

Coal Energy Conversion via Combustion in Supercritical Aquifer Water: An Approach to Electric Power Generation without Atmospheric Emissions

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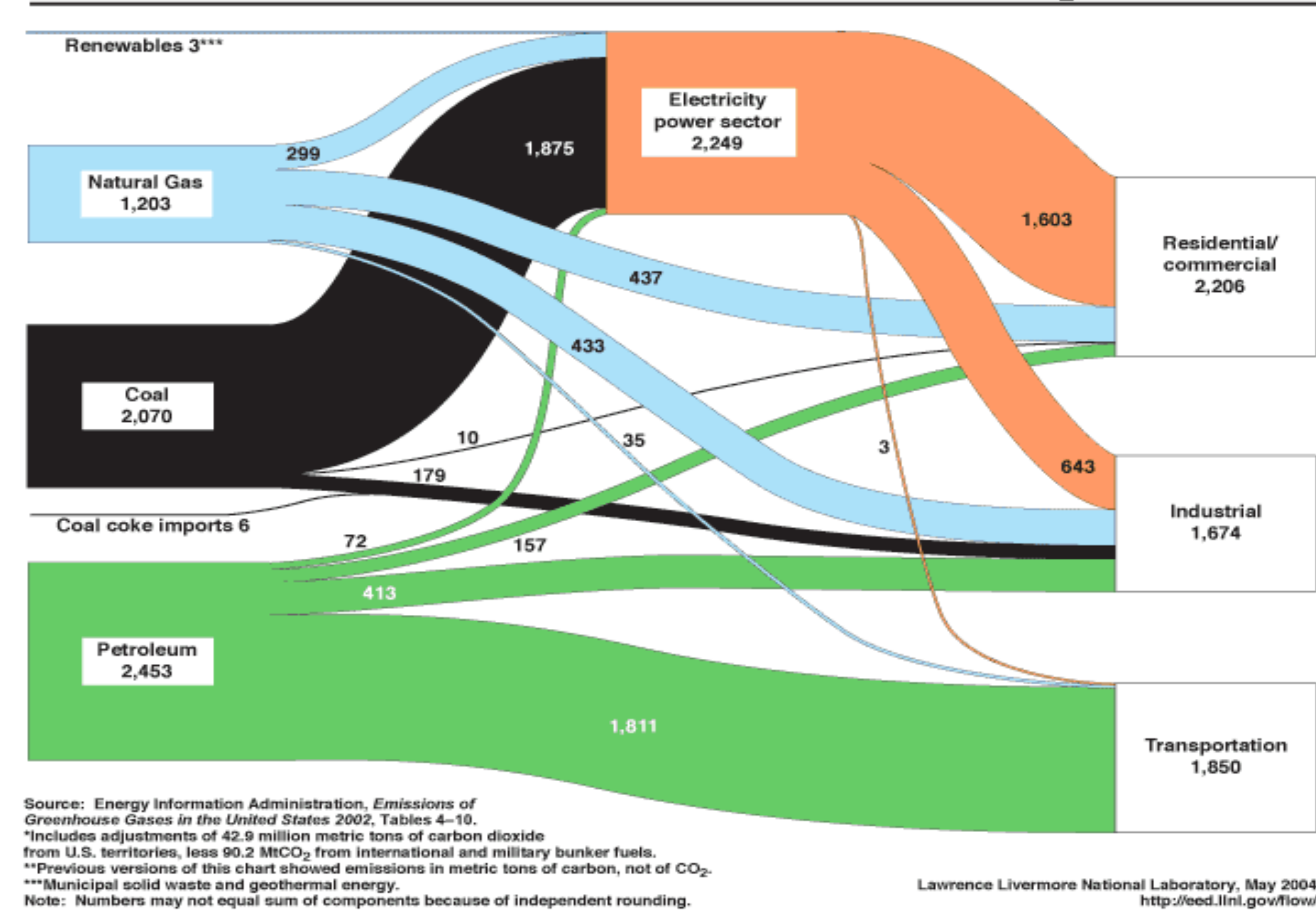
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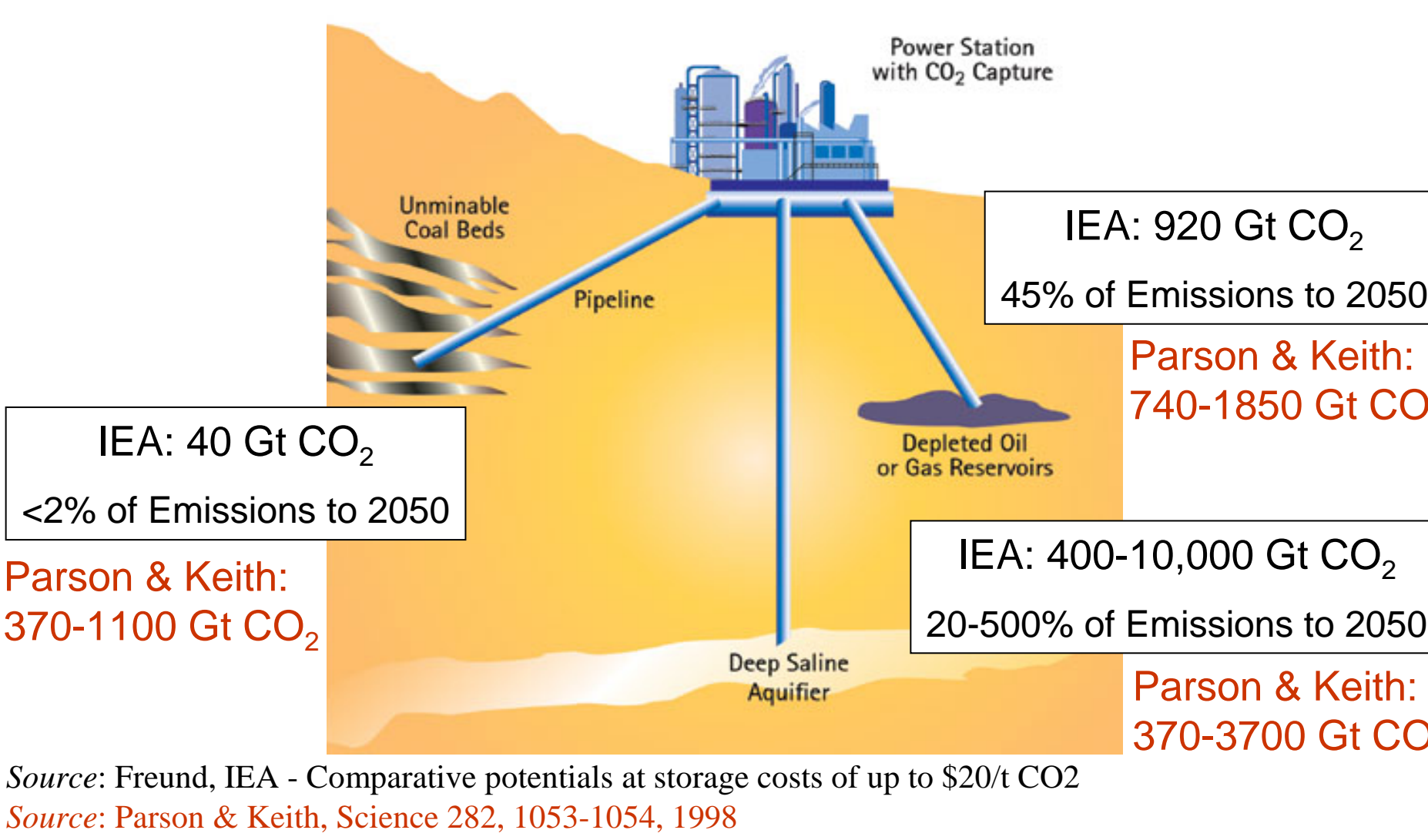
Motivation

