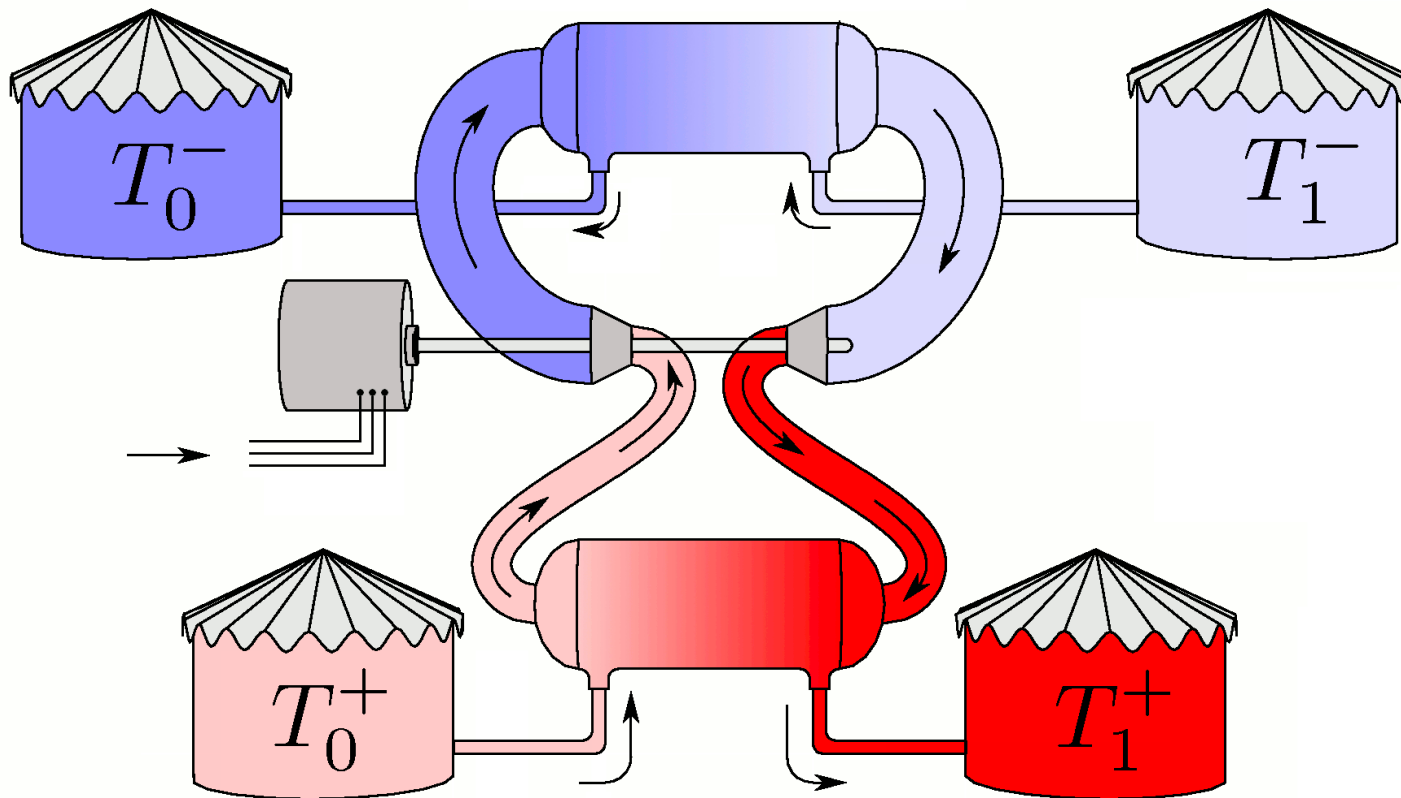
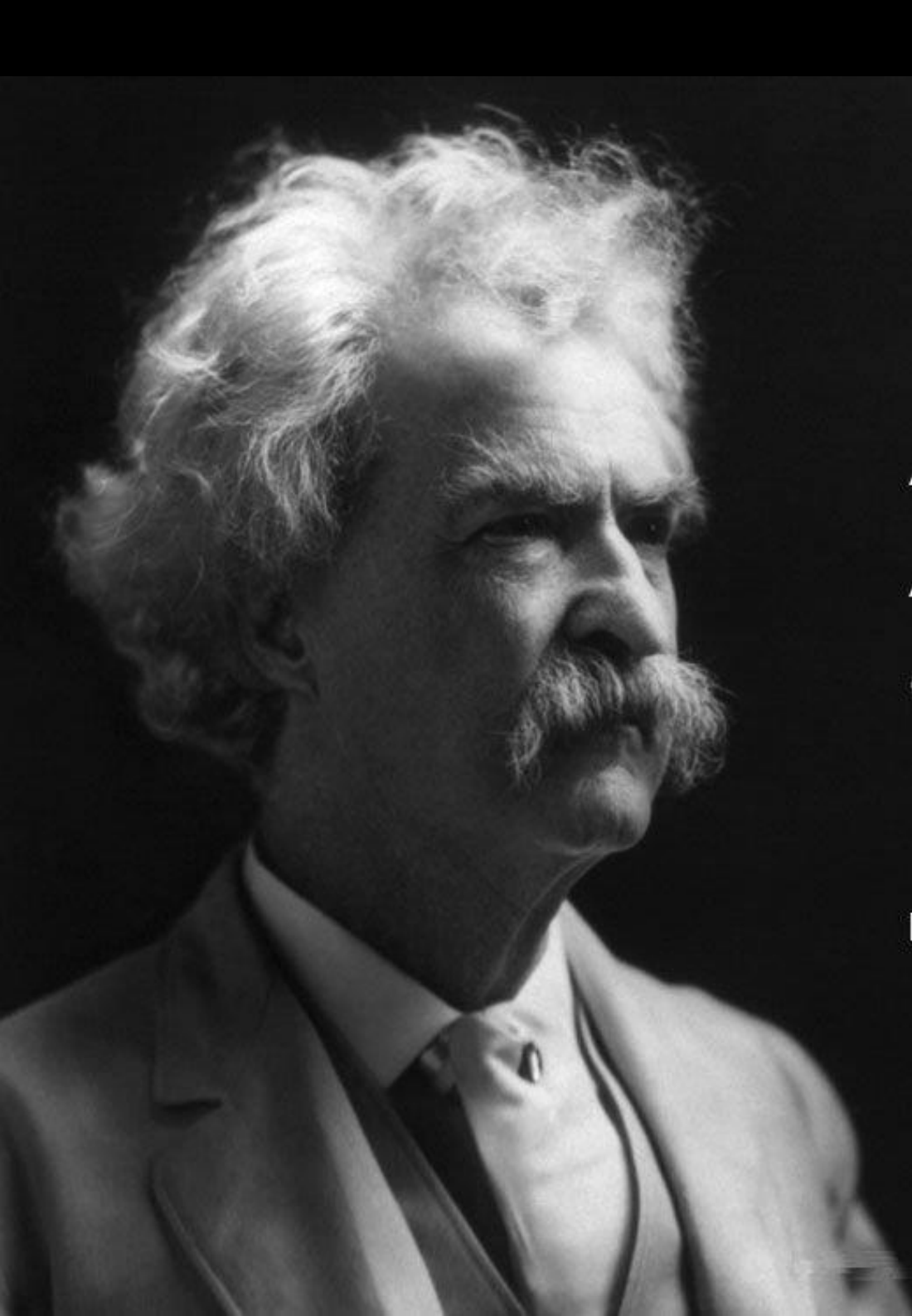


