Methods and Procedural Considerations in Demolishing Tall Concrete Chimneys

By Kenneth K. Walker,[1] Cliff Schexnayder,[2] Fellow, ASCE,
Richard E. Mayo,[3] Member, ASCE, and Kenneth D. Walsh,[4] Member, ASCE

Abstract: This paper reports on a study of possible demolition methods for tall concrete chimneys. In particular it discusses a case where the adjoining plant functions had to remain fully operational during the demolition process. Therefore, both operational and cost concerns in relation to demolition methods and procedures are discussed. In fact, operational risk factors can be critical in the selection of demolition methods. It was found that when diamond sawing was chosen as the method for demolishing reinforced-concrete structures, the cutting pattern can have a significant impact on project cost.

INTRODUCTION

The chimneys which served as the basis of this study were located at an electric generating station operated by the Salt River Project in Page, Arizona. As part of an environmental upgrade of the station, replacement chimneys were to be constructed, making it necessary to demolish the existing chimneys for aerodynamic reasons. Specifically, there was concern that in the case of high winds having to pass between two sets of three chimneys, vortexes could be created, causing unanticipated forces on these tall structures.

The three existing chimneys were constructed in the mid 1970s using a jump-form concrete placement construction method. The concrete was placed in 2.3 m (7.5 ft) high lifts, except for the final lift, which was 2.6 m (8.5 ft) high. The total height of each chimney was 235.8 m (773.5 ft), with 103 lifts.

Concrete shell thickness generally decreased with increasing elevation. However, there were some noticeable exceptions as shown in Fig. 1. The concrete shell increased in thickness between the 22.9 m (75 ft) and 45.7 m (150 ft) elevation because the flue gas ductwork emptied into the chimney in that section. The increased thickness at the 106.7 m (350 ft) (lift 57) and 231.6 m (760 ft) (lift 2) elevations were for structural support of the interior steel liner. The maximum shell thickness was 914 mm (36 in.) at the ductwork openings and the minimum was 203 mm (8 in.) at the top of the chimney. The exterior diameter of the chimney was 16.1 m (52 ft 11 in.) at the bottom and 8.3 m (27 ft 1 5/8 in.) at the top.

There were many openings in the concrete shell but only three were large enough to be significant with respect to demolition considerations. The first opening was an access door at the base of the chimney. The door had a height of 4.3 m (14 ft) and a width of 3.7 m (12 ft). The other two openings were for ductwork and were each 13.3 m (43.5 ft) high by 5.8 m (19 ft) wide. The elevation of the bottom of both ductwork openings was 30.0 m (98.5 ft) above the base, and the top was 43.3 m (142 ft) above the base. The thickness of the shell at all three of these locations was in excess of 762 mm (30 in.).

The percentage of concrete volume above each level in the chimney shell is shown in Fig. 2. Approximately half of the concrete volume was contained in the lower 59.4 m (195 ft) of the chimney, below lift number 77. Stated another way, there is as much concrete contained in the bottom 59.4 m (195 ft) of each chimney as there is in the upper 176.3 m (578.5 ft). The bottom elevation of lift number 77 is 59.4 m (195 ft).

REINFORCING STEEL

The existing chimneys had vertical reinforcing steel ranging in size from number four to number eleven bars, with number eight bars used in the majority of lifts. Horizontal reinforcing bars ranged in size from number four to number eight, with number four bars used in more than three-fourth of the lifts. The reinforcing steel was placed as two mats, one imbedded in the interior face of the shell and one imbedded in the exterior face. Typically, each mat had number eight bars placed vertically on 305 mm (12-in.) centers and number four bars horizontally on 254 mm (10-in.) centers. All reinforcing steel was ASTM A615-68 grade 40, except for the vertical bars in the exterior mat, which were grade 60.

CONSTRAINTS ON DEMOLITION METHODS

The critical constraint limiting the selection of a chimney demolition method at the generating station was the requirement that generating capacity would not be interrupted at any time. The replacement chimneys would be constructed and in operation before any demolition activities would begin. After construction of the replacement chimneys the physical position of the existing chimneys would be between the generating units and the replacement chimneys, with all of the flue gas and scrubber equipment mechanicals stretched around the existing chimneys' bases. Fig. 3 shows the ductwork extending from the plant on the left to the existing chimney in the middle of the picture. The replacement chimney is on the right. At the time of the photograph the ductwork had not been extended to the replacement chimney. The approximate position of the extended ductwork is indicated on the picture.

The arrangement of the ductwork and mechanicals was necessitated by the requirement for continuous operation of the generators during construction of the replacement chimneys. However, this physical layout introduced special challenges for the demolition of the existing chimneys at the facility. No demolition procedure was acceptable which could possibly cause a shutdown of the station's generators. Within 9 m (30 ft) of each chimney's exterior face there were three critical station functions that would be placed at risk during demolition operations. Those functions were:

1. Exhaust fans for the coal combustion draft system: Vibration of the fan motors (lower left of Fig. 3) could

[1]Captain, U.S. Air Force, Luke AFB, AZ.
[2]Eminent Scholar, Del E. Webb School of Constr., Arizona State Univ., Tempe, AZ 85287.
[3]Assoc. Prof., Del E. Webb School of Constr., Arizona State Univ., Tempe, AZ.
[4]Asst. Prof., Del E. Webb School of Constr., Arizona State Univ., Tempe, AZ.

