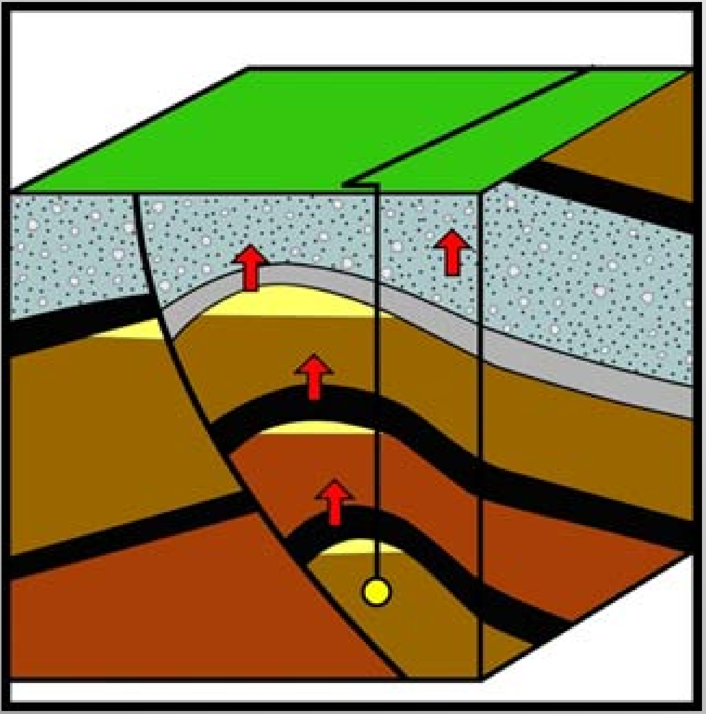


NRAP Risk Assessment Tool Webinar Series

Webinar 2

NRAP Seal Reduced-Order-Model (NSealR): A Method to Evaluate Uncertainties in Caprock Flow

Tuesday October 20, 2015

Presenter: **Ernest N Lindner**
AECOM (at NETL)

NRAP National Risk Assessment Partnership

NETL Berkeley Lab Los Alamos National Laboratory Pacific Northwest National Laboratory

U.S. DEPARTMENT OF ENERGY

Presentation Outline

I. Introduction to NRAP

II. Description of the NSealR Program

III. Navigating the Interface

IV. Example Cases

V. Quality Assurance & Future Development

VI. Questions and Open Discussion

Please Use Land-Lines for Audio; Please Mute Your Phone.

I. Introduction to NRAP

Welcome and Overview of NRAP – Technical Approach and Tool Development (Robert Dilmore)

- *Please Keep Your Phone Line Muted Until You Ask a Question*

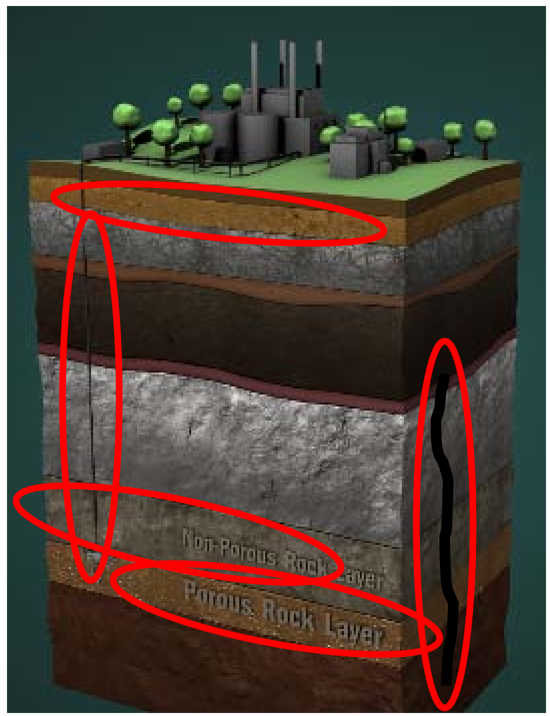
National Risk Assessment Partnership (NRAP)

NRAP leverages DOE's capabilities to help quantify uncertainties and risks necessary to remove barriers to full-scale CO_2 storage deployment.

Objective: Building toolset and improving the science base to address key questions about potential impacts related to release of CO_2 or brine from the storage reservoir, and potential ground-motion impacts due to injection of CO_2

Technical Team

NETL
Berkeley Lab
Los Alamos National Laboratory Est. 1943
Pacific Northwest National Laboratory

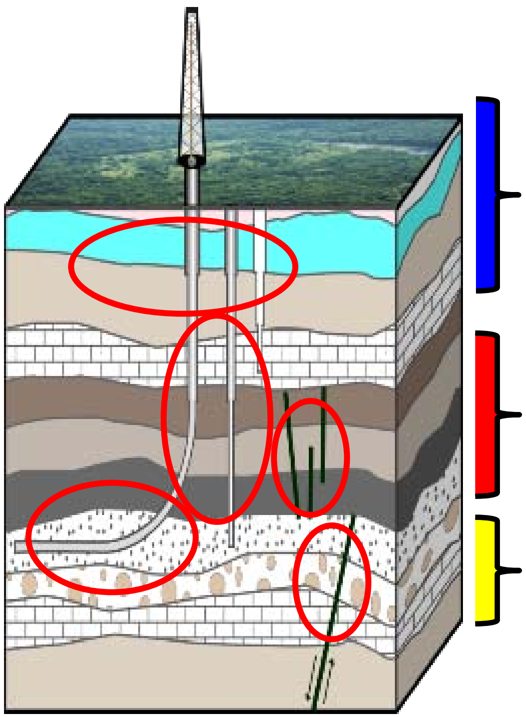


Stakeholder Group

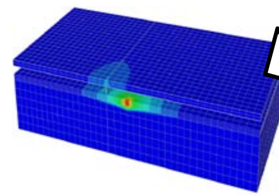
AEP American Electric Power
Blue Source
bp
EPA United States Environmental Protection Agency
ExxonMobil
ieaghg
IEc
MIT
NRDC
Schlumberger
Southern States Energy Board
Stanford University
Texas Railroad Commission
USGS
The University of Utah
Wade, LLC
Whiting
Zurich Because change happenz

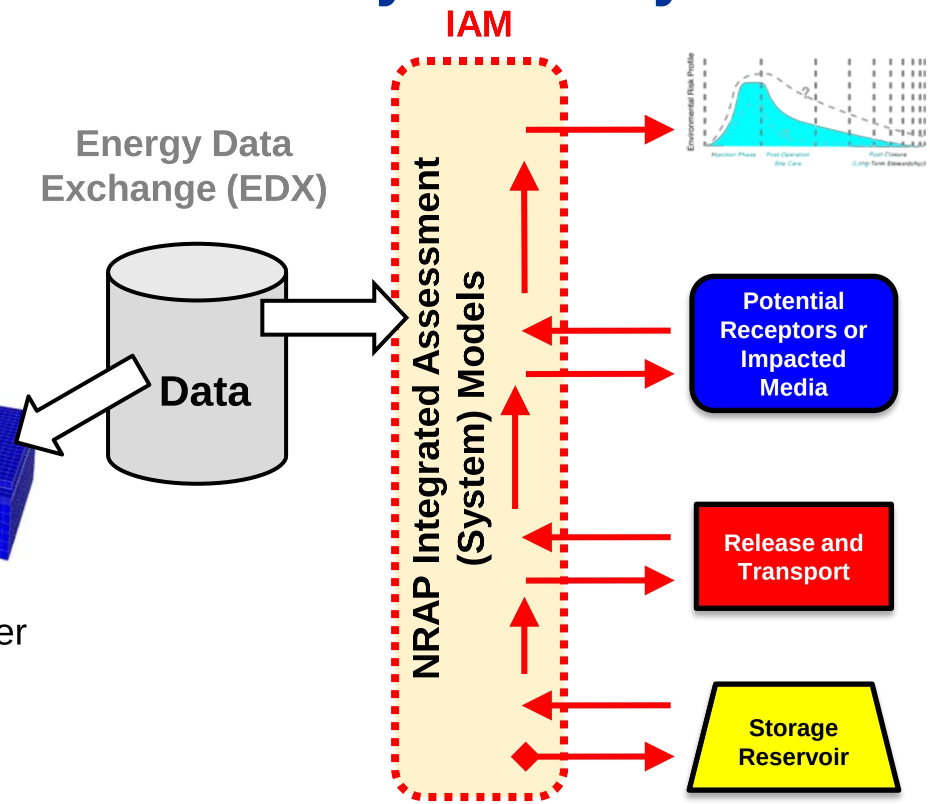
NRAP's approach to quantifying performance relies on reduced-order models to probe uncertainty in the system.