Reversing Turbomachinery: A Central Enabling Technology of Thermal Grid Storage

R. B. Laughlin
TMCES, Pittsburgh, 3 Feb 20

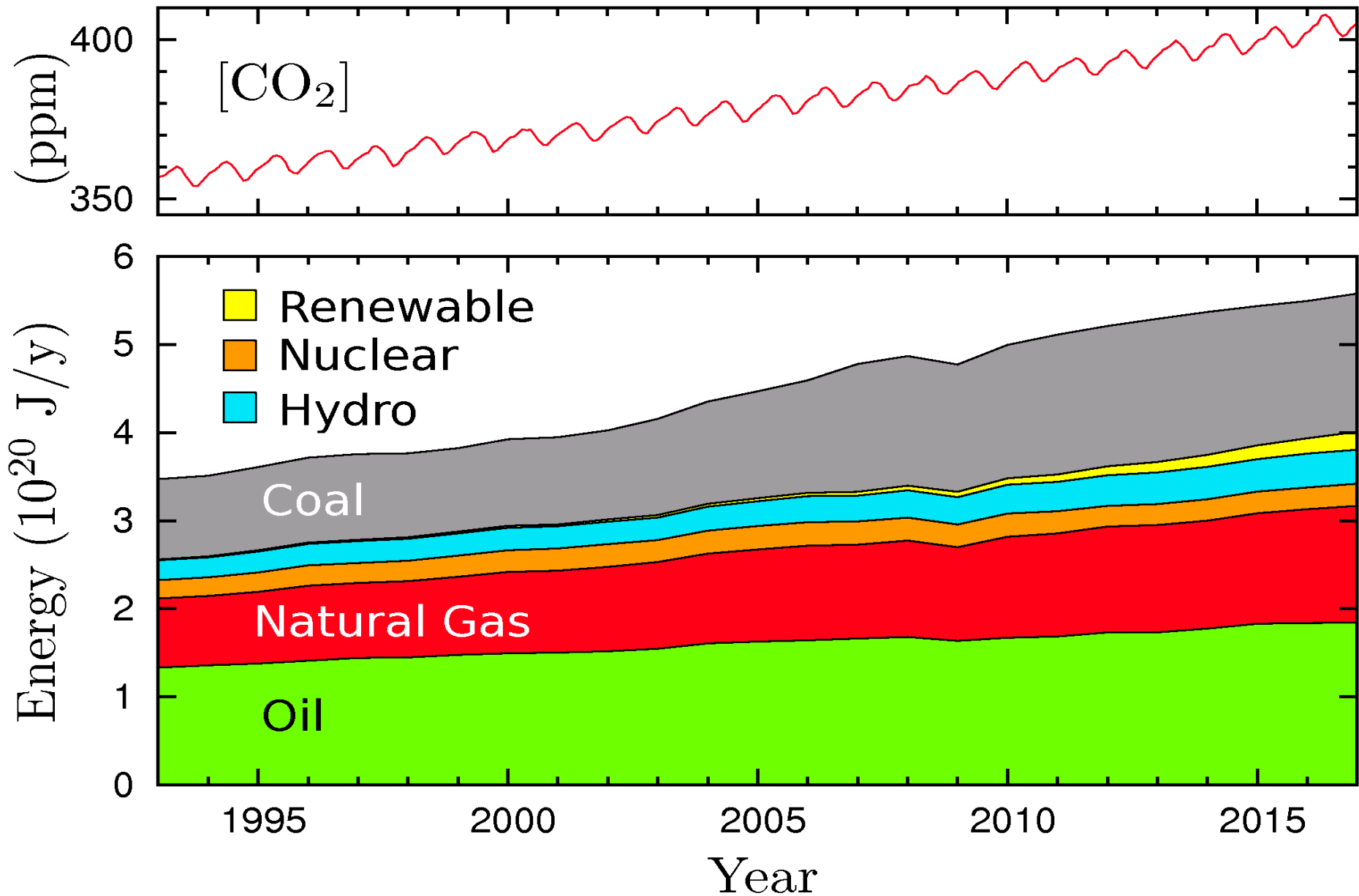




A PERSON WITH
A NEW IDEA IS A
CRANK UNTIL THE
IDEA SUCCEEDS

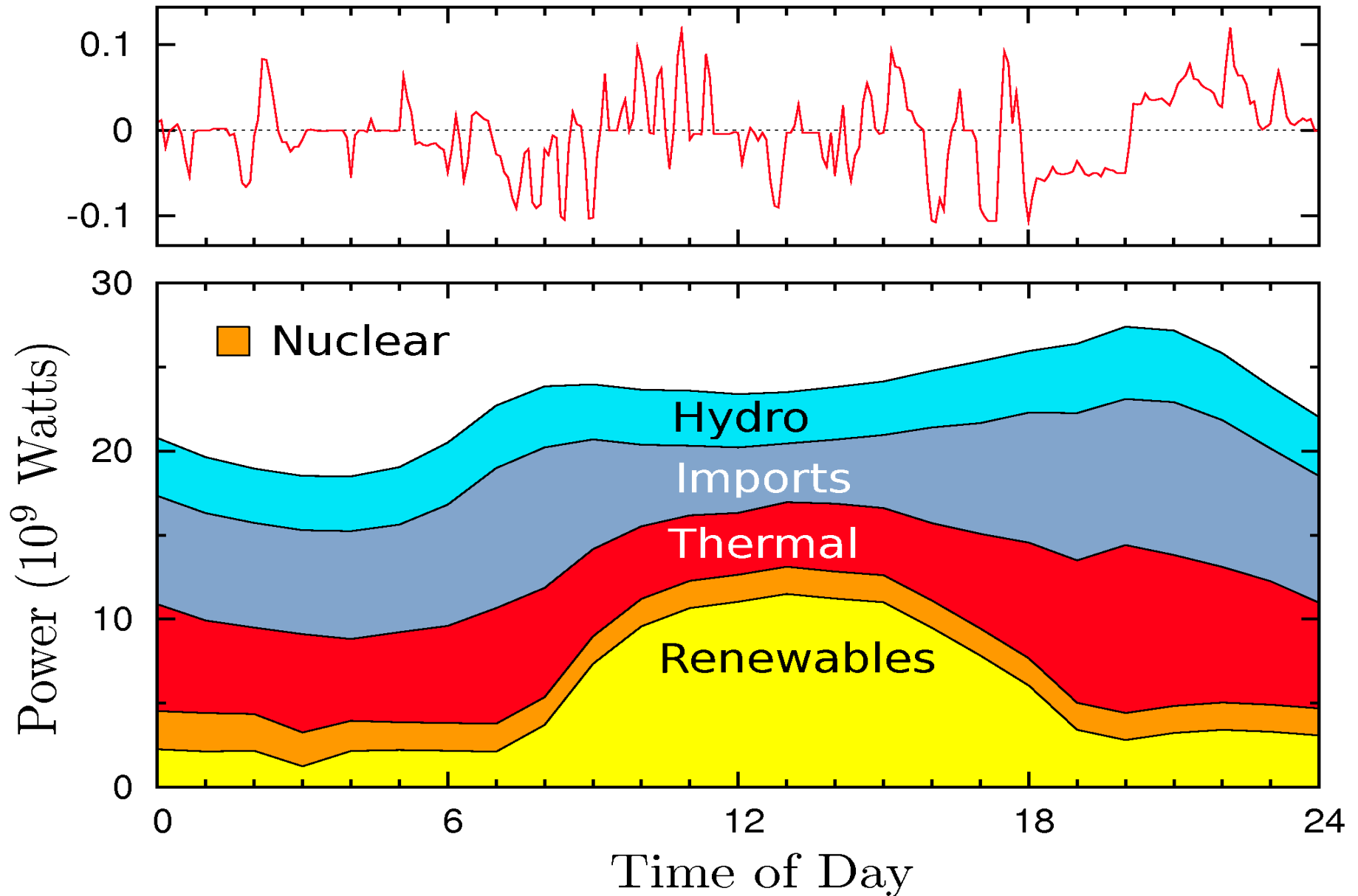
MARK TWAIN

The Problem – Part I



Source: "BP Statistical Review of World Energy 2018," British Petroleum, June 2018.

The Problem – Part II



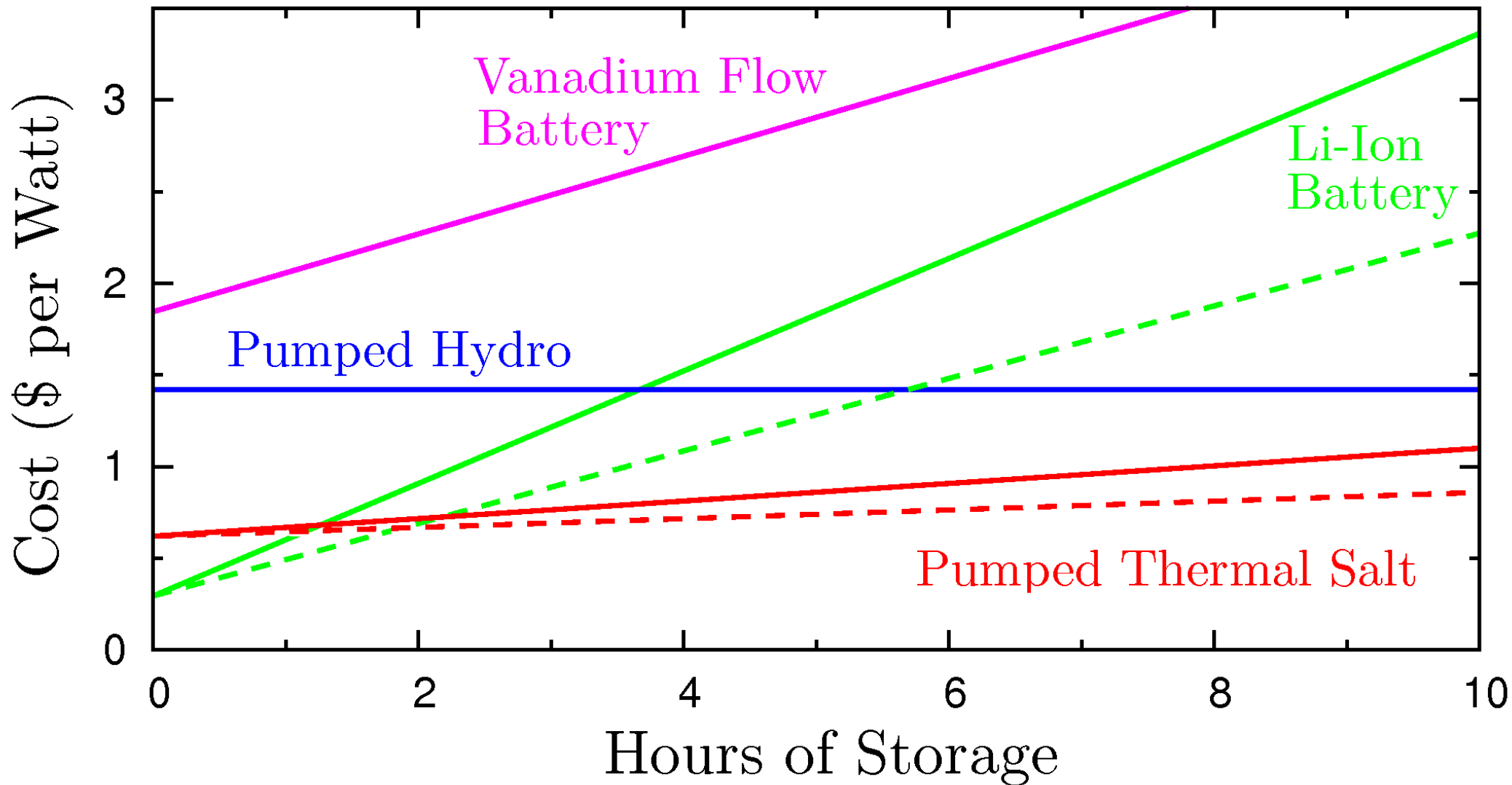
Source: "Renewables Watch for Operating Day: Monday, 01 April, 2019," California Independent System Operator, 2019.

YOU HAVE JUST
CROSSED OVER INTO...

THE
TWILIGHT
ZONE

The title 'THE TWILIGHT ZONE' is rendered in a white, gothic-style font. It is centered within a circular graphic composed of several overlapping, semi-transparent, brownish-gold rings. The entire composition is set against a black background and is surrounded by numerous small, white, dot-like particles, some of which appear to be moving or glowing, creating a sense of depth and a cosmic or mysterious atmosphere.

The Problem – Part III



Sources: R. Fu et al., NREL/TP-6A20-7174, Nov. 18; S. Few *et al.*, Energy Policy **114**, 578 (2018); D. Feldman *et al.*, NREL/TP-6A20-66592, Aug. 16; T. Key *et al.*, EPRI 1023144, Feb 13; T. Lüth *et al.*, Energy Proc. **155**, 379 (2018); C. S. Turchi *et al.*, NREL/TP-5506-22856, May 19; N. Diorio *et al.*, NREL/TP-6A20/64987, Nov. 15.

Idea!



