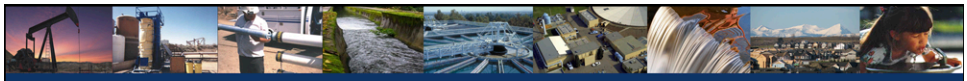


Kennedy/Jenks Consultants
Engineers & Scientists

COLORADOSCHOOLOFMINES
EARTH • ENERGY • ENVIRONMENT

Argonne NATIONAL LABORATORY

Novel Thermally/Chemically Resistant Nanofiltration Membranes for Sustainable Reclamation of CBM Produced Water

Andrew Wait, Tzahi Cath, Nathan Hancock, Xanthe Mayer, Katharine Dahm, Dean Heil, Pei Xu, and Jörg Drewes

Colorado School of Mines

Wayne Buschmann

Eltron Research

17th International Petroleum and Biofuels Environmental Conference (IPEC)

San Antonio, TX, September 1st, 2010

RPSEA
Research Partnership to Secure Energy for America

Outline

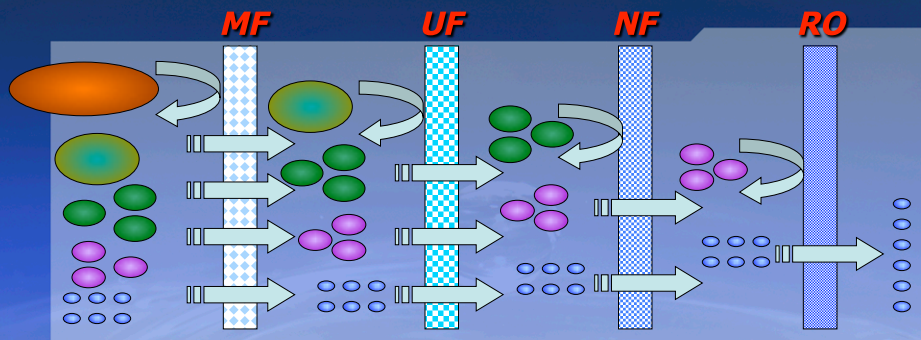
- Membrane processes for treatment of produced water
  - Pretreatment and challenges
  - Treatment and challenges
- Why nanofiltration?
  - Current nanofiltration technology
  - Novel nanofiltration technologies
    - what are they?
    - who are the players?
- Preliminary results from laboratory and field testing

COLORADOSCHOOLOFMINES
engineering the way

Kennedy/Jenks Consultants
Engineers & Scientists

Argonne NATIONAL LABORATORY

Pressure Driven Membrane Processes



Suspended Solids (Particles)

Macromolecules (Humics)

Multivalent Ions (Hardness)

Monovalent Ions (Na^+,Cl^-)

Water Molecules

Kennedy/Jenks Consultants
Engineers & Scientists

Argonne NATIONAL LABORATORY

Advantages of Membrane Processes

- Small footprint
- Modular and portable
- Easily automated
- Consistent product water quality
- Broad range of applications
  - Pretreatment (microfiltration (MF) / ultrafiltration (UF))
  - Treatment/desalination (nanofiltration (NF) / reverse osmosis (RO))

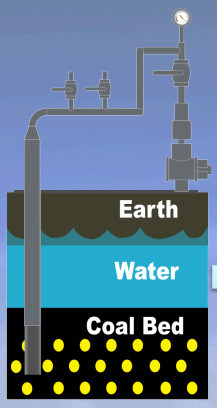
→ *Well suited for treatment of produced water in the field*

COLORADO SCHOOL OF MINES
engineering the way

Kennedy/Jenks Consultants
Engineers & Scientists

Argonne NATIONAL LABORATORY

Membrane Processes for Treatment of Produced Water



Membrane Pretreatment → Membrane Treatment / Desalination

COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Membrane Pretreatment: Challenges

- Consistency of water quality with time
- Type of foulants (colloidal, organics, biological, oil & grease…)
- Chemical conditioning
- Solids handling
- Chemical and thermal stability of membrane materials
  - During operation
  - During maintenance

COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

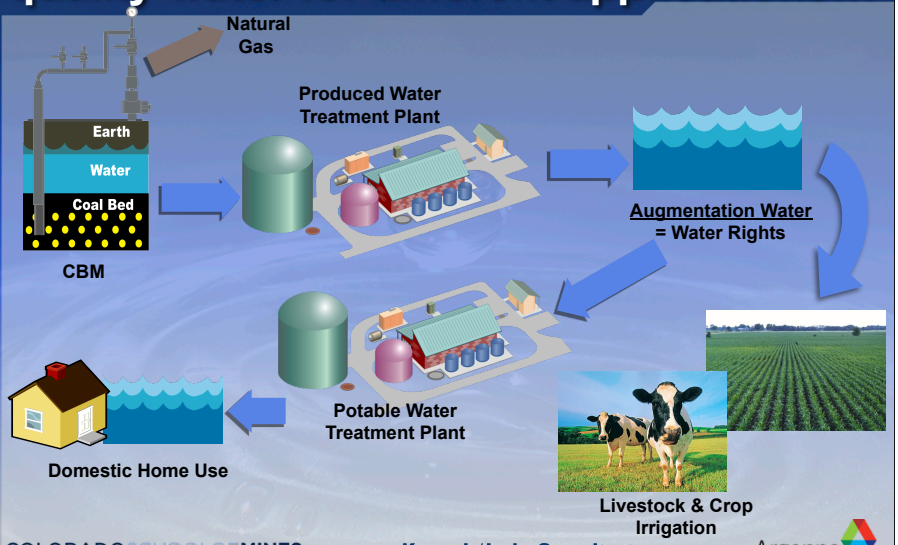
Argonne NATIONAL LABORATORY

Membrane Treatment/Desal: Challenges

- Consistency of water quality with time
- Type of foulants (organic, inorganic, biological)
- Chemical conditioning (scale inhibition, iron/ manganese removal…)
- Brine handling
- Chemical and thermal stability of membrane materials
  - During operation
  - During maintenance
- Energy

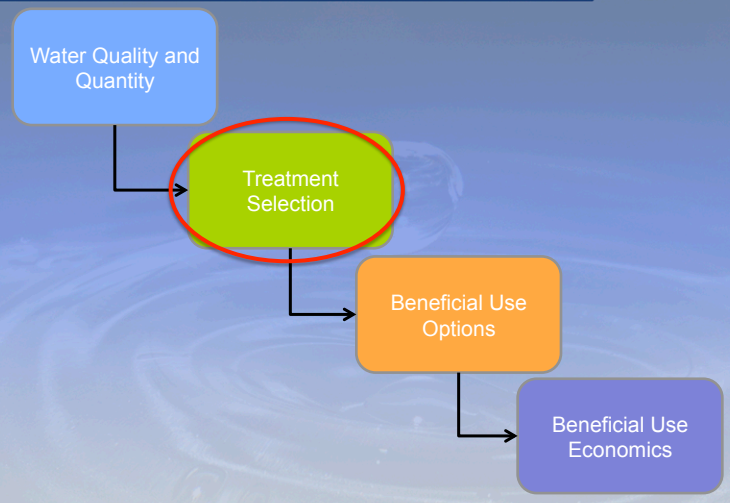
COLORADO SCHOOL OF MINES engineering the way | Kennedy/Jenks Consultants Engineers & Scientists | Argonne NATIONAL LABORATORY

But… membranes can produce high quality water for different applications…



COLORADO SCHOOL OF MINES engineering the way | Kennedy/Jenks Consultants Engineers & Scientists | Argonne NATIONAL LABORATORY

The Integrated Framework



Kennedy/Jenks Consultants
Engineers & Scientists

Argonne NATIONAL LABORATORY

An Integrated Framework for Treatment and Management of Produced Water

- **Task 2 - Selection and Testing of Treatment Technologies for Produced Water**
  - Identification and evaluation of robust, low-maintenance, modular pre-treatment and desalination technologies as well as brine management and disposal strategies (considering both well-established conventional as well as emerging desalination technologies):
    Treatment Technology Assessment Report
  - Explore most appropriate and cost-efficient technologies for treatment of produced water considering water quality of produced water and targeted beneficial use: Treatment Selection Module (TSM)
  - Pilot-scale treatment trains are currently being designed, assembled and tested at laboratory setting and representative production sites for field-scale validation
  - Develop cost modules for management options

