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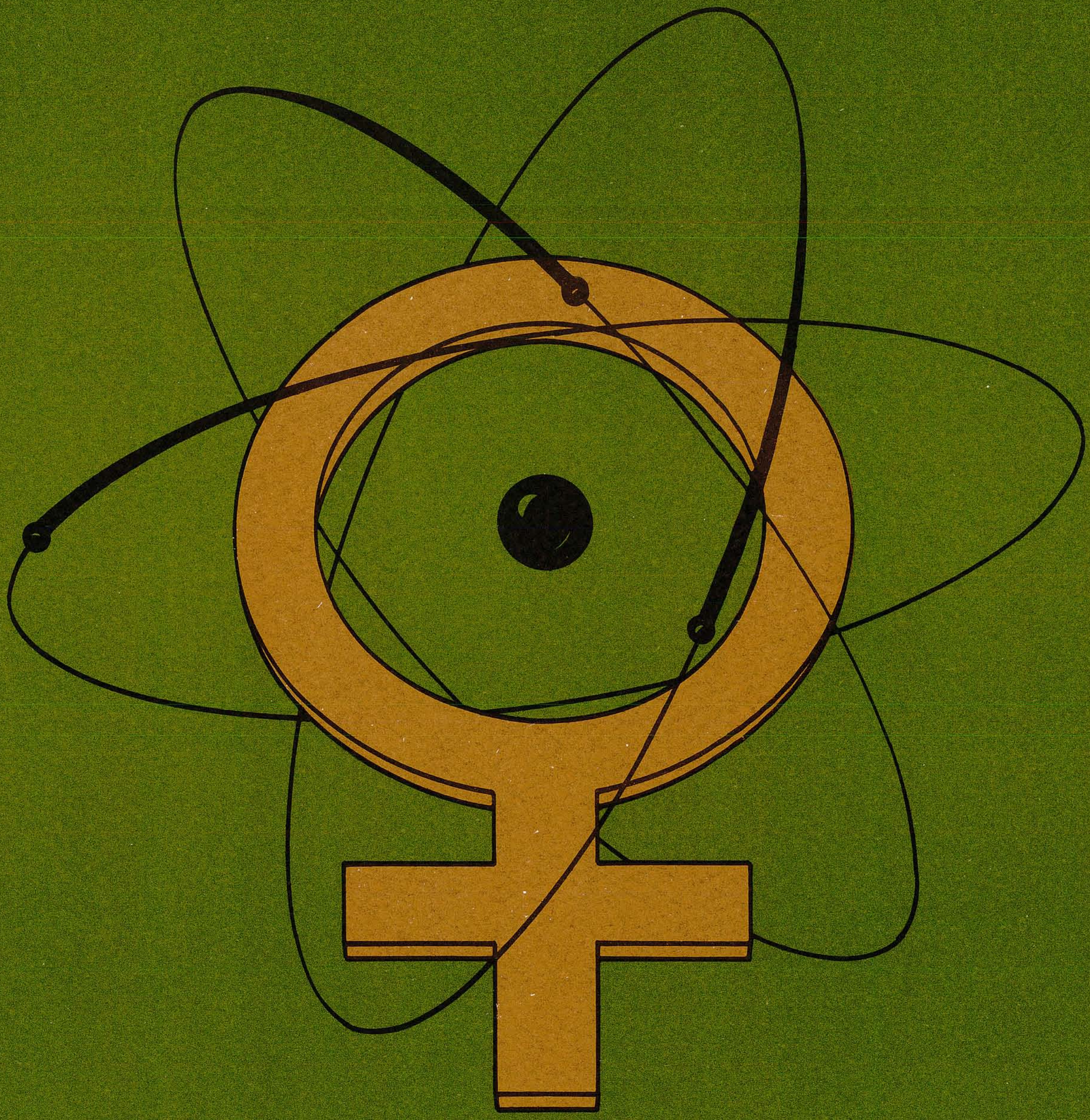
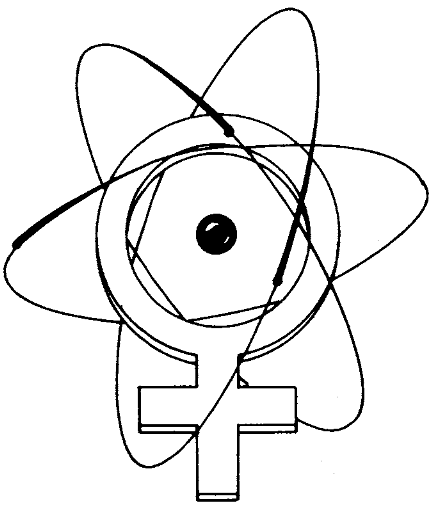
SLOOP



KENNECOTT COPPER CORPORATION
UNITED STATES ATOMIC ENERGY COMMISSION
UNITED STATES BUREAU OF MINES
LAWRENCE RADIATION LABORATORY

PNE 1300
Nuclear Explosives – Peaceful Applications



THE COVER

Copper tools, which made possible the building of the pyramids, impressed the Egyptian laborers with their durability. Soon the "ankh" — Egyptian symbol for everlasting life — became the symbol for copper — the everlasting metal. It's the symbol that is used to this day.

The combination of the "ankh" with the atom — symbol of atomic energy — represents the application of nuclear technology to the extraction of the everlasting metal.

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SLOOP

A study of the feasibility of fracturing copper orebodies with nuclear explosives, and the extraction of copper by in-situ leaching methods.

Prepared by the San Francisco Operations Office of the United States Atomic Energy Commission, the United States Bureau of Mines, the Lawrence Radiation Laboratory, the Kennecott Copper Corporation, and with the technical assistance of the Oak Ridge National Laboratory.

June 1, 1967

ABSTRACT

The San Francisco Operations Office of the United States Atomic Energy Commission, the Lawrence Radiation Laboratory, the United States Bureau of Mines, and the Kennecott Copper Corporation, with the technical assistance of the Oak Ridge National Laboratory, have cooperatively investigated the feasibility of fracturing low-grade copper deposits with nuclear explosives in preparation for extracting copper by in-place (in-situ) leaching methods.

The study was conducted as part of the U.S. Atomic Energy Commission's Plowshare Program. It includes detailed investigations of both the explosive fracturing and the leaching aspects, and includes the design of an experiment (Project Sloop) to field test the application.

If successful, the utilization of nuclear explosives for this application would:

1. Allow recovery of copper by in-situ leaching methods and eliminate the necessity of mining and bringing to the surface huge quantities of material for recovery treatment.
2. Increase the Nation's available domestic copper supply by allowing the economic development of vast resources of low-grade copper deposits now beyond the scope of conventional mining processes.
3. Permit large scale mining operations on a number of deep low-grade deposits with a minimum disturbance of the natural landscape.

A low-grade copper deposit near Safford, Arizona, was investigated as a possible site to test the concepts. Under the most advanced conventional mining and treatment methods, the copper in this deposit cannot currently be recovered at an attractive profit. Nevertheless, the deposit contains millions of tons of copper. The study indicates that a deeply buried nuclear explosive can adequately fracture a portion of the deposit for the test. Based on previous test work, the ore mineralization should respond favorably to leaching recovery methods. The study also concludes that an effective experiment at the Safford site can be designed which would satisfy both the technical objectives and meet all safety requirements.

Possible radioactive contamination of the copper is considered to be a manageable problem both for the experiment and for general application. Radioactivity in the leaching solutions should be at low enough levels that shielding should not be required for personnel protection.

The report recommends a field experiment to test the concepts. The estimated total cost of an experimental test, including one year of continuous leaching, is $13,175,000. It is emphasized in the report that Sloop is an experiment to test the combining of two technologies into a new mining concept and that additional experiments may be necessary before the technique can be developed into general commercial practice.

ACKNOWLEDGMENTS

The prepartion of this report was a joint effort of the San Francisco Operations Office of the U.S. Atomic Energy Commission, the Lawrence Radiation Laboratory, the U.S. Bureau of Mines and the Kennecott Copper Corporation, with extensive technical contributions from the Oak Ridge National Laboratory.

The report was compiled and edited by Peter F. Zimmer of the Kennecott Copper Corporation and M. A. Lekas of the AEC's San Francisco Operations Office. Others responsible for contributions to the study were: D. D. Rabb and Dr. Spenst M. Hansen of the Lawrence Radiation Laboratory; Paul L. Russell and William R. Hardwick of the U.S. Bureau of Mines; David J. Crouse, W. D. Arnold and F. J. Hurst of the Oak Ridge National Laboratory and Harold W. Bishop of Kennecott.

Guidance, technical assistance and supervision were provided by S. D. Michaelson and E. E. Malouf of Kennecott, John F. Philip of the AEC's San Francisco Office, and Dr. Gary H. Higgins of Lawrence Radiation Laboratory, Livermore, California.

A feasibility study for a proposed project of this scope and advanced technology required the efforts of many people in the participating organizations. It is not practicable to name all these individuals, even though their contributions are included in this study. The cooperation of all was essential and is appreciated by the sponsors of this study report.

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I. INTRODUCTION

A. General

The gradual evolution of the development of explosives has historically led to new and more efficient applications of blasting in the modern mining industry. Since the crude beginning with the discovery of black powder, the entire field of explosive technology has steadily improved. The significant resulting effect on costs has contributed to the mining of increasingly lower grade mineral deposits. With the atomic age more than two decades old, the utilization of the world's most powerful explosive offers the promise of further substantial reductions in the costs of mining the earth's mineral resources.

Fracturing copper bearing orebodies with nuclear explosives and leaching the copper minerals from the ore in place appears to present a low-cost method for recovering copper from deposits that are not economically minable by other methods. Development of such a method could offer the means for recovering millions of tons of copper for the uses of industry and the Nation.

The Sloop feasibility study was undertaken as a detailed investigation of this concept. The investigations are a joint effort of the Atomic Energy Commission, the U.S. Bureau of Mines and the Kennecott Copper Corporation. This report presents the conclusions of the studies by these organizations and includes an evaluation of a proposed test site located near Safford, Arizona.

The Lawrence Radiation Laboratory, which is operated for the Atomic Energy Commission by the University of California, provided the technical design of the pre- and post-shot exploration program, the nuclear detonation, and the prediction of hazards involved in the experiment described in this report. The Nevada Operations Office of the AEC provided the operational safety plan and the preliminary cost estimate. The Oak Ridge National Laboratory provided consulting services to determine methods of preventing or eliminating radioactive contamination of the copper. The USBM investigated the domestic reserves of copper orebodies that could utilize such an in-place (in-situ) mining and leaching method. The Bureau of Mines also explored the projected impact on the Nation's available copper resources which might result from development of this technique. Kennecott Copper Corporation provided the geologic and environmental studies of the proposed test deposit and developed the design for the leaching portion of the experiment.

The primary purpose of this study report is to provide Kennecott, the AEC and the USBM with information upon which to evaluate this concept.

No authorizations or approvals have been given or sought for initiating work on the experiment described in this study report. Before such an experiment could be initiated an acceptable proposal would be required by the AEC from Kennecott, and subsequently would involve a number of government approvals and authorizations. The first step must be a determination by the policy making bodies of both the AEC and Kennecott that this experiment is a worthwhile project in the Nation's interest for sponsorship under the Plowshare Program.

B. The Plowshare Program

The Plowshare Program was established by the U.S. Atomic Energy Commission in 1957, to investigate and develop peaceful uses for nuclear explosives. Primary research and development for the Atomic Energy Commission is carried out by the Lawrence Radiation Laboratory. Other research work is conducted by the Oak Ridge National Laboratory; the Sandia Corporation; the Los Alamos Scientific Laboratory; the Savannah River Laboratory; the U.S. Bureau of Mines; and the U.S. Geological Survey. In addition to government organizations, several private industrial companies have cooperated with the AEC in carrying out Plowshare research work.

As a result of the nuclear experiments conducted by the AEC a significant body of information and understanding pertaining to the physical effects which are produced by nuclear explosions in various types of rock has been accumulated.[3, 4, 5, 6, 7, 8, 10] The data obtained from these field experiments, when combined with laboratory experiments and theoretical investigations, provides the Plowshare Program with the capability to predict certain physical effects of a nuclear explosion with fair accuracy. While such data provides a substantial base for screening possible industrial applications, only an actual field experiment with the explosive in the specific industrial situation can effectively evaluate a proposed application.

C. Availability of Explosives

At the present time the AEC is not authorized to supply explosives and the required support services on a commercial basis. The AEC can, however, under the Atomic Energy Act of 1954, utilize nuclear explosives in cooperative research and development arrangements with industry, including demonstrations of particular applications. At such time as Plowshare technology advances to the stage where it is economically and technically practicable and there is an active industrial demand for explosives, Congressional action would be required to make nuclear explosives available for commercial purposes. Under any forseeable circumstances, the Federal Government is expected to retain certain responsibilities for transportation and detonation to assure the safety of the general public.

In order to assist industry in evaluating possible future uses, the AEC has published projected charges for nuclear explosives for use as a guide in evaluating Plowshare excavation applications. Table I shows charges for specific yields picked from the published chart. The AEC believes that the projected charges are sufficiently representative of the future situation to warrant their use in feasibility studies. While these charges are for explosives designed for excavation purposes, they are presented here for illustrative purposes.

TABLE I

Projected Charges for Thermonuclear Explosive

Yield, Kilotons	*Approx. Charge*
10	$350,000
50	425,000
100	460,000
350	500,000
500	535,000
1,000	570,000
2,000	600,000

These charges cover nuclear materials, fabrication and assembly, and arming and firing services. Significant related services which are not covered by these projected charges are safety studies, site preparation including construction of emplacement holes, transportation and emplacement of the explosives, and support of the operations in the field. The charges are based on a projection to a time when explosives would be produced in quantity for routine commercial utilization. It is possible that reductions in these charges could occur as a result of future technological developments.

II. COPPER: NEED-TECHNOLOGY-RESOURCES

World consumption and production of copper has risen progressively from about 18,000 tons in 1800, to more than 6 million tons in 1965. The U.S. Bureau of Mines reports that the United States refined copper consumption increased from 1.35 million tons in 1960 to 2.35 million tons in 1966. This represents an increase of 74 percent in the last six years. The annual rate of increase has more than doubled, from 8 percent in 1961 to 17 percent in 1966. This rapid increase has been much greater than either consumers or producers had anticipated, and is a combination of population growth, business upsurge and exceptional military need. Although the recent consumption rate may have been inflated by the present extraordinary defense requirements and may tend to level off, a more moderate but sustained annual increase of 4 to 5 percent appears inevitable.

Mine productive capacity in the United States has remained substantially constant at 1.7 million tons from World War I to the present with a 10 percent increase effected in the last two years. Prior to World War II, the United States possessed a high degree of self-sufficiency in copper and exported substantial quantities to other users. Today this basic metal is in short supply in the United States with the result that the country, to satisfy its industrial and defense demands, is in the unfavorable position of being a net importer of copper. This dependency on imports is expected to continue since the higher grade domestic reserves have become depleted while richer reserves still remain to be developed in other parts of the world. Rising standards of living and increasing populations in these developing nations indicate a growth in consumption for the world approximately twice the United States level. The availability of, and competition for, metal to import will be more difficult in the future.

The U.S. Government's current minimum copper stockpile objective, for strategic defense purposes, is 775,000 tons. The size of this objective has created some confusion since it has been changed frequently and presently, because of the extrordinary demand, the reserve has been depleted to about 260,000 tons. To meet its needs, the Government has been required to adopt a "set aside" policy for defense which now amounts to 29 percent of the domestic producers' copper production.

To insure adequate supplies of this strategic commodity at reasonable prices for industrial and defense needs, the copper industry has intensified its efforts to discover and develop deposits in the country. Some additional copper production will come from expansion of existing operations and from new deposits with ore grades equal to those now being mined. However, the major portion, in the long run, must come from development and utilization of deposits with ore grades not presently considered economic.

Exploration for new deposits is born of the necessity to replace the depleting deposits being mined. Its targets and successes are rigidly controlled by the economics that determine whether a mineral deposit can be developed into a successful mine. These economic criteria are not fixed, and the industry has been able in the past to gradually alter them. Copper represents a triumph for the technology that now permits profitable extraction from a grade of material that not so long ago could only be classified at best as a potential resource. Development of a low cost nuclear fracturing - in-situ leaching method of recovery may still further increase the domestic ore reserves and provide the needed copper from vast quantities of material never before considered economic for mining.

How large are the United States' reserves of copper? The answer depends upon which authority one consults. In a 1960 survey the U.S. Bureau of Mines estimated the United States to have 32.5 of the world's 212 million tons of copper in ores averaging 0.9 percent copper. In 1965 these domestic reserves were indicated to be 75 million tons in ores averaging 0.86 percent. Reported reserves have always been only a fraction of what the earth will ultimately yield. Large sums of money are required to outline a deposit sufficiently for it to be classed as a mining reserve. Producers can only justify investigating that portion of the total that offers a reasonable promise of profitable operation. If many years of potential production exisit with presently commercial grade material, there is often little impetus for diverting funds to prove the existence of sub-ore material. As producers approach their known ore reserve limits, they attempt to develop additional reserves. These additions can be obtained by new discoveries, by lowering recovery costs through advances in technology, or raising the price. Thus, the border between mineral reserves and mineral resources is constantly shifting.

It would be very difficult to establish reliable figures for the amount of sub-ore material that could be reclassified as ore reserves by the development of a mining method that would allow a substantial lowering of the present economic grade limits. The closest approximation is available in what is often referred to as "potential" ore, namely, material known by its location and quality and considered likely to be profitably minable in the future.

The amount of such potential reserves is known to be enormous. Vast tonnages of sub-ore material exists as halos around the economic limits of operating properties in this country. Exploration activities, presently on a 100 million dollar a year quest for additional ore, often observe, partially define, and are forced to abandon great quantities of this type of material in the search for today's commercial ores. The U.S. Bureau of Mines estimates that an additional 58 million tons of copper probably exist in potential ores averaging about 0.47 percent (9.4 pounds of copper in 1 ton of ore). Some definite information is available for eighteen such deposits containing about 16 million tons of copper.

A complete answer to the question of how much copper is in the United States in a sub-ore resource category will be determined only when a new method of mining technology is tried and proven, giving industry an impetus to fully explore the extent of these resources.

III. LEACHING OF COPPER ORES

Leaching is the process of dissolving metal values from an ore by means of a solvent, removing the resulting solution from the undissolved materials, and extracting the valuable constituents from the solutions.

