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FROM THE SPENT FUEL TEST - CLIMAX

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OPERATIONAL AND TECHNICAL RESULTS FROM THE SPENT FUEL TEST - CLIMAX*
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ABSTRACT

The technical feasibility of short-term storage and retrieval of spent nuclear fuel assemblies has recently been demonstrated in a test of deep geologic storage at the U.S. Department of Energy Nevada Test Site (NTS). Handling systems and procedures developed and deployed on this test functioned safely and reliably to emplace eleven intact spent-fuel assemblies and retrieve them three years later. Three exchanges of spent fuel were conducted at regular intervals during the storage period to maintain the proficiency of personnel and the readiness of the handling system.

Technical data was collected using nearly 1,000 instruments. These data show that the mechanical and thermal properties of granites are compatible with nuclear waste isolation objectives. Measured and calculated temperatures are in excellent agreement, confirming the adequacy of available heat transfer codes. Radiation transport calculations were of high quality, exceeding the accuracy of available long-term dosimetry techniques which were used on the test. We also found good agreement between measured and calculated displacements within the rock mass.

INTRODUCTION

The concept for the Spent Fuel Test-Climax (SFT-C) [1] grew out of the recognition that there was a broad lack of public confidence in the ability to dispose of the highly radioactive by-products of the commercial nuclear power industry. The SFT-C was planned and conducted under the technical direction of the Lawrence Livermore National Laboratory to provide a realistic engineering demonstration of spent-fuel handling and storage operations and to provide scientific data pertinent to the generic qualifications of granite as a medium for geologic disposal of high-level nuclear waste. Reynolds Electrical and Engineering Company was responsible for construction activities for the SFT-C while Holmes and Narver and Fenix and Scisson provided architect-engineering services. The Westinghouse Electric Corporation was responsible for encapsulating the spent-fuel assemblies. The ECRG Company provided electronics support for instrumentation of the test.

Funding for the test began in June 1978, as part of the Nevada Nuclear Waste Storage Investigations

of the U.S. Department of Energy's National Waste Terminal Storage Program. Facility construction and systems fabrication culminated in the initiation of spent fuel emplacement 420 m below ground surface on April 18, 1980. The eleven spent-fuel assemblies were retrieved and returned to a surface storage facility at the NTS beginning March 3, 1983. Approximately 15.3×10^6 points of data were collected during the three-year spent-fuel storage phase and the subsequent six-month cooling period of the test.

TEST OBJECTIVES

The overall objective of the SFT-C was to demonstrate the safe and reliable packaging, handling, storage, and retrieval of spent nuclear reactor fuel in a deep geologic media. A number of technical objectives were developed to address the ultimate qualification of granite as a medium for nuclear waste emplacement and to provide data useful in designing a waste repository [1]. Evaluation of geotechnical instrumentation was added as an objective midway in the test. Hydrological, radionuclide migration, and waste package studies were not included in the scope of this test.

In order to meet test objectives, it was necessary to design a facility which would simulate the conditions anticipated to be present in a full-scale repository of the future. Thermal analyses showed that this simulation could be obtained using three parallel rows of thermal sources (Fig. 1). The center 15×15 m region of the test array experienced the same thermal regime present in a 8,000 canister array of a repository [2].

Also shown in Figure 1 are six electrical simulators which were interspersed with the spent fuel assemblies in the regions outside the 15×15 m repository model cell. This arrangement allows a comparison of the effects on granite of heat alone (where the simulators are present) with the combined effects of heat and ionizing radiation (where the spent-fuel assemblies are present).

Fig. 1 Plan view of the Spent Fuel Test-Climax showing repository model cell and radiation effects experiment.

SITE CHARACTERIZATION

Site characterization relied on available data during the early phases of planning the test [3]. Later, four 76 mm (NX) diameter exploratory cores were obtained to investigate the lateral and vertical variability of the rock mass prior to construction. These cores and others (obtained from instrumentation and heater holes) account for a total of 1570 m of core obtained and analyzed [4].

From mapping progressed in parallel with the excavation of the subsurface facility and eventually resulted in the mapping of over 2500 geologic features [5]. Structurally significant features have been identified and are included in analyses of rock responses [6].

Both laboratory [7] and in situ [8] testing provided mechanical and thermal properties data as input to calculations of rock response. Key properties were measured before and after the episode of heating to determine the extent and magnitude of changes in pertinent rock properties. In situ stresses were also measured at various locations in the vicinity of the SFT-C [9,10].

