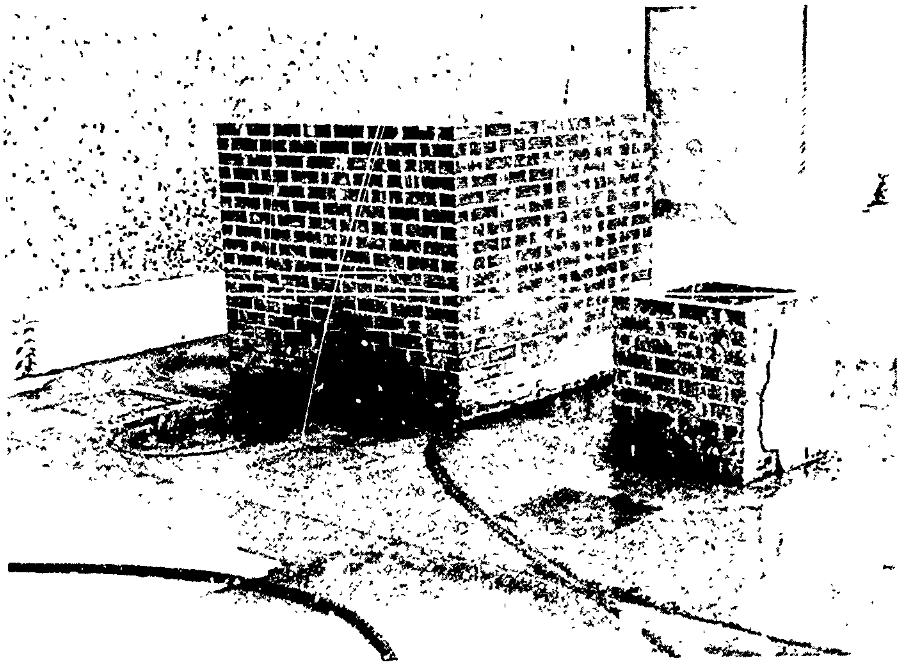
b. Plastic sheeting covering brick wall

Figure 51. Plastic sheeting and seal strip

Figure 52. Commercially available seal strip



a. Front view



b. Side view

Figure 53. Dye in water leaking from large brick cube

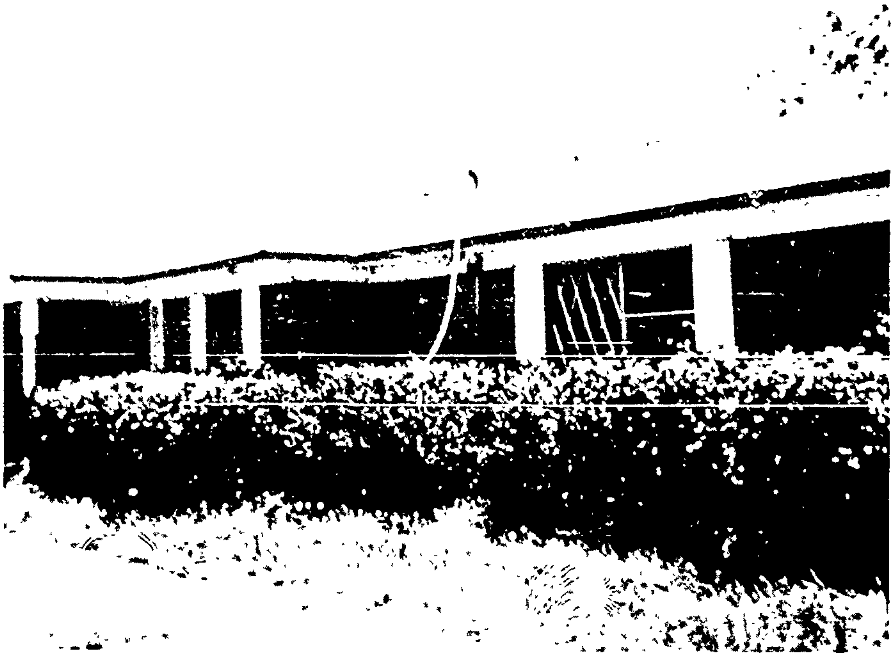


Figure 54. Prototype house, Tulsa, Oklahoma

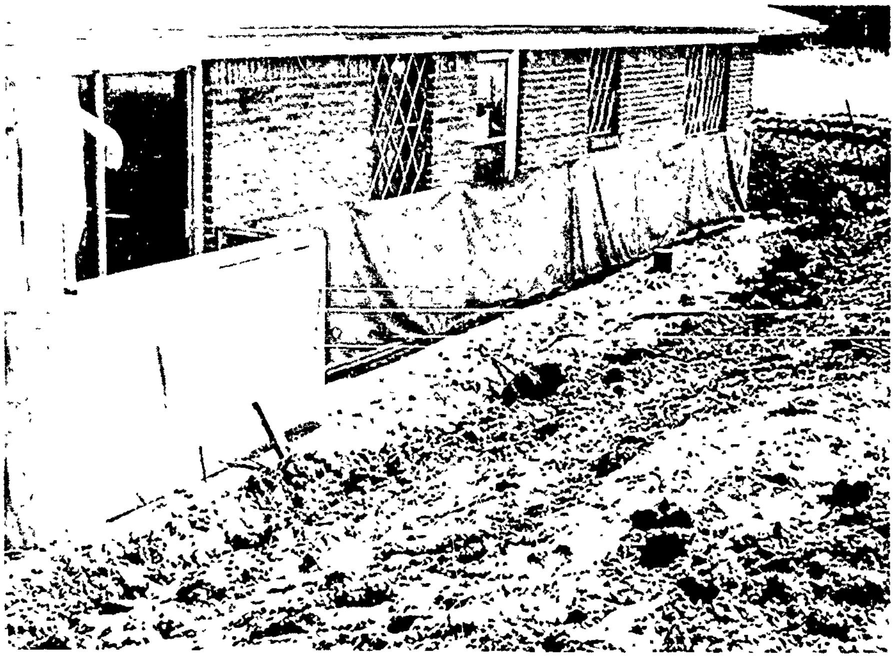


Figure 55. Vinyl-coated nylon fabric used in preparing house to resist floodwaters

