CARBON DIOXIDE CAPTURE AND SEQUESTRATION BY INTEGRATING PRESSURE SWING ADSORPTION WITH AN OPEN CYCLE SUPERCRITICAL CO_2 BRAYTON POWER GENERATION SYSTEM

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(Presented by Mark Anderson, Concepts NREC)

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sCO2 Supercritical CO_2 Power Cycles Symposium

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Outline

- Sequestration and Carbon Capture
- Pressure Swing Absorption
- Cycle Overview
- Implementation and Impact
- Summary

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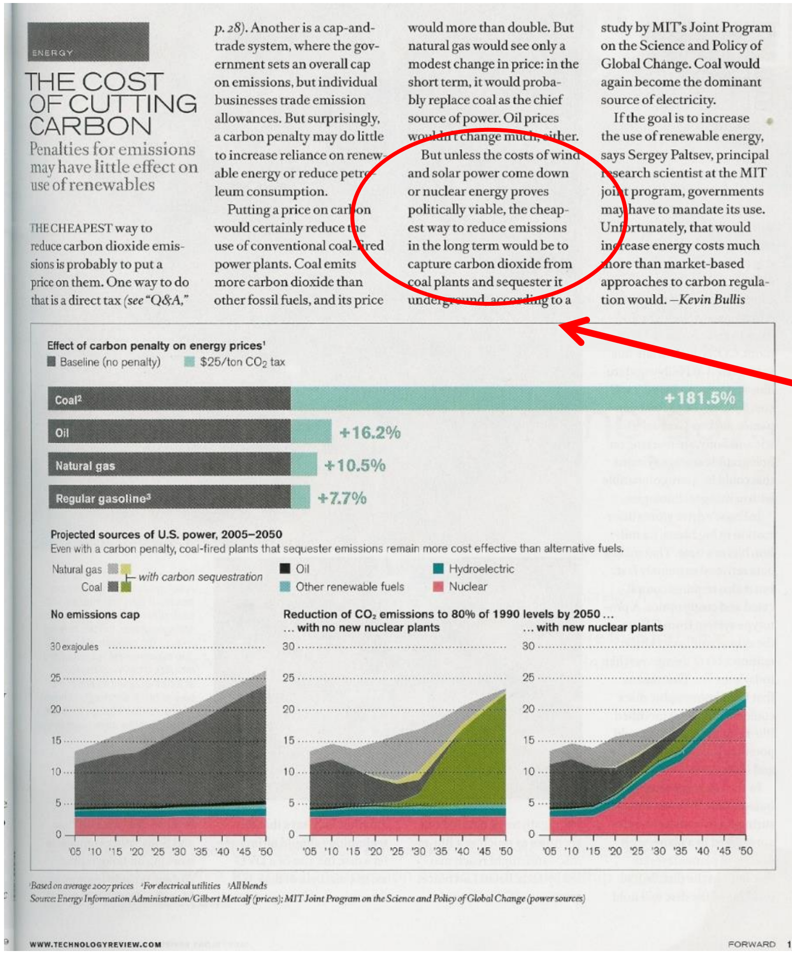
Some Background to Identify the Significance of Problem

- 2015 Paris Climate (COP21) Conference goal: Markedly reduce CO2 Emissions by 2020
- US and China Lead in CO_2 Emissions
- Coal combustion is a major cause of CO_2 Emissions: 24 LbmCO_2/therm) vs. 12 Lbm CO_2/therm for CH_4
- Utility Power generation by Coal is still 48% of total Electric Power generation in the U.S. and will remain a high fraction for the immediate future.

CO_2 Sequestration Cost Study



ENERGY

THE COST OF CUTTING CARBON

Penalties for emissions may have little effect on use of renewables

THE CHEAPEST way to reduce carbon dioxide emissions is probably to put a price on them. One way to do that is a direct tax (*see* "Q&A," *p. 28*). Another is a cap-and-trade system, where the government sets an overall cap on emissions, but individual businesses trade emission allowances. But surprisingly, a carbon penalty may do little to increase reliance on renewable energy or reduce petroleum consumption.

Putting a price on carbon would certainly reduce the use of conventional coal-fired power plants. Coal emits more carbon dioxide than other fossil fuels, and its price would more than double. But natural gas would see only a modest change in price: in the short term, it would probably replace coal as the chief source of power. Oil prices wouldn't change much, either.

But unless the costs of wind and solar power come down or nuclear energy proves politically viable, the cheapest way to reduce emissions in the long term would be to capture carbon dioxide from coal plants and sequester it underground, according to a study by MIT's Joint Program on the Science and Policy of Global Change. Coal would again become the dominant source of electricity.

If the goal is to increase the use of renewable energy, says Sergey Paltsev, principal research scientist at the MIT joint program, governments may have to mandate its use. Unfortunately, that would increase energy costs much more than market-based approaches to carbon regulation would. —*Kevin Bullis*

[1]Based on average 2007 prices [2]For electrical utilities [3]All blends

Source: Energy Information Administration/Gilbert Metcalf (prices); MIT Joint Program on the Science and Policy of Global Change (power sources)

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FORWARD 15

"But unless the costs of wind and solar power come down or nuclear energy proves politically viable, the cheapest way to reduce emissions in the long term would be to capture carbon dioxide from coal plants and sequester it underground"

Source: EIA - MIT Program on the Science and Policy of Global Change

CO_2 Sequestration continues to attract attention and may be mandated in the future

Greenhouse gas storage is feasible, MIT study says

By John Donnelly
GLOBE STAFF

WASHINGTON — A long-awaited Massachusetts Institute of Technology study on the future of coal says the technology needed to capture greenhouse gas emissions from plants and store them underground apparently is sound, and urged Congress to swiftly pass controls on gases that contribute to global warming.

The MIT report, released yesterday, recommended the immediate construction of large-scale projects using new technology to capture emissions. It suggested that countries around the world build about 10 such systems into large coal plants — including three in the United States — in order to test the technology in different underground conditions.

Written by a group of academics from several fields after more than two years of research, the MIT report expressed confidence that large-scale carbon-capture projects could be run safely. But the study cautioned that the handful of prototype facilities in operation are not large enough to solve several technological riddles.

CHARLIE RIEDEL/ASSOCIATED PRESS

Sunflower Electric Cooperative's coal-fired power plant churned out electricity last month in Holcomb, Kan.

Ernest J. Moniz, a physics professor who co-led the project with chemistry professor John Deutch, said that the researchers assumed three points: that coal is a major contributor to global warming, that "we are going to have a national climate policy, and we are going to have more coal use."

Currently, coal plants produce half of the electricity used in the United States. Because coal is cheap and widely available in the United States, China, India, and many other nations, the report concluded, its use as an energy source is almost surely going to increase worldwide.

Moniz said in an interview that the study's authors found a "lack of urgency in many directions" on US policy related to coal, including implementing a program to capture emissions and store them underground. While many environmentalists yesterday applauded the report's sense of urgency, one member of the advisory panel said the study did not go far enough.

"I said to them, 'You are missing the boat here,'" said David Hawkins, director of the Climate Center at the Natural Resources Defense Council. "They ought to be recommending all new coal plants have capture and storage built into them."

Hawkins said he worried that while the government studies new technologies in capturing and storing emissions, "that really could lead to a situation where a lot of conventional coal plants get built" before legislation is enacted to limit those emissions.

Moniz, a former undersecretary of energy in the Clinton administration, said he personally agrees with Hawkins's theory, but "that's a place we weren't going" in the report. The MIT study "is not a report about recommending a carbon policy."

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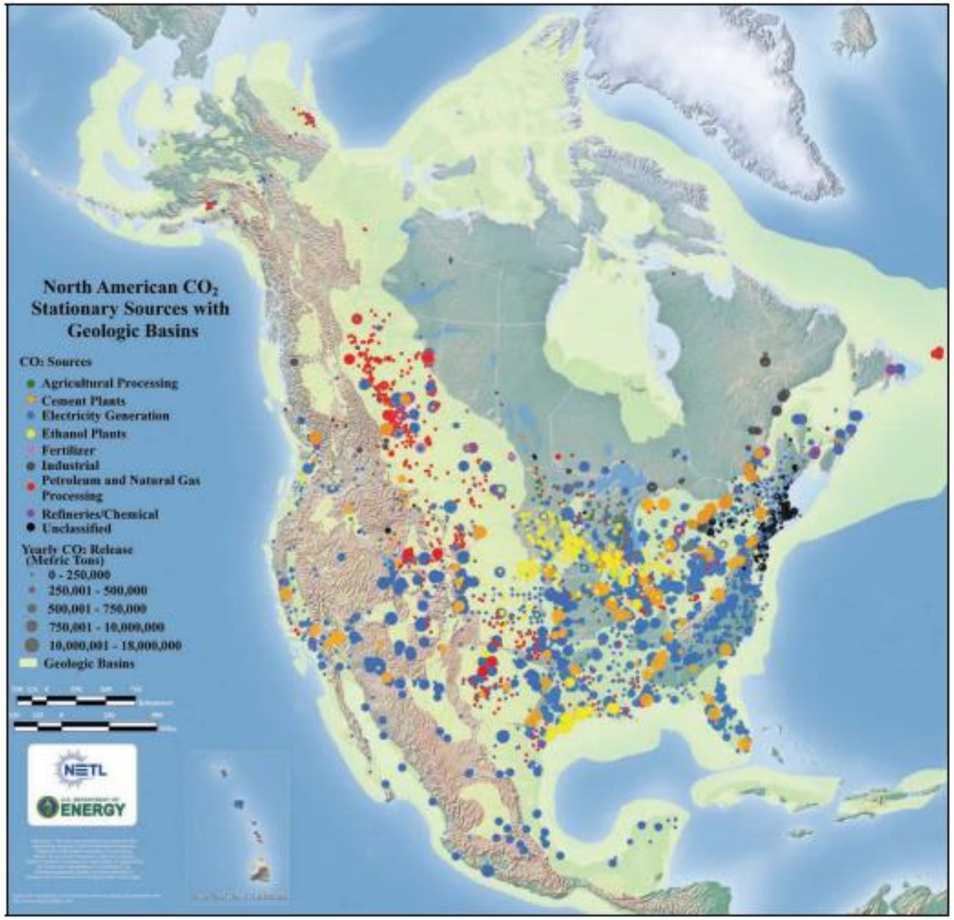
1. **Boston Globe story (2005) describes an effort to reduce the CO_2 emissions into the atmosphere by sequestrating the gases. That is, by compressing the gases and injecting the gas into the ground. There are many other ways of using the gases in a chemical reaction that produce a valuable or at least a benign byproduct. This method is very straightforward in that the CO_2 is simply compressed. *However,* what are the power requirements compared to the amount of power generated by the prime mover?**

Stationary Sources of CO_2 in No. America and Underlying Geologic Basins



Source: U.S. Department of Energy, National Energy Technology Laboratory, "2010 Carbon Sequestration Atlas of the United States and Canada, Third Edition," http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIII/index.html.

