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Desert Research Institute
Division of Earth and Ecosystem Sciences
Las Vegas, Nevada

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Robert C. Jones, Harold Drollinger, Thomas F. Bullard,
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Division of Earth and Ecosystem Sciences
Desert Research Institute, Las Vegas, Nevada

Prepared for

U.S. Department of Energy
National Nuclear Security Administration
Nevada Site Office
Las Vegas, Nevada
and
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Defense Threat Reduction Agency
Albuquerque, New Mexico

Colleen M. Beck, Project Director
Desert Research Institute
Division of Earth and Ecosystem Sciences
Las Vegas, Nevada

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ABSTRACT

This report presents a historical evaluation of the U16a Tunnel on the Nevada National Security Site in southern Nevada. The work was conducted by the Desert Research Institute at the request of the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office and the U.S. Department of Defense, Defense Threat Reduction Agency. The U16a Tunnel was used for underground nuclear weapons effects tests in Shoshone Mountain in Area 16 of the Nevada National Security Site. Six nuclear tests were conducted in the U16a Tunnel from 1962 to 1971. These tests are Marshmallow, Gum Drop, Double Play, Ming Vase, Diamond Dust, and Diamond Mine. The U.S. Department of Defense Threat Reduction Agency, with participation from Lawrence Livermore National Laboratory and Las Alamos National Laboratory, sponsored the tests. Fifteen high explosives tests were also conducted at the tunnel. Two were calibration tests during nuclear testing and the remaining were U.S. Department of Defense, Defense Threat Reduction Agency tunnel defeat tests.

The U16a Tunnel complex is on the top and slopes of Shoshone Mountain, encompassing an area of approximately 16.7 hectares (41.1 acres). Major modifications to the landscape are a result of three principal activities, road construction and maintenance, mining activities related to development of the tunnel complex, and site preparation for activities related to testing. Forty-seven cultural features were recorded at the portal and on the slopes of Shoshone Mountain. At the portal area, features relate to the mining, construction, testing, and general every day operational support activities within the tunnel. These include concrete foundations for buildings, equipment pads, and rail lines. Features on the slopes above the tunnel relate to tunnel ventilation, borehole drilling, and data recording. Feature types include soil-covered bunkers, concrete foundations, instrument cable holes, drill holes, and ventilation shafts.

The U16a Tunnel complex is eligible to the National Register of Historic Places under criteria a and c, consideration g of 36 CFR Part 60.4 as a historic landscape. Scientific research conducted at the tunnel has made significant contributions to the broad patterns of our history, particularly in regard to the Cold War era that was characterized by competing social, economic, and political ideologies between the former Soviet Union and the United States. The tunnel also possesses distinctive construction and engineering methods for conducting underground nuclear tests. The Desert Research Institute recommends that the U16a Tunnel area be left in place in its current condition and that the U16a Tunnel historic landscape be included in the Nevada National Security Site monitoring program and monitored on a regular basis.

ACKNOWLEDGMENTS

This research was conducted under the direction of Linda Cohn, U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office Cultural Resources Manager for the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office (NNSA/NFO), and Jeffrey Fraher of the U.S. Department of Defense Threat Reduction Agency (DTRA). Colleen M. Beck, Desert Research Institute (DRI), was project director and the cultural resources field work was conducted under the supervision of Robert C. Jones and assisted by Barbara Holz, Tatiana Menocal, and Justin DeMaio, DRI. Thomas F. Bullard, DRI, conducted the geomorphological study.

Special thanks are due to a number of unique persons willing to share their knowledge and past experiences at the tunnels in recorded video and audio interviews. We would like to thank Laurence Ashbaugh, a former DTRA Test Group Engineer, Chief of Engineering, and Manager of the DTRA Nevada Site Office, and Wayne Griffin, a former DTRA Test Group Engineer and Assistant Tunnel Superintendent for Reynolds Electrical and Engineering Co. Inc. (REECo), who discussed the operations and purpose of the tunnel and coauthored the report. Thanks to Bill Flangas, a former Mine Superintendent, Project Manager, Department Manager, and Operations and Maintenance Division Manager for REECo, and Vice President of REECo, for his time and effort in providing information and giving an interview about the U16a Tunnel. Richard Wyman, who was present during early testing at U16a, gave personal information in an interview about the tunnel. Byron Ristvet, former Containment Scientist for DTRA, provided an interview on the history of U16a Tunnel. Margaret Townsend, geologist with National Security Technologies (NSTec), provided information and an interview about the U16a Tunnel. Keith Kolb, videographer for NSTec, provided his skills and experience to make the video interviews possible. Martha DeMarre helped in providing historic documents and photographs on file at the Nuclear Testing Archive, Las Vegas. Loretta Bush at the NNSA/NFO Technical Library, North Las Vegas helped in obtaining key scientific reports for the various nuclear tests conducted in the U16a Tunnel. Connie Salus allowed us access to the documents on file at the Defense Threat Reduction Information Analysis Center, Kirtland Air Force Base, New Mexico. Troy Leonard provided engineering drawings on file at the Archives and Records Center, Mercury, Nevada. Mary Scodwell was instrumental in providing photographs on file at the Remote Sensing Laboratory, Las Vegas.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The U.S. Department of Energy (DOE), National Nuclear Security Administration Nevada Site Office (NNSA/NFO) requested the Desert Research Institute (DRI) to conduct a historical evaluation of the U16a Tunnel in Area 16 of the Nevada National Security Site (NNSS), Nye County, Nevada (Figure 1 and 2). The intent of this historical evaluation is in reference to Section 110 of the National Historic Preservation Act of 1966, as amended, and involves the identification and evaluation of historic properties.

The U16a Tunnel and portal area were utilized for 6 nuclear weapons effects tests and 15 high explosives tests from 1962 to 2001. The U.S. Department of Defense Threat Reduction Agency (DTRA), with participation from Lawrence Livermore National Laboratory (LLNL) and Las Alamos National Laboratories (LANL), sponsored the tests (DOE 2000). Fifteen high explosives tests were also conducted at the tunnel. Two were calibration tests during nuclear testing and the remaining were DTRA tunnel defeat tests.

The U16a Tunnel complex investigation encompassed 16.7 hectares (41.1 acres) on the side and top of Shoshone Mountain at the NNSS. Modifications to the landscape have resulted from development of the tunnel complex and 47 cultural features associated with this activity have been recorded. The U16a Tunnel complex is eligible to the National Register of Historic Places (NRHP) as a historic landscape under criteria a and c, consideration g of 36 CFR Part 60.4. It is eligible under criterion a because of its historic significance at the NNSS and its role in national defense during the Cold War between the United States and the former Soviet Union. It is eligible under criterion c because of specialized engineering techniques and achievements developed to carry out nuclear tests underground. Because of the nature and significance of the property, the U16a Tunnel complex is recommended to be maintained in situ as a historic landscape. A historic landscape is one associated with a historic event or series of events, where the landscape has been planned, altered because of a desired function, and has a discernable pattern. The U16a Tunnel complex is also recommended to be included in the NNSS cultural resources monitoring program to be monitored on a regular basis.

The following sections of this report are the research design and methods for this historic evaluation; historic context for nuclear testing at the NNSS, with an emphasis on underground testing; environmental setting of the U16a Tunnel that discusses the location, geology, topography, and natural resources; description of the U16a Tunnel that presents summaries of the nuclear tests conducted in the tunnel, the geomorphology, and descriptions of the cultural features; and, overall summary, with National Register eligibility and management recommendations.

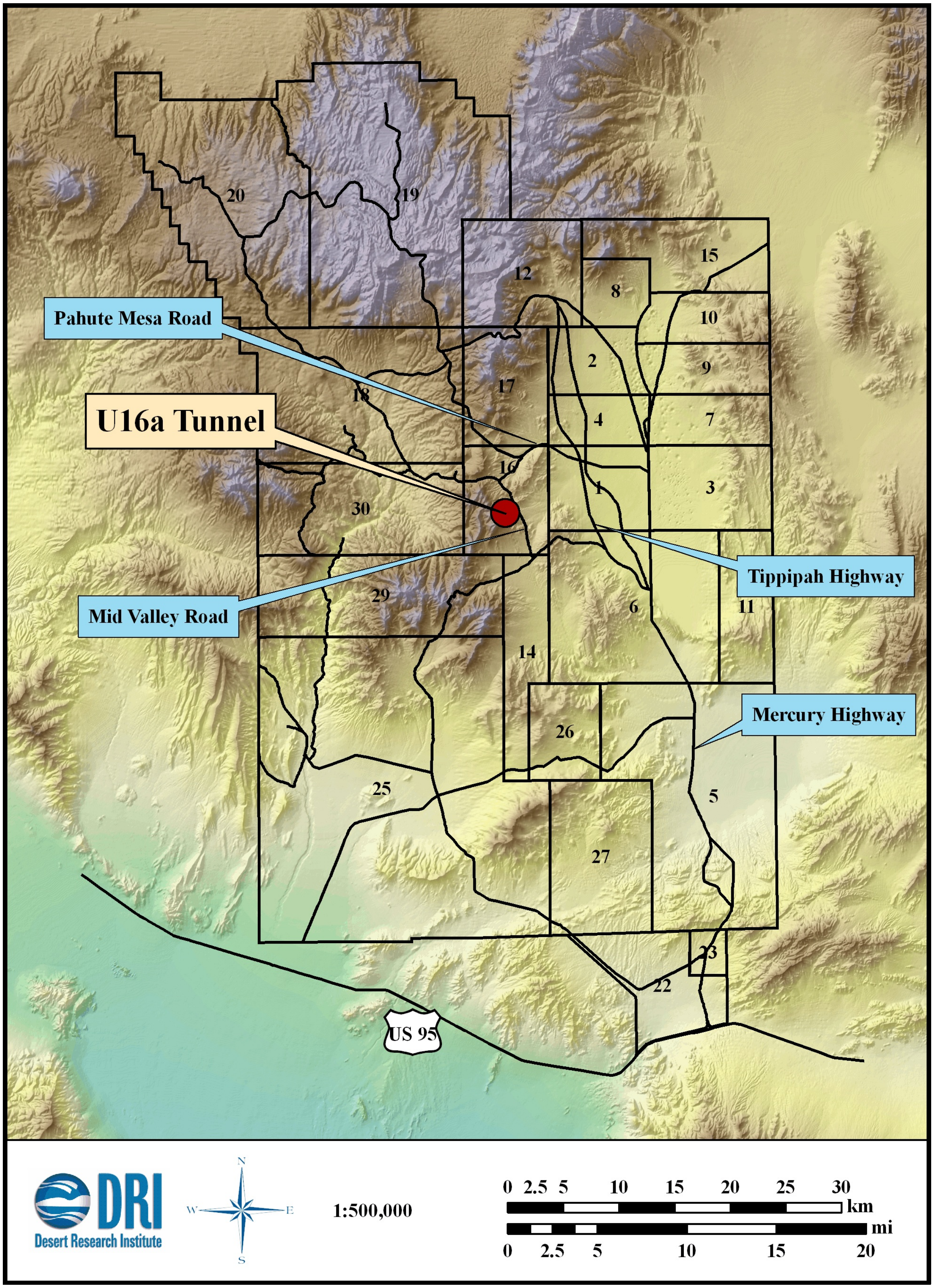

Figure 1. Location of the U16a Tunnel complex on the NNSS.

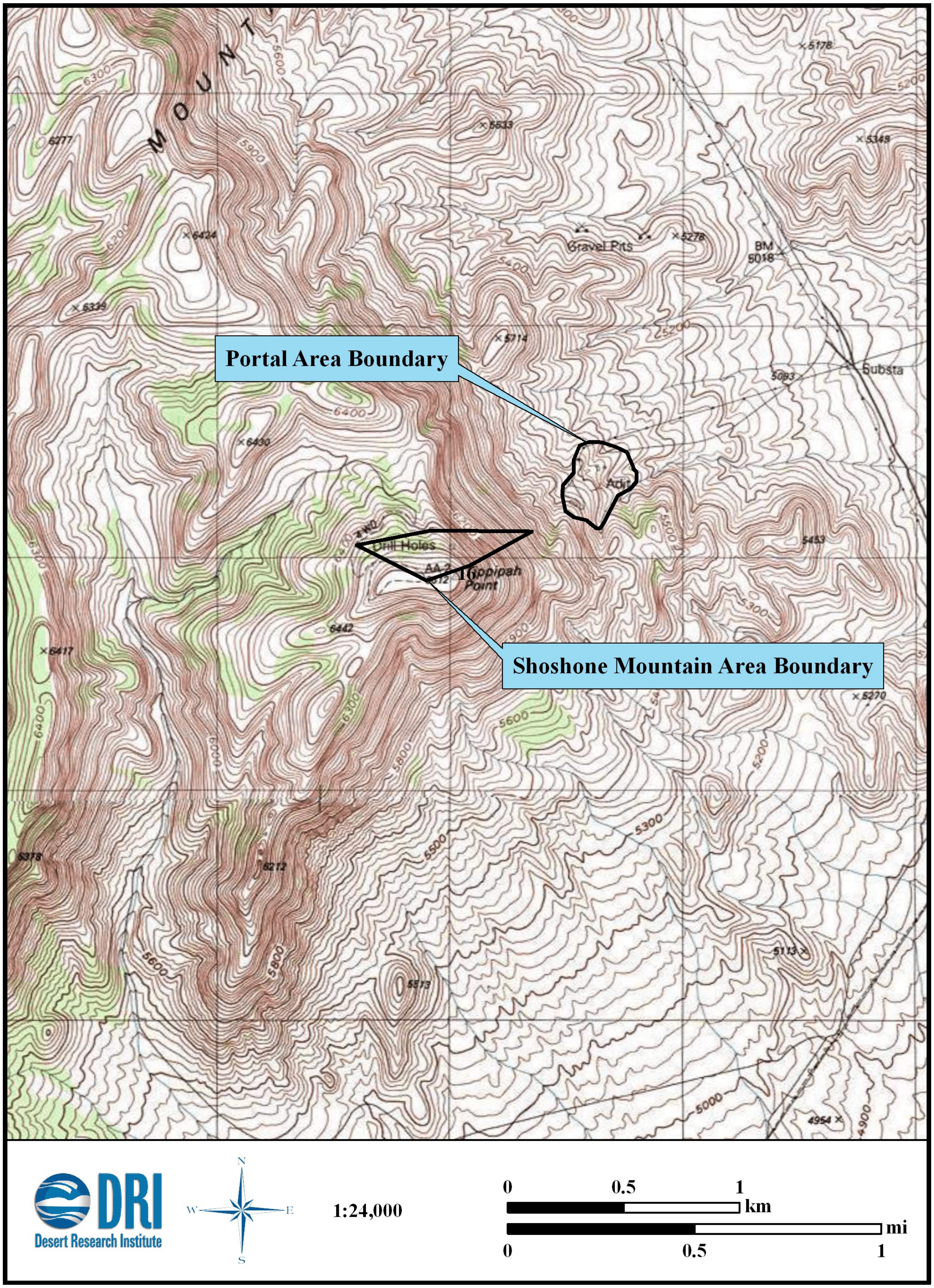

Figure 2. Survey areas for the U16a Tunnel complex on the NNSS.

RESEARCH DESIGN AND METHODS

The U16a Tunnel historical evaluation is the fifth study of a nuclear testing tunnel at the NNSS. The other four are the U-12b Tunnel (Jones et al. 2006), the U12e Tunnel (Drollinger et al. 2007), the U12t Tunnel (Drollinger et al. 2009), and the U12n Tunnel (Drollinger et al. 2010). Historic themes for these studies are nuclear testing and national defense. Other studies of cultural resources on the NNSS with similar historic themes are the Area 2 Equipment Support Yard (Johnson 1994), the Japanese Village (Johnson and Edwards 1996), Camp Desert Rock (Edwards 1997), the Apple-2 Historic District in Yucca Flat (Johnson and Edwards 2000), the Frenchman Flat Historic District (Johnson et al. 2000), the Yucca Lake Historic District (Jones et al. 2005), underground nuclear test locations in Frenchman Flat (Jones and Drollinger 2001), bunkers used in atmospheric nuclear tests (Edwards and Johnson 1995; Johnson 2002; Jones 2003, 2004), benches for viewing atmospheric nuclear tests (Jones 2005), buildings in the Area 6 control point area (Drollinger et al. 2003), the Super Kukla facility (Drollinger et al. 2000; Drollinger and Goldenberg 2004), and the Pluto Control Facility Historic District (Drollinger et al. 2005).

Cultural resources determined eligible to the NRHP from the above studies include structures in the Frenchman Flat and Yucca Lake Historic Districts, houses and other structures in the Apple-2 Historic District, the Japanese Village, atmospheric testing bunkers, atmospheric testing viewing benches, buildings in the control point, the Super Kukla facility, the Pluto Control facility, and the U12b, U12e, U12t, and U12n tunnels. The crater from the Sedan test, a Plowshare nuclear experiment conducted in 1962 on the NNSS, is listed on the NRHP. All of these historic properties date to the Cold War era and are representative of the various nuclear testing activities carried out at the NNSS during this period.

The research design for this historical evaluation of the U16a Tunnel complex consisted of background research, interviews, and field documentation. A major focus for this study was to obtain documents to describe the historic context of the U16a Tunnel in order to evaluate its historic significance and exceptional importance for eligibility to the NRHP. Historic information for this evaluation is based on available unclassified records and interviews. These include documents and photographs from the NNSA/NFO Nuclear Testing Archive, Las Vegas; the NNSA/NFO Technical Library, North Las Vegas; the NNSA/NFO Remote Sensing Laboratory, Las Vegas; the Archives and Records Center, Mercury, Nevada; and the Defense Threat Reduction Information Analysis Center (DTRIAC), Kirtland Air Force Base, New Mexico. In addition, DRI in Las Vegas maintains records of the cultural resources inventories, historic evaluations, mitigations, and archaeological site information for the NNSS. Interviews were conducted with key personnel who worked at U16a Tunnel. All photographs and drawings in this report have been approved for public release.

A second major focus of this study was the physical setting and description of the U16a Tunnel complex and consisted of on-site visits, photographs, mapping and measurements of extant features, and mapping of the geology and geomorphology. Components of the U16a Tunnel complex are shown in Figure 2. Surface area investigated for the tunnel complex was 16.7 hectares (41.1 acres), 7.8 hectares (19.2 acres) at the portal and 8.9 hectares (21.9 acres) on the top of Shoshone Mountain. Fieldwork for the U16a Tunnel complex consisted of eight intermittent days in June, July, and August, 2011. The fieldwork was restricted to the exterior settings of the portal and slopes of Shoshone Mountain. Boundaries of the U16a Tunnel historic landscape and the geomorphology study area were based on these field recordings and available documents. The field work was conducted by archaeologists Robert Jones, Barbara Holz, Tatianna Menocal, and Justin DeMaio, DRI, Las Vegas and geomorphologist Thomas F. Bullard, DRI, Reno. Forty-seven cultural features, 41 at the portal area and 6 on the upper slopes of Shoshone Mountain, were recorded. Overall dimensions were recorded and digital, color, and black-and-white photographs were taken of each feature. The negatives of the photographs and electronic copies of the digital photographs are on file at the NNSA/NFO Curation Facility, Frank H. Rogers Building, DRI, Las Vegas.

The purpose of the geomorphology study was to document the changes in the landscape as a result of site preparation and tunneling activities. This study, conducted in June 2011, was accomplished by making a reconnaissance-level map of the surficial and bedrock geology at the site. During field visits, the extent of waste rock or muck from mining operations, fill emplacements, cut slopes, material side-cast during road construction activities, and building pad preparations were mapped. No surface disturbing activities (e.g., digging) or detailed field descriptions of bedrock or soils were undertaken.

The general geologic framework of the area was based on published literature, interviews, geological survey reports of rock units encountered during tunnel construction, and the distribution of muck and change in surface characteristics. During the nuclear weapons testing period in the U16a Tunnel, geological studies were carried out by the United States Geological Survey (USGS) and Fenix and Scisson, Inc., to address the geology and structure, mineralogy and chemistry of rock units, and to thoroughly characterize geophysical and physical properties of the tunnel rocks. Surface and subsurface geologic mapping was performed along with a number of geophysical investigations both in situ (for example spontaneous potential logs and sonic logs) as well as inspection and testing of borehole cores for mineralogy, chemistry, and geophysical properties, and vertical and lateral porosity and permeability.

HISTORIC CONTEXT

The historic context for the U16a Tunnel complex is both local and national because of its role in the United States nuclear weapons testing program at the NNSS during the Cold War with the former Soviet Union. A result of this confrontation was an ever-escalating arms race for nuclear weapon superiority (Anders 1978:4; Loeber 2002:80; Ogle 1985:20). This led to numerous nuclear detonations worldwide in the atmosphere, outer space, underwater, and underground. The description below is the history of U.S. nuclear testing and the generalized procedures for nuclear tests in tunnels.

U.S. DEPARTMENT OF ENERGY

Shortly after World War II, the Atomic Energy Commission (AEC), now the U.S. Department of Energy (DOE), was established when President Harry Truman signed the Atomic Energy Act of 1946. The purpose of the act was to address government control of fissionable material, nuclear experiments for military applications, and regulations pertaining to the release of scientific and other related data. The function of the DOE was to maintain civilian government control of the research, development, and production of atomic weapons for the military (Anders 1978:2). Nuclear weapons research was conducted at the Los Alamos Scientific Laboratory (LASL), now the Los Alamos National Laboratory (LANL), New Mexico, established in 1943 as part of the Manhattan Engineer District. Development and production of the weapons took place at Sandia Laboratory, now the Sandia National Laboratories (SNL), New Mexico, established in 1948; the Y-12 Plant in Oak Ridge, Tennessee; at Hanford, Washington; and the Rock Island Arsenal in Illinois (Anders 1978:3; Brady et al.1989:18-19; Stapp 1997). Following the first nuclear detonation by the former Soviet Union in 1949 (Anders 1978:4; Ogle 1985:20), increased efforts for research and production were implemented in the United States. A second nuclear weapons research laboratory was established in 1952 at Livermore, California (Brady et al.1989:18). The Livermore laboratory was initially designated as the University of California Radiation Laboratory, a branch of the Berkeley Radiation Laboratory, and then in 1958 it became the Lawrence Radiation Laboratory. In 1971, it separated from the Berkeley laboratory to become a national laboratory, and in 1982, it became the Lawrence Livermore National Laboratory (LLNL) (DOE 1997:203). Other facilities added to the nuclear weapons industry in the 1950s included manufacturing plants at Rocky Flats near Golden, Colorado; the Kansas City Plant in Missouri; the Burlington Army Ordnance Plant in Iowa; the Pinellas Plant in Largo, Florida; Mound Laboratory in Miamsburg, Ohio; and the Pantex Plant near Amarillo, Texas (Anders 1978:4; DOE 1997:27).

The United States and the former Soviet Union ceased nuclear testing in 1958 by self-imposed moratoriums at the urging of internal and external forces (Ogle 1985:30-31), but by 1961 both superpowers were once again conducting nuclear tests. Except for a few surface and near-surface tests, most of the tests were placed underground, and after ratification of the Limited Test Ban Treaty by the United States, the former Soviet Union, and Great Britain in 1963, all nuclear tests were underground (Friesen 1995:6). According to the treaty, no tests could be conducted in the atmosphere, outer space, or underwater. Furthermore, certain safeguards for the United States were established in order for the U.S. Senate to ratify the treaty (DTRA 2002:246). These safeguards were an intensive underground testing program, maintenance of the weapons laboratories, the ability to resume atmospheric testing on short notice, and improvements in verifying compliance to the treaty. In 1974, the United States and the former Soviet Union agreed to the Threshold Test Ban Treaty and, in 1976, to the Peaceful Nuclear Explosions Treaty in order to restrict nuclear test explosions to a defined test site and to yields no greater than 150 kilotons. A second self-imposed moratorium on nuclear testing by the United States was established in 1992, and in 1996, the United States signed the Comprehensive Test Ban Treaty banning all nuclear tests. This latter treaty, however, has yet to be ratified by the U.S. Senate.

U.S. DEPARTMENT OF DEFENSE

The U.S. Department of Defense (DoD), with the establishment of the Armed Forces Special Weapons Project (AFSWP) in 1947, had a continuing role post-World War II in the testing of nuclear weapons at the Pacific Proving Grounds and later at the NNSS (DTRA 2002). This group evolved over the years through reorganization and mission change into the Defense Atomic Support Agency (DASA) from 1959 to 1971, the Defense Nuclear Agency (DNA) from 1971 to 1996, the Defense Special Weapons Agency (DSWA) from 1996 to 1998, and currently as DTRA, established in 1998. General L.R. Groves, who was instrumental in developing the first nuclear weapon during the Manhattan Project and in keeping the military active in the nuclear weapons industry after the war, was appointed chief of AFSWP in early 1947 (DTRA 2002:35). The primary mission was to train military personnel in the assembly, storage, and firing of the atomic weapon, tasks previously conducted primarily by civilian scientists.

By 1949, when AFSWP was set up and operating, it was assigned the tasks of studying the effects of nuclear weapons on targets underwater, underground, and in the atmosphere and for radiological warfare (DTRA 2002:71-72). More tasks soon followed as the agency and the nuclear weapons industry as a whole became more adept. For example, the agency began to provide specialized training and technical support, coordinated storage and oversight of the ever-expanding nuclear weapons stockpile, and became more involved in the planning and operation of the weapons tests (DTRA 2002:80, 104). Most important, for the first time the defense agency participated in the development of the nuclear weapons and associated systems. Defense Atomic Support Agency (DASA) became the new name for the organization in 1959, and with the change, the added responsibility for the supervision of weapons effects tests for all the different military branches (DTRA 2002:149). The agency by this time also served as an integral information source in Cold War strategy for the United States.

Significant changes occurred in the agency during the 1960s. The number and diversity of nuclear weapons, including the associated delivery and defense systems increased dramatically in response to the high state of nuclear readiness of the Cold War policy (DTRA 2002:173). DTRA had to modify the weapons effects tests and management of the weapons stockpile accordingly. It also meant changes or upgrades in scientific and technical staff within the organization to increase research and development. At the same time, as the role and prominence of the agency changed, control of the agency was placed directly under the civilian Secretary of Defense rather than the joint chiefs of the military services. In addition, because of the current situations and readiness for immediate response in case of attack, custody of the nuclear weapons stockpile was formally transferred from the DOE to the DoD (DTRA 2002:178). It was agreed that the DOE would be responsible for weapons development, quality assurance of the weapons stockpile, effects tests on warhead components, and management of the NNSS; while DoD through DTRA would provide testing facilities, certain hardware for diagnostics and data recording, field support, and funding (Brady et al. 1989:9; DTRA

2002:180). Both agencies would still be able to conduct nuclear tests, with devices supplied by the Livermore or Los Alamos national laboratories through the DOE, and both would do research in detecting nuclear tests by other nations.

A major difference in research objectives also occurred between the DOE and DTRA (DTRA 2002:189). DTRA began to emphasize research on the actual use and effects of the nuclear weapon by the military. This emphasis contrasted with the research interests and desires of the weapon developers for the DOE, whose main focus was on developing the weapon and not how it was going to be used. Because of limits imposed on testing in 1963, three methods of nuclear weapons effects tests were implemented by the defense agency (DTRA 2002:191). The first was improvement in underground testing techniques, particularly for containment; the second was the use of high explosives rather than nuclear explosives for some of the effects tests; and the third was the use of simulators, such as reactors, in some of the effects tests. Large scale simulators, once constructed and operating, could do a series of tests in one day compared to a single nuclear test in a tunnel or shaft that could take up to two years to conduct (DTRA 2002:239). High explosive testing could also be prepared faster and easier than a nuclear test and with less safety and security concerns. These types of tests and simulations, however, could not replicate all the experiments and effects that could be conducted with a nuclear explosion, so nuclear testing was still considered necessary. It was found that nearly all the military systems, when fully assembled and all components interacting together, initially failed during an actual nuclear weapons effects test (Ristvet et al. 2007). Nuclear testing was also considered necessary for testing the reliability of the weapons stockpile (DTRA 2002:250).

Several important changes were made in the 1970s. One was the reorganization of the DOE due to conflicts of interest in regulating itself. It was divided in 1974 into the Energy Research and Development Administration (ERDA) and the Nuclear Regulatory Commission to solve the problem (Buck 1983:8; DTRA 2002:216). Soon thereafter, in 1977, ERDA was incorporated into a cabinet level organization as DOE. A second change was the reorganization and reduced responsibilities of the DTRA, including a new name, the DNA (DTRA 2002:216). The DNA's primary mission now consisted of nuclear weapons management, nuclear weapons testing, and nuclear weapons effects research. Reduction in personnel at the agency was also implemented and reflected the military branches increasing supervision of the nation's nuclear weapons, particularly by the U.S. Air Force. In Albuquerque, New Mexico, the Kirtland Air Force Base, the Sandia Base, and the Manzano Base came under the control of the Air Force; Johnston Atoll remained under the management of the Air Force, with a lesser role by the DNA; and training in nuclear weapons became the responsibility of each of the military branches. Nuclear weapons training would return to the DNA in the early 1990s, however.

In the late 1970s and early 1980s, DNA had an important role in the buildup of the military and national defense of the United States (DTRA 2002:259). The central theme of this role was survivability from a nuclear weapons attack, particularly the improvement and hardening of the various military weapons systems against such an attack. Efforts were also made to improve and harden communication systems, airplanes, airplane components, missiles, missile components, and underground bunkers. These efforts often used high explosives tests in order to simulate open air reactions or blast effects to the materials and structures as in an actual attack. Earlier weapons effects data from atmospheric nuclear tests at the NNSS were also used to bolster these efforts.

The late 1980s and early 1990s heralded the end of the Cold War and an assortment of treaties calling for the reduction of strategic and tactical weapons (DTRA 2002:282, 294). In 1992, the Hunters Trophy test conducted in the U12n Tunnel was the last nuclear weapons effects test at the NNSS (DTRA 2002:296). Since then, the NNSS has served as a testing ground for non-nuclear munitions against hardened installations. Also, because of changing world conditions and the emergence of weapons of mass destruction and terrorism, the mission of the DNA was re-evaluated and a reorganization was sought that reflected these conditions and the perceived needs of the military. Consequently, the DNA was replaced by the Defense Special Weapons Agency (DSWA) in 1996 with a new mission focusing on threat reduction, arms control, and support for counter proliferation activities (DTRA 2002:314). DSWA still performed the previous tasks, including the management of the military nuclear weapons stockpile. Tantamount to this was the vast amount of information the agency possessed from its inception about nuclear weapons (DTRA 2002:318-319). Programs, such as the Data Archival and Retrieval Enhancement Program, were initiated to assemble data about the technical history of atmospheric and underground nuclear weapons effects testing. These programs enabled the information already gathered over the years to be stored for future use and provide new defense projects the research material about nuclear weapons effects without having to repeat the tests.

DTRA was created in 1998, incorporating DSWA, the On-Site Inspection Agency, the Defense Technology Security Administration, and some staff from DoD (DTRA 2002:322). While it still retained its nuclear stewardship responsibilities, this newest agency would concentrate on perceived defense threats. Its mission statement is to reduce threats to the United States and its allies from nuclear, biological, chemical, conventional, and special weapons (DTRA 2002:323). These tasks, though somewhat altered due to evolving technologies and management roles, still conform to the mission when the agency first started and it still maintains a key presence in the testing programs at the NNSS today.

NEVADA NATIONAL SECURITY SITE

During the late 1940s, a search was conducted to establish a test site in the continental United States, remote from the populace and near the research laboratories. The main reasons for this were security, shorter travel times, and economic costs in the transportation of people and equipment (Lay 1950; Ogle 1985:44; Tlachac 1991). At the time, testing was conducted at the Proving Grounds in the Pacific Ocean and was expensive in both cost and time. Security at the Pacific locale became a major concern due to the situation developing in Korea (DTRA 2002:77). Four places in the United States were seriously considered for a continental testing ground: Camp Lejeune in North Carolina, Dugway Proving Ground in Utah, White Sands Proving Ground in New Mexico, and the Las Vegas Bombing and Gunnery Range in southern Nevada (Lay 1950). The ideal location, in addition to the attributes described above, was to have favorable and predictable weather and terrain conditions to be able to test year round, be under federal control, and have an infrastructure already in place (Lay 1950; Tlachac 1991).

The bombing and gunnery range in southern Nevada was the place chosen that best met the conditions for the continental test site. The first nuclear weapon test, Able of Operation Ranger, was carried out in Frenchman Flat on January 27, 1951 (Ogle 1985:43-44; Titus 1986:58). Construction of the facilities for the Nevada Proving Grounds, as it was originally designated, began soon afterwards.

After a series of name changes, it became the Nevada Test Site on the last day of 1954 and remained so until August 23, 2010 when the name was changed to Nevada National Security Site. The first land withdrawal by the DOE establishing the official nuclear weapons testing ground in the continental United States was February 12, 1952 under Public Land Order 805. Additional land parcels were obtained under public orders and memorandum of agreements. Today the NNSS encompasses an area of approximately 1,360 square miles (3,522 sq km), and spans approximately 55 miles (89 km) north-south and 30 miles (50 km) east-west.

A total of 928 atmospheric and underground nuclear tests have been conducted at the NNSS, with 120 performed in the 1950s and 808 after 1961 (DOE/NV 2000; Friesen 1995:6, 10). Atmospheric tests number 100, and most were conducted on Frenchman Flat or Yucca Flat during the 1950s. Three atmospheric nuclear tests were conducted in the upper Fortymile Canyon area. Most of the underground nuclear tests were either in vertical shafts on Pahute Mesa and Yucca and Frenchman Flats or in horizontal tunnels mined into the sides of Aqueduct and Rainier Mesas. Some underground tests were on Buckboard Mesa, Oak Butte, and Dome and Shoshone Mountains.

