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National Energy Technology Laboratory (NETL)

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A Nonconventional CO_2-EOR Target in the Illinois Basin: Oil Reservoirs of the Thick Cypress Sandstone

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Reporting Period End Date: 9/30/2018
Report Term: Quarterly

Signature of Submitting Official:

Nathan D. Webb: 

2. ACCOMPLISHMENTS

What was done? What was learned?

Major accomplishments include:

- A preliminary CO_2 storage and EOR resource assessment of the Cypress Sandstone ROZ play was completed. Using the median S_{or} from well log analysis of 23%, an estimated 1.7 billion barrels of ROZ oil in place is contained within defined prospects, of which up to 168 million barrels is estimated recoverable using a continuous CO_2 flood EOR factor of 9.9%, assuming miscible conditions. Associated CO_2 storage in the ROZs, not accounting for main pay zones or underlying brine aquifers, is estimated to be 7.6 billion tonnes, assuming 45 tonnes/1000 barrels.

What are the major goals of the project and what was accomplished under these goals?

The major goals of the project include identifying and quantifying nonconventional carbon dioxide (CO_2) storage and enhanced oil recovery (EOR) opportunities in the thick Cypress Sandstone in the Illinois Basin through geologic reservoir characterization, three-dimensional geocellular modeling, fluid properties and interaction modeling, and reservoir simulation. A study of the economics of potential storage and EOR programs in the thick Cypress will be made with considerations for production of net carbon negative oil. Field development strategies will be recommended with emphasis on near-term deployment. Accomplishments towards these goals are listed below by task as outlined in the SOPO.

Task 1.0–Project Management and Planning (on schedule)

- Progress on completion of tasks, subtasks, deliverables, and milestones is tracked using Microsoft Project to ensure timely completion. Overall, this project is on schedule.
- Principal investigator (PI) Nathan Webb and co-PI Scott Frailey, along with Nathan Grigsby, met weekly to discuss project management.
- There were regular meetings with the PI and subtask leaders for active subtasks.
- Daniel Byers, Damon Garner, and Nathan Webb have packaged data and imagery from the two cores collected for the project for online core visualization using the accessible PDF portfolio format. The core visualizations portfolios will be available on the Illinois

Oil and Gas Online Resources (ILOIL) map and data viewer system (http://maps.isgs.illinois.edu/ILOIL/). An example from the Tripp #1 core is available at https://uofi.box.com/v/Tripp-Core

Task 2.0–Geology and Reservoir Characterization (on schedule)

Subtask 2.1–Literature Review and Oilfield Selection

- Subtask concluded on 6/30/2015.

Subtask 2.2–Petrophysical Analysis

- Subtask concluded 10/31/2017.
- Nathan Grigsby and Scott Frailey continued work on a publication tentatively titled "Methodology for using well logs to identify residual oil zones: An example from Noble Field, Illinois." This method provides a screening tool to assess ROZ potential using existing well logs.

Subtask 2.3–Geologic Model Development

- Subtask concluded on 2/28/2018.
- Kalin Howell, Nathan Webb, and collaborators from the University of Illinois Geology department continued work on a manuscript that details the Cypress Sandstone geologic model with implications for reservoir properties titled "The Sedimentology of a Large Fine-Grained Carboniferous River: Facies, Palaeohydraulics, and Implications for Reservoir Heterogeneity"

Task 3.0–Geocellular and Reservoir Modeling (on schedule)

Subtask 3.1–Historical Production and Injection Data Analysis

- Subtask concluded 3/31/2016.

Subtask 3.2–Illinois Basin Crude Oil/Brine-CO_2 Fluid Property Characterization

- Dmytro Lukhtai conducted ambient-condition core flood experiments, using surrogate fluids to determine the irreducible water saturation (S_{wirr}) and residual saturation (S_{or}) of Cypress Sandstone and analogous Pennsylvanian core plugs continued. These

experiments are necessary to determine typical S_{or} that may be encountered in a Cypress ROZ to validate well log techniques (Archie equation) of saturation determination.