From: Carbon Capture and Sequestration (CCS)- A Primer Congressional Research Service (CRS) Report R41325; July , 2013

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Geological Sequestration Potential for the U.S. and Parts of Canada

(billion metric tons of CO_2)

Reservoir type	Lower estimate (2010)	Lower estimate (2012)	% Change	Upper estimate (2010)	Upper estimate (2012)	% Change
Oil and gas fields	143	226	+58%	143	226	+58%
Deep saline formations	1,653	2,102	+27%	20,213	20,043	-0.8%
Unmineable coal seams	60	56	-7%	117	114	-3%
Totals	**1,856**	**2,384**	**+28%**	**20,473**	**20,383**	**-0.04%**

Source: 2010 and 2012 Carbon Sequestration Atlases.

From: Carbon Capture and Sequestration (CCS)- A Primer
Congressional Research Service (CRS) Report R41325; July , 2013

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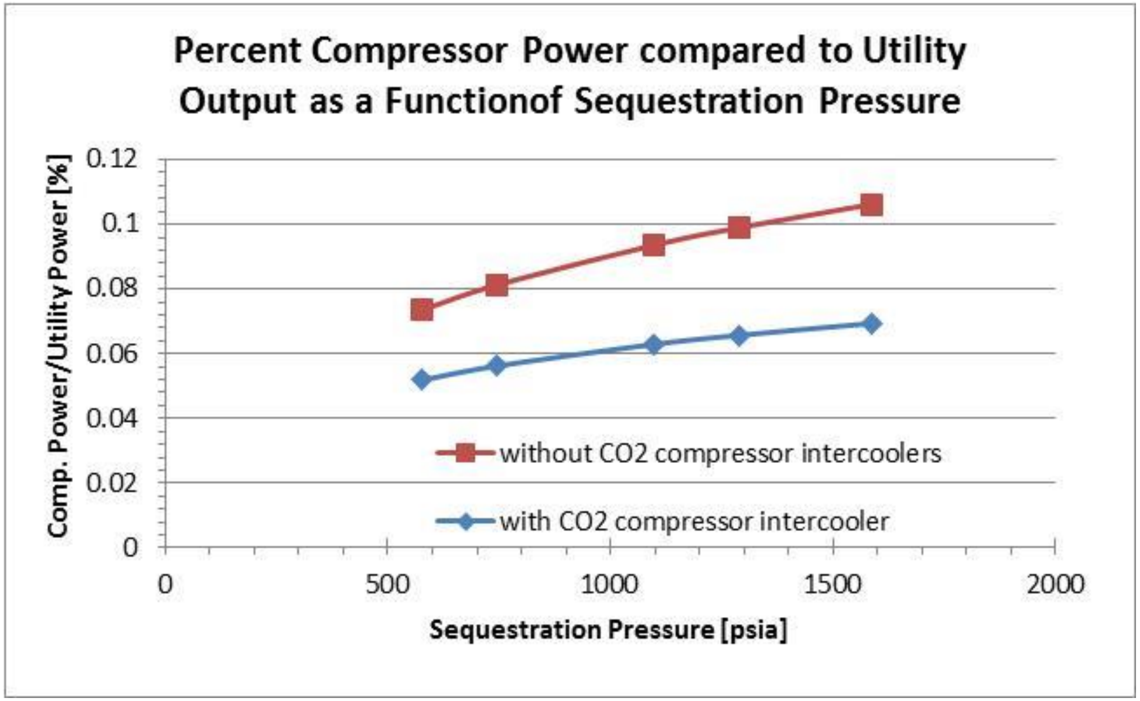
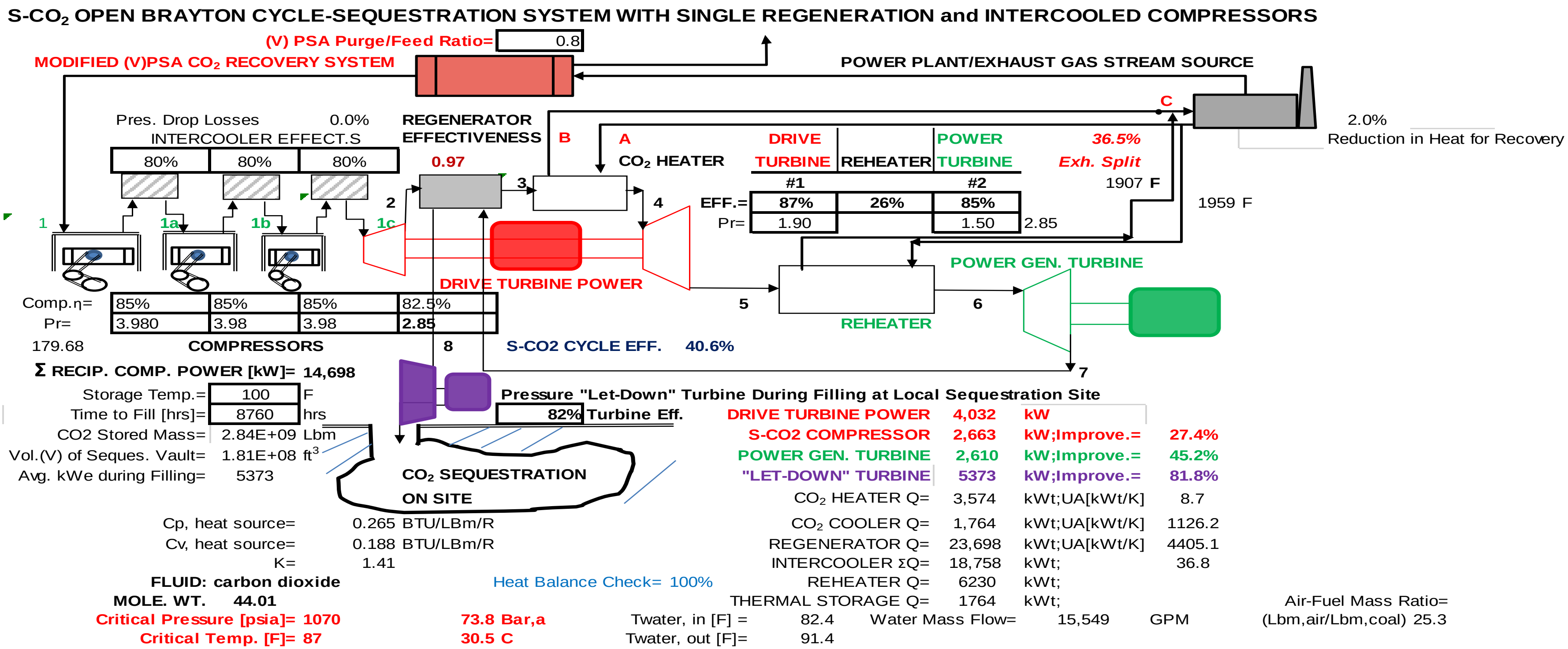
Power Parasitic for CO_2 Sequestration as a percentage of Utility Power Plant Output



Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization



Pressure Swing Adsorption

Wikipedia

Pressure swing adsorption (PSA) is a technique used to separate some gas species from a mixture of gases (typically air) under pressure according to the species' molecular characteristics and affinity for an adsorbent material. It operates at near-ambient temperature and significantly differs from the cryogenic distillation commonly used to separate gases.

Pressure Swing Adsorption for Post-Combustion CO2 Capture

Current independent studies indicate that the new cycle could utilize K-promoted hydrotalcite in a high-pressure, high-temperature PSA system, to recover CO_2 from utility power plant exhaust gas.

REFERENCES

[1] Gomes, V. G., and Yee, K. W.K., "Pressure Swing Adsorption for Carbon Dioxide Sequestration from Exhaust Gases", Separation and Purification Technology, 28 (2002) 161-171.

[2] Reynolds, S. P., Ebner, A. D., and Ritter, J. A., "New Pressure Swing Adsorption Cycles for Carbon Dioxide Sequestration", Adsorption, 11:531-536, 2005.

[3] Boon, J., Cobden, P. D., van Dijk, H. A. J., Hoogland, C., van Selow, E. R., and van Sint Annaland, M., "Isotherm Model for High-Temperature, High-Pressure Adsorption of CO_2 and H_2O on K-Promoted Hydrotalcite", Chemical Engineering Journal, 248 (2014) 406-414.

[4] Takamura, Y., Narita, S., Aoki, J., Hironaka, S., and Uchida, S., "Evaluation of Dual-Bed Pressure Swing Adsorption for CO_2 Recovery from Boiler Exhaust Gas", Separation and Purification Technology, 24 (2001) 519-528.

