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UCRL-CONF-220026

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March 23, 2006

CMWR XVI - Computational Methods in Water Resources
Copenhagen, Denmark
June 19, 2006 through June 22, 2006

A SERENDIPITOUS, LONG-TERM INFILTRATION EXPERIMENT: WATER AND RADIONUCLIDE CIRCULATION BENEATH THE CAMBRIC TRENCH AT THE NEVADA TEST SITE.

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ABSTRACT

Underground atomic weapons testing at the Nevada Test Site introduced numerous radionuclides that may be used to characterize subsurface hydrologic transport processes in arid climates. Beginning in 1975, groundwater adjacent to the CAMBRIC test, conducted beneath Frenchman Flat in 1965, was pumped steadily for 16 years to elicit experimental information on the migration of residual radioactivity through the saturated zone. Radionuclides in the pumping well effluent, including tritium, ^{36}Cl, and ^{85}Kr, were extensively monitored prior to their discharge into an unlined ditch flowing toward a dry lake bed over a kilometer away. We have applied a large (6km x 6km x 1km) and highly resolved (4 m) variably saturated flow model to investigate infiltration into the 220-m vadose zone underlying the ditch as well as subsequent groundwater recharge and well recirculation processes. A Lagrangian particle-tracking model has been used to compute flow pathways and estimate radionuclide travel and residence times in various parts of the system based upon the flow model. Results are consistent with rising tritium levels observed in a monitoring well since 1991. They suggest that recirculation of the ditch effluent through the vadose zone, into groundwater, and back to the test cavity and pumping well are responsible for diluted, tritium-based groundwater age dates observed in 2000 at these locations, as well as for increased tailing effects observed in the pumping well elution curves. Altogether, the models and experimental observations provide an improved basis to understand both historical and future movements of test-related radionuclides in groundwater near CAMBRIC.

1. INTRODUCTION

The CAMBRIC underground nuclear test was conducted beneath Frenchman Flat at NTS on May 14, 1965 (USDOE, 2000; Figure 1). The test device was positioned in heterogeneous alluvium, 294 m beneath the ground surface, and approximately 74 m beneath the ambient water table. The announced energy-equivalent yield of the test was 0.75 kilotons. The explosion created a detonation cavity approximately 27 m in diameter that was subsequently filled in by collapsed alluvium and saturated with ground water (Bryant et al, 1992; Hoffman et al, 1977). The collapsed "chimney" did not extend as far as the ground surface as there was no observable crater. Beginning in October 1975, approximately 10 years after the test, ground water adjacent to the test cavity was pumped steadily for 16 years, with a few short interruptions, in order to elicit information on test-related radionuclide migration in the saturated zone. Over the 16 year experiment, ^{3}H (as HTO), ^{14}C, ^{36}Cl, ^{85}Kr, ^{99}Tc, ^{129}I, ^{106}Ru were measured in the pumping well (Tompson et al, 2005).