Coal is a plentiful, domestic energy resource that accounts for one-half of U.S. electricity generating capacity and one-third of U.S. carbon dioxide emissions. Because of its importance, there is a critical need to find ways to use coal in a more efficient and environmentally sound manner.

U.S. 2002 Carbon Dioxide Emissions from Energy Consumption — 5,682* Million Metric Tons of CO₂**

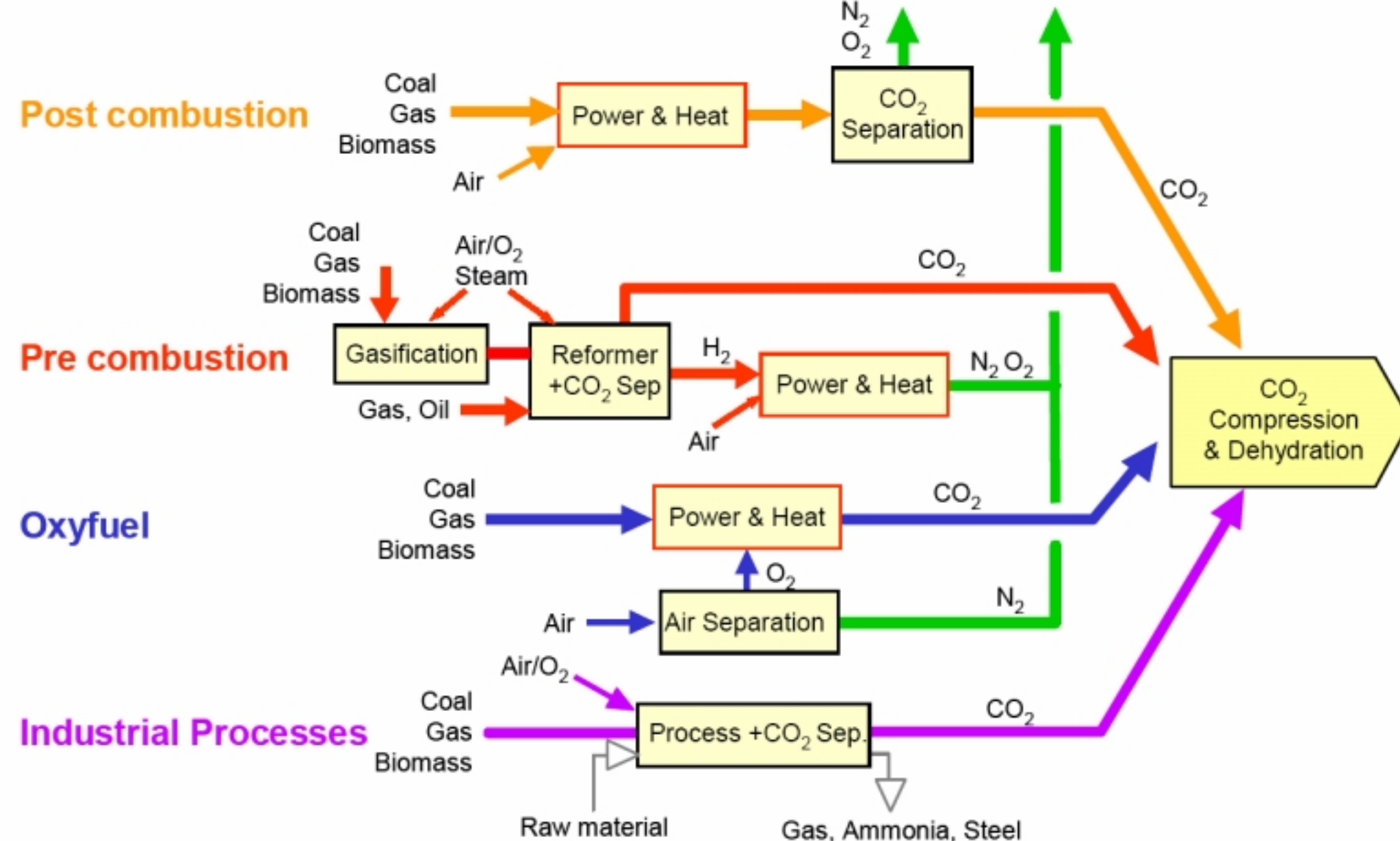


Geologic carbon sequestration has been proposed as a possible solution to enable the continued use of carbon-based fuels. Of the three major options being considered, storage in deep saline aquifers appears to be the most promising based on overall capacity and geographic distribution.



