TEST STORAGE OF SPENT REACTOR FUEL IN THE CLIMAX GRANITE AT THE NEVADA TEST SITE*

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ABSTRACT

A test of retrievable dry geologic storage of spent fuel assemblies from an operating commercial nuclear reactor is underway at the Nevada Test Site (NTS) of the U.S. Department of Energy (DOE). This generic test is located 420 m below the surface in the Climax granitic stock. Eleven canisters of spent fuel approximately 2.3 years out of reactor core (about 2 kW/canister thermal output) will be emplaced in a storage drift along with 6 electrical simulator canisters and their effects will be compared. Two adjacent drifts will contain electrical heaters, which will be operated to simulate within the test array the thermal field of a large repository. The test objectives, technical concepts and rationale, and details of the test are stated and discussed.

INTRODUCTION

The Lawrence Livermore Laboratory (LLL), as a participant in the Nevada Nuclear Waste Storage Investigations (NNWSI) program, is responsible for the technical direction of a test of geologic storage of spent reactor fuel in the Climax granite at the Nevada Test Site (generally referred to as the Spent Fuel Test-Climax or SFT-C). There is significant technical participation by the Advanced Energy Systems Division (AESD) of Westinghouse. The NNWSI is part of the commercial waste management activities of the

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National Waste Terminal Storage (NWTS) program of the Department of Energy (DOE). The SFT-C (and the NNWSI) is managed by the Nevada Operations Office of the DOE.

The Nevada Test Site (NTS) is ideally suited for test storage of spent fuel or other high-level waste. The E-MAD (Engine Maintenance, Assembly, and Disassembly) facility in southwestern NTS (Fig. 1) has the capability to encapsulate spent fuel assemblies in canisters suitable for geologic storage. All of the remote handling equipment and interim storage facilities needed to support a geologic storage test are available as part of the Commercial Waste and Spent Fuel Packaging Program of the NWTS.

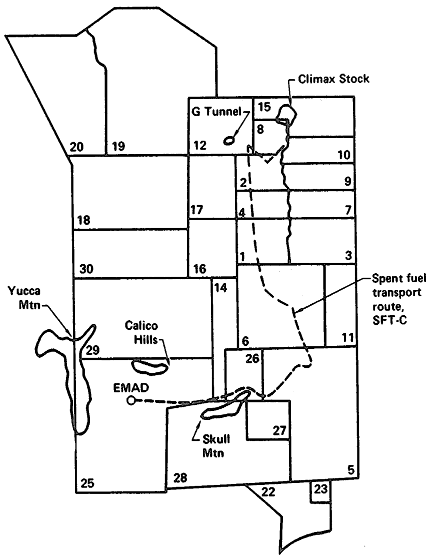

Fig. 1. Location of the Climax stock and E-MAD facility at the U.S. Department of Energy's Nevada Test Site.

A second advantage of the NTS is the availability of existing appropriate underground facilities. One of these provided access to an intrusive granitic stock (Climax stock, Fig. 1) at a depth of 420 m, which is comparable to that being considered for geologic repositories.

A third advantage of NTS is the existing administrative framework for site control and handling of radioactive materials. This allowed significant cost-savings in design of the test-specific fuel handling system. For example, the surface transporter is designed for fuel transfer outside a hot cell, which led to a low over-the-road speed. Both features are more easily accomodated in the controlled environment of the NTS.

PURPOSE AND OBJECTIVES

There are a number of reasons for carrying out a field test of spent-reactor-fuel storage. It is not widely understood by the public that spent-fuel handling is a straightforward engineering problem, involving available technology. For this reason, such a test has educational value. There are also technical benefits to be gained. Unless one carries out generic tests such as this, the first test emplacement of high-level waste will not occur until we are ready to build an actual repository, and this is a decade or more away. Even though much information can be gained from laboratory measurements and computer modeling, we can only address the question of unpredicted negative synergistic effects during storage in an actual field test. Thus, the technical purpose of the test is to provide early field measurements of the effects of high-level-waste emplacement on a crystalline igneous rock mass.

Stated in terms of objectives, there are both general objectives and technical objectives. The overall general objective of our test is to evaluate the feasibility of safe and reliable short-term storage of spent reactor fuel assemblies at a plausible repository depth in a typical granitic rock, and to retrieve the fuel afterwards.

