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Canal Lining Demonstration Project – Year 25 Durability Report

Research and Development Office
Science and Technology Program
Final Report ST-2019-1743-01, 8540-2019-33

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Research and Development Office

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14. ABSTRACT Between 1991 and 2001, a total of 24 test sections were installed in the Arnold, North Unit and Ochoco Irrigation Districts in Central Oregon as part of a canal lining demonstration project. Of the 24 test sections, 7 have since been removed. This report evaluates the condition of the 17 remaining test sections after up to 25 years of service, including a failure analysis of the removed test sections, visual inspections, coupon testing, and a benefit/cost analysis aimed at determining the most cost-effective lining systems.

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Acronyms and Abbreviations

%	Percent
B/C	Benefit/cost
CFS	Cubic feet per second
CL	Thin geomembrane on back side
CSPE-R	Reinforced chlorosulfonated polyethylene
DN	Double nonwoven
EPDM	Ethylene propylene diene monomer
GCL	Geosynthetic clay liner
GM	Geomembrane
GRI	Geosynthetic research institute
HDPE	High-density polyethylene
IN	Inch
LB	Pound
LLDPE	Linear low-density polyethylene
MB	Moisture Barrier
MIN	Minutes
N/A	Not Applicable
PE	Polyethylene
PSI	Pounds per square inch
PVC	Polyvinyl chloride
QC	Quality control
RCC	Roller-compacted concrete
Reclamation	Bureau of Reclamation
SPUF	Spray-applied polyurethane foam
UV	Ultraviolet
VLDPE	Very low-density polyethylene

Executive Summary

Between 1991 and 2001, a total of 34 test sections were installed in 4 different states as part of a canal-lining demonstration project led by Swihart and Haynes. At the time of the study, common canal-lining materials included compacted clay and unreinforced or reinforced concrete. In many instances, these traditional lining methods were not a viable option. The goal of the study was to evaluate specialized lining technologies that would perform well over difficult subgrades, in situations where traditional lining methods are less desirable.

This report presents the condition and performance of the 24 test sections installed in the Arnold, North Unit, and Ochoco canals in Central Oregon after up to 25 years of service. Lining types include concrete, concrete over geomembrane, and exposed geomembrane liners. The test sections range from 16 to 25 years old. The outcome of the study is valuable data and information that can be used as a canal lining selection guide for future projects, as well as for the broader geosynthetics industry.

Researchers performed visual condition assessments to make service life (durability) predictions for each test section. The results were combined with maintenance costs, construction costs, effectiveness, and other parameters to calculate benefit/cost (B/C) ratios. The B/C ratio results showed that concrete over geomembrane liners offer the best combination of reliable performance, long-term durability, and effectiveness. The table below summarizes B/C ratio ranges for the three major lining types and other key details.

Table ES-1. Benefit/Cost Summary for the Three Major Lining Types

Liner Type	Advantages / Disadvantages	Durability (years)	Effective-ness (%)	Maintenance ($/ft^2·yr)	B/C Ratio
Concrete	Excellent durability, low initial maintenance costs, prevents soil migration, and maintains canal capacity; provides lowest effectiveness	50	70	0.005	3.0-3.3
Concrete over Geomembrane	Favorable durability, effectiveness, and maintenance costs, prevents soil migration and liner uplift, maintains canal capacity; most expensive lining type	50	95	0.005	3.5-3.7
Exposed Geomembrane	Low initial construction costs, high effectiveness and in certain cases can deliver long service lives; performance highly dependent on service conditions, subject to soil migration, liner whales, liner uplift, damage from ice, and capacity reductions, maintenance can be difficult and expensive for field crews	15-30	90	0.010	2.2-3.8

Six exposed geomembrane test sections from the Arnold and Ochoco canals received sample coupon testing at the Geosynthetic Research Institute (GRI) in Folsom, Pennsylvania. Visual inspection showed that geomembrane test sections appear to be in good to excellent condition; however, GRI testing revealed changes in physical and chemical properties, which indicates that all six materials experienced degradation to some degree. This deterioration indicates how far along in the degradation process each material is, and in turn, how likely damage is to occur. Ultimately service conditions will play the largest role in a material's effectiveness and longevity. The table below summarizes the results, including the percent reduction in properties compared to the GRI quality control (QC) standard.

Table ES-2. Exposed Geomembrane Coupon Test Results

Test Section	Material	Condition (25 yr)	Property Testing (% below GRI QC standard)
A-3	80-mil high-density polyethylene (HDPE)	Excellent	Elongation: 58% Oxidative induction time (OIT): 66%
A-4	30-mil polyvinyl chloride (PVC)	Failed	Elongation: 30% Tear: 39% Puncture: 16%
A-5	45-mil Hypalon	Failed	Tear: 36%
A-6	36-mil Hypalon	Failed	Tear: 15%
O-3b	45-mil ethylene propylene diene monomer (EPDM)	Good (17 years)	Elongation: 87% Tear: 46%
O-4	30-mil linear low-density polyethylene (LLDPE)	Good (17 years)	Elongation: 25% OIT: 81%

Recommended future work includes seepage studies for the highest-performing test sections (A-1, A-2, A-3, A-7, A-8, O-3, and O-4). Liner selection will become increasingly important, particularly as the value of water resources continues to rise. A seepage study would provide valuable real-world data that could be combined with condition assessments and coupon sample testing to improve accuracy of the B/C ratio. This would allow the Bureau of Reclamation, and the geosynthetics industry, to make more informed decisions on future canal lining projects.

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Introduction

In the early 1990s, three engineers from the Bureau of Reclamation (Reclamation) began a canal-lining demonstration project in the Upper Deschutes River Basin near Bend, Oregon. At the time of the study, common canal lining materials included compacted clay and unreinforced or reinforced concrete. For numerous reasons, such as cost and availability, it was becoming increasingly common to work on jobs where these traditional lining methods were not a viable option. The goal of the study was to evaluate specialized lining technologies that would perform well over difficult subgrades, in situations where traditional lining methods are less desirable.

The Upper Deschutes River Basin in Central Oregon was chosen as the location of this study because of its volcanic geology. The canals in this area consist of highly permeable rocky side slopes and fractured basalt inverts. These geologic characteristics not only make excavation difficult, but also promote high seepage rates. Canals in the area will lose anywhere between 35 and 50 percent of their water due to seepage. For this study, lining systems were chosen that were less expensive than traditional liners, easier to install, and were compatible with difficult subgrades.

Over a 10-year period, six reports were written about this study. An original construction report titled "*Deschutes – Canal – Lining Demonstration Project Construction Report*" (Reclamation Report R-94-06, 1994) details the installation of 18 test sections in the Arnold (10 test sections) and North Main Unit Canals (8 test sections) between 1991 and 1993. The test sections were between 300 and 1,000 linear feet (15,000 to 30,000 square feet). The Arnold canal is smaller and contains more sand/silt sediment compared to the North Main Unit Canal. Therefore, test sections requiring greater subgrade preparation were constructed in the Arnold Canal (exposed geomembranes, shotcrete covered geomembranes, and grout mattress covered geomembranes). Test sections requiring less subgrade preparation were installed in the North Main Unit Canal (geofoams, elastomeric coatings, and reinforced or unreinforced shotcrete). The report includes detailed descriptions of the lining materials, construction costs, installation techniques, and pre/post-construction seepage studies.

The second report titled "*Deschutes – Canal – Lining Demonstration Project Durability Report – Year 2*" (Reclamation Report R-97-01) was finished in September of 1994 and analyzes the condition of the original 18 test sections installed in the Arnold and North Main Unit Canal after roughly 2 years of field exposure. The report includes visual condition assessments, maintenance history, and future work.

The third report titled "*Deschutes – Canal – Lining Demonstration Project Year 5 Durability Report*" (Reclamation Report R-97-01) was finished in January of 1997 and analyzes the condition of the original 18 test sections after roughly 5 years of field exposure. The report also details the construction and condition assessment of 4 additional test sections. The condition assessment took place after roughly 2 years of service. Canal sections ranged from 75 to 2,400 linear feet (1,575 to 70,000 square feet).

