



DISPOSAL CANISTER SHOCK ABSORBER TESTS AND ANALYSIS

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ABSTRACT

In the Finnish final disposal plan the spent fuel canister will be transferred to an underground repository at 400-450 meters below ground surface by a vertical lift. This paper considers the postulated accident scenario where the disposal canister falls during transportation. In case of free fall, the 25-ton disposal canister can reach a velocity of 90 m/s before impacting the shock absorber. The shock absorber is designed to consist of cohesionless granular lightweight expanded clay aggregate (LECA) material that will decelerate the disposal canister in a controlled manner. By utilizing the IMPACT test facility at VTT Technical Research Centre of Finland, laboratory scale shock absorber tests have been carried out. A rigid scale model of the disposal canister was shot into a shock absorber pipe in a horizontal setting with a realistic velocity. A total of 21 tests have been carried out with velocities ranging from 38 m/s to 97 m/s using disposal canister scale models with diameters from 63 mm to 150 mm. Other dimensions in the testing were scaled correspondingly. The aim of the experiments and numerical analysis was to assess the behavior of LECA as shock absorbing material and determine both the required depth of the shock absorber and loading subjected to the disposal canister. LECA used in the tests had grain size of 4-10 mm. The test results show a clear trend of penetration distance increasing as the impact velocity increases and some scatter. No distinctive effect of the test scale was seen in the results.

INTRODUCTION

The spent nuclear fuel accumulated from the nuclear power plants in Olkiluoto and HÄstholmen in Finland will be disposed of in Olkiluoto. The repository facility complex will be constructed at Olkiluoto, and it will consist of two nuclear waste facilities. The two facilities are the encapsulation plant that is constructed to encapsulate spent nuclear fuel and the disposal facility consisting of the underground repository and other underground rooms and the above ground service spaces. The repository is planned to be excavated at a depth of 400 to 450 meters. Access routes to the disposal facility consist of an inclined access tunnel, and vertical shafts. The fuel is encapsulated above ground and transferred to the disposal facility in the canister lift that operates in a vertical shaft. The canisters are deposited in the deposition holes which are bored in the floors of the deposition tunnels. The canisters are then lined and covered with bentonite blocks.

This investigation is done for the operational safety assessment of the facility. One of the targets of this investigation is to give basic dimensioning information for the shock absorber structure that is planned to be added to the bottom of the about 450 m deep canister shaft, through which the spent fuel canisters weighting from 19 to 29 tons depending on the fuel type are lowered down to the repository level for disposal.

The behavior of the spent nuclear fuel disposal canister during impact caused by canister falling is studied in this paper as well as the behavior of the shock absorbing material. In the postulated accident scenario the disposal canister falls into the canister shaft shock absorber that is designed to be a cylindrical hole filled with cohesionless granular lightweight expanded clay aggregate (LECA). During

canister impact it will penetrate into the LECA shock absorbing material. The canister can experience high decelerations and contact loads and its structure may be damaged due to these loads.

The canister impact scenario was studied using a scaled experimental setup with the aim to model the behavior of the canister shaft shock absorber material and determine the loading caused to the disposal canister. The experimental tests are briefly presented in this paper followed by dimensional analysis to draw conclusions on the full scale disposal canister impact behavior. The usage of LECA as a shock absorber material was first discussed by Kukkola (2005). A more thorough discussion on the current experiments is presented by Kuutti et al. (2012). In that work the experiments were also studied numerically to assess in more detail the loading subjected to the disposal canister and the integrity of the canister during impact. Another aim of the studies is to provide information on the dimensioning of the canister shaft shock absorber.

LECA SHOCK ABSORBER TESTS

Experimental setup and test matrix

Shock absorber tests for LECA material were carried out in three different scales at the VTT laboratory facilities during 2011 and 2012. In these tests a rigid projectile representing the disposal canister was shot into a LECA filled shock absorber pipe in a horizontal setting. Impact velocities in the tests were in the range of 40 m/s to 90 m/s. LECA types used in the tests were KS410 (grain size 4-10 mm) and KS04 (grain size 0-4 mm). The results presented in this paper are those for LECA KS410. All test results are presented by Kuutti et al. (2012). The tests are similar to the tests reported by Kukkola (2005) but with higher velocity and a horizontal setting.

A schematic drawing of the test setup is shown in Figure 1. The testing instrumentation consists of force transducer to measure pipe end reaction forces, strain gauges at the pipe exterior surface to measure LECA internal pressure, laser sensors to measure canister projectile velocity prior to impact and a high speed camera to record the event. In some tests there was an acceleration sensor installed inside the canister mock-up to measure deceleration during the impact. In the tests with the smallest projectile the acceleration piston was not used but the canister was accelerated directly with compressed air.