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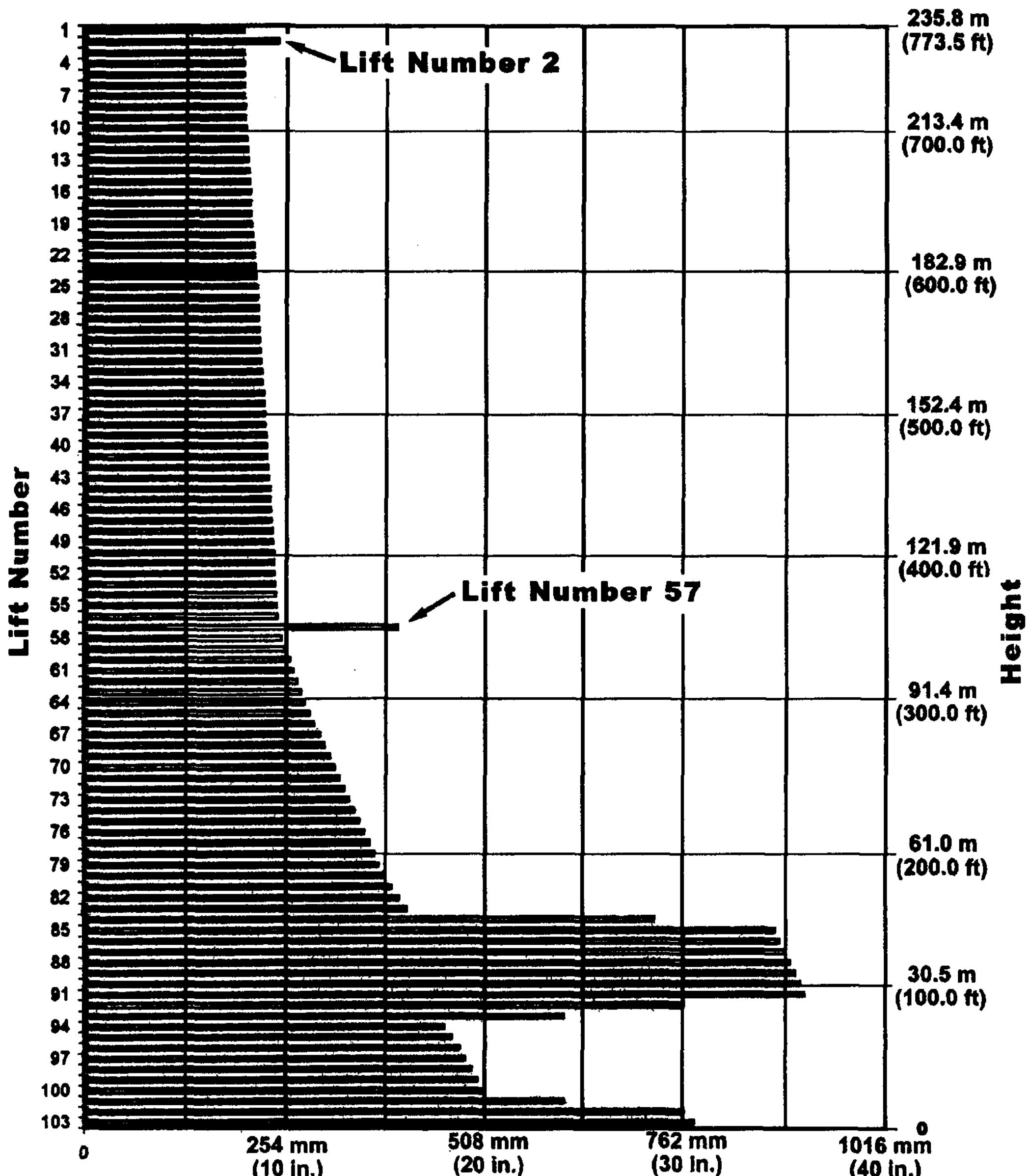

FIG. 1. Concrete Shell Thickness of Each Lift

cause the fans to automatically shut down as their shafts were equipped with motion detectors. This automatic shutdown system was in place because of the danger that vibrations could place the fans in a harmonic condition leading to self-destruction. Any shutdown of a fan would force the affected generator to also be shut down.

2. Draft system ductwork between the chimney and the fans: If the draft system ductwork to the chimney were punctured by falling debris, tools, or equipment, the affected generator would have to be shut down because the coal combustion procedure would not operate properly. In addition, a puncture would allow the release of pollutants into the atmosphere.
3. Exhaust fan cooling water system: The exhaust fan motors for all three boilers were cooled by a continuous loop water system. This water system is located within the truss work shown in Fig. 3 between the existing and replacement chimneys. A rupture to a single line in the water system would force the shut down of all three station generators.

Each of these situations creates a repair cost requirement to the directly affected system. But more important, the revenue lost to the owner during generator downtime created staggering incentives to prevent such damage at all costs. Furthermore, restarting the generators after an unplanned shutdown is a difficult and time-consuming process. Each potential demolition method therefore had to be evaluated with respect to its potential to affect the operation of the generating station. Evaluations of demolition methods based on these critical station functions are outlined below.

