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MONITORING AND MODELLING UNSATURATED AND SATURATED FLOW TO EVALUATE PERFORMANCE OF SLURRY WALLS IN RHO (ITALY)

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ABSTRACT. *A former chemical district close to Milan (Italy) is still source of contamination by chlorinated solvents in aquifers that supply drinking water, though slurry walls were built in the eighties to prevent spreading. An unsaturated-saturated numerical model was performed to assess overall performance of this physical confinement, and to infer hydraulic properties and estimated geometry of the barriers and the aquitard at this specific scale. Water leaking from the source and recharge of the aquifer under different scenario simulation were assumed as global performance indicators. Results showed that incidental material buried in the shallower portion of the investigated aquifer (bricks, waste material) dramatically affect the natural recharge of the encapsulated area. The decrease of ratio between leakage from lateral barriers and leakage from the bottom interface to the aquitard, from early stages of wet conditions (when saturated front is higher) to drought stages, was also computed.*

RESUMEN. *Un antiguo polígono químico industrial cerca de Milán (Italia) es fuente de contaminación de disolventes clorados en los acuíferos explotados para consumo humano, aun cuando un sistema de pantallas enterradas fue construido en los ochenta para evitar desprendimiento. Un modelo numérico saturado-insaturado fue realizado para evaluar rendimientos del confinamiento físico, deducir propiedades hidráulicas y la geometría tanto de las barreras como del acuitardo a escala local. Como indicadores globales del rendimiento se asumieron el goteo de agua desde la fuente y la recarga del acuífero bajo distintas hipótesis. Los resultados demuestran que materiales incidentales enterrados en los horizontes someros del acuífero estudiado (ladrillo, material residual) afectan dramáticamente la recarga natural de la zona encapsulada. La disminución del radio entre goteo desde las barreras laterales y el goteo a través de la base del acuífero hacia el acuitardo, desde momentos iniciales con condiciones húmedas a condiciones de sequía, fue también calculada.*

1. INTRODUCTION

Vertical barriers have been used since the late 1970s for containment and environmental pollution control at hazardous sites. Some examples in Italy are given Rolle et al. 2009. The lifetimes of these systems, therefore, range from about 50 to 1000 years (Inyang 2004).

In this study, a specific two-year program of monitoring and testing both the vadose zone and the saturated zone, coupled with a numerical analysis, was performed to evaluate the overall performance of slurry wall systems for contaminated area containment. The activities were focused on finding out whether deficiencies in the integrity of the vertical barrier systems or the local geological conditions could be more likely to determine the release of contaminants into the aquifers.

Due to restrictions of the local Environmental Agency, all the activities have to be done using only noninvasive techniques on the slurry wall systems. The aim was to:

1) Assess failures in the containment systems, including deficient cut-off walls or inappropriate design of the geological scheme;

2) Estimate the water budget in an equilibrium state and the discharge/recharge behaviour,

3) Define reliable hydraulic parameters to support successive remediation action;

4) Obtain a quantitative evaluation of groundwater losses through the confined area, in order to support future analysis of the fate of chlorinated compounds released into the aquifers.

2. THE STUDY AREA

The former "Bianchi" chemical facility at the Rho district, located few km northwest to the city of Milan (Fig. 1A.) is a typical example of how the industrial growth in northern Italy that occurred over the last 50 to 70 years, together with the lack of specific laws on waste management, has contributed to the gradual depletion of vulnerable groundwater resources.

In the late 1970s, the first evidence of intense contamination with chlorinated compounds arose and the supposed main source was immediately confined in a specific area (Fig. 1B) through the construction of vertical slurry cut-off walls keyed into a low hydraulic conductivity layer (aquitard). The geometry and the characteristics of the containment system are only partially known, but it is commonly referred to as a "sarcophagus-shape" polygon (Figs. 1B), keyed into the aquitard. The composition is composed of typical cut-off slurry backfilled walls.

