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A REVIEW OF METHODS FOR CONCRETE REMOVAL

by

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P. O. Box 631, Vicksburg, Miss. 39180

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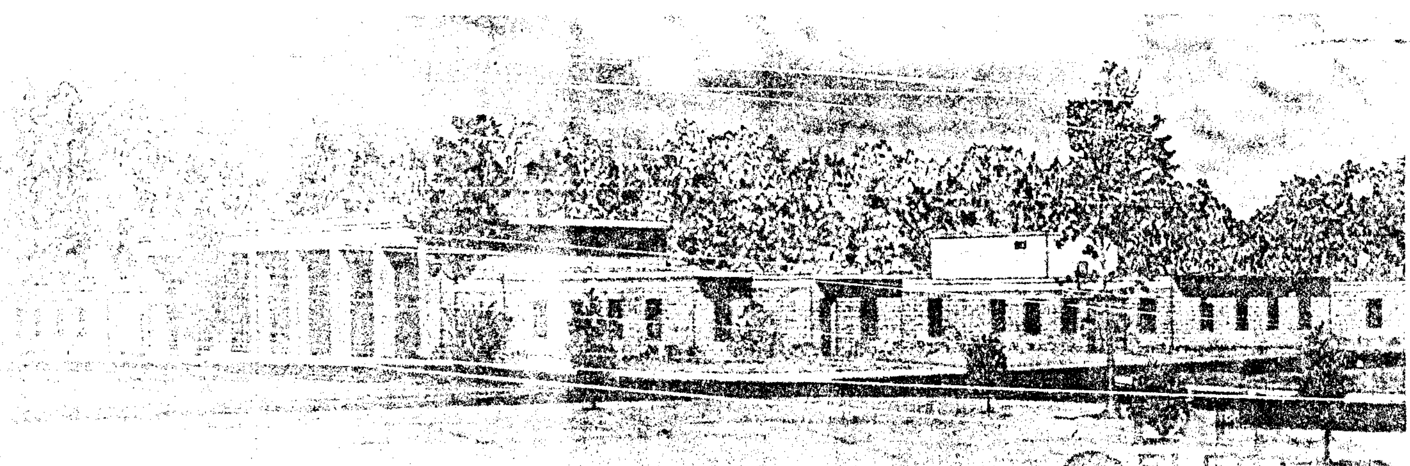

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Borehole notching	Diamond saw
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Concrete removal	Electrothermal lance
Concrete spaller	Expansive agent

(Continued)

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

The purpose of this report is to aid the engineer in his selection of applicable means of removal of distressed or deteriorated concrete for maintenance and preservation work at Corps projects. The report reviews methods of concrete removal and the particular devices that are presently being used or have potential for use in removal of distressed or deteriorated surfaces from mass concrete structures. The report presents the main advantages and disadvantages of each of the following means:

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19. KEY WORDS (Continued).

Explosive blasting
Hand-held breaker
High-pressure carbon dioxide blaster
Hydraulic rock-breaker
Powder lance
Powder torch
Thermal lance
Vehicle-mounted breaker
Water cannon
Water jet

20. ABSTRACT (Continued).

- a. Acetylene-air rock-breaker.
- b. Concrete spaller.
- c. Concrete splitter.
- d. Diamond saw.
- e. Electric-arc equipment.
- f. Explosive blasting.
- g. Expansive agent.
- h. Hand-held breaker.
- i. High-pressure carbon dioxide blaster.
- j. High-pressure water jet.
- k. Hydraulic rock-breaker.
- l. Powder lance.
- m. Powder torch.
- n. Thermal lance.
- o. Vehicle-mounted breaker.
- p. Water cannon.

Also reviewed is a borehole notching technique that appears to enhance the performance and crack control for some means, such as explosive blasting and the use of an expansive agent, that require boreholes.

Of the removal means reviewed, explosive blasting is considered to be the most cost-effective and expedient for surface removal of large volumes of material from mass concrete structures. In situations where explosive blasting cannot be used, the following have potential as alternates:

- a. Acetylene-air rock-breaker.
- b. Concrete splitter.
- c. Expansive agent.
- d. High-pressure carbon dioxide blaster.
- e. High-pressure water jet (in situations where reinforcement is to be preserved for reuse).

It is recommended that a field comparison study of these potential alternates, including an evaluation of the borehole notching technique, be carried out as part of the scheduled repair and rehabilitation work at a Corps project. The principal determinations to be made for comparison should be:

- a. Cost.
- b. Rates of removal.
- c. Extent of damage to concrete that remains.
- d. Problem areas.

PREFACE

This report was prepared at the Structures Laboratory (SL) of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Office, Chief of Engineers (OCE), U. S. Army, as a part of Civil Works Investigation Studies Work Unit 31553, Maintenance and Preservation of Civil Works Structures. Mr. Fred Anderson (DAEN-CWE-DC) served as OCE Technical Monitor.

The study was conducted under the general supervision of Mr. Bryant Mather, Chief, Structures Laboratory (SL), and Mr. John Scanlon, Chief, Concrete Technology Division, SL; and under the direct supervision of Mr. James E. McDonald, Chief, Evaluation and Monitoring Group, SL. This report was prepared by Mr. Roy L. Campbell, Sr.

The Commanders and Directors of WES during this study and the preparation and publication of this report were COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Mr. F. R. Brown was Technical Director.

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

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

Multiply	By	To Obtain
inches	0.0254	metres
feet	0.3048	metres
pounds (force)	4.448222	newtons
pounds (force) per square inch (psi)	0.006894757	megapascals
inches per second	0.0254	metres per second
cycles per second	1.0000	hertz
pounds (mass)	0.45359237	kilograms
grains (mass) per foot	0.2125948	grams per metre
foot-pounds (force)	1.355818	joules
pounds (force)-seconds squared per inch to the fourth power	10686896.	kilograms per cubic metre
feet per second	0.3048	metres per second
square inches per minute	0.00064516	square metres per minute
cubic feet per hour	0.02831685	cubic metres per hour
gallons (U. S. liquid) per minute	3.785412	litres per minute
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvins (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

A REVIEW OF METHODS FOR CONCRETE REMOVAL

PART I: INTRODUCTION

1. The Corps has many concrete Civil Works structures, a number of which either need repair to extend their service lives or have outlived their usefulness and are in need of replacement. In recent years, environmental restraints and high construction costs have often slowed and sometimes stopped planning and construction of replacement structures, and repair work has often been required to extend service life. The increased demand for repair and rehabilitation work will continue in the future as other structures approach a state of disrepair or need replacing, but cannot be replaced.

2. To prepare its engineers to deal better with present and future demands, the Corps is in the process of updating its technology regarding maintenance and rehabilitation of concrete structures. This report is a part of this effort. It is written to aid the engineer in his/her selection of applicable methods and means of removal of distressed or deteriorated concrete for maintenance and rehabilitation work at Corps projects.

3. The report includes means that are presently being used and those that have a potential for use in the removal of distressed or deteriorated concrete. For presentation purposes these various means of removal have been grouped into five basic categories: blasting, cutting, impacting, presplitting, and mechanical spalling. The application of these means and the methods used is limited to removal of surfaces from mass concrete structures and is not intended for the total demolition of a structure. Also included in this report is a review of a crack control technique that appears to improve the performance of some of the removal means that require borehole drilling.

PART II: BLASTING

4. Blasting methods employ rapidly expanding gas(es) confined within a series of boreholes to produce controlled fracture and removal of the concrete. In general, blasting methods are efficient means of removing large volumes of distressed or deteriorated concrete. However, due to dangers inherent in handling and usage, these methods are considered the most dangerous and require more stringent controls than any of the others. Planning a blasting project requires three basic areas of concern:

a. The safety of personnel involved and the general public.

b. Damage to adjacent structures.

c. Damage to the concrete that remains.

Although the contractor may be liable for these concerns, the engineer will want to implement controls that monitor and evaluate the performance of the blasting operation.

5. "Safety and Health Requirements Manual," Engineer Manual 385-1-1 (U. S. Army Corps of Engineers 1981), offers guidance to the engineer in maintaining a safe operation. All phases of the blasting operation should be monitored for compliance with EM 385-1-1 by qualified personnel.

6. Criteria for limiting damage to adjacent structures due to blasting are set forth in EM 385-1-1. For ground vibrations, it limits the total energy ratio to a maximum value of 1.00, or the total peak particle velocity to a maximum value of 2 in./sec.* The energy ratio for a specified plane of motion is defined in EM 385-1-1 as:

$$ER = (3.29\ FA)^2$$

where

ER = energy ratio

F = frequency of vibration, cps

A = amplitude (displacement) of vibration, in.

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* A table of factors for converting non-SI units of measurement to metric (SI) units is presented on page 3.

The total energy ratio is the vector sum of the energy ratios of three mutually perpendicular planes of motion at any one instant in time. It should be noted, however, that the total energy limit is seldom used as a present-day criterion for limiting damage to adjacent structures. Total peak particle velocity is the vector sum of the peak particle velocities along three mutually perpendicular planes of motion at any one instant in time.

7. The peak particle velocity limit of 2 in./sec is widely accepted as a safe level for blasting vibrations and has been adopted as a legal standard in some states. However, there are differences of opinion as to what value(s) the limiting peak particle velocity should have. For example, a study by the Bureau of Mines (Siskind et al 1980) concluded that practical safe peak particle velocity criteria for blasts that generate ground frequencies of 40 Hz or less are 0.75 in./sec for modern gypsum board houses and 0.50 in./sec for plaster or lath interiors. The study also concluded that, for frequencies above 40 Hz, a safe maximum particle velocity of 2 in./sec is recommended for all houses.

8. When planning a blasting project, the persons selected to perform and control the blast design and operation should be of proven experience and ability. Also, it is recommended that when possible a pilot test program be implemented to evaluate the blast design and operation. For a blast design using explosives, the total peak particle velocity transmitted to adjacent structures can be estimated from the design parameters by the following equation (Du Pont 1977):

$$V = 160\left(\frac{D}{\sqrt{W}}\right)^{-1.6}$$

where

V = estimated total peak particle velocity, in./sec

D = distance between blast and structure, ft

W = maximum mass of explosive to be used per delay period of 8 msec or more, lb

9. Monitoring for ground vibrations due to blasting is required when it is estimated that damage may occur or, for explosive blasting, when scaled distance is less than 50 $ft/lb^{1/2}$. Scaled distance is defined in EM 385-1-1 as:

$$S = \frac{D}{\sqrt{W}}$$

where

S = scaled distance, $ft/lb^{1/2}$

D = distance between blast and structure, ft

W = maximum mass of explosive per delay, lb

Monitoring for ground vibrations can be performed with a three-component seismograph and should be accomplished, along with recording and interpreting of ground vibrations, by qualified personnel.

10. For limiting the damage to adjacent structures due to airblast, the safe blasting criterion presented in EM 385-1-1 limits airblast pressures exerted on structures to less than 0.1 psi. Airblast gages can be used to monitor pressure variations.

11. The extent of damage to the concrete that remains after blasting is usually evaluated by visual inspection of the remaining surfaces, but, for a more detailed evaluation, a monitoring program can be implemented. The program may consist of taking cores before and after blasting and making visual, microscopic, and pulse velocity studies and ultimate strength tests of the cores and may include a pulse velocity study of the in situ concrete. A comparison of the before and after data can be used to determine the extent of damage. To further document the extent of damage, an instrumentation program may be added. One approach is to cut the cores taken before blasting in half along the axis of drilling and to instrument one half with strain gages and accelerometers (Plump 1980). The instrumented halves are then placed back into the core holes and grouted into place. The strain and peak velocity data obtained can be combined with other data to form conclusions regarding the extent of damage.