Proposed "Cross-Over" Approach that Utilizes US and World's Coal Reserves Using SCO2 Technology

- Combine a Supercritical CO_2 Power Cycle (700C and 200 bar,a) as a Topping Cycle in a Coal Fired Power Plant with a carbon capture system (such as a Pressure Swing Adsorption-PSA) and use the power to sequester all of the CO_2 emissions from the Power Plant

- A 10 MWe SCO_2 System can sequester all of the CO_2 from a 335 Mwe Coal–Fired Power plant. The power savings for the CO_2 Sequestration system is 30-50%
  - can approach 80% if the pressure let-down turbine power is considered for low pressure injection

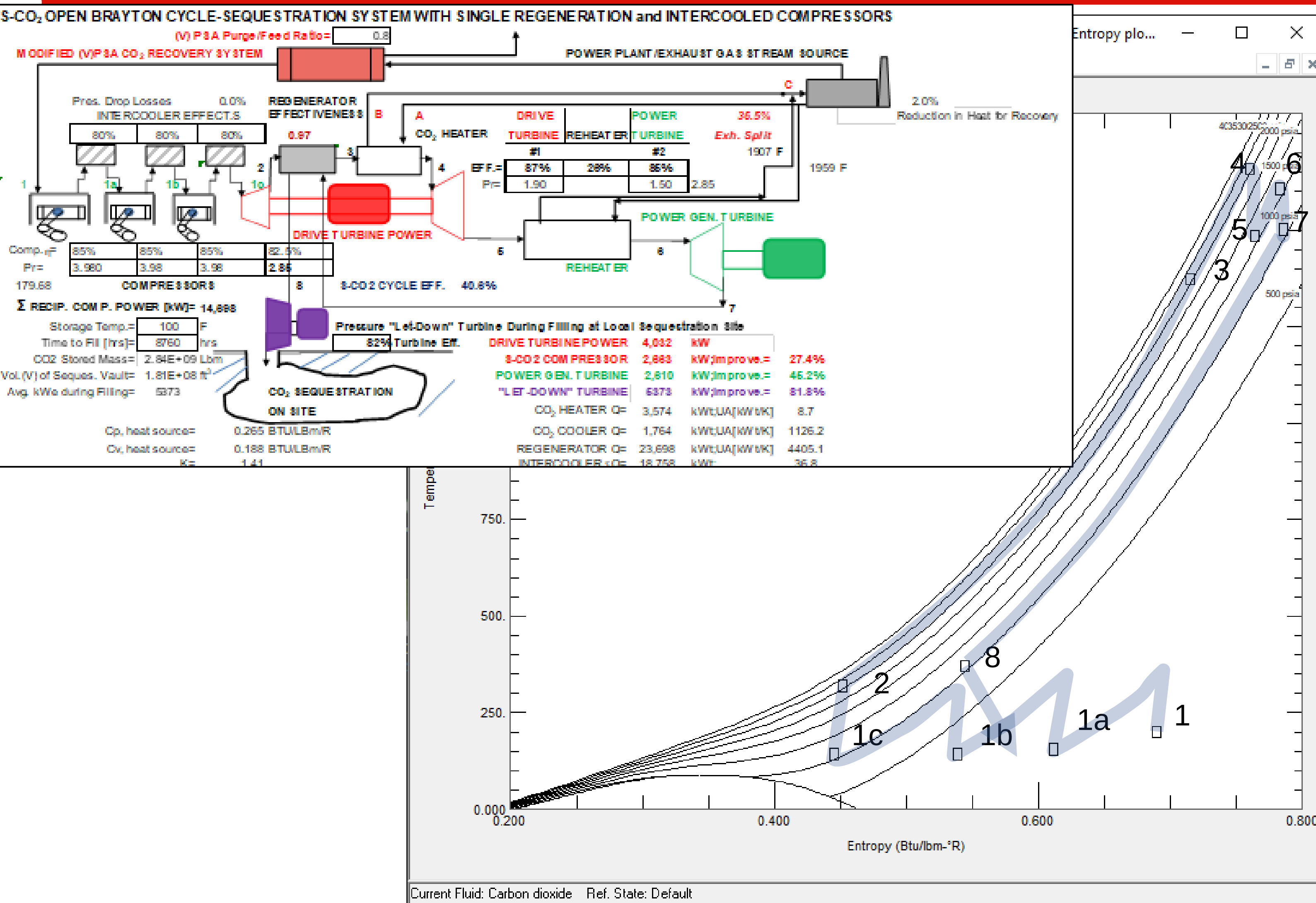
- The cycle is thought to satisfy the need to reduce the atmospheric release of CO2 from, in particular, coal-fueled power plants, until such time as the coal plants can be replaced by renewable energy sources and/or power plants that use cleaner-burning fuels

- Suitable for retrofitting of existing coal fired plants

Underlaying Assumptions

- 1-2% of the primary cycle heat is available for the sCO2 exhaust cycle
- Total pressure ratio of 2.8 in the sCO2 exhaust cycle
- Maximum temperature in the sCO2 cycle of 1659 F
- 2nd reheat turbine in the sCO2 cycle
- Final "let down turbine" for energy extraction before ground injection in the sCO2 cycle

Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization



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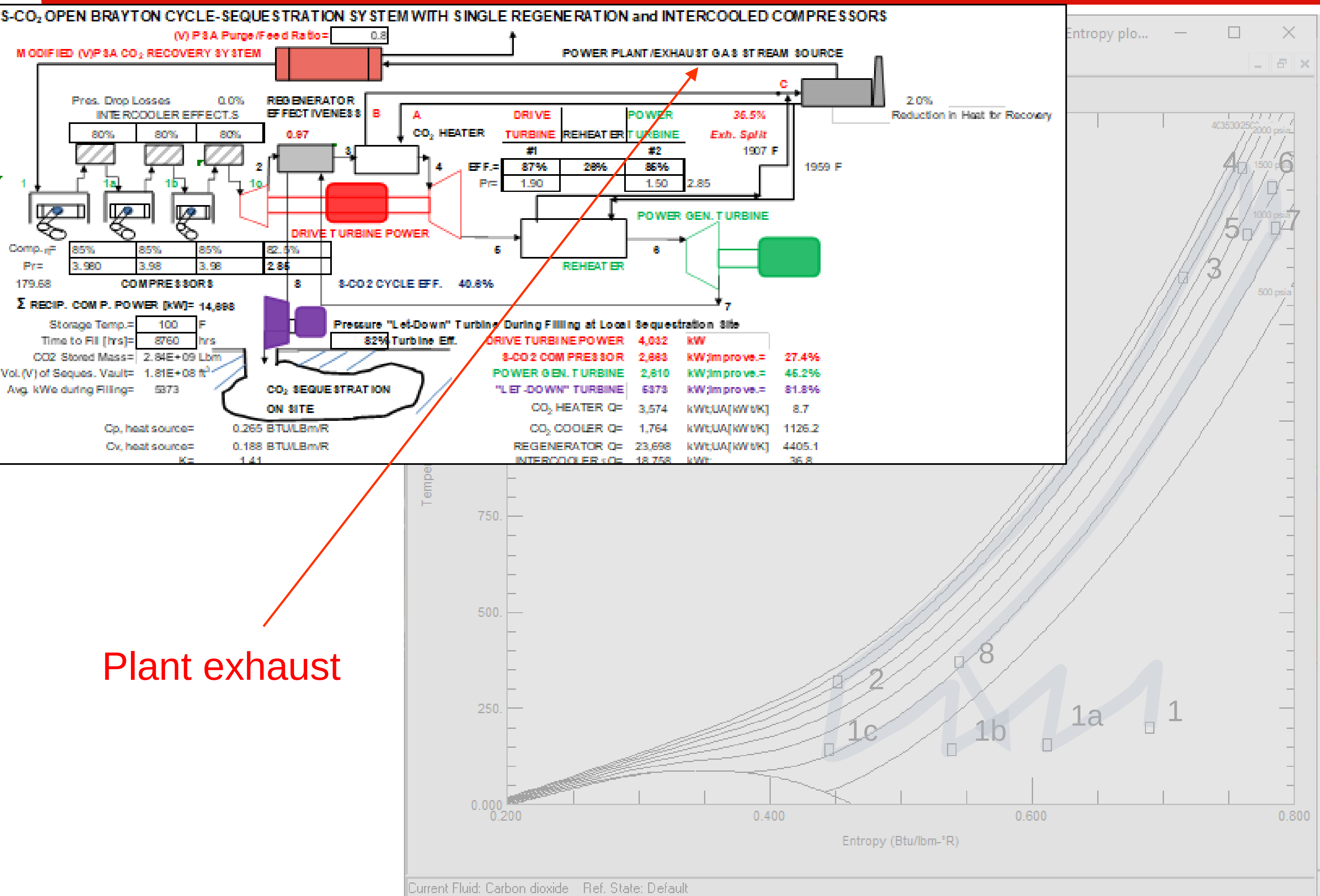

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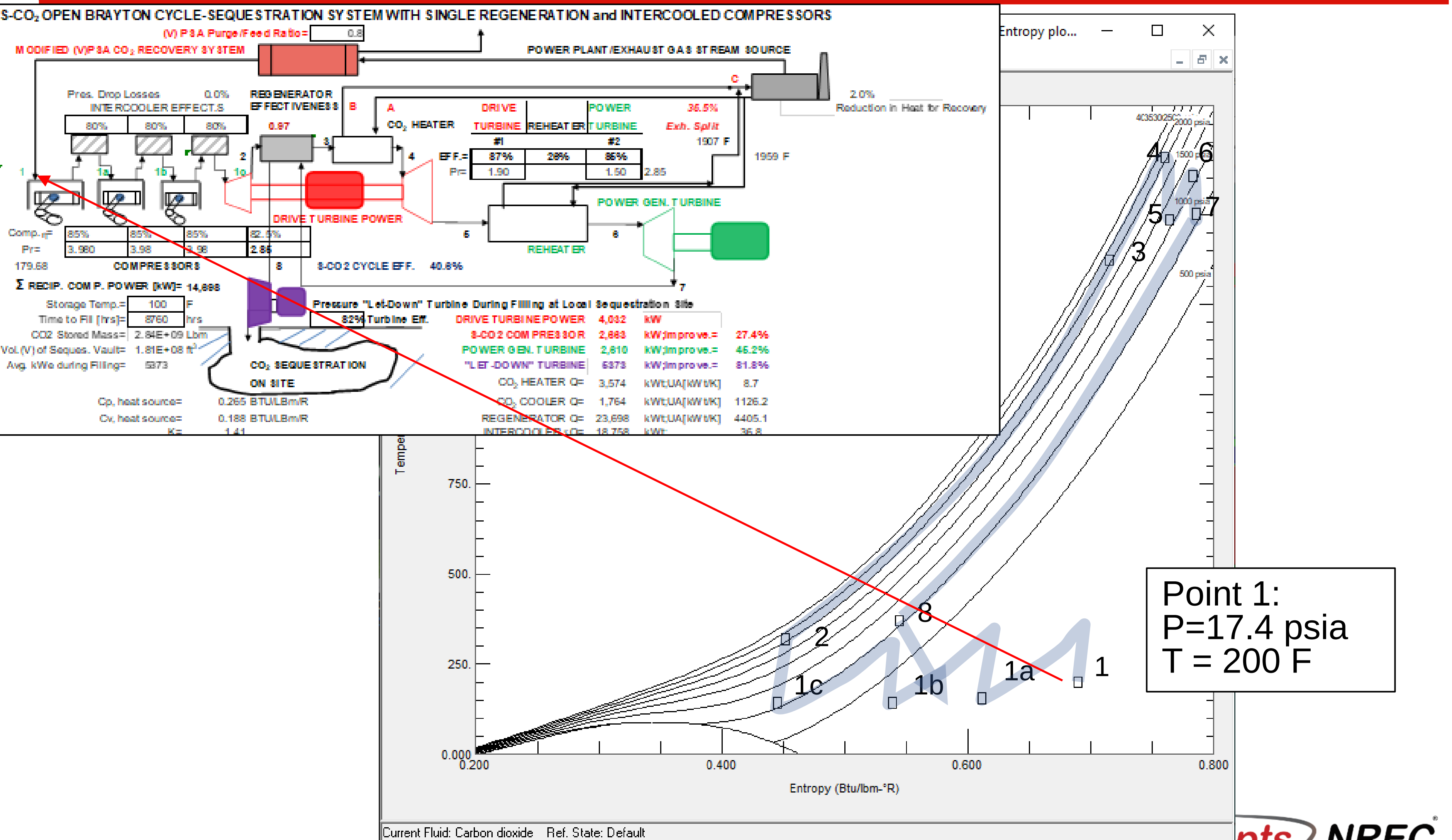