- 15 plugs representing the range of porosity (10 to 25%) and permeability (50 mD to 1 D) typically encountered in the Cypress were selected for flooding. S_{wirr} and S_{or} are determined by three methods to increase confidence in results: 1) mass of the saturated plug, 2) Archie equation using the resistivity of the saturated plug, and 3) volume of the effluent produced during the core flood.
- Results from the first five plugs show typical S_{or} values that may be expected in a Cypress ROZ are in the mid-30% range (Table 1). In general, the Archie equation, which is used in well log analysis, underestimates the S_{or}.

Subtask 3.3–Geocellular Modeling of Interwell Reservoir Characteristics

- Subtask concluded on 3/1/2018.
- The report titled "Assessing the Cypress Sandstone for CO_2-Enhanced Oil Recovery and Carbon Storage: Part II - Leveraging geologic characterization to develop a representative geocellular model for Noble Oil Field, Western Richland County, Illinois" has been approved for publication.

Subtask 3.4–Reservoir Modeling

- Subtask concluded on 4/3/2018.

Task 4.0–CO_2 EOR and Storage Development Strategies (on schedule)

Subtask 4.1–Field Development Strategies

- To improve the Noble Field history match of from the main pay zone and prepare for full-field development simulations, Fang Yang, Roland Okwen, and Scott Frailey have:
    a. Performed sensitivity analyses to calibrate the static model of the Noble Field.
    b. Generated input files of selected field development strategy scenarios as selected based on pattern modeling results.
- Nathan Grigsby determined pore volumes and OOIPs for 40 and 80 acre patterns used for the Noble model (Table 2). These numbers will help determine how effective the

reservoir simulations are (how much of the pore space is filled with CO_2 and how much of the oil was produced).

Subtask 4.2–CO_2 EOR and Storage Resource Assessment

- In collaboration with Drs. Steve Henderson and George Asquith (Texas Tech University), Nathan Grigsby continued to refine the regional well log analysis by identifying erroneous resistivity of mud filtrate (Rmf), and calibrating resistivity of formation water (Rw) and cementation exponents.
- Nathan Grigsby re-evaluated wells from Kenner West Field to determine if old e-logs can be used to identify ROZs as part of the regional resource assessment. Nine wells from the 1990s with neutron/density porosity and resistivity/spontaneous potential logs are being used to estimate input parameters for 27 wells from the 1940s have only old e-logs.
    - Oil production from the Cypress between the 1940s and 1990s is expected to move the producing oil water contact (top of ROZ) up, but the oil water contact (base of ROZ) is expected to stay constant. If this outcome can be observed from the log analysis, then the old e-log analysis may prove useful for the regional resource assessment.
- Nathan Webb, Nathan Grigsby, Scott Frailey, and Chris Korose completed the preliminary CO_2 Storage and EOR Resource Assessment of the Cypress Sandstone Residual Oil Zone Play in the Illinois Basin.
    - 27 Cypress ROZ prospects, defined as areas within the ROZ fairway that meet the criteria of having both well log analysis and historical records indicative of the presence of a ROZ, were identified in the Illinois Basin (Figure 1).
    - Using the median S_{or} from well log analysis of 23%, an estimated 1.7 billion barrels of ROZ oil in place is contained within defined prospects, of which up to 168 million barrels is estimated recoverable using a continuous CO_2 flood EOR factor of 9.9% assuming miscible conditions. Associated CO_2 storage in the ROZs, not accounting for main pay zones or underlying brine aquifers, is estimated to be 7.6 billion tonnes, assuming 45 tonnes/1000 barrels.

Subtask 4.3–Economic Analysis

- Scott Frailey selected development scenarios from the results of the new pattern model simulations to use in the revised Noble static model simulations. These scenarios will be used to for the economic analyses of to identify economically feasible CO_2-EOR and storage strategies for the Cypress ROZ in the ILB.