Leaching of copper ores is not a new process. It was used as early as 2,500 B.C. in Cyprus, and perhaps in other historical copper producing areas of the Middle East. With the development of open pit copper mining operations on low-grade ores in the 1930's, the production of leach copper in the U.S. was greatly increased. To extract additional copper, the mining companies began to leach the dumps of sub-ore material that had been excavated in the mine stripping operations. By 1963, dump or "heap" leaching accounted for 9 percent of the 1,200,000 tons of copper produced in the U.S. By 1965, copper from leaching had grown to 12 percent of the domestic production.

Successful practice of in-situ leaching methods has been previously restricted to the abandoned workings of old higher grade underground mines. Mines in Butte, Montana; Ray and Miami, Arizona; and Bingham Canyon, Utah, have practiced in-situ leaching to a limited extent in the mined out areas of old block caving operations. The zones treated by leaching were well fractured and had been made permeable by the previous mining operations. Solution recovery in these operations was generally accomplished by using the existing underground openings.

The investigations of a nuclear blasting technique are principally concerned with the development of deposits that are not currently economic. These deposits currently cannot be economically mined by conventional methods but none the less contain millions of tons of recoverable copper. Types of presently uneconomic deposits to which in-situ leaching techniques may be applied include:

1. Large low-grade deposits in which the copper content of the ore is insufficient to justify mining the ores and concentrating the copper minerals; and
2. Small high-grade deposits in which the copper content is insufficient to permit direct smelting and for which the available ore reserves are too small to justify the large expenditure for treatment plant facilities.

Other considerations including physical and geographic location, characteristic metallurgy, depth and ground water, can also significantly influence the applicability of the techniques to a prospective deposit.

Present leaching technology is generally concerned with two types of copper mineralization, the oxide state and the non-oxide or sulfide state. Bornite and chalcopyrite are considered to be "primary" sulfide minerals deposited from igneous sources. Covellite and chalocite are largely "secondary" sulfide formations naturally leached from sulfides near the surface and precipitated near the water level. The oxide minerals such as chrysocolla, malachite and brochantite were formed through oxidation of surface sulfides and are also secondary.

Copper is extractable from both types of mineralization by a number of common acid and alkali leaching agents. However, aqueous leaching is far more rapid and efficient when applied to the oxide mineral types. Several operating mines with oxide ore reserves utilize in-plant leaching as the primary copper extraction process. The sulfide minerals must be oxidized for effective leaching recovery. This may be by weathering or by employing oxidizing leach solutions. The "primary" sulfides are especially resistant and conventional practice has been to employ the flotation process for recovery of copper from these ores.

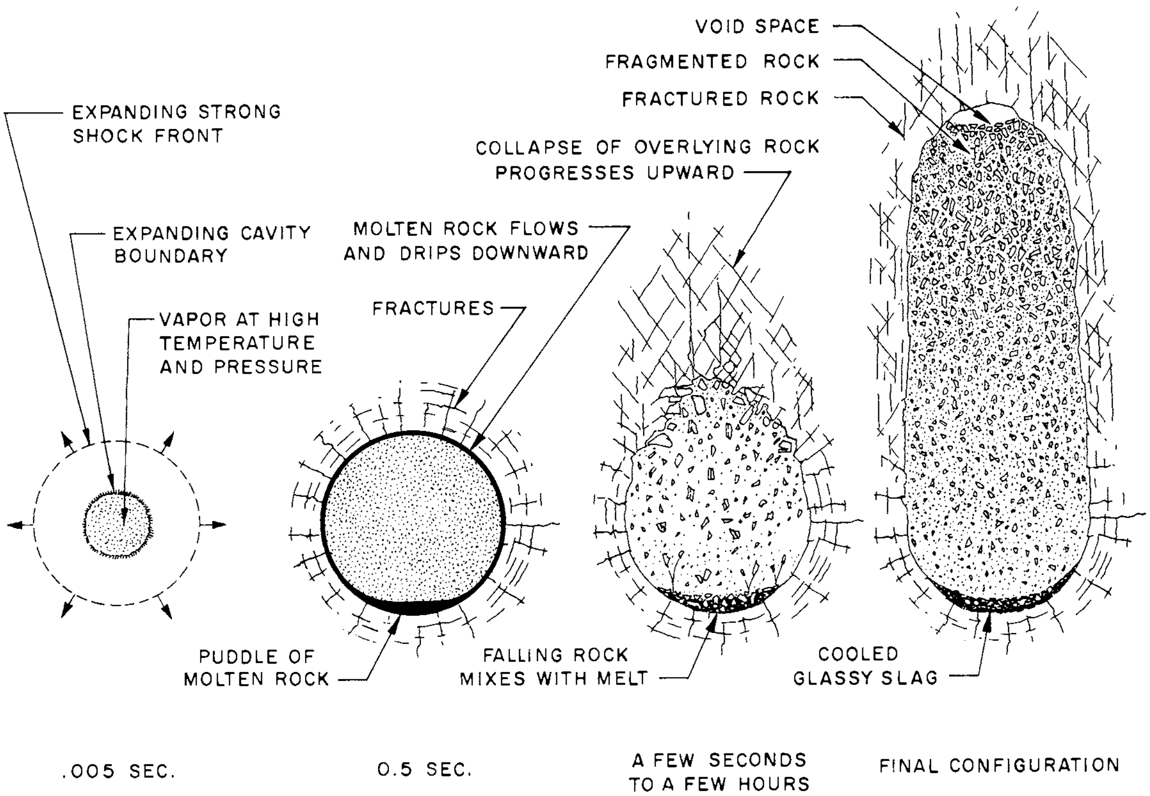
In-situ leaching eliminates the high costs of excavating and transporting the material to a plant for further treatment. To be economically effective, this method of leaching requires preparation of the deposit so that the dissolution process may proceed at an economic rate. The deposit must be shattered and broken to develop the permeability required to allow air and leaching solutions adequate contact with the minerals. A suitable means for collecting the copper leaching solution must also be provided so that the dissolved copper is not lost in the ground.

IV. EFFECTS OF NUCLEAR EXPLOSIVES

A. Rock Breaking

There are two general types of explosive emplacement configurations that could be used to fracture an orebody for leaching purposes. They are distinguished by the resulting fracturing effect which is dependent on the depth of explosive burial. If the explosive is deeply buried, the forces would not be sufficient to break through to the surface. The force would remain contained within the earth and create a completely buried cylinder of broken rock. At a shallower depth, determined by the explosive size and rock type, the blast can break through to the surface and heave the ground upward leaving a cone of broken rock. Instead of a buried cylinder, an inverted cone of broken rock extending from the shot point to the surface would be formed. Although the shallower emplacement yields about seven times more broken rock than a fully contained blast, it would permit some venting of radioactive gases to the atmosphere. All discussions in this report refer only to the contained emplacement configuration.

Upon detonation, the energy of an underground nuclear explosive is released in a fraction of a microsecond and vaporizes, melts and crushes the surrounding rock (Figure 1). A cavity forms and expands spherically around the blast center following the outward moving shock wave until the cavity gas pressure approaches equilibrium with the weight of the overlying rock. The molten rock that initially lines the cavity walls will flow and form a pool on the cavity bottom. As this material cools and solidifies into a relatively inert glass, it traps and retains up to 90 percent of the radioactive fission products generated by the explosion. The roof over the cavity, having been fractured by the shockwave and effectively undercut, will start to collapse and a cylindrical chimney of caved and very permeable broken rock will develop upward. The chimney would have a radius that approximates that of the cavity and would normally extend to a height of four or five cavity radii. Chimney material formed by nuclear explosions in granitic rock is extremely permeable, and has been observed to have about 25 percent void space with 75 percent of the particles smaller than 12 inches in size. The force of the explosion would also fracture rock out beyond the chimney boundary. This outside fracturing would increase the rock's original permeability for a distance approaching three cavity radii. However, without the physical displacement caused by cavity collapse, this additional permeability would be very much lower than that within the chimney zone.



Sequence of Cavity — Chimney Formation
FIGURE I

B. Safety Considerations

The major safety considerations for a deeply buried and fully contained nuclear explosion for leaching experiments are the direct effects of the blast and the indirect effects of the leaching program. The principal effects at the time of the blast are ground motion, possible accidental venting of radioactive gases to the atmosphere and the possibility of radioactivity from the explosion entering the ground water system. These "operational" safety considerations are discussed on page 32 and in Appendix A.

During the leaching portion of the experiment, the primary concern would be for potential industrial radiological safety problems that might be encountered as a result of solution treatment of rock broken by the nuclear explosive. These would be primarily due to tritium and to acid soluble fission products entering the circulating leach solutions. Investigations indicate that radiation from the leaching process solutions would be at such low levels that no shielding would be required for personnel protection.* Very little additional operating cost would be incurred by the housekeeping type precautions required to assure complete operational safety in handling these solutions. Tritiated water vapor from the leach solutions could constitute a hazard in the underground workings or in the precipitation plant, if allowed to collect and concentrate where it could be inhaled or absorbed through the skin. Process plant design specifying enclosed pipeline handling of the solutions and adequate ventilation would minimize this potential hazard.

The tritium content of the process solutions could be greatly reduced by initially flushing the chimney with water prior to the start of leaching. The flushing fluids would be chemically controlled in order to dissolve a minimum amount of copper. If contaminated, the flushing fluids would be disposed of in compliance with established AEC and State regulations.

C. Contamination of Copper*

Extensive laboratory scale experiments have been performed to investigate the possibility of radioactive contamination of the finished copper causing a potential health hazard or marketing difficulty. The investigations have indicated that the normal industry sequence of leaching and precipitation followed by smelting and refining, would result in a finished copper that is essentially free of any radioactivity.

* See Appendix B

The copper itself is not rendered radioactive by the nuclear explosive for any significant period of time. The radionuclides of copper formed by the explosion are very short lived and decay rapidly. Most of the fission products of the explosion are trapped at the bottom of the chimney in the relatively insoluble slag formed from vaporized and melted rock created by the detonation. Some fission products would be dispersed in the chimney in a more leachable form, but many of these would be strongly held on the ore by adsorption mechanisms and would not build up to significant concentrations in the circulating solutions.

Metallic copper is extracted from the leach solutions by precipitation with metallic iron. The only important long-lived radioisotope that would precipitate with the copper is ruthenium 106. Most of the ruthenium impurity would remain with the copper through the semi-finished smelting step; however, nearly all of the ruthenium would be removed during the electrolytic refining process. The refined copper product should contain less than 1 to 2 percent of the original small quantity of ruthenium that enters the leach solutions.

Substantial quantities of cement copper would be produced during the leaching tests conducted as part of the Sloop experiment. Decisions regarding the handling, smelting and refining of this copper and the resulting by-products and waste material would have to be based upon safety investigations and analysis of samples of the actual materials. After the experimental requirements of Sloop are satisfied, commercial usage of copper from Sloop could be permissible under suitable regulatory arrangements. Marketing of the copper could be permitted after a determination has been made that the sale and use of the copper produced from the experiment would not result in a significant increase in the radiation exposure normally received by the general public.

* See Appendix B for detailed discussion.

V. THE SAFFORD DEPOSIT — A PROPOSED TEST SITE

The Safford deposit of Kennecott Copper Corporation is located in the Lone Star mining district of southeastern Arizona approximately nine miles northeast of the town of Safford (Figure 2). The test site is located on the northern flank of this large disseminated deposit, which is situated within the Gila Mountains at an elevation of 5,000 feet. Safford, the Graham County Seat with a population of 4,700, is located adjacent to the Gila River at an elevation of 2,920 feet. The climate is typical of the southwestern desert, with little rainfall, hot summers and mild winters.

The recorded metal production for the Lone Star mining district amounted to 194,270 pounds of copper and insignificant amounts of gold, silver and lead. All of this was intermittently produced from several small mines, over the last 75 years. The nearest significant producing mine is the large open pit copper operation at Morenci, 20 miles to the northeast.

Bear Creek Mining Company, the domestic exploration subsidiary of Kennecott Copper Corporation, began a geological and exploration reconnaisance of the area in 1955. When it became apparent that exploratory drilling indicated the possibility of a large low-grade porphyry-type copper deposit at depth, Kennecott purchased the property in 1959 (Figure 3).

A. Geology

The geologic formations of the Lone Star district exposed in the Gila Mountains are predominately volcanics with some intrusives. The oldest pre-mineral rocks in the district are predominately andesitic volcanics believed to be Cretaceous. These andesites are cut by several strong, broad, northeasterly trending fracture zones. Most of the fractures were intruded by Early Tertiary igneous bodies of rhyolite, latite, quartz monzonite, granodiorite, and quartz diorite. This complex is overlain by two series of post-ore volcanics with a total thickness ranging from 200 to 800 feet. The older of these consists of flows of andesite and dacite. The youngest volcanic rock, which caps the Gila Mountain Range, consists of Quaternary basalt flows and some interbedded tuff beds. These rocks decrease in thickness and pinch out in the vicinity of the Kennecott deposit, and are not found on the south side of the range.

The copper mineralization occurs in the Cretaceous and Early Tertiary volcanic rocks under generally rugged surface topography (Figure 4). The deposit, in cross-section, is in the shape of an irregular ellipsoid 3,600 to 4,000 feet long and approximately 1,600 feet thick as shown in Figure 5. The entire deposit is overlain with a leached capping and barren volcanic rock that varies from 500 to 1,300 feet in thickness. Approximately one half of the indicated reserve is relatively enriched oxide ore. The principal copper minerals in this portion are chrysocolla and brochantite. About one-third of the total ore consists of a mixture of oxides, and primary and secondary sulfides. In addition to the oxide copper minerals mentioned, other ore minerals include chalcopyrite, chalcocite, covellite and minor amounts of bornite and molybdenite at depth in the sulfide zone.

The deposit is dry and above any known water table. Exploration holes on the north flank of the deposit, near the proposed test site, have penetrated to depths of 3,000 feet and no ground water has ever been encountered here or in the underground workings. A water well field has been drilled near the town of Safford that is estimated to be capable of developing an 8,000 gpm supply (Figure 6).

At the conclusion of the development drilling, an estimated 2-billion-ton reserve had been indicated for the deposit, consisting of a combination of oxide, mixed oxide-sulfide and sulfide mineralization, averaging a probable 0.41 percent total copper.

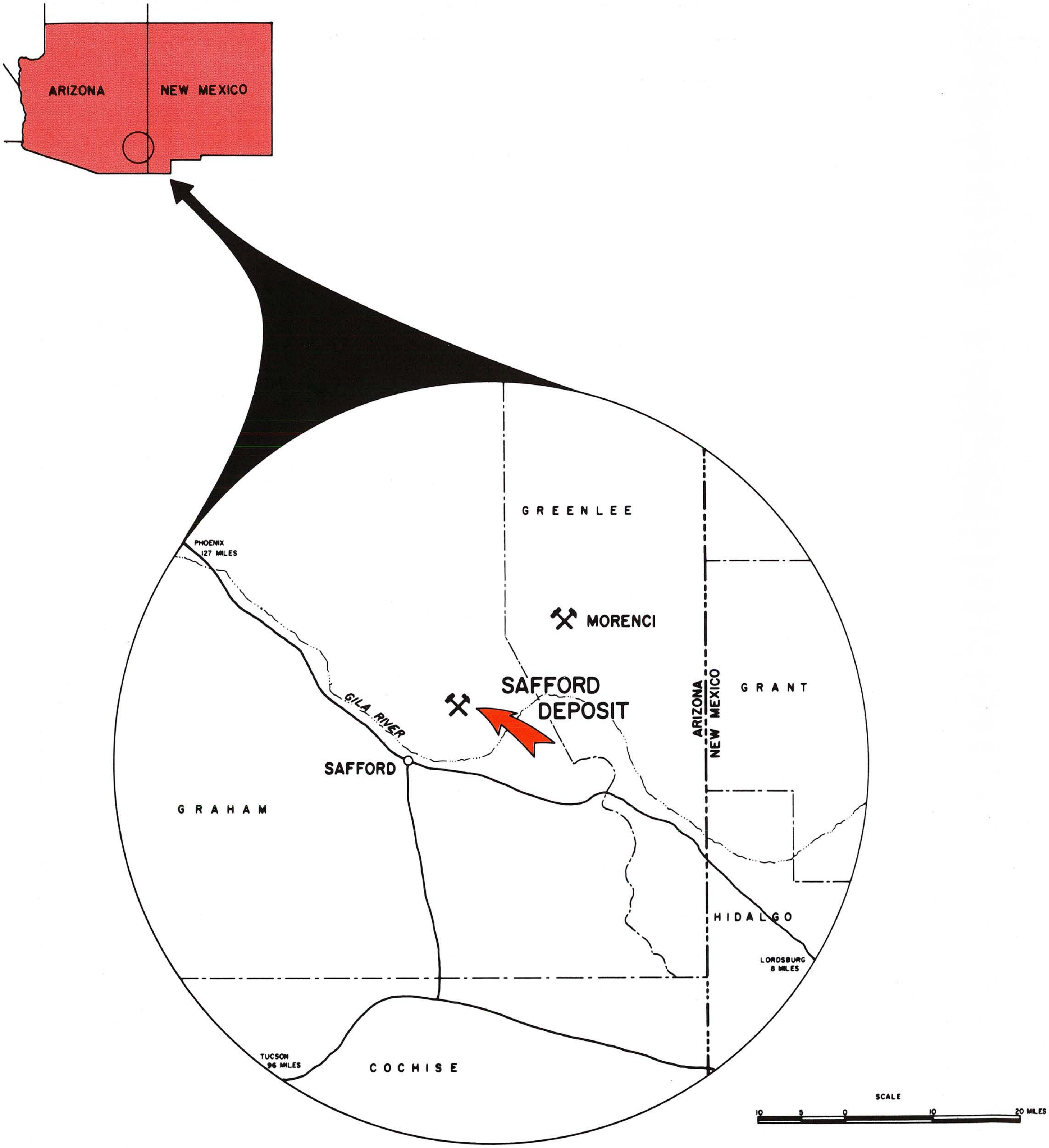
B. Leachability of Safford Ore

The initial metallurgical processing studies for recovery of copper from ores of the Safford deposit were begun in 1957. These studies were conducted on samples of diamond drill core obtained from the early exploration holes. The results of these laboratory scale studies on the higher grade oxide ore indicated that an acid leaching process would be required to extract and recover copper from this type of Safford ore. Utilizing these results, it was projected that vat leaching would recover about 76 percent of the copper from ores assaying 0.96 percent copper, and 85 percent recovery could be anticipated for higher grade ores averaging 1.00 percent copper. The studies also projected that acid consumption as a leaching reagent would be approximately 40 pounds of sulfuric acid per ton of ore.