COLORADO SCHOOL OF MINES
engineering the way

Kennedy/Jenks Consultants
Engineers & Scientists

Argonne NATIONAL LABORATORY

An Integrated Framework for Treatment and Management of Produced Water

- **Task 4 - Field Validation of Viable Treatment Processes for Produced Water**
  - Bench/pilot-scale treatment trains were designed, constructed and being tested at representative production site for field-scale validation
  - Data is being analyzed to determine the effectiveness, robustness, and ease of operation of treatment strategies
  - Testing results will provide validation of the integrated decision making framework

Why Nanofiltration for Treatment of PW?

- Lower energy (pressure) operation
- High throughput
- Can remove many constituents from water, including dissolved organic compounds, hardness, and some sodium and chloride
- Established technology

COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Novel Nanofiltration Membranes

- Existing/commercial nanofiltration membranes are polymeric and have limited range of operating conditions (temperature, water flux, tolerance to aggressive chemicals…)
- For sustainable operation with PW feed, membranes have to be more chemically and thermally stable
- Possible solutions:
  - Different polymer chemistry
  - Use of inorganic membranes (ceramics)

COLORADO SCHOOL OF MINES engineering the way | Kennedy/Jenks Consultants Engineers & Scientists | Argonne NATIONAL LABORATORY

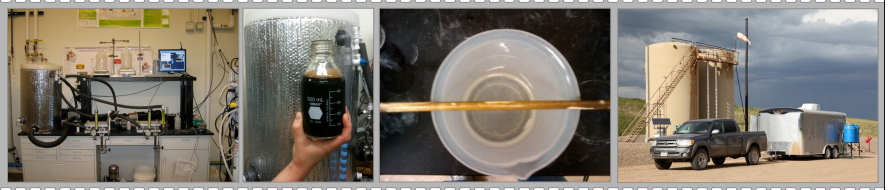
Novel Nanofiltration Membranes

- In this study, four different novel nanofiltration membranes are being evaluated:
  - Eltron Research novel composite ceramic-polymeric membranes
  - Eltron Research novel polymeric membranes
  - BPT novel polymeric membranes
  - Inopor novel ceramic membrane
- The membranes are at different stages of development
- They are being tested in the laboratory and in the field with synthetic and CBM produced water

COLORADO SCHOOL OF MINES engineering the way | Kennedy/Jenks Consultants Engineers & Scientists | Argonne NATIONAL LABORATORY

Research Highlights

- Test setup capable of operating at high pressures and temperatures and with different types and membrane configurations
- Fully SCADA controlled system to maintain constant operating conditions and to continuously compile and collect data in real time
- Portable in the new mobile laboratory



Eltron Research Novel Composite Ceramic-Polymeric Membranes

- Eltron Research is a partner on this project
- Novel polymeric chemistry on top of ultrafiltration ceramic substrate
- Currently tubular membranes configuration (¼" OD)
- Early stages of development
- Four different prototypes were tested in the laboratory with synthetic water and CBM produced water from the field

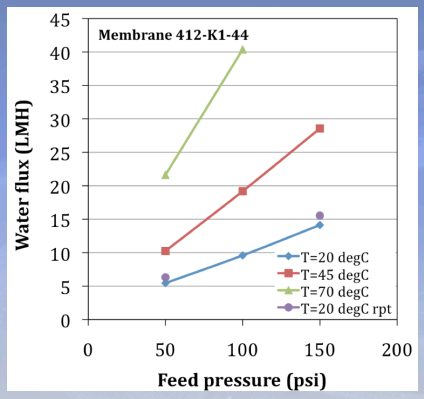
COLORADO SCHOOL OF MINES engineering the way