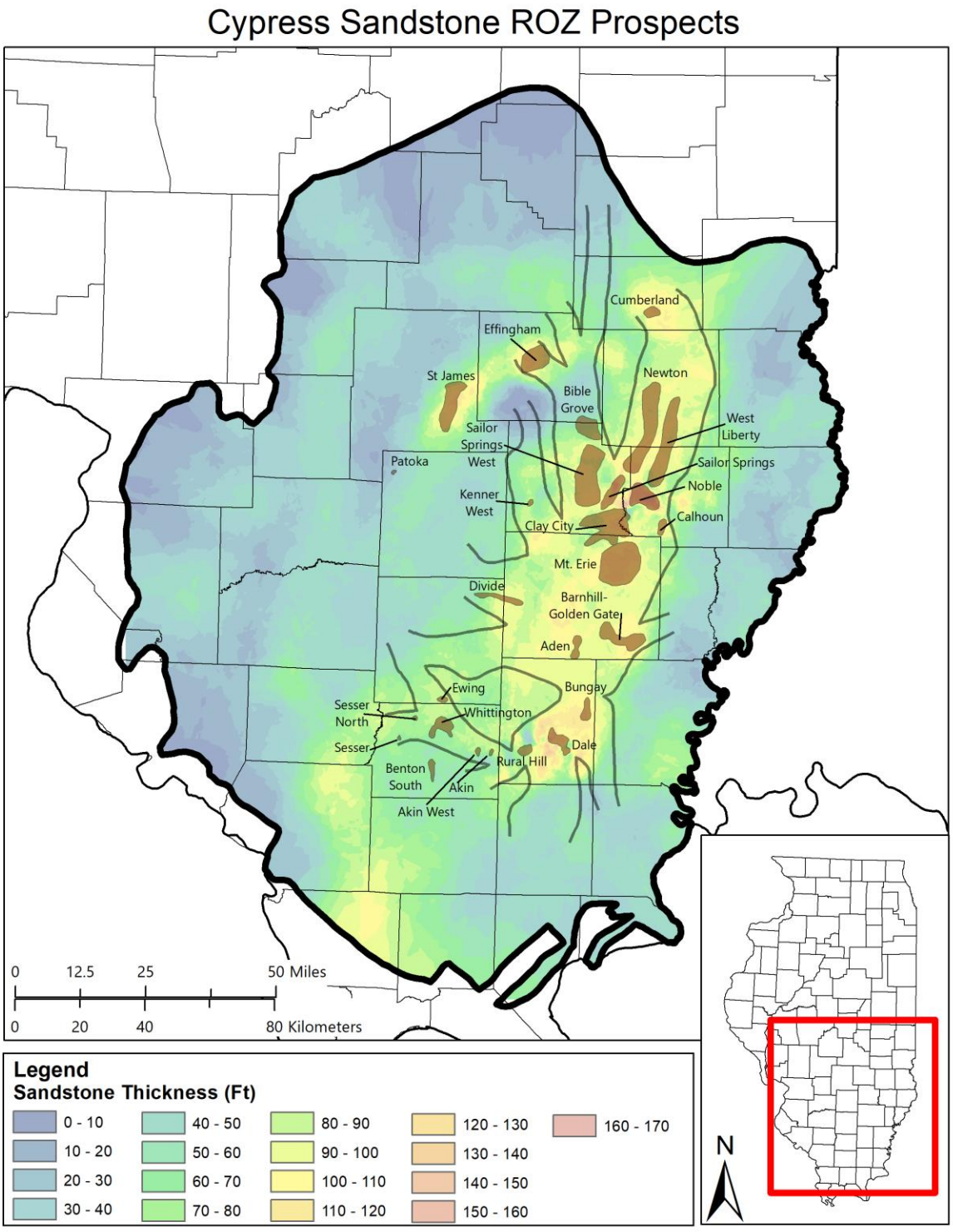

Figure 1. Map of potential ROZ prospects within the Cypress ROZ Fairway. The fairway boundaries are outlined in black and the prospects are shaded in brown. The prospect polygons are overlaid on the regional net isopach map.

Table 1. Results of first five core flood experiments.

Well	Plug Depth	Porosity	Permeability	Mass Swirr	Archie Swirr	Vol Swirr	Mass Sor	Archie Sor	Vol Sor
121592648800	2757.7	16.87%	374.8	23.0%	20.9%	19.8%	31.0%	35.0%	31.9%
121012872700	940.5	22.63%	428.2	16.0%	21.5%	13.5%	36.0%	36.0%	45.0%
121012872700	927.8	24.92%	406.9	21.0%	25.9%	26.9%	42.0%	37.0%	44.9%
120650139400	2989.4	13.69%	49.5	24.0%	24.8%	21.0%	35.0%	33.0%	34.8%
121592648800	2728.9	19.23%	821.7	21.0%	23.8%	23.4%	33.0%	29.0%	31.8%

Table 2. Pore volume and OOIPs for the Noble geocellular model. Volumes shown for the entire model and contained within the 40 and 80 Acre patterns.