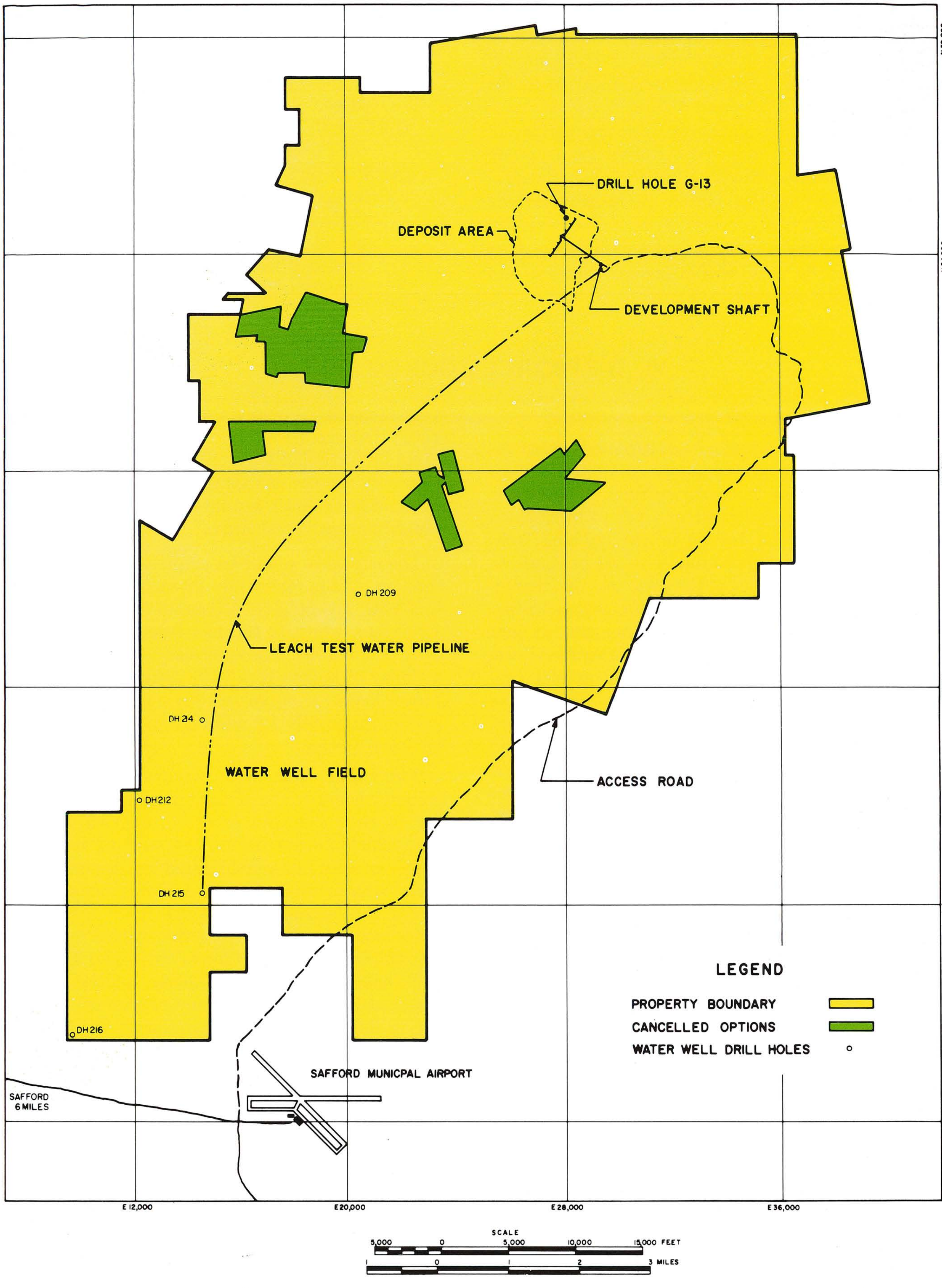
The surface exploration drilling of the Safford deposit had been done on a fairly wide grid system. As the apparent limits of the deposit became defined, additional extensive drilling programs were undertaken to confirm the indicated ore reserve tonnages and grades. An 800 foot development shaft and 3,000 feet of underground workings were driven into the oxide ore horizon where some 52,000 feet of underground core drilling was completed in 1961. The drill core and excavated material from the workings provided bulk samples used for the design of metallurgical treatment processes. A one-ton per day pilot leaching plant was designed and constructed adjacent to the shaft site. The plant was operated on oxide copper ores excavated from the underground development headings.

The pilot plant was equipped to treat ore samples by a process involving continuous leaching followed by a washing cycle. An electrolytic section for recovery of the copper from the pregnant leach solutions was also provided. The principal objective of the pilot operation was to try the process flowsheet on a larger than laboratory scale, using bulk material and to utilize and determine the effects, if any, of the rather saline well water developed by Kennecott near Safford. This water would most likely be the only process water available for a production operation, and any effect on the predicated metallurgy or economics could be significant.

While the pilot plant was in operation, additional laboratory amenability testing was done on pilot plant



Location Map, Project Sloop
FIGURE 2



Property Ownership Map, Safford Deposit
FIGURE 3

samples. These laboratory scale studies provided a check for the pilot plant results and provided data on acid consumption, copper extraction and the proportions of sulfide and non-sulfide mineralization in the ore.

Although the pilot plant test work was performed to design a leaching plant for a conventional mining operation, certain conclusions can be drawn concerning the behavior of this ore in an in-situ leaching operation:

(1) Safford ore can be treated for the recovery of copper by a moderate strength sulfuric acid leaching process.

(2) In the pilot plant testing, the overall copper recovery on oxide ore grade material ranged from 70 to 80 percent. In an in-situ situation a somewhat lower recovery may be anticipated.

(3) Overall acid reagent consumption in the test work averaged 40 pounds per tone of ore.

(4) High purity copper, approaching that of electro-refining methods, can be produced by electrolysis of strong leach solutions with no special purification of the feed solutions indicated other than a dechloridization step.*

* Analyses of the effects of a nuclear explosive on copper purity are given in Appendix B.

VI. THE PROJECT SLOOP EXPERIMENT

A. Experiment Design

As presently conceived, the experiment would involve detonating an approximately 20 kiloton nuclear explosive at a site in the northern flank of the oxide portion of the Safford deposit in order to fragment a zone of copper ore for testing in-situ leaching techniques. Pre- and post-shot studies would be made to record physical properties of the rock and the characteristics of the nuclear chimney. Sub-surface instrumentation would record shock measurements at shot time. A pilot leaching plant having commercial size equipment, would be built to leach and extract copper from the broken ore. A schematic view of the experiment is shown in Figure 7. It is anticipated that at least one year of leaching tests would be required to provide the conclusive results sought by the experiment. A tentative location for the test shot has been selected adjacent to the existing exploration drill hole G-13. This site is located far enough away to minimize damage to the existing shaft. The geologic information from this hole was used in the design of the experiment (Figure 8).

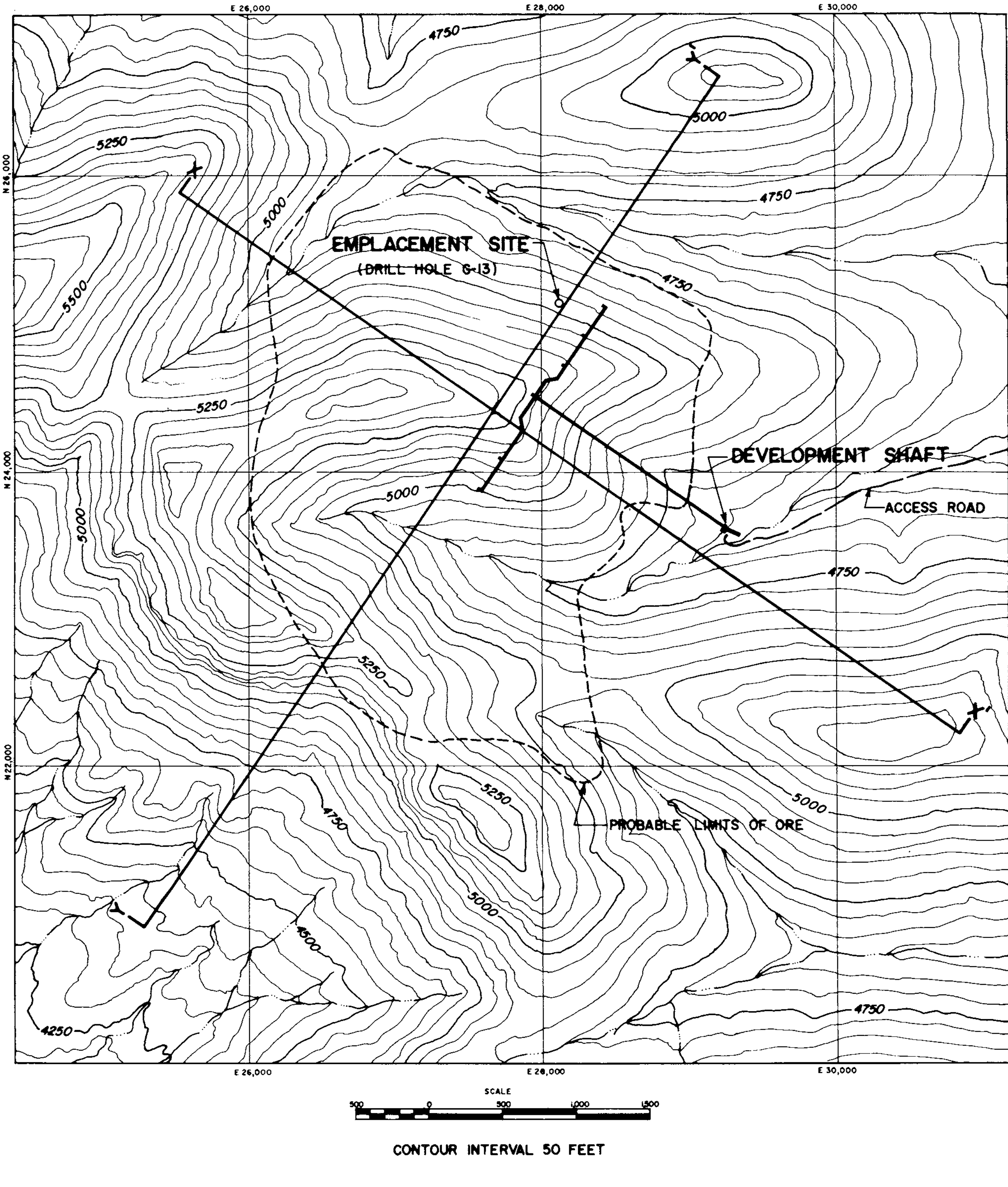
Before authorizing a nuclear explosion, the AEC and the Lawrence Radiation Laboratory would make detailed field investigations to confirm the suitability of this proposed site. These investigations would provide information needed to complete the safety evaluation of the site, the final design of the experiment, including the selection of the nuclear explosive, its yield, and mode of emplacement and would provide the basis for determining that the explosion could be conducted safely, and with satisfactory technical results.

Four surface sample holes would be drilled in the chimney area prior to detonation to establish the distribution and mineralogy of the copper. One hole would be drilled outside the chimney area to verify geologic data and would be instrumented for shock time - of - arrival, pressure, and particle velocity measurements. Preliminary investigations have indicated that explosives with yields of up to 100 kilotons could be successfully contained in the Safford deposit. However, the use of explosives of this size would not be considered until results from a smaller test shot were thoroughly evaluated.

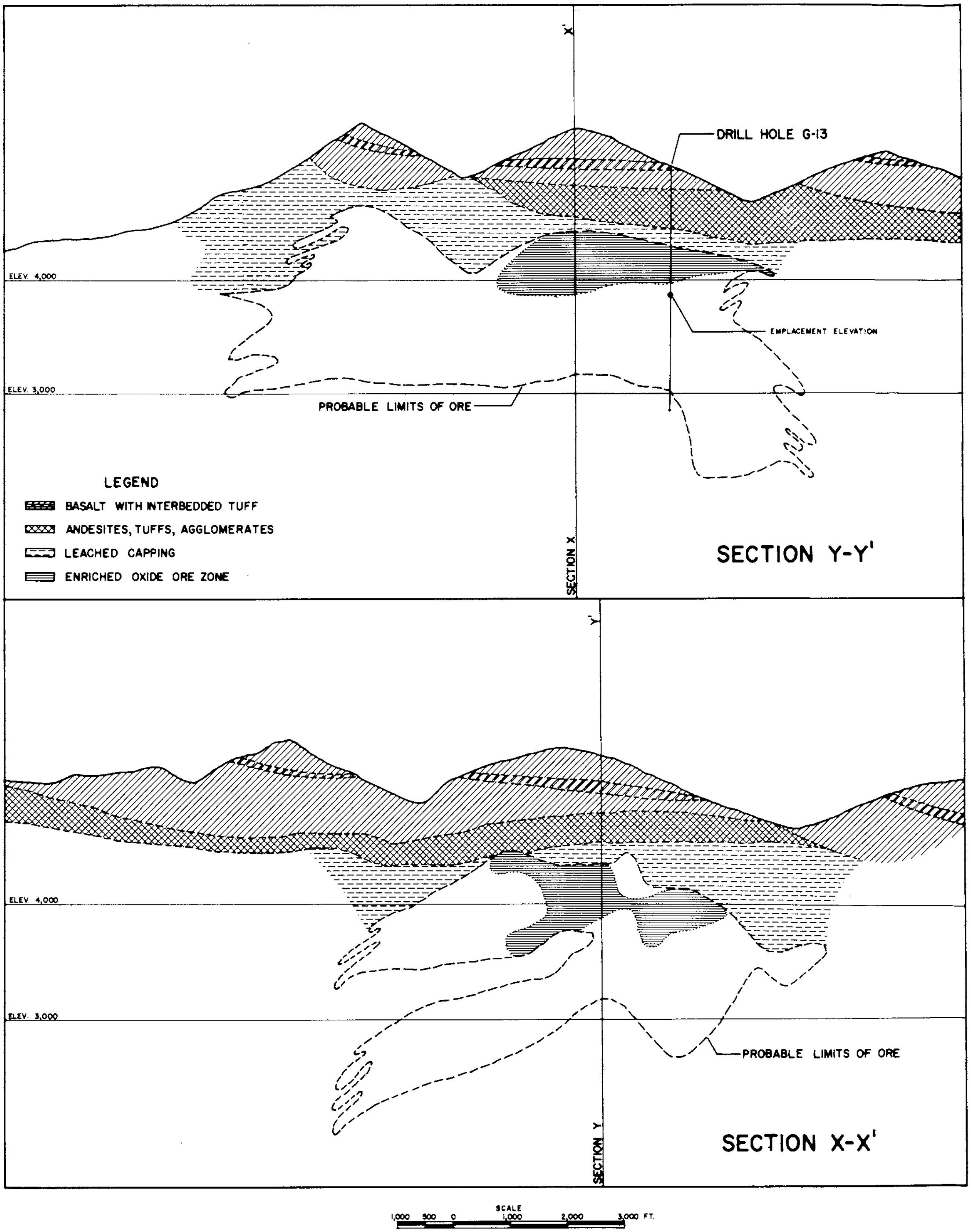
The explosive would be emplaced from the surface through an approximately 20-inch diameter uncased drill hole. It would be detonated at a depth of about 1,200 feet, which is 100 feet below the existing drift level in the mine. The explosion is expected to create a chiney of broken rock with a diameter of about 200 feet, a height of approximately 440 feet, and containing approximately 1.3 million tons of broken material for leach testing.

Two surface holes would be drilled adjacent to the chimney boundary to investigate the extent of fracturing in that area. As soon as the post-shot safety requirements are satisfied, the existing underground openings would be rehabilitated for inspection and to install the facilities for the leaching tests.

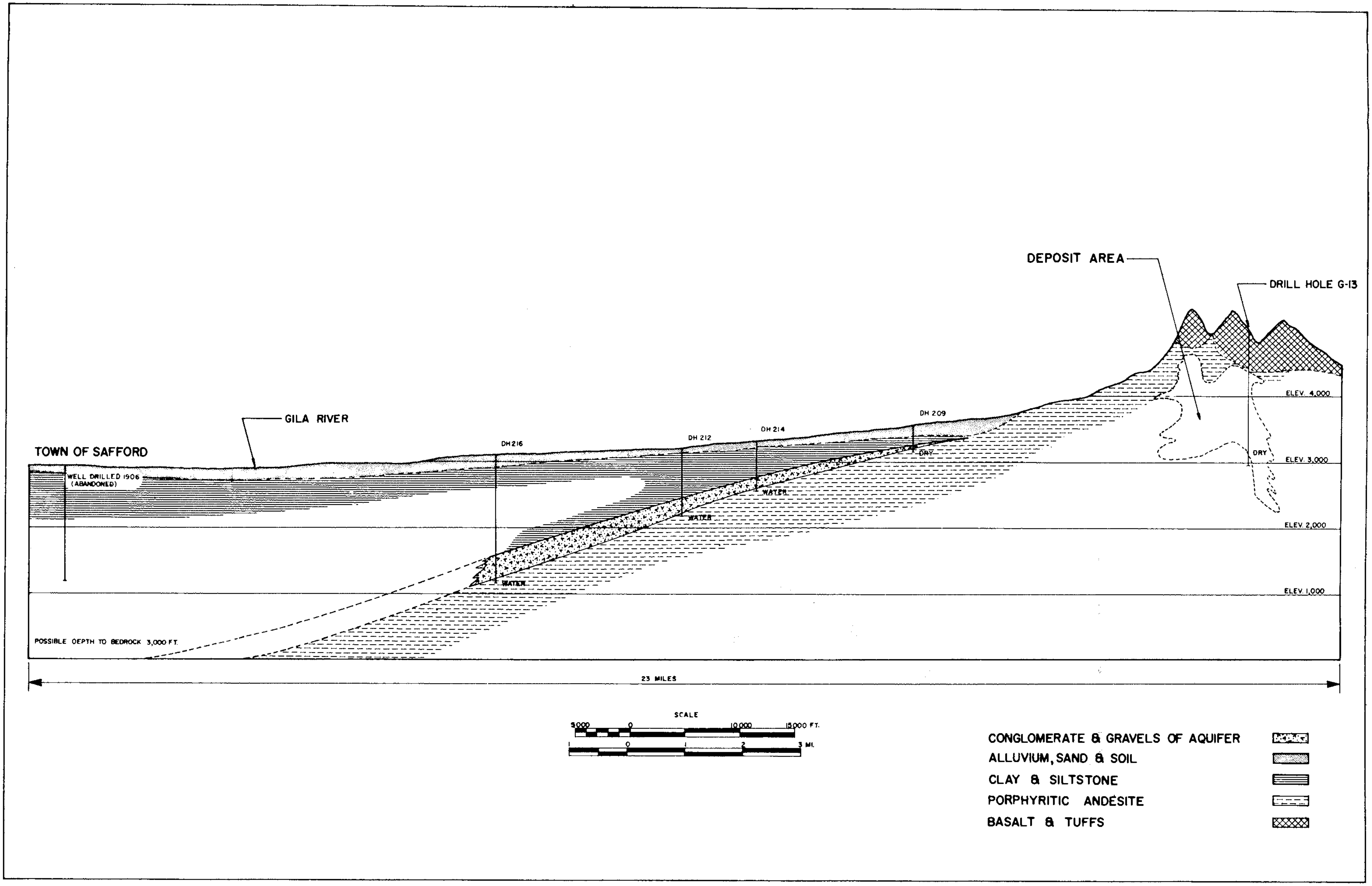
For the leaching tests, three leach solution input holes would be drilled from the surface to the top of the chimney zone. An access drift and a system of drill holes to collect the leach solution would be installed beneath the chimney (Figure 9). A precipitation plant using cone precipitators similar to those now used at Kennecott's western mines would be constructed near the shaft. The plant would be capable of treating a throughput of about 2,600 gallons per minute of pregnant (metal-bearing) solutions obtained from the collection system, and of returning the barren (stripped) solutions to the chimney zone. The plant would include facilities for make-up water, solution pumping, acid storage, and iron and copper precipitate handling and storage. Process water for the plant operation would be obtained from the well field near the town of Safford. The pilot leaching flowsheet is shown in Figure 10.