A. Divide system into discrete components



B. Develop detailed component models that are validated against lab/field data





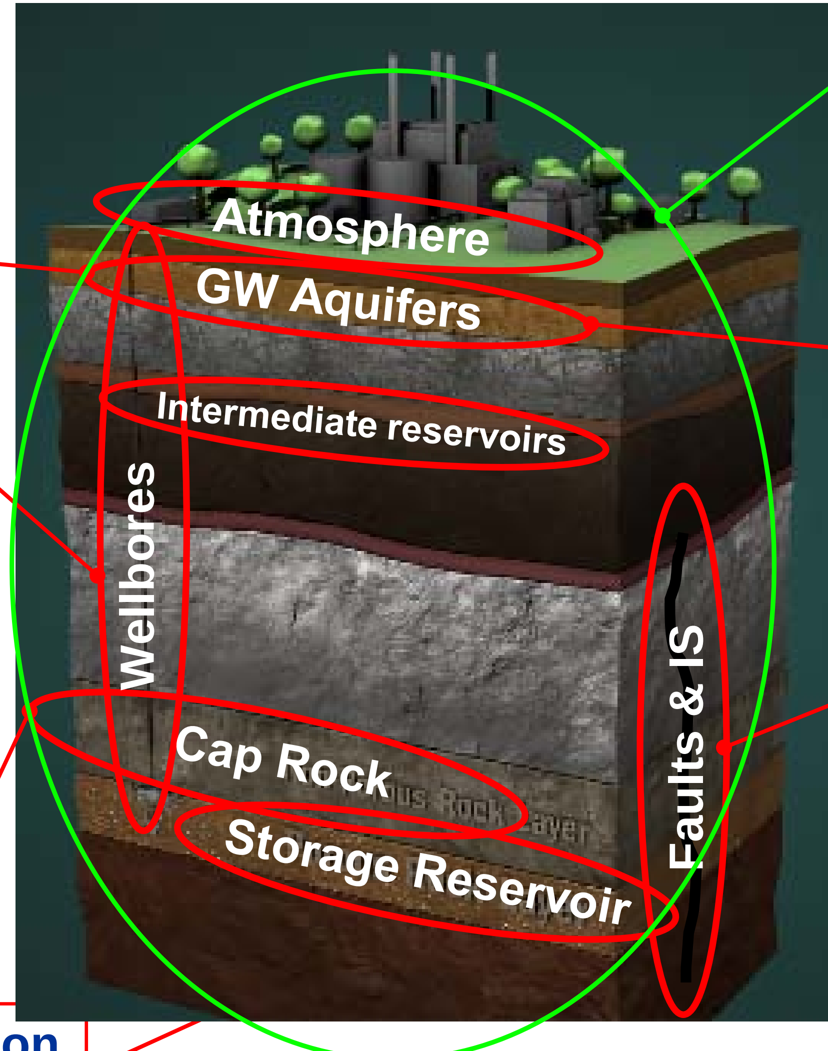
C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions

D. Link ROMs via integrated assessment models (IAMs) to predict system performance & risk; calibrate using lab/field data from NRAP and other sources

E. Develop strategic monitoring protocols that allow verification of predicted system performance

NRAP Tools

Now available for beta testing



NRAP-IAM-CS

Design for Risk Evaluation and Monitoring

Aquifer Impact Model

Wellbore Leakage Analysis Tool

Short Term Seismic Forecasting

Natural Seal ROM

Reservoir Evaluation and Visualization

www.edx.netl.doe.gov/nrap → *TOOL BETA TESTING link*

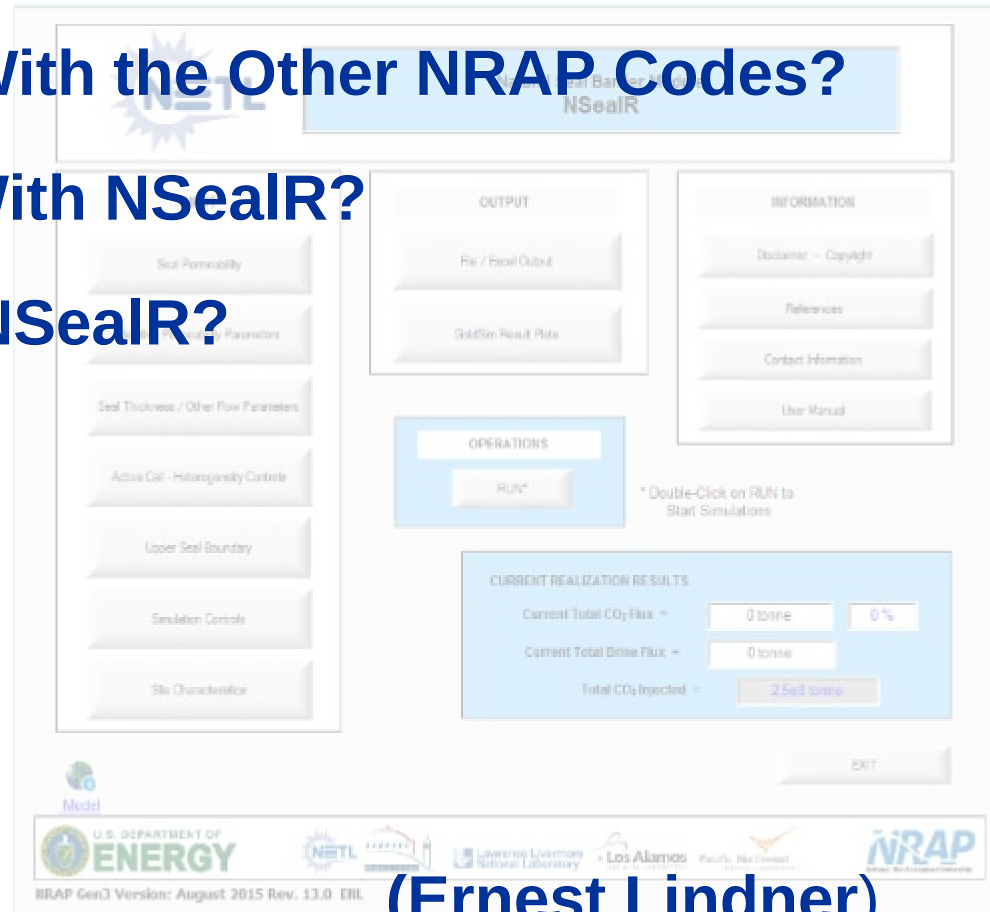
Schedule for NRAP Tool Webinar Series

Date/ Time	Tool	Presenter(s)
October 13 **Time: 1pm ET**	Integrated Assessment Model–Carbon Storage (NRAP-IAM-CS) (2.5 hours)	Rajesh Pawar
October 19 **Time: 1pm ET**	Natural Seal ROM (NSealR) (1 hour)	Nicolas Huerta, Ernest Lindner
October 26 **Time: 1pm ET**	Reservoir Evaluation and Visualization (REV) Tool (1 hour)	Seth King
November 2 **Time: 1pm ET**	Wellbore Leakage Analysis Tool (WLAT) (1.5 hour)	Nicholas Huerta
November 9 **Time: 1pm ET**	Aquifer Impact Model (AIM) (1.5 hour)	Diana Bacon
November 16 **Time: 1pm ET**	Design for Risk Evaluation and Monitoring (DREAM) (1 hour)	Catherine Ruprecht
November 30 **Time: 1pm ET**	Short Term Seismic Forecasting (STSF) (1 hour)	Josh White, Corinne Bachman
December 7 **Time: 1pm ET**	TBD	

Check for updates at www.edx.netl.doe.gov/nrap

II. Description of the NSealR Program

- What is NSealR?
- How Does It Fit-In With the Other NRAP Codes?
- What Can You Do With NSealR?
- How Can I Access NSealR?