The fourth report titled "*Canal Lining Demonstration Project Year 7 Durability Report*" (Reclamation Report R-99-06) was finished in September of 1999 and analyzes the condition of the previous 22 test sections after roughly 7 1/2 years of field exposure. A benefit/cost (B/C) analysis was done on all the lining systems based on construction cost, durability, maintenance, and effectiveness. The report also details the construction of 5 new test sections in the Juniper Flat, Ochoco, Frenchtown, and the North Unit Irrigation Districts.

A supplemental report titled *"Canal Lining Demonstration Project 2000 Supplemental Report"* (Reclamation Report R-00-01) was finished in January of 2000 and outlines the construction of two new test sections in the Ochoco Irrigation District.

The last report titled *"Canal Lining Demonstration Project Year 10 Final Report"* (Reclamation Report R-02-03) was finished in November of 2002 and describes the construction of 5 new test sections in Twin Falls, Lewiston Orchards, Ochoco Irrigation District, Buffalo Rapids Irrigation Project, and Bitter Root Irrigation District. The report also analyzes the condition of all 34 test sections with up to 10 years of service. The report contains initial construction costs, maintenance history, visual inspection details, seepage studies, B/C analysis, coupon testing, and a description of possible future work.

Between 1991 and 2001, a total of 24 test sections were installed in the Arnold, North Unit, and Ochoco Irrigation Districts in central Oregon as part of the Swihart and Haynes canal lining demonstration project. Of the 24 test sections, 7 have been removed from the study. The focus of this report will be on the current condition of the 17 remaining test sections after up to 25 years of service. The report will include failure analysis of the 7 failed/removed test sections, visual inspections, coupon testing, and a B/C analysis aimed at determining the most cost-effective liners. This report provides valuable data, information, and conclusions for Reclamation and the broader geosynthetics industry that can be used as a canal lining selection guide for future projects.

Failure Analysis of Removed Test Sections

A total of 24 test sections were installed in canals near Central Oregon as part of the Swihart and Haynes canal-lining demonstration project. Over the last 25 years, approximately 30 percent of the test sections failed or were removed from the study. This section describes the failure mechanisms of those test sections, providing valuable information for future canal lining projects, and providing a more holistic view of the study. Table 1 summarizes the failure modes of all 7 test sections. More detailed material descriptions can be found in the report titled *"Canal Lining Demonstration Project Year 10 Final Report"* (Reclamation Report R-02-03).

Table 1. Service Life Summary for Failed Test Sections

Test Section	Material	Service Life (years)	Failure Mode
A-9	Very low-density polyethylene (VLDPE) with geotextile cushion and 3-inch grout filled mattress on side slopes	2 1/2	Liner "whales"

Test Section	Material	Service Life (years)	Failure Mode
A-10	High-density polyethylene (HDPE) with geotextile cushion and 3-inch grout filled mattress on side slopes	2 1/2	Liner "whales"
N-1	Spray applied polyurethane foam (SPUF) with Futura 500/550 protective coating	5 to 7	Coating disbonded, foam washout
N-2	SPUF with Geothane 5020 protective coating	5 to 7	Foam washout
N-3	Tietex geotextile with Geothane 5020 protective coating	7 months	Tore at the anchor trench
N-4	Phillips geotextile with Geothane 5020 protective coating	7 months	Tore at the anchor trench
O-2a & O-2b	Exposed geosynthetic clay liner (GCL) – (Bentomat DN)	3	UV degradation

Arnold Canal - Test Section A-9

Material: 60-mil VLDPE geomembrane with a geotextile cushion and 3-inch grout mattress on the side slopes only; **Installation**: November 1992/30,000 square feet/$1.79 per square foot

Failure Analysis: Figure 1 shows a downstream view of test section A-9. The liner was installed in late 1992 and began to experience problems almost immediately. During the 1993 irrigation season, cuts were made in the liner to ease pressure caused by “whales”. Liner whales are caused by water, sand, gas, sediment, or other materials that become trapped underneath the liner. In this case, the whales were caused by gas, water, and sand. Sand and water were able to penetrate the liner through tears, cuts, and punctures along the length of the canal. Poly-Flex, Inc. attempted to repair the liner on multiple occasions in 1994 and 1995. The problems persisted and the decision was made to remove the invert liner after 28 months of service. In the future it would be advisable to extend the grout mattress cover across the entirety of the canal. The cover serves three main functions: (1) protection of the underlying membrane from mechanical damage from wildlife, debris, and vandals, (2) protection of the underlying membrane from ultraviolet (UV) degradation, and (3) preventing liner whale formation. Test section A-7, a 3-inch grout mattress (across the entire canal) over a PVC membrane, resulted in a much better B/C ratio than test section A-9 for the above reasons.

Figure 1. View of test section A-9 with standing water in the invert. Note: The 3-inch grout mattress is still functioning while the geomembrane has been removed from the invert. Vegetation can be seen growing on the side slopes. A small amount of geomembrane liner can be seen in the invert at the grout mattress interface.

Arnold Canal - Test Section A-10

Material: 60-mil HDPE geomembrane with a geotextile cushion and a 3-inch grout mattress on the side slopes only; **Installation**: November 1992/30,000 square feet/$1.79 per square foot

Failure Analysis: This test section was also abandoned after 28 months because of whales in the liner. Refer to the failure analysis of test section A-9 for a more detailed explanation of the failure mechanism. Unlike test section A-9, this test section contained Portland cement deposits throughout the length of the canal. The liner was likely damaged as a result, causing more significant liner whales. The cement likely came from the grout mattress in A-10 and/or upstream from other grout mattress test sections. However, a definitive explanation was never found. Like test section A-9, it is recommended to extend the grout mattress cover across the entirety of the canal rather than leaving an exposed geomembrane invert.

Figure 2. View of test section A-10 with fractured basalt invert. Note: The 3-inch grout mattress is still functioning while the section of exposed geomembrane has been removed from the invert.

North Unit Canal - Test Section N-1

Material: SPUF base with Futura 500/550 protective coating; **Installation**: October 1992/18,000 square feet/$4.33 per square foot

Failure Analysis: During the first few weeks of service, large sections of foam began to wash out from the canal invert. The foam washout originated in areas of loose sand and gravel. These areas could not prevent the buoyant foam from pulling away from the subgrade and floating down the canal. After these weak points failed, high velocity water was able to wash out other areas from the test section. Additionally, large sections of foam lost their protective coating due to a poor bond. This was expected because of the long duration between foam installation and protective coating application. After 5 years of service, approximately half of the foam had washed away, and the test section was removed from the study. Due to the high initial construction cost and potential failure mechanisms, these canal lining systems are not recommended in canals of similar size and subgrade. This test section was replaced with a roller compacted concrete (RCC) invert (1998) and shotcrete side slope liner (1999).

North Unit Canal - Test Section N-2

Material: SPUF base with Geothane 5020 protective coating; **Installation**: October 1992/18,000 square feet/$4.33 per square foot

Failure Analysis: Lining failure originated in areas of loose sand and gravel in test section N-1. High velocity water caused the lining failure to spread into test section N-2 where foam washed out in other areas of loose sand and gravel. The same outcome would likely have occurred even if these two test sections had not been next to each other. Anything that damages the liner will lead to water penetration and lifting of the buoyant foam in areas of loose sand and gravel (improper installation, rocks/debris, wildlife, vandalism, etc.). Unlike test section N-1, a good bond between the protective coating and foam was achieved. This was likely a result of simultaneous foam installation and protective coating application. After 5 years of service, approximately half of the foam had washed away, and the test section was removed from the study. Due to the high initial construction cost and numerous potential failure mechanisms, these canal lining systems are not recommended in canals of similar size and subgrade. The risk is too high to justify the use in similar canal lining scenarios. This test section was replaced with an RCC invert (1998) and shotcrete side slope liner (1999).

North Unit Canal - Test Section N-3

Material: Tietex geotextile with spray applied Geothane 5020 membrane; **Installation**: October 1992/18,000 square feet/$2.64 per square foot

Failure Analysis: After 7 months of service, this lining system was removed from the study. During the liner's first fill in 1993, high velocity water moving through the canal ripped the geotextile at the anchor trench causing the liner to float down the canal and damage a pipeline crossing. Perhaps a similar lining system would have worked in a smaller canal where hydraulic forces are significantly reduced. In canals of similar size and hydraulic flow it is not recommended to use this type of lining system. This test section was replaced with an RCC invert (1998) and shotcrete side slope (1999) liner.

