APPENDIX J – ENGINEERING DESIGN CONSIDERATIONS

ENGINEERING DESIGN CONSIDERATIONS

1.0 MINED-ROCK CAVERNS

1.1 Infrastructure Requirements, Timeline and Anticipated Costs

Significant infrastructure requirements exist for construction of mined-rock caverns. These include power (5.0 MVA or greater) to enable use of hoists, ventilation fans and water pumps; road access; and labor, as "the required skilled construction labor force is greater for mined-rock caverns than either salt caverns or oil and gas reservoir storage" (Nelson and others, 2011). Mined-rock caverns have several characteristics that make them a more environmentally benign process; namely, a smaller footprint, decreased water requirements, and minimal waste production. In addition, the limestone produced from mining may be of suitable lithology for use in other aspects of the storage hub network, such as pipeline corridors, access roads, or site construction.

Mined-rock storage caverns in the United States are constructed in several different lithologies. Most are built in extremely low-permeability shales, with others constructed in dolomite, limestone and granite. Hard-rock cavern storage volumes range from 20,000 to 1,400,000 barrels (BBL) (average of 320,000 BBL). Worldwide, the maximum volume is 5 million BBL. A potential mined-rock cavern project has a step economic of scale curve; costs are fixed with regard to initial activities, such as geological investigation, shaft sinking, and initial development mining, so overall project cost per barrel decreases with increasing cavern volume. Nelson and others (2011) estimated a mined-rock cavern in the Greenbrier could host a volume between 2.0 and 2.5 million BBL.

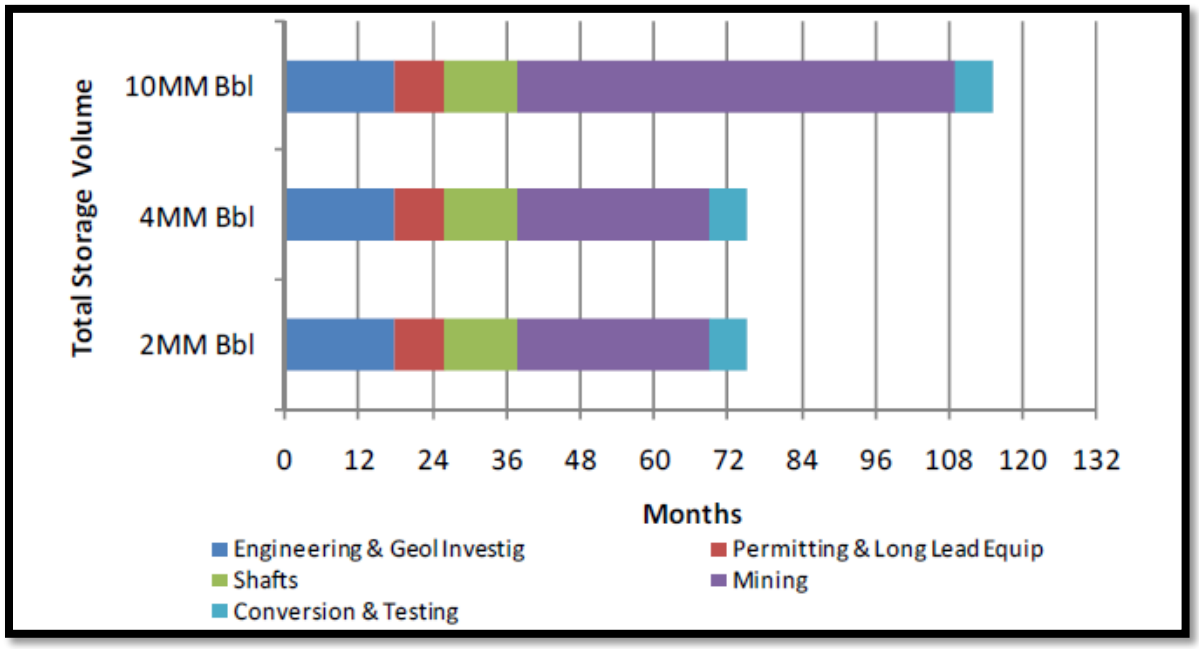


Figure 1. Rough Order of Magnitude (ROM) timeline for construction of a mined-rock cavern.

