ATLAS	Admissible Thermal Loading for Argillaceous Storage	
Type of test: Thermo-hydro-mechanical response of Boom Clay to thermal loading	**Collaborating partners**	**Period:** 1992-2012

BACKGROUND

Vitrified high-level radioactive waste and spent fuel generate considerable amounts of heat. After disposal in a geological repository, the host formation will be subject to significant temperature gradients. In a low-permeable clay formation, due to the differential rate of thermal expansion of the clay skeleton, solid phase and water, an increase in temperature will also temporarily generate excess pore water pressures. These in turn cause hydraulic gradients and a change in effective stresses that significantly affect the hydraulic and mechanical behaviour of the material. To assess the hydro-mechanical effects of the thermal transient on the Boom Clay, various in-situ heating tests have been performed in the HADES underground research laboratory on different scales. While the CERBERUS (1985-1999) and CACTUS (1990-1994) experiments focused on the effects of heat (and in the case of CERBERUS, combined with radiation) on the Boom Clay in the immediate vicinity of the heated borehole, the ATLAS heating tests examined the integrated thermo-hydro-mechanical (THM) response of the Boom Clay up to several metres from the heated borehole. In parallel, coupled THM numerical analyses have been carried out to enhance understanding of the THM behaviour of the Boom Clay.

OBJECTIVES

The small-scale in-situ ATLAS heating tests (phase I to phase IV) were performed at the HADES URL in Mol, Belgium:

- to verify that the thermally induced excess pore water pressure will not reach hydraulic fracture conditions and to thereby determine the admissible thermal loading for the Boom Clay;
- to confirm and update the THM characteristics of the Boom Clay, especially the anisotropic thermal and mechanical properties (observation boreholes were installed in directions parallel and perpendicular to the bedding plane of the Boom Clay);
- to prepare for the PRACLAY Heater test, which is a large-scale heater test in the Boom Clay, intended to simulate the heat production around a disposal gallery on a representative scale.

Since the ATLAS heating tests focused on the Boom Clay and not on the engineered barrier system (EBS), it was possible to establish a set-up with a simple geometry and well-defined boundary conditions. This facilitated the comparison between field measurements and numerical modelling.

DESIGN & INSTALLATION

The original test set-up for ATLAS was established in 1992 by SCK•CEN within the framework of the European project Interclay II (1990–1994). During the first phase of the heating test programme, later named ATLAS I, the test set-up consisted of a heater borehole (AT89E), two horizontal observation boreholes (AT85E and AT93E) (see Figure 1), and a constant 900W heat source, which was used from July 1993 to June 1996. During the second phase (ATLAS II), the power was increased to 1800W and maintained at that level from June 1996 until May 1997. This was followed by shutdown and natural cooling, starting in June 1997. After the set-up had been extended in 2006 by drilling one downward inclined observation borehole AT97E and one horizontal borehole AT98E (also shown in Figure 1) to enlarge the test zone and investigate the THM anisotropic behaviour of the Boom Clay, the heater was switched on again from April 2007 to April 2008 with a stepwise power increase, followed by an instantaneous shutdown. This phase is called ATLAS III. In 2010, an additional inclined observation borehole AT90IU was drilled above the heater borehole AT89E (see Figure 2) to further examine the anisotropic THM response. The heater was switched on from 2011 to 2012 to start a new phase of the heating test (ATLAS IV), and the same heating strategy as that for ATLAS III was applied to facilitate the interpretation and comparison between ATLAS III and ATLAS IV.

