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National Uranium Resource Evaluation

A MODEL FOR WATER FACTOR MEASUREMENTS WITH FISSION-NEUTRON LOGGING TOOLS

Bendix Field Engineering Corporation
Grand Junction, Colorado

May 1983

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Nuclear Energy
Grand Junction Area Office, Colorado

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ABSTRACT

During 1977 and 1978, a Fission Neutron Water Factor Model was designed and constructed by Bendix Field Engineering Corporation (BFEC) for the United States Department of Energy (DOE) at the Grand Junction facility. This model features seven water-filled boreholes with different diameters. All of these boreholes penetrate, in order from the top of the model, a 5-foot-thick (1.52 m), uniform, concrete upper "barren zone;" a 6-foot-thick (1.83 m), uniform, uranium-enriched, concrete "ore zone;" and a 4-foot-thick (1.22 m), uniform, concrete lower "barren zone."

The response of a fission neutron logging tool in a water-filled borehole is affected by variations in the borehole diameter. This diameter-dependent effect can be deduced from logs run in several different boreholes of the Fission Neutron Water Factor Model.

This report describes the construction of the Fission Neutron Water Factor Model and also presents values for model parameters which are of interest in fission-neutron logging.

INTRODUCTION

All fission-neutron logging tools have components that produce neutrons and systems for the detection of neutrons. These tools operate by irradiating the object formation with neutrons, then interrogating the neutron flux in the borehole. If the neutrons from the tool encounter uranium in the rock formation, then uranium-fission events will be induced. These uranium-fission reactions and the subsequent decay of unstable fission fragments liberate energetic neutrons, some of which transport to the neutron detector of the tool in the borehole. Anomalies in some specific neutron flux component indicate that the borehole neutron flux has been augmented by fission reactions in the rock.

Fission-neutron tools may produce neutrons by neutron generators (such as a deuterium accelerator with a tritium target) or by neutron sources (such as californium-252 or a photoneutron reaction such as $^{9}Be(\gamma,n)$. Neutrons that leave the logging tool are moderated within the borehole water (if water is present) and within the irradiated rock formation. Many neutrons eventually reach the thermal energy domain within the rock formation. Uranium-235 has a large, thermal neutron fission cross section, so if uranium is present, some of the thermal neutrons will induce fission events in uranium-235. These fission reactions spawn neutrons that fall into the two classes described below.

Prompt fission neutrons (PFN) are liberated immediately by the fission events. Each fission event yields, on the average, about 2.5 PFN with energies of approximately 2 MeV.

Delayed fission neutrons (DFN) are emitted by unstable fission fragments during an interval that ranges from about 0.2 seconds to about 60 seconds following a uranium-235 fission event. The average energy of these DFN is about 0.6 MeV.

After the formation has been irradiated, the logging tool must detect neutrons from fission or post-fission events. Several methods have been demonstrated. If, for example, the irradiation has been accomplished by the $^{9}Be(\gamma,n)$ reaction, then the source neutrons from the tool are of lower energy than the PFN. The signal due to the low energy source neutrons can be effectively eliminated from the PFN signal by proper energy biasing of a helium-4 detector.

Tools that employ neutron generators may irradiate the formation then deactivate the generator. A uranium-induced PFN signal is then revealed by a time-dependent anomaly in the epithermal neutron population. This anomaly can be measured with a helium-3 detector with proper time gating.

One type of californium-252 based tool allows the californium source to irradiate the formation, then transfers the source to a distant position within the tool. Following the source transfer, a time-gated bank of helium-3 detectors located near the irradiated zone (i.e., the position of the neutron source before transfer) begins to interrogate for a DFN signal. This signal, which represents a delayed enhancement of the thermal neutron flux, arises from DFN which have thermalized within the rock formation before reaching the detector in the tool.

The above fission-neutron methods, and others, are described in the papers cited in the references.

If the success of fission-neutron methods depends on the thermalization of source neutrons and the interaction of source neutrons with uranium-235, then certain conclusions may be drawn regarding fission neutron logging parameters of importance.

Thermalization of source neutrons depends strongly on the hydrogen content of the moderating medium which surrounds the logging tool. The relevant parameters are the type of borehole fluid, the borehole diameter (especially if the borehole is water-filled), and the porosity and saturation of the rock formation.

The reaction rate of thermal neutrons with uranium-235 is governed by the mass of uranium per unit volume of formation and also by the concentration of "neutron poisons" in the formation.

The mass of uranium per unit volume is not the conventional measure of uranium concentration. Concentration is customarily reported as mass of uranium per unit mass of rock. However, if two formations of different density have the same mass of uranium per unit rock mass, the denser formation will produce the greater response in a fission neutron tool. This is due to the fact that the denser formation has a greater mass of uranium per unit volume than the less dense formation, even though the two formations have the same conventional uranium concentration. This density effect contrasts with the relative insensitivity to density that characterizes passive, gamma-ray logging measurements.

Neutron poisons are nuclides which have large, thermal, neutron capture cross sections, and therefore compete with uranium-235 for the thermal neutrons. Examples are gadolinium-155 (capture cross section = 70×10^3 barns), gadolinium-157 (160×10^3 b), boron-10 (3.8×10^3 b), and cadmium-113 (21×10^3 b). (Compare these cross sections with 8×10^{-3} b for silicon-28, 0.2×10^{-3} b for oxygen-16, 230×10^{-3} b for aluminum-27, and a fission cross section of 580 b for uranium-235.)

The comments of the last several paragraphs indicate that a calibration facility for fission neutron logging tools should include models that allow measurements of the following types:

1. Determine tool response as a function of uranium concentration.
2. Measure the effect of changes in formation porosity on tool response.
3. Measure the effect of formation density changes on tool response.
4. Measure the effect of average formation thermal neutron cross section on tool response.
5. Measure the dependence of tool response on the diameter of the water-filled borehole.

A set of six borehole calibration models known as the Fission Neutron Calibration Models (or "A Models") exists at the DOE facility in Grand Junction, Colorado. These models serve for measurements 1 through 4 in the above list. Measurement 5 can be performed in the DOE Fission Neutron Water

Factor Model ("D Model") at Grand Junction. The Fission Neutron Calibration Models are described in a DOE open-file report by Koizumi (1981a). The remainder of this report is devoted to descriptions of the specifications, construction details, and physical characterisitics of the Fission Neutron Water Factor Model.

PHYSICAL DESCRIPTION

Plan and section views of the Fission Neutron Water Factor Model are shown in Figure 1. The model is a right circular cylinder of 16 foot (4.88 m) diameter and height of 29 feet (8.84 m). The model is oriented so that the cylinder axis is vertical, and it is buried such that only the upper 1 foot (approximately) protrudes above the ground. The side and bottom of the model are bounded by a steel shell.

The model is partitioned by horizontal plane boundaries into four zones, each of which is a right circular cylinder of 16 foot (4.88 m) diameter. All of these zones are made of concretes which contain fine aggregate, coarse aggregate, cement, and water. The concretes and materials are described in the "Construction" and "Characterization" sections of this report.

The uppermost zone, designated "upper barren zone," is a 5-foot-thick (1.52 m), uniform, concrete cylinder. The concrete is barren in the sense that the concrete mix was not artificially enriched with uranium-bearing minerals.

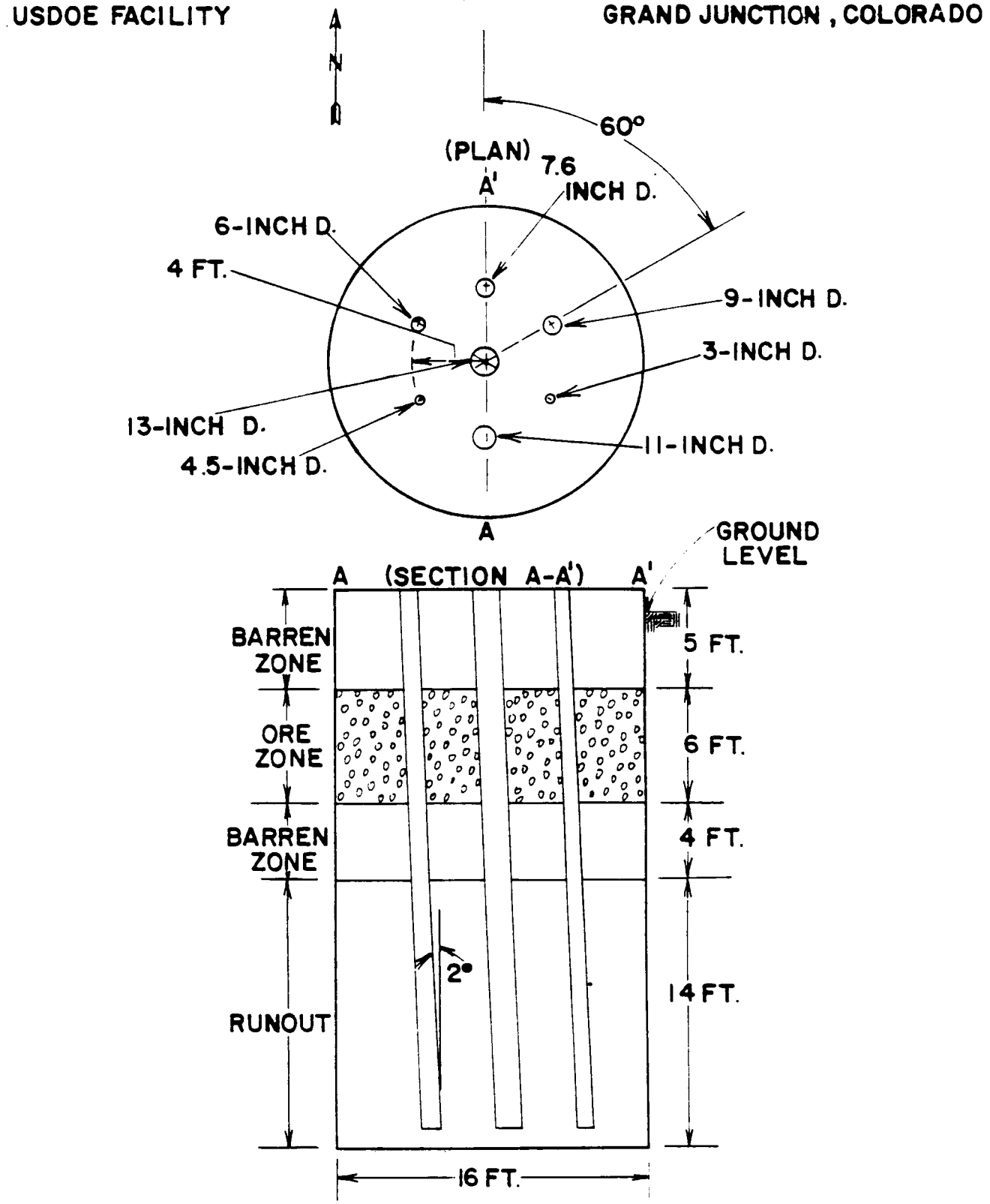
The second zone from the top, designated "ore zone," is a 6-foot-thick (1.83 m), uniform, concrete cylinder. This concrete is uranium enriched. Enrichment was accomplished by replacing sand in the concrete mix with a blended mixture of sand and crushed uranium-mineral-bearing rock. These materials are described in the "Characterization" section.