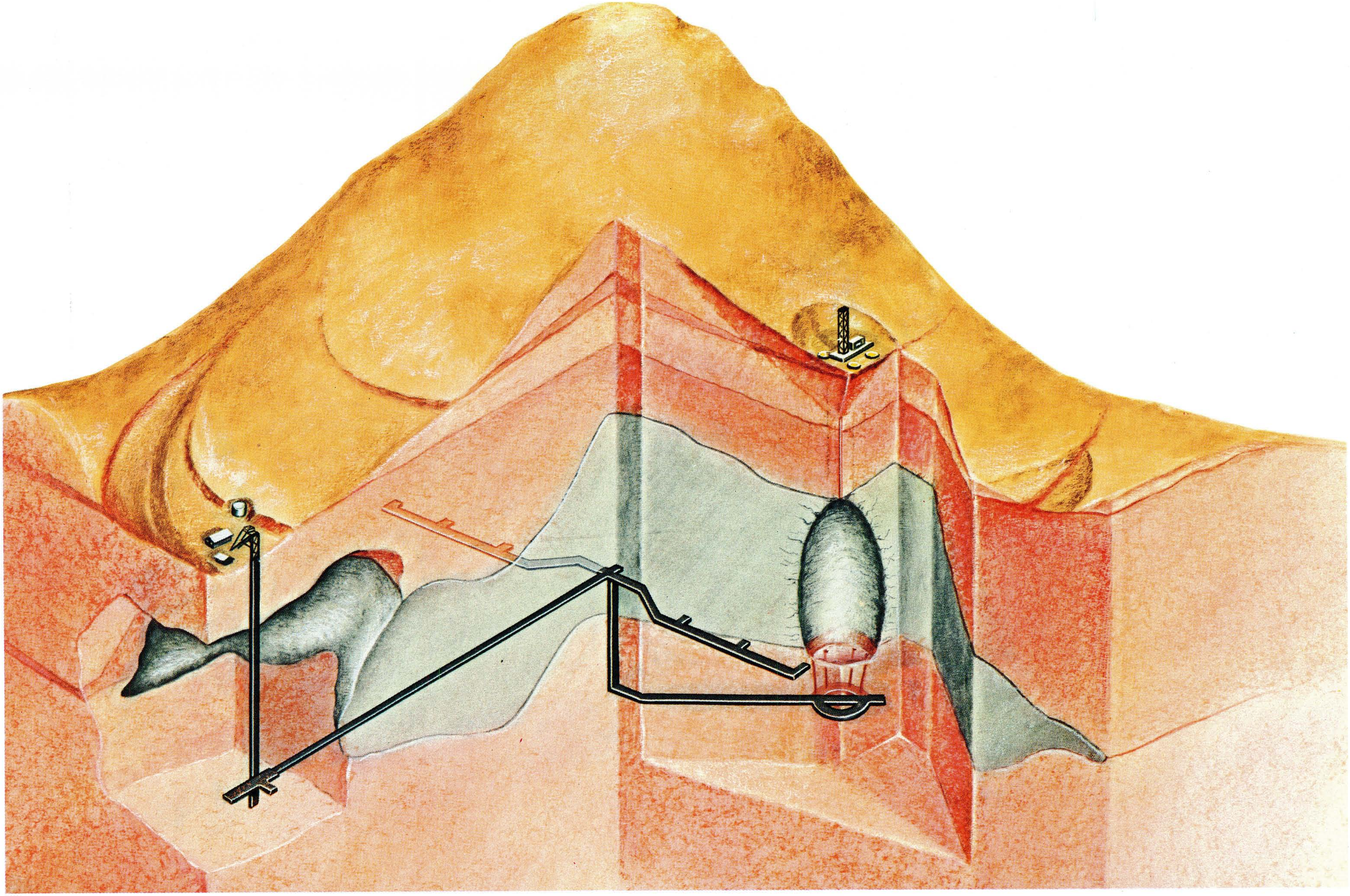
Topographic Map of Sloop Site Area
FIGURE 4



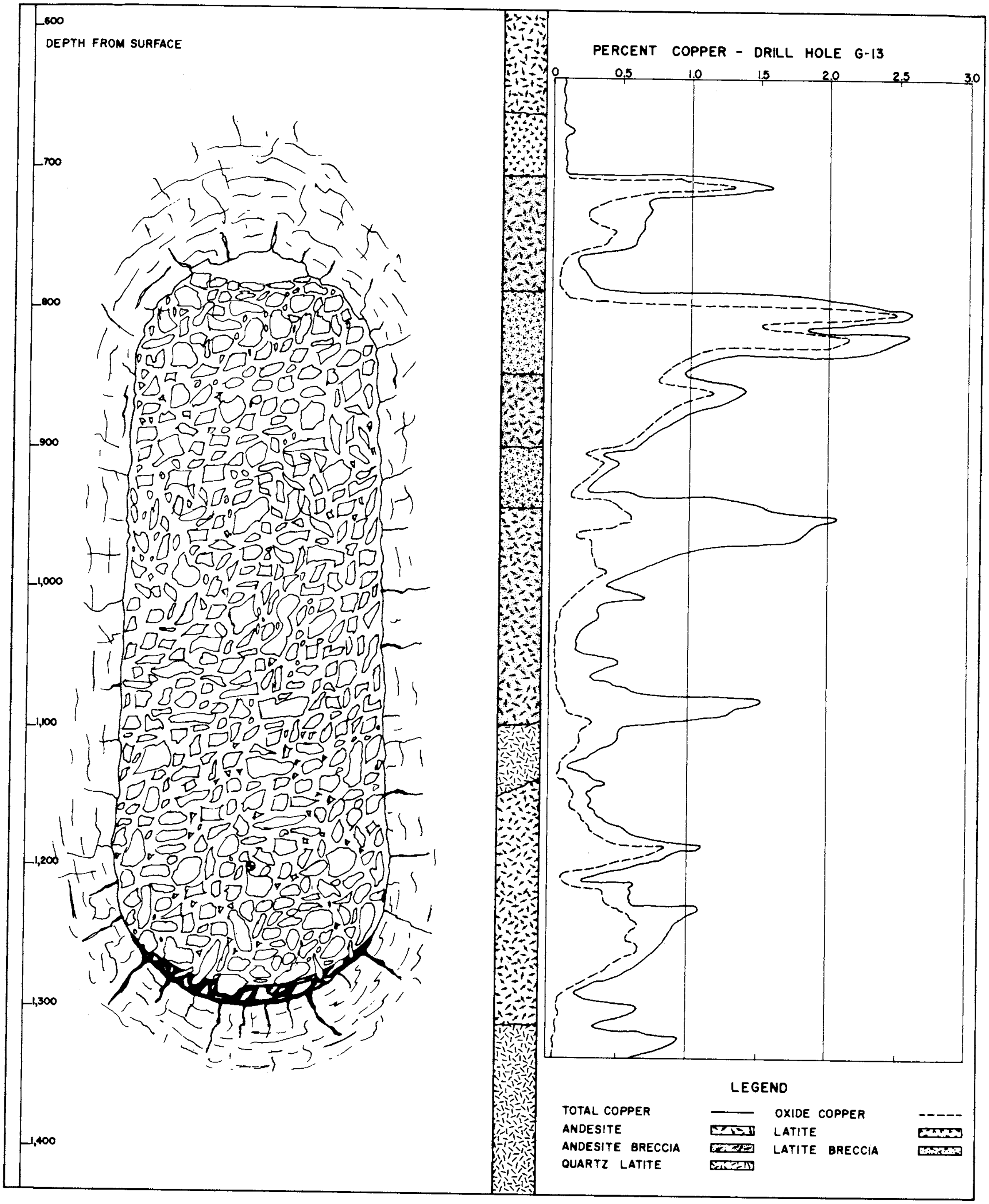
Safford Deposit — Sections
FIGURE 5



Ground Water Section
FIGURE 6



Schematic Drawing — Project Sloop Experiment
FIGURE 7



Log of Drill Hole G-13
FIGURE 8

Quantitative test results, including leaching rates, percent copper recovery, and operating costs, could be expected after leaching for a minimum of one year. Concurrently, the operating techniques for this process would be sufficiently developed to provide data for a realistic economic evaluation of a commercial fracturing-leaching process. After the test leaching has been completed, comprehensive sampling of the chimney and fractured zone would be conducted to evaluate the leaching recovery and the reaction of chimney material to leaching solutions.

The operation of the pilot leaching plant would probably produce a considerable amount of copper that could be made available for sale. However, because of the research nature of the experiment and the primary objectives of developing operational criteria for a commercial process, any prediction of the quantity of salable copper that might be produced would be conjectural.

A portion of the copper precipitates would be used for development studies to determine the most efficient process for refining the leached copper for marketing in a commercial scale operation. Solvent extraction methods, electrolysis of dissolved precipitates in strong acid solutions and conventional smelting followed by electro-refining methods would be investigated.

The experiment has been designed to include geologic, physical, chemical and metallurgical measurements. While there has been extensive experience with underground nuclear explosions, the leaching of a nuclear chimney of copper bearing rocks has never been attempted. The experiment has been designed with the flexibility to cope with changing technical considerations.

It must be emphasized that this project is basically experimental in nature, and that additional experiments may be necessary to develop the technique into commercial practice.

B. Operational Safety Program for the Experiment

The AEC's Nevada Operations Office, which is responsible for the conduct of all AEC nuclear detonations, would review the approved field program to insure conformity to the established safety criteria. It would assume responsibility for the on- and off-site safety of personnel and property. The Project Sloop experiment has been designed with full consideration for safety factors, namely for the possibilities of damage resulting from ground motion; venting of radioactive material to the atmosphere, either from gas seepage through the ground or from subsequent flushing of the explosion chimney; or radioactive material entering ground water. The procedures that would be followed to protect public health and safety for the experiment are similar to those used by the AEC for other contained nuclear detonations located both on and off the Nevada Test Site.

1. Ground Motion Effects

The ground motion resulting from an underground nuclear detonation can, if sufficiently intense, result in damage to nearby structures. The explosive yield and location for Project Sloop have been carefully selected to minimize the danger of any such possible damage. The intensity of the movement to be experienced at any point is a function of the following:

a. Energy yield of explosive.

b. Nature of rock in which explosive is emplaced.

c. Geologic characteristics of the path followed by the shock wave.

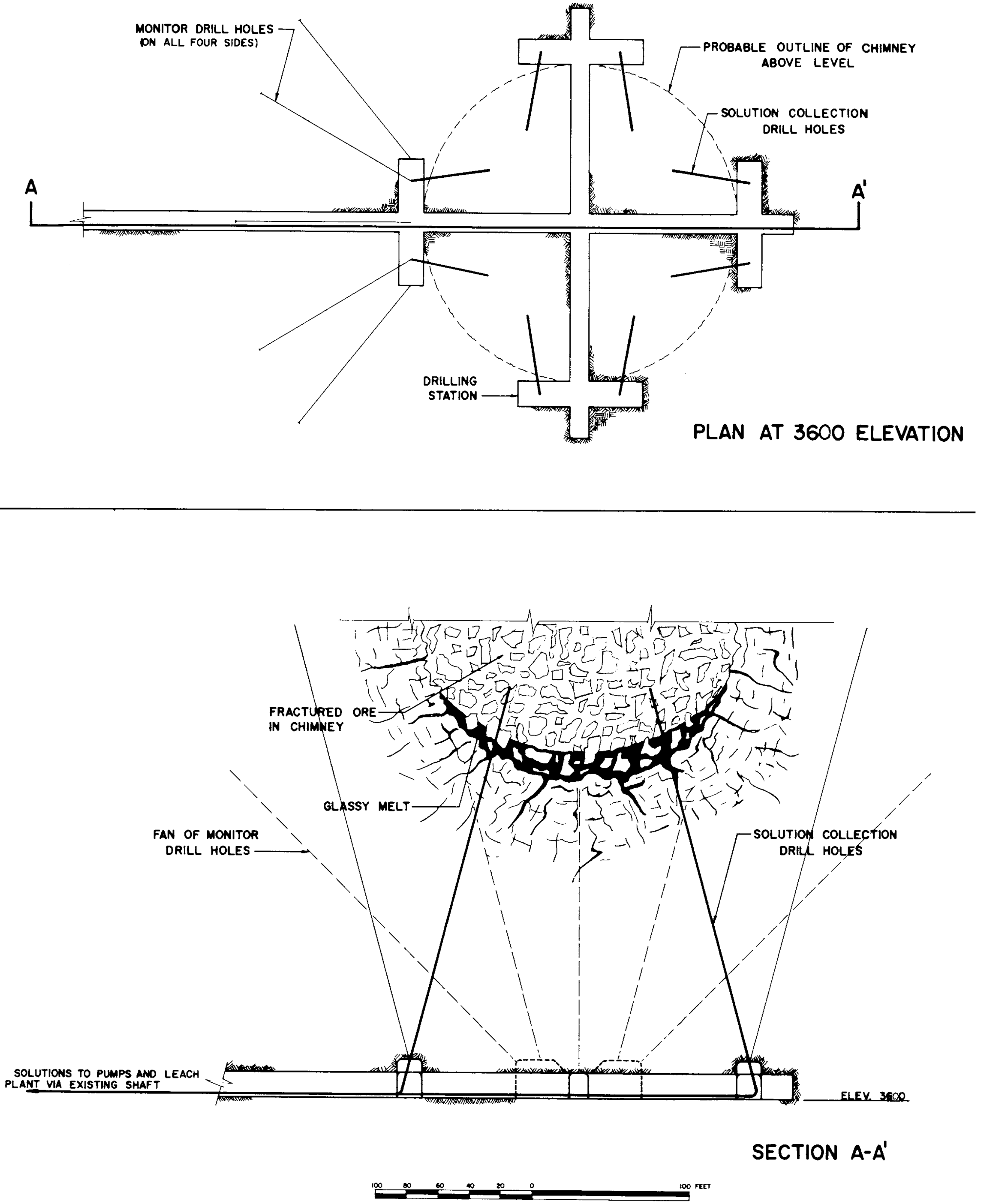
d. The nature of material upon which the structure subjected to the ground motion is constructed.

e. Distance of the structure from the shot point.

It is believed that none of the buildings in the communities surrounding the Project Sloop location would be structurally damaged or weakened. However, it is possible that some structures could receive minor damage consisting of hairline cracks in plaster and in concrete block walls. The effects of ground motion will be thoroughly studied during the pre-shot investigations.

2. Atmospheric Contamination

The proposed burial depth of the explosive is considerably greater than that which is normally required for full containment of an explosive at this yield. Based on AEC's experience with over 200 contained nuclear explosions, the release of any radioactivity to the atmosphere from the Sloop detonation, in amounts which could be hazardous, is considered remote. Although no venting is expected, full safety precautions would be developed and implemented to contend with any unexpected venting of radioactive material to the atmosphere. Such preparations involve the development of a hypothetical maximum credible release model from which meteorologists would prepare fallout pattern predictions. These predictions would be based on a study of the meteorology of the area and the detailed design of the nuclear emplacement. The time of detonation would be determined by favorable weather conditions so that any conceivable release of radioactivity could be restricted to an acceptable area. An investigation of the potential fallout area would be made by the U.S. Public Health Service



Underground Solution Collection Facilities

FIGURE 9

(USPHS) to determine if any hazard could result from accidental venting and to anticipate the precautions necessary to safeguard public health and safety. This would involve complete USPHS pre-shot surveys of human and livestock populations and distribution. The USPHS would also perform its customary pre- and post-shot radiological monitoring programs of the off-site area. This includes collection of air, water, milk and vegetation samples for analyses. The post-shot drilling and testing programs would remain under the control of the AEC as long as is necessary to protect the health and safety of both the public and project personnel. A monitoring program would be instituted during post-shot drilling to detect the presence of any radioactivity and to effect control measures if needed.

A public information program would be undertaken to acquaint state and local officials and the people in the area of the purpose and progress of the experiment, and of the public safety measures being developed.

3. Ground Water Contamination

Careful consideration has been given to the possibility of contamination of local ground water supplies by solutions escaping from the leach system. It is concluded that this is highly improbable, for the following reasons:

a. The rock formations in which the experiment is proposed are very impermeable, and resist transmission of water.
b. The deposit is dry. No ground water has ever been encountered in underground workings or in deep exploratory holes in the orebody (Figure 6).
c. Every effort will be made to prevent loss of fluids from the chimney area. An extensive system of drainage drifts and monitoring holes beneath and alongside the chimney will be constructed to assure this. In addition to safety considerations, this installation is required to recover all solutions for the experiment and to provide design criteria for a commercial collection system. Pre-shot investigations would determine, in greater detail, the existing hydrologic conditions that would influence the movement of underground water.