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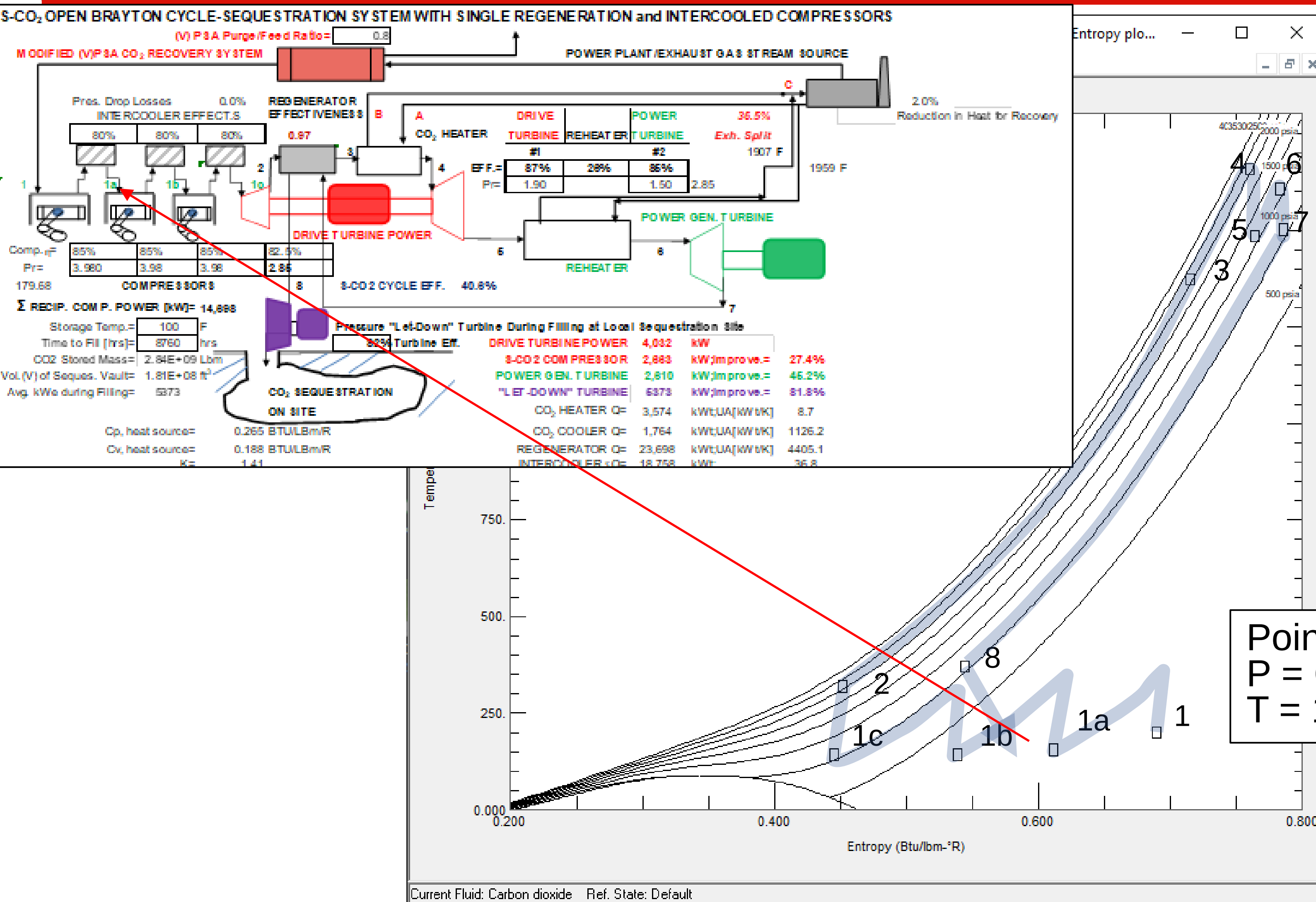
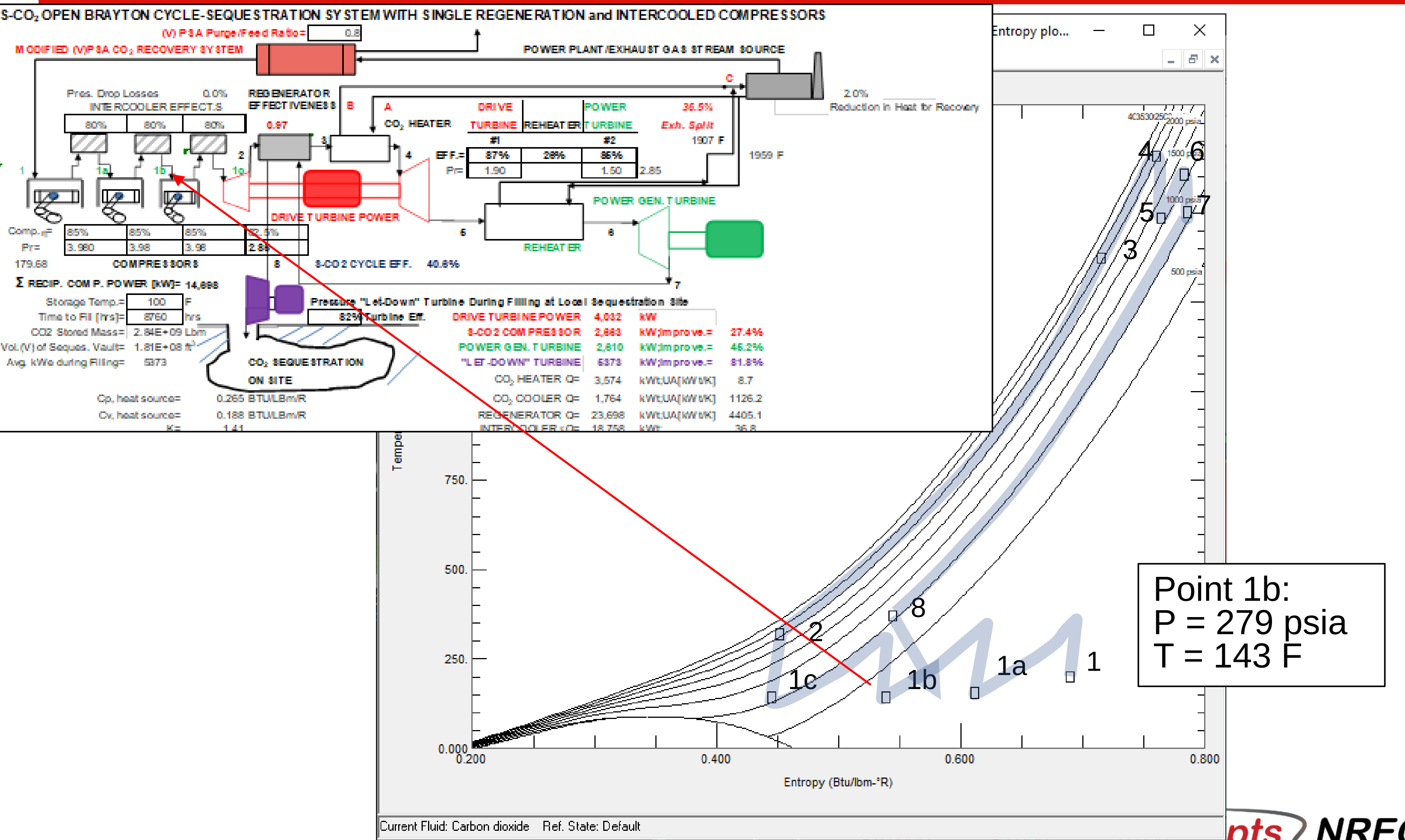


Point 1a:
P = 69 psia
T = 154 F

Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization



Pres. Drop Losses	0.0%			
INTERCOOLER EFFECTS	80%	80%	80%	
Comp. η=	85%	85%	85%	82.5%
Pr=	3.980	3.98	3.98	2.89