Below the ore zone lies a zone designated "lower barren zone." It is a 4-foot-thick (1.22 m), uniform, concrete cylinder with composition virtually identical to that of the upper barren zone.

A "runout" zone occupies the lower 14 feet (4.27 m) of the model. This zone consists of concrete of the same type as used in the two barren zones. The runout zone allows logging tools to approach the upper three zones of the model from below. Since no borehole measurements are to be made in the runout zone, only brief mention of it will appear in this report.

Seven model boreholes penetrate the four zones of the model. As shown in Figure 1, the borehole diameters range from 3 inches (7.62 cm) to 13 inches (33.02 cm). The borehole axes deviate from vertical by 2 degrees; each borehole axis plunges toward the north at 88 degrees from vertical. This orientation insures that logging tools will be sidewalled when measurements are being made.

The location of the Fission Neutron Water Factor Model relative to the other DOE Grand Junction models is shown in Figure 2. The model is formally designated the "D" model in other publications which reference calibration models at Grand Junction, and the model is shown as the D-model in Figure 2.



*Designated as the "D" model in other publications.

Figure 1. Plan and Section Views of the Fission Neutron Water Factor Model*

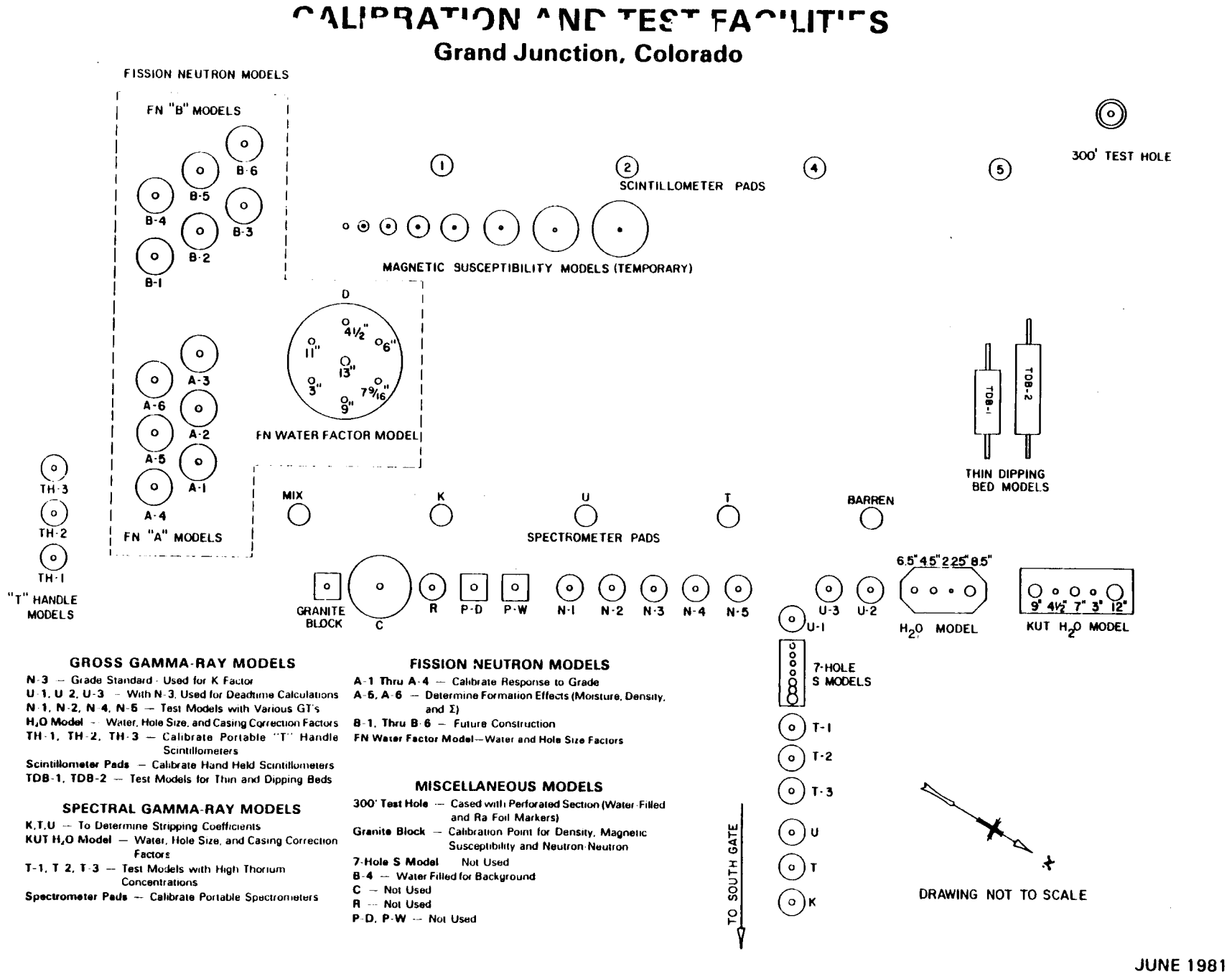


Figure 2. Layout of Grand Junction Calibration and Test Site

CONSTRUCTION

The Fission Neutron Water Factor Model was constructed in five steps: (1) a cylindrical steel container for the model concrete was designed and fabricated; (2) the model site was excavated and the steel container installed; (3) concrete mix formulas for the model zones were developed; (4) the model concrete mixes were batched and installed in the steel container; and (5) the model boreholes were core drilled. Steps (1), (2), (4), and (5) were accomplished or supervised by personnel of the BFEC Operations Division. Details about these construction steps are presented in the following paragraphs.

FABRICATION OF THE STEEL SHELL

The steel container, or shell, and the model site were designed by D. Price of the BFEC Operations Division. The design is shown in Figure 3. This shell was fabricated from a 1/4-inch plate by Doughty Steel and Machine of Delta, Colorado. All plate-to-plate welds are full penetration, and the outside of the shell has a rust-preventive coating.

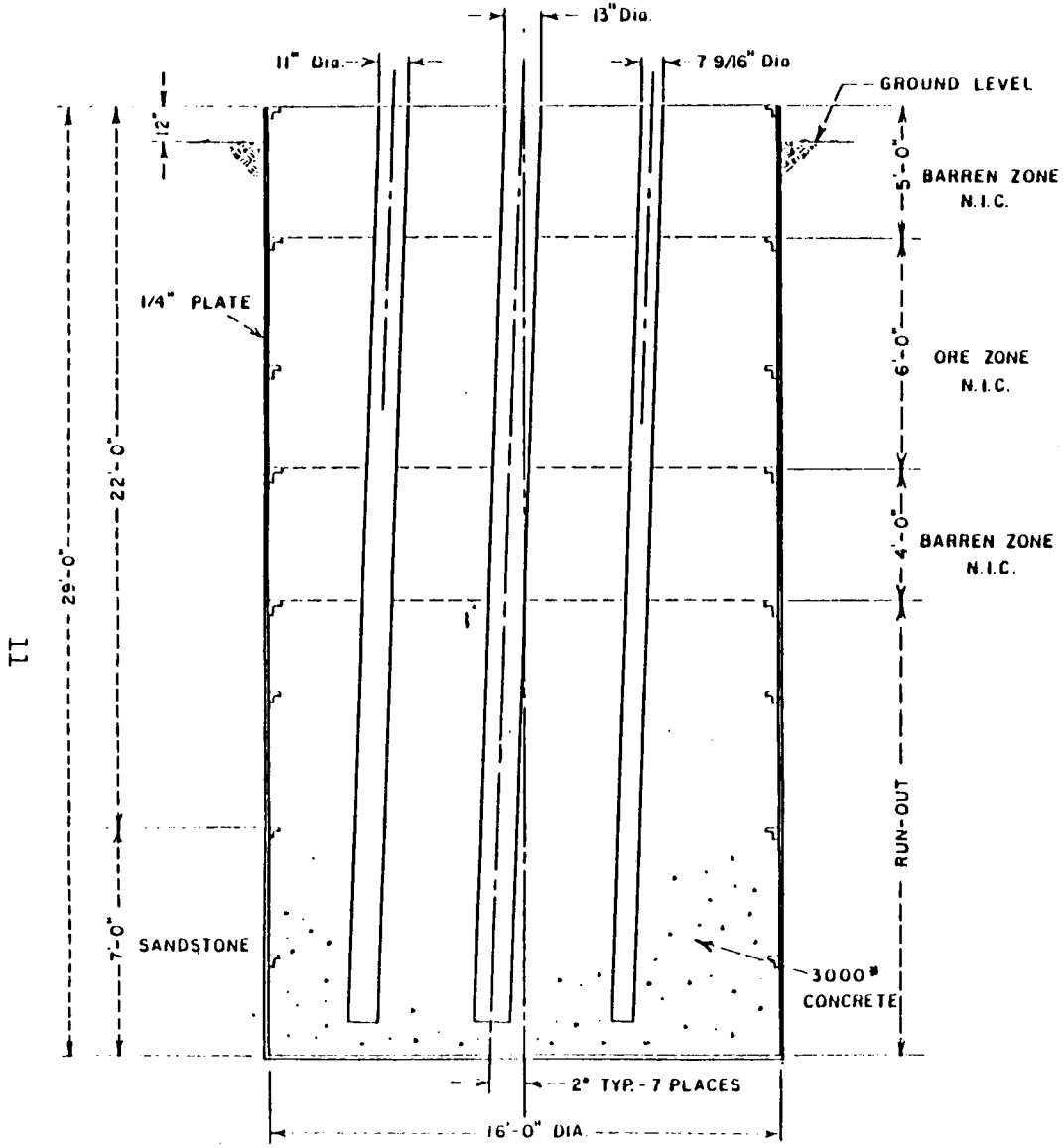
EXCAVATION OF THE SITE AND INSTALLATION OF THE SHELL

The hole for the model container was prepared by Steamboat Masonry of Grand Junction. Excavation of the approximately 30-foot-deep hole required the removal of about 26 feet of alluvium and about 4 feet of bedrock. A flat, level concrete pad was installed on the bedrock at the bottom of the hole. W. R. Hall of Grand Junction placed the model shell on this pad with a crane, then the void surrounding the shell was backfilled by Steamboat Masonry. These procedures are illustrated in Figures 4 through 8.