Where consistent with the above objective, a secondary general objective is to obtain technical data to address two subjects: (1) the evaluation of granite as a medium for deep geologic disposal of high-level reactor waste, and (2) the design of a repository in granite.

In order to achieve the general objectives, two main technical objectives have been defined:

- To simulate the effect of thousands of canisters of nuclear waste emplaced in geologic media, using only a small number of spent fuel assemblies and electrical heaters.

- To evaluate the difference, if any, between the effect of an actual radioactive waste source and an electrical simulator on the test environment.

There are also some secondary technical objectives:

- To compare the magnitude of displacement and stress effects from mining alone with that of thermally induced displacement and stress that occurs after the spent fuel is introduced.

- To document quantitatively the amount of heat (about one-third, according to calculations) removed by mine ventilation.

- To compare the response to thermal load of relatively more fractured and less fractured rock.

- To evaluate the performance of various backfill materials, if this can be achieved as a mid-test add-on.

TECHNICAL CONCEPTS AND RATIONALE

Given that one wishes to emplace high level waste to gain information leading to establishing a repository in granite, there are numerous decisions in test design. Fundamentally they reduce to how many for how long in what geometry. The number of canisters of waste proposed for such tests have literally ranged from 1 to 1000. Proposed test durations have ranged from a few years to a few decades. And there has been a correspondingly wide range of suggested geometries for repository design.

In order to provide a technical basis for decision, numerous thermal scoping calculations varied the number of canisters, age of waste at emplacement, and geometry. Ultimately we arrived at a layout in which the early time, close-in thermal history of a repository is simulated with 11 canisters of spent fuel, 6 electrically heated simulator canisters, and 20 auxiliary electrical heaters. In this configuration the effects on granite of heat alone (from electrical simulators) can be compared with the effects of heat plus radiation (from the spent fuel).

Scoping calculations of a hypothetical repository revealed that the thermal history of the rock wall around the canister varies significantly with the age of spent fuel at emplacement (Fig. 2). Our initial design attempts focused on attempting to reproduce the shape of the 100 year trace for 5-year-old waste by using 2-1/2 year-old fuel and large numbers of auxiliary heaters throughout a 10 year test. Using such an approach would have led to a significant (>50°C) thermal overtest, but had the disadvantages of long test duration, large electrical power requirements, and complex and costly layout. It would also have been difficult to achieve a reasonable thermal simulation for any significant rock volume. The final design therefore settled on simulating the first 5 years' temperature-time history for a

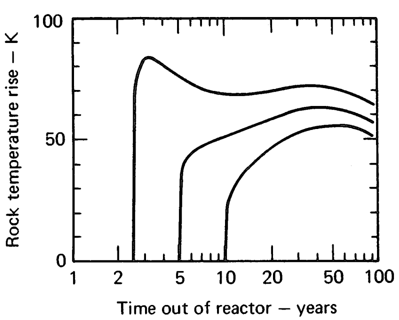

Fig. 2. Temperature history of the rock surface at fuel-assembly midpoint in the center hole of a hypothetical repository, calculated for spent fuel emplaced 2.5, 5, and 10 years after discharge. The spent-fuel canisters are spaced 3-m apart in parallel rows spaced on 15-m centers.

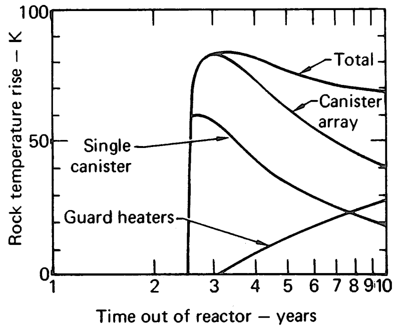

Fig. 3. Calculated contributions to temperature history of the rock surface at fuel-assembly midpoint in the center hole of a 17-canister spent-fuel-storage array. The spent fuel electrical simulators, and heatters are deployed as shown in Fig. 4.

repository loaded with 2-1/2-year-old fuel, using 2-1/2-year-old fuel and electrical heaters. Although such a repository will almost certainly never exist, the 2-1/2-year-old fuel case represents the most extreme conditions likely in a spent fuel repository and represents about a 30°C overtest compared with 10-year-old spent fuel (Fig. 2).

