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Penetration Resistance Tests of Reinforced Concrete Barriers

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tion Processing Technology Division
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Interim Report for Period October 31 – November 3, 1972

Prepared for
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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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by
R. T. Moore

SUMMARY

This report describes the results of a series of penetration tests on six concrete slabs. The tests were conducted at the U. S. Army Corps of Engineers Construction Engineering Research Laboratory in Champaign, Illinois, during the period October 31 through November 3, 1972. Several alternative methods of attack were employed, and the time to penetrate, and in some instances, to produce a 96-inch^2 opening, was measured, and estimates were developed regarding the acoustic, ultrasonic and vibrational disturbances produced by the attacks.

Depending upon the attack technique, a man-passable opening can be made in four-inch thick reinforced concrete in times ranging from 4 to nearly 15 minutes. The corresponding times for eight-inch thick reinforced regular concrete range from about 7 to 25 minutes and from about 20 to 30 minutes for fibrous concrete.

With the exception of the diamond core drill, detection should be relatively easy by the combined acoustic, ultrasonic or vibrational disturbances produced by the attacks even though not all techniques produce all three types of disturbances.

ACKNOWLEDGMENTS

These tests were accomplished through the support and active participation of many individuals in several organizations. In particular, we wish to thank Col. Reisacher, E. A. Lotz, Bob Gray, Frank Kearney and Bob Gunkle of CERL for preparation of the test specimens, provision of the test site, instrumentation support and general support to the visiting test participants. The penetrations were made by Frank C. Veirs, Lt. V. Sunderdic and Spc. P. Schmidt of the Intelligence Materiel Development Office which also provided much of the attack tooling and key portions of the instrumentation. Photographic coverage of the tests was provided by IIT Research Institute through the courtesy of R. J. Bouk and the Federal Reserve Board. Sound level measurements, test timing and data recording were accomplished by R. Blackmon, Naval Security Group, and John Cecilio, Naval Facilities Engineering Command. Vibrational data acquisition was handled by John Ramboz and R. Koyanagi of the NBS Vibration Section.

The tests were sponsored by Defense Nuclear Agency under the direction of Marvin C. Beasley who arranged the multi-agency participation and was directly involved in all phases of the test activities.

Figure 1. Configuration of Test Slabs

Figure 2. Slabs Prior to Beginning of Tests

1. TEST SPECIMENS

The six test specimens were reinforced concrete slabs five feet by seven and one-half feet in size. Three of the slabs were cast using a fibrous concrete mix and the other three were made using a regular concrete mix in accordance with the mix design shown in table 1. Each slab was given an identifying number of from one to six with the odd numbers being assigned to the slabs made from regular concrete and the even numbers fibrous concrete.

Slabs 1 and 2 were four inches thick and were reinforced with number 5 bars in the center of the slab on five-inch centers both ways.

Slabs 5 and 6 were eight inches thick and with the same reinforcing rod configuration.

Slabs 3 and 4 were eight inches thick but with a different reinforcing pattern. One-quarter inch welded steel mesh with a six-inch mesh size was located two inches inside each face of the slab. The two layers of mesh were staggered from each other three inches in each direction.

At the time the slabs were cast, samples of each mix were cast as columns and beams for compression, splitting tensile and flexural strength testing. These samples were cured with the slabs in a temperature and humidity-controlled curing room and were subjected to strength tests on the day that slab penetration tests were started. The test results are shown in table 2.

A few days prior to the scheduled start of penetration testing the slabs and mix sample test pieces were removed from the curing room. The slabs were moved outside to a black top parking area at the east end of the building and placed on edge in a hexagonal configuration and wooden timbers were attached across their tops so as to provide bracing and support.(See fig. 1.) On the day prior to the start of testing, attack locations were laid out on the slabs and identified by spray paint lettering. The general arrangement is shown in figure 2.

In addition, vibration transducers were mounted on slabs 1, 2 and 3 on the inside at the center at a point about six inches below the top edge as shown in figure 3.

Table 1. Mix Design

CONCRETE	PLAIN	FIBROUS
Cement, lbs. 94#/sack	564	517
Fly Ash, lbs. 75#/sack)	---	225
Water, lbs.	250	320
Fine Aggregate, lbs.	1300	1400
Coarse Aggregate, lbs. (Fibrous 3/8" Max.,Plain 3/4" Max.)	1675	1400
Air Entrancement Agent, fl. oz. (3/4 oz./sack of cement)	4-1/2	3
Water Reducer, fl. oz. (9 oz./sack of cement)	---	50
Fiber, lbs. (Steel 0.010 x 0.022 x 1.0 in.)	---	200

Table 2. Mix Sample Test Results

	Plain Concrete		
	Compression	Splitting Tensile	Flexural
#1	5730 psi	385 psi	515 psi
#2	6150 psi	464 psi	595 psi
#3	6150 psi	---	655 psi 580 psi
Avg.	6010 psi	424 psi	585 psi
	Fibrous Concrete		
	Compression	Splitting Tensile	Flexural
	7090 psi	765 psi	1200 psi
	5780 psi	796 psi	1195 psi
			1015 psi
			1075 psi
Avg.	6440 psi	780 psi	1120 psi

Figure 3. Vibration Transducer Location

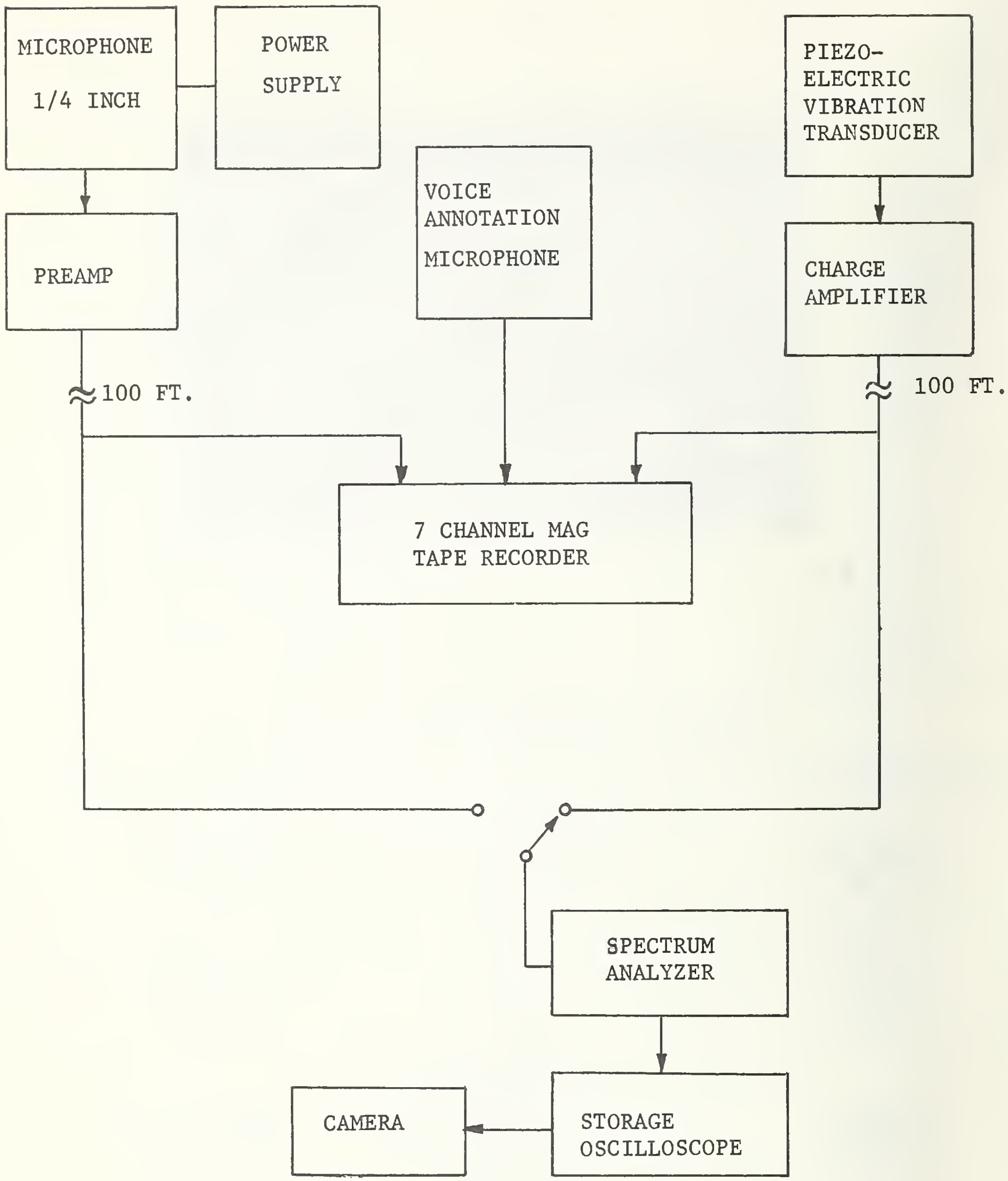

Figure 4. ACOUSTIC, ULTRASONIC AND VIBRATIONAL DATA RECORDING INSTRUMENTATION

2. TEST INSTRUMENTATION

Penetration time was recorded manually using a stopwatch. The times reported represent only those time intervals when the attack was actually underway. Time intervals used to set up tooling, to change tools, or to consider new methods of attack were excluded. The probable error in timing data is believed to be on the order of ± 5 seconds, except, in the case of short attacks where no change of tooling occurred, measurements are believed to be within ± 1 second.

Acoustic, ultrasonic and vibrational data collection was accomplished using instrumentation as shown in figure 4. A 1/4-inch capacitance microphone, together with its power supply and preamplifer, was mounted on a roller-equipped tripod. This was positioned at a nominal distance of 10 feet from each attack point. A 100-foot length of coaxial cable was led back inside the building to the magnetic tape recorder and spectrum analyzer. The charge amplifier associated with the vibration transducer was located within the hexagonal area enclosed by the slabs and connected to a second length of coaxial cable. Magnetic tape recordings were made of both data channels but only one channel at a time could be connected to the spectrum analyzer. The output of the spectrum analyzer was used to drive the storage oscilloscope which permitted capture and subsequent photography of sample spectra during the course of the tests.

The microphone preamplifier gain was set to +20 dB for all penetration tests and overall calibration was performed using a calibrator which provides a reference sound pressure level of +124 dB at 250 Hz. Vibration transducers were calibrated and full scale g values related to charge amplifier gain settings and peak voltages prior to the test series. Transfer of calibrations to the spectrum analyzer was accomplished with a signal generator and digital voltmeter. The uncertainty associated with data derived from either the acoustic or vibrational channel is estimated to be on the order of 3 dB and is small compared to the influence of other uncontrolled factors.

In particular, it is important to recognize that the acoustic, ultrasonic and vibrational data which were observed in this test series may not be representative of those which might result from a similar attack on the same materials if they were employed in the construction of a vault or room. In most of the test series, each slab was resting on one edge and the other three edges were free. Thus, it is possible that vibrational modes may have existed which would not occur in a similar slab which was bonded on all edges to form a structure. These modes, if present, could also influence the observed sound levels which may be further affected by reverberation and reflection from nearby objects.

The frequency response of both the acoustic-ultrasonic and the vibration transducer and their respective amplifiers is reasonably flat to well above 50 kHz and this frequency was selected as the upper limit in the spectrum analyzer. All spectral samples appearing in this report were obtained with a 500 Hz analyzer bandwidth, 5 kHz per cm sweep, and 25 kHz center frequency. Amplitude reponse is logarithmic, 10 dB per cm, and the scale was adjustable in 20 dB steps with the input attenuator of the spectrum analyzer.

Where temperature rise measurements were made, a resistance thermometer was employed in conjunction with a digital ohmmeter. Ohmmeter readings were recorded manually and converted to temperature values using a calibration chart furnished by the manufacturer who claims accuracy of $\pm 1^{\circ}$F in the observed temperature range.

Two portable sound level meters were also used and data from these was recorded manually. One was operated in the linear mode providing an indication of peak sound pressure levels at frequencies up to about 50 kHz. This meter was positioned at a distance of about eight feet from the attack point except where otherwise noted.

A second Sound Level Meter, USASI Type 3, was operated with an A weighting network. dBa sound pressure levels were observed at a distance of 30 feet from the attack point unless otherwise noted.

Photographic coverage of the test series included 35 mm color still photographs (slides) and 16 mm color motion picture footage of selected highlight activities.

3. ATTACK DESIGNATION AND TOOLING DESCRIPTION *

Each attack was assigned an identifying letter. This was associated with the physical location of the attack point on the slab and was kept the same from slab to slab to the greatest extent practical. It also identified the primary attack tooling or technique which was employed as follows:

A. Sledgehammer

Sledgehammers were available in weights of 10, 12, 16, and 20 pounds. In practice the 10- and 16-pound weights were used almost exclusively.

B. Rotohammer

A Skil model 736 rotohammer was used with 3/4", 7/8", 1", and 1-1/2" diameter masonry bits and a 1-1/2" toothed chisel.

C. Diamond Drill

A 3-1/2" diameter water-lubricated core drill was operated at 900 r.p.m. The drill was mounted in a portable press stand which was equipped with a motor current monitoring meter. Drill pressure was manually applied so as to develop a drill motor current of 7 to 7-1/2A, 110 VAC.

D. Burning Bar

The bar was one-half inch black iron pipe with nineteen iron and one aluminum filler rods. The bar had been cut to five-foot lengths to facilitate shipment. Operation during all tests was at 200 p.s.i. oxygen pressure. This high pressure, together with the short lengths between couplings, occasionally resulted in ejection of filler rods.

E. Jet Ax

This is a commercially available linear-shaped charge mounted in a foamed plastic damper and equipped with a 30- to 45-foot long detonator cord terminated with a screw-on, hand operated, percussion initiator. Three different sizes were used in the test series. The JA-3 has 5.6 ounces of explosive arranged to make a 24" X 36" rectangular cut (.04 oz. per linear inch). The JA-4 has 5.6 ounces of explosive arranged to make a 17" diameter circular cut (.104 oz. per linear inch). The JA-5 has 3.4 ounces of explosive arranged to make a 10" diameter circular cut (.108 oz. per linear inch).

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* See footnote at bottom of page 16.