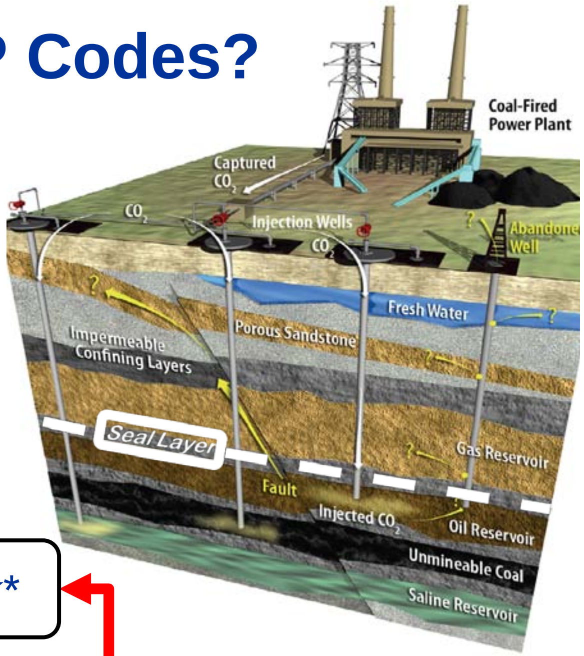


(Ernest Lindner)

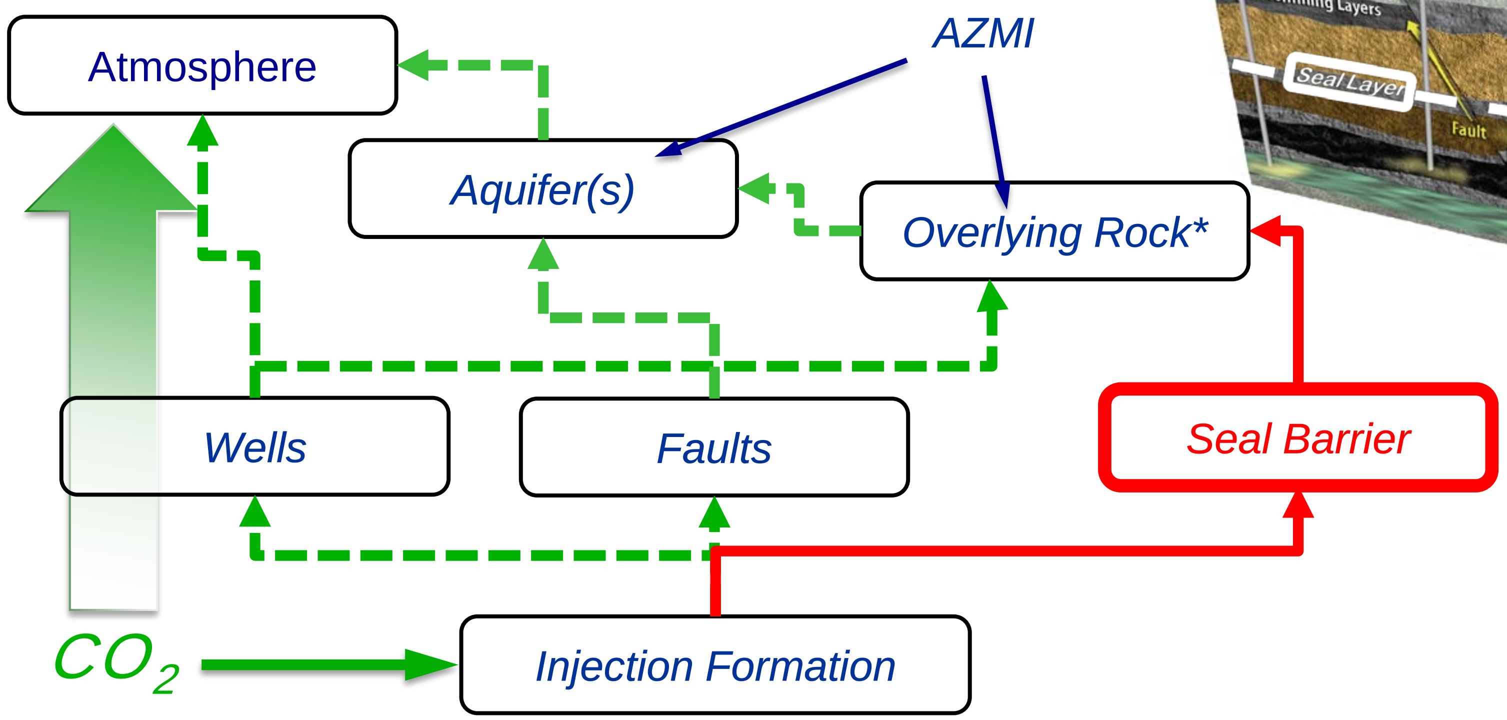
What is NSealR?

- Program (ROM Module) to Compute CO_2 Flow Through a Seal (Caprock) Layer for Risk Sequestration Analyses
- Constructed Using the GoldSim© Framework Model
- Uses Dashboard (Window) Input with Various Options to Model Response – From Simple to Complex
- Computes Two-Phase (Brine & Supercritical CO_2) Flow and Includes Fluid Thermal/Pressure Dependence
- Describes Parameters Using a Variety of Stochastic Functions

How Does It Fit-In With the Other NRAP Codes?



IAM ROM Submodels:

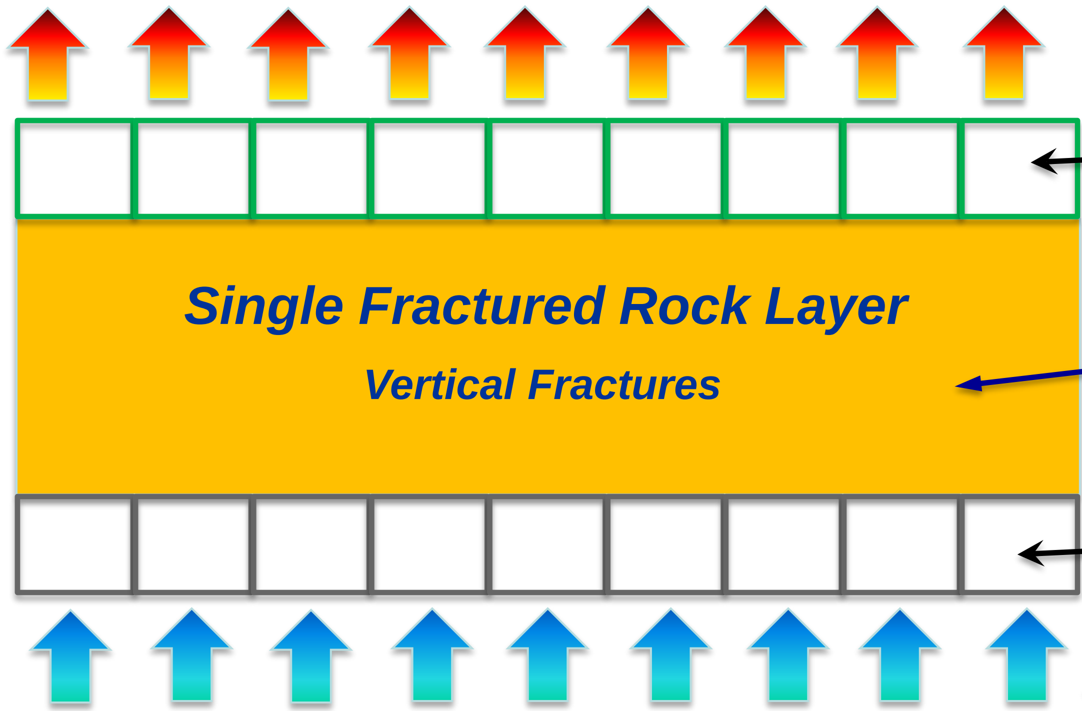


ROM = Reduced Order Model
IAM = Integrated Assessment Model
AZMI = Above Zone Monitoring Interval

**** Containing Non-Potable Groundwater***

NSealR Conceptual Model

OUTPUT: Brine Flow Rate and CO_2 Flow Rate to Aquifer/Groundwater Model



Groundwater Layer (100 x 100 Element Grid)

Two-Phase Fracture Flow of Brine & Supercritical CO_2

Reservoir Layer (100 x 100 Element Grid)

As a Function of Time / Location

INPUT: CO_2 Pressure & Saturation for Each Grid Element From Reservoir Model

What Can You Do With NSealR?