There are numerous considerations in the choice of a test duration, including early demonstration of retrievability, the added costs of a longer test, and the need to operate the test long enough to observe any time-dependent deleterious effects. As can be seen in Fig. 2, the peak temperature on the borehole wall for 2-1/2-year-old fuel will be attained in about 10 months, after which the temperature will decline for about 7 years and then gradually increase. After 5 years of storage, the temperature will be within a few degrees of its lowest value until 70 years in this configuration. Therefore 5 years seems an adequate maximum test duration.

With regard to the minimum test duration, other calculations show that the peak temperatures at the edges of the 15 x 15 m repository-model cell will be attained at about 2 years after the test is started. For planning, a minimum test duration of 3 years has been selected.

Once the conditions to be simulated were defined, the simulation array was scoped. Figure 3 shows the calculated contribution of a single canister, the canister array, and the auxiliary heaters to the total temperature-time history of the test array. The calculated temperature history of the test array matches that of the conceptual repository within 1°C for the first 7-1/2 years of storage.

As few as 11 canisters in the test array would have produced acceptable thermal results on a single center canister but it is desirable to include a greater volume in the simulation. The final 17-canister array is sufficient to prevent end effects in a 15 x 15 m central cell during a 5-year test. However, the additional 6 canisters represent a signficant cost. During evaluation of the cost versus benefit of the 17-canister array, we realized that, outside the central cell, a combination of spent fuel and electrical simulators could be used. Although the ultimate result gave little or no reduction in cost, what is potentially the most significant technical part of the experiment was added -- a direct comparison of the effect on the rock of spent fuel versus electrical simulators. This will be accomplished by two methods: direct monitoring of thermal history of the canisters and adjacent rock during the test, and laboratory analysis of rock samples recovered from the storage hole walls after the test.

The basic test layout resulting from the above considerations is shown in Fig. 4. More specific details of the final calculations and other issues considered in the test design are given in Reference 1.

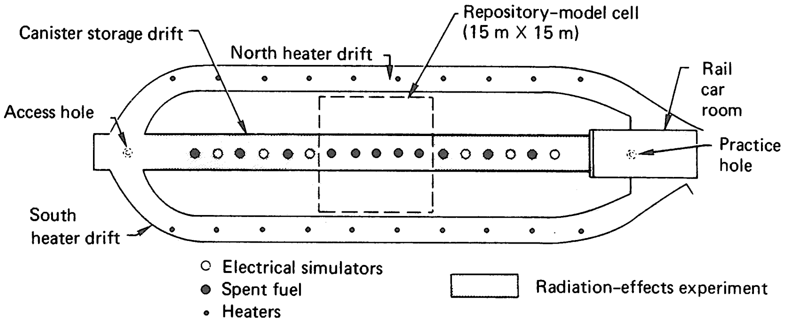

Fig. 4 Plan view of the Climax granite spent-fuel-storage test.

TEST LAYOUT AND CONSTRUCTION

The basic test layout is shown in Fig. 4. The main canister storage drift extends 64 m (210-ft.) and, in order to accommodate the 5.2 m long transfer cask, the drift is 6 m (20.5-ft.) high by 4.6 m (15-ft.) wide. This drift was mined in two passes, with the top heading being completely removed before any benching operations were started.

Prior to mining the canister storage drift, the north and south heater drifts, which measure 3.4 x 3.4 m (11 x 11-ft.), were fully excavated. Displacement and stress instrumentation was emplaced in order to monitor the response of the rock to mining of the canister storage drift. These measurements of the purely mechanical response of the rock to mining will be compared with later measurements of the response to thermal loads from the spent fuel and simulators.

Several other features of the test layout are shown in Fig. 4. The fuel is transferred from the surface through a canister access hole which was drilled at .76 m (30-in.) and cased to .485 m (19.1-in.) ID. It is received underground by a rail-mounted transfer cask, which is stored in the railcar room at the opposite end of the storage drift. There are 17 storage holes, which are 609 mm (24-in.) diameter by 6-m (20-ft.) deep. The storage holes contain a 457 mm (18-in.) steel liner. The purpose of this liner is to ensure that the spent fuel canisters will be retrievable in the event of surface decrepitation of the granite into the storage holes.

