Chapter 3

Containing Underground Nuclear Explosions

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Underground nuclear tests are designed and reviewed for containment, with redundancy and conservatism in each step.

INTRODUCTION

The United States' first underground nuclear test, codenamed "Pascal-A," was detonated at the bottom of a 499-foot open drill-hole on July 26, 1957.[1] Although Pascal-A marked the beginning of underground testing, above ground testing continued for another 6 years. With testing simultaneously occurring aboveground, the release of radioactive material from underground explosions was at first not a major concern. Consequently, Pascal-A, like many of the early underground tests that were to follow, was conducted "reman candle' style in an open shaft that allowed venting.[2]

As public sensitivity to fallout increased, guidelines for testing in Nevada became more stringent. In 1956, the weapons laboratories pursued efforts to reduce fallout by using the lowest possible test yields, by applying reduced fission yield or clean technology, and by containing explosions underground. Of these approaches, only underground testing offered hope for eliminating fallout. The objective was to contain the radioactive material, yet still collect all required information. The first experiment designed to contain an explosion completely underground was the "Rainier" test, which was detonated on September 19, 1957. A nuclear device with a known yield of 1.7 kilotons was selected for the test. The test was designed with two objectives: 1) to prevent the release of radioactivity to the atmosphere, and 2) to determine whether diagnostic information could be obtained from an underground test. The test was successful in both objectives. Five more tests were conducted the following year to confirm the adequacy of such testing for nuclear weapons development.

In November 1958, public concern over radioactive fallout brought about a nuclear testing moratorium that lasted nearly 3 years. After the United States resumed testing in September, 1961, almost all testing in Nevada was done underground, while atmospheric testing was conducted in the Christmas Island and Johnston Island area of the Pacific. From 1961 through 1963, many of the underground tests vented radioactive material. The amounts were small, however, in comparison to releases from aboveground testing also occurring at that time.

With the success of the Rainier test, efforts were made to understand the basic phenomenology of contained underground explosions. Field efforts included tunneling into the radioactive zone, laboratory measurements, and theoretical work to model the containment process. Through additional tests, experience was gained in tunnel-stemming processes and the effects of changing yields. The early attempts to explain the physical reason why underground nuclear explosions do not always fracture rock to the surface did little more than postulate the hypothetical existence of a "mystical magical membrane." In fact, it took more than a decade of underground testing before theories for the physical basis for containment were developed.

In 1963, U.S. atmospheric testing ended when the United States signed the Limited Test Ban Treaty prohibiting nuclear test explosions in any environment other than underground. The treaty also prohibits any explosion that:

> . . . causes radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted.[3]

With the venting of radioactive debris from underground explosions restricted by treaty, containment techniques improved. Although many U.S. tests continued to produce accidental releases of radioactive material, most releases were only detectable within the boundaries of the Nevada Test Site. In 1970, however, a test codenamed "Baneberry" resulted in a prompt, massive venting. Radioactive material from Baneberry was tracked as far as the Canadian border and focused concern about both the environmental safety and the treaty compliance of

[1] The first underground test was the United Slates' 100th nuclear explosion.

[2] It is interesting to note that even with an open shaft, 90% of the fission products created by Pascal-A were contained Underground

[3] Article I, 1 (b).1963 Limited Test Ban Treaty

the testing program.[4] Testing was suspended for 7 months while a detailed examination of testing practices was conducted by the Atomic Energy Commission. The examination resulted in new testing procedures and specific recommendations for review of test containment. The procedures initiated as a consequence of Baneberry are the basis of present-day testing practices.

Today, safety is an overriding concern throughout every step in the planning and execution of an underground nuclear test. Underground nuclear test explosions are designed to be contained, reviewed for containment, and conducted to minimize even the most remote chance of an accidental release of radioactive material. Each step of the testing authorization procedure is concerned with safety; and conservatism and redundancy are built into the system.[5]

WHAT HAPPENS DURING AN UNDERGROUND NUCLEAR EXPLOSION

The detonation of a nuclear explosion underground creates phenomena that occur within the following time flames:

Microseconds

Within a microsecond (one-millionth of a second), the billions of atoms involved in a nuclear explosion release their energy. Pressures within the exploding nuclear weapon reach several million pounds per square inch; and temperatures are as high as 100 million degrees Centigrade. A strong shock wave is created by the explosion and moves outward from the point of detonation.

Milliseconds

Within tens of milliseconds (thousandths of a second), the metal canister and surrounding rock are vaporized, creating a bubble of high pressure steam and gas. A cavity is then formed both by the pressure of the gas bubble and by the explosive momentum imparted to the surrounding rock,

Tenths of a Second

As the cavity continues to expand, the internal pressure decreases. Within a few tenths of a second, the pressure has dropped to a level roughly comparable to the weight of the overlying rock. At this point, the cavity has reached its largest size and can no longer grow.[6] Meanwhile, the shockwave created by the explosion has traveled outward from the cavity, crushing and fracturing rock. Eventually, the shock wave weakens to the point where the rock is no longer crushed, but is merely compressed and then returns to its original state. This compression and relaxation phase becomes seismic waves that travel through the Earth in the same manner as seismic waves formed by an earthquake.

A Few Seconds

After a few seconds, the molten rock begins to collect and solidify in a puddle at the bottom of the cavity.[7] Eventually, cooling causes the gas pressure within the cavity to decrease.

Minutes to Days

When the gas pressure in the cavity declines to the point where it is no longer able to support the overlying rock, the cavity may collapse. The collapse occurs as overlying rock breaks into rubble and falls into the cavity void. As the process continues, the void region moves upward as rubble falls downward. The "chimneying" continues until:

- the void volume within the chimney completely fills with loose rubble,
- the chimney reaches a level where the shape of the void region and the strength of the rock can support the overburden material. or
- the chimney reaches the surface.

If the chimney reaches the surface, the ground sinks forming a saucer-like subsidence crater. Cavity collapse and chimney formation typically occur within a few hours of the detonation but sometimes take days or months.

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4 See for example, Bruce A. Bolt, Nuclear *Explosions and Earthquakes San* Francisco, CA. (W.H. Freeman & CO., 1976).

5 See "Detonation Authority and Procedures" (ch. 2).

6 See the next section, "How explosions remain contained," for a detailed explanation of cavity formation.

7 The solidified rock contains most of the radioactive products from the explosion. The performance of the nuclear weapon is analyzed when samples of this material are recovered by drilling back into the cavity.

Box 3-A—Baneberry

The exact cause of the 1970 Baneberry venting still remains a mystery. The original explanation postulated the existence of an undetected water table. It assumed that the high temperatures of the explosion produced steam that vented to the surface. Later analysis, however, discredited this explanation and proposed an alternative scenario based on three geologic features of the Baneberry site: water-saturated clay, a buried scarp of hard rock, and a nearby fault. It is thought that the weak, water-saturated clay was unable to support the containment structure: the hard scarp strongly reflected back the energy of the explosion increasing its force; and the nearby fault provided a pathway that gases could travel along. All three of these features seem to have contributed to the venting. Whatever its cause, the Baneberry venting increased attention on containment and, in doing so, marked the beginning of the present-day containment practices.

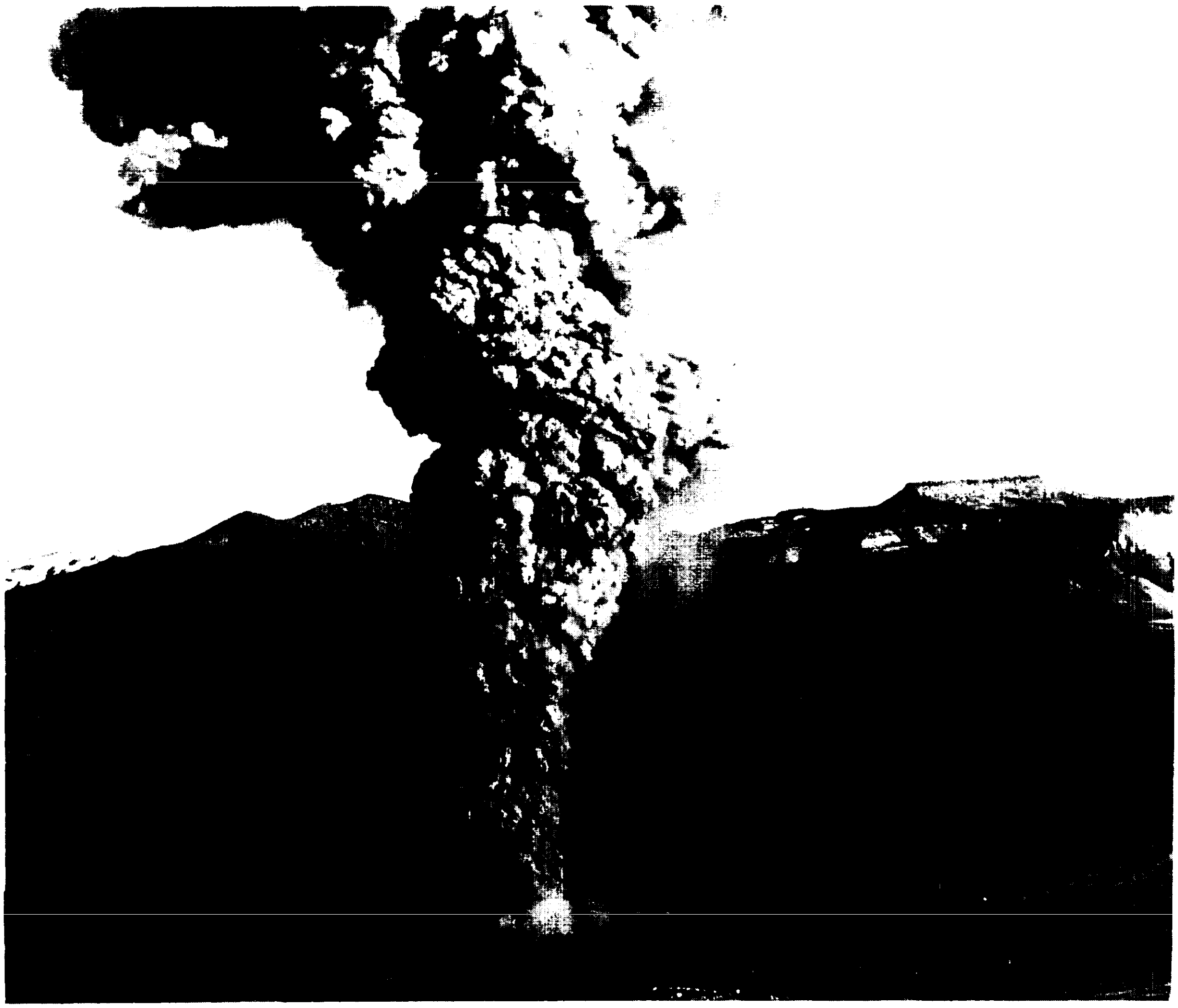


Photo credit: Department of Energy

The venting of Baneberry, 1970.

