## Greek Letters

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| $\alpha$ | brine thermal-expansion coefficient, $^o$C$^{-1}$ |
| $\beta$ | cavern compressibility factor, Pa$^{-1}$ |
| $\beta_g$ | gas compressibility factor, Pa$^{-1}$ |
| $\beta_{pore}$ | salt pore compressibility factor, Pa$^{-1}$ |
| $\dot{\varepsilon}$ | cavern brine volume-change rate at constant pressure, $s^{-1}$ |
| $\dot{\varepsilon}_{creep}$ | creep rate, s$^{-1}$ |
| $\dot{\varepsilon}^t_{creep}$ | transient creep rate, s$^{-1}$ |
| $\dot{\varepsilon}_{dis}$ | relative volume-change rate due to dissolution, s$^{-1}$ |
| $\dot{\varepsilon}_{perm}$ | relative brine seepage rate through cavern walls, s$^{-1}$ |
| $\dot{\varepsilon}^t_{perm}$ | relative transient brine-seepage rate, s$^{-1}$ |
| $\dot{\varepsilon}_{therm}$ | brine thermal expansion rate, s$^{-1}$ |
| $\eta$ | fluid dynamic viscosity, Pa s |
| $\phi$ | porosity of rock salt |
| $\rho$ | nitrogen density, kg/m$^3$ |
| $\rho_b$ | brine density, kg/m$^3$ |
| $\rho_f$ | fuel-oil density, kg/m$^3$ |
| $\Sigma$ | annular space cross-section area, m$^2$ |
| $\theta_o$ | brine temperature at the end of leaching, $^o$C |
| $\theta_R$ | natural rock temperature at cavern depth, $^o$C |
| $\chi$ | ratio between gas density and gas pressure, kg/m$^3$/Pa |

## INTRODUCTION

Tightness is a fundamental prerequisite for many underground works where minimum product leakage is required. Natural gas is stored in depleted reservoirs or aquifers; LPG is stored in unlined galleries; and various hydrocarbons, from hydrogen and natural gas to crude oil, are stored in salt caverns. Nuclear waste are planned to be disposed of in deep geological formations. Salt caverns are also being considered as disposal sites for non-hazardous wastes (Veil et al., 1997) or tritiated waters (Bérest et al., 1997). Abandoned oil-production wells must be sealed efficiently to avoid later circulation of fluids between layers that were separated by impervious layers in the natural configuration.

The aim of tightness has no absolute nature, but, rather, depends upon specific sensitivity of the environment and the economic context. Radionuclides become harmless after a certain period of time: provided the process is slow enough, penetration of nuclides into the rock mass adjacent to the disposal galleries may not impair storage safety. Air, natural gas, butane and propane are not poisonous from the perspective of underground-water protection: the leakage of sufficiently diluted natural gas into underground water has minor consequences for water quality. This would not apply to other products, such as crude oil.

From the viewpoint of ground-surface protection, the most significant risk is the accumulation of flamable gas near the surface. In this situation, gases that are heavier than air (propane, ethylene, propylene) are more dangerous than natural gas.

The economic viewpoint depends basically on the speed of the stock rotation and the nature of the products stored. For example, when storing compressed air to absorb daily excess electric power, a loss of 1% per day can be considered as reasonable. When storing oil for strategic reasons, (e.g., oil which will be used only during a crisis), a loss of 1% per year is a maximum value.

In this paper, we will focus on the tightness of salt caverns used for storing hydrocarbons. The paper is divided in five parts. Part 1 explains the main factors contributing to the leakage (fluid pressure distribution, geological environment and well architecture), and a typical accident is described. The second part concerns tightness testing; a list of the main factors contributing to the misinterpretation of tightness tests is provided. In Part 3, this is applied to the “fuel-oil leak test” and an example of a very accurate in-situ test is described. Part 4 proposes a mathematical theory for the “nitrogen leak test” and Part 5 describes an actual test aimed at validating this test method and the equations deduced in Part 4.

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