North Unit Canal - Test Section N-4

Material: Phillips geotextile with spray-applied Geothane 5020 membrane; **Installation**: October 1992/18,000 square feet/$2.64 per square foot

Failure Analysis: After 7 months of service this lining system was removed from the study. During the liner's first fill in 1993, high velocity water moving through the canal ripped the geotextile at the anchor trench causing the liner to float down the canal and damage a pipeline crossing. Perhaps a similar lining system would have worked in a smaller canal where hydraulic forces are significantly reduced. In canals of similar size and hydraulic flow it is not recommended to use this type of lining system. This test section was replaced with an RCC invert (1998) and shotcrete side slope (1999) liner.

Note: Test section N-3 and N-4 are identical except for the brand and style of geotextile. The two test sections failed in the same way suggesting that the brand or type of geotextile does not play a role in liner performance.

Ochoco Canal - Test Section O-2a and O-2b

Material: Exposed Bentomat DN (double nonwoven) GCL and Exposed Bentomat CL (thin geomembrane on back side) GCL; **Installation**: April 1999/17,500 square feet/$0.76 and $0.81 per square foot

Failure Analysis: The exposed GCL liners were buried after 3 years of service due to advanced degradation from environmental exposure. On exposed sections above the waterline, the GCL began to experience surface cracking. Areas that were covered by sediment/dirt or water did not appear to crack. The GCL experienced lengthwise shrinking on the side slopes causing the seams to curl upwards and separate. This test section is no longer a part of the study. Defer to test sections O-1a and O-1b for a detailed condition assessment of the buried version. The 10-year durability report explains that the manufacturer recommends a 1-foot soil cover to provide protection and confining stress for the GCL.

Durability (Condition Assessment)

The durability section will include detailed visual inspections aimed at determining the current performance and long-term durability of each of the 17 remaining test sections. Visual inspections will analyze factors like UV damage, tears, punctures, cracks, voids, erosion, discoloration, and sediment build-up to formulate a service life prediction. Test sections range from 16 to 25 years old. More detailed material descriptions can be found in the report titled *"Canal Lining Demonstration Project Year 10 Final Report"* (Reclamation Report R-02-03).

Arnold Irrigation District – Main Canal

Apart from test sections A-9 and A-10 (described in the failure analysis section) which were removed from the study, Table 2 below summarizes all conditions assessments performed on test sections in the Arnold canal as part of the canal lining demonstration project. The table tracks the condition and performance of each liner between 2 and 25 years of age. Over the 25-year tracking period, including the 2017 condition assessment, 5 of the original 10 test sections failed, leaving only 5 test sections currently performing as intended. The following section gives a detailed condition assessment of the 8 test sections evaluated in the Arnold Canal during the 2017 condition assessment (25 years of service).

Table 2. Arnold Canal Condition Assessment Summary Table

Test Section	Material	Condition (2 yr)	Condition (5 yr)	Condition (7 yr)	Condition (10 yr)	Condition (25 yr)
A-1	Petromat Moisture Barrier (MB) II with 3-inch shotcrete cover	Excellent	Excellent	Excellent	Excellent	Excellent

Test Section	Material	Condition (2 yr)	Condition (5 yr)	Condition (7 yr)	Condition (10 yr)	Condition (25 yr)
A-2	VLDPE with 16-oz cushion and 3-inch shotcrete cover	Excellent	Excellent	Excellent	Excellent	Excellent
A-3	Exposed 80-mil HDPE	Excellent	Very Good	Very Good	Excellent	Excellent
A-4	Exposed 30-mil polyvinyl chloride (PVC) geomembrane with geotextile UV cover	Excellent	Very Good	Good	Good	Failed
A-5	Exposed 45-mil Hypalon with 16-oz geotextile cushion	Excellent	Very Good	Very Good	Fair	Failed
A-6	Exposed 36-mil Hypalon with 8-oz geotextile cushion	Very Good to Excellent	Very Good	Very Good	Fair	Failed
A-7	PVC with 3-inch grout filled mattress	Excellent	Excellent	Excellent	Excellent	Excellent
A-8	3-inch grout filled mattress	Excellent	Excellent	Excellent	Excellent	Excellent

Note: Test section A-3 was returned to an excellent designation by previous researchers during the 10-year condition assessment due to the liner's performance with respect to its age.

Arnold Canal - Test Section A-1

Material: Petromat MB II (Geoseal) with 3-inch shotcrete cover; **Installation**: February 1992/30,000 square feet/$1.38 per square foot

Condition (25 years): Excellent – the shotcrete cover is performing very well and still adequately protecting the underlying geomembrane liner. The cover holds the membrane in place, preventing movement and providing tear protection. Small cracks and other minor imperfections are present above the waterline. The cracks are not wide enough to expose the underlying geomembrane layer to UV degradation. Most of the cracking is located near the anchor trench where the shotcrete was tapered down from 3 inches to approximately 1 inch. In future projects, shotcrete thickness should remain constant at all locations. Shotcrete repair should be performed at consistent intervals to optimize service life. Figure 3 shows rocks and debris that have settled in the canal invert impeding water flow. Concrete liners provide ballast for the canal. This ballast prevents liner uplift and soil migration which allows the canal to retain its overall capacity and efficiency. Concrete covers also provide protection from physical (wildlife/debris) and UV damage. An estimated service life for this material is 50 years, assuming continuation of the presently observed degradation at a constant rate.

Figure 3. Debris and rocks in the invert of test section A-1 (test section begins on the far side of the bridge). Shotcrete is in good shape and functioning properly.

Arnold Canal - Test Section A-2

Material: 30-mil textured VLDPE geomembrane with a 16-oz geotextile cushion and a 3-inch shotcrete cover; **Installation**: October 1992/15,000 square feet/$2.14 per square foot

Condition (25 years): Excellent – there is no visible difference between test section A-1 and A2. The shotcrete cover is performing very well and still adequately protecting the underlying geomembrane liner. Small cracks and other minor imperfections are present above the waterline. Most of the cracking is located near the anchor trench where the shotcrete was tapered down from 3 inches to approximately 1 inch. In future projects, shotcrete thickness should remain constant at all locations. Shotcrete repair should be performed at consistent intervals to optimize service life. Small amounts of sediment and debris can be seen in the canal invert. Figure 4 shows standing water that may be present year-round. Standing water in the canal invert indicates that the liner is providing effective seepage control. During winter months, this water can turn to ice, minimizing water flow, and potentially damaging the liner. Neither the rocks, debris, or ice seem to have damaged the shotcrete cover or compromised its performance. Canal capacity and efficiency remain unchanged from the time of construction due to ballast and protection provided by the concrete liner. Seepage studies should be done on test section A-1 and A-2. This would provide valuable information to determine which geomembrane materials/thicknesses are most cost effective underneath concrete covers. An estimated service life for this material is 50 years, assuming a continuation of the presently observed degradation at a constant rate, and consistent maintenance practices.

Figure 4. Debris, rocks, and standing water in the invert test section A-2. Shotcrete is in good shape and functioning properly.

Arnold Canal - Test Section A-3

Material: Exposed 80-mil Textured HDPE; **Installation**: October 1992/15,000 square feet/$1.38 per square foot

Condition (25 years): Excellent – at one location above the waterline a piece of rebar was driven through the liner, causing a 6-inch crack to form. This was most likely a result of stress cracking due to HDPE's high propensity for this type of damage. Several small cracks and/or tears were observed in the geomembrane liner but do not appear to be affecting performance. Discoloration can be seen on the surface of the liner in Figure 5, which is likely a result of organic material deposits. Figure 5 also shows slight displacement from soil migration underneath the liner. The displacement is minimal and does not appear to have caused any damage; however, this should be monitored moving forward. The soil migration could be a result of ground water, side slope sloughing, and/or voids in the liner (unlikely to be caused by voids in this case as the liner has very few). Figure 5 shows pools of water in the canal invert from the uneven subgrade. This is another indication of soil migration, but also suggests that the liner is still adequately preventing seepage. A small amount (under 2 inches) of sediment can be seen in areas where water has pooled. Grass and vegetation have grown over the top of the liner on the side slopes but have not penetrated the membrane. The metal batten strips attaching the membrane to the bridge abutment are in excellent shape. An estimated service life for this material is 30 years, based on current performance, material thickness, service conditions, coupon testing, and knowledge of HDPE.