An hydraulic barrier was set only much later, in 2006, as an additional remediation system,. However, in 2007, concentrations of chlorinated solvents were measured up to 110 mg/l near the source at the area of the former "Bianchi" chemical facility, in the southern side of the municipality. Pollution has been detected within a depth of 45 m. The vulnerable aquifer is the uppermost, multilayered aquifer (A), which is commonly detected within a depth of 60 m in the whole western part of the Milan province. However, several fine layers with low hydraulic conductivity divide this layer into two semi-confined aquifers (A1 and A2), even if, in some zones, the subunits merge because of a thickness reduction or local lack of such low conductivity horizons. On the top of the A1 aquifer, an unconfined (or sometimes perched) aquifer (A0) occasionally appears. This A0 aquifer has a variable depth (7-9 m from the ground surface), and overlays a semi-permeable, discontinuous aquitard.

At the former chemical domain scale, the discontinuous geometry of the aquitard, and the consequent dependence on DNAPL migration to small-scale anomalies, are already shown in Pedretti et al. (in press). The recharge of aquifers is mainly due to precipitation and irrigation water (with a period going from April to mid October), while the contribution of the small river crossing the area is negligible (Alberti et al. 2007). Within the containment area, recharge is given by precipitation only, even if the nature of backfilling dramatically affects the recharge rate and dynamics, as described later.

Focusing on the containment system, some aspects become strategic in the conceptual model describing the general water balance. The aquifer connections and the recharge/discharge relationship through the vadose zone affect DNAPLs fate in the groundwater, involving various aspects of the migration of contaminants (acting physical and chemical properties of the compounds). Large uncertainties are thus associated with the vertical barrier system, especially in term of its hydraulic conductivity, that have never been tested in the past and that are not possible to test currently due to the risk of enhancing contaminant migration in the subsoil.

Only a small amount of historical monitoring data was available; moreover, these data were extremely discontinuous and basically were not very useful. The only reliable and available historical data were the chlorinated compound concentrations in wells and in piezometers downgradient from the containment area.

At the Rho site, the high and continuous contaminant concentrations in groundwater indicated that the containment system seems to have lost its effectiveness since it was constructed in 1981. Two possible conceptual models are most likely to explain this:

1) A consistent flow occurs outward from the encapsulated area due to lateral spreading and the fact that the aquitard is almost impermeable below source area; the A1 aquifer is polluted by deepening of DNAPLs through discontinuities in the aquitard, and from long-term diffusion processes;

2) Flow comes from lateral spreading directly into the A0 aquifer, and into the A1 aquifer through the bottom aquitard. The integrity and efficiency of the lateral barrier is contrasted by poor hydrodynamic efficiency of the geological barriers.