DEMOLITION METHODS

Explosives

The most common method for demolishing chimneys is by the use of explosives, either by imploding the chimney or by causing it to topple over, much like felling a tree (''Florida'' 1993). Both explosive methods were unsuitable at the site as there was insufficient clear space available to implode the chimneys, and there was certainly no direction in which a chimney could be toppled. The new ductwork system passed on three sides of each existing chimney, and the plant was on the fourth side. In addition, vibrations would be caused by the explosions. As these factors placed not one, but all three sen-

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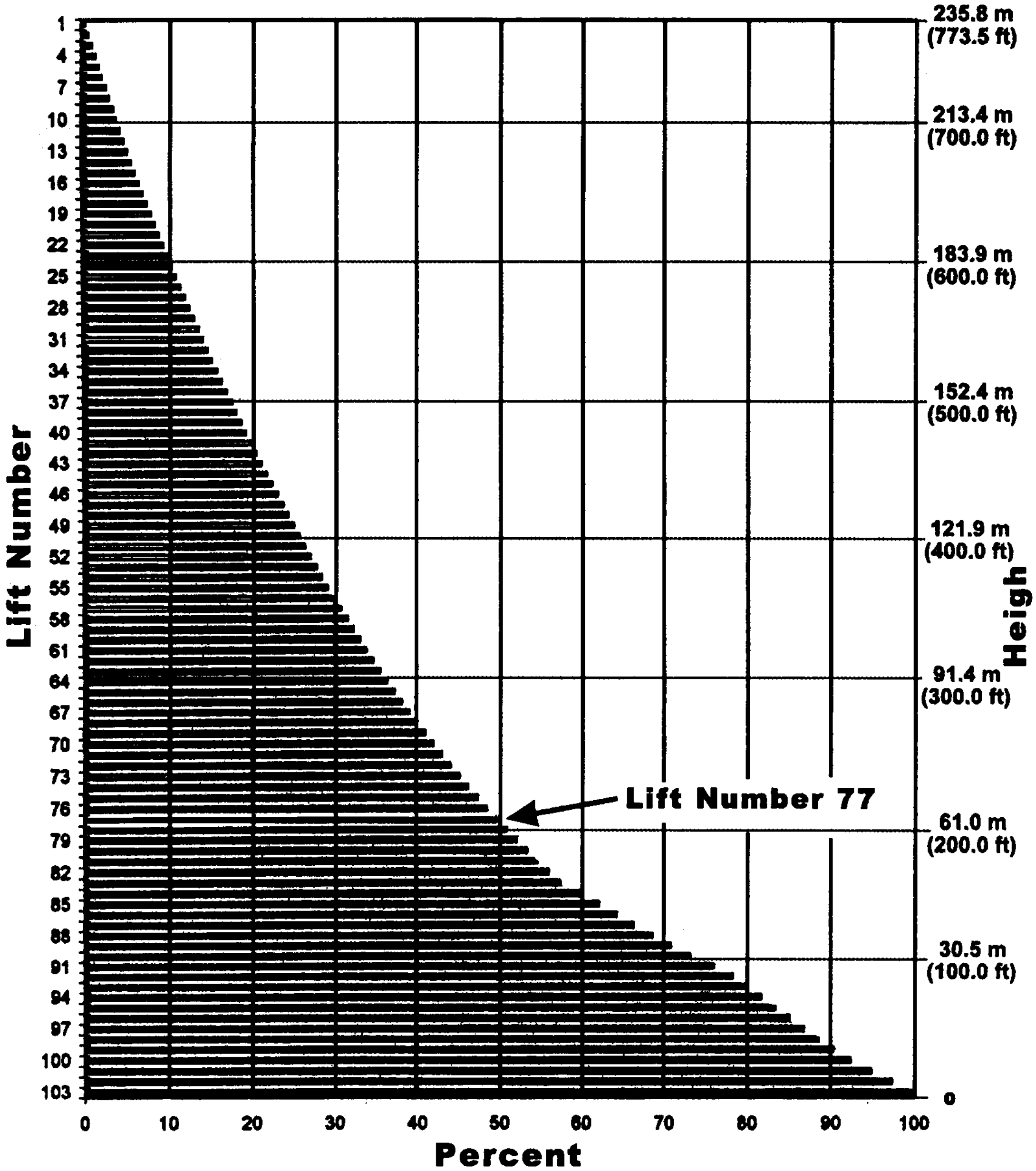

FIG. 2. Cumulative Percent of Concrete Volume by Lift

sitive functions at risk, explosive demolition was a totally unacceptable method.

Mechanical

Following the use of explosive demolition, probably the most common concrete demolition technique is mechanical crushing and breaking. This technique uses pneumatic or hydraulic impact and crushing tools to fracture the concrete. Many chimney demolition contractors use these techniques to break the concrete into approximately basketball-size pieces. The resulting debris is then allowed to free fall down the inside of the chimney. This was not an acceptable method for two reasons.