Figure 5. View of the HDPE liner in test section A-3 looking toward the bridge. Note: Grass has grown over the top of the liner on the side slopes but has not penetrated the liner. Soil migration is apparent based on the uneven subgrade which is common with exposed geomembranes.

Arnold Canal - Test Section A-4

Material: Inverted PVC/geotextile geocomposite with 6-oz geotextile cushion; **Installation**: March 1992/30,000 square feet/$1.05 per square foot

Condition (25 years): Failed - the PVC membrane has tears on both the invert and side slopes. Substantial degradation can be seen throughout the length of the canal. The liner has stiffened considerably as a result of leaching plasticizer, which has led to significant cracking. In some locations above the waterline, the geomembrane was completely missing. Figure 6 shows wrinkling in the invert and on the side slopes, as well as vegetation growing within the protective geotextile top layer, which has accelerated degradation and decreased service life. Punctures can be seen caused by sharp rocks on the subgrade. The liner was installed with the protective layer up leaving the liner susceptible to tears from the rocky subgrade. This was done to help protect the PVC from UV degradation (old PVC formulations had poor UV stabilization). This liner has exceeded its useful service life, no longer provides adequate seepage control, and should be replaced when viable. The 10-year condition assessment noted significant liner stiffening and minor tears/cracking. Based on the materials thickness (30-mil), formulation, and previous condition assessments, an estimated service life for this material is between 11 and 20 years. For calculation purposes, a value of 15 years will be used.

Figure 6. An area in test section A-4 where a sample was removed from the invert for coupon testing. Note: Grass and vegetation has grown within the geotextile protective layer.

Arnold Canal - Test Section A-5

Material: 45-mil CSPE-R (Reinforced Chlorosulfonated Polyethylene) geomembrane with a 16-oz geotextile cushion; **Installation**: March 1992/30,000 square feet/$1.05 per square foot

Condition (25 years): Failed – the Hypalon membrane has experienced tears, UV embrittlement, wrinkling, and degradation. Large tears (Figure 8) in the invert of the canal are allowing water and sediment to migrate under the liner, decreasing canal capacity and efficiency. A large amount of sediment and debris is sitting in the invert (Figure 7). Sitting water will freeze during the winter and turn to ice. During winter run-offs the ice can collect at structures (ice jamming), reducing efficiency and, in some cases, causing canal overflow. The ice can also cause damage to the liner as it makes its way down the canal. Sediment buildup will also decrease capacity, diminishing the canal's ability to deliver water downstream to irrigation districts. This liner has exceeded its useful service life and should be replaced when viable. During liner replacement, excavation will be necessary to repair the subgrade and restore canal capacity. Based on liner thickness (45-mil), and all previous condition assessments, an estimated service life for this material is between 11 and 25 years. An 18-year service life will be used for all calculations in this report

Figure 7. Downstream view of CSPE liner in test section A-5. Note: sediment and water can be seen in the canal invert. Tears have allowed water and sediment to migrate underneath the liner.

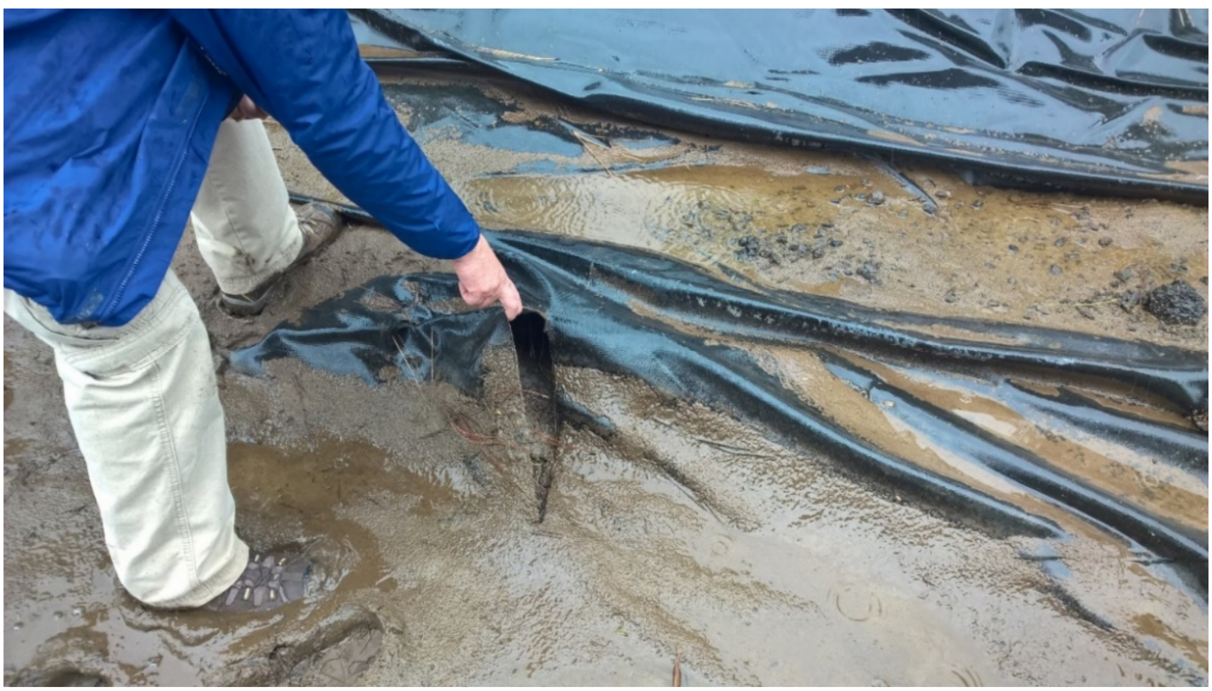

Figure 8. A large tear in the liner on the canal invert in test section A-5. Tears allow sediment and water to migrate underneath the liner, decreasing canal capacity and efficiency.

Arnold Canal - Test Section A-6

Material: 36-mil Terra-Tuff geocomposite; **Installation**: March 1992/15,000 square feet/$1.03 per square foot

Condition (25 years): Failed – Test section A-6 is in similar but slightly worse condition compared to test section A-5. Wrinkles, sediment build up, UV embrittlement, and tears are all slightly more pronounced. This is likely due to differences in thickness and reinforcement between the liners. Large tears in the invert of the canal are allowing water and sediment migration under the liner, (Figure 9) decreasing canal capacity and efficiency. A large amount of sediment and debris is sitting in the invert, similarly to test section A-6. This test section experiences ice jamming which is explained in the condition assessment for test section A-5 above. This liner has exceeded its useful service life, no longer provides seepage control, and should be replaced when viable. Based off test section A-5 (thicker than A-6 and reinforced), an estimated service life for this material is between 11 and 20 years. A 15-year service life will be used for all calculations in this report.

Figure 9. Downstream view of the liner in test section A-6. Sediment and water can be seen in the invert. Tears have allowed sediment migration under the liner. Canal capacity has diminished.

Arnold Canal - Test Section A-7

Material: 40-mil PVC geomembrane with a 3-inch grout filled mattress cover; **Installation**: November 1991/24,000 square feet/$2.36 per square foot

Condition (25 years): Excellent – the grout filled mattress is in excellent condition after 25 years of service. The cover has provided protection from UV degradation and held fixed the underlying liner material, providing a measure of tear protection. The cover has also protected the underlying liner from physical damage. The grout filled mattress does not appear to have experienced any freeze-thaw damage; however, some of the grout has begun to degrade above the waterline. Additional grout should be applied to these areas to mitigate further degradation. The darker color seen in Figure 10 towards the top of the canal is dirt that has settled on the grout mattress but does not appear to be affecting liner performance. Below the waterline appears to be in excellent condition. A small amount of sediment can be seen in the canal invert which is likely a result of slow-moving water. The grout mattress provides ballast for the canal, preventing liner uplift and soil migration. This test section appears to be sufficiently preventing seepage. An estimated service life for this material is 50 years, assuming continuation of the presently observed degradation at a constant rate.