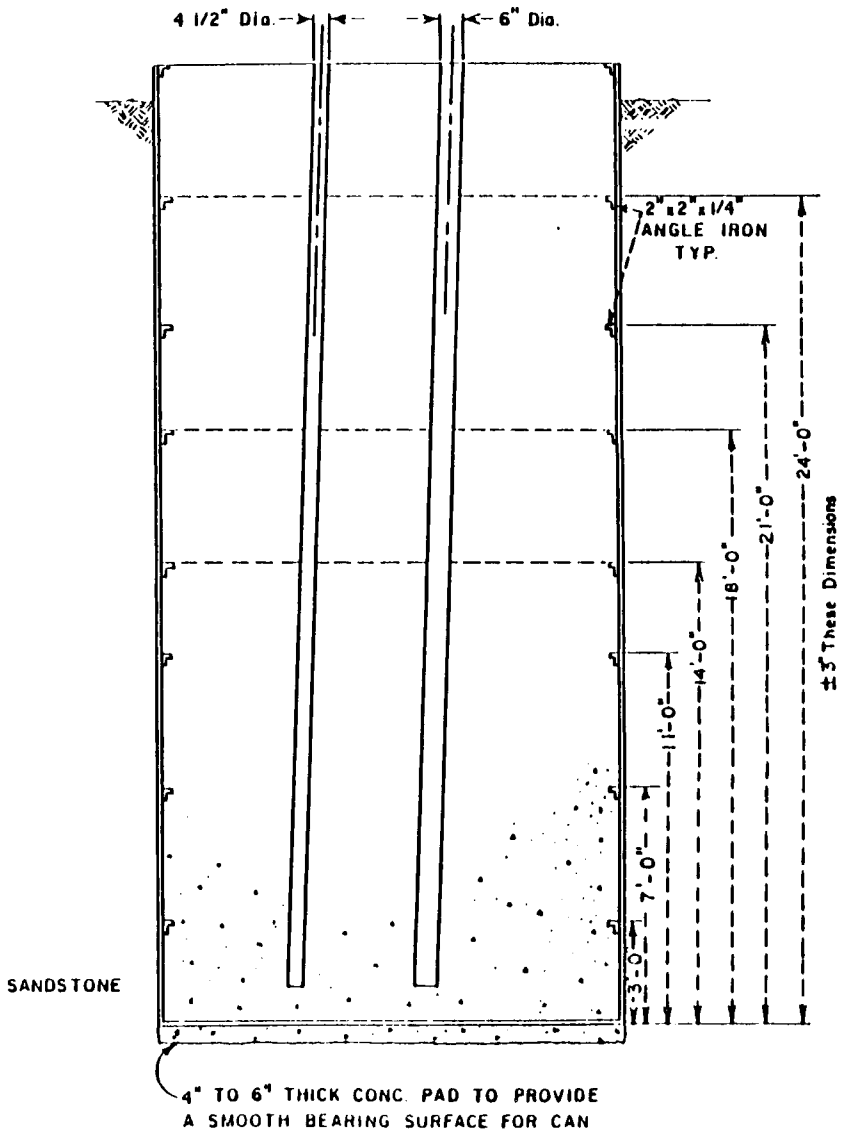
After the excavated site was backfilled, the concrete mix for the runout zone was poured into the lower 14 feet of the shell. The 105 cubic yards of concrete mix were prepared and poured by Whitewater Building Materials of Grand Junction. This runout zone concrete was allowed to cure for several months before the upper three model zones were installed.

MODEL CONCRETES

The concrete mixes for the ore zone and the two barren zones were formulated, prepared, and emplaced according to the procedures which were developed for the construction of Fission Neutron Calibration Models A-5 and A-6. These procedures, and the arguments that stimulated their development, are documented in detail in the report "Logging Calibration Models for Fission Neutron Sondes" (Koizumi, 1981a). The procedures are summarized in the following paragraphs.



A. Section through the 11-inch, 13-inch, and 7-9/16-inch holes



B. Section through the 6-inch and 4-1/2-inch holes

Figure 3. Section Views - Steel Can Designs

Figure 4. Site Excavation-- Initial Stage

Figure 5. Site Excavation--Advanced Stage

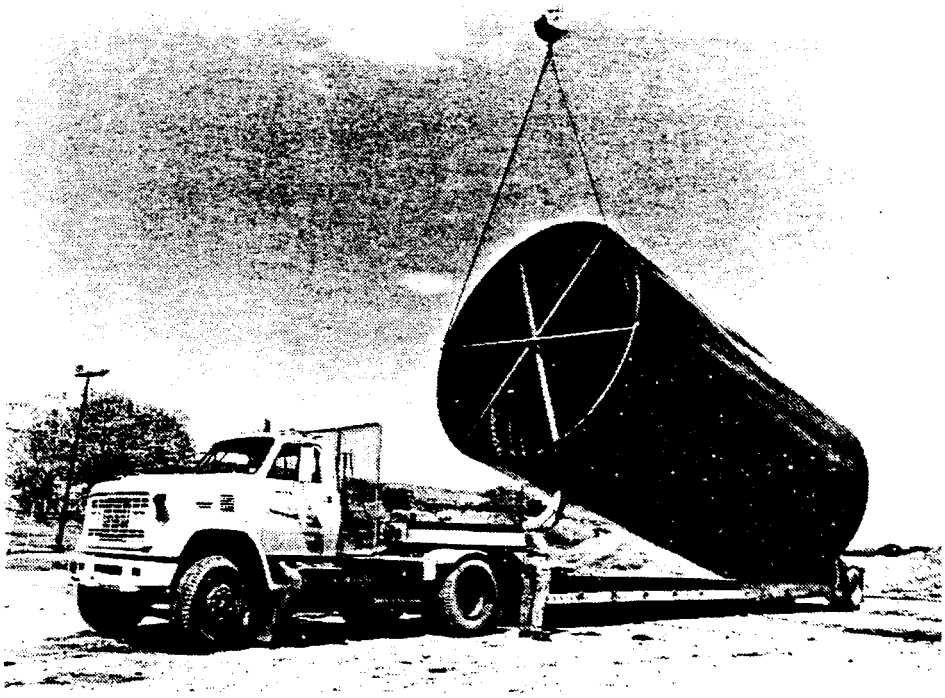


Figure 6. Lifting the Steel Shell

The shell was transported to the model site by the truck.

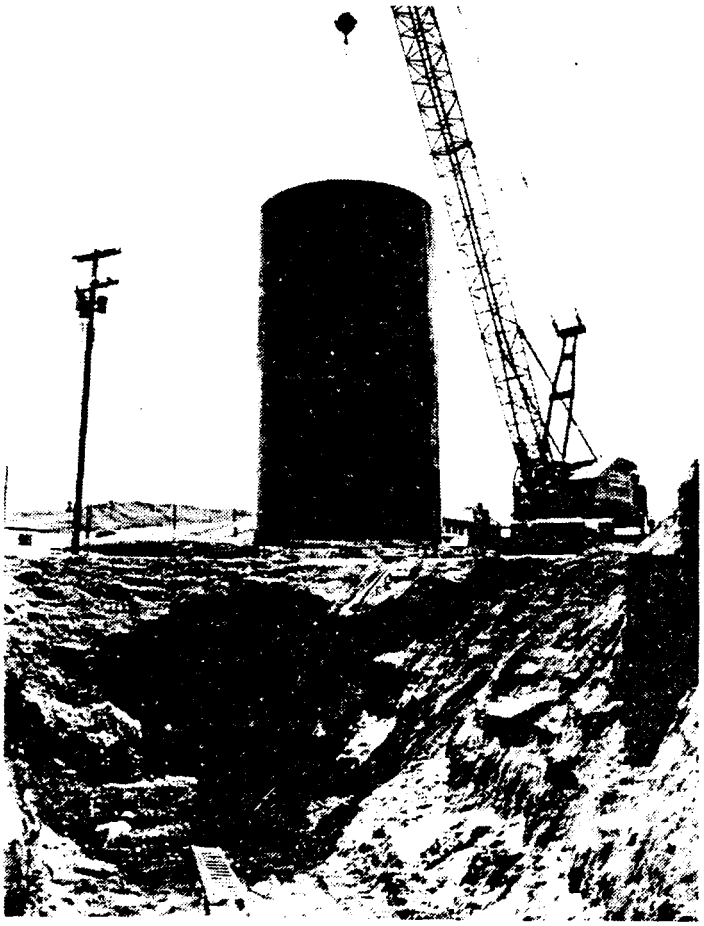


Figure 7. Lowering the Steel Shell Into Place

Figure 8. Steel Shell Emplacement

The shell is about to make contact with the concrete pad on which it will rest. The site was backfilled soon after the shell was installed.

Basic Concrete Formula

The barren zone concrete mixes for the Fission Neutron Water Factor Model consisted of mixtures of fine aggregate (masonry sand), coarse aggregate (3/4-inch rock), cement, and water. The proportions of these materials in the barren zone concretes are shown in Table 1.

Table 1. Basic Concrete Formula

Volume of Cured Concrete	Dry Masonry Sand	Dry 3/4-Inch Rock	Type II Cement	Water
1 ft^3	45.0797 lb	66.8523 lb	21.2820 lb	11.8060 lb
1 m^3	722.108 kg	1070.871 kg	340.905 kg	189.114 kg

The amounts of the various materials that were actually used in the barren zone concrete batches are listed in Table 2.

Table 2. Actual Barren Zone Concrete Mix Constituents

Zone	Dry Masonry Sand	Dry 3/4-Inch Rock	Cement	Water
Upper Barren	52,116 lb 23,640 kg	77,287 lb 35,057 kg	24,606 lb 11,161 kg	13,468 lb 6,109 kg
Lower Barren	39,885 lb 18,092 kg	59,145 lb 26,828 kg	18,826 lb 8,540 kg	9,989 lb 4,531 kg

The volumes of the two concrete batches of Table 2 exceed the respective volumes of the two model barren zones by about 10 percent. This is due to a precaution that is normally invoked for model construction: in anticipation of possible errors in calculation, or accidental loss of concrete mix, a slight excess of mix is prepared to insure the availability of sufficient material to complete each pour.