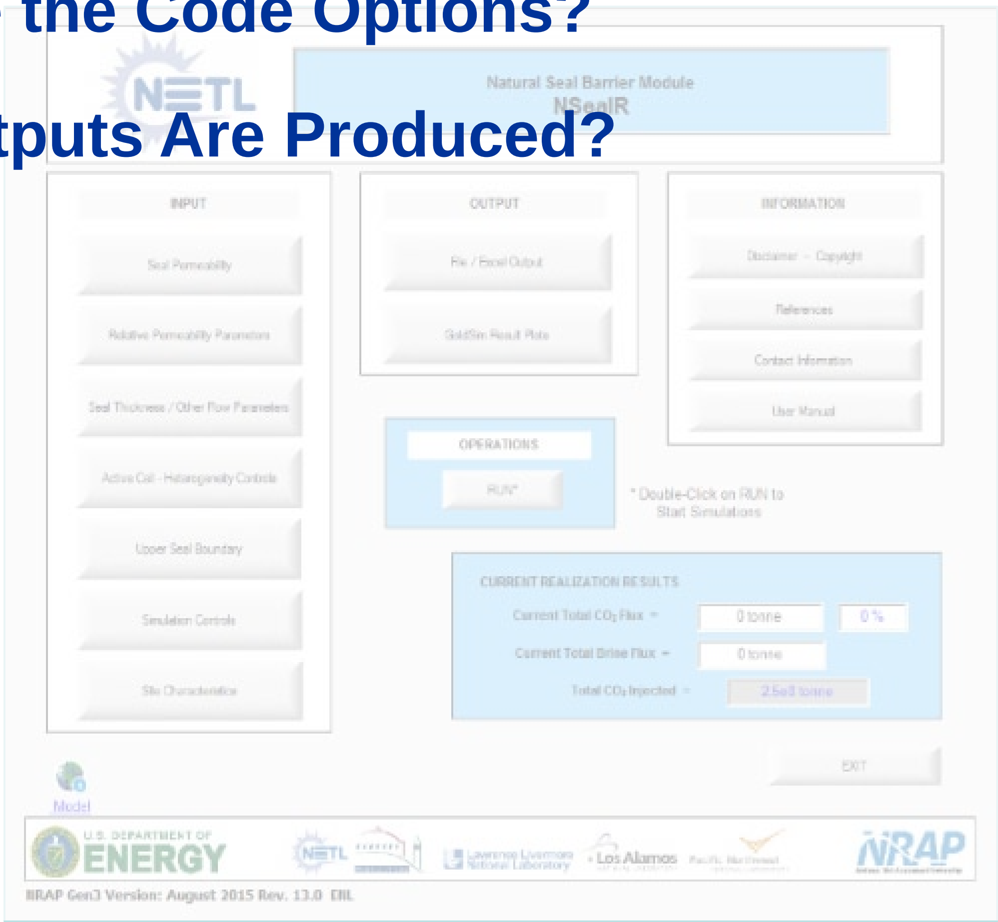
- Capture Important System Behavior to:
  - Evaluate the Probability of Potential Flow Volume from the Reservoir into Overlying Rock Units
  - Determine the Impact of System Parameters and Uncertainties on the Potential Amount of Flow
  - Evaluate Impacts on Groundwater Aquifers Based on Threshold Values
  - Conduct Informed Decision Processes Considering Uncertain Site Characteristics

How Can I Access NSealR?

- ***Where Is It?*** On EDX System at *http://edx.netl.doe.gov*
- ***Do I Need a License?*** No, but Registration is Required
- ***What Platform Will It Need to Run?*** Windows 7+
- ***How Do I Install?*** (1) Download and Unzip the NSealR Code Files and Directories from the EDX System (User Manuals are Provided in Download); (2) Install GoldSim Model or Player Framework Code (Player Code Available Free from *http://www.goldsim.com/Web/Downloads/*)
- ***How Do I run it?*** NSealR has a Simple-to-Use, Windows-Based Interface; Complex Cases Require Text File Input; Start by Clicking on **.gsm* or **.gsp* file
- ***What Do I Do If There are Questions or Bugs?*** Feedback Forms Are Available at Website. Address Questions to *NRAP@netl.doe.gov*

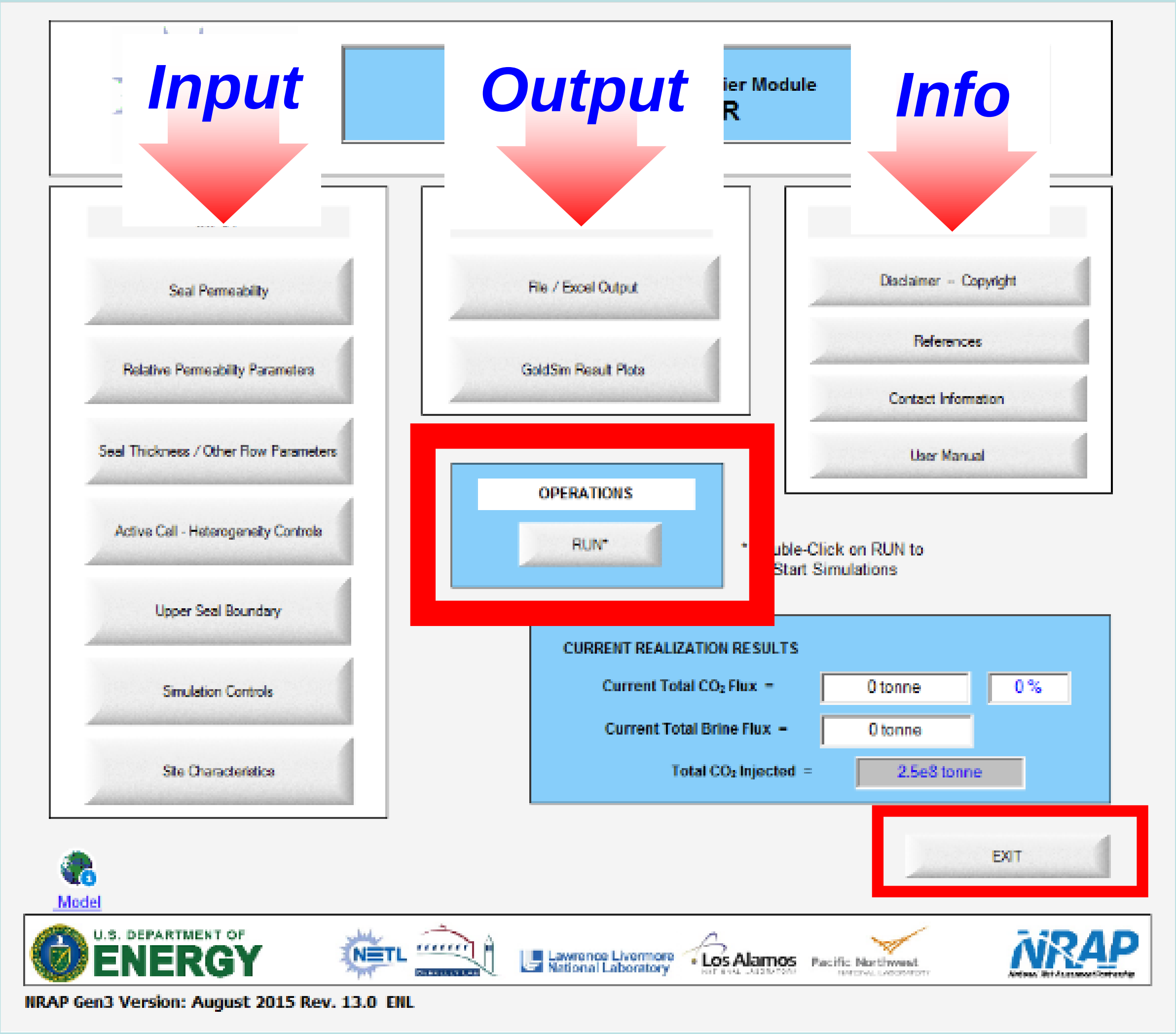
III. Navigating the Interface

- What Does the NSEALR Interface Look Like?
- What Are the Code Options?
- What Outputs Are Produced?