ATMOSPHERIC NUCLEAR TESTING

In the 1950s, the nuclear devices were initially dropped from airplanes for the atmospheric nuclear tests on the NNSS, but due to efforts for greater monitoring and a general lack of control on air drops, the devices were placed near the ground, on top of towers, and eventually elevated by balloons to the desired height. Also at this time in the Pacific arena, high altitude tests of large yield were being performed, mostly by balloon, a few on rockets into outer space, although some tests were on barges and underwater (Ogle 1985:49-50). Main objectives of the testing were for monitoring, measuring, perfecting techniques, and technological improvements of the nuclear weapons (Ogle 1985:84-85). Other objectives included physical effects (DTRA 2002:106). Some of the earliest experiments determined the physical effects from a nuclear detonation on naval ships, while later experiments evaluated physical effects on airplanes, tanks, jeeps, automobiles, clothing, docks, and different types of houses, underground structures, and radio and radar transmissions. At the NNSS, various structure and building designs were included for civil defense, such as underground shelters, domed subterranean structures, concrete and brick buildings, residential houses, a metal bridge, and a bank vault. In some cases, U.S. Army personnel participated in the tests in preparation for nuclear warfare. Camp Desert Rock, located at the south edge of the NNSS, was created to house military and other personnel involved in the nuclear tests as participants or as observers (DTRA 2002:80, 85; Edwards 1997:1).

UNDERGROUND NUCLEAR TESTING

The concept of the underground test, versus atmospheric, was not acted upon until the late 1950s when containment of the nuclear explosions became a major issue (Carothers 1995:16, 20; Johnson et al. 1959:2; Malik et al 1981:12; Byron Ristvet, personal communication 2006). Radioactive fallout was a safety and health concern for both the workers doing the tests and for the public at large. Following the signing of the Limited Test Ban Treaty in 1963, all nuclear tests were designed to be contained underground except for four Plowshare cratering experiments (Schoengold et al. 1996:2). Initially, this posed a new engineering challenge and learning experience and not all tests were able to be contained right away. After a number of underground nuclear tests had been completed, it was determined that radioactive material from nuclear tests could be satisfactorily contained with proper depths of burial, stemming of the drill hole or tunnel, blocking seeps around cables and pipes, and understanding the surrounding geology for possible cracks or other weaknesses (Malik et al 1981:12-15).

Most of the underground nuclear tests at the NNSS have been for either weapons development or for weapons effects (DOE/NV 2000). A few tests had other purposes, such as safety experiments, industrial engineering for the Plowshare program, and seismic monitoring. Weapons development tests evaluated the performance of the nuclear device itself and were usually placed in vertical shafts; whereas, weapons effects tests evaluated the effects on critical components of missiles and warheads, and sometimes entire systems, and were usually conducted in horizontal tunnels deep underground (Brady et al. 1989:2; Wolff 1984). Generally, two to four years went into the planning, preparation, construction, and post test analyses of a single underground nuclear weapons effects test.

At DTRA in the early 1960s, a shift toward weapons effects rather than the interests of the weapon developers guided the research (DTRA 2002:189). The effectiveness of the weapons systems during a nuclear attack was a primary concern. To further advance this research and because the treaty required testing to be conducted underground, new methods of testing had to be devised. A range of underground testing options was explored from line-of-sight pipe systems assembled within vertical shafts and horizontal tunnels to cavities and underground structure experiments mined or constructed within a tunnel complex or at the bottom of a vertical shaft. The underground nuclear weapons effects tests sponsored by DTRA used each or a combination of these options. The primary objectives of a DTRA underground nuclear weapons effects test were to construct a facility in which to install, expose, and protect the experiments; record data obtained from the experiments; contain the nuclear detonation and its byproducts underground; and recover the experiments and equipment after a test.

As underground testing techniques improved, horizontal tunnels increasingly were preferred over vertical shafts by DTRA because of the flexibility they provided (DTRA 2002:193-194). For example, rooms could be readily mined to appropriate dimensions to house various sized equipment, including entire systems rather than just parts of systems, and secondary drifts could be added or drifts from a previous test could be used to place additional experiments and equipment. In contrast, the number and size of experiments were more limited in vertical shafts. Moreover, when line-of-sight pipes were constructed in vertical shafts, experiments and signal conditioning equipment positioned over the shaft had to be quickly pulled off the test locale to keep them from falling into the subsidence crater that often developed shortly after the test.

Recovering equipment and experiments from the tunnels was standard practice and undertaken with great caution because the nuclear explosion potentially created hazardous physical conditions and the possibility of high radiation levels (LRL 1961). Hazardous conditions included damage from the shock wave, which could result in a total or partial collapse of the test drift or the main tunnel; upheaval of the floor or movement along fault lines; damage to the utility infrastructure, such as ventilation; and the presence of trapped toxic and explosive gases.

Rainier Mesa and Shoshone Mountain

DTRA and the national research laboratories began studies in the mid 1950s on the development of underground complexes to meet their testing needs. These studies, which included high explosives testing and geology, indicated that the Rainier Mesa area would be a good location for underground nuclear testing. High explosive tests conducted in the U12a Tunnel supported the concept and Rainier Mesa was subsequently selected for this purpose. LLNL started work in Rainier Mesa by developing the U12b, U12c, U12d, U12e, and U12f tunnel complexes in the mid to late 1950s. The first underground nuclear test in a tunnel, code named Saturn, was a safety experiment that took place at the U12c Tunnel in August 1957 (DOE/NV 2000:8). The Saturn test had zero yield. The Rainier nuclear weapons-related test with a yield of 1.7 kilotons was conducted in the U12b Tunnel a month later and was the first contained underground nuclear detonation in the world (Carothers 1995:31; DOE/NV 2000:10).

Geology of Rainier Mesa, an erosional volcanic remnant, basically consists of 610 to 914 m (2,000 to 3,000 ft) of volcanic ash-fall tuff resting on earlier granitic and sedimentary rock (LaComb et al. 1996:11). Stratigraphically, it is capped at the surface by welded or rhyolitic ash-flow tuff, 46 to 91 m (150 to 300 ft) thick, more dense and stronger than the underlying tuff. Below the caprock is an unsaturated section of friable and vitric bedded tuff 183 to 244 m (600 to 800 ft) thick and below that is a thin section of welded tuff, followed by a thick section of zeolitized and water-saturated bedded tuff lying on older granitic and sedimentary rocks (LaComb et al. 1996:11). This lower bedded zeolitized tuff section is between 198 and 351 m (650 and 1,150 ft) thick and is where most of the tunnel complexes were mined. It is divided into Tunnel Beds 1 to 4, with Tunnel Bed 1 being the lowest.

Originally, the Marshmallow test was scheduled to occur in the 01 drift of the U12e Tunnel in Area 12. However, damage to the tunnel caused by the Antler test provided information that seismic activity resulting from adjacent events required that the project be moved to a remote area that was relatively seismically quiet. Geology of Shoshone Mountain in the area chosen for the U16a Tunnel consists of approximately 305 m (1,000 ft) of layered volcanic ash-fall tuff (Davis and Hoover 1962). The layers through which the tunnel was excavated are generally thin to thick beds of zeolitized tuff. Above this is a layer of pink and gray bedded zeolitized tuff followed by a massive zeolitized tuff. Overlaying these are a nonwelded sandy tuff, a welded tuff, and capped by a non welded tuff.

The degree of water or air-void content of the geologic formations was found to affect the speed of the shock wave traveling through the rock and that certain locations for the working point, also known as ground zero or zero point, were better suited than others for the best transmission of the shock wave. Geologic samples by way of exploratory drill holes were taken of the rock formations before mining of the tunnel drifts in order to place the nuclear device in the most optimum location. Horizontal exploratory core holes drilled from within the tunnel were typically 8.26 cm (3.25 inches) in diameter and from 305 m to 762 m (2,500 ft) in length. Cores from these holes were tested for such things as bulk density, moisture content, grain density, porosity, compressive strength, triaxial compression, ultrasonic shear and compressive wave velocity (Horton et al. 1987:12). This testing was usually performed for DTRA by Holmes and Narver in the materials testing laboratory at the NNSS, TerraTek Corporation in Salt Lake City, Utah, and the U.S. Army Corps of Engineers, Waterways Experiment Station in Vicksburg, Mississippi. These data were required to map and understand the surrounding geology of a planned test in order to design and construct the test bed facility and protect the experiments and the environment both inside and outside the tunnel complex.

Experiment Protection

Because the 1963 Limited Nuclear Test Ban Treaty required nuclear tests to be conducted underground, new methods of testing had to be devised. New concepts and improved methods for mining, drilling and underground construction; containment of the nuclear detonation; experiment protection and recovery; data collection and data transfer evolved throughout the duration of the underground nuclear testing program to achieve very high quality.

A steel pipe, hundreds of feet long attached to a steel box (A-box) containing the nuclear device, was soon discovered to be a solution. This configuration, called a line-of-sight pipe, was placed in a horizontal or vertical position depending on where the test was located, in a tunnel or shaft, and served to enclose and protect experiments from the surrounding geologic media. It was also possible to create a vacuum inside the line-of-site pipe to simulate a high altitude atmospheric or exoatmospheric environment.

The horizontal line-of-sight pipe used in tunnels was tapered to support an expanding cone of radiation which emanated from the nuclear explosion. The horizontal line-of-sight pipes were as small as 4 inches (10 cm) in diameter at the end nearest the nuclear device and from 3 m (10 ft) to 8 m (27 ft) in diameter at the portal end; lengths varied from 30.5 m (100 ft) to 580 m (1,900 ft). Samples or experiments were placed in test chambers located at the portal end of the pipes and were exposed to the radiation effects of the nuclear detonation as they passed through the pipes. The pipes were constantly checked with lasers for proper alignment during construction. Following pipe installation and alignment, an extensive vacuum check was conducted to determine if any leaks were in the pipe system or if there were any foreign materials in the pipe that would out gas, thereby lowering the ability to obtain the desired vacuum. Leaks were repaired and stemming of the annulus between the pipe exterior and the tunnel wall was started following a successful vacuum check. This stemming was done early to allow the heat of hydration generated by the curing grout to decrease to a level that would not distort the laser beam during installation and critical alignment of the experiments.

Experiments were mounted on special non-metallic bulkheads in test chambers. Experiments were also placed in an assortment of stub pipes at the end of the pipe. The stub pipes functioned to reduce the fluence level traveling down the horizontal line-of-sight pipe as required for some experiments, support increased vacuum requirements for some experiments, or create a specific environment for experiments where isolation from the test chamber was required.

As a final check, just prior to installing the device in the A-box at the working point, an x-ray source was used to verify alignment of each experiment in relationship to other experiments and to the eventual nuclear exposure. The temporary x-ray source was placed at the working point and the exposure face (working point side) of each experiment was covered with photographic film. Following exposure to the x-rays, the film was developed and carefully reviewed to verify that all experiments would be fully exposed to the nuclear source and that no experiment would shadow another.

Another challenge for underground nuclear weapons effects tests was preservation of the samples or equipment being tested (DTRA 2002:193). The objective of the test was to produce radiation from the nuclear explosion, allow it to travel through the line-of-sight pipe at the speed of light, and irradiate the experiments. The problem was that debris and gases from the explosion, also traveling down the line-of-sight pipe but at a lesser velocity than the radiation, could strike and potentially destroy the experiments. The solution was to install a series of fast-closing gates or closures that effectively closed the pipe after the radiation had passed, thereby, preventing the debris from damaging or destroying the experiments. The first of these gates was the fast acting closure located closest to the working point, about 61 m (200 ft) away. The fast acting closure had a 76 cm (30 inch) diameter line-of-sight opening, surrounded by a copper sleeve that was surrounded by an aluminum sleeve. The sleeves were encircled with 500 pounds of high explosive data sheet and the explosive was surrounded by lead. The high explosive drove the copper and aluminum sleeves into the line-of-sight opening, creating a plug and closing the line-of-sight pipe within one millisecond after detonation of the nuclear device. The gas seal auxiliary closure was the next in line, about 122 m (400 ft) from the working point. The line-of-sight opening in the gas seal auxiliary closure was about 152 cm (60 inches). The closure had two 30 cm (1 ft) thick high-strength aluminum alloy doors that slid across the line-of-sight opening from opposite sides, sealing it within 30 milliseconds. Its function was to stop debris and provide a tight closure so gases would not escape. The tunnel-and-pipe-seal was the third and final closure in the series. The tunnel-and-pipe-seal, positioned about 152 m (500 ft) from the working point and weighing approximately 40,823 kg (45 tons), included a massive round steel door, hinged at the roof, and held open in a horizontal position by an explosive bolt. The bolt released the 4,536 kg (5 ton) door at exactly the same time device detonation occurred, allowing the door to free fall, close, and seal the pipe in about 750 milliseconds. The purpose of the tunnel-and-pipe-seal was to prevent radioactive gases and any debris that might get past the first two closures from damaging experiments in the test chambers. The tunnel-and-pipe-seal was designed to withstand 1,000 degrees Fahrenheit and 6.9 Mpa (1,000 psi) gas pressure for a period of two hours. A decoupler was located in the line-of-sight pipe about 183 m (600 ft) from the working point, just outside the end of stemming. The decoupler was specifically designed with flexible segments to mitigate the effects of the shockwave traveling down the line-of-sight pipe to avoid damage to experiments in the test chambers. For some tests, a muffler was installed in the line-of-sight pipe near the device. This was an expanded section of pipe that created turbulence and stagnation, thereby reducing the flow of energy down the pipe.

The horizontal line-of-sight pipe, device canister (A-box), test chambers, test chamber experiment bulkheads, and vacuum systems were manufactured at the Lockheed Shipbuilding and Construction Company in Seattle, Washington. If the shipyard facilities were not available, the pipe system fabrication was subcontracted to either American Pipe and Construction Company of Portland, Oregon or Welk Brothers, Inc., of Spokane, Washington. The horizontal line-of-sight pipe system was trucked to the NNSS in sections by Widing Transportation, Inc., of Portland, Oregon. Prior to shipment, the test chambers and bulkheads were taken to the Lockheed shipyard facilities in Seattle and assembled with mock experiments (wood templates) to verify the critical fit and proper alignment. When the pipe sections arrived at the NNSS, they were transported underground on the tunnel train system for final assembly. Lockheed Missiles and Space Company provided technical guidance during the installation. Design, procurement, and shipping of mechanical closures was provided by SNL.

Data Recording

Initially, data were gathered from the underground tests by sensors and cables stretching from the experiments mounted in the test chambers and other underground instrumentation to recorders in trailers positioned outside the portal (DTRA 2002:196). Cables also extended from the nuclear device to the portal. The ability to drill large diameter holes had been developed by the time DTRA began testing at the tunnel complexes. These large diameter holes made it more economical to drill cable holes vertically into the tunnel complex from the instrument trailers on top of the mesa and install a permanent cable plant in the tunnels. This was a shorter path than to the portal and cut the costs in cable lengths. The shorter cable lengths also provided a better and faster signal to the recording instruments (Ristvet et al. 2007). All cables installed in the drill holes were gas blocked at the bottom where they entered the tunnel and at the top where they exited the hole on the mesa. The entire cable hole was grouted for containment purposes. The underground cable runs consisted of jumper cables from the experiments in the test chambers to a gas block connector in the wall of the line-of-sight pipe, and then to a signal-conditioning equipment alcove located within a few hundred feet of each test chamber. The conditioned signals were then routed via cables to the underground splice alcove at the bottom of the cable hole where each cable was attached to a gas block connector. On the mesa, one end of another jumper cable was attached to a gas block at the top of the cable hole and the other end was connected to an instrumentation trailer where the signal was recorded.

The test equipment was ready for signal dry runs following installation of temporary signal generators in the test chambers, configuration of the instrumentation equipment in the alcoves and on the mesa, and set up of the control room in the DTRA data recording station at the main control point in Area 6. Signal dry runs were necessary to work out any flaws in the instrumentation recording systems. The temporary signal generators were each activated by a timing and firing signal initiated at the Area 6 control point. The temporary signals were then sent through the entire instrumentation system to the final recording station. The DTRA scientific director was in charge the signal dry runs. The control room was operated for DTRA by Edgerton, Germeshausen, and Grier, Inc., Las Vegas. Signal dry runs were conducted until every experiment and associated recording device operated flawlessly. This process could take up to two months. The final signal dry run was referred to as the mandatory full participation dry run. Upon conducting a successful mandatory full participation dry run, the test bed was ready for installation of the nuclear device. After the nuclear device was installed, the final containment stemming operation took place.

Eventually, the original mix of cables became outdated when faster signals were required and not enough coaxial cables were available in the existing cable holes to the mesa. To satisfy the requirement, a new recording system was developed, the Recorder and Oscilloscope Sealed Environmental System (ROSES). The ROSES was a portable climate-controlled mini-version of an instrumentation trailer used underground to house electronic equipment for recording data from the experiments. As such, the system reduced the quantity of downhole cables, the number of tunnel cable runs and gas blocking, and the use of the mesa trailer park. An experiment using a single ROSES unit was conducted during the Husky Ace test in 1973 in the U12n Tunnel (Sites and Wetzel 1975). Later, multiple ROSES were employed in 1975 on the Dining Car test in the U12e Tunnel in order to validate the system during an actual test. The ROSES was designed by electrical engineer Robert L. Shirkey of the DTRA Nevada Operations Office, who was also responsible for their procurement and monitoring during their initial use. The ROSES units, holding up to six racks of electronic recording equipment, could be placed underground and closer to the test chambers than was possible with the instrumentation trailers on the surface. This allowed for faster recording of high-speed data generated from the later tests. The ROSES units were shock-mounted with crushable foam pads in a manner similar to the instrumentation trailers and anchored to the back and invert of the drift to keep them from tipping over. A 250-ton combination underground and surface chilled water system cooled the ROSES units.

The ROSES was successfully used on all tests from Dining Car in the U12e Tunnel through Midas Myth/Milagro in the U12t Tunnel. During the Midas Myth/Milagro test, the tunnel walls and roof collapsed and destroyed most of the ROSES units. Fortunately, during the interval that the ROSES units were being used, a recording system that utilized fiber optic cables was being developed. The loss of the ROSES units and final development of the fiber optic recording system coincided enough that the newer system was soon implemented. Configuration of the new fiber optic system began with data from the experiments to underground recording alcoves being transmitted primarily on fiber optic cables. In 1983, the Midnight Zephyr test in the U12n Tunnel was the first to be fully recorded using the fiber optic system (DTRA 2002:388). Instrumentation racks, assembled in groups of four to ten and mounted on wheels, were transported underground by train, offloaded at the entrance to recording alcoves, and rolled into position. The racks were shock mounted and tied off to the back and floor of the tunnel for stability during ground shock. The recording alcoves created a pressurized and sealed environment with a concrete alcove protection plug placed in the entrance to protect the recording equipment and data. An alcove protection plug, with a 91 cm (36 inch) to 122 cm (48 inch) diameter crawl tube through it for personnel access to the alcove, was built after the recording equipment was installed. The crawl tube was closed during tunnel button-up and the alcove was pressurized to five pounds per square inch prior to the test to prevent any post test residual radiation from getting into the alcove.

The data were recorded in the instrumentation alcoves and transmitted to a secondary data recording station at the portal, called a portal recording station. The portal recording station transmitted the data a distance of 32 km (20 miles) over fiber optic links to a third recording station at the Area 6 control point. There, the data were printed out soon after the test so technical personnel and test group staff could quickly evaluate the data quality and quantity. Prior to employing this new fiber optic system, along with the underground recording capability, data had to be manually retrieved from recording equipment at the portal, on the mesa, or from the ROSES underground. This type of data recovery could take days and even weeks, and sometimes the instruments recording the data were destroyed or contaminated.

Containment

Containment of tunnel tests was developed and continually refined as a result of lessons learned during postshot analyses of expended tests and the in-depth technical calculations that resulted in the design of what is described as the three nested vessel system. The first of these, Vessel I, is the horizontal and vertical region surrounding the working point and extending out for a distance of about 183 m (600 ft) to the ends of stemming in both the bypass and line-of-site drifts. It was designed to withstand the effects of ground shock and contain the cavity temperature, pressure, and radiation. Immediately following insertion of the device in the A-box, the zero room was filled with sandbags to eliminate as many voids as possible and to aid in keeping the room dry. Stemming in each drift consisted of similar types of cement grout, with stemming of the line-of-site drift normally completed two to three months prior to final button-up of the bypass drift. Three types of grout were used: rock-matching grout, super lean grout, and high strength grout. Rock-matching grout, designed to match the shock velocity and other characteristics of the surrounding natural rock, was used in the first zone of stemming extending outward from the zero room. The purpose of rock-matching grout was to allow the nuclear cavity to grow uniformly as much as possible. The next stemming section was called super lean grout. Super lean grout was designed to have the consistency and behave like toothpaste. It would easily flow when compressed by the shock wave, filling any natural or shock induced fractures in the rock. In the early development of super lean grout, sections with different colors were placed in the line-of-site drift. Reentry drifts which were mined post test to evaluate the containment design would encounter the different colors of super lean grout, thereby enabling the containment scientist to determine how far it traveled. Continuing beyond the super lean grout region was a mixture called high strength grout. High strength grout was used for the last several hundred feet or to the end of stemming and was designed to act like a high strength plug or anchor. Finally, all mechanical and electrical penetrations that exited the end of stemming were protected with redundant 1,000 psi and 1,000 degree Fahrenheit rated valves and cable connectors.

Vessel II in the nested vessel containment system included Vessel I and extended out to the overburden plug. The objective of Vessel II was to provide a larger tunnel volume to dissipate energy in case of a containment failure in Vessel I. The overburden plug was designed to contain any radioactive gases that could potentially seep from the line-of-site pipe or from the end of stemming. The overburden plug was located within the tunnel complex so that the depth of rock over the plug would have an overburden pressure equal to or greater than 1,000 psi. All electrical and mechanical features that extended through the overburden plug had gas block connectors or containment valves on both sides of the plug with a design rating of 1,000 psi and 1,000 degrees Fahrenheit for a minimum of one hour. The containment valves at the overburden plug could be opened or closed underground, from the portal, or from the Area 6 control point.

Vessel III in the nested vessel containment system included Vessels I and II and extended out to the gas seal plug usually located in the tunnel's main access drift. Its primary purpose was to ensure that no radiation escaped to the atmosphere if the first two containment vessels failed. The gas seal plug, a concrete mass approximately 4.6 m (15 ft) thick, was located within the tunnel complex so that the depth of rock over the plug would have an overburden pressure equal to or greater than 3.45 Mpa (500 psi). The gas seal plug was placed far enough away from the overburden plug to provide a tunnel volume large enough to reduce the design to 3.45 Mpa and 500 degrees Fahrenheit for one hour. The same cable connectors and mechanical valves used on the overburden plug were used on the gas seal plug, but only on the portal side of the plug.

The gas seal plug was a later addition to the containment scheme. Originally a steel door, known as the gas seal door and located closer to the portal, was used in conjunction with the overburden plug. The gas seal door was designed for 517 kPa (75 psi) for one hour. The gas seal door was closed and pressure checked for leaks just after completion of the stemming operations and prior to test zero time. After several uses, however, it was discovered just prior to a test that ground shock from the previous test had distorted the concrete and steel door frame and the gas seal door would no longer hold pressure. This created an urgent need for a new plug that had to be built before the current test could be conducted. A new concrete plug was hastily constructed between the gas seal door and the overburden plug so as not to delay the test any longer than necessary. As a result, this plug was called the "hasty plug." The name lasted until the gas seal plug concept was developed and a permanent, reuseable gas seal plug was constructed. Even though the old gas seal door would not hold pressure, it was still closed on button-up as a redundant plug to stop any debris that traveled that far.

Button-Up Activities

Tunnel button-up activities normally involved at least one representative from every agency associated with the test. Button-up normally started the day before the test, known as D-1, and extended straight through until completed, just prior to test time. The button-up team consisted of a team chief and his deputy, both of whom were DTRA personnel from the Nevada Operations Office; members of the test group directors staff, including the test construction engineer and the cable coordinator; the architectural and engineering project engineer and his deputy; the construction contractors staff, including the project manager and the mining, mechanical, and electrical superintendents; and the DOE project engineer for mining. The function of the button-up team was to verify that all experiment requirements, both mechanical and electrical, were in test configuration; all features, structural, mechanical, and electrical, were in test configuration; and that the entire tunnel complex was configured to support post test activities.

Prior to button-up, a DTRA staff engineer and the cable coordinator developed detailed mechanical and electrical systems check lists to show how the facility would be configured at test time. The button-up check lists generally filled a thick notebook binder and covered all features within the entire tunnel complex. Button-up of items and areas of the tunnel not directly related to the current test were completed on D-1. Test related activities, such as recording alcoves, were buttoned-up as the experimenters completed their activities and were ready to depart the tunnel. All other button-up activities, starting at the end of stemming in both the line-of-sight pipe drift and the bypass drift, through the containment plugs and out to and including the portal, were started as soon as the laboratory device engineers completed their work and turned the complex over to the button-up team. Construction crafts completed last minute tasks, such as closing gates, late time sandbag shielding, and removing blocks from under recording equipment racks to allow contact with the shock mounting material. At this time, the button-up team, the laboratory device arming team, and the Wackenhut Services, Inc., security force were the only people in the tunnel.

Following the arming of the device, the button-up team started working its way out the tunnel, checking every item on its respective check lists. As the button-up progressed, the security force secured areas within the tunnel. At the overburden plug, the gas seal plug, and the gas seal door, all mechanical features were closed per containment requirements (i.e., tunnel ventilation ducts, water lines, and compressed air lines). As each was closed, the status of the button-up was reported to personnel in the monitoring room at the control point. The monitoring room personnel monitored all systems and tracked the progress of the button-up team so, if necessary, a problem could be repaired before continuing. When the button-up team reached the portal, the electrical team component completed their checklists by placing the portal electrical systems in shot and reentry configuration. The mechanical team component verified that the retention ponds downslope were empty. When the button-up was completed, the team chief notified the DOE test controller's office that the team was on its way to the control point. The Wackenhut Services security force escorted the team. After a final all-is-ok meeting, the DOE test controller gave the laboratory device engineer the okay to start the final countdown.

Detonation

When the firing signal was sent to the nuclear device for a typical DTRA underground nuclear weapons effects tunnel test, there was a sequence of significant events that happened upon detonation (DOE/NNSA 2004:126-127; U.S. Congress 1989:32). The events began within a few nanoseconds of the detonation and included the prompt release of radiation down the line-of-sight pipe to expose the experiments; the mechanical closures (e.g., fast acting closure and tunnel-and-pipe-seal) were triggered; and a shockwave, essential for closing the line-of-sight pipe and containing the extremely high temperatures and pressures created in the nuclear cavity, began to expand radially from the device.

The energy of the shockwave eventually overcame the line-of-sight pipe, the surrounding super lean grout, thereby collapsing and closing the tunnel and the line-of-sight pipe before it reached the mechanical closures. The collapsing and closing of approximately the first 61 m (200 ft) of the tunnel and line-of-site pipe supported the containment of Vessel I. The shockwave, depending on the size of the test, could be monitored many thousands of miles away from the detonation point as seismic waves.

A cavity surrounding the working point was forming at the same moment the experiments were being exposed to radiation generated during the detonation and ground shock was beginning to close the line-of-sight pipe. The thermal energy reached several million degrees Kelvin and instantly vaporized the device canister, the sand bag fill, and the surrounding rock. As the cavity expanded outward it reached its maximum size when the pressure was equal to the overburden pressure of the surrounding rock. The final diameter of the cavity was therefore dependent upon both the yield and the depth of burial of the device. The expanding shockwave crushed and fractured the rock until it became so weak that it no longer had an effect on the rock. At the cavity, thermal energy melted the surrounding rock and it condensed in the bottom of the cavity. The growth of the cavity stopped when the stress field in the surrounding rock was greater than the pressure in the cavity. Within minutes and up to days following detonation, the cavity pressure decreased to the point that it no longer supported the overlying rock and the roof collapsed into the cavity void. This further weakened the rock above the cavity where additional rock collapse occurred. This process continued until the rubble-filled chimney stopped growing. The height of the rubble-filled chimney for a tunnel nuclear weapons effects test may extend to the underside of the overlying cap rock on the mesa.

Reentry and Recovery

After detonation of the nuclear device, the DOE test controller and his staff monitored the data from the remote area monitoring system units inside the tunnel and outside at the portal and on the mesa. These units detected and measured gamma radiation. The weather at the NNSS, as well as in the surrounding areas, continued to be monitored. When all conditions were correct, the DOE test controller gave permission to prepare for manned reentry to the portal area and to trailer parks on the mesa. The reentry teams assembled at the construction trailer located at the control point. Following a briefing to the teams on current status of the areas, the DOE test controller gave permission to proceed to the portal first. The portal reentry team, upon arrival at the portal, quickly assessed the condition of the area. If all appeared safe and the readings from the remote area monitoring system units were normal, the team started to reestablish the portal power. Experiment recovery teams for both the mesa and portal trailer parks would depart the control point area while portal power was being re-established. Power to the trailers on the mesa would also be re-established and data recovery would start soon after.

Tunnel reentry and experiment recovery operations required more precise industrial hygiene monitoring than most other operations within the tunnels. This was due to the potentially hazardous environment that industrial hygiene and radiation-safety personnel, construction crafts, and scientist could encounter during reentry and recovery operations. Prior to sending reentry and recovery personnel underground, the remote area monitoring system was used to determine if radiation, toxic gasses, or explosive mixtures were present and, if so, at what concentration. The health physicist then used that information to determine what level of personnel protective equipment was required to protect members of the reentry and recovery teams.

Tunnels were routinely ventilated by way of controlled releases after each test so workers could work in them without unnecessary exposure to toxic, explosive, or radioactive gases. During a controlled release, the air was discharged in measured amounts which would then be diluted by the atmosphere to trace amounts so as not to endanger anyone's health. Depending on the conditions within the tunnel and the weather for the next few days, tunnel ventilation could be re-established between the portal and the gas seal door. After ventilation, the portal reentry teams would then depart the portal area. Security would remain on the access road to both the portal and the mesa until work crews arrived the next morning. The following morning the reentry control staff would meet at the control point to assess the current status of the remote area monitoring system units in the tunnel and the weather report for the day.

During the time the reentry control staff was being briefed, the tunnel reentry teams would be getting prepared to go underground. Anti-contamination suits and self contained breathing apparatus were worn for the initial reentry into the tunnel. Three reentry teams would suit up, two for reentry and one for rescue, if required. If tunnel conditions up to the gas seal door were acceptable and permission was received from the test controller, a work team would go to the gas seal door, open it, and reestablish the rail line through it so the reentry teams could ride a train to the gas seal plug. The work team would establish a communication line so the reentry teams could maintain constant communication with the reentry control staff at the portal. Ventilation was also re-established through the gas seal door to the portal side of the gas seal plug.

As soon as the teams were suited up and ready and the gas seal door had been opened, the staff health physicist briefed them on the current status of the tunnel based on latest readings from the remote area monitoring system. When the briefing was completed and with the DOE test controller's permission, the primary reentry team would enter the tunnel and proceed to the gas seal plug using the man train. No electrical power was established until the initial reentry and tunnel condition assessment was completed. So, except for their headlamps, the reentry team worked in total darkness. At the gas seal plug, the team checked for radiation and any gases that might be present on the working point side of the plug and reported the data to the reentry control staff at the portal. With approval of the DOE test controller, the team then opened the ventilation line containment doors and reconnected the ventilation ducts so air could be circulated to the portal side of the overburden plug. The crawl tube door in the gas seal plug was then opened and the team proceeded to the overburden plug using the man train that was purposely left on the working point side of the gas seal plug by the button-up team. At the overburden plug, the procedure was repeated. The reentry team then proceeded to the line-of-sight pipe drift and the test chamber area. There they assessed tunnel conditions, took radiation and gas measurements, and checked for fallen rock, bad ground, or any other debris that could hamper experiment recovery. If all was okay outside the line-of-sight pipe and test chamber, the team remotely sampled for radiation and gases inside the pipe. If levels inside the pipe were acceptable, the team opened the test chamber doors far enough to get a quick look inside at the experiments. The reentry team then returned to the portal where they were checked for any contamination. They then removed the anti-contamination clothing, showered, and dressed. If conditions were acceptable, the experimenters would enter the tunnel to begin recovering their experiments and data.

Responsibilities

The manager of the DOE, Nevada Operations Office administered all activities at the NNSS, including real estate and facilities, support services, and the planning and execution of nuclear tests. The manager delegated authority to execute a nuclear test to a DOE test controller, who assumed responsibility for the safe conduct of the test. The test controller had authority to delay, postpone, or proceed with a nuclear test. The test controller assumed complete operational control of the NNSS during the test execution period which started the day before the test, D-1, through to completion of the initial reentry following the test. The NNSS returned to normal operations only when the test controller determined it was safe for employees and the environment.

Test group directors, appointed by DoD, DTRA, or the national laboratories (i.e., LLNL or LANL), directed the fielding and technical aspects of experiments and tests and were also responsible for compliance with applicable environmental laws and regulations. The LLNL or LANL test group director, depending on which laboratory supplied the nuclear device, assumed responsibility for radiological safety from the time the device was delivered to the tunnel until it was detonated. After detonation, the DOE test controller assumed responsibility for radiological safety until it was determined that no uncontrolled venting had occurred. The tunnel was then transferred back to the DTRA test group director for post test reentry and recovery operations.

Reynolds Electrical and Engineering Company, Inc., Environmental Sciences Department performed all radiological safety services for the tests and was accountable to each of the test group directors before and after the tests (Mullen and Eubank 1977). Agencies or experimenters with experiments on a test were responsible for design, preparation, installation, post test removal, and analyzing and reporting experiment data. Reynolds Electrical and Engineering Company, Inc., was responsible for installing and maintaining the remote area monitoring system. They also ensured calibrated radiation monitoring instruments and an adequate supply of personal protective equipment, i.e., self-contained breathing apparatus and anti-contamination clothing, were available. A log was maintained by the Reynolds Electrical and Engineering Company, Inc., lead health physicist; thereby, providing DTRA and DOE with complete documentation of the reentry and recovery operations for each test.