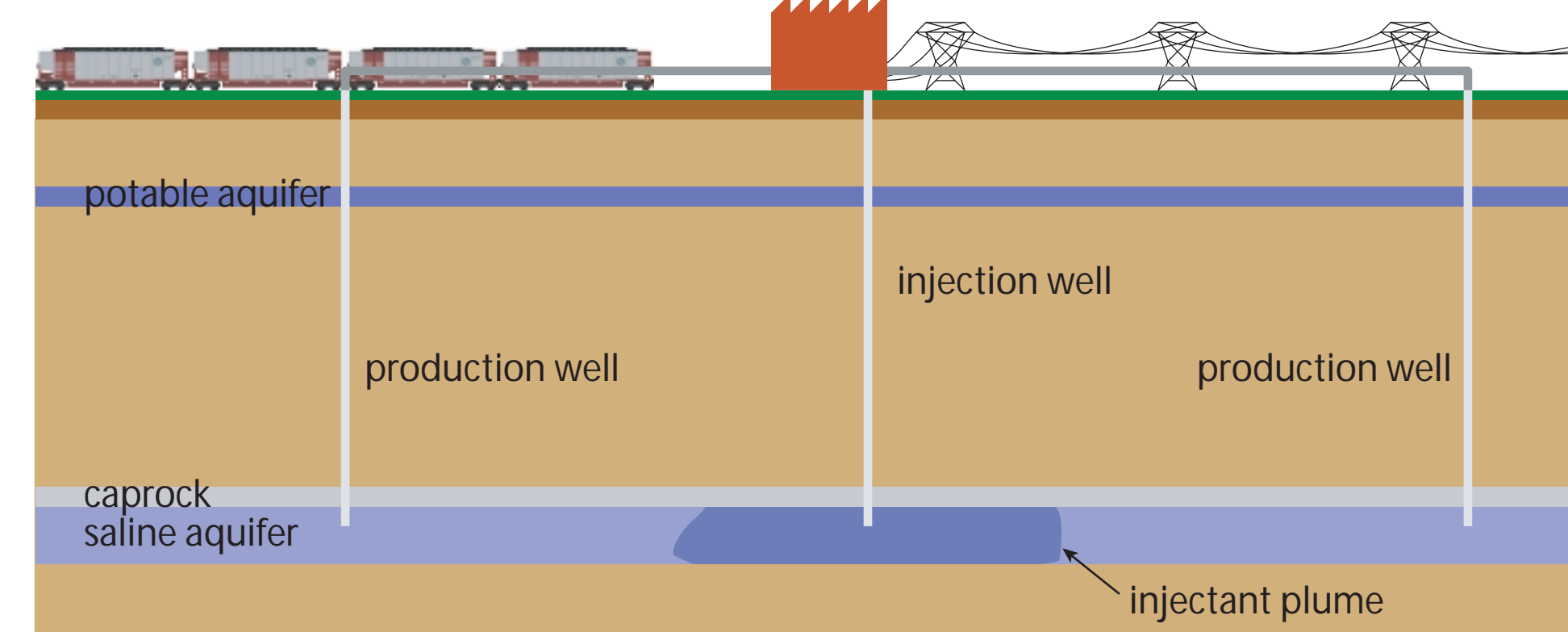
Most of today's research into reduced carbon emission energy systems centers around separating a relatively pure stream of CO₂ from either the fuel or the product gases. This stream would then be sent by pipeline to an aquifer for injection, monitoring, and verification of the permanency of storage.

Two disadvantages with this strategy are that the efficiency loss due to separation of the CO₂ is significant, and that the plume of CO₂ injected into the aquifer would remain buoyant for a significant time period since it would initially not be dissolved in the aquifer water. This buoyancy would tend to drive the CO₂ back towards the surface through any available route.