FACILITY DEVELOPMENT AND GEOMETRY

Development of the SFT-C took advantage of two existing facilities at the NTS. The first is the "Piledriver" subsurface complex which included a personnel and materials shaft, hoist and headframe, and associated surface plant that were used for nuclear weapons effects testing at the site in the 1960s. The second is the Engine Maintenance, Assembly, and Disassembly (E-MAD) facility which was developed for the nuclear rocket program and is operated for the DOE by Westinghouse Electric Corp.

The Piledriver shaft provided access to the 420 m test depth. Underground construction for the SFT-C included driving two 3.4 x 3.4 m heater drifts and a 4.6 x 6.1 m high canister storage drift. In addition, a shaft was bored 0.76 m diameter by 420 m deep. This shaft provides access for lowering and raising the encapsulated spent fuel between the surface and the underground workings [11]. Seventeen 0.61 m diameter by 5.2 m deep canister emplacement boreholes were drilled vertically downward on 3 m centers to accommodate the 11 spent fuel canisters and 6 electrical simulators. An eighteenth hole was provided for practice fuel-handling operations. These holes were lined with 0.46 m diameter carbon steel liners to insure the retrievability of the spent fuel.

An array of nearly 1,000 instruments was installed to measure temperatures, displacements, stresses, air quality, radiation dose to granite and personnel, and acoustic emissions (Figs. 2 and 3). Details of the instrumentation plan are provided by Brough and Patrick [12]. The acquisition of test data from most of these instruments was performed by a dual disc-based HP1000 mini-computer system [13].

Fig. 2 Spent Fuel Test-Climax, showing location of intermediate-field thermocouples.

SPENT FUEL HANDLING SYSTEM

A three-component system was developed to facilitate transport of the spent fuel assemblies on the NTS [14,15]. The spent fuel was shipped from the Turkey Point #3 (Florida) pressurized water reactor to NTS via licensed transporter. Subsequent to encapsulation at the E-MAD facility in southwest NTS, the canisters were moved to the SFT-C in a shielded surface transport vehicle (STV). The STV is comprised of a large shielding cask mounted on a specially designed trailer which is pulled by a commercial tractor unit. The cask provides 330 mm of iron shielding for a single intact, encapsulated spent-fuel assembly. It has remotely actuated top and bottom closures which provide for loading and unloading the cask when it is in the vertical position. The cask is reclined to provide for stable transport.

At the start of a spent-fuel handling operation, the cask of the STV was positioned in a recess at the top of the access shaft and the Underground Transfer Vehicle (UTV) was positioned in a recess at the base of the shaft. The canister lowering system (CLS) lowered and raised the canisters through the previously described drilled access shaft. The CLS consists of an electrically driven hoist, associated controls, and a "fail safe" braking system. The hoist cable is both a loading-bearing member and communication conduit. Signal wires in the core of the cable are used to activate a grapple. This grapple attaches to a spherical lifting fixture which is integral with

Fig. 3 Schematic of thermal phase displacement and stress instrumentation.

the top of the spent-fuel canister. In the event the canister begins to free-fall, a load cell senses a decrease in the load carried by the grapple and a braking system mounted above the grapple stops the descent of the canister.

The UTV was designed to receive the spent-fuel canister underground and transfer it to and emplace or retrieve it at one of the 17 storage boreholes. It consists of a shielding cask, similar to the one on the STV, which is mounted on a remotely controlled rail-mounted vehicle. Although adequate radiation shielding is provided, as an additional safety precaution, in general, no personnel were underground during spent-fuel handling operations.

RESULTS OF SPENT FUEL HANDLING OPERATIONS

The spent-fuel handling operations conducted at the SFT-C clearly demonstrate the feasibility of deep geologic storage of nuclear wastes. The 11 encapsulated spent-fuel assemblies were placed in temporary storage at the SFT-C during April and May 1980. Exchanges of spent-fuel canisters between the SFT-C and E-MAD were conducted on a periodic basis to insure that personnel and handling systems were qualified and operational. Three such exchanges--in January 1981, October 1981, and August 1982--were conducted. Retrieval of the 11 assemblies in March and April 1983 completed the successful engineering demonstration.

No release of gaseous or particulate radioactive effluent occurred during the test. Radiation exposures to operating personnel for the duration of the SFT-C were less than 0.4 person-rem [16]. This exposure may be normalized with respect to the energy generated by the fuel assemblies while they were in the reactor to obtain a relative measure of the additional dose commitment associated with retrievable storage. We calculate that a normalized radiation exposure of 0.002 person-rem/MW·y (electric) occurred at the SFT-C. This is a very small fraction of the one-to-four person-rem/MW·y (electric) received during normal operation of nuclear power reactors [17].