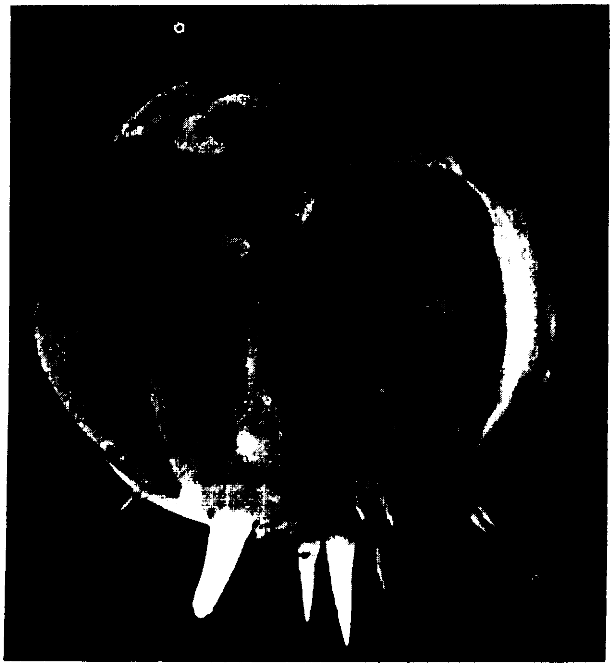


Photo credit Harold E. Edgerton

Early phase of fireball from nuclear explosion.

WHY NUCLEAR EXPLOSIONS REMAIN CONTAINED

Radioactive material produced by a nuclear explosion remains underground due to the combined efforts of:

- the sealing nature of compressed rock around the cavity,
- the porosity of the rock,
- the depth of burial,
- the strength of the rock, and
- the stemming of the emplacement hole.

Counter to intuition, only minimal rock strength is required for containment.

At first, the explosion creates a pressurized cavity filled with gas that is mostly steam. As the cavity pushes outward, the surrounding rock is compressed (figure 3-l(a)). Because there is essentially a fixed quantity of gas within the cavity, the pressure decreases as the cavity expands. Eventually the pressure drops below the level required to deform the surrounding material (figure 3-l(b)). Meanwhile, the shock wave has imparted outward motion to the material around the cavity. Once the shock wave has passed, however, the material tries to return (rebound) to its original position (figure 3-l(c)). The rebound creates a large compressive stress field, called a stress "containment cage' around the cavity (figure 3-1 (d)). The physics of the stress containment cage is somewhat analogous to how stone archways support themselves. In the case of a stone archway, the weight of each stone pushes against the others and supports the archway. In the case of an underground explosion, the rebounded rock locks around the cavity forming a stress field that is stronger than the pressure inside the cavity. The stress "containment cage" closes any fractures that may have begun and prevents new fractures from forming.

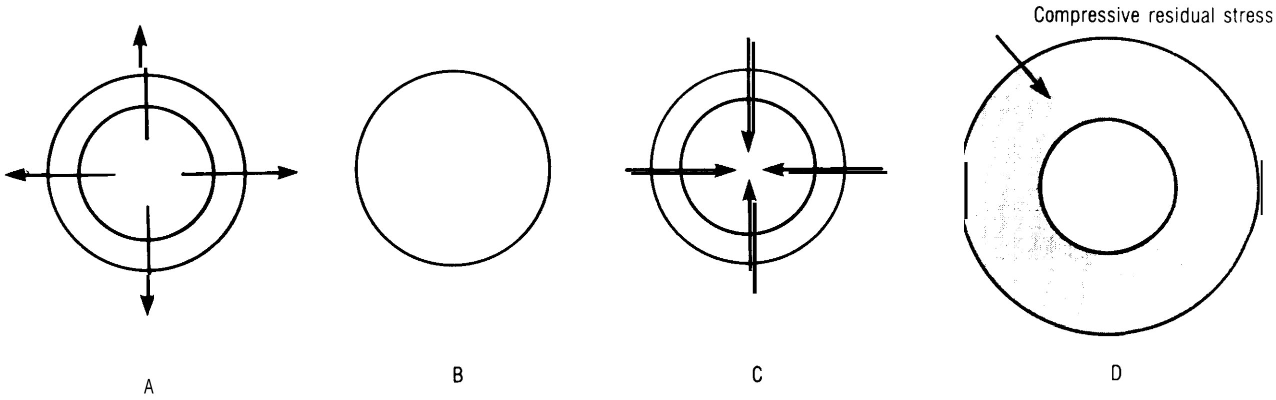
The predominantly steam-filled cavity eventually collapses forming a chimney. When collapse occurs, the steam in the cavity is condensed through contact with the cold rock falling into the cavity. The noncondensible gases remain within the lower chimney at low pressure. Once collapse occurs, high-pressure steam is no longer present to drive gases from the cavity region to the surface.

If the testis conducted in porous material, such as alluvium or tuff, the porosity of the medium will provide volume to absorb gases produced by the explosion. For example, all of the steam generated by a 150 kiloton explosion beneath the water table can be contained in a condensed state within the volume of pore space that exists in a hemispherical pile of alluvium 200 to 300 feet high. Although most steam condenses before leaving the cavity region, the porosity helps to contain noncondensible gases such as carbon dioxide (CO_2) and hydrogen (H_2). The gas diffuses into the interconnected pore space and the pressure is reduced to a level that is too low to drive the fractures. The deep water table and high porosity of rocks at the Nevada Test Site facilitate containment.

Containment also occurs because of the pressure of overlying rock. The depth of burial provides a stress that limits fracture growth. For example, as a fracture initiated from the cavity grows, gas seeps from the fracture into the surrounding material. Eventually, the pressure within the fracture decreases below what is needed to extend the fracture. At this point, growth of the fracture stops and the gas simply leaks into the surrounding material.

Rock strength is also an important aspect of containment, but only in the sense that an extremely weak rock (such as water-saturated clay) cannot

Figure 3-1—Formation of Stress "Containment Cage"



1) Cavity expands outward and deforms surrounding rock. 2) Natural resistance to deformation stops expansion. 3) Cavity contracts (rebounds) from elastic unloading of distant rock. 4) Rebound locks in compressive residual stress around cavity.

SOURCE: Modified from Lawrence Livermore National Laboratory.

support a stress containment cage. Detonation within weak, saturated clay is thought to have been a factor in the release of the Baneberry test. As a result, sites containing large amounts of water-saturated clay are now avoided.

The final aspect of containment is the stemming that is put in a vertical hole after the nuclear device has been emplaced. Stemming is designed to prevent gas from traveling up the emplacement hole. Impermeable plugs, located at various distances along the stemming column, force the gases into the surrounding rock where it is ''sponged up' in the pore spaces.

How the various containment features perform depends on many variables: the size of the explosion, the depth of burial, the water content of the rock, the geologic structure, etc. Problems may occur when the containment cage does not form completely and gas from the cavity flows either through the emplacement hole or the overburden material.[8] When the cavity collapses, the steam condenses and only noncondensible gases such as carbon dioxide (CO_2) and hydrogen (H_2) remain in the cavity.[9] The CO_2 and H_2 remain in the chimney if there is available pore space. If the quantity of noncondensible gases is large, however, they can act as a driving force to transport radioactivity through the chimney or the overlying rock. Consequently, the amount of carbonate material and water in the rock near the explosion and the amount of iron available for reaction are considered when evaluating containment.[10]

SELECTING LOCATION, DEPTH, AND SPACING

The site for conducting a nuclear test is, at first, selected only on a tentative basis. The final decision is made after various site characteristics have been reviewed. The location, depth of burial, and spacing are based on the maximum expected yield for the nuclear device, the required geometry of the test, and the practical considerations of scheduling, convenience, and available holes. If none of the inventory holes are suitable, a site is selected and a hole drilled.[11]

The first scale for determining how deep an explosion should be buried was derived from the Rainier test in 1957. The depth. based on the cube root of the yield, was originally:

$$\text{Depth} = 300\ (\text{yield})^{1/3}$$

where depth was measured in feet and yield in

[8] Lack of a stress ''containment cage' may not be a serious problem if the medium is sufficently porous or if the depth of burial is sufficent.

[9] The CO_2 is formed from the vaporization of carbonate material; while the H_2 is formed when water reacts with the iron in the nuclear device and diagnostics equipment.

[10] The carbonate material in Frenchman Flat created CO_2 that is thought to have caused a seep during the Diagonal Line test (Nov. 24, 197 1). Diagonal Line was the last test on Frenchman Flat; the area is currently considered impractical for underground testing largely because of the carbonate material.

[11] See ch. 2, ''The Nevada Test Site," for a description of the areas each Laboratory uses for testing.

Photo credit: Department of *Energy*

Blanca containment failure, 1958.

kilotons. The first few tests after Rainier, however, were detonated at greater depths than this formula requires because it was more convenient to mine tunnels deeper in the Mesa. It was not until "Blanca," October 30, 1958, that a test was conducted exactly at 300 (yield) $^{1/3}$ feet to test the depth scale. The containment of the Blanca explosion, however, was unsuccessful and resulted in a surface venting of radioactive material. As a consequence, the depth scale was modified to include the addition of a few hundred feet as a safety factor and thus became: 300 (yield)'/' "plus-a-few-hundred-feet.

Today, the general depth of burial can be approximated by the equation:

Depth = 400 (yield)' /q,

where depth is measured in feet and yield in kilotons.[12] The minimum depth of burial, however, is 600 feet.[13] Consequently, depths of burial vary from 600 feet for a low-yield device, to about 2,100 feet for a large-yield test. The depth is scaled to the

12 "Public Safety for Nuclear Weapons Tests," United States Environmental Protection Agency, January, 1984.

13 The 600-foot depth was chosen as a minimum after a statistical study showed that the likelihood of a seep of radioactive material to the surface for explosions buried 600 feet or more was about 1/2 as great as for explosions at less than 500 feet, even if they were buried at the same scale-depth in eaeh case.

‘‘maximum credible yield’ that the nuclear device is thought physically capable of producing, not to the design yield or most likely yield. [14]

Whether a test will be conducted on Pahute Mesa or Yucca Flat depends on the maximum credible yield. Yucca Flat is closer to support facilities and therefore more convenient, while the deep water table at Pahute Mesa is more economical for large yield tests that need deep, large diameter emplacement holes. Large yield tests in small diameter holes (less than 7 feet) can be conducted in Yucca Flat. A test area may also be chosen to avoid scheduling conflicts that might result in a test damaging the hole or diagnostic equipment of another nearby test. Once the area has been chosen, several candidate sites are selected based on such features as: proximity to previous tests or existing drill holes; geologic features such as faults, depth to basement rock, and the presence of clays or carbonate materials; and practical considerations such as proximity to power lines, roads, etc.

In areas well suited for testing, an additional site selection restriction is the proximity to previous tests. For vertical drill hole tests, the minimum shot separation distance is about one-half the depth of burial for the new shot (figure 3-2). For shallow shots, this separation distance allows tests to be spaced so close together that in some cases, the surface collapse craters coalesce. The 1/2 depth of burial distance is a convention of convenience, rather than a criterion for containment.[15] It is, for example, difficult to safely place a drilling rig too close to an existing collapse crater.

Horizontal tunnel tests are generally spaced with a minimum shot separation distance of twice the combined cavity radius plus 100 feet, measured from the point of detonation (called the “working point”) (figure 3-3). In other words, two tests with 100 foot radius cavities would be separated by 300 feet between cavities, or 500 feet (center to center). The size of a cavity formed by an explosion is proportional to the cube root of the yield and can be estimated by:

Radius = 55 (yield) ’h,

where the radius is measured in feet and the yield in kilotons. For example, an 8 kiloton explosion would be expected to produce an underground cavity with approximately a 110 foot radius. Two such test explosions would require a minimum separation distance of 320 feet between cavities or 540 feet between working points.