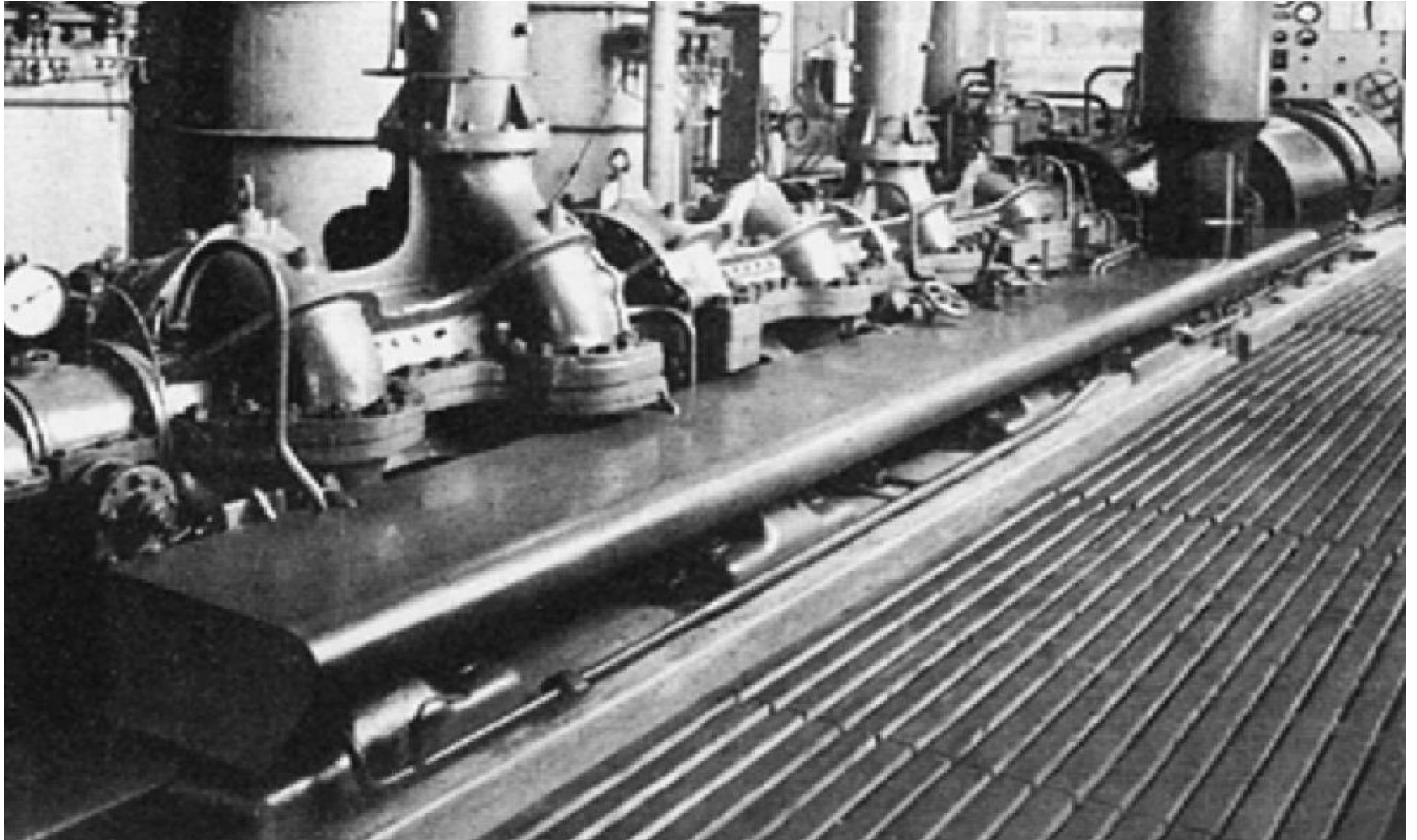
Marry Salt Tanks from Andasol ...





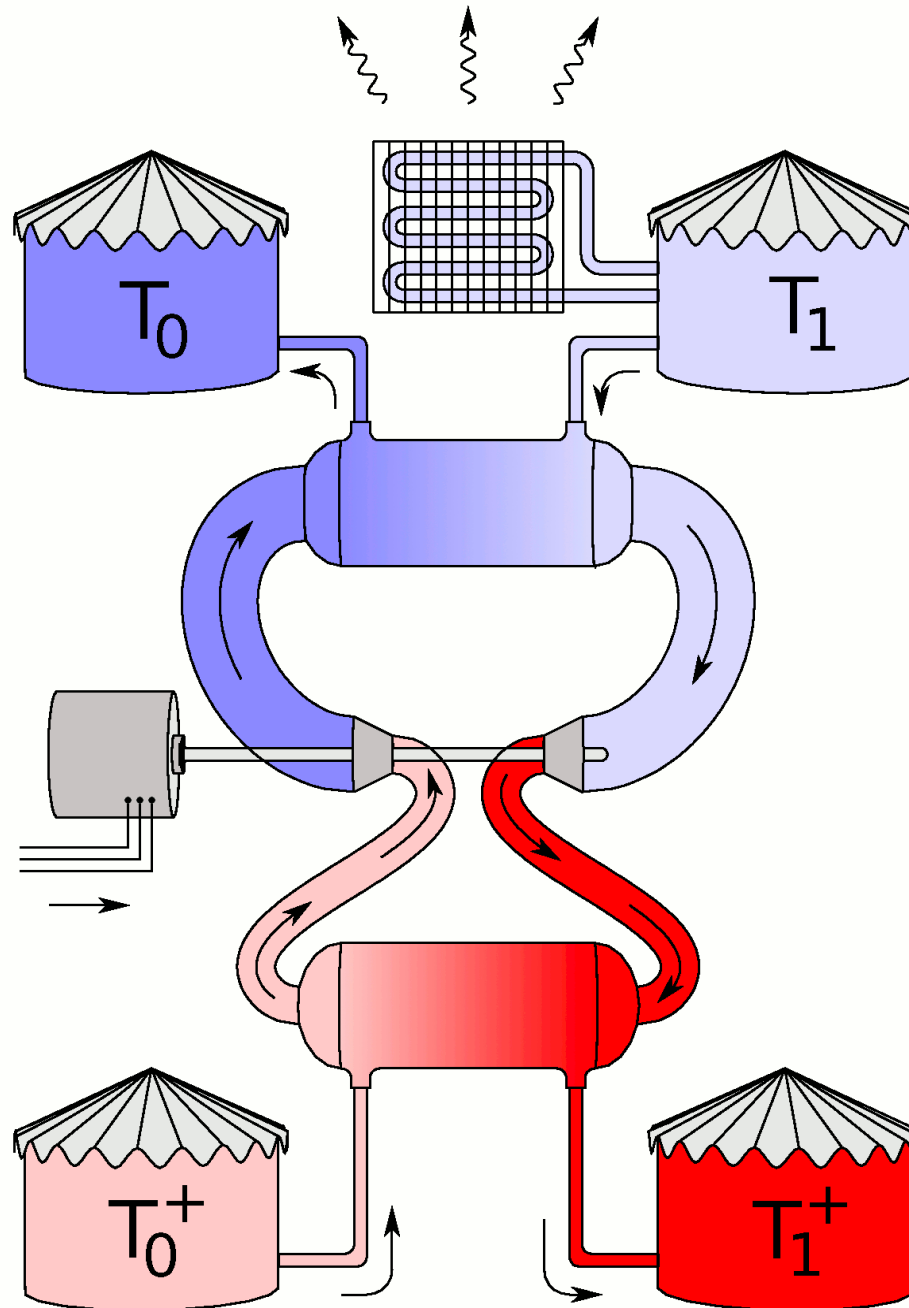
Source: "The Parabolic Trough Plants Andasol 1 to 3," Solar Millenium AG, December 2008.

With Closed-Cycle Brayton Engine

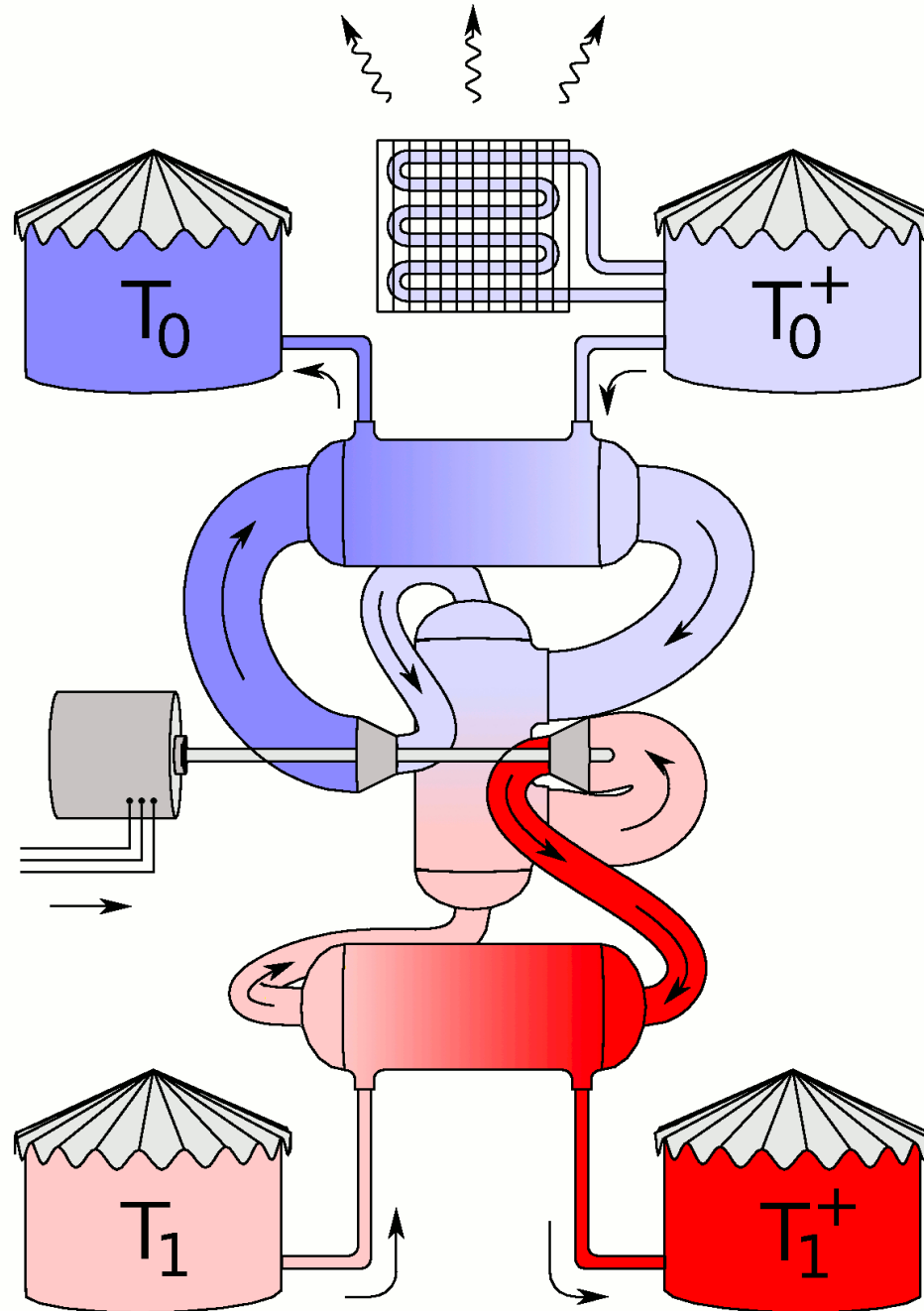


Source: J. Ackeret u D. C. Keller, "Aerodynamische Brennkraftmaschine mit geschlossenem Kreislauf," Zeitschrift des Vereines Deutscher Ingenieure **85**, No. 22, 491 (1941).