The SFT-C also established the technical viability of two spent-fuel handling concepts. First, we developed a rail-mounted (rather than tire-mounted) underground transport system which offers substantial simplification for remote-control operation. Second, we utilized earth shielding rather than lowering the spent-fuel to the storage level in a massive shielding cask. Because the hoisted payload was lighter and smaller for our earth-shielded system, the handling system is intrinsically simpler and safer.

RESULTS OF TECHNICAL MEASUREMENTS PROGRAM

The extensive field and laboratory measurements provided data which show that the thermal and mechanical properties of granites similar to the Climax stock are compatible with nuclear waste disposal. The hydrologic and radionuclide retention properties of the stock were not investigated at the SFT-C.

Data Acquisition and Instrumentation

The reliable performance of the data acquisition system and instrumentation were essential to meeting the technical objectives of the test. The HP1000-based data acquisition system which recorded data from nearly 1,000 instruments functioned reliably throughout the test. System availability averaged 96%. With few exceptions, system accuracy was maintained within specified ranges for the measuring instruments.

Instrumentation also functioned reliably with two exceptions. First, a group of linear potentiometers failed by becoming nonlinear in resistance. Second, nearly all of 18 vibrating-wire stressmeters failed due to internal corrosion [18]. Failure of these transducers led us to add instrumentation evaluation as a specific test objective. The transducers which failed were replaced and evaluated through the remainder of the test. Detailed analysis of instrumentation performance is in progress.

Comparison of Data and Calculations

Agreement between calculated temperatures and those measured throughout the SFT-C were in excellent agreement throughout the heated phase of the test (Fig. 4). More than a gigawatt-hour of thermal energy was deposited in the rock mass during this period. The only significant differences occurred near the extreme ends of the facility and in the ventilation airstream [19]. Agreement during the six-month period of cooling which followed spent-fuel retrieval was acceptable but not as good. Measured temperatures were consistently 1 to 5°C cooler than calculated, probably as a result of inadequacies in the ventilation model. Refinements to the model are in progress.

The behavior of the rock mass comprising the SFT-C facility was monitored using three types of displacement instruments. Borehole extensometers measured displacements within the rock mass, wire extensometers measured changes in the dimensions of the underground openings, and fracture monitors measured displacements of discrete geologic features such as faults and shear zones. The rock displacements recorded during the heated phase were generally less than 2 mm and in good agreement with values calculated using the ADINA/ADINAT codes [19,20]. Rock responses were calculated to be very small during the cooling period and, in fact, were smaller than the resolution of some of the measurement systems [21].

Fig. 4 Calculated and measured temperature histories throughout the heating and cooling phases of the SFT-C. Temperatures at various radial locations at the axial midplane of CEH09.

An array of acoustic emission detectors was very responsive to changes in the rate of thermal energy deposition [21]. Changes in heater power levels and emplacement or retrieval of spent-fuel assemblies resulted in swarms of acoustic emissions which quickly subsided to background levels, indicating continued stability of the underground facility and the storage boreholes. This may prove to be a valuable technique for remote monitoring of the stability of a large-scale repository.

We found that a Monte Carlo code was capable of accurately calculating radiation transport for the rather complex spent-fuel emplacement borehole geometry [22]. Long-term dosimetry using an optical absorption technique proved to be adequate. Time- and temperature-induced fading of these dosimeters is not fully understood, however [23]. We augmented this technique with short-term thermoluminescent dosimetry and obtained a much more consistent data set which was in better agreement with calculations [22,24].

Radiation and Thermal Effects

Several studies have been conducted to evaluate potential radiation- and heat-induced effects in the Climax granite. We found that the heterogeneity of the rock on all scales was such that statistically designed experiments were often necessary to obtain meaningful results. An initial laboratory study of radiation effects on elastic modulus and strength showed that both these properties decreased in value as a result of intense gamma irradiation dose of 13 MGy [25]. Because this result was not anticipated based on previous studies in crystalline rocks, a larger, statistically designed study was conducted [26]. The latter study established with high statistical confidence that a radiation effect was not present. A related study attempted to detect microstructural changes which may have resulted from irradiation [27]. Changes were not discernable due to the high background level of microfracturing.

A recently completed investigation of thermal effects showed that no statistically significant changes in microfracturing or mineralogy occurred in samples obtained from near auxiliary heaters [28]. These samples were at temperatures near 350°C for the three-year heated phase of the test. A companion study of thermal and combined thermal and radiation effects is in progress at this time. Potential changes in mineralogy and petrology are being studied by examining paired samples which were obtained adjacent to the emplacement boreholes before and after the SFT-C.