Fenix & Scisson, Inc., designed and engineered the tunnels and drill holes; Reynolds Electrical and Engineering Company, Inc., constructed the tunnels; and Lockheed Missiles and Space Company developed the test beds, specifically, the line-of-site pipes used to house and protect experiments, and the vacuum systems to reduce the internal pressure in the line-of-sight pipe to represent deep outer space. Holmes and Narver, Inc., and later Raytheon Services, Nevada, provided architectural and engineering services for the NNSS. They provided civil, structural, electrical, and mechanical design support for the NNSS including development of the tunnels. LLNL and LANL provided the nuclear devices, while SNL was responsible for arming and firing the LLNL devices. LANL conducted their own device arming and firing. Edgerton, Germeshausen, and Grier, Inc., supplied instrumentation for the national laboratories, while Bendix Corporation, and later Honeywell, Inc., supplied instrumentation for DTRA experiment recording. The U.S. Geological Survey, and later Fenix & Scisson, Inc., provided detailed mapping of the geology (Ristvet et al. 2007; Townsend 2007). The U.S. Army Corps of Engineers, Waterways Experiment Station was responsible for designing and developing concrete and grout mixes and for quality control during the blending and batching process in preparation for stemming placement. Reynolds Electrical and Engineering Company, Inc., performed all mining and construction and was responsible for operating and maintaining the tunnel complexes.

ENVIRONMENTAL SETTING OF U16a TUNNEL

LOCATION

The NNSS is approximately 105 km (65 miles) northwest of Las Vegas by way of U.S. Highway 95 and lies within the southern portion of the Great Basin, characterized by high mountain ranges interspersed by valleys and bolsons (Dohrenwend 1987). Climate is generally of limited precipitation, low humidity, and extreme daily temperature ranges. The lower elevations of the NNSS have dry, hot summers and mild winters, while the higher elevations have increased precipitation and lower temperatures. Most of the precipitation is in the form of snow and winter rainstorms, with an occasional storm during the fall and spring. Rainstorms do occur in the summer, but are rare. Permanent natural water sources for the NNSS are springs and seeps, and in the nearby area of the U16a Tunnel are Tippipah and Topopah springs and Wildhorse and Little Wildhorse seeps.

The U16a Tunnel complex is reached from Mercury, located toward the southeast corner of the NNSS, by initially traveling north on the Mercury Highway for about 34 km (21 miles), over Checkpoint Pass, through Frenchman Flat, over Yucca Pass, and into Yucca Flat to the Tippipah Highway intersection (Figure 1). Turning west onto the Tippipah Highway, which curves back to the north and parallels the west side of Yucca Flat, proceed another 14.8 km (8.8 miles) to where the Tippipah Highway intersects with Pahute Mesa Road in Area 1. From the intersection, travel west 6.3 km (3.9 miles) along Pahute Mesa Road to the intersection of the 16-02 road (Mid Valley Road). Turn south and travel 5.1 km (3.2 miles) to the U16a access road. Turn west and travel 1.3 km (0.8 miles) to the U16a Tunnel portal.

The U16a Tunnel portal area is on the lower flanks of the east slope of Shoshone Mountain (Figure 2) at an elevation of 1,649 m (5,410 ft). Just 0.8 km (2,690 ft) southwest of the portal is Tippipah Point at an elevation of 2,015 m (6,612 ft). Topography on the east slope of Shoshone Mountain is steep and rugged with narrow stream valleys emptying into Barren Wash in Mid Valley to the east and south. The project area for the U16a Tunnel consists of 16.7 hectares (41.1 acres), on the east slope and top of Shoshone Mountain. The principal access road leading to the U16a Tunnel is along an alluvial fan that extends from Shoshone Mountain into Mid Valley. The top of Shoshone Mountain is presently accessed from the south side using the 16-04 road which winds through a steep canyon on the west side of Tippipah Point.

VEGETATION

The project area for the U16a Tunnel complex extends from the Transition Zone into the Great Basin Desert. Vegetation around the U16a Tunnel area in the Transition Zone is classified as a Coleogyne ramosissima-Ephedra nevadensis Shrubland (Ostler et al. 2000). This shrubland occurs primarily on upper piedmont slopes such as in Mid Valley. It is dominated by blackbrush (56 percent) and lesser amounts of Nevada jointfir (*Ephedra nevadensis*), White burrobush (*Hymenociea salsola*), and Anderson's wolfberry (*Lycium andersonii*). However, fires have reduced much of the blackbrush in Mid Valley. In the higher elevations on Shoshone Mountain, the Great Basin Desert Pinus monophylla/Artemisia nova Woodland Association is found (Ostler et al. 2000). It is co-dominated by black sagebrush (*Artemisia nova*) and singleleaf pinyon (*Pinus monophylla*). Other shrubs and trees include Utah juniper (*Juniperus ostgeosperma*), green rabbitbrush (*Chrysothamnus* *viscidiflorus*), basin big sagebrush (*Artemisia tridentata*), and granite prickly gilia *(Leptodactylon pungens*).

FAUNA

Nearly 80 percent of the fauna on the NNSS consists of insects, and of these, most are ants, termites, and beetles (Castetter and Hill 1979; Greger 1994; Medica 1990; O'Farrell and Emery 1976). The more noticeable fauna near the U16a Tunnel are coyote (*Canis latrans*), badger (*Taxidea taxus*), kit fox (*Vulpes macrotis*), mule deer (*Odocoileus hemionus*), raven (*Corvus corax*), red-tailed hawk (*Buteo jamaicensis*), chukar (*Alectoris chukar*), quail (*Callipepla gambelii*), jay (*Aphelocoma coerulescens*), golden eagle (*Aquila chrysaetos*), mice (*Perognathus parvus*), kangaroo rats (*Dipodomys microps*, *Dipodomys ordii*), squirrels (*Ammospermophilus leucurus*, *Spermophilus townsendii*, *Spermophilus variegatus*), jackrabbits (*Lepus californicus*), cottontails (*Sylvilagus audubonii*, *Sylvilagus nuttallii*), lizards (*Sceloporus graciousus*, *Sceloporus occidentalis*, *Eumeces skiltonianus*), and snakes (*Chionactis occipitalis*, *Pituophis melanoleucus*, *Crotalus mitchellii*, *Crotalus lutosus*, *Crotalus stephensi*). Other animals known to occur in the region are mountain lion (*Felis concolor*), pronghorn antelope (*Antilocapra americana*), and the occasional bighorn sheep (*Ovis canadensis*).

DESCRIPTION OF U16a TUNNEL AND TESTS

The U16a Tunnel complex consists of the U16a portal and six underground drifts, U16a through U16a.06, used for nuclear and high explosive tests (Figure 3). Numerous structures and equipment were built in the portal area to support tunnel operations. These are rail lines and switches, a camel back dump to empty the trains of muck cars used to haul waste rock and debris out of the tunnel; electrical substations, air compressors, ventilation fans, water storage tanks, offices, recording stations, workshops, and storage (Figure 4). Instrumentation trailers containing data recording equipment were placed at Fort Morgan (Figure 5) on the slope above the portal face and were connected to experiments underground by way of vertical cable holes drilled into the tunnel. Additionally, timing and firing equipment was located at the tunnel portal. Two or more retention ponds were constructed downslope from the muck pile but no documentation has been found in the archives that the ponds were ever used. Also, the area in which the ponds were constructed is within a restricted area and not entered during this investigation. The Area 16 Man Camp was constructed approximately 4 miles north of 16a Tunnel to provide living facilities for the 200 men working in the tunnel (Figure 6).

Previous tunnel testing had been undertaken in Rainier and Aqueduct mesas but vacuum system design considerations for the up-coming Marshmallow test required a move to a quieter seismic area. The Marshmallow test was initially planned for the U12e.01 drift in the U12e Tunnel in Rainier Mesa. Mining of the U12e.01 drift was completed in December 1959 (Reeves 1963:11). However, because of ongoing testing in the area, it soon became apparent that the drift was unsuitable because of nearby underground nuclear tests. In late September 1961, it was decided that the vacuum system could not be maintained in the U12e.01 drift because of intense man-made seismic activity. Eventually, the Marshmallow test site was moved to the U16a Tunnel. The tunnel was closed and reopened several times between 1962 and 1973 for both nuclear and high explosive testing. Later the U16a Drift, portal side of the gas seal door, was used for high explosives tests between 1995 and 2001. Three holes were drilled between the back of the tunnel and the surface in the U16a Drift to support the latter high explosives tests.

A total of four kilometers (2.49 mi) were mined in U16a Tunnel. All mining in the U16a Tunnel was done using a common drill-and-blast technique. The first step of this technique consisted of drilling a series of horizontal holes about 3 m (10 ft) in length into the rock face. The number of horizontal holes depended on the size of the drift and ranged from an average of 35 holes for the smaller drifts to 45 holes for the larger ones (Flangas 2009). The correct amount of explosives for each hole was determined based on the skill and experience of the miners, and was usually one stick of dynamite per drilled foot. After detonation, the resulting rock rubble was mucked out to the portal by trains of muck cars on rails and deposited at the camel back dump on the edge of the muck pile. The muck pile became the portal pad and was extended as more rubble was deposited along the pad edge. The rail lines were extended further in the tunnel as construction progressed and the process was repeated after each blast. This construction method was also used during post test reentry mining.

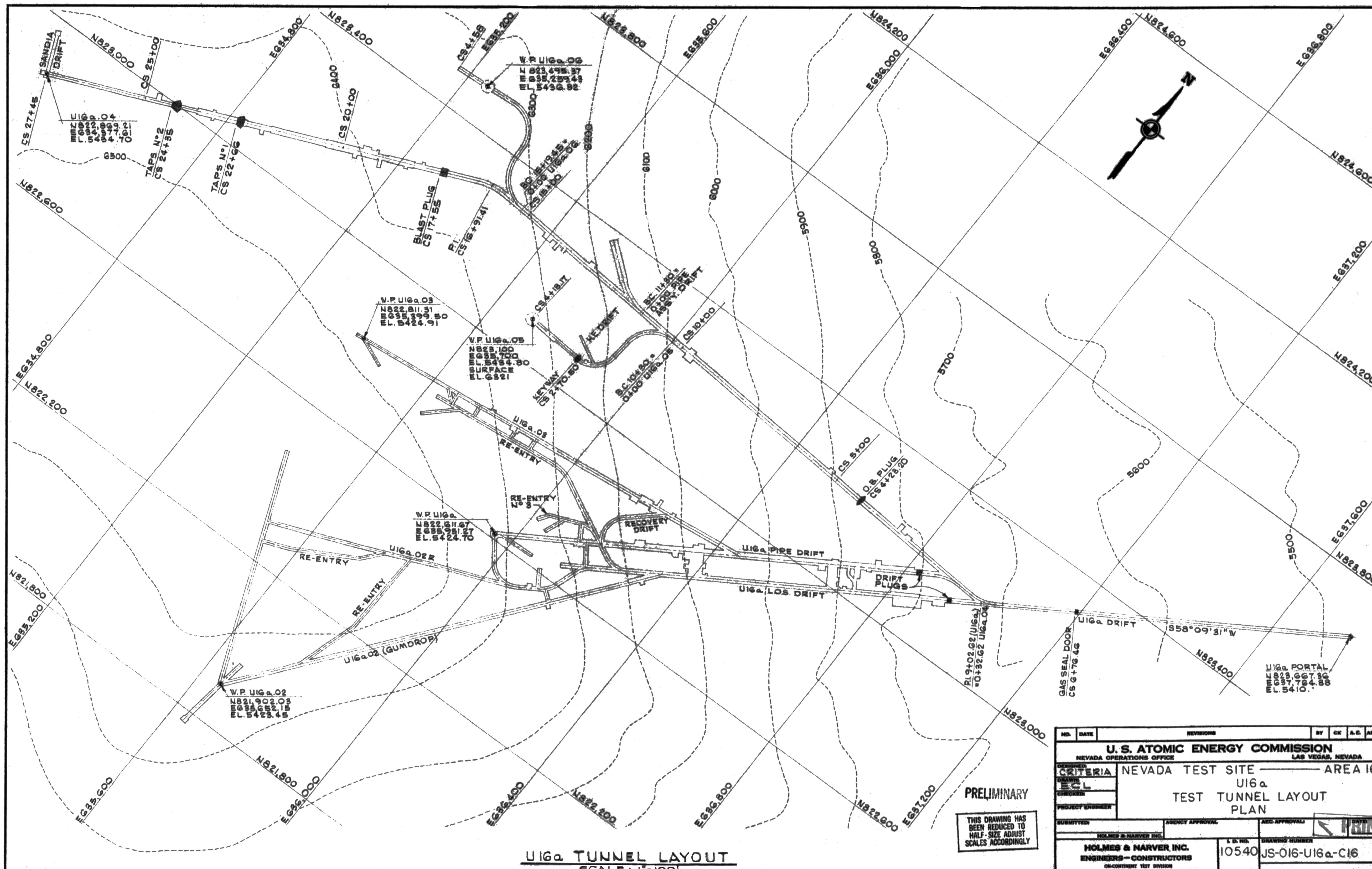

Figure 3. U16a Tunnel layout, no date (on file at the DOE Archives and Records Center).

Figure 4. Overview of the U16a Tunnel portal area, view northwest (1962 - photograph on file at NNSA/NFO Technical Library).

Figure 5. U16a Tunnel trailer park, Ft. Morgan, view southeast (1962 - photograph on file at NNSA/NFO Technical Library).

Figure 6. Overview of the Area 16 Man Camp, view west, 1962 (photograph 1314-2 on file at the DOE Nuclear Testing Archive).

A total of 6 nuclear and 15 high explosive tests were carried out in or at the portal of the U16a Tunnel (Tables 1 and 2). The nuclear tests were Marshmallow, Gum Drop, Double Play, Ming Vase, Diamond Dust, and Diamond Mine. The first nuclear test at U16a Tunnel was conducted in June 1962 and the last in August 1971. The high explosive tests were Diamond Dust and Mine Dust calibration shots; the Hard Target Defeat/Tunnel Defeat Demonstration conventional high explosive tests were completed as part of the Dipole Hail, Dipole West, and Divine Kingfisher series. High explosive testing ended in 2001. DTRA sponsored all nuclear and high explosive tests at U16a Tunnel. LLNL provided three nuclear devices and LANL provided three. The overall objective of the nuclear tests was to evaluate the weapons effects of a nuclear detonation on equipment and material with some at a simulated high altitude. The first four tests utilized a line-of-sight pipe, or pipes, in which the nuclear device was placed in an A-box attached to the small tapered end of the line-of-sight pipe. The last two tests were cavity tests. All of the tests were conducted separately. The conventional high explosive Hard Target Defeat program was an effort to detect, neutralize, and assess the damage inflicted to underground tunnel structures and assets. The following is a description of the nuclear and high explosives testing conducted at the U16a Tunnel complex.

NUCLEAR TESTS

U16a Drift - Marshmallow

The Marshmallow test was the first underground horizontal line-of-sight pipe test sponsored by DTRA. The nuclear weapons effects test had a yield of less than 20 kt. It was conducted on June 28, 1962 at 10:00 am pacific daylight time in Area 16 of the NNSS (DOE/NV 2000). The test was to determine the effects of a nuclear detonation on equipment and material at a high altitude (Brady et al. 1984). The high altitude was simulated by creating a vacuum in a dual, large diameter, line-of-sight pipe system. Alignment of the line-of-sight pipes was within 1/8 inch (0.03 cm) and the internal vacuum pressure at the time of the test was 1 micron.

The Marshmallow test was originally scheduled to occur in the U12e.01 drift at the U12e Tunnel in Area 12. Damage to the tunnel, however, during the Antler test in the U12e.03 drift on September 15, 1961 and the predicted seismic activity resulting from future scheduled testing required the project be moved to a relatively quiet area. The DASA Field Command Engineering and Construction Division of the Weapons Effects and Test Group chose Area 16 as the most suitable location. The Marshmallow test was designed to study the effects of a nuclear detonation in a high altitude environment. Marshmallow was a follow up to the LLNL's Logan test at U12e Tunnel in 1958 (DASA 1964).

For the Marshmallow test, responsibilities for the activities at the tunnel were as described previously or subject of separate actions between Field Command, DASA and the AEC. The device was provided by LLNL, EG&G provided the firing circuits and timing signals, and Sandia National Laboratory (SNL) was responsible for stemming and device arming. Experiments conducted on the test were for DTRA and fielded by the following agencies: EG&G, LMSC, Stanford Research Institute, Allied Research, American Science and Engineering, U.S. Coast & Geodetic Survey, Air Force Special Weapons Center, and Field Command, DASA. DTRA was responsible for pre-test installation and post-test removal of equipment.

Table 1. Nuclear Tests at the U16a Tunnel (DOE/NV 2000).

Test	Operation	Date	Drift	Sponsor
Marshmallow	Nougat	6/28/62	U16a	DoD/LLNL
Gum Drop	Whetstone	4/21/65	U16a.02	DoD/LLNL
Double Play	Flintlock	6/15/66	U16a.03	DoD/LLNL
Ming Vase	Bowline	11/20/68	U16a.04	DoD/LANL
Diamond Dust	Mandrel	5/12/70	U16a.05	DoD/LANL
Diamond Mine	Grommet	7/1/71	U16a.06	DoD/LANL

Table 2. High Explosives Tests at the U16a Tunnel.

Test	Date	Location
Diamond Mine Calibration Shot	2/4/71	U16a.05
Mine Dust Calibration Shot	5/10/72	U16a.05
Dipole Hail #1	5/95	Inside 16a Tunnel
Dipole Hail #2	6/95	Inside U16aTunnel
Dipole Hail #3	7/95	Inside U16a Tunnel
Dipole Hail #6	5/96	Surface above U16a Tunnel
Dipole Hail #7	6/96	Surface above U16a Tunnel
Dipole Hail #8	7/06	Surface above U16a Tunnel
Dipole Hail #18	4/2/97	Hole from surface into U16a Tunnel
Dipole Hail #20	4/7/97	Hole from surface into U16a Tunnel
Dipole Hail #21	9/16/98	Inside U16a Tunnel
Dipole West #4	3/19/99	U16a portal
Dipole West #5	5/21/99	Vent into U16a Tunnel
Dipole Hail #24	12/8/99	Above U16a portal
Divine Kingfisher #31	11/1/01	U16a portal

The Marshmallow test was designed during the 1958 to 1961 testing moratorium. The experiment stations, experiment support bulkheads, and some experiment containers were built and stored. Experiments were partially designed and also mothballed until resurrected in late 1961. Mining and construction began at 16a Tunnel in early November 1961 and the tunnel was portalled on November 27. Tunnel excavation advanced utilizing 3 shifts on a seven day a week schedule. The U16a Complex was excavated using the drill and blast technique. One new practice in the excavation was the use of air instead of drilling mud when drilling the blasting holes. The use of air greatly increased the amount of material excavated, up to 50ft (15.2 m) per day. Mining of the U16a Complex for Marshmallow was completed on March 5, 1962 and consisted of the U16a Drift, U16a line-of-sight Drift, U16a Pipe Drift, and cross cuts between the line-of-sight Drift and the Pipe Drift for a total length of 3,005 ft (915.9 m) and 28,450 yds3 (21,751.6 m^3) of rock excavated (Figure 7).

Marshmallow was a one-of a-kind test. The test bed consisted of three unique features that supported five experiment stations. The unique features included, 1) a Hohlraum; 2) a 6 ft. (1.8 m) diameter by 35.25 ft. (10.74 m) long vacuum pipe imploder; and 3) two 792.5 feet (241.6 m) long, stacked line-of-sight pipes. The first unique feature, the Hohlraum consisted of a one-half circle pipe, standing vertically, with its curved end at Ground Zero and the portal side butted against a 78.5 in. (199.4 cm) diameter flange section (Figure 8). Ground Zero, Scientific Station (SS) 0+00, was at the working point (WP) face of the Hohlraum. A four-wheeled carriage was used to move the Hohlraum into position. The curved section had two openings on the WP side. The lower one was 14 in. (35.0 cm) in diameter and the upper one was 22 in. (55.9 cm) in diameter. There were also two openings in the flange plate on the portal side of the Hohlraum that were 24 in. (61.0 cm) in diameter. The centerlines of these holes were 54 in. (137.2 cm) and 84 in. (213.4 cm) above the reference floor level. These centerlines matched all other centerlines in the entire stacked line-of-sight Pipe System. The Hohlraum section ended at SS 0+02.5 where it was attached to a vacuum pipe imploder system.

The second unique feature was a vacuum pipe imploder and it was 6 ft. (1.8 m) in diameter and 34.3 ft. (10.5m) long. It encircled the two-stacked line-of-sight pipes from SS 0+2.5 to SS 0+35.25 and it was made up of 4 pipe sections. The first, beginning at SS 0+2.5, was called Unit Section “B” and it supported the first two pipes containing the vacuum systems. The second Unit, Section “A”, was made up of the third and forth pipe sections and it housed a number of experiments. The four sections were 7.5, 10.0, 10.0, and 6.8 feet (2.3, 3.0, 3.0, and 2.1 meters) long respectively. Supporting the vacuum pipe imploder was an angle Drift that had its point of intersection (PI) at SS 0+19 on the centerline of the line-of-sight pipes. It was oriented at S 88 degrees, 9 minutes, 31 seconds W or 30 degrees clockwise from the centerline of the pipes, looking toward the portal. As measured from the PI, the drift was 80 ft. (24.4 m) long and 7 ft (2.1 m) high and 5.3 ft. (1.6 m) wide. It was lined with a 10 mil thickness of lead. The lead stopped at a point 4 ft (1.2 m) from the left side of the 6 ft (1.8 m) diameter pipe near the pipe stubs.

The third unique feature of the Marshmallow test was the stacked line of site pipe system, one pipe mounted above the other, which started 7.5 ft. (2.3m) portal side of the Hohlraum section, inside the 6 ft (1.8m) diameter vacuum pipe imploder (Figure 8). Both the upper and lower line-of-sight pipes began with outside diameters of 16 in. (40.6 cm). The diameters subsequently changed by -2, +2, +4,

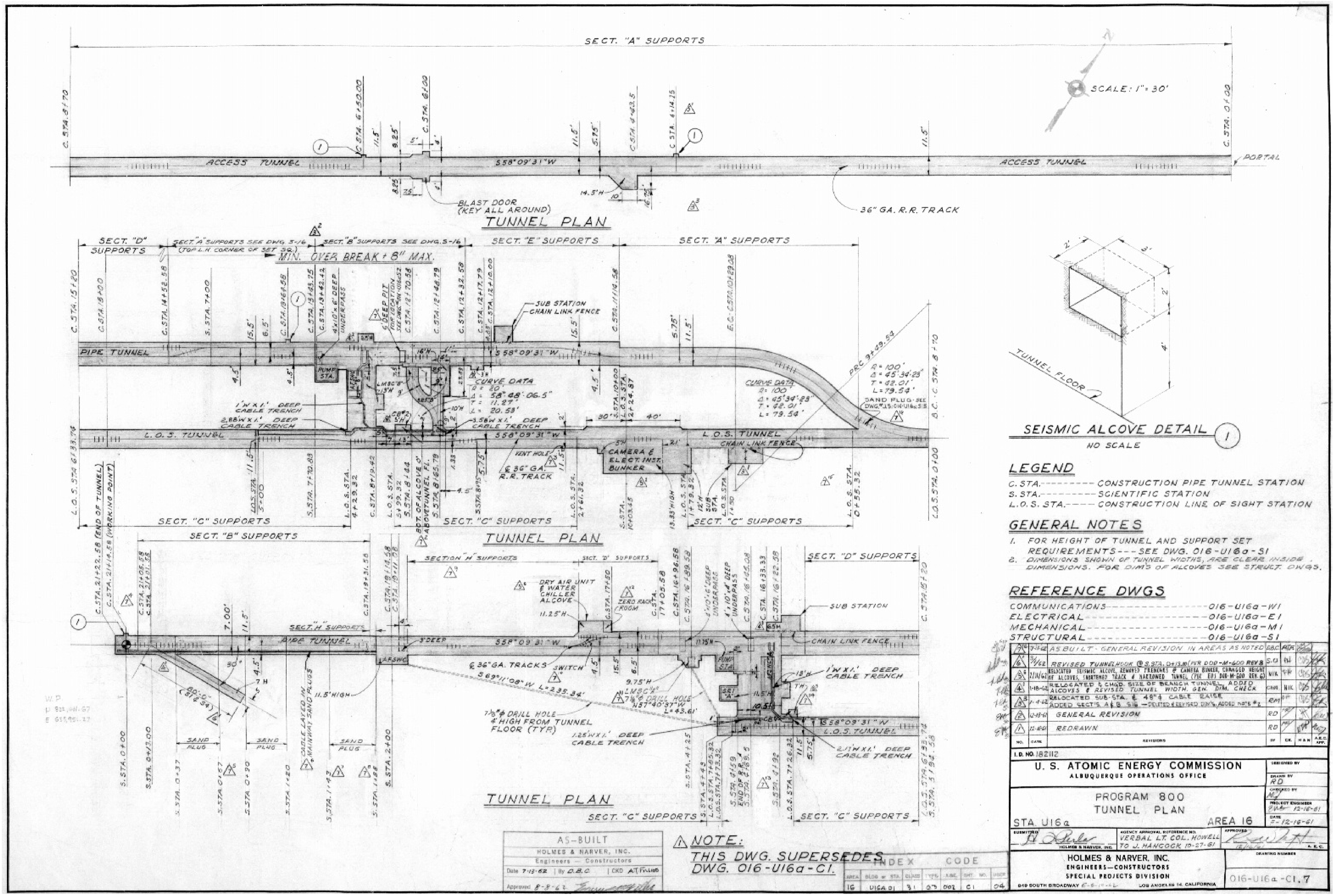

Figure 7. U16a Tunnel Marshmallow test tunnel plan (1962 - on file at DOE Archives and Records Center).

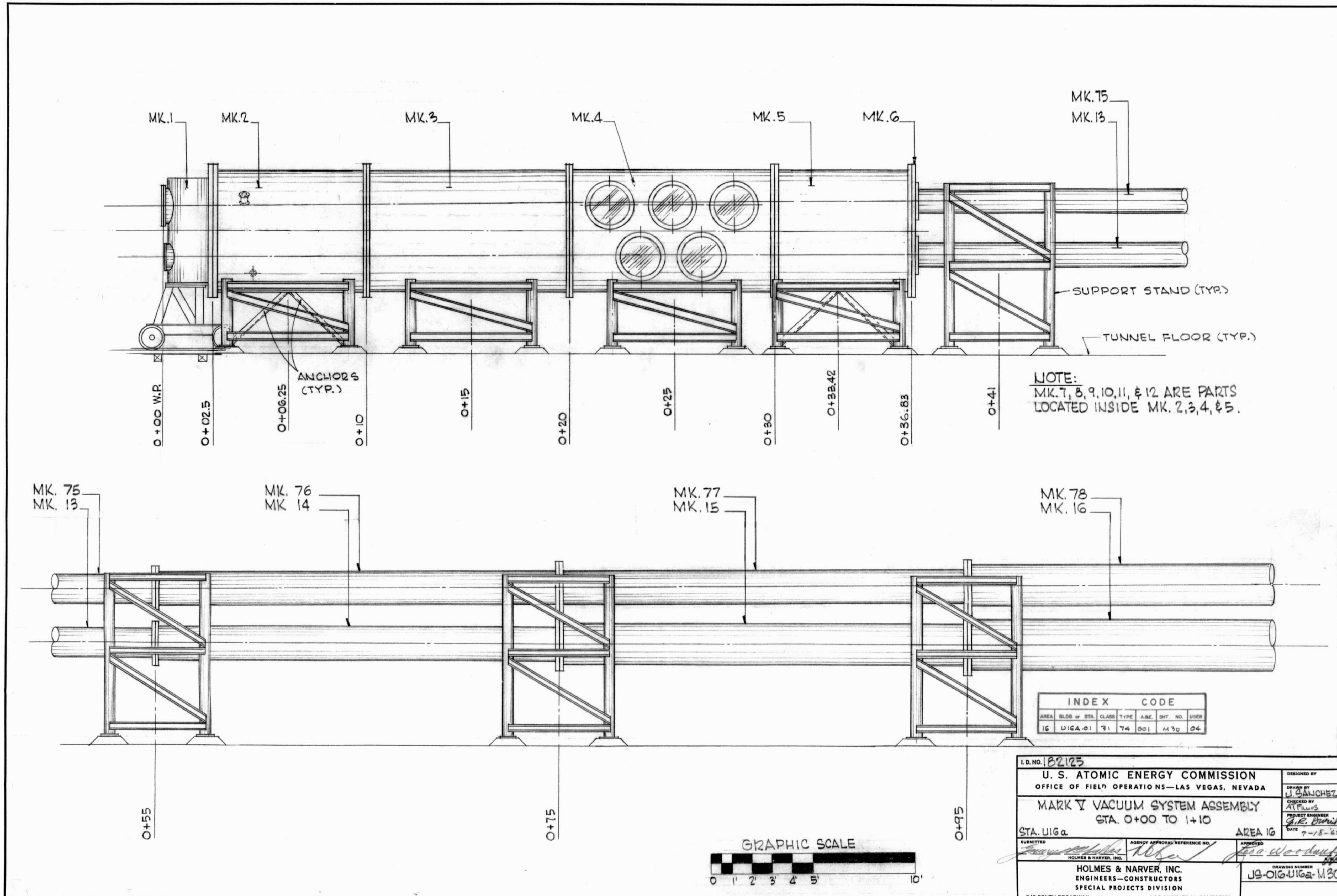

Figure 8. U16a Tunnel Marshmallow test vacuum system with Hohlraum at MK.1 (1962 - on file at DOE Archives and Records Center).

or +6 inch (-5.1, +5.1, +10.2, or + 15.2 cm) increments until the upper pipe reached 42 in. (106.7 cm) and the lower pipe reached 66 in. (167.6 cm) at SS 4+75. On the portal side of SS 4+75 the two pipes continued with a 24 in (61 cm) outside diameter for the upper pipe and a 42 in. (107 cm) diameter for the lower pipe. The diameters increased again, as before, to a final diameter of 42 in. (106.7 cm) for the upper pipe and 66 in. (176.7 cm) diameter for the lower pipe at SS 8+00. The pipe sections were moved into final position using two trolleys, one motorized and the other following to carry the load. Each pipe section had a mating flange attached to each end. The flanges had a series of bolt holes that matched the flange on the next pipe section. All the pipe sections in the system were bolted in together. Each pair of mating flanges had groves that supported an ”O” ring to seal the connection. Structural steel support stands were constructed to hold the two line-of sight pipes in their final position.

Five experiment stations were within or extended beyond the end of the two-stacked line-of-sight pipes. The first experiment station was in the third pipe section portal side of GZ within in the 6 ft (1.8 m) diameter imploder pipe. It consisted of 5 pipe stubs located on the left side of the pipe. The angle drift experiments were associated with these stubs. The second experimental station was located at SS 1+35 between the 5th and 6th pipe sections. The third experiment station had user stations between SS 4+55 and SS 4+90. It was the largest experiment station in the pipe system. The fourth experiment station was between SS 7+80 and the portal end of the two line-of-sight pipes at SS 8+00. The fifth and last experiment station was constructed from the end of the stacked vacuum pipes at SS 8+00 to where the line-of-sight pipes ended at SS 8+60. It consisted of two pipes with diameters of 35.5 in (90.2 cm) and 58.5 in. (148.6 cm). Both pipes had their lower edge mating with the lower edge of the upper and lower line-of-sight pipes that ended at SS 8+00. The primary users in the fifth experiment station were LRL with 10 locations and LMSC with 5 locations.

Each of the several hundred experiments tested on Marshmallow was housed in an individual container to protect it from the effects of ground shock at detonation time. Experiment containers mounted on bulkheads inside the four test chambers had radiation-activated tabs for closure of the container. Containers mounted on vacuum pipes that extended from the portal end of the last test chamber in the main line-of-sight pipe had High Explosive collars to close the protective containers at detonation time.

Finishing or dressing the drifts, alcoves, and shield wall; pulling instrumentation and electrical cables and installing mechanical systems required an additional 2 1/2 months (DASA 1964). The device for the Marshmallow test was placed 2,160 ft (658.4 m) from the tunnel portal with approximately 1,000 ft (305 m) of overburden (Brady et al. 1984). Electrical, water, ventilation, and recording equipment along with offices, shops, and instrument trailers were in place in early 1962 (Figure 9). Cables from the instrument trailers parked in Fort Morgan extended over the face of the slope at the portal, into the tunnel, through the Gas Seal Door, sand plugs, and blast door to instruments within the tunnel. Cable holes were drilled from the surface into the tunnel however, one hole missed the tunnel and all efforts to find where the drill was in relation to the tunnel failed. One of the miners told how cats were used in Europe to detect where two tunnels would intersect. In an effort to locate the cable hole, a cat was brought to the tunnel to detect vibrations in the rock produced during drilling (Figure 10). The cat located the drill and adjustments were made (Flangas and Wyman 2010).