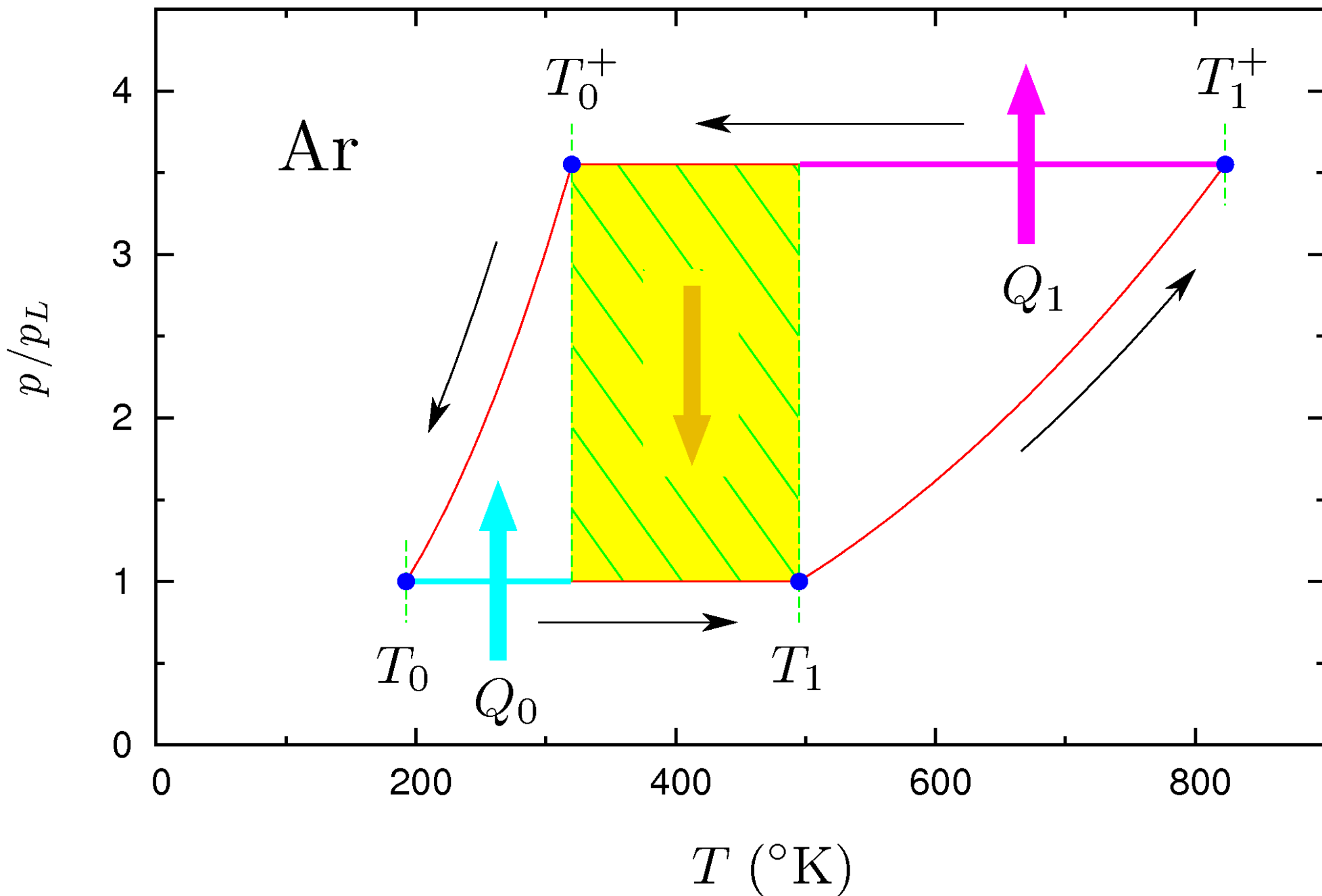
Viola! Reversible Thermal Storage



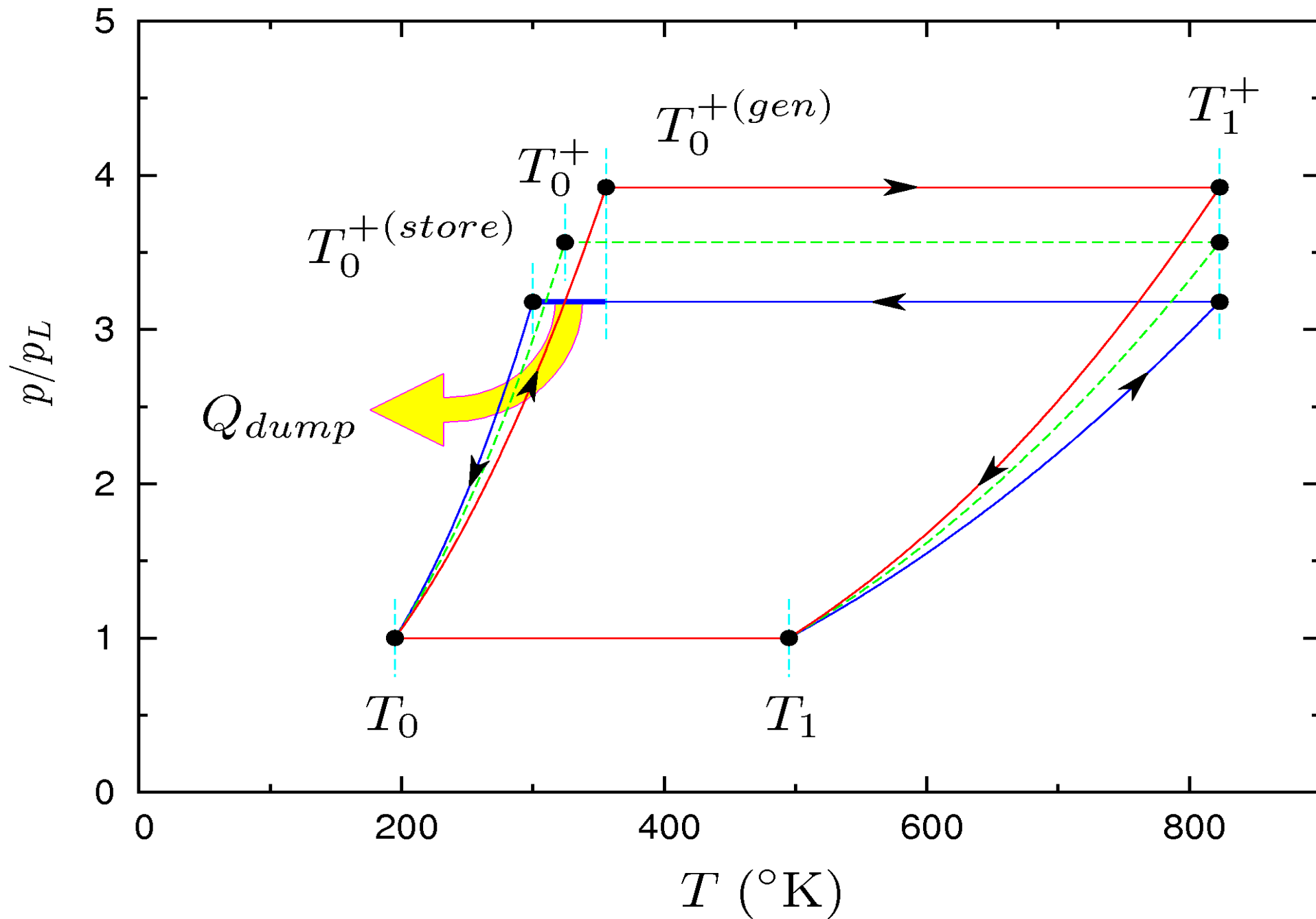
Recuperated Version



Ideal Adiabatic Cycle



Actual Cycle



Relevant Equations

Ideal Adiabatic: $\frac{dT}{T} = \left(\frac{\gamma - 1}{\gamma}\right) \frac{dp}{p}$ $T = \text{Temperature}$
 $p = \text{Pressure}$