12. In order to estimate the peak particle velocity that would damage the remaining concrete at Lock and Dam No. 1 on the Mississippi River, the St. Paul District used the following equation (Plump 1980):

$$V = \frac{\sigma}{pc}$$

where

V = estimated peak particle velocity that would damage the concrete, in./sec

σ = ultimate tensile or compressive strength of the concrete, psi

p = mass density of the concrete, $\mathrm{lbf \cdot sec^2/in.^4}$

c = compressive wave pulse velocity of the concrete, in./sec

A test blasting design was made using the velocity estimate. The execution of the blast design showed the estimated peak particle velocity to be lower than those measured. Estimates made using this equation are considered conservative and can be used to design blast tests at other blasting projects.

Explosives

13. Explosive blasting is a demolition method that employs rapidly expanding gases produced by the detonation of an explosive to fracture and remove the concrete. It has been used successfully numerous times in the past at Corps projects to remove large volumes of distressed and deteriorated concrete. The blast removal work generally involves drilling a line of boreholes paralled to the removal face, placing the explosive in each hole, and detonating the explosive with electric blasting caps.

14. In the mid-1950's dynamite was the most widely used commercial explosive. Since then ammonium-nitrate prill products and water gels have generally replaced dynamite. The advantage of the ammonium-nitrate prill products is their low sensitivity to impact; however, the disadvantages include their lack of water resistance (except when packaged in water-resistant containers), low density, lack of ability to propagate

in small-diameter holes (unless confined), and cap insensitivity. Water gels do not share these disadvantages and also exhibit a low sensitivity to impact.

15. Detonating cord is one of the most versatile explosive products on the market. It can be used to do blasting, detonate other high explosives, or transmit detonation waves to other detonating cords. Its main advantages are its water resistance, relatively low sensitivity to impact, cap sensitivity, and desirable handling characteristics, such as tensile strength, durability, and flexibility.

16. At Corps projects, all explosive detonations are initiated using electric blasting caps. Recently, a new type of blasting cap called a Magnadet (Anonymous 1981) has been developed that is reported to be safer than the conventional electric blasting cap. It is designed to detonate only when the current frequency is greater than 15 kHz. This would reduce the chance of premature detonation due to standard electric current (110 and 220 v), lightning, static electricity, or currents generated by radio transmissions to almost zero.

17. Controlled blasting techniques for explosives have been developed to minimize damage to the material that remains after blasting. One such technique, known as cushion blasting (Du Pont 1977), involves drilling 3-in.-diam or smaller holes, loading each hole with light charges distributed along its depth, and cushioning the charges by completely *stemming* each hole. The distributing and cushioning of the light charges produce a relatively sound surface with very little overbreak. Another technique, called smooth blasting (Du Pont 1977), is the same as cushion blasting except that the cushion is not included. Also used for controlled blasting are electrical blasting-cap delay series that employ proper timing sequences to provide greater control in reducing ground vibration, noise, and fly rock. Note that the delay caps of different manufacturers should not be mixed in the same series. An incompatibility may exist between systems that could cause misfires and result in serious injury.

18. In the recent past, controlled blasting has been used successfully at Corps projects to remove distressed and deteriorated concrete.

For one such project, Emsworth Lock in the Pittsburgh District, a pilot test program was implemented to evaluate removal techniques for future work on the lock. For the explosive blasting portion of this program, boreholes were located 1 ft behind the lock face and vertically drilled to a depth of approximately 26 ft. The removal area was divided into sections and the hole spacing varied among sections. Satisfactory results were obtained for both 9- and 12-in. spacings using a detonating cord strength of around 100 grains/ft in each hole. Figure 1 shows the structure after removal.

Figure 1. Surface removal of deteriorated concrete by explosive blasting

19. For the engineer or his/her representative who needs more background for monitoring and evaluating blasting projects, the U. S. Army Engineer Waterways Experiment Station (WES) offers a course on blasting called "Systematic Drilling and Blasting." Although this course is oriented toward quarry blasting, much of the information presented

can be applied toward blast removal of concrete. Another source of information regarding the use of an explosive is the manufacturer, especially when a new product is to be used.

20. The advantages of explosive blasting are:

a. It is the most expedient and economical method for removing large volumes of concrete.

b. Good fragmentation of concrete debris is produced for handling.

21. The disadvantages are:

a. Highly skilled personnel are required for design and execution of such projects.

b. Stringent safety regulations must be imposed due to the inherent dangers in handling and usage of explosives.

c. Explosive blasting has the potential to produce unwanted levels of noise, ground vibration, gas fumes, and fly rock.

d. Special control techniques are required to limit damage to concrete that remains.

High-Pressure Carbon Dioxide Blaster

22. The high-pressure carbon dioxide blaster is a blasting device that employs high-pressure carbon dioxide gas to break down masses of material. First introduced around 1930 for breaking coal, it has since been used in coal mines in many countries and has reportedly (Pikrose undated) been used for breaking down concrete, rock, and stone; underwater work in reinforced concrete and rock; and bridge demolition. Figure 2 shows a concrete foundation that has been presplit using high-pressure carbon dioxide blasting.

23. The blaster consists of a power supply, switch, electrical cable, and a reusable cartridge. Power can come from any reasonable source, such as a 110- or 220-v power supply, a blasting battery, or a couple of dry-cell batteries. The switch controls the power to the cables and cartridge. The cartridge, which is illustrated in Figure 3, is a hollow steel tube fitted with a screw-on activating (firing) head at one end and a screw-on discharge head at the other. The firing head contains a filling valve and a pair of electrical connections. An

Figure 2. Concrete foundation presplit by high-pressure carbon dioxide blasting (courtesy of Pikrose and Co., Ltd., Manchester, U. K.)

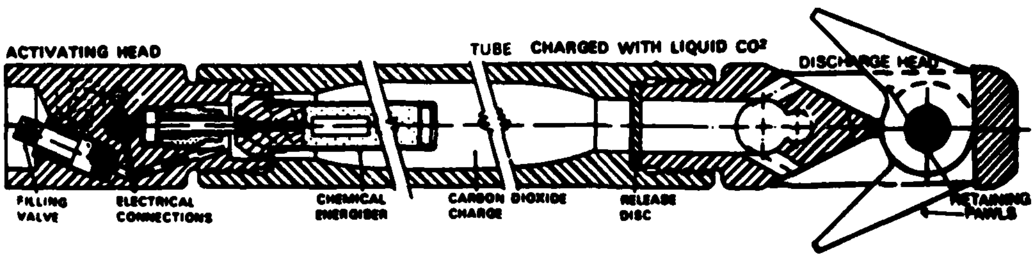

Figure 3. Drawing of high-pressure carbon dioxide cartridge (Pikrose, undated) (courtesy of Pikrose and Co., Ltd., Manchester, U. K.)

expendable chemical energizer connects to the end of the firing head and extends into the storage chamber, which is filled with liquid carbon dioxide. The discharge head contains a release (shear) disc that serves as an exhaust valve.

24. In general, the field operation consists of drilling boreholes to the desired depth, placing the cartridges into designated holes and detonating them, removing the cartridges from the debris, and then removing the debris. Recommended borehole diameters (Pikrose undated) range between 2-1/4 and 3 in. and are approximately 1/8 in. greater than the size cartridge being used. Only one cartridge per hole is recommended. For deep removals, holes must be redrilled for each additional cartridge required. The blast is initiated when electrical power is switched to activate the chemical energizer. The energizer provides heat that increases the pressure within the storage chamber. The pressure will continue to increase until the shear disc yields, allowing gas to flow into the borehole. When the carbon dioxide changes from liquid to gas, there is a sudden drop in temperature in the hole. The pressure exerted in the borehole breaks up the concrete material by the gentle heaving action of the spreading volume of gas. Since the rate and magnitude of pressure are low, no crushing of the material around the borehole occurs; therefore, very little damage occurs to the material that remains.

25. The reusable cartridges and equipment for recharging them can be purchased or rented. Since carbon dioxide at 87.8° F (31.0° C) starts to turn from a liquid into a gas, for efficient transfer of liquid in hot climates it is recommended that the recharging of cartridges be performed in an air-conditioned environment. It is also recommended that the empty cartridges be precooled in a freezer, if possible, for a couple of hours before filling. The supply bottles containing the liquid carbon dioxide should have siphon tubes to avoid having to invert the bottles for gravity flows into the cartridges.

26. The advantages of high-pressure carbon dioxide blasting are:

a. Less violent breaking action occurs than with conventional explosives, thereby resulting in less noise, ground vibration, fly rock, and damage to concrete that remains.

b. No crushing of material occurs around boreholes, therefore, minimum dust is produced.

c. No toxic fumes are produced.

d. Noninflammable carbon dioxide gas is released.

e. Safety requirements are fewer than those for conventional explosives for transportation, handling, storage, and use due to a, b, c, and d above.

f. Cartridges are reusable.

27. The disadvantages are:

a. Highly skilled personnel are required for blast design.

b Skilled personnel are required for execution of blast design.

c. Some stringent safety regulations and precautions must be imposed because the method uses compressed gas (see EM 385-1-1).

d. Although the cartridge has retaining pawls to prevent it from being expelled out of the borehole, a retaining weight must be placed over the hole as an added precaution against expulsion.

e. Initial investment may be high.

f. Only one cartridge per hole is recommended; therefore, for deep removals, holes must be redrilled for each additional cartridge required.

g. Refilling of cartridges requires special equipment and, for hot climates, an air-conditioned environment.

Acetylene-Air Rock-Breaker

28. The acetylene-air rock-breaker is a new device still in the development stage that employs the detonation of acetylene and air under pressure for breaking rock. This device, which is detailed in Figure 4, is electrically fired and consists of a steel-tubed body with a firing head at one end and an exhaust port assembly at the other. The firing head contains a gas loading bore (filling port) and a detonating fuse. The exhaust port assembly contains exhaust ports and a rupture disc, which serves as an exhaust valve. The acetylene and air mixture is stored under pressure within the chamber of the tube between the firing head and the exhaust port assembly.