1. The vibration potential from falling concrete pieces is very difficult to quantify as the resulting size of the individual pieces cannot be forecast with complete accuracy.
2. Even though an acceptable plan would be to drop everything inside the chimney column, there would be the constant danger of some problem concrete and/or reinforcing steel pieces falling outside of the chimney and damaging either the ductwork or the cooling water piping.

Moreover, mechanical crushing is a very time-consuming process. But the controlling decision parameter was that all three sensitive functions were judged as being placed at an unacceptably high risk by the method.

Special Methods

Several relatively new concrete demolition methods were studied for possible use on the project. Those potential methods included:

1. Controlled blasting: This method generally involves a single row of explosive boreholes along a removal line. Each borehole is loaded with a light charge that is distributed along the hole's entire depth (Campbell 1985). The technique produces very little overbreak, still there is the problem of some flying debris. In addition, there is an element of uncertainty in breakage control which

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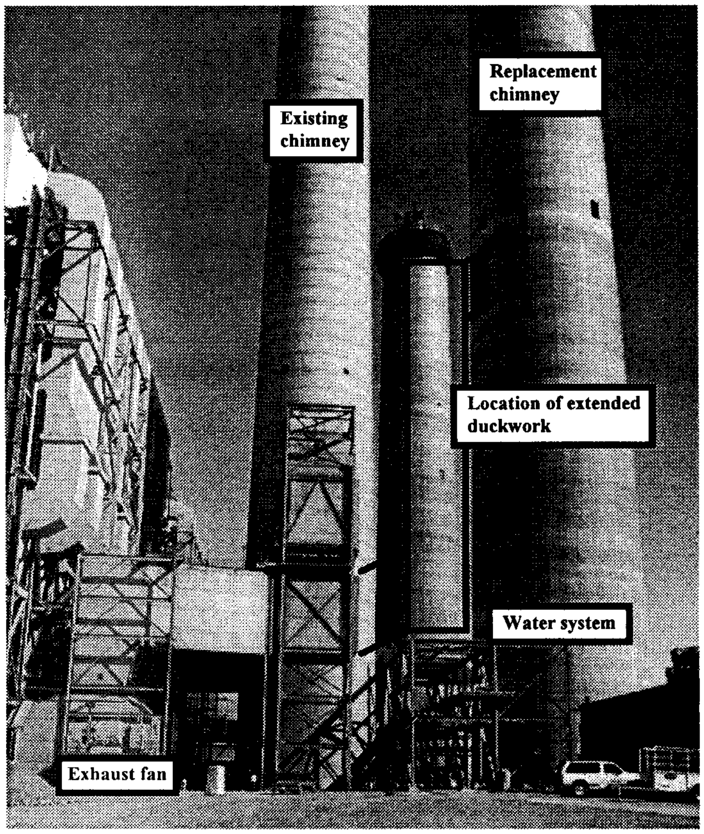

FIG. 3. View of Existing and Replacement Chimney Locations

would lead to variability in debris block size. Such a condition would cause concern about the safety limits of the hoisting mechanism, which is discussed in the "Cutting Pattern" section.

2. Soundless chemical demolition agents (SCDAs) (Hinze and Brown 1994): Expansive agents can be used to fracture concrete. There is the prerequisite to drill properly spaced and sized boreholes in which to place the agent, and after the fracture is produced there is still a requirement to cut the reinforcing steel. The time duration for such agents to work is 10–20 hours, which would greatly affect production. Because of productivity concerns this method was judged unacceptable.
3. Thermal concrete demolition: With this process low carbon rods are packed in an oxygen environment. When they are ignited, temperatures between 2,200°C and 3,870°C (4,000°F and 7,000°F) result. Penetration rates of 51–76 mm/min (2–3 in./min) can be achieved for 51 mm (2-in.) diameter holes (Hudgins 1987). The process does create smoke and fire hazards. Therefore, because of safety concerns the method was not considered viable for this project.
4. Hydrodemolition: Usually this method is used in removing areas of deteriorated concrete, though there are a few water jet "saws" available for pavement cutting. The commercially available systems typically require 26,500–37,850 L (7,000–10,000 gal.) of water during an 8-h operating shift (Campbell 1985). This chimney project required the removal of mass concrete, and there was the question of providing water to the work platform 213 m (700 ft) above ground level. Because of the problem providing and controlling the water at the top of the chimney, this method was judged to be unacceptable.

Because of the reasons stated, none of the foregoing methods was acceptable as a production demolition method for this particular project.

Sawing, Cutting, and Controlled Lowering

The use of diamond blade sawing or diamond wire cutting is applicable to work that requires control of overbreakage and adherence to specific removal boundaries (Jennings 1988). The precision cuts needed to control individual piece size and to alleviate rigging concerns on this project can be made with either of these two techniques. The diamond wire cutting technique is used in areas where the depths of cut are greater than those that can be economically cut with a diamond blade saw. No dust is produced when wet cutting is performed, as the water used to cool the blade traps the dust. However, wet cutting will result in water in the work area, introducing great housekeeping and safety concerns. The power units of some saws can be very loud and operating personnel must be protected from overexposure to high levels of noise. Hydraulically powered saws and sound-dampened blades can be used to reduce noise levels. There is little noise produced by wire cutting.