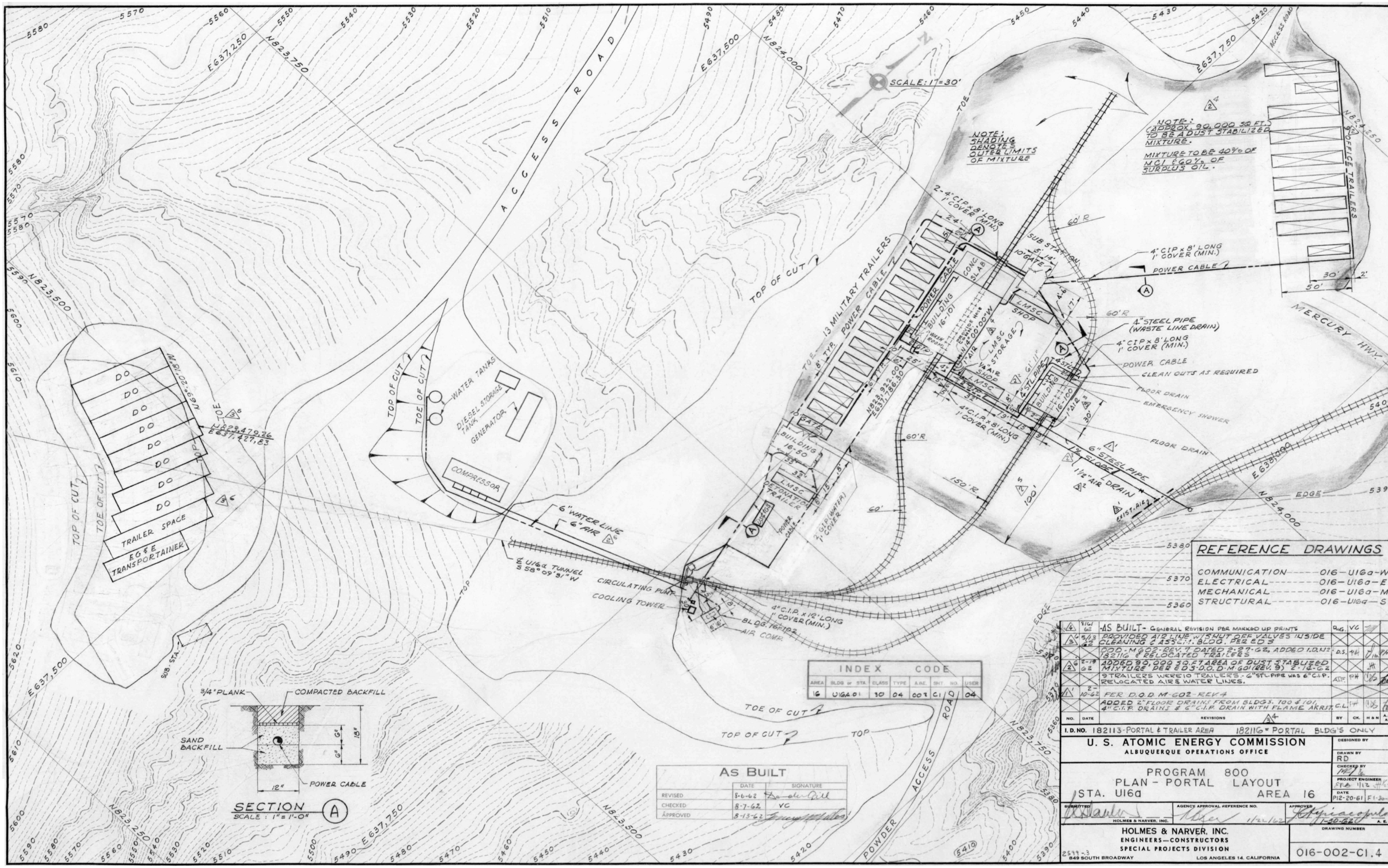

Figure 9. U16a Tunnel portal layout for Marshmallow test, 1962 (on file at the DOE Archives and Records Center).

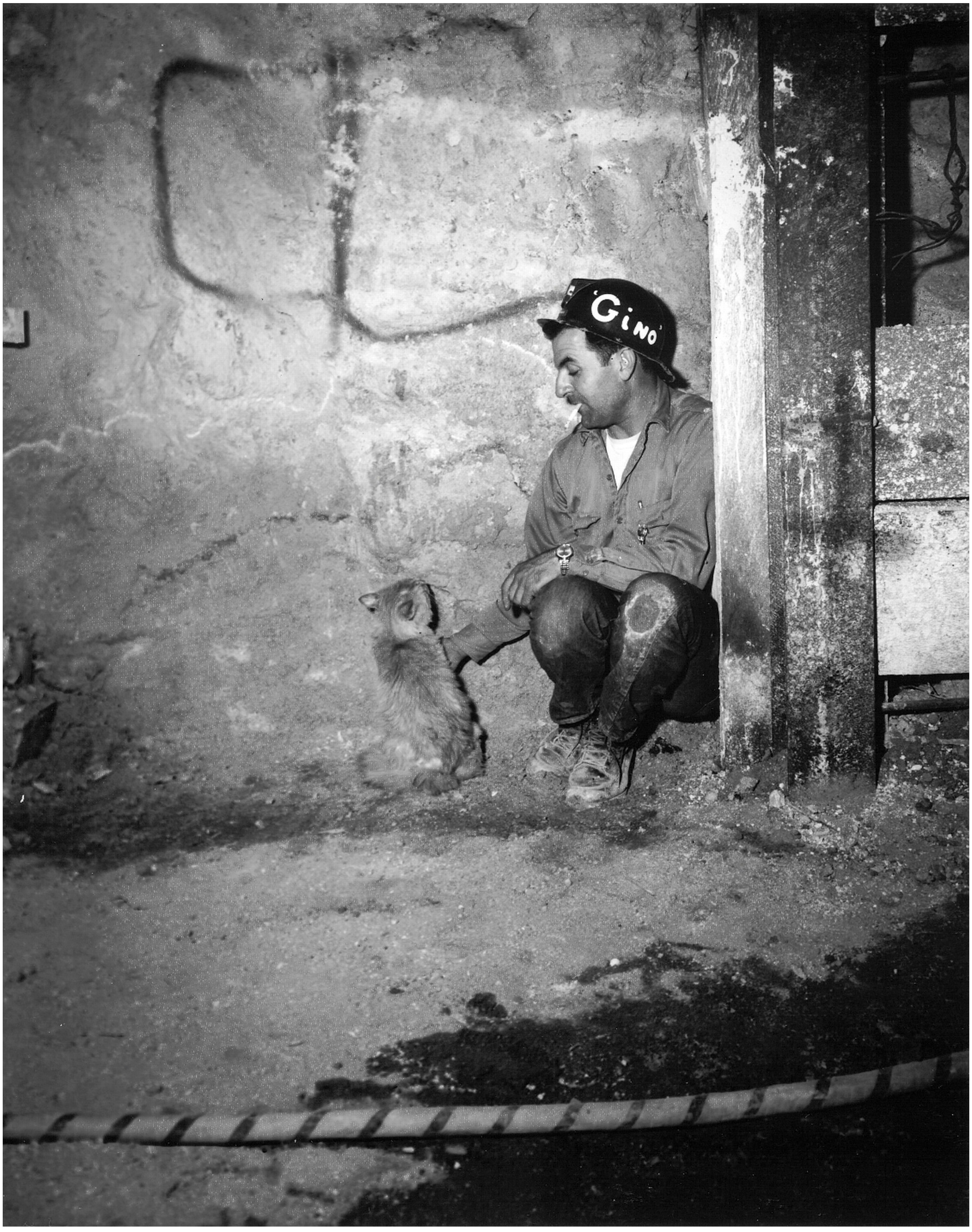

Figure 10. Cat in the U16a Tunnel Marshmallow drift (1962 - photograph on file at the NNSA/NFO Technical Library).

Upon reentry into the tunnel after detonation, all the external experiment containers were essentially in place and nearly all the internal containers were subsequently recovered. The two line-of-sight pipes in the stacked pipe system had been mounted in saddles but not anchored to the tunnel outside the stemmed area. During reentry, the upper pipe was observed to have moved approximately 15 feet toward the portal, while the lower pipe had telescoped into the experiment station bulkhead at Scientific Station (SS) 475. As a result, the lower pipe from SS 475 to SS 800 had only moved about 8 feet toward the portal. While there was little damage to the tunnel and the pipe system outside the stemmed area, recovery of the internal containers disclosed large deposits of siliceous, iron-containing slag on all vertical surfaces.

Of primary importance was the recovery of data recorded above ground as soon as possible after the test. The Marshmallow Reentry Plan and stemming design incorporated pretest and post test procedures to conduct a safe and economical reentry (Brady et al. 1984). A 14 inch (35.6 cm) diameter vertical vent hole to the surface at approximately1,000 ft (305 m) from ground zero (GZ) in the line-of-sight drift provided pressure relief, if required, to protect the blast door. A second hole, the U16a-1 vent, the same diameter, at 1,500 ft (457 m) from GZ, provided ventilation for reentry. The Y, at 1,200 ft (366 m) from the GZ, was suspected to be a weak point in the tunnel and vulnerable to collapse (Brady et al. 1984). A sand plug was installed at the Y to provide additional ground support. Access through the sand plug during final button up and reentry into the drifts was through a 6 ft diameter pipe. The pipe, with a door on the WP end, was filled with sand bags for the test. Air quality sampling post test was through the blast door and the camera bunker to test conditions forward of these points. Lead plates were placed over the camera ports after zero time to shield the film from transient radiation in the tunnel. Extra blowers for the ventilation system and the U16a-1 vent hole were available in case existing blowers were damaged during the test.

Radiological safety procedures were designed prior to the test (Brady et al. 1984). Reference information including fallout trays, radiation decay recorders, air samplers, film dosimeters, and other devices were marked on maps and positioned in the test area. Reentry routes were established and dry runs were performed. Personnel at manned stations were provided with anti-contamination clothing and equipment and Radsafe provided monitoring for aerial survey, initial surface radiation survey, and tunnel reentry teams. They also, provided emergency support, issued anti-contamination equipment, instruments and dosimeters, operated the area control stations, and performed personnel, equipment, and vehicle decontamination as required.

Telemetry support was in the form of remote area monitoring stations (RAMS) installed and calibrated at underground and surface locations (Brady et al. 1984). Within the tunnel the RAMS units were outside and inside the Gas Seal Door, outside the Y, at 1,230 ft (375 m) from GZ, in the camera bunker at cross drifts SS 8+00 and SS 8+65. On the surface the RAMS units were at the intersection of the main access road and the Forward Control Point, main access road at the portal pad, tunnel portal, 0.5 and 0.25 miles (800 and 400 m) from the trailer park, transformer station, outside and inside the trailer park, at the vent lines, and 3 mi (4.8 km) south of the portal. Telemetry was used to transmit RAMS readings to the Forward Control Point and from there they were reported by radio.

At 6:00 pm on June 27, 1962, muster and control stations were established. The main control and muster station was at the main access road approximately 5,000 ft (1,525 m) east of the portal. The manned control stations were on the Pole Line Road 2 mi (3.2 km) east of the portal, at the junction of all roads exiting Area 16 and 2,500 ft (760 m) west on the access road to the drill rig area above the U16a portal.

A Piasecki H-21 Workhorse/Shawnee Air Force helicopter with a pilot, crew chief, Radsafe health physicist, and Radsafe electronics specialist was to monitor the portal and scientific trailer areas immediately after the detonation to determine any release of radioactivity that might damage recording film. If damage did occur, the helicopter would transport recovery personnel to the trailers to recovery the film. However, the H-21 crashed at the Danny Boy crater on May 22, 1962 (Brady et al. 1984). For Marshmallow, a Marine Corps Kaman HH-43 Huskie helicopter was assigned for monitoring and possible recovery operations. Aerial survey of a possible radioactive cloud for the test was to be conducted by the U.S. Public Health Service (PHS) in an Air Force Cessna U-3A "Blue Canoe" aircraft. A DoD team in an Air Force H-21 was to fly upwind from the zero point from 15 minutes before to 45 minutes after detonation to provide photographic coverage of the area. An Air Force De Havilland L-20A (U-6A) 'Beaver' with a pilot and security officer were to perform security sweeps from two hours until 30 minutes before the detonation.

Prior to the detonation, DoD and Allied Research personnel tested voltage on power lines. LMSC calibrated instrumentation at recording trailers and conducted dry runs. Stanford Research Institute and EG&G personnel loaded film in cameras both in the tunnel and on the surface of the U16a Tunnel. They performed the final checkout of electronic equipment and monitored pumps and the vacuum system. LMSC and Special Weapons Center (SWC) personnel installed the detonators on conventional explosives systems in the tunnel. A Test Manager's weather briefing was held at 4:00 pm on June 27, 1962 and the decision was made to proceed with the final test preparations.

On D-day, LMSC and SWC completed the installation of the detonators and armed the camera and closure systems (Brady et al. 1984). Allied Research, DoD, and EG&G personnel made final checks and measurements of electrical equipment and loaded cameras and oscilloscopes. All personnel were cleared of the tunnel by 4:00 am on June 28, 1962. At 5:00 am, the arming party left for U16a Tunnel. At 7:00 am, the final weather briefing was conducted and the arming party received permission from the Test Group Director to arm the device. The arming party was in the tunnel for three hours and then returned to CP-1. At this time, the main control and muster station moved near the Forward Control Point, an observer area approximately 2 mi (3.2 km) east of the U16a portal. Manned control stations were established near Area 16 Camp and on Tippipah Springs Road on the west side of Area 16. The initial recovery parties were near the observer area east of the tunnel portal. From 8:00 am to 9:30 am, the L-20A aircraft made a final security sweep of the area to confirm no unauthorized personnel were in the vicinity. The U-3A cloud monitoring aircraft departed Indian Springs Air Force Base 40 minutes prior to detonation and the H-21 photographic helicopter was at 800 ft (244 m) above the ground and 1,500 ft (457 m) south of the U16a portal 15 minutes before zero time. The UH-43D monitoring helicopter was in the same area. The countdown began before the detonation and was broadcast via the radio. At ten minutes before the detonation, the siren at CP-1 was sounded for 30 seconds and the red lights on top of the building were turned on until after the detonation. Detonation of the Marshmallow test occurred at 10:00 am pacific daylight time on June 28, 1962 (DOE/NV 2000).

After the detonation the U-3A cloud monitoring aircraft made two passes though a small dust cloud over the U16a zero point. No elevated readings were detected. Meanwhile, the HH-43 monitoring helicopter began surveying the portal and trailer park areas. Radiation levels were less than amounts needed to damage film records and no immediate recovery was needed. An increasing level of radiation was noted near the U16a-1 vent pipe but it was more than 600 ft (183 m) upslope from the trailer park and was diluted as it moved north and did not affect the film in the trailer park. The Radiation effluent from the vent pipe and the portal moved north in a cloud toward Area 12. The cloud was monitored on its path north and ranged in size from 3 mi (4.8 km) wide north of U16a Tunnel to 4 mi (6.4 km) wide over Area 12 Camp. Telemetry units on the surface were at background until five minutes after detonation. These readings increased until 11:25 am when they decreased but fluctuated. Units at the trailer park were normal until 12 minutes after the detonation and increased into the night resulting from escaping gases from the vent pipe. The portal was normal until 15 minutes after detonation and increased until 2:30 pm. Ground radiation survey began at 10:55 am by teams dressed in full radex clothing and gas masks. Each team was equipped with explosimeters, carbon monoxide detectors, beta-gamma detectors, alpha detectors, and a velometer. The teams monitored the roads to the portal, instrumentation areas, office trailers, and near the U16a-1 vent hole area. They proceeded in vehicles along the road to the main access road and then the portal area. This survey confirmed telemetry data from recording units at all surface locations except the vent hole which were not approached. In the tunnel, telemetry units indicated background one minute after zero time except for the cross drift at SS 8+65. All units measured above background at 12 minutes after detonation and increased until 45 minutes after detonation.

Reentry on the day of detonation consisted of recovery of film records from the trailer park and near the portal. Data was recovered by 31 personnel and exposures were checked by Radsafe workers after exiting the areas. Radsafe continued monitoring telemetry equipment until 8:00 am on July 5, 1962. Radiation surveys of the U16a-1 vent hole on the surface continued and radex safety clothing was required at the portal area. Tunnel access was controlled by security personnel from 6:00 am on D-1 until D+3.

By 8:45 on D+1, all telemetry units except those at the vent pipe and inside and outside of the Gas Seal Door were at background levels. The initial reentry team consisted of a Chief of Party, radiation and industrial safety monitor, mining engineer, and miner. All were certified by the Bureau of Mines as having completed training with the two hour McCaa breathing apparatus as well as mine rescue procedures. Their equipment consisted of anti-contamination clothing, two self-reading pocket dosimeters, one two hour McCaa breathing device, a hard hat mounted miners light with battery pack, and a Mine Safety Appliances explosion proof flashlight. A second team or rescue party was on standby in case they were needed. The team entered the tunnel and proceeded to the GSD. A section of the tunnel vent line had been removed before the test at the door. The vent line had been sealed with a flange plate which was removed and the vent line was reinstalled. The team then exited the tunnel. The vent fan was turned on and radiation readings outside the GSD increased until 12:45 pm and then began to decrease. Radiation readings at the portal area after the fan was turned on increased initially but then declined steadily until June 29, 1962. Critical data recovery from the tunnel was completed on July 2, 1962, D+4. Sample recovery from the line-of-sight pipe began on July 5, 1962 and was completed on August 12, 1962. Telemetry readings were discontinued on July 5, 1962. Mining to clear debris, investigate rock stress, and explore the areas near GZ continued intermittently until August 22, 1963. Reentry revealed that the tunnel collapsed to about 300 ft (91 m) from GZ and an additional collapse occurred at 380 ft (116 m) due to a fault.

In total, 1,447 personnel were involved in entries into radex areas in the U16a Tunnel from June 28, 1962 to August 22, 1963. Personnel exposures recorded during this time were nominal and no radiation was detected offsite and no ground deposited radioactivity was detected at the work site or any other NNSS work location from the minor releases of gaseous radioactivity.

Because the surface above the trailer park consisted of loose alluvial materials, the trailers were placed within structures constructed of steel sets with wood lagging and covered by sand bags and loose soil (Figures 11 and 12). The trailer park, referred to as Fort Morgan, was respectfully named after Lt. Col. George Morgan who was the DASA Field Command manager for the Marshmallow test. After the test, the surface in the general area of the tunnel was remapped by the U.S. Geologic Survey to determine the extent and character of explosive induced fractures and other ground damage (Davis and Snyder 1962). Visible fractures in the bedrock increased from 5,675 ft (1,730 m) to 6,581 feet (2,006 m), the top of Tippipah Point. Most of the damage occurred from 6,100 to 6,200 ft (1,859 to 1,890 m) in the bedrock and are probably tension cracks that resulted from uplift on the rigid part of the slope. The cracks are generally 2 to 5 ft (0.6 to 1.5 m) long and trend parallel to the contours of the slope. The maximum vertical displacement is 6 inches (15 cm).

U16a.02 Drift - Gum Drop

The Gum Drop test was a DoD sponsored underground nuclear detonation with a yield of less than 20 kt. It was conducted at 2:00 pm Pacific Standard Time on April 21, 1965 in the U16a.02 drift (DOE/NV 2000:38) (Figures 3 and 13). Gum Drop was a weapons effects test to investigate the response of equipment and materials to a nuclear detonation (Brady et al. 1984). The device was placed at the end of a new 320 m (1,050 ft) U16a.02 drift that turned to the left from the existing U16a line-of-sight drift. The new drift housed a 244 m line-of-sight pipe that extended from the working point in a northeasterly direction and a second 195 m (640 ft) line-of-sight pipe drift extending to the north from the working point (Figure 14). A third drift for cables extended from the 195 m pipe drift to the hook on the U16a Re-Entry drift. Most of the electrical, water, ventilation, offices, and shops in place from the Marshmallow test were reused for the Gum Drop test.

The DoD Test Group Director, Air Force Colonel John (Jack) Neuer, was responsible for safe operation of all Gum Drop activities (Brady et al. 1984:176). Responsibilities of DOE and DOE contractor personnel had been established by DOE/DoD agreements. Timing and firing systems were by SNL, Edgerton, Germeshausen, and Grier, Inc. personnel armed and fired the device. SNL was responsible for the stemming design and installation of measuring devices and equipment to indicate the post test tunnel condition. DoD provided oversight for the pre- and post test installation and removal of equipment.

The Gum Drop Reentry Plan was developed for pretest preparations and post test procedures for safe and economical reentry and recovery activities (Brady et al. 1984:177). The stemming design provided for maximum safety during reentry. To provide post test data on tunnel conditions, eight tunnel condition monitors were installed within the U16a.02 drifts. Each consisted of a wooden box that could withstand considerable shock and falling debris. If the box was crushed, a plastic blade cut

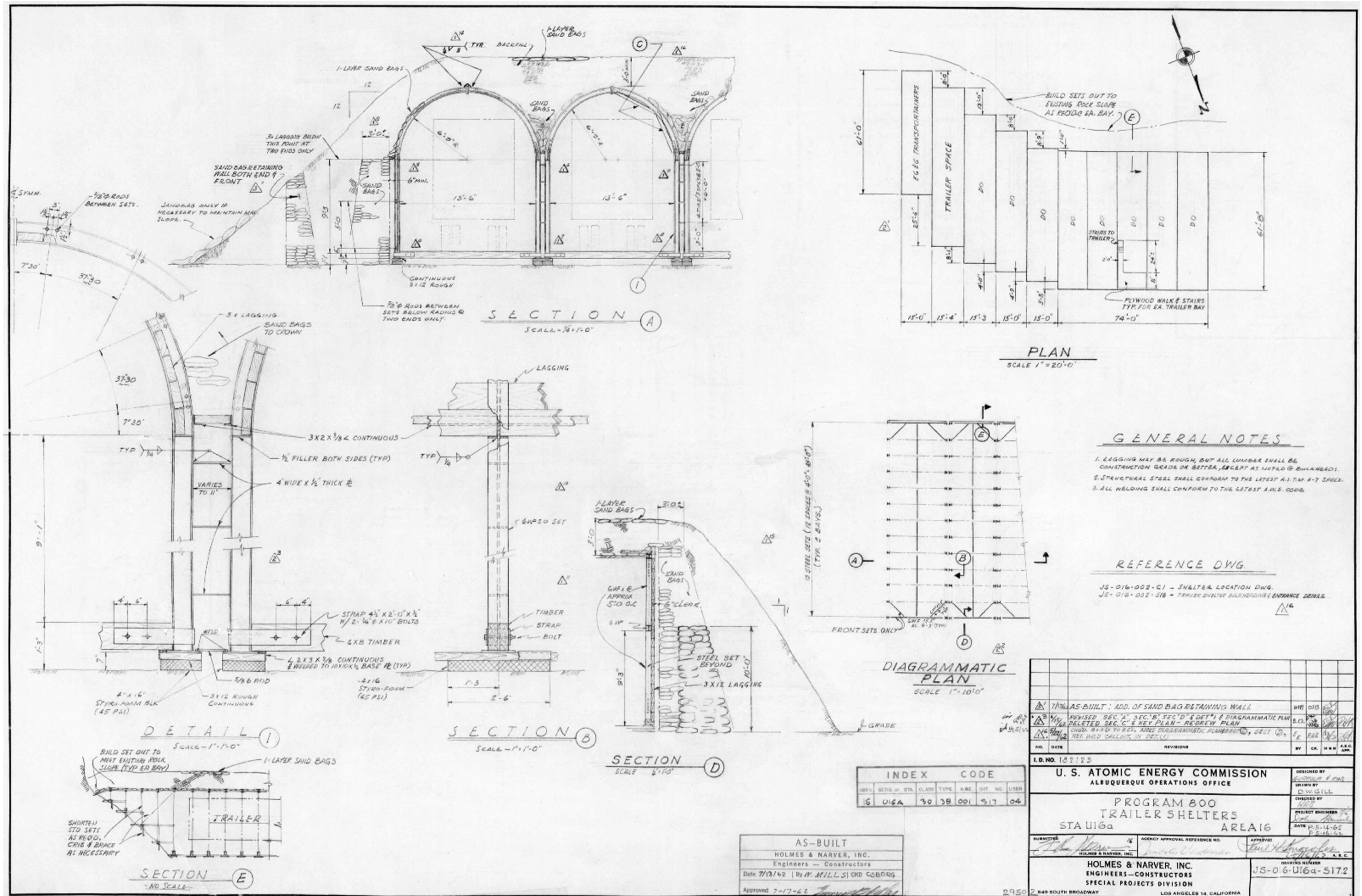

Figure 11. U16a Tunnel trailer park, Ft. Morgan, trailer shelters construction (1962 - on file at DOE Archives and Records Center).

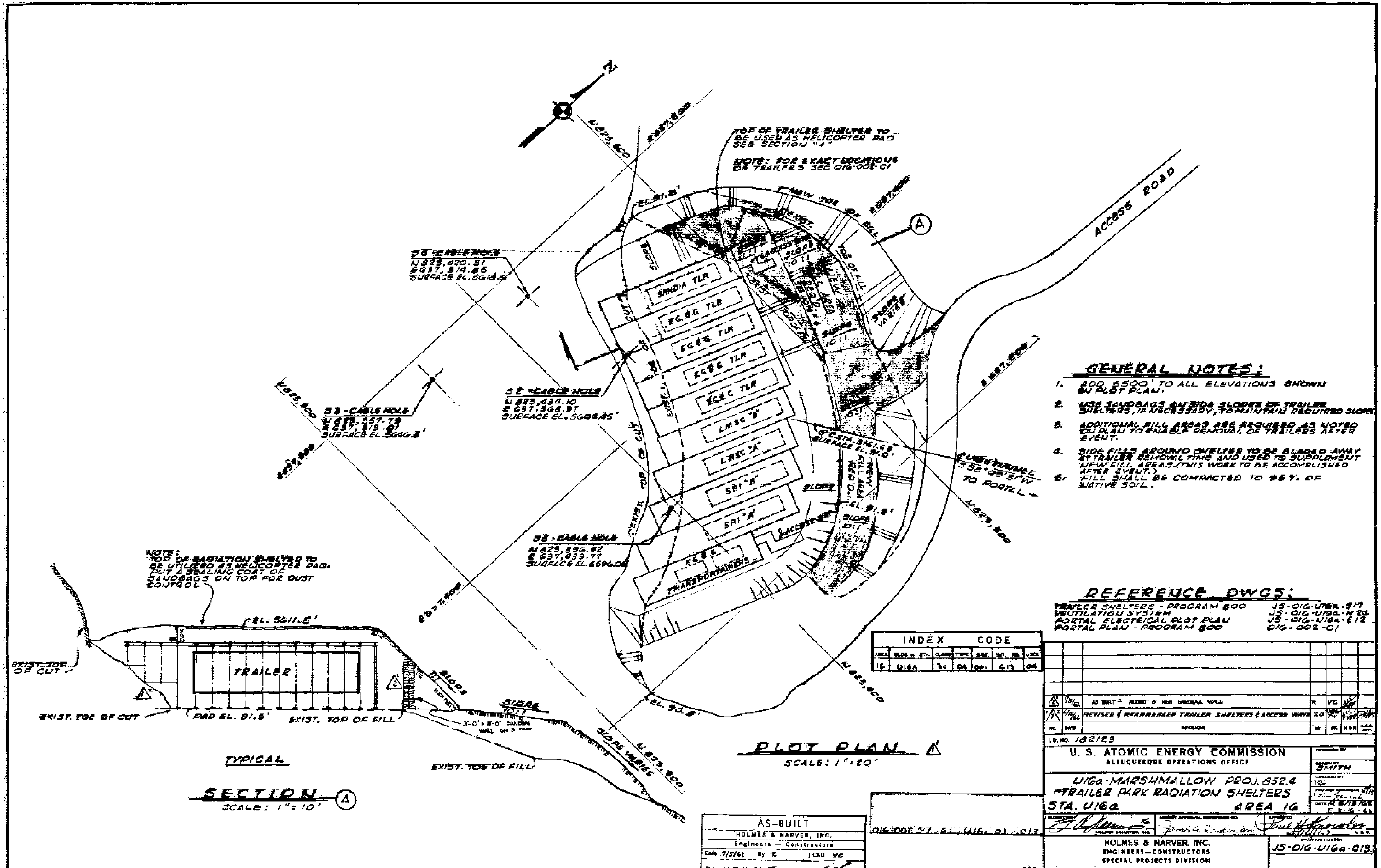

Figure 12. U16a Tunnel trailer park, Ft. Morgan, layout (1962 - on file at DOE Archives and Records Center).

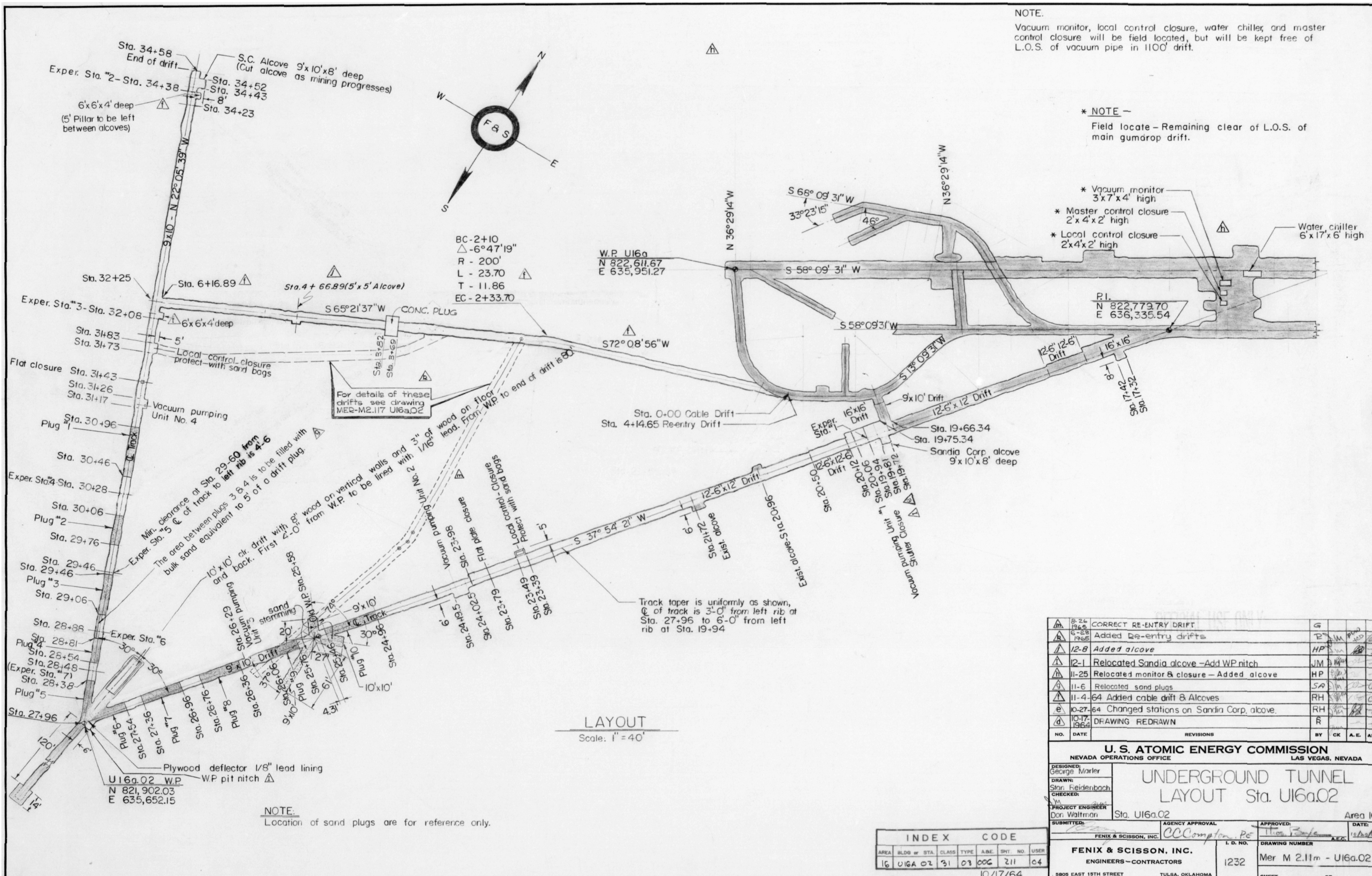

Figure 13. U16a.02 drift for Gum Drop test, 1965 (on file at the DOE Archives and Records Center).

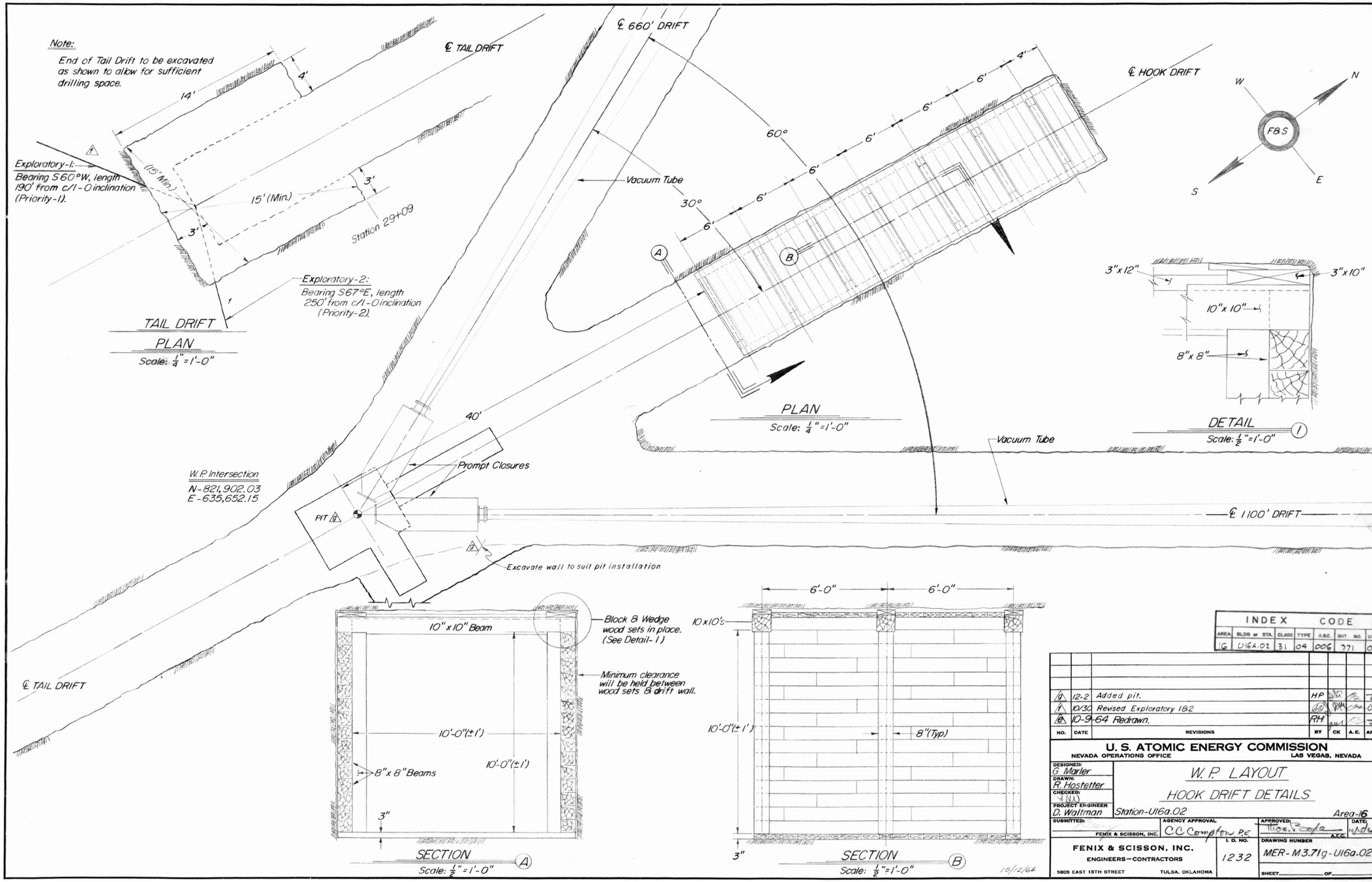

Figure 14. U16a.02 drift for Gum Drop test, working point layout, 1964 (on file at the DOE Archives and Records Center) .

the interior wiring causing a change in the circuit resistance which was detected in the reentry safety trailer. Six geophones were installed underground and two at the portal area. The phones were placed in 1.22 m (4 ft) deep in 30.5 cm (12 inch) diameter holes that were compacted with sand after installation. Signals from the geophones were received in the geophone transmitter truck located at the Forward Control Point. The signals were placed on magnetic tape and converted to analog signals that could be read visually on monitors. They were then sent by microwave link to Area 3 and finally by retransmission to CP-1.