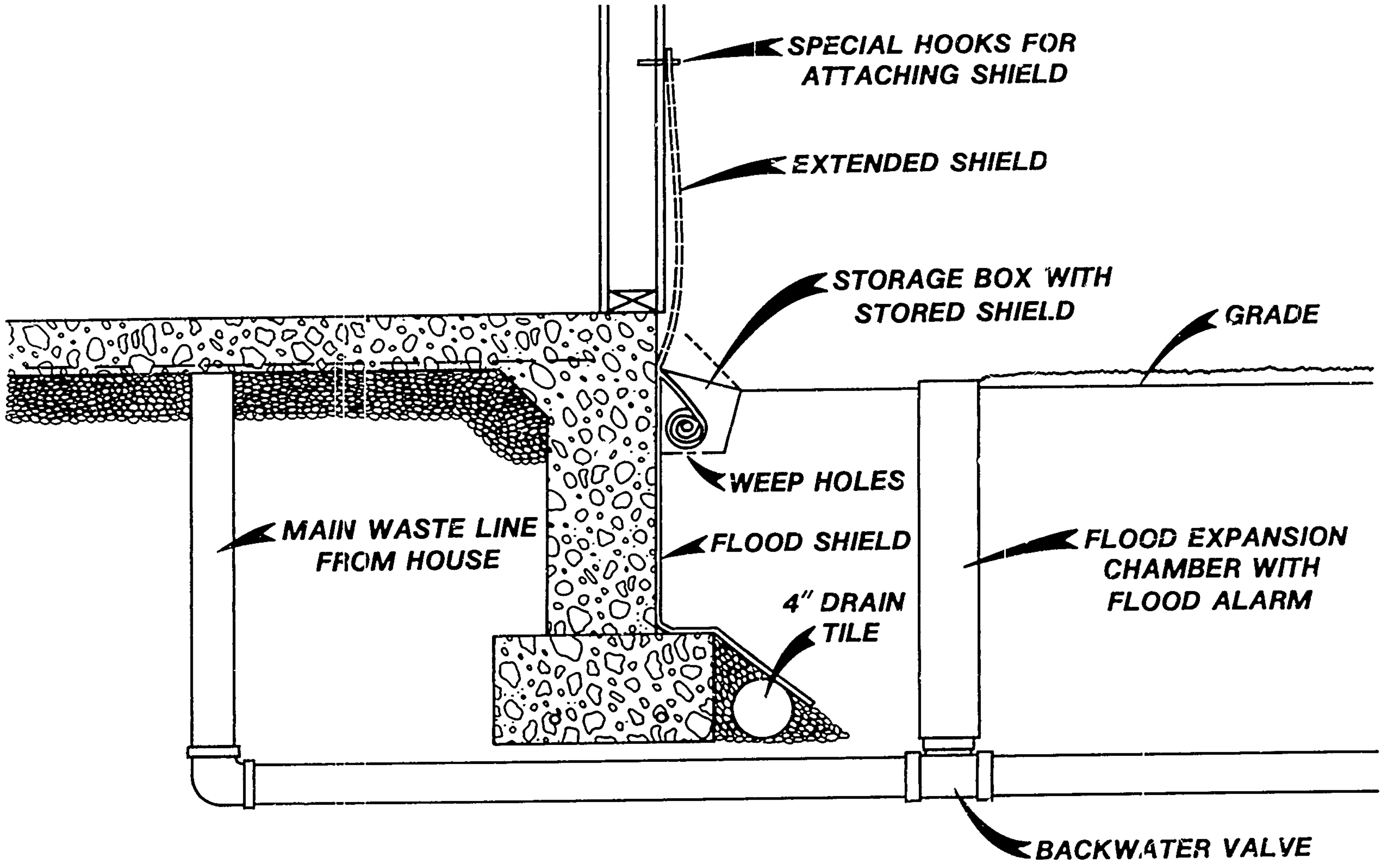


Figure 56. Schematic of embedded fabric and drainage system making up the installed flood shield