C. Project Management

Because of the different technologies involved and the legal requirements for control of nuclear explosives, the execution of the Sloop experiment would require the joint efforts of the Atomic Energy Commission and Kennecott Copper Corporation. The Atomic Energy Commission through its Nevada Operations Office would assume responsibility for public safety, explosive protection, and detonation. The AEC would also provide assurance that all phases of the nuclear operation would be conducted in accordance with AEC policies and procedures. The AEC would provide an on-site representative who would coordinate the activities of the AEC contractors, and monitor the progress of work to assure conformity with approved plans. The AEC would also provide for monitoring the post-shot activities with respect to radiological safety and possible release of contaminated material. The portions of the experiment dealing with site evaluation and confirmation, the nuclear detonation, and chimney environment measurements would be conducted under the overall technical direction of the Lawrence Radiation Laboratory.

Kennecott Copper Corporation would be primarily responsible for the leaching phase of the experiment* and would coordinate the leaching activities with the AEC to ensure radiological safety is maintained. Kennecott would direct the construction of the leaching facilities and provide personnel as required for the leaching and process recovery tests.

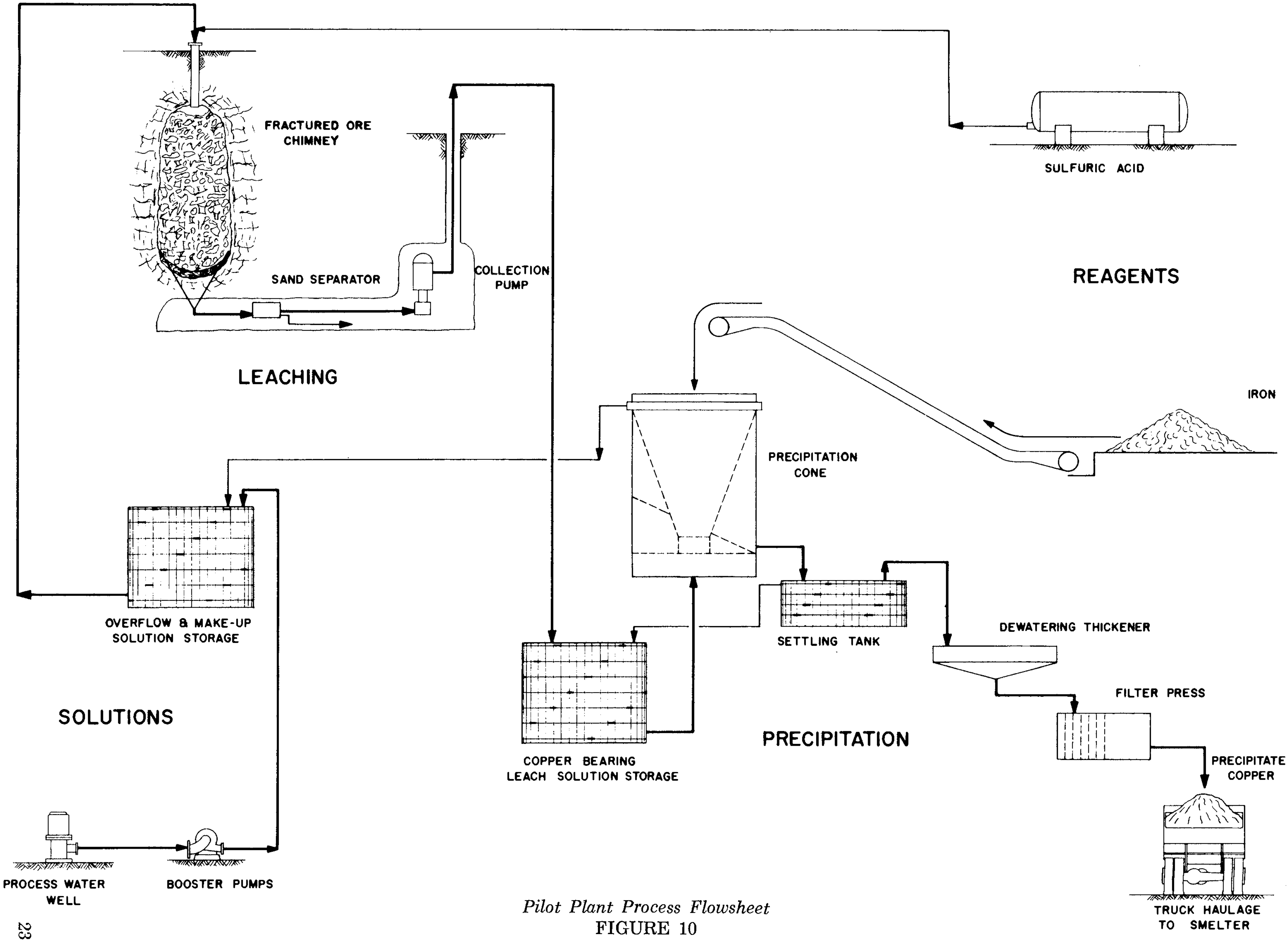
At the conclusion of the field test program, detailed reports would be published by Kennecott, the Bureau of Mines, the Atomic Energy Commission and Lawrence Radiation Laboratory to fully evaluate the feasibility of a commercial operation at Safford and to set up guidelines for the use of this technique on other suitable deposits.

D. Project Cost and Schedule

The preliminary estimate of the total cost of the experiment including operation of the leaching system for one year is $13,175,000. The major project costs are summarized in Table II.

A time schedule for the work to be performed in the project is given in Table III. It is estimated that nine months would be required from the authorization date until detonation of the explosive. In an additional nine months, after detonation and evaluation of the explosive effects, the leaching tests could begin. It is estimated that a minimum of one year of leaching would be required to accumulate sufficient data to evaluate the techniques. The overall project time from authorization to evaluation would approximate 30 months. Leaching might possibly be continued for a number of years, to obtain additional information.

* Phase III, page 24.



Pilot Plant Process Flowsheet
FIGURE 10

TABLE II

PROJECT SLOOP COST ESTIMATE

PHASE I

Field Start-Up and Initial Support Facilities
Pre-Shot Sampling Holes
Site Safety Studies

Total Phase I	$750,000

PHASE II

Project Start-Up and Support Facilities
Rehabilitation of Existing Workings
Scientific Programs and Explosive Diagnostics
Pre-Shot Instrument Holes
Emplacement Hole
Emplacement, Stemming
Operational Support
Communications
Post-Shot Drilling, Re-Entry and Testing
Miscellaneous Construction
Engineering and Inspection

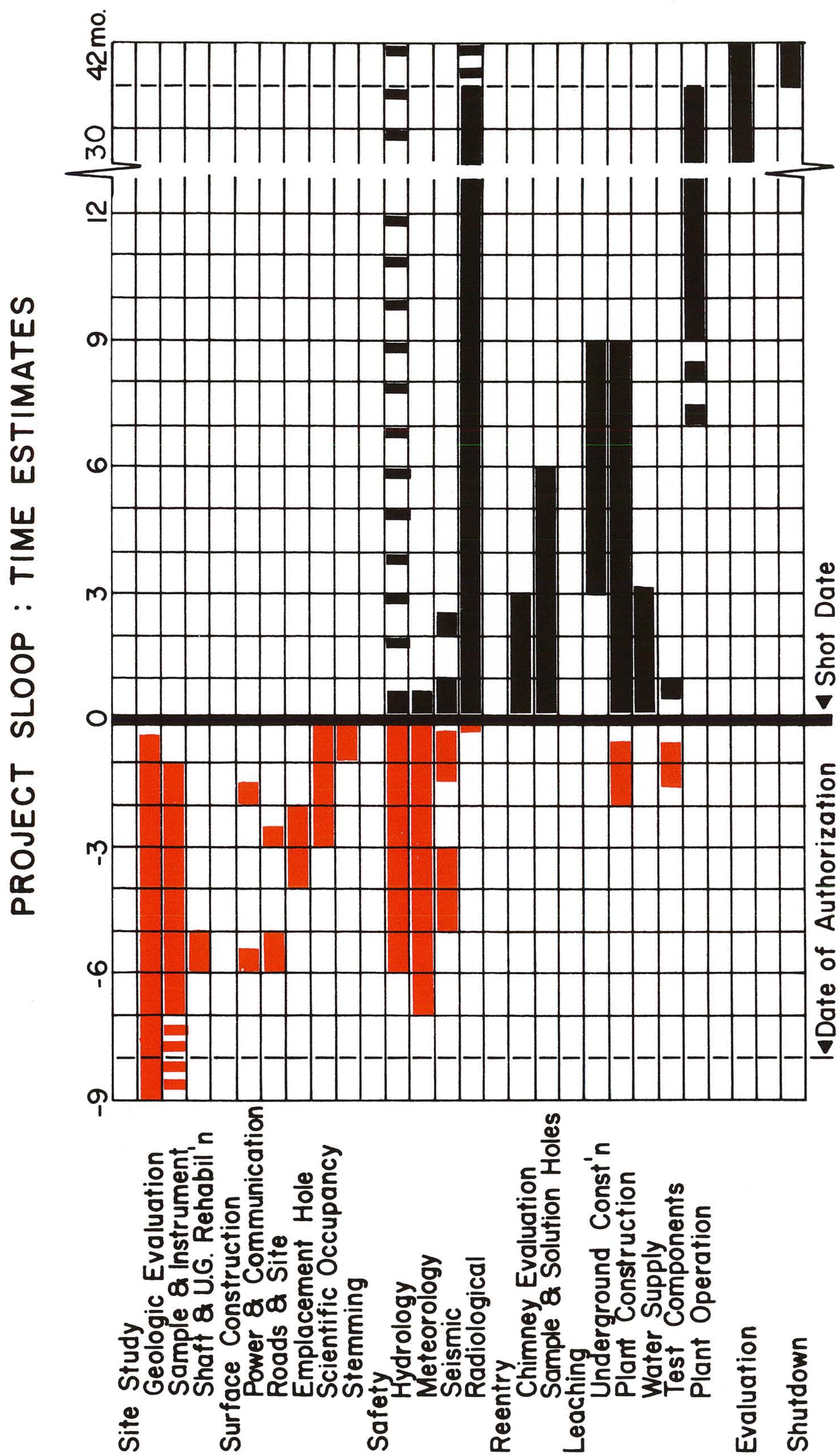
Total Phase II	$5,750,000

PHASE III

Underground Re-Entry and Rehabilitation
Leach Solution and Recovery System
Post-Shot Sample and Solution Input Holes
Underground Process Piping and Pumping System
Copper Precipitation Plant
Process Water Supply
Leach Plant Operating Costs — 1 Year
Public and Industrial Safety Monitoring
Project Evaluation

Total Phase III	$6,675,000
TOTAL COST — PROJECT SLOOP	$13,175,000

TABLE III
PROJECT SLOOP: TIME ESTIMATES



VII. ECONOMIC CONSIDERATIONS — COMMERCIAL SCALE IN-SITU OPERATION

Minerals in varying percentages make up the crust of the earth. Although the amount of each mineral in a particular rock may be small, the total amount that exists in the earth dwarfs the imagination. The distribution of minerals is not homogeneous as many past geologic processes have resulted in concentrations of specific minerals in percentages that are far higher than the average for the crust. The mineral industry recovers its material from these deposits, but these random concentrations are hard to locate and develop.

Discovery of a deposit is the first step, although this does not guarantee the development of a new mine into production. The development of a mineral deposit is, at the very least, a rigidly controlled economic venture. To warrant development, a deposit must be large enough, high enough in grade, and well enough located to be mined at a profit. The distinction between uneconomic mineralized material and economic ore is determined by the total costs involved in the operation. The ability of the copper industry to control these costs by constantly improving technology is mandatory if it is to sustain itself as a healthy and growing industry.

As man's use of copper increased beyond the limits of the accessible and easily recoverable deposits, the importance of cost controlling technology became enormous. The average grade of copper ore mined in the United States has declined from about 3 percent in 1880 to about 2 percent by 1910. In 1880 deposits of less than 3 percent would not have been considered to be economic ore for they could not produce a competitively priced product at the then current level of technological development.

Large-scale mining of low-grade ores is a development of the Twentieth Century. The potential of massive lower grade deposits was first released when D. C. Jackling developed concentration methods to treat this type of ore at the now famous open-pit mine at Bingham Canyon, Utah. Introduction of the flotation process in the 1920's improved mineral recoveries and permitted the economic processing of far lower-grade ores. This stimulated the development of the low-grade deposits of the Southwest which now account for the bulk of the United States copper production.

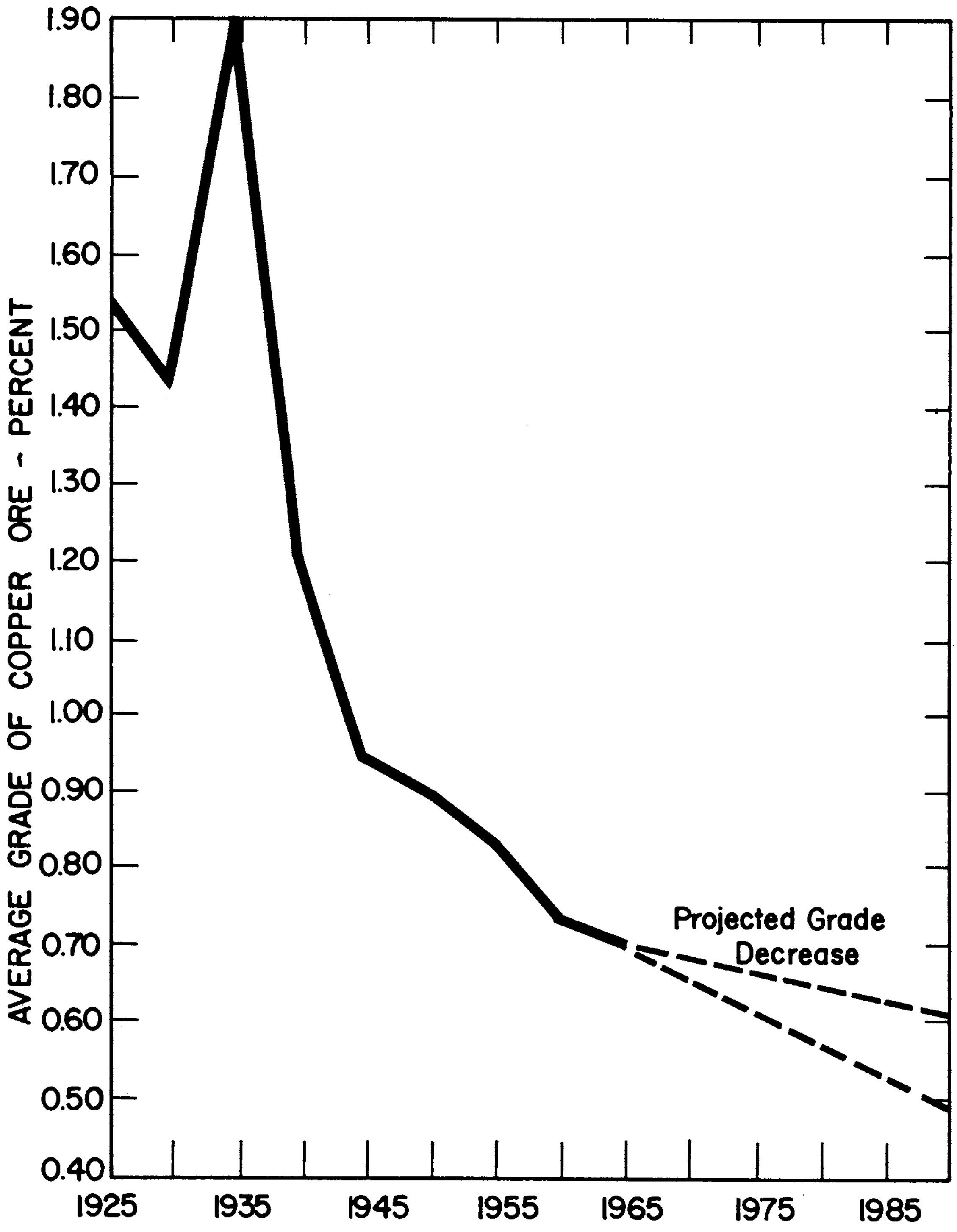
The result of these technological advancements permitted exploitation of lower-grade ores as the high-grade deposits became depleted. Average ore grades in the 1941-50 period declined to 1 percent and by 1960 this average was reduced to about 0.7 percent.

Today with the average of copper ores about 0.7 percent (14 pounds of copper in 1 ton of ore) and with this grade forecasted to decline further (Figure 11), the ability to competitively produce domestic copper in quantities to meet the projected demands will require even more accelerated improvements in the cost control of the present production methods and the development of new methods.