Cutting rates and performance are dependent on the hardness of the aggregate contained in the concrete and the presence of reinforcement steel. The harder the aggregate the slower the cutting rate. Likewise, both the time and cost of cutting increase significantly with the percentage of reinforcing steel in the cut area. The saw blade (diamond type and metal bond) must be matched to the physical parameters of the material being cut. Concrete having a compressive strength of 55,100 kPa (8,000 psi) was cut at Marseilles Dam on the Illinois River. This Corps of Engineers project demonstrated the ability of diamond sawing to effectively cut high-strength concrete.

Because of the aforementioned project constraints, techniques such as diamond sawing and diamond wire cutting were recommended for use on the project so that there would be no free flying or falling debris which would endanger plant operations. The approach examined was to cut individual pieces and to control-lower the pieces down the inside of the chimney. Following were the advantages of diamond sawing and cutting with controlled lowering:

- Control of debris.
- Individual pieces could be cut to controlled sizes consistent with hoisting equipment capability.
- The cutting process would not induce vibrations.
- Individual pieces could be rigged to a hoisting mechanism, and controlled lowering could be accomplished within the chimney column.
- The work platform and hoisting mechanism used for construction of the new chimneys could be used for the demolition process.

CUTTING PATTERN

To control the risks to the generating units, which had to remain operational at all times, it was proposed to diamond saw cut the concrete chimney shell into pieces weighing approximately 3,630 kg (8,000 lb) and to control-lower each piece within the chimney column. Fig. 4 shows a piece of chimney being lifted off the diamond saw just prior to lowering. This picture is from a similar project located in Ohio. The 3,630 kg (8,000 lb) weight limit was imposed because of the capacity of the proposed suspended work platform and the derrick, which would be mounted on top of the work platform. The platform would be suspended from the top of the chimney, a reverse slipform system, and the derrick would provide the mechanism for lowering the pieces.

With a slipform system the work platform is constantly moving upward on tendons placed in the wall section being constructed. During demolition the wall section is being re-

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moved. Therefore, the proposed demolition work platform would be supported by two sets of beams. One set would bear on the wall while cutting operations were being completed beneath the second set. After the wall was cut and removed from under the nonbearing set of beams they would be lowered onto the wall to support the platform. At that point the original bearing set of beams would be raised slightly and the wall beneath would be removed. Step by step the process is repeated until the entire chimney is removed.

As the first step in analyzing cutting patterns, a complete numerical model of the chimney geometry was created. Then the effect of cutting pattern on the total demolition cost was investigated by testing three possible cutting patterns (Fig. 5).

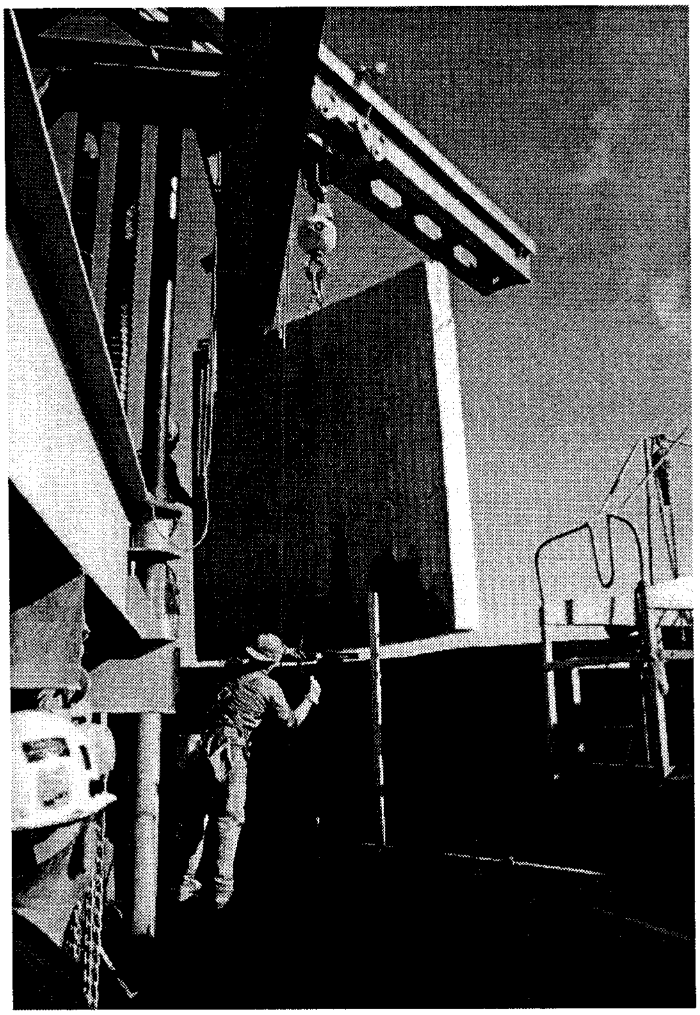

FIG. 4. Lifting a Diamond Saw Cut Piece of Chimney

1. Horizontal cut along the construction joint: To make each horizontal cut along the concrete shell lift construction joints and adjust the vertical cut spacing to ensure that all pieces weigh less than 3,630 kg (8,000 lb).
2. Minimized total length of cutting: To minimize the total length of cutting for 3,630 kg (8,000 lb) pieces requires that the width and height of a cut be equal.
3. Minimum unit cutting cost: To minimize the cutting cost per 3,630 kg (8,000 lb) piece requires that the pieces have a height to width ratio inverse of the respective cost of cutting in the two dimensions.