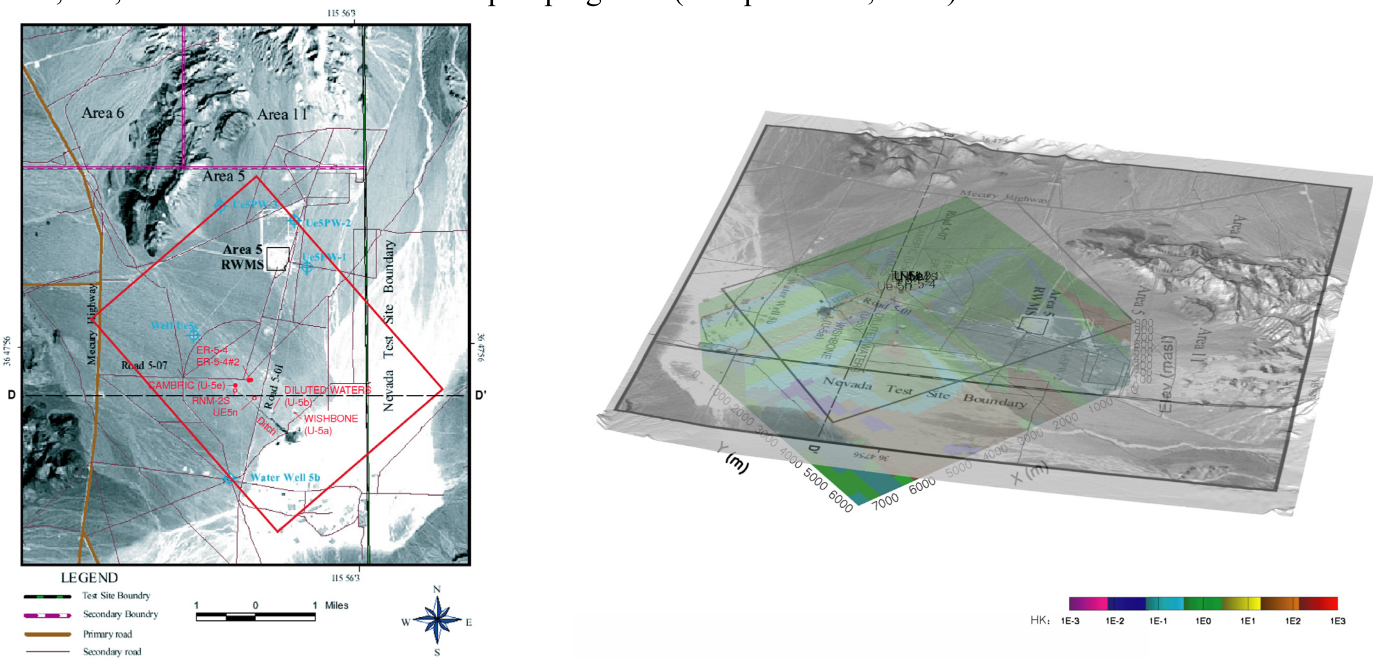

FIGURE 1. Aerial view of Frenchman Flat, NTS, showing locations of CAMBRIC (U-5e), nearby boreholes and monitoring wells, the CAMBRIC ditch, as well as DILUTED WATERS (U-5a) and WISHBONE (U-5b). Red box indicates horizontal extent of model domain used for HST simulations. Model domain shown in right panel with surface relief added to aerial view.

Figure 2 illustrates the configuration of the original CAMBRIC device emplacement hole (U-5e), the associated test cavity and chimney, the diagnostic, post-test drill back well (RNM-1), the experimental pumping well (RNM-2S) and a nearby monitoring well (UE-5n). As shown in this schematic, the pumping well (RNM-2S) was located approximately 91m south of the emplacement hole (U-5e), and is screened over an approximately 25m interval between depths of 318 and 343m, slightly below the test cavity. The monitoring well, located 500 m away from the pumping well and 106 m perpendicular to the ditch, is screened in the saturated zone over a 3m interval just below the water table.

2. MODEL DOMAIN

The ParFlow model domain (Figure 3) is a combination of a larger scale geologic model (SNJV, 2004; Warren et al, 2002) and a series of alluvial layers calibrated to a pumping test (Carle et al, 2006). Heterogeneity in hydraulic conductivity is included via a Gaussian random field approach in the fine mesh region around the test cavity. This heterogenous, fine mesh region extends along the trench and up the 220m thick vadose zone to the ground surface. The model grid totals approximately 25 million nodes.