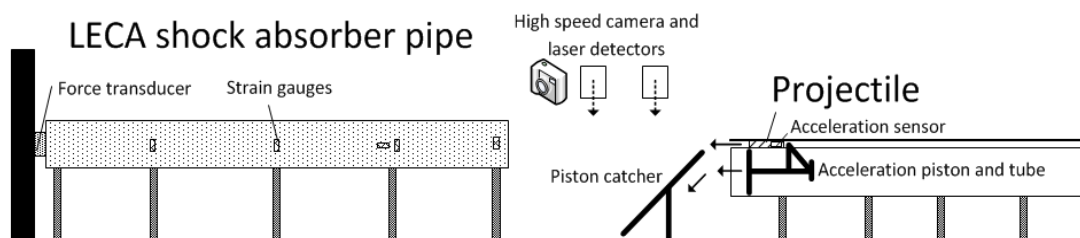


Figure 1. Schematic drawing of the test setup.

Table 1. Shock absorber pipe and canister properties for each scale of LECA shock absorber tests.

Shock absorber pipe diameter (mm)	Shock absorber pipe length (mm)	Canister diameter (mm)	Canister length (mm)	Canister mass (kg)
400	4000	63	430	5.3
600	7500	112	525	30.5
800	7500	150	685	71.3

Photographs of the test setup are shown in Figure 2 and Figure 3. The test setup where canister diameter was 63 mm is shown in Figure 2 and the test setup where canister diameter was 112 mm is shown in Figure 3. The test matrix for all LECA shock absorber tests is presented in Table 2. The penetration distances measured in each test that are the most important results are included in the table. In

the first 14 tests the LECA material was not watered and the shock absorber pipe was only filled and stirred between the tests. This may have altered the grain size distribution slightly. In the remaining tests LECA was watered completely and changed before each test. The watering simulates the leaking ground water of the bedrock disposal facility.



Figure 2. Test setup where shock absorber diameter was 400 mm and canister diameter 63 mm.



Figure 3. Test setup where shock absorber diameter was 600 mm and canister diameter 112 mm.

Test results

The canister projectile after impact is shown on the right hand side of Figures 2 and 3. Results indicated that granular LECA material decelerates the canister in a controlled manner and some LECA grains are crushed to smaller particles during impact. Closer inspection showed smaller or broken LECA grains are blended in with intact grains. In some tests the canister projectile did not maintain its orientation aligned with the shock absorber pipe axis during the impact and the projectile was located close to the upper wall of the pipe after the test. Because the LECA shock absorber was horizontally oriented, the self-pressure state in the upper parts of the pipe can be smaller than in the lower parts allowing the canister to travel with less resistance in the upper parts.

Canister impact velocity, penetration distance, LECA pipe support force and LECA pipe strains were measured in all tests. The penetration distances for each test are visualized in Figure 4. The plotted penetration distance results are scaled using the canister projectile diameter. Typical results obtained in the test series are shown in Figures 5, 6 and 7. These figures show the acceleration and deceleration measured within the canister projectile. The measured acceleration values are integrated with respect to

time to obtain projectile velocity and displacement during impact. The measured shock absorber pipe end support forces are included in the figures.

Table 2. Main test results for all LECA shock absorber tests.

Test	Shock absorber pipe diameter (mm)	Canister diameter (mm)	Canister mass (kg)	Impact velocity (m/s)	Penetration distance (cm)	Notes
1	400	63	5.3	38	124	Dry LECA
2	400	63	5.3	52	155	Dry LECA
3	400	63	5.3	65	194	Dry LECA
4	400	63	5.3	67	174	Dry LECA
5	400	63	5.3	66	150	Dry LECA
6	400	63	5.3	72	158	Dry LECA
7	400	63	5.3	86	201	Dry LECA
8	400	63	5.3	84	271	Dry LECA
9	400	63	5.3	65	169	Dry LECA
10	400	63	5.3	58	142	Dry LECA
11	400	63	5.3	84	205	Dry LECA
12	400	63	5.3	63	143	Dry LECA
13	400	63	5.3	88	220	Dry LECA
14	400	63	5.3	88	245	Dry LECA
15	400	63	5.3	87	203	Wet LECA
16	400	63	5.3	89	208	Wet LECA
17	600	112	30.5	73	345	Wet LECA
18	600	112	30.5	95	499	Wet LECA
19	600	112	30.5	97	544	Wet LECA
20	800	150	71.3	74	534	Wet LECA, LECA pipe rupture
21	800	150	71.3	57	299	Wet LECA

