APPENDIX A
BACKGROUND AND HISTORY OF ROCK REINFORCEMENT

A-1. The use of rock bolts and anchor bars to reinforce rock was initiated by the mining industry. Although the exact origin is unknown, it is said that a form of the slot and wedge type bolt was in existence[50] during the days of the Roman Empire. In more recent times, isolated instances of the use of rock bolts or pins to attach insecure rock to secure rock have been reported in the late Nineteenth Century. In North Wales prior to 1890 steel pegs or bolts were used for reinforcing overhanging brows in slate quarries. In the United States, rock (roof) bolts were reportedly used in coal mine roofs as early as 1905. In 1917 rock bolts were successfully installed over the main haulway in the Sagamore mine of the Pocahontas Fuel Company. The bolt installation was still intact when studied by the U. S. Bureau of Mines some 30 years later (Gibson[31]).

A-2. The first known published account of bolting was a German article titled, "Versuche und Verbesserungen geim Bergwerksbetriebe in Preussen Wahrend des Jahres 1918,"[51] which described experiments made in mines in Upper Silesia prior to the end of World War I. This short article discussed the use of bolts in conjunction with the support of concrete reinforced roadways in longwall areas and the bolting of weak shale or self-supporting sandstone above. The experiments were halted by the war and were not resumed.

A-3. The St. Joseph Lead Company, operating in southeastern Missouri, is credited with being the first large mining company to demonstrate the practicability of reinforcing mine roofs through the use of systematic bolting. The interest in rock bolting was largely due to the introduction of mechanical, full-revolving loading shovels which required maneuver room free of the conventional timber posts used to support bad ground in the roof of stopes. The results of this work, which began in the late 1920's, included the development of a technique for reinforcing the rock below the natural arch line and anchoring it to the solid rock above the opening and to the rock above the pillars. In this technique, lengths of 4-inch channel iron were bent to conform to the immediate contours of the mine roof and bolted to the roof with 1-inch-diameter slot and wedge bolts (6 to 10 feet long) anchored in firm rock above the insecure rock. The bolts were installed inclined to the roof through holes in the channels at about 4-foot centers. In average bad ground, the channels were placed 5 to 10 feet apart. Because the bedded dolomitic rock formation had numerous randomly oriented vertical slips, the suspension supports were sometimes placed to cross a maximum number of slips rather than parallel to each other at constant distance intervals. The combination of channel iron and rock bolts

later became known as "suspension roof supports." Small areas of insecure roof were suspended with the use of square bearing plates and single rock bolts placed either vertically or at an angle. The single bolt installations were known as "shin plasters."

A-4. In this early work, the success of the suspension supports in preventing roof failure was attributed to two functions. One was the suspension of the insecure rock below the natural arch from the secure rock above to prevent loosening of the insecure rock. The other recognized that roof failure was progressive in action. Quoting from W.W.Weigel's article,[53] "If the lower layers are caught and held tight, the upper ones do not cause trouble. The succession of thin layers (of rock) thus become one thick, heavy beam of sufficient strength to carry from pillar to pillar." The same article also described the strengthening of pillars by bending channel irons around the pillars and then bolting the channels to the pillars with 4- to 6-foot-long bolts.

A-5. Other mining companies were also installing or experimenting with rock bolts and rock anchors during the same period of time. The Homestake Mining Company in South Dakota used steel pins grouted into holes to reinforce the hanging walls of shrinkage stopes during the 1920's. The Empire Zinc Company at Gillman, Colorado, used rock bolts to support the large openings which housed its underground mill constructed during the late 1920's. The Anaconda Mining Company of Butte, Montana, began making rock bolt installations in 1939. In that year, an exhaust air crosscut was rock bolted and shotcreted at the time it was driven. The crosscut was still being used to exhaust hot humid air from the 3400 level of the Belmont mine many years later. In 1942, rock bolting experiments were carried out at the Washington-Glebe Colliery in England, but were not entirely successful. In the Forchaman Colliery in South Wales, a 60-foot-long section of roadway roof was systematically rock bolted with slot and wedge bolts in 1944. The work was terminated because of a shortage of materials, but the installation was still in good condition in 1958.

A-6. Examples of early attempts to devise mechanical anchorages for firmly anchoring rock bolts are interesting. The external area around the slot was sometimes roughened with chisel cuts with the hope of improving the holding power. Circumferential beads were also sometimes welded near the back of the bolt to increase the bolt diameter for use in 1-1/2-inch diameter holes. Both of these techniques were later discarded. A technique was developed during the same period of time by the Missouri Portland Cement Company at Sugar Creek, Missouri, for improving the slot and wedge anchorage where soft rock was encountered. After the slotted rod was driven over the wedge, a steel tube, 8 to 14 inches long and with three fourths of its length slit into four

sections, was slipped over the rod and driven tightly between the wedged end and the rock to reinforce the anchorage.