F. Demolition Saw

A rotary saw powered by a 5-horsepower gasoline engine and equipped with a 16" diameter abrasive cutoff wheel.

G. Pneumatic Jackhammer

A pneumatic jackhammer operated at 100 p.s.i. air pressure from a gasoline engine powered air compressor mounted on a small trailer. Tool size was 1-1/4" (across flats of the hexagonal shaft) and a spike point and 3" spade point tool were used.

4. ROUND VERSUS RECTANGULAR HOLES

It is generally conceded that a small man can squeeze through an opening having an area of 96 square inches provided that one dimension of the opening is at least 6 inches. The required area can result from a circular opening having a diameter of just over 11 inches or from a rectangular opening having dimensions of 8 by 12 inches, for example. We believe that the rectangular opening may admit a slightly larger man than the circular opening of equivalent area as it better accommodates human shoulders and hips. Because of this, most of the penetration tests were targeted toward the production of a rectangular opening except in instances where the physical nature of the attack tooling dictated otherwise. A 96 $in.^2$ circular opening has a perimeter length of 34.73 inches while an 8" X 12" rectangular opening has a perimeter length of 40 inches. As a result, whenever penetration time is a linear function of perimeter length, it is likely that the rectangular opening may have taken on the order of 115 percent of the time which might have been required for a circular opening. Obviously this does not hold in the case of tooling such as the abrasive cutoff saw which is only useful for making straight-line cuts or for tooling such as the sledgehammer which is used for volumetric removal of material over the entire area of the opening. In selected instances, calculations have been made of the time which might be required to produce openings of both shapes to illustrate the difference.

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* Certain commercial equipment and materials are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

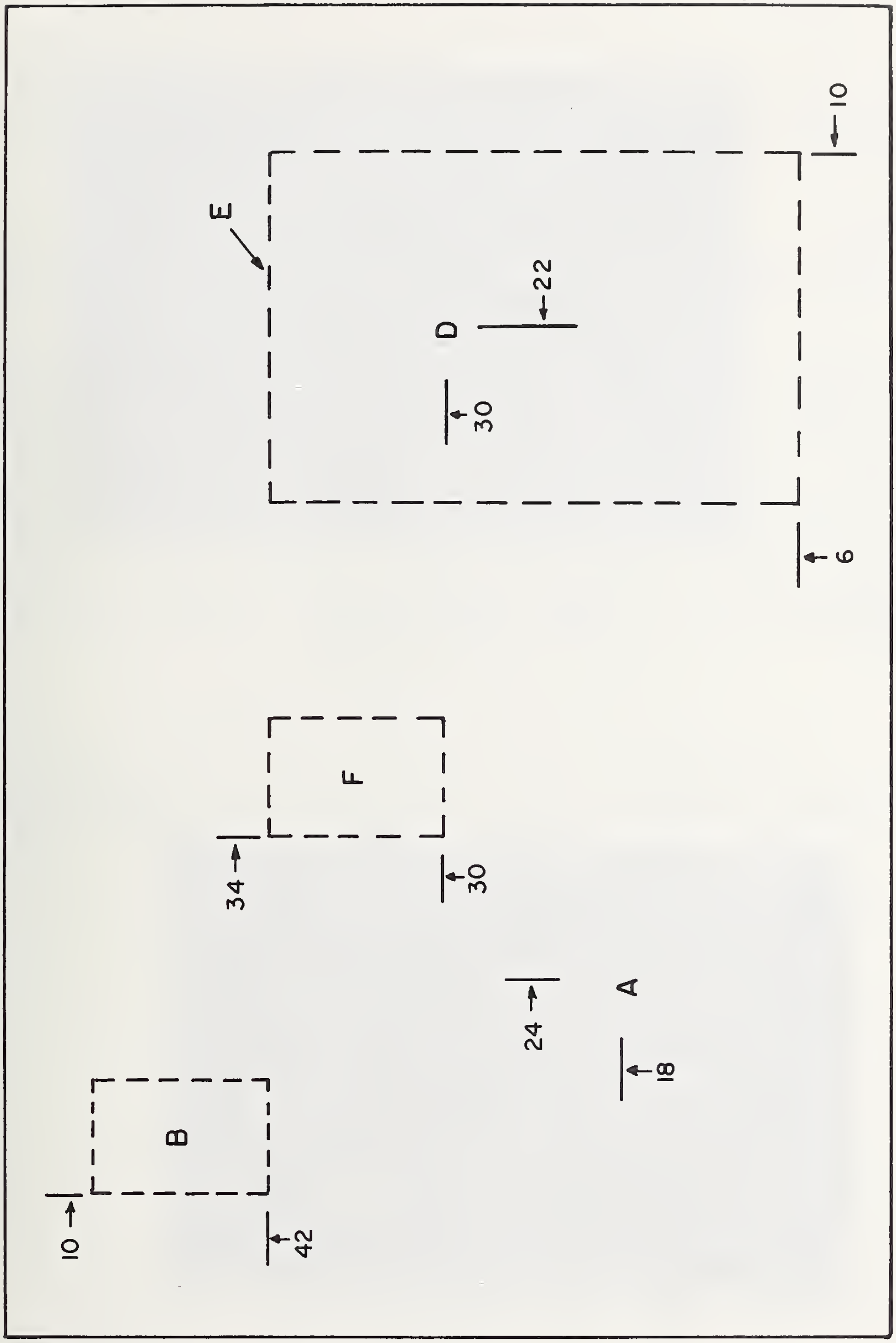


Figure 5. Target Attack Locations, Slab 1

5. ATTACK RESULTS

SLAB 1

Slab 1 was 4-inch thick ordinary concrete with 5/8" reinforcing rods in the middle of the slab on 5-inch centers vertically and horizontally. The target attack locations are dimensioned in figure 5.

ATTACK A

This attack was conducted with a 10 lb. sledgehammer to break out the concrete to expose the reinforcing rods for cutting.

After 29 blows in 52 seconds, a depression was well developed on the front surface and a large circular crack could be observed on on the rear surface. After 53 blows and 1:30 minutes, an opening of approximately 22 in.^{2} was developed through the slab between the re-rods. A much larger area spalled away from the re-rod in the rear. After 2 minutes and 73 blows, the opening had been enlarged to approximately 75 in.^{2} with maximum dimensions on the order of 10" X 8". At 90 blows and 2.43 minutes, the opening had maximum dimensions of 11" X 14" and a clear area of about 100 in.^{2} and the sledgehammer portion of the attack was judged completed. (See figs. 6 and 7.)

Figure 6. Exterior View of 1A

Figure 7. Interior View of 1A

Figure 8 is a multiple sweep exposure of the spectrum analyzer output showing sound pressure level observed during the hammer attack. dBa readings ranged from 83 to 86.

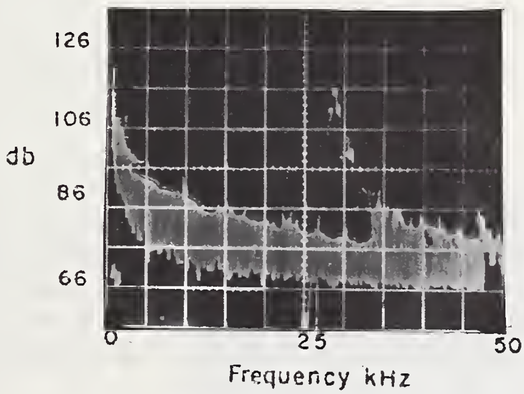


Figure 8. 1A1, Sound, Multiple Sweep

Figure 9 is a multiple sweep exposure of the vibrational spectrum. It should be borne in mind that the spectrum analyzer is repetitively sweeping the frequency range from a few Hertz to 50 kHz. When a transient, such as a hammer blow, occurs, only those spectral components which are within the passband of the analyzer at that time will be displayed. Thus, the total spectrum might be approximated by a curve connecting the peaks of the multiple sweep traces.

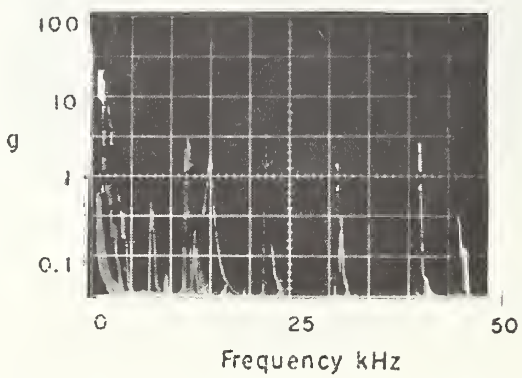


Figure 9. 1A1, Vibration, Multiple Sweep

To cut the re-rod remaining in the opening developed by the sledgehammer attack, an oxygen MAPS torch was employed after it was found that No. 3, 36" long bolt cutters could not handle the 5/8" rod. The torch cutting required 2.05 minutes to make eight cuts and release four sections of rod, yielding a total penetration time of 4.48 minutes.

Acoustical and vibrational spectra from the cutting torch are shown in figures 10 and 11, respectively. The dBa readings ranged from 56 to 68.

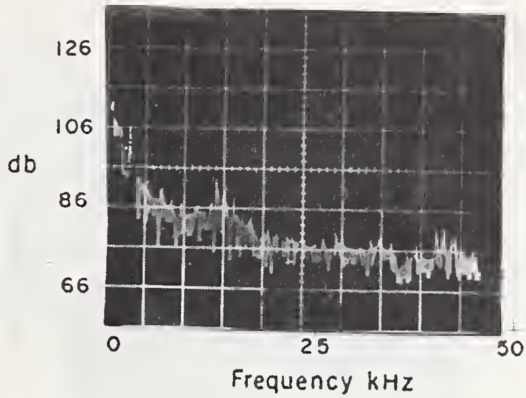


Figure 10. 1A3, Sound from Cutting Torch

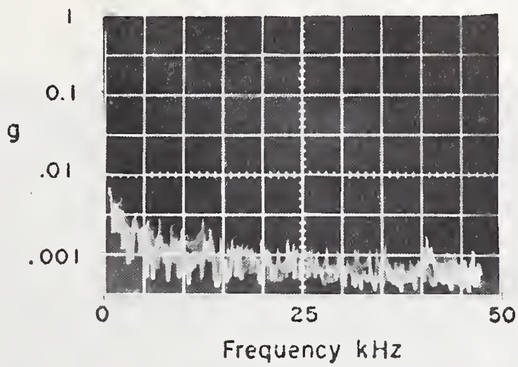


Figure 11. 1A3, Vibration from Torch

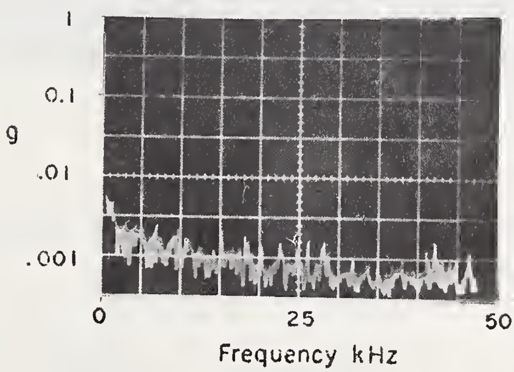


Figure 12. Background Noise, Vibration

Figure 12 shows the background noise level with no attack in progress. It is not at all clear that any vibrational disturbances introduced by the cutting torch rose above the noise.

ATTACK B

This attack involved the use of a Skil model 736 Rotohammer to drill a series of holes around the perimeter of a 6-1/2" X 15" opening and to chisel out the web between holes to expose the reinforcing rods enough that they be cut with a demolition saw equipped with a 12" diameter abrasive cutoff wheel.

Drilling eighteen holes one inch in diameter required 7 .125 minutes for an average time of 23.75 seconds per hole (see fig. 13).

Figure 13. Drilling with Rotohammer

The acoustical and vibrational disturbances produced by the rotohammer and drill are shown in figures 14 and 15. The dBa readings were 84 to 92. Peak linear sound pressure level readings of 104 to 110 dB were obtained with the sound level meter inside the hexagonal enclosure formed by the six slabs.

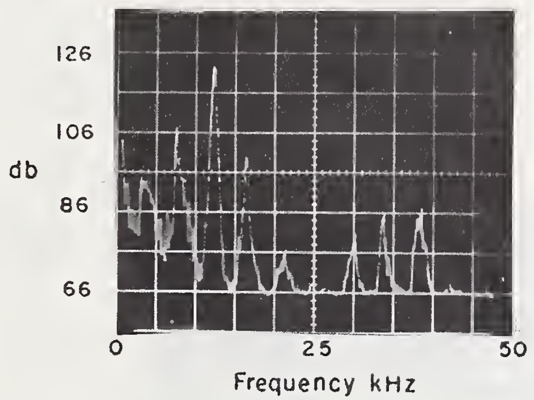


Figure 14. 1B1, Acoustical Disturbances from the Rotohammer and Drill

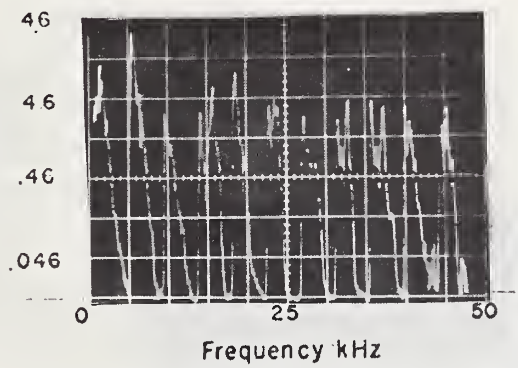


Figure 15. 1B1, Vibrational Disturbances from the Rotohammer and Drill

With a 1-1/2" chisel in the rotohammer, it took 3.66 minutes to chisel out the 18 webs between holes for an average time of 12.36 seconds per web. With a 43" perimeter and 18 one-inch holes, the length of material chiseled was 25" or 8.8 seconds per inch.

It required 10.79 minutes to drill and chisel an aperture perimeter 43 inches long. The average rate of perimeter extension was slightly over 15 seconds per inch.

The acoustical and vibration spectra are shown in figures 16 and 17.