The masonry sand, 3/4-inch rock, cement, and water were furnished by Whitewater Building Materials. Samples of the sand and rock were examined by the Petrology Laboratory of the BFEC Geochemical Support Department; summaries of these studies are shown in the "Characterization" section and in Appendix I of this report.

The ore zone concrete mix was also a mixture of fine aggregate, 3/4-inch rock, cement, and water; the proportions of these materials were the same as shown in Table 1. The difference between the barren zone mixes and the ore zone mix lay in the composition of the fine aggregate. For the ore zone, this material consisted of a blended mixture of masonry sand and crushed uranium-mineral-bearing rock. The masonry sand was purchased from the Dri-Mix Concrete Company of Grand Junction. Sand samples were examined by the BFEC Petrology Laboratory. Results appear in the "Characterization" section and in Appendix I.

Uranium-rich rock for the model was purchased from the Schwartzwalder Mine, Jefferson County, Colorado, and from the Radium King Mine, San Juan County, Utah. Uraninite was the principal uranium mineral in both cases. Summaries of the BFEC Petrology Laboratory investigations of these materials are shown in the "Characterization" section and in Appendix I.

Preparation of Materials for Model Concretes

None of the raw materials for the barren zone concretes required special treatment. Consequently, barren zone concrete loads were batched and mixed according to Whitewater Building Materials' standard procedures for ordinary construction projects.

The 3/4-inch rock for the ore zone received no special treatment. However, the fine aggregate was processed to insure that the uranium would be distributed as uniformly as possible throughout the ore zone.

The blended mixture of masonry sand and crushed uranium-rich rock for the ore zone fine aggregate was prepared in the following way. The Chemistry Laboratory of BFEC's Geochemical Support Department crushed the uranium-rich rock so that the grains were 28 mesh and smaller. Each batch of crushed rock was dried and blended, then sealed in a 55-gallon steel drum.

The BFEC Chemistry Laboratory collected samples of this material and determined the uranium concentration for each batch. The batch masses and uranium concentrations are listed in Table 3. These concentration data were used to calculate the masses of crushed rock to incorporate in the concrete mixes to attain the model design grade of 0.08 percent U_3O_8. As used here, the unit "percent U_3O_8" denotes the mass-based concentration of U_3O_8 that would exist in a sample if all of the uranium in the sample were converted into U_3O_8. One percent U_3O_8 is equivalent to 8480 parts per million (ppm) uranium. The required masses of rock and other materials were established as follows.

Table 3. Uranium-Mineralized Rock Used in Model Ore Zone

Origin	Uranium Concentration	Amount Used
Schwartzwalder Mine	2.9 % U_3O_8	422 lb 191 kg
Radium King Mine	0.4 % U_3O_8	29,239 lb 13,263 kg

Requirements for masonry sand, 3/4-inch rock, and cement were deduced by multiplying the volume of the ore zone (1206 ft^3 or 44.7 yd^3) by the appropriate entries of Table 1. All of the results were then increased by 0.5 percent, for reasons cited earlier. These calculations yielded the amounts of 3/4-inch rock and cement that were actually used in the ore zone concrete mix. The calculations also gave a masonry sand requirement for a barren concrete. The uranium enrichment was accomplished by replacing this quantity of masonry sand with the mixture of crushed uranium-rich rock and masonry sand. The mixture was formulated so that the mass of the mixture was equal to the mass of masonry sand which was to be replaced. This mixture mass stipulation

$$\begin{pmatrix}\text{mass of crushed}\\ \text{uranium-rich rock}\end{pmatrix} + \begin{pmatrix}\text{mass of}\\ \text{masonry sand}\end{pmatrix} = \begin{pmatrix}\text{mass of masonry sand}\\ \text{in identical volume}\\ \text{of barren concrete}\end{pmatrix},$$

and the design grade relation

$$\text{design grade} = \frac{\text{mass of } U_3O_8 \text{ in zone}}{\text{mass of crushed uranium-rich rock} + \text{mass of masonry sand} + \text{mass of 3/4-inch rock} + \text{mass of cement}},$$

where

$$\text{mass of } U_3O_8 \text{ in zone} = \text{concentration of } U_3O_8 \text{ in crushed rock} + \text{mass of crushed rock},$$

were used to find the required amounts of crushed rock and masonry sand. The amounts of materials used in the ore-zone concrete mix are shown in Table 4.

Table 4. Actual Ore Zone Concrete Mix Constituents

Dry, Blended Mixture of Crushed Uranium-Rich Rock and Masonry Sand	Dry 3/4-Inch Rock	Cement	Water
54,652 lb	81,053 lb	25,803 lb	20,777 lb
24,790 kg	36,765 kg	11,704 kg	9,424 kg

After the formula for the fine aggregate mixture was determined, the mixture itself was prepared by blending appropriate amounts of crushed rock and masonry sand in a twin shell blender. This was done by the BFEC Chemistry Laboratory. Sixty-seven 816-pound batches were blended, each for about 30 minutes. The batches were stored in sealed 55-gallon steel drums. Specifications for a single batch are shown in Table 5.

Table 5. Materials in a Single Blended Batch of Ore Zone Fine Aggregate

Dri-Mix Masonry Sand	Radium King Uranium-Bearing Rock	Schwartzwalder Uranium-Bearing Rock
373.0 lb	436.4 lb	6.3 lb
169.2 kg	197.9 kg	2.9 kg

BATCHING AND MIXING TECHNIQUE FOR ORE ZONE CONCRETE

The preparation of ore-zone concrete mixes began at the Whitewater Building Materials plant in Grand Junction, where the concrete trucks were loaded with the required amounts of 3/4-inch rock. The trucks then proceeded to the BFEC Chemistry Laboratory at the Department of Energy facility, so that the blended, uranium-enriched fine aggregate could be loaded (Figure 9). Next, the trucks returned to the Whitewater Building Materials plant to receive cement and water. Finally, the trucks returned to the model site on the DOE facility to pour the concrete mix. This sequence of events was followed because dry fine aggregates tend to "cake" on the inside of a concrete truck drum. The 3/4-inch rock was loaded before the fine aggregate because rock scours a truck drum and thereby prevents the fine aggregate from caking.

EMPLACEMENT OF MODEL CONCRETES

The model concretes (except for the concrete in the runout zone) were installed by methods which were used in the construction of models A-5 and A-6 of the Fission Neutron Calibration Models ("A Models"). These methods are documented in the report "Logging Calibration Models for Fission Neutron Sondes" (Koizumi, 1981a).

As described in the referenced report, the three model zones were installed in quick succession. The lower barren zone concrete mix was poured, then allowed to set until, in the opinion of on-site personnel, it was able to withstand the weight of the ore zone mix. The setting time was about 2 hours. At that time, the ore zone concrete pour commenced. No concrete bonding agents were applied to the top of the lower barren zone. The ore-zone concrete mix constituents, as listed in Table 4, were mixed in nine equal portions by nine concrete trucks. The pouring of the ore zone mix is illustrated in Figures 11 and 12. After a setup time of about 2 hours for the ore zone, the upper barren zone concrete mix was poured. As before, no bonding agents were applied at the interface. The pouring of all three zones was completed in about 12 hours. Figures 10 through 15 illustrate the emplacement of the model concretes.

The above procedures for concrete installation were followed so that differential expansion and contraction between concretes in adjacent zones would be minimized during the curing process. The goal was to prevent the formation of wide cracks between zones. Such cracks are undesirable in a neutron model because they will fill with water and thereby introduce a sheet of strong neutron moderator between model zones.

MODEL BOREHOLES

The core drilling of the model boreholes was undertaken after the model concrete had cured for about 5 weeks. The holes were cored by Himes Drilling Company of Grand Junction. All water used for coolant during drilling operations was collected and discarded at a disposal site that is distant from the calibration area. Upon coring completion the boreholes were filled with water. The boreholes are normally maintained in water-filled condition, although the water can be pumped if dry borehole measurements are desired.

Figure 9. Loading the Uranium-Enriched Fine Aggregate Into a Concrete Truck

The ore zone fine aggregate mixtures of masonry sand and crushed uranium-bearing rock were stored at the BFEC Sample Plant in 55-gallon drums. Here, Sample Plant personnel load a drum of mixture into a Whitewater Building Materials concrete truck.

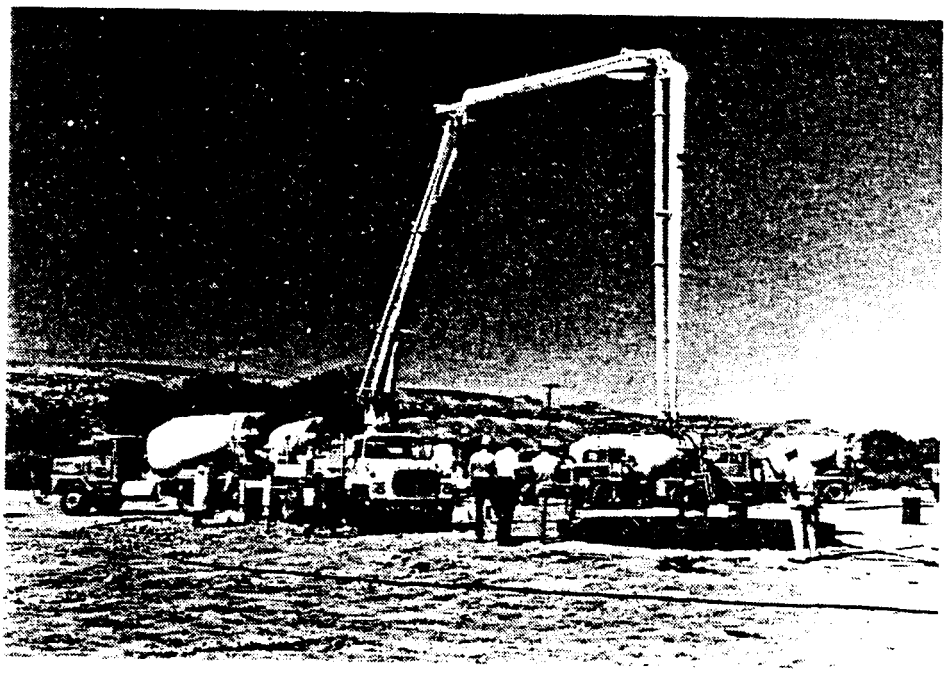


Figure 10. Pumping Model Concrete Mix

This method was used to emplace the concrete mix for the lower barren zone. The ore zone concrete was too stiff for the pumping unit, therefore this method was abandoned at the start of the ore zone pour.