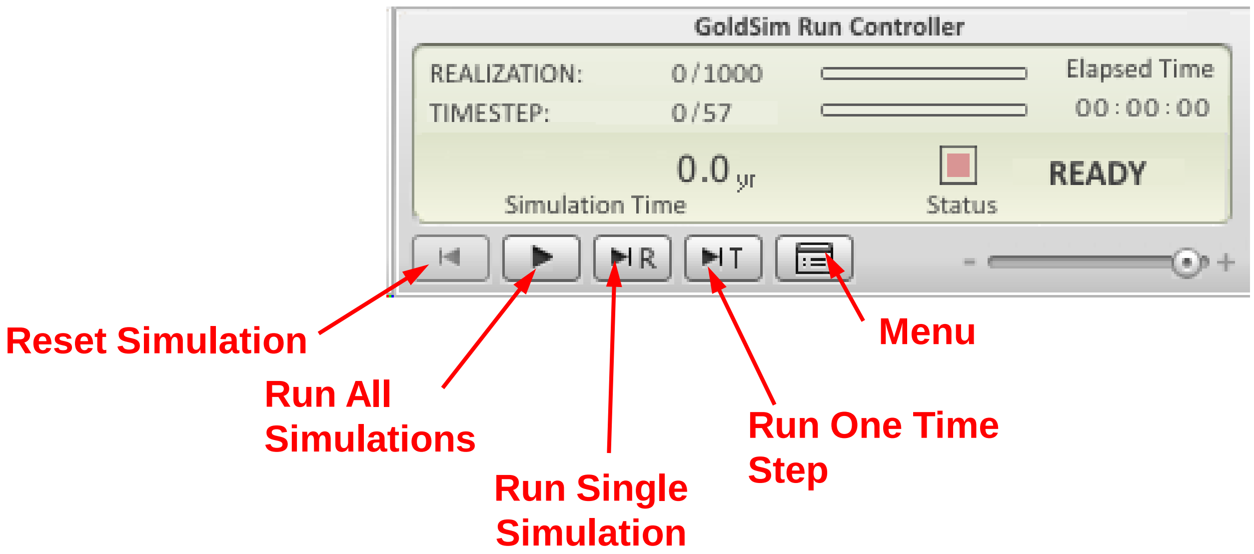
What Does the Interface Look Like?

NSealR Main Dashboard:



GoldSim Run Controller

- A Second, “Run Controller" Dashboard Also Appears with the Main Dashboard:



What Are the Code Options?

Input Topics - Under Each Topic, Options Provided to Reflect Increasing User Knowledge / Complexity

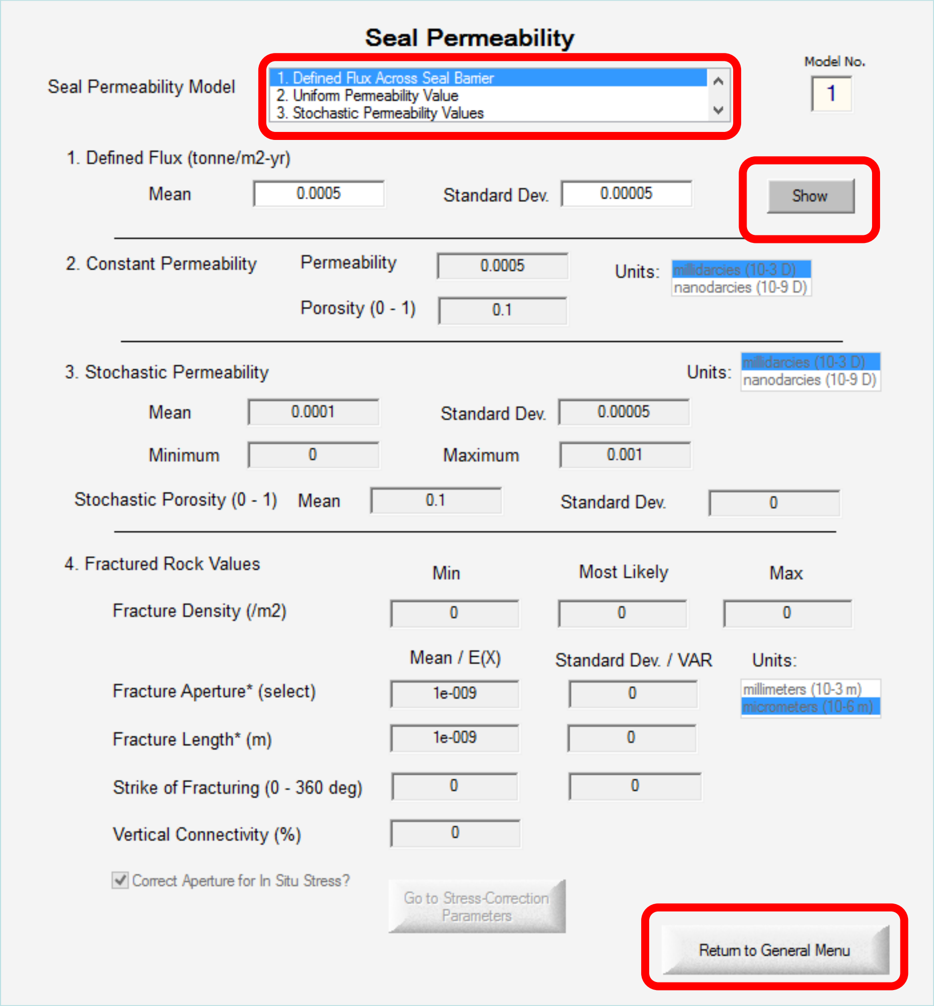
Topics:

1) **Permeability – 5 Options***
2) **Relative Permeability – 4 Models**
3) **Thickness Options – 2 Options***
4) **Cell Temperature – 3 Options***
5) **Definition of Active Cells***
6) **Additional Heterogeneity**
7) **Upper Boundary – 3 Options***
8) **Site Dimensions – 2 Options***
9) **Site Elevations*– 2 Options***

* Input Text File Option

Example - Permeability Dashboard

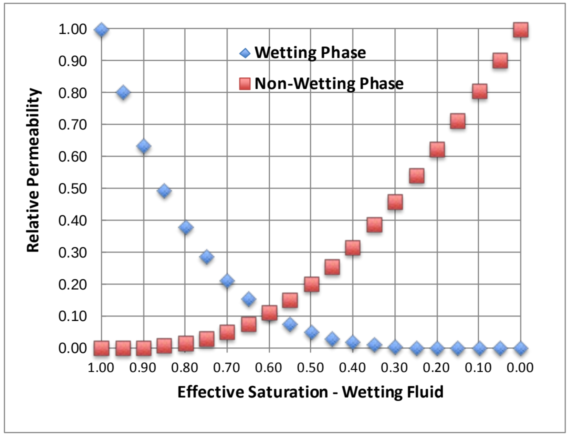
- A Scroll Menu is Used to Select an Option
- Input Boxes Are Enabled by Selected Option
- "Show" Button will Show Distribution Plot**
- Input Boxes Prevent "Bad" Values
- For Complex Cases, Program will Import Data from Text Files*