Occasionally, a hole or tunnel is found to be unsuitable for the proposed test. Such a situation, however, is rare, occurring at a rate of about 1 out of 25 for a drill hole test and about 1 out of 15 for a tunnel test. [16] Usually, a particular hole that is found unacceptable for one test can be used for another test at a lower yield.

REVIEWING A TEST SITE LOCATION

Once the general parameters for a drill-hole have been selected, the sponsoring laboratory requests a pre-drill Geologic Data Summary (GDS) from the U.S. Geological Survey. The GDS is a geologic interpretation of the area that reviews the three basic elements: the structures, the rock type, and the water content. The U.S. Geological Survey looks for features that have caused containment problems in the past. Of particular concern is the presence of any faults that might become pathways for the release of radioactive material, and the close location of hard basement rock that may reflect the energy created by the explosion, Review of the rock type checks for features such as clay content which would indicate a weak area where it may be difficult for the hole to remain intact, and the presence of carbonate rock that could produce CO_2. Water content is also reviewed to predict the amount of steam and H_2 that might be produced. If the geology indicates less than ideal conditions, alternate locations may be suggested that vary from less than a few hundred feet from the proposed site to an entirely different area of the test site.

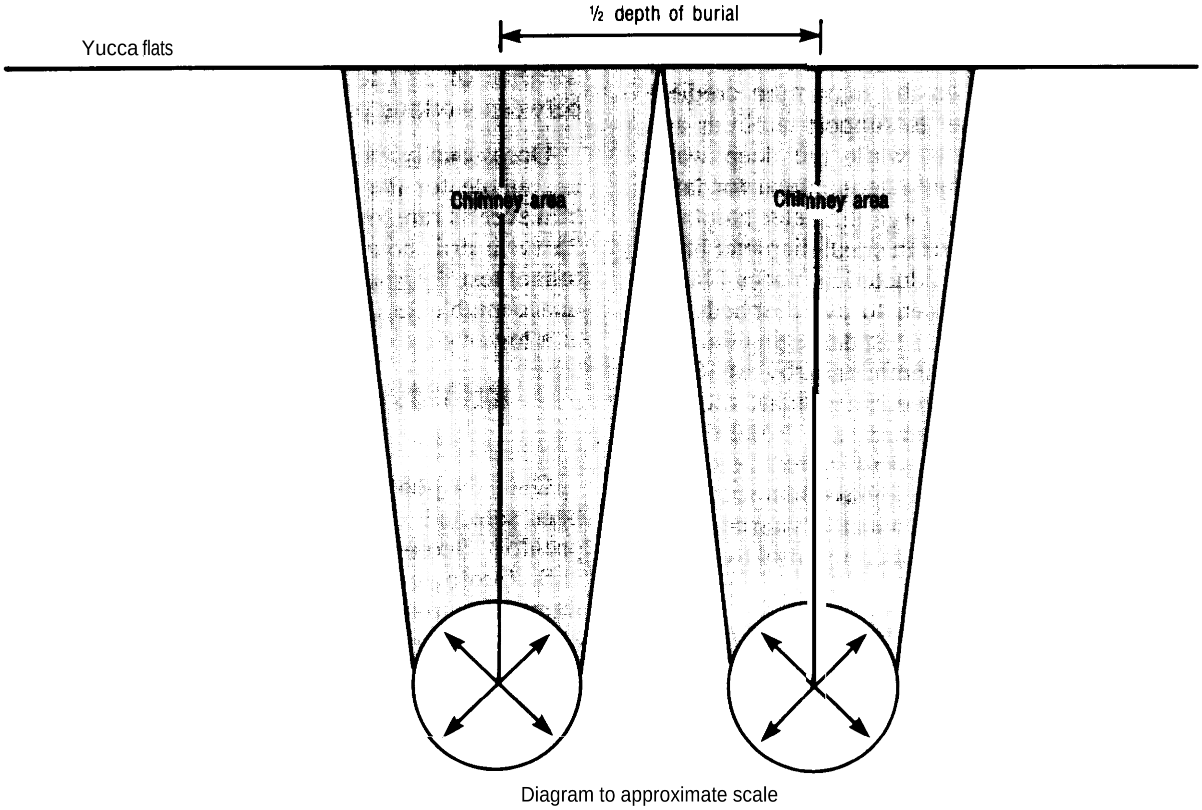
When the final site location is drilled, data are collected and evaluated by the sponsoring laboratory. Samples and geophysical logs, including downhole photography, are collected and analyzed. The U.S. Geological Survey reviews the data, consults with the laboratory throughout the process, and reviews the accuracy of the geologic interpretations.

[14] In many cases the maximum credible yield is significantly larger than the expected yield for a nuclear device.

[15] As discussed later, testing in previously fractured rock is not considered a containment risk in most instances.

[16] On three occasions tunnels have been abandoned because of unanticipated conditions such as the discovery of a fault or the presence of too much water,

Figure 3-2-Minimum Shot Separation for Drill Hole Tests



Scale illustration of the minimum separation distance (1/2 depth of burial) for vertical drill hole tests. The depth of burial is based on the maximum credible yield.

SOURCE: Office of Technology Assessment, 1989

To confirm the accuracy of the geologic description and review and evaluate containment considerations, the Survey also attends the host laboratory's site proposal presentation to the Containment Evaluation Panel.

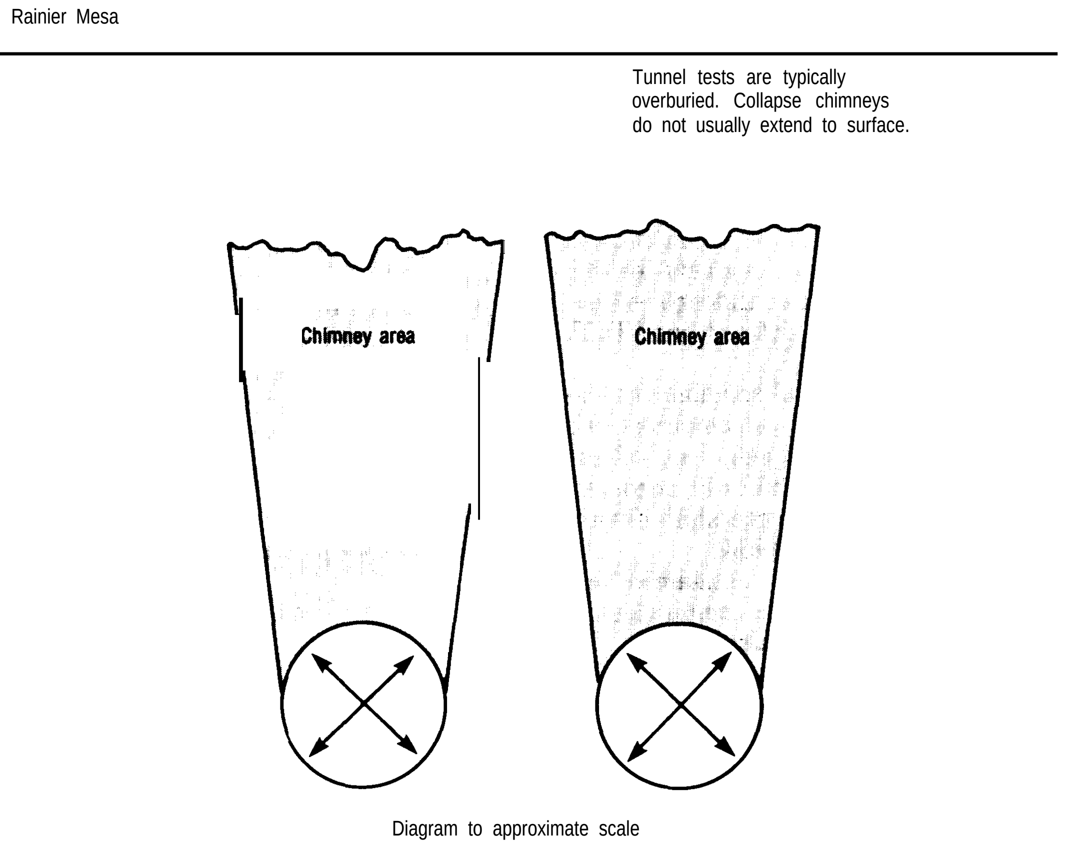
CONTAINMENT EVALUATION PANEL

One consequence of the Baneberry review was the restructuring of what was then called the Test Evaluation Panel. The panel was reorganized and new members with a wider range of geologic and hydrologic expertise were added. The new panel was named the Containment Evaluation Panel (CEP); and their first meeting was held in March, 1971.

The Containment Evaluation Panel presently consists of a Chairman and up to 11 panel members. Six of the panel members are representatives from Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Defense Nuclear Agency, Sandia National Laboratory, U.S. Geological Survey, and the Desert Research Institute. An additional 3 to 5 members are also included for their expertise in disciplines related to containment. The chairman of the panel is appointed by the Manager of Nevada Operations (Department of Energy), and panel members are nominated by the member institution with the concurrence of the chairman and approval of the Manager. The panel reports to the Manager of Nevada Operations.

Practices of the Containment Evaluation Panel have evolved throughout the past 18 years; however, their purpose, as described by the Containment

Figure 3-3--Minimum Shot Separation for Tunnel Tests



Scale illustration of the minimum separation distance (2 combined cavity radii plus 100 feet) for horizontal tunnel tests. Tunnel tests are typically overburied. Collapse chimneys do not usually extend to the surface.

SOURCE: Office of Technology Assessment, 1989

Evaluation Charter, remains specifically defined as follows:[17]

1. **evaluate, as** an independent organization reporting to the Manager of Nevada Operations, the containment design of each proposed nuclear test;
2. assure that all relevant data available for proper evaluation are considered;
3. advise the manager of Nevada Operations of the technical adequacy of such design from the viewpoint of containment, thus providing the manager a basis on which to request detonation authority; and
4. maintain a historical record of each evaluation and of the data, proceedings, and discussions pertaining thereto.

Although the CEP is charged with rendering a judgment as to the adequacy of the design of the containment, the panel does not vote. Each member provides his independent judgment as to the prospect of containment, usually addressing his own area of expertise but free to comment on any aspect of the test. The Chairman is in charge of summarizing these statements in a recommendation to the manager on whether to proceed with the test, based only on the containment aspects. Containment Evaluation Panel guidelines instruct members to make their judgments in such a way that:

17 Containment Evaluation Charter, June 1, 1986, Section II.

> Considerations of cost, schedules, and test objectives shall not enter into the review of the technical adequacy of any test from the viewpoint of containment.[18]

Along with their judgments on containment, each panel member evaluates the probability of containment using the following four categories:[19]

1. *Category A:* Considering all containment features and appropriate historical, empirical, and analytical data, the best judgment of the member indicates a high confidence in successful containment as defined in VIII.F. below.
2. *Category B:* Considering all containment features and appropriate historical, empirical, and analytical data, the best judgment of the member indicates a less, but still adequate, degree of confidence in successful containment as defined in VIII.F. below.
3. *Category C':* Considering all containment features and appropriate historical, empirical, and analytical data, the best judgment of the member indicates some doubt that successful containment, as described in VIII.F. below, will be achieved.
4. *Unable to Categorize*

Successful containment is defined for the CEP as:

> . . . no radioactivity detectable off-site as measured by normal monitoring equipment and no unanticipated release of activity on-site.

The Containment Evaluation Panel does not have the direct authority to prevent a test from being conducted. Their judgment, both as individuals and as summarized by the Chairman, is presented to the Manager. The Manager makes the decision as to whether a Detonation Authority Request will be made. The statements and categorization from each CEP member are included as part of the permanent Detonation Authority Request.