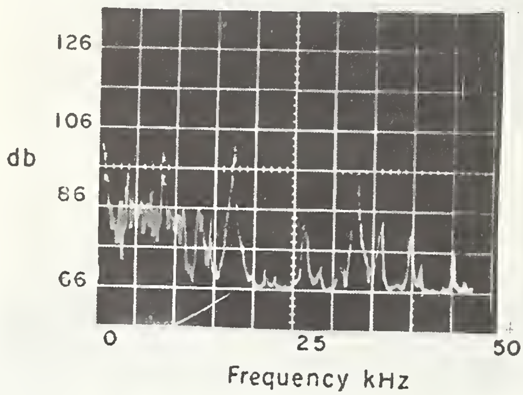


Figure 16. 1B2, Acoustical Disturbance from Rotohammer and Chisel

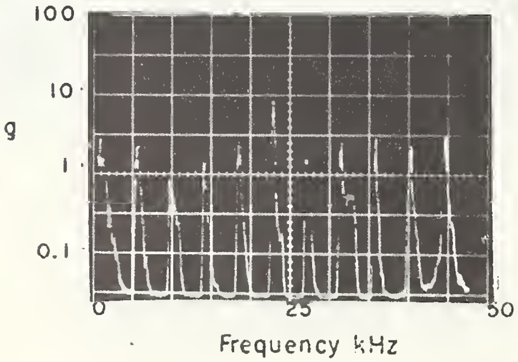


Figure 17. 1B2, Vibrational Disturbance from Rotohammer and Drill

During the chiseling, sound level meter readings of 87 to 90 dBa were observed. Peak linear values of 102 - 108 dB were observed from within the hexagonal enclosure.

Cutting the reinforcing rods with the demolition saw took 1.23 minutes giving a total penetration time of 12.025 minutes.

ATTACK D

This attack employed a burning bar. Two holes were melted through the slab; one required 29 seconds and used 20-1/2 inches of bar, the other took 20 seconds and used 21 inches of bar.

A resistance thermometer element was mounted on the back face of the slab. Burn-through of the first hole occurred 2-1/2 inches away from the element and produced the following time versus temperature profile:

Time (Sec.)	Temp. ^{o}F
0 (breakthrough)	53
25	55
35	58
60	56

The second hole burned through only 1/16-inch below the element and produced the following profile:

Time (Sec.)	Temp. ^{o}F
0	63
35	108
57	157

Using an optical pyrometer, the apparent temperature of the molten ejecta coming from the slab during the burn was $2000^{o}C$. Since the emissivity of this material is not known, the true temperature is undetermined.

Figure 18 shows the exterior of the slab. This photograph was taken only a few moments after completion of the second burn. Figure 19 is an interior view of the slab.

Figure 18. 1D2, Front of Slab 1 after Burning Bar Attack

Figure 19. 1D2, Interior of Slab 1 after Burn-through

Sound levels of 71-92 dBa were observed and a peak linear level of 102 dB was observed at a distance of 12 feet. Vibrational disturbances are shown in figure 20.

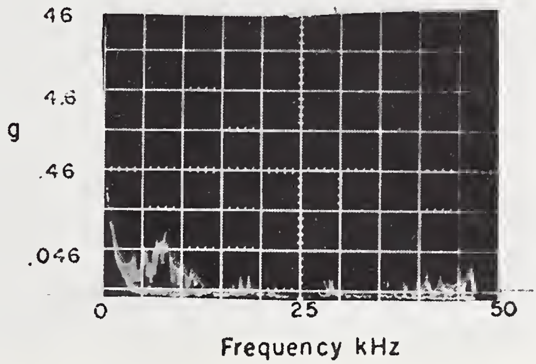


Figure 20. 1D, Vibrational Disturbances from Burning Bar

Although a complete penetration was not made using the burning bar, the time which would be required to do this is calculated as follows:

Assume 12 holes equally spaced along the circumference of an 11" diameter circle. This would provide a nominal center-to-center hole spacing of 2.9 inches. With average burn time of 24.5 seconds per hole, the total burn time is estimated to be 294 seconds. An estimated 246 inches of bar would be required based on the observed average consumption of 20.5 inches per hole.

Assuming the holes are one inch in diameter, then if the 22.5 linear inches of webs between burn holes are chiseled out using the rotohammer and 1-1/2 inch chisel at 8.8 seconds per inch, the estimated time to chisel the 12 webs is 199 seconds.

We now assume that the reinforcing rod was not aligned with the holes and cut by the burning bar in more than about half of the necessary instances,so an estimated 60 seconds is allowed to make four cuts using the torch employed to ignite the burning bar.

Finally, we assume that 15 seconds might be required with a sledgehammer to knock out the remaining plug and thus develop an estimated penetration time of 567 seconds or 9.45 minutes.

To provide a more direct comparison with the results in Attack 1B, let us assume a rectangular opening of 8" X 12" is to be produced by burning 20 holes around this perimeter. This would require an estimated 510 seconds. Chiseling out the remaining 20 inches of web would require 176 seconds. Add to this 60 seconds of torch time and 15 seconds of sledgehammer time under the assumptions stated above and the total penetration time is 761 seconds or 12.68 minutes.

ATTACK E

This attack involved the use of a Jet-Ax, size JA-3, with a 5.6 ounce linear-shaped charge arranged to cut a 24" X 36" rectangular opening.

Actual setup times were not measured. It is estimated that a hangar nail could be placed in one minute and that another 1.50 minutes would permit placing the charge connecting the detonator and actuating the device.

Figure 21 shows the Jet-Ax in place ready for firing and figures 22 and 23 show the results which it produced.

Figure 21. Jet-Ax Ready for Firing

Figure 22. Effects of JA-3, Outside of Slab 1

Figure 23. Effects of JA-3, Inside of Slab 1

Sound level meter readings were off scale on this shot but data was obtained on later Jet-Ax tests.

The JA-3 caused partial penetration of the slab such that 22 blows of a 10-pound sledgehammer in 40 seconds time were adequate to completely expose the reinforcing rod in a 24" X 31" area. The Jet-Ax detonation also shifted end of the slab back approximately 1-1/2 inches and the other end was shifted, together with slab 3 which was against it, back 2-1/4 inches.

Figure 24 shows the interior view after the sledgehammer attack cleared most of the shattered concrete from the reinforcing bars.

Figure 24. Interior View of Slab 1 after Jet-Ax and Sledgehammer Attack

If we assume two minutes with the cutting torch to cut the reinforcing rods, the estimated total time to penetrate is 5.17 minutes; however, this results in an opening considerably larger than the 96 in.^{2} minimum used in other calculations. If the opening size is restricted to the specified minimum,torch time could probably reduced by one minute and sledgehammer time reduced by 10 seconds to give an estimated penetration time of only 4·0 minutes.

ATTACK F

It was planned to cut an 8" X 12" perimeter with the demolition saw to a depth of about 3 - 3$^1/2$ inches and then knock the resulting plug out with a sledgehammer.

The attack was aborted after a single cut when it was reported that the saw was not operating properly. The single cut was 14" long on the surface and approximately 2" deep and took 55 seconds to make. Allowing for the 6" radius of the abrasive wheel, the full depth of the cut would only extend for 5.4 inches.

Sound levels were 104 - 108 dBa and 105 - 106 dB linear.

Figure 25 shows the vibrational disturbances produced by this attack. The spectrum is noteworthy in that amplitude does not fall but increases with increasing frequencies.

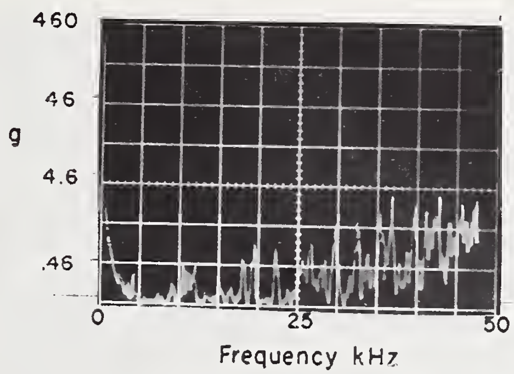


Figure 25. 1F1, Vibrational Disturbance from Demolition Saw and Abrasive Cutoff Wheel

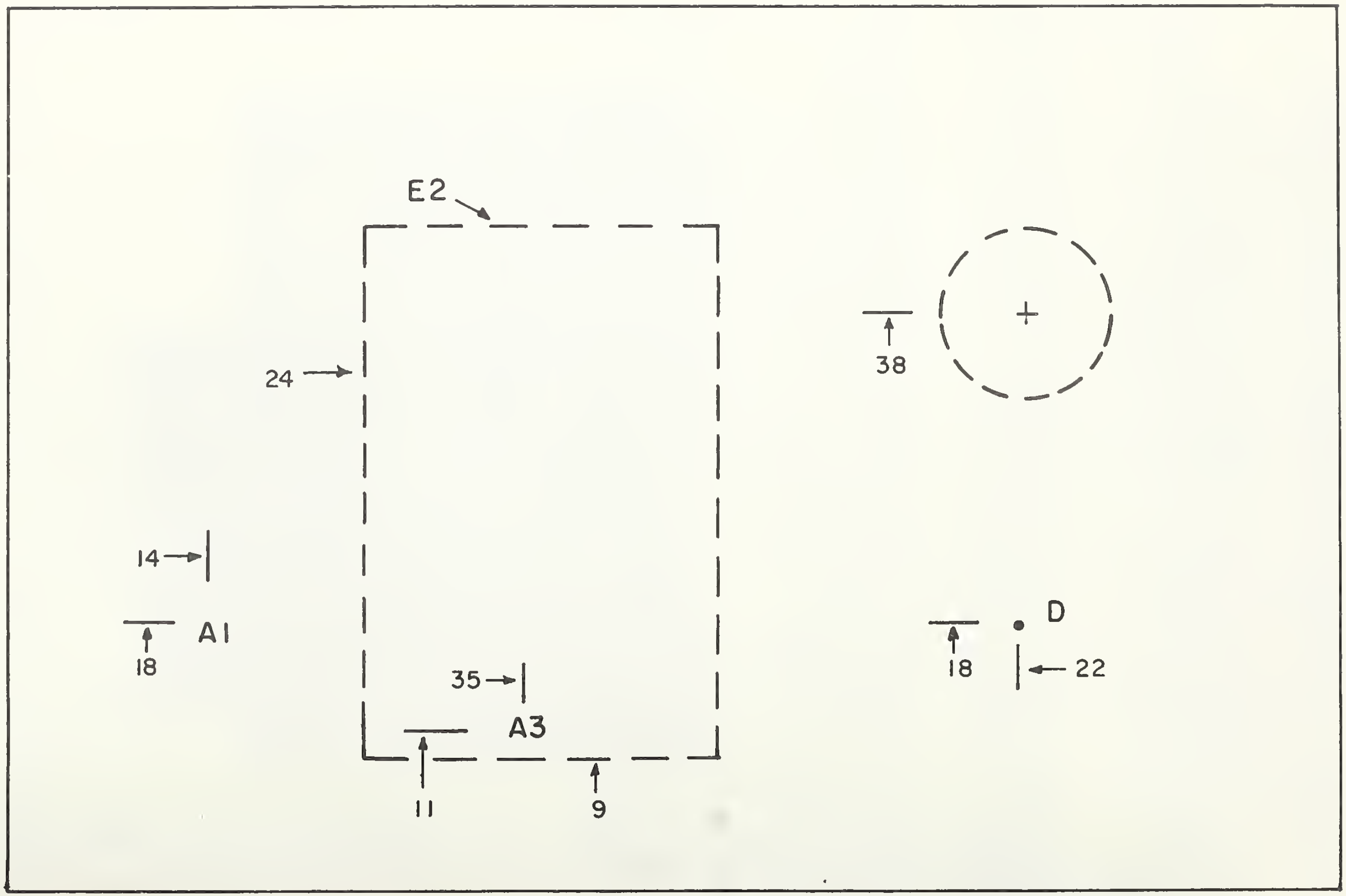


Figure 26. Target Attack Locations, Slab 2

To calculate the penetration time, we assume that a 12-inch diameter abrasive wheel cutoff saw, operating normally, could cut to a depth of three inches and extend the cut at this depth at a rate of 10 seconds per inch, thus the 40-inch perimeter would require 400 seconds. The remaining inch of concrete beyond the depth of the perimeter cut would probably yield to 30 seconds of sledgehammer attack giving an estimated total penetration time of 430 seconds or 7.16 minutes.

SLAB 2

Slab 2 was a 4-inch thick slab of fibrous reinforced concrete which was otherwise identical to Slab 1. Target areas for Attacks B and F were the same as on Slab 1 (see fig. 5). Figure 26 shows the locations of Attacks A1, A3, D, E1, and E2.

ATTACK A1

Attack A1 on this slab was similar to that conducted on Slab 1, i.e., a 10-pound sledgehammer attack to expose the reinforcing followed by use of a cutting torch on the rods.

The first interior crack appeared after 110 blows and 2.93 minutes. Initial breakthrough occurred at 129 blows and 3.42 minutes. The reinforcing rod was exposed in an opening 9-1/4" X 10-1/4" at 288 blows and 8.0 minutes. The resulting opening is shown in figures 27 and 28. Note that the broken areas all occurred within the spaces between reinforcing bars. In the regular concrete of Slab 1, the extent of spalling and breakthrough was not constrained by the reinforcing bars in this way (see figs. 6 and 7).

Figure 27. Exterior, Slab 2, Attack A1, after Breakthrough

Figure 28. Interior, Slab 2, Attack A1 after Breakthrough

Vibration spectra are shown in figure 29 which is a multiple trace exposure in which seven hammer blows appear. Visual monitoring of the output of the spectrum analyzer showed disturbances in the range of 10 to 30 g at frequencies below 5 kHz.

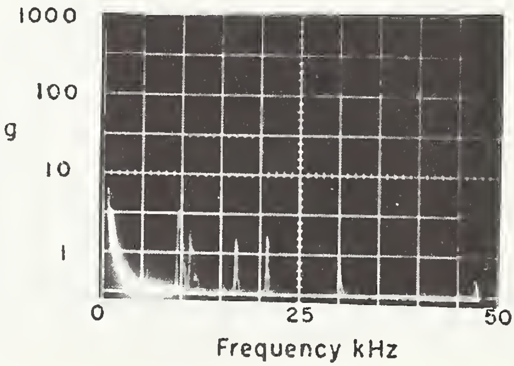


Figure 29. 2A, Vibrational Disturbances

Sound pressure levels observed ranged from 86 to 96 dBa (30 ft.) and peak linear values of 122 dB were observed at 8 feet from the attack point on the outside and 135 dB inside the hexagonal enclosure.