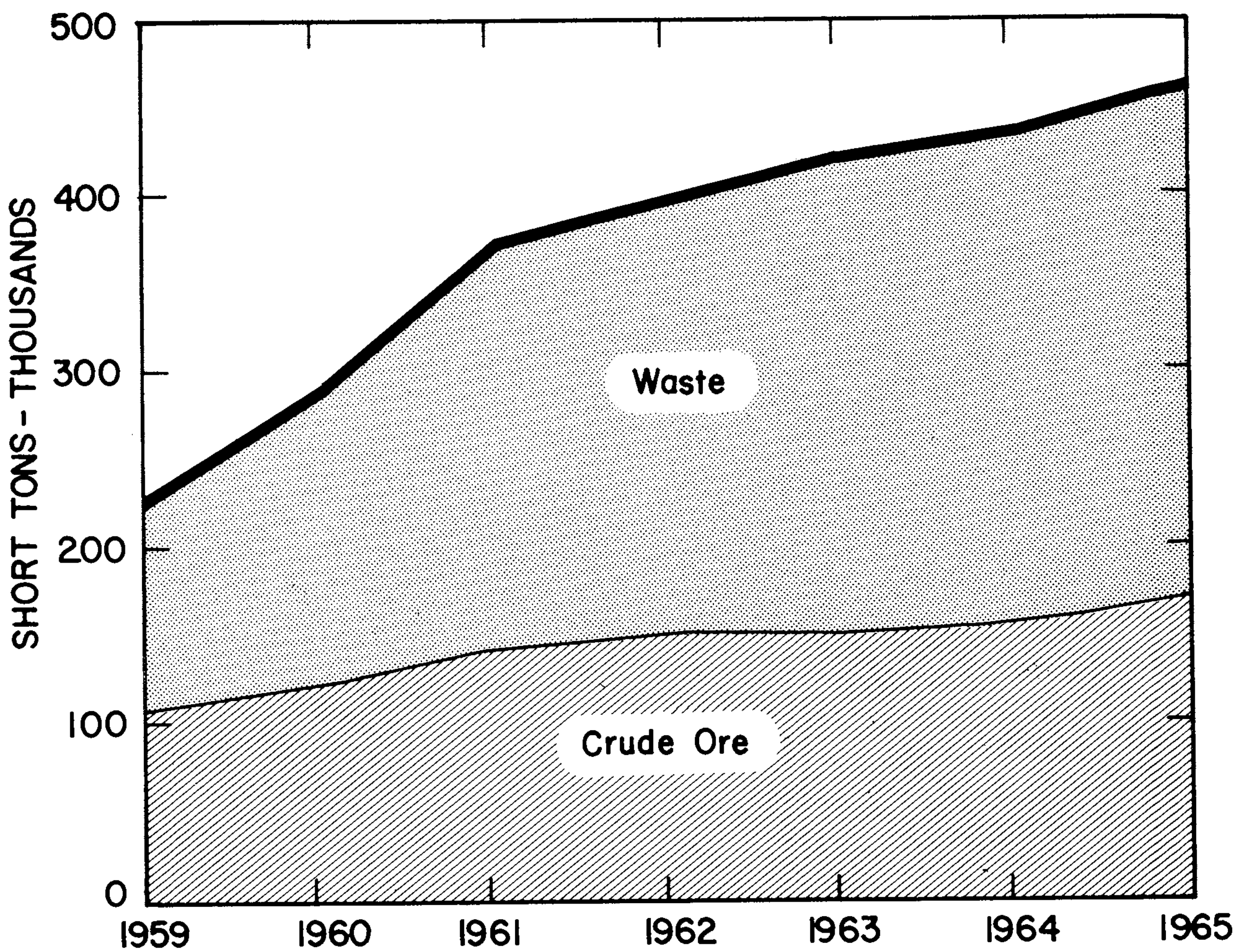
Despite the inevitable future improvement in exploration and conventional mining methods, the major problem of domestic operations will continue to be rising costs and depletion of higher-grade ores. In nearly all the available ores, the copper and by-product minerals occur in a very small proportion of the mass of rock that must be mined and processed to recover them. Figure 12 shows the increasing ratio of total material handled to crude ore obtained. Bulk handling of such low yield material is economic only under rigorously planned and supervised operations. Reliable determination of the size, configuration, mineral content, and rock properties of an ore body are necessary and costly prerequisites. Preparing an ore body for mining by open-pit or caving methods requires a large initial expenditure of both time and money. As the depth of underground mining increases, the hazards and cost multiply. In open-pit mining, the ratio of waste removal to ore extraction increases geometrically with depth. Concentration, like mining, has problems of efficiently handling bulk materials. Changes in the character of mineralization require adjustments of concentration practices and may affect reduction capacity. Reduction is cumbersome, costly, and energy-consuming.

The commercial application of in-situ methods of leaching metallurgically acceptable copper deposits, prepared by fracturing with nuclear explosives, involves a new technology and a whole new structure of costs. Potentially these costs could be significantly lower than the recovery and treatment costs for conventional mining of 0.4 to 0.7 percent ores. Physical excavation of waste and ores for metal recovery would not be required. In-place leaching methods would eliminate large and costly treatment facilities, involving complex processing in favor of smaller, less expensive facilities with a considerably simpler treatment process.

The Safford deposit presents a promising potential for developing a commercial scale in-situ leaching operation. The deposit contains both oxide and sulfide mineralization at an average grade typical of the projected future domestic ores. Detailed investigations of this deposit have been made which will significantly reduce the time and expenditures required to develop and prove the technique as a potential process for domestic low-grade ores.



Decline in recoverable copper from domestic ore
FIGURE 11



Material handled at Copper Mines
FIGURE 12

Preliminary economic analyses have been undertaken in order to predict the economic potential of a nuclear fracturing - in-situ leaching method in low-grade deposits similar to the proposed Safford test site. The potential production scale operation assumes that larger than test yield explosives, up to 100 kilotons, would be used to prepare a 240,000,000 ton leaching reserve averaging approximately 0.55 percent copper. Plant facilities and operating costs were conservatively estimated using present levels of labor, material and construction costs. The operation was sized to treat about 5,000,000 gallons of solutions and produce about 100 tons of marketable pure copper at the installation each operating day.

The analyses show that a commercial size fracturing-leaching recovery facility would be able to produce copper from lower-grade ores at today's cost levels that would be completely competitive with copper now being produced conventionally from higher-grade ores.

VIII. CONCLUSIONS & RECOMMENDATIONS

A. *Conclusions*:

The United States as well as the world demand for copper has been increasing at an accelerating rate over the past century. In order to assure adequate supplies of copper at reasonable prices to meet industrial and defense needs and help reduce the balance of payments deficit, the copper industry must continue to discover and develop copper deposits located in this country. This will require the utilization of lower-grade reserves by means of new and improved technology.

The nuclear fracturing and in-situ leaching method of copper recovery holds a promise of being a major breakthrough in the treatment of vast resources of lower-grade ores that are beyond the scope of present economical and technological conditions. The development of an operable process using this low-cost recovery method would allow the immediate exploitation of large, marginal low-grade deposits at production costs that would be completely competitive with the copper now being produced conventionally from higher-grade ores. Successful development of such a mining process would increase the recoverable ore reserves from the available domestic resources for the benefit of the Nation's current and future metal requirements.

The present technology of fragmenting and fracturing hard rock with nuclear explosives is well-developed. The technology of leaching masses of broken copper ore is an old art that is rapidly being perfected as a major method for copper recovery. This feasibility study indicates that these two technologies can be combined into an economically attractive industrial process.

An experiment is needed to provide further data for development of this concept and to assess its technical and economic feasibility. The experiment suggested in this study report should be capable of execution without compromising public safety and should provide the data needed to meet the technical objectives set forth in the study. It should also provide the information to evaluate the economic potential of this new metal recovery technique.

It should be noted, however, that this concept is still in an experimental and developmental stage. While this study finds no important reasons which would render it infeasible, it should be recognized that additional experiments may be necessary before this technique could be developed into a general commercial recovery practice.

B. *Recommendation*:

It is recommended that the site investigations proposed for Project Sloop in this report be conducted to confirm the site assumptions upon which the report is based, and if the site is found to be acceptable, then to proceed with the required steps leading to a suitable nuclear project for copper leaching.

APPENDIX A

CONCEPT FOR PROJECT SLOOP:

A Copper Leaching Experiment
Lawrence Radiation Laboratory

May 4, 1967

I. SUMMARY

This Appendix sets forth the concept for the nuclear explosion portion of Sloop. It is proposed that a 20-kt nuclear explosive be detonated at a depth of about 1,200 ft. in the Safford (Arizona) copper deposit of the Kennecott Copper Corporation (KCC). The purpose of the experiment is to determine whether copper can be commercially produced from the rubble pile created by an underground nuclear explosion. The principal technical program associated with the detonation phase includes emplacement and detonation of the explosive, shock wave and seismic measurements, as well as pre- and post-shot investigations related to explosion-induced fracturing. The safety program would include on- and off-site radiological safety, and seismic safety.

The experiment has been divided into three phases: I. Site investigation and confirmation; II. pre-shot construction and preparation, the nuclear detonation, and post-shot drilling to define the chimney characteristics; and III. construction and operation of an in-situ copper leaching and recovery plant. The objectives of the experiment can be achieved only by completion of all three phases. Phase I and II would be executed by the Atomic Energy Commission under the technical direction of the Lawrence Radiation Laboratory (LRL) with technical advice from the U.S. Bureau of Mines (USBM) and the KCC. It is estimated that the execution of Phases I and II would require about 15 months from the date of an agreement and would cost about $6.5 million exclusive of the cost of ground motion considerations. This concept assumes that KCC would contribute a number of specific items of work; however, the above cost estimate was proposed assuming the AEC would perform all indicated work.

Phase III would be designed and conducted by KCC with the advice and participation of the AEC, LRL, and the USBM.

II. BACKGROUND

This experiment is designed to answer several fundamental questions which have arisen as a result of a joint feasibility study (Sloop) conducted by AEC, USBM, and KCC. From these studies, the potential for use of nuclear explosives in copper leaching appears to be very attractive. However, without this experiment, it is improbable that a definite conclusion can be reached.

III. OBJECTIVES

A copper leaching experiment would include three basic objectives:

A. To determine what fraction of the contained copper can be recovered by leaching a nuclear explosion chimney;
B. To investigate how radionuclides generated by the explosion behave during the leaching process and what measures, if any, are necessary to provide for radiation control and decontamination of the copper; and
C. To test and demonstrate the ability to predict the physical effects of a nuclear explosion in a new medium and at a new location.

Attainment of these objectives would provide information necessary to extrapolate a large-yield or multiple-detonation applications necessary in order to prove the general potential of this technology, although the feasibility of leaching individual orebodies would vary from site to site.

IV. SITE

The deposit is located approximately 9 miles northeast of Safford, Arizona (see Figure 1). It occurs within volcanic andesite country rock and is overlain by 500 to 1,300 ft. of andesite and basalt volcanic rocks. About 900 million tons are reported to assay greater than 0.4% copper. The upper portion of the mineralized zone (average about 400 ft. thick) contains secondary (oxidized) copper minerals with some enrichment. The lower portion contains primary copper sulfides and is known to extend to a depth of more than 2,000 ft. below the top of the 0.4% copper zone. Between the upper and lower portions, a zone of mixed mineralogy averaging about 200 ft. thick contains both oxidized and primáry sulfide copper minerals (see Figure 2). The entire deposit is in very dry, relatively hard, brittle rock. Fracture frequency is between 4 and 7 per foot. The majority of the copper mineralization has occurred along the fractures, and cannot be economically recovered with conventional mining methods. The upper oxidized portion is known to be amenable to leaching.

V. DESCRIPTION OF THE EXPERIMENT

A. Pre-Shot Program

Four pre-shot holes, in addition to the emplacement hole would be drilled to 200 ft. below shot depth in the vicinity of the shot point to provide an accurate measurement of the amount of copper present and the detailed nature of the deposit around the detonation point. Cores and geophysical logs would be obtained to make chemical and physical property measurement. Bore-hole photography and drill stem pressurization tests would be conducted to determine in-situ fracture distribution and permeability. Additional studies by the AEC would be conducted to obtain data for prediction of structural damage and meteorology.

B. Explosive, Emplacement and Detonation

A yield of about 20 kilotons is proposed for this site. The proximity of a sizable town (population 5,000) at a range of approximately 15 km (9 miles) restricts the yield of a first experiment to about the proposed level. The experiment would be conducted at a depth of about 1,200 ft. below the ground surface near the Kennecott exploration hole G-13 in the northern half, Section 8, Township 6 South, Range 27 East of Graham County, Arizona. It is planned to emplace by means of an uncased drill hole approximately 20 inches in diameter with surface collar conductor casing as required. It is not planned to re-enter the emplacement hole post-shot. Stemming would be accomplished by grout plugs and pea gravel. A nearby existing shaft would be stemmed for approximately 50 ft. with local surface material and 50 ft. of sand, charcoal, and asphalt. All drill holes within 1,000 ft. of the shot point would also be stemmed.

Measurements would be made to confirm the performance of the nuclear explosive. Physical effects measurements would be made in the emplacement hole and in one satellite hole (see Figures 3 and 4). Mine workings and the ground surface in the general area of the shot would be instrumented for the earth motion. Seismic data would be recorded at various ranges, particularly near centers of population.

C. Predicted Effects

The cavity radius and chimney height are predicted to be about 100 ft. and 440 ft. respectively. Shot-induced increases in fracture permeability are expected to extend to between 250 and 375 ft. beyond the chimney edge. The chimney itself would contain about 1.3 million tons of fragmented rock, containing more than 8 million pounds of copper (0.4% minimum grade assumed). The close-in surface motion expected is indicated in Figure 5. The anticipated long-range surface motion, as a function of distance, is shown in Figure 6 for structures located on hard rock or alluvium. It is expected that there would be no radioactivity vented. A more detailed discussion of the safety hazards is given in Section VI of this Appendix.

D. Post-Shot Studies

After the detonation, an 8¾ inch vertical hole, S-7, will be drilled near the emplacement hole. This hole would enter the apical void at the top of the chimney and be used for defining characteristics of the chimney and for leaching studies in Phase III (see Figures 3 and 4).

Two additional post-shot holes, S-8 and S-9, would be drilled to 1,400 ft. in areas immediately outside the expected chimney edge (see Figure 3). Two whipstock holes would be drilled from each of these last two holes so as to intersect the chimney-edge and cavity bottom (see Figure 4).

Samples of the atmosphere and a complete set of geophysical logs, cores, downhole photography and downhole TV will be taken in all holes. Chimney volume and fracture permeability will be studied by pumping compressed air into one of the holes intersecting the chimney. Data from the logs and samples, photography and TV would provide an assessment of the distribution of heat energy and radioactivity, the chimney particle size distribution and associated permeability in the fractured zone.

The above preliminary assessment would conclude the AEC's responsibility in Phase II. To proceed to Phase III, a method for introducing leach solutions onto the broken ore would be developed and a copper recovery plant would be constructed. Detailed design of the leaching system will be made at a later date, but it is expected that the design and construction of the system would be the responsibility of the KCC, with the cooperation of the AEC and USBM. The existing shaft would probably be rehabilitated, the drift extended, and other underground development undertaken, as indicated in Figure 4. Solutions would be injected into the upper region of the chimney and recovered in holes into or near the bottom of the chimney. The solution would be passed through a copper recovery plant and re-injected into the top of the chimney. While this important phase is proceeding, it would be necessary to monitor all product and waste streams and equipment for the levels of specific radionuclides. Periodically, collected samples would be analyzed for about 20 radioactive species for about a year, or longer if required.

VI. SAFETY CONSIDERATIONS

A. Dynamic Venting

The scaled depth of burial proposed for this experiment is about 400 ft./kt$^{1/3}$, which is greater than that which is normally deemed to be required for safety from the standpoint of containment. The probability of a stemming failure would appear to be extremely small; however, the possibility of some minor venting cannot be ruled out. Because of the competence of the overlying formations, it has been estimated that, in the worst credible case, no more than about 5 x 10^7 curies (at one minute) could be released through a fissure and be injected into the atmosphere. In such an eventuality, the predominant nuclides in the radioactive cloud would be Kr, Xe, I, and their decay products. The distribution and intensity of this fallout can be controlled by detonating the explosive under specified meteorological conditions. However, even under adverse meteorological conditions, the radiation field due to fallout would be about 5mR/hr (milliroentgen per hour) one hour after detonation ten miles downwind from the detonation site. At this range, levels of I^{131} in milk under these conditions might reach 2,000 picocuries*/liter, assuming dry deposition. Hot spot formation or deposition during rainfall could possibly increase the I^{131} in milk by two orders of magnitude.

It is the judgment of LRL that in no case will iodine levels exceed values which, with proper operational control and monitoring, could lead to excessive exposure to individuals in the public. In making this judgment, radiation protection guidance published by the Federal Radiation Council is assumed to apply to projects such as Sloop.

B. Ground Water

The deepest exploratory holes in the area, 3,000 ft. deep, are dry. Therefore, the radioactivity from this detonation is not expected to contact any ground water.

C. Seismic

Figures 5 and 6 indicate the expected peak velocities as a function of distance from the shot point. A peak surface velocity of 5 to 10 cm/sec has been considered threshold by the USBM for damage to residential structures.

D. Monitoring for Contamination

In addition to monitoring the nearest local ground water after the shot and during subsequent leaching, monitoring of the leach circuit and copper is anticipated, as described later.

E. Distribution for Radioactivity During Leaching Operations

The primary purpose of Sloop is to demonstrate that marketable copper can be produced from the in-situ leaching of a nuclear chimney in low-grade ore.

The only long-lived soluble fission products which may interfere are: Cs^{137}, RU^{106}, Zr-Nb^{95}, Ce^{144}, Ce^{141}, Y^{91}, Pm^{147}, Sr^{90}, and Sr^{89}. Based on past experience at the Nevada Test Site, almost all are trapped in an essentially-insoluble glassy matrix near the bottom of the chimney. Less than 5% of the total activity is solubilized in normal leaching of the glass at pH 1.5 to 2.0. Ce^{141}, Sr^{90}, and Cs^{137}, however, have gaeeous precursors and $Ru^{103\text{-}106}$ is a volatile compound that can be deposited on readily-accessible broken rock at considerable distances from the melt zone. These four, particularly the Sr, are more readily leachable from the surfaces of the chimney rubble, and in laboratory experiments have constituted the bulk of the activity in the first increment of solution through the leach bed. Ce and Ru are about ten times more soluble at a pH of 1.5 than at 3.1.

Studies by ORNL on the neutron induced activities in reactor-irradiated Safford ore indicated that Sc and Fe are significant at early times, but Co, Zr and Se are most important later.

A series of recent laboratory experiments at Oak Ridge and LRL have indicated that Cs, Zr-Nb, and Ag in the leaching solution are quickly adsorbed by the clays and rock minerals. Ce and Y stayed in the leaching solutions. Strontium adsorption ranged from 10 to 70%, depending on pH. For Ru, less than 5% was retained in the ore at pH 2, 40% at pH 3, and 95% at pH 4. In studies of copper reduction from the solutions, no isotopes except Ru and Zr-Nb were precipitated with the cement copper. Over 50% of the soluble Ru followed the copper. Oak Ridge tests determined that 20% of the Zr-Nb also followed the copper.

Direct smelting of the Ru-contaminated

* A picocurie (PiC) is 10-12 curies.

cement copper by ORNL showed that all the Ru in the cement copper appeared in the blister copper; however, electrolytic refining gave a relatively pure copper cathode. Sixty-six percent of the Ru stayed in the electrolyte, 33% went to the mud, and only 1% followed the copper. Of the total induced activity, only 5% went into solution and only 6% of this soluble fraction, principally Zr and Se, ended up with the cement copper and these dropped out in the slag during the smelting.

If the neutrons from a 20-kt explosion produced the only tritium activity, the resulting 1 nanocurie* of tritium per gram of rubble, produced from the 10 ppm of lithium in the ore, would be one of the most abundant radionuclides in the chimney. However, in laboratory tests it was possible to flush out 95% of the tritium in a small volume, piston-displacement of solution which contained only 5% of the copper. It cannot be reduced in concentration by ion exchange. No tritium follows the cement copper.