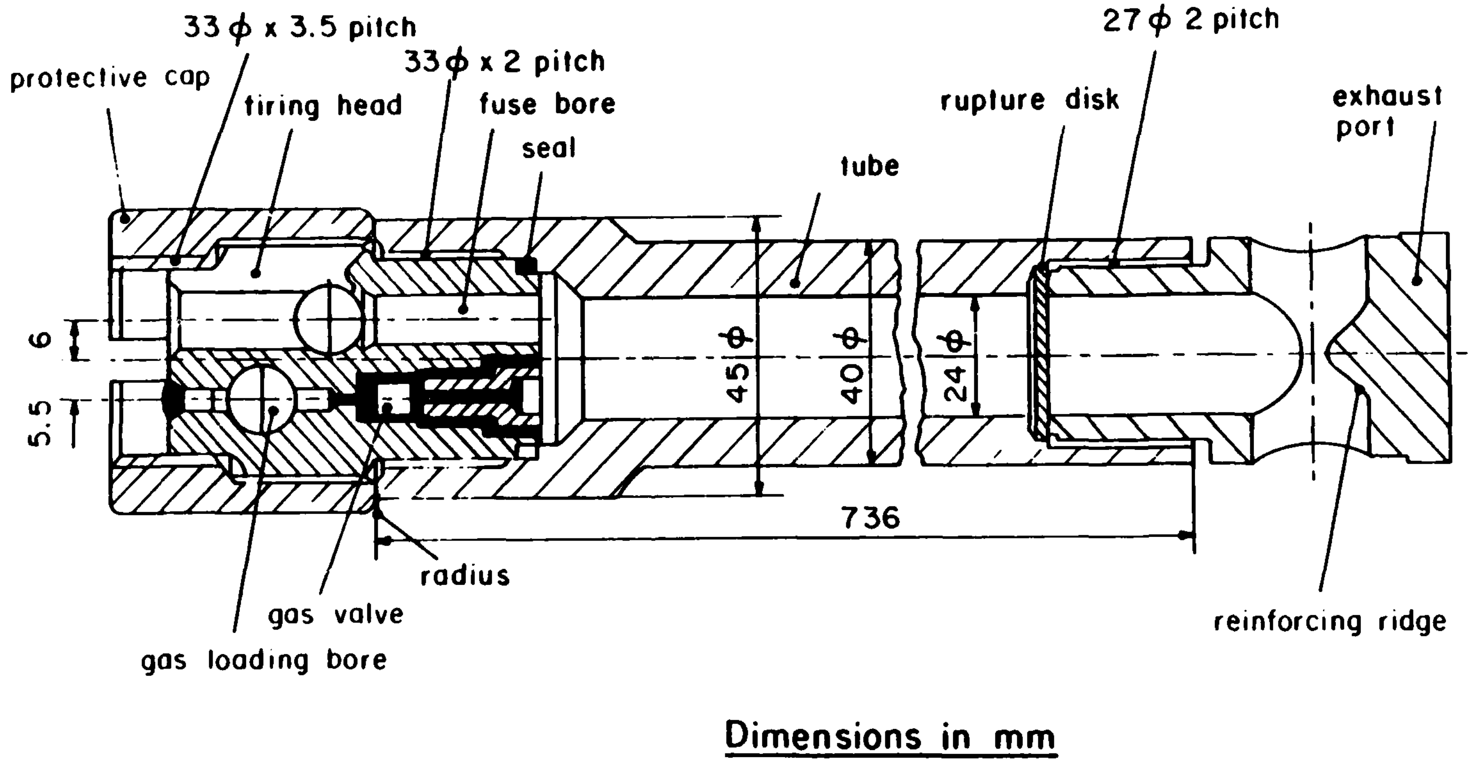

Figure 4. Detail drawing of acetylene-air rock-breaker (Bligh 1977) (courtesy of Thomas P. Bligh, Associate Professor, Massachusetts Institute of Technology, Cambridge, Mass.)

29. Because this device is still in the development stage, recommended procedures for its operation have not been established. The operation and results, however, will probably be similar to those of the high-pressure carbon dioxide cartridge, with the following exceptions:

- a. The acetylene-air mixture is used instead of liquid carbon dioxide.
- b. Recommended borehole diameters are slightly smaller.
- c. The acetylene-air mixture is detonated electrically by a fuse.
- d. High heat is generated by detonation.

30. This device has been tested in limestone and granite quarries and has shown great potential for excavation and mining work. It has also been tested in the partial demolition of a massive concrete foundation that contained reinforcing steel. The results showed promise, but Bligh (1977) suggests that more work is needed before its capabilities can be ascertained.

31. The advantages of the acetylene-air rock-breaker are:

- a. Less violent breaking action occurs than with conventional explosives, thereby resulting in less noise, ground vibration, fly rock, and damage to concrete that remains.
- b. No crushing of material occurs around boreholes; therefore, mimimum dust is produced.
- c. No toxic fumes are produced.
- d. Safety requirements are fewer than those for conventional explosives for transportation, handling, storage, and use due to a, b, and c above.
- e. The device is reusable.
- f. Danger of the device being ejected out of borehole is reduced. Bligh (1974) states: "Pressure rises comparatively rapidly so that there is insufficient time during which to accelerate the shell out of the drillhole, due to its inertia. Therefore, if the hole is not overburdened, the maximum pressure is reached rapidly and the rock broken before the shell is ejected."

32. The disadvantages are:

- a. Highly skilled personnel are required for blast design.
- b. Skilled personnel are required for execution of the blast design.

c. Relatively stringent safety regulations and precautions must be imposed because the device contains combustible gas under pressure (see EM 385-1-1).

d. Initial investment may be high.

e. At present, the device is in the development stage and will require significant testing and documentation before it can be commercially marketed for removal of concrete.

PART III: CUTTING

33. Cutting methods are generally used to remove sections of a structure by cutting along the perimeter of the section and removing it with equipment of the proper size. These sections are usually a part of a wall or slab containing reinforcement and vary in thickness from several inches to several feet. The depth of the perimeter cut depends on the cutting tool used. In general, cutting methods are considered slow and costly for removal of large volumes of material from mass concrete structures. However, these may be secondary concerns when demolition criteria demand precision, reduced vibration, and reduced damage to the material that remains.

Diamond Saw

34. Rotary-action diamond saws are the most common type of saw used to cut concrete. These saws produce straight precision cuts up to 21 in. deep in concrete by the high-speed grinding action of the saw blade, and they cause minimal vibration and damage to the concrete that remains. In the past, rotary-action diamond saws have been successfully used for structural and highway demolition. In particular, these saws have been cost-effective for removal of free-standing walls and bridge deckings. Figure 5 shows a bridge deck being cut with a rotary-action diamond saw.

35. In general, the rotary-action diamond saw can be electrically or hydraulically powered or driven by a combustion engine. The blade is a thin rotary disc with diamond-tipped teeth along its outer perimeter. Lubricant is supplied to the blade through a hose connected to a lubricant storage container.

36. Before a cutting operation begins, utility lines within the concrete in the vicinity of the cutting should be located and marked. The size and location of the reinforcement should also be determined before starting an operation. During the cutting operation, lubricant must be continuously applied to the blade to cool it and protect it from

Figure 5. Bridge deck being cut with a rotary-action diamond saw (courtesy of Concrete Coring Company, Hawthorne, Calif.)

excessive wear. The cutting pattern should yield sections of satisfactory size to ensure safe handling for the equipment available for removal. During a cutting operation, the hearing of the operator must be protected from the noise generated by operation.

37. The cutting rate generally ranges from 20 to 200 $in.^2/min$ (Palovchik 1975). This rate is dependent on many factors which include the abrasion resistance of the concrete and the amount of reinforcement in the cut.

38. Reciprocating-action (sabre) diamond saws have also been employed to cut concrete sections up to 4 ft thick (Lazenby and Phillips 1978). Cuts are started at a free surface or from a predrilled borehole, as shown in Figure 6. A cutting rate of around 28 $in.^2/min$ (Lazenby and Phillips 1978) in average-quality reinforced concrete has reportedly been achieved. However, the reciprocating saw is not considered applicable for most surface removal work involving mass concrete structures.

39. The advantages of rotary-action sawing are:

a. Precision cuts can be made with minimal vibration and damage to concrete that remains.

b. Relatively large sections can be removed at one time.

c. No dust is produced.

d. A relatively safe operation can be maintained.

40. The disadvantages are:

a. The cutting operation is slow and costly.

b. Cutting depths are limited.

c. The number of shapes that can be cut is limited.

d. Cutting reinforced concrete increases blade wear and hence operation costs.

e. Some additional safety requirements and procedures are necessary due to the high level of noise produced (see EM 385-1-1).

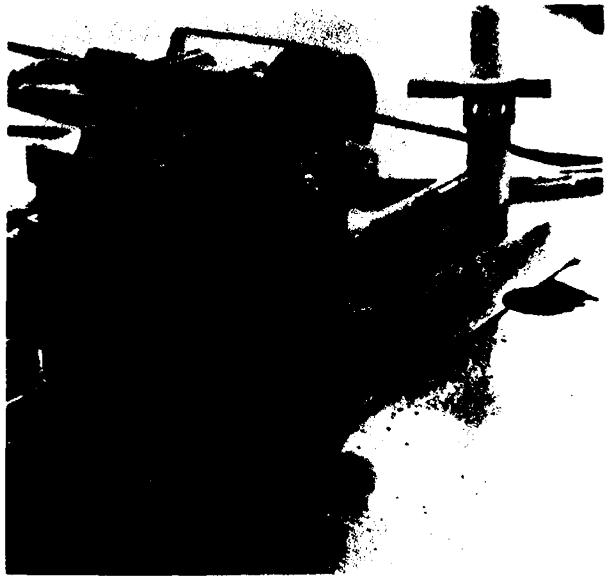

Figure 6. Floor slab being cut by reciprocating-action diamond saw (Lazenby and Phillips 1978) (courtesy of The Architectural Press, London, U. K.)

Powder Torch

41. The powder torch is a cutting tool that employs intense heat generated by the reaction between oxygen and powdered iron and aluminum to melt a cut into concrete. The torch has been successfully used in the past to cut reinforced concrete slabs and walls up to 3.3 ft thick (Lazenby and Phillips 1978). It has been reported that narrow cuts with excellent finish can be made. Figure 7 shows a powder torch being used to cut through a 24-in. section of concrete.

42. The torch consists of a torch body fitted with hose connections for oxygen-acetylene or propane, powder injection, and cooling water. The gases are contained in pressure vessels; the powder is dispensed from a pressurized vessel by means of nitrogen gas or compressed air; the torch is water-cooled to prevent it from becoming a part of the reaction. Flexible pressure hoses link these vessels and the water supply

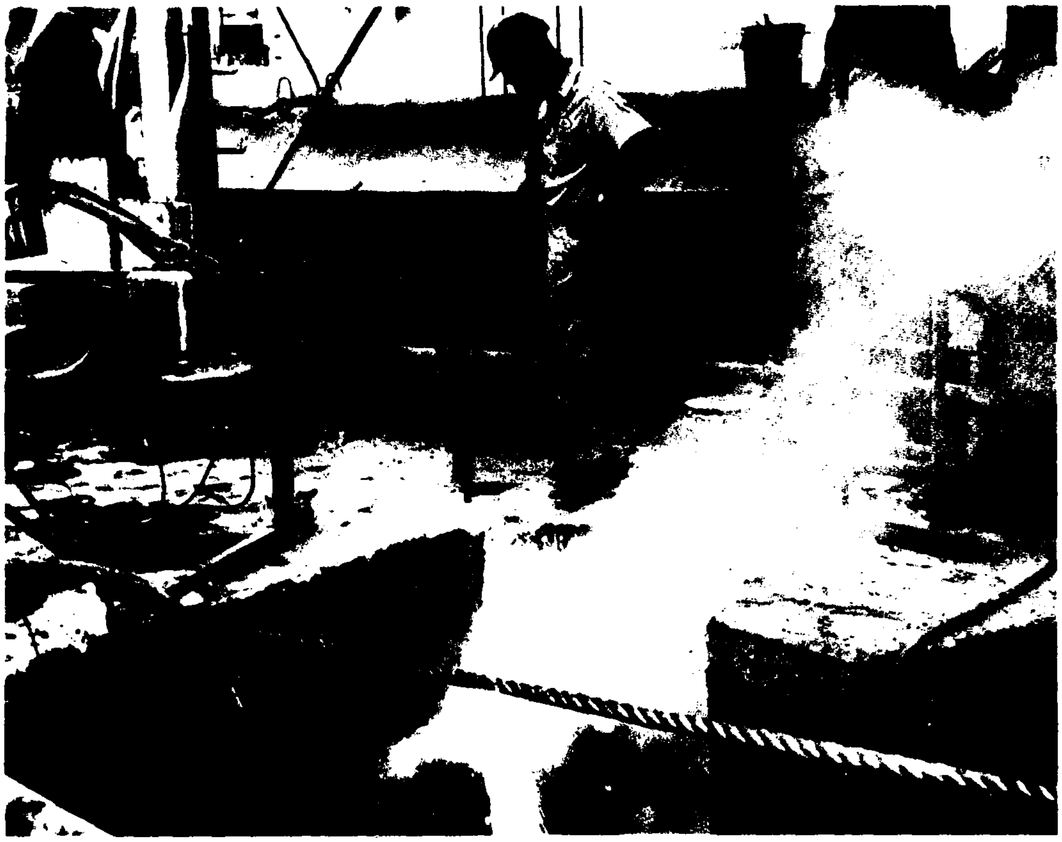

Figure 7. Powder torch being used to cut a 24-in.-thick concrete section (Lazenby and Phillips 1978) (courtesy of Concrete Coring Company, Hawthorne, Calif.)

with the torch. The torch can be a part of an automatic-feed mechanism, a feature which offers a significant advantage because more of the variables can be controlled.