After the completion of the sledgehammer attack, the reinforcing was removed with an Oxy-MAPS cutting torch. This involved seven cuts and took 1.43 minutes, giving a total time to penetrate of 9.43 minutes. The acoustical spectra showed 85 to 90 dB below 5 kHz falling to 65 - 75 dB at 20 - 25 kHz as shown in figure 30.

Sound levels of 57 to 70 dBa were observed at 30 feet.

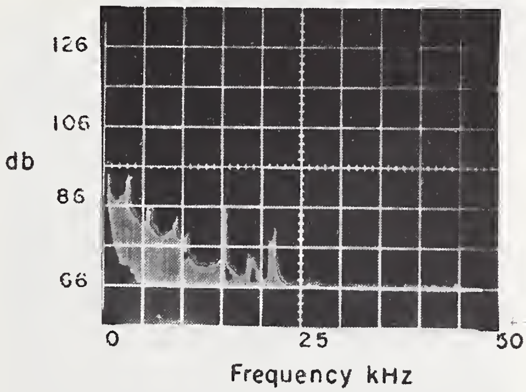


Figure 30. Acoustical Spectra of Cutting Torch

Then, in order to assess the influence of sledgehammer weight, an attack was mounted with a 16 pound sledgehammer at an adjacent but undamaged area of the slab. The first visible internal crack was developed after 55 blows and 1.62 minutes; breakthrough occurred at 105 blows and 3.07 minutes.

Vibration showed 80 g below 5 kHz dropping to about 10 g at 15 - 17 kHz and 3 g at 40 kHz (see figs. 31 and 32).

Sound level was 120 - 122.5 dB on the linear meter.

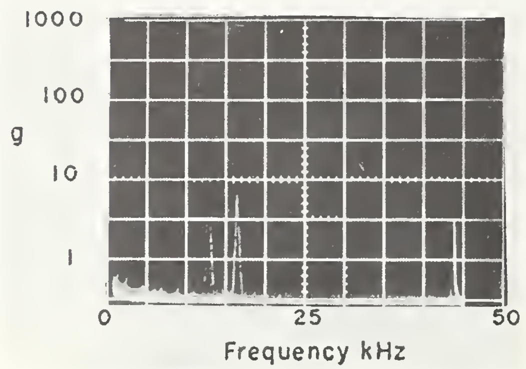


Figure 31. 2A3, 16 lb. Sledgehammer on Slab 2

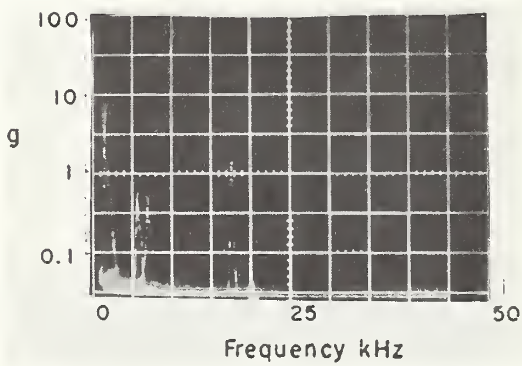


Figure 32. 2A3, 16 lb. Sledgehammer on Slab 2

ATTACK B

This attack paralleled Attack B on Slab 1 in that the roto-hammer was employed to drill and chisel, but only an 8" length of perimeter was cut on the assumption that the time required for this could be extrapolated (see fig. 33)

Drilling five 1" diameter holes took 2.07 minutes for an average of 24.8 seconds per hole.

The vibrational spectra were relatively flat and in the range of 5 to 20 g at all frequencies up to 45 kHz. Figure 34 is a multiple trace exposure of the vibrational spectra.

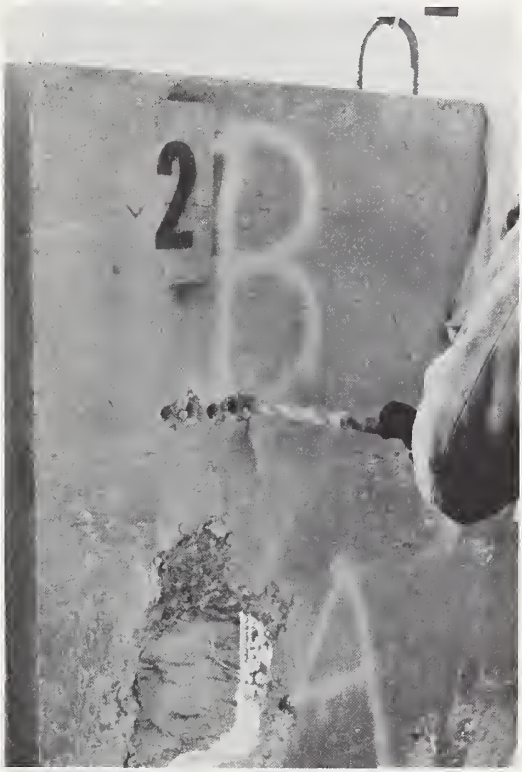
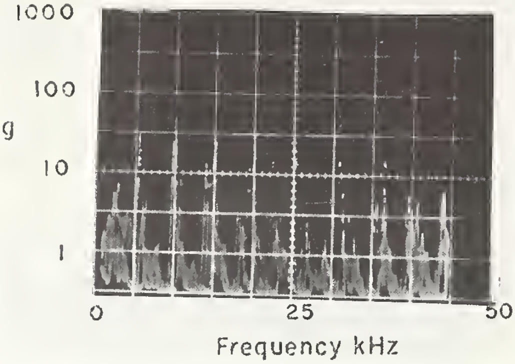


Figure 33. Attack 2B



Fibure 34. Vibrational Spectra from Rotohammer Drilling, Slab 2

As shown in figure 35, the acoustical spectra showed levels above 100 dB out to 20 kHz then dropping to about 75 dB at 45 kHz. 108 - 112 dB was observed on the linear meter at five feet and 88 - 91 dBa was observed.

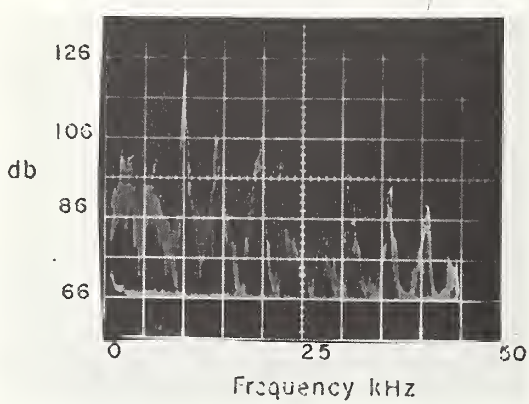


Figure 35. Acoustical Spectra of Rotohammer Drilling, Slab 2

Chiseling out the four webs between the holes took 30 seconds to remove 3 linear inches of material; thus, the total time to cut 8 linear inches of perimeter was 2.57, corresponding to an average rate of 19.25 seconds per inch. This time is a little over 4 seconds per inch greater than the average on Slab 1.

At 19.25 seconds per inch, it would require an estimated 770 seconds to complete a 40-inch perimeter. Allowing another 120 seconds to cut the reinforcing rod, the estimated total time to penetrate is 890 seconds or 14.83 minutes.

As shown in figure 36, the vibrational spectra were relatively flat ranging from 10 - 30 g at all frequencies up to 42 kHz. Sound levels were 105 dB up to about 15 kHz falling to 70 - 80 dB between 17 and 45 kHz (see fig. 37).

111 - 112 dB linear and 88 - 94 dBa levels were observed at the usual 8-foot and 30-foot, respective, distances.

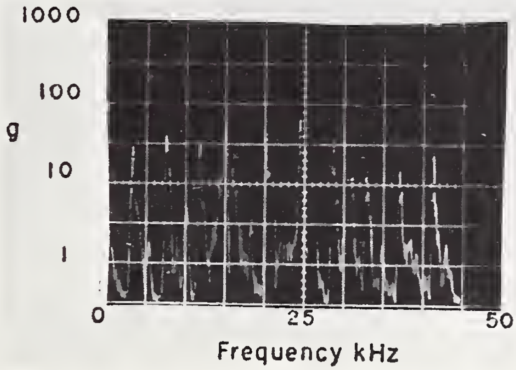


Figure 36. Vibrational Spectra from Rotohammer and Chisel on Slab 2

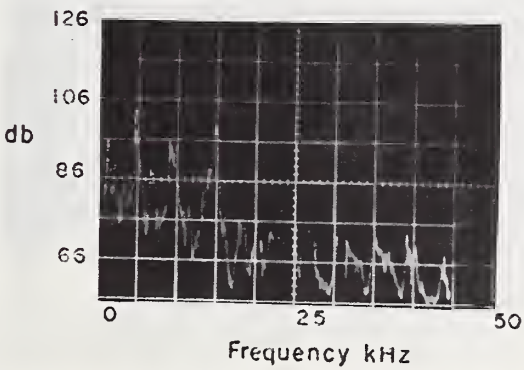


Figure 37. Acoustical Spectra from Rotohammer and Chisel on Slab 2

ATTACK D

The burning bar was employed to make two holes; each required 24 seconds; one hole used 18-1/2" of bar and the other used 25" (see fig. 38).

The average burning bar penetration time of 24.5 seconds for the fibrous concrete of this slab was the same as the average for the regular concrete in Slab 1. Chiseling the web out between holes required 10 seconds per linear inch, however, as contrasted to only 8.8 seconds per linear inch in the regular concrete. Thus, to estimate the time required to complete a penetration with an 11-inch diameter circular opening, we add 1.2 seconds per inch times 22.5 linear inches or 27 seconds to the time calculated for Attack 1D to get a total time of 9.90 minutes. In the case of an 8" X 12" rectangular opening, there are 20 linear inches of web assumed and the added time factor over the value calculated for Slab 1 is 24 seconds giving a total penetration time of 13.08 minutes.

Figure 38. Burning Bar Attack on Slab 2

During this attack with the burning bar on Slab 2, sound pressure levels of 110 to 113 dB linear and 74 to 80 dBa were observed. Acoustical and vibrational spectra are shown in figures 39 and 40.

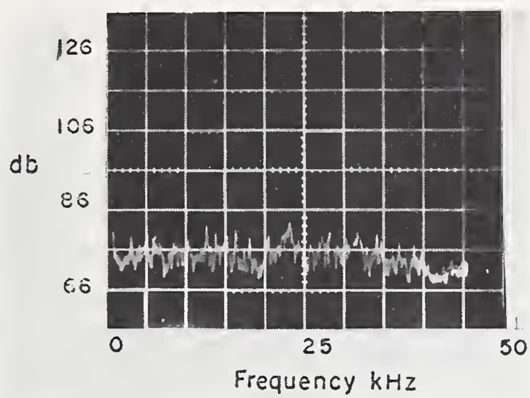


Figure 39. Acoustical Spectra from Burning Bar Attack on Slab 2

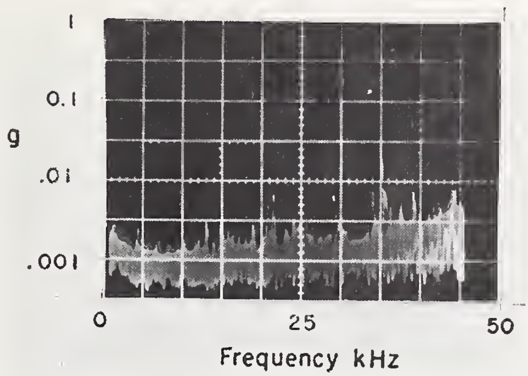


Figure 40. Vibrational Spectra from Burning Bar Attack on Slab 2

ATTACK F

The demolition saw was used to cut an 8" X 12" rectangular perimeter to a depth of 2-1/8 to 2-1/2 inches (insufficient to cut through the reinforcing rod). This required a total of 8.78 minutes and corresponds to a rate of slightly over 13 seconds per linear inch. (See fig. 41.)

Figure 41. Demolition Saw, Slab 2

The nominal 2-1/4 inch depth of penetration achieved by the demolition saw could probably have been extended to 3 inches with the installation of an unworn abrasive cutoff wheel. This would involve cutting to a depth one-third greater so we assume that the 13 seconds per linear inch cutting rate would be increased proportionately to a value of 17.3 seconds per inch. The 40-inch perimeter cut would then have required 693 seconds. It is assumed now that with the reinforcing rod cut, the 30-second sledgehammer attack would have been successful in knocking out the remaining plug. This would yield a total penetration time of 723 seconds or 12.08 minutes.

The acoustical and vibrational spectra produced by the demolition saw are shown in figures 42 and 43. Sound levels of 104.5 dB linear and 90-98 dBa were observed.

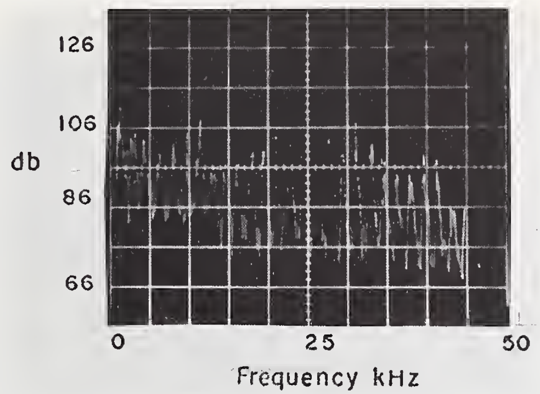


Figure 42. Acoustical Spectra from Demolition Saw

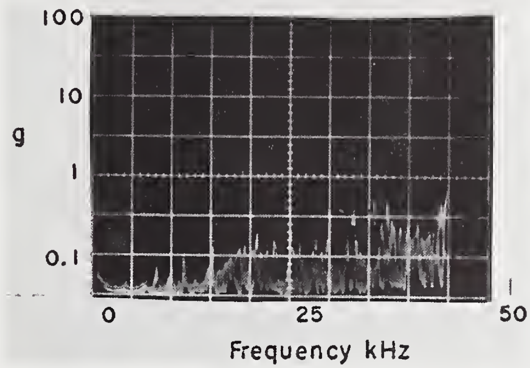


Figure 43. Vibrational Spectra from Demolition Saw

As noted above, the perimeter cut which was made was not deep enough to completely cut through the reinforcing bars, so the effort to knock out the remaining plug was rather superficial. When 30 seconds and 16 blows of the 16-pound sledgehammer, figure 44, were ineffective,the attack was abandoned,since the elapsed time was now nearly as great as that required for the total penetration in Attack A.

