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X-ray Computed Tomography on UNESE Core: FY20 Data Report to Support Fracture and Multiphase Fluid Flow Studies

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ABSTRACT

Natural and induced fractures are potential preferential pathways for migration of radioactive gases to earth's surface from underground nuclear explosions (UNEs). This report documents X-ray computed tomography (XRCT) imaging on 26 samples of rock core that was collected to support the Underground Nuclear Explosion Signatures Experiment (UNESE) program. The XRCT datasets are intended to help fill a data gap on the three-dimensional (3D) characteristics of natural and/or induced fractures at the centimeter and smaller scale, which may strongly influence multiphase fluid flow and transport properties of preferential flow paths and interaction with the matrix of the surrounding host rock. Pre- and post-UNE rock samples were carefully chosen to enable comparison of fractures as a function of lithologic and petrophysical properties, as well as distance to the past UNEs. This report serves as documentation for the data, including an introduction with the research motivation, a methods and materials section, descriptions of the XRCT datasets without post-processing, and recommendations for 3D quantification via image analysis and digital rock physics.

ACKNOWLEDGEMENTS

The Underground Nuclear Explosion Signatures Experiment (UNESE) was created to apply a broad range of research and development (R&D) techniques and technologies to nuclear explosion monitoring and nuclear nonproliferation. It is a multi-year research and development project sponsored by NNSA DNN R&D, and is collaboratively executed by Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Mission Support and Test Services, Pacific Northwest National Laboratory, and Sandia National Laboratories.

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CONTENTS

LIST OF FIGURES

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
CFD	computational fluid dynamics
DOE	U.S. Department of Energy
GFM	Geologic Framework Model
NNSS	Nevada National Security Site
FY20	fiscal year 2020
UNE	underground nuclear explosion
UNESE	Underground Nuclear Explosions Signatures Experiment
XRCT	X-ray computed tomography

1. INTRODUCTION

Fractures are potential pathways for the migration of radioactive gases to earth's surface from underground nuclear explosions (UNEs; Jordan et al., 2014; 2016; Bourret et al., 2019; Carrigan et al., 2020). Recent field and modeling studies for the U.S. Department of Energy (DOE) Underground Nuclear Explosion Signatures Experiment (UNESE) program have directly documented and/or inferred fracture characteristics from locations of past UNEs at UNESE test beds at Aqueduct and Pahute Mesas at the Nevada National Security Site (NNSS).

The UNESE efforts have examined fractures using borehole geophysical image logging and geologic descriptions of previous core and/or new core collected at the Aqueduct Mesa P-Tunnel complex and the UE-20az site on Pahute Mesa (Prothro, 2016; Prothro, 2018; Huckins-Gang and Townsend, 2018; Wagner et al. 2018). Fracture characterization includes fracture type (i.e., natural versus induced), orientation (i.e., dip), and for some samples, microfracture density and mineralogy of fill material via thin section observations (Broome et al., 2019). Distinguishing between drilling or core-handling induced fractures from explosion-induced fractures is difficult, especially using image log data (Wagner et al., 2018). The UNESE P-Tunnel Geologic Framework Model (GFM) at Aqueduct Mesa includes digitized oriented fracture planes for display within the model that were observed during tunnel construction but were not directly integrated in the GFM in terms of fluid flow properties (Prothro, 2018).

Flow and transport studies of gas and radionuclides estimate fracture characteristics from fitting dual permeability models to measured barometric pressure, injection-gas pressure, and/or Freon gas tracer measurements, depending on the given study, for idealized host rock geology and past UNE-chimney structure (Bourret et al., 2019; Carrigan et al., 2020). The modeling assumes a mobile gas phase and an immobile water phase. Measurement of multiphase fluid flow and transport properties of several key lithologies from P-Tunnel and UE-20az have been made to support future modeling of potentially mobile water and mobile gas as based on subsamples of UNESE core from pre- and post-UNE core (Heath et al., submitted).