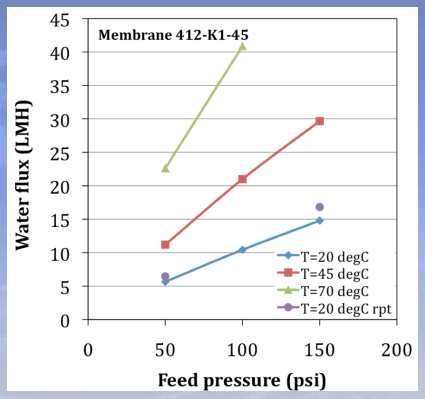
Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Eltron Research Novel Composite Ceramic-Polymeric Membranes

- Feed solution 2,000 ppm $MgSO_4$





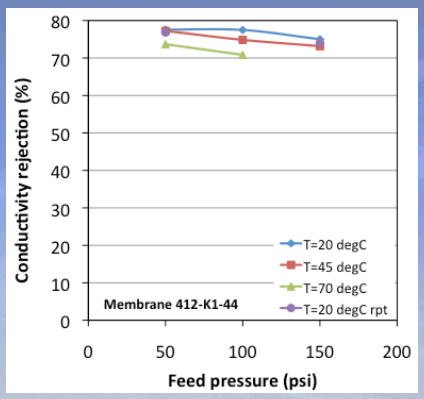
COLORADO SCHOOL OF MINES engineering the way

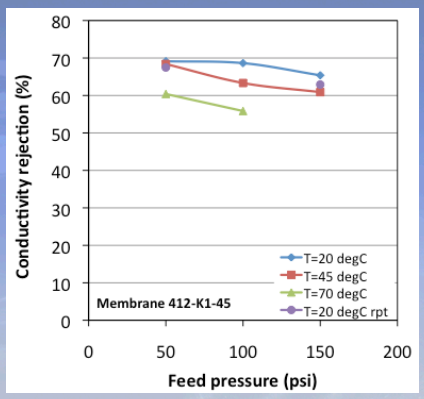
Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Eltron Research Novel Composite Ceramic-Polymeric Membranes

- Feed solution 2,000 ppm $MgSO_4$





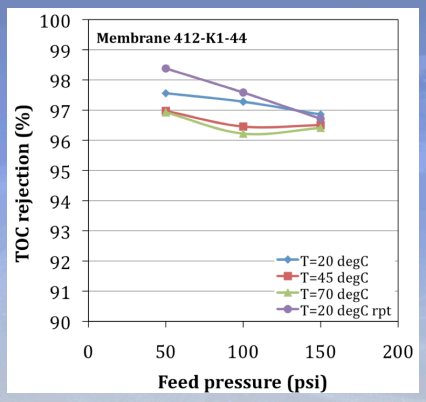
COLORADO SCHOOL OF MINES engineering the way

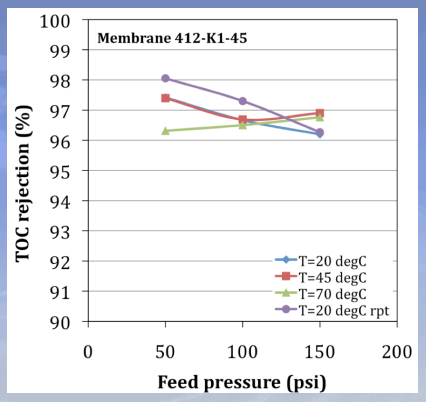
Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Eltron Research Novel Composite Ceramic-Polymeric Membranes

- Feed solution 50 mg/L humic acid





COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Eltron Research Novel Composite Ceramic-Polymeric Membranes

- The membranes were tested with CBM PW from the Raton Basin (Colorado)
- Water flux levels were high but rejection of salts and total organic carbon (TOC) were relatively low, most likely due to the low TOC concentration in the feed water
- New generation of membranes are being developed

COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Eltron Research Novel Polymeric Membranes

- Currently in flat sheet membranes configuration
- Early stages of development
- Ten different prototypes were tested in the laboratory with synthetic water