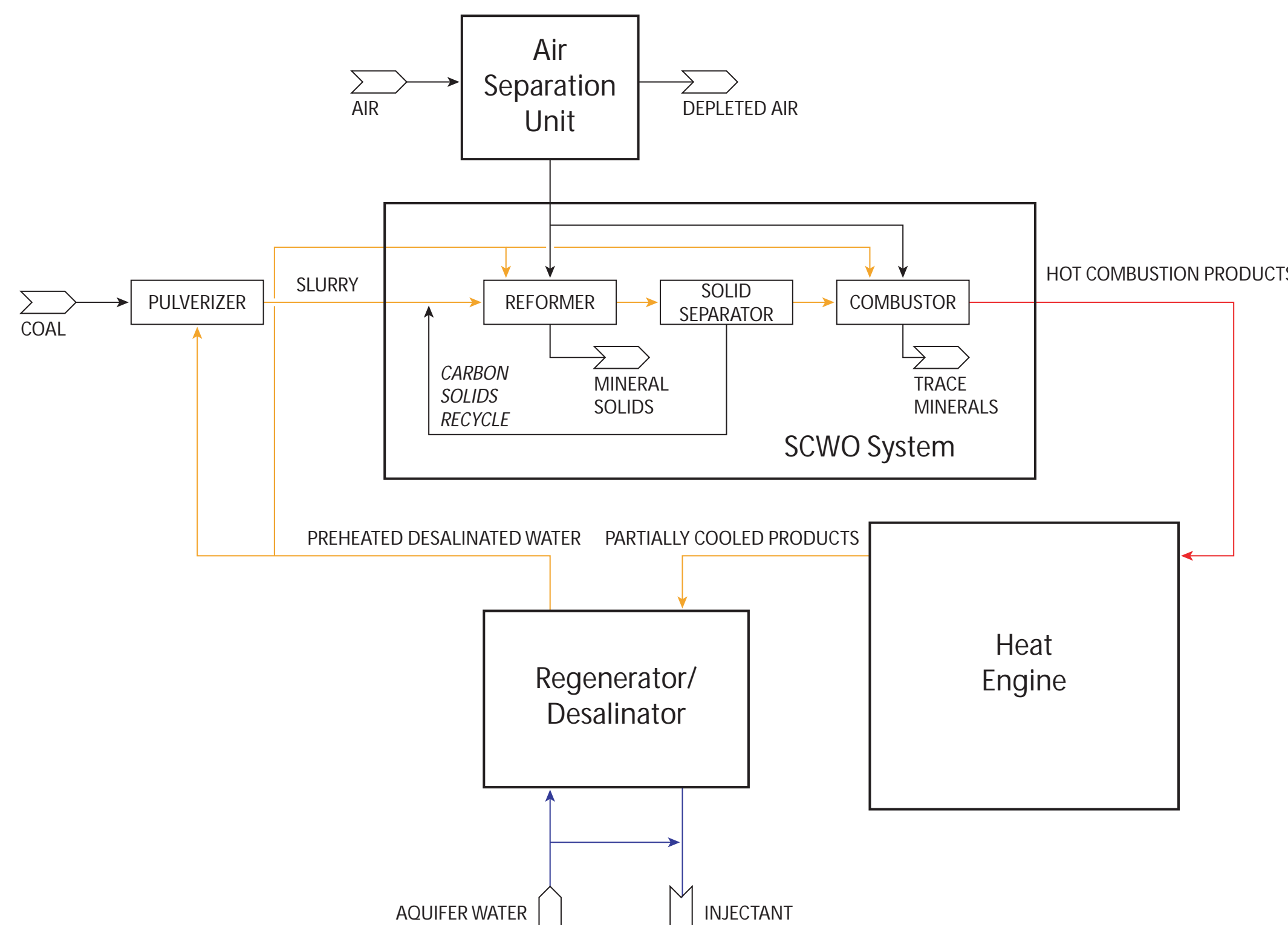


System Concept

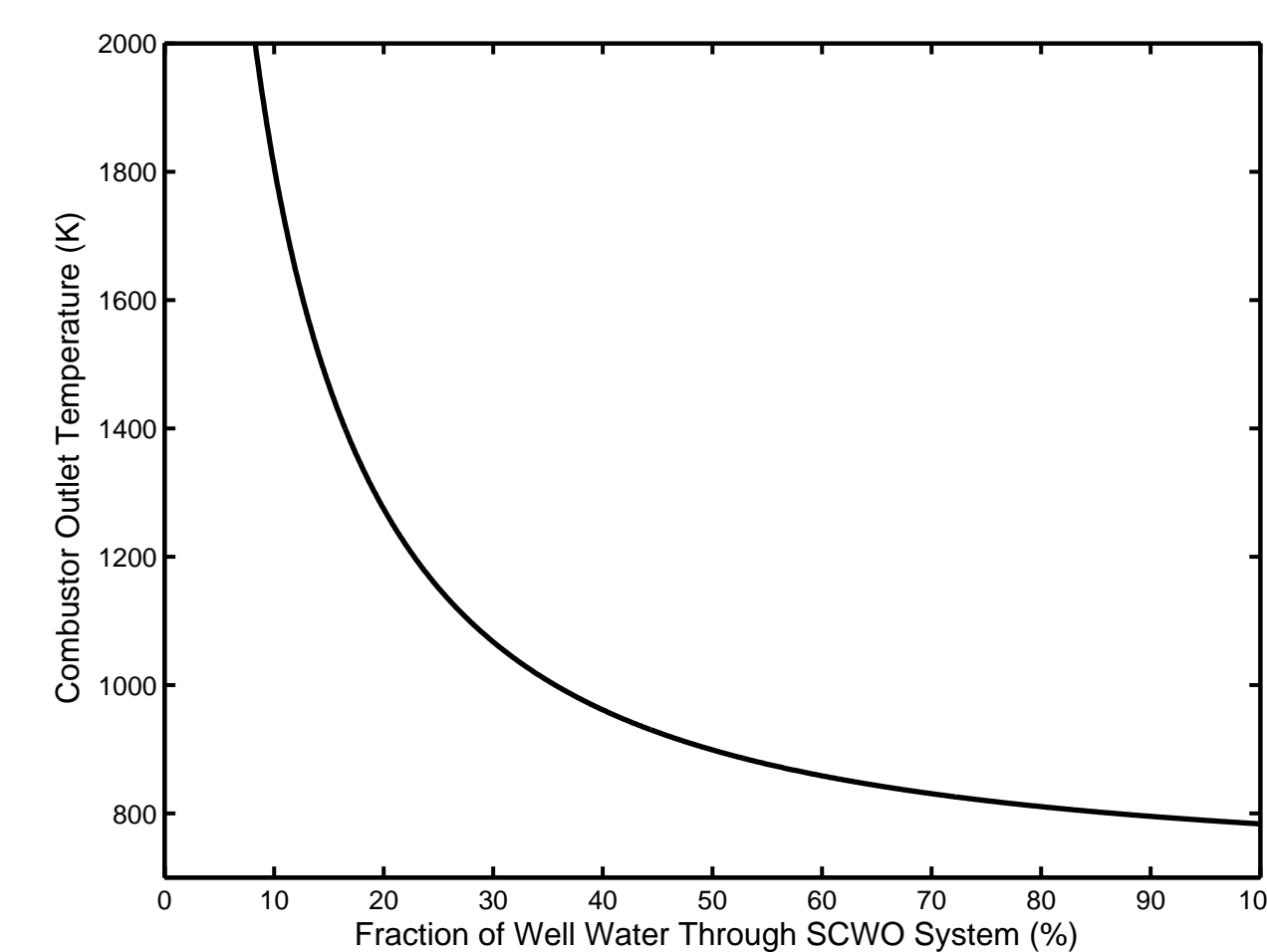
Instead of separating and sequestering CO₂, we propose to combine the energy transformation system with the sequestration medium by using aquifer water as a reaction moderator for the combustion process. Specifically, we consider using supercritical water to reform the coal into a wet supercritical fuel, combusting that fuel in a high-pressure, high-temperature environment suitable for driving a heat engine, and equilibrating the carbonated water to aquifer conditions before re-injection. Our aim is to achieve an efficient method of coal energy conversion that has no matter transfer to the atmosphere and that sequesters the carbon from the coal in the aquifer at near chemical equilibrium—and therefore non-buoyant—conditions.