To complement the recent UNESE studies, we performed X-ray computed tomography (XRCT) imaging on 26 samples from UNESE core. Pre- and post-UNE samples were selected to enable quantification of the three-dimensional (3D) geometry, connectivity, and percolation characteristics of natural versus UNE-induced fractures. Direct observation of fracture characteristics may improve conceptual and numerical model development that in turn may improve understanding and prediction of radionuclide gas signatures associated with UNEs. This data report thus describes sample selection, XRCT imaging methods, and the XRCT datasets. Recommendations for future work on addressing specific research questions are given in the final section.

2. METHODS AND MATERIALS

Samples were selected from UNESE cores at several distances from the past UNEs to the surface to investigate fracturing mechanisms, natural versus induced fracture interaction, post-fracturing mineralization, and micro-scale fracture intensity by lithology. The sample locations correspond to locations of previous petrographic and petrophysical studies (Broome et al., 2019; Heath et al., submitted.) The XRCT data will complement previous work by allowing examination of fracture geometries, topologies, and percolating length scales (for the given total sample size) in the context of the host rock lithology. All XRCT data was collected at ambient pressure and temperature conditions.

The samples were obtained from the following:

- two Pahute Mesa (Barnwell) core holes started from the land surface, UE-20az NG-4 and UE-20az NG-6;
- two Aqueduct Mesa (P-Tunnel, Disko Elm) core holes started from the land surface, UE-12p#4 and UE-12p#7; and
- one Aqueduct Mesa (P-Tunnel, Disko Elm) core hole started from the tunnel level, U12p.03 RE-7.

Figure 1 shows the location of core holes UE-20az NG-4 and UE-20az NG-6. Figure 2 shows the location of core holes UE-12p#4, UE-12p#7, and U12p.03 RE-7.

Imaging by XRCT with vortex (i.e., helical) scans was performed using a North Star Imaging X50 micro-CT scanner and PaxScan 2520DX Digital Image detector. North Star efX-DR and efX-CT software were used for image acquisition and reconstruction, respectively, producing registered tomographic reconstructions as tiff image stacks.