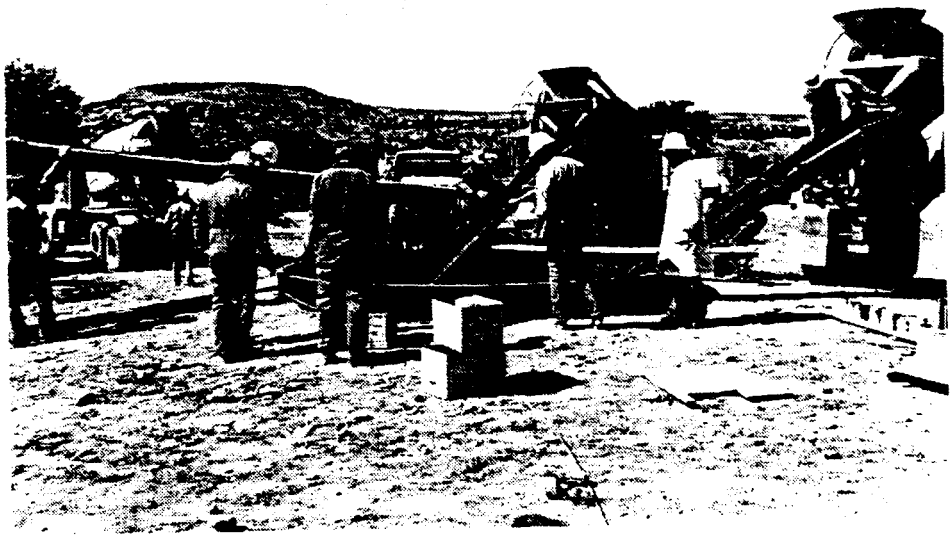


Figure 11. Installation of Model Concrete Mix

Concrete mixes for the ore zone and the upper barren zone were installed as shown in this figure.

Figure 12. Pouring the Ore Zone Concrete Mix

Figure 13. Collecting Samples of Concrete Mix

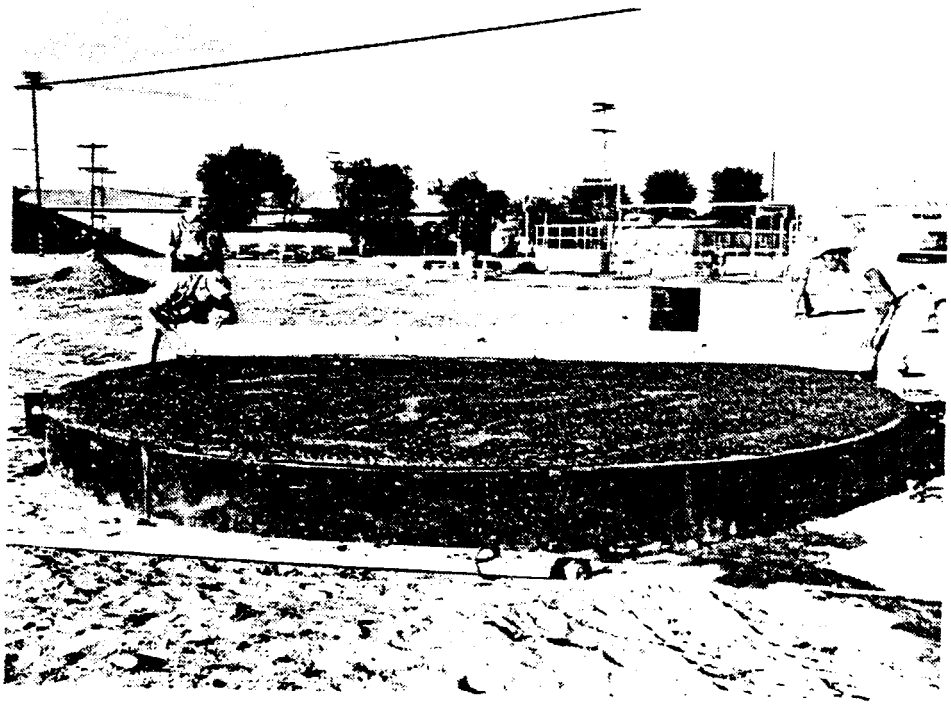


Figure 14. Leveling the Concrete Surface

Figure 15. Finishing the Concrete Surface

Selected core samples were submitted to the BFEC Chemistry Laboratory for model characterization analyses. The results are described in the "Characterization" section.

CHARACTERIZATION

This section furnishes details about model materials and parameters of the Fission Neutron Water Factor Model which are important in fission neuton logging. Topics to be discussed include the dimensions and spacing of the model boreholes, the characteristics of the raw materials for the model concretes, the characteristics of the finished model concretes, and certain characteristics of the model which have been deduced from special studies.

Model Borehole Parameters

The boreholes of the Fission Neutron Water Factor Model have diameters of 3 inches (7.62 cm), 4-1/2 inches (11.43 cm), 6 inches (15.24 cm), 7-9/16 inches (19.21 cm), 9 inches (22.86 cm), 11 inches (27.94 cm), and 13 inches (33.02 cm). All of the borehole axes plunge to the north at 2 degrees from vertical. A logging tool in any borehole will therefore tend to lie against the southern part of the borehole wall.

As indicated in Figure 1, a minimum distance of 4 feet (1.22 m) separates the center of any borehole from any adjacent borehole center. Also, the minimum radial distance from any borehole center to the edge of the model is 4 feet. Each borehole is therefore surrounded in all radial directions by a 4-foot thick zone of model material into which no model boundaries or adjacent boreholes intrude. The results of neutron transport calculations for a logging tool with 14-MeV neutron source were used by Koizumi (1981a) to show that a zone of this size satisfactorily simulates a medium of infinite radial extent. To the tool in the borehole, the ore zone appears as a slab of 6-foot vertical thickness and infinite horizontal extent.

Raw Materials

Type II cement for all of the zones of the Fission Neutron Water Factor Model was supplied by Whitewater Building Materials of Grand Junction. A sample of cement was submitted to the BFEC Chemistry Laboratory for radioelements analysis. This sample was analyzed on a NaI(Tl) gamma-ray spectroscopy system, with results as follows:

potassium concentration = 0.47 percent,
uranium concentration = 3.1 ppm, eU,
thorium concentration = 6.0 ppm, eTh.

The Chemistry Laboratory's analytical methods are briefly described in the "General Assay Discussion" of the "Finished Concrete" section of this paper.

Masonry sand for the model ore zone was purchased from the Dri-Mix Concrete Company of Grand Junction. One sample of sand was inspected by the BFEC Petrology Laboratory. Quartz was the most plentiful component of this sample. Other major components were sedimentary rock fragments (carbonates, cherts, claystones, siltstones, and others), volcanic rock fragments (tuffs, basaltic rocks, andesitic rocks, and others), and orthoclase. The petrology report is reproduced in Appendix I.

The barren zones of the model contain masonry sand from Whitewater Building Materials of Grand Junction. The BFEC Petrology Laboratory examined one sample of this sand. The major components were volcanic rock fragments (basalts, tuffaceous rocks, andesitic rocks, and others), quartz, orthoclase, and sedimentary rock fragments (cherts, claystones, and others). The petrology report is reproduced in Appendix I.

Whitewater Building Materials also supplied the 3/4-inch rock that was used throughout the model. The BFEC Petrology Laboratory determined that the major components of a sample of this rock were volcanic rock fragments (olivine basalt, andesite, and others), sedimentary rock fragments (quartz wacke, chert- and carbonate-cemented quartz arenite, and others), plutonic rock fragments (diorite, monzonite, and others), and metamorphic rock fragments (granite gneiss and others). Appendix I contains a reproduction of the petrology report.

The Schwartzwalder uranium-mineralized rock was obtained from the Schwartzwalder Mine in Jefferson County, Colorado. The ore was mined from a vein-type primary deposit of pitchblende in Precambrian host rock. In this

deposit, the uranium decay series is known to be in secular equilibrium. A sample of the uranium ore was examined by the BFEC Petrology Laboratory. The principal minerals in the sample were calcite, quartz, orthoclase, muscovite, uraninite, pyrite, and hematite. Appendix I contains the complete Petrology Laboratory report.

Uranium ore from the Radium King Mine in San Juan County, Utah, was mined from a copper-uranium deposit in the Triassic-age Shinarump (conglomerate) member of the Chinle formation. A grain-mount analysis performed by the BFEC Petrology Laboratory on a sample of crushed ore indicated that most of the material consisted of sedimentary rock fragments (mainly quartz wacke siltstones) and quartz. Small quantities of orthoclase and plagioclase were found, as were traces of chalcopyrite, galena, chalococite, covellite, and uraninite. Uraninite was the only uranium mineral observed. The complete Petrology Laboratory report is shown in Appendix I.

Before the Radium King Mine ore was purchased, a sample was obtained and tested for uranium-series secular equilibrium and for the presence of certain neutron poisons. For the secular equilibrium test, three sample splits were analyzed by the BFEC Chemistry Laboratory for uranium by a colorimetric method, and three other splits were subjected to total-gamma-ray radiometric analysis. The results are shown in Table 6.

Table 6. Secular Equilibrium Test for Radium King Ore

Sample	Uranium Concentration, Colorimetric (ppm)	Uranium Concentration Radiometric (ppm)
1	3930	3840
2	3850	3830
3	3710	3520

The close agreement between colorimetric and radiometric assays implies that the uranium decay series is in secular equilibrium, or is nearly so.

For the neutron poison investigation, the three ore sample splits for the colorimetric tests were analyzed for lithium, boron, and chlorine. Average concentrations for the three samples were 5 ppm lithium, 0.002 percent boron, and less than 50 ppm chlorine.

The thermal neutron absorption cross sections for lithium and chlorine are, respectively, about 9 percent and about 4 percent of the corresponding cross section for boron. Since the concentrations of lithium and chlorine are much smaller than the concentration of boron, the contributions of lithium and chlorine to the average thermal absorption cross section of the model material

are negligible in comparison with the boron contribution. This boron contribution is itself negligible because of the degree to which the Radium King ore was diluted. The Radium King ore comprised only 18 percent of the dry concrete mix material for the model ore zone, so the boron concentration in the zone due to Radium King ore is about 3.6 ppm (the product of 18 percent and 0.002 percent). This is much smaller than the average boron concentration of sandstones studied by Harder (1959).