Item	Option 1	Option 2	Option 3
Storage Volume (millions of barrels)	2	4	10
Number of Caverns	1	2	4
Fixed Costs ($ millions)			
Engineering	$1.5	$1.5	$1.5
Geological Investigation	$2.0	$2.0	$2.0
Mainshaft	$9.0	$18.0	$36.0
Mainshaft Conversion	$2.0	$4.0	$8.0
Pump/Vent Wells	$8.4	$16.8	$33.6
Hoist and Headframe	$5.0	$10.0	$10.0
Breakout Mining	$2.0	$4.1	$8.1
Variable Costs ($ millions)			
Production Mining	$150.0	$300.0	$750.0
Convert and Outfit	$9.0	$15.0	$33.0
Test and Purge	$1.6	$3.1	$7.7
Total Cost	**$190.5**	**$374.5**	**$889.9**
Unit Cost ($/barrel)	**$95.3**	**$93.6**	**$89.0**
Lower Range ($/barrel)	**$79.0**	**$78.0**	**$74.0**
Upper Range ($/barrel)	**$114.0**	**$112.0**	**$107.0**

Figure 2. Mined rock cavern details and estimated costs (Nelson and others, 2011).

1.2 Host Rock Requirements and Cavern Design

Structural stability and low permeability to groundwater flow are the two main host rock criteria for a mined-rock cavern. The cavern operates under hydraulic containment – the surrounding natural hydrostatic pressure must be greater than the pressure of the stored product. This ensures containment of the product; a leak path will result in water flowing in, rather than flowing out and causing product to escape.

Modern mined-rock caverns are typically equipped with three shafts. An 8- to 14- foot (ft) diameter main shaft serves as an access point during initial construction and waste disposal tasks. Upon completion, this shaft is used for the cavern's instrumentation, piping and pump systems. A smaller set of two 36- to 48-inch (in) vent/pump shafts are used for ventilation in the construction phases and are then recompleted to serve as submersible pump wells in the production phase (Figure 3).