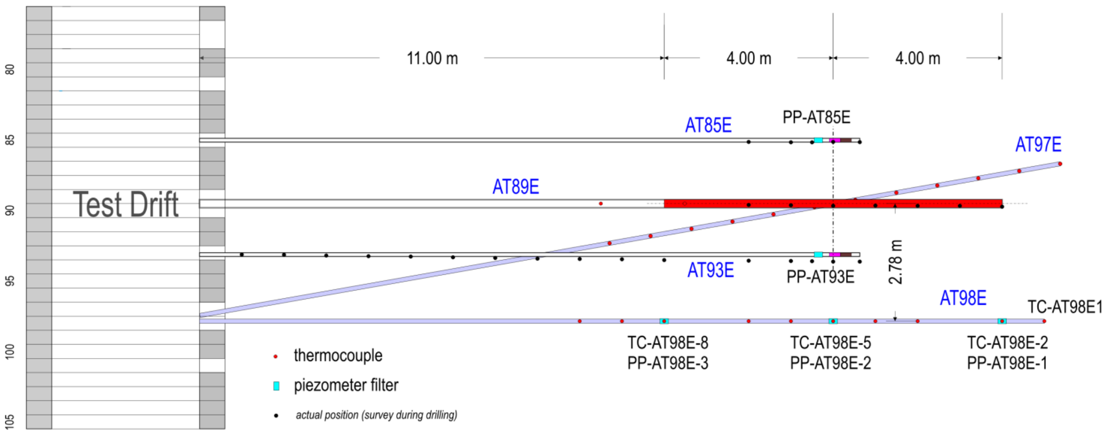

Figure 1 - Schematic horizontal view of the ATLAS test set-up

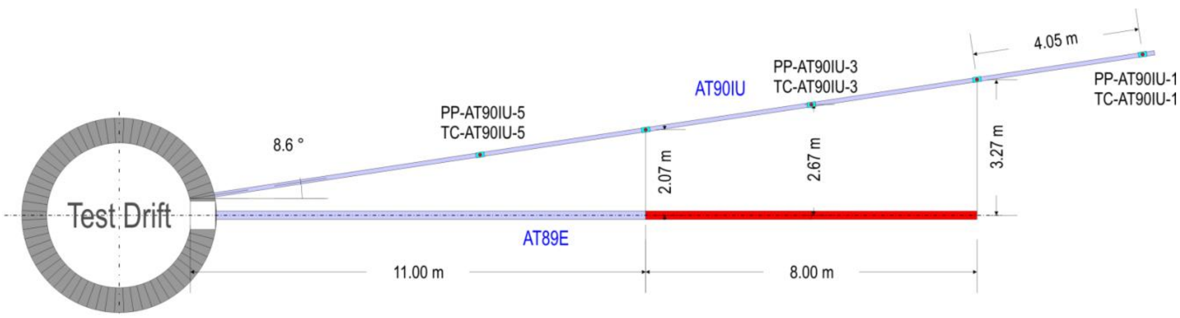

Figure 2 - Schematic vertical and upward view of the ATLAS test set-up

TIMING

1992: installation of the heating borehole (AT89E) and instrumented boreholes (AT85E & AT93E)
1993 - 1996: ATLAS I heating test
1996 - 1997: ATLAS II heating test
2006: installation of instrumented boreholes AT97E and AT98E
2007 - 2008: ATLAS III heating test
2010: installation of an additional instrumented borehole AT90IU
2011 - 2012: ATLAS IV heating test

RESULTS

Figure 3 shows the evolution of the pore water pressure, the total stress and temperature measured during the heating phase of the ATLAS I & II tests. These measurements show that the pore water pressure remains lower than the total stress (horizontal and vertical). This means that the hydraulic fracturing condition was never reached during the 6-years of heating and cooling.

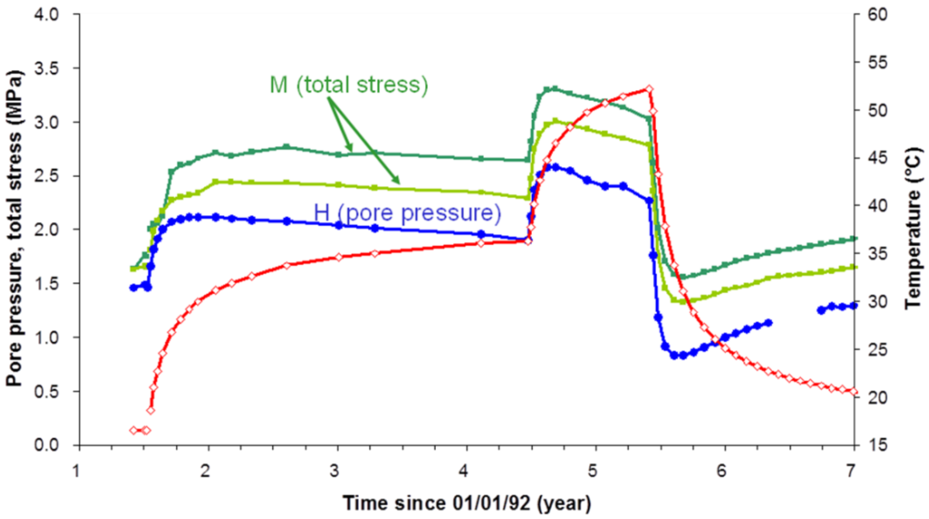

Figure 3 - Pore water pressure, total stress (vertical and horizontal) and temperature measured at the end of borehole AT93E (ATLAS I & II)

During the ATLAS III and IV test, excellent agreement was observed between the measurements of temperature and pore water pressure and the numerical modelling (see Figures 4 and 5, respectively). This yielded a set of anisotropic THM properties, and increases our confidence in the capability of current models and codes.