Although the panel only advises the Manager, it would be unlikely for the Manager to request detonation if the request included a judgment by the CEP that the explosion might not be contained. The record indicates the influence of the CEP. Since formation of the panel in 1970, there has never been a Detonation Authority Request submitted for approval with a containment plan that received a "C" ("some doubt") categorization from even one member.[20 21]

The Containment Evaluation Panel serves an additional role in improving containment as a consequence of their meetings. The discussions of the CEP provide an ongoing forum for technical discussions of containment concepts and practices. As a consequence, general improvements to containment design have evolved through the panel discussions and debate.

CONTAINING VERTICAL SHAFT TESTS

Once a hole has been selected and reviewed, a stemming plan is made for the individual hole. The stemming plan is usually formulated by adapting previously successful stemming plans to the particularities of a given hole. The objective of the plan is to prevent the emplacement hole from being the path of least resistance for the flow of radioactive material. In doing so, the stemming plan must take into account the possibility of only a partial collapse: if the chimney collapse extends only halfway to the surface, the stemming above the collapse must remain intact.

Lowering the nuclear device with the diagnostics down the emplacement hole can take up to 5 days. A typical test will have between 50 and 250 diagnostic cables with diameters as great as 15/~ inches packaged in bundles through the stemming column. After the nuclear device is lowered into the emplacement hole, the stemming is installed. Figure 3-4 shows a typical stemming plan for a Lawrence

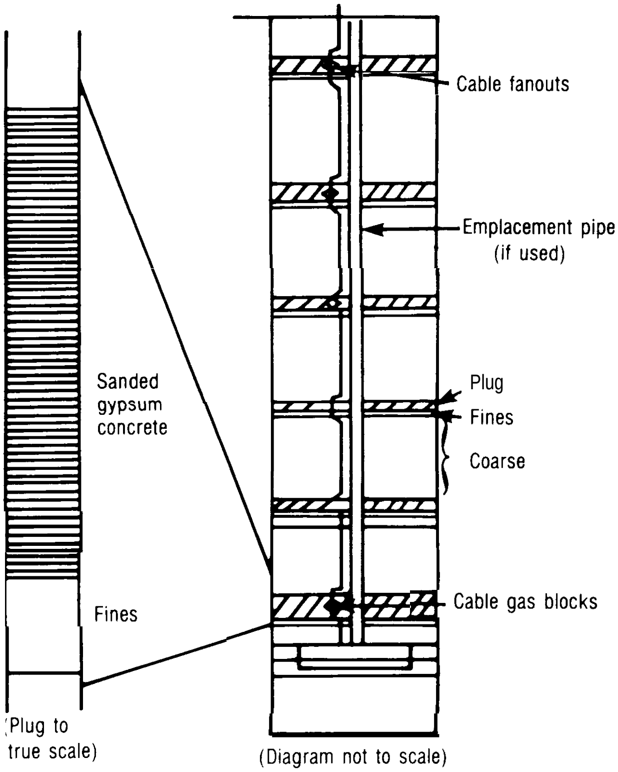
[18] Containment Evaluation P,,e] Charter, June 1, 1986, Section III.D.

[19] Containment Evaluation Panel Charter, June 1, 1986, Section VII.

[20] The grading system for containment plans has evolved since the early 1970's. Prior to April, 1977, the Containment Evacuation Panel categorized tests using the Roman numerals (I-IV) where I-III had about the same meaning as A-C and IV was a D which eventually was dropped as a letter and just became "unable to categorize."

[21] However, one shot (Mundo) was submitted with an "unable to categorize" categorization, Mundo was a joint US-UK test conducted on May 1, 1984.

Figure 3-4--"Typical" Stemming Plan



Typical stemming sequence of coarse material, fine material, and sanded gypsum plug used by Lawrence Livermore National Laboratory for vertical drill hole tests.

SOURCE: Modified from Lawrence Livermore National Laboratory.

Livermore test with six sanded gypsum concrete plugs.[22] The plugs have two purposes: 1) to impede gas flow, and 2) to serve as structural platforms that prevent the stemming from falling out if only a partial collapse occurs. Under each plug is a layer of sand-size fine material. The sand provides a base for the plug. Alternating between the plugs and the fines, coarse gravel is used to fill in the rest of the stemming. The typical repeating pattern used for stemming by Los Alamos, for example, is 50 feet of gravel, 10 feet of sand, and a plug.

All the diagnostic cables from the nuclear device are blocked to prevent gas from finding a pathway through the cables and traveling to the surface. Cable fan-out zones physically separate the cables at plugs so that the grout and fines can seal between them. Frequently, radiation detectors are installed between plugs to monitor the post-shot flow of radiation through the stemming column.

CONTAINING HORIZONTAL TUNNEL TESTS

The containment of a horizontal tunnel test is different from the containment of a vertical drill hole test because the experimental apparatus is intended to be recovered. In most tests, the objective is to allow direct radiation from a nuclear explosion to reach the experiment, but prevent the explosive debris and fission products from destroying it. Therefore, the containment is designed for two tasks: 1) to prevent the uncontrolled release of radioactive material into the atmosphere for public safety, and 2) to prevent explosive debris from reaching the experimental test chamber.

Both types of horizontal tunnel tests (effects tests and cavity tests) use the same containment concept of three redundant containment ''vessels' that nest inside each other and are separated by plugs (figure 3-5).[23] Each vessel is designed to independently contain the nuclear explosion, even if the other vessels fail. If, for example, gas leaks from vessel I into vessel II, vessel II has a volume large enough so that the resulting gas temperatures and pressures would be well within the limits that the plugs are designed to withstand. The vessels are organized as follows:

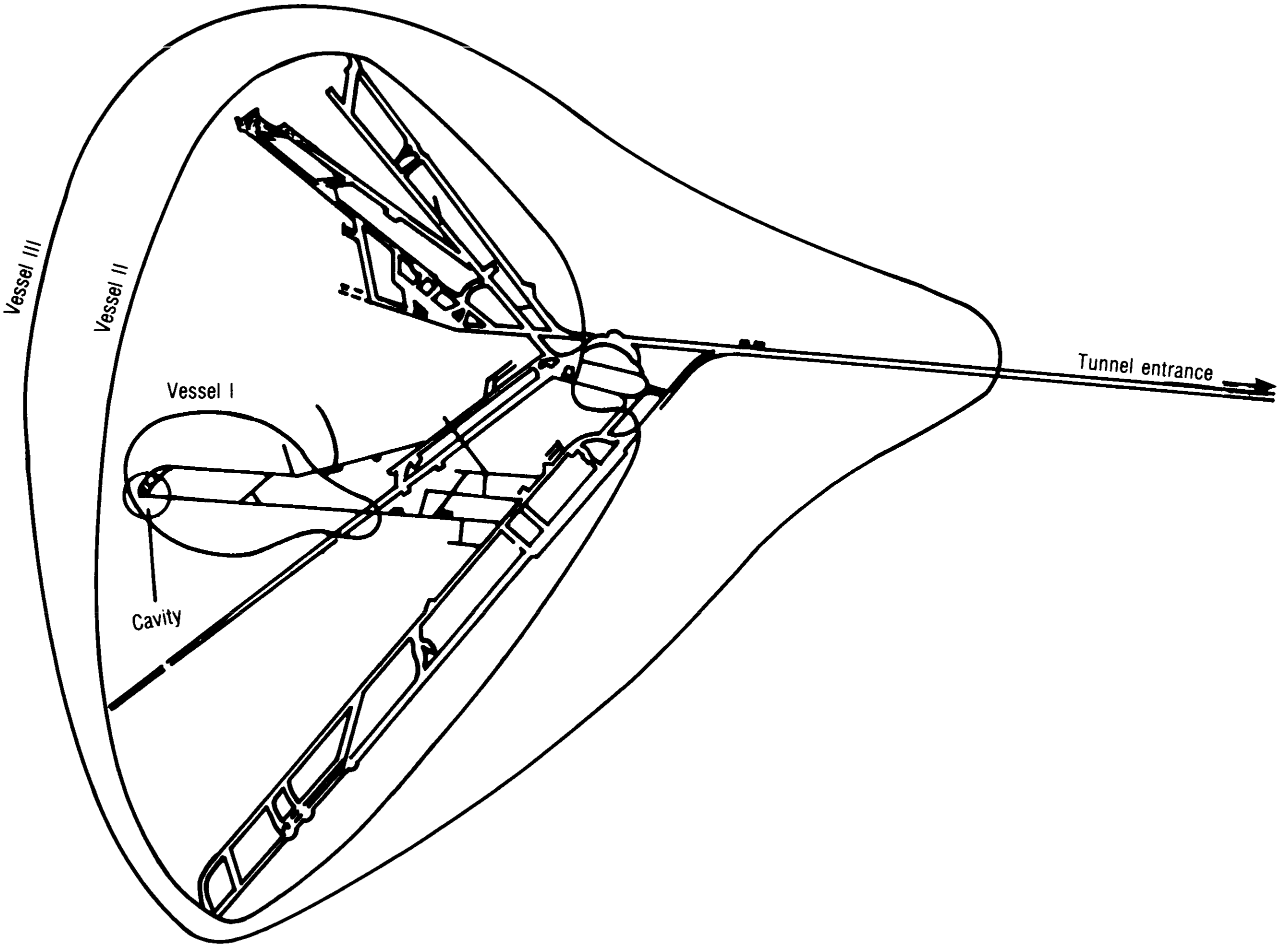
> Vessel I is designed to protect the experiment by preventing damage to the equipment and allowing it to be recovered.
>
> Vessel II is designed to protect the tunnel system so that it can be reused even if vessel I fails and the experimental equipment is lost.
>
> Vessel III is designed purely for containment, such that even if the experimental equipment is lost and the tunnel system contaminated, radioactive material will not escape to the atmosphere.

In addition to the three containment vessels, there is a gas seal door at the entrance of the tunnel system that serves as an additional safety measure. The gas seal door is closed prior to detonation and the area

22 Although Livermore and Los Alamos use the same general stemming philosophy, there are some differences: For example, Liver-more uses sanded gypsum concrete plugs while Los Alamos uses plugs made of epoxy. Also, Livermore uses an emplacement pipe for lowering the device downhole, while Los Alamos lowers the device and diagnostic cannister on a wire rope harness.

23 See ch. 2 for a discussion of types of nuclear tests.

Figure 3-5-Three Redundant Containment Vessels (Plan View)



Three containment vessels for the Mighty Oak Test conducted in the T-Tunnel Complex.

SOURCE: Modified from Defense Nuclear Agency.

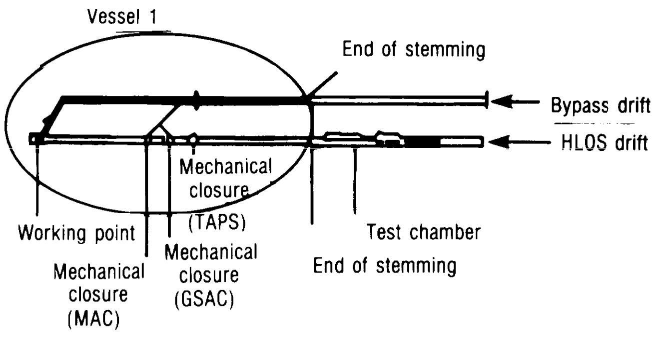
between it and the vessel III plug is pressurized to approximately 10 pounds per square inch.