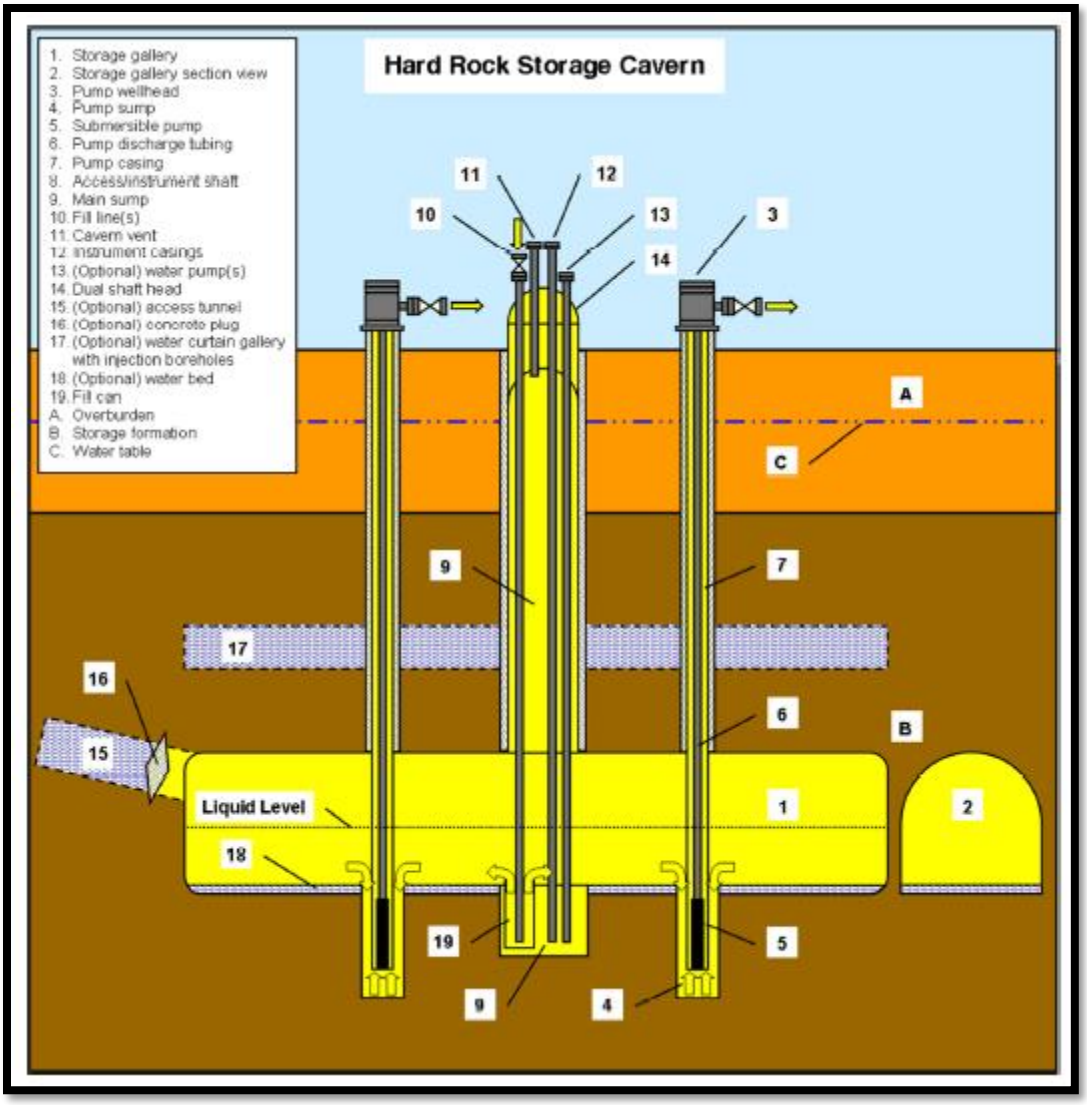


Figure 3. Schematic (cross section view) design of a mined-rock cavern.

A typical hard-rock cavern design operates using a brine-compensated style. This type of cavern remains full of liquid at all times. During product injection, the brine is displaced and the brine is re-injected to deliver the product and to regulate reservoir pressure. Nelson and others (2011) estimates the following pressure ranges:

- Minimum ethane wellhead pressure to ensure product remains liquid = 900 to 1,200 pounds per square inch (psi)
- Operating pressure gradients = 0.55 to 0.85 psi per ft
- Brine pressures for hydrocarbon storage caverns = 25 to 100 psi

Given these pressure ranges the authors suggest a cavern depth of 1,000 to 3,000 ft and warn that construction of a cavern at depths shallower than 1,000 ft would require higher brine pressures to maintain minimum ethane wellhead pressure.