Gas sampling lines within the U16a.02 drift consisted of 0.9 cm (3/8 inch) copper tubing. One line extended from Scientific Station No.1 and one from the working point side of the main blast door to the reentry safety trailer at the portal. Each sampling line had a 120v closed solenoid valve outside of the main blast door, an off-line 29 kg/sq cm (10 PSI) pressure gauge, and valves to control flow through the tubing. The line was tested at 585 kg/sq cm (200 PSI) for 24 hours and could have no more than a 138 kPa (20 PSI) drop in pressure. After passing the test, the lines were cleaned with chlorothene (Brady et al. 1984:180). Two other lines sampled gases from the tunnel ventilation system at the portal. The sample lines extended from the ventilation ducts to the reentry safety trailer. Shorter lines to sample gases at the portal also extended to reentry safety trailer. Pressure gauges were also placed on the working point side of the main blast door and at Scientific Station No.1 and they were read at the reentry safety trailer. Tunnel ventilation passed through two charcoal and one absolute filters. Positive displacement blowers overcame the ventilation line resistance created by the filters.

The objectives of the reentry plan were to provide qualified personnel and appropriate instrumentation to ensure the safety of personnel during post shot reentry and scientific recovery (Kingsley et al. 1966:9). Reentry plans were provided to participating agencies before the test. Maps had appropriate reference points for, location markers, radiation recorders, and air sampling equipment. Reentry routes were tested by reentry team members during pretest dry runs. Radiation monitors were briefed on surface reentry, sample recovery, and manned and security station requirements. Thirty-five telemetry stations were in operation with 9 inside the tunnel and 26 on the surface (Brady et al. 1984:181; Kingsley et al. et al. 1966:11). In the tunnel, the detectors were placed in foam jackets inside explosion proof steel boxes. The detectors were wired to the reentry safety trailer. RAMS units were placed to detect airborne radioactivity and fallout in case of venting for Test Ban Treaty compliance. The surface air sampling units were placed on the surface based on terrain and practicality of installation and surface meteorology predicted at the time of the test. These were placed and activated three hours prior to the detonation by RADSAFE personnel. All personnel at manned stations were provided with appropriate anti-contamination clothing and equipment. RADSAFE provided monitoring teams and supervisory personnel for surface and aerial radiation surveys and tunnel reentry teams. RADSAFE also provided radiation surveys, issued anti-contamination clothing, equipment, portable instruments, dosimeters, performed decontamination procedures on personnel and equipment, and provided emergency rescue and support as needed.

Approximately 2.4 km (1.5 miles) east of U16a Portal, a muster station was established on test day and a control station was manned on the Area 16 Road south of the Area 16 Man Camp. Three hours before zero time, all personnel were cleared from the area except the arming party and others that were authorized to be in the area. From 2 hours to 30 minutes before zero time, an L-20A aircraft made a final security sweep of the area. A De Havilland U-6A Beaver aircraft performed a Air Force photography mission and the UH-43D helicopter flew a DoD photography mission. The L-20A then performed aerial surveys while two Beechcraft C-45 Expeditors and a U3A aircraft did cloud tracking. The post test American Aerial Survey was undertaken in a Cessna 185.

On the day of the test, SNL personnel installed and performed maintenance of instrumentation, made final adjustments on geophones, and checked instruments in the portal area. Edgerton, Germeshausen, and Grier, Inc. had set up recording trailers at Ft. Morgan above the portal and checked monitoring equipment in the tunnel and on the surface. Stanford Research Institute, Lockheed Missiles and Space Company, and LLNL personnel performed calibration checks, activated equipment, and button up activities. DoD coordinated overall activities and inspected the tunnel, portal area, and forward control point.

The security muster station was activated at 2:00 am and, at 4:45 am, a security sweep of the area was started. Permission to arm the device was given by the DOE Test Manager and the arming team entered the tunnel at 6:20 am. A final weather briefing was conducted at 8:00 am. The test was scheduled for 10:00 am but delayed for four hours (no reason given). The countdown began on the radio at 10 minutes before detonation, the siren on CP-1 ran for 30 seconds, and the red lights on the building were turned on until after the detonation. Detonation for the Gum Drop test was at 2:00 pm on April 21, 1965 (DOE/NV 2000:38).

At zero time, a cloud of dust was observed that moved north to northeast. The cavity collapsed but containment was successful. This was verified by four passes of the U3A aircraft at 1,798 m (5,900 ft) that initially entered the cloud between 2:02 and 2:05 pm. Surface ground zero for the test was monitored at 2:06 pm at 2,042 m (6,700 ft) with negative results. Additional passes over the portal area and in the general vicinity produced background readings. Flights were stopped at 2:45 because of severe turbulence. All RAMS stations, except 1 through 4, provided background readings to pretest background levels within 20 minutes of the detonation. Gaseous products generated by the detonation had entered the tunnel but diffused in the 800 ft (244m) long line-of-sight pipe drift. Detectors in the 195 m line-of-sight pipe drift indicated a shorted condition due to rock spall in the drift inside of the concrete plug (Brady et al. 1984:187). No radioactivity was recorded above background levels on or off site by ground or aerial monitoring or by dose rate recorders or environmental samples.

The tunnel condition monitors indicated normal conditions. None of the monitors had been crushed. Debris fell on tunnel condition monitor number one, but it remained undamaged. After zero time signals had ceased, all was quiet until 6 minutes after detonation when sporadic signals were received and a large signal was received at 7 minutes and 35 seconds after detonation indicating the collapse of the cavity. At zero time to 4 minutes after detonation, gas samples were drawn from the two tunnel vents that detected only oxygen, nitrogen, and ethane gases. At 1 hour and 20 minutes after detonation, power had been restored and samples were taken from the working point side of the gas seal door at Scientific Station No.1. Several gases were present but in less than explosive amounts. Samples from the blast door were less than lower explosive limits and returned to normal before 2 hours and 30 minutes after detonation when the monitor was turned off in preparation for initial reentry. No change in ambient pressure was noted after zero time.

At 2:40 pm, two RADSAFE parties in vehicles were released to enter the area. They proceeded from the Forward Control Point to the Area 16 main road and then to the tunnel portal area. One team surveyed the portal entrance and the portal area. The second party proceeded to the Ft. Morgan trailer park and the road to the post test drill hole. After survey, both parties returned to the temporary mobile check station. The initial surface radiation survey began at 2:44 pm and ended at 2:49 pm. All measurements were at background radiation levels. After the initial survey, recovery teams from Edgerton, Germeshausen, and Grier, Inc., LLNL, SNL, Stanford Research Institute, Lockheed Missiles and Space Company, and Air Force Special Weapons Center began to collect critical data. At 5:30 pm the tunnel ventilation was turned on before reentering the tunnel. A controlled release of radioactivity, mainly noble gases, through filtered lines was accomplished between 3.5 and 44 hours after detonation. There was some indication that re-suspended fission products from the Marshmallow test were detected during the release.

At 5:45 pm on April 21, 1965, the reentry team was cleared by the DoD Test Group Director to begin the initial entry into the tunnel (Brady et al. 1984:191; Kingsley et al.1966:19). The initial reentry team consisted of a Chief of Party, a radiation safety and industrial hygiene monitor, a mining engineer, and a miner. All were certified by the Bureau of Mines, having completed training with the two-hour McCaa breathing apparatus as well as mine rescue procedures. Their equipment consisted of anti-contamination clothing, two self-reading pocket dosimeters, one two-hour McCaa breathing device, a hard hat mounted miners light with battery pack, and a Mine Safety Appliances explosion proof flashlight. A second team or rescue party was on standby in case they were needed. The team proceeded to the blast door, monitoring for radioactivity and toxic gases. They opened the blast door and went to Experiment Station No.1. All equipment at the station was checked and they continued forward within the tunnel past the cable drift up to the concrete plug. After checking for radiation and toxic gases, they began their exit checking tunnel conditions and monitoring for radioactivity and toxic gases as they proceeded. The team was in the tunnel for one hour and 28 minutes. At 7:45 pm on the day of the detonation, one scientific reentry team entered the tunnel, followed by a second at 11:45 pm. The first team recovered dosimetry at Experiment Station No.1 and exited the tunnel. The second team was to do extensive recovery but experienced technical difficulties and exited the tunnel.

Recovery of data and instruments continued on the days following the detonation. Reentry into the pipe drift was not a priority and was not a part of the early recovery schedule. Samples were taken through the concrete plug in the cable drift and the blast door was opened. The area was checked for hazards of which none were found. RAM telemetry readings were terminated on April 24, 1965. Post test drilling began on April 27, 1965 above the tunnel complex. Three holes were drilled to obtain samples from the cavity area.

U16a.03 Drift - Double Play

The Double Play test was a DoD sponsored underground nuclear detonation with a yield of less than 20 kt. It was conducted at 10:00 am Pacific Daylight Time on June 15, 1966 in the U16a.03 drift (DOE/NV 2000:42) (Figures 3 and 15). Double Play was a weapons effects test to investigate the response of equipment and materials to a nuclear detonation (Horton et al. 1987). The device was placed at 323 m (1,061 ft) within a 328 m (1,076 ft) long drift that turned to the right from the

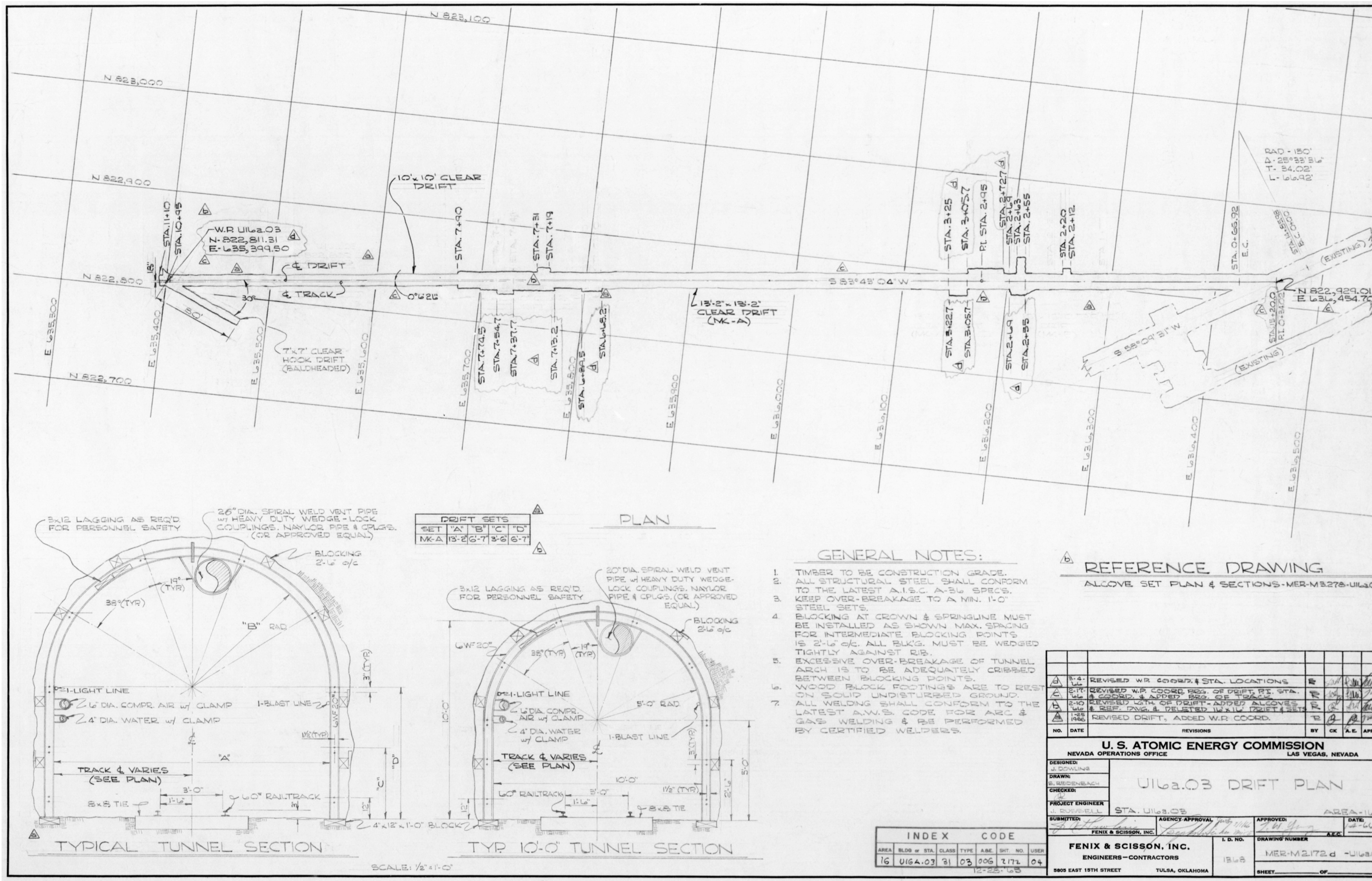

Figure 15. U16a.03 Double Play drift plan, 1966 (on file at the DOE Archives and Records Center).

existing U16a pipe drift. Most of the electrical, water, ventilation, offices, and shops were re-used from the earlier tests. The DoD Test Group Director, Ben Grody, was responsible for safe operation of all Gum Drop activities (Horton et al. 1987:142). Responsibilities of DOE and DOE contractor personnel had been established by DOE/DoD agreements. Lawrence Livermore National Laboratory was responsible for the device and surface drill back, SNL and DoD provided the post test recovery, and DoD provided oversight of the pretest installation and post test removal of equipment.

The Double Play Reentry Plan was developed for pretest preparations and post test procedures for safe and economical reentry and recovery activities (Horton et al. 1987:144). The stemming design provided for maximum safety during reentry. Test area maps were marked with location points, radiation recorders, and air samplers. Reentry routes were established and radiation monitors were briefed on procedures and requirements. Anti-contamination materials were provided to appropriate personnel, surface and aerial radiation survey and reentry parties. Thirty-five RAMS units were calibrated and placed with 9 inside the tunnel and 26 above ground at various locations. Air sampling was conducted at 19 trailers on the surface. Muster and control stations were established on the day of the test. Security by Wackenhut Security Inc. was controlled by administrative controls and physical barriers. A UH-43D helicopter manned by personnel from the Army Pictorial Center provided the aerial still photography at 457 m in elevation and upwind from the tunnel (Horton et al. 1987:148). A U-6A aircraft manned by Lookout Mountain Air Force Station personnel took motion picture footage at 914 m in elevation. The United States Public Health Service provided a U-3A and C-45 aircraft for cloud tracking with a Turbo Beechcraft (possibly a T-34C Turbo Mentor) on standby if needed. Wackenhut Security Inc. used a U-6A aircraft for security sweeps with a UH-43D helicopter on standby. Edgerton, Germeshausen, and Grier, Inc. /Nevada Aerial Tracking System had a Martin 4-0-4 on standby if needed for cloud tracking.

On the day of the test from 12:01 am to 6:40 am, RADSAFE began air sampling at the trailers, Lockheed Missiles and Space Company checked pumps and television systems in the test chamber and assembly building, Edgerton, Germeshausen, and Grier, Inc. checked photographic stations, SNL made instrument checks at recording trailers and within the tunnel, and General Electric personnel checked out instruments. DoD personnel checked cables at the test chamber, made instrument checks, and inspected the tunnel and portal area. Stanford Research Institute personnel completed their operations. The arming party entered the area at 3:05 am and Wackenhut Security Inc. checked the area at 6:40 am to make sure only the arming party was in the area. A briefing was conducted at 8:00 am and permission was given to arm the device. The U-6A aircraft made security sweeps 30 minutes before the scheduled detonation. The device was armed and the arming party left the area at 9:26 am. At 10 minutes before the detonation, the siren at CP-1 was sounded for 30 seconds and the red lights on top the building were turned on until after the detonation. Detonation for the Double Play test occurred at 10:00 am Pacific Daylight Time on June 15, 1966 (DOE/NV 2000:42).

Test area monitoring began at 10:01 on June 15 and continued until 10:00 pm on July 11, 1966. Four effluent releases were monitored. Initial radiation surveys began at 11:07 am and ended at 11:16 am on D-day. Two RADSAFE teams proceeded from the Forward Control Point along the access road to Area 16 and then to the portal area. One team surveyed the portal area and the second team surveyed the Ft. Morgan trailer park. They both returned to a preestablished point outside the radiation exclusion area by the office trailers.

Four effluent releases followed the Double Play test (Horton et al. 1987:150). The first at 2 minutes after detonation was through the cable hole used during the Marshmallow test. A work party was sent in to apply water glass (sodium metasilicate, Na2SiO3) to the leaks at 7:45 am, June 16, 1966. Normal radiation background readings were reached by 5:00 pm on June 19, 1966. The second release was through the portal and began at 10:05 am on June 15. It continued until 11:51 on June 17, 1966, when the tunnel ventilation was turned on. Radiation readings steadily decreased to normal at midnight on July 1, 1966. The third release was on June 17, 1966, at 11:51 am when the tunnel ventilation was turned on and it continued until 1:36 pm on the same day, when the system was turned off. The last release began when the ventilation system was restarted at 3:36 pm on June 17, 1966, to expel explosive gases that had accumulated in the tunnel complex. The ventilation continued until 9:00 am on June 18, 1966. RAMS telemetry was discontinued at 10:00 pm on July 11, 1966.

Forty-five minutes after detonation, recovery teams retrieved film and tape at the portal area. The portal and reentry safety trailer were surveyed and all activities were completed by 11:35 am. Due to the presence of radioactive effluent, the area was cleared and surveillance was continued. Recovery parties reentered the area on June 16, 1966, and removed cameras from the Edgerton, Germeshausen, and Grier, Inc. bunker. The Edgerton, Germeshausen, and Grier, Inc. /Nevada Aerial Tracking System aircraft made contact with the effluent cloud 14 minutes after detonation at 2,286 m (7,500 ft) one-half mile south of Tippipah Spring Horton et al. 1987:155). The cloud dissipated within 322 km (200 mi) northeast of the test location where normal radiation levels were recorded (Horton et al. 1987:156). Further tracking was discontinued due to adverse weather conditions. The United States Public Health Service made two aerial sampling flights on D-day to detect the effluent cloud and determine its volume. Elevated readings were detected but only within 37 km (23 mi) of the portal.

On July 12, 1966, initial tunnel reentry began at 10:45 am and was completed by 12:10 pm (Horton et al. 1987). A second reentry was started at 3:00 pm and completed by 3:33 pm. At 3:40, a third party, data recovery, entered the tunnel and recovered tapes and cameras from the alcove at 495 m (1,624 ft) within the tunnel. Washing down the tunnel began on July 12, 1966 and was completed the next day. The washing was to settle dust and reduce contamination. Sand was spread on the floor at the blast plug.

A reentry party took radiation readings at the blast door on July 14, 1966, and recovered film and other samples. Wash down was undertaken at the Gum Drop and Marshmallow Y. On July 18, 1966, a new crew was brought in because personnel from the first party were reaching their maximum quarterly exposure level. General Electric personnel and miners recovered equipment at the 495 m alcove on July 19, 1966. A vent line through the overburden plug was completed on July 19, 1966 and from July 21 to July 28, the tunnel was washed down and sand spread on the floor.

On July 28, 1966, the blast door was opened by a reentry party who installed an electrical supply line for the air sampler at the test chamber. No toxic or explosive gases were detected, but radiation levels were elevated. The test chamber was entered at 11:00 am by the Test Group Director and a recovery party to take photographs of the chamber (Horton et al. 1987:159). Damage to the Gum Drop reentry drift was investigated on July 29, 1966. Waterglass was sprayed on the ribs and back of the tunnel from the gas seal door to the Y. A second party entered the test chamber on August 2, 1966, and detected no toxic gases or explosive mixtures beyond the blast door in the line-of-sight pipe. Experiment recovery from the test chamber began on August 3, 1966, at 10:30 am and was completed by 3:25 pm. The line-of-sight pipe was inspected beginning at 10:22 am and completed by 10:50 am on August 10, 1966. A Lockheed Missiles and Space Company team proceeded 9.8 m (32 ft) beyond the blast door in a recovery operation at 12:10 pm on August 15, 1966, and a second team recovered additional experiments at 2:45 pm. No further recoveries were undertaken until September 16, 1966, when Lockheed Missiles and Space Company personnel removed two cameras from the test chamber. Additional recovery activities by DoD, Lockheed Missiles and Space Company, and SNL personnel continued through September 23, 1966. The test chamber was secured on that date. Work continued into the Double Play drift on October 7, 1966 and samples were recovered on October 20 and 21, 1966 by DOD, Ken O'Brien Associates, and SNL personnel. Photographic documentation was by DoD personnel. On October 25, 1966, a SNL party reentered the tunnel, inspected the Double Play test chamber, reentry drifts (1, 2, and 3), and alcoves (1-5). On November 14, 1966, a gate was placed at the entrance to the Marshmallow drift, a second gate and radiation signs were placed at 342 m (1,125 ft) in the 16a Drift (Horton et al. 1987:160). On July 22, 1966, drilling for post shot hole PS #1A began to recover melt samples for analysis. The hole was drilled to 364 m (1,195 ft) with directional surveys and gamma logging accomplished as it was drilled. It was closed on July 28, 1966. RADSAFE support at the tunnel for the Double Play event was discontinued on December 2, 1966.

U16a.04 Drift - Ming Vase

The Ming Vase test was a DoD sponsored underground nuclear detonation with a yield of less than 20 kt. It was conducted at 10:00 am Pacific Standard Time on November 20, 1968 in the U16a.04 drift (DOE/NV 2000:52) (Figures 3 and 16). Ming Vase was a weapons effects test to investigate the response of equipment and materials to a nuclear detonation (Horton et al. 1985:157). The Working Point was at 838 m (2,745 ft) within the 839 m (2,752 ft) U16a.04 drift that turned to the right starting at the Marshmallow pipe drift (Figure 17). Most of the electrical, water, ventilation, offices, and shops were in place from the earlier tests.

The DoD Test Group Director was responsible for the safe operation of all Ming Vase activities (Horton et al. 1985:157). Responsibilities of DOE and DOE contractor personnel had been established by DOE/DoD agreements. LANL provided the device and the LANL Test Group Director was responsible to the DOE Test Manager for a 1,372 m (4,500 ft) area around ground zero. This was in effect from the time the device was placed within the tunnel and ended with its detonation. At zero time, the DOE Test Manager relieved the LANL Test Group Director of his responsibility and placed the DoD Test Group Director in charge. DoD managed the pretest installation and post test removal of equipment.

During construction, sand stemming and plugs along with concrete blast plugs were emplaced within the tunnel. These were to contain any radioactivity and minimize reentry problems. Blast doors within the line-of-sight pipe were designed to contain any debris that might get past the line-of-sight pipe closures. RAMS units were placed within the tunnel and on the surface to monitor tunnel and area conditions. Appropriate safety measures were taken to protect mining and laboratory personnel. Industrial safety codes, mining codes, tunneling, and drilling procedures were established by

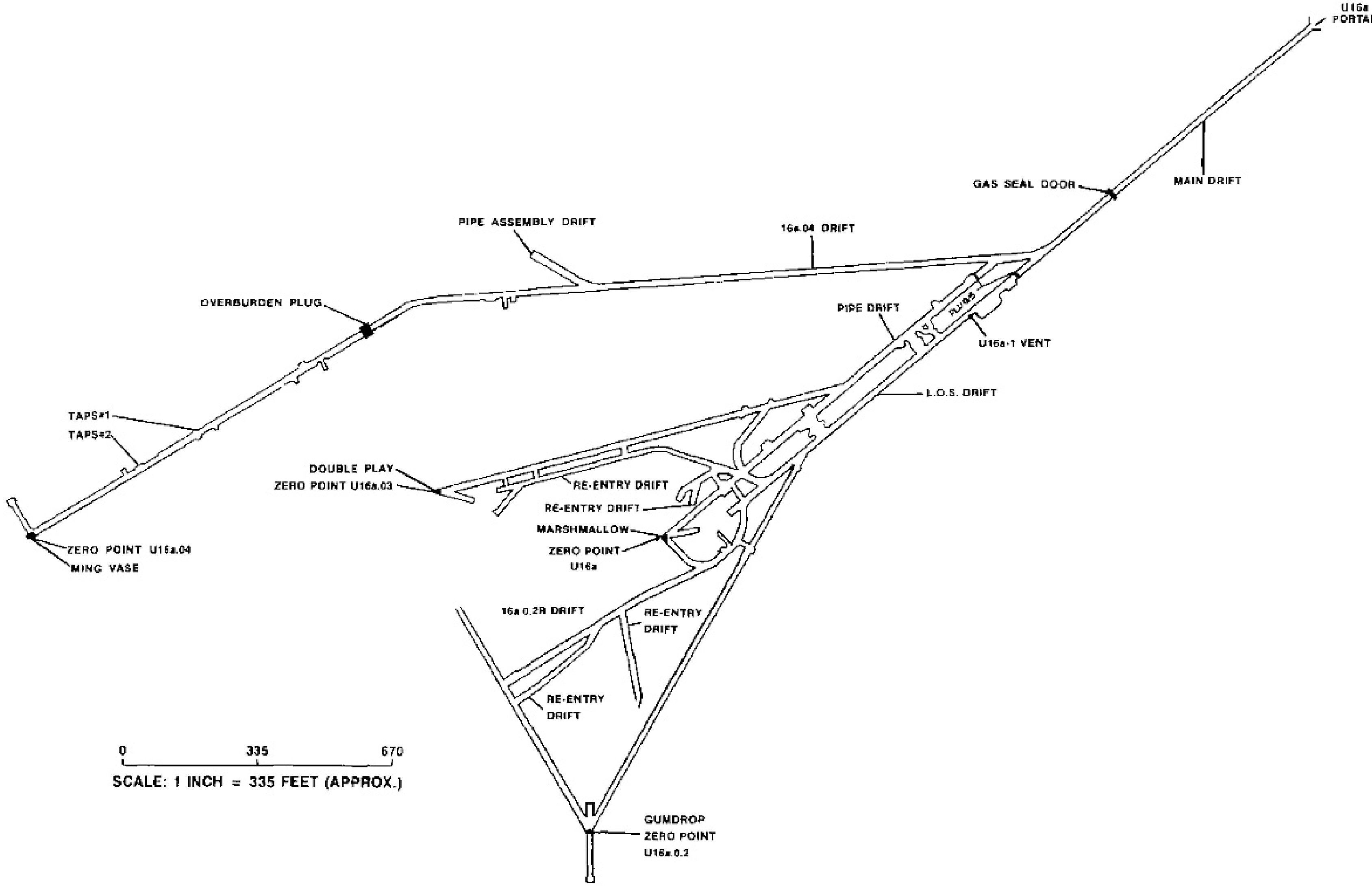

Figure 16. U16a.04 Ming Vase drift (from Horton et al. 1985).

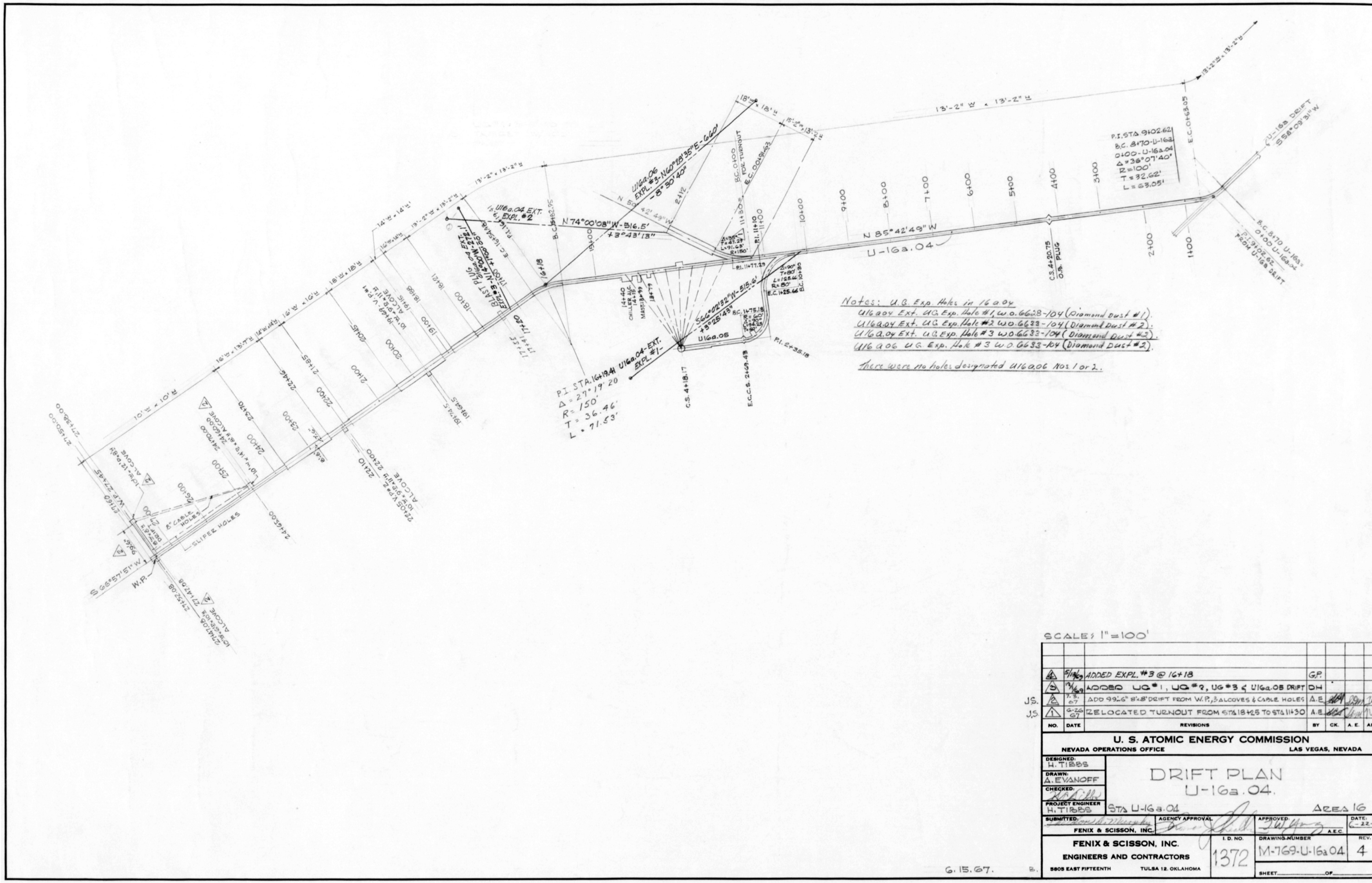

Figure 17. U16a.04 Ming Vase drift plan, 1967 (on file at the DOE Archives and Records Center).

Reynolds Electrical and Engineering Co. Inc. All electro-explosive components and toxic and radioactive materials were stored in accordance with the Army Material Command Regulations. The Ming Vase Reentry Plan was developed during pretest preparations for safe and economical post test reentry and recovery activities (Horton et al. 1985:159). RADSAFE was provided with detailed reentry procedures. The stemming design provided for maximum safety from zero time and during reentry. Test area maps were marked with reference points, radiation recorders, and air samplers. Reentry routes were established by DoD and radiation monitoring personnel were briefed on procedures and requirements. Anti-contamination materials were provided to appropriate personnel, surface and aerial radiation survey and reentry parties.

Instruments installed within the U16a.04 drift were for measuring particle velocity, acceleration, earth and air pressure, strain, displacement, temperature, time of arrival of temperature and pressure, and shock time of arrival (Coye 1970:3). Gauge installation began in August 1968 and continued until October 1968 when a mandatory signal dry run was performed on the system. Two recording trailers used for the Hudson Seal test at U12n Tunnel were moved to the U16a portal. Seventeen radiation area monitors (RAMS) were calibrated and placed inside the tunnel and within 683 m (2,240 ft) from the portal on the surface. Air sampling was provided by four samplers at the portal and at surface ground zero. Two air samplers were at 152 m from surface ground zero, one at 116 m (381 ft) from the portal, and one at 15 m (50 ft) from the portal. The United States Public Health Service had 105 air samplers at offsite locations with 20 personnel at offsite locations. Muster and control station were established and security was controlled by Wackenhut Security Inc. administrative controls and physical barriers.

Wackenhut Security Inc. had a U-6A aircraft for D-day sweeps of the area. A UH-43D helicopter manned by personnel from the Army Pictorial Center provided the aerial still photography at 457 m in elevation and upwind from the tunnel (Horton et al. 1985). A U-6A aircraft manned by Lookout Mountain Air Force Station personnel took motion picture footage at 914 m in elevation. The United States Public Health Service provided a U-3A and C-45 aircraft for cloud tracking with a Turbo Beechcraft on standby if needed. Wackenhut Security Inc. used a U-6A aircraft for security sweeps with a UH-43D helicopter on standby. Edgerton, Germeshausen, and Grier, Inc. /Nevada Aerial Tracking System had a Martin 4-0-4 aircraft on standby if needed for cloud tracking. Lookout Mountain Air Force Station provided a Bell UH-1F Iroquois helicopter for aerial closed circuit television coverage. A second UH-1F was on standby for the DOE Test Manager. Cloud tracking was provided by a U-3A and two Turbo Beechcraft provided by the USAF and United States Public Health Service and a Martin 4-0-4 provided by Edgerton, Germeshausen, and Grier, Inc./Nevada Aerial Tracking System. A Cessna 206 was provided by American Aerial Survey for post test survey. The first security sweep of the closed area was at 12:00 am on November 20, 1968.