The plugs that separate the vessels are constructed of high strength grout or concrete 10 to 30 feet thick. The sides of the vessel II plugs facing the working point are constructed of steel. Vessel II plugs are designed to withstand pressures up to 1,000 pounds per square inch and temperatures up to 1,000 °F. Vessel 111 plugs are constructed of massive concrete and are designed to withstand pressures up to 500 pounds per square inch and temperatures up to 500 “F.

Before each test, the tunnel system is checked for leaks. The entire system is closed off and pressurized to 2 pounds per square inch with a gas containing tracers in it. The surrounding area is then monitored for the presence of the tracer gas. Frequently, the chimney formed by the explosion is also subjected to a post-shot pressurization test to ensure that no radioactive material could leak through the chimney to the surface.

The structure of vessel I, as shown in figure 3-6, is designed to withstand the effects of ground shock and contain the pressure, temperatures, and radiation of the explosion. The nuclear explosive is located at the working point, also known as the “zero room. ” A long, tapered, horizontal line-of-sight (HLOS) pipe extends 1,000 feet or more from the working point to the test chamber where the experimental equipment is located. The diameter of the pipe may only be a few inches at the working point, but typically increases to about 10 feet before it reaches

Figure 3-6--Vessel I



Key: GSAC = gas seal auxiliary closure; MAC = modified auxiliary closure; TAPS = Tunnel and pipe seal

The HLOS Vessel I is designed to protect the experimental equipment after allowing radiation to travel down the pipe.

SOURCE: Modified from Defense Nuclear Agency.

the test chamber.[24] The entire pipe is vacuum pumped to simulate the conditions of space and to minimize the attenuation of radiation. The bypass drift (an access tunnel), located next to the line of sight pipe, is created to provide access to the closures and to different parts of the tunnel system. These drifts allow for the nuclear device to be placed in the zero room and for late-time emplacement of test equipment. After the device has been emplaced at the working point, the bypass drift is completely filled with grout. After the experiment, parts of the bypass drift will be reexcavated to permit access to the tunnel system to recover the pipe and experimental equipment.

The area around the HLOS pipe is also filled with grout, leaving only the HLOS pipe as a clear pathway between the explosion and the test chamber. Near the explosion, grout with properties similar to the surrounding rock is used so as not to interfere with the formation of the stress containment cage. Near the end of the pipe strong grout or concrete is used to support the pipe and closures. In between, the stemming is filled with super-lean grout designed to flow under moderate stress. The super-lean grout is designed to fill in and effectively plug any fractures that may form as the ground shock collapses the pipe and creates a stemming plug.

As illustrated in figure 3-6, the principal components of an HLOS pipe system include a working point room, a muffler, a modified auxiliary closure (MAC), a gas seal auxiliary closure (GSAC), and a tunnel and pipe seal (TAPS). All these closures are installed primarily to protect the experimental equipment. The closures are designed to shut off the pipe after the radiation created by the explosion has traveled down to the test chamber, but before material from the blast can fly down the pipe and destroy the equipment.

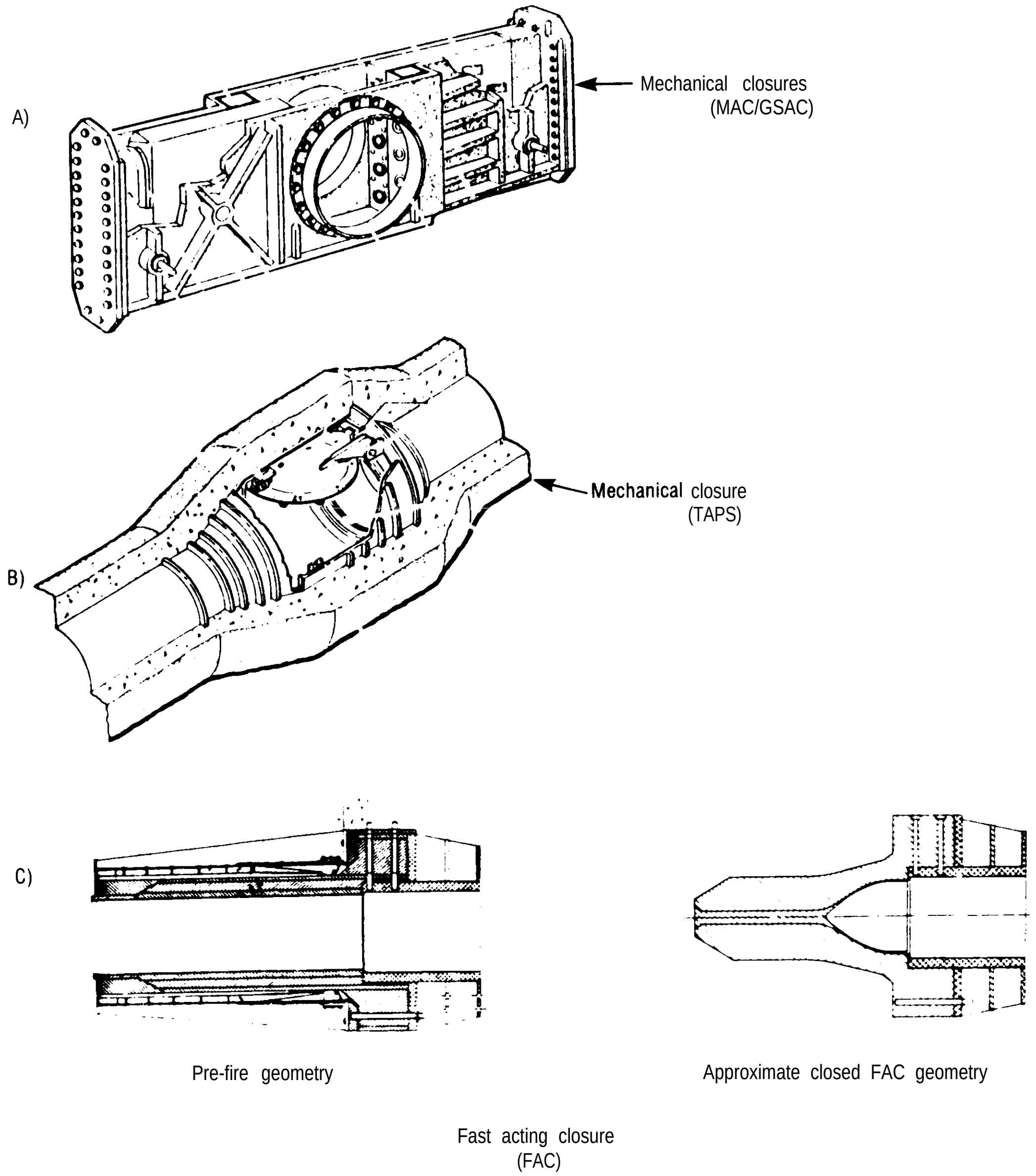
The working point room is a box designed to house the nuclear device. The muffler is an expanded region of the HLOS pipe that is designed to reduce flow down the pipe by allowing expansion and creating turbulence and stagnation. The MAC (figure 3-7(a)) is a heavy steel housing that contains two 12-inch-thick forged-aluminum doors designed to close openings up to 84 inches in diameter. The doors are installed opposite each other, perpendicular to the pipe. The doors are shut by high pressure gas that is triggered at the time of detonation. Although the doors close completely within 0.03 seconds (overlapping so that each door fills the tunnel), in half that time they have met in the middle and obscure the pipe. The GSAC is similar to the MAC except that it is designed to provide a gas-tight closure. The TAPS closure weighs 40 tons and the design (figure 3-7(b)) resembles a large toilet seat, The door, which weighs up to 9 tons, is hinged on the top edge and held in the horizontal (open) position. When the door is released, it swings down by gravity and slams shut in about 0.75 seconds. Any pressure remaining in the pipe pushes on the door making the seal tighter. The MAC and GSAC will withstand pressures up to 10,000 pounds per square inch. The TAPS is designed to withstand pressures up to 1,000 pounds per square inch, and temperatures up to 1,000 ‘F.

When the explosion is detonated radiation travels down the HLOS pipe at the speed of light, The containment process (figure 3-8 (a-e), triggered at the time of detonation, occurs in the following sequence to protect experimental equipment and contain radioactive material produced by the explosion:

. After 0.03 seconds (b), the cavity created by the explosion expands and the shock wave moves away from the working point and approaches the MAC. The shock wave collapses the pipe, squeezing it shut, and forms a stemming “plug.’ Both the MAC and the GSAC shut off

[24] On occasion, the diameter of the pipe has increased 1020 feet.

Figure 3-7—Vessel I Closures



A) Mechanical Closures (MAC/GSAC)
B) Tunnel and Pipe Seal (TAPS)
C) Fast Acting Closure (FAC)

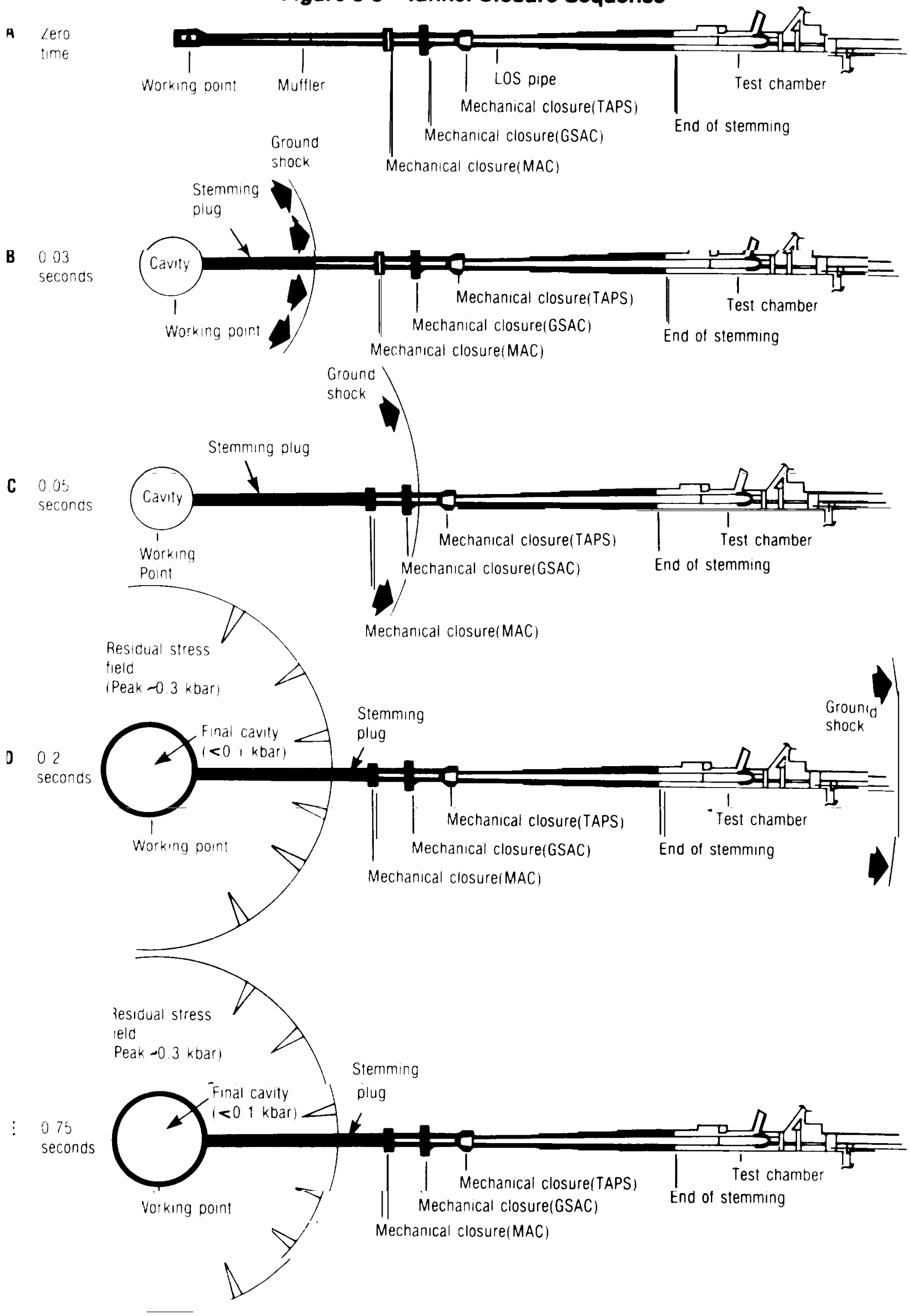
SOURCE: Modified from Defense Nuclear Agency.

the pipe ahead of the shock wave to prevent early flow of high-velocity gas and debris into the experiment chamber.