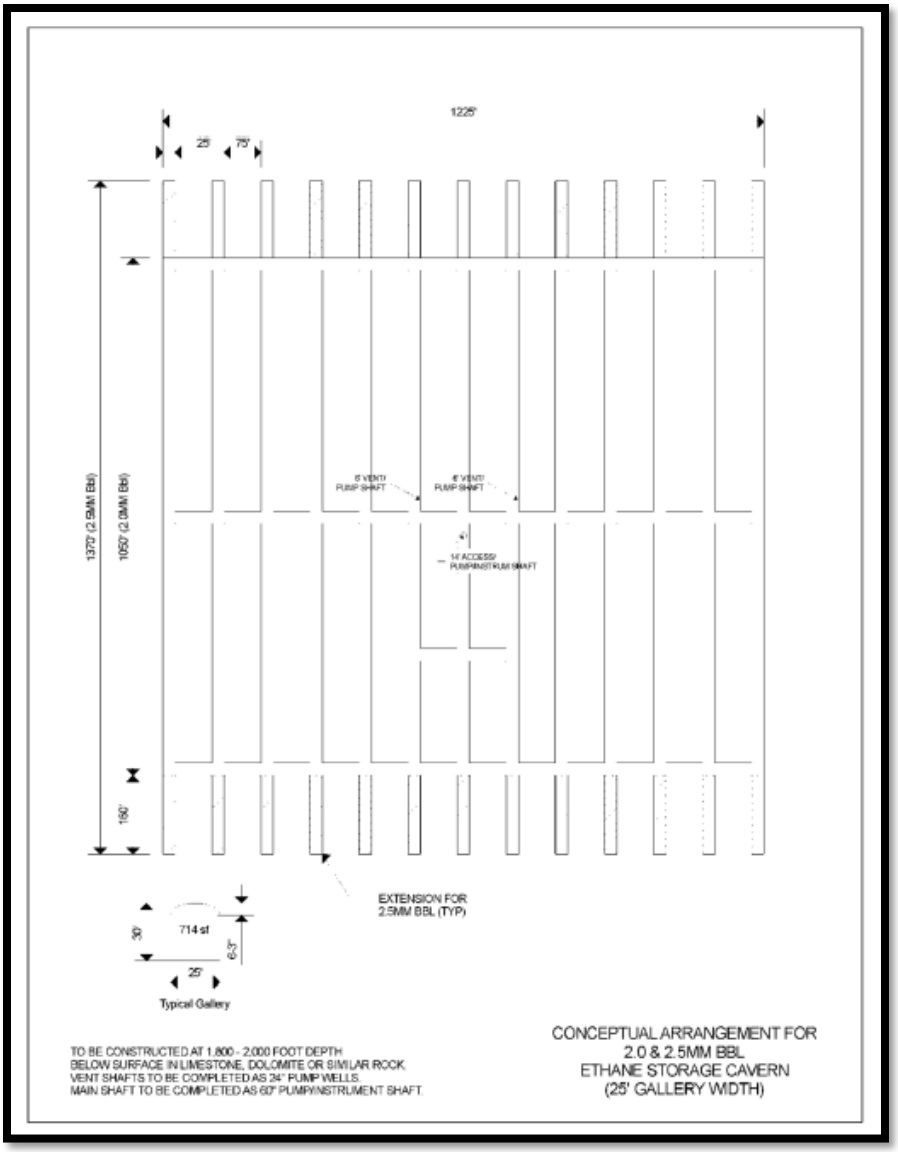


Figure 4. Plan view conceptual design for a mined-rock cavern (Nelson and others, 2011).

In a "brine-compensated storage" cavern, brine is injected when product is withdrawn and vice versa. Therefore, surface storage (brine ponds) must be provided for the product-displacement brine. Subsurface brine storage (in caverns with a nitrogen surcharge) is possible. However, roughly 3 BBL of cavern space is required for every barrel of stored brine to ensure that the nitrogen pressure (following brine withdrawal) is sufficient for cavern structural support.

The following equation can be used to compute the gross volume of a mined-rock cavern, where cross-sectional area of a room [length (l) * width (w)] is multiplied by its (height (h) to determine volume in cubic feet (ft^3). The volume is divided by 5.615 to convert units of cubic ft^3 to BBL.

$$V = (l \times w \times h)/5.615$$

Additional factors or corrections (not given here) will need to be applied to this equation to account for the pressure-dependence of ethane or other NGLs at reservoir depth, as well as the portion of the cavern's volume used for product vs. brine.

2.0 SALT CAVERNS

2.1 Infrastructure requirements, Timeline and Anticipated Costs

The main infrastructure requirements for salt cavern construction are related to transportation corridors for water and brine, brine disposal requirements, fresh water source(s) to leach the cavern, and 2.0 to 5.0 MVA capacity electrical service. Many of these requirements are already in-place in the region surrounding the Ohio River. This is especially true in the tri-state region of eastern Ohio, northern West Virginia and western Pennsylvania where the thickest salt intervals are observed. The maximum thickness of the Salina F4 salt in the ASH area of interest typically does not exceed 100 ft. Given a cavern width of 200 ft, a typical cavern volume is approximately 200,000 BBL. Therefore, multiple caverns would be necessary to obtain overall storage volumes of a million barrels or more. Figure 5 shows the Rough Order of Magnitude (ROM) timeline for construction of a salt-brine cavern complex (Nelson and others, 2011).