The BFEC Chemistry Laboratory qualitatively analyzed one sample each of Schwartzwalder ore and Radium King ore by X-ray diffraction scan. This test revealed only one significant difference between the two ores: The Radium King ore had an appreciably higher concentration of copper than the Schwartzwalder ore. This is not surprising considering the Radium King ore contained chalcopyrite, chalcocite, and covellite. The effect of copper on the neutron transport properties of the model ore zone will be further discussed in the "Finished Concrete" section of this report.

Magnetic susceptibility measurements were made by the BFEC Chemistry Laboratory on three samples each of Radium King and Schwartzwalder ores. Average results were 31 x 10^{-6} cgs for the Radium King samples and 209 x 10^{-6} cgs for the Schwartzwalder samples.

Finished Concrete

1. Sample Types

Three types of concrete samples were collected at various stages of the construction of the Fission Neutron Water Factor Model. Concrete mix samples of approximately 1 kilogram each were collected directly from the chutes of the concrete trucks while the concrete mixes were being poured. Because these samples were immediately packed into aluminum gamma-ray spectroscopy cans, they will henceforth be referred to as "can samples." Also collected during the concrete pours were mix samples of 2 to 4 kilograms each. These were quickly packed into half-gallon cardboard ice cream cartons and will therefore be labeled "carton samples".

After the concrete in the model had cured for about 5 weeks, the seven model boreholes were core drilled. The core samples were collected and carefully labeled according to the depth in the model from which they were taken.

2. General Assay Discussion: Can and Carton Samples

The laboratory work described in this section was performed by the BFEC Chemistry Laboratory.

Data from one sequence of measurements were used to estimate the total water content of the model concrete. This sequence began with the measurement of sample weights at the time the samples were collected from the concrete truck chutes. The samples were weighed again after they had cured for 12 weeks or more in a storage area which was sheltered but not temperature controlled. Next, cured samples were dried in an oven at 110 degrees Centigrade, then weighed. Finally, pulverized samples of cured, dried material were weighed, placed in crucibles, and heated to 1000 degrees Centigrade, in the presence of air. These samples were weighed after returning to room temperature.

The percentages of sample mass lost during the curing process and during the oven drying process are labeled, respectively, the loss-on-curing (LOC) and the loss-on-drying (LOD). The percentage of sample mass lost during the 1000 degree treatment is called loss-on-ignition (LOI).

LOC and LOD are primarily due to the departure of water from the samples. In this report, the water which can be driven from a sample by the combination of LOC and LOD will be referred to as "free water." Free water occupies pore spaces in the concrete matrix and is not considered to be chemically bound to the matrix.

Concrete also contains water which is a chemical constituent of the silica networks that bind the aggregate particles together. This water will be called the "bound water" or "water of hydration." Bound water is liberated from concrete samples by the LOI procedure. Unfortunately, the LOI does not furnish a measurement of bound water only, because certain other concrete constituents may be vaporized at 1000 degrees. For example, the thermal decomposition of calcium carbonate ($CaCO_3$ $CaO + CO_2$) occurs below that temperature. The problem of determining the water content of concrete is discussed by Koizumi (1981b).

In preparation for radioelement assays, oven-dried samples were hermetically sealed in aluminum gamma-ray spectroscopy cans. After the cans were sealed, they were left undisturbed for 20 days or more to allow radium-radon equilibrium to be established within each sample. The samples were then assayed through spectral analysis of the gamma rays emitted by radioelements in the samples. Gamma-ray counting for can samples was done on a Ge(Li) system, and concentrations of potassium, uranium, and thorium were calculated (see note for Table 7), respectively, from the amplitudes of the 1461-keV line of potassium-40, the 1764-keV line of bismuth-214, and the 2615-keV line of thallium-208. Core samples were assayed on a NaI(Tl) system. This system sorted gamma-ray pulses according to gamma-ray energy, then analyzed gamma-ray count rates in three energy windows. The potassium window extended from 1320 keV to 1575 keV; it enclosed the 1461-keV line of potassium-40. The uranium and thorium windows were set, respectively, at 1650 keV to 2390 keV to 2750 keV. The uranium window bracketed the 1764-keV and the 2204-keV lines of bismuth-214, and the thorium window enclosed the 2614-keV line of thallium-208. Note that for both counting systems the uranium and thorium assays were actually based on the concentrations of radioactive daughters of uranium and thorium: Bismuth-214.is the ninth daughter of uranium-238, and thallium-208 is the ninth daughter of thorium-232. The concentration calculations for uranium and thorium explicitly assume that the decay chains are in secular equilibrium. For this reason, the results of the radiometric uranium and thorium assays are reported in units of "eU" and "eTh," where the "e" denotes radiometric equivalent.

The "wet chemical" analyses determine the concentrations of radioelements directly. Samples to be tested are put into solution. Potassium concentrations are measured through atomic absorption spectrometry. Thorium concentrations are assayed by X-ray fluorescence spectrometry. The uranium assay method depends on the uranium concentration. A fluorometric analysis is done on samples with uranium concentrations less than about 500 ppm, and samples with higher uranium concentrations are assayed by a colorimetric method.

3. Assay Results

As previously described, the can samples were taken through the LOC and LOD procedures, then sealed in gamma-ray spectroscopy cans and assayed 20 days later. Radioelement concentrations were calculated from gamma-ray count rate data that were collected with a Ge(Li) system. After the LOC, LOD, and radioelement concentrations were determined for each individual sample, means and standard deviations were calculated for the sample sets from each model zone. These results appear in Table 7. The certificates of assay issued by the BFEC Chemistry Laboratory are reproduced in Appendix II.

Table 7. Assay Results for Can Samples

(Each uncertainty represents one standard deviation with respect to variations among individual sample assays.)

Model Zone	Number of Samples	Mean Potassium Grade (% K)	Mean Uranium Grade (ppm eU*)	Mean Thorium Grade (ppm eTh)	Mean LOD (%)	Mean LOC (%)
Upper Barren	20	1.98±0.12	3.8±1.1	7.6±1.1	--	6.76±0.20
Ore	60	1.78±0.26	576±76	7.7±1.7	1.11±0.09	7.74±0.38
Lower Barren	20	1.98±0.13	3.5±0.7	8.9±1.5	--	6.42±0.35

*Equivalent uranium (ppm eU) concentrations can be converted to equivalent U_3O_8 (eU_3O_8) concentrations through the conversion 8480 ppm eU = 1 percent eU_3O_8.

Note: Within each can sample, the concrete exists as a solid mass. However, the canned material which the BFEC Chemistry Laboratory uses to calibrate the gamma-ray systems is crushed. A typical concrete can sample therefore has a significantly greater mass than a can of calibration material. Consequently, radiometric assays for can samples require density corrections, which in the present case will increase the calculated uranium concentrations. Work on density corrections has not been completed, and the entries on this table are uncorrected. See the note for Table 8.

The uranium concentrations of Tables 7 and 9 are reported in the conventional way. That is, the uranium concentration in each sample was determined as the ratio of mass of uranium to sample mass, then this ration was multiplied by 10^6 to produce a parts-per-million mass-based concentration. These concentration results can be converted into grams of uranium per cubic

Table 8. Assay Results for Carton Samples

Model Zone	Number of Samples	Mean Potassium Grade (% K)	Mean Uranium Grade (ppm U)	Mean Thorium Grade (ppm Th)	Mean Dry Bulk Density (g/cm^3)	Mean Grain Density (g/cm^3)	Mean Magnetic Susceptibility (X 10^{-6} cgs*)	Mean LOD (%)	Mean LOI (%)
Upper Barren	15	1.78±0.26	2.6±0.9	<5	2.217±0.012	2.681±0.039	1133±54	1.42±0.11	5.49±0.61
Ore	40	1.53±0.08	676±47	<5	2.116±0.031	2.716±0.068	826±47	1.62±0.15	4.92±0.33
Lower Barren	5	1.69±0.38	2.8±1.1	<5	2.224±0.009	2.692±0.026	1088±65	1.53±0.08	4.90±0.65

* Magnetic susceptibility is dimensionless, but the numerical value depends on the units in which the magnetic induction (B) and the magnetic field strength (H) are measured. The tabulated results were derived from measurements made in the cgs system.

Note: Under a request prepared by Heistand and George (1981), crushed carton sample material was packed into gamma-ray spectroscopy cans, sealed, and assayed on the BFEC Chemistry Laboratory's Ge(Li) system. The ore zone uranium concentration was found to be 643±42 ppm equivalent uranium (0.0758±0.0049 percent equivalent U_3O_8).

Analyses of Heistand's data and gamma-ray logging data yield a gamma-ray logging grade of 667 ppm uranium (0.0786 percent equivalent U_3O_8) for the model ore zone. This result will be discussed in a pending BFEC internal report "Interim Grade Reassignments for GJO Calibration Models" by B. Heistand, D. George, and J. Krabacher.

Table 9. Assay Results for Core Samples

Model Zone	Depth Interval (inches)	Radiometric Assay: Potassium Grade (% K)	Radiometric Assay: Uranium Grade (ppm eU)	Radiometric Assay: Thorium Grade (ppm eTh)	Chemical Assay: Potassium Grade (% K)	Chemical Assay: Uranium Grade (ppm U)	Chemical Assay: Thorium Grade (ppm Th)	Dry Bulk Density (g/cm^3)	Grain Density (g/cm^3)	Magnetic Susceptibility (10^{-6} cgs)
Upper Barren	0-7	2.11	4	7	1.90	3		2.33	2.66	968
	7-14				1.73	4		2.27	2.64	864
	14-21				1.79	3		2.24	2.64	1103
	21-26				1.70				2.67	
	26-31	1.80	3	6	1.83	3		2.26	2.75	1067
	31-36	1.97	3	8	1.80	3		2.27	2.83	1075
	36-42	2.02	3	7	1.88	3		2.29	2.62	1036
	42-54	1.90	3	8	1.80	3		2.30	2.65	1013
	54-60	1.99	3	8	1.76	3		2.39	2.78	1065
Ore	60-77	4.68	648	25	1.51	664		2.19	2.67	702
	77-91	6.76	618	31	1.52	841		2.04	2.67	677
	91-100	8.86	552	43	1.52	509		2.22	2.90	833
	100-113				1.55	673		2.28	2.66	813
	113-122	9.82	525	47	1.55	665		2.34	2.70	807
	122-132	10.20	474	46	1.52	682		2.39	2.68	821
Lower Barren	132-152				1.79	5		2.27	2.74	971
	152-166				1.81	3		2.17	2.58	1038
	166-180	2.10	3	5	1.77	3		2.52	2.66	1077
Runout	180-189	2.22	4	7	1.76	3		2.02	2.72	914
	189-204	2.30	3	7	1.77	1		2.28	2.69	942
	224-233	2.28	4	5	1.83	2		2.69	2.71	1065
	281-287	2.27	3	9	1.93	3		2.26	2.78	965
	296-300	2.37	3	7	1.88	1		2.37	2.62	977
	318-324	2.19	3	9	1.91	2		2.22	2.65	1098

centimeter (volume-based concentration) by, for example, dividing each uranium ppm concentration in Table 7 by 10^6, then multiplying the result by the appropriate dry bulk density from Table 8.