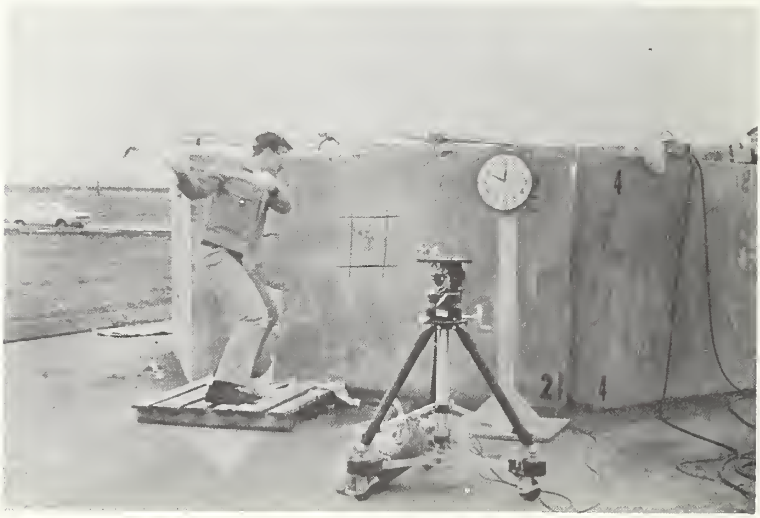


Figure 44. Hammering on Plug Left in Slab 2 by Demolition Saw

ATTACK E

A size JA-5 Jet-Ax was tested against Slab 2 and produced a 10-1/2 inch diameter opening which was clear of all material except the reinforcing rods. These were slightly bowed but showed no evidence of any cutting action from the shaped charge. Exterior and interior views of the opening are shown in figures 45 and 46.

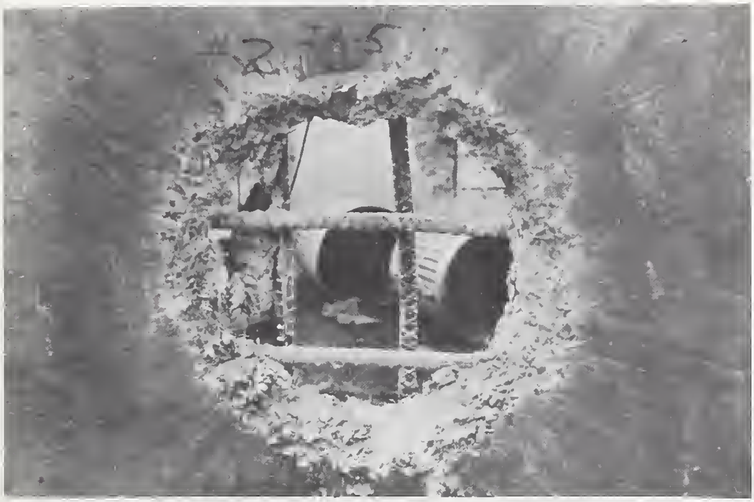


Figure 45. Exterior after JA-5

Figure 46. Interior after JA-5

As shown in figure 47, a Jet-Ax, size JA-3, produced external spalling to a depth of 3/4" to 1" in a rectangular area having external dimensions of 27" X 39" and internal dimensions of 21" X 33", and produced a hairline interior crack, figure 48, along this perimeter. The JA-3 was judged to be relatively ineffective in marked contrast to its performance on Slab 1.

Figure 47. Exterior after JA-3 on Slab 2

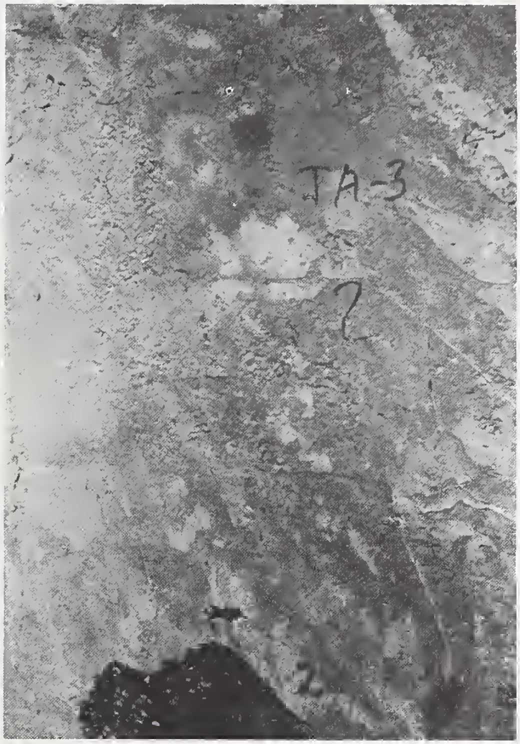
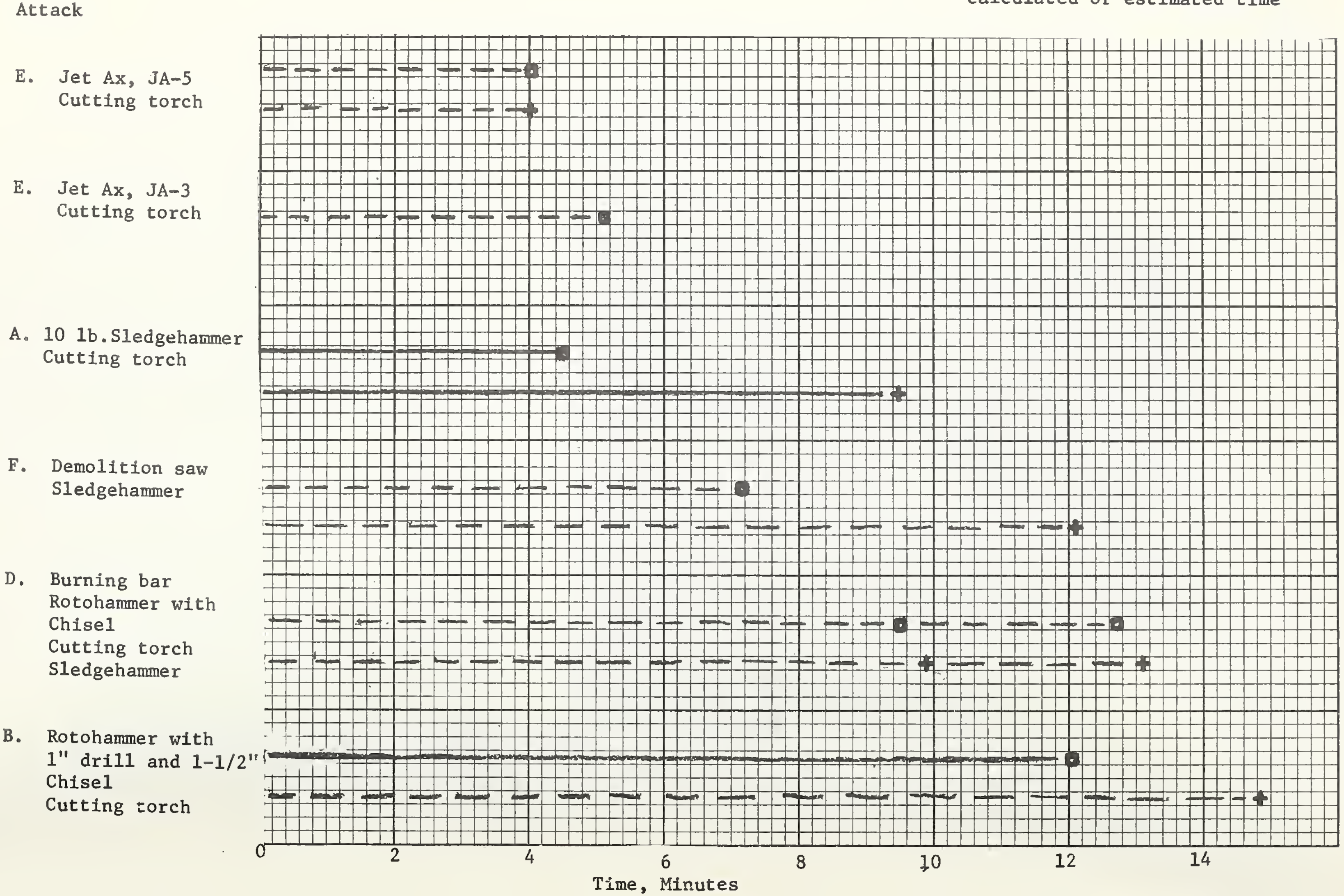


Figure 48. Interior after JA-3 on Slab 2

Fig. 49 Comparison of measured or calculated penetration times for four-inch thick reinforced concrete slabs.

Legend:
- Regular concrete
- Fibrous concrete
- measured time
- calculated or estimated time



Note in Figure 47 how the force of the Jet-Ax has driven the top of the slab back so that it is only restrained from falling by the bracing timbers which fastened all six slabs together.

COMPARISON OF RESULTS ON 4-INCH THICK
FIBROUS AND REGULAR CONCRETE SLABS

In figure 49, the measured or calculated penetration time for the various attack methods tested on the 4-inch thick slabs are summarized in the form of a graph. Inspection of this shows that the fibrous concrete tested was significantly more penetration resistant to every method of attack used except the large Jet-Ax. The penetration resistance of the fibrous concrete exceeds 9 minutes for any of the other attack techniques used. Its superiority is most pronounced against the sledgehammer and is least noticeable with the burning bar.

SLAB 3

Slab 3 was constructed of ordinary concrete 8" thick. It was reinforced with two layers of 1/4" diameter welded steel mesh with 6" center-to-center spacing vertically and horizontally. One layer of mesh was placed 2" from each face of the slab and the two layers were staggered 3" from each other vertically and horizontally.

Only attacks A, sledgehammer, D, burning bar, and E, Jet-Ax, were conducted on this slab. The target location for these attacks is as shown in figure 5.

ATTACK A

A 16-pound sledgehammer was used in an attempt to break through. The attack was conducted in a series of 30-second duration efforts each of which yielded 15 - 19 blows (see fig. 50).

After 5.00 minutes and 162 blows, spalling had occurred sufficiently to yield a penetration depth of approximately 2". After 8.75 minutes and 298 blows, the penetration depth had been increased to 3" and a hairline crack was observed on the rear of the slab. Since a Jet-Ax attack had already been conducted on this slab, it is uncertain whether the hairline crack was initiated by that or by the sledgehammer attack.

After 12.10 minutes and 443 blows, the penetration depth had reached 3-5/8" (see fig. 51) and it became apparent that it would be necessary to enlarge the attack area considerably to avoid striking the edges of the hole with the hammer handle. The attack was aborted at this point in concession to this and to the advanced fatigue of the hammer swingers.

Figure 50. 16 lb. Sledgehammer Attack on Slab 3

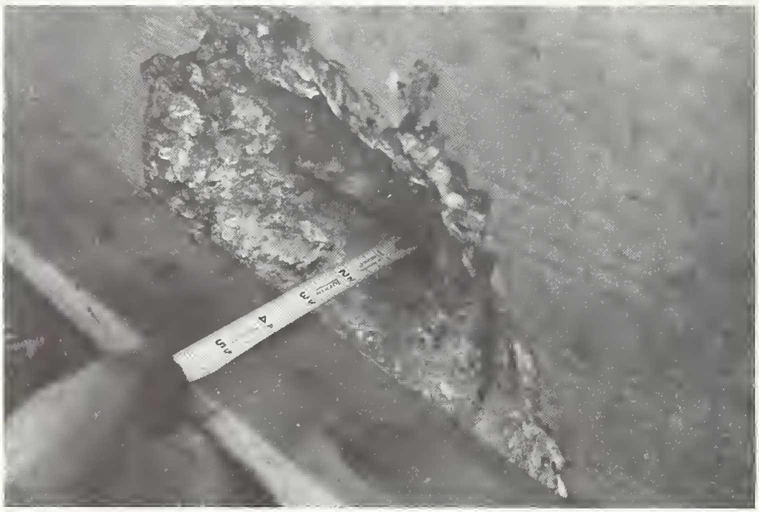


Figure 51. Spalling Produced by 12.10 Minutes of Attack by 16 lb. Sledgehammer

ATTACK D

A single penetration was made with the burning bar. It took 52 seconds and burned 46" of bar. Oxygen pressure was again 200 p.s.i. Figure 52 shows the hole which was melted through.

Figure 52. Attack 3D, Burning Bar Hole

Vibrational disturbances were not visible above the background noise level at frequencies below about 10 kHz, but climbed to about 5 dB above the noise at 45 kHz. Typical amplitude in the middle frequency range (25 - 35 kHz) was about .01 g.

Figures 53 and 54 show the vibrational background noise and the slight increase in the disturbance level produced when the burning bar was in operation.

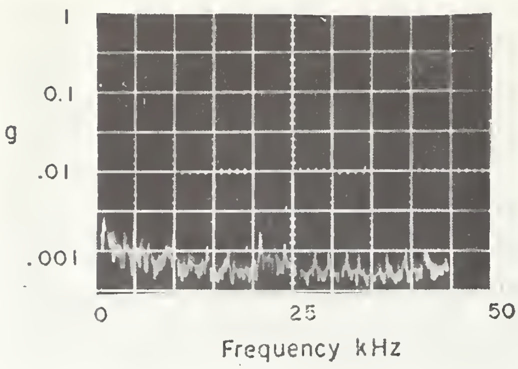


Figure 53. Background Vibrational Noise

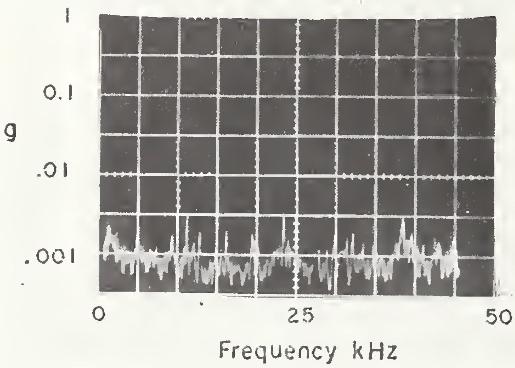


Figure 54. Vibrational Disturbance from Burning Bar

Sound levels of 76 - 88 dBa and 100 dB linear were observed. The apparent ejecta temperature was 1850°C.