At 5:00 am before the detonation, a security sweep was made of the area and the final readiness briefing for the DOE Test Manager was conducted at 8:00 am. The DOE Test Manager gave permission to arm the device at 8:05 am (Horton et al. 1985:163). Wackenhut Security Inc. completed their final security sweep and the arming party armed the device and left the area by 9:45 am. Ming Vase was detonated at 10:00 am Pacific Standard Time on November 20, 1968 (DOE/NV 2000:52).

Surface safety and radiological surveys began at 10:42 am and continued until 11:05 am (Horton et al. 1985:163). The radiological survey recorded normal background radiation levels at the portal. Data were reported to the RADSAFE trailer at the Forward Control Point. Film, tape, and instruments recovery began at 11:12 am with no detectable radiation. Surface experiment recovery continued until December 3, 1968 (Horton et al. 1985:164). Tunnel ventilation began at 1:25 pm on November 20, 1968. Initial tunnel reentry began at 3:30 pm and it was decided that the Scott-Draeger breathing equipment would be replaced with the Mine Safety Appliances all purpose mask. This was due to no radiological or industrial hygiene hazards being found within the tunnel. The reentry team opened the gas seal door at 4:10 pm and found a residual radioactivity reading from a previous test. No explosive or toxic gases were detected. On November 21, 1968, a reentry team entered the tunnel at 9:10 am and proceeded to and opened the overburden plug door (Horton et al 1985:165). They entered the door and went to test chamber number 1 and opened the door. Radiation measurements were taken along the way and the team exited the portal area at 11:00 am. A second reentry team entered the tunnel at 12:45 pm, established ventilation to the test chambers, and left at 1:35 pm. At 3:04 pm a third reentry team and experiment recovery party entered the tunnel and proceeded beyond the overburden plug. They completed their recovery and exited the tunnel at 4:00 pm. On November 22, 1968, the line-of-sight pipe was inspected and radiation readings were taken. After the early tunnel surveys were completed and the ventilation restored, experiments in the tunnel were recovered by the various organizations. Recovery activities were completed on January 17, 1969.

Drilling the post-shot drill hole PS #1V began at 12:55 pm on December 9, 1968 (Bennett 1991) and was completed on December 10, 1968 (Horton et al. 1985:166). Core samples, gamma logs, and directional surveys were taken. Eight RAMS units were placed on a 274 m (900 ft) circle around the drill hole. No radiation was detected. The PS #1V drill hole was left for use in future mining operations.

U16a.05 Drift - Diamond Dust

The Diamond Dust test was a DoD sponsored underground nuclear detonation with a yield of less than 20 kt. It was conducted at 7:00 am Pacific Daylight Time on May 12, 1970 in the U16a.05 drift (DOE/NV 2000:58) (Figures 3 and 18). Diamond Dust was a Vela Uniform test to investigate the feasibility of concealing a nuclear underground explosion from seismic detection (Brown 1979:3; Trulio and Perl 1974:5; Whitener 1970:iii). The U16a.05 drift was 125 m (410 ft) long. It turned to the left from construction station (CS) 10+30 in the existing U16a.04 drift with the nuclear device placed at the center of a 9.8 m (32 ft) diameter cavity at the end of the drift. Most of the electrical, water, ventilation, offices, and shops were in place from the earlier tests.

Diamond Dust was relocated from the right hand rib of the U16a.04 drift at CS15+19.5 to the left hand rib at CS 10+30 (Schoenholzer 1970:4). The move was made because cores from the original location indicated that the geology was probably not suitable for the test. Cores showed that the probability of containment was greater within the new location. Also, this was the location for Diamond Dust #2 that was later changed to Diamond Mine. Cabling could be re-used from the Ming Vase test. The new drift was 2.7 m (9 ft) wide by 3 m in height except for the last 18 m (60 ft) where its size was increased to 3 m wide and 3.7 m (12 ft) in height. Originally, the cavity was to be 9.8 m (32 ft) in diameter (Brown 1970). At the equator of the sphere, eight radial drill holes were used for instrument installation. A small alcove at the end of the stemming plug, on the right hand side

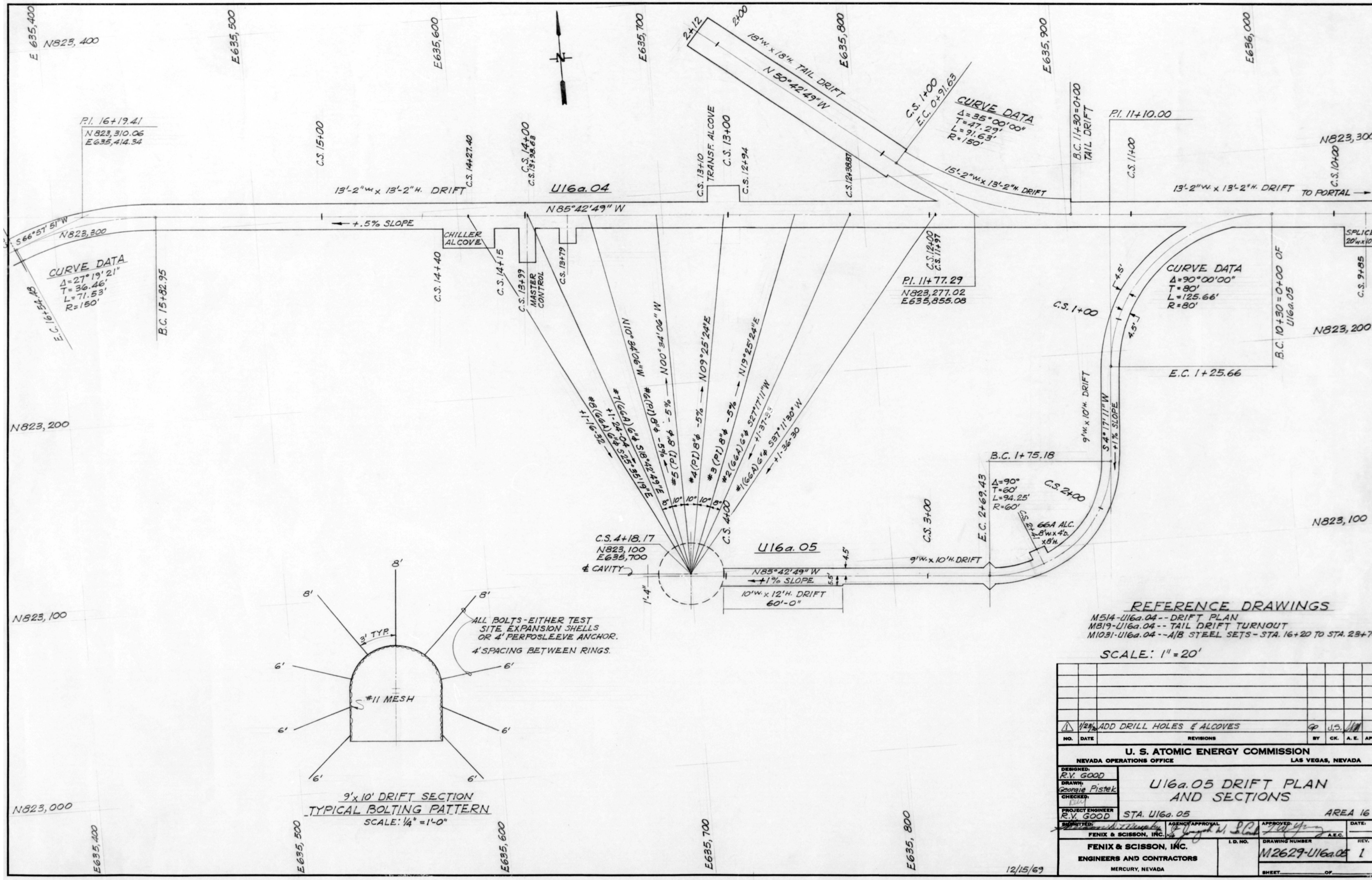

Figure 18. U16a.05 Diamond Dust drift plan and sections, 1970 (on file at the DOE Archives and Records Center).

of the access drift, was excavated for a cable splice alcove. A 0.9 m keyway was mined 39.6 m (140.5 ft) from the cavity to provide anchoring of the stemming material to the rock walls of the tunnel. At CS 10+00, a splice alcove was excavated on the left hand rib of the U16a.04 drift for existing cables from the Ming Vase test. An overburden plug was placed at CS 4+28.2 in the U16a.04 drift.

Construction at the U16a.05 drift began on December 9, 1969 and was completed on January 9, 1970 (Schoenholzer 1970:4). Initial construction began with cleaning the U16a.04 drift, installing new lagging and checking out the power system. Originally, rock bolts and wire mesh were to be used to support the U16a.05 drift (Diamond Dust), but steel sets and lagging had to be used from the turnout of the U16a.04 drift to CS 1+50 in the Diamond Dust drift. This was due to the highly fractured and blocky material encountered. The remaining 79 m (258 ft) used the rock bolts and wire mesh tunnel support system. At the same time the Diamond Dust drift was being mined, four of the eight instrument holes to be drilled into the cavity were started from the left rib of the U16a.04 drift. Of the four holes drilled, only one was acceptable. After re-drilling, a second hole was considered acceptable. Finally, five additional holes were drilled from the cavity into the U16a.04 drift for a total of seven holes.

The mining of the cavity began by extending the tunnel to about midpoint of the cavity, 127.4 m (418 ft) (Schoenholzer 1970:5). A 2.4 x 2.4 m (8 x 8 ft) raise was excavated to the back (top) of the cavity. The bottom (invert) of the cavity was excavated using a series of blasting and mucking operations. The back (upper portion) of the cavity was mined by blasting and hand mucking (Schoenholzer 1970:5). The upper portion of the cavity was secured with rock bolts and wire mesh. A work platform was emplaced by securing steel beams to rock bolts in the side of the cavity and placing 0.3 x 0.3 m (12 x 12 in) wood columns horizontally between the beams and vertically as legs between the steel beams and the bottom of the cavity. Expanded metal was placed over the beams as decking. The deck was of sufficient strength to hold a drill rig and capable of disassembly to pass through a 0.9 x 3.7 m (3 x 12 ft) opening. Five gauge holes were drilled from a platform to the U16a.04 drift. Instrumentation and cables were placed in the holes prior to grouting with rock matching grout. On March 6, 1970, fine fractures were found near the drill holes that were the result of stress relief in the rock (Brown 1970:26). The problem was corrected by placing 24 rock bolts around the five drill holes. Portland cement was placed behind each rock bolt plate to help distribute the load. Also, the rock bolts that supported the beams for the work deck were filled with cement. Finally, all cracks were grouted to prevent gas leakage.

The platform was then used for the installation of the heat sink and diagnostic equipment as well as the device. A small air driven tugger (mover) was use to hoist the heavier gauges into position (Schoenholzer 1970:6). The lighter gauges were pulled into the cavity by hand. A 6.1 m (20 ft) long by 20.3 cm (8 inch) deep concrete pad was installed in the invert to serve as footing for the gauge support rack. The pad was placed over the cable trench that extended into the U16a.05 drift. The cables were gas sealed and the trench filled with grout.

For the Diamond Dust test, the Rand heat sink concept to be used had been tested and developed at Gulf General Atomic in a series of small high explosive experiments (Trulio and Perl 1974:11). The heat sink was a metal sphere suspended by four sets of three cables hung from the back of the cavity. The twelve of the cables were for support and four other cables were for stabilization. The sphere was 3 m in diameter, weighed 1,090 lbs, and was constructed by Rohr Corporation (Schoenholzer 1970:9) (Figure 19). It was built in four sections composed of steel rods bent in half circles and attached to 1.27 cm (1/2 inch) thick steel honeycomb members. Two quarter sections were joined to form two hemispherical sections that were to be filled with graphite. Each section was lined with a nylon bag to hold the graphite which had to be poured in powder form (Whitener 1970:3). The heat sink consisted of graphite manufactured by Great Lakes Carbon Corporation. The graphite for the heat sink was 98 percent pure. The hemispherical sections remained apart until the device was put in place.

After placement of the gauges, the pre-stemming plug was placed to serve as an insulator for the heat to be generated during the test (Schoenholzer 1970:10). It was 6 m long and 2.1 m (7 ft) wide. After changing the formula of the stemming material, the last 40.2 m (132 ft) of the plug was placed totaling 46.3 m (152 ft). Gauge strings were then placed and cabling for the gauge strings was completed. Some of the cabling was run through pipe and into the plug for about 24.4 m (80 ft). The pipes were sealed with grout. All multi-conductor cabling within the drift was gas blocked. Coaxial cables were gas blocked by use of a splice bulkhead on which a vacuum pass through was mounted (Schoenholzer 1970). Gauges were installed in the drift to provide motion and radioactivity measurements. The drift was then stemmed by placing grout in two lifts (pours). The first lift placed stemming material against a steel door which filled a 1.5 m by 0.9 m (5 x 3 ft) recess within the pre-stemming plug. The remaining 1.4 m (4.5 ft) was filled with grout. The second lift was undertaken 24 hours later.

The overburden plug was a single unit monolithic pour at CS 4+23.2 in the U16a.04 drift (Schoenholzer 1970:12). No knockout plug was placed because of possible problems providing a gas tight seal around the plug. Access through the plug was the existing Ming Vase door. Scientific cables pierced the plug about 1.4 m to 1.5 m above the invert and were gas blocked by using a 91 cm (30 inch) pass through pipe that was filled with grout which encapsulated the cables. Ming Vase cables were cut at the DoD cable splice alcove at CS 9+87 in the U16a.04 drift and new cables for the Diamond Dust test were spliced to the older ones. All cables were reconnected with a gas tight connector and sealed with epoxy. These included the timing and firing, diagnostic, gauge strings, RAMS units, movement, and pressure gauge cables. Cabling to the portal for Diamond Dust exited through the U16a.04 drift overburden plug at CS 4+28.2.

Diamond Dust was the first shot in Area 16 fired from CP-1 (Brown 1970:44). One hundred pairs of cables were laid between Area 16 and CP-1 to accomplish the firing. Two weather briefings were held, one on May 11 and one on May 12, 1970 at 5:00 am. It was decided to fire the device at 7:00 am on May 12, 1970. The countdown began at ten minutes before detonation. At ten minutes before detonation, the power to all oil filled gauges was turned on; tape recorders were started at -1 minute and backups at -30 seconds, power to all gauges at -5 seconds, and firing at zero time. Cameras of the portal area were turned on at -2 minutes, -6 seconds, -5 seconds, +3 minutes and +60 minutes. A UH1F helicopter provided closed circuit television coverage of the portal area. A U3B aircraft made pre-shot safety sweeps of the area. A United States Public Health Service Turbo Beechcraft provided cloud sampling and a second Turbo Beechcraft was available for backup. After detonation, the ventilation system was reestablished between the gas seal door and the overburden plug and forward of the overburden plug.

Figure 19. Sphere for Diamond Dust test, 1970 (from Brown 1970).

The portal trailer park was reentered at 9:00 am on May 12, 1970. The reentry route was from Orange Road to Pahute Mesa Road to 16-02 Road. The reentry party was in direct communication with the DoD monitor room, RAMS monitor room, and the operations control center at CP-1. The initial reentry party consisted of a RADSAFE team, electrical disconnect team, emergency medical team, DoD photographers, and the agency recovery teams. Aerial reconnaissance was to report post shot conditions to the reentry officer and the reentry began with a convoy from the control points. The RADSAFE team entered the trailer park to determine the safety of the area. Upon finding the Portal safe, the electrical disconnect team entered the Portal area and grounded each trailer and examined the area for electrical hazards. All the cables exiting the tunnel were disconnected except those for ventilation, gas sampling, RAMS and geophones, and those belonging to Gulf General Atomic. After the electrical disconnect team finished its activities, the agency recovery teams entered the portal area and recovered all the data from the instrument trailers.

RAMS units within the U16a Tunnel indicated that a minor leak occurred somewhere in the stemming. It was concluded that the radioactive material, probably gaseous fission products, from the cavity reached the U16a.04 drift through the grout stemmed instrument drill holes or motion gauge drill holes. It then drifted to the overburden plug and in the opposite direction. One RAMS monitor detected the leakage behind the Gum Drop overburden plug indicating the material had entered the Double Play, Marshmallow, and Gum Drop complex. Gas samples were drawn from the tunnel by way of the Sutorbilt ventilation fan and filter system at the portal. All contamination was contained behind the gas seal door. No significant radiation passed through the U16a.05 drift stemming plug. At 4:34 pm on May 12, 1970, the analysis of the sample for explosive gas mixtures was complete. Hydrogen was present within the tunnel and all electrical power was disconnected. The hydrogen level dropped after ventilation was established.

U16a.06 Drift - Diamond Mine

Diamond Mine was the last nuclear test conducted at U16a tunnel. It was a DoD sponsored underground nuclear detonation with a yield of less than 20 kt. It was conducted at 7:00 am Pacific Daylight Time on July 1, 1971 in the U16a.06 drift (DOE/NV 2000:62) (Figures 3 and 20). Diamond Mine was a Vela Uniform test to investigate the feasibility of concealing a nuclear underground explosion from seismic detection (Davis 1972:3; Directorate of Test Operations 1970:2; DOE/NV 2000:62). Most of the electrical, water, ventilation, offices, and shops were in place from the earlier tests.

Mining of the drift began on October 22, 1970 from the right rib of the U16a.04 drift at CS 15+19.5 (Davis 1972:14). The drift was to be 2.7 m wide by 3m in height. Two keyways were mined in the drift to aid in stemming. Work continued until blocky and broken tuff was encountered at CS 4+25. Mining of the drift was terminated at CS 4+58. The working point was then relocated to CS 3+75 and excavation of the cavity began. The cavity was 9.8 m in diameter, the invert mining was completed by December 17, 1970, and the cavity mining was completed, due to a delay, at the end of February 1971. The delay in finishing the cavity was due to the leakage from the Baneberry test on December 17, 1970. All construction was suspended until January 4, 1971 and nuclear testing was not resumed until June 16, 1971 (Davis 1972:25). At this point, the DOE imposed stricter requirements on cable gas blocks, stemming and tunnel pressure testing. The final approval for the Diamond Mine test was not received until May 17, 1971.

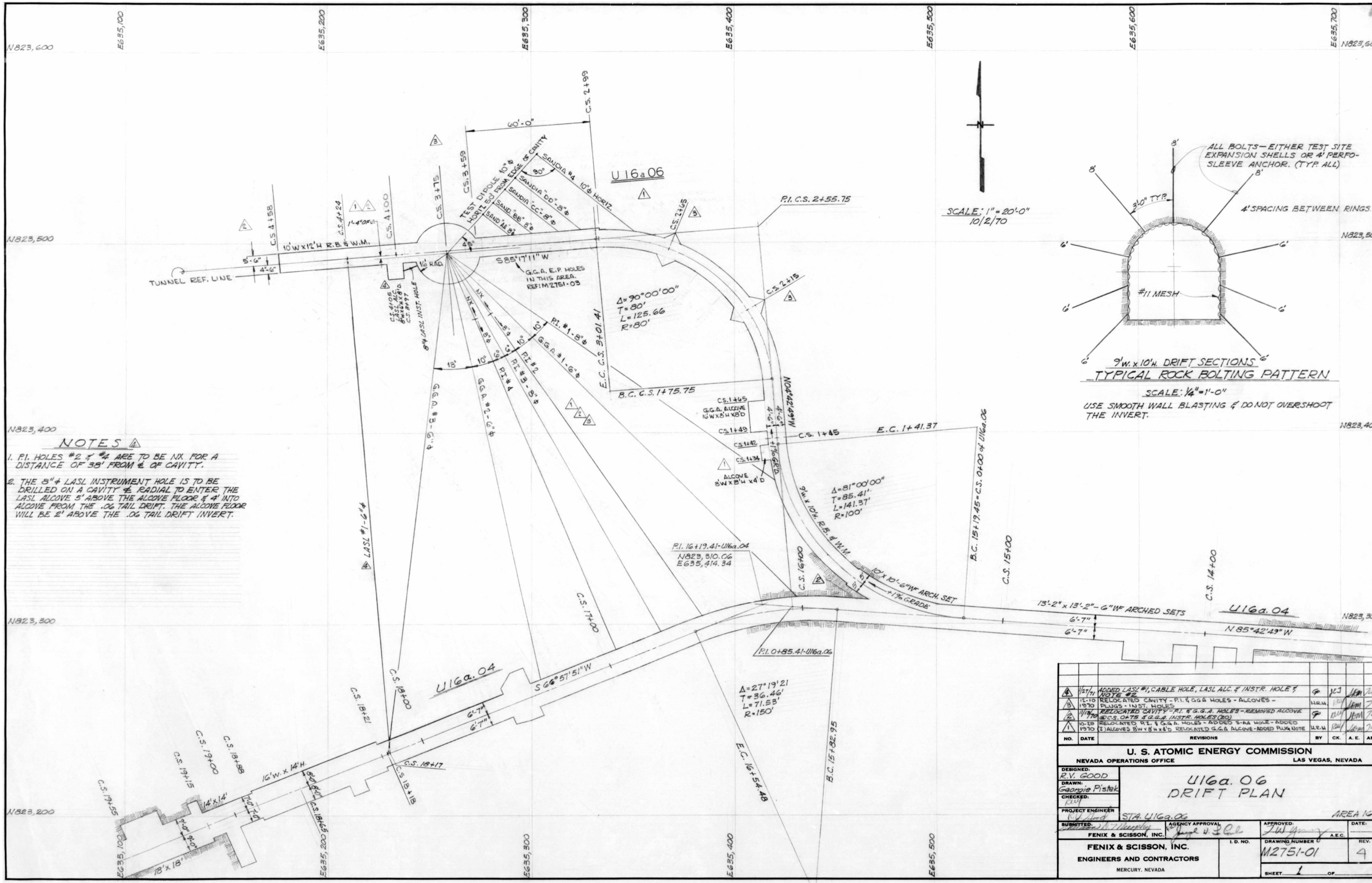

Figure 20. U16a.06 Diamond Mine drift plan, 1971 (on file at DOE Archives and Records Center).

Within the U16a.06 drift, the tail drift and walkway to the gamma-ray spectrometer alcove on the far side of the cavity were filled with grout. A stemming plug, consisting of 50 m (164 ft) of expansive grout, was placed within the U16a.06 drift from CS 1+95 to the cavity wall at CS 3+59 (Davis 1972). It was poured in sections to prevent high temperatures. A man way was left through the plug to allow access to the cavity until placement of the device. After the device was in place, the steel door on the cavity end was shut and the man way was filled with grout. The stemming plug was anchored to the tuff by two mined key ways at CS 2+15 and CS 2+68. The Ming Vase overburden plug in the U16a.04 drift had been reconstructed and was sealed with grout. A pressure relief valve was installed in the overburden plug to release overpressure to the portal side of the plug. A 61 cm (24 inch) man way was installed to provide access through the plug. A closure mechanism was installed on the working point side of the man way during button up activities. Ventilation lines were sealed on each end with welded blind flanges. The man way and vent lines were gas blocked with external flanges. The gas seal door at CS 6+76 in the U16a drift, used for Double Play, Ming Vase, and Diamond Dust tests, was reused for Diamond Mine. After the overburden plug was reconstructed, the tunnel ventilation system was disconnected. Air was then supplied by a compressed air line through the man way door. During button-up activities, the air line was closed and the tunnel was sealed at the overburden plug and gas seal door. A ventilation line from the portal to the gas seal door remained open. During reentry, the ventilation line was reconnected at the gas seal door and the overburden plug as soon as it was unsealed.

Seven radial instrument holes were drilled between the Diamond Mine Cavity and the U16a.04 drift, and four gauge strings and three wall motion gauges were installed and grouted in place by late February (Davis 1972:14). Twenty-five instrument holes were drilled in the left rib of the U16a.06 drift and cavity. Twenty-eight earth pressure gauges and six accelerometers were installed in the instrument holes. Five holes were drilled near the cavity for electromagnetic pulse experiments. A gauge rack was constructed to hold fifteen cavity pressure gauges. Installation of the instruments was completed on May 5, 1971. Instrument holes in the U16a.04 and U16a.06 drifts were grouted with various grout types.

As in the Diamond Dust test, cabling was reused to save cost and speed up construction time. The Diamond Mine test used the existing cable plant from Ming Vase and Diamond Dust tests from the portal splice rack to the DoD cable splice alcove in the U16a.04 drift. New cables were pulled from the splice alcove to the gage terminations in the U16a.04 and U16a.06 drifts and outside from the portal splice rack to the instrument trailers. The number of cables used for the Diamond Mine test was considerably less than for the Diamond Dust test. The extra cables were cut off and sealed at the working point side of the gas seal door (Davis 1972:33). The timing and firing cables between Area 16 and CP-1 were reused for the Diamond Mine test. Gas blocks within most of the cabling required two blocks per cable within the stemming. Also, gas blocks were placed on all cables that passed through the gas seal door. Because of the Baneberry test, the U16a Tunnel complex was pressure tested for possible leak paths from April 12 to April 18, 1971. Numerous holes were drilled in the U16a.04 and U16a.06 drifts, around the key ways and into the tail drift, and around the overburden plug and gas seal door. These were all pressure grouted with various strength grouts. Pressure testing of the tunnel also indicated that drill holes between the surface and the tunnel from previous tests were to be sealed by using blind flanges or concrete.

Wall motion pressure gauges were mounted to the cavity wall by an anchor plate centered on a long shaft embedded in the tuff. Earth pressure gauges were set at radial distances of 21 to 100 ft (6.4 to 30.5 m) from the working point at 5 ft (1.5 m) intervals. Six accelerometers were placed in holes at 23, 27, 35, 55, 75, and 99 ft (7.0, 8.2, 10.7, 16.8, 22.9, and 30.2 m) from the working point. Temperature gauges and pressure sensors were placed in the U16a.06 drift and on the working point side of the gas seal door and overburden plug to monitor the tunnel environment. Particle velocity gauges and accelerometers were placed between 18 and 175 ft (5.5 and 53.3 m) from the working point. Various instrumentation was placed to measure electromagnetic pulses. Alpha and gamma detectors were placed within the cavity. A gamma-ray spectrometer was in an alcove in the U16a.06 tail drift. Seismic stations were 1.6 mi (2.5 km) and 3.8 mi (6 km) from surface ground zero.

The Diamond Mine test was conducted at 7:00 am Pacific Daylight Time on July 1, 1971. Reentry began from the control point at the intersection of Orange Road and Pole Line Road. The route was via Orange Road to Pahute Mesa Road to 16-02 Road. The portal trailer park was reentered at 8:40 am July 1, 1971, D-day. Communications from the control point to CP-1 was via land lines and the reentry party used radios. In the reentry party were the RADSAFE team, electrical disconnect and damage assessment team, portal data recovery team, and seismic data recovery team. At shot time the reentry parties were in the CP-1 area or in Mercury. The Test Manager released the reentry team at CP-1 to proceed to the portal area. The remaining parties in Mercury proceeded to the reentry control points. The RADSAFE team reentered the portal area, took readings, and reported to the Reentry Control Officer. The electrical disconnect team proceeded to the portal, grounded the instrument trailers, and examined the area for electrical hazards. The seismic data recovery team and RADSAFE monitors went to the portal area and recovered all data.

HIGH EXPLOSIVES TESTS

Diamond Mine Calibration Shot

The Diamond Mine high explosive calibration shot was fired on February 4, 1971 in a short drift mined off the right rib of the U16a.05 drift in the U16a Tunnel complex (Figure 18 and 21). Excavation of the high explosive drift began in December 1970 and was completed on January 11, 1971. A 0.9 m diameter spherical container was filled with 985 lbs (447 kg) of nitromethane for the explosive. The shot was undertaken to obtain ground motion wave forms to aid in the development of a strain-rate dependent materials property model in tuff (Kratz and Hartenbaum 1972:1). The shot was in the same geologic formation as the Diamond Dust and Diamond Mine nuclear tests.

Five seismic stations were set up on the surface by the University of Michigan. Underground, four vertical gage emplacement holes, 10.2 cm (4 inches) in diameter, were drilled into the floor (invert) of the tunnel (Swink et al. 1971:5). The holes were drilled on a radial line at 3.44 m (11.3 ft), 4.78 m (15.7 ft), 4.85 m (15.9 ft), and 6.28 m (20.5 ft) from the high explosive charge. Two gage systems were employed. System A was gauges set at each of the four ranges that were used to obtain both acceleration and velocity measurements. System B was gauges built by Gulf Radiation Technology that would also be used in the upcoming Diamond Mine nuclear test. They measured velocity only.

The aluminum sphere was rock bolted to the working point. The sphere was then grouted in place with fill and vent lines for the nitromethane extending through the grout bulkhead. On fill day, only

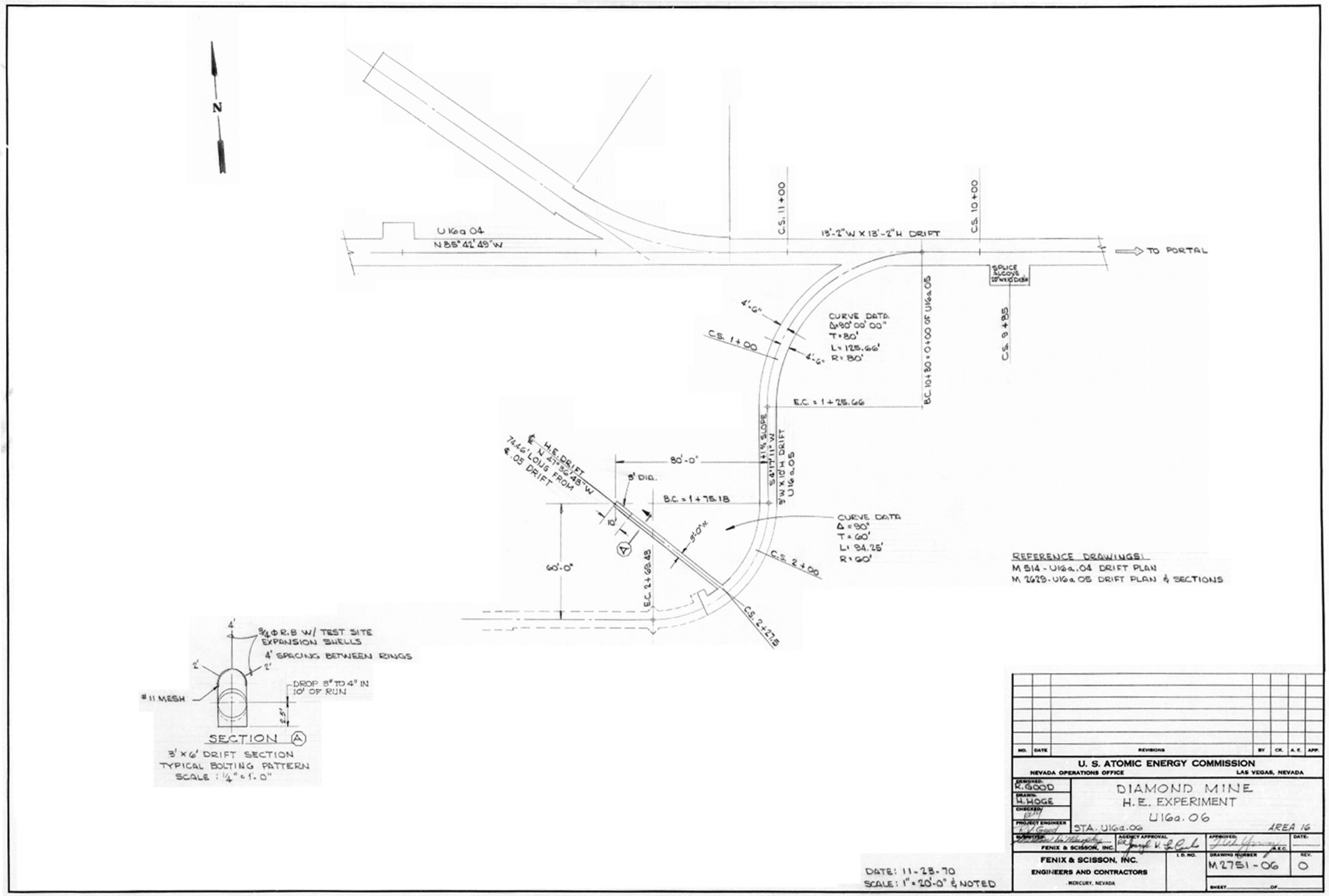

Figure 21. U16a Tunnel Diamond Mine high explosive drift within the U16a.06 drift (no date - on file at DOE Archives and Records Center).

personnel directly involved in the nitromethane fill operation were allowed access to U16a Tunnel. The nitromethane was pumped into the sphere using the fill and vent lines. The U16a Tunnel was then left open with the tunnel ventilation system running. Stemming for the high explosive test consisted of a grout plug filling the high explosive drift and the U16a.05 drift adjacent to the High explosive drift. On detonation day, the high explosive device was armed and the shot was fired from CP-1 by LANL personnel. For reentry, a gas sample was taken at the end of the U16a.05 drift at the intersection of the U16a.04 drift. The ventilation system remained running during and after the test. A geophone was installed in the U16a.04 drift. Sandia Laboratories Environmental Health Department was in control of reentry when the portal area and tunnel were released by the DOE Test Manager.

Mine Dust Calibration Shot

A stemming mechanics study, nitromethane calibration shot for the Mine Dust test was fired in the U16a.05 drift on May 10, 1972 (Brackett 1972:ii). A 0.9 m diameter spherical container was filled with 952 lbs (432 kgs) of nitromethane for the explosive. The shot used a high explosive charge to determine the stress, velocity, and seismic characteristics of the tuff in the U16a Tunnel. The test was a follow on to the Diamond Mine Calibration shot in the U16a Tunnel, the Hudson Moon Calibration shot in the U12e Tunnel, and the Diana Mist Calibration shot in the U12n Tunnel. The shot was designed to provide predictive data for the Mine Dust test from a similar geologic medium.