Horizontal Cut along Construction Joint

Given the 3,630 kg (8,000 lb) weight limit of a concrete piece, and a specified height determined by the original lift construction sequence, the only remaining degree of freedom for each piece was the spacing between the vertical cuts. As the thickness and diameter of the shell changed, the number and spacing of vertical cuts would also change. To calculate the spacing, the volume of concrete in each lift was first calculated. The lift volume was then multiplied by the concrete unit weight to yield a lift weight. Each lift weight was divided by the 3,630 kg (8,000 lb) hoisting limit, and the resulting number was rounded up to the next integer. This was the minimum number of pieces, "N," having unit weights of less than 3,630 kg (8,000 lb) in each 2.3 m (7.5 ft) lift. The vertical cut spacing, "W," was found by dividing the bottom exterior circumference of the lift by the calculated number of pieces in the lift.

Minimized Total Length of Cutting

Since a square has the least perimeter for a given area of a four-sided figure, a cutting pattern utilizing square pieces will minimize the total cutting length. With diamond sawing, it is really the total surface area of the cuts (Fig. 6) that controls production and cost. But, by assuming that the thickness of the concrete shell is essentially constant in any one lift, only the length of cut needs to be considered. In the case of these chimneys, the variation in thickness across a cut section is less than 3.5%. Therefore, the effect of thickness was not significant.

To calculate the dimensions of a square of concrete as near as possible to the 3,630 kg (8,000 lb) weight limit without

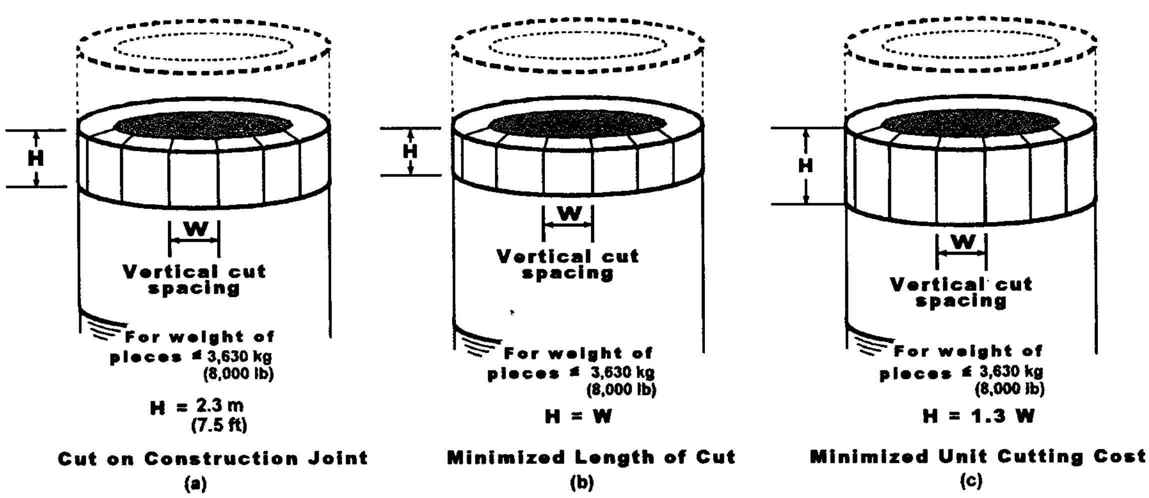

FIG. 5. Chimney Cutting Patterns

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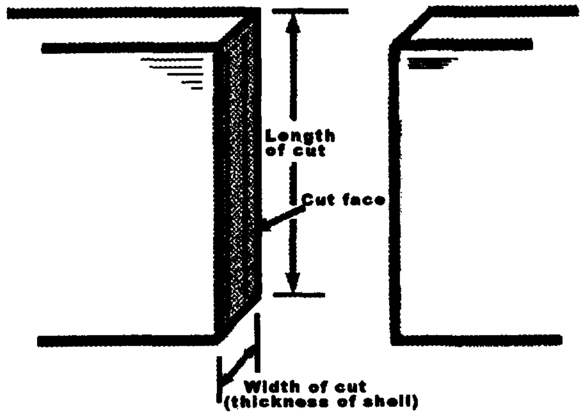

FIG. 6. Surface Area of a Cut

TABLE 1. Summary of the Effect of Cutting Pattern

Affected parameter (1)	Horizontal cut along construction joint (2)	Minimized total length of cutting (3)	Minimum unit cutting cost (4)
Total horizontal area of cut	13,348 m² (14,368 sq ft)	16,075 m² (17,304 sq ft)	14,026 m² (15,098 sq ft)
Total area of cut	21,845 m² (23,514 sq ft)	16,683 m² (17, 958 sq ft)	19,057 m² (20,513 sq ft)
Number of pieces	2,083	2,054	2,053
Number of lifts	103	106	93
Total time to demolish a chimney	8.9 months	8.7 months	8.5 months

exceeding that limit, an iterative procedure was utilized. The height of the lift was varied until the calculated width of a section was very close to the height. The number of pieces in the lift was determined. Then the height was increased in 30.5 mm (0.1 ft) increments until the weight of the pieces was as close as possible to the 3,630 kg (8,000 lb) limit without changing the number of pieces contained in the lift. This usually resulted in pieces having a height slightly larger than their width. However, the shape of the pieces was very close to square.