ATTACK E

A size JA-4 Jet-Ax with a 5.6-ounce charge arranged to cut a 17" diameter circle produced front surface spalling to a depth of 1-1/4" - 1-1/2" in an annular ring with an outside diameter of approximately 22" and an inner diameter of about 10". The center area inside the ring was deflected inward approximately 1/16" and a 3/8" bulge was produced on the back side of the slab. A rather extensive network of cracks was also produced and the free end of the slab was driven back about 3/8".

Figures 55 and 56 show exterior and interior views following the Jet-Ax attack.

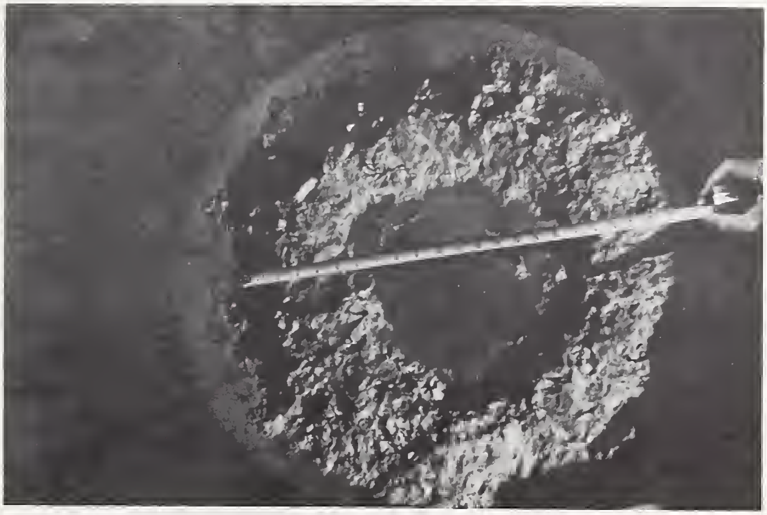


Figure 55. Exterior View of JA-4 Effects on Slab 3

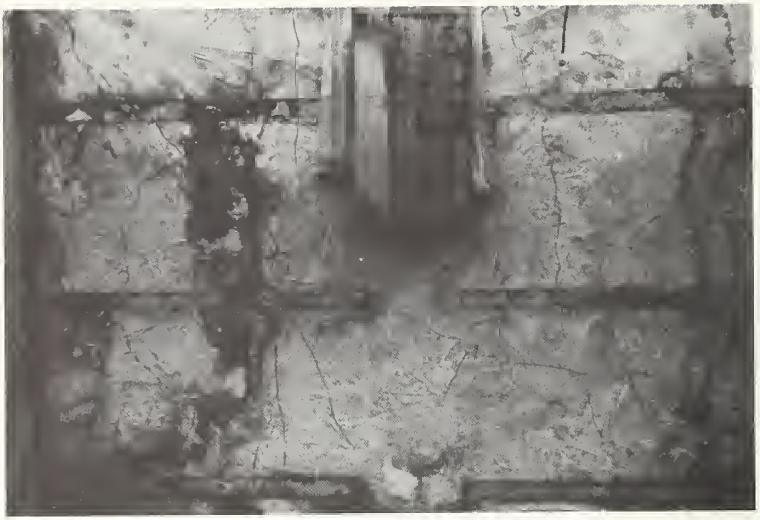


Figure 56. Interior View of Slab 3 after JA-4 Attack

The sound levels produced by this and the other JA-4 Jet-Axes ranged from 141 to 147 dB on the linear meter at distances of 75 to 126 feet from the detonation.

SLAB 4

Slab 4 was a replica of Slab 3 (8" thick, double mesh reinforcing) except constructed with fibrous reinforced concrete.

ATTACK B

The rotohammer was used to drill several holes of different diameters with the following results:

Diam. (in.)	Time (sec.)
3/4	33.5
7/8	45
1	55
1	59
1-1/2	246

The times required for hole sizes below 1" diameter show that drilling rate is inversely proportional to the volume of material removed. The 1-1/2" diameter size, however, departs drastically from this behavior and takes nearly twice as long as would be expected on the basis of volumetric material removal.

The vibrational effects were similar for all drill sizes except the 1-1/2". Figure 57 shows vibrational spectra from the 1" drill, which was very similar to that recorded from the smaller drill sizes, while figure 58 is from the 1-1/2" size. There are less high frequency components in the latter trace. In both cases the separation between transducer and attack point was about 3-1/2 feet.

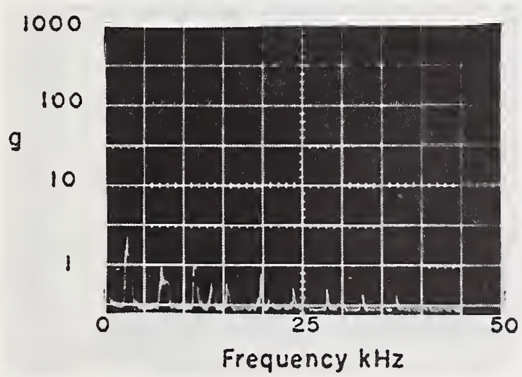


Figure 57. Vibration from 1" Drill

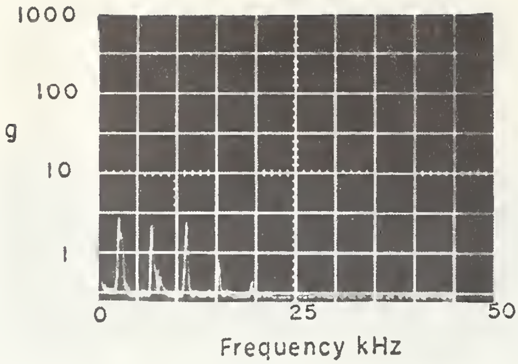


Figure 58. Vibration from 1-1/2" Drill

ATTACK E

A size JA-4 Jet-Ax produced a 21" OD X 12" ID annulus of spalling to an approximate depth of 1-1/4". The central area inside the ring of spalling appeared to have been depressed about 1/16" inward. Cracks on the inside of the slab were less pronounced than on Slab 3. The detonation moved one end of the slab inward 3/8" and the other end 1-1/4".

The spalling is shown in figure 59.

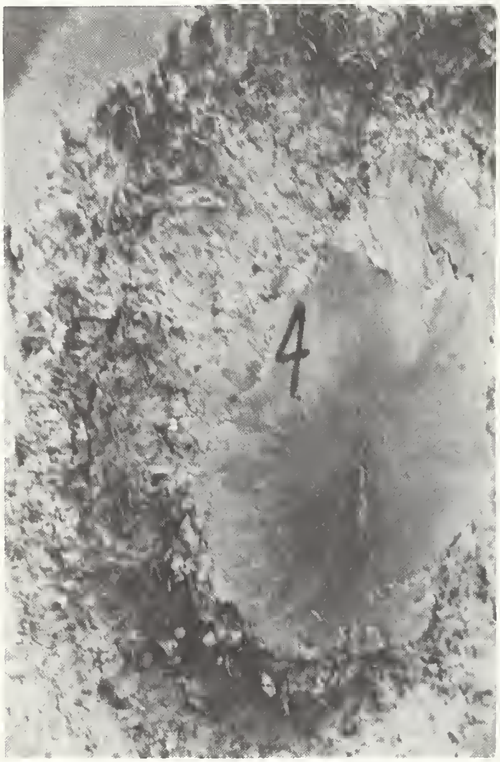


Figure 59. Spalling Produced by Jet-Ax on Slab 4

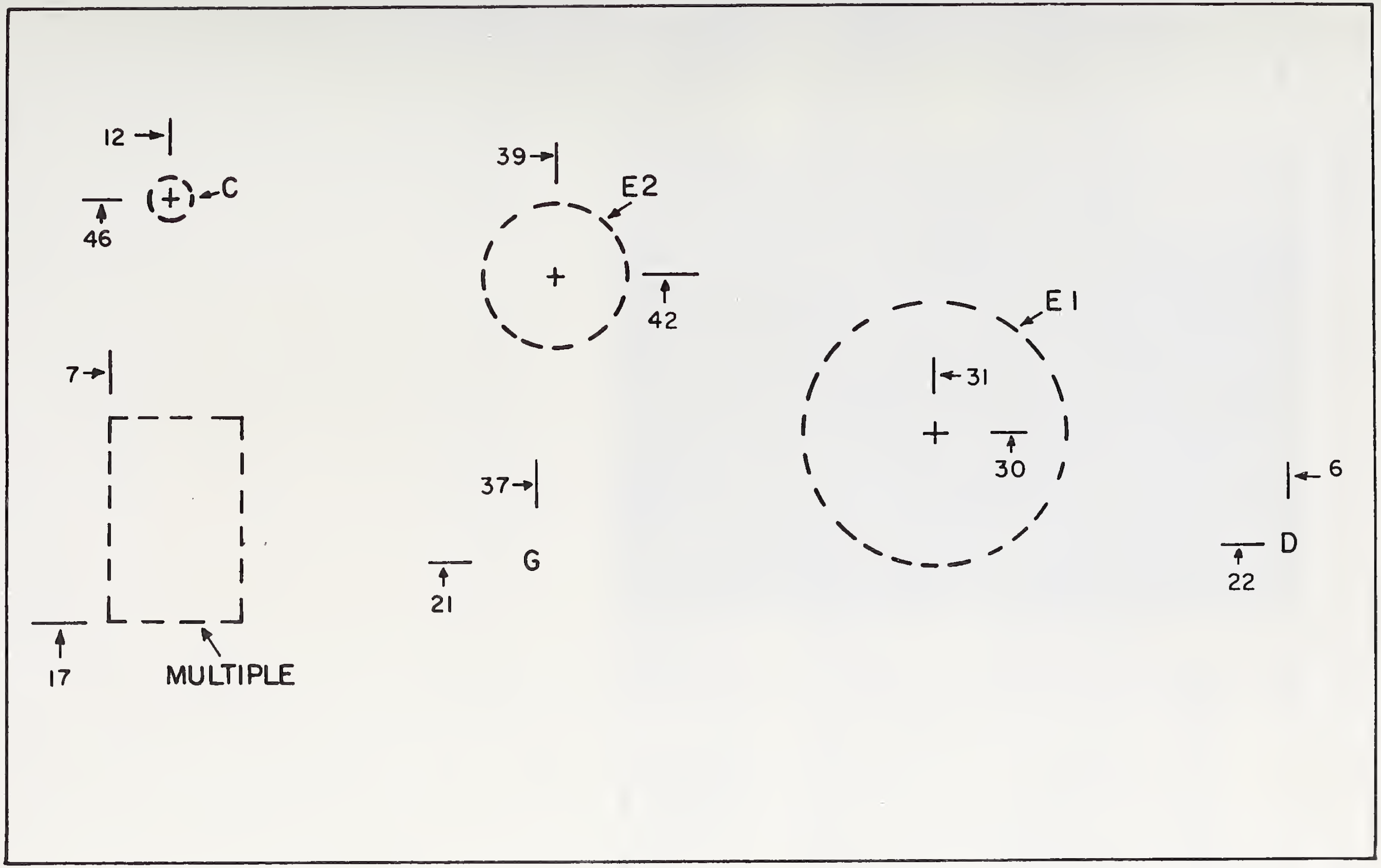


Figure 60. Slab 5, Target Attack Locations

SLAB 5

Slab 5 was 8" thick, ordinary concrete with 5/8" reinforcing rod on 5" centers, vertically and horizontally centered in the slab.

The target locations of the attacks made on this slab are shown in figure 60.

MULTIPLE TOOL ATTACK

In order to get information on the total time that might be required to make a man-passable opening in this type of slab, a "minimum time" attack was mounted. In this attack, the objective was to attempt to use whatever tooling appeared most appropriate at any stage of the process. A 9" X 14" aperture was produced in 30.257 minutes of attack time which involved 1 hour and 42 minutes total elapsed time.

The sequence of activities began with rotohammering 23 holes, 3/4" diameter, through the slab, along the periphery of the intended opening. This required 10.106 minutes for an average time of 26.36 seconds per hole. (Compare with 23.75 seconds for drilling 1" diameter holes through the 4" thick ordinary concrete.)

A couple of holes were then drilled half way through the slab near the central area of the central area of the plug and a superficial attempt was made to spall off the concrete on the interior (see fig. 61). A suitable bull point punch was not available however, and this approach was quickly abandoned.

Figure 61.   Early in Multiple Tool Attack

Then with the 1-1/2" chisel in the rotohammer, the webs between holes on the left side (14", vertical) of the hole were chiseled out about half way through the slab. The time required was 1.48 minutes or 6.35 seconds per inch of perimeter.

Then the demolition saw was used to cut the webs on the remaining three sides to a depth of about 3" as limited by the diameter of the slightly worn abrasive wheel. The time was 3.358 minutes or 6.3 seconds per inch of perimeter. A new abrasive cutoff wheel was then installed in the saw and cutting was resumed for 1.65 minutes in an attempt to get through the reinforcing rods in the center of the slab. Some of this time was wasted as the hub of the demolition saw was limiting wheel penetration for a while before the operator became aware of the problem.

Then the rotohammer and 1-1/2" chisel was used to remove material so as to make room for the saw hub in an effort to provide for greater penetration of the abrasive wheel. The chiseling time was 1.35 minutes. This was followed by 51 seconds with the demolition saw, another 2.23 minutes of chiseling and another 1.32 minutes with the demolition saw.

See figures 62 and 63.

Figure 62. Material Chiseled Out of Plug to Make Room for Saw Hub

Figure 63. Sawing Reinforcing Rods

At this point, the plug was struck 5 blows with the 16-pound sledgehammer in 10 seconds with no significant effect. Close examination showed that the reinforcing rods had not yet been fully cut through and the demolition saw was used for another 1.17 minutes with the guard removed to try to get additional penetration. This was successful and the reinforcing bars were finally cut.

The plug was then ineffectively attacked with the 16-pound sledgehammer for 21 blows and 37.5 seconds.