If electrolytic refining is not desirable, liquid ion exchange treatment would remove the Cu and leave the residual Ru in the stripped solutions. Treatment with various filter materials such as copper beads or charcoal would not affect the Ru concentration. Additional studies would be conducted; however, it is already apparent that radioactive contamination would not materially complicate conventional copper recovery processes and that the product should be commercially pure.

VII. TIME AND COST ESTIMATES

From the time a formal approval to proceed is granted, approximately 15 months would be needed to complete the detonation and make preliminary evacuations of the explosive effects. The leaching studies are expected to take between one and three years. A bar chart of major activities is shown in Figure 7.

Conceptual costs of the experiment are outlined in Table II. No provision for damage claims is included in the budget estimate.

VIII. CONCLUSION

LRL believes that execution of Phase I and II of the proposed experiment would provide the technical information needed to assess copper leaching in a nuclear chimney in the Safford Deposit and provide sufficient information to make preliminary extrapolations to other copper mineral deposits.

On the basis of information presently available, it is the opinion of the AEC's Nevada Operations Office that the explosion portion should be capable of execution safely and within the funds tentatively identified for Phase I and II in Table 1, subject to proposed field work confirming the present predictions.

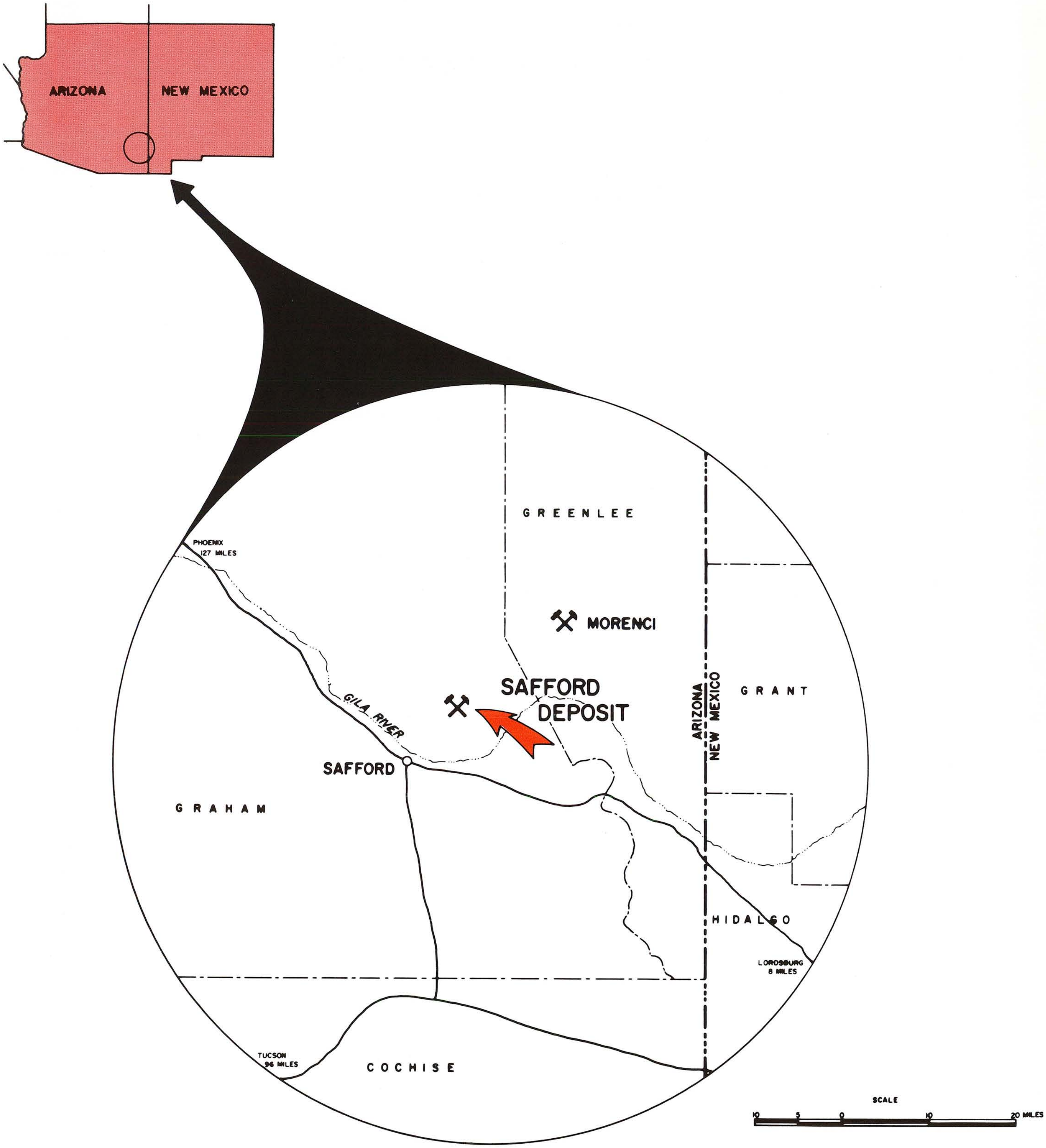
It is recommended that this experiment be executed, providing the site proves to have the characteristics assumed. It must be recognized that the time, cost and safety analyses have been prepared without field survey and are, therefore, subject to revision.

* A nanocurie (nCi) is 10^{-9} curies.

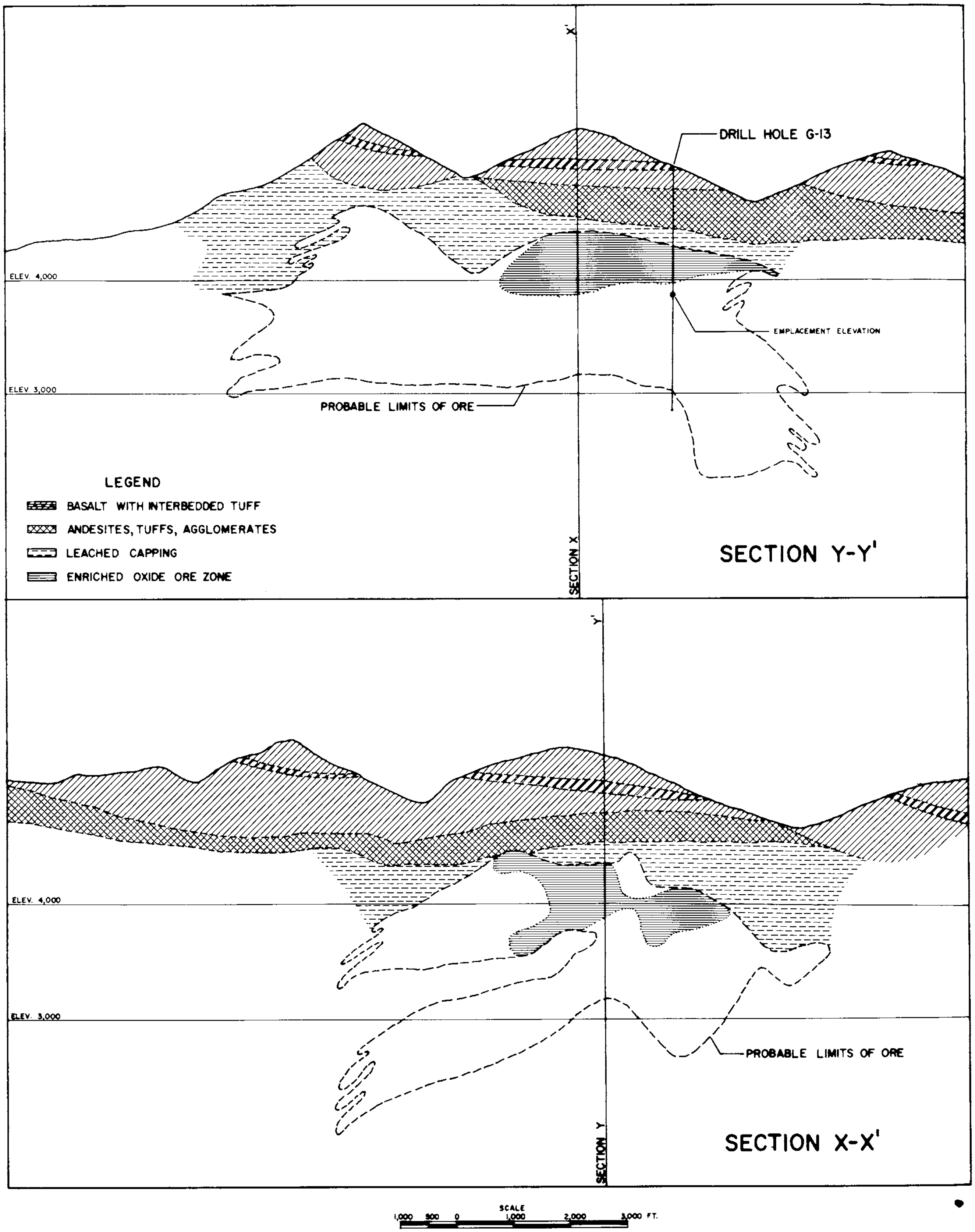
TABLE I

PROJECT SLOOP COST ESTIMATE

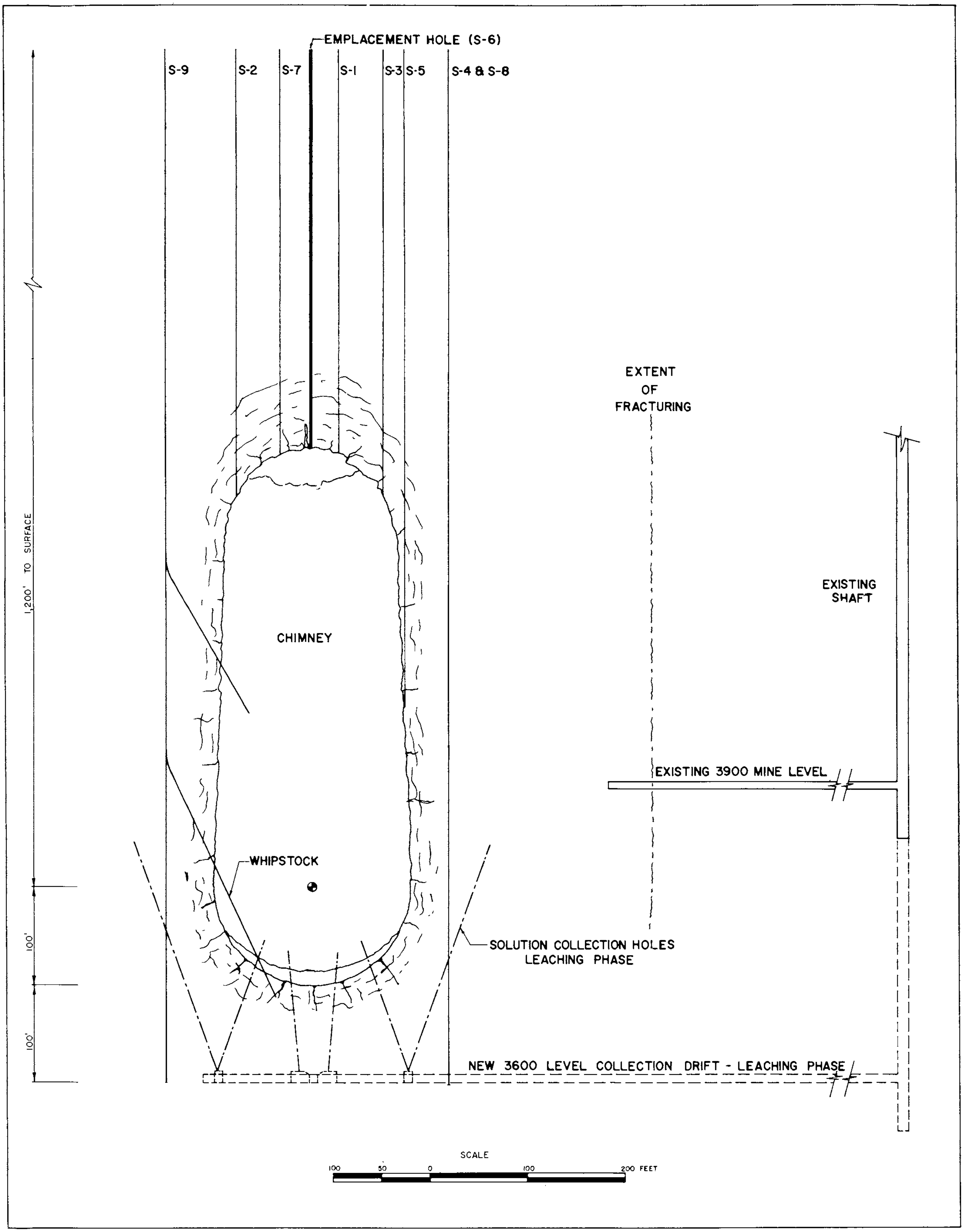
PHASE I	
Field Start-Up and Initial Support Facilities	
Pre-Shot Sampling Holes	
Site Safety Studies	
Total Phase I	$750,000
PHASE II	
Project Start-up and Support Facilities	
Rehabilitation of Existing Workings	
Scientific Programs and Explosive Diagnostics	
Pre-Shot Instrument Holes	
Emplacement Hole	
Emplacement, Stemming	
Operational Support	
Communications	
Post-Shot Drilling, Re-Entry and Testing	
Miscellaneous Construction	
Engineering and Inspection	
Total Phase II	$5,750,000
PHASE III	
Underground Re-Entry and Rehabilitation	
Leach Solution and Recovery System	
Post-Shot Sample and Solution Input Holes	
Underground Process Piping and Pumping System	
Copper Precipitation Plant	
Process Water Supply	
Leach Plant Operating Costs — 1 Year	
Public and Industrial Safety Monitoring	
Project Evaluation	
Total Phase III	$6,675,000
TOTAL COST — PROJECT SLOOP	$13,175,000



Location Map, Project Sloop
FIGURE 1



Safford Deposit — Sections
FIGURE 2



Elevation — Test Site Area
FIGURE 3

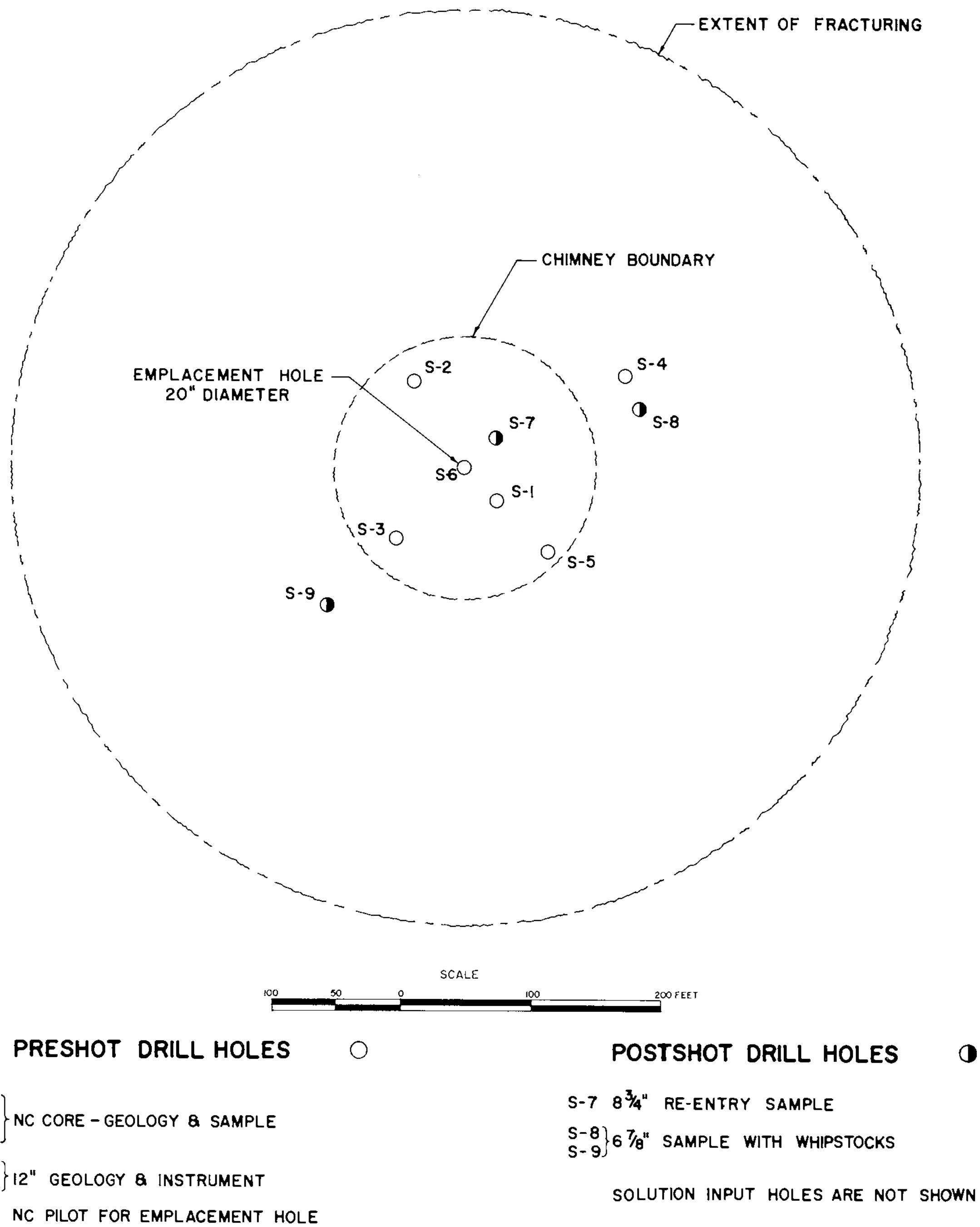
SUMMARY OF DRILL HOLES

Pre-Shot:
- Two — 12″ to 1,400 ft.
- Three — NC (= 4.7″) to 1,400 ft.
- One — 20″ emplacement hole to 1,280 ft.*

Post-Shot:
- One — 8¾″ diameter post-shot chimney re-entry hole.
- Two — 8″ to 1,400 ft.