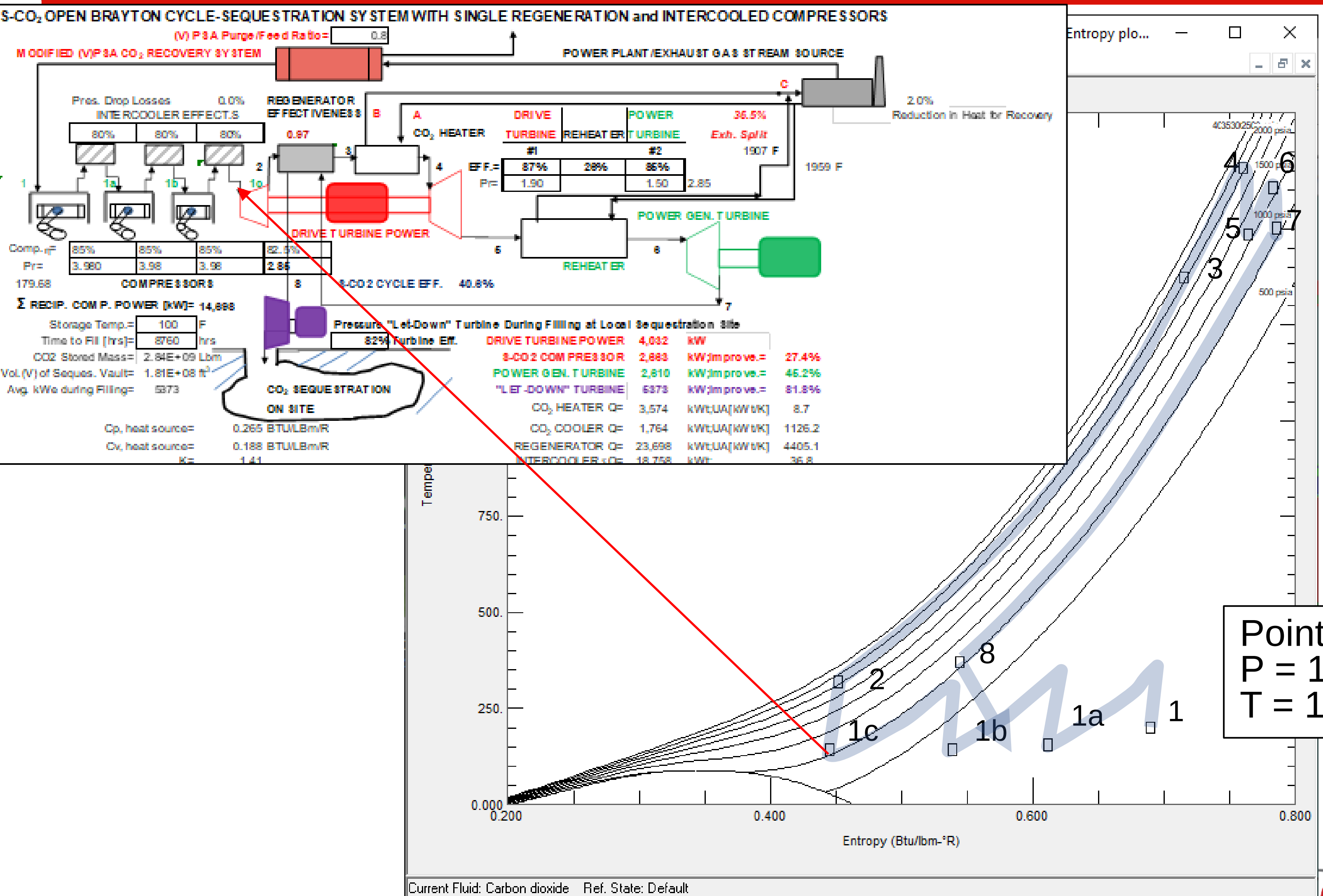
	#1		#2
EFF.=	87%	28%	85%
Pr=	1.90		1.50

Storage Temp.=	100	F
Time to Fill [hrs]=	8760	hrs
CO2 Stored Mass=	2.84E+09	Lbm
Vol. (V) of Seques. Vault=	1.81E+08	ft^3
Avg. kWe during Filling=	5373	
Cp, heat source=	0.265	BTU/LBm/R
Cv, heat source=	0.188	BTU/LBm/R
K=	1.41	

82% Turbine Eff.

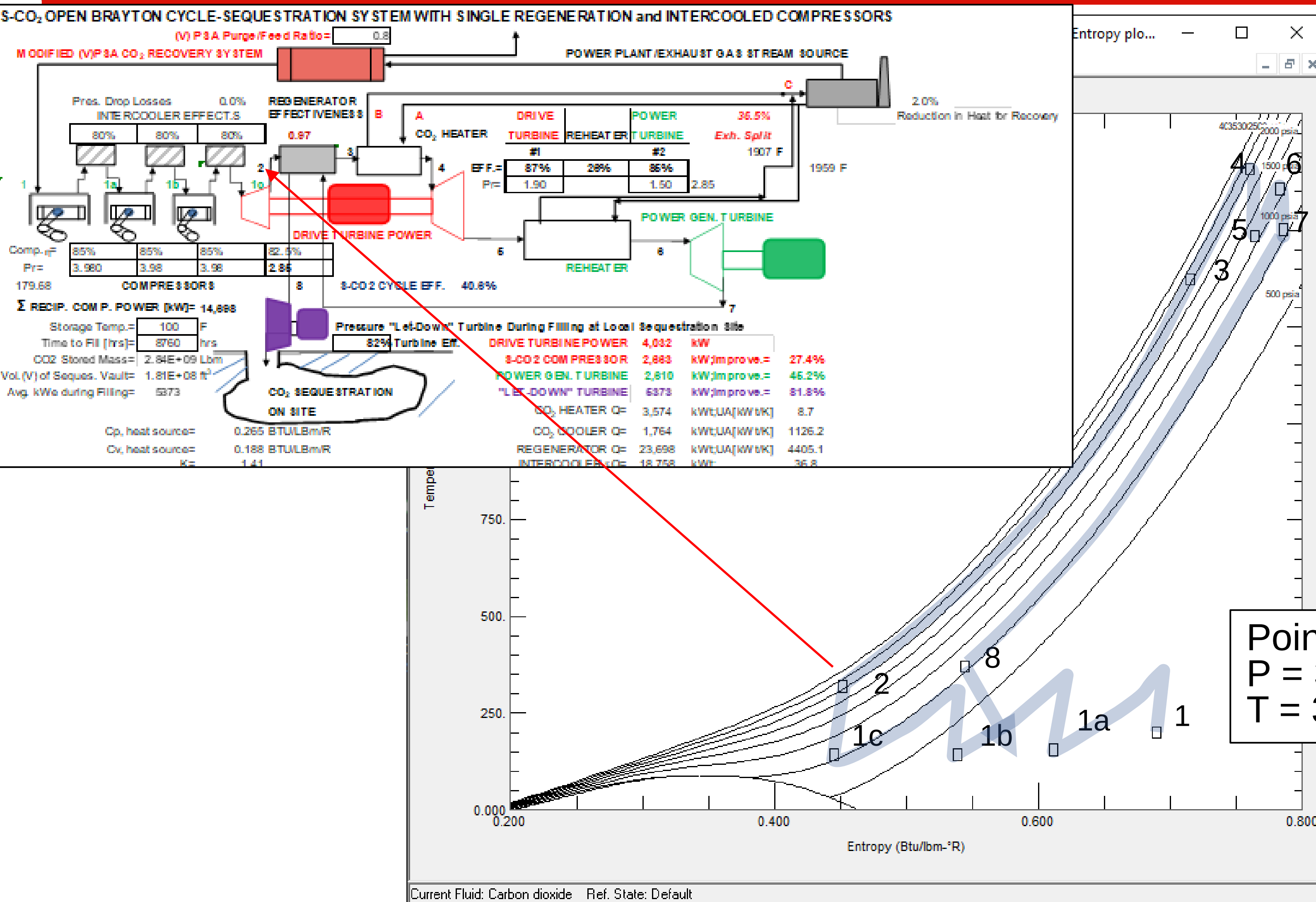
DRIVE TURBINE POWER	4,032	kW		
S-CO2 COMPRESSOR	2,883	kW;Improve.=	27.4%	
POWER GEN. TURBINE	2,810	kW;Improve.=	45.2%	
"LET-DOWN" TURBINE	5373	kW;Improve.=	81.8%	
CO_2 HEATER Q=	3,574	kWt;UA[kWt/K]	8.7	
CO_2 COOLER Q=	1,764	kWt;UA[kWt/K]	1126.2	
REGENERATOR Q=	23,698	kWt;UA[kWt/K]	4405.1	
INTERCOOLERS Q=	18,758	kWt	36.8	

Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization



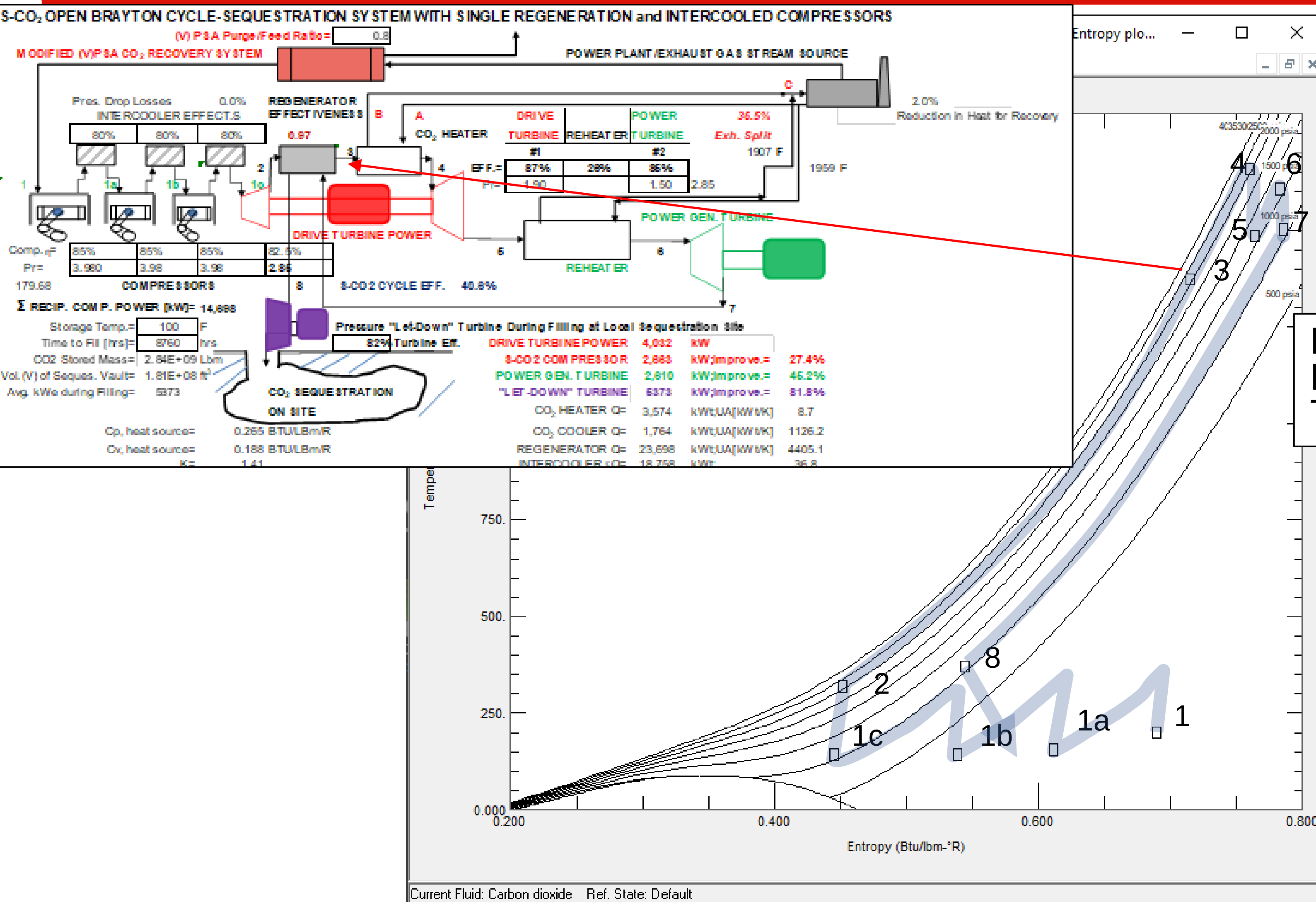
Point 1c:
P = 1097 psia
T = 142 F

Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization



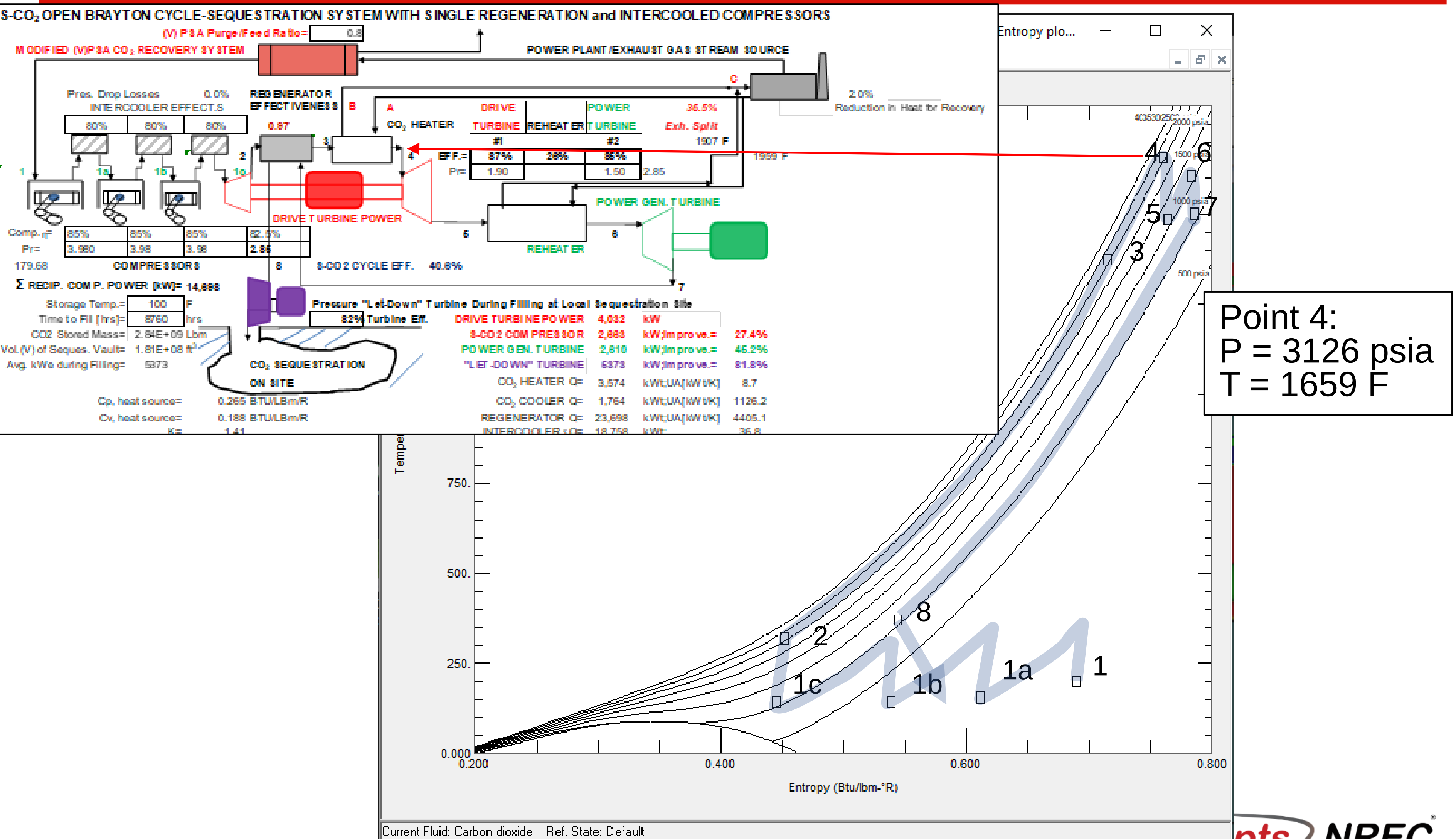
Point 2:
P = 3126 psia
T = 319 F

Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization

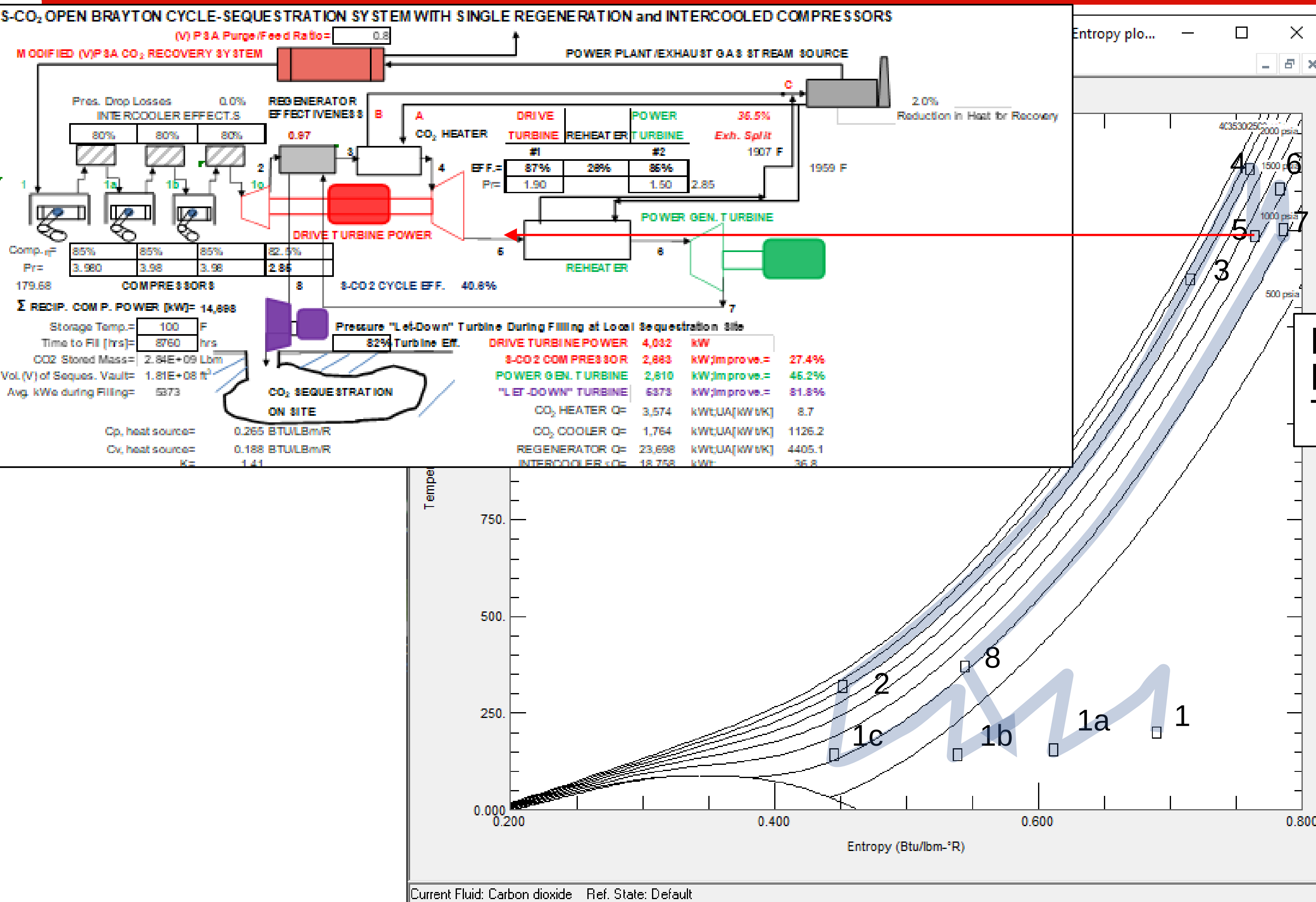


Point 3:
P = 3126 psia
T = 1373 F

Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization

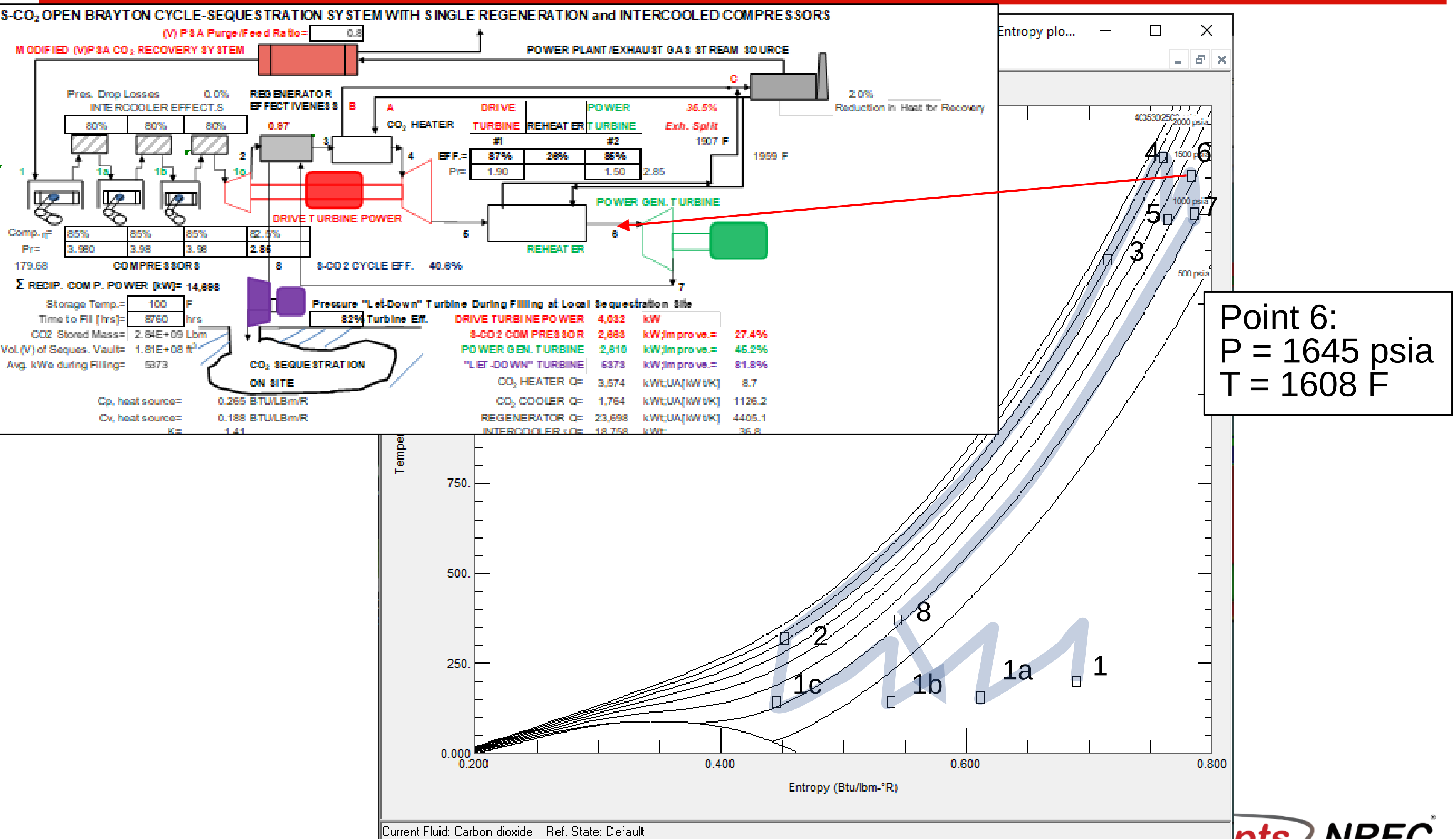


Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization

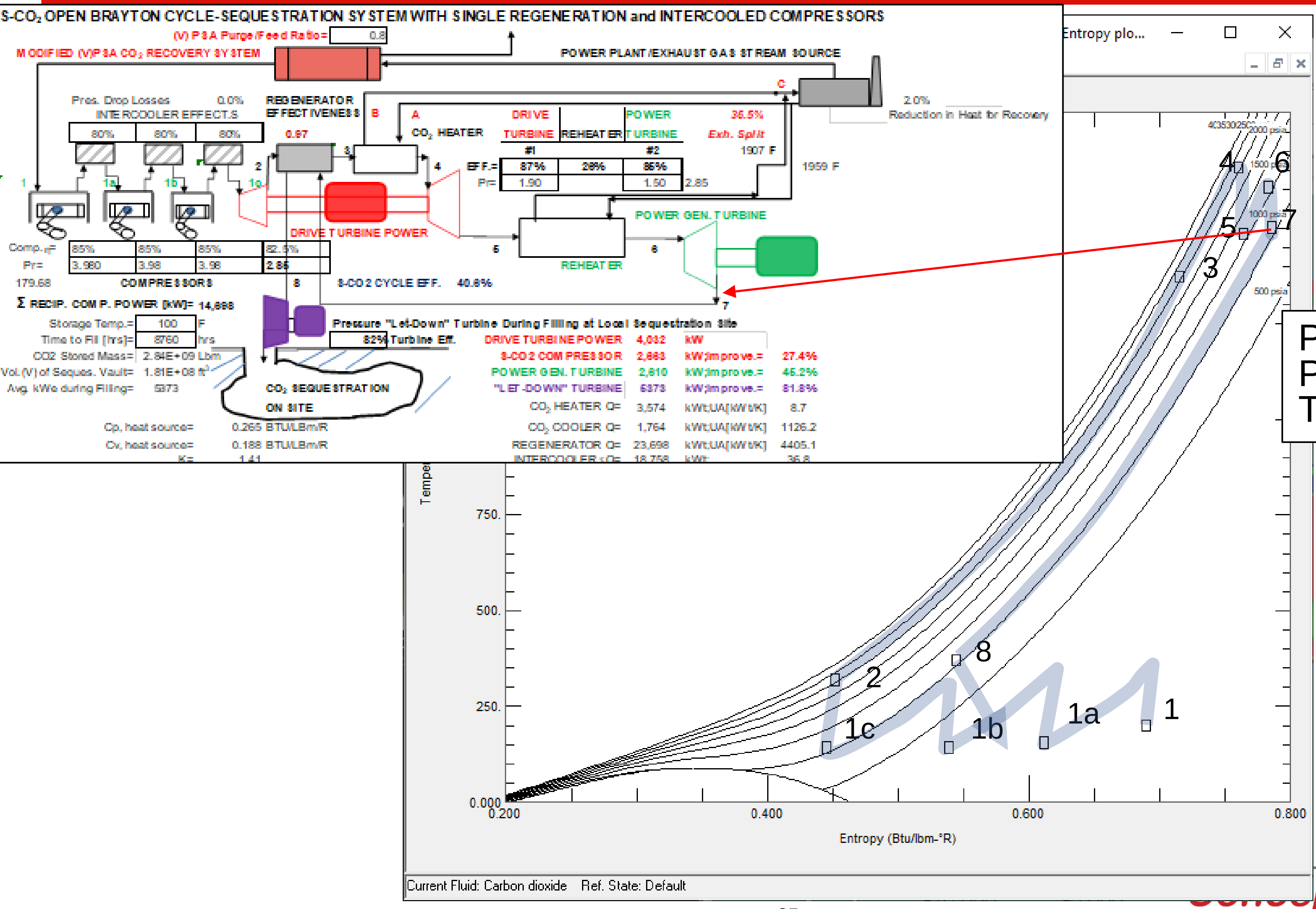


Point 5:
P = 1645 psia
T = 1485 F

Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization

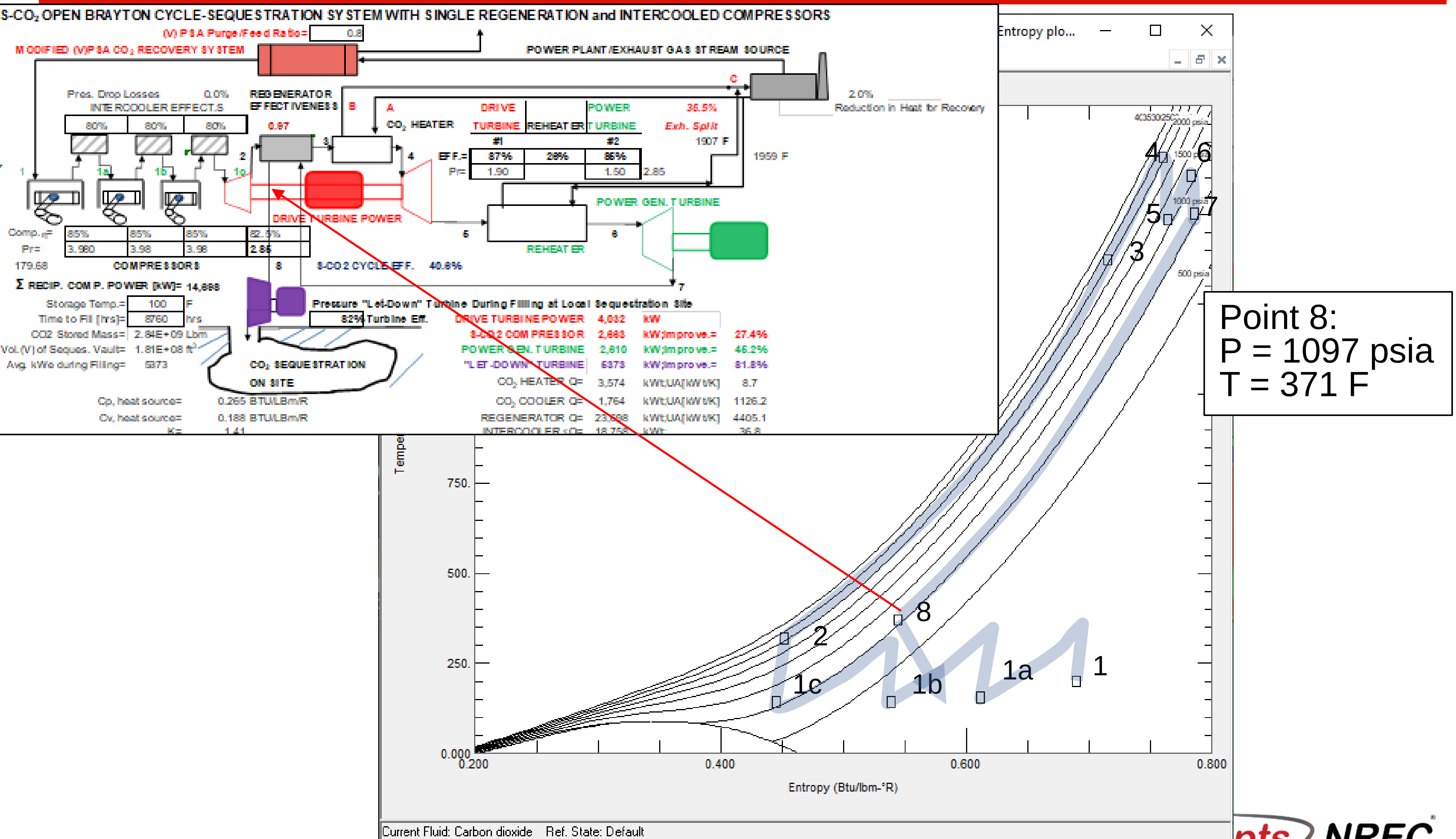


Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization

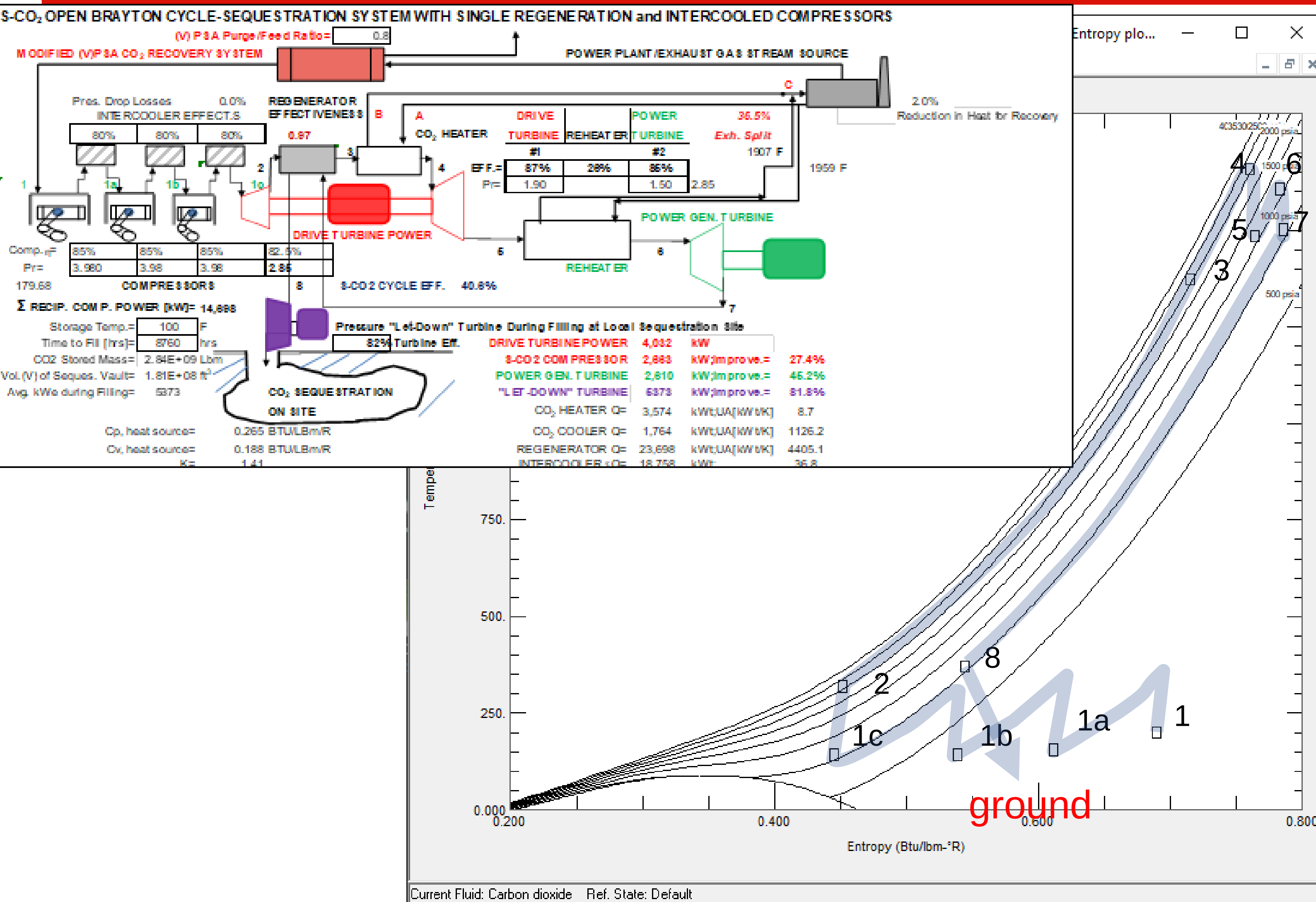


Point 7:
P = 1097 psia
T = 1503 F

Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization

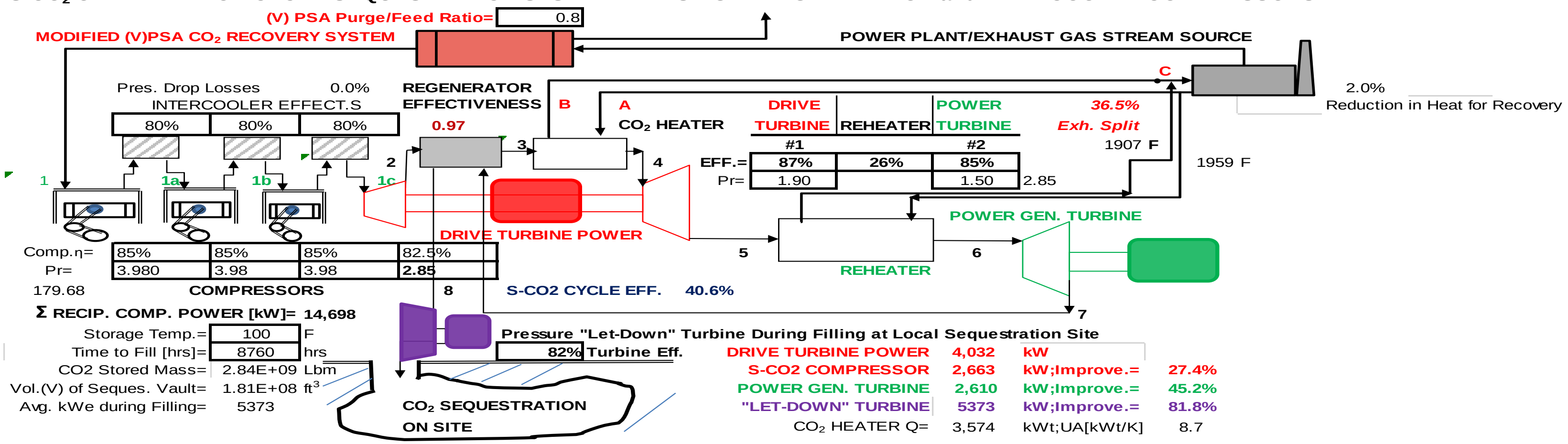


Detail of SCO_2 –CO_2 Sequestration Cycle using Positive Displacement Primary Compressors for Initial CO2 Pressurization



Same Cycle BUT NOW with STATE POINTS of Pressure and Temperature

S-CO_2 OPEN BRAYTON CYCLE-SEQUESTRATION SYSTEM WITH SINGLE REGENERATION and INTERCOOLED COMPRESSORS



Cp, heat source= 0.265 BTU/LBm/R

Cv, heat source= 0.188 BTU/LBm/R

K= 1.41

FLUID: carbon dioxide

MOLE. WT. 44.01