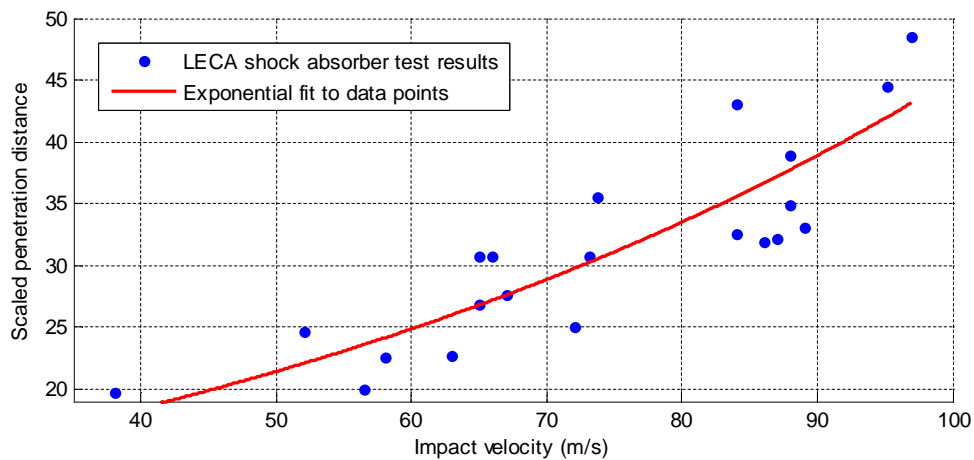


Figure 4. Canister mock-up penetration distances scaled with canister diameter for all LECA shock absorber tests.

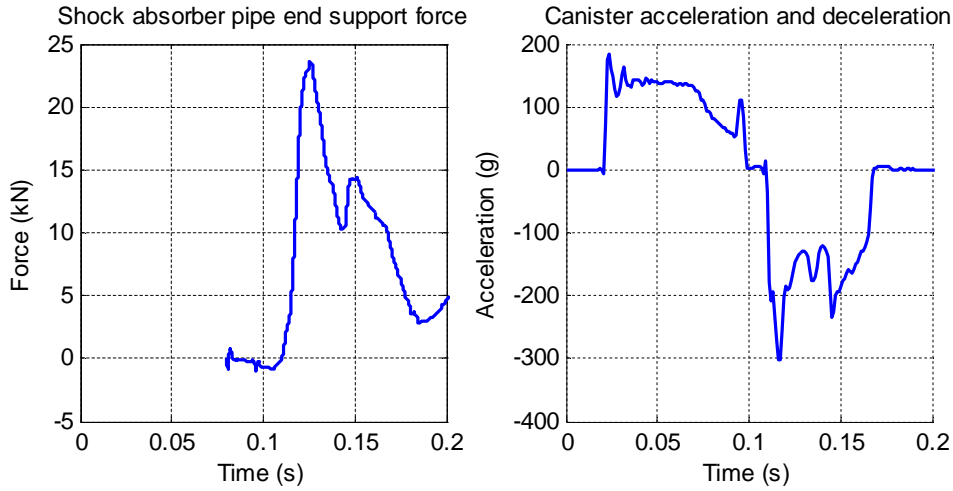


Figure 5. Shock absorber pipe support force and canister acceleration in test 14 where canister diameter was 63 mm, mass 5.3 kg and impact velocity 88 m/s.

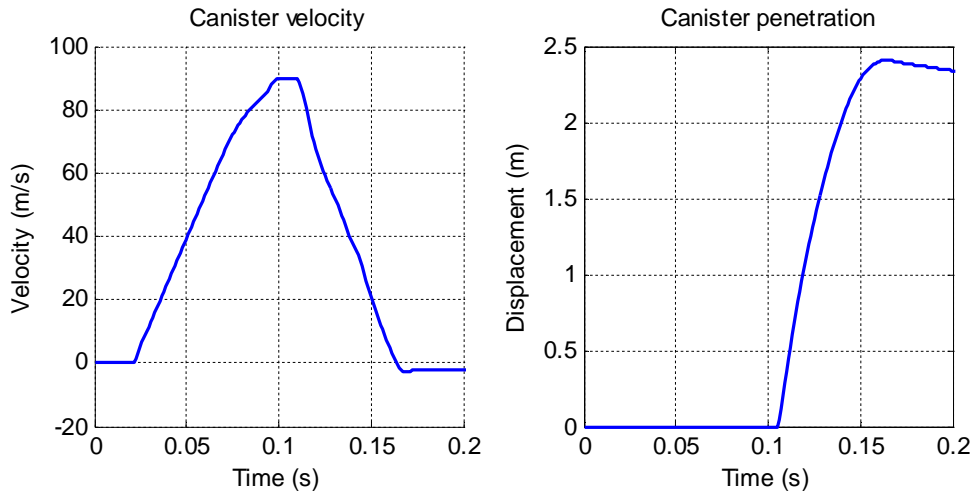


Figure 6. Canister velocity and movement in test 14.