43. Propane or oxygen-acetylene flame is used to start the reaction between the oxygen and powder which generates temperatures in excess of $12,000^{o}$ F ($6,650^{o}$ C). Wall cuts are made at angles that allow gravitational flow of slag. Floor slab cuts are usually started from an existing hole or free surface where the slag is free to flow. The resulting cut is generally from 1-1/2 to 2 in. wide and advances at a

cutting rate of approximately 20 in.^{2}/min. The more steel reinforcing in the concrete, the faster the cutting rate.

44. The advantages of the powder torch are:

- a. It is an effective means of cutting reinforced concrete up to 3.3 ft thick.
- b. Irregular shapes can be cut.
- c. Minimal noise, vibration, and dust are produced.

45. The disadvantages are:

- a. The cutting operation is slow and costly.
- b. Initial investment is high.
- c. Torch operation is somewhat cumbersome due to the number of different components used.
- d. The torch is not suitable for cuts where slag flow is restricted.
- e. Smoke and fumes are produced.
- f. Increased safety requirements are necessary due to the fire hazard presented by the combustible gases used and the explosion hazard of the gases under pressure (see EM 385-1-1).
- g. At present, no information can be found that documents the condition of the concrete that remains. (It is reasonable to assume that damage will occur; however, the extent of such is not known.)

Thermal Lance

46. The thermal lance is the simplest of the flame tools for cutting concrete. It employs intense heat generated by the reaction between oxygen and mild steel rods to melt a cut into concrete. In the past, the lance has been successfully used to cut openings in reinforced concrete walls and floors reportedly as thick as 19.7 ft (Lazenby and Phillips 1978). Figure 8 shows a thermal lance being used to cut through a concrete wall by making a series of individual holes.

47. The lance system consists of an iron or steel pipe, a handle, flexible pressure hose, an oxygen supply, and an acetylene or propane supply system. The pipe is filled with mild steel rods and comes in sections that are threaded and socketed for connection to the lance

Figure 8. Thermal lance being used to cut through a concrete wall (Lazenby and Phillips (1978) (courtesy of the Architectural Press, London, U. K.)

handle and to other pipe sections, when necessary. The gases used in the system are stored in pressure vessels. The handle is fitted with a connection for the pipe and a connection for the oxygen supply.

48. During the operation, oxygen is forced through the pipe. An oxygen-acetylene or propane flame is used to start the reaction between the oxygen and steel rods at the open end of the pipe. Once the reaction has started, it becomes self-supporting. As the reaction continues, the pipe and rods are consumed by the reaction. New sections of pipe filled with rods are added to the handle end of the pipe to replace those

that are consumed. The resulting cut is around 1-1/2 to 2 in. wide and advances at an approximate cutting rate of 20 $in.^2/min$. The more steel reinforcement in the concrete, the faster the cutting rate.

49. The thermal lance works best when used for punching holes in reinforced concrete at angles that allow gravity flow of slag. For angles that restrict flow, the oxygen pressure has to be increased to blow slag out of the cut. The effective cutting depth for a vertical hole is between 24 and 30 in. (Lazenby and Phillips 1978). Deeper vertical cuts are possible if the cut is started at a vertical face where the slag is free to drain.

50. The advantages of the thermal lance are:

- a. It is one of the most effective means of cutting reinforced concrete.
- b. It is the simplest of the flame tools.
- c. Deep cuts can be made in areas where slag is free to flow.
- d. Irregular shapes can be cut.
- e. Minimal noise, vibration, and dust are produced.

51. The disadvantages are:

- a. The cutting operation is slow and costly.
- b. Initial investment is high.
- c. The thermal lance is not suitable for cuts where slag flow is restricted.
- d. Smoke and fumes are produced.
- e. Increased safety requirements are necessary due to fire hazard presented by the combustible gases used and the explosion hazard of the gases under pressure (see EM 385-1-1).
- f. The operator must be protected against possible burns.
- g. The extent of damage to concrete that remains is unknown.

Powder Lance

52. The powder lance is a manually operated tool for cutting concrete that combines some of the features of the powder torch and the thermal lance. It employs intense heat generated by the reaction between

oxygen and powdered metals to melt a cut into concrete. In the past, the lance has been successfully used to cut openings in reinforced concrete walls and floors, reportedly as thick as 12 ft (Lazenby and Phillips 1978).

53. The lance system consists of a black iron pipe, a handle, flexible pressure hoses, an oxygen supply, an acetylene or propane supply, and a powdered metal supply system. The iron pipe comes in sections that are threaded and socketed for connection to the lance handle and other pipe sections. The gases used in the system are stored in pressure vessels. The handle is fitted with three connections: one for the iron pipe, one for the oxygen supply, and one for the powdered metal supply. The metal powders used are iron and aluminum and are supplied from a pressurized vessel by means of nitrogen or compressed-air gas.

54. During the operation, the powders are mixed with oxygen in the handle and are ignited with an oxygen-acetylene or propane flame at the open end of the iron pipe. Once the reaction has started, it becomes self-supporting. As the reaction continues, the iron pipe is melted and consumed by the cutting flame, and new sections of pipe are added to the handle end of the pipe. The resulting cut is around 1-1/2 to 2 in. wide and advances at an approximate cutting rate of 20 $in.^2$/min. The more steel reinforcing in the concrete, the faster the cutting rate.

55. The lance works best when used for punching holes in reinforced concrete at angles that allow gravity flow of slag. For angles that restrict flow, the oxygen pressure has to be increased to blow slag out of the cut. The effective cutting depth for a vertical hole is around 30 in. Deeper vertical cuts are possible if the cut is started at a vertical face where the slag is free to drain.

56. The advantages of the powder lance are:

- a. It is one of the most effective means of cutting reinforced concrete.
- b. Deep cuts can be made in areas where slag is free to flow.
- c. Irregular shapes can be cut.
- d. Minimal noise, vibration, and dust are produced.

e. The powder lance weighs much less than the thermal lance (since the pipe is empty for the powder lance and filled with rods for the thermal lance).

57. The disadvantages are:

a. The cutting operation is slow and costly.

b. Initial investment is high.

c. The powder lance is not suitable for cuts where slag flow is restricted.

d. Smoke and fumes are produced.

e. Increased safety requirements are necessary due to the fire hazard presented by the combustible gases used and the explosion hazard of the gases under pressure (see EM 385-1-1).

f. The operator must be protected against possible burns.

g. The extent of damage to concrete that remains is unknown.

Electric-Arc Equipment

58. Electric-arc equipment (Goriainov and Antropov 1967) employs a thermal device that was developed and tested in the USSR for cutting openings and recesses in brick and reinforced concrete. Its operating principle is based on fusion of concrete materials by electric arc at temperatures ranging from 7,200 to 14,400° F (4,000 to 8,000° C). Cutting depths up to 12 in. have been achieved in tests.

59. In general, the equipment consists of two graphite electrodes with holders, a stand, and a welding transformer with supply cables. The frame allows the electrodes a maximum movement of 19.7 in. in two perpendicular directions in a plane parallel to the cutting surface. The supply cables are rubber-insulated and are sheathed over with braided asbestos for a distance of 6.6 ft from the equipment.

60. Before beginning operation, electrical ground connections and cable insulation must be inspected to help ensure a safe operation. The electric arc is initiated by plugging in the transformer, whereupon contact is made with the electrodes and an ionized zone forms; the fused slag is ejected from the fusion zone by the resultant electrodynamic forces. During the operation, the closest distance to the electrodes at

which the operator can safely work is approximately 3 ft. The concrete that remains after cutting is damaged to a depth of 0.4 to 0.6 in. from the edge of the cut.

61. The advantages of the electric-arc equipment are:

- a. It is an effective means of cutting irregular shapes in plain or reinforced concrete.
- b. Minimal noise, vibration, and dust are produced.

62. The disadvantages are:

- a. Electric-arc cutting is slow and costly.
- b. Concrete that remains is damaged to a depth of 0.4 to 0.6 in. from the edge of the cut.
- c. During operation, the operator cannot get closer than approximately 3 ft from electrodes to make adjustments or repairs.
- d. The operator must be protected against burning slag.
- e. Fumes are produced.
- f. Increased safety requirements are necessary due to the danger electrical shock (see EM 385-1-1).
- g. The electric-arc equipment is not commercially available.

High-Pressure Water Jet

63. The high-pressure water jet is a cutting tool that employs a small jet of water driven at high velocities to erode a cut into concrete. There are a number of different types of water jets that are presently being used. The most promising of these appear to be the ultrahigh-pressure jet and the cavitating jet. In the past, both types have been used for grooving and cutting of concrete pavement for highways. Figure 9 shows a reinforced concrete wall that was cut using a water jet. Note that the reinforcing steel was not damaged by the action of the jet.

64. In general, the water jet can be frame-mounted and automated, or portable. The jet system basically consists of a motor, a hydraulic oil system, an intensifier, a water system, and a control system. The hydraulic oil system consists of a filter, a pump, hydraulic lines, and a cooling system. The intensifier is a hydraulically driven reciprocating

Figure 9. Reinforced concrete wall cut with a water jet (Lazenby and Phillips 1978) (courtesy of The Architectural Press, London, U. K.)

plunger pump. (One such unit reportedly boosts the water pressure to 20 times the applied pressure (Olsen 1980).) The water system contains a water supply, an accumulator, flexible high-pressure lines, and a sapphire nozzle. The accumulator is a pressure vessel of water that acts as a reservoir for maintaining a working level pressure within the water system to produce a smooth flow of water at the nozzle. The nozzle forms the water jet. The diameter of the nozzle opening, which can range from 0.003 to 0.020 in. (Olsen 1980), and the water pressure at the nozzle determine the flow rate of the jet. The control system regulates the flow of water by controlling the power transmitted to the hydraulic oil pump.

65. In general, the water jet works like this: the motor provides power to the pump; the pump generates the oil pressure to drive the intensifier; the intensifier boosts the pressure in the water system to a working level; and the nozzle forms the jet for cutting the concrete. During the cutting operation, the chief causes of failure of nozzles are dirt particles in water or deposits formed by hard water near the orifice. The depth of cut depends mainly on the number of repeated passes over the cut. Large fragments of aggregate and other debris are sometimes dislodged and ejected from the cut with considerable force. This hazard requires the operator to wear adequate protection and the cutting area to be kept clear of other personnel.

66. In a recent study of highway surface maintenance (Hilaris 1980), a cutting rate of approximately 140 $in.^2$/min was achieved using an ultrahigh-pressure jet. In a partial depth repair test for removing surface-deteriorated concrete from a bridge deck, the same study showed a volume removal rate of approximately 2.5 ft^3/hr. The jet system for this was operated at 40,000-psi pressure to produce a 4.5-gpm flow rate through dual nozzles of 0.020-in. diameter.