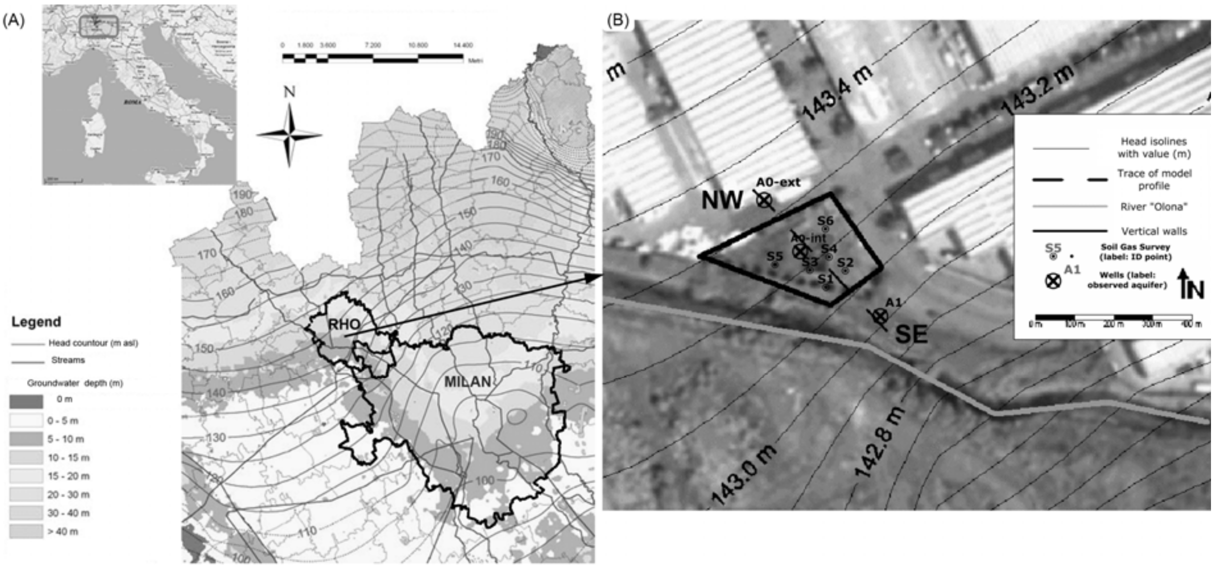

Figure 1. (A) Location of the area and main hydrogeological features (mod. from www.provincia.milano.it); (B) Synthetic sketch of the local set-up, depicting piezometric isolines (m) of the A0 aquifer (taken from regional piezometry), SEEP model A'-A trace; the relative position of observation wells and small boreholes.

3. DATA COLLECTION: IN-SITU MONITORING AND LABORATORY TESTS

A two-year monitoring and testing program was developed, due to the need to obtain the necessary information in order to increase the knowledge of the contaminant migration and to support the ultimate remediation design.

Because the major uncertainty came from the unknown geometry and permeability of the barrier, there was a need to deeply investigate the geological features of both the vadose zone and the saturated domain in the source area. To avoid the risk of further spreading the contamination by direct surveys in the slurry wall, a monitoring system of both the vadose zone and the aquifers was designed in order to support the definition of a reliable conceptual model (Hudak and Loaiciga 1999). The system was also used for groundwater modelling in the unsaturated and saturated conditions (Chen et al. 1999). Standard monitoring of groundwater level and contaminant concentration of the A0 and A1 aquifers and a specific detailed program of activities was planned within the encapsulated Zone 1, as following described.

1) Drilling six small boreholes with the direct push technique, to the maximum depth of 3.6 m, for a detailed reconstruction of the stratigraphy of the vadose zone, including the partial recovery of drilled

soils. Deposits in Zone 1 resulted very heterogeneous, probably due to the different nature of backfill used and to the presence of the remains of ancient anthropogenic structures in the subsoil. At a depth of approximately 1-2 m, an undistinguished, fine, reddish horizon can be found locally; it is mainly constituted by bricks and other waste material (Fig. 5). This horizon is not continuous and has also been found randomly in the containment area during some surveys performed in the past;

2) Performing double-ring infiltrometer tests to determine the vertical saturated conductivity of superficial soils, and pumping and slug tests on aquifers and aquitard A0-A1. The surficial layer showed different degrees of compaction. This significantly affects infiltration at a local scale, even if the actual influence of this factor on the overall infiltration in zone 1 needs to be investigated through a numerical analysis. Overall results are presented in Table 1

3) Installing two instruments, based on the frequency domain reflectometry (FDR) technique, with four probes each, located at different depths and connected to a recording device for the automatic monitoring of soil moisture content to a maximum depth of 150 cm. Column 2 (EVS2) was located in a sector with the anthropogenic fine and strongly consolidated deposits. Probes at 90 and 120 cm depth (EVS2_90 and EVS2_120) indicated almost constant soil moisture content, probably because these deposits remained almost constantly saturated during the period due to their low hydraulic conductivity (the functionality of probes was manually tested with occasional surveys). A different problem was seen for the 30 cm depth probe (EVS2_30), which showed an unrealistically fast response to precipitation, probably due to preferential flow (poor adhesion of the sensors to the soil at low depth).

4) Installing three tensiometers at different depth for the measure of porewater pressure in the vadose zone (manual reading) to a maximum depth of 120 cm.

5) A recording station for temperature and rainfall.

6) Standard laboratory tests on sampled soil have been done, including grain size analysis, organic content, specific weight and permeability tests. These operation were carried out in order to better characterize the stratigraphy of the upper 3.6 m and to obtain data to indirectly derive the hydraulic function of sediments in the vadose zone.

7) Groundwater heads monitoring. The aim was to detect different hydraulic behaviours of the inner and outer zones of the isolated A0 aquifer, in comparison with the A1 aquifer. Measurements in a long, dry period allowed us to observe that the progressive decrease of groundwater head at points A0_int, A0_ext and A1_ext occurred with three different rates (Fig. 9). As they were not influenced by external factors such as precipitation or well pumping, they were considered optimal for model calibration.