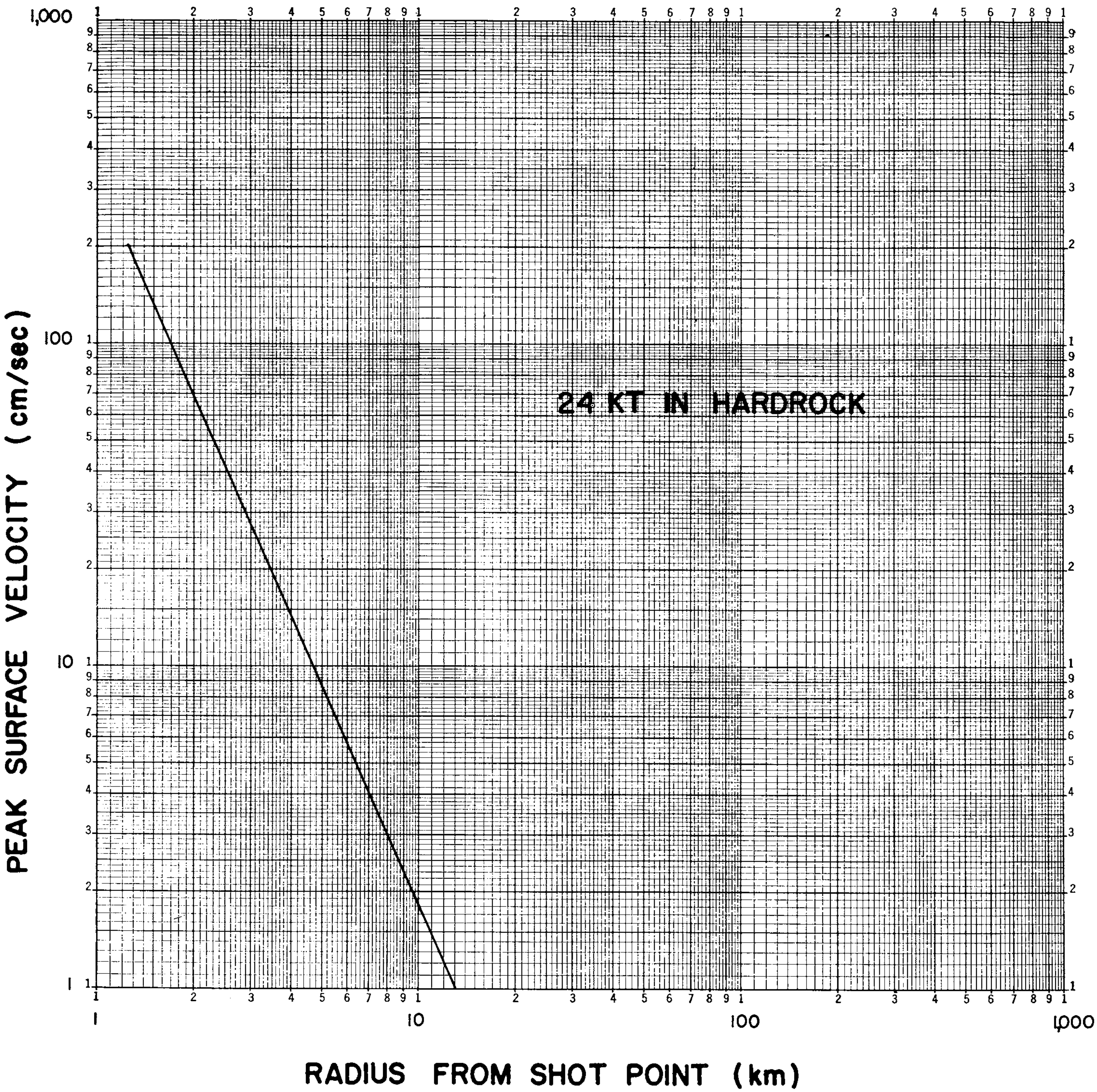
Leaching:
- Three — 6″ to about 800 ft. (may use the above post-shot holes).

* If the exploratory hole proves the rock unsuitable for an uncased emplacement hole, it will be drilled at 24″ with a standard 20″ casing.

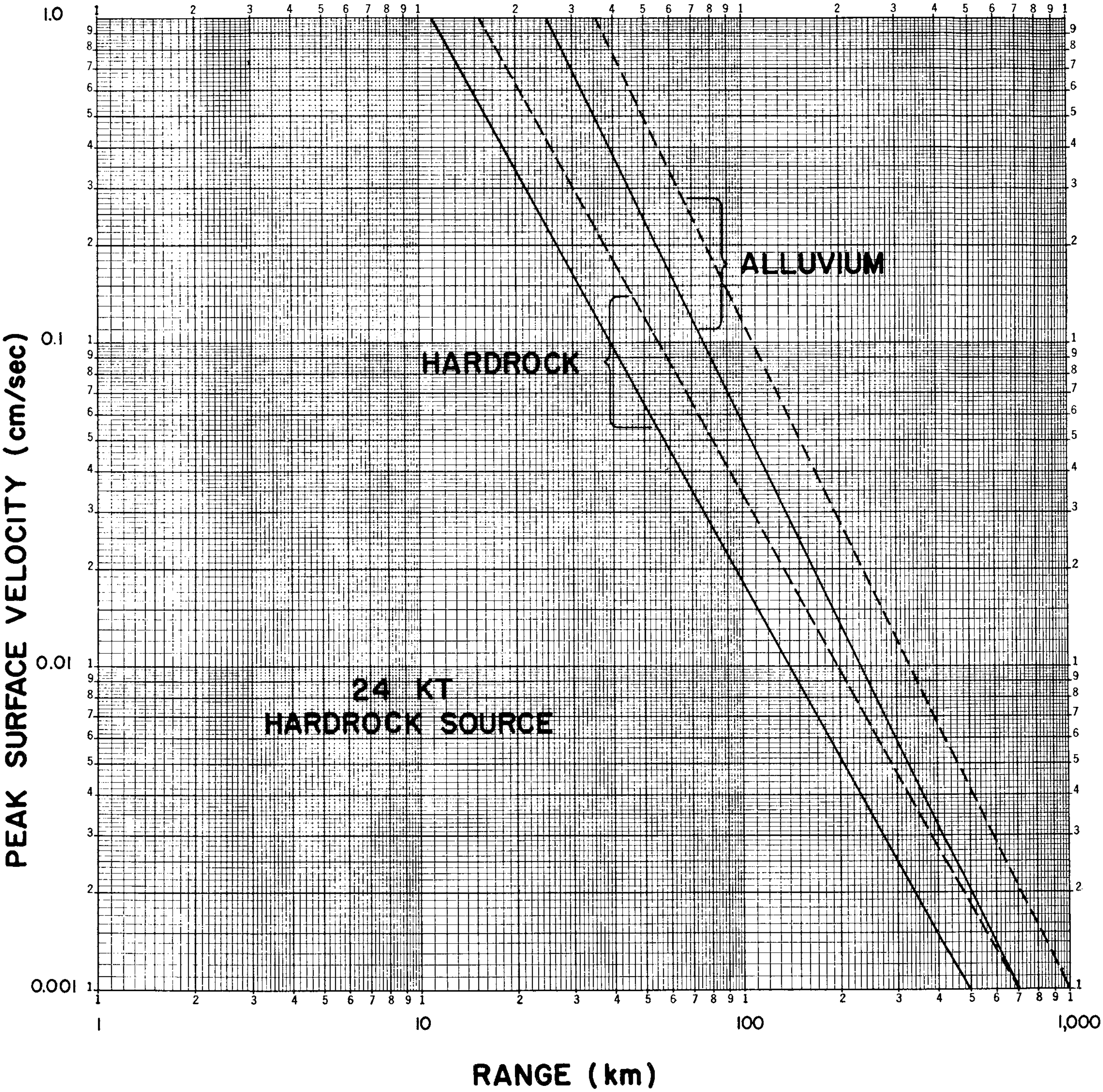


Drill Hole Plan — Test Site Area

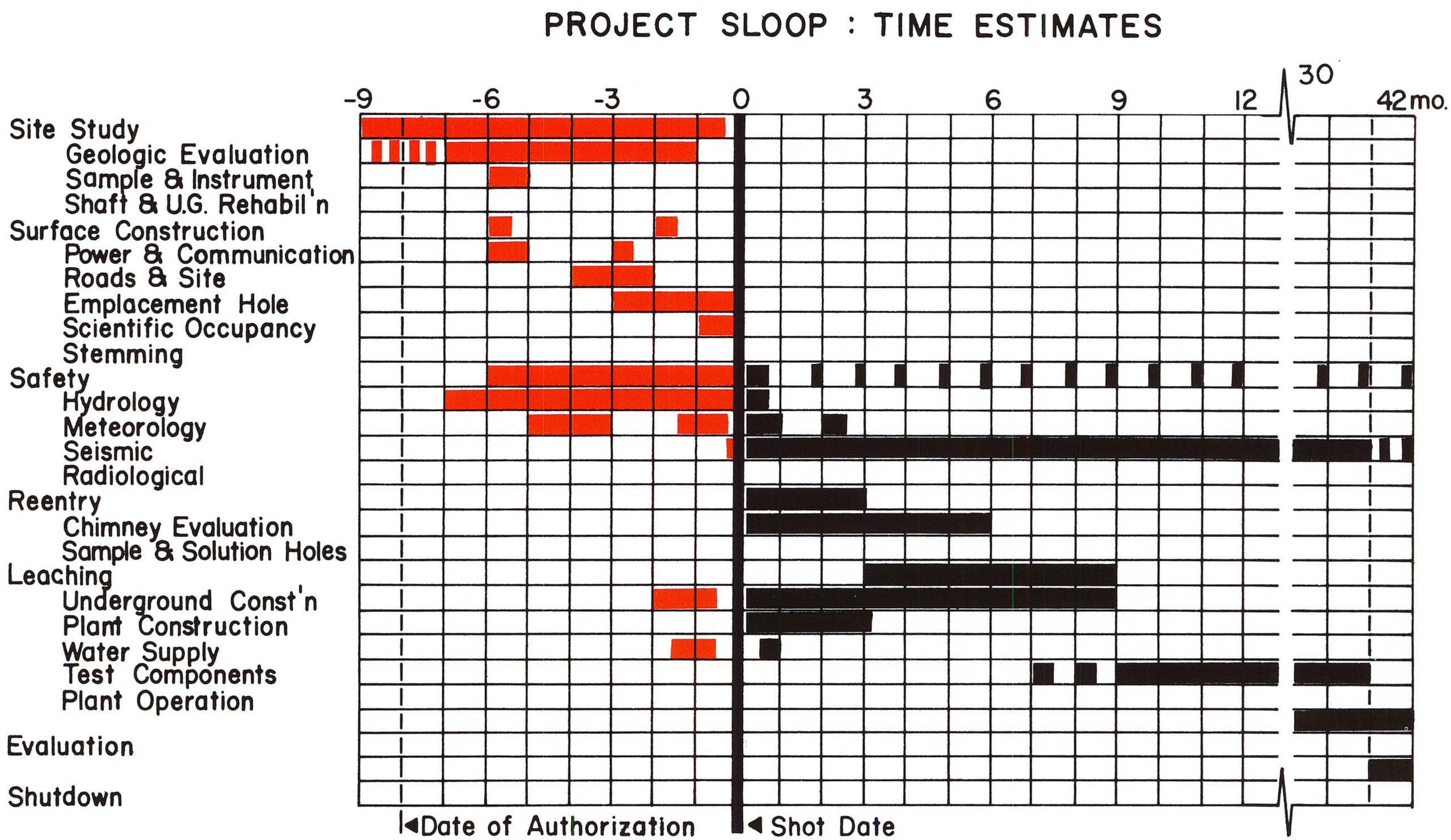
FIGURE 4



Predicted Short-Range Surface Motion
FIGURE 5



Predicted Long-Range Surface Motion
FIGURE 6



Project Sloop — Time Estimate
FIGURE 7

APPENDIX B

POTENTIAL PROBLEMS DUE TO RADIOACTIVE CONTAMINANTS IN TREATING NUCLEAR-BROKEN COPPER ORE

by

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I. Radionuclides Present

The amounts of the individual fission products and tritium produced by a detonation of a given yield depend, of course, on the type of device used. It has been assumed in investigations that most of the energy would be derived from fusion.

At 8 or 10 months after a 20 kt shot, the tritium activity would be much higher than the total fission product activities. In addition, radionuclides formed by neutron activation of the ore surrounding the explosive would be present. The amounts of these radionuclides formed is dependent on the chemical composition of the copper ore and certain conditions of the experiment. Irradiation of Safford copper ore in the Oak Ridge Research Reactor indicated that Sc^{46}, Co^{60}, Mn^{54}, Fe^{59}, Zn^{65}, and Se^{75} would probably be the most important of the long-lived induced radionuclides. Possible contamination of the copper with radioactive copper is not of concern since all of the radioactive copper isotopes have very short half-lives and any formed decay almost completely prior to the start of leaching.

II. Radionuclides Dissolved

It is known from experience that most of the fission products and induced radionuclides are trapped fairly efficiently in the fused melt that accumulates at the bottom of the chimney and that this fused material is not very leachable. However, appreciable amounts of certain fission products, for example Sr^{90} and Cs^{137}, which have gaseous precursors, and ruthenium, which forms volatile compounds, move up into the chimney and are deposited on the rubble. That portion of each radioisotope deposited on the rubble would be expected to be much more leachable than the portion trapped in the melt. Batch leaching tests in which radioactive debris from one of the Nevada Test Site shots was leached with sulfuric acid confirmed this expected behavior.

The ion exchange properties of the copper ore are highly important in regulating the quantities of certain radionuclides that dissolve from the ore. Safford ore adsorbed Cs^{137} and $Zr\text{-}Nb^{95}$ very strongly from leach liquors. Strontium was adsorbed much less, although still significantly. In an in-situ leaching operation, the chimney of broken ore would function as an ion-exchange column several hundred feet high. Radionuclides dissolved from the ore in the early phases of the leaching cycle would tend to be adsorbed on the ore as the leach solution was recycled through the ore column. This would limit the build-up in concentrations of certain radionuclides in the leach liquor to levels far below those that would be predicted on the basis of simple batch leaching tests. A cyclic column leaching test in which soluble radioisotopes were added to the system confirmed this expected behavior. Those isotopes that are adsorbed strongly were not found in significant amounts in the effluent.

Radionuclides formed by neutron activation of the copper ore should not be of importance in processing nuclear-broken ore. In a column leaching test, only small fractions of the major long-lived radionuclides formed by irradiation of copper ores in a nuclear reactor were dissolved. In a nuclear detonation, the activation products should be entrained in the melt rock and, therefore, would be much less soluble than was observed in the test with reactor-irradiated ore.

III. Contamination of the Cement Copper

In conventional copper leaching practice, the pregnant leach solutions are stripped of their dissolved copper by precipitation of the copper on metallic iron. This precipitate is known as "cement copper". Cementation tests showed that, of the important fission products, only Ru^{106} and $Zr\text{-}Nb^{95}$ cement with the copper to a significant extent. Certain potential activation products, such as silver and mercury, cement quantitatively with the copper. However, after considering the quantities of each of the various radionuclides that would be expected to be present in the leach liquor, it was concluded that Ru^{106} is the only radioisotope that appears important with respect to contamination of the cement copper. This assumes that the cement copper would be adequately washed to remove occluded leach liquor containing soluble radioisotopes.

Attempts to remove ruthenium from the leach liquor with various absorbents prior to cementation have not been very effective. Most of the ruthenium can be removed from the recycle liquor by partial neutralization with lime but essentially continuous lime treatment would be required for this control method to be very effective. This, however, would destroy the liquor's usefulness as a leaching solvent and would require reacidification in each cycle which would be too expensive.

IV. Effect of Smelting and Electrolysis on Radioactive Contaminants

As pointed out above, the cement copper concentrate is expected to be contaminated with Ru^{106}. The cement copper usually is smelted to produce impure copper metal in the form of a consumable anode which is then converted to electrolytic copper in an electrolyic cell. Small-scale laboratory tests simulating the smelting and electrolysis operations indicate that essentially all of the ruthenium impurity follows the copper through the smelting process. However, an efficient separation occurs during electrolysis with the electrolytic copper being esssentially free of ruthenium. The ruthenium accumulates in the cell electrolyte with some of it dropping out in the "anode mud" that accumulates at the bottom of the cell. About 1% of the total ruthenium in the anode was found in the electrolytic copper. Some provision in the process would have to be made to prevent excessive build-up of Ru^{106} in the cell electrolyte and to handle the anode mud, should its radioactive content become too high.

V. Solvent Extraction of Copper from Leach Liquors

Recovery of copper from the leach liquor by solvent extraction is a potential alternative to the cementation method. The extracted copper can be stripped from the solvent with 2 M H_2SO_4 and this solution can be fed directly to electrolysis. Preliminary tests indicated good separation of copper from ruthenium as well as all other important fission products, except possibly $Zr\text{-}Nb^{95}$. Solvent extraction could be an attractive alternative to cementation provided the projected economics of this recovery process are competitive for a commercial size operation.

VI. Potential Radiation Hazards to Leach Plant Operating Personnel

Based on an estimate of the concentrations of each of the radionuclides that might be present in the circulating leach liquor it was concluded that with the exception of tritium, the concentrations would be very low, certainly far below the level that would require shielding of the process equipment to prevent radiation exposure. In making the estimate, it was assumed that the radioisotopes would be *uniformly dispersed* in the total volume of leach liquor and that leaching would begin no sooner than 8 months following the shot. No allowance was made in the estimate for the possibility of "cleaning up" the chimney by flushing with air or water prior to commencing leaching. A substantial reduction in the tritium available for circulation in the leach fluid might be achieved by initially flushing the chimney with water or air and disposing of this product prior to introducing the leach solution*

The principal hazard from tritium would be from inhalation of tritiated water vapor. Therefore, it would be of greatest concern in underground operations such as in an open liquor collection tunnel and pump sumps for pumping to the surface.

VII. Summary and Conclusion

In summary, at this stage of the studies it is tentatively concluded that potential problems associated with the introduction of radioactivity into the leach system do not constitute an important obstacle to use of nuclear explosives in copper ore processing. Radio-contamination of the cement copper with ruthenium will occur. However, ruthenium in cement copper is largely eliminated in the electrolytic refining process. It appears therefore, that radio-contamination of the final copper product would be very low and should not be hazardous to the customer. With respect to hazards to plant personnel due to radioactivity, tritium is identified as the radioisotope of most concern. It does not appear to be a significant concern except possibly in underground operations. The expected concentrations of radionuclides in the circulating leach liquor are sufficiently low so that shielding of process equipment would not be required. However, the process facility should be designed to minimize spillage of leach solutions and to minimize contact of the operating personnel with the ruthenium-contaminated cement copper.

* Any disposal of radioactive waste would be in compliance with established AEC and Arizona State regulations.1

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