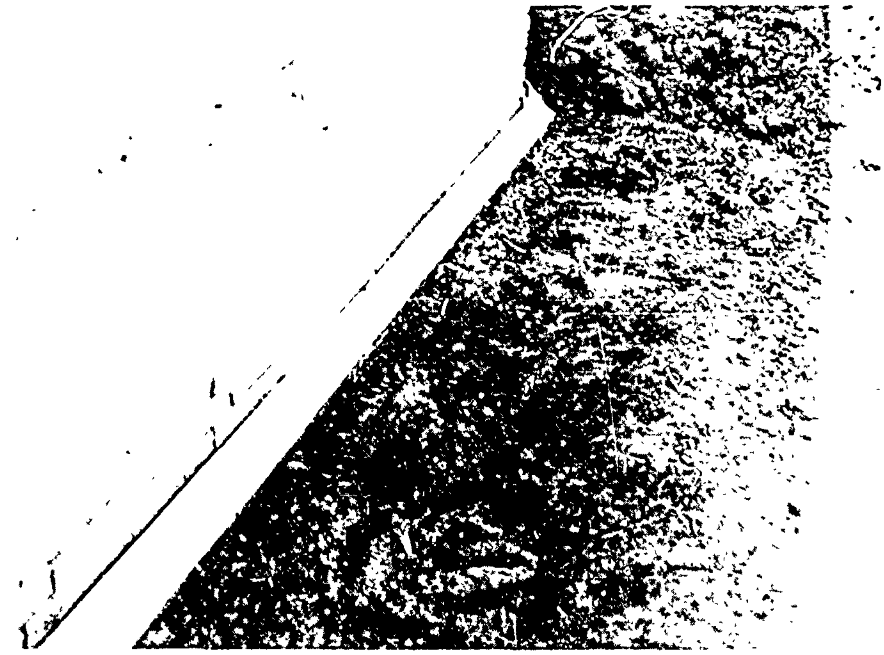


Figure 57. Trough in which protective fabric is permanently stored

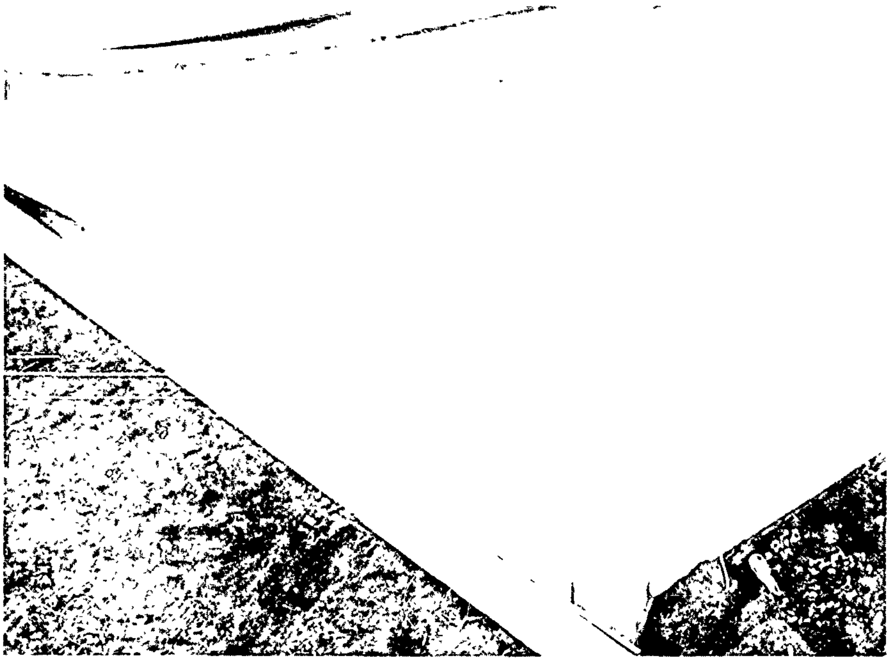


Figure 58. Protective fabric being removed from storage container and attached to the house at the desired elevation