Critical Pressure [psia]= 1070 **73.8 Bar,a**

Critical Temp. [F]= 87 **30.5 C**

Heat Balance Check= 100%

CO_2 HEATER Q= 3,574 kWt;UA[kWt/K] 8.7

CO_2 COOLER Q= 1,764 kWt;UA[kWt/K] 1126.2

REGENERATOR Q= 23,698 kWt;UA[kWt/K] 4405.1

INTERCOOLER ΣQ= 18,758 kWt; 36.8

REHEATER Q= 6230 kWt;

THERMAL STORAGE Q= 1764 kWt;

Twater, in [F] = 82.4 Water Mass Flow= 15,549 GPM

Twater, out [F]= 91.4

Air-Fuel Mass Ratio= (Lbm,air/Lbm,coal) 25.3

	1	1a	1b	1c	2	3	4	5	6	7	8	9	A	B	C
Pres. [psia]	17.4	69	276	1097	3126	3126	3126	1645	1645	1097	1097		14.9	14.7	14.7
Temp. [F]	200	154.4	143.7	142.5	319	1134	1259	1109	1330	1235	341		1959	1907	1907
Enthalpy [Btu/lbm]	243.5	232.6	225.6	200.8	228.8	478.4	516.0	473.5	539.1	511.6	262.1		519.1	505.3	505.3
Density [Lbm/ft^3]	0.11	0.47	2.01	10.78	21.07	7.71	7.12	4.22	3.68	2.62	6.15		0.017	0.017	0.017
Flow rate [Lbm/s]	90.03	90.03	90.03	90.03	90.03	90.03	90.03	90.03	90.03	90.03	90.03		245	245	672
Entropy [Btu/Lbm/R]	0.6899	0.6109	0.5391	0.4451	0.4515	0.6731	0.6958	0.6999	0.7390	0.7419	0.5339				
CO_2 Cp	0.22	0.22	0.23	0.42	0.39	0.30	0.30	0.29	0.30	0.30	0.27				
Pres. bar,a	1.2	4.8	19.0	75.7	215.6	215.6	215.6	113.4	113.4	75.6	75.6		1	1	1
Temp. [K]	366.3	341.0	335.0	334.4	432.3	885.3	954.6	871.2	994.0	941.3	444.8		1343.5	1314.5	1314.5
Enthalpy [KJ/kG]	565	540	524	466	531	1111	1198	1100	1252	1188	609		1205	1173	1173
Temp. [C]	93	68	62	61	159	612	682	598	721	668	172				