Figure 10. The part of the canal where test sections A-6 and A-7 meet. Note: standing water and sediment in the canal invert.

Arnold Canal - Test Section A-8

Material: 3-inch grout filled mattress; **Installation**: November 1991&1992/15,000 square feet/$1.03 per square foot

Condition (25 years): Excellent – the grout filled mattress is in excellent condition after 25 years of service. There is no visible difference between test section A-7 and A-8. Some of the grout has begun to degrade above the waterline. Grout should be applied to these areas to mitigate further degradation; however, no major repairs are required at this time. Sediment and dirt deposits have caused a small amount of discoloration but does not appear to be affecting liner performance. Below the waterline appeared to be in excellent condition. Seepage studies should be carried out to determine the difference in effectiveness between test sections A-7 and A-8. An estimated service life for this material is 50 years, assuming continuation of the presently observed degradation at a constant rate

Note: Researchers failed to take photos of test section A-8 for unknown reasons. Test section A-8 is in similar condition to test section A-7.

North Unit Irrigation District – Main Canal

Except for test sections N-1 thru N-4 (described in the failure analysis section) which have been removed from the study, Table 3 summarizes all condition assessments performed on test sections in the North Unit canal as part of the canal lining demonstration project. The table tracks the condition and performance of each liner between 2 and 25 years of age (see note below table). Over the 25-year tracking period, including the 2017 condition assessment, 4 (N-1 thru N-4) of the 9 test sections failed, leaving only 5 test sections performing adequately. The following section gives a detailed condition assessment of these 5 test sections.

Table 3. North Unit Canal Condition Assessment Summary Table

Test Section	Material	Condtion (2 yr)	Condtion (5 yr)	Condtion (7 yr)	Condtion (10 yr)	Condtion (25 yr)
N-5	RCC Invert with shotcrete side slopes	N/A	N/A	Installed RCC and shotcrete (0 yr)	Very good to Excellent (3 yr)	Very Good to Excellent (18 yr)
N-6	Shotcrete with steel fibers	Excellent	Excellent	Excellent	Excellent	Very Good to Excellent
N-7	Shotcrete with polyfibers	Excellent	Excellent	Excellent	Excellent	Very Good to Excellent
N-8	Shotcrete with polyfibers	Excellent	Excellent	Excellent	Excellent	Very Good to Excellent
N-9	Unreinforced shotcrete	Excellent	Excellent	Excellent	Excellent	Very Good to Excellent

Note: Test section N-5 was 18 to 19 years old at the time of the 25-year inspection. The test section was not installed on the original construction date due to complications with the supplier.

North Unit Canal - Test Section N-5

Material: RCC invert with shotcrete side slopes; **Installation**: March 1998 & 1999/60,000 square feet/$2.00 per square foot

Condition (18-19 years): Very Good to Excellent - Installed RCC invert and shotcrete side slopes between 1998 and 1999. The rather thick RCC invert has decreased canal capacity from 1,000 cubic feet per second (cfs) to 800 cfs. The canal invert and side slopes are in very good to excellent condition (Figure 11); however, some repairs have been required over the years (Figures 12 and 13). Areas of erosion can be seen throughout the invert in and around cat tracks (Caterpillar heavy machinery). Locations where cat tracks are not present remain in excellent condition. Minor cracking can be seen on the side slopes. Further repairs will need to be made to limit concrete degradation and maintain performance. The repairs have proved very effective at maintaining seepage control in the canal and will go a long way towards maximizing service life. An estimated service life for this material is 50 years, assuming continuation of the presently observed degradation at a constant rate.

Note: the following figures are from test sections N-1 thru N-5 (all currently RCC/shotcrete liners) and are intended to be used as a visual representation of an RCC canal invert with shotcrete side slopes. All test sections are in similar condition and will be evaluated as such.

Figure 11. View of RCC invert canal looking upstream. Some sitting water can be seen in the invert.

Figure 12. Repairs made to the RCC invert. The repairs proved to be very effective.

Figure 13. Repairs made to the shotcrete side slopes. The repairs proved to be very effective

North Unit Canal - Test Section N-6

Material: 3-inch shotcrete reinforced with Novocon steel fibers at 50 lb/yd^3 fiber dosage for the first half of the canal and 25 lb/yd^3 fiber dosage for the second half; **Installation**: February 1992/30,000 square feet/$2.33 and $2.20 per square foot

Condition (25 years): Very Good to Excellent – overall the test section is in very good condition. Figure 14 is a close-up view of the 1 ½ inch Novocon steel fibers imbedded in the shotcrete. The value of the steel fibers was indeterminate; in addition, no difference was observed between the first and second half of the test section containing 50 and 25 lb/yd^3 of fiber respectively. Small to medium sized voids can be seen in the invert of the canal which is somewhat common in shotcrete test sections. District personnel have been very diligent with concrete repair, which should maximize service life and minimize seepage. Small cracks were observed on the invert and side slopes. Figure 15 shows sediment build up on the canal invert, which was likely deposited from slow-moving water. Rocks and debris are scattered throughout the invert and could be removed; however, the impact on canal flow is likely negligible, so any removal efforts are unlikely. An estimated service life for this material is 50 years, assuming continuation of the presently observed degradation at a constant rate.

Figure 14. Steel fibers embedded in the shotcrete side slope in test section N-6. Shotcrete appears to be in very good condition in the surrounding area with no visible cracks.

Figure 15. Sediment build up in the canal invert in test section N-6 that will decrease overall efficiency and capacity.

North Unit Canal - Test Section N-7

Material: 3-inch shotcrete reinforced with Phillips Polyfiber at 3 lb/yd^3 fiber dosage for the first half of the canal and 1 ½ lb/yd^3 fiber dosage for the second half; **Installation**: February 1992/30,000 square feet/$2.21 and $2.14 per square foot

Condition (25 years): Very Good to Excellent – overall the test section is in very good condition, similar to test section N-6. Figure 16 shows an area of erosion where water has pooled in the invert. Large rocks and other debris are scattered around the invert which may have contributed to the minimal shotcrete damage seen. The water line on the side slopes is visible in Figure 16. Small cracks and voids were observed throughout the invert and side slopes. District personnel have been very diligent with concrete repair which should maximize service life by preventing further degradation. The value of polyfibers was indeterminate; in addition, no difference was observed between the first and second half of the test section containing 3 and 1 ½ lb/yd^3 of fiber respectively. If continued maintenance occurs, an estimated service life for this material is 50 years, assuming continuation of the presently observed degradation at a constant rate.

Figure 16. Downstream canal view in test section N-7. Note: sitting water and rocks scattered throughout the invert of the canal.

North Unit Canal - Test Section N-8

Material: 3-inch shotcrete reinforced with Fibermesh Polyfiber at 3 lb/yd^3 fiber dosage for the first half of the canal and 1 ½ lb/yd^3 fiber dosage for the second half; **Installation**: February 1992/30,000 square feet/$2.21 and $2.14 per square foot

Condition (25 years): Very Good to Excellent – overall the test section is in very good condition, similar to test section N-6. Figure 17 shows an area of erosion where water has pooled in the invert. Large rocks and other debris are scattered around the invert which may have contributed to damaging the shotcrete. The water line on the side slopes is visible in Figure 17. Small cracks and voids are visible throughout the invert and side slopes. District personnel have been very diligent with concrete repair which should maximize service life by preventing further degradation. The value of polyfibers was indeterminate; in addition, no difference was seen between the first and second half of the test section containing 3 and 1 ½ lb/yd^3 of fiber respectively. If continued maintenance occurs, an estimated service life for this material is 50 years, assuming continuation of the presently observed degradation at a constant rate.

Figure 17. Group of rocks in the canal invert. Small void can be seen on the right, filled with water. A long but narrow crack can be seen on the side slope. Overall the test section is in very good condition.