The proposed system consists of an air separation unit (ASU), the supercritical water oxidation (SCWO) system, a regenerator/desalinater, and a heat engine. The ASU provides oxygen for combustion; the low solubility of nitrogen in water precludes the use of air as the oxidizer. The SCWO system consists of a reformer, a solids separator (for inorganic matter), and the combustor. The hot combustion products are used to drive a heat engine, after which they are cooled by regenerative heat exchange before being returned to the aquifer. In the process of heating the aquifer water to the critical point, the salts present in the aquifer water precipitate out of solution and are mechanically separated.



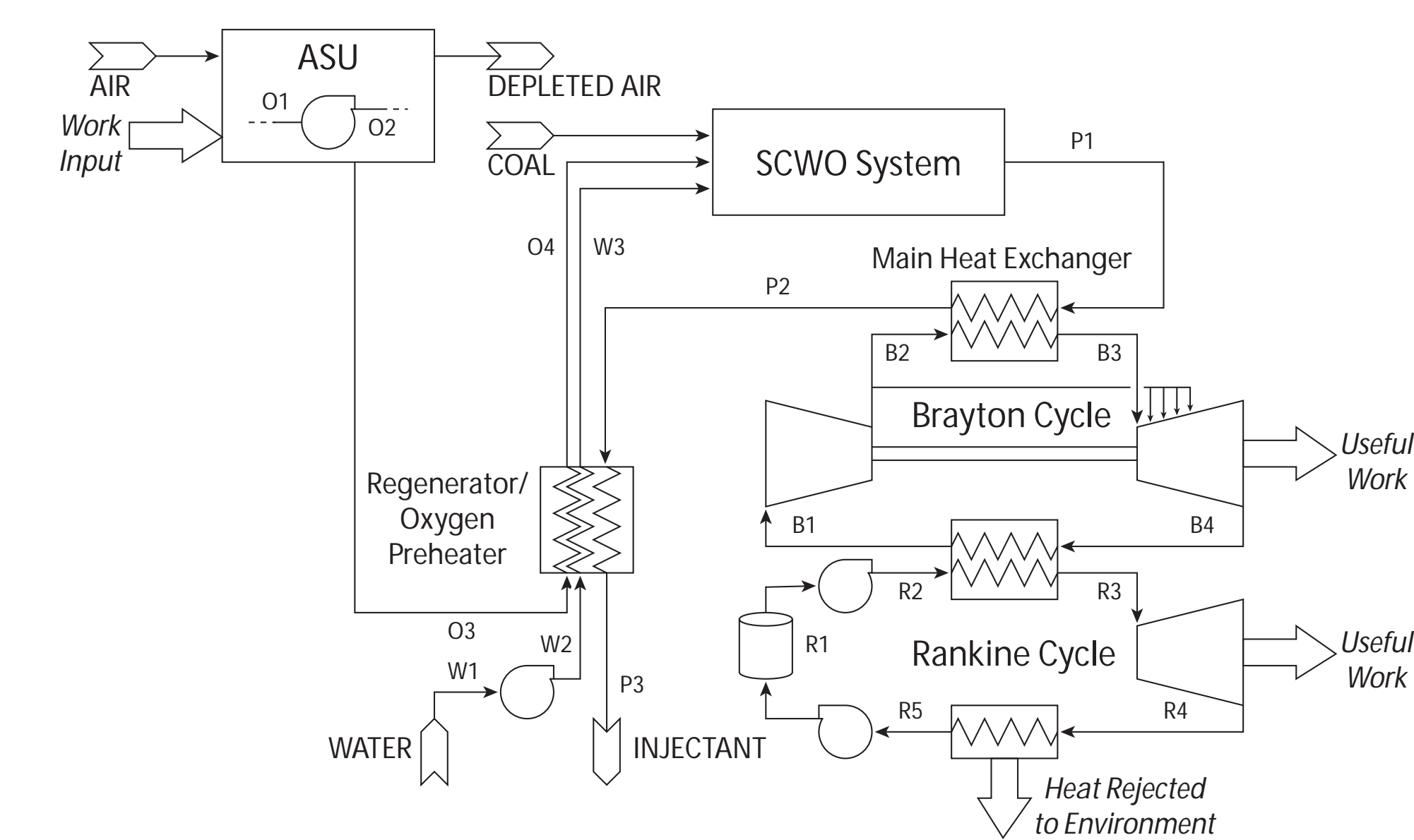
About 77 kg of water is required to dissolve the CO₂ from 1 kg of coal (at aquifer conditions). Not all of this water is required for the purposes of energy processing. As shown below, only a fraction of the water is involved in the combustion process. The remaining water is used for CO₂ dissolution only.