67. In some systems, the ultrahigh-pressure water jet has been designed to operate at stagnation pressures up to 60,000 psi (Olsen 1980). At this pressure, velocities around 3,000 ft/sec can be achieved by using a nozzle diameter of 0.008 in. An abrasive water-jet system is presently under development that will be more productive than the regular ultrahigh-pressure jet yet will require significantly less pressure and power to operate. This system will have another advantage: it will be capable of cutting steel reinforcing. In the past, additives to the water jet fluid have had the drawbacks of increasing cost and system complexity.

68. The cavitating water jet controls water flow through its nozzle to produce cavitation at the concrete surface. This jet operates at stagnation pressures of 12,000 to 15,000 psi, a range which is considerably lower than that for the ultrahigh-pressure jets. As the cavitation

phenomenon occurs only within a limited range of standoff distances, maintaining an optimal rate of removal depends on standoff distance more for cavitating jets than for ultrahigh-pressure jets. Work is currently being done for the U. S. Department of Transportation to develop a cavitating water jet capable of removing concrete bridge deck surfaces at the rate of 6 ft^3/hr.

69. Several low-pressure, high-flow cavitating water jets are presently under development for cutting concrete. They operate at stagnation pressures around 10,000 psi and flow rates of 4 to 15 gpm, depending on the nozzle diameters and the horsepower of the pump used. The high flow rates allow the same cutting penetration at lower stagnation pressures. These jets use rotating dual nozzles to cut a wide slot into concrete; the width of the slot is controlled by adjusting the angle of one of the nozzles. When the nozzle is adjusted for the maximum size of aggregate in the concrete, the water jet can more easily erode the cement matrix from around the aggregate to remove the aggregate with minimal energy spent on cutting the aggregate. The low-pressure, high-flow cavitating water jet at its present stage of development is less efficient, however, than either the ultrahigh-pressure or the higher pressure cavitating jets.

70. The advantages of the water jet are:

a. Minimal damage is produced to the concrete that remains.

b. The cutting operation can be automated.

c. Irregular shapes can be cut.

d. No heat, vibration, or dust is produced by the cutting action.

e. In some cases, exposed steel that remains after removal can be used in the resurfacing operation to transfer loads between old and new concrete.

f. Water jets can be used to cut concrete under water with little loss of efficiency.

71. The disadvantages are:

a. The cutting operation is slow and costly.

b. Initial investment is high.

c. Systems that are presently available cannot cut reinforcing steel or extremely abrasion-resistant aggregate.

d. Some additional safety requirements and procedures are required due to the high pressures of the water-jet system (see EM 385-1-1).

PART IV: IMPACTING

72. Impacting methods have been used in the past to remove surfaces from mass concrete structures. Such methods involve the repeated striking of a surface with a mass to fracture and spall it. The productivity for this group of impacting methods varies widely and is basically a function of energy delivered per volume removed.

Hand-Held Breaker

73. The hand-held breaker is an impact tool that employs a rapid succession of light blows and the wedging action of its breaking bit to fracture and spall the concrete. It is normally used to aid other removal methods when work involves removal of large volumes of concrete from mass concrete surfaces.

74. A hand-held breaker such as the one shown in Figure 10 consists of a backhead group, a cylinder group, and a fronthead group (U. S. Army Engineer School 1967). The backhead group contains a handle for holding the breaker, a power source or power connection, and operating controls. The cylinder group drives the breaker attachment and consists of a cylinder, piston, and valve assembly. The fronthead group provides a socket for holding the breaker bit or attachment. The breaker is operated from one of four power sources: a compressed-air system, a hydraulic system, a self-contained gasoline engine, or a self-contained electric motor.

75. The pneumatic breaker, operated by compressed air, is the most common type of hand-held breaker. In general, the pneumatic breaker requires less maintenance and is more rugged than the other types of breakers. No special care is required during transportation or storage. In extreme cold, it may be necessary to add antifreeze solution to the air line to prevent the exhaust port from being iced shut.

76. The hand-held breaker is best suited for downward breaking action for which breakers in the 50- to 90-lb class should be used. For a heavy breaker with a moil point on nonreinforced concrete, a breaking rate in the vicinity of 25 ft^3/hr (U. S. Army Engineer School 1967) has

Figure 10. Hand-held breaker

been achieved. For reinforced areas, this rate will be considerably lower depending on the amount of reinforcement present. Lighter breakers are required when breaking action is in a direction other than downward. Both the size of the breaker and the working angle significantly influence the productivity of the operation.

77. Hand-held breakers can be operated by unskilled labor. However, the more experience and ability the operator has, the greater his/her productivity. The choice of tool point and the age and strength of the concrete also affect the productivity of the breaking operation. During the breaking, the operator must wear hearing protection due to the noise generated by the operation.

78. The advantages of the hand-held breaker are:

- a. Capital costs are low.
- b. The breaker can be operated by unskilled labor.
- c. It can be used in areas of limited work space.
- d. It is readily available commercially.

79. The disadvantages are:

a. Productivity is slow.

b. The breaker is generally limited to downward breaking action.

c. Dust and vibrations are produced.

d. A high level of noise is produced.

Vehicle-Mounted Breaker

80. The vehicle-mounted breaker is an impact tool that employs a relatively rapid succession of heavy blows and the wedging action of its breaking bit to fracture and break concrete. The vehicle-mounted breaker has been used for the removal of concrete from a variety of concrete structures which includes pavements, bridges, and structural floor and wall slabs and from mass concrete. These jobs usually involve removal of large volumes of concrete within a limited time frame.

81. The breaker tool design is somewhat similar to that of the hand-held breaker except that it is mechanically operated and considerably more massive. The tool is normally attached to the hydraulically operated arm of a digging machine as shown in Figure 11 and is operated by compressed air or hydraulic pressure. The reach of the hydraulic arm enables the tool to be used on walls at a considerable distance above and below the level of the machine.

82. The productivity of the vehicle-mounted breaker is much greater than that of the hand-held breaker due to its increased mass and power. The performance of a breaker is directly proportional to the blow energy it delivers; the maximum blow energy of most breakers ranges between 200 and 20,000 ft-lb. Specific energy (Wayment and Grantmyer 1976) is sometimes used to evaluate breaking performance when such factors as concrete properties, fragmentation method, operator skill, and tool design are considered. In these cases, specific energy is the measure of the blow energy delivered per unit volume removed.

83. The high cyclic impact energy delivered to a structure by a vehicle-mounted breaker generates vibrations that may adversely affect

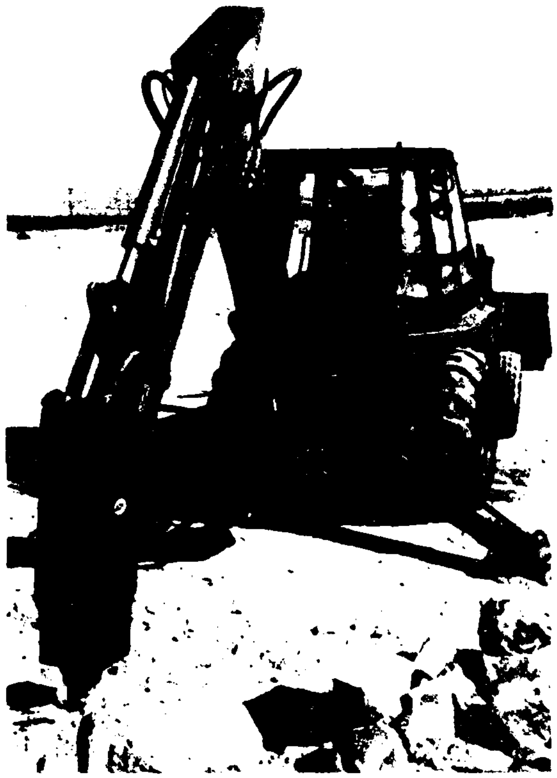

Figure 11. Vehicle-mounted breaker (courtesy of Joy Manufacturing Co., Denver, Colo.)

the integrity of the structure. To keep such vibrations at a safe level, one Corps office has placed a 150-ft-lb limit on the blow energy allowed for removal work at its locks and dams. Such action has eliminated the use of most vehicle-mounted breakers at these projects.

84. The advantages of the vehicle-mounted breaker are:

- a. It is an efficient tool for removing large volumes of concrete.
- b. It is an efficient tool for removing concrete from wall surfaces.
- c. It is readily available commercially.

85. The disadvantages are:

- a. High cyclic energy applied to a structure over a period of time may have an adverse effect on the integrity of the structure.

b. Concrete that remains may have significant damage due to high cyclic energy applied during breaking.

c. Use of the breaker is restricted in areas of limited work space.

d. A high level of noise is produced.

e. Dust is produced.

Water Cannon

86. The water cannon is an impact device that uses a jet spurt of liquid propelled at a very high velocity to impact and spall a concrete surface. The resulting debris is trapped by the protective shield of the cannon and is coated with the impacting liquid, thereby minimizing airborne particles and dust. Two versions of the water cannon were tested and evaluated by the Pacific Northwest Laboratory for removal of contaminated concrete in nuclear facilities (LaGuardia 1980).

87. One version of the water cannon tested was a .458 magnum (11.63-mm) rifle. It was modified by replacing its standard barrel with a shorter smooth-bored barrel, adding a jet nozzle and a funnel-shaped shield to the open end of the barrel, and including a vacuum system connected by a hose to the shield. The shield of the rifle is placed against the concrete surface as illustrated in Figure 12. The gunpowder is fired propelling a cylindrically shaped projectile of solidified glycerine down the barrel and out the nozzle at a very high velocity. The debris from the impact is removed by the vacuum system through the hose connection in the shield.

88. The second version of the water cannon tested was a water jet propelled by a compressed-air-driven piston. The cannon is added as a bit to the tool end of the impactor of a vehicle-mounted breaker. As the impactor is operated, the cannon fires a jet of water as illustrated in Figure 13. The impact of the water spalls the concrete from the surface.

89. Tests using both versions of the water cannon were conducted on nuclear reactor-grade concrete. Results (LaGuardia 1980) showed that

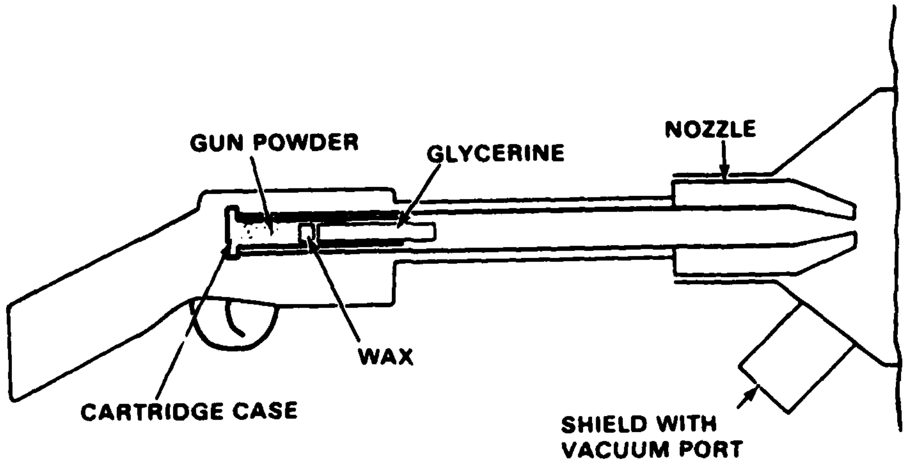

Figure 12. Drawing illustrating the .458 magnum water cannon (LaGuardia 1980)

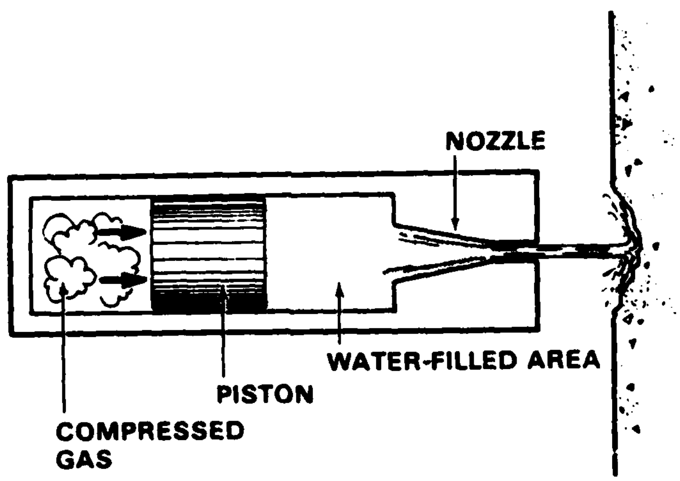

Figure 13. Drawing illustrating the piston-propelled water cannon (LaGuardia 1980)

a single shot by the modified .458 magnum rifle made an average spall of 3 to 4 in. in diameter and approximately 0.75 in. deep at the center. It required 5 to 6 min and 24 shots to remove 1 ft^2 of surface. The piston-propelled cannon fires up to five times a second and required 15 min to remove 1 ft^2 of surface. This represents removal rates of less than 1 ft^3/hr for both the rifle and the piston-propelled cannons.