Although not a specific objective of the SFT-C, post-test analyses provided some data on corrosion of metals used in the test. Nitric acid formed by radiolysis accelerated corrosion of the carbon steel emplacement borehole liners. There are also limited cases of corrosion in nickel alloys such as stainless steel sampling tubes, Inconel 600 thermocouple sheaths, and Superinvar extensometer connecting rods [21].

CONCLUSIONS

The SFT-C clearly demonstrated that spent nuclear fuel assemblies may be safely encapsulated, emplaced in a geologic medium, and retrieved when necessary. The results of this study are pertinent to the preclosure period for a permanent repository and to current concepts for monitored retrieval storage in geologic media. The long-term post-closure aspects of nuclear waste isolation have not been addressed in this study.

Documentation of the results of the SFT-C have been ongoing throughout the testing period. The remaining studies will be completed and reported by the end of this year.

The SFT-C facility continues to be maintained by the U.S. Department of Energy's Nevada Operations Office. The DOE provides access to the facility for the public and other interested groups. Site visits are provided to focus public awareness on the National problem created by the accumulation of spent nuclear-reactor fuel in this country and on the DOE's efforts toward developing geologic repositories as a permanent solution to the problem. The spent-fuel assemblies remain in safe temporary dry storage at the E-MAD facility in southwest NTS. Shipment of the assemblies to the Idaho National Engineering Laboratory for use in further tests is being contemplated.

REFERENCES

1. L. D. Ramspott, L. B. Ballou, R. C. Carlson, D. N. Montan, T. R. Butkovich, J. E. Duncan, W. C. Patrick, D. G. Wilder, W. G. Brough, and M. C. Mayr, "Technical Concept for a Test of Geologic Storage of Spent Reactor Fuel in the Climax Granite, Nevada Test Site", Lawrence Livermore National Laboratory Report UCRL-52796, June 1979.
2. D. Montan and W. Patrick, "Thermal Calculations for the Design, Construction, Operation, and Evaluation of the Spent Fuel Test-Climax, Nevada Test Site", Lawrence Livermore National Laboratory Report UCRL-53238, September 1981.
3. F. Maldonado, "Summary of the Geology and Physical Properties of the Climax Stock, Nevada Test Site, U.S. Geological Survey Open File Report 77-356, 1977.
4. D. Wilder, J. Yow, Jr., and R. Thorpe, "Core Logging for Site Investigation and Instrumentation, Spent Fuel Test-Climax", Lawrence Livermore National Laboratory Report UCRL-19646, May 1982.
5. D. Wilder and J. Yow, Jr., "Fracture Mapping at the Spent Fuel Test-Climax", Lawrence Livermore National Laboratory Report UCRL-53201, May 1981.
6. F. E. Heuze, T. R. Butkovich, J. C. Peterson, "An Analysis of the 'Mine-by' Experiment, Climax Granite, Nevada Test Site", Lawrence Livermore National Laboratory Report UCRL-53133, June 1981.