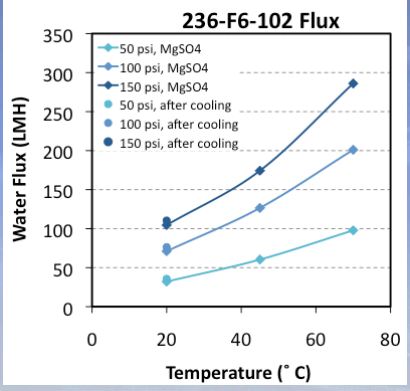
COLORADO SCHOOL OF MINES engineering the way

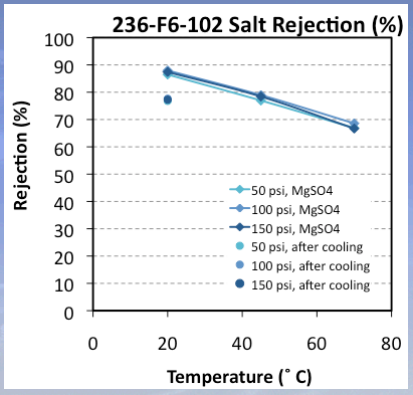
Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Eltron Research Novel Polymeric Membranes

- Typical challenge with $MgSO_4$ feed water (2000 ppm)





COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Eltron Research Novel Polymeric Membranes

- All membranes exhibited very high flux
- Membrane integrity was not compromised during testing at high temperatures and pressures
- Salt rejection was very high, always above 70% and in most cases above 80%
- Membrane development is ongoing

COLORADO SCHOOL OF MINES engineering the way | Kennedy/Jenks Consultants Engineers & Scientists | Argonne NATIONAL LABORATORY

BPT Novel Polymeric Membranes

- BPT makes membranes for industrial applications
- Membranes are highly chemically resistant (can operate with 70% sulfuric acid…)
- Membranes are highly temperature tolerant
  - Temperature resistant glue used in packaging of the membranes (glue lines of membrane)
  - Special temperature resistant feed and permeate flow spacers were developed
- Five different membranes were tested and compared to commercial NF

COLORADO SCHOOL OF MINES engineering the way | Kennedy/Jenks Consultants Engineers & Scientists | Argonne NATIONAL LABORATORY

BPT Novel Polymeric Membranes

			Water Flux (LMH)								
			20 °C			45 °C			70 °C		
Memb.	salt	Cf (g/L)	50 psi	100 psi	150 psi	50 psi	100 psi	150 psi	50 psi	100 psi	150 psi
270	NaCl	2	45	100	150	-	-	-	-	-	-
270	MgSO4	2	32	70	110	65	145	210	105	230	330
1500	MgSO4	2	7	14	21	13	27	41	21	46	70
1200	MgSO4	2	75	160	240	120	270	400	200	440	-
1300	MgSO4	2	65	110	150	-	-	-	-	-	-
1520	MgSO4	2	5	10	17	9	23	37	18	41	65
1530	MgSO4	2	14	30	44	26	55	83	47	94	-

			Rejection - conductivity (%)								
			20 °C			45 °C			70 °C		
Memb.	salt	Cf (g/L)	50 psi	100 psi	150 psi	50 psi	100 psi	150 psi	50 psi	100 psi	150 psi
270	NaCl	2	44	47.5	48.5	-	-	-	-	-	-
270	MgSO4	2	91	94	95	94	94.5	94.5	95	95.5	96
1500	MgSO4	2	60.4	63.6	72.2	56.4	54	55.1	50.1	54	55.1
1200	MgSO4	2	53	51	50	44	44	44.5	42	40	-
1300	MgSO4	2	19	20	20	-	-	-	-	-	-
1520	MgSO4	2	90.5	90	89.5	86	87.5	87	85.5	89	90
1530	MgSO4	2	54	60	65	49	53	61	51	58	-

COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

BPT Novel Polymeric Membranes

- Testing is still on going
- New membranes from BPT are being tested

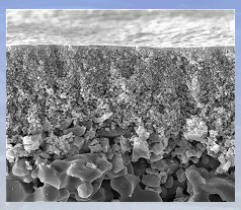
COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Inopor® Novel Ceramic Membranes