				Cubic Feet	**US Barrels**
Whole Model	12% porosity cutoff	whole model	Pore Volume	1.35E+10	2.40E+09
		oil bearing rock		1.33E+09	2.37E+08
		All oil (1.033 formation factor)	OOIP	4.99E+08	8.89E+07
		MPZ : layers 59-72 So=65%		2.89E+08	5.15E+07
		ROZ: layers: 54-58 So=25%		2.10E+08	3.75E+07
40 Acre		oil bearing pore volume	Pore Volume	7.94E+08	1.41E+08
		MPZ : layers 59-72		3.93E+08	6.99E+07
		ROZ: layers: 54-58		4.02E+08	7.16E+07
		all oil	OOIP	3.44E+08	6.13E+07
		MPZ : layers 59-72 So=65%		2.47E+08	4.40E+07
		ROZ: layers: 54-58 So=25%		9.73E+07	1.73E+07
80 Acre		oil bearing pore volume	Pore Volume	7.77E+08	1.38E+08
		MPZ : layers 59-72		3.97E+08	7.06E+07
		ROZ: layers: 54-58		3.80E+08	6.78E+07
		all oil	OOIP	3.42E+08	6.09E+07
		MPZ : layers 59-72 So=65%		2.50E+08	4.45E+07
		ROZ: layers: 54-58 So=25%		9.21E+07	1.64E+07

What opportunities for training and professional development has the project provided?

Three undergraduate students and one recent MS graduate have been involved in research on the project during the quarter. Under advisement of project staff and University of Illinois professors, each student is developing skills in a particular discipline, such as routine and advanced core analysis, thin section petrography, and stratigraphy and sedimentology. The students are learning various techniques for their respective disciplines, and they are meeting and sharing findings with each other to better understand their roles in the larger framework of the project and to gain experience in presenting their research.

How have the results been disseminated to communities of interest?

- The project website (http://isgs.illinois.edu/research/ERD/NCO2EOR) hosts a project summary, staff bios, and downloadable reports and presentations to disseminate project information and findings to the public and other interested parties.
- Draft manuscripts include:
    - Giannetta, L.G., N.D. Webb, S.K. Butler, and N.P. Grigsby, Using clay microporosity to improve formation evaluation in potential residual oil zones: Cypress Sandstone, Illinois Basin.
    - Grigsby, N.P, and S.M Frailey, Methodology for using well logs to identify residual oil zones: An example from Noble Field, Illinois.
    - Grigsby, N.P., and N.D. Webb, A method for developing the production history of Illinois Basin geologic formations.
    - Grigsby, N.P., and N.D. Webb, Assessing the Cypress Sandstone for CO_2-Enhanced Oil Recovery and Carbon Storage: Part II - Leveraging geologic characterization to develop a representative geocellular model for Noble Oil Field, Western Richland County, Illinois.
    - Howell, K.J., Sedimentology of multistory fluvial sandstones of the Mississippian Cypress Formation, Illinois, USA: MS Thesis.
    - Howell, K.J., N.D. Webb, J.L. Best, and E.W. Prokocki, The Sedimentology of a Large Carboniferous Fine-Grained River: Facies, Paleohydraulics, and Implications for Reservoir Heterogeneity

- Webb, N.D., and N.P. Grigsby, Assessing the Cypress Sandstone for CO_2-Enhanced Oil Recovery and Carbon Storage: Part I - Reservoir Characterization of Noble Oil Field, Western Richland County, Illinois.
- Webb, N.D., N.P. Grigsby, and S.M. Frailey, CO_2 Storage and EOR Resource Assessment of the Cypress Sandstone Residual Oil Zone Play in the Illinois Basin
- Yang, F., R.T. Okwen, N.D. Webb, N.P. Grigsby, and S.M. Frailey, CO_2-EOR Development Guidelines for Brown Field Residual Oil Zones in A Fluvial Sandstone.