Minimum Unit Cutting Cost

The effect of reinforcing steel on saw cutting rates is significant. Therefore, because the vertical steel (number eight bars used in the majority of lifts) was larger than the horizontal steel (number four bars used in more than three-fourth of the lifts), the estimated unit cutting cost of a horizontal cut was greater than the unit cutting cost of a vertical cut. A 3,630 kg (8,000 lb) piece with dimensions that made the cost of the vertical cut equal to the cost of the horizontal cut resulted in a minimum cutting cost for removing each piece. The required dimensions were found by matching the aspect ratio of the piece with the ratio of the respective cutting costs. Based on the reinforcing steel that was to be encountered, the expected ratio of cutting cost for these chimneys was 1.3. That is, the expected horizontal cost of cutting was expected to be 30% greater than the cost for vertical cuts.

To obtain a 3,630 kg (8,000 lb) piece with a height approximately 1.3 times the width, an iterative procedure similar to that described earlier for square pieces was used. The resulting pieces were of slightly greater height than the ratio because of the decision to have pieces weigh as close to 3,630 kg (8,000 lb) as possible. The average aspect ratio for the entire chimney was 1.36.

The effect of the different cutting patterns is summarized in Table 1. With the information on cutting length, the cost and production rate estimate for saw cutting could be developed. The information on the number of pieces allowed the estimates for lowering to be developed. The combined cutting and lowering estimates for each of the three alternative cutting approaches provided the owner with definite information for evaluation demolition procedures.

CUTTING PATTERN EFFECT ON PROJECT COST

Three demolition cost estimates were developed based on the three proposed cutting patterns. The demolition steps which controlled the estimated project duration were:

1. Erect and lift the work platform/derrick to the top of the chimney.
2. Cut a lift according to the respective cutting pattern.
3. Lower the individual pieces of each lift.
4. Lower the work platform/derrick to the next lift.

The time and effort required for step 1 was identical in the case of all three patterns. The time to cut a lift, step 2, varied with the reinforcing steel encountered and with the area cut. The time required to lower the individual pieces, step 3, varied with the number of pieces. The rate of lowering was assumed to be constant even though there was some expected variation in individual piece sizes caused by the cutting pattern. The time to lower the work platform/derrick one lift, step 4, was the same in the case of all three methods but the number of movements varied with the cutting pattern, i.e., the number of lifts.

The estimated time to remove a single chimney was 8.9 months using the horizontal cut along the construction joint cutting pattern; 8.7 months using the minimized total length of cutting pattern; and 8.5 months if the minimum unit cutting cost pattern was used. Therefore, the cutting pattern affected not only the direct cutting cost, but also impacted the job overhead cost. In the case of this particular project the lowest cost estimate was the one based on the minimum unit cutting cost. The estimated cost difference for the horizontal cut along the construction joint cutting pattern and the minimized total length of cutting pattern, compared to the minimum unit cutting cost pattern estimate, was 7% and 2%, respectively.

The three estimates demonstrated the time and cost effect of the concrete cutting pattern. A difference of 7% in estimated cost caused by construction technique is significant on most construction projects. The impact of cutting pattern on time was minimal, a saving of eight days between the horizontal cut along the construction joint cutting pattern and the minimum unit cutting cost pattern.

The minimum unit cutting cost pattern produced 2,053 pieces having an average of 3,595 kg (7,925 lb). The theoretical absolute minimum number of 3,630 kg (8,000 lb) pieces contained in the shell is 2,034, based on the total shell volume and a concrete unit weight of 68 kg (150 lb), and assuming that every piece could be cut to exactly 3,630 kg (8,000 lb). Therefore, theoretically there could be further savings by eliminating those extra 19 pieces. But physical constraints such as the fixed locations of the opening would probably keep those savings from being realized. Operationally, further refinement of the pattern would require greater precision in the field for laying out the cut pattern and setting up the saws. The precision of the calculations can be easily improved, but it is a different matter to hold the cutting process to such tolerances, on a work platform 213 m (700 ft) in the air.