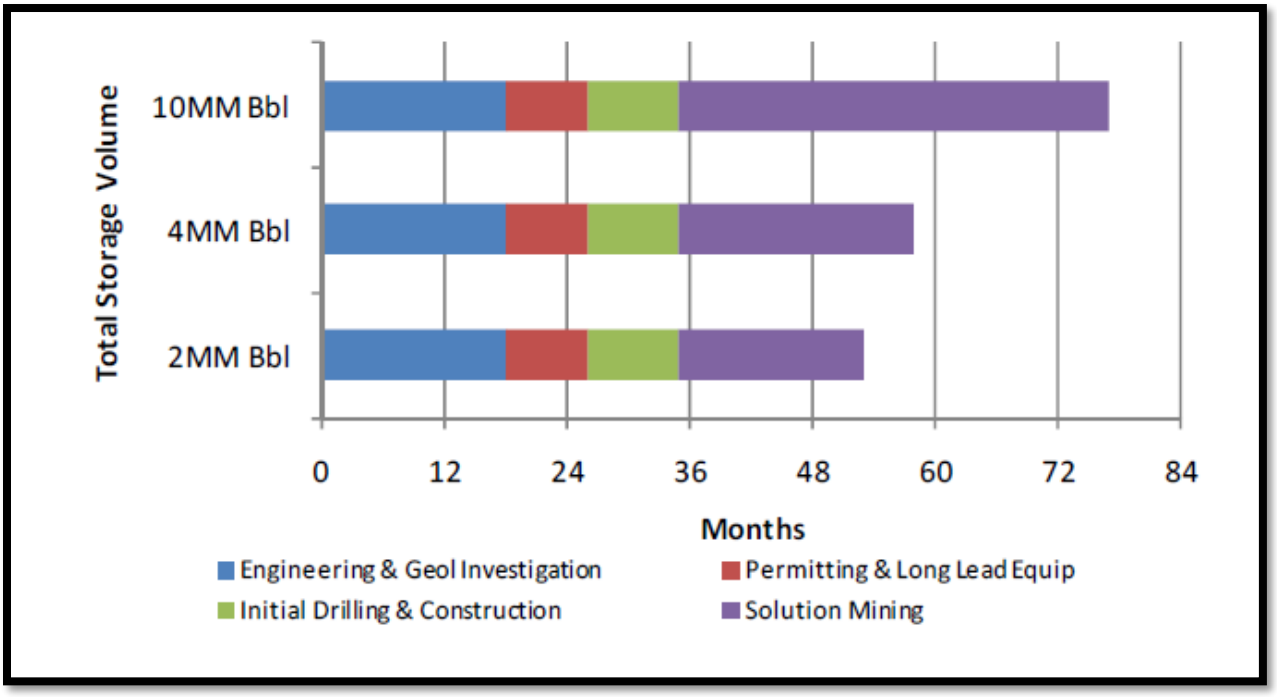


Figure 5. ROM timeline for construction of a salt-brine cavern complex.

Estimated costs for a salt brine cavern (Figure 6) depend on cavern depth (the cost generally increases with depth), as well as the volume of brine disposal necessary to complete

the project. Figure 6 gives an estimate (Nelson and others, 2011) of costs assuming brine disposal into a saline aquifer.

Item	Option 1	Option 2	Option 3
Storage Volume (millions of barrels)	2	4	10
Number of Caverns	10	20	50
Number of Brine Disposal Wells	35	53	71
Leach Rate (gpm)	1,000	1,500	2,000
Leach Pumping (days)	412	550	1,031
Overall Leaching Duration (months)	18	23	42
Fixed Costs ($ millions)			
Engineering	$2.0	$2.0	$2.0
Geological Investigation	$2.0	$2.0	$2.0
Leach Plant	$3.0	$3.0	$3.0
Leach Headers	$0.6	$0.6	$0.6
Brine Disposal Wells	$157.5	$238.5	$319.5
Variable Costs ($ millions)			
Storage Wells (13⅜ inch)	$85.0	$170.0	$425.0
Brine Ponds	$10.0	$20.0	$50.0
Leach Plant	$6.0	$8.0	$12.0
Leaching Pipelines	$8.1	$13.1	$21.8
Leaching O&M	$3.0	$6.0	$15.0
Conversion	$4.3	$8.5	$21.3
Total Cost	**$281.5**	**$471.7**	**$872.1**
Unit Cost ($/barrel)	**$140.7**	**$117.9**	**$87.2**
Lower Range ($/barrel)	**$117**	**$98**	**$73**
Upper Range ($/barrel)	**$169**	**$142**	**$105**

Figure 6. Estimate of costs associated with salt cavern construction assuming brine disposal into a saline aquifer (Nelson and others, 2011).

2.2 Host Rock Requirements and Cavern Design

In terms of cavern development, a very important consideration is the nature of salt bed accumulation in a potential location. As opposed to storage in a pure salt column or diapir, the Salina F4 and associated units are bedded salts; that is, interlayered evaporite and non-evaporite units of varying "purity." Therefore, the targeted salt bed must be of a thickness to allow cavern dissolution of the desired height while allowing for accumulation of the insoluble lithologies at

the cavern's base. These insoluble/impure materials tend to expand as they are immersed and accumulate at the cavern base; this "bulking factor" is typically around 50 percent of the initial material volume. A final consideration for the target salt bed is that it must be of adequate thickness to allow for sufficient preservation of roof material (often referred to as a 'saltback').