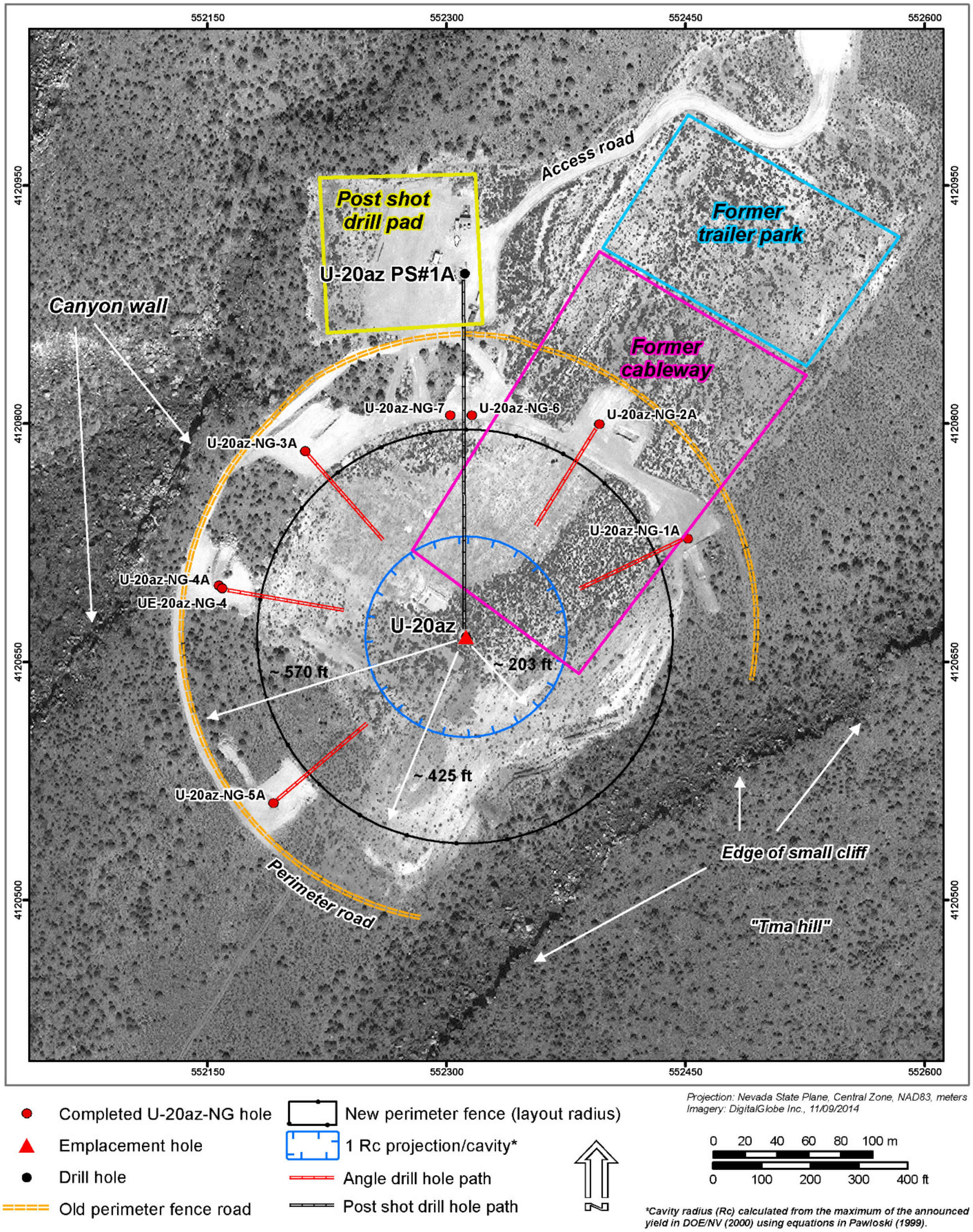

Figure 1. Reference map for the UNESE Pahute Mesa surface test bed (from Mercadante et al., 2017). Core holes UE-20az NG-4 post-UNE and UE-20az NG-6 post-UNE are shown.