Prior to major construction activities, 4 cored NX-size exploratory holes totalling 480 m (1575-ft.) were drilled through and beyond the test location to assure rock quality. In addition to the storage holes and the exploratory holes, there were 170 other holes drilled to emplace instrumentation in the test array, to perform rock properties tests, or to obtain record cores. These 170 holes range from EX (38 mm) to 609 mm (24-in.) diameter and from .15 m (6-in.) to 16.5 m (54-ft.) depth. These holes totalled 1147 m (3762-ft.) of drilling, of which 610 m (2000-ft.) were cored.

An instrumentation alcove was constructed to house the underground part of the data acquisition system: instrumentation channel scanners, precision digital voltmeters, and radiation detection electronics. A battery-powered uninterruptible power supply (UPS), air-conditioning, and an automatic fire-suppression system protect the electronics. The data will be digitized underground and transmitted to the surface to a computer housed in a data-acquisition-system trailer. This trailer contains a computer room, a terminal room, an electronics maintenance shop, an office area, and is also equipped with UPS, air-conditioning, and an automatic fire-suppression system.

Previously existing mining facilities included a shaft to the 420 m level drifts, a mine hoist and headframe, ventilation equipment, utilities, and numerous support facilities. A separate canister access-hole, an access-hole hoist house, and a headframe and a separate ventilation system were constructed for the SFT-C.

Construction of the facility was accomplished between June 1978 and February 1980. Construction was done by REECo, Inc., the prime NTS operating contractor, with A-E services provided by Holmes and Narver (for general civil engineering) and Fenix and Scisson (for mining and drilling). Management of the construction activities was provided by the Nevada Test Site Support Office of the DOE based on criteria furnished by the LLL and approved by the Project Manager of the DOE NNWSI.

SPENT FUEL HANDLING SYSTEM

For the test, LLL has designed, fabricated, and will operate a spent fuel canister handling system that safely and reliably transports the fuel canisters from the encapsulation facility (E-MAD) to the test area, lowers them underground and positions them in vertical storage holes in the test array. The fuel canisters are in a heavily shielded configuration at all times, and the sequence is reversible for retrieval at any time.

In order to achieve the test objectives at as low a cost as possible consistent with safe operation and an expeditious schedule, several basic design decisions were made very early: (1) transfer operations in the field would not require a hot cell to be constructed, (2) the spent fuel canister already developed by Westinghouse for the Spent Fuel Handling and Packaging Demonstration[2] at E-MAD would be used for the SFT-C, and (3) existing technology would be used throughout the test.

The fuel assemblies are encapsulated by Westinghouse at E-MAD in a stainless steel canister (14-in. diameter by 14-ft. length) which is welded closed and backfilled with helium at 1-atm pressure. A temporary top shield plug is attached to the canister during storage at E-MAD. When the canister is to be transferred to the SFT-C, it is suspended from a carbon steel shield plug (18-in. diameter by 1-ft. thick) topped by a stainless steel lifting knob. This assembly is loaded into the LLL-furnished transport system in the hot bay. All further handling is done outside a hot cell.

All further canister handling operations, except over-the-road transport, are remotely controlled for minimum personal exposure. Special attention has been given to shielding, component redundancy and accessibility to permit recovery from abnormal operations due to malfunctions.

The canister handling system has three basic subsystems: a Surface Transport Vehicle (STV), an Access Hole Lowering System, and an Underground Transfer Vehicle (UTV).

The STV is a 10-ft. wide, 60-ton lowboy trailer and a standard heavy-duty diesel-powered tractor. The trailer carries a 45-ton steel transport cask, 45-in. in diameter and 18-ft. in length. The cask is trunnion-mounted on hydraulic jacks and is rotated from a near-horizontal transport position to vertical loading/unloading attitude by hydraulic actuators. A hydraulically operated hinged-top cover and an electrically powered sliding bottom gate permit loading or unloading through either end. On-board electrically powered hydraulic pumps and controls are remotely controlled through umbilicals. Manually installed locking pins secure the cask closures and the cask to the trailer during transport. The STV is driven under convoy approximately 55 miles over NTS roads from the E-MAD encapsulation facility to the test area at a maximum road speed of 30 mph.

The Access Hole Lowering System transfers the fuel canisters from the surface to the underground test area. It consists of a 19-in. diameter steel-cased hole 1350-ft. deep, a headframe over the access hole, and an electrically powered hoist, which spools a special composite structural/electrical cable. The end of this cable is fitted with a remotely operated grapple and a grapple brake safety device. The access hole is fitted with shielding collars at both top and bottom. The top collar accepts the bottom gate of the surface transport cask to provide a step-joint shielding configuration as the fuel canister is transferred from the cask into the access hole. A similar geometry at the bottom of the access hole is employed as the fuel canister emerges from the hole and enters the transfer cask on the UTV.