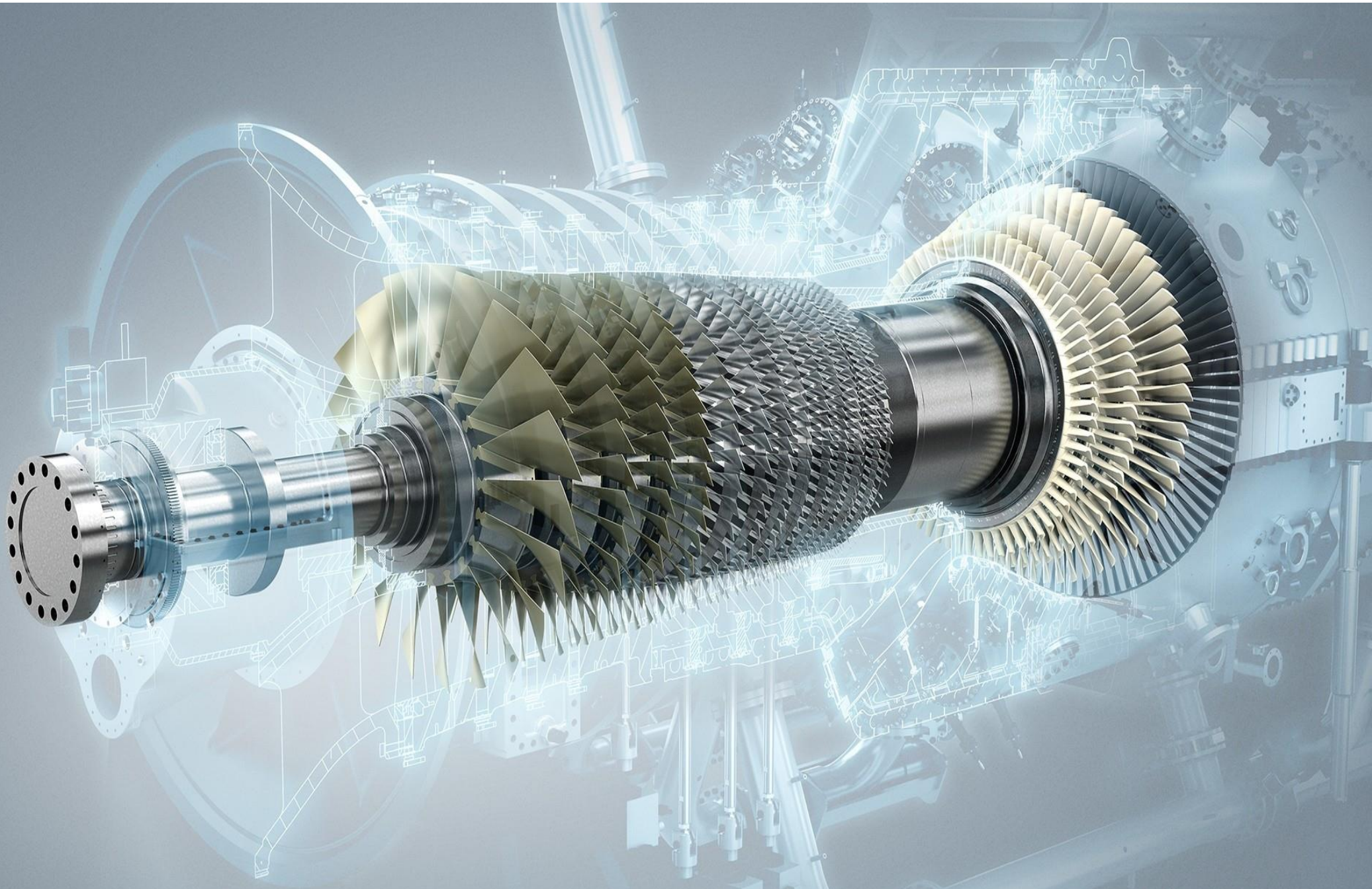
Compressor: $\frac{dT}{T} = \frac{1}{\eta_c} \left(\frac{\gamma - 1}{\gamma}\right) \frac{dp}{p}$ $\gamma = \text{Specific Heat Ratio}$

Turbine: $\frac{dT}{T} = \eta_t \left(\frac{\gamma - 1}{\gamma}\right) \frac{dp}{p}$ $\eta_c = 0.91$
 $\eta_t = 0.93$

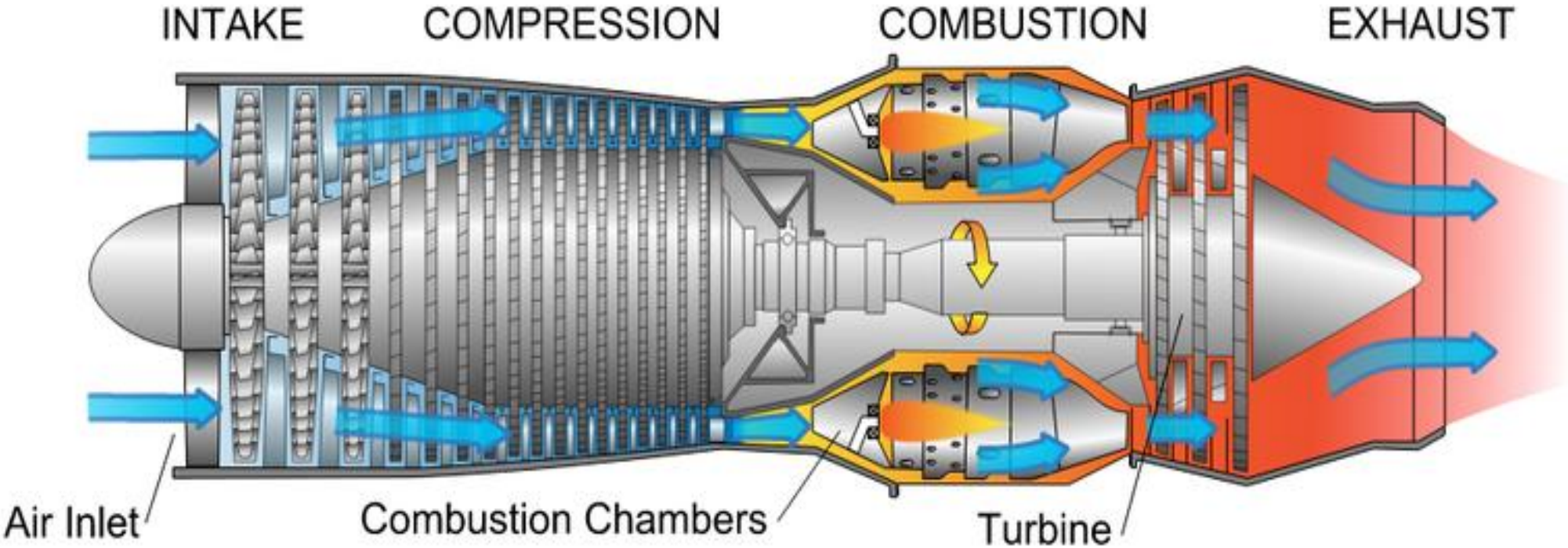
$$\xi = T_0^+ / T_0 = T_1^+ / T_1$$

$$\eta_{store} < 1 - \frac{2T_{Dump}}{T_1 - T_0} \left(\frac{1}{\eta_c} - \eta_t\right) \frac{\ln(\xi)}{\xi - 1} = 0.7$$

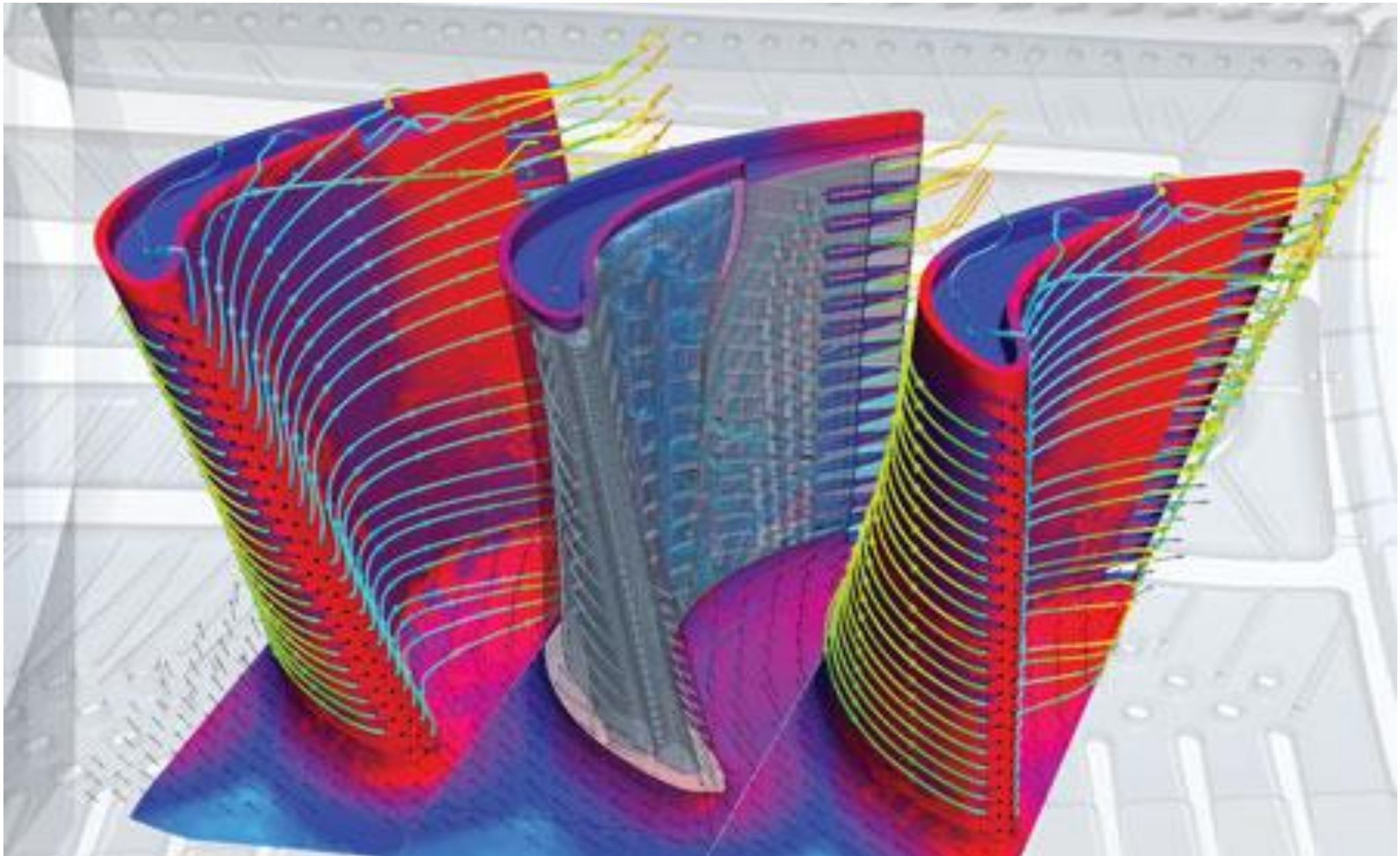
The Problem – Part IV



Old Mandate: Minimize **Weight!**



... Load Turbine Stages **Heavily!**



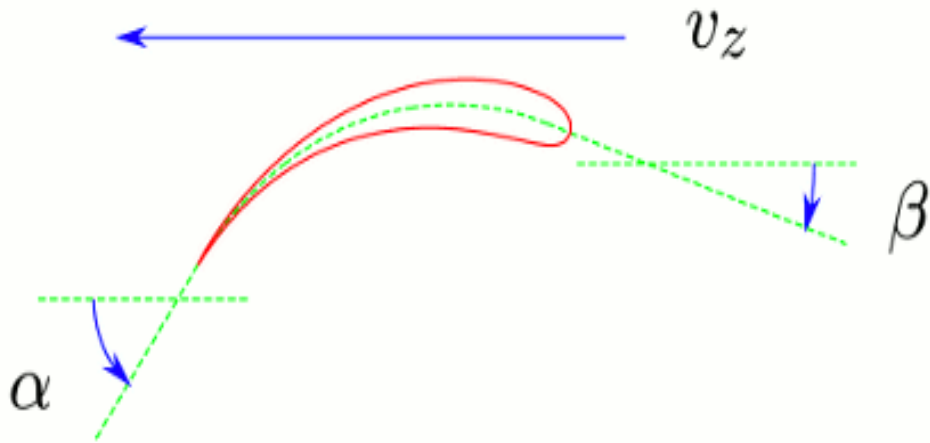
Source: M. Kazari and R. Tanaka, "Improving Cooling Effectiveness of Gas Turbines Through Design Exploration," *Power Engineering International*, 1 Nov 16.