90. The advantages of the modified .458 magnum rifle as a water cannon are:

- a. It is relatively safe to operate.
- b. It can be used on wall surfaces and in areas of limited work space.
- c. Limited skills are required by the operator.
- d. The rifle cannon is relatively lightweight.
- e. Fly rock and dust are minimized.
- f. The rifle cannon is more productive than the piston-propelled cannon.

91. The disadvantages of the rifle cannon are:

- a. It is not an efficient or a productive means of removing large volumes of concrete.
- b. Fumes from firing of gunpowder are produced.
- c. Shot noise is excessive.
- d. It is not commercially available.

92. The advantages of the piston-propelled water cannon are:

- a. It can be used to remove concrete from wall surfaces.
- b. Fly rock and dust are minimized.

93. The disadvantages of the piston-propelled cannon are:

- a. It is not an efficient or a productive means of removing large volumes of concrete.
- b. Excessive noise is produced.
- c. It is not suited for use in areas of limited work space.
- d. It is not commercially available.

PART V: PRESPLITTING

94. Presplitting methods employ wedge mechanisms in boreholes drilled at points along a predetermined plane to propagate a crack plane for removal of a distressed or deteriorated section of concrete. The pattern and spacing of boreholes and the depth of the boreholes affect the direction and extent of the crack planes that propagate. Secondary methods of breakage are often required to complete the removal.

Concrete Splitter

95. The concrete splitter is a wedging device that is used at predrilled boreholes to split concrete into sections. Splitters have been used at Corps projects such as Hiram M. Chittenden Lock (Anonymous 1975a), Seattle District, in the removal of an existing fish ladder structure and Markland Dam (Anonymous 1975b), Louisville District, in the removal of pairs of reinforced blocks atop downstream pier stems. Splitters have been used on a variety of other types of structures such as bridges, nuclear reactors, retaining walls, and concrete bank vault walls. Figure 14 shows splitters being used to presplit an 8-ft reinforced concrete wall.

96. In general, the concrete splitter system consists of a hydraulic system and a splitter. The hydraulic system contains hydraulic hoses, a hydraulic pump, and a power source which can be an air compressor, gasoline engine, or electric motor. The splitter, as illustrated in Figure 15, contains a plug, feathers, cylinders, a piston, a commanding valve, and a control lever. Several splitters can be operated using one hydraulic system.

97. The drilling operation generates both noise and dust. Required hole diameters range from 1-3/16 to 1-3/4 in. (EMACO 1977) and minimum hole depths from 12 to 26 in., depending on the model of splitter used. The splitters may vary in weight from 39 to 78 lb (EMACO 1977) and can develop maximum splitting forces of around 440,000 to 700,000 lbf.

Figure 14. Concrete splitters being used to presplit a reinforced concrete wall (courtesy of EMACO, Inc., Elmwood Park, N. J.)

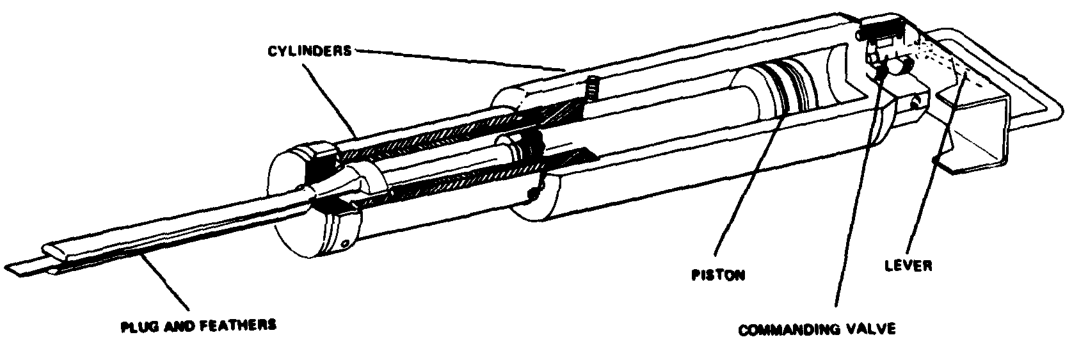

Figure 15. Drawing of a concrete splitter (EMACO 1977) (courtesy of EMACO, Inc., Elmwood Park, N. J.)

98. The control lever operates the commanding valve that directs pressure to the piston for advancing or retracting the plug. As the plug advances, the feathers are wedged against the sides of the borehole generating a crack plane that propagates out from opposite sides of the hole at the spaces between the feathers. The pattern, spacing, and depth of holes; the orientation of the feathers; and the number of splitters used affect the direction and extent of crack planes that propagate.

99. The advantages of the concrete splitter are:

- a. It is safe to use.
- b. It can be used to presplit and separate large sections of concrete for removal.
- c. It can be used on wall surfaces and in areas of limited work space.
- d. Limited skills are required by the operator.
- e. No vibration, fly rock, or dust is produced other than that yielded by drilling and secondary breaking operations.

100. The disadvantages are:

- a. For removal of surfaces from mass concrete structures, control of crack plane depth is somewhat limited.
- b. For reinforced concrete structures, other means are required to cut reinforcing that links the split section with the main body of the structure.
- c. Secondary means of breakage are often required to separate and break sections to increase efficiency in handling and removal work.

Expansive Agent

101. An expansive agent when correctly mixed will undergo a large increase in volume over a period of time. By placement of the agent slurry in boreholes that are located in a predetermined pattern within a concrete structure, the concrete can be presplit in a controlled manner for removal.

102. The agent comes in powder form and is mixed with water to form a slurry. As the agent will irritate the skin and eyes, rubber gloves and goggles are worn to protect the worker. Boreholes that contain water

are lined with plastic or other suitable material to prevent dilution of the slurry. Boreholes that are suspected of containing large voids should also be lined to prevent slurry from entering the voids. When the slurry is poured into the holes, it solidifies and expands producing tensile stress concentrations on the inner surface of the hole. The tensile stress that develops will generally exceed the tensile strength of the concrete within 10 to 20 hr (Onoda undated) after pouring. A crack will begin to propagate out from the hole due to the resulting overstress and may continue for a couple of days before reaching optimum. Secondary means of breakage are employed to complete separation and removal of concrete. For reinforced concrete, a means of cutting reinforcement must also be employed.

103. In November 1980 at Emsworth Lock in the Pittsburgh District, a pilot test program was implemented to evaluate removal techniques for future work on the lock. One portion of the program involved evaluating the use of an expansive agent for presplitting and ease of removal. Work for this involved removing 1 ft of deteriorated concrete from a 6-ft-wide and 26-ft-high area of lock face. For such, 2-in.-diam boreholes were located 1 ft behind the lock face on 6-in. centers and vertically drilled to a depth of 26 ft. Alternate holes were lined with plastic and filled with slurry. The plastic liners were intended to prevent the slurry from being diluted by water in the bottoms of holes but were easily torn and punctured by the abrasive sides of the boreholes. Figure 16 shows the presplitting crack that propagated between boreholes approximately 20 hr after the slurry was placed. Figure 17 shows the resulting surface after removal of the presplit section of the lock face. The removal was completed by using a crane to drop a large I-beam with a fabricated chisel point into the presplit crack.

104. In December of 1980, the same expansive product was used for the same type of repair and rehabilitation work at Dresden Island Lock in the Rock Island District, and presplitting was less than desired. The poor performance of the agent is believed to have been caused by the adverse effects resulting from one or more of the following conditions:

Figure 16. Crack propagation approximately 20 hr after pouring expansive agent slurry

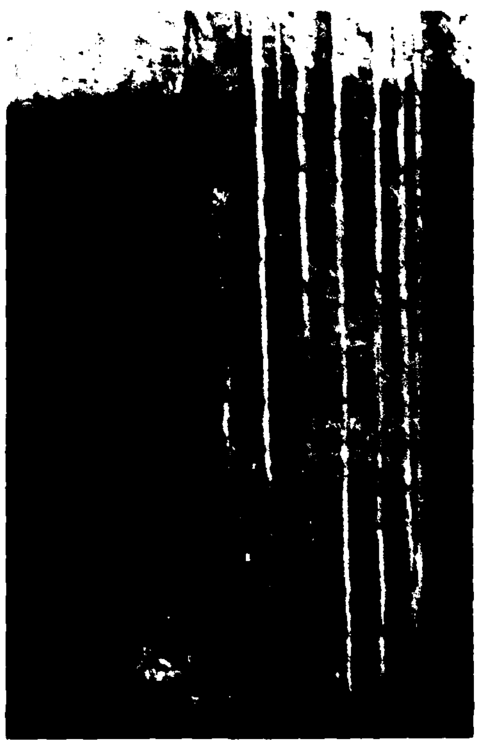

Figure 17. Lock face after removal of presplit section of face

a. Mixing water was heated too high, producing a slurry temperature above recommended values for optimum performance.

b. No liners were used in the boreholes; the slurry became diluted by water already in the holes.

c. Freezing temperatures partially froze the slurry.

d. Presplitting between the boreholes was difficult to achieve due to stress relief provided by the very weak material that existed between the boreholes and the lock face.

105. The advantages of the expansive agent are:

a. Reasonably safe operation can be maintained.

b. It can be used to presplit large sections of concrete for removal.

c. It can be used to propagate vertical crack planes of significant depth for controlled presplitting within a mass concrete structure.

d. Limited skills are required by field personnel.

e. No noise, vibration, fly rock, or dust is produced other than that produced by drilling and secondary removal methods.

106. The disadvantages are:

a. The agent is expensive.

b. The overall operation is somewhat costly when drilling and secondary removal expenses are included.

c. Control of crack plane depth is somewhat limited.

d. The agent may not be effective if the slurry is allowed to freeze or overheat.

e. Secondary means are required to complete separation and removal of the concrete section from the structure.

f. For reinforced concrete, a means of cutting the reinforcement must be employed.

g. A couple of days may be required before presplitting becomes optimum.

h. Any large voids in a borehole are usually not detected until an excessive amount of slurry has been used.