The UTV is an electrically powered railcar that carries a 50-ton transfer cask and operates between the bottom of the access hole and each of the fuel canister storage holes in the 160-ft.-long test storage array. The transfer cask, similar in dimensions to the STV cask, has two-piece sliding gates both top and bottom to complete the shield configuration during the transfer operations and to permit top loading (from the access hole) and bottom unloading (into the storage holes). The cask is raised into the access hole shielding collar during loading, lowered to a mid-position while it is being moved to the storage hole location, and lowered into a similar shielding collar at each storage hole. The UTV is also equipped with an on-board jib-mounted hoist and canister grapple that is used to lower the fuel canisters into the storage holes and to handle concrete-filled shield plugs that cover the fuel canisters in the final storage configuration. With the shield plug in place, the radiation level at floor contact above the stored spent fuel is designed to be less than 0.5 m R/h.

All three of these subsystems are operated from a single control room, which is located on the surface above the test array and adjacent to the access hole hoist. Control consoles, closed-circuit television monitors, remote radiation level displays, and test ventilation system controls are located in this control room and operated by a three-man crew when fuel is handled.

Shipment from the E-MAD encapsulation facility to the test area, transfer to the test level, and emplacement of a fuel canister into the storage array are planned to require one 10-hr. shift. At the end of the storage period or at any interim time, the canisters can be retrieved by reversing the above procedures.

INSTRUMENTATION AND DATA ACQUISITION

The large number of canisters (17) deployed in the spent-fuel-storage test and the need for detailed thermal surveillance of each one require a large number of data-acquisition channels. When safety radiation monitors are added (each recorded on two channels for redundancy), we find that associated rock mechanics instrumentation must be limited if the amount of data collected is to be kept within manageable bounds. The intense gamma and neutron fields associated with the spent-fuel canisters further limit the type and location of instrumentaion. The instruments used must be known to operate in the radiation field at the desired level of accuracy, and radiation shine paths to the drift must be avoided.

The instrumentation is primarily designed to confirm that the test objective of safe and retrievable storage of the fuel canisters is achieved. Radiation-detection instrumentation will be deployed to monitor and control personnel exposures during fuel-canister-handling operations and to document any changes in radiation levels during the storage test phase. Appropriate local and remote alarm capability will be provided on all data channels. Should any unanticipated effect jeopardize test objectives, the instrumentation will provide early warning of impending problems to permit timely remedial action.

In addition to the surveillance function, thermal, displacement, and stress instrumentation will document the response of the test area to various loads, including those imposed by the mining operations during construction of the test and those imposed by heat from the fuel canisters and associated electrical simulators and heaters.

Rock temperatures, stresses, and displacements will be measured continually during the storage period at more than 600 locations. In addition there will be 21 locations for radiation monitoring, and 67 channels of the Data Acquisition System (DAS) will be devoted to monitoring the status of various other utility and safety systems.

There are 487 thermocouples and 18 stress meters of the vibrating wire type. Twenty-six rod extensometers with a total of 116 anchor points are set in boreholes, and 34 wire extensometers measure convergence in the drifts. Three-directional discrete joint motion will be monitored at 7 stations. All of these instruments are automatically read and recorded at pre-selected intervals by the DAS. In addition, there are 22 convergence heads for displacement readings involving a manually read tape-extensometer; and there are a number of manually read displacement pins set across significant joints to monitor discrete joint motion. Two dew-point monitors and an air-flow rate monitor complete the technical instrumentation.

The primary thermocouples are relatively uniformly distributed throughout the test array, with 18 at each of the 17 storage locations. About 120 secondary thermocouples are required for the extensometer anchors and stressmeters. This stress and displacement instrumentation is concentrated at two of the 17 storage locations in the canister drift and at two other locations along the heater drifts. To have monitored stress and displacement as thoroughly as temperature would have required at least a doubling of the current 830 channel DAS requirement. Each of the two instrumented storage holes has 3 stressmeters and 24 extensometer anchors, with 27 associated thermocouples.