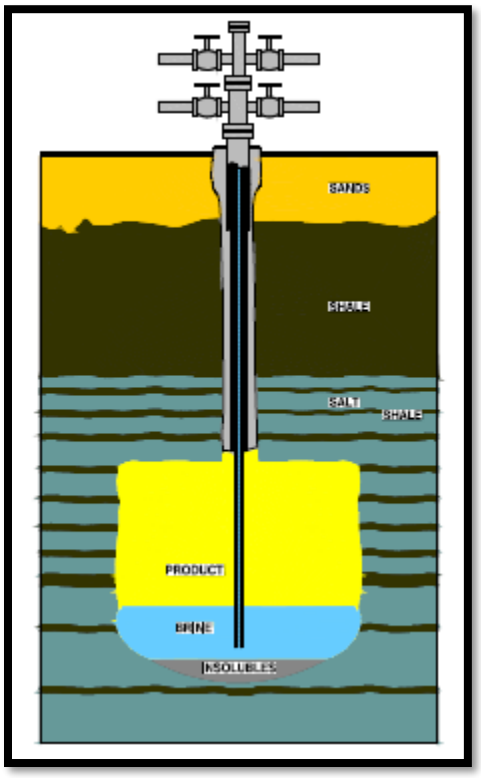


Figure 7. Schematic diagram of a salt cavern (Nelson and others, 2011).

Parameters	Value		
Volume (thousands of barrels)	200	200	200
Well Diameter (inches)	13⅜	13⅜	13⅜
Leaching Tubulars (inches)	7 × 4½	10¾ × 7	10¾ × 7
Leach Rate (gpm)	500	1,000	1,500
Max Injection/Delivery Rate (gpm)	1,300	1,300	1,300
Injection/Delivery Rate (barrels per day)	44,600	44,600	44,600
Overall Leaching Duration (days)	132	77	59
Approx. Leach Injection Pressure (psi)	2,000	1,550	2,750
Assumed Brine Injection Pressure (psi)	1,200	1,200	1,200
Approx. Leaching Power (horsepower)	1,400	2,500	5,200
Approx. Leaching Power Usage (Megawatt hours)	2,400	2,150	3.000

[10] Salt concentration at saturation increases with temperature.

Figure 8. Design parameters for a salt cavern (Nelson and others, 2011).

The following equation can be used to compute the gross volume of a solution-mined salt cavern, where cross-sectional area is circular [π * radius $(r)^2$] is multiplied by its (height (h) to determine volume in ft^3. The volume is divided by 5.615 to convert units of ft^3 to BBL.

$$V = (\pi \times r^2 \times h)/5.615$$

Additional factors or corrections (not given here) will need to be applied to this equation to account for the pressure-dependence of ethane or other NGLs at reservoir depth, as well as the portion of the cavern's volume used for product vs. brine.

3.0 RESERVOIR STORAGE

3.1 Infrastructure requirements, Timeline and Anticipated Costs

Main infrastructure requirements for reservoir storage will depend on the type, age and depth of the target field. Existing gas storage fields represent the lowest infrastructure requirements, as it is assumed much of the necessary infrastructure is in-place and field limits (trap integrity) considerations have already been addressed. Depleted fields that have not been converted to storage will have varying infrastructure needs, including (but not limited to) access roads, pipeline rights-of-ways and mitigation costs associated with identification and mitigation/plugging of legacy wells. Given the decreased infrastructure and construction

requirements associated with reservoir storage, timeline for development is shorter than for either mined-rock or salt cavern construction (Figure 9). The estimated costs are also significantly lowered (Figure 10).