A-7. Although slot and wedge bolts were the most common in this early work, others were experimenting with expansion shell anchorages. In a series of articles appearing in Colliery Engineering in 1945 and 1946, Z. S. Beyl, a mining engineer of Delft, Holland, proposed a method of reinforcing the roof in longwall mining that incorporated the use of vertical rods with expansion shell anchors. Beyl's method was based on experiments made in British mines during World War II. An early use of specially designed expansion shells was in the No. 7 mine of the Consolidated Coal Co., Staunton, Illinois.

A-8. Following the publishing of Mr. Weigel's article in 1943, a great deal of interest in rock bolting applications was generated throughout the mining industry. Because of the steel shortage during World War II however, further development was delayed until 1947. At this time, the U. S. Bureau of Mines, in coordination with the mining industry and State agencies, initiated rock bolt developmental work in an effort to reduce the existing high rate of accidents resulting from roof falls. By May 1949, 114 mines were involved in experimental rock bolting work, primarily in connection with suspension roof supports. Research into the theory and practice of rock bolting, as well as other means of roof control, was by now also being conducted by the Bureau of Mines and other agencies. The results of this work demonstrated that rock bolting offered the mining industry a safe, efficient method of roof support. This is not to say that all roof problems could be solved through the application of rock bolts. It became apparent that careful study of the rock conditions, accompanied with closely supervised experimentation and rock bolt installation, greatly increased the chances of making successful installations. The failures that did occur served to stimulate further interest among the researchers and members of the mining industry.

A-9. Beginning with 1949, rock bolts began replacing timber supports in U. S. mines at a rapid rate. By the end of 1952, over 2,000,000 rock bolts per month were being installed. By 1954, 800 mines had adopted rock bolting for systematic reinforcement. By 1957, over three million rock bolts per month were being installed. Almost 90 percent of these were being installed in bituminous coal mines east of the Mississippi River. Of the remaining 10 percent used in the western United States, two thirds were being used in coal and nonmetallic mines, and one third in metal mines.[46] In Canada, systematic bolting of rooms with slot and wedge bolts began in 1950 in Breton coal and metal mines and developed rapidly in the middle 1950's. In Europe the mining of coal generally by the longwall system provided less opportunity for applying rock

bolts than did the room-and-pillar system used in American mines. In 1958 approximately 33,000 bolts were used in the Saar Basin, 112,000 in France, and 250,000 in Great Britain.[54] Most of these were used in strenthening the roof of roadways. In the metal mines of Lorraine, over 100,000 rock bolts per month were being used in 1959.[33] Rock bolts were reported being used in the Kolar Gold Field, South India, at depths of 9,000 to 10,000 feet prior to 1957.[41] In South Africa, expansion shell rock bolts were used on a minor scale as far back as 1951. In 1964, 120,000 to 140,000 rock bolts per month were being used in South African mines.[49]

A-10. By 1957, rock bolting had been generally adopted in U. S. mines and had gained acceptance in many other countries. The "explosion" in rock bolt use over a span of a few years, after laying dormant for so long, can be attributed to other significant mining developments.

A-11. For centuries prior to the early 1950's, the mucking of ore and fractured material had always been done by hand. Following the introduction of pneumatic loaders in the United States, the mechanization of mining equipment gained momentum so that by 1950, many mines throughout the world had discontinued manual mucking. Mechanized mining equipment created a need for maneuverability space which was satisfied by the substitution of rock bolts for timbering.

A-12. The time and expense involved in drilling holes for installing rock bolts, however, was another matter. Although a steam driven rotary drill had been invented as early as 1813, the first major use of mechanical drills was made in the 1860's in the Frejus, the first long Alpine tunnel, and the Hoosac, a long railroad tunnel in Massachusetts.[45] The difficulties encountered in these early projects directed the interest of numerous inventors in Great Britain, Germany, Italy, France, and the United States to the development of rock drilling machines. Many improvements were made in the years that followed. Up until 1945 the drilling of rock was still time-consuming in spite of almost a century of developmental work. In that year a historic conversion from alloyed steels to tungsten carbide steel for drill bits took place in a Swedish power tunnel. Tungsten carbide was almost unknown at the start of World War II, except in Germany where it was being used primarily to speed up machine tool operations. Tungsten carbide tipped steels, first tried in German mines in 1928, and developed into a stable production item in Sweden in the late 1940's, were supplanting steel drills in mines throughout the world in 1950. Holes for installing rock bolts could be drilled much more rapidly and less expensively. With this impetus the phenomenal growth of rock bolt application and manufacturing was on its way.