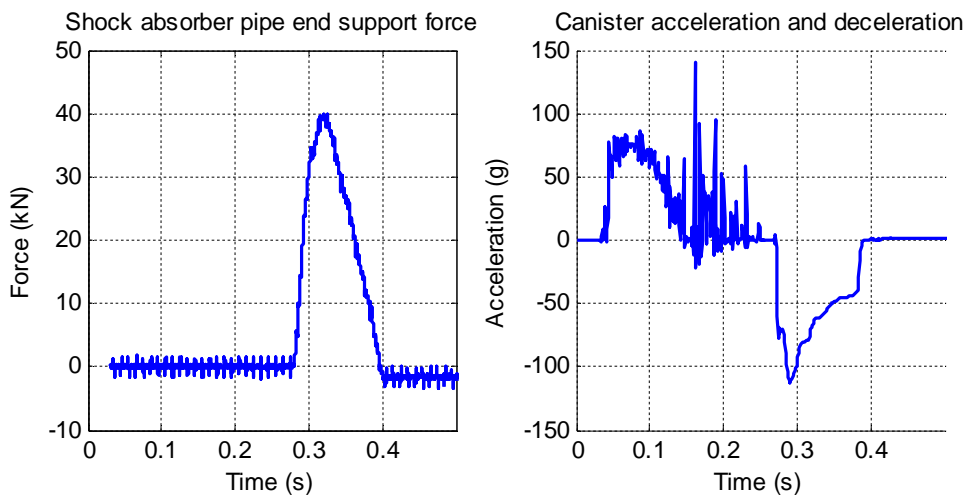


Figure 7. Shock absorber pipe support force and canister acceleration in test 17 where canister diameter was 112 mm, mass 30.5 kg and impact velocity 73 m/s.

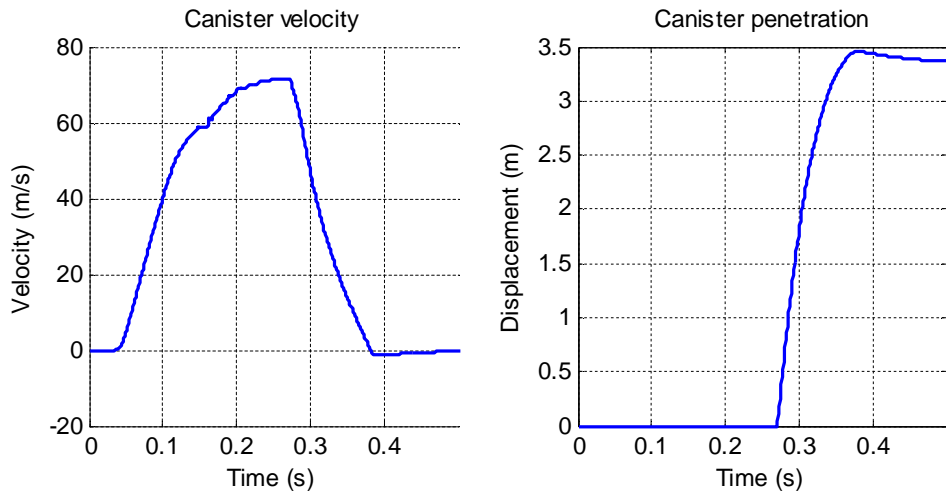


Figure 8. Canister velocity and movement in test 17.