The thermal anisotropy of the Boom Clay is confirmed by the measurements from the new sensors. As shown in Figure 4, the temperature evolution measured by AT90IU-3 is quite different from that measured by AT98E5. Both are at almost the same distance from the heater centre but in mutually perpendicular directions (horizontal vs vertical).

The instantaneous but temporary pore water pressure decrease (increase) after each power increase step (cooling) is observed from the measurements in the boreholes in the horizontal plane (AT85E, AT93E & AT98E, Figure 5), but these subtle features were not observed in the new drilled upward borehole AT90IU (Figure 2). Numerical analyses based on a coupled theoretical formulation that incorporates constitutive laws with consideration of anisotropy indicated that these instantaneous but temporary pore water pressure variations are due to mechanical anisotropy.

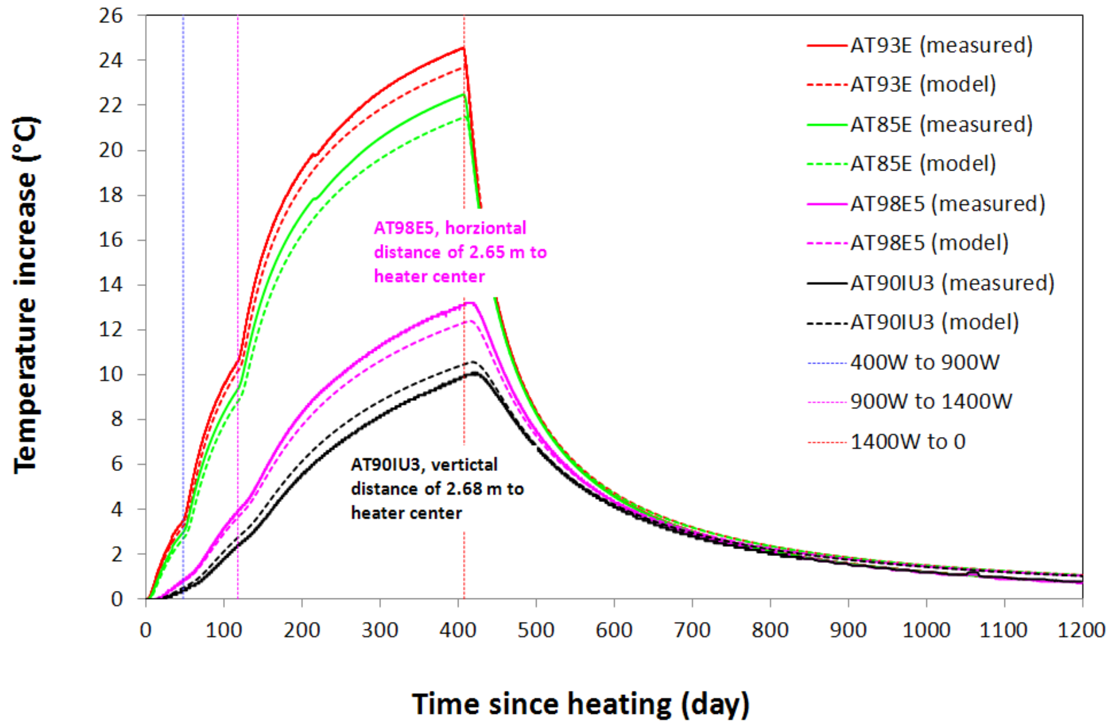

Figure 4 - Comparison of temperature at representative points between measurements and modelling