Chiseling was then resumed with the rotohammer and material was removed from most of the webs through the full thickness of the slab (see fig. 64). This required 5.52 minutes.

Figure 64. Chiseling Webs between Holes on the Inner Half of the Opening

Finally, 15 more blows from the 16-pound sledgehammer knocked the plug out in 26 seconds (see fig. 65).

Figure 65. Final 9 X 14-inch Opening

Not counting the minute or two expended on the abandoned spalling attempt, the attack times for each type of tooling are summarized below:

Tool	Time (min.)
Rotohammer with 3/4" drill	10.106
Rotohammer with 1-1/2" chisel	10.583
Demolition saw	8.341
Hammer	1.225
Total	30.255

This attack was clearly suboptimal in a number of respects. First, the opening was larger than necessary. A 9 X 14 inch opening has an area of 126 in.^{2} and a perimeter 46 inches. This is a perimeter length nearly one-seventh greater than that of the nominal 8 X 12 inch opening.

Second, the abrasive cutoff wheel was rather ineffective. A 12-inch diameter wheel does not have enough radius outside its hub to reach the reinforcing rods in the center of an 8-inch slab. A minimum cutting depth of 4-5/8 inches is needed if the reinforcing rods are accurately centered, and even more depth of cut is required if they are displaced toward the inside of the slab.

A large volume of the material in the plug had to be chiseled away in an effort to provide clearance for the hub of the abrasive cutoff wheel to obtain greater penetration. This clearance was also needed in order to provide chisel access to the webs between the holes on the inner half of the slab (inside the reinforcing rods). It seems likely that most of the time used with the demolition saw to cut along the perimeter of the opening did little to reduce the volume of material which had to be chiseled out. Also, it probably did not have a large influence on the time that the chiseling required. It is probable that its only real contribution to the penetration effort was in cutting the reinforcing rods.

Additionally, all but the last 26 seconds of time used with the sledgehammer was ineffective and therefore wasted.

Finally, it is believed that the lack of a suitable bull-point punch and the consequent abandonment of the internal spalling attempts was a major factor in the inordinately long time used in this penetration. In Attack 1-A it was demonstrated that a 10-pound sledgehammer could break through 4 inches of reinforced concrete in about 2-1/2 minutes. It should be easier to break out 4 inches of concrete by impacting it from a point behind the reinforcing bars than 4 inches of concrete which has the reinforcing in the center.

A hypothetical penetration will be outlined using time information developed in the course of these tests as follows:

1.	Drill 20 holes, 3/4" diameter on 2" centers (same spacing used before) along an 8 X 12" perimeter. Drill alternate holes 6" and 4" deep. Total drilling depth 100". Average rate 3.295 seconds per inch (same as before).	Time: 329.5 sec.
2.	Using bull-point punch in 6" holes, spall off 2" from interior of slab. Then repeat in 4" holes to produce interior spalling to a depth of 4" around the perimeter (time allowance the same as for the sledge attack on Slab 1).	146.0 sec.
3.	On outside, chisel 25 linear inches of web between the 20 holes at 8.8 seconds per inch, to a depth of 4 inches (same chiseling rate as developed in 1B).	220.0 sec.
4.	Cut reinforcing rod with torch.	120.0 sec.
5.	Knock out plug with sledgehammer.	30.0 sec.
		Total Time: 845.5 sec. or 14.091 minutes.

Even without the use of the bull-point punch as described in the hypothetical penetration but employing the same tooling used in the actual penetration, it seems likely that the opening could have been made in less than 25 minutes by elimination of the ineffective portion of the abrasive cutoff wheel time.

ATTACK D

The burning bar made a hole through the 8" slab in 66 seconds consuming 58-1/4" bar. Apparent ejecta temperature was 1905^{o}C and sound levels were 80 - 89 dBa and 102 dB on the linear meter. Figure 66 is a close-up view of the hole which was produced.

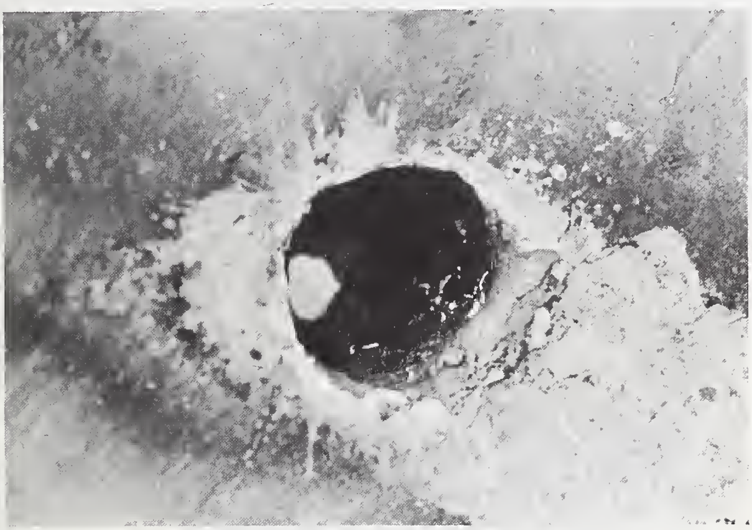


Figure 66. Close-up of Slab 5 Burning Bar Results

ATTACK E

Two Jet-Axes were used against Slab 5. The JA-4 size produced a 22-1/2" OD by 11" ID annulus that was spalled to a depth of about 1-1/2". The center area within the annular ring was depressed approximately 1/32". One end of the slab was shifted back about 3" and the other end, resting against another slab, bounced forward about an inch. The cracking produced was significant but less extensive than Slab 3.

Figures 67 and 68 show the exterior and figure 69 the interior of Slab 5 after the attack by the first Jet-Ax.

Figure 67. Results of JA-4 on Exterior of Slab 5

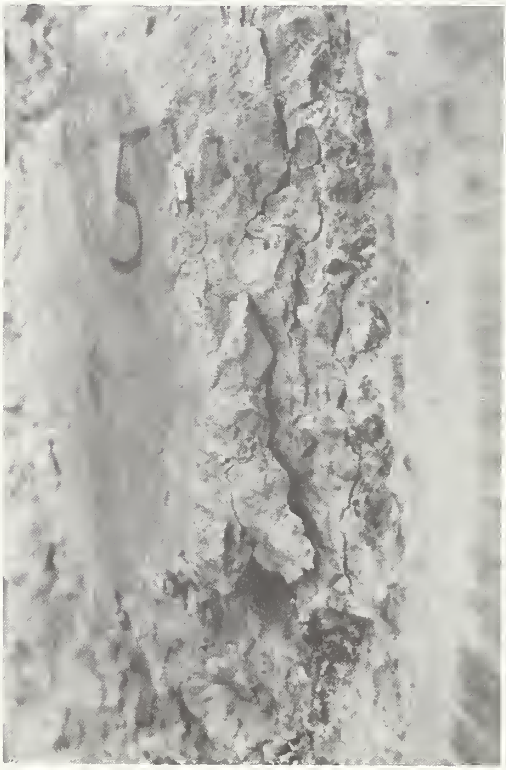


Figure 68. Close-up of Exterior Spalling

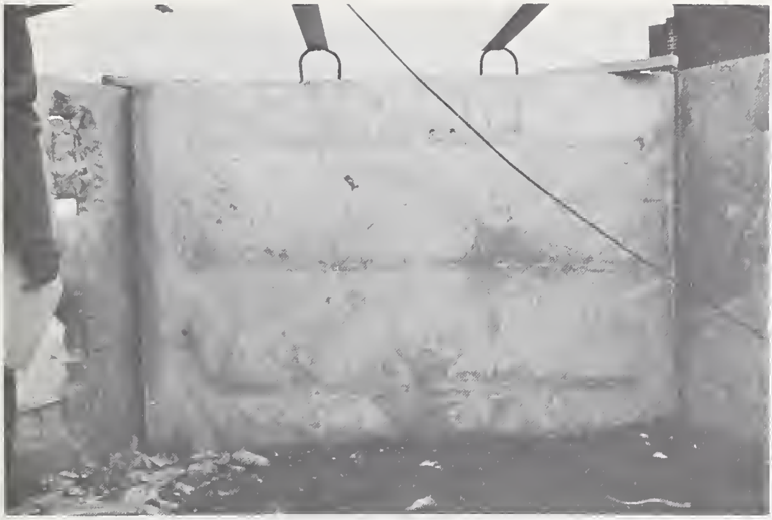


Figure 69. Interior Cracking Produced by JA-4

The size JA-5 produced a 15" OD X 4" ID annulus that was spalled to a depth of about 1-1/2", and a 1" bulge was produced on the interior of the slab.

Figure 70 shows the Jet-Ax in place, figure 71 shows the exterior spalling it produced, and figure 72 shows the interior bulge and cracking.

Figure 70. JA-5 in Place

Figure 71. External Spalling from JA-5

Figure 72. Interior Cracking Produced by JA-5

SLAB 6

Slab 6 was 8" thick fibrous concrete with 5/8" reinforcing rods on 5" centers vertically and horizontally in the center of the slab.

ATTACK D

The burning bar made a penetration in 40 seconds and consumed 39" of bar. The apparent temperature of the ejecta was 1860°C and a sound level of 77 to 86 dBa was observed.

ATTACK E

A size JA-4 Jet-Ax produced a 21" OD, 11" ID annulus with a penetration depth of about 1-1/4". The center area within the ring showed an inward deflection of about 1/16".

Figures 73 and 74 show external and internal views of Slab 6 after these attacks.

Figure 73. External View of Slab 6 after Burning Bar and Jet-Ax Attacks

Figure 74. Interior View of Slab 6 after JA-4 Attack

This concluded the tests which were conducted with the slabs in a vertical position. The hexagonal configuration was torn down and Slabs 5 and 6 were supported in a horizontal position with heavy timbers under two edges for penumatic jack-hammer and diamond core drill tests.

SLAB 5

ATTACK G

With the slab horizontal as described above, an attack was made with a pneumatic jackhammer (see fig. 75). The jackhammer was operated at 100 p.s.i.air pressure, and both spike point and 3" spade point tools were used. Initial breakthrough occurred in 2.55 minutes and by 5.55 minutes concrete had been cleared from an area 11" X 11". The reinforcing rods were not cut, see figure 76.

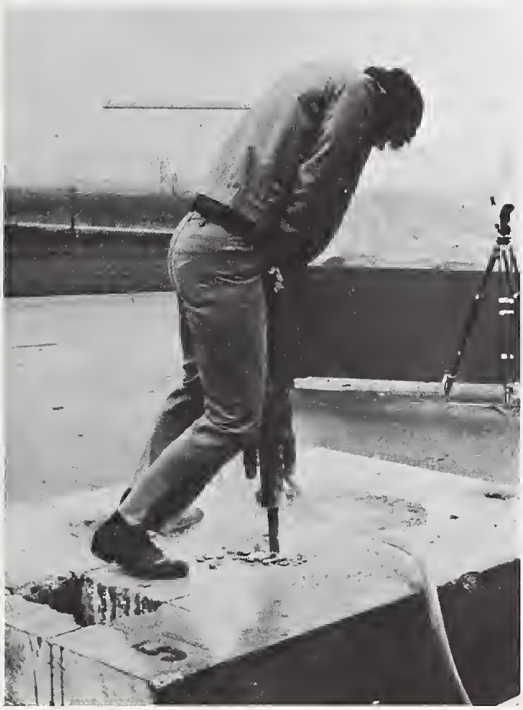


Figure 75. Pneumatic Jackhammer on Slab 5

Figure 76. Opening Made by Jackhammer

ATTACK C

A 3-1/2" diameter water-cooled diamond core drill was run for 3.92 minutes and penetrated 3-5/8". The core drill was mounted in a semiportable drill press arrangement and was powered by a drill running at 900 RPM and operating at 7 - 7.5 amps. 110 Vac. (see figure 77).

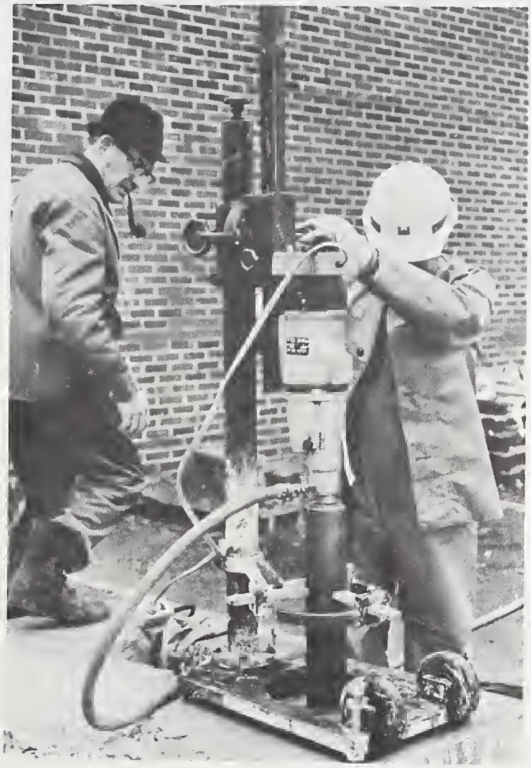


Figure 77. Diamond Core Drill

The vibrational disturbances produced by the diamond core drill covered a broad range of frequencies but were quite low in amplitude as shown in figure 78.

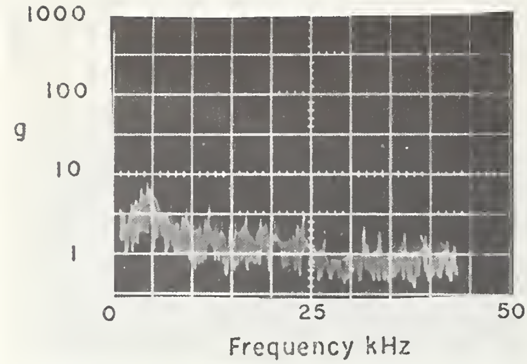


Figure 78. Vibration from Diamond Core Drill

SLAB 6

ATTACK C

With the slab in a horizontal position supported on timbers, the 3-1/2" diameter diamond core drill was operated for 3.92 minutes. The depth of penetration was 2-11/16". This rate of penetration in the fibrous concrete was 87.4 seconds per inch which can be compared with the rate of 64.8 seconds per inch in the regular concrete of Slab 5.