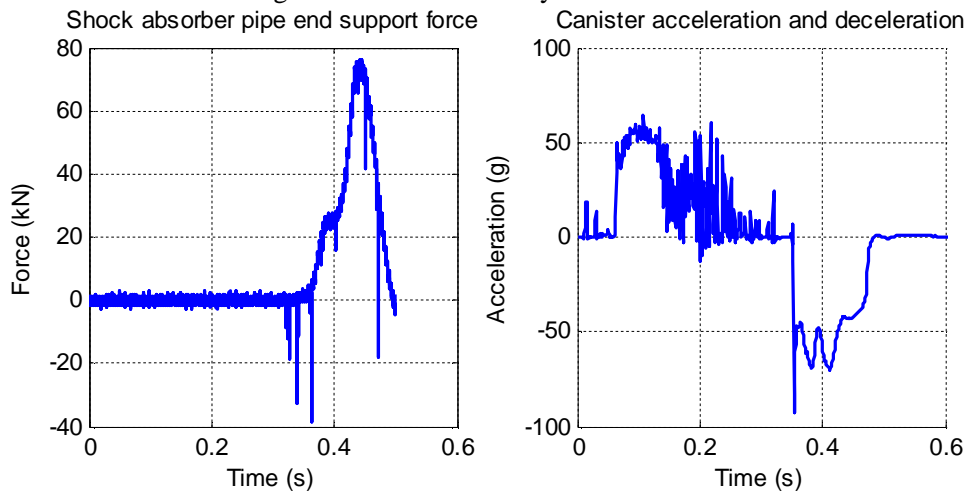


Figure 9. Shock absorber pipe support force and canister acceleration in test 21 where canister diameter was 150 mm, mass 71.3 kg and impact velocity 57 m/s.

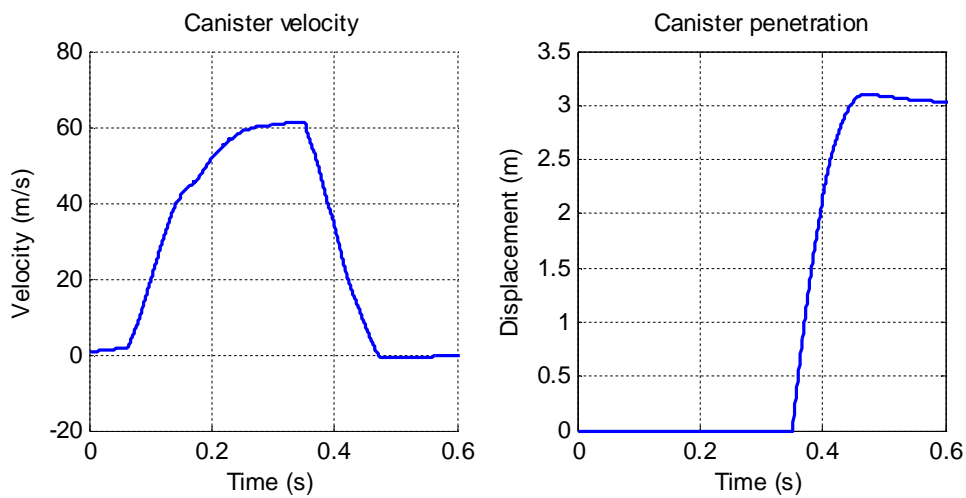


Figure 10. Canister velocity and movement in test 21.

DIMENSIONAL ANALYSIS

Basic dimensional analysis can be applied to make predictions on the full scale disposal canister impact behavior and assess whether the selected scaling assumptions hold. The dimensional analysis is based on the Buckingham π -theorem and it is used to form relations of physical quantities using their dimensions. See e.g. Gibbins (2011) for comprehensive review on the theoretical basis and applications of dimensional analysis. Now it is assumed that the canister impact to the LECA shock absorbing material can be characterized by one variable that in this case is the impact force F . We identify now that the following variables have an effect on the impact force: impact velocity V [m/s], canister diameter D [m], canister mass M_C [kg], canister length L_C [m], LECA elastic modulus E [Pa], LECA crushing strength σ [Pa], LECA density ρ [kg/m³], strain rate in LECA $\dot{\epsilon}$ [1/s], shock absorber width W [m], shock absorber height H [m], LECA viscosity μ [Ns/m²] and gravitational acceleration g [m/s²].

The canister impact force can be written as a function of the 10 parameters:

$$F = F(V, D, M_C, L_C, E, \sigma, \rho, \dot{\epsilon}, W, H, \mu, g) \quad (1)$$

The repeating variables are selected from the arguments of F to be D, V, σ as they characterize the scale effects, material effects and velocity effects. A π -term is solved for each variable by first writing out a product of the quantity and the repeating variables. We obtain the dimensionless groups listed in Table 3.

Table 3. Dimensionless groups for canister impact to LECA shock absorbing material.