System Analysis

A thermodynamic systems analysis has been performed based on the flow sheet shown below.

- ASU details are not modeled except for the high pressure liquid oxygen pump (which is not part of a standard cryogenic ASU). The work input requirement is specified according to reported state of the art values.
- Since the internal details of the SCWO system are not required for an equilibrium systems analysis, only its inlet and outlet states are considered.
- A heat engine configuration consisting of a closed helium Brayton topping cycle and a Rankine bottoming cycle was selected.

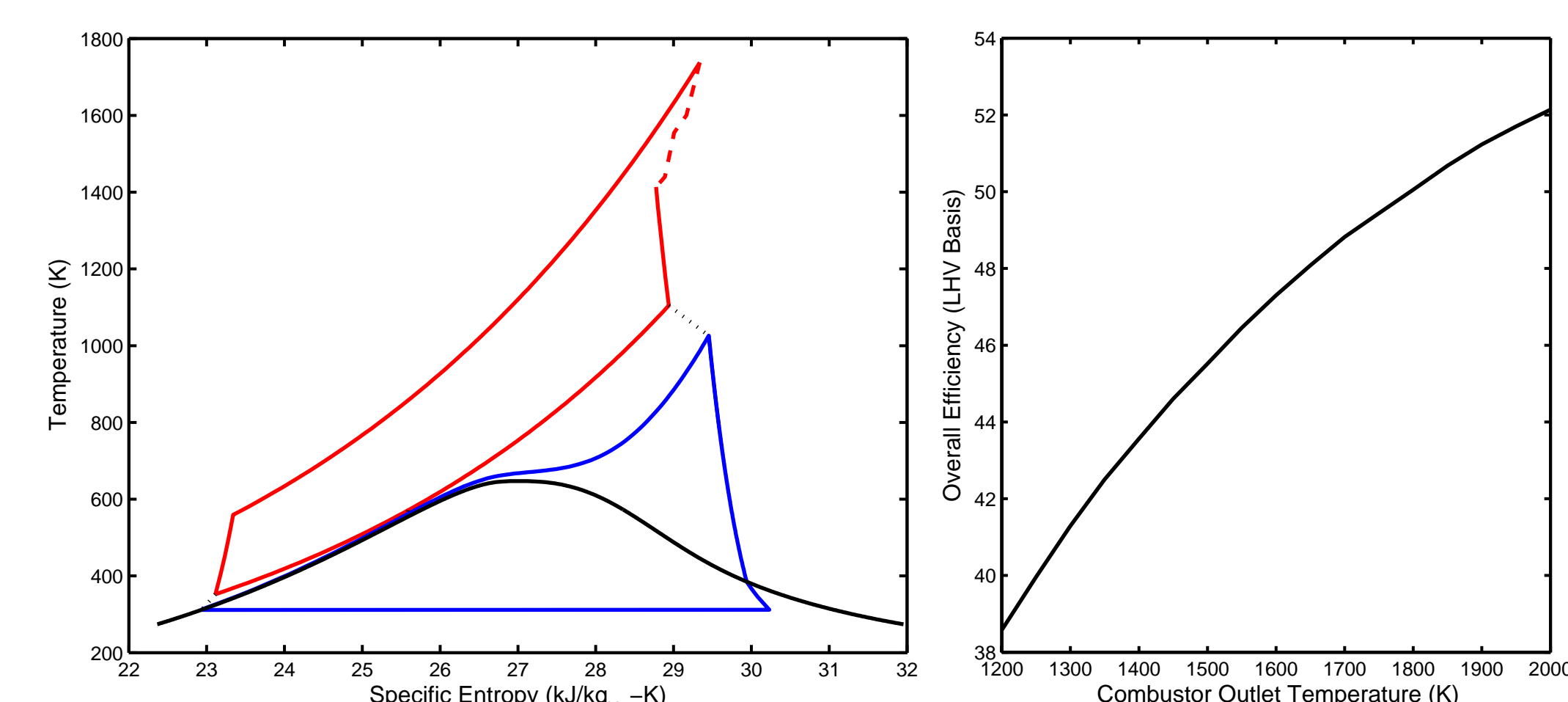


The table below gives the flow rates required for a system of 500 MW scale along with the coal-specific flow rates. Of particular interest are the relative proportions of coal, oxygen, SCWO water, and the total water requirement for CO₂ dissolution. Performance of the system with 1800K combustor exit temperature is summarized in the table to the right below.