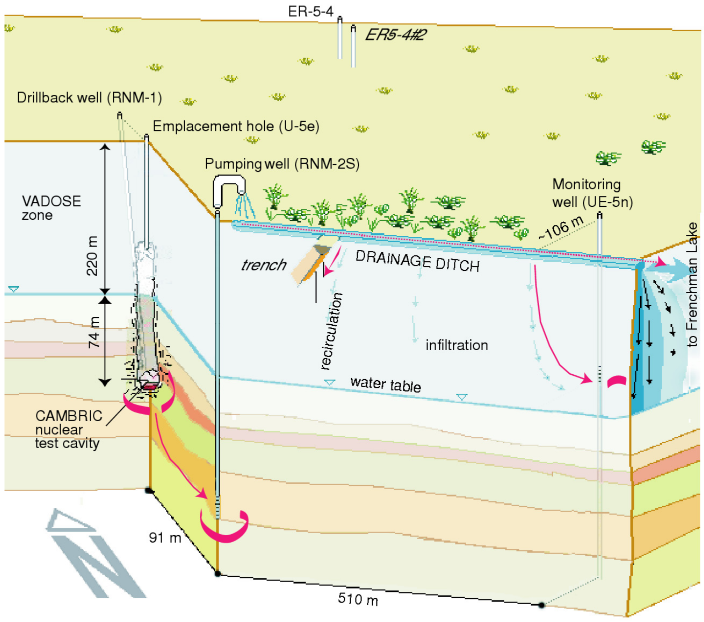

Figure 2: Schematic of the CAMBRIC test area in Frenchman Flat at the Nevada Test Site, showing the test emplacement hole (U-5e), cavity and collapsed chimney, pumping well RNM-2S, drainage ditch, lysimeter trench, and monitoring wells UE-5n, ER-5-4, and ER-5-4#2. Known tritium pathways shown in red.

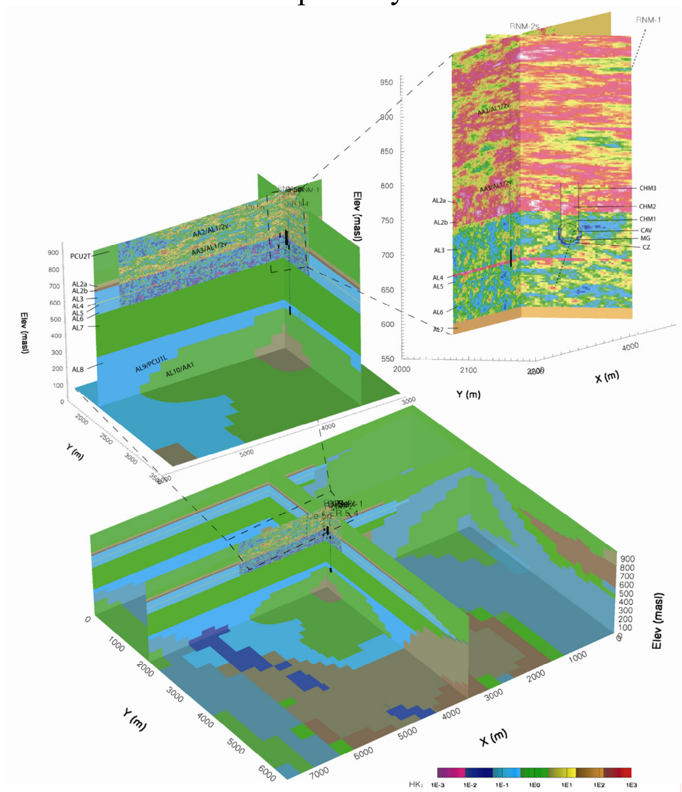

Figure 3. The ParFlow modeling domain showing the hydraulic conductivity values and two different regions of grid refinement. Insets show the area around the heterogeneous, fine mesh region and the area around the cavity, respectively.

3. FLOW RESULTS

The parallel flow code ParFlow (Asby and Falgout, 1996; Jones and Woodward, 2003) was used to simulate the flow field under the influence of pumping at RNM-2S and trench infiltration. Figure 4 shows a snapshot of saturation during this simulation and Figure 5 compares simulated and observed water levels at UE-5n. The underlying conceptual model and parameterization of the transient variably-saturated flow model are consistent with extensive observations and interpretations of a variety of data.