7. H. Pratt, R. Lingle, T. Schrauf, "Laboratory Measured Material Properties of Quartz Monzonite, Climax Stock, Nevada Test Site". Submitted to Lawrence Livermore National Laboratory by Terra Tek, Inc., Contractor Report UCRL-15073, June 1979.
8. F. Heuze, W. Patrick, T. Butkovich, J. Peterson, R. V. de la Cruz, and C. F. Voss, "Rock Mechanics Studies of Mining in the Climax Granite", Int. Jour. Rock Mech. Min. Sci., Vol. 19, pp 167-183, 1982.
9. W. L. Ellis and J. E. Magner, "Determination of the In Situ State of Stress at the Spent Fuel Test Climax Site, Climax Stock, Nevada Test Site", U.S. Geological Survey Open File Report 62-458, 1982.
10. J. B. Creveling, F. S. Shuri, K. M. Foster, S. V. Mills, Foundation Sciences, Inc., "In Situ Stress Measurements at the Spent Fuel Test-Climax Facility". Submitted to Lawrence Livermore National Laboratory by Foundation Sciences, Inc., Portland, OR, Contractor Report, UCRL-15628, May 1984.
11. W. C. Patrick and M. C. Mayr, "Excavation and Drilling Activities at a Spent Fuel Test Facility in Granitic Rock", Lawrence Livermore National Laboratory Report UCRL-53227, November 1981.
12. W. Brough and W. Patrick, "Instrumentation Report #1: Specification, Design, Calibration, and Installation of Instrumentation for an Experimental, High Level, Nuclear Waste Storage Facility", Lawrence Livermore National Laboratory Report UCRL-53248, January 1982.
13. R. A. Nyholm, W. G. Brough, and N. L. Rector, "SFT-Climax Data Acquisition System Integration Report", Lawrence Livermore National Laboratory Report UCRL-53304, June 1982.
14. J. E. Duncan, P. A. House, and G. W. Wright, "Spent Fuel Handling System for a Geologic Storage Test at the Nevada Test Site", presented at the American Nuclear Society Meeting, Las Vegas, NV, June 1980; Lawrence Livermore National Laboratory Report UCRL-83728, May 1980.
15. L. B. Ballou, "Handling Encapsulated Spent Fuel in a Geologic Repository Environment", Radioactive Waste Management, Vol. 3, pp. 463-472, IAEA-CN-43/223, International Atomic Energy Agency, Vienna, Austria, 1984.
16. K. E. Raschke, W. C. Patrick, T. C. Roy, T. Straume, "Radiation Dosimetry and Monitoring for a Test of Geologic Storage of Spent Nuclear Fuel", Lawrence Livermore National Laboratory Report UCRL-53498, November 30, 1983.
17. L. A. Cross, "Comparing Nuclear Power Plant Exposure Histories", in Proceedings of the International Atomic Energy Agency, Vienna, Austria, IAEA-SM-242/49 (1980).
18. W. Patrick, R. Carlson, and N. Rector, "Instrumentation Report #2: Identification, Evaluation, and Remedial Actions Related to Transducer Failures at the Spent Fuel Test-Climax", Lawrence Livermore National Laboratory Report UCRL-53251, November 1981.
19. W. Patrick, L. Ballou, T. Butkovich, R. Carlson, W. Durham, G. Hage, E. Majer, D. Montan, R. Nyholm, N. Rector, D. Wilder, and J. Yow, Jr., "Spent Fuel Test-Climax Technical Measurements Interim Report FY81", Lawrence Livermore National Laboratory Report UCRL-53294, April 1982.
20. W. Patrick, L. Ballou, T. Butkovich, R. Carlson, W. Durham, G. Hage, E. Majer, D. Montan, R. Nyholm, N. Rector, D. Wilder, and J. Yow, Jr., "Spent Fuel Test-Climax Technical Measurements Interim Report FY82", Lawrence Livermore National Laboratory Report UCRL-53294-82, February 1983.
21. W. C. Patrick, T. R. Butkovich, R. C. Carlson, W. B. Durham, H. C. Ganow, G. L. Hage, E. L. Majer, D. N. Montan, R. A. Nyholm, N. L. Rector, F. J. Ryerson, H. Weiss and J. L. Yow, Jr., "Spent Fuel Test-Climax: Technical Measurements Interim Report Fiscal Year 83", Lawrence Livermore National Laboratory Report UCRL-53294-83, February 1984.
22. R. Van Konynenburg, "Radiation Doses in Granite Around Emplacement Holes in the SFT-C", Lawrence Livermore National Laboratory Report UCRL-53580, July 1984.
23. Quam, W., and T. DeVore, "Climax Spent Fuel Dosimetry Progress Report Sept. 82-Jan 84". Submitted to Lawrence Livermore National Laboratory by EG&G, Santa Barbara, CA, Contractor Report UCRL-15419-2, June 1984.
24. Quam, W., and T. DeVore, "Climax Spent Fuel Dosimetry, Short Term Exposure". Submitted to Lawrence Livermore National Laboratory by EG&G, Santa Barbara, CA, Contract Report UCRL-15419-3, June 1984.
25. W. B. Durham, "The Effect of Gamma Irradiation on the Strength of Climax Stock Quartz Monzonite", Lawrence Livermore National Laboratory Report UCRL-87475, March 1982.
26. W. Durham, J. Beiriger, M. Axelrod, S. Trettenero, "The Effect of Gamma Irradiation on the Strength and Elasticity of Climax Stock and Westerly Granites", Lawrence Livermore National Laboratory Report, July 1984.
27. J. Beiriger, W. Durham, "SEM Studies of Stressed and Irradiated Climax Stock Quartz Monzonite", Lawrence Livermore National Laboratory Report UCRL-20052, February 1984.
28. J. M. Beiriger, W. B. Durham, F. J. Ryerson, "Physical and Chemical Changes to Rock Near Electrically Heated Boreholes at Spent Fuel Test-Climax", Lawrence Livermore National Laboratory Report, UCRL in preparation, 1984.