Carton samples were allowed to cure for about 15 weeks, after which each cylindrical sample was sawed in half lengthwise (that is, the saw cuts were made along the cylinder axes) with a diamond saw. Half of each sample was placed in permanent storage in the Chemistry Laboratory's sample archive. The sample halves which were not placed in archive were analyzed as follows.

Bulk densities were determined by measuring the mass and volume of each sample. The samples were then crushed (grain sizes of approximately 28 mesh and smaller) and grain densities were determined with a pycnometer. Magnetic susceptibilities were also determined by analyzing crushed material with a magnetic susceptibility bridge. A portion of each crushed sample was put into solution and analyzed by wet chemical methods for potassium, uranium, and thorium.

The density, radioelement concentration, and magnetic susceptibility results for the carton samples are listed in Table 8. Each entry represents a mean and standard deviation of the individual assay results for samples from a given model zone. As in Table 7, the radioelement concentrations are expressed in parts per million of dry sample mass. Each concentration can be converted into a mass per unit volume concentration by dividing by 10^6 then multiplying by the appropriate dry bulk density. Certificates of assay issued by the BFEC Chemistry Laboratory are reproduced in Appendix II.

Core samples from the 4-1/2-inch model hole were sawed in half lengthwise with a diamond saw. Half of each sample was placed in the BFEC core archive. The remaining sample halves were analyzed according to the same procedures as used for the carton samples. In addition, crushed and dried core samples were sealed in aluminum gamma-ray spectroscopy cans then assayed on a NaI(Tl) system. These results are presented in Table 9 and the certificates of assay are reproduced in Appendix II. A semiquantitative emission spectroscopy analysis was also run on each core sample. These results are tabulated in Appendix II.

4. Special Analyses

The signal detected by a fission-neutron logging system depends on the rate at which thermal neutrons interact with uranium-235 in the rock formation near the logging tool. In this rock, the concentrations of elements with large thermal neutron absorption cross sections are important fission-neutron logging parameters because such elements absorb large numbers of thermal neutrons that would otherwise have reacted with uranium-235. For example, Baker and others (1980) made fission neutron measurements in the DOE Grand Junction fission-neutron calibration models with a photoneutron-source-based logging system. A reduction in the ratio of fission-neutron count rate to uranium concentration was observed in the calibration model zone which contains an elevated concentration of boron.

Table 10. Trace-Element Concentrations for Fission Neutron Model Samples

These elemental concentration data were issued by the Los Alamos National Laboratory. All concentrations are expressed in parts per million. In parentheses below each element is the element's microscopic thermal neutron absorption cross section, in barns. The sample numbers are 032279 (A-2-T), 032205 (A-2-C), 047718, 047720 (Fission Neutron Water Factor, upper barren zone), 047682, 047700, (FNWFM, ore zone).

Elements and Concentrations

Fission Neuton Model	Ag (64)	Bi (0.034)	Cd (2500)	Cu (3.8)	Nb (1.1)	Ni (4.4)	Pb (0.17)	Sn (6.3)	W (18)	As (4.4)	Se (12)	Li (71)	B (760)	Ba (1.3)	Gd (49000)
A-2-T (barren)	<5	<5	<5	42	<19	<14	16	<10	<15	<5	<5	20	15	800	<50
A-2-C (ore)	<5	<5	<5	23	<19	<14	40	<10	20	<5	<5	20	15	800	<50
FNWFM (upper barren)	<5	<5	<5	28	24	<14	20	<10	<15	6	<5	20	10	700	<50
FNWFM (ore)	<5	<5	<5	2449	<19	16	35	10	<15	13	<5	20	15	750	<50

Since the presence of elements with large thermal neutron absorption cross sections affects the signal detected by a fission-neutron logging system, preliminary investigations were undertaken to determine the concentrations of certain "neutron poisons," and estimate the total thermal neutron absorption cross section for Fission Neutron Water Factor Model material.

Under arrangements made by M. Baker, Q Division, Los Alamos National Laboratory, samples from model A-2 of the DOE Fission Neutron Calibration Models and samples from the Fission Neutron Water Factor Model were analyzed by the Los Alamos Chemical and Instrumental Analysis Group, which is headed by G. Waterbury. An X-ray fluorescence analysis yielded sample concentrations of silver (Ag), bismuth (Bi), cadmium (Cd), copper (Cu), niobium (Nb), nickel (Ni), lead (Pb), tungsten (W), arsenic (As), and selenium (Se). Atomic emission spectroscopy measurements were performed to determine the sample concentrations of lithium (Li), boron (B), cadmium (Cd), barium (Ba), and gadolinium (Gd). Results are shown in Table 10.

Under the guidance of H. Bivens, Special Applications Division, Sandia National Laboratories, a sample from model A-2 was analyzed by prompt gamma-ray activation analysis at the National Bureau of Standards. At Sandia, the Bureau of Standards data were used by J. Harris to calculate the total thermal neutron absorption cross section of the sample material. These results are shown in Table 11.

Table 11. Thermal Neutron Cross Section Data

These data for sample 32205, DOE fission neutron calibration model A-2-C, were issued by Sandia National Laboratories. The total macroscopic thermal neutron cross section is 9.478×10^{-3} cm^{-1}. The uranium (concentration = 640 ppm) contribution is insignificant.

Element	Element Concentration (ppm)	Macroscopic Thermal Neutron Cross Section (cm^{-1})	Contribution of Macroscopic Cross Section to Total (%)
B	2.092×10^{1}	1.919×10^{-3}	20.3
Na	1.513×10^{4}	4.592×10^{-4}	4.8
Mg	0.000	0.000	0.0
Al	4.790×10^{4}	5.371×10^{-4}	5.7
Si	2.806×10^{5}	2.101×10^{-3}	22.2
Cl	0.000	0.000	0.0
K	1.486×10^{4}	1.070×10^{-3}	11.3
Ca	8.785×10^{4}	1.240×10^{-3}	13.1
Ti	1.920×10^{3}	3.192×10^{-4}	3.4
Fe	2.196×10^{4}	1.304×10^{-4}	1.4
Cd	0.000	0.000	0.0
Sm	3.670×10^{0}	1.783×10^{-4}	1.9
Gd	4.580×10^{0}	1.523×10^{-3}	16.1

5. Comments on Finished Concrete Studies

Radioelement Concentrations

The chemical uranium grades should be used in association with fission neutron tool measurements. Radiometric grades are not relevant because fission neutron tools do not interrogate for gamma rays emitted by uranium daughters. The chemical uranium grades are shown in Table 12. The grades are reported in the conventional way (mass of uranium per mass of sample) and also in terms of mass of uranium per unit volume of concrete.

Table 12. Chemical Uranium Grades for the Fission Neutron Water Factor Model

Zone	Uranium Concentration (ppm)	Uranium Concentration (% U_3O_8)	Uranium Concentration (micrograms/cm^3)
Upper Barren	2.6±0.9	(3.1±1.1) x 10^{-4}	5.8±2.0
Ore	676±47	0.0797±0.0055	1430±99
Lower Barren	2.8±1.1	(3.3±1.3) x 10^{-4}	6.2±2.4

On occasion, members of the BFEC research staff have used the Fission Neutron Water Factor Model for gamma-ray measurements. For example, the upper barren zone has been used to determine the potassium water factor corrections for various spectral gamma-ray logging tools. Whenever the model is used for gamma-ray measurements, radiometric grades are appropriate.

Water Content of the Model Ore Zone

Because water is an effective moderator of neutrons, and because thermal neutrons interact with hydrogen nuclei via an (n, γ) reaction, the water content of the model concrete is an important fission-neutron logging parameter. Although a direct, in-situ water content measurement has not been made, the grain density, dry bulk density, loss-on-curing, loss-on-drying, and loss-on-ignition data can be used to attain an estimate of this parameter.

The dry bulk density and the grain density of model ore zone concrete were established from carton sample data. The results appear in Table 8. These results are virtually identical to the corresponding core results (Table 9); this observation validates the use of carton sample data to infer in-situ properties of the concrete in the model.

If the porosity (ϕ) is related to the dry bulk density (ρ_B) and the grain density (ρ_G) by

$$\phi = \frac{\rho_G - \rho_B}{\rho_G} ,$$

then the ore-zone density data imply that

$$\phi = 22.1 \text{ percent.}$$

Upon completion of the model borehole drilling, the boreholes were filled with water. Experiments carried out at BFEC (Koizumi, 1981b) indicate that cured concrete which is immersed in water contains about the same amount of water as the original concrete mix, and that the saturation of the concrete is close to 100 percent. If these findings apply to the model ore zone concrete, then 100 percent of the concrete pore space is occupied by free water. Since 1 cubic centimeter of dry concrete has a mass of 2.116 grams and a pore volume of 0.221 cubic centimeters, and since water has a density of 1.00 gram per cubic centimeter, the in-situ saturated bulk density of the concrete is 2.337 grams per cubic centimeter.

Of the 2.337 grams in each cubic centimeter of material, 0.221 grams is free water (water in concrete pore spaces) and 2.116 grams consist of dry aggregate and bound water (water of hydration). The proportions of free and bound water can be estimated through the use of the carton sample data and the concrete mix composition data in Table 4.