What do you plan to do during the next reporting period to accomplish the goals?

Task 1.0–Project Management and Planning (on schedule)

- Progress on completion of tasks, subtasks, deliverables, and milestones will continue to be tracked using Microsoft Project to ensure timely completion.
- The PI and co-PIs will continue to meet weekly to discuss project management.
- Regular meetings with the PI and subtask leaders will continue for active subtasks.
- Work will conclude with the availability of core visualization portfolios on the ILOIL website.

Task 2.0–Geology and Reservoir Characterization (on schedule)

Subtask 2.1–Literature Review and Oilfield Selection

- Subtask concluded on 6/30/2015.

Subtask 2.2–Petrophysical Analysis

- Subtask concluded 10/31/2017.
- Nathan Grigsby and Scott Frailey will continue to work on a paper tentatively titled "Methodology for using well logs to identify residual oil zones: An example from Noble Field, Illinois."

Subtask 2.3–Geologic Model Development

- Subtask concluded 2/28/2018.
- Kalin Howell, Nathan Webb, and collaborators from the University of Illinois Geology department will continue work on a manuscript that discusses the geologic model of the Cypress Sandstone an implications for reservoir properties titled "The Sedimentology of

a Large Fine-Grained Carboniferous River: Facies, Palaeohydraulics, and Implications for Reservoir Heterogeneity"

Task 3.0–Geocellular and Reservoir Modeling (on schedule)

Subtask 3.1–Historical Production and Injection Data Analysis

- Subtask concluded on 3/31/2016.

Subtask 3.2–Illinois Basin Crude Oil/Brine-CO_2 Fluid Property Characterization

- S_{OR} core-flood experiments using analog fluids will continue to provide important calibration data for well log analyses.

Subtask 3.3–Geocellular Modeling of Interwell Reservoir Characteristics

- Subtask concluded on 3/1/2018.

Subtask 3.4–Reservoir Modeling

- Subtask concluded on 4/3/2018.

Task 4.0–CO_2 EOR and Storage Development Strategies (on schedule)

Subtask 4.1–Field Development Strategies

- Roland Okwen, Scott Frailey and Fang Yang will complete:
    - History-matching the updated Noble Field reservoir model;
    - Full-field development simulations of selected development strategies based on pattern model results after calibration of static reservoir model;
    - Analysis, interpretation, and reporting of results.

Subtask 4.2–CO_2 EOR and Storage Resource Assessment

- Nathan Grigsby and Scott Frailey will continue to work with Drs. Steve Henderson and George Asquith (Texas Tech University) to determine how widespread erroneous Rmfs are and to develop a method to compensate for them.
- Nathan Grigsby will continue to refine the method of using old e-logs to identify ROZs, and attempt to use it in other fields that have many e-logs and few or no neutron/density porosity logs.

- Nathan Webb, Nathan Grigsby, Scott Frailey, and Chris Korose will continue to refine the regional play analyses of the Cypress ROZ.

Subtask 4.3–Economic Analysis

- Scott Frailey will conclude the final economic analysis once the final results of the simulated CO_2-EOR scenarios are available.

Project Milestone Log

Task	Calendar Year	Milestone Title/Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments
1.0	1	Project Management Plan	12/31/2014	12/15/2014	PMP File	100% Complete
1.0	1	Kickoff Meeting	12/31/2014	12/4/2014	Presentation File	100% Complete
2.0	2	Final selection of oilfields for study	3/31/2015	3/20/2015	Agreement between ISGS and DOE project manager to proceed with specific areas of study	100% Complete
2.0	2	Oilfield data synthesis and analysis	10/31/2015	10/21/2015	Wells/leases grouped into classes representing relative degree of productivity	100% Complete
2.0	3	Analogous Lower Pennsylvanian study areas selected	4/30/2016	4/29/2016	Agreement between ISGS and DOE project manager to proceed with specific areas of study	100% Complete
2.0, 3.0	3	Complete petrophysical analysis, geologic and geocellular modeling of the thick Cypress	10/31/2016	10/31/2016	Completion of draft topical report on geology of the thick Cypress in the ILB	100% Complete
2.0	4	Complete new coring near outcrop belt	9/30/2017	9/21/2017	Send DOE confirmation that core has been obtained and is in ISGS warehouse	100% Complete
4.0	3	Complete guidelines to develop thin oil zones and store CO_2 in the thick Cypress	12/31/2017	1/31/2018	Completion of draft topical report on guidelines to develop thin oil zones in the thick Cypress	100% Complete
4.0	4	Complete estimates of CO_2-EOR and storage potential and economic analysis of implementing program	8/31/2018	8/31/2018	Completion of draft topical report on CO_2-EOR, storage, and economics of the thick Cypress in the ILB	100% Complete
All	4	Document project results	10/31/2018		Complete final report	In progress