... Load Turbine Stages **Lightly!**

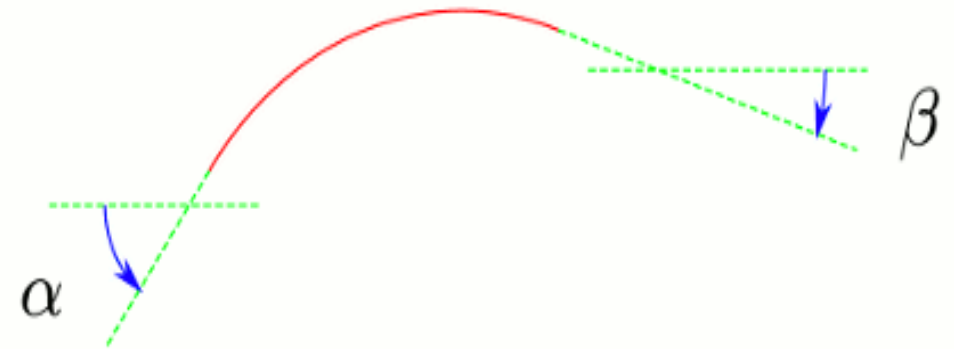


Reversible Blading Strategy

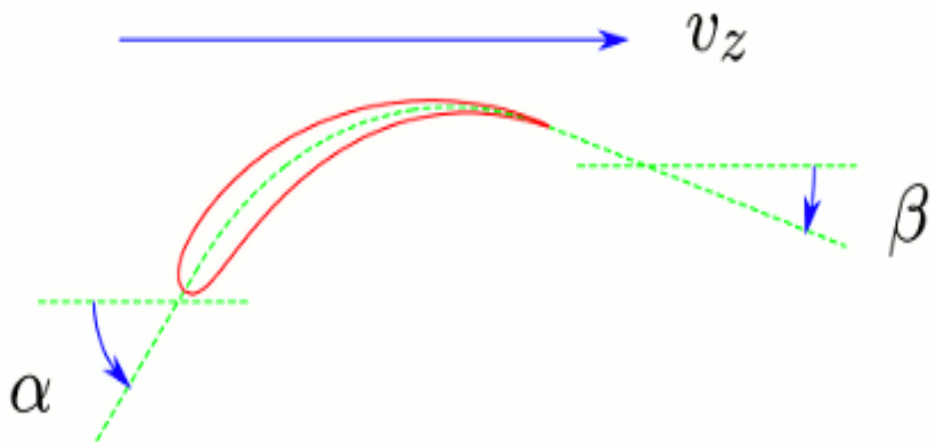
Turbine



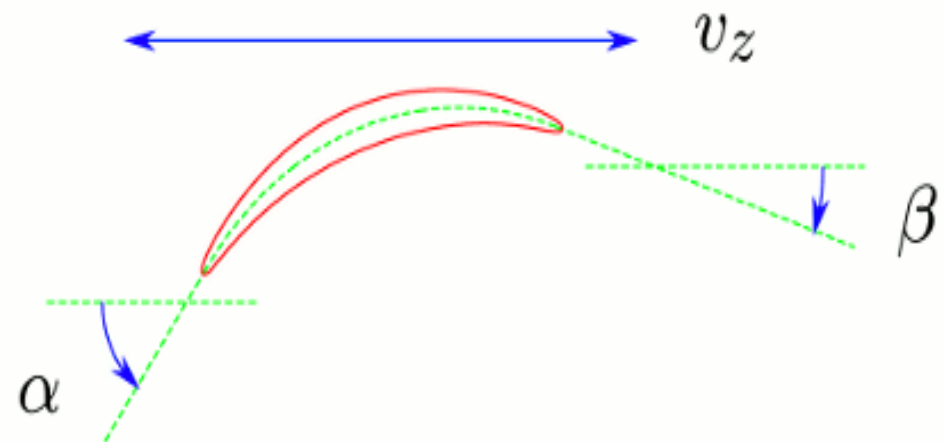
Blade Arc



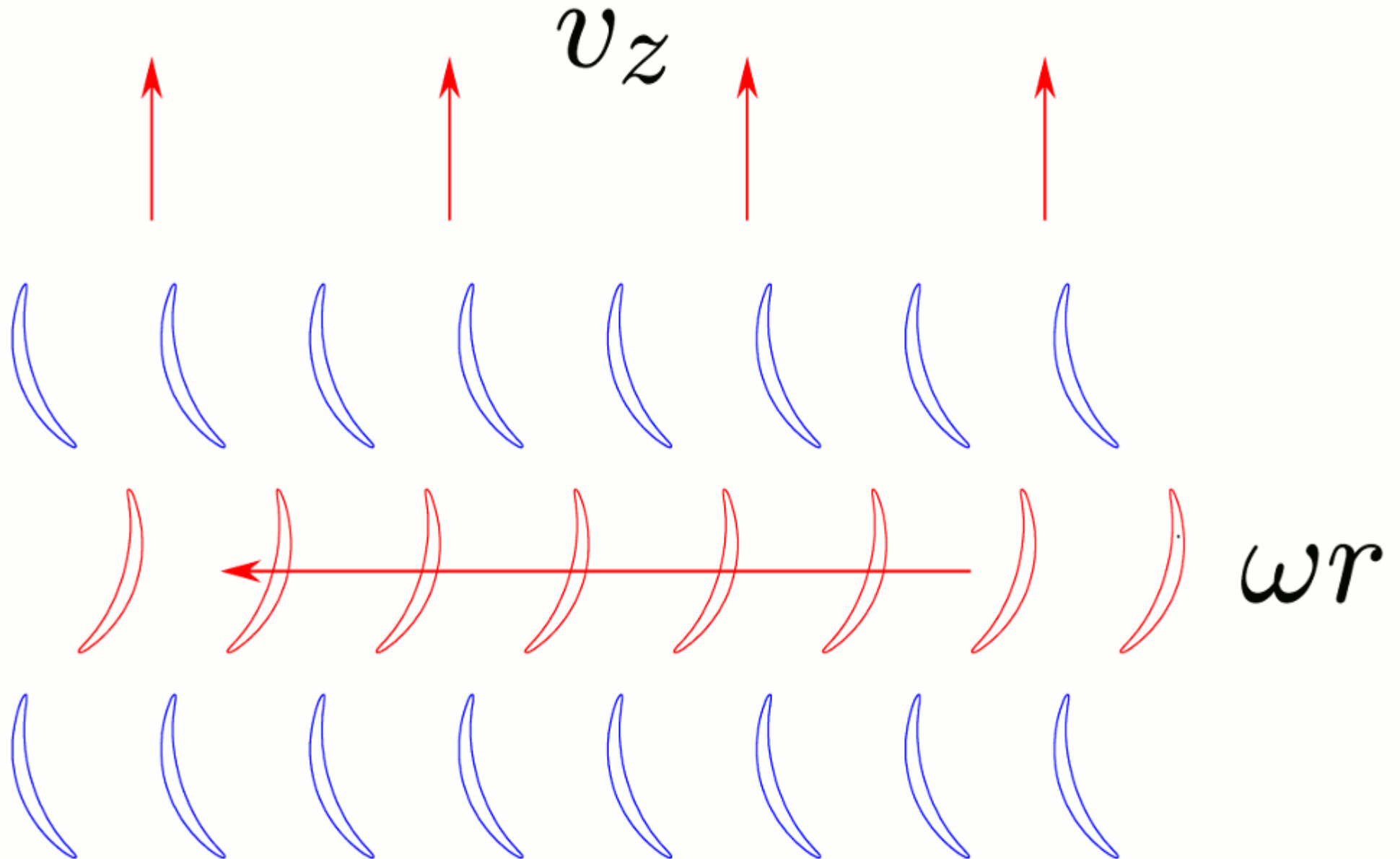
Compressor