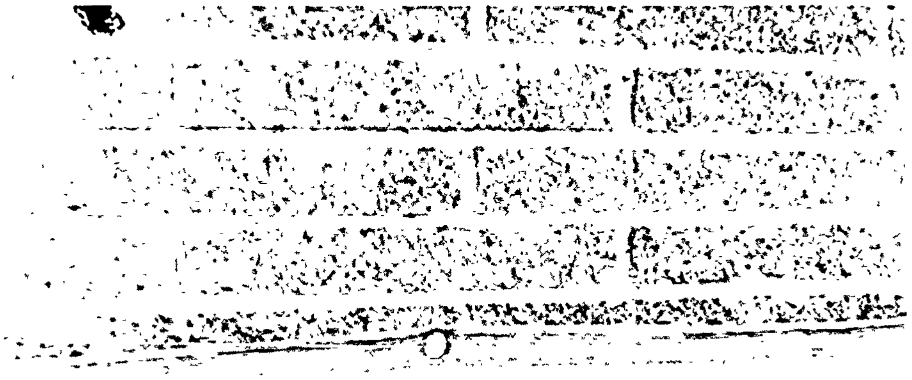


Figure 59. Permanent snap connected to the protective fabric

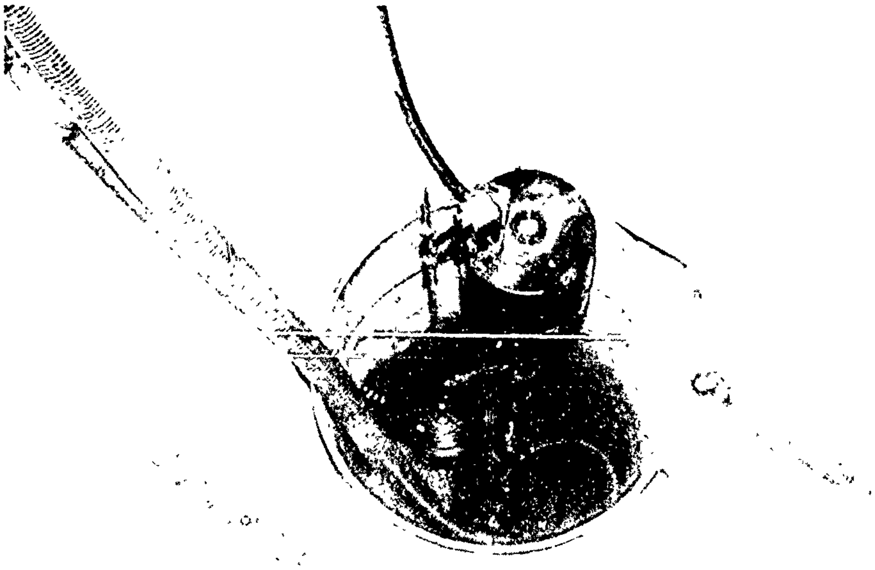


Figure 60. Sump which collects underseepage

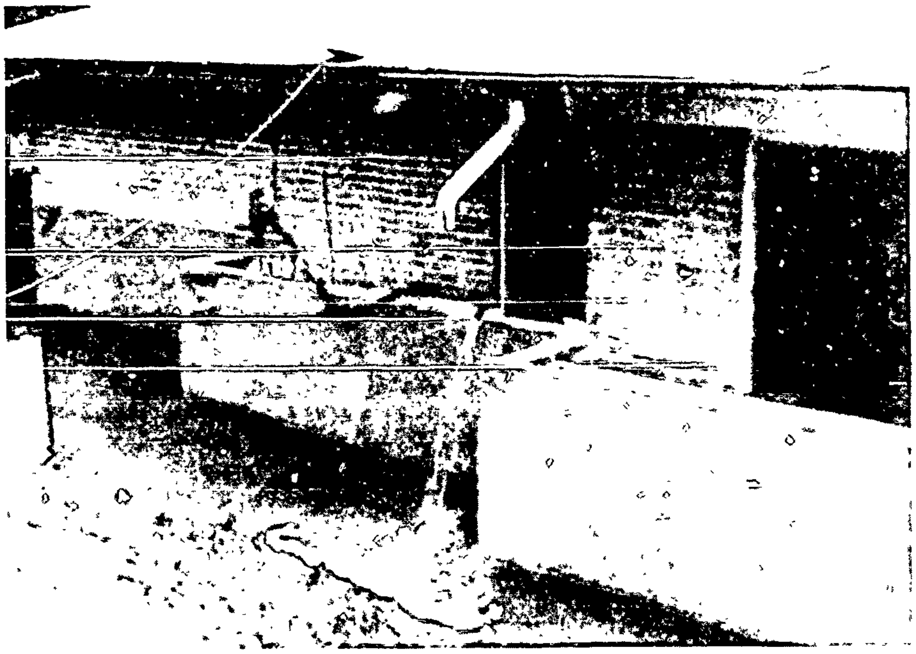


Figure 61. Water being pumped outside the protected area