* Text File Format, Names and Directories Defined in Manual

** Stochastic Distribution Types Discussed in Manual

Relative Permeability Models



- **Code Employs a Relative Permeability Concept* & Darcy 1-D Flow for Each Cell**
- **Fluid Parameters are Temperature / Pressure / Salinity Dependent (Code Uses a Lookup Table)**
- **Models: Purcell, Brooks-Corey, van Genuchten, LET**
- **Incorporates Residual Saturations & Threshold Pressure Concepts**

$$u_w = \frac{k_t k_{rw}(S_e)}{\mu_w}\left(-\nabla p_w + \rho_w g\right)$$

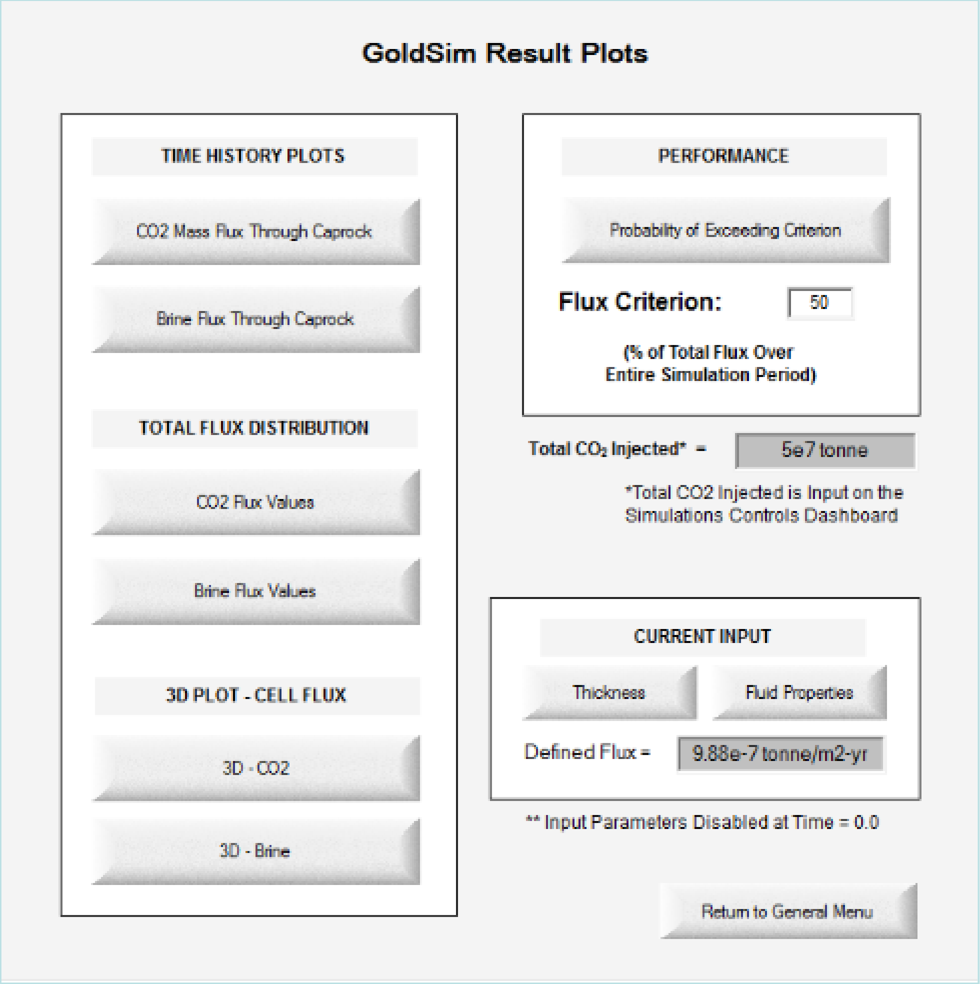
*** Brine Defined as the Wetting Phase Fluid**

What Outputs Are Produced?

Two Menus:

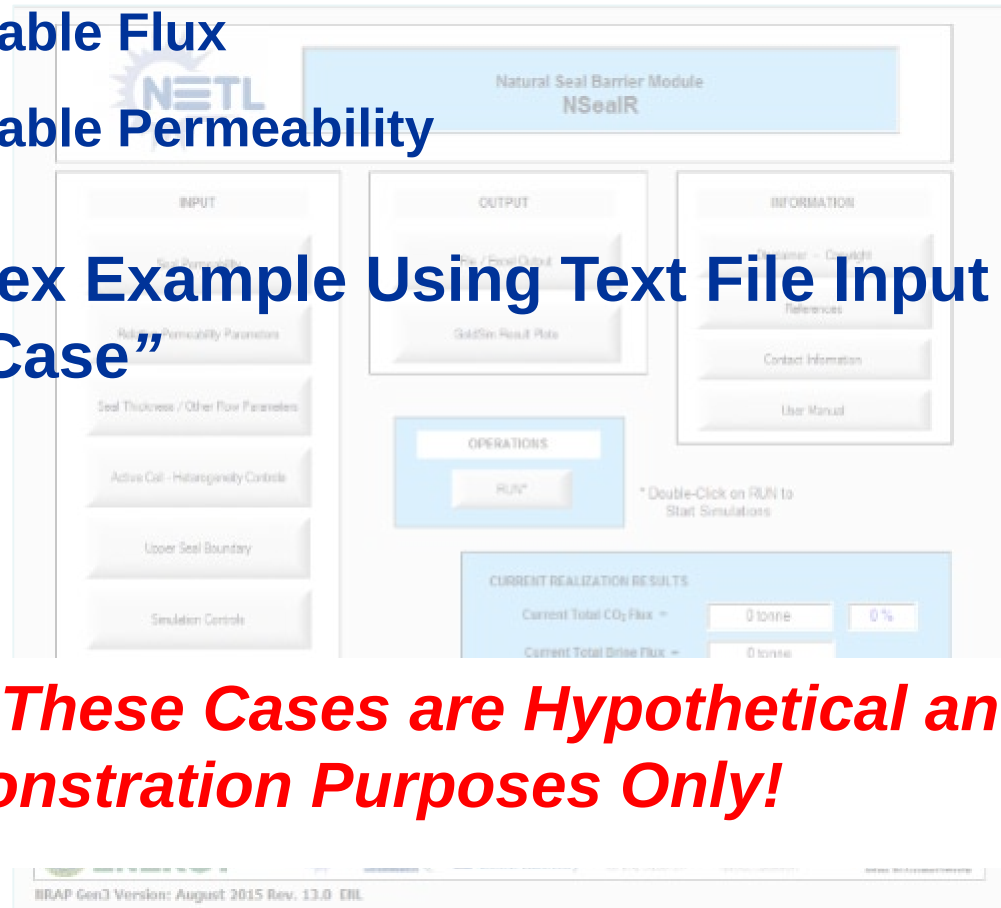
1. **First Menu Provides for Text File Output of a Simulation or Output to an Excel File. Input can Also be Echoed to Text Files**

2. **Second Menu Provides for Graphical Output Using GoldSim© Utilities (See Dashboard at Right) and a Current Properties Snapshot**



IV. Example Cases

- **Case A. Simple Example Using Keyboard Input**
  - **Case A-1: Variable Flux**
  - **Case A-2: Variable Permeability**



- **Case B. Complex Example Using Text File Input – "Kimberlina Case"**

Please Note That All These Cases are Hypothetical and are for Demonstration Purposes Only!

Simple Case A-1: Setup

- **Case A-1 Includes:**
  - **Defined Variable Flux at Top of Seal**
  - **Variable Flux: Mean: 8.0×10^{-5} tonne/m^2-yr ,**
    Std. Deviation: 4.0×10^{-5} tonne/m^2-yr
  - **Constant Seal Layer Thickness: 100 m***
  - **Constant Temperature: 155^{o}C***
  - **All Cells Active, No Additional Heterogeneity**
  - **Static Pressure Conditions at Top of Layer (Defined by Reference Pressure and Depth)***
  - **Simulation Domain – Square Area: 10 km on Side**
  - **Simple Model - Elevations: 0 m at Surface, -2660 m at Top of Reservoir***

*** No Influence on Flux Calculation**

Hypothetical Scenario for Demonstration Purposes Only

Code Demonstration – Cases A-1 and A-2

- Use of NSealR Player Version to Define Simple Cases
- No Input Files Are Used Except Reservoir Files (in Case A-2)
- Sequence: Enter Input Using the Dashboards, Then Run the Model, and Finally, Examine the Output Using GoldSim Utilities
- Limited Number of Realizations Used: 50
- Assumed Evaluation Period: 200 years

Hypothetical Scenario for Demonstration Purposes Only

Use of NSealR
Example A-1

(Reset Player)

Simple Case A-2: Setup (Slide 1 of 2)