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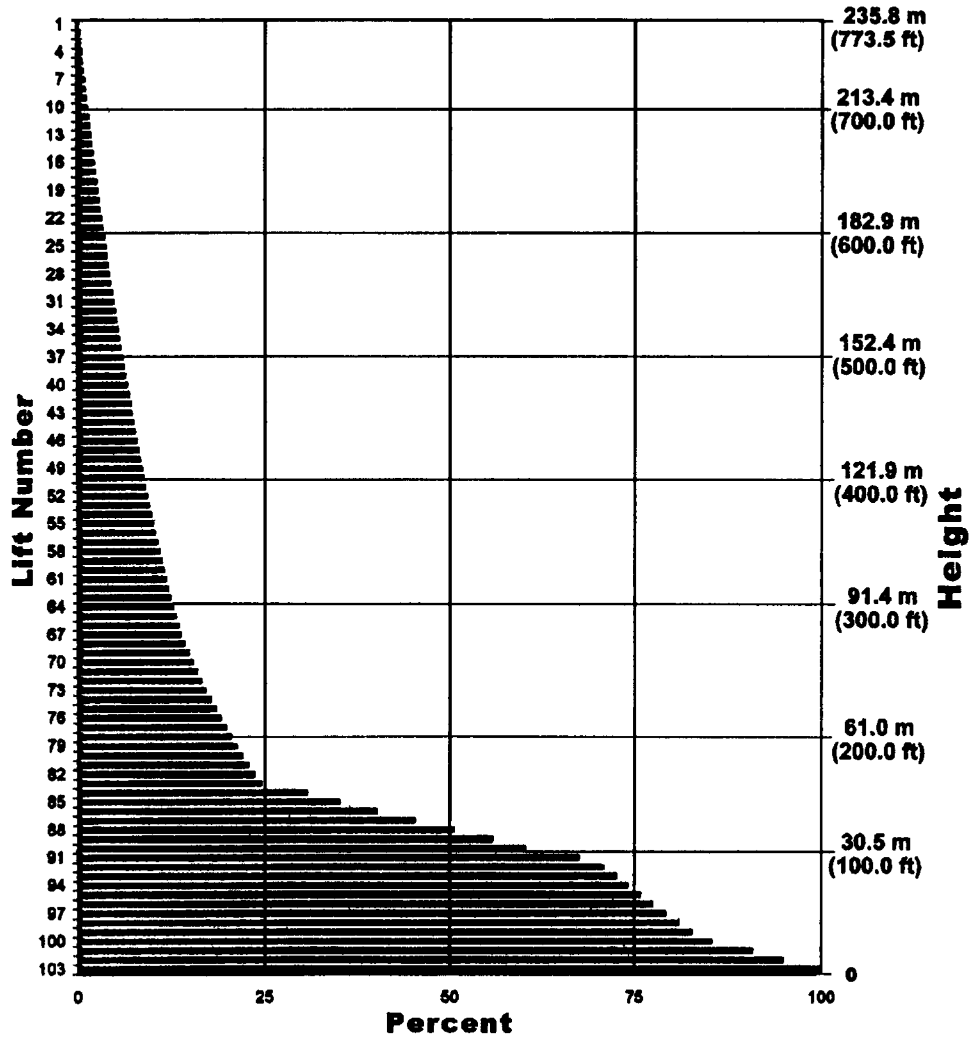

FIG. 7. Cumulative Percentage of Total Cutting Cost by Lift

OTHER ALTERNATIVES FOR REDUCING DEMOLITION COST

There were two other possible alternatives explored in the effort to reduce the demolition cost of these chimneys. The first was to only partially demolish the chimney, and the second was to increase the size of the cut pieces.

Partial Demolition

One concept for reducing the project cost was to only partially demolish the chimneys. Fig. 7 shows the cumulative percentage of cutting cost above each level for cutting the concrete shell using the horizontal cut along the construction joint cutting pattern. Approximately 75% of the cutting cost is incurred in the bottom 20 lifts [46 m (150 ft)] of the chimney, where roughly 50% of the total concrete volume is located. Removal of only the upper 183–189 m (600–620 ft) of the chimney was, therefore, recommended to the owner as an option that would significantly reduce demolition cost of the concrete shell.

Cutting Larger Pieces

Cutting larger pieces of concrete would reduce the amount of cutting required and the number of pieces which have to be handled. But cutting larger pieces would increase the weight of the individual pieces. The geometry of a piece requires that the weight of each piece be quadrupled to reduce the amount of cutting by 50%. Because of the height of these chimneys, the only feasible method of providing the work platform and derrick system was by suspending them from the top of the chimney. Increases in hoisting capacity are achievable only by increasing the structural capacity of the entire suspension system and derrick. A platform and suspension system were available from the erection process, but if greater capacity would be desired a single-use device would be required. Consequently, it was not considered desirable to increase the size of the individual pieces.

CONCLUSIONS

Each demolition method had to be considered in relation to the constraints imposed by operation of the generating station. In light of those constraints, saw cutting and controlled lowering was determined to be the only feasible method of chimney demolition.

The impact on the estimate caused by the geometry of the saw cutting was significant. A 7% reduction in cost was possible simply by careful selection of the piece shape. Project margins are often within the range of this cost differential.

Completion of the detailed demolition approaches and their resulting cost estimates allowed for full evaluation of cost saving measures to include consideration of partial demolition. Consideration of the methods could only take place after a complete numerical model of the chimney geometry was developed.

At the time this paper was prepared the actual demolition had not been performed. From discussions with the owner and

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the contractors it appears that a cutting and lowering process very similar to the one described here will be used. The owner is seriously considering the partial demolition option, and contractors are carefully analyzing the capacity of the hoisting equipment as that criterion controls piece weight.

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