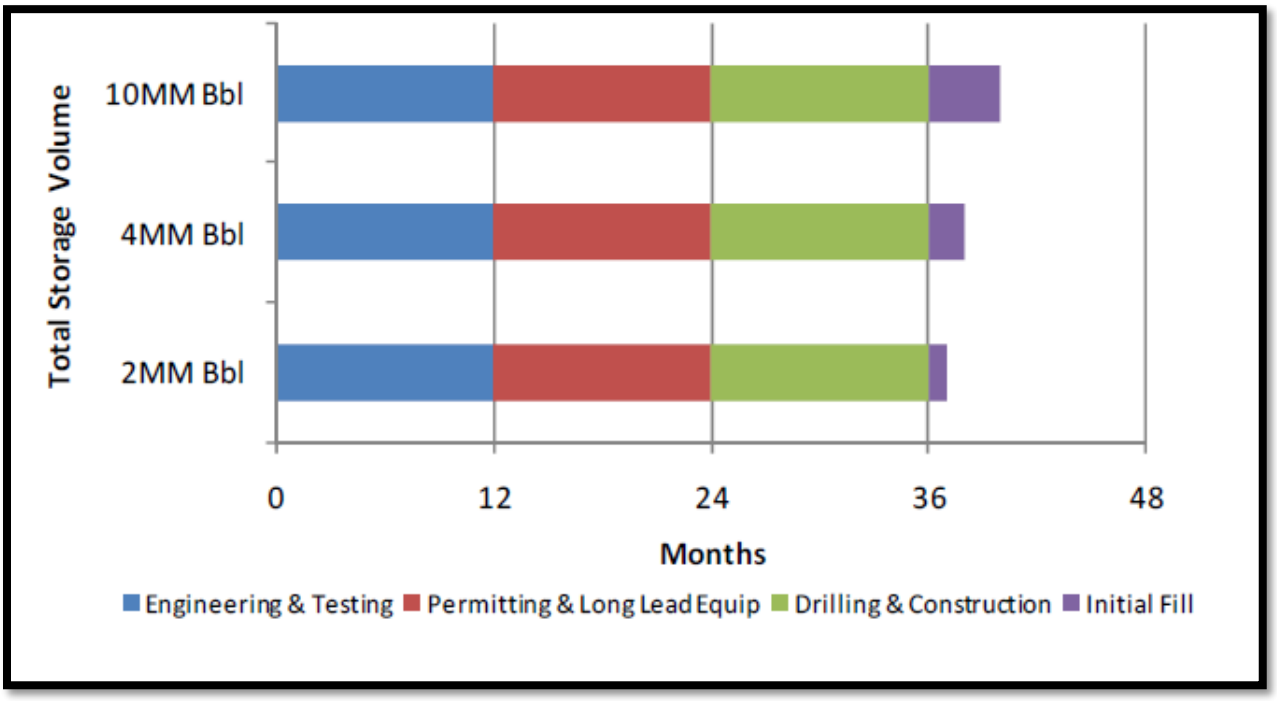


Figure 9. ROM timeline for construction of reservoir storage (Nelson and others, 2011).

Item	Small	Medium	Large
Storage Volume (millions of barrels)	2	4	10
Number of Horizontal Wells	6	6	6
Fixed Costs ($ millions)			
Engineering	$1.0	$1.0	$1.0
Reservoir Test/Characterize	$0.5	$0.5	$0.5
Pipeline (20 mi, 10 inch)	$29.6	$29.6	$29.6
Compression	$6.1	$6.1	$6.1
Gas Processing	$2.0	$2.0	$2.0
Variable Costs ($ millions)			
New Horizontal Wells	$36.0	$36.0	$36.0
Gas in Place ($/MMbbl/Ethane)	$1.0	$2.0	$5.0
Total Cost	**$76.2**	**$77.2**	**$80.2**
Unit Cost ($/barrel)	**$38.1**	**$19.3**	**$8.0**
Lower Range ($/barrel)	**$25.1**	**$12.8**	**$5.4**
Upper Range ($/barrel)	**$67.6**	**$34.0**	**$13.9**

Figure 10. Estimate of costs associated with reservoir construction (Nelson and others, 2011).

In order to compute the storage capacity of a depleted reservoir to store ethane, the produced volume and reservoir pressure conditions must be known for the area being converted to storage. As reported by Nelson and others (2011), the storage capacity can be estimated by dividing the cumulative production of natural gas from the reservoir by the ratio of reservoir pressure to atmospheric pressure (i.e., at standard temperature and pressure conditions). The resulting volume is divided by 5.615 to convert units of ft^3 to BBL.

4.0 PROJECT COMPARISON

Each of these three potential storage options has relative strengths and weaknesses when compared to one another. For example, deliverability is highest in mined-rock and salt cavern options; these options also require the highest capital investment costs. Figure 11 lists the advantages and disadvantages of the various storage options. The costs associated with each design option also vary with overall storage volume; a comparison of these relative costs is provided in Figure 12.

Storage Option	Advantages	Disadvantages
Salt Caverns Without Brine Takeaway	• Ability to meet a very high deliverability (80,000 bbls/day per well).	• Generally the largest unit cost. • Significant brine disposal cost. • Large acreage requirement. • Requires large surface brine ponds. • Cavern depth outside industry experience. • Limited site options.
Salt Caverns With Brine Takeaway	• Ability to meet a very high deliverability (80,000 bbls/day per well).	• Large unit cost. • Considerable brine disposal cost for 4 and 10 MMbbls of storage. • Large acreage requirement. Requires large surface brine ponds. • Cavern depth outside industry experience. • Limited site options.
Mined-Rock Caverns	• Ability to meet a very high deliverability. • Least risk of environmental impact. • Smallest acreage requirement.	• Large unit cost. • Longest development time.
Oil and Gas Reservoir	• Lowest unit cost: $38.1, $19.3, and $8.0/bbl for 2, 4, and 10 MMbbls of storage. • Shortest development time: 37, 38, and 40 months for 2, 4, and 10 MMbbls of storage. • Greatest flexibility of site options.	• Would require processing to separate hydrocarbons.