3. THE NUMERICAL MODEL: SETTINGS AND CALIBRATION/VALIDATION

We developed a finite elements model using the code SEEP/W (GEO-SLOPE Intl. 2002). The conceptual model used in the numerical analyses covers the entire containment (about 25 m width, see Fig. 2), up to an average depth of 30 m, and according to the local hydrostratigraphic scheme, the model is composed by : 1) a shallow aquifer (A0), from the ground surface to a depth of 9 m; 2) a fine-grained aquitard (A0-A1), which divides A0 from the lower semi-confined aquifer and has been located from a depth of 9 to 11 m; 3) the second main aquifer (A1), from a depth of 11to 30 m; and 4) the lowest fine-grained aquitard (A1-A2), up to a depth of 33 m.

For the top layer, a finer vertical discretization was chosen to take into account the upper, thin heterogeneities and to increase the ability of the model to effectively evaluate their influence on the recharge dynamics. For the first attempt, the layer was divided according to the position of the device sensors for the water content and tensiometers.

The vertical barrier is represented by means of fine-grained materials located from the top surface to a depth of 9.30 m (30 cm inside the aquitard, to represent the keying). The barrier system is 17-meters-wide, and occupies one-third of the total depth of aquifer A.

The profile is oriented along the local groundwater flux in the A0 and A1 aquifer, according to Pedretti et al. (in press). An imposed-valued function (Dirichlet conditions) was adopted as boundary conditions on the lateral sides. SEEP/W allows the use of "infinite elements" to simulate far conditions, limiting border effects on the model (GEO-SLOPE Intl. 2002). The bottom side has an imposed derivative function (Neuman condition), for which no flux was assigned for this problem, since leakages through the second aquitard are considered negligible

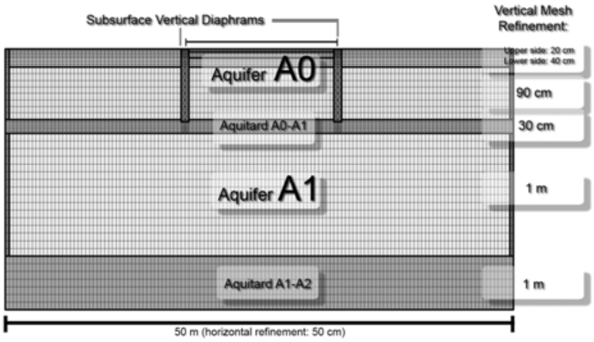

Figure 2. Hydrogeological conceptual model for numerical analysis

Calibration and validation were followed though trial and error procedure. Different sets of data, derived
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from the monitoring activities, have been chosen for optimisation.

1) Agreement with pore-water pressure obtained by tensiometers monitoring and with soil moisture content measured by means of electric probes (steady state): soil moisture content and pore-water pressures have been used, and the model was considered calibrated when there was a good agreement (residual lower than 5%) between experimental and calculated data. Soil retention curves were changed to reach this result, where points with the pair of pore-water pressure and soil moisture content measured at the same depth in the same time were considered as fixedand to validate the model

2) Agreement with head values in observation boreholes close to the studied domain (transient state): a long, dry period was chosen in order to recreate a groundwater head drawdown trend of the system (drainage conditions) The outputs of the transient state simulation were verified by comparing the observed exhaustion curve in aquifer A0 piezometers and the computed head.

Example of good fitting of simulated vs. observed data are show in fig. 3. The simulated soil moisture content fits when a fine-grained layer was assumed at a shallow depth into the soil (Fig. 3A,B for different temporal moments). This layer was configured with high moisture content and abrupt transitions to upper and lower horizons. he first shallow layer of the model a saturated hydraulic conductivity Ksat= 5·10-6 m/s; unsaturated hydraulic parameters were then derived from typical low-permeability materials, for example, adopting retention curves that showed a softer decrease of hydraulic conductivity with suction. In this case, however, volumetric soil moisture content holds saturation close to 100 %, and the retention curve is not influential. Initial parameter values were assigned according to laboratory measurements and the in situ test results described in the previous paragraph. Also, for the vertical barriers, since no hydrodynamic information was available, an initial range of low-permeability values from 5·10-7 m/s (i.e., similar to the aquitard vertical conductivity evaluated by laboratory test) to around 5·10-9 m/s (typical values of well-consolidated slurry cut-off walls) was considered.