The sphere was placed in a 12.2 m (40 ft) long drift that turned off the right rib of the U16a.05 drift at CS 1+25. The drift was 1.8 m wide and ranged from 2.1 to 2.4 m (7 to 8 ft) in height. At the end of the drift a vertical shaft was mined to a depth of 4.7 m (15 ft 6 inches). The bottom of the vertical shaft was a hemispherical excavation large enough to hold the sphere. Rock bolts were cemented to the floor to mount the sphere. This was the same design as used in the previous tests and was made by Atlas Metal Spinning Company. The nitromethane fill and vent lines extended from the sphere to the U16a.05 drift. The firing line ran parallel to the fill and vent lines near the back of the drift. Stemming material was a rock matching grout poured in multiple lifts. Instrumentation was provided by Stanford Research Institute and Gulf Radiation Technology.

The nitromethane was placed in the sphere after midnight on May 9, 1972. Only fill personnel were allowed access to the U16a Tunnel during the fill. The fill and vent lines were left open after the fill which ended a 3:05 am. All personnel left the tunnel and portal area and Wackenhut Security Inc. locked the portal gates. At 5:00 am on May 9, 1972, the arming party entered the tunnel and made the final connections. They left the tunnel at 5:15 am. The ventilation system was left on for the shot. The final countdown began at 5:44 am and proceeded to zero time at 6:00 am. The firing signal was sent but failed to detonate the High explosive device. After 30 minutes, the arming party reentered the tunnel and checked all connections. No cause for the misfire was found. The shot was postponed until May 10, 1972. Several dry runs of the system were made and the system was determined normal. The only conclusion for the misfire was a drop in utility power. At 4:00 am on May 10, 1972, the arming party reentered the tunnel, armed the device, and departed at 4:15 am. The final countdown began at 4:44 am and proceeded to zero time at 5:00 am. At zero time the firing signal was sent and the high explosive device detonated. After detonation, gas samples were taken in the U16a.04 and U16a.05 drifts. SNL provided control of the reentry after the portal and tunnel were released by the DOE Test Manager. Reentry followed normal procedures outlined in the operation and safety plan.

Dipole Hail

The Dipole Hail test series is part of the Counterproliferation Program sponsored by the DTRA (Babcock and Rocco 2000:1). The test program is part of DTRA's effort to detect, neutralize, and assess the damage inflicted to underground adit (tunnel) structures (Rinehart 1998:3). These weapons effects tests include the use of generic warheads, scaled warheads, earth penetrating warheads, and missiles (Carter et al 1995:1-1). A primary objective of the Dipole Hail tests was to improve the DoD's capability to accurately predict the response of tunnel sections, portals, and equipment/personnel to weapons effects produced by conventional penetrating weapons. Dipole Hail is a series of tests to assess battle damage resulting from explosions conducted near a tunnel surface in tuff (Garbin 1999:8). Of primary interest is the size of the rubble pile produced by the explosion. This can be measured directly by surveying the rubble volume. Of additional interest is the time required to remove the debris so the tunnel can be reused. In Dipole Hail, both of these quantities were measured post-test. Not all of the Dipole Hail tests were conducted at the NNSS.

Dipole Hail 1 - 3

Dipole Hail 1 - 3 tests were detonations within the U16a drift between CS 0+00 and CS 6+50 on May 10, June 7, and July 12, 1995 respectively. Each warhead was filled with tritonal and suspended within vertical holes drilled from the surface to the back of the tunnel. The Dipole Hail #1 warhead was suspended in a drill hole 7 m (23 ft) above the back of the tunnel, Dipole Hail #2 was 5.5 m (18 ft) above the back, and Dipole Hail #3 was 4 m (13 ft) above the back of the tunnel (Carter 1995:11-1). Each emplacement hole was stemmed with rock matching grout prior to the detonation. Instrumentation for the tests consists of airblast and acceleration gauges and high speed video cameras. Reentry into the tunnel after the test was to determine the amount of rubble produce by the explosion.

Dipole Hail 6 - 8

Dipole Hail 6 - 8 tests were conducted on May 15, June 27, and July 31, 1995 respectively. Each tritonal-filled warhead was suspended within a drill hole above the U16a drift between CS 0+00 and CS 6+50 (Hunt 2001).

Dipole Hail 18 and 20

Dipole Hail 18 and 20 were conducted in the U16a drift between CS 0+00 and CS 6+50 and executed on April 2 and 7, 1997 respectively. These tests were to help in the characterization of the vulnerability of tunnel portals (Rinehart 1998:12). The test objectives were to evaluate the functional disruption to an underground tunnel facility, looking at the response of the tunnel sections, portal and equipment/personnel to effects from a conventional penetrator weapon. A warhead was statically emplaced in a 20-inch diameter drill hole for each test at various standoff distances and orientations from the inside surface of the tunnel. Dipole 18 was placed 103 m (339 ft) from the portal (Hunt

2001). Dipole Hail 20 differed slightly from previous tests in that the warhead was placed horizontally in a drill hole directly above the portal entrance.

Dipole Hail 21

Dipole Hail 21 was conducted in the U16a drift on September 16, 1998 (McMullan 2004:15). The warhead was suspended vertically at CS 4+00 of the drift and 55.9 cm (22 inches) above the invert. Four vehicles and one steel witness plate were placed on the portal apron to evaluate blast effects. Instrumentation included 22 pressure gauges, 3 thermocouples, and 66 time of arrival crystals in the tunnel. Photography included 3 high speed video cameras, 3 standard video cameras and a remote beta-cam.

Dipole Hail 24

Dipole Hail 24 was conducted on December 8, 1999 at the U16a portal (McMullan 2004:15). The overall objective of the Dipole Hail 24 test was to demonstrate the lethality of a large explosive charge placed at or near a tunnel portal (Babcock and Rocco 2000:4). The test consisted of the static detonation of 12,600 lbs of explosive. The warhead was placed 4 m (13 ft) from the tunnel portal and detonated to see how non-penetrator munitions can functionally disrupt tunnel operations. Instrumentation included 20 in-tunnel pressure gauges and 8 time of arrival crystals around the warhead to measure detonation velocity. Photography included 2 video cameras, 1 Hycam in the tunnel, 2 Hycams outside the tunnel, and 2 video cameras outside the tunnel (Babcock and Rocco 2000:11). Demonstration equipment included a 2 1/2-ton truck in the tunnel at CS 4+06. At the portal were, a pickup truck 36.6 m (120 ft) from the warhead, an armored personnel carrier 67 m (220 ft) from the warhead, a 2-ton van 77.7 m (255 ft) from the warhead, and 2 metal buildings 74.7 m (245 ft) and 85.3 m (280 ft) from the warhead. The resulting crater was 1.25 m (4.1 ft) deep and 12.2 m (40 ft) in diameter. The 2 1/2-ton truck in the tunnel was severely damaged. The pickup truck outside was demolished. The armored personnel carrier and 2-ton van were undamaged. The ends of both buildings were blown out (Babcock and Rocco 2000:53).

Dipole West

The Dipole West tests were to test a feasible alternative to physical destruction of a tunneled target to functionally disrupt, neutralize, or destroy its capabilities by means that do not place a weapon in the center of the target itself (McMullan 2004:30). The objective of Dipole West was to conduct feasibility studies to support the Divine Kingfisher Program. Not all of the Dipole West tests were conducted at the NNSS.

Dipole West 4 and 5

Dipole West 4 and 5 consisted of dropping 4 (2 each) inert warheads to develop attack planning for skipping warheads down existing tunnels and demonstrate attack feasibility for targeting (McMullan 2004:30). The test took place between January and May 1999. Instrumentation for Dipole West 4 consisted of 1 acceleration package, 30 seismic stations and 7 test videos, 2 laser spot, 5 Hycam, and 2 closed circuit television cameras. Instrumentation for Dipole West 5 consisted of 2 acceleration packages, 6 seismic acoustic stations, 1 electronic station, 30 seismic stations, 5 test videos, 1 laser spot, 4 Hycam, and 2 closed circuit television cameras. A mobile aircraft tracking radar station was provided by SNL.

Divine Kingfisher

The DK series focuses on the demonstration part of the Tunnel Defeat Demonstration series that is part of the Hard and Deeply Buried Target Defeat Program (McMullan 2004:78). Divine Kingfisher tests are focusing on using air delivery of current weapon systems, but employing new and advanced tactics, as well as elements of current tactics. Not all of the Divine Kingfisher tests were conducted at the NNSS.

Divine Kingfisher 31

Divine Kingfisher 31 used a tritonal filled warhead statically placed at the U16a portal on November 14, 2001 (McMullan 2004:84). Pressure gauges, heat flux gauges, photo diodes, and cameras documented the test.

GEOMORPHOLOGY OF U16a TUNNEL AREA

INTRODUCTION

The U16a Tunnel is one of a number of tunnels at the Nevada National Security Site (NNSS) that was used for scientific tests involving underground nuclear tests and high explosives detonations. U16a Tunnel is located beneath Shoshone Mountain in Area 16 of the NNSS. The site location is found on the U.S. Geological Survey Tippipah Springs 7.5' topographic quadrangle. It is situated between two ephemeral stream drainages on the east flank of Shoshone Mountain (Figure 22).

The purpose of this study was to document the changes in the landscape in the U16a Tunnel area as a result of surface disturbing activities at the site. The current study was accomplished by making a reconnaissance-level map of the surficial and bedrock geology at the site. The area was visited in June 2011 in the company of Mr. Robert Jones and Ms. Barbara Holz of the Desert Research Institute, at which time field reconnaissance and mapping was conducted. During the field visit, the extent of tailings from mining operations, fill emplacements, cut slopes, material side cast during road construction activities, and drilling pad preparations at the site were mapped to the degree that time and access permitted. A map depicting surface modifications was prepared in ArcMap. No surface disturbing activities (e.g., digging) or detailed field descriptions of bedrock or soils were undertaken.

This report summarizes the bedrock and surficial geology, and surface disturbance affection the landscape in the U16a Tunnel area in Area 16 of the NNSS as a result of scientific test activities.

GEOMORPHOLOGY AND GEOLOGY OF THE U16A TUNNEL

Study Area

The geomorphic study covers about 165 acres (67 hectares) in and around the U16a Tunnel portal area and on Shoshone Mountain near Tippipah Point (Figures 23-27). Total relief is about 425 m (1,400 ft). The bedrock and surficial geology of the U16a Tunnel area was mapped as two discrete areas using Arc Map: (1) the U16a Tunnel portal area (Figures 23 and 26), and (2) near Tippipah Point (Figure 27). Both map areas include bedrock and surficial geology and areas of surface disturbance.

The map for the portal area is an elongated, east-west oriented polygon about 900 m (3000 ft) long and about 370 m (1200 ft) at the widest point; the U16a Tunnel portal is situated near the west end of the map polygon. The Tippipah Point map on Shoshone Mountain is an east-west oriented rectangle that is about 770 m (2,500 ft) long in the east-west direction and about 500 m (1,650 ft) wide in the north-south direction.

Description of the U16a Tunnel Area. The U16a Tunnel complex consists of the following: the main tunnel; side drifts; a terraced tailings pile fronting the portal; and remnants of various associated structural features on the tailings pile and pads for power lines and various equipment storage areas around and upslope of the portal. Remnants of drill pads occupied for post-test drill holes are situated on the top of Shoshone Mountain near Tippipah Point. The small network of access roads

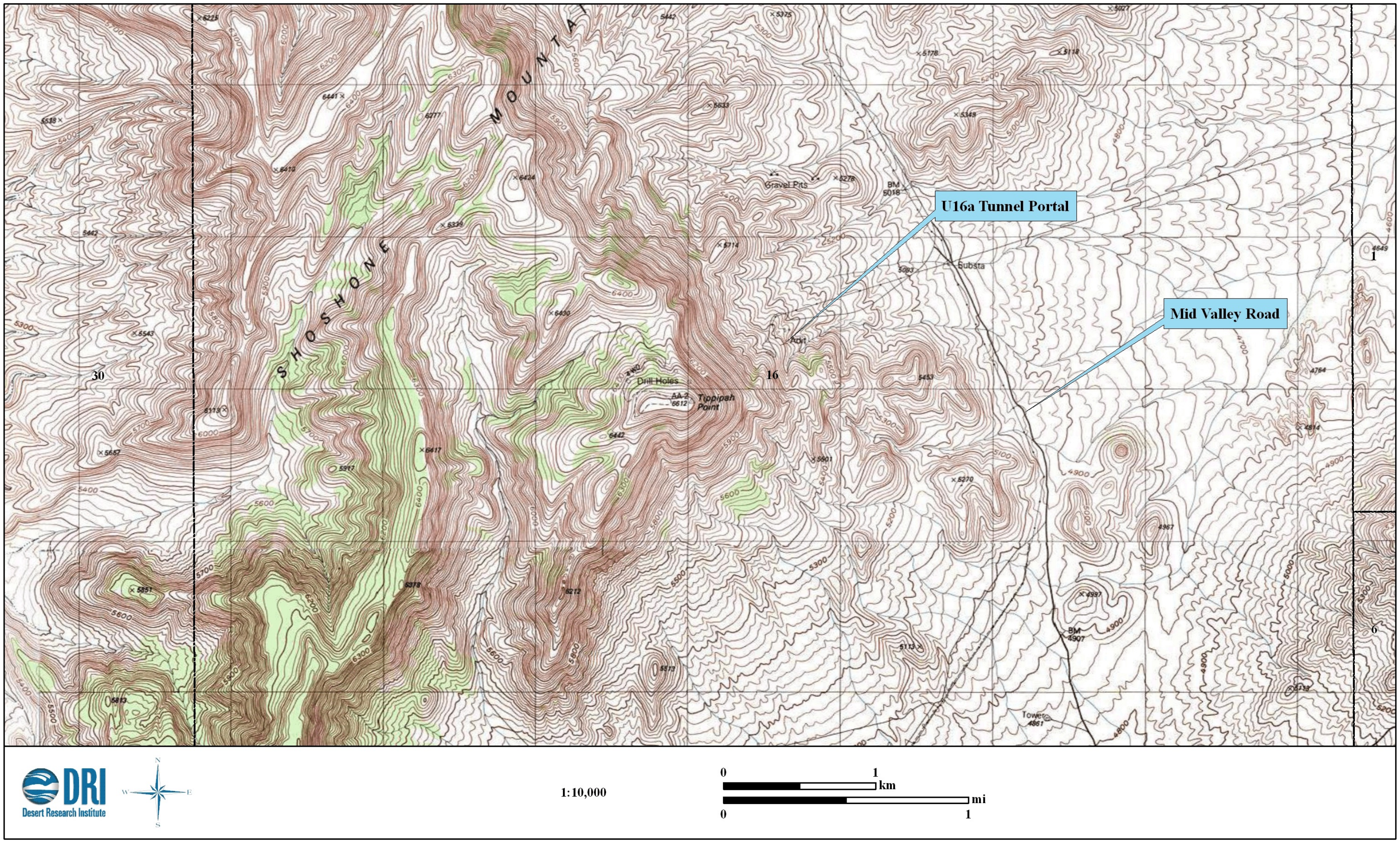

Figure 22. Map showing the location of U16a Tunnel portal and Mid Valley road.

Figure 23. Oblique air photo of the U16a Tunnel portal area (photo from the RSL archives)

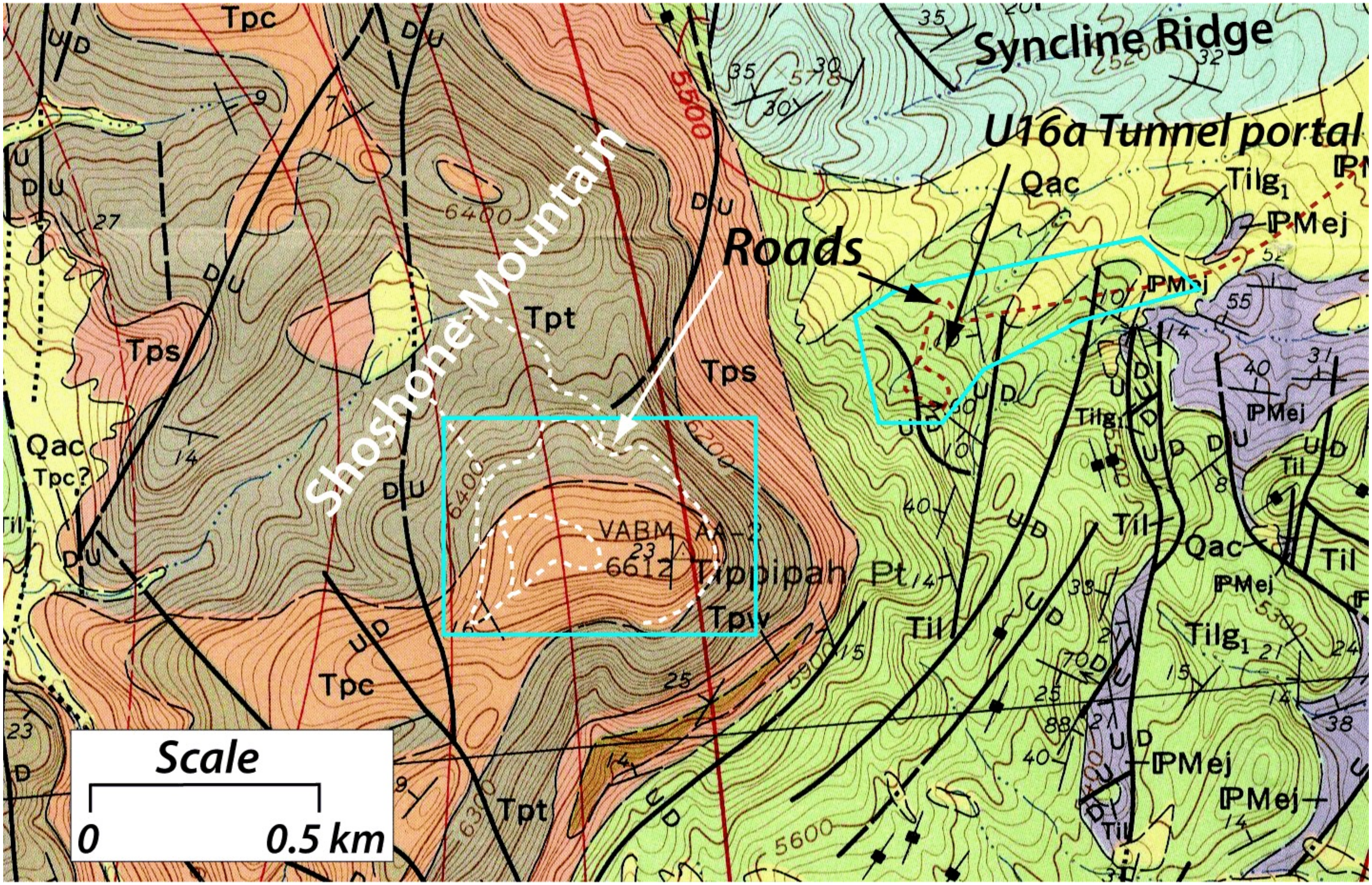

Figure 24. General geologic map of the U16a Tunnel site area showing areas of interest and roads mentioned in the report.

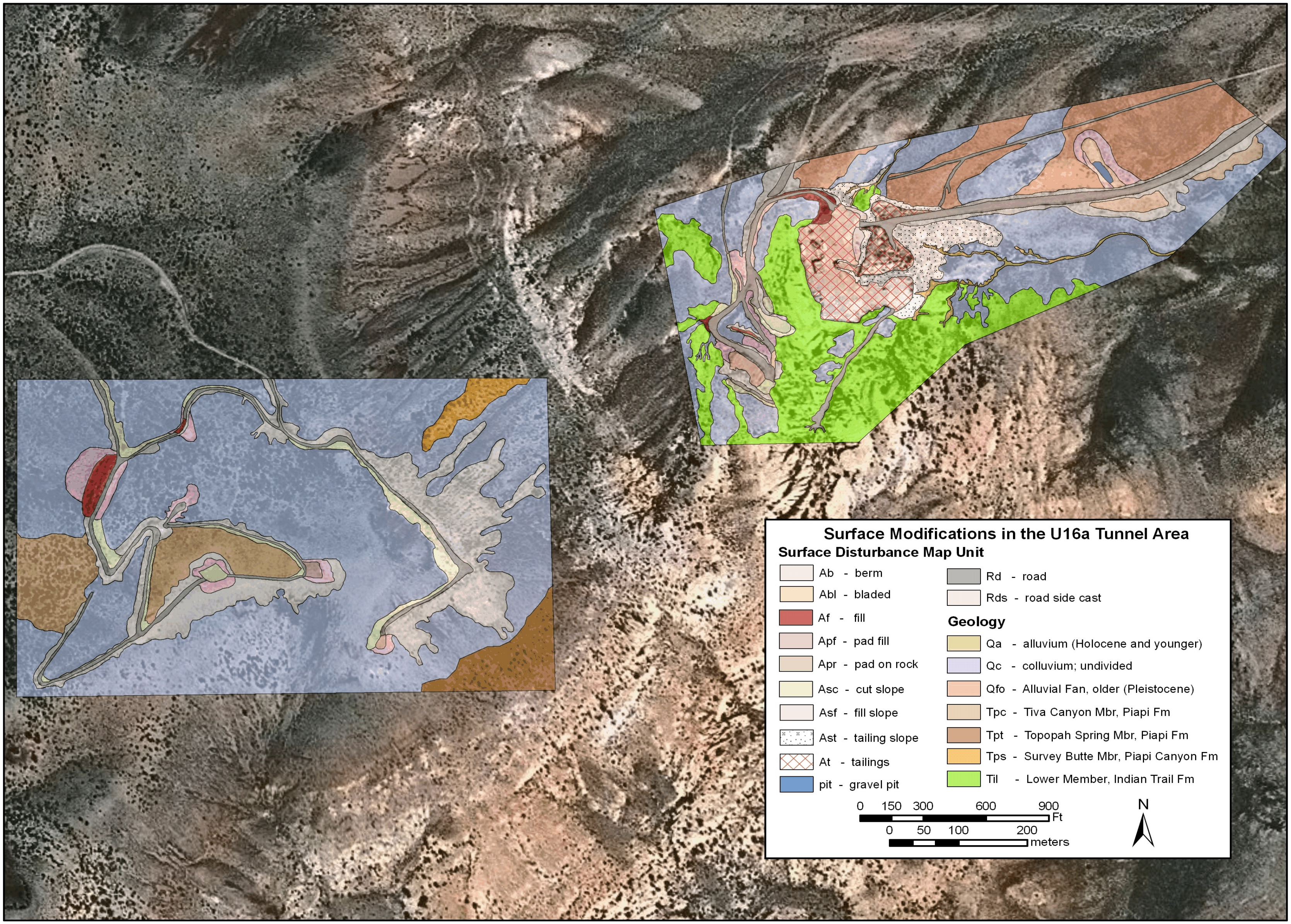

Figure 25. Surface disturbance map for the U16a Tunnel portal and Shoshone Mountain area.

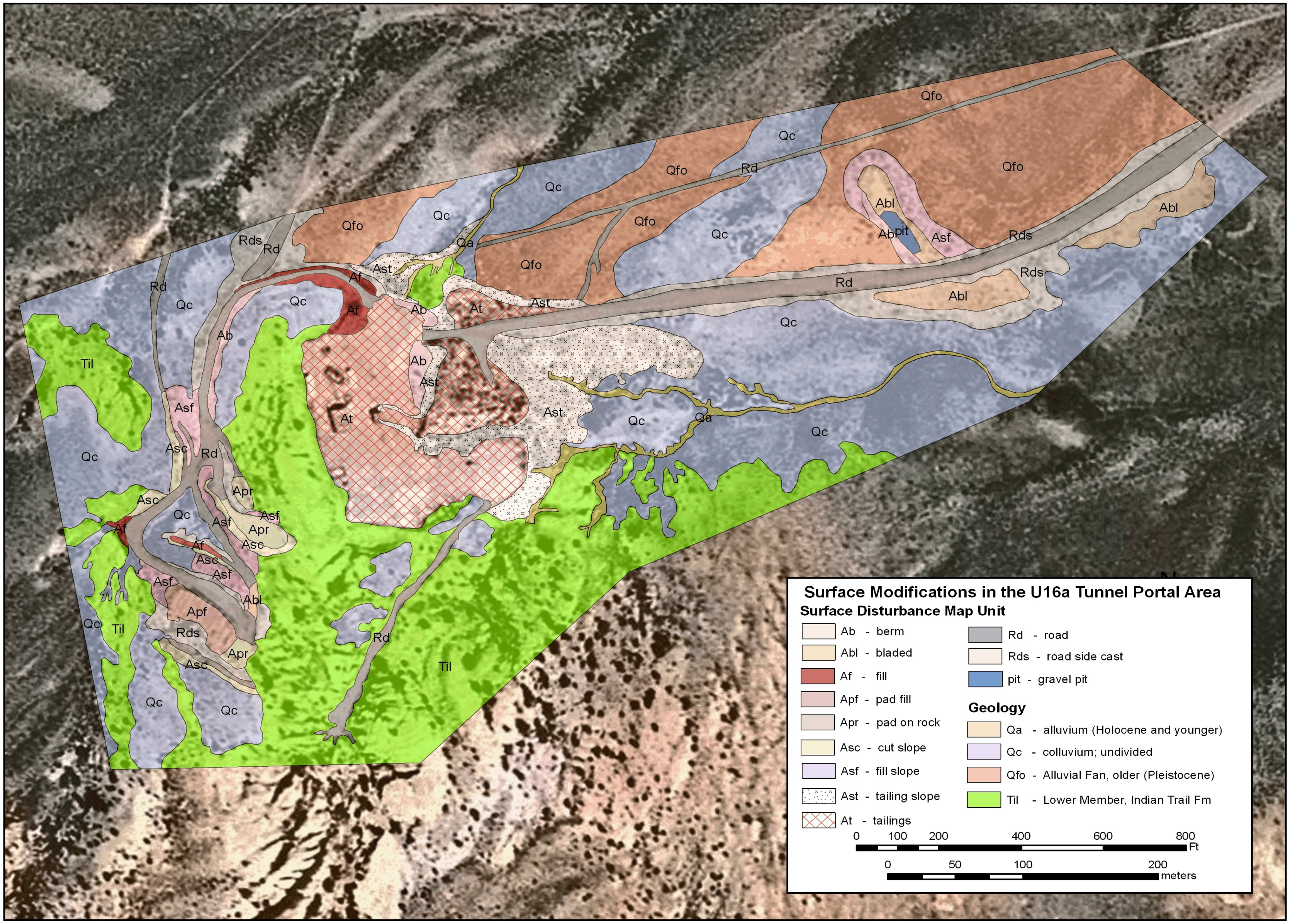

Figure 26. Surface disturbance map for the U16a Tunnel portal area.

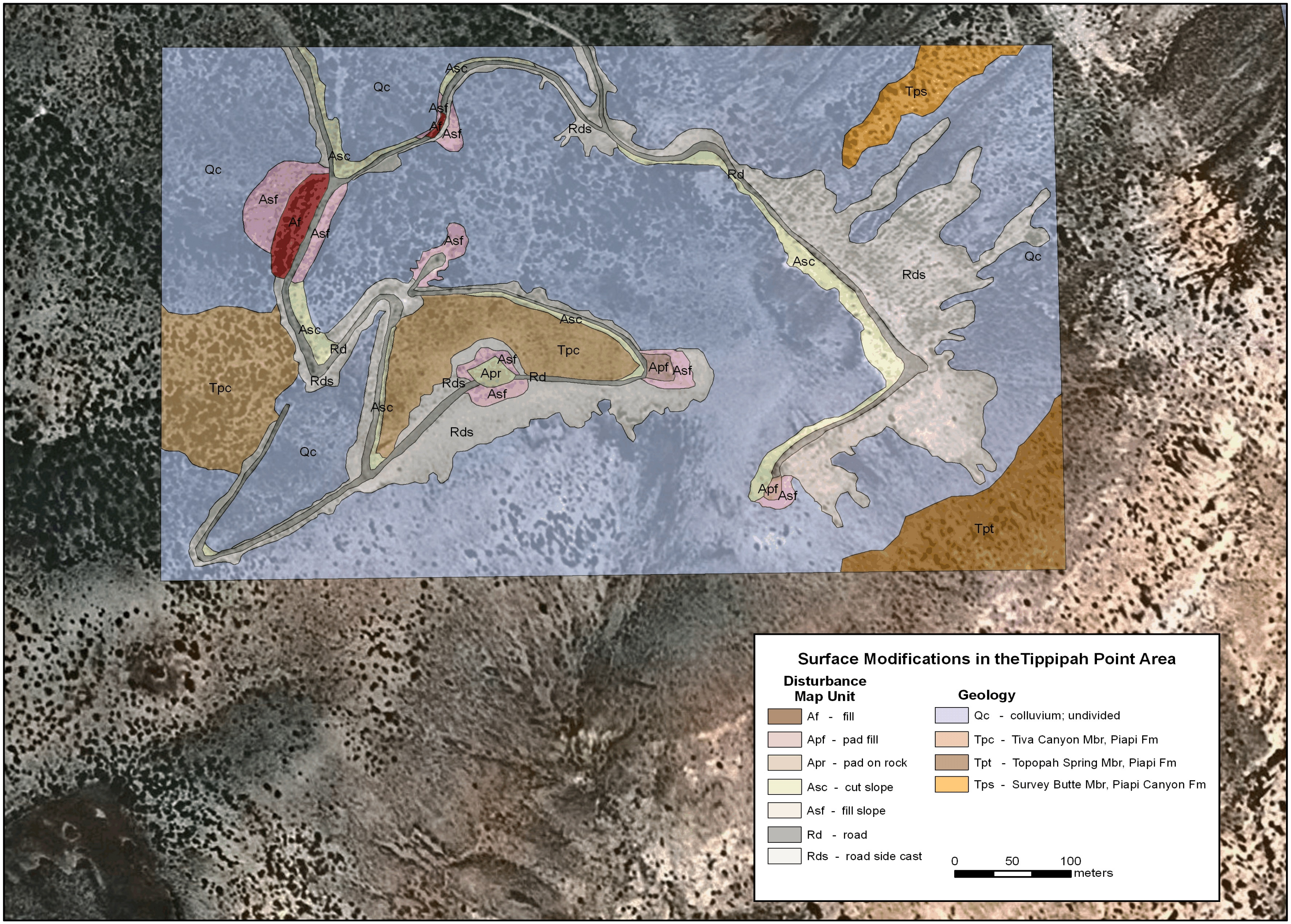

Figure 27. Surface disturbance map of Shoshone Mountain near Tippipah Point.

to the area above the U16a Tunnel portal includes graded roads, as well as unimproved two-track roads and trails for communications and power transmission lines.

The U16a Tunnel portal is situated on the lower eastern flank of Shoshone Mountain at an elevation of about 1,675 m (5,500 ft). Shoshone Mountain rises to about 2,015 m (6,612 ft) at Tippipah Point. U16a Tunnel portal is located near the apex of an east sloping Pleistocene alluvial fan complex. Syncline Ridge, a prominent geologic structure composed of folded Paleozoic marine deposits, is located northeast of the U16a Tunnel portal area. The portal area is situated at and near the head of pre-existing drainages immediately north, east, and south of the portal.

Topography on the east slope of Shoshone Mountain is steep, rugged, and stream valleys are generally narrow and have steep gradients. Fluvial systems in the area include numerous intermittent stream tributaries that originate on Shoshone Mountain and drain northeast to Yucca Flat. Streams originating near Tippipah Point flow to the south and west toward Frenchman Flat via Mid Valley and Barren Wash.

Principal access to U16a Tunnel is from the east via a road from Mid Valley Road. The prepared road ascends the east-sloping piedmont alluvial fan complex. The top of Shoshone Mountain at Tippipah Point is accessed from the south and west via 16-04 Road from Mid Valley.

Geology

Previous to, and following, nuclear testing in the U16a Tunnel complex, geological studies commonly were carried out by the U.S. Geological Survey to assess the geology and structure in the U16a Tunnel and the surrounding area (Davis and Hoover, 1962; Davis and Snyder, 1966; USGS, 1983). Subsequent studies by the USGS and other government agencies, and contractors were performed in accordance with other test activities (DOE, 2005), environmental compliance at the NNSS (e.g., DOE, 2006 a, b, 2011), as well as closure studies at U16a Tunnel (National Security Technologies LLC, 2009).

In the U16a Tunnel portal area, geology of the Shoshone Mountain area (Figure 24) consists of about 1,500 ft (460 m) of west and southwest dipping, layered calc-alkaline Tertiary ash fall and ash flow tuff, peralkaline ash fall and zeolitized tuff of the undivided Lower Member of the Indian Trail Formation in the portal area (Til of Orkild, 1963; Ash Fall Tuff [Ta_1] and Lithic Ridge Tuff [Tlr] of Frizzell and Schulters, 1990; Lithic Ridge Tuff [Tlr] of Slate et al., 1999). The steep slopes between the U16a Tunnel portal and Tippipah Point consist of, in ascending order, the ash-fall and ash-flow tuffs of the Survey Butte (Tps), Topopah Spring (Tpt), and Tiva Canyon (Tpc) Members of the Piapi Canyon Formation (Orkild, 1963; Ash Fall Tuff [Ta_2], Topopah Spring Member [Tpt], and Tiva Canyon Member [Tpc] of the Paintbrush and related lavas of Frizzell and Schulters, 1990; Slate et al., 1999) (Table 3). Early mapping (Orkild, 1963) assigned the Indian Trail Formation to the Miocene and the Piapi Canyon Formation to the Pliocene. More recent mapping investigations and compilations, including geochronology data, assign the rocks to the Miocene (e.g., Frizzell and Schulters, 1990; Sawyer et al., 1994; Slate et al., 1999). The volcanic rocks were deposited on an irregular surface of Paleozoic age sedimentary rocks comprised of carbonate and clastic rocks (Orkild, 1963; Frizzell and Schulters, 1990; Slate et al., 1999). A north to northwest trending normal fault is

Table 3. Nomenclature of geologic units in the U16a Tunnel area.