Impact force $\pi_1 = \frac{F}{\sigma D^2}$	Canister mass $\pi_2 = \frac{M_C V^2}{\sigma D^3}$	Canister length $\pi_3 = \frac{L_C}{D}$	LECA stiffness $\pi_4 = \frac{E}{\sigma}$	LECA density $\pi_5 = \frac{\rho V^2}{\sigma}$
LECA deformation strain rate $\pi_6 = \frac{\dot{\epsilon} D}{V}$	LECA viscosity $\pi_7 = \frac{\mu V}{D \sigma}$	LECA shock absorber width $\pi_8 = \frac{W}{D}$	LECA shock absorber length $\pi_9 = \frac{H}{D}$	Gravitational acceleration $\pi_{10} = \frac{g D}{V^2}$

The selection of variables that affect the impact force and related subsequent analysis does not indicate the importance of each variable compared to the other variables. In order for the small scale testing to represent the full scale application accurately the most important dimensionless groups listed in Table 3 must be equal. The obtained dimensionless terms can be combined together to make new dimensionless terms that are as valid as those presented in Table 3.

The small scale and medium scale tests have been carried out nearly in scale with the full scale falling scenario, i.e. geometric similarity is satisfied for the main dimensions. Therefore terms π_3, π_8 and π_9 are satisfied by the test setup. The LECA material used in the tests is assumed to be identical to the LECA material designed to be used in the actual shock absorber. Also, the canister material is in a continuum sense identical in small scale and full scale indicating that the mass is related by the third power of scaling factor β . The material similarity satisfies term π_3 . By equating the dimensionless term π_5 for the small scale model to the same term for the full scale model we observe that the velocity should not be scaled, i.e. impact velocity for the small scale must be same as in the full scale scenario. Term π_2 provides the same information. When the material similarity is satisfied, analysis of the dimensionless term π_1 indicates that the impact force in small scale is related to the full scale impact force by β^2 .

There are however terms that are not satisfied by the test setup. If effects of the strain rate in the shock absorbing LECA material are important, equality of term π_6 requires that the velocity should be scaled by the geometric scaling factor. The same conclusion can be drawn from the viscosity related term π_7 which in fact combined with term π_5 gives the Reynolds number $\mu / \rho V L$ that is well-known in fluid mechanics. The term related to gravity, π_{10} , is also identified in fluid mechanics. Its square root is the

Froude number and equating it between the small scale and full scale models requires that the impact velocity must be scaled by the square root of the scaling factor.

All tests have been carried out assuming that viscous and gravity effects can be neglected and velocity was not scaled. Also, the grain size of the granular shock absorbing LECA material was not scaled in the model tests to keep the density and strength of the material constant in a continuum sense. These assumptions are now evaluated by comparing the test results in a dimensionless form. The penetration distances for different sized canister projectiles scaled with the canister diameter for all tests were shown in Figure 4. The non-dimensional results agree with the geometric scaling using the scale factor between different scales.

To produce a dimensionless force term using the known canister dimensions and masses terms π_1 and π_2 are combined to produce a dimensionless force $FD / (M_c V^2)$. Time axis is scaled using the impact velocity and canister projectile diameter as TV / D . This scaling is used to compare the measured support and contact forces in Figure 11. These results also agree with the scaling assumptions, although there are some deviations in the contact force calculated from the canister projectile deceleration.

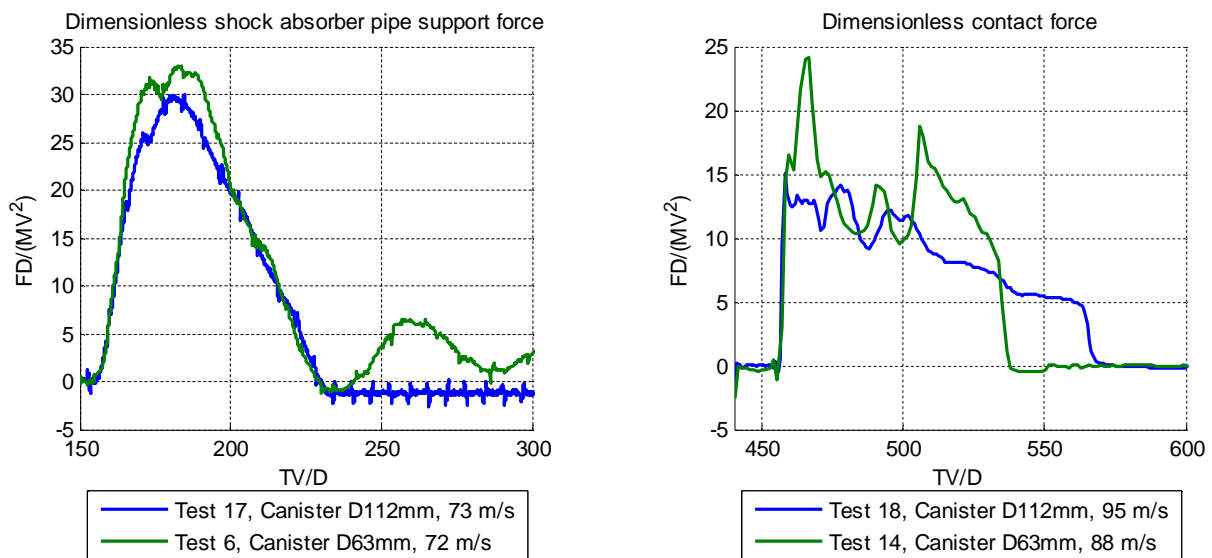


Figure 11. Comparison of non-dimensional support force and contact force for tests with different scales.