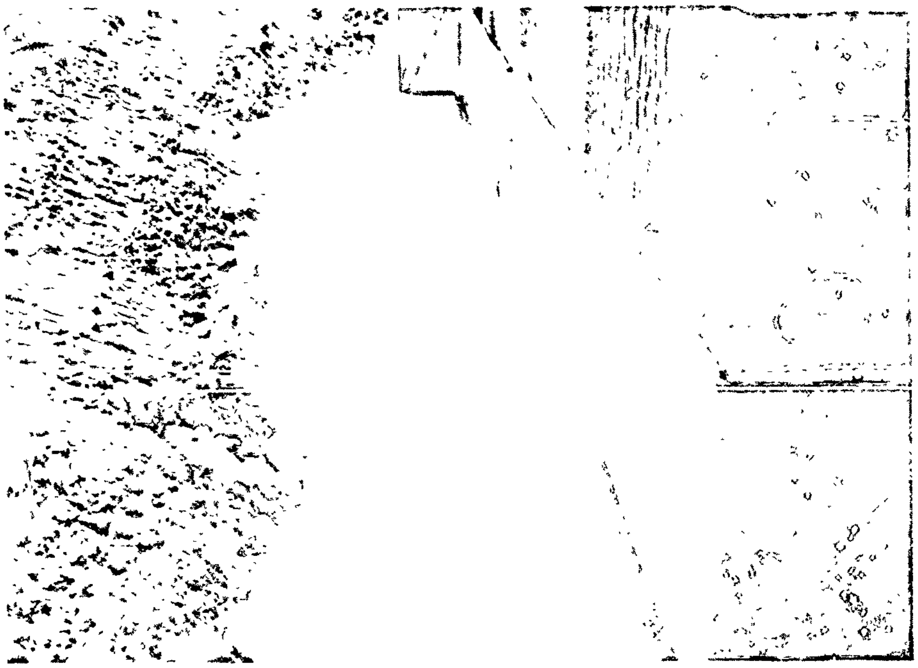


Figure 62. Beginning of water being pumped between flood shield and dike

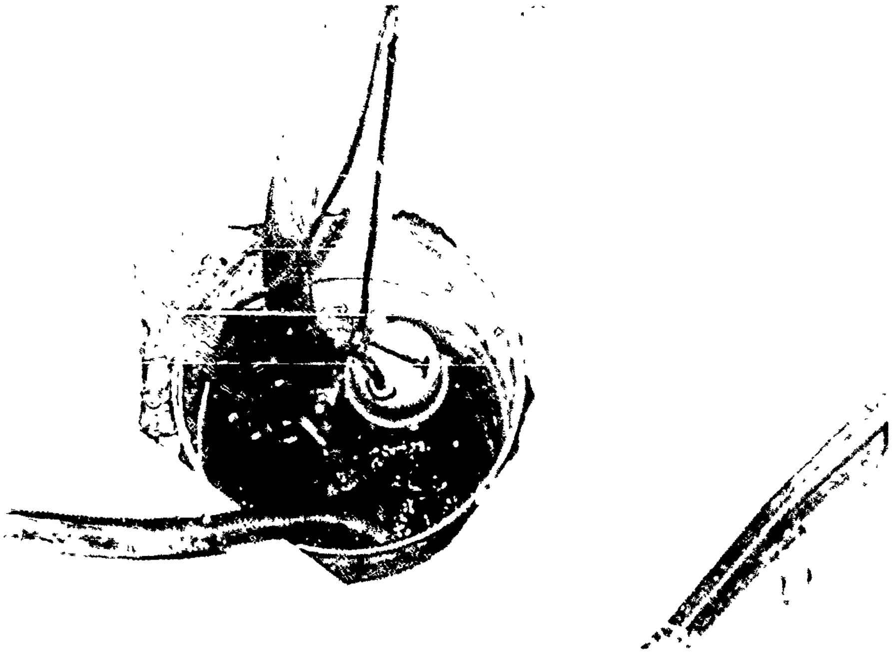


Figure 63. Pump used to keep water level low in sump

Figure 64. Water seeping under garage door