3. PRODUCTS

What has the project produced?

a. Publications, conference papers, and presentations

Presentations and manuscripts listed on pages 9-10.

b. Website(s) or other Internet site(s)

The project website is located at http://www.isgs.illinois.edu/research/erd/nco2eor.

4. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Nothing to report.

5. IMPACT

Nothing to report.

6. CHANGES/PROBLEMS

Changes in approach and reasons for change

There have been no changes in approach on this project.

Actual or anticipated problems or delays and actions or plans to resolve them

There are currently no anticipated problems or delays in the project.

Changes that have a significant impact on expenditures

As no changes have been made or are anticipated, none are expected to impact expenditures.

Significant changes in use or care of human subjects, vertebrate animals, and/or Biohazards

Not applicable.

Change of primary performance site location from that originally proposed

Not applicable.

7. Special Reporting Requirements

Nothing to report.

8. Budgetary Information

Financial Reporting Table

Baseline Reporting	Budget Period 1 11/01/14 - 10/31/17													Budget Period 2 11/01/17 - 10/31/18					Total
	FY15 Q1	FY15 Q2	FY15 Q3	FY15 Q4	FY16 Q1	FY16 Q2	FY16 Q3	FY16 Q4	FY17 Q1	FY17 Q2	FY17 Q3	FY17 Q4	FY18 Q1	FY18 Q1	FY18 Q2	FY18 Q3	FY18 Q4	FY19 Q1	
Baseline Federal Share	192,267	192,267	192,265	193,061	205,360	205,360	205,360	205,359	121,852	121,852	121,853	121,852	58,543	117,085	175,628	175,628	117,085	58,544	2,781,221
Baseline non-Federal Share	30,889	46,334	46,334	46,334	44,028	44,028	44,028	44,028	44,028	44,028	44,028	44,028	15,444	29,253	43,880	43,880	43,880	14,627	713,079
Total Baseline Cumulative Cost	223,156	238,601	238,599	239,395	249,388	249,388	249,388	249,387	165,880	165,880	165,881	165,880	73,987	146,338	219,508	219,508	160,965	73,171	3,494,300
Actual Federal Share	9,661	82,633	112,827	147,250	124,049	114,637	164,036	164,146	158,143	177,806	251,648	147,697	78,072	143,560	165,525	173,034	142,424		2,357,149
Actual non-Federal Share	29,328	48,918	47,155	43,688	43,603	48,447	44,874	45,329	45,391	45,680	37,277	34,701	11,711	23,423	34,419	38,146	39,916		662,004
Total Actual Cumulative Cost	38,989	131,551	159,982	190,937	167,652	163,083	208,909	209,475	203,534	223,486	288,925	182,398	89,784	166,983	199,943	211,180	182,340	0	3,019,153
Variance Federal Share	182,606	109,634	79,438	45,811	81,311	90,723	41,324	41,213	(36,291)	(55,954)	(129,795)	(25,845)	(19,529)	(26,475)	10,103	2,594	(25,339)	58,544	424,072
Variance non-Federal Share	1,561	(2,584)	(821)	2,646	425	(4,419)	(846)	(1,301)	(1,363)	(1,652)	6,751	9,327	3,733	5,830	9,461	5,734	3,964	14,627	51,075
Total Variance Cumulative Cost	184,167	107,050	78,617	48,458	81,734	86,305	40,478	39,912	(37,654)	(57,606)	(123,044)	(16,518)	(15,797)	(20,645)	19,564	8,328	(21,375)	73,171	475,147