A-13. The quantity of use of a method is not necessarily related to progress in its development and application. Although the coal mining industry was consuming over 90 percent of the rock bolts used in the United States in the 1950's, the contributions made in connection with the metal mining industry were equally significant. By the same token the relatively small number of rock bolts used in Europe and other parts of the world did not limit the number of rock reinforcement techniques that came from those countries.

A-14. The work done by the U. S. Bureau of Mines and other agencies in connection with the reinforcement of mine roofs did not go unnoticed by the designers and builders of civil engineering structures. Just as the miners had adapted the techniques developed by the tunnelers of using explosives and mechanized equipment to drill, breakup, and haul away rock, so did the tunnelers adapt mining rock reinforcement techniques to their uses.

A-15. The first major use of rock bolts in civil engineering underground installations was in the Keyhole Dam Diversion Tunnel[40] in Wyoming in 1950, and in one 238-foot section of the 6-mile Duchesne Tunnel in Utah, both U. S. Bureau of Reclamation projects. At the Keyhole Dam, 1-inch diameter by 6-foot-long slot and wedge type bolts were used to tie loose blocks of rock in the roof of the 650-foot-long outlet tunnel driven through sandstone. At the start of tunneling operations, four bolts were installed at 4-foot intervals along the tunnel. After improved rock conditions were encountered and after experimenting with the bolt spacing, the use of two rock bolts for each 6 feet of tunnel proved satisfactory. Additional bolts were installed where seams or joints angled across the tunnel. In this project 27 longer rock bolts were also installed to reinforce the rock at the outlet portal face. At the Duchesne tunnel, 1-inch-diameter by 5- and 6-foot slot and wedge bolts spaced at 4 to 5 feet were used to control "popping" and slabbing of the rock in the tunnel. The U. S. Bureau of Mines provided assistance in both cf these projects.

A-16. The largest early installation of rock bolts in a tunnel, from 1950 to 1952, was in the east Delaware Tunnel, part of New York's Delaware Aqueduct, where 1-inch-diameter, 6-foot slot and wedge type bolts and steel channels were used in approximately 3-foot centers to stabilize the rock in over 30,000 feet of tunnel.[40] The number, location, and spacing of bolts were varied to meet the condition of the generally flat-bedded red shale and thinly laminated gray sandstone that existed in the tunneling zone.

A-17. The use of rock bolting for permanent support was greatly advanced by construction of the Snowy Mountain Scheme[39] in Australia

between 1952 and 1962. Experimental work led to greater acceptance of rock reinforcement as permanent support. The successful use of grouted slot and wedge and hollow core groutable rock bolts provided a strong argument for future use of permanent reinforcement in tunnels and large caverns.

A-18. The Haas Hydroelectric Power Project, California, was the first large underground power plant built in the United States. Constructed in 1957, the rock of the underground chamber was reinforced with fully grouted untensioned deformed bar elements.

A-19. In 1961 and 1962 an underground complex was mined in Cheyenne Mountain near Colorado Springs, Colorado, for the NORAD defense installation.[52] Rock bolts and anchors were used almost exclusively for stabilization of the jointed granite around the chambers. Experience gained on this project provided impetus to the use of fully grouted rock reinforcement on many projects in the United States.

A-20. The construction of other large underground power plant chambers followed in the 1960's. These were the Morrow Point, Oroville, Boundary, Churchill Falls, and Northfield projects. Rock reinforcement on all of these projects consisted of long tensioned fully grouted expansion shell rock bolts, mostly of the hollow core type.

A-21. The use of fully grouted rock reinforcement developed more slowly in tunneling and slope stability work, but by 1970 very few ungrouted reinforcement elements were being installed on civil engineering works.

A-22. During the 1960's new types of rock bolts were developed, some on an experimental basis. These included explosively anchored bolts, "strippable" or "yieldable" bolts, and bolts utilizing epoxy or polyester resin for the element bonding medium or for the element itself. None of these were widely used on civil engineering works.

A-23. By 1972, prepackaged polyester resin systems were developed, tested, and marketed. These systems made possible the development of positive anchorage, tensioning, and full-length bonding within minutes in almost any type of rock. These systems quickly gained acceptance on civil engineering works and are being widely used along with groutable rock bolts of the hollow core type.

A-24. The future may see a greater utilization of fully grouted, untensioned rock anchor systems (reference Appendix E) for underground work where a minimum amount of initial rock movement is acceptable or desirable at times to fully develop arch action. However, for surface slope reinforcement, pretensioned rock bolts or tendons are the only practical

means by which significant increases of normal forces on incipient failure planes can be achieved to prevent first movement. By preventing first movement of unstable rock slopes, existing asperities are preserved on the sliding surface, thereby ensuring that peak strength will be utilized in lieu of the lower residual strength.