Over a 5-year test duration, an immense amount of data will be generated from the more than 600 instrumentation transducers. In addition continuous monitoring of both the technical and safety aspects of the test is desired. Therefore, the test will be controlled by a digital-computer-based data-acquisition-system (DAS). This DAS will acquire, analyze, and store data, and it will monitor the status of both technical and safety systems.

The DAS consists of 4 parts: an underground instrumentation alcove, a surface instrumentation trailer, an LLL-Livermore terminal, and an NTS alarm terminal. The underground instrumentation alcove houses the instrumentation channel scanners, precision digital voltmeters, and radiation detection electronics. Upon command from the computer system, a scanner connects the requested instrument's analog output to the digital voltmeter. The analog value is then digitized and transmitted to the computer system, which is housed in the surface instrumentation trailer. The scanning sequence and frequency are user selectable.

The surface instrumentation trailer contains a computer room, a terminal room, an electronics maintenance shop, and an office area. The computer system consists of two Hewlett-Packard 21 MXE processors, each with a 20-megabyte moving head disk and a magnetic tape drive. Each computer processor operates independently and is connected to only one of the two scanner systems. Critical channels are connected to both scanner systems. Each processor independently requests input from its instrumentation system.

As the data are received from the scanner systems, an analysis identifies alarm conditions or equipment failure. If a problem condition is detected, the computers will report the condition along with a recommended action by means of an automatic phone dialer and modem system. Problem reports can be sent to the NTS alarm terminal, or the LLL-Livermore terminal. Both the underground and surface facilities are equipped with uninterruptible power systems. Any failure of a system terminal will be detected and reported on the other terminals.

A preprogrammed daily status report will be automatically transmitted to Livermore. The Livermore terminal will be capable of remotely interrogating the field data base and commanding modifications to the DAS.

The basic data recording is on magnetic tape. A single 2400-ft. tape will contain all the data collected for a period of about 25 days. These data tapes will be shipped to Livermore and copied to the main LLL computer system for analysis and long-term storage.

Although the basic operation of the test is remote, physical inspection of the facility will be carried out on a regularly scheduled basis. As noted earlier, some data acquisition is manual.

TEST PLANS

The SFT-C in its present configuration will be operated for 3 to 5 years, after which the spent fuel will be retrieved and returned to E-MAD. During this time it is expected that the maximum rock temperature anywhere in the test array will not exceed 100°C. Within the 15 x 15 m cell, the initial thermal loading is 44 W/m^2 (178 kW/acre) which is in the range of most preconceptual repository designs. Each canister will have an initial thermal output of about 2 kW, decaying to 0.7 kW in 5 years.

The comparison between spent fuel and electrical simulators will be indirect during the test, based on comparison of thermal profiles. After the test, a core of the storage hole sidewall will be taken and the samples examined in detail in the laboratory. Based on preliminary laboratory measurements and evaluation of available literature, little if any deleterious effect from the radiation flux on the granite is expected. The temperatures generated by the spent fuel are not high enough to initite decrepitation of the borehole walls as observed in the Stripa tests or in England.

Although no effects are deemed likely on the granite, the combination of heat and radiation could cause significant deleterious effects on backfill materials of the bentonite-zeolite types currently under consideration. One test option is to reconfigure the storage holes to include backfill and reinstall the spent fuel for a follow-on test. Evaluation of this option is currently planned.

Another test option following removal of the spent fuel is to reinstall the liners and operate the test at increasing thermal loads stepping up to as high as 20 kW/canister. This would constitute a severe overtest, and some deleterious effects would almost certainly be observed.

From a technical standpoint, the main output of the test will be evaluation and documentation of how well computational models can predict and match the temperature, stress, and displacement histories at the various measuring stations. At the outset of the test, we expect the thermal calculations to match very well, with greater uncertainties in the thermomechanical calculations. However, the heat balance aspects of this test are the first attempt at such fine tuning and problems may arise in the thermal analysis.

At the time of test design, it was assumed that adjacent and complementary rock mechanics testing using non-radioactive heat sources in optimal test configurations would be carried out. At present, funding for such tests is uncertain and some basic in situ rock mechanics measurements may be required in order to properly interpret the data from the SFT-C. Fortunately, such data can be obtained during the test in adjacent locations. Definition of such programs will await decisions on co-use of the facility.

Although the basic plan for the test is established, review of plans on a yearly (or more frequent) basis is expected. Significant changes will be circulated for comment by the technical community prior to implementation.

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