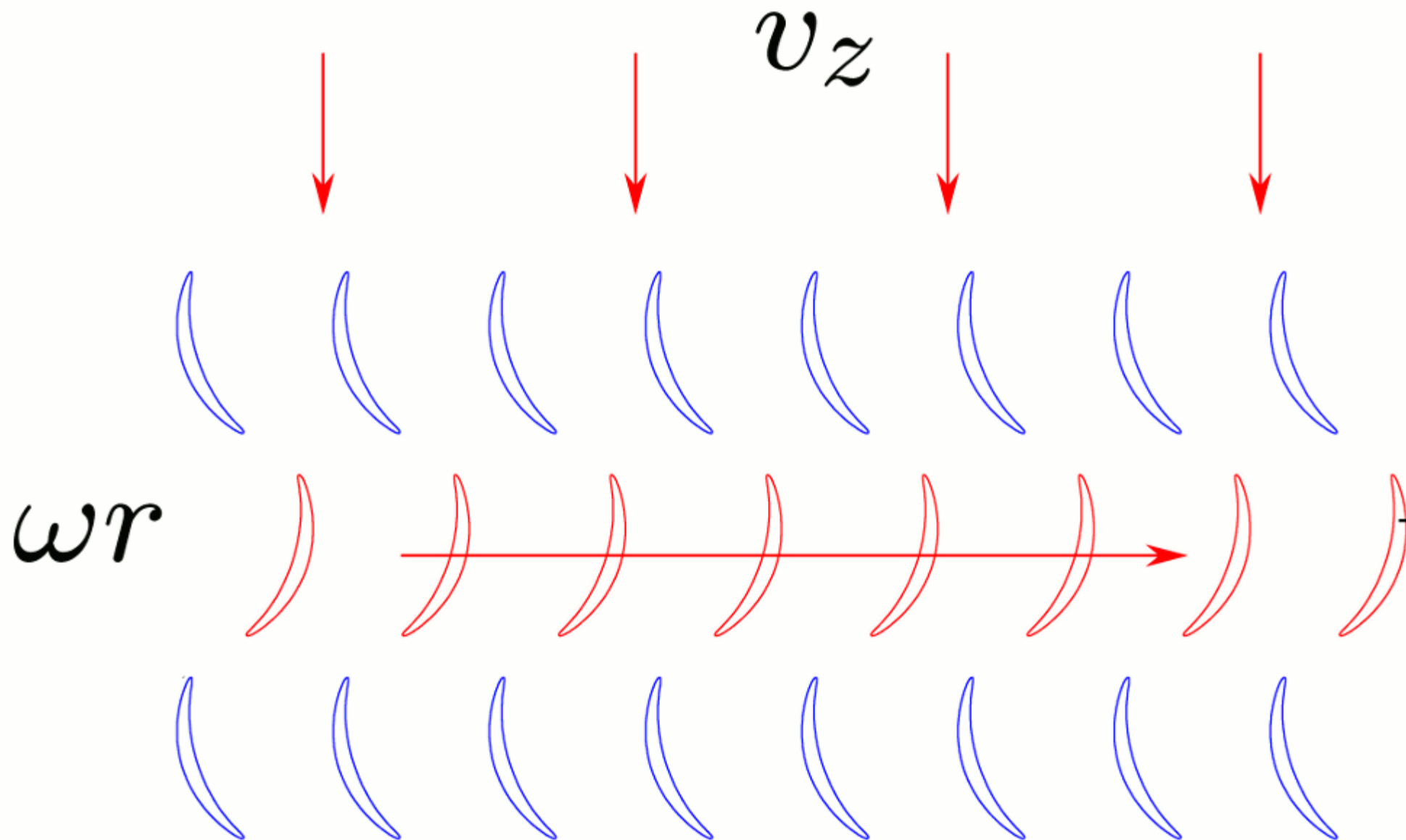
Reversible



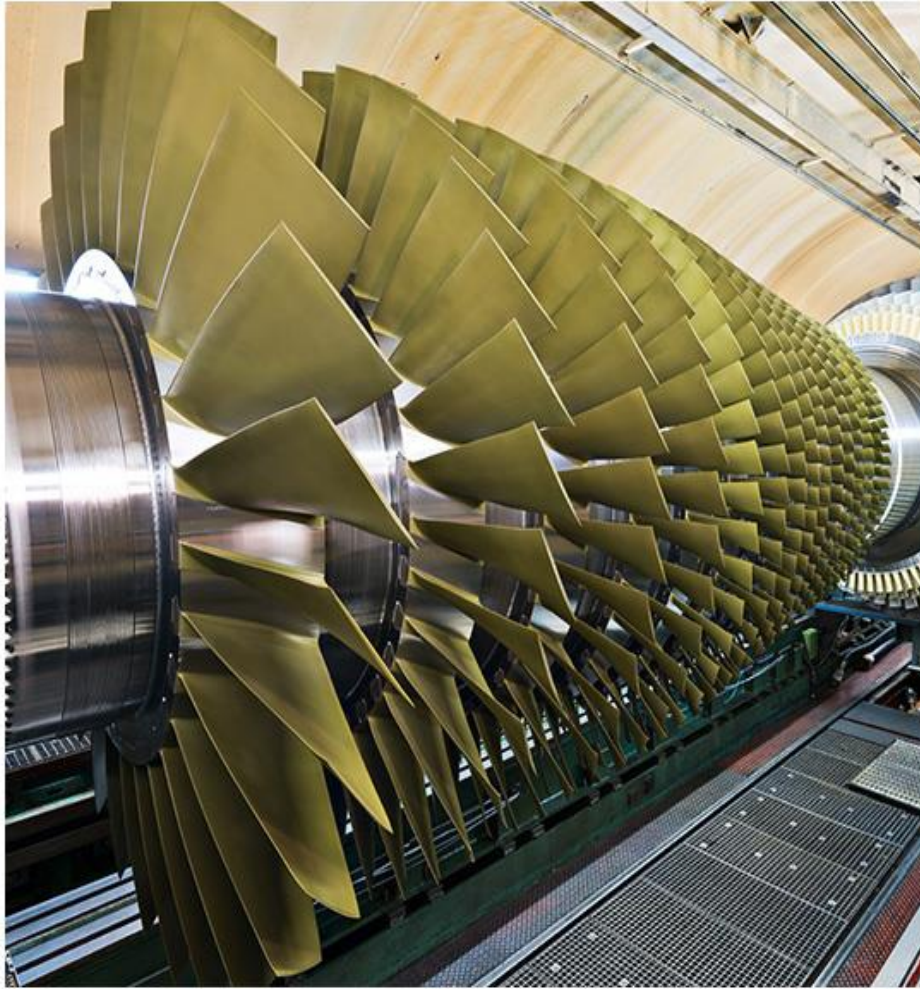
Reversible Compressor



Reversible Turbine

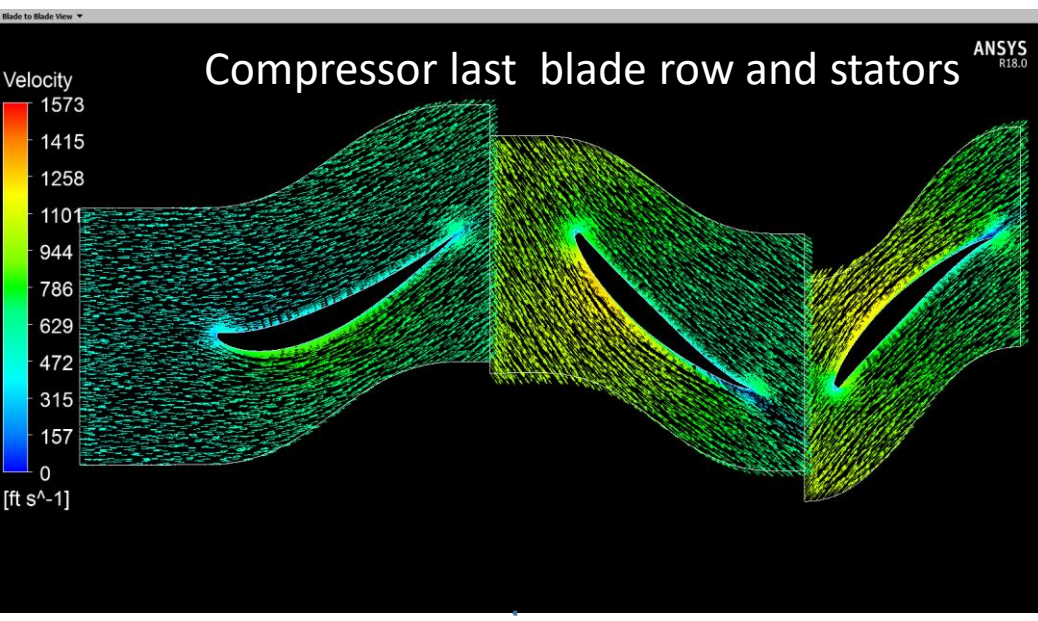
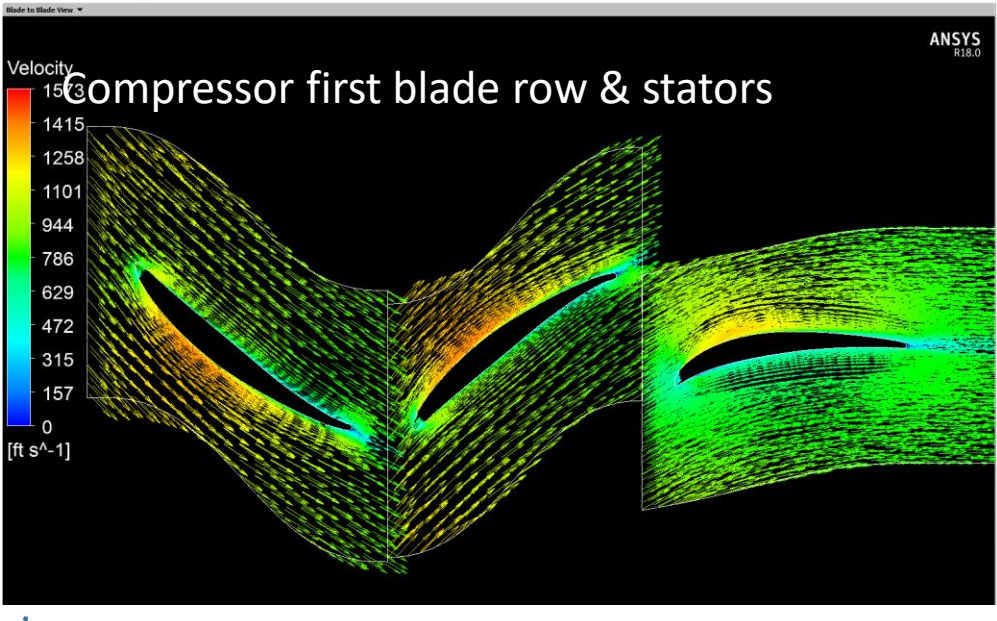
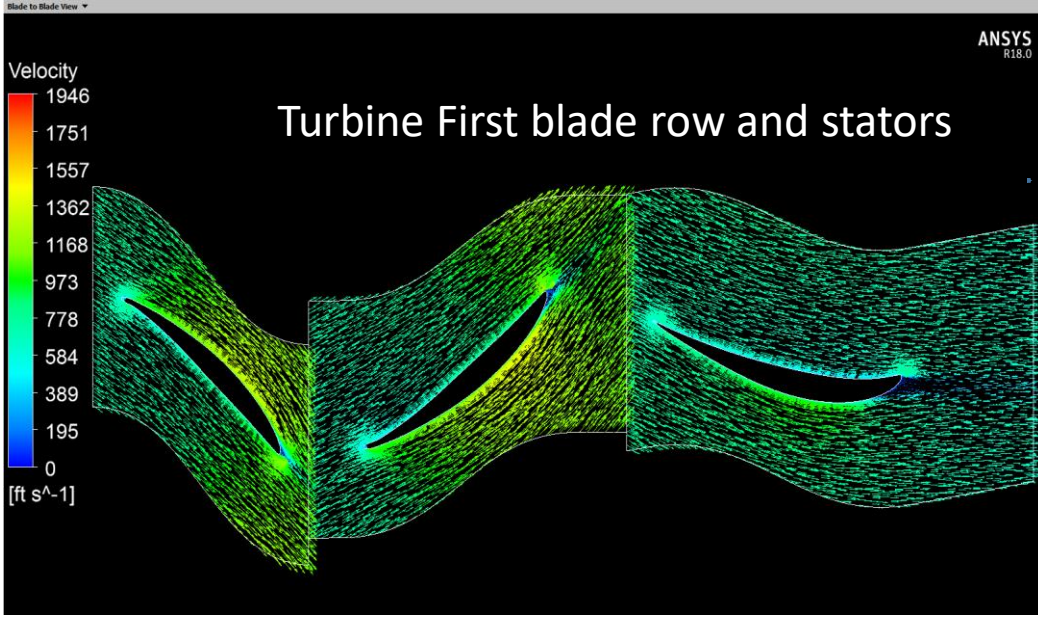
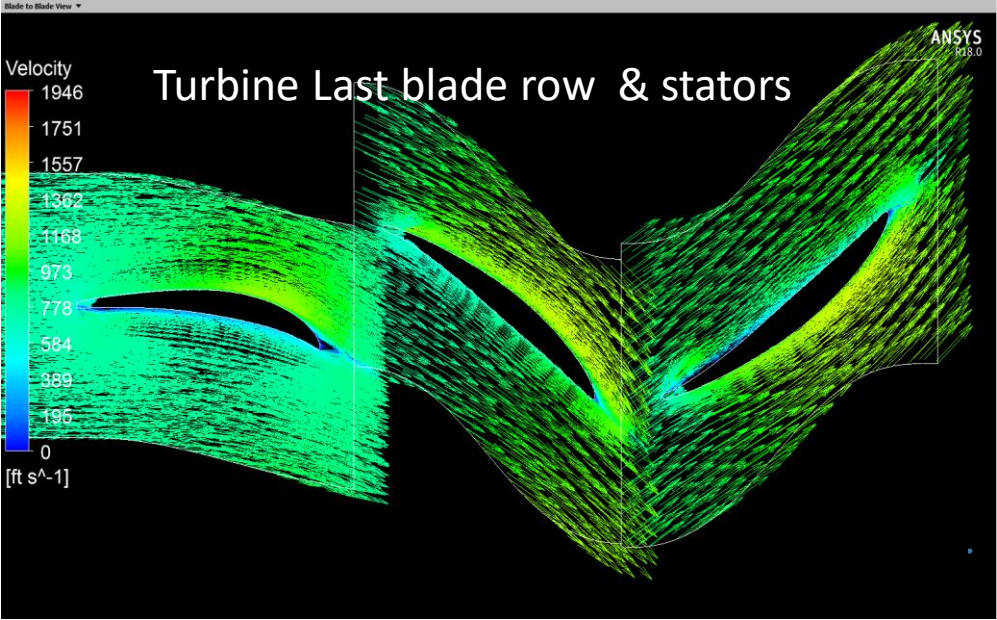