PART VI: MECHANICAL SPALLING

107. Mechanical spalling methods employ tensile stressing devices that pull small chunks of concrete from concrete surfaces. The devices are hydraulically operated and require a borehole of a specified depth for each chunk removed. This results in a lot of drilling and redrilling. For removal of large volumes of concrete, these methods are slow and costly.

Hydraulic Rock-Breaker

108. The hydraulic rock-breaker is a spalling device for breaking concrete and rock. It operates on a concept similar to that of an anchor being pulled from its place of embedment. Inserted into a predrilled borehole, the device jacks against the bottom of the hole while gripping the inner surface of the hole. This pushes the concrete between the gripped inner surface and the top of the hole outward. The jacking continues until the concrete becomes overstressed and spalls.

109. The breaker is relatively light, weighing approximately 25 lb (Cooley 1980). It is being developed and tested through funding provided by the National Science Foundation. Its development is a part of an effort to provide environmentally acceptable demolition and excavation tools for removing rock and concrete. Its operating system is composed of a hydraulic pump, hydraulic hoses, and the breaker device. The breaker device, which is detailed in Figure 18, basically contains a jack and a notching unit consisting of a sleeve and handle. The sleeve is threaded at one end and has flexible fingers at the other. At the end of each finger is a blade for notching and gripping the inner wall of a borehole.

110. The breaker device with jack piston retracted is inserted into a 2.5-in.-diam borehole until the piston contacts the bottom of hole at a depth of 12 to 17 in. (Cooley 1980). The device is pressed against the bottom of the hole by the operator until the fingers of the notching unit override the conical end of the jack. The notching handle is turned

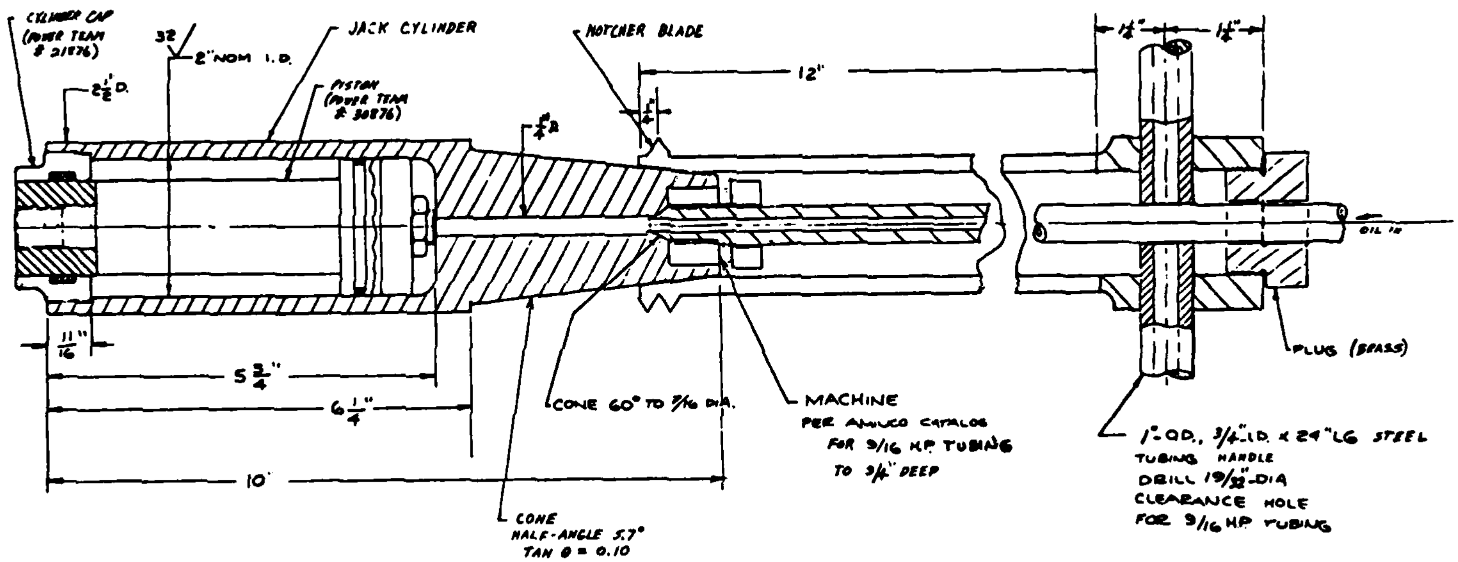

Figure 18. Detail drawing of hydraulic rock-breaker (Cooley 1980)
(courtesy of National Science Foundation)

clockwise until the fingers of the notching unit spread enough to lightly set the notching blades into the inner face of the hole. Hydraulic pressure is applied to the jack forcing the notching blades deeper into the inner face and thereby creating a circumferential notch and line of weakness in the hole face. As the hydraulic pressure is increased, the portion of the hole between the notch and the top of the hole is pushed outward until the concrete becomes overstressed and spalls.

111. The advantages of the hydraulic rock-breaker are:

a. Reasonably safe operation can be maintained.

b. The breaker can be used on wall surfaces and in areas of limited work space.

c. Limited skills are required by the operator.

d. The breaker is relatively lightweight.

e. No vibration, fly rock, or dust is produced other than that produced by the drilling operation.

112. The disadvantages are:

a. Operation is slow for removal of large volumes of concrete.

b. Drilling cost may be high due to the number of holes required for removal of large volumes of concrete and for removal of concrete surfaces of significant thickness that require redrilling of holes to complete removal.

c. The breaker is not commercially available; it is still in the experimental and test stages of development.

Concrete Spaller

113. The concrete spaller is a spalling device developed and tested by the Pacific Northwest Laboratory (Halter and Sullivan 1980) for removing thin layers of contaminated concrete surfaces in nuclear facilities. The operation of the device combines the wedge concept with a concept similar to that of an anchor being pulled from its place of embedment. When the spaller is inserted into a predrilled borehole, the tapered end of the spaller push rod is driven by hydraulic pressure through the hollow bit toward the bottom of the hole wedging outward the feathers of the bit against the inner face of the hole. As the bit contacts the bottom of the hole, the tips of the bit feathers grip the inner surface

pushing the concrete between the gripped area and the top of the hole outward. The hydraulic pressure is increased on the push rod until the concrete becomes overstressed and spalls.

114. The concrete spaller system contains a hydraulic power supply system and the spaller device. The spaller device, as shown in Figure 19, basically consists of a hydraulic cylinder, a push rod, and a bit. The push rod has a pressure plate at one end and a tapered point at the other end. The bit is a piece of circular tubing that is slotted at one end to make four equal feathers. At the tip of each feather is a spike for gripping the inner surface of the wall.

115. The testing program (Halter and Sullivan 1980) indicated that boreholes 1 in. in diameter and 2 in. in depth produced optimum removal when located in a triangular pattern 8 in. apart. Test results showed removal rates for such to be approximately 5 ft^3/hr. This included both drilling and spalling operations and required two workers and an automated air drill system. For additional surface removal, holes can be redrilled and spalled again.

116. The advantages of the concrete spaller are:

a. It is safe to operate.

b. It can be used on wall surfaces and in areas of limited work space.

c. Limited skills are required by the operator.

d. The device is relatively lightweight.

e. No vibration, fly rock, or dust is produced other than that produced by the drilling operation.

117. The disadvantages are:

a. It is a slow and inefficient means of removing large volumes of concrete.

b. Drilling cost may be high due to the number of holes required.

c. The spaller is not commercially available.

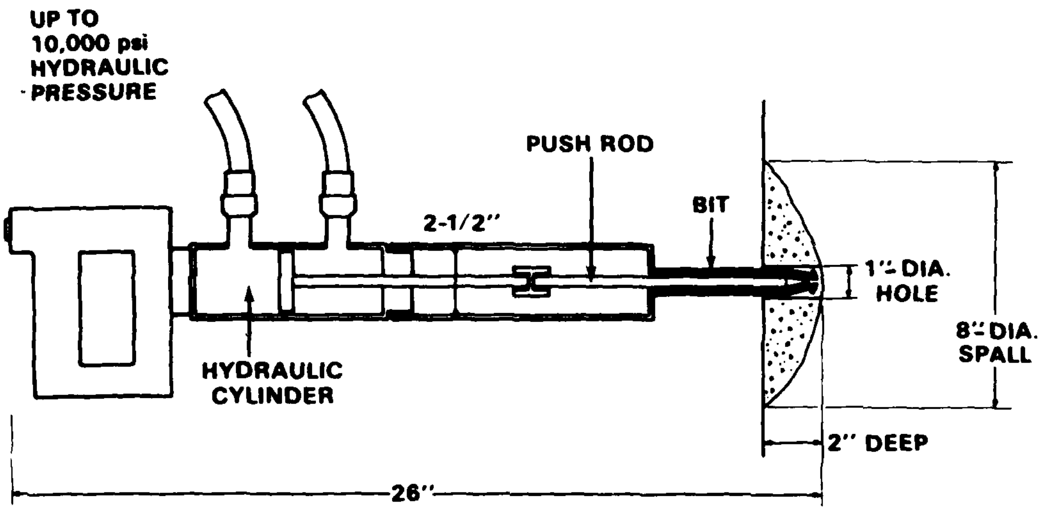

Figure 19. Concrete spaller (Halter and Sullivan 1980)

PART VII: BOREHOLE NOTCHING TECHNIQUE

118. Borehole notching is a crack control technique that has been tested for use in tunnel blasting of rock for the U. S. Department of Transportation (Thompson et al. 1979) and in blast removal of deteriorated concrete surfaces at Lock and Dam 1 on the Mississippi River in the St. Paul District. The general procedure for both projects was first to predrill boreholes and later to come back and notch them. The notches penetrate 1/4 in. into the inner face of the hole and are located on opposite sides along the length of the hole. They create lines of weakness on the inner face of the hole and thereby reduce the amount of force required to initiate and propagate a crack plane from the hole. As a result, hole spacings can be increased without reducing the efficiency of the removal method.

119. For both projects, notching of the boreholes allowed a reduction in the number of holes and the amount of explosive required. However, at Lock and Dam 1, borehole notching was not used for project work after the pilot test program was complete because it offered no savings in time. The time required to reenter and notch each of the predrilled holes was about equal to the time required to drill the extra holes saved by notching.

120. In concrete that is extremely deteriorated or that has other weaknesses, random undesired crack planes may result due to the use of blasting or an expansive agent. For such situations, borehole notching may provide the desired crack control that could not otherwise be achieved.

121. The notching bits used in these tests were specifically fabricated for such and are not commercially available at present. Several preliminary designs have been made of a single tool that combines the drilling and notching operation into one. The development of this tool has been halted until an interested sponsor can be found. Figure 20 details a bit recommended by Thompson et al. (1979) for notching predrilled boreholes; figure 21 is a conceptual sketch of a single-pass combination drilling and notching tool also mentioned by Thompson et al.

