Thermodynamic assessment of liquid metal–steam USC binary plants to break 50% efficiency in pulverized coal plants

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[3]UNIVERSITÀ DEGLI STUDI DI BRESCIA

IEA CLEAN COAL CENTRE
3RD WORKSHOP
ADVANCED ULTRASUPERCRITICAL POWER PLANT
13-14 DECEMBER 2017, ROME
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OUR RESEARCH GROUP
a brief introduction

GECOS GROUP @ Energy Department of Politecnico di Milano

Gecos Group is the largest and most qualified academic research group in Italy focused on power production and energy systems.

Group of Energy COnversion Systems

POLITECNICO MILANO 1863

Our main research topics are:

- Large scale energy conversion systems: Gas Turbines, Steam cycles and CC
- Carbon Capture and Sequestration with absorption and CaLooping techniques
- Cogeneration on large and microscale, hydrogen production and fuel cells
- Biomass and waste to energy technology
- Renewable energies: CSP, wind energy, geothermal and minihydro
- Organic Rankine Cycles
- Microgrids design optimization and optimal operation strategy

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How we work:

- We cooperate with many other universities, research centers and companies with a continuous flow of people and knowledge