Frizzell and Shulters (1990); Slate et al. (1999)		Orklid (1963)	
Paintbrush Tuff and related lavas (Miocene)		Piapi Canyon Formation (Pliocene)	
Tpc	Tiva Canyon Member, Main Part (Miocene) - compositionally zoned compound cooling unit ash-flow tuff. Upper quartz latite caprock; middle rhyolite; lower high-silica rhyolite, less than 150 m thick.	Tpc	Tiva Canyon Member (Pliocene) - multiple-flow, simple cooling unit of gray, purple, and brown densely welded ash-flow tuffs; non-welded ash-flow and ash fall tuff at base. Thickness ~ 80m.
Tpt	Topopah Spring Member (Miocene) - multiple- flow compound cooling unit, densely welded, zoned rhyolite to quartz latite ash-flow tuff. More than 100 m thick.	Tpt	Topopah Spring Member (Pliocene) - multiple-flow, simple cooling unit of tray, purple, and brown densely welded ash-flow tuffs; non-welded ash-flow and ash fall tuff at base. Thickness ranges from 20 to 130 m.
Ta2	Ash-fall tuff (Miocene) - Thin- to thick-bedded, locally massive ash-fall tuff, well-bedded reworked tuffaceous sedimentary rock, and minor tuffaceous agglomerate. Thickness variable, up to 200 m.	Tps	Survey Butte Member (Pliocene) - pale-gray and brown well-bedded ash-fall tuff composed of vitric, fine to course pumice, volcanic fragments, glass globules, locally zeolitized at base. Interfingers with Stockade Wash, Topopah Spring, and Tiva Canyon members. Thickness ranges from 20 to 215 m.
Belted Range Tuff, Grouse Canyon FM		Indian Trail Formation (Miocene)	
Tlr	Lithic Ridge Tuff (Miocene) - moderately to weakly welded rhyolite ash-flow tuff, mostly zeolitized. More than 250 m thick.	Til	Lower Member, Undivided (Miocene) - gray, yellow, brown, red lenticular nonwelded ash-flow and ash-fall tuffs; zeolitic and locally siliceous; north of U16a Tunnel the Lower Member is divided into Tunnel Beds and tuffs at Grouse Canyon. Thickness ranges from about 180 to 335 m.
Ta1	Ash-fall tuff (Miocene) - Laminated to thick-bedded ash-fall tuff, reworked tuffaceous sandstone and conglomerate, and nonwelded ash-flow tuff; locally zeolitized. As much as 700 m thick.		

mapped in the vicinity of the portal (Orkild, 1963) as well as northeast trending faults in the Indian Trail Formation southeast of the portal (Orkild, 1963; Frizzell and Schulters, 1990).

Surficial Geology

In addition to anthropogenic deposits, natural surficial deposits are present in the U16a Tunnel area. Deposits consist of alluvium, alluvial fans, and colluvium (Figures 24 -27). Alluvial fans (Qfo) mapped in the U16a Tunnel area are likely Pleistocene age based on observed reddening of the soil and presence of accumulations of calcium carbonate, which typically signify appreciable soil development and hence age (Figure 28). Some small remnants of soils on colluvial deposits are found in the area around and above the U16a Tunnel portal. The steep slopes contribute to the absence of well-developed soils because soil mixing by mass wasting processes precludes stability necessary to form strongly developed soils.

Quaternary alluvium (Qa) is mapped along ephemeral stream channels. Alluvium consists of thin deposits of unconsolidated fluvial silt, sand, and gravel transported and deposited during rain and snow melt events of magnitudes sufficient to generate runoff.

Quaternary colluvium (Qc) is mapped throughout the area and consists of a very thin veneer, generally 0.5 m (1.5 ft) or less of silt, sand, gravel, angular cobbles, and angular boulders derived from bedded tuff and welded tuff. Locally, colluvial deposits at the base of slopes can be thick (1.5 to 3 m; 5 to 10 ft). Colluvium covers about half of the study area, although much of the area mapped as bedrock on the flanks of Shoshone Mountain could be considered to have a very thin mantle of colluvium.

Soils

Soils found on the NNSS are similar to those found in surrounding areas and include Aridisols and Entisols (Peterson 1988; Taylor 1986; Wesling et al. 1992; Whitney et al. 1986). In general, Entisols are young, weakly developed soils. In the U16a Tunnel area these soil types are found on steep mountain slopes and in stream valleys along active washes. Aridisols, which typically have well-developed, reddened B horizons and calcium carbonate accumulations, commonly are found on more stable alluvial fans and stream terraces. In the U16a Tunnel area, older soils formed on colluvium derived from Tertiary rocks have well developed B horizons that contain accumulations of calcium carbonate on the undersides of stones. A few exposures of well-developed soils are observed at U16a Tunnel where road and construction activities cut through colluvial mantles. Elsewhere, soils formed on natural slopes are patchy, thin, and weakly developed, minimally developed on tailings slopes, and weak to undeveloped along the stream channels situated near the base of the tailings pile. An exposure of alluvial fan sediments and associated soil in a borrow pit east of the tunnel portal (Figure 28) has a reddened B horizon with calcium carbonate accumulations indicative of substantial age to the older alluvial fans in this area.

LANDSCAPE MODIFICATION IN THE U16A TUNNEL AREA

Assessing landscape changes in the U16a Tunnel area included mapping of the bedrock and surficial geology to provide context for interpreting the general degree of surface disturbance. Bedrock and

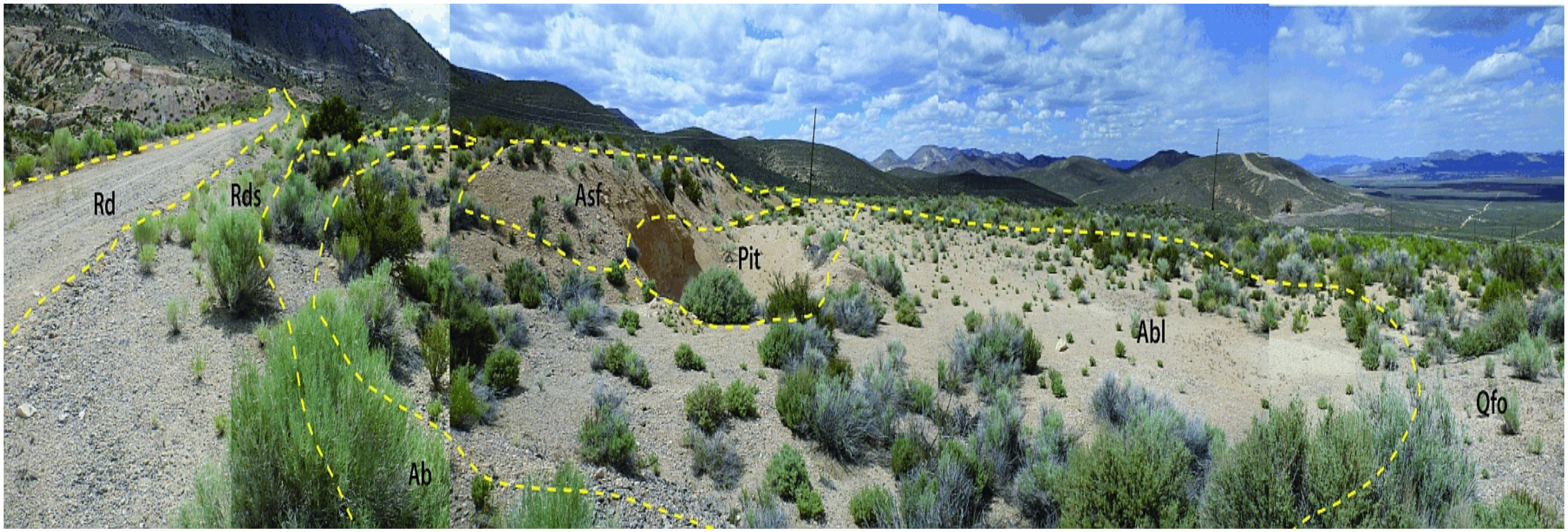

Figure 28. Example of a well-developed soil exposed in walls of gravel pit (pit) that was excavated into alluvial fan sediments (Qfo) east of the U16a Tunnel. Also shown are the principal access road (Rd), road side cast (Rds), bladed areas (Abl), and slope formed on fill (Asf).

surficial geology of the U16a Tunnel area was mapped both in the field and from imagery and compiled as a digital map using *ArcMap* (Figures 25-27). The mapping also included the types and extent of surface modification that likely occurred during development at the U16a Tunnel complex including road building and infrastructure construction. Map unit descriptions are provided in Table 4.

Landscape Change in the U16a Tunnel Portal Area

The character and form of the landscape of the portal area has been modified slightly over time by natural processes in addition to landform changes caused by tunneling and adding or deleting structures to meet the needs of various operations conducted at the tunnel. It appears that relatively few modifications to the valley floors adjacent to the U16a Tunnel portal were made to accommodate the tailings area. As a result, the disposal of mine muck at the front of the U16a Tunnel portal forms a pile about 18 m (60 ft) thick. In addition to the muck pile, the greatest surface modification is related to construction of the principal access road and a borrow pit on the north side of the road about 500 m east of the portal. The access road to pad areas on the steep slopes adjacent to the portal traverses artificial fill, colluvium, and bedrock. In most parts of the road network, surface geologic deposits were stripped to bedrock and commonly disposed on steep slopes. In some places, the surface deposits were removed for fill needed elsewhere at the site. Most recently, closure activities at U16a Tunnel (National Securities Technology LLC, 2009) have had minor effects on the geomorphology at the site manifested as small piles of muck and some redistributed tailings during maintenance operations and apparent erosion control activities. Subtle changes in the geomorphic system (slopes and drainages) have resulted from direct impact of dumping tailings into valleys, as well as from indirect impacts caused by increased surface runoff, erosion, and sedimentation related to geomorphic response to altered slope conditions.

Landscape Modifications in the Tippipah Point Area

The small area of the U16a Tunnel complex at Tippipah Point consists of mesa-like topography with deeply incised drainages on the north and west, and steep, colluvial covered bedrock slopes to the south and east. Features resulting from surface disturbance near Tippipah Point include access roads, drill pads, cut slopes in bedrock and colluvium, local fills for roads crossing incised drainages, and bedrock fracturing related to underground testing.

Drill pad sites were formed primarily by blading and fill construction techniques that resulted in low, vertical bedrock cuts and fill pads derived from excavated bedrock, thin surficial deposits, and colluvium. Drill pads typically retain a low (0.6 m; 2 ft) berm on the outboard edge to inhibit surface runoff to slopes. Surface disturbance related to roads in the Tippipah Point area are similar to those near the portal, although the regolith on the mesa top is generally thin and the road bed is commonly at or near bedrock. Landscape changes as the direct or subsequent result of nuclear detonations were not observed during the field visit, although post-test studies indicated evidence of increased fracturing, formation of small fissures, and local areas of rock slides above ground zero (Davis and Snyder, 1962).

Table 4. List of map units in the U16a Tunnel portal and Tippipah Point areas

Map Symbol	Map Unit	Description
Ab	Berm – road and tailings	Low berm along margins of roads and tailing, generally a foot or less in height; purpose is to control runoff from road surface; along edge of tailing pile, the berms may be 3 to 4 ft high
Abl	Bladed area	Areas characterized by shallow blading and/or removal of colluvium and thin surface mantle; commonly results in bedrock surfaces
Af	Artificial fill	Mechanically placed fill derived primarily from tunnel development
Apf	Artificial pad – fill	Fill placed at sites for drill pads, buildings, and utilities
Apr	Artificial pad – rock	Bladed areas, typically cut into bedrock, covered with thin layer of fill for drill pads, buildings, and utilities
Asc	Artificial cut slope	Slopes cut in bedrock or colluvium during road construction or site preparation
Asf	Artificial fill slope	Slopes formed adjacent to artificial fill, building pads, drill pads, etc.
Ast	Tailing slope	Slope formed on tailings deposits
At	Tailings	Mine waste dumped on hill slopes; stable tailings vegetated
pit	Borrow pit	Excavation in piedmont alluvial fan deposits as source of gravel
Rd	Road	Principal access roads for the U16a Tunnel complex and workings on Shoshone Mountain
Rds	Road side-cast	Slope wash deposits resulting from road grading and fill emplacement
Qa	Alluvium	Late Holocene deposits associated with ephemeral stream channels
Qc	Colluvium	Late Holocene mantle of bedrock derived colluvium and weathered surficial mantle
Qfo	Alluvial fan	Pleistocene age alluvial fans consisting of silt, sand, gravel, and cobbles; characterized by well developed soil having a reddened B horizon and accumulation of calcium carbonate
Tpc	Piapi Canyon Formation, Tiva Canyon Member	Multiple-flow, simple cooling unit of gray, purple, and brown densely welded ash-flow tuffs; non0welded ash-flow and ash fall tuff at base.
Tpt	Piapi Canyon Formation, Topopah Spring Member	Multiple-flow, simple cooling unit of gray, purple, and brown densely welded ash-flow tuffs; non- welded ash-flow and ash fall tuff at base.
Tps	Piapi Canyon Formation, Survey Butte Member	Pale-gray and brown well-bedded ash-fall tuff composed of vitric, fine to coarse pumice, volcanic fragments, glass globules, locally zeolitized at base. Interfingers with Stockade Wash, Topopah Spring, and Tiva Canyon members.
Til	Indian Trail Formation, Lower Member	Composite map unit including massive to bedded, reworked ash-fall tuff member and tuffaceous sandstone members of the Timber Mountain Tuff and Belted Range Tuff (Indian Trail Formation), and the Miocene age pale gray and red bedded ash-fall tuff and tuffaceous sandstone of the Lower Member of the Indian Trail Formation.

MAPPING THE IMPACTS OF U16A TUNNEL ACTIVITIES ON THE LOCAL GEOMORPHOLOGY

At the U16a Tunnel, modifications to the landscape have resulted from three principal activities: (1) road construction that cut through bedrock and colluvial mantled slopes to create an access road to the U16a Tunnel and the top of Shoshone Mountain and related road maintenance operations, (2) site preparation for activities related to experiments and testing in the U16a Tunnel complex and on Shoshone Mountain, and (3) mining activities related to development of the U16a Tunnel. These modifications were mapped and identified with unique map unit designations (Table 4). The surface area of the units is provided in Table 5. Landscape modifications occurred in association with: 1) Road building, including berms along the margin of roads (Ab), areas bladed by bulldozer or grader (Abl), cut slopes in bedrock and fill (Asc), road side cast material (Rds) and a gravel quarry (pit) (Figures 28-31); 2) Use of mine tailings (At) and reworked natural deposits (Af) as fill in construction of building and drill pads (Apf), road widening, road turnouts, benched fill for staging areas and slopes associated with large fill areas (Asf) (Figures 23 and 28-31); 3) Disposal of mine tailings (muck; At) on natural slopes during tunnel development, associated tailings pile slopes (Ast), and construction of berms (Ab) 1 to 4 ft (.3 to 1.3 m) high to control surface runoff (Figures 32-34). Subsequent erosion of tailings and gullied tailings, rilled tailings, and small drainages and associated alluvium established on the tailings can be mapped as discrete units, although, most if not all of the rilling is too small to map; thus, individual gullies and rills were not mapped (Figure 35).

Road Construction

Roads (Rd) are included as separate units of historic deposits and landscape modifications. Figures 3, 4, and 5 show the distribution of many of these map units in the U16a Tunnel portal and Tippipah Point areas.

The principal impact of road building at U16a Tunnel has been on erosion and transport of sediment. Erosion on and adjacent to roads relates to construction as well as maintenance operations before, during, and after test activity. Subsequent deterioration of the roadbed and roadside drainage systems occurred as the site was gradually taken out of service. Most of the road surfaces act as sources of sediment. Direct precipitation on the road surfaces generates runoff into roadside ditches supplying sediment to tributary streams. On the steeper sections of the road, particularly as it climbs the flanks of Shoshone Mountain, most construction consisted of excavating colluvium and scraping bedrock. Excavating and scraping resulted in minor yet perceptible changes in bedrock outcrop morphology. In places, particularly on the east flank of Tippipah Point it is possible (but not known) that some blasting was necessary to create a road on slopes underlain by the welded tuff of Tiva Canyon Member (Tpt) of the Piapi Canyon Formation. The most obvious effect of road construction consists of the material pushed off the edge of roads and fill piles (side cast). Side cast typically is restricted to a narrow corridor less than 3 m (10 ft) along the road, but in some cases the material has moved tens of meters down slope impinging on, or burying vegetation and altering local surface hydrology and drainage. In the area around Tippipah Point, roads were constructed across streams by installing a culvert and placing fill over the culvert. In some locations substantial fill was placed across drainages to create a favorable driving surface. Infrequent culvert maintenance results in restricted stream flow through culverts, and sediment tends to backfill valleys immediately upstream. The long

Table 5. Total areas of units mapped in the vicinity of U16a Tunnel portal and Tippipah Point.

Map Unit	Km^2	Hectares	Acres
Ab	0.0	0.1	0.5
Abl	0.0	0.5	1.4
Af	0.0	0.4	1.0
Apf	0.0	0.1	0.3
Apr	0.0	0.1	0.4
Asc	0.0	1.1	2.7
Asf	0.0	1.3	3.2
Ast	0.0	1.3	3.3
At	0.0	2.0	5.0
Rd	0.0	3.0	7.5
Rds	0.1	6.9	17.1
pit	0.0	<0.1	0.1
Qa	0.0	0.3	0.8
Qc	0.3	33.7	83.2
Qfo	0.0	4.3	10.6

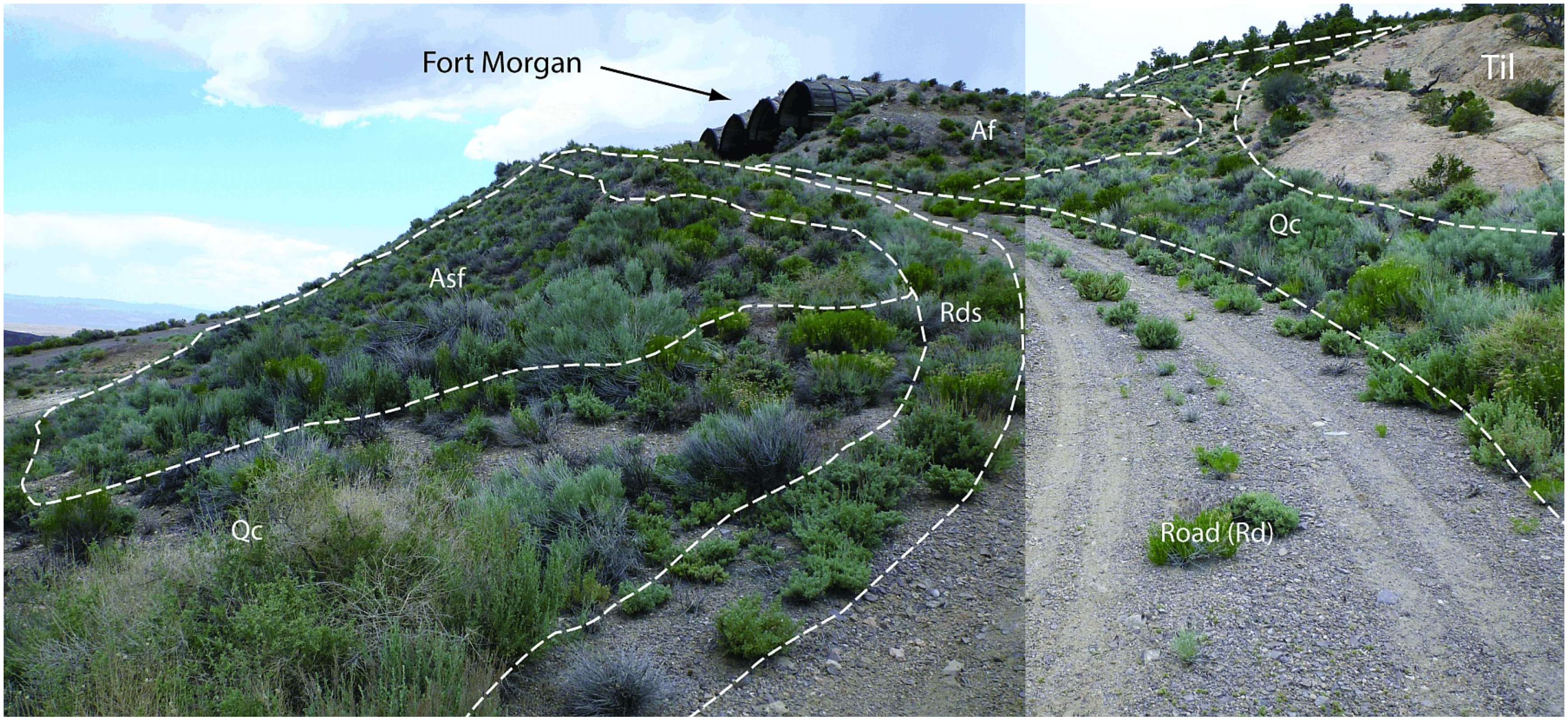

Figure 29. Above U16a Tunnel portal showing road that is cut into colluvium (Qc), road side cast (Rds), as well as where the road is on artificial fill (Af) near Feature 39 (Fort Morgan).

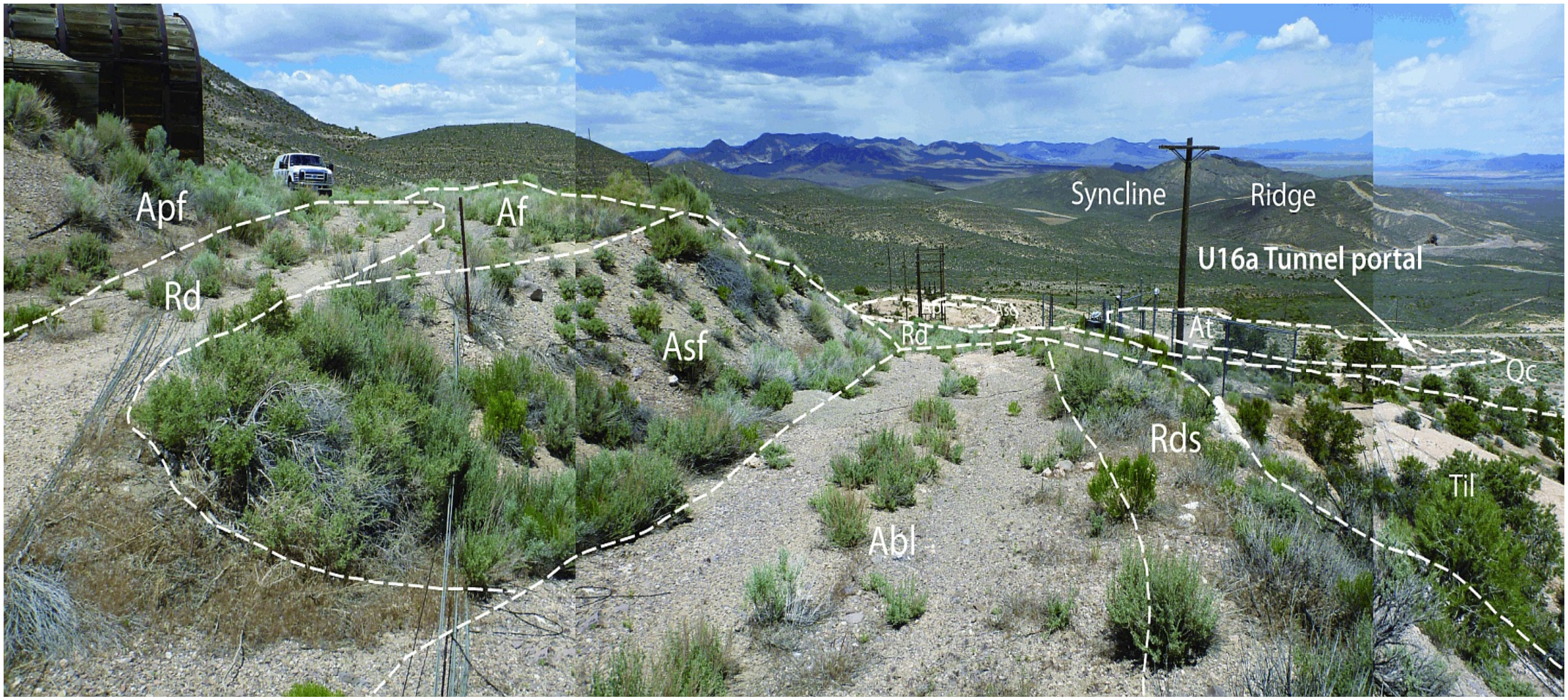

Figure 30. Photograph viewed to the north showing the location of U16a Tunnel relative to Syncline Ridge. The Fort Morgan trailer park on the left is situated on a pad of artificial fill (Apf, Af). Examples of artificial fill slope (Asf), road side cast (Rds), and a portion of the road bladed on bedrock (Abl).

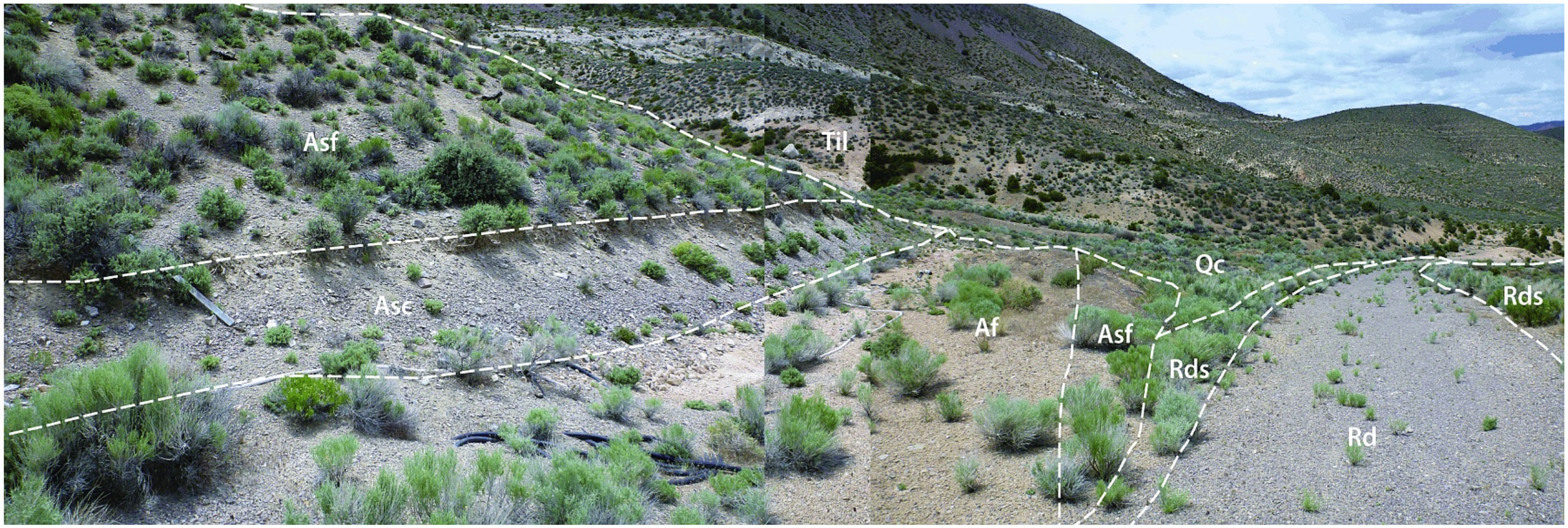

Figure 31. Example of a cut slope in colluvium (Asc), slopes on artificial fill (Asf), road side cast (Rds), and colluvium (Qc). The slope on the left (Asf) above the cut slope is fill that partially buries a pre-existing colluvial slope.

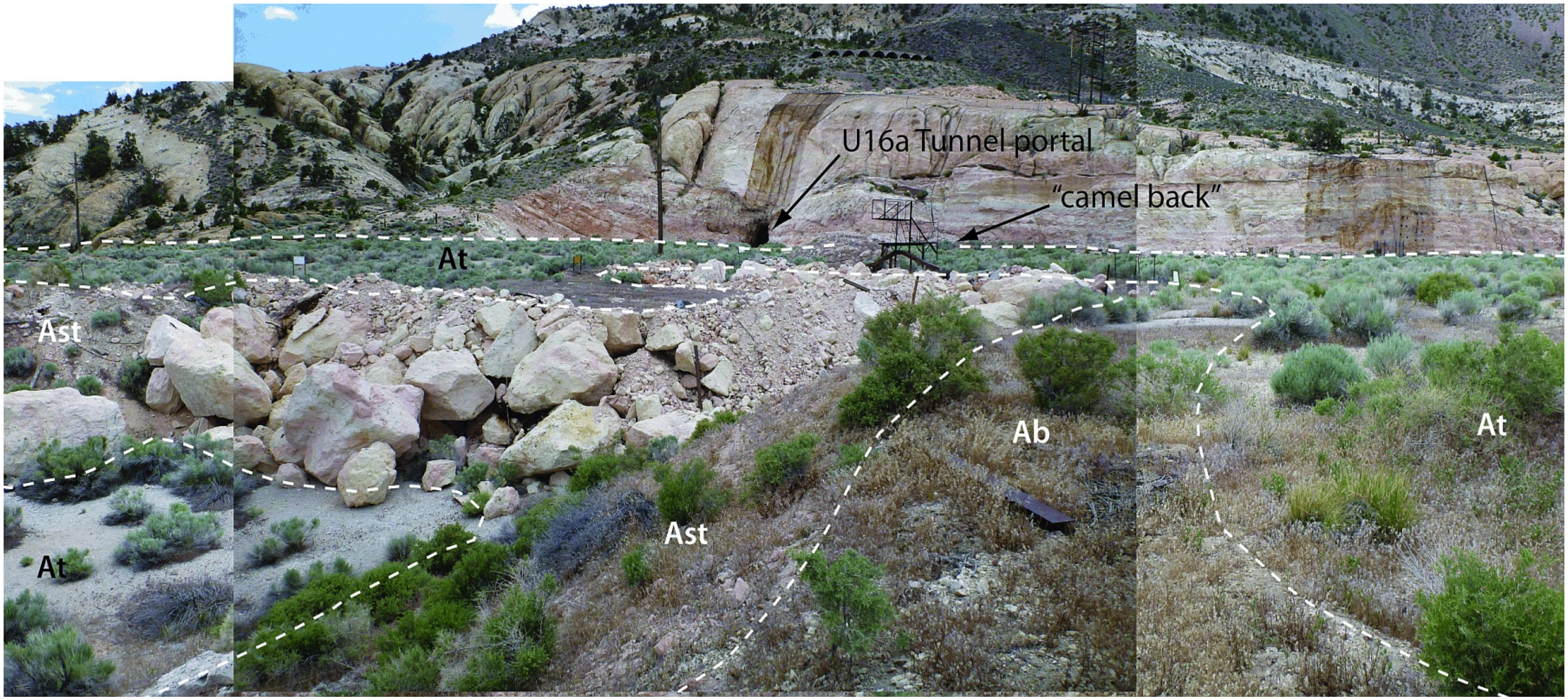

Figure 32. Panoramic view to the west of the tailings area at the U16a Tunnel portal area situated at the base of Shoshone Mountain. Tailings (At) and tailings slopes (Ast) have revegetated with a variety of grasses and sage. A berm (Ab) has been constructed along the edge of the tailings. The "camel back" dumping station is observed at the edge of the tailings slope in the mid-ground of the photograph.

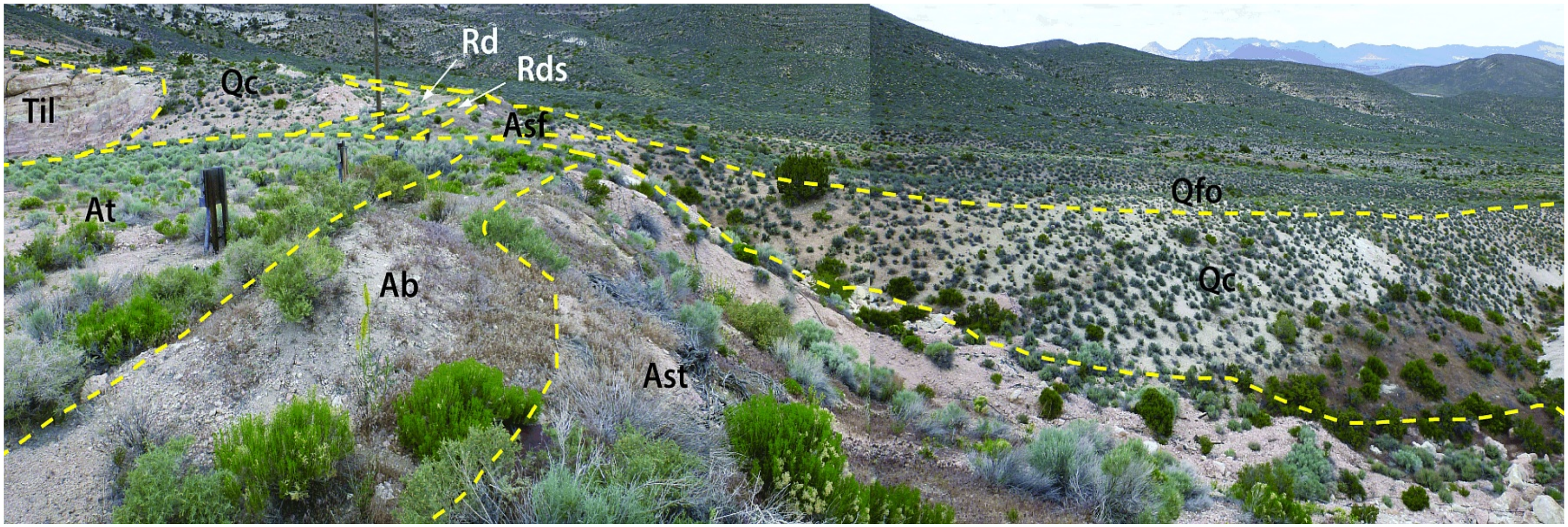

Figure 33. Photograph viewed north along the east edge of the tailings area showing the tailings slope (Ast) and the prominent berm (Ab) constructed along the edge.