ATTACK G

The pneumatic jackhammer required 2.78 minutes to make an initial breakthrough and 18.07 minutes to clear material away and expose the reinforcing rods in an open area having dimensions of approximately 7" X 12-1/2" (see fig. 79). This is more than three times as long as was required on Slab 5.

In using the jackhammer on the fibrous concrete, the point of the tool became stuck on several occasions. It was then necessary to release the tool point from the hammer, install another tool point and cut out additional material around the stuck point to free it. (See fig. 80)

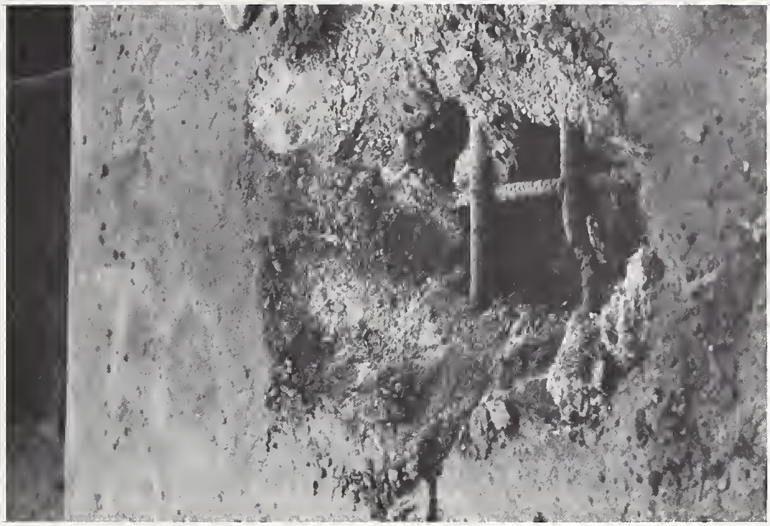


Figure 79. Opening Made in Fibrous Concrete by 18-minute Jackhammer Attack

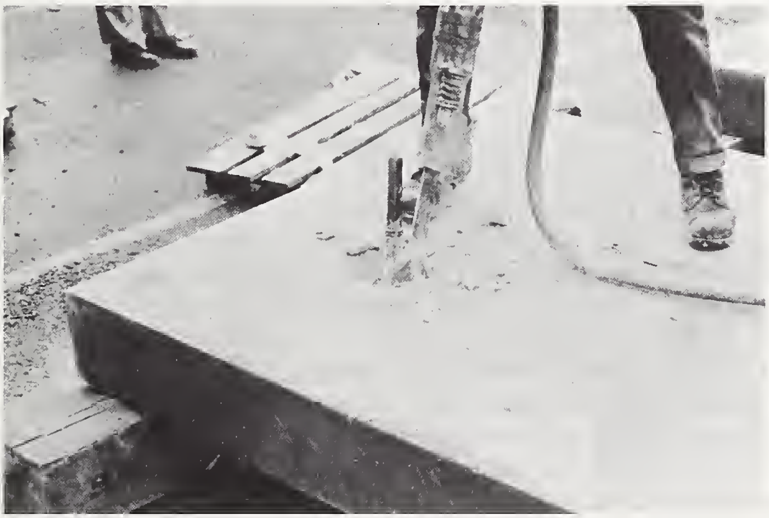


Figure 80. Stuck Jackhammer Tool Point

6. CONCLUSIONS

At the time the test plan was formulated for this series of tests it was anticipated that it would be possible to complete the same series of tests on the eight-inch thick slabs that were done on the four-inch thick pair. Due to unusually adverse weather conditions this was not possible even though the test duration was extended a day. As a result, several of the planned penetrations of the eight-inch sections were either cut short or eliminated. Despite this, enough test data was obtained to support a number of conclusions regarding the penetration resistance of reinforced concrete and the characteristics of detection equipment which might be useful in alarming as a result of attempted penetrations.

There is usually a factor of more than three to one between the penetration times for the slowest and the fastest methods of attack that were tested in regular concrete, but this difference is significantly narrowed in fibrous concrete. Most of the narrowing in range is due to the increased resistance of fibrous concrete to impactive attack, in particular by sledgehammer and pneumatic jackhammer. Here differences of more than two to one were observed in tests 1A versus 1B and 5G versus 6G. The fibrous concrete suffered less damage from the Jet-Ax than did the regular concrete, but in the four-inch thickness both are readily penetrated by one or more of the sizes which are available. None of the Jet-Axes cleanly penetrated the eight-inch slabs of either type of concrete but the rather extensive cracking produced by the size JA-5 in Slab 5 would probably have yielded to a fairly brief sledgehammer attack.

The drilling, chiseling and cutting resistance of fibrous concrete is also greater than that of regular concrete. Drilling rates are shown in figure 81 for both materials. This figure shows inches per second versus drill diameter squared. A rate that is inversely proportional to volume of material removed plots as a straight line in this form of presentation. The dashed line indicates the expected rate for the 1-1/2 inch drill if it followed that pattern in the same way as the smaller drill sizes. For equivalent drill sizes of one inch or less the rates in fibrous concrete are about 25 percent slower than in regular concrete. Drilling rate with the diamond core drill was 34 percent slower in fibrous concrete. Chiseling rate using the rotohammer and 1-1/2 inch chisel was 13 percent slower in fibrous concrete based on the times required to chisel out webs between holes. Cutting rates with the abrasive cutoff wheel appear to be somewhat slower in fibrous concrete but the variations in operating circumstances with this tool did not provide completely reproducible data to allow for a quantitative determination of the relative cutting rates.

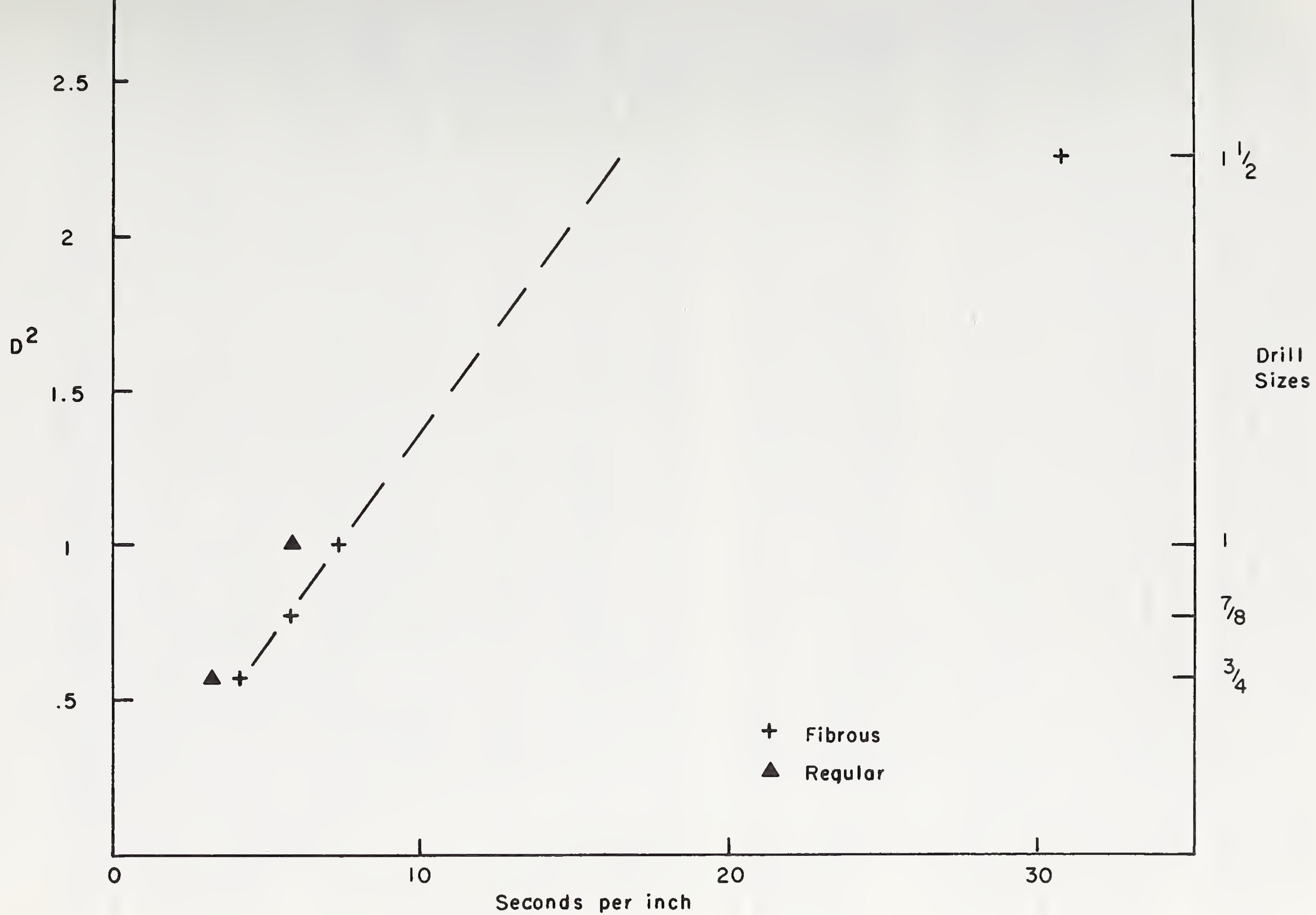


Figure 81. Drilling Rate in Concrete vs. Drill Size

There was no significant difference in the melting rates of regular and fibrous concrete using the burning bar, but this is not considered significant as the burning bar represents a rather poor choice of attack tooling for concrete barriers in the four- to eight-inch thickness range.

The test data indicates than an eight-inch thick regular reinforced concrete barrier can be penetrated in about seven minutes with a pneumatic jackhammer and cutting torch. Although not demonstrated, it is likely that use of a second Jet-Ax at the attack point might make a penetration possible in about the same amount of time, particularly in the case of a double mesh reinforced barrier such as Slab 3 which sustained rather extensive external and internal cracking from a single Jet-Ax. The concept of double reinforcing as a penetration deterrent is good, but the size of the reinforcing used in Slab 3 was probably too small to fully exploit this concept.

If the use of the pneumatic jackhammer and Jet-Ax is excluded, the time required to penetrate an eight-inch thick regular concrete barrier increases to values in the range of 14 to 25 minutes. The penetration resistance time of the eight-inch fibrous reinforced concrete appears likely to start with values on the order of 18 to 20 minutes using the pneumatic jackhammer and extend upwards to perhaps 25 to 30 minutes against other types of attack.

A review of the acoustic, ultrasonic and vibrational disturbance data collected during the test series provides an indication of the detection sensitivities which might be required in intrusion alarm equipments. For example, assuming a passive ultrasonic detector with a one-third octave bandwidth centered at 25 kHz and a detection threshold of 60 dB located 10 feet from the attack point, all of the impactive tooling, the abrasive cutoff wheel, the torch and the burning bar would have been readily detected. A vibrational detector at the same frequency and bandwidth and a detection threshold of 0.1 g located four feet from the attack point would have alarmed on all but the torch, burning bar, the 1-1/2 inch drill with rotohammer and the diamond core drill. The diamond drill was probably the quietest of the attack tools tested. Vibrational disturbances were quite low, generally below .05 g, and while acoustical measurements were not obtained, the noise in the audible range at least appeared to be lower than any of the other tools tested. If the drilling rate in regular concrete is extrapolated and one minute of added time allowed for cutting through the reinforcing, it would require about 9-1/2 minutes to make a single 3-1/2 inch diameter hole. Such a hole might admit an intruder's arm but it would probably require seven or eight more such holes to develop a pattern which would admit his body. This would involve at least an hour of working time. Since the drill must be water-cooled and lubricated during this period, the use of a moisture sensitive detector might be a useful technique to consider if the protected area is in an interior location and not exposed to weather.

In summary, all of the attack techniques tested except the diamond drill produced noise or vibration levels, or both, which should be easily detected by sensor equipment which is operated with its alarm threshold set high enough to provide an acceptable nuisance alarm rate. Detection of the higher frequency components of the disturbances is particularly attractive from the standpoint of minimizing the nuisance alarm rate. Many of the potential sources of nuisance alarms are either low in high frequency energy or have it heavily attenuated during propagation to a sensor.

7. RECOMMENDATIONS

This series of tests leaves unanswered a number of interesting questions, such as:

1. On figure 80, is there a break in the curve between the drilling rate that is inversely proportional to volumetric material removal and the rate for the 1-1/2 inch size drill that is not, or is there a gradual transition? Does regular concrete exhibit similar characteristics.

2. Would the hypothetical attack on Slab 5 be as rapid as the calculated time?

3. What would be the performance of a larger, say 16-inch diameter, abrasive cutoff wheel?

4. How long would it take to complete penetrations in the areas damaged by the Jet-Ax on the eight-inch thick concrete slabs?

5. Would a 200- to 250-pound battering ram be an effective penetration tool?

6. Would an eight-inch thick fibrous reinforced concrete barrier with two layers of No. 5 bars on five-inch centers both ways located two inches in from each face and staggered with respect to each other offer 25 minutes minimum resistance to any of the attack methods tested plus use of multiple Jet-Axes at the same location?

Further tests are recommended to try to develop answers to these and other related questions.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

SUMMARY. This report describes the results of a series of penetration tests on six concrete slabs. The tests were conducted at the U. S. Army Corps of Engineers Construction Engineering Research Laboratory in Champaign, Illinois, during the period October 31 through November 3, 1972. Several alternative methods of attack were employed, and the time to penetrate, and in some instances, to produce a 96-inch^2 opening, was measured, and estimates were developed regarding the acoustic, ultrasonic and vibrational disturbances produced by the attacks.

Depending upon the attack technique, a man-passable opening can be made in four-inch thick reinforced concrete in times ranging from 4 to nearly 15 minutes. The corresponding times for eight-inch thick reinforced regular concrete range from about 7 to 25 minutes and from about 20 to 30 minutes for fibrous concrete.

With the exception of the diamond core drill, detection should be relatively easy by the combined acoustic, ultrasonic or vibrational disturbances produced by the attacks even though not all attack techniques produce all three types of disturbances.

17. KEY WORDS (Alphabetical order, separated by semicolons)

barrier penetration; intrusion detection; physical security; reinforced concrete

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