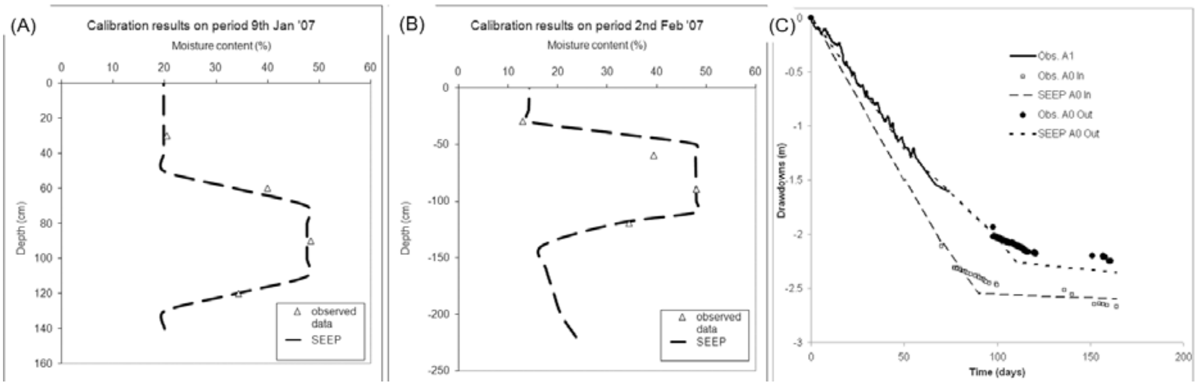

Figure 3. (A),(B) Results of model calibration for unsaturated flow in two time periods; (C) Observed and simulated drawdown data at two observation points. Value 0 (zero) on drawdown axis represents the reference data measured in the aquifers at the beginning of the drawdown phase.

4. MODEL RESULTS ON WATER LEAKAGES AND RECHARGE AMOUNTS

Water release incidents occurring from the isolated zone were assessed by evaluating flux sections on the lateral and bottom surfaces of the isolated area. An average value (the integral) of the total leakage from one boundary was then calculated. Figure 4 shows a synthetic plot of calculated water leakage. While values at the bottom surface seem to maintain a generally stable amount at 0.5 m2/d during the simulation, lateral values seems to decrease from an initial 0.75 to 0.65 m2/d in the simulation time (180 days), delivering a general reduction of about 20% in terms of lateral vs. bottom spreading ratio. It is interesting to note that losses are generally higher through the slurry walls, with values reaching about 18 m3/d, while the discharge through the bottom is about 13 m3/d. This gives a value for total losses of more than 30 m3/d, which represent a significant amount of contaminated water released by the containment system.

Two simple scenarios were set up to compare significant differences in infiltration contribution from recharge at the ground surface, when the hydrogeological background was maintained with conditions identical to the calibration processes, i.e. occurrence of buried waste materials (scenario A) and when the same Neuman boundary conditions are applied to a homogenous aquifer.

The results revealed the importance of the human impact in the dynamics of aquifer, affecting the vertical recharge profile, and thus the calculated leakages, both through the lateral and bottom sides. Figure 11 shows that leakages from lateral conditions are much higher in the case of incidental heterogeneities in the soil (case A, dark continuous line) than in the case of homogeneous conditions (case B, grey continuous line). On the other hand, the homogeneous aquifer (case B) reacts promptly to instantaneous recharge; bottom leakages react quickly, but then reach an asymptotic value close to 0 m2/d. Only lateral flux exists, but lateral leakages become stable at least until the end of the simulation.

For the heterogeneous case (A), leakages react later but asymptotic values with non-negligible values are obtained. This behaviour contrasts with the assumed hypothesis that in homogeneous conditions (B), infiltration could have been more effective, reaching the bottom of the aquifer, and generating bottom flux. On the other hand, higher values are obtained from lateral spreading in heterogeneous case (A). We can give a physical explanation assuming that the heterogeneous layer, made up by impermeable but saturated media, acts as a "barrier" which makes preferential paths diverge in lateral directions rather than vertically downwards. Since it is located at shallower depths, water avoids infiltrating into larger unsaturated volumes, which would retain more water and take longer for enough soil moisture content to accumulate in order to permit gravitic seepage. Therefore, since fewer volumes are affected, seepage occurs rapidly and diverges.