Now, assuming that the dimensional analysis presented above holds and assumption of geometric scaling is valid, the test selected test results presented in Figures 5-10 are transferred to full scale. Now it is assumed that the spent nuclear fuel disposal canister is a BWR-type canister designed to be utilized in the Finnish disposal scheme (Raiko 2012). In Posiva's design, the BWR-type disposal canister has a cylindrical shape with external diameter of 1050 mm, total length of 4752 mm and total canister mass of 24500 kg. Thus the scale used in scaling the test results ranges from 16.7 to 7.0. The results obtained in small scale tests 14, 17 and 21 transferred to full scale are presented in Figure 12.

The scaled results predict that the canister can experience contact loads in the region of 2.0 MN to 4.5 MN or deceleration from 8 g to 18 g. This yields to penetration distances in the region of 20 m to 40 m, depending on the initial velocity. Penetration distances and scatter can be assessed in more detail from the test results presented in Figure 4.

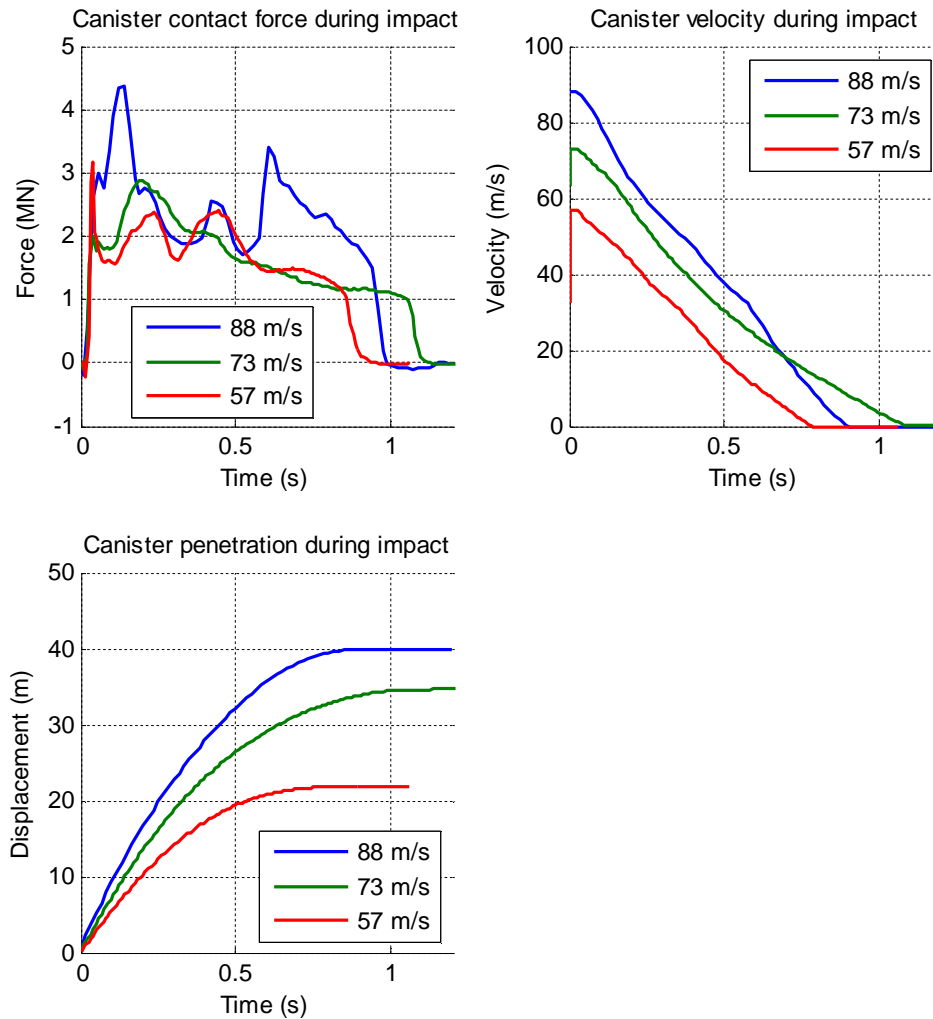


Figure 12. Results of tests 14, 17 and 21 transferred to full scale using dimensional analysis.