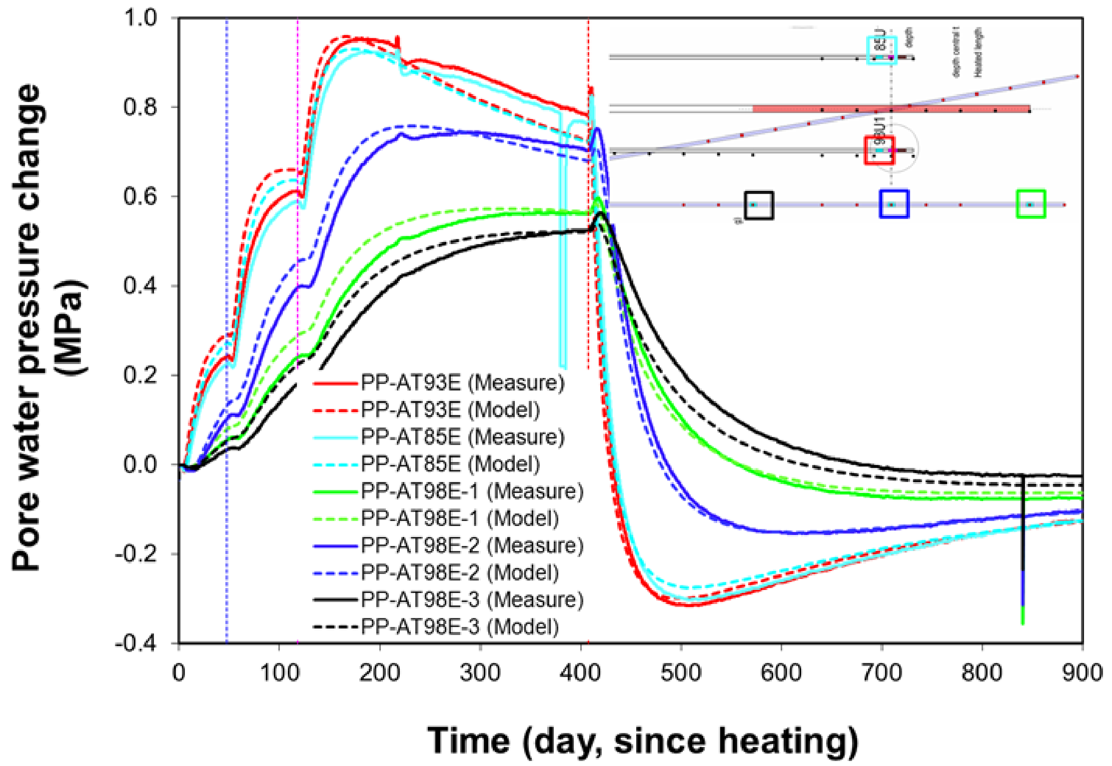

Figure 5 - Comparison of pore water pressure at some points between measurements and modelling

CONCLUSIONS AND IMPLICATIONS

The ATLAS small-scale in-situ tests (phase I - phase IV) were developed to assess the hydro-mechanical effects of the thermal transient on the Boom Clay. The tests provided a large set of good-quality, well-documented data on temperature, pore water pressure and total stress. Many noteworthy observations were made. The extended measurements of the temperature field provided clear evidence of thermal anisotropy. The tests had a simple geometry with well-defined boundary conditions and depended essentially on a single material (Boom Clay), which facilitated the comparison between the measurements and the numerical modelling. Successful reproduction, by numerical modelling, of the instantaneous but temporary pore water pressure decrease after increasing power and the temporary pore water pressure increase after cooling confirm the mechanical anisotropy of the Boom Clay. Good agreement between the temperatures and pore water pressures measured and the results obtained by modelling yielded a set of anisotropic THM properties, which increases confidence in the capability of current models and codes to satisfactorily predict the evolution of temperature and pore water pressure around disposal galleries (up to a distance of several gallery diameters) for heat-emitting high-level radioactive waste.

PUBLICATIONS

De Bruyn D., Serge L. - The second phase of ATLAS: the continuation of a running THM test in the HADES underground research facility at Mol. – In: Engineering Geology, 64(2002), pp. 309–316. - ISSN 0013-7952

François B., Laloui L., Laurent C. - Thermo-hydro-mechanical simulation of ATLAS in situ large scale test in Boom Clay. - In: Computers and Geotechnics, 36(2009), pp. 626-640. - ISSN 0266-352X

Chen G.J., Sillen X., Verstricht J., Li X.L. - ATLAS III in situ heating test in Boom Clay: Field data, observation and interpretation. - In: Computers and Geotechnics, 38(2011), pp. 683-696. - ISSN 0266-352X