- **Model A-2 Includes:**
  - **Variable-Permeability Caprock**
  - **Permeability: Mean 1.95 x 10^{-4} mD,**
    Std. Deviation: 3.0 x 10^{-4} mD
  - **Relative Permeability Model: Brooks-Corey (BC)**
  - **BC Lambda: 2.5 (Deterministic)**
  - **BC Bubbling Pressure: 0.32 MPa (Deterministic)**
  - **Residual Brine Saturation: 0.20**
  - **Residual CO_2 Saturation: 0.28**
  - **Threshold Pressure: 0.1 MPa**
  - **Constant Seal Layer Thickness: 100 m**
  - **Constant Temperature: 155^{o}C**

Hypothetical Scenario for Demonstration Purposes Only

Simple Case A-2: Setup (Slide 2 of 2)

- **Model A-2 Includes:**
  - **Saline Brine: 80,000 ppm**
  - **All Cells Active, No Additional Heterogeneity**
  - **Static Pressure Conditions at Top of Layer (Defined by Reference Pressure and Depth)**
  - **Simulation Domain – Square Area: 10 km on Side**
  - **Simple Model - Elevations: 0 m at Surface, -2660 m at Top of Reservoir**
  - **Reservoir Text Files: Located in Subdirectory "..\Lookup_Tables\transfer_data";**
    Pressure at Top = 32 MPa, Saturation = 0.5 (All Times/ All Cells)

Hypothetical Scenario for Demonstration Purposes Only

Use of NSealR
Example A-2

Example B: Setup (Slide 1 of 2)

- **Complex Case - A Saline Reservoir**
  - **Reservoir Assumed to be Similar to Vedder Sandstone Unit in South Central California**
  - **Sandstone Unit Inclined Upward to the East and is Irregular in Shape**
  - **Overall Dimensions: 72.1 x 92.6 km; Area ~ 6671 km^2**
  - **Input Based on Based on Kimberlina Data Files from IAM Modeling with CO2-PENS (see Keating et al, 2009); Detailed Description of Case is Provided and Included with NSealR Files**

Example B: Setup (Slide 2 of 2)

- **Complex Case - Saline Reservoir at ~ -2765 m**
  - **Variable-Permeability: 0.001 mD / 0.005 mD**
  - **Relative Perm Model: van Genuchten-Mualem (vG)**
  - **vG m-Factor: 0.457 (Deterministic)**
  - **vG Alpha-Prime: 4.26 E-6 (Deterministic)**
  - **vG Beta Exponent: 0.50 (Deterministic)**
  - **vG Gamma Exponent : 0.333 (Deterministic)**
  - **Residual Brine and CO2 Saturations: 0.20 & 0.28**
  - **Threshold Pressure: 0.1 MPa**
  - **Constant Seal Layer Thickness: 100 m**
  - **Static Top Boundary Conditions (Defined by Reference Pressure / Depth: 30.45 MPa @ -2600 m)**

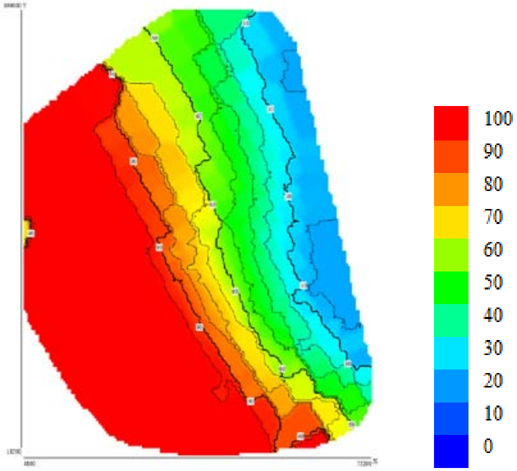
Hypothetical Scenario for Demonstration Purposes Only

Code Demonstration – Case B

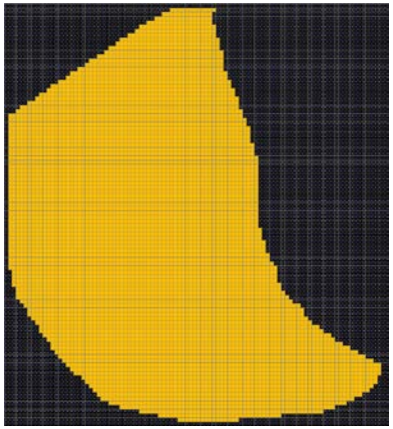
- Use of NSealR Player Version to Input / Define Permeability Input and Select Models
- Input Text Files Are Linked to Code (Using GoldSim Model) for Temperature, Active Cells, Elevations, Coordinates as Well as Input (see subdirectories under ..\Lookup_Tables\Kimberlina)
- Process: The Permeability Input is First Entered Using the Input to Dashboards, Running Model, and Then Examining Output Using GoldSim Utilities
- Limited Number of Realizations Used: 50
- Assumed Evaluation Period: 200 years

Text Files Data – Example Input (Contoured)

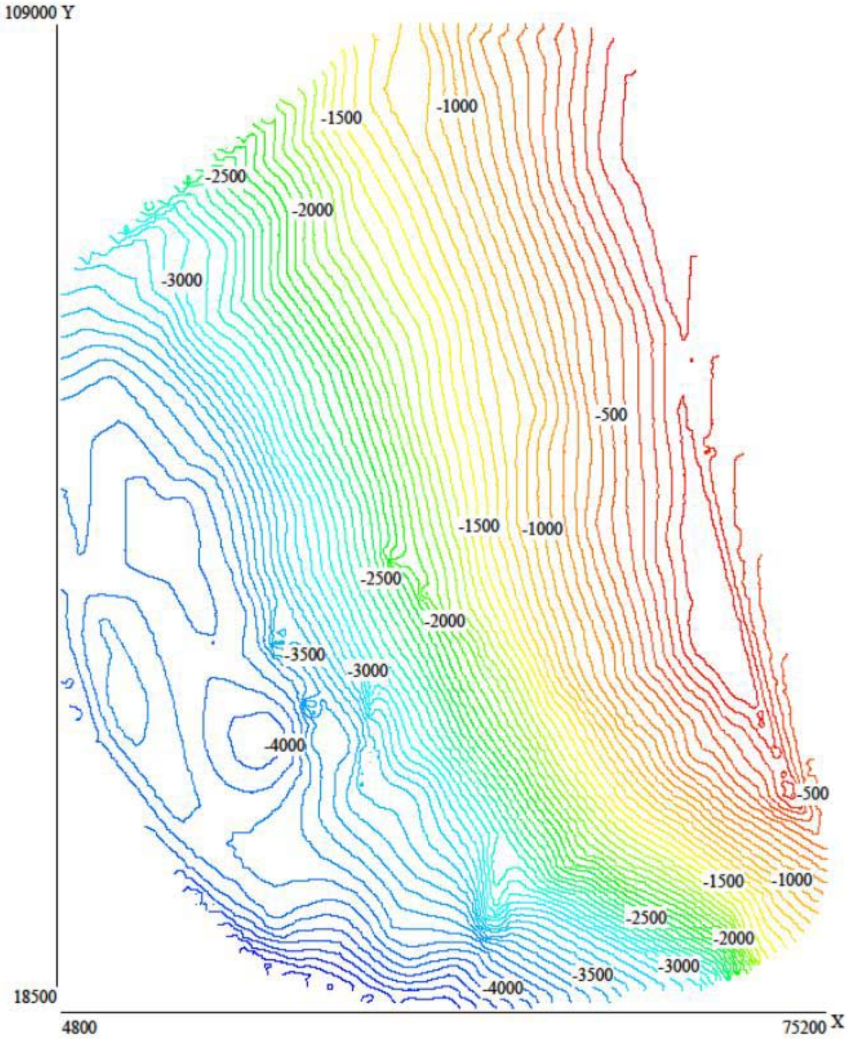
Temperature:



Active Cells:



Reservoir Elevations:



Use of NSealR
Example B

V. NSealR QA/QC Process & Future Development

Quality Assurance/Quality Checks (QA/QC):

- *Verification Activities in Planning*
- Various Hand-Calculations Have Been Performed to Verify Basic Calculations
- Reports Will be Posted on EDX