due to allowing excessive water height in sump

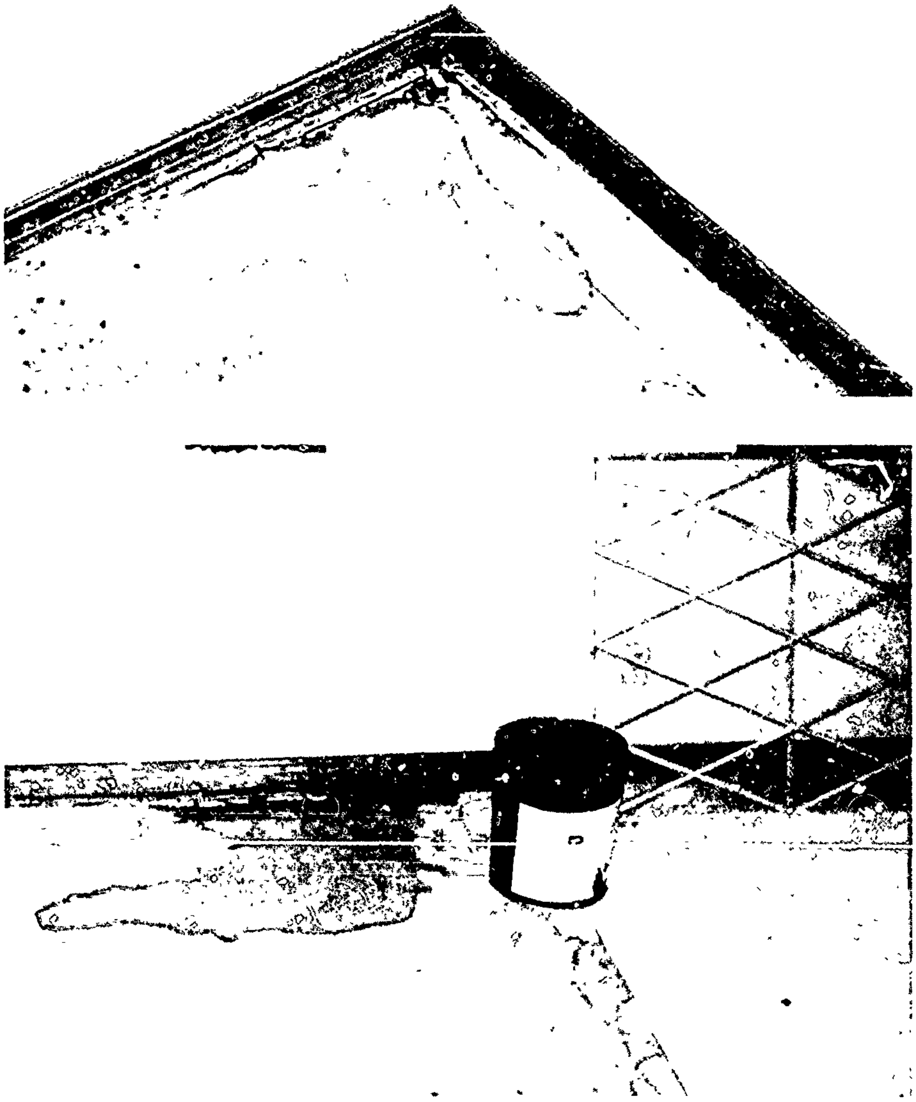


Figure 65. Seepage along baseboard due to leak in lap of fabric

a. Storage of waterproof membrane

b. Membrane being pulled up and connected to house

Figure 66. Flood-resistant system