Stream	Flow Rate in 500MW Plant (kg/s)	Relative Flow Rate (kg/kg maf coal)	Component	Power (MW)
Moisture & Ash Free (MAF) Coal	33.4	1	Brayton Cycle Compressor Turbine	-209.9 / 456.3
Oxygen	75.3	2.25	Rankine Cycle Condensate Pump	-0.22
Total Aquifer Water	2583	77.2	Feed Pump Turbine	-7.3 / 323.8
Aquifer Water Through SCWO System	178	5.33	Net ASU (w/ O ₂ Pump) Water Pump	-61.5 / -1.5
Brayton Cycle Helium	195	5.84	Overall Plant Fuel Heat Rate (LHV)	500.0 / 999.0
Rankine Cycle Steam	206	6.16	Combined Cycle Efficiency	55.8%
			Overall Efficiency	50.1%

In analyzing the combined cycle heat engine, analyses of turbine stage cooling requirements were included so as to obtain realistic estimates as the combustor outlet temperature was varied. These included strategies from uncooled turbines for low inlet temperatures up to the use of six stages of cooling for the highest temperatures. The red dashed section of the T-s diagram below represents the states of the Brayton cycle helium through four cooled stages.

Optimization of the matching conditions (pressure ratios and pinch point) between the topping and bottoming cycles was also included in the analysis.



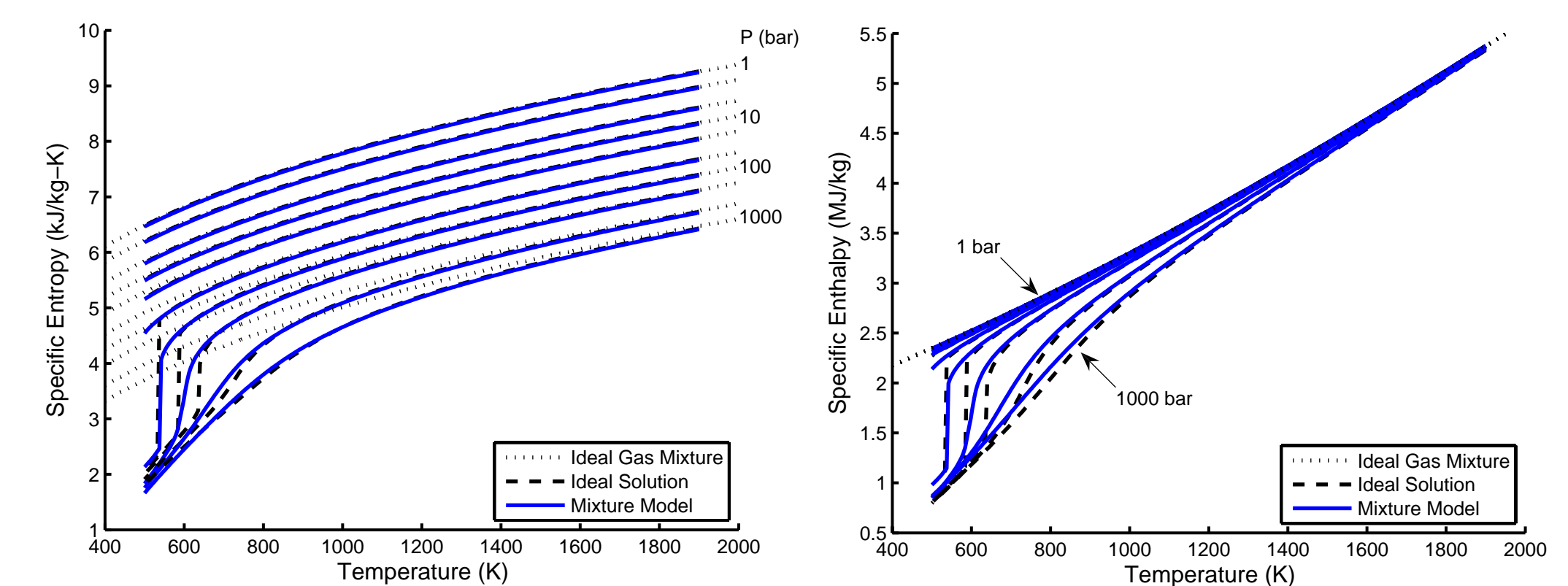
Combustor outlet temperature, limited by material properties in a practical device, is the key driver of overall system efficiency. The above right figure shows this relationship.

Current Research

Real Solution Property Data:

Accurate thermodynamic property data are needed to calculate the flows in the supercritical water system and the amount of water needed to dissolve all of the CO₂ produced. This is being approached using a Lemmon-Jacobson style mixture model for the fundamental relation of the mixed CO₂-H₂O system in the single-phase region. A Peng-Robinson mixture model is used for predicting vapor-liquid equilibrium.