... But Modern Turbocompressors Already Have This Property!

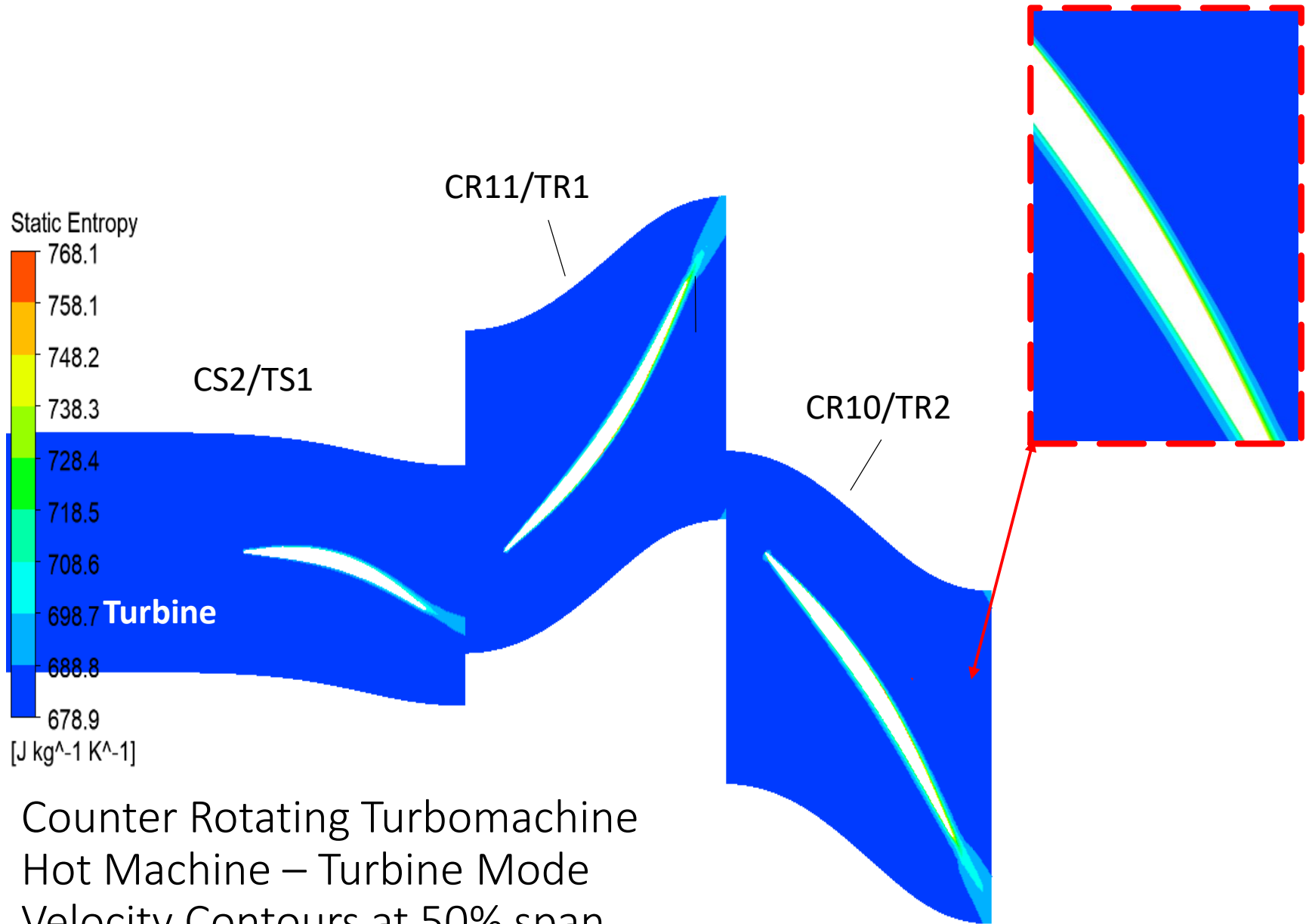


Left: Rotor of Siemens SGT5 series power gas turbine. (Courtesy of Siemens AG) **Right:** Stators of General Electric J79 aircraft engine (progenitor of LM1500 stationary gas turbines) on display at Deutsches Museum in Munich. (Credit: O. Cleynen).

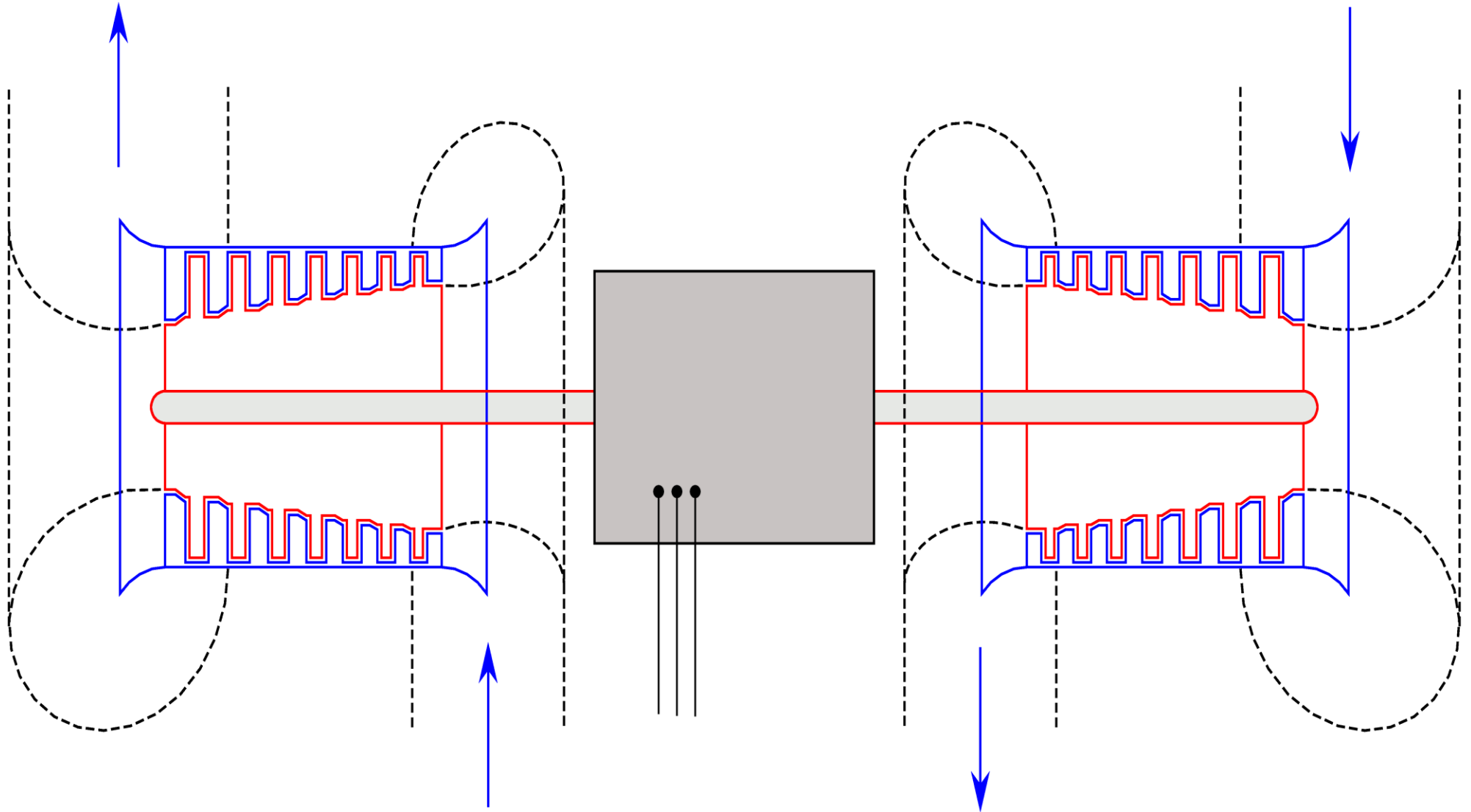
Designed as a *Charge Compressor*, it functions reaso



Majority of the entropy is generated in the w  Brayton Energy LLC ence



The Reversible Turbomachine Is Essential Because ...



... It Reduces the \$ per Engine Watt
by a Factor of 2