North Unit Canal - Test Section N-9

Material: 3-inch unreinforced shotcrete; **Installation**: February 1992/30,000 square feet/$2.07 per square foot

Condition (25 years): Very Good to Excellent – there is no visible difference between reinforced and unreinforced shotcrete. Seepage studies should be considered in the future to provide valuable performance data that a condition assessment cannot. Small voids and cracks are present throughout the test section. District personnel has been diligent with concrete repairs which increases service life and effectiveness of the liner. Overall this test section is still in very good condition and functioning efficiently. An estimated service life for this material is 50 years, assuming continuation of the presently observed degradation at a constant rate.

Figure 18. Portion of canal in test section N-9. Marks can be seen on the side slopes where kayakers have tied off. Water line is visually represented as a color transition on the side slopes. Small voids can be seen in the canal invert.

Ochoco Irrigation District – Main Canal

The table below summarizes all condition assessments performed on test sections in the Ochoco Canal (excluding test section O-2) as part of the canal lining demonstration project. The table serves as a tool to track the condition and performance of each liner between 1 1/2 and 18 years of age. Over the 18-year tracking period, 1 of the 5 test sections was removed from the study (O-2), leaving only 4 test sections performing as intended at the time of the inspection. This following section gives a detailed condition assessment of the 4 remaining test sections after up to 18-years of service.

Table 4. Ochoco Canal Condition Assessment Summary Table

Test Section	Material	Age at Assessment #1 (years)	Condition	Age at Assessment #2 (years)	Condition
O-1a	Covered GCL – (Bentomat DN)	3	Very Good	18	Fair to Good

Test Section	Material	Age at Assessment #1 (years)	Condition	Age at Assessment #2 (years)	Condition
O-1b	Covered GCL – (Bentomat CL)	3	Very Good	18	Fair to Good
O-3a	Exposed 45-mil ethylene propylene diene monomer (EPDM)	2 ½	Excellent	17	Good
O-3b	Exposed 45-mil EPDM with soil covered invert	2 ½	Excellent	17	Good
O-4	Exposed 30-mil linear low-density polyethylene (LLDPE)	2 ½	Excellent	17	Good
O-5	Exposed 160-mil Colas Bitumous Geomembrane	1 ½	Excellent	16	Good

Note: Test sections were installed at different times, resulting in variable assessment ages.

Ochoco Canal - Test Section O-1a and O-1b

Material: Covered Bentomat DN GCL and Covered Bentomat CL GCL; **Installation**: April 1999/32,500 square feet/$0.82 and $0.87 per square foot

Condition (18 years): Fair to Good – all cover material has sloughed into the canal invert, resulting in exposed side slopes and roughly 6-8 inches of cover material in the invert. Cracking is prevalent on exposed sections of the GCL along the side slopes of the canal. This is likely due to expansion/contraction cycles the GCL has experienced from exposure to wet and dry conditions. Soil covers prevent this type of cycle by providing confining stress and protection from the environment. A small amount of tearing can also be seen in these areas along the side slope. To stop degradation, the district explored re-covering the liner several years ago. However, due to questionable side slope stability, the idea was abandoned. Side slope sloughing will be closely tied to the service life of this liner. In speaking with the researchers who conducted the 2017 condition assessment, it was noted that the soil cover had almost completely sloughed off the side slopes 5 years prior, and that degradation of the side slopes was just beginning. Based on this knowledge, and the 2017 condition assessment, an estimated service life for this material is 15 years.

Note: Researchers failed to take photos of test section O-1a and O-1b for unknown reasons.

Ochoco Canal - Test Section O-3a and O-3b

Material: Exposed 45-mil EPDM with geotextile cushion on side slopes and Exposed 45-mil EPDM with geotextile cushion on side slopes with a covered invert; **Installation**: November 1999/63,000 square feet/$0.84 and $0.87 per square foot

Condition (17 years): Good – the exposed and covered EPDM membrane both appear to be in good condition. EPDM has excellent weathering properties due to its chemical structure. However, the liner is still susceptible to degradation from environmental factors. The covered invert and running water did not allow for detailed inspection of the canal invert. No visible tears or rips were observed on the side slopes; however, small holes can be seen near the water line, which were likely caused by wildlife. Figure 19 shows discoloration below the water line on the side slopes, which is likely a result of organic material deposits on the liner. Coupon sample testing will reveal more about the degradation level of the liner. Based on the visual condition assessment, an estimated service life for this material is 20 years, assuming continuation of the presently observed degradation at a constant rate.

Figure 19. Shows exposed EPDM liner in test section O-3a and O-3b with covered invert. Note: discoloration on the side slopes up to the water line due to organic material deposits. Debris and sediment build-up can be seen in the canal invert.

Ochoco Canal - Test Section O-4

Material: Exposed 30-mil LLDPE geomembrane with a geotextile cushion on side slopes; **Installation**: November 1999/48,000 square feet/$0.78 per square foot

Condition (17 years): Good – the exposed LLDPE liner is in good condition after 17 years of service. Little to no maintenance has been done over the last 14 years. District personnel would like to remove the sediment in the invert to increase flow but have not done so due to concerns about damaging the liner. The canal section seems to flush out enough sediment so that additional sediment removal is not necessary. There is minor tearing and wrinkling throughout the canal; however, the wrinkling does not appear to have caused any damage which is likely a result of LLDPE's elongation properties. Wrinkling is an indication of subgrade movement which could lead to future liner damage. Exposed geomembranes are susceptible to physical (wildlife and debris) and thermo-oxidative (light and heat) damage. Over time this can lead to soil migration, reduced capacity, and loss of functionality. Based on the visual condition assessment, an estimated service life for this material is 20 years, assuming continuation of the presently observed degradation at a constant rate

Figure 20. Exposed 30-mil LLDPE liner in test section O-4. Note: wrinkles can be seen throughout the liner and sediment deposits can be seen in the invert.

Ochoco Canal - Test Section O-5

Material: Exposed 160-mil Coletanche NTP 2 ES; **Installation**: November 2000/28,000 square feet/$1.51 per square foot

Condition (16 years): Good – the exposed bituminous liner is in good condition after 16 years of service. Sediment and vegetation can be seen in the invert. Small tears, and rips are visible in the liner above the water line. Small holes, most likely caused by wildlife, can be seen on the side slopes. Alligator cracking on the surface of the liner is prevalent. The cracking does not appear to have penetrated the liner but should be monitored moving forward. Water in the canal prevented a close inspection of the invert. The field located below the canal appears dry, indicating that the liner is maintaining a good seal. Based on the visual condition assessment, an estimated service life for this material is 20 years, assuming continuation of the presently observed degradation at a constant rate

Note: Researchers failed to take photos of test section O-5 for unknown reasons.

Sample Testing

Sample coupon testing was originally performed in 2002 as part of the 10-year durability report. Coupons of exposed geomembrane were taken from 6 test sections in the Arnold and Ochoco canals. This test data can be found in the report titled *"Canal Lining Demonstration Project Year 10 Final Report"* (Reclamation Report R-02-03). As part of the 25-year durability report, sample testing was again performed on the same 6 test sections, in hopes of making comparisons between 10-year and 25-year results. Unfortunately, test methodology was not properly recorded in the 10-year report, making any comparison to this data suspect. For this reason, 25-year sample testing utilized ASTM test methods and compared the results to established GRI QC standards, or ASTM QC standards when no GRI standard was available.

The QC standards detail the minimum or maximum values required to pass a quality check and be considered field ready. Significant deviation outside of this range indicates a propensity for degradation and/or damage of the material. The goal of sample testing is to make broad correlations between the physical and chemical properties of the geomembrane and its ability to provide adequate seepage control, not to provide service life predictions. Ultimately, service conditions will play the largest role in determining if a liner will be damaged by movement, impact, and/or thermal changes (e.g. debris, wildlife, vandalism, environmental factors, water table, gases, etc.). Even if the geomembrane's properties have diminished, it can still perform adequately in the absence of damage. Below is a detailed explanation of the important test parameters:

- **Strength & Elongation** – A significant increase in tensile strength and decrease in tensile elongation can indicate that a material has become brittle. A brittle material is more susceptible to damage from impact or stress cracking than a flexible (new) material.

- **Tear & Puncture Resistance –** An indication of the geomembrane's ability to resist damage from a tear or puncture. Low resistance signifies that the liner is susceptible to this type of damage.