- After 0.05 seconds (c), the ground shock moves past the second closure and is no longer strong enough to squeeze the pipe shut. The stemming plug stops forming at about the distance where the first mechanical pipe closure is located.

- After 0.2 seconds (d), the cavity growth is complete. The rebound from the explosion

Figure 3-8—Tunnel Closure Sequence



A) Zero Time: Explosion is detonated and the first two mechanical closures are fired. B) Within 0,03 seconds, a stemming plug is being formed and mechanical pipe closure has occurred. C) Within 0.05 seconds, the stemming plug has formed. D) Within 0.2 seconds, cavity growth is complete and a surrounding compressive residual stress field has formed, E) Within 0.75 seconds, closure is complete.

SOURCE. Modified from Defense Nuclear Agency.

locks in the residual stress field, thereby forming a containment cage. The shock wave passes the test chamber.

. After 0.75 seconds (e), the final mechanical seal (TAPS) closes, preventing late-time explosive and radioactive gases from entering the test chamber.

The entire closure process for containment takes less than 3/4 of a second. Because the tests are typically buried at a depth greater than necessary for containment, the chimney does not reach the surface and a collapse crater normally does not form. A typical post-shot chimney configuration with its approximate boundaries is shown in figure 3-9.

In lower yield tests, such as those conducted in the P-tunnel complex, the first mechanical closure is a Fast Acting Closure (FAC) rather than a MAC.[25] The FAC (figure 3-7(c)) closes in 0.001 seconds and can withstand pressures of 30,000 pounds per square inch. The FAC acts like a cork, blocking off the HLOS pipe early, and preventing debris and stemming material from flying down the pipe. A similar closure is currently being developed for larger yield tunnel tests.

TYPES OF RADIATION RELEASES

Terms describing the release or containment of underground nuclear explosions have been refined to account for the volume of the material and the conditions of the release. The commonly used terms are described below.

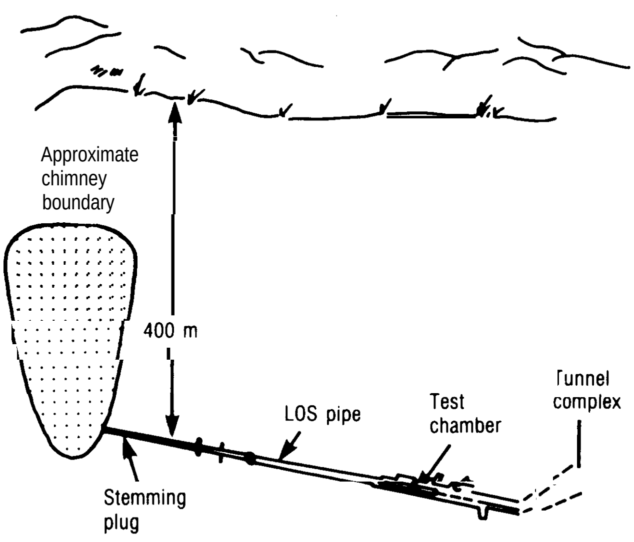
Containment Failure

Containment failures are releases of radioactive material that do not fall within the strict definition of successful containment, which is described by the Department of Energy as:

> Containment such that a test results in no radioactivity detectable off site as measured by normal monitoring equipment and no unanticipated release of radioactivity onsite. Detection of noble gases that appear onsite long after an event, due to changing atmospheric conditions, is not unanticipated. Anticipated releases will be designed to conform to specific guidance from DOE/HQ.[26]

Containment failures are commonly described as:

Figure 3-9—Typical Post-Shot Configuration



Tunnel shots are typically overburied and the collapse chimney rarely extends to the surface.

SOURCE: Modified from Defense Nuclear Agency.

Ventings

Ventings are prompt, massive, uncontrolled releases of radioactive material. They are characterized as active releases under pressure, such as when radioactive material is driven out of the ground by steam or gas. ‘‘ Baneberry,’ in 1970, is the last example of an explosion that ‘‘vented. ”

Seeps

Seeps, which are not visible, can only be detected by measuring for radiation. Seeps are characterized as uncontrolled slow releases of radioactive material with little or no energy.

Late-Time Seep

Late-time seeps are small releases of noncondensable gases that usually occur days or weeks after a vertical drill hole test. The noncondensable gases diffuse up through the pore spaces of the overlying rock and are thought to be drawn to the surface by a decrease in atmospheric pressure (called “atmospheric pumping”).

[25] The P-tunnel complex is mined in Aqueduct Mesa and has less overburden than the N-tunnel complex in Rainier Mesa. Therefore, P-tunnel is generally used for lower yield tests.

[26] Section VIII.F, Containment Evaluation Panel Charter.

Photo credit: David Graham

Fast acting closure.

Controlled Tunnel Purging

Controlled tunnel purging is an intentional release of radioactive material to recover experimental equipment and ventilate test tunnels. During a controlled tunnel purging, gases from the tunnel are filtered, mixed with air to reduce the concentration, and released over time when weather conditions are favorable for dispersion into sparsely populated areas.

Operational Release

Operational releases are small releases of radioactivity resulting from operational aspects of vertical drill hole tests. Activities that often result in operational releases include: drilling back down to the location of the explosion to collect core samples (called “drill back”), collecting gas samples from the explosion (called “gas sampling’ “), and sealing the drill back holes (called “cement back”)

RECORD OF CONTAINMENT

The containment of underground nuclear explosions is a process that has continually evolved through learning, experimentation, and experience. The record of containment illustrates the various types of releases and their relative impact.

Containment Evaluation Panel

The Containment Evaluation Panel defines successful containment as no radioactivity detectable offsite and no unanticipated release of activity onsite. By this definition, the CEP has failed to predict unsuccessful containment on four occasions since 1970:

Camphor: June 29, 1971, horizontal tunnel test, less than 20 kilotons, radioactivity detected only on-site.

Diagonal Line: November 24, 1971, vertical shaft test, less than 20 kilotons, radioactivity detected off-site.

Riola: September 25, 1980, vertical shaft test, less than 20 kilotons, radioactivity detected off-site.

Agrini: March 31, 1984, vertical shaft test, less than 20 kilotons, radioactivity detected only on-site.

These are the only tests (out of more than 200) where radioactive material has been unintentionally released to the atmosphere due to containment failure. In only two of the cases was the radioactivity detected outside the geographic boundary of the Nevada Test Site.

There have, however, been several other instances where conditions developed that were not expected. For example, during the Midas Myth test on February 15, 1984, an unexpected collapse crater occurred above the test tunnel causing injuries to personnel. In addition, the tunnel partially collapsed, damaging experimental equipment. During the Mighty Oak test on April 10, 1986, radioactive material penetrated through two of the three containment vessels. Experimental equipment worth $32 million was destroyed and the tunnel system ventilation required a large controlled release of radioactive material (table 3-1). In the case of Midas Myth, no radioactive material was released (in fact, all radioactive material was contained within vessel I). In the case of Mighty Oak, the release of radioactive material was intentional and controlled. Consequently, neither of these tests are considered containment failures by the CEP.

Vertical Drill Hole Tests

As discussed previously, vertical drill-hole tests commonly use a stemming plan with six sanded gypsum plugs or three epoxy plugs. Approximately 50 percent of the vertical drill hole tests show all radiation being contained below the first plug, In some cases, radiation above the plug may not signify plug failure, but rather may indicate that radioactive material has traveled through the medium around the plug.

Table 3-1--Releases From Underground Wats
(normalized to 12 hours after event)

All releases 1971-1988:	
Containment Failures:	
Camphor, 1971 [b]	360 Ci
Diagonal Line, 1971	6,800
Riola, 1980	3,100
Agrini, 1984	690
Late-time Seeps:	
Kappeli, 1984	12
Tierra, 1984	600
Labquark, 1986	20
Bodie, 1986 [c]	52
Controlled Tunnel Purgings:	
Hybla Fair, 1974	500
Hybla Gold, 1977	0.005
Miners Iron, 1980	0.3
Huron Landing, 1982	280
Mini Jade, 1983	1
Mill Yard, 1985	5.9
Diamond Beech, 1985	1.1
Misty Rain, 1985	63
Mighty Oak, 1986	36,000
Mission Ghost, 1987 [c]	3
Operational Releases:	
108 tests from 1970-1988 [d]	5,500
Total since Baneberry:	54,000 Ci
Major pre-1971 releases:	
Platte, 1962	1,900,000 Ci
Eel, 1962	1,900,000
Des Moines, 1962	11,000,000
Baneberry, 1970	6,700,000
26 others from 1958-1970	3,800,000
Total:	25,300,000 Ci
Other Releases for Reference	
NTS Atmospheric Testing 1951-1963:	12,000,000,000 Ci
1 Kiloton Aboveground Explosion:	10,000,000
Chernobyl (estimate):	81,000,000

[a] R+12 values apply only to containment failures, others are at time of release.
[b] The Camphor failure includes 140 Ci from tunnel purging.
[c] Bodie and Mission Ghost also had drill-back releases.
[d] Many of these Operational releases are associated with tests that were not announced.

SOURCE: Office of Technology Assessment, 1989.

All three of the vertical drill hole tests that released radioactive material through containment failure were low yield tests of less than 20 kilotons. In general, the higher the yield, the less chance there is that a vertical drill hole test will release radioactivity.[27]

Horizontal Tunnel Tests

There have been no **uncontrolled** releases of radioactive material detected **offsite** in the 31 tunnel tests conducted since 1970. Furthermore, all but one test, Mighty Oak, have allowed successful recovery

[27] Higher yield tests are more likely t. produce a containment cage and result in the formation of a collapse crater. As discussed earlier in this chapter "why nuclear explosions remain contained," such features contribute to the containment of the explosion.

of the experimental equipment. Mighty Oak and Camphor are the only tests where radioactivity escaped out of vessel II. In no test, other than Camphor, has radioactive material escaped out of vessel III. Camphor resulted in an **uncontrolled** release of radioactive material that was detected only **on site.**

There have been several instances when small amounts of radioactivity were released intentionally to the atmosphere through **controlled** purging. In these cases, the decision was made to vent the tunnel and release the radioactivity so the experimental results and equipment could be recovered. The events that required such a controlled release are the 10 tests where radioactive material escaped out of vessel I and into vessel II, namely:

Hybla Fair, October 28, 1974.