Isobars for a 10 mol% CO₂ solution are shown on s-T and h-T diagrams below for three property calculation methods: as a mixture of ideal gases, as an ideal solution of real fluids (as presently used in the system model), and as a real mixture of real fluids. At low temperatures (below the critical point of water) the actual specific enthalpy of the mixture is above that of an ideal solution. As a result, the specific work with respect to combustor fluid flow will be lower than in the current model, and the water flow rate through the combustor required for a chosen outlet temperature will be higher than in the results shown.



Supercritical Reformer & Solid Separator:

Coal processing is divided into a reformer and combustor so that inorganic solids may be removed at a low temperature. The reformer will deliver a single-phase supercritical water solution of synthesis fuel to the combustor.

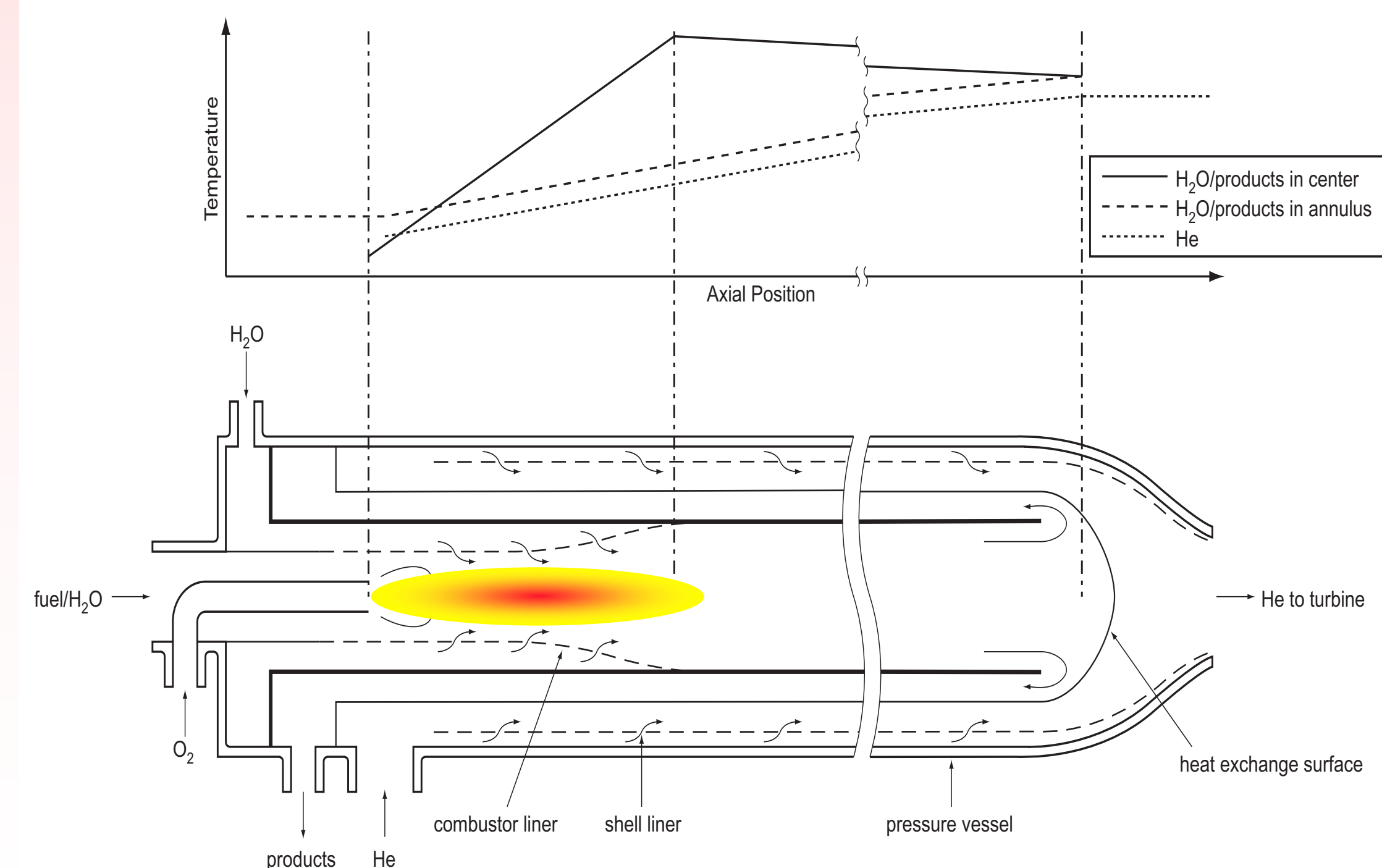
Work on this component is being performed by B. J. Kim and colleagues in the group of Professor R. E. Mitchell.

Supercritical Combustor:

The supercritical combustor accepts the synthesis fuel solution from the reformer, brings it to chemical equilibrium, and delivers the products at high temperature for use by the heat engine. Since both the fuel (ultimately coal) and the oxidizer (from the ASU) have significant costs, the combustor should operate near stoichiometric conditions and with maximum outlet temperature.

Our approach follows a gas turbine based design paradigm wherein fluid mechanics is used to achieve reaction stabilization, overall fluid mixing, and control of hot product interactions with the liner wall.

Shown below is a concept schematic of the design currently being developed, including integration of the requisite heat exchange surface with the helium working fluid of the Brayton topping cycle.



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