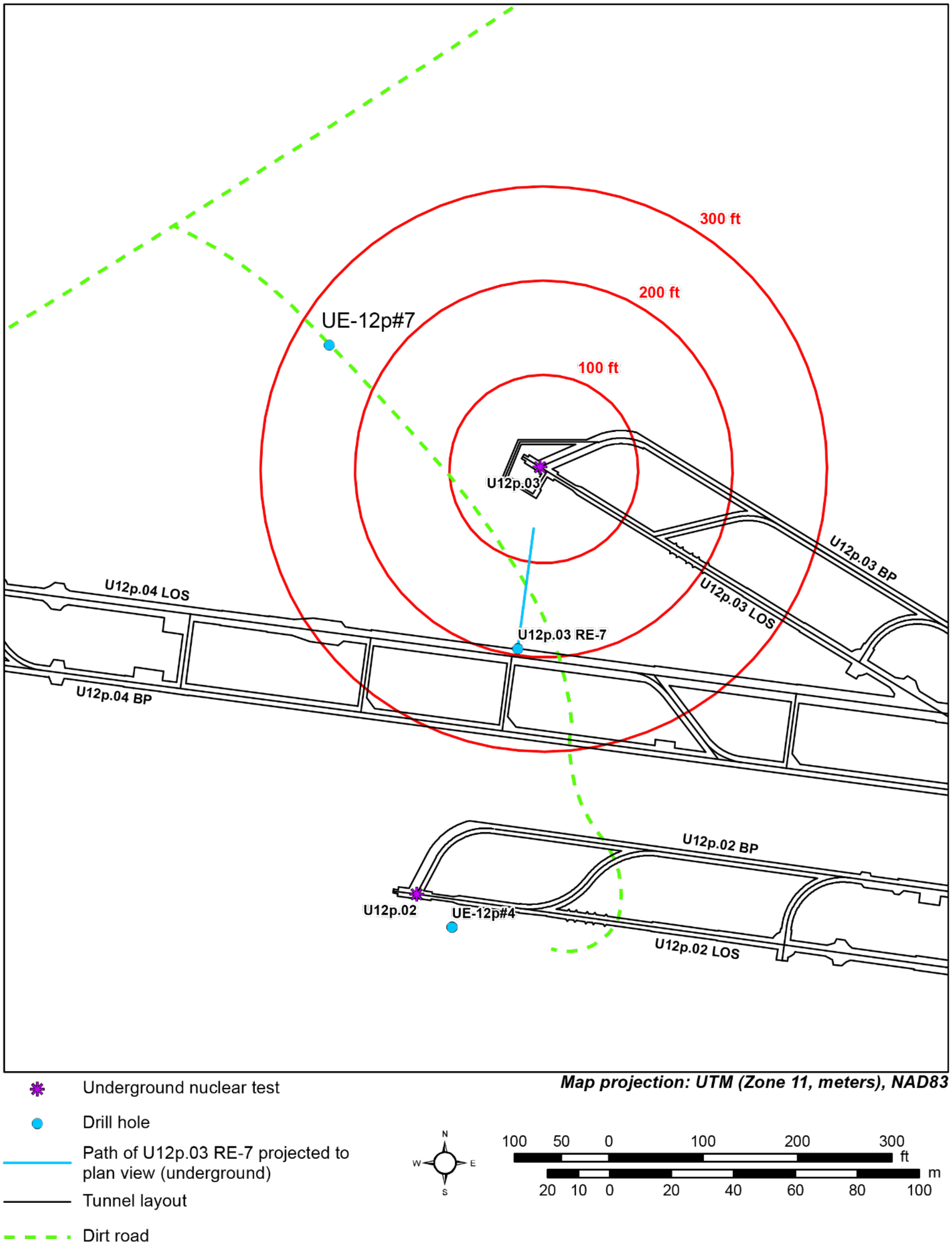

Figure 2. Reference map for the UNESE Aqueduct Mesa surface test bed (map provided by Mission Support and Test Services, LLC). Core holes UE-12p#4 (pre-UNE), U12p.03 RE-7 (post-UNE), and UE-12p#7 (post-UNE) are shown. U12p.03 RE-7 was drilled 30 degrees from horizontal and in the upward direction from the U12p.04 LOS drift.

3. RESULTS

Twenty-six UNESE subsamples of core were imaged by XRCT. The following information was compiled for each sample and XRCT datatset:

- the main folder name for a dataset for a given sample;
- the size of the image stack;
- the voxel resolution;
- the sample lithology;
- the sample ID based on type as to pre or post-UNE, core hole name, and depth;
- petrographic notes from previous thin section analysis on nearby samples;
- identification of which pre- and post-samples correspond with each other;
- a “yes” or “no” recommendation for further segmentation and quantification of fractures based on an initial visual examination of the image stacks and volume renderings; and
- reasons for recommended further analysis, typically based on the visibility of the fractures and their likelihood or not being induced from core-handling.

Image stacks range in size from 2.71 to 43.2 GB depending on the physical size of the sample and the resolution of the imaging. Voxel resolution varies from 15.2 to 38.2 microns. Eleven samples have visible fractures that are suited and recommended for further analysis. As an example, sample U12p.03 RE7-38.6-39.6 has fractures with a dark grayscale value, which would be easily segmented by image processing (Figure 3). Segmentation is the process of assigning pixels or voxels to classes (Schluter et al., 2014) such as open fractures, filled fractures, and or other phases in the images.

The XRCT datasets—in addition to the image stacks that should be used for digital reconstruction and further post-processing—include several images and movie files of the reconstructed samples for rapid exploration of the results.