- One of very few ceramic nanofiltration membranes in the market
- Molecular weight cut off (200 Da) is relatively high
- Tested mostly in the field with CBM PW at the Raton Basin
- Was tested side by side with ceramic UF membranes

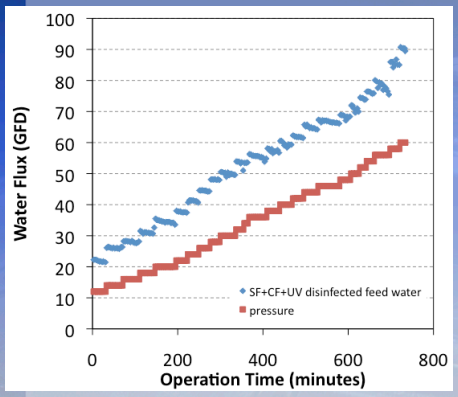


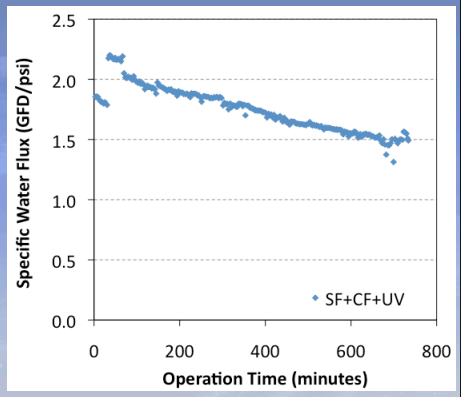
COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Inopor® Novel Ceramic Membranes: Results from Field Testing



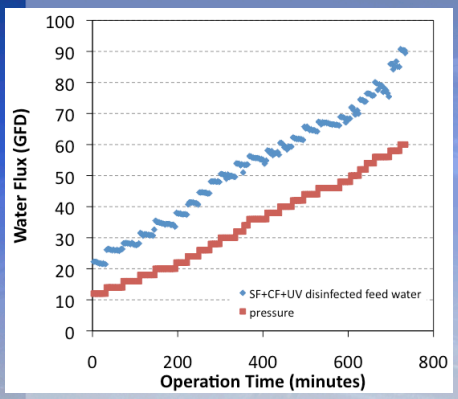


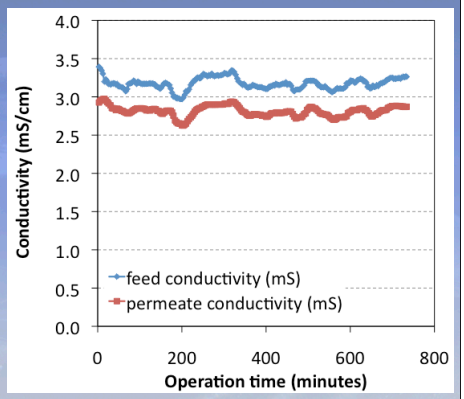
COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Inopor® Novel Ceramic Membranes: Results from Field Testing





COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY

Concluding Remarks

- Further development of novel nanofiltration membrane is needed and is ongoing
- Ceramic membranes are robust and need to be tested under challenging conditions to identify all their limitations
- The performance of novel thermally/chemically resistant polymeric nanofiltration membranes is approaching that of commercial nanofiltration membranes
- Further testing with CBM PW of different chemistries

COLORADO SCHOOL OF MINES engineering the way

Kennedy/Jenks Consultants Engineers & Scientists

Argonne NATIONAL LABORATORY


An Integrated Framework for Treatment and Management of Produced Water
SPONSORED BY:
RPSEA
Research Partnership to Secure Energy for America
Acknowledgment
RPSEA Stakeholder Advisory Committee (SAC) and the Industry Advisory Council (IAC)
Industry Sponsors
U.S. Bureau of Reclamation
RPSEA
COLORADO SCHOOL OF MINES engineering the way
Kennedy/Jenks Consultants Engineers & Scientists
Argonne NATIONAL LABORATORY