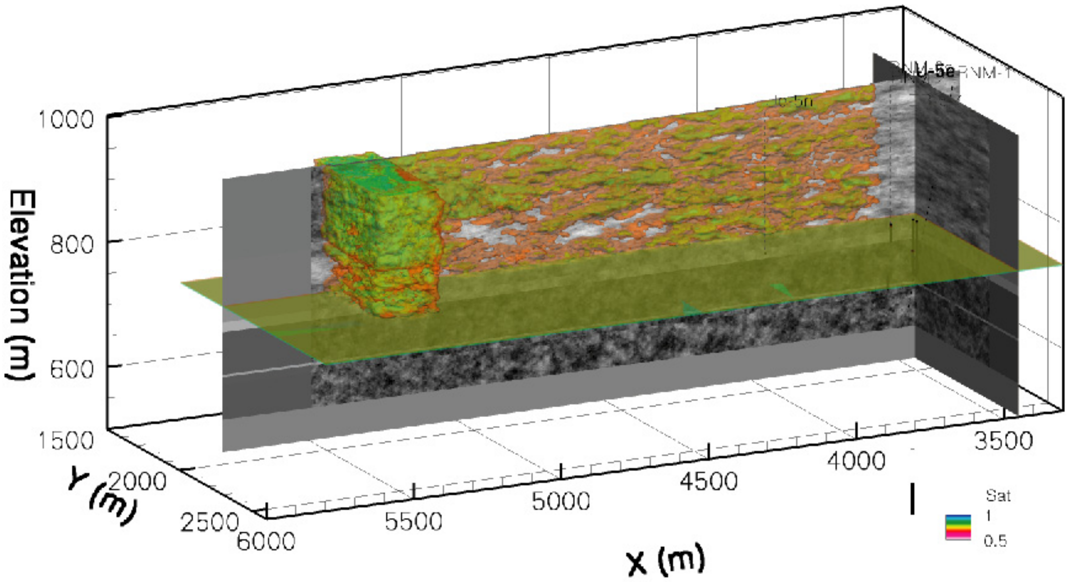

Figure 4. Simulated saturation profile after 18 years of pumping and ditch infiltration (1983).

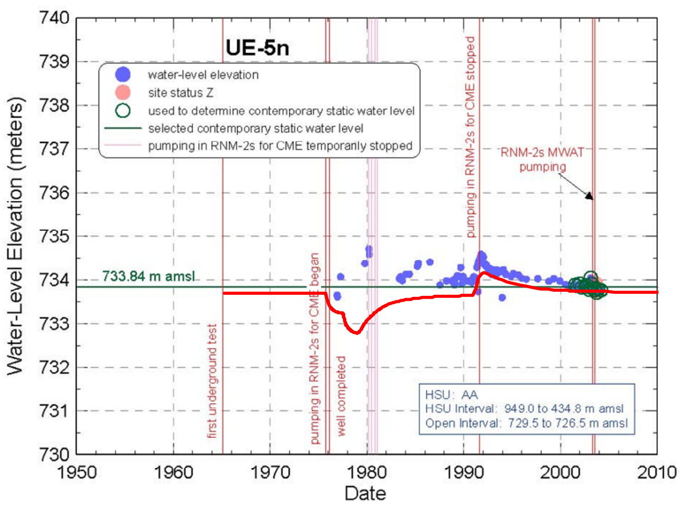

Figure 5. Observed and simulated water levels at UE-5n, a well that is located 100m away from the trench. Observed values are plotted as symbols and the solid red line is the ParFlow simulation. Figure modified from SJNV (2004).

4. TRANSPORT RESULTS

Transport of radionuclides was simulated using a Lagrangian, particle tracking model. In this study, both the Hoffman et al (1977) and Bowen et al (2001) source terms were used to specify the initial distribution of radionuclides near the test cavity. Figure 6 shows several snapshots of tracer concentration during the pumping and recession phases of the migration experiment. Importantly, the particle model was modified to track the potential recirculation of radionuclides from the ditch, back to the water table, and back into the pumping well. This behavior was suggested by recent isotopic measurements (Tompson et al., 2006). The recirculation effects can be seen in Figures 7 and 8.