Future Development:

- Additional Model Development is Under Review
- Module Also Being Coded in C++ to be Linked with Other Python-Based tools (e.g., NRAP's REV tool)

VI. Questions and Open Discussion

- To Manage Q&A Session, We Request That You "Raise Your Hand" In The Webex Comment Window. The Speaker Will Call On Meeting Participants Consecutively From The Queue Of Questions One At A Time
- Please Keep Your Phone Line Muted Until Your Name Is Called
- Questions/Comments Not Addressed During the Scheduled Meeting Time Can Be Addressed to NRAP@netl.doe.gov

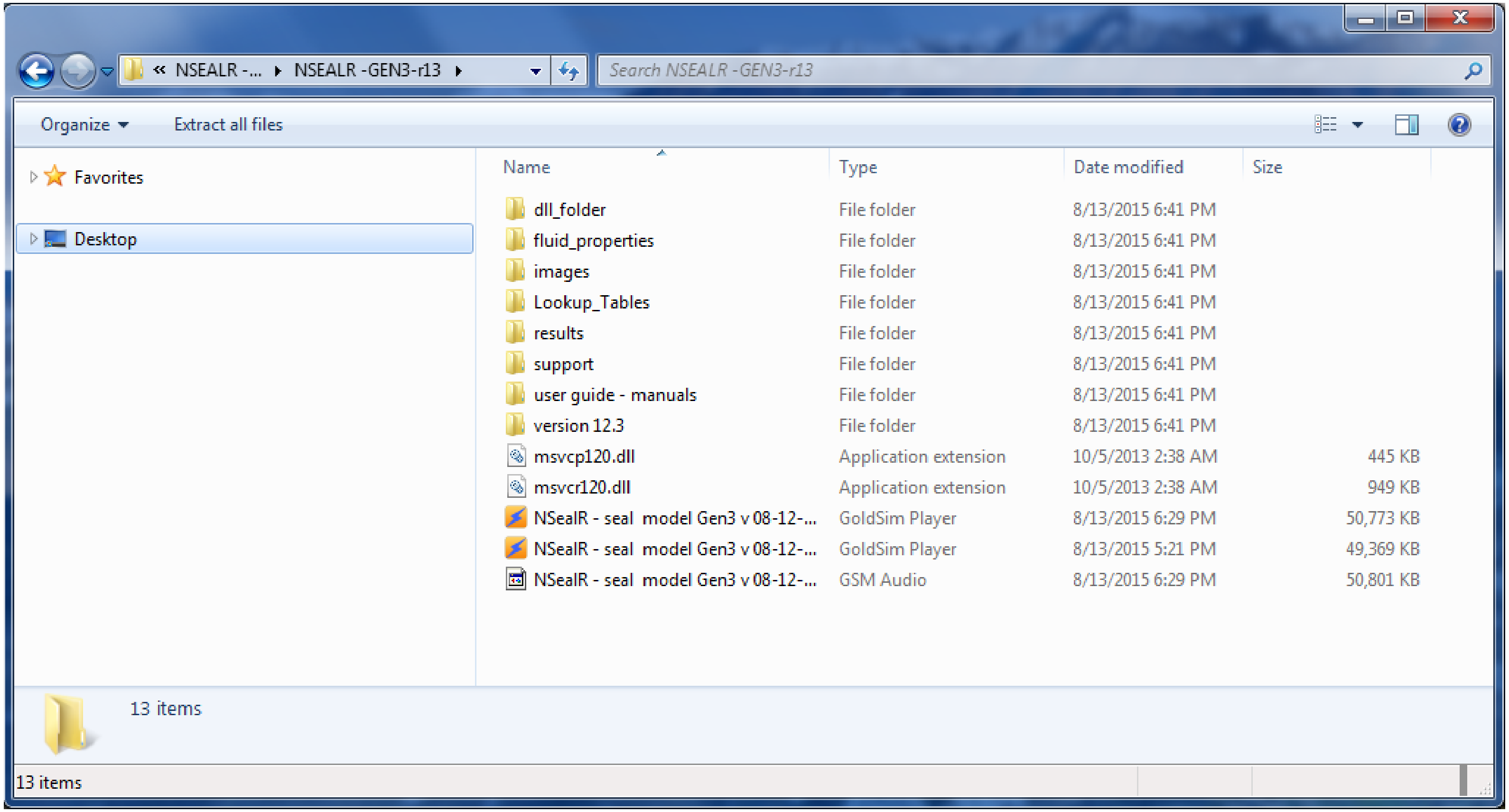
Thank you!

References

Keating, G. N.; Stauffer, P. H.; Viswanathan, H. S.; Chu, S; Letellier, B. C.; Carey, J. W.; Sanzo, D. L.; Cheung, M.; Pawar, R. J. *CO2-PENS Version 2009, User's Guide*; LANL Software LA-CC 08-075; Los Alamos National Laboratory: Los Alamos, NM, 2009.

Supporting Slides

NSealR File System



Purcell Relative Permeability Model

The wetting phase relative permeability (k_{rw}) is expressed in terms of the Effective Saturation (S_e) and a lambda exponent as:

$$k_{rw} = S_e^{\frac{2+\lambda}{\lambda}}$$

The nonwetting phase relative permeability (k_{rw}) is:

$$k_{nw} = (1 - S_e)^{\frac{2+\lambda}{\lambda}}$$

The Capillary Pressure (P_c) is represented in terms of the Entry (Threshold) Pressure (P_e) as:

$$P_c = \left\{ \frac{P_e}{S_e^{\frac{1}{\lambda}}} \right\}$$

Note: S_e is the Normalized Wetting-Phase Saturation as Described in the User Manual

Brooks-Corey Relative Permeability Model

The wetting phase relative permeability (k_{rw}) is expressed in terms of the Effective Saturation (S_e) and a lambda term as:

$$k_{rw} = S_e^{\left[\frac{2+3\lambda}{\lambda}\right]}$$

The nonwetting phase relative permeability (k_{rw}) as:

$$k_{rn} = (1 - S_e)^2 \left\{1 - S_e^{\left[\frac{2+\lambda}{\lambda}\right]}\right\}$$

The Capillary Pressure (P_c) is represented in terms of the Bubbling Pressure (P_b) and the Effective Saturation as:

$$P_c = \left\{\frac{P_b}{(S_e)^{\frac{1}{\lambda}}}\right\} \qquad \text{if } S_e \geq 0.01$$

Modified van Genuchten-Mualem Relative Permeability Model

The wetting phase relative permeability (k_{rw}) is expressed as in terms of the Effective Saturation (S_e), a "m" parameter and a beta exponent as:

$$k_{rw} = (S_e)^{\beta}\left[1-\left(1-S_e^{\left(\frac{1}{m}\right)}\right)^{m}\right]^{2}$$

The nonwetting phase relative permeability (k_{rw}) is expressed in terms of the Effective Saturation (Se), a "m" parameter and a gamma exponent as:

$$k_{rn} = (1-S_e)^{\gamma}\left[1-S_e^{\left(\frac{1}{m}\right)}\right]^{2m}$$

The Capillary Pressure (P_c) is represented in terms of the Effective Saturation and a alpha-prime factor as:

$$P_c = \frac{1}{\alpha'}\left\{S_e^{\left(-\frac{1}{m}\right)} - 1\right\}^{1-m}$$

LET Relative Permeability Model

The wetting phase relative permeability (*k_{rw}*) is expressed in terms of the Effective Saturation (*S_e*) and three factors (L_w, E_w, T_w) as:

$$k_{rw} = \frac{{S_e}^{Lw}}{{S_e}^{Lw} + E_w (1 - S_e)^{Tw}}$$

The nonwetting phase relative permeability (*k_{rw}*) is expressed with three additional factors (L_n, E_n, T_n) and a ratio term to the total (or wet) permeability (*R_n*):

$$k_{nw} = \frac{R_n (1 - S_e)^{Ln}}{(1 - S_e)^{Ln} + E_n {S_e}^{Tn}}$$

The Capillary Pressure (P_c) is represented in terms of the Entry (Threshold) Pressure (*P_e*) as:

$$P_c = B \left\{ \frac{P_e}{{S_e}^{A}} \right\}$$