- **Stress Cracking –** Cracking in a plastic caused by a sustained stress that is below the materials short-time mechanical strength. Materials with high crystallinity (e.g. HDPE) are more susceptible to stress cracking. Low resistance to stress cracking indicates an increased probability of this type of damage.

- **Carbon Black Content & Dispersion –** Carbon black is used as a UV stabilizer to prevent degradation from the sun. If the carbon black content dips too low or is not dispersed properly, the geomembrane is more susceptible to accelerated UV degradation and failure.

- **Oxidative Induction Time (OIT) –** Anti-oxidants are added to geomembrane formulations to prevent oxidative degradation. This test measures anti-oxidant levels in the material. Low anti-oxidant levels indicate susceptibility to degradation and damage.

Sample A-3 (HDPE)

Table 5 shows the result for Sample A-3 (HDPE). High strength values and a drop-in elongation (below GRI QC standards) suggest a loss in flexibility, making the material more susceptible to damage. Tear, puncture, and stress crack resistance all meet GRI QC standards. Oxidative induction time is significantly below the standard, indicating a loss of anti-oxidants leaving the geomembrane more susceptible to oxidative degradation. Carbon black content and dispersion remain high which has helped slow thermo-oxidative (UV) degradation.

Table 5. GRI Test Results for Sample A-3

Test Property	Test Method	Units	GM-13 Standard	GRI Result
Yield Strength	D6693	lb/in. (pound/inch)	168	266.7
Break Strength	D6693	lb/in.	120	166.5
Yield Elongation	D6693	% (percent)	12	10.6
Break Elongation	D6693	%	100	41.8
Tear Resistance	D1004	lb	56	86.3
Puncture Resistance	D4833	lb	120	206.3
Stress Crack Resistance	D5397 (App.)	hr.	500	>500
Carbon Black Content	D4218	%	2 to 3	2.4
Carbon Black Dispersion	D5596	NA (Not Applicable)	1 to 2	1
Oxidative Induction Time	D3895	min. (minutes)	100	33.3

Sample A-4 (PVC)

Table 7 shows the result for Sample A-4 (PVC). Break strength and hydrostatic resistance both meet GRI QC standards. Elongation, tear resistance, and puncture resistance are all below GRI standards, indicating that the liner has become brittle and is more susceptible to damage via impact, stress cracking, tears, and punctures. Test data suggests that the geomembrane is far along in the degradation process.

Table 6. GRI Test Results for Sample A-4

Test Property	Test Method	Units	ASTM D7176 Test Standard (No GRI Standard for PVC)	GRI Result
Break Strength	D6693	lb/in.	120	135.4
Break Elongation	D6693	%	100	69.6
Tear Resistance	D1004	lb	56	34.3
Puncture Resistance	D4833	lb	120	100.8
Hydrostatic Resistance	D751	Psi (pounds per square inch)	100	297

Sample A-5 (Hypalon)

Table 8 shows the result for Sample A-5 (Hypalon). Break strength, break elongation, puncture resistance, and carbon black content all meet GRI QC standards, indicating that the material has remained flexible and is less prone to these types of damage. Tear resistance is below the acceptable QC value indicating that the liner is susceptible to damage from a tear.

Table 7. GRI Test Results for Sample A-5

Test	Test Method	Units	GRI GM-28 Standard	GRI Result
Break Strength	D7004	lb	250	354
Break Elongation	D7004	%	15	23.8

Test	Test Method	Units	GRI GM-28 Standard	GRI Result
Tear Resistance Tongue Method	D5884	lb	70	45
Puncture Resistance	D4833	lb	85	159.7
Carbon Black Content	D4218	%	5 to 36	18.9

Sample A-6 (Hypalon)

Table 9 shows the result for Sample A-6 (Hypalon). Break strength, break elongation, puncture resistance, and carbon black content all meet GRI QC standards indicating that the material has remained flexible and is less prone to these types of damage. Tear resistance is below the acceptable QC value indicating that the liner is susceptible to damage from a tear.

Table 8. GRI Test Results for Sample A-6

Test	Test Method	Units	GRI GM-28 Standard	GRI Result
Break Strength	D7004	lb	250	353
Break Elongation	D7004	%	15	23.7
Tear Resistance MD	D5884	lb	70	59.6
Puncture Resistance	D4833	lb	85	155.8
Carbon Black Content	D4218	%	5 to 36	22.1

Sample O-3b (EPDM)

Table 10 shows the result for Sample O-3b (EPDM). Break strength and puncture resistance meet GRI QC standards. Tear resistance and elongation are substantially below the acceptable value. Test data indicates that the sample is brittle (increase in strength and decrease in elongation) and very susceptible to damage from a tear.

Table 9. GRI Test Results for Sample O-3b

Test	Test Method	Units	GRI GM-21 Standard	GRI Result
Break Strength	D7004	lb	1200	1610
Break Elongation	D7004	%	800	108
Tear Resistance MD	D5884	lb	16	8.6
Puncture Resistance	D4833	lb	42	46.6

Sample O-4 (LLDPE)

Table 11 shows the result for Sample O-4 (LLDPE). Break strength, tear resistance, puncture resistance, and carbon black content and dispersion all meet GRI QC standards. Break elongation, while still high, is below the acceptable level, indicating a loss in flexibility. Oxidative induction time is well below the standard, indicating low antioxidant levels and a susceptibility to oxidative degradation.

Table 10. GRI Test Results for Sample O-4

Tensile Properties	Test Method	Units	GRI GM-17 Standard	GRI Result
Break Strength	D6693	lb/in.	114	155.5
Break Elongation	D6693	%	800	597
Tear Resistance	D1004	lb	16	23
Puncture Resistance	D4833	lb	42	62.8
Carbon Black Content	D4218	%	2 to 3	2.4
Carbon Black Dispersion	D5596	NA	1 to 2	1
Oxidative Induction Time	D3895	min.	100	19.27

Value of Sample Testing

Based on the above test results and the visual condition assessment, it is reasonable to suggest that coupon testing alone is not an adequate measure of exposed geomembrane performance. Contradictions can be seen between coupon test data and visual assessments in the field. It is necessary to consider visual condition, sample test data, and seepage studies to gain a full understanding of exposed geomembrane liner condition and performance. While testing can provide valuable data signifying how far along a material is in the degradation process, test results alone lead to speculation rather than conclusive evidence. As mentioned previously, diminished properties increase the likelihood of damage to the liner, but do not guarantee that damage has occurred or will occur. Service conditions will ultimately play the greatest role in determining an exposed geomembrane's service life, as damage requires movement, impact, and/or thermal changes to occur.

Benefit/Cost Analysis

The B/C ratio represents the cost effectiveness of each lining system. The B/C ratio equation can be found below along with a detailed explanation of how each variable was determined. Calculation results are summarized in Table 12.

Benefit/Cost Equation

Benefit = E * S * I * V ($\$/ft^2 \cdot yr$)

E = effectiveness (%)
S = pre-construction seepage rate ($ft^3/ft^2 \cdot day$)
I = irrigation season (days)
V = value of water ($/acre-ft)

Cost = (K/D) + M ($\$/ft^2 \cdot yr$)

K = construction cost ($\$/ft^2$)
D = durability (years)
M = maintenance cost ($\$/ft^2 \cdot yr$)

Benefit/Cost Parameters

Pre-construction ponding tests were carried out in the Arnold and North Unit canals. Seepage rates ranged from 0.64 to 4.2 $ft^3/ft^2 \cdot day$. For this report, a value of 1 $ft^3/ft^2 \cdot day$ will be used for all test sections. The goal of the B/C analysis is to compare the cost effectiveness of each lining system. Making pre-construction seepage rates a constant value optimizes the comparison.

Effectiveness is a measure of the reduction in seepage when comparing pre-construction and post-construction seepage values. Seepage studies for the Arnold, North Unit, and Ochoco canals are detailed in the report titled *"Canal Lining Demonstration Project Year 10 Final*

Report" (Reclamation Report R-02-03). Seepage studies were used to predict a long-term seepage reduction value (effectiveness) for concrete over geomembrane, exposed geomembrane, and concrete liners. This report applies a predictive value based on current and previous results.