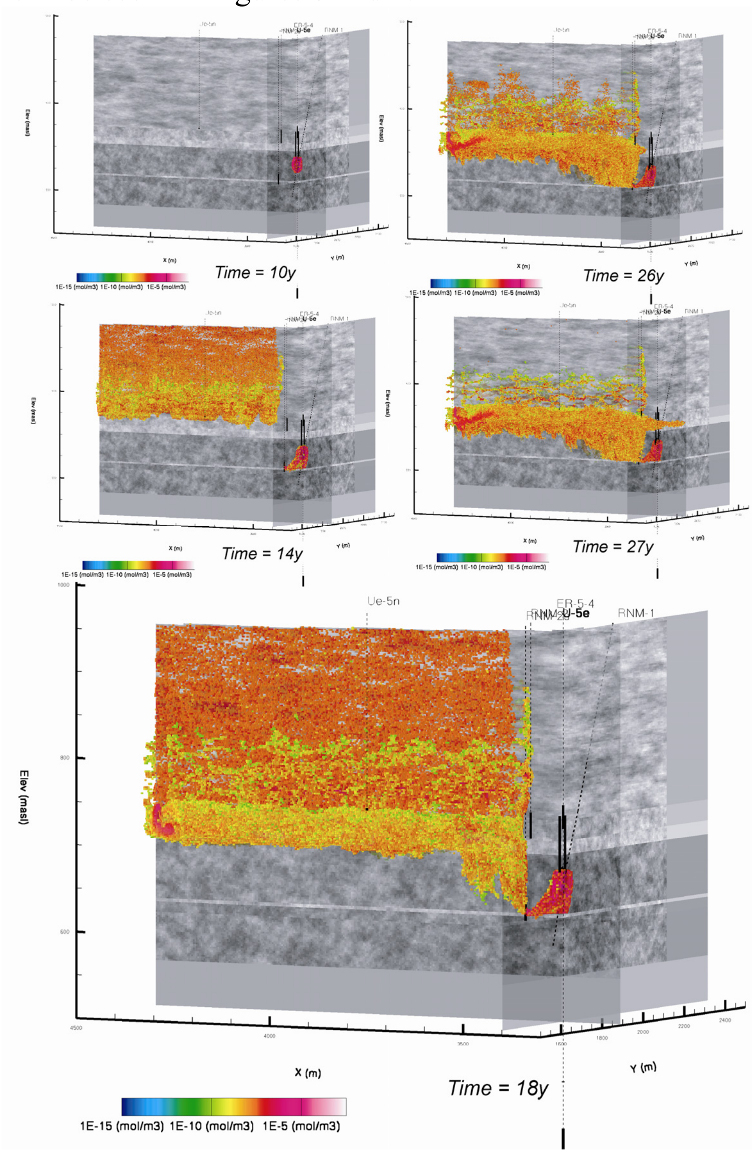

Figure 6. Results for tracer transport at different points in time during the simulation (10, 14, 18, 26, 27y) focused on the region near the cavity. The upper panel is after 10.4 years of ambient migration, just before the onset of pumping, the last panel is for 27 years, two years after the cessation of pumping. Note the pathway from cavity to well and from ditch to water table.

5. RNM-2S BREAKTHROUGH AND RADIONUCLIDE CIRCULATION

The particle transport model was used to assess breakthrough and circulation of ^3H and other radionuclides in RNM-2s. Figure 7 compares breakthrough with and without the trench recirculation and shows the importance of recirculation on enhanced tailing of ^3H. Transport and breakthrough for other radionuclides was also simulated and the effect of trench breakthrough was explored. Figure 8 plots the fraction of mass as a function of number of trench recirculation passes for each radionuclide.

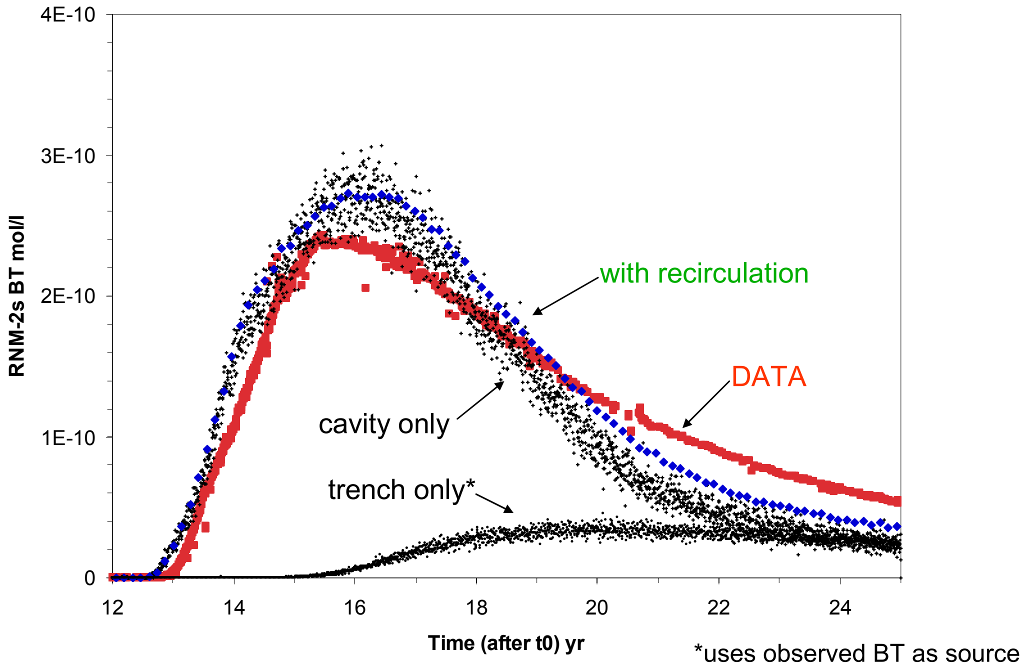

Figure 7. Simulated and observed tritium breakthrough at RNM-2S. Simulated breakthrough includes source from the cavity and trench only and mass that has recycled through the well-ditch system. Note the trench only source uses the observations as a trench initial concentration.

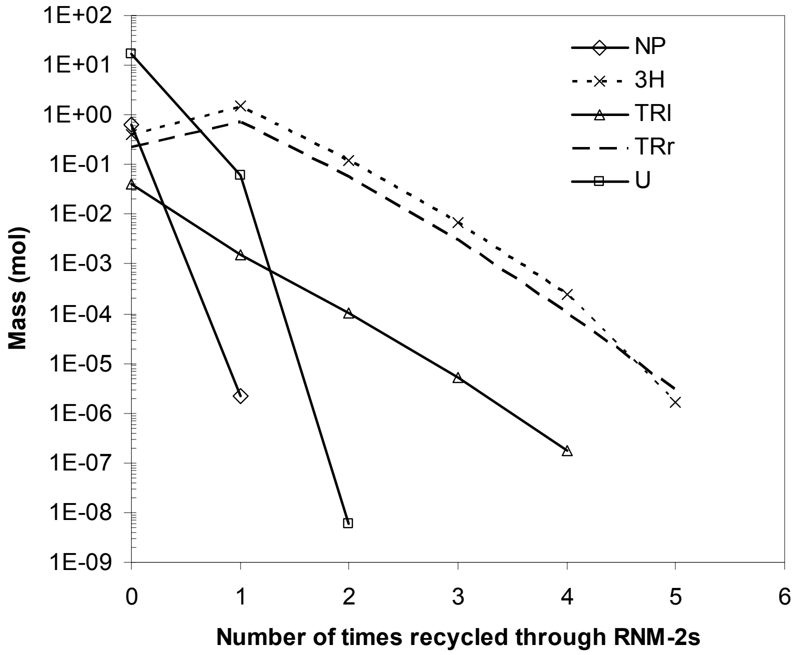

Figure 8. Plot of total radionuclide mass as a function of number of times it arrived at RNM-2S. Mass totals to the initial condition in cavity, disturbed zone and melt glass. Mass corresponding to a zero on the x-axis never reaches the well, where mass plotted two or greater recycles between the well and trench.

6. CONCLUSIONS

This study yielded many key findings:

1. **30-y field test:** Overall history of activities at the site has provided a wealth of field data for analyzing the movement of several radionuclides through a saturated and unsaturated environment over a very long period of time.
2. **Valuable calibration process:** The underlying conceptual model and parameterization of the models are consistent with extensive observations and interpretations of borehole geologic and hydraulic data, a multiple well aquifer test conducted on the site in 2003, measured ditch inflow and evapotranspiration losses, RN concentration histories in the saturated and vadose zones, and isotopically determined groundwater age dates.
3. **Simulation results consistent with new observations:** ^{237}Np - a sorbing RN - was predicted to arrive at well UE-5n, even though there was no supporting historical data in earlier observations at UE-5n and the pumping well. However, ^{237}Np **has** just been detected at UE-5n, consistent with the model. In addition, the model is consistent with the observation of ^{3}H below the water table at well ER-5-4 during its construction. Heretofore, this observation was considered more of an anomaly without any rational explanation.
4. **Large Scale Model:** Effective calibration and application achieved through use of accurate and efficient large scale simulation codes.

7. ACKNOWLEDGEMENTS

This work was conducted under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory (LLNL) under contract W-7405-Eng-48. This work was funded by the UGTA program of the U. S. Department of Energy

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