Hybla Gold, November 1, 1977.

Miners Iron, October 31, 1980.

Huron Landing, September 23, 1982.

Mini Jade, May 26, 1983.

Mill Yard, October 9, 1985.

Diamond Beech, October 9, 1985.

Misty Rain, April 6, 1985.

Mighty Oak, April 10, 1986.

Mission Ghost, June 20, 1987[28]

In most cases, the release was due to the failure of some part of the experiment protection system.

Table 3-1 includes every instance (for both announced and unannounced tests) where radioactive material has reached the atmosphere under *any circumstances whatsoever* from 1971 through 1988. The lower part of table 3-1 summarizes underground tests prior to 1971 and provides a comparison with other releases of radioactive material.

Since 1970, 126 tests have resulted in radioactive material reaching the atmosphere with a total release of about 54,000 Curies. Of this amount, 11,500 Ci were due to containment failure and late-time seeps. The remaining 42,500 Ci were operational releases and controlled tunnel ventilations—with Mighty Oak (36,000 Ci) as the main source. Section 3 of the table shows that the release of radioactive material from underground nuclear testing since Baneberry (54,000 Ci) is extremely small in comparison to the amount of material released by pre-Baneberry underground tests (25,300,000 Ci), the early atmospheric tests at the Nevada Test Site, or even the amount that would be released by a l-kiloton explosion conducted above ground (l0,000,000 Ci).

From the Perspective of Human Health Risk

If a single person had been standing at the boundary of the Nevada Test Site in the area of maximum concentration of radioactivity for every test since Baneberry (1970), that person's total exposure would be equivalent to 32 extra minutes of normal background exposure (or the equivalent of 1/1000 of a single chest x-ray).

A FEW EXAMPLES:

Although over 90 percent of all test explosions occur as predicted, occasionally something goes wrong. In some cases, the failure results in the loss of experimental equipment or requires the controlled ventilation of a tunnel system. In even more rare cases (less than 3 percent), the failure results in the unintentional release of radioactive material to the atmosphere. A look at examples shows situations where an unexpected sequence of events contribute to create an unpredicted situation (as occurred in Baneberry (see box 3-l)), and also situations where the full reason for containment failure still remains a mystery.

1. *Camphor* (June 29, 1971, horizontal tunnel test, less than 20 kilotons, radioactivity detected only on-site,)

The ground shock produced by the Camphor explosion failed to close the HLOS pipe fully. After about 10 seconds, gases leaked through and eroded the stemming plug. As gases flowed through the stemming plug, pressure increased on the closure door behind the experiment. Gases leaked around the cable passage ways and eroded open a hole. Pressure was then placed on the final door, which held but leaked slightly. Prior to the test, the containment plan for Camphor received six ''I' from the CEP.[29]

28The Mission Ghost release was due to a post-shot drill hole.

29Op. cit., footnote 20.

2. *Diagonal Line* (November 24, 1971, vertical shaft test, less than 20 kilotons, radioactivity detected off-site.)

In a sense, the Diagonal Line seep was predicted by the CEP. Prior to the test, Diagonal Line received all "A" categorizations, except from one member who gave it a' 'B.'[30] It was a conclusion of the panel that due to the high CO_2 content, a late-time (hours or days after detonation) seepage was a high probability. They did not believe, however, that the level of radiation would be high enough to be detectable off-site. Permission to detonate was requested and granted because the test objectives were judged to outweigh the risk. Diagonal Line was conducted in the northern part of Frenchman Flat. It is speculated that carbonate material released CO_2 gas that forced radioactive material to leak to the surface. Diagonal Line was the last test detonated on Frenchman Flat.

3. *Riola* (September 25, 1980, vertical shaft test, less than 20 kilotons, radioactivity detected off-site.)

Ironically, Riola was originally proposed for a different location. The Containment Evaluation Panel, however, did not approve the first location and so the test was moved. At its new location, Riola was characterized by the CEP prior to the test with 8 "A"s. Riola exploded with only a small fraction of the expected yield. A surface collapse occurred and the failure of a containment plug resulted in the release of radioactive material.

4. *Agrini* (March 31, 1984, vertical shaft test, less than 20 kilotons, radioactivity detected only on-site.)

The Agrini explosion formed a deep subsidence crater 60 feet west of the emplacement hole. A small amount of radioactive material was pushed through the chimney by noncondensible gas pressure and was detected onsite. The containment plan for Agrini received seven ''A' and two 'B from the CEP prior to the test. The ''B'*s were due to the use of a new stemming plan.

5. *Midas Myth* (February 15, 1984, horizontal tunnel test, less than 20 kilotons, no release of radioactive material.)

All of the radioactive material produced by the Midas Myth test was contained within vessel I, with no release of radioactivity to either the atmosphere or the tunnel system. It is therefore not considered a containment failure. Three hours after the test, however, the cavity collapsed and the chimney reached the surface forming an unanticipated subsidence crater. Equipment trailers were damaged and personnel were injured (one person later died as a result of complications from his injuries) when the collapse crater formed.[31] Analysis conducted after the test indicated that the formation of the collapse crater should have been expected. Shots conducted on Yucca Flat with the same yield and at the same depth of burial did, at times, produce surface collapse craters. In the case of Midas Myth, collapse was not predicted because there had never been a collapse crater for a tunnel event and so the analysis was not made prior to the accident. After analyzing the test, the conclusion of the Surface Subsidence Review Committee was:

> That the crater is not an indication of some unusual, anomalous occurrence specific to the U12T.04 emplacement site. Given the normal variation in explosion phenomena, along with yield, depth of burial, and geologic setting, experience indicates an appreciable chance for the formation of a surface subsidence crater for Midas Myth.

Prior to the test, the Containment Evaluation Panel characterized Midas Myth with nine "A"s.

6. *Misty Rain (* April 6, 1985, horizontal tunnel test, less than 20 kilotons, no unintentional release of radioactive material.)

Misty Rain is unusual in that it is the only tunnel test since 1970 that did not have three containment vessels. In the Misty Rain test, the decision was made that because the tunnel system was so large, a vessel II was not needed.[32] Despite the lack of a vessel II, the CEP categorized the containment of Misty Rain with eight 'A' 's, and one 'B.'[33] During the test, an early flow of energy down the HLOS pipe prevented the complete closure of the MAC doors. The MAC doors overlapped, but stopped a couple inches short of full closure. The TAPS door closed only 20 percent before the deformation from ground shock prevented it from closing. A small amount of

[30] Ibid.

[31] The injuries were due to the physical circumstances of the collapse. There was no radiation exposure.

[32] The drifts i, the tunnel system created over 4 million cubic feet of open volume.

[33] One CEP member did not initially Categorize the test, after receiving additional information concerning the test, he categorized the test with an '' A.

radioactive material escaped down the pipe and then seeped from the HLOS pipe tunnel into the bypass tunnel. Subsequently, the tunnel was intentionally vented so that experimental equipment could be recovered.

7. *Mighty Oak* (April 10, 1986, horizontal tunnel test, less than 20 kilotons, no unintentional release of radioactive material.)

During the Mighty Oak test, the closure system near the working point was over-pressured and failed. The escaped pressure and temperature caused both the MAC and the GSAC to fail. The loss of the stemming plug near the working point left the tunnel an open pathway from the cavity. Temperatures and pressures on the closed TAPS door reached 2,000"F and 1,400 pounds per square inch. After 50 seconds, the center part (approximately 6 feet in diameter) of the TAPS door broke through. With the closures removed, the stemming column squeezed out through the tunnel. Radioactive material leaked from vessel I, into vessel II, and into vessel III, where it was successfully contained. Approximately 85 percent of the data from the prime test objectives was recovered, although about $32 million of normally recoverable and reusable equipment was lost.[34] Controlled purging of the tunnel began 12 days after the test and continued intermittently from April 22 to May 19, when weather conditions were favorable. A total of 36,000 Ci were released to the atmosphere during this period.

IS THERE A REAL ESTATE PROBLEM AT NTS?

There have been over 600 underground and 100 aboveground nuclear test explosions at the Nevada Test Site. With testing continuing at a rate of about a dozen tests a year, the question of whether there will eventually be no more room to test has been raised. While such a concern may be justified for the most convenient areas under the simplest arrangements, it is not justified for the test area in general. Using the drill-hole spacing of approximately one-half the depth of burial, high-yield tests can be spaced about 1,000 feet apart, and low-yield tests can be spaced at distances of a few hundred feet. Consequently, a suitable square mile of test site may provide space for up to 25 high-yield tests or over 300 low-yield tests. Even with testing occurring at a rate of 12 tests a year, the 1,350 square miles of test site provide considerable space suitable for testing.

In recent years, attempts have been made to use space more economically, so that the most convenient locations will remain available. Tests have traditionally been spaced in only 2-dimensions. It may be possible to space tests 3-dimensionally, that is, with testing located below or above earlier tests. Additionally, the test spacing has been mostly for convenience. If available testing areas become scarce, it may become possible to test at closer spacing, or even to test at the same location as a previous test.

Area for horizontal tunnel tests will also be available for the future. The N-tunnel area has been extended and has a sizable area for future testing. P-tunnel, which is used for low-yield effects tests, has only been started. (See figure 2-4 inch. 2 of this report.) Within Rainier and Aqueduct Mesa alone, there is enough area to continue tunnel tests at a rate of two a year for at least the next 30 years. Consequently, lack of adequate real estate will not be a problem for nuclear testing for at least several more decades.

TIRED MOUNTAIN SYNDROME?

The "Tired Mountain Syndrome" hypothesis postulates that repeated testing in Rainier Mesa has created a "tired" mountain that no longer has the strength to contain future tests. Support for this concern has come from the observation of cracks in the ground on top of the Mesa and from seismological measurements, indicating that large volumes of rock lose strength during an underground test. Debate exists, however, over both the inference that the weakened rock is a danger to containment, and the premise that large volumes of rock are being weakened by nuclear testing.

Basic to the concern over tired mountain syndrome is the assumption that weakened rock will adversely affect containment. As discussed previously, only in an extreme situation, such as detonating an explosion in water-saturated clay, would rock strength be a factor in contributing to a leak of radioactive material. [35] For example, many tests have

[34] *Containment and Safety Review for the Mighty Oak Nuclear Weapon Effects Test*, U.S. Department of Energy, Nevada Operations Office, NVO-3 11, May 1, 1987.

[35] See earlier section "Why do nuclear tests remain contained?"

Photo credit: Department of Energy

Fracture on Rainier Mesa.

been detonated in alluvial deposits, which are essentially big piles of sediment with nearly no internal strength in an unconfined state. Despite the weakness and lack of cohesiveness of the material, such explosions remain well contained.