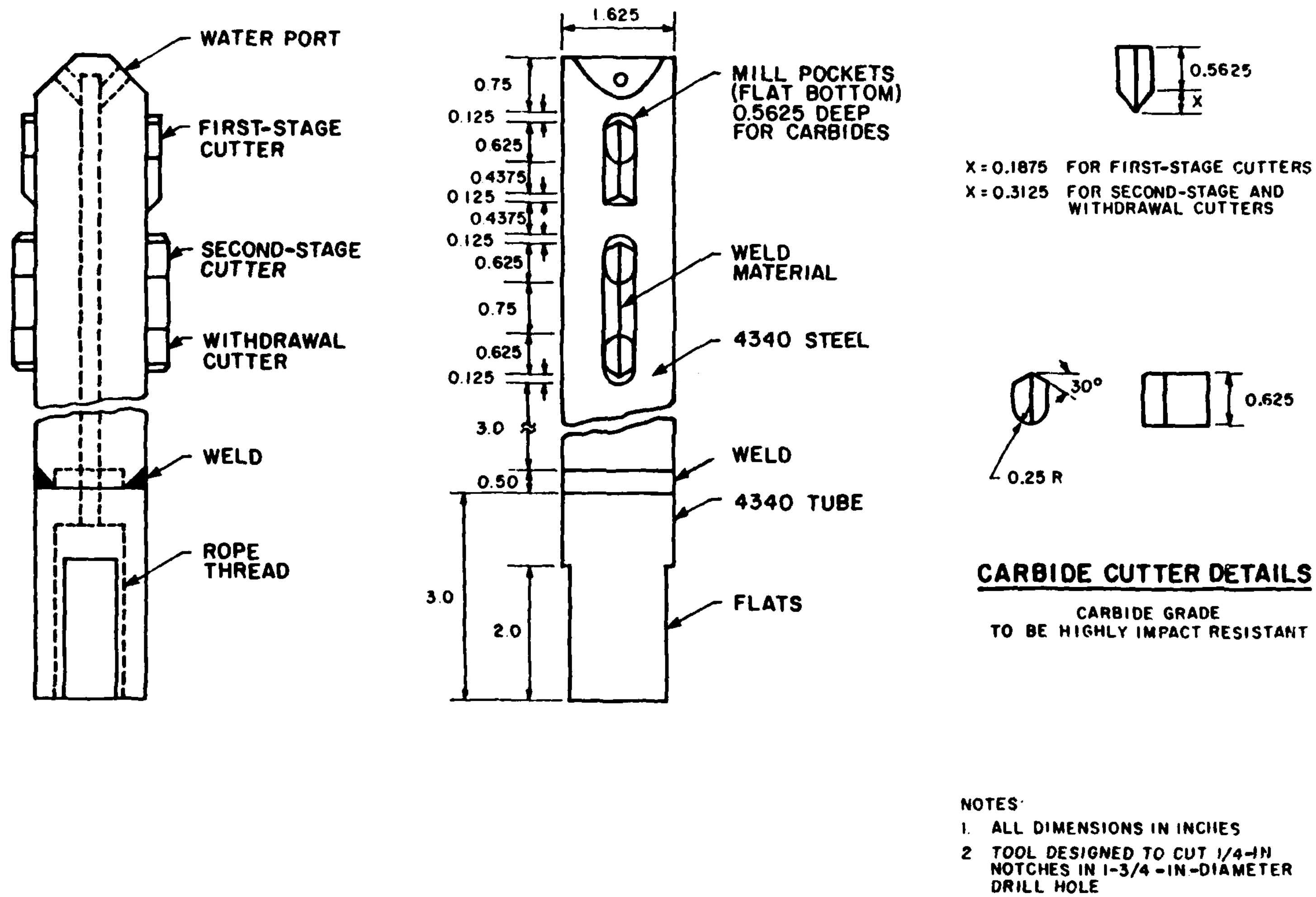

Figure 20. Detail drawing of recommended bit for notching predrilled boreholes (Thompson et al. 1979) (courtesy of U. S. Department of Transporation)

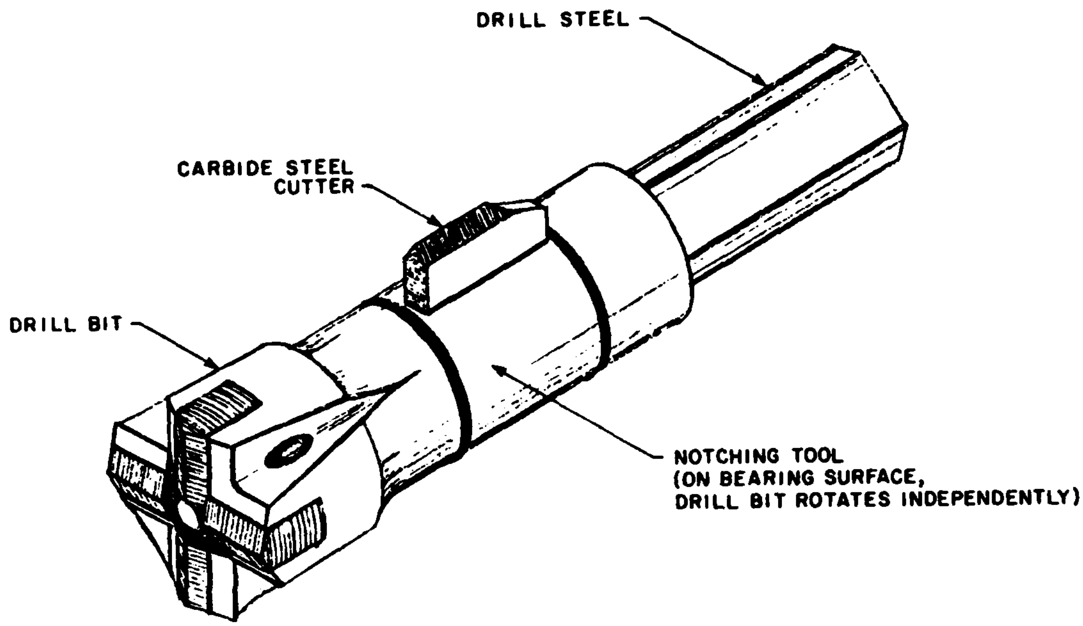

Figure 21. Conceptual sketch of a single-pass combination drilling and notching tool (Thompson et al. 1979) (courtesy of U. S. Department of Transportation)

122. The advantages of the borehole notching technique are:

<u>a</u>. Better crack control is achieved in concrete that is deteriorated or has other weaknesses that might cause undesired random cracking.

<u>b</u>. The amount of force required to achieve desired crack propagation is reduced.

<u>c</u>. The number of holes that are required to be drilled is reduced.

<u>d</u>. The amount of expansive agent or explosive is reduced.

<u>e</u>. Reduction in blast effect occurs due to reduction in the amount of explosives used.

123. The disadvantages are:

<u>a</u>. Holes have to be reentered in order to be notched; the time gained by drilling fewer holes is lost.

<u>b</u>. At present, the borehole notching tool is not commercially available.

PART VIII: DISCUSSION AND RECOMMENDATIONS

Discussion

124. Most repair and rehabilitation work at Corps projects involves removal of large volumes of distressed or deteriorated concrete. At present, the most cost-effective and expedient means for such removal is explosive blasting. However, for areas where explosive blasting is restricted or presents a hazard, other means of removal must be employed.

125. The high-pressure carbon dioxide blaster has been suggested as an alternate to explosives (Pikrose undated). It is a less violent but less powerful means of removal than explosives. The device is commercially available in Europe but may be a little more difficult to get in the United States. Its actual performance in removing concrete surfaces has not been established; however, it does appear to have potential in this area. Redrilling of holes that require more than one cartridge and the use of cartridges requiring holes larger than 2 in. in diameter increase the drilling cost and may make the blaster too expensive to use.

126. The acetylene-air rock-breaker is a blasting tool that is under development and, therefore, cannot be considered for present removal work. It does appear to have potential similar to that of the high-pressure carbon dioxide blaster, but it will require a significant amount of testing and documenting before it can be commercially marketed for concrete removal.

127. Diamond saw cutting is slow and costly, and the saw has a very limited cutting depth. It is therefore considered impractical in most applications for surface removal from mass concrete structures. However, a diamond saw can be used with other methods to improve crack control and reduce overbreakage by making a cut through the area in which a crack plane is to be propagated or where overbreakage is to be limited.

128. Applicability of the powder torch, thermal lance, and powder lance for removing surfaces from mass concrete structures will mainly

depend on the rate at which the resulting slag can flow from the cut. For vertical cuts of significant depth and limited slag flow, these cutting devices are not practical. However, the powder torch, thermal lance, and powder lance may be used like the diamond saw to improve crack control and reduce overbreaking. They are especially effective for cutting reinforced concrete; however, in general, they are considered somewhat slow and costly.

129. The electric-arc cutting method developed in the USSR uses an electric power source to melt the concrete. Like the other thermal devices which melt concrete, its success in cutting concrete will mainly depend on the rate at which the slag can flow from the cut. In Switzerland, an electrothermal lance (Lazenby and Phillips 1978) is being developed for cutting reinforced concrete. The lance has advantages and disadvantages similar to those of the electric-arc, except that it is capable of making deeper cuts more efficiently. Neither the electric-arc nor the electrothermal lance is commercially available at present. If available, these devices would be more effectively used in supporting other methods of removal rather than as the primary means of surface removal for mass concrete structures.

130. The productivity of the water jet has greatly improved over the last decade, and it is now becoming competitive with some of the other removal devices. Improvements that are under development should make the water jet even more competitive. The water jet has the potential for being a primary means for removal when it is desired to preserve the reinforcement within the removal area for reuse. However, at present, the water jet, like other cutting devices, may be better used in support of primary removal methods.

131. None of the impact methods mentioned appear to be suitable as a primary method of removal. The hand-held breaker has a low productivity rate which makes it undesirable for expedient removal of large volumes of concrete. The hand-held breaker is, however, suitable for use in support of primary means of removal. The vehicle-mounted breaker is a highly productive means of removing concrete; but because of the dangers associated with the high energy and vibration it transmits through

the structure, it is not recommended for repair and rehabilitation work at Corps locks and dams, except for projects where blow energy is to be restricted to a proven safe level. The water cannon, because of its low productivity and because it is not commercially available, is not considered applicable for this type of work.

132. Presplitting methods have potential as primary means of removing large volumes of material from mass concrete structures. For both the concrete splitter and the expansive agent, secondary means of separating and removing the concrete usually must be employed. This adds to the cost of removal. The splitter is best suited for shallow holes at any angle; the expansive agent is best suited for use in vertical holes of significant depth. The high cost of the agent may make the splitter more desirable when both methods are applicable.

133. Mechanical spalling methods have low productivity rates that make them unattractive as primary means of removal. The hydraulic rock-breaker is not commercially available at present, but appears to have potential as a secondary means of removal. The mechanical spaller is more applicable to shallow removal of limited volumes of concrete.

134. The borehole notching technique promises to enhance the blasting and expansive agent methods by reducing the number of holes needed and producing better control for crack plane propagations. In the past, drilling and notching of the holes were separate operations. Several preliminary designs have been made that combine these operations into one. These designs are presently waiting for a sponsor to fund their development.

135. To reiterate, explosive blasting is the most cost-effective and expedient means of surface removal of large volumes of material from mass concrete structures at Corps projects. In a situation where explosive blasting cannot be used, an alternate means of removal must be selected. Of those reviewed, the following appear to have potential as alternate means of removal:

a. Acetylene-air rock-breaker.

b. Concrete splitter.

c. Expansive agent.

d. High-pressure carbon dioxide blaster.

e. High-pressure water jet (in situations where reinforcement is to be preserved for reuse).

Recommendations

136. To complete the update of Corps technology on removal of distressed or deteriorated surfaces from mass concrete structures, it is recommended that a field comparison study be made. Selection of removal methods for such a study would be made from those reported to have potential as primary means of removal. It is felt that some of those having potential as secondary means of removal should also be evaluated. The study would be included as a part of scheduled repair and rehabilitation work at a Corps project. As many variables as possible would be held constant to ensure meaningful comparisons. The principal determinations to be made for comparison would be:

a. Cost.

b. Removal rates.

c. Extent of damage to concrete that remains.

d. Problem areas.

It is also recommended that the borehole notching technique be evaluated as a part of this study.

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