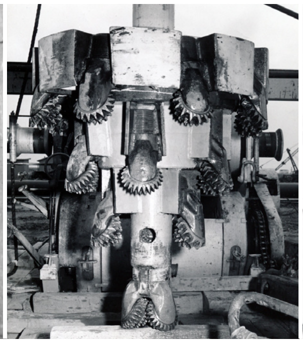

Underground Storage Caverns

Introduction

Currently there are two locations in New Jersey where underground storage caverns, hundreds of feet below the surface, store petroleum products. One is at the Phillips 66 Bayway Refinery in Linden, Union County and the other is at the former E. I. DuPont de Nemours and Company, DuPont Repauno Works in Gibbstown, Gloucester County (fig. 1). These caverns were not excavated to obtain minerals. Instead, they were dug in order to create a void for the temporary storage of liquid petroleum gas (LPG) at Linden and anhydrous ammonia at the Gibbstown site. LPG is a product of natural gas processing as well as petroleum refining and it refers to propane and butane.

Propane is commonly used as a fuel and butane is blended into gasoline as an additive. In winter, the demand rises dramatically when the weather is cold, then demand for these products declines as the weather gets warmer. Excess production in the summer is stored to meet peak winter demand. Underground storage of LPG plays a critical role throughout the United States in maintaining the reliability of gas supplies and ensuring stable prices for consumers. Millions of barrels of LPG are safely stored throughout the United States in underground caverns until it can be sold.

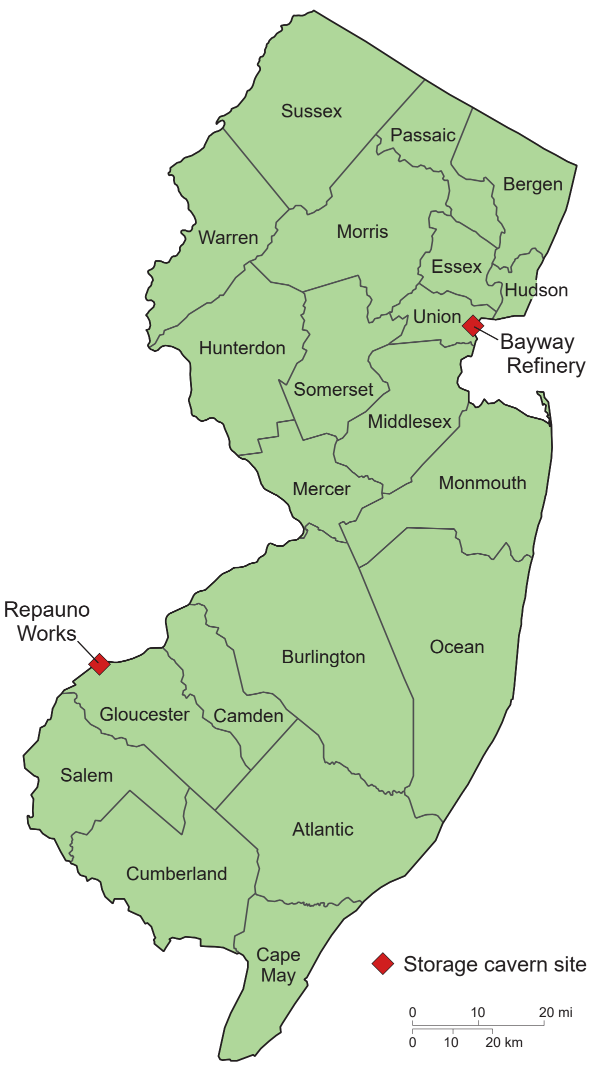

Figure 1. Underground liquid petroleum gas storage sites in New Jersey.

Hard Rock Storage Caverns

Initially in the United States, LPG was stored underground in dissolved out salt domes on the Gulf Coast. In 1950, a chamber dissolved out of a salt bed in the Keystone oil field of Winkler County, Texas, was the first project of any practical significance. The project received wide publicity because it was an immediate success and proved the favorable economics of underground storage (Interstate Oil Compact Commission, 1955). The mining of hard-rock storage caverns for LPG was pioneered in the United States in 1950, when the first mined cavern was completed in a shale formation in Texas (Lindblom, 1989). In 1957, a report by the National Petroleum Council, *Underground Storage for Petroleum,* advocated expansion of underground storage of LPG for economic and national security reasons. As of 2017, there were at least 70 mined hard rock underground caverns in use for storing petroleum products in the United States with the majority located in the eastern half of the country (Site visit, Robinson Butane Cavern No. 1. Marathon Petroleum Company, April 11, 2017)

Most of the mined hard rock LPG storage caverns in the United States, including the caverns at the Phillips 66 Bayway Refinery and the Repauno Works in Gibbstown, were designed and constructed by one company, Fenix and Scission, Inc. They were a pioneer in the construction of underground storage facilities for petroleum products.