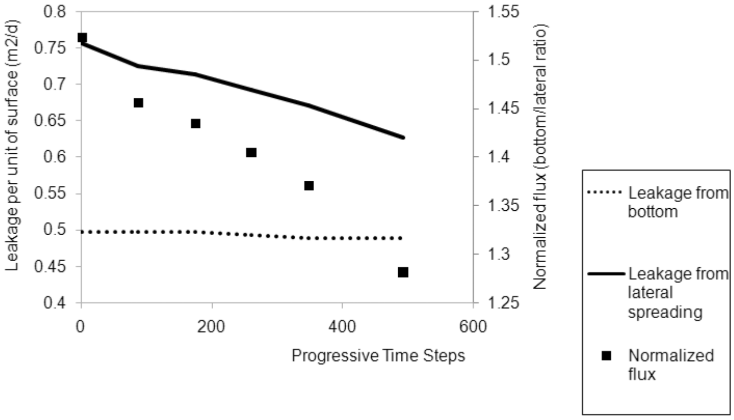

Figure 4. Leakage through the containment system

5. DISCUSSION

The results showed that the poor global performance of the containment system stems from a lack of knowledge about the geologic structure of the area. In fact, a remarkable exchange between the inner and the outer part of the confined source area occurs through the aquitard horizon. The slurry walls seem to have lost most of their containment properties and presently they have almost the same amount of losses as the aquitard. However, it is probable that in the past, when walls were close to the top of the performance, they may have played a role as a funnel and allowed the plume to head even more directly towards the lower layers. The lack of any other remediation system coupled with the main system contributed to the development of the present groundwater contamination in an extended area. This indicates, firstly, the need for a revision of the existing remedial action, which can be effectively designed only with the addition of reliable knowledge of processes analysed and quantified, both in the vadose zone and in the aquifer, through a complete and calibrated numerical model. Other, further enhancements may include a better knowledge of the spatial distribution of heterogeneities in the soils. This is remarkably important, especially for anomalous features, to better assess the local influence of infiltration to the general behaviour of the source area. Further solutions by indirect analysis (via numerical method) allowed us to estimate the approximate assets of the subsurface engineering structures. The system seems particularly sensitive to:

1) The state of the slurry walls, in terms of hydraulic retention capacity;

2) The geometry and the extension of the aquitard on a detailed spatial scale;

3) Abrupt changes in the composition of the soil, due to the presence of waste backfilled materials.

Slurry walls are only partly responsible for the lack in performance of the containment system. A non-negligible flux takes place through the aquitard and inevitably contributes to the spread of the plume. Waste backfill could intervene in the alteration of the natural infiltration process of the encapsulated aquifer. The low transmissivity of this fine-grained horizon, even if it is located in heterogeneous and isolated spots, tends to reduce and delay the water infiltration into the shallow confined aquifer.

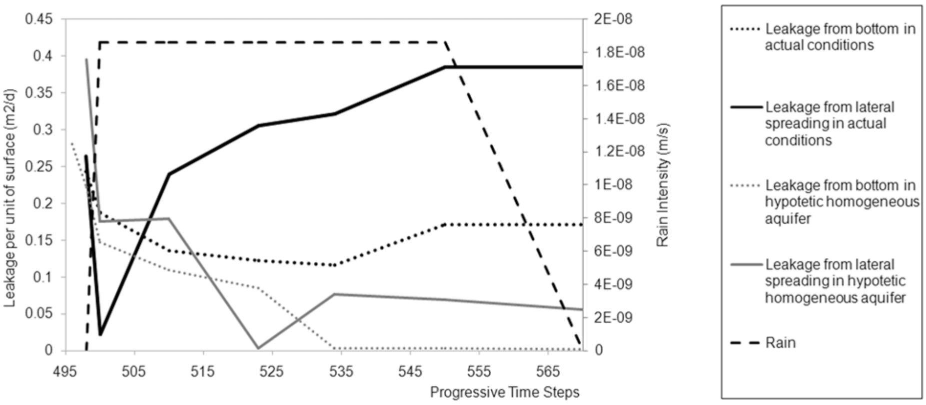

Figure 5. Leakage through the containment system under recharge for different scenarios

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