Figure 11. Comparison of various NGL storage options (Nelson and others, 2011).

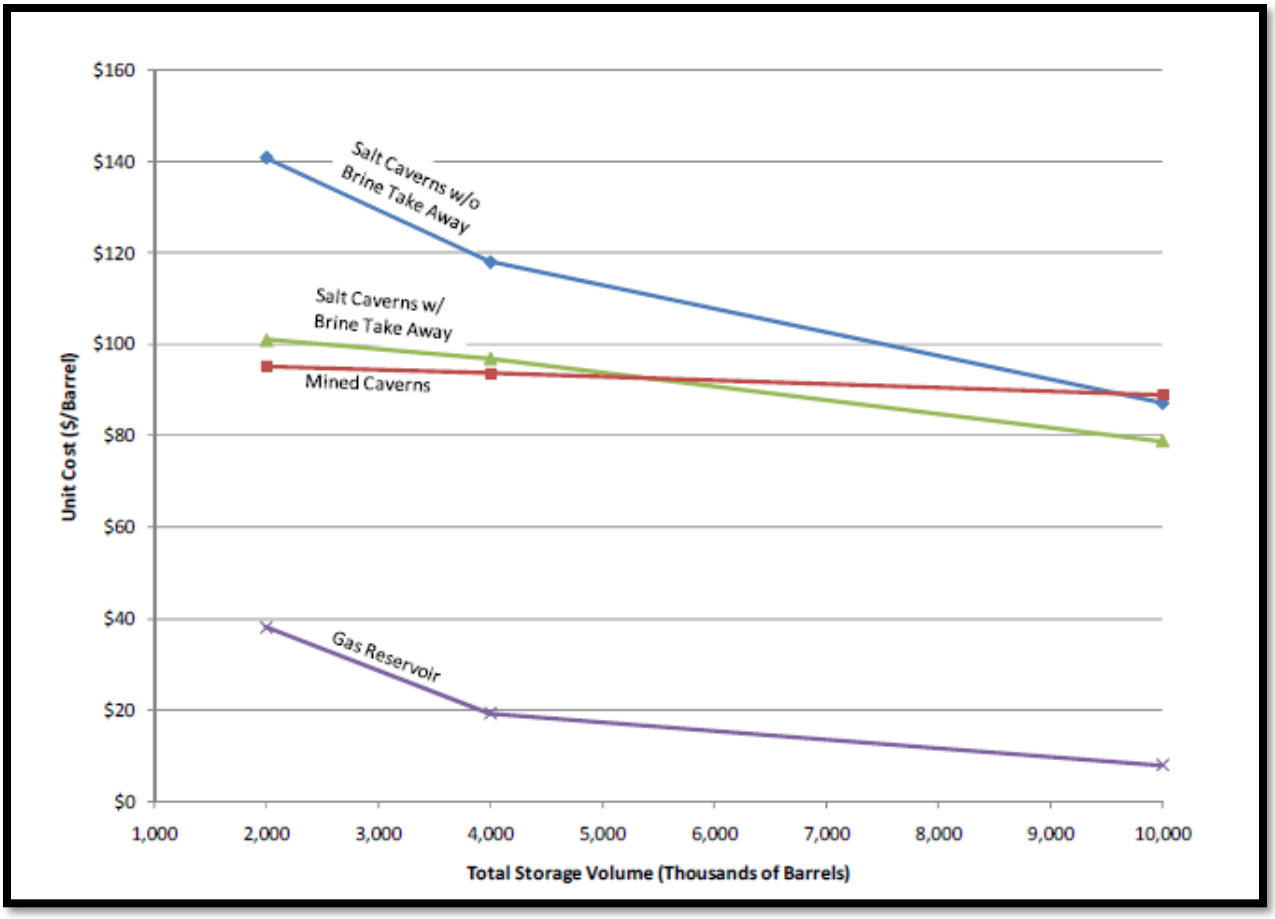


Figure 11. Comparison of unit costs associated with different storage types and volumes (Nelson and others, 2011).