The entries of Table 4 show that the concrete mix contained 21,572 pounds of water and 160,713 pounds of dry material (sand, crushed mineralized rock, 3/4-inch rock, and cement). Then the total mass of water in the mix [that is, the sum of the mass of free water (H_f) and the mass of bound water (H_b)] is

$$H_f + H_b = 21{,}572 \text{ pounds.}$$

The density and saturation results show that

$$\frac{\text{free water content}}{\text{dry material + bound water}} = \frac{H_f}{D + H_b} = \frac{0.221 \text{ grams}}{2.116 \text{ grams}} .$$

Thus

$$H_f + H_b = 21{,}572 \text{ pounds,}$$

and

$$\frac{H_f}{D + H_b} = 0.1044,$$

where

$$D = 160{,}713 \text{ pounds.}$$

The solutions for H_f and H_b are

$$H_f = 4334 \text{ pounds},$$

and

$$H_b = 17{,}238 \text{ pounds}.$$

Then the free water content, expressed as a percentage of the dry concrete mass, is

$$100 \frac{H_f}{D + H_b} = 10.4 \text{ percent},$$

and the bound water content, expressed in the same terms, is

$$100 \frac{H_b}{D + H_b} = 2.6 \text{ percent},$$

and the total water content, which is the parameter of importance in fission neutron logging, is 13.0 percent.

The above figures are supported by the loss-on-curing (LOC), loss-on-drying (LOD), and loss-on-ignition (LOI) data of Table 7.

Let M_O, M_C, and M_D represent, respectively, the mass of a canned sample at the time it was collected, the mass of the sample after it had cured, and the mass of the sample after it had been dried in an oven. Then the LOC and LOD were calculated according to

$$LOC = \frac{M_O - M_C}{M_O} = 1 - M_C/M_O$$

and

$$LOD = \frac{M_C - M_D}{M_C} = 1 - M_D/M_C.$$

These are the quantities which are listed in Table 7. Before comparison with previous results, the LOC and LOD must be converted to a per-unit-dry-sample-mass basis:

$$LOC_D = \frac{M_O - M_C}{M_D},$$

$$LOD_D = \frac{M_C - M_D}{M_D},$$

Algebraic manipulations give

$$LOC_D = LOC/(1 - LOD)(1 - LOD)$$

and

$$LOD_D = LOD/(1 - LOD).$$

When LOC and LOD results from Table 7 are substituted into the above,

LOC_D = 8.5 percent, and

LOD_D = 1.1 percent

result. These imply that the concrete free water, expressed as a percentage of the dry sample mass, is

$$LOC_D + LOD_D = 9.6 \text{ percent.}$$

This agrees with the 10.4 percent that was deduced by the previous analysis.

The LOI is difficult to relate to the sample bound water because the LOI process liberates materials other than water from the samples. However, the LOI result does obey the inequality

bound water content < LOI.

That is,

2.6 percent < 4.9 percent.

Thermal Neutron Absorption Cross Sections

For samples taken from the Fission Neutron Water Factor Model and from one of the Fission Neutron Calibration Models, Table 10 lists the concentrations of various elements which have relatively large thermal neutron absorption cross sections. Model A-2, of which A-2-C is a uranium-enriched zone and A-2-T is a barren zone, is one of the DOE standard fission neutron calibration models. Table 10 shows that with respect to the elements for which concentrations were determined, the barren zone of the Fission Neutron Water Factor Model is

virtually identical to zones A-2-C and A-2-T. The ore zone of the Fission Neutron Water Factor Model is also quite similar to those zones, except in copper concentration. This observation will receive more attention later in this section.

The four columns of Table 11 list, respectively, the elements detected, the element concentrations, the macroscopic thermal neutron absorption cross section* due to each element, and the contribution of each macroscopic absorption cross section to the total macroscopic cross section for a sample from A-2-C. Uranium does not appear in the table because its concentration of 640 parts per million and its macroscopic thermal neutron absorption cross section of 2.67×10^{-5} cm^{-1} account for a mere 0.3 percent of the total macroscopic cross section.

If the composition of the Fission Neutron Water Factor Model ore zone and zone A-2-C actually differ only in the concentration of copper, then the data of Table 11 can be used to deduce the role of copper in the total macroscopic thermal neutron cross section of the Fission Neutron Water Factor Model ore zone. For the composition indicated in Table 11, an addition of 2450 parts per million of copper would increase the total macroscopic thermal neutron cross section from 9.478×10^{-3} cm^{-1} to 9.667×10^{-3} cm^{-1}, and the copper itself would account for 2 percent of this total.

The above observations imply that the fission neutron count rate per unit uranium concentration will be slightly lower in the 4.5-inch hole of the Fission Neutron Water Factor Model relative to the corresponding measurement in model A-2-C. This small suppression in count rate may or may not be detectable, depending on the sensitivity of the particular logging tool. Whether detectable or not, the count rate suppression due to copper does not detract from the intended purpose of the Fission Neutron Water Factor Model. The copper anomaly is uniform throughout the model ore zone, so borehole diameter is the only parameter which varies between boreholes.

These cross section remarks are based on data (Tables 10 and 11) which were available at the time this report was written. One must recognize that additional and more accurate sample analyses are needed to completely characterize the neutron transport properties of the model concretes. For example, the gadolinium assay (Table 10) indicates that the gadolinium concentration of the Fission Neutron Water Factor Model sample was below the detection limit of 50 parts per million. It is obviously desirable to determine the gadolinium concentration more accurately than this.

The thermal neutron absorption cross section of gadolinium is so large (4.9×10^4 barns per atom) that 0.5 parts per million of gadolinium would have the same effect on the total thermal neutron absorption cross section as the 2450 parts per million of copper.

*The macroscopic thermal neutron absorption cross section is the product of the number of relevant atoms per unit volume and the microscopic thermal neutron absorption cross section per atom.

SUMMARY

The Fission Neutron Water Factor Model was designed and constructed at the Grand Junction DOE facility by BFEC, the prime operating contractor for the DOE. The three model zones accommodate seven boreholes of different diameters. Since borehole diameter is the only logging variable among the holes, the fission neutron log effect of variations in hole diameter can be measured directly with any fission neutron logging system.

The BFEC Chemistry Laboratory is presently engaged in two activities which may result in future changes for some of the Fission Neutron Water Factor Model parameters. In one activity, the Chemistry Laboratory is evaluating new computer software for the analysis of laboratory gamma-ray assay data which are collected with Ge(Li) detectors. The software will allow, for example, the simultaneous determination of true uranium concentration (from the amplitude of the 1001-keV line of protactinium-234) and radiometric (or radium) equivalent uranium concentration (from the amplitude of the 1764-keV line of bismuth-214).

The other activity is in cooperation with the New Brunswick Laboratory (NBL) and concerns the problem of standards for laboratory gamma-ray counting. The uranium standards which the Chemistry Laboratory uses to calibrate the gamma-ray counting systems are not certified for such use. The BFEC/NBL program will culminate with the certification of selected uranium-bearing materials for the calibration of gamma-ray counting systems.

When the software evaluation is complete and the new standards adopted, the Fission Neutron Water Factor Model samples will be reanalyzed, and the results may be slightly different from those presented in this report.

Another BFEC activity which may affect the assigned Fission Neutron Water Factor Model parameters is presently underway in the Calibration and Quality Assurance Department. Logging data are being collected from all of the DOE Grand Junction models with a recently developed system known as the Calibration Facility Monitoring System (CFMS). Sample results for the Fission Neutron Water Factor Model are shown in Appendix III. The analyses of these data may also have a role in the revision of model parameters.

Future model characterization studies may require additional or different types of sample assays than discussed in this report. Samples will always be available for such assays because all of the samples from the model, including the borehole core samples, have been deposited in the permanent BFEC Chemistry Laboratory sample archive. Samples can be retrieved from archive through reference to the sample numbers and laboratory requisition numbers are shown in Appendix II.

The model parameters, as presently assigned, are tabulated below.

Boreholes

Diameters: 3 inches (7.6 cm), 4-1/2 inches (11.4 cm), 6 inches (15.2 cm), 7-9/16 inches (19.2 cm), 9 inches (22.9 cm), 11 inches (27.9 cm), 13 inches (33.0 cm).
Orientation: 2 degrees off vertical, plunge 88 degrees toward north.
Length: 27.5 feet (8.4 m).

Upper Barren Zone

Thickness: 5 feet (152 cm).
Radioelement concentrations (by radiometric assay): 1.98±0.12 percent potassium, 3.8±1.1 ppm equivalent uranium, 7.6±1.1 ppm equivalent thorium.
Radioelement concentrations (by chemical assay): 1.78±0.16 percent potassium, 2.6±0.9 ppm uranium, less than 5 ppm thorium.
Grain density: 2.68±0.04 grams per cubic centimeter.
Dry bulk density: 2.22±0.01 grams per cubic centimeter.
Porosity (estimated): 17.3±1.3 percent.
Magnetic susceptibility: 1133±54 micro-cgs.

Ore Zone

Thickness: 6 feet (183 cm).
Radioelement concentrations (by radiometric assay): 1.78±0.26 percent potassium, 643±42 ppm equivalent uranium (0.0758±0.0049 percent equivalent U_3O_8), 7.7±1.7 ppm equivalent thorium. [Uranium result from Heistand (81)].
Radioelement concentrations (by chemical assay): 1.53±0.08 percent potassium, 676±47 ppm uranium (0.0797±0.0055 percent U_3O_8), less than 5 ppm thorium.
Uranium concentration (by gamma-ray logging): 667 ppm equivalent uranium (0.0786 percent eU_3O_8) (from pending BFEC Internal Report "Interim Grade Reassignments for GJO Calibration Models" by B. Heistand, D. George, and J. Krabacher.)
Other abundant element: 2450 ppm copper.
Magnetic susceptibility: 826±47 micro-cgs.
Grain density: 2.72±0.07 grams per cubic centimeter.
Dry bulk density: 2.12±0.03 grams per cubic centimeter.
Porosity (estimated): 22.1±0.1 percent.
In-situ bulk density (estimated): 2.34 grams per cubic centimeter.
Total water content (estimated): 13 percent, by mass.

Lower Barren Zone

Thickness: 4 feet (122 cm).
Radioelement concentrations (by radiometric assay): 1.98±0.13 percent potassium, 3.5±0.7 ppm equivalent uranium, 8.9±1.5 ppm equivalent thorium.
Radioelement concentrations (by chemical assay): 1.69±0.38 percent potassium, 2.8±1.1 ppm uranium, less than 5 ppm thorium.
Grain density: 2.69±0.03 grams per cubic centimeter.
Dry bulk density: 2.22±0.01 grams per cubic centimeter.
Porosity (estimated): 17.4±0.01 percent.
Magnetic susceptibility: 1088±65 micro-cgs.

Persons who wish to inquire about Fission Neutron Water Factor Model parameter revisions or who wish to use the model for borehole measurements may do so by contacting the prime operating contractor:

Bendix Field Engineering Corporation
Minerals Evaluation Division
Calibration and Quality Assurance Department
P.O Box 1569
Grand Junction, Colorado 81502-1569
Telephone (303) 242-8621

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