Density [kG/m^3]	2	8	32	173	338	124	114	68	59	42	99		0	0	0
Mass Flow [Kg/s]	40.92	40.92	40.92	40.92	40.92	40.92	40.92	40.92	40.92	40.92	40.92		111.33	111.33	305.37
Vol. Flow [Nm^3/hr]	79820	79820	79820	79820	79820	79820	79820	79820	79820	79820	79820		331745	331745	909933

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Implementation and Impact

- Make the sequestering of CO2 in coal-fired power plants more economical and thus more marketable by reduce the power consumption required for sequestering CO_2 by 30-50%, higher levels possible with lower injection pressures

- Maintains U.S. Leadership in CO_2 Reduction from Power plants while utilizing U.S. inventory of coal

- Can Benefit Countries that must depend on Coal Combustion for major Utility Power production

Summary

- The proposed SCO2/PSA hybrid system will reduce the net Power parasitic for a CO_2 sequestration system in a fossil fuel power plant.
- Concepts NREC's preliminary feasibility study has demonstrated that a 10 MWe SCO2/PSA system can service a 335 MWe coal-fired power plant. The proposed hybrid system enables CO_2 sequestration at 1,000 psig, and could provide as much as 80% all of the necessary CO2 compression power.
- The next steps in the development process
  - Study the optimum size of the turbomachinery, PSA system, and heat exchangers
  - Evaluate the cost of the proposed hybrid system

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