Irrigation seasons in the Arnold, North Unit and Ochoco irrigation districts are approximately 180 days per year.

The six previous Reclamation reports on the Upper Deschutes Canal Lining Demonstration Project have all used $50 per acre-foot as the value of water. Those reports explain that district water assessments range from $10 to $25 and water on the open market can be sold for up to $300 per acre-foot. For consistency and comparison, the $50 per acre-foot value will be used for the B/C calculations in this report.

Construction costs are detailed in the report titled "*Deschutes – Canal – Lining Demonstration Project Construction Report"* (Reclamation Report R-94-06, 1994). Total cost includes the material, subgrade preparation, installation, overhead, and contractor's profit.

Durability is a service life prediction based on the visual condition assessments done for each lining system. Tears, punctures, discoloration, sediment build-up, etc., all play a role in this determination. This is one of the most important contributions of this report as it improves accuracy of the B/C ratio.

Initially, maintenance costs for each test section were recorded; however, as the study progressed, maintenance became less common and record-keeping was no longer a priority. For this reason, an annualized cost prediction was determined for calculation purposes. Most irrigation districts are more familiar with concrete repair as opposed to geomembrane repair; additionally, concrete repair is generally considered the easier of the two. For these reasons, shotcrete and shotcrete over geomembrane test sections will use a value of $0.005 per square foot as an annualized maintenance cost. Exposed geomembrane test sections will use a value of $0.010 per square foot.

Table 11. Benefit/Cost Ratio Summary Table for all Test Sections

Test Section	Construction Cost ($/ft^2)	Durability Estimate (years)	Maintenance Cost ($/ft^2-yr)	Seepage Reduction Effectiveness (%)	B/C Ratio
A-1	2.43	50	0.005	95	3.7
A-2	2.52	50	0.005	95	3.5
A-3	1.38	30	0.010	90	3.3
A-4	1.05	15	0.010	90	2.3
A-5	1.11	18	0.010	90	2.6
A-6	1.03	15	0.010	90	2.4

Test Section	Construction Cost ($/ft^2)	Durability Estimate (years)	Maintenance Cost ($/ft^2-yr)	Seepage Reduction Effectiveness (%)	B/C Ratio
A-7	2.54	50	0.005	95	3.5
A-8	1.92	50	0.005	70	3.3
N-5	2	50	0.005	70	3.2
N-6	2.2	50	0.005	70	3.0
N-7	2.14	50	0.005	70	3.0
N-8	2.14	50	0.005	70	3.0
N-9	2.07	50	0.005	70	3.1
O-1	0.87	15	0.005	95	3.1
O-3	0.87	20	0.010	90	3.5
O-4	0.78	20	0.010	90	3.8
O-5	1.51	20	0.010	90	2.2

Performance Summary

Shotcrete/Grout Mattress/RCC & Shotcrete (B/C = 3.0 to 3.3)

Concrete lining systems provide superior durability and prevent soil migration, which ensures that canal capacity will remain unchanged throughout the liner's service life. Concrete maintenance practices are well-known and relatively easy to carry out, increasing the probability that field crews will keep up with maintenance schedules. Effectiveness is not a strong suit, estimated at approximately 70% over the lifetime of the liner. However, easy maintenance and high durability make up for shortcomings in seepage control and initial construction costs. Concrete liners should be considered in controlled seepage applications where limiting groundwater losses to communities bordering the canal is a high priority. In applications where seepage control is the main priority, other lining options will provide better performance.

Shotcrete/Grout Mattress over Geomembrane (B/C = 3.5 to 3.7)

Concrete over geomembrane lining systems have proven to be some of the most reliable and cost-effective lining types. The shotcrete/grout mattress cover protects the underlying liner against factors such as: thermo-oxidative damage (UV and heat), physical damage, uplift, and sediment migration. The concrete cover also provides a certain degree pf seepage control, and if the cover is damaged, the underlying liner will maintain positive seepage control until repairs are made. Since concrete maintenance practices are relatively easy to carry out, there is a greater probability that field crews will keep up with maintenance schedules, and if properly maintained, these protective covers can last 50 years or longer. The durability, effectiveness, aesthetic appeal, and ease of maintenance outweigh the high initial construction cost.

Exposed Geomembrane (B/C = 2.2 to 3.8)

Exposed lining systems have low initial construction costs and provide great seepage reduction when new. However, these liners are susceptible to physical and thermo-oxidative damage, compromising performance over time. The exposed membranes do not have concrete cover ballast, allowing sediment, ground water, gases, and sloughing to lift the liner and cause damage. Tears, punctures, and other damage provide pathways for water and sediment to migrate underneath the liner, which can drastically affect canal capacity and efficiency. Maintenance is considered difficult, and most irrigation district personnel are not trained on geomembrane repair techniques. With that said, select B/C ratios are favorable, indicating that certain geomembrane materials perform well exposed, while others are better suited for covered applications. Geomembrane thickness, resin material, and additive levels are all important factors to consider. Ultimately, service conditions will play the largest role in exposed liner performance, which explains the wide variance in B/C ratios.

Conclusions

- Three canal lining types (concrete, concrete over geomembrane, and exposed geomembrane) were covered in this report. B/C ratio numbers varied between 2.2 and 3.8. Table 12 below summarizes the main parameters used to determine the B/C ratio, resulting range for each lining type, and other key details.

Table 12. Major Liner Type Summary

Liner Type	Advantages / Disadvantages	Durability (years)	Effective-ness (%)	Maintenance ($/ft²·yr)	B/C Ratio
Concrete	Excellent durability, low maintenance costs, prevents soil migration, and maintains canal capacity; lowest effectiveness	50	70	0.005	3.0-3.3
Concrete over Geomembrane	Favorable durability, effectiveness, and maintenance costs, prevents soil migration and liner uplift, maintains canal capacity; most expensive lining type	50	95	0.005	3.5-3.7
Exposed Geomembrane	Low initial construction costs, high effectiveness and in certain cases can deliver long service lives; performance highly dependent on service conditions, subject to soil migration, liner whales, liner uplift, damage from ice, and capacity reductions, maintenance can be difficult and expensive for field crews	15-30	90	0.010	2.2-3.8

- Canal failure must be considered in addition to liner failure when selecting liner materials. Exposed geomembranes are susceptible to soil migration and capacity reductions, which can lead to canal failure even if the liner is still performing well.

- Coupon testing alone is not an adequate measure of canal performance when evaluating exposed geomembranes. It is necessary to account for visual condition, sample test data, and seepage studies (future work) to gain a full understanding of liner condition and performance. Diminished test properties indicate increased susceptibility to damage, but do not guarantee it. Ultimately, service conditions play the greatest role in determining an exposed geomembrane's service life.

- Any performance differences between steel, Phillips, and Fibermesh reinforcement fibers is indiscernible to the eye. Additionally, there was no visible difference between reinforced and un-reinforced shotcrete test sections.

- Elastomeric coatings over geofoam or geomembrane liners are not well suited for large canals. High velocity water can cause damage and lead to liner failure.

- Grout mattress covers should be extended across the entirety of the canal. Leaving the invert geomembrane exposed can lead to "liner whales" which impedes water flow and reduces canal efficiency. Exposed geomembranes are also susceptible to physical and UV damage which can significantly reduce the service life.

- GCL liners should be covered in all applications to provide confining stress and protection (cracking and seam separation) for the GCL.

- Exposed geomembrane thickness plays a large role in antioxidant retention and the long-term durability of the liner.

References

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Data Sets that Support the Final Report

- Share Drive folder name and path where data are stored: T:\Jobs\DO_NonFeature\Science and Technology\2017-PRG-Canal Lining Demo Durability\DATA
- Point of contact name, email, and telephone: Brian Baumgarten, bbaumgarten@usbr.gov, 303-445-2399
- Short description of the data: Geosynthetic Research Institute coupon sample test data of exposed geomembrane test sections from the Upper Deschutes River Basin Canal Linings Demonstration Project in Central Oregon.
- Keywords: Coupon testing, canal linings, canal seepage, canal durability, demonstration project, geomembrane, geosynthetic, Oregon
- Approximate total size of all files: 121 KB