Compared to vertical drill hole tests, tunnel tests are overburied and conservatively spaced. The tunnel system in Rainier Mesa is at a depth of 1,300 feet. By the standards for vertical drill hole tests (using the scaled depth formula[36]), this is deep enough to test at yields of up to 34 kilotons; and yet all tunnel tests are less than 20 kilotons.[37] Consequently, all tunnel tests in Rainier Mesa are buried at depths comparatively greater than vertical drill hole tests on Yucca Flat. Furthermore, the minimum separation distance of tunnel shots (twice the combined cavity radii plus 100 feet) results in a greater separation distance than the minimum separation distance of vertical drill hole shots (1/2 depth of burial) for tests of the same yield (compare figures 3-2 and 3-3). **Consequently, neither material strength, burial depth, nor separation distance would make leakage to the surface more likely for a tunnel test on Rainier Mesa than for a vertical drill hole tests on Yucca Flat.**

Despite the relative lack of importance of strength in preventing possible leakage to the surface, the volume of material weakened or fractured by an explosion is of interest because it could affect the performance of the tunnel closures and possible leakage of cavity gas to the tunnel complex. Dispute over the amount of rock fractured by an underground nuclear explosion stems from the following two, seemingly contradictory, but in fact consistent observations:

1. Post-shot measurements of rock samples taken from the tunnel complex generally show no change in the properties of the rock at a distance greater than 3 cavity radii from the point of the explosion. This observation implies that rock strength is measurably decreased only within the small volume of radius = 165 $(\text{yield})^{1/3}$,[38] where the radius is measured in feet from the point of the explosion and the yield is measured in kilotons (figure 3-10).

2. Seismic recordings of underground explosions at Rainier Mesa include signals that indicate the loss of strength in a volume of rock whose radius is slightly larger than the scaled depth of burial. This observation implies that the rock strength is decreased throughout the large volume of radius = 500 $(\text{yield})^{1/3}$, where the radius is measured in feet from the point of the explosion and the yield is measured in kilotons (figure 3-11). The loss of strength in a large volume seems to be further supported by cracks in the ground at the top of Rainier Mesa that were created by nuclear tests.

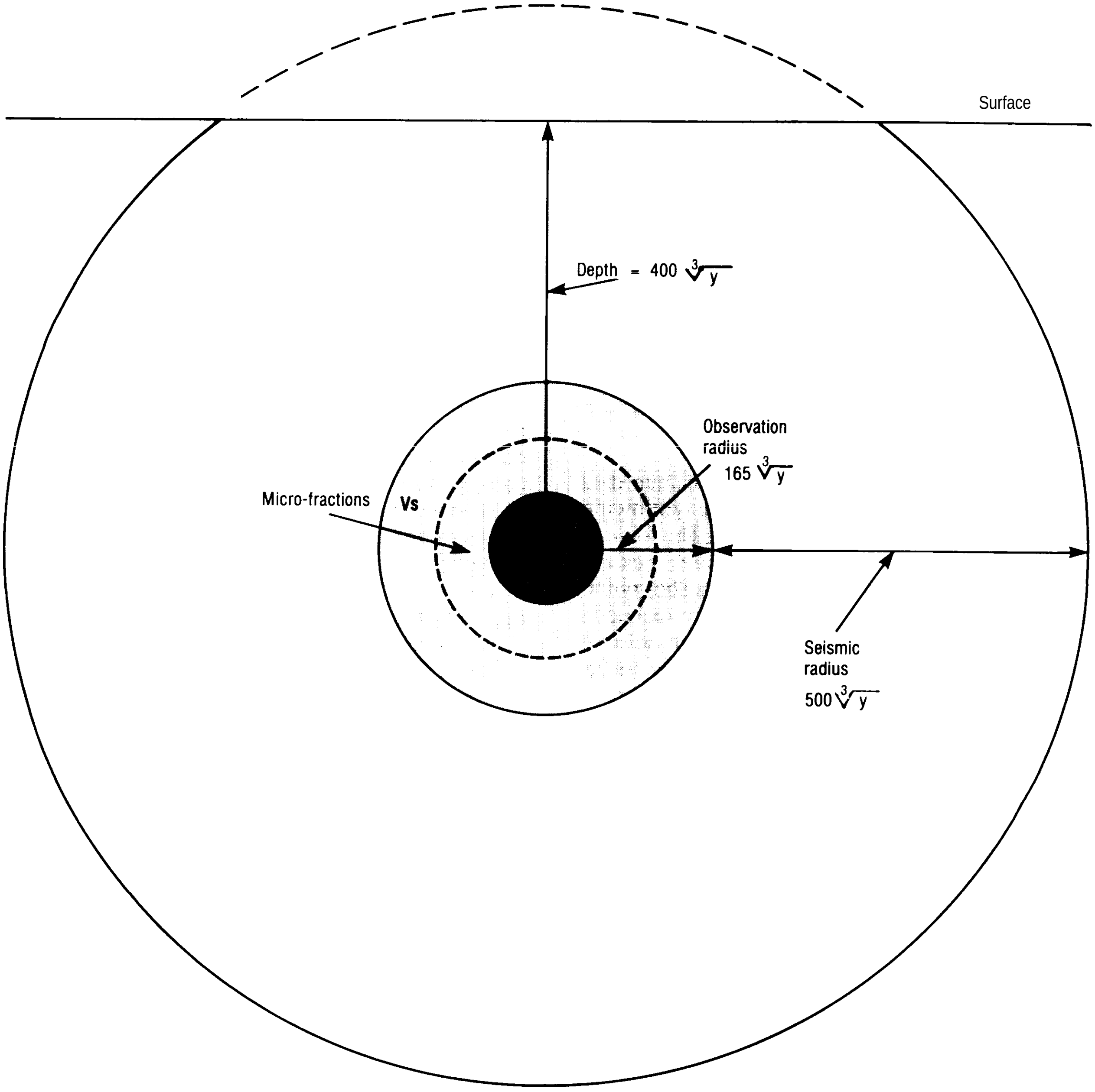
The first observation is based on tests of samples obtained from drilling back into the rock surrounding the tunnel complex after a test explosion, The core samples contain microfractures out to a distance from the shot point equal to two cavity radii. Although microfractures are not seen past two cavity radii, measurements of seismic shear velocities

[36] Depth(ft) = 400 $(\text{yield(kt)})^{1/3}$

[37] 'Announced United States Nuclear Tests, July 1945 through December 1987,' United States Department of Energy, NVO-209 (Rev.8), April, 1988.

[38] If the radius of a cavity produced by an explosion is equal to 55 $(\text{yield})^{1/3}$, a distance of three cavity radii would be equal to three times this, or 165 $(\text{yield})^{1/3}$.

Figure 3-10—Radius of Decrease in Rock Strength



Seismic measurements and measurements taken from drill-back samples indicate a seemingly contradictory (but in fact consistent) radius of decrease in rock strength.

SOURCE: Office of Technology Assessment, 1989.

continue to be low out to a distance of three cavity radii, The decrease in seismic shear velocity indicates that the rock has been stressed and the strength decreased. At distances greater than three cavity radii, seismic velocity measurements and strength tests typically show no change from their pre-shot values, although small disturbances along bedding planes are occasionally seen when the tunnels are recentered after the test. Such measurements suggest that the explosion only affects rock strength to a distance from the shot point to about three cavity radii (165 (yield)$^{1/3}$).

The second observation, obtained from seismic measurements of tectonic release, suggests a larger radius for the volume of rock affected by an explosion. The seismic signals from underground nuclear explosions frequently contain signals created by what is called "tectonic release. " By fracturing the rock, the explosion releases any preexisting natural stress that was locked within the rock. The release of the stress is similar to a small earthquake. The tectonic release observed in the seismic recordings of underground explosions from Rainier Mesa indicate the loss of strength in a volume of rock with a minimum radius equal to **500** (yield)$^{1/3}$.

Although the drill samples and the seismic data appear to contradict each other, the following explanation appears to account for both: The force of the explosion creates a cavity and fractures rock out to the distance of 2 cavity radii from the shot point. Out to 3 cavity radii, existing cracks are extended and connected, resulting in a decrease in seismic shear velocity. Outside 3 cavity radii, no new cracks form. At this distance, existing cracks are opened and strength is reduced, but only temporarily. The open cracks close immediately after the shock wave passes due to the pressure exerted by the overlying rock. Because the cracks close and no new cracks are formed, the rock properties are not changed. Post-shot tests of seismic shear velocity and strength are the same as pre-shot measurements. This is consistent with both the observations of surface fractures and the slight disturbances seen along bedding planes at distances greater than 3 cavity radii. The surface fractures are due to surface span, which would indicate that the rock was overloaded by the shock wave. The disturbances of the bedding planes would indicate that fractures are being opened out to greater distances than 3 cavity radii. In fact, the bedding plane disturbances are seen out to a distance of 600 (yield)$^{1/3}$, which is consistent with the radius determined from tectonic release.

The large radius of weak rock derived from tectonic release measurements represents the **transient** weakening from the shot. The small radius of weak rock derived from the post-shot tests represents the volume where the rock properties have been **permanently** changed. From the point of view of the integrity of the tunnel system, it is the smaller area where the rock properties have been permanently changed (radius = 165 (yield)$^{1/3}$) that should be considered for containment. **Because the line-of-sight tunnel is located so that the stemming plug region and closures are outside the region of permanently weakened or fractured material, the closure system is not degraded.**

HOW SAFE IS SAFE ENOUGH?

Every nuclear test is designed to be contained and is reviewed for containment. In each step of the test procedure there is built-in redundancy and conservatism. Every attempt is made to keep the chance of containment failure as remote as possible. This conservatism and redundancy is essential, however; because no matter how perfect the process may be, it operates in an imperfect setting. For each test, the containment analysis is based on samples, estimates, and models that can only simplify and (at best) approximate the real complexities of the Earth. As a result, predictions about containment depend largely on judgments developed from past experience. Most of what is known to cause problems-carbonate material, water, faults, scarps, clays, etc.—was learned through experience. To withstand the consequences of a possible surprise, redundancy and conservatism is a requirement not an extravagance. Consequently, all efforts undertaken to ensure a safe testing program are necessary, and they must continue to be vigorously pursued.

Deciding whether the testing program is safe requires a judgement of how safe is safe enough. The subjective nature of this judgement is illustrated through the decision-making process of the CEP, which reviews and assesses the containment of each test.[39] They evaluate whether a test will be contained using the categorizations of ''high confidence, ' ''adequate degree of confidence, and some doubt. But, the CEP has no guidelines that attempt to quantify or describe in probabilistic terms what constitutes for example, an ''adequate degree of confidence. Obviously one can never have 100 percent confidence that a test will not release radioactive material. Whether "adequate confi-

[39] The Containment Evaluation Panel is a group of representatives from various laboratories and technical consulting organizations who evaluate the proposed containment plan for each test without regard to cost or other outside considerations (see ch. 2 for a complete discussion).

dence" translates into a chance of 1 in 100, 1 in 1,000, or 1 in 1,000,000, requires a decision about what is an acceptable risk level. In turn, decisions of acceptable risk level can only be made by weighing the costs of an unintentional release against the benefits of testing. Consequently, those who feel that testing is important for our national security will accept greater risk, and those who oppose nuclear testing will find even small risks unacceptable.

Establishing an acceptable level of risk is difficult not only because of value judgments associated with nuclear testing, but also because the risk is not seen as voluntary to those outside the testing program. Much higher risks associated with voluntary, every-day activities may be acceptable even though the much lower risks associated with the nuclear test site may still be considered unacceptable.

The question of whether the testing program is ''safe enough' will ultimately remain a value judgment that weighs the importance of testing against the risk to health and environment. In this sense, concern about safety will continue, largely fueled by concern about the nuclear testing program itself. However, given the continuance of testing and the acceptance of the associated environmental damage, the question of 'adequate safety' becomes replaced with the less subjective question of whether any improvements can be made to reduce the chances of an accidental release, In this regard, no areas for improvement have been identified. This is not to say that future improvements will not be made as experience increases, but only that essentially all suggestions that increase the safety margin have been implemented. **The safeguards built into each test make the chances of an accidental release of radioactive material as remote as possible.**