NUMERICAL SIMULATIONS

The canister projectile impact to LECA shock absorber has been also studied using explicit dynamics and finite element analysis. The numerical models utilize the Drucker-Prager-Cap model that is a traditional Drucker-Prager model typical for granular materials with an additional cap yield surface to model both the pressure dependent frictional shear and compaction at high pressures. In order to tackle the large deformations during canister penetration, arbitrary Lagrangian-Eulerian (ALE) adaptive computational technique is utilized. The most important material parameters for the LECA shock absorbing material that are the friction angle and stiffness and compaction behavior are obtained with experimental direct shear tests and compaction tests. The material was assumed to be cohesionless in the simulations. The details of the numerical aspects are presented by Kuutti et al. (2012) and are not repeated here.

The simulations are carried out for all test scales. Based on the calibrations done in the tests scale, the simulations are repeated for the full scale disposal canister impact scenario. The simulated canister penetration distances for all test scales and full scale are presented non-dimensionally in Figure 13. The simulations in part confirm with the dimensional analysis when predicting full scale disposal canister impact behavior.

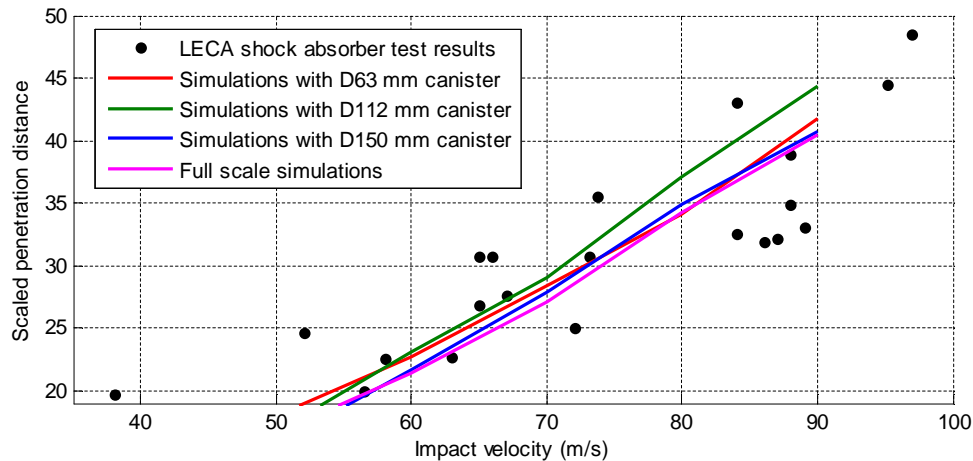


Figure 13. Scaled penetration distances obtained from the numerical analyses.

CONCLUSIONS

This work considers an accident scenario where spent nuclear fuel disposal canister falls during transport in a vertical lift shaft and impacts a shock absorber filled with granular LECA material. The impact scenario was studied using a scaled experimental setup. A rigid scale model of the disposal canister was shot into a shock absorber pipe in a horizontal setting with a realistic velocity. A total of 21 tests have been carried out with velocities ranging from 38 m/s to 97 m/s using disposal canister scale models with diameters from 63 mm to 150 mm. The aim of the experiments and numerical analysis was to assess the suitability of LECA as shock absorbing material and determine both the required depth of the shock absorber and loading subjected to the disposal canister. The tests with LECA shock absorber show a clear trend of penetration distance increasing as the impact velocity increases and some scatter. No distinctive effect of the test scale could be observed from the results. The effects of LECA watering fall within the scatter as well.

The scaling issues related to small scale testing and full scale canister impact were addressed with dimensional analysis. The analysis indicated that while there are scale related issues, the most important parameters can be scaled using the geometric scale factor. The non-dimensionalization of the test results from different scales supported this assumption. The tests have been numerically simulated using finite element analysis and explicit dynamics. The models were calibrated based on the experimental results and have been utilized in simulating the postulated full scale accident scenario for evaluating the loads subjected to the disposal canister during impact and required shock absorber depth. The simulations in part confirm with the dimensional analysis when predicting full scale disposal canister impact behavior.

The model testing combined with dimensional analysis and numerical simulations predict that in a full scale falling accident scenario the disposal canister penetration distance can be nearly 50 meters if the falling height is 450 meters. During deceleration the disposal canister can experience contact loads in the region of 2.0 MN to 4.5 MN or deceleration from 8 g to 18 g, depending on the falling height.

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