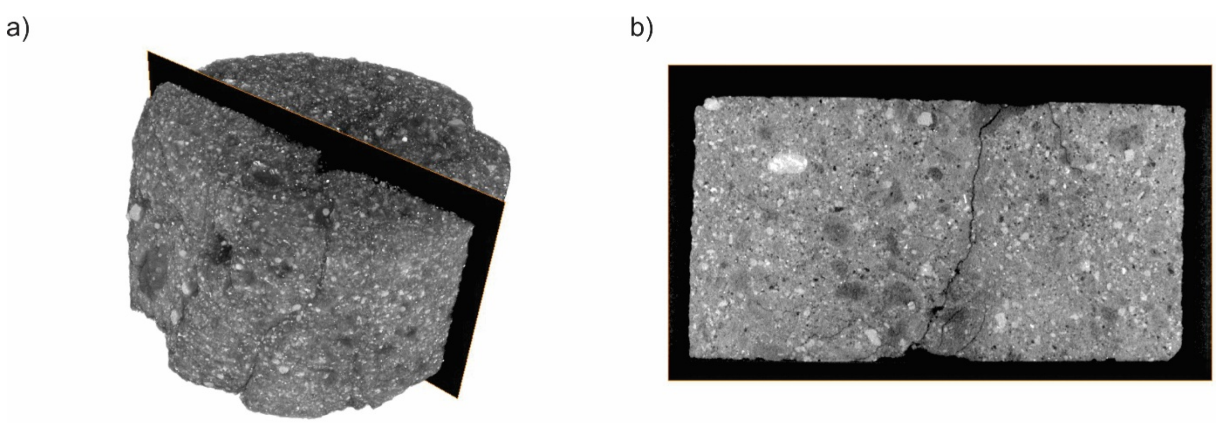

Figure 3. XRCT results for sample U12p.03 RE7-38.6-39.6. a) Volume rendering with the plane of the XZ ortho slice visible. b) XZ ortho slice. The width of the sample in this view is ~ 59 mm.

4. RECOMMENDATIONS FOR FUTURE WORK

Research questions that drove the collection of the XRCT datasets include the following:

- How do natural versus induced fracture characteristics differ?
- What is the variation in fracture geometry, connectivity, and percolation for induced and natural fractures as a function of lithology?
- How do induced fracture characteristics vary by fracturing mechanisms, e.g., spall versus other mechanisms?
- Do natural fractures have a control on induced fracture? For example, do induced fractures curve into or have a geometry that is affected by the pre-existing natural fractures?
- What is the evolving air-filled tortuosity of core-scale fractures as a function of water saturation?

The XRCT datasets can be post-processed using various software such as Matlab®, Avizo, or ilastik to segment the fractures and mineral phases. Image processing techniques can then quantify the geometry and topology of the segmented phases such as the fractures, including orientation, size, and percolation (connectivity) length across the sample. The segmented fractures could be meshed and imported into software such as OpenFOAM or COMSOL Multiphysics® for pore-scale modeling and determination of fluid flow properties. Pore network and/or computational fluid dynamics (CFD) modeling on the fracture pore space could estimate core-scale fracture permeability. Natural and induced fractures can evolve over time. Digitally removing any fracture fill could estimate the original induced fracture permeability prior to any clay or other precipitation. These approaches could be used to help answer the above questions.

Note that the XRCT datasets were collected at ambient conditions—imaging under realistic confining stress in an X-ray transparent pressure vessel would be better to potentially restore fracture apertures to their *in situ* geometry and apertures, which in turn may impact the pore network modeling and CFD modeling and permeability estimations. Fracture tortuosity, percolation, and connectivity may be affected by sample confining stress. The current XRCT datasets are offered as the first foray into 3D core-scale XRCT imaging of UNESE core at voxel resolution of approximately ~15 to 38 microns to address the above research questions. We feel that the relative comparison of natural versus induced fractures are probably reasonable as both natural and induced fractures would probably be affected equally by coring and release of *in situ* confining pressure.

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