Hard-rock caverns are excavated from various rock types including granite, gneiss, limestone, dolomite, chalk, sandstone and shale. One of the basic requirements to create a hard-rock underground cavern for LPG storage is that the rock is competent; in other words it needs to be strong enough to support the weight of overlying material. The mining process requires several shafts to allow access during construction. A narrow shaft provides both access for the miners and waste rock removal, and separate ventilation and escape shafts are required. The site chosen for underground storage caverns also needs available surface space nearby for disposal of the excavated material.

In addition to the requirement for cavern stability, the main challenge comes from the prevention of LPG leakage. In unlined rock caverns the design uses the principles of permeability control and hydraulic containment (Grøv, 2006). Permeability control means that leakage control is achieved by maintaining a specific low permeability of the rock mass. This can be achieved by locating the rock caverns in a rock that is naturally tight enough to satisfy the specified permeability. If the rock units are discontinuous and contains numerous joints, faults, or other more permeable zones, the permeability control can be preserved by artificially creating impermeable zones or barriers surrounding the rock caverns by a) grout sealing the most permeable discontinuities in the rock mass; or b) lowering the rock temperature enough to freeze the free water in the rock mass or c) a combination of both methods (Grøv, 2006). Hydraulic containment utilizes the fact groundwater is present in discontinuities (joints and cracks) in the rock and that this groundwater has a static head that exceeds the internal storage pressure. In practical terms it means that there is a positive groundwater gradient towards the storage cavern. In general, sufficient groundwater pressure is obtained by a) a deep-seated storage location which provides the sufficient natural groundwater pressure, or b) by an additional artificial groundwater such as provided by 'water curtains' and similar arrangements. This hydraulic control results in groundwater leaking inwards toward the cavern preventing the product from leaking outward (Site Visit, Robinson Butane Cavern No. 1. Marathon Petroleum Company, April 11, 2017).

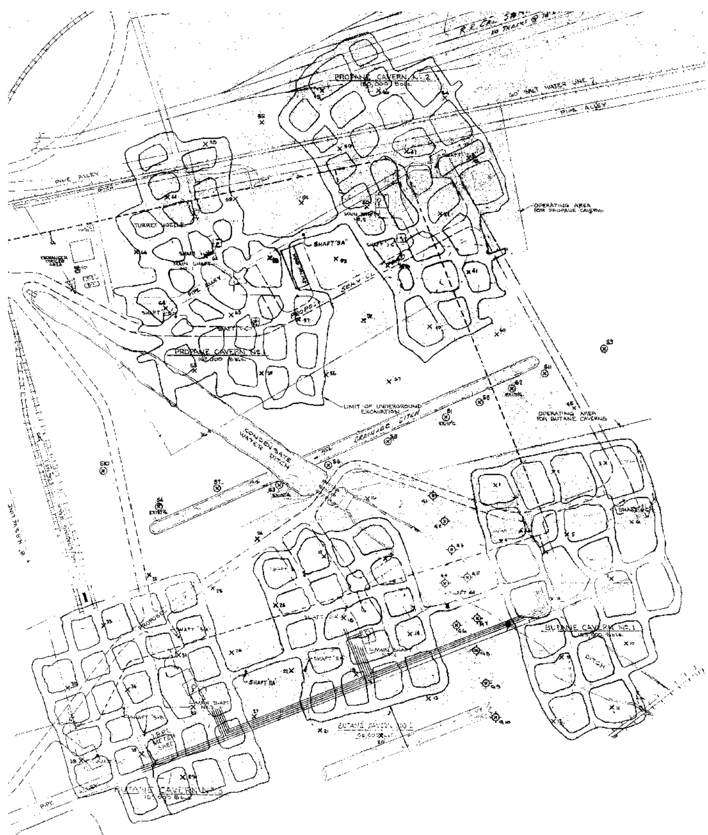

Figure 2. *Propane and Butane Caverns, Location of Observation Shafts*, Esso Standard Oil Company, Bayway Refinery, Linden, NJ. May 20, 1959. Map on file at the New Jersey Geological and Water Survey.

Bayway Refinery

In New Jersey, the excavation and operation of underground storage caverns is governed by a 1951 law, (P.L. 1951 ch. 80; see NJSA 58:10-35, seq). New Jersey's first underground storage caverns were built to store propane and butane in Linden at the Bayway Refinery between 1954 and 1958 by the Esso Standard Oil Company. The Bayway refinery opened in 1909 and is now owned by Phillips 66. At Bayway there are a total of five caverns. two butane and three propane which have a total storage capacity of 705,000 barrels (29.61 million gallons) of LPG. The caverns are constructed in the Passaic Formation (shale, siltstone and sandstone) and consist of honeycombs of tunnels separated by large rock pillars to maintain overhead stability (fig. 2). The distance between the propane and butane caverns is about 160 feet. Construction was by conventional room and pillar mining with the rooms being 15 feet wide and 18 feet high. Supporting pillars were 45 feet square. Roof control was achieved by the utilization of roof bolts on a four by four foot pattern (Cobbs, 1975). Liquid fuels such as propane and butane are by-products of petroleum refining. The Bayway caverns are filled with product created at the on-site refinery.

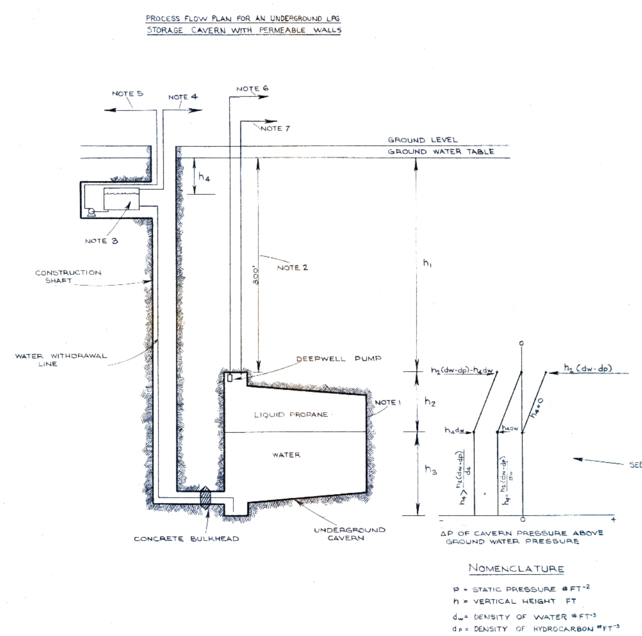

Figure 3. *Process Flow Plan for an Underground LPG Storage cavern with Permeable Walls,* Esso Standard Oil Company, Bayway Refinery, Linden, NJ. 1954. Map on file at the New Jersey Geological and Water Survey.

At Bayway, the LPG is contained in the caverns by the hydrostatic pressure of the surrounding rock (fig. 3). The liquefaction may be realized by pressurization or cooling. Propane exists in its liquid form at or below its boiling point (-44°F) or when pressurized to 172 PSI at 100 F. Butane becomes liquid at about the freezing temperature (31.1 F) or if under pressure of 32 PSI at 68 F. At atmospheric pressure, propane and butane turn to vapor. The reason that the petroleum gases are stored in liquid phase is due to its efficiency. The ratio of the volume of the vaporized gas to that of the liquefied gas is typically around 250:1, depending on composition, pressure and temperature.

When the caverns at the Bayway Refinery were completed in 1958, the added underground storage space made larger quantities of propane and butane available while decreasing the danger from fires, storms and corrosion of surface storage (Chemical Engineering News, 1958). In addition, the cost of constructing and maintaining underground storage was less than above ground LPG storage infrastructure. When the caverns at Bayway were excavated, they cost about 50% less than surface storage would have cost to construct (Chemical Engineering News, 1958). Up until then, the most economical surface storage of LPG required very large refrigerated tanks. These tanks and their associated plant are costly to build, maintain and have a finite life of less than 30 years. Another advantage of underground storage is that it does not intrude on the surface environment.

Repauno Works

The second underground storage site in New Jersey is at the former Repauno Works in Gibbstown which DuPont operated as a chemical plant and dynamite factory from 1880 to 1999. The underground storage cavern was excavated between 1966 and 1968 and the roof of the cavern is between 325 and 330 feet below land surface. The floor is between 340 and 357 feet below the surface. A single cavern of 180,000 barrels or 1,010,000 cubic feet capacity was constructed at this site. Construction was by conventional room and pillar mining with the rooms being 20 feet wide and 30 feet high. Supporting pillars were 30 feet square (Cobbs, 1975). The cavern originally stored anhydrous ammonia at -12°F.

The cavern is unique in that it served as a receiving vessel for anhydrous ammonia and furnished a steady supply of ammonia for a chemical process. Ammonia was received into the cavern from refrigerated barges at -28°F. Depending upon whether a shipment was being received or not the effluent temperature of the ammonia going to the process plant varied from -0° to about -15°F. The temperature extremes that this cavern had been subjected to had no discernible adverse affects upon the operation of the cavern or its integrity (Cobbs, 1975).

In 2016, the cavern was repurposed by Delaware River Partners LLC to store butane after a mechanical integrity test. The butane stored at the Repauno Works cavern is extracted elsewhere and transported to the Repauno Works site for storage. Currently, this single cavern has a storage capacity of 186,025 barrels (7.81 million gallons) (Pb Energy Storage Services, unpublished report, April 1-10, 2016), and was carved from solid gneiss.

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2019

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Banner photograph *(left to right)***:**
Ammonia cavern shaft bottom area during construction, circa 1967, Figure 6-8, Geologic/Geotechnical Feasibility Report for Construction of Hard Rock Caverns at Repauno Port and Rail Terminal, prepared by Agapito Associates, Inc, August 2018.
Men in bucket being lowered down Shaft 1, February 15, 1957, *photo from Esso Standard Oil Co., Bayway Refinery.*
Drill bit, November 8, 1957, *photo from Esso Standard Oil Co., Bayway Refinery.*
Miners beginning drifting operation at bottom of Shaft 1, February 15, 1957, *photo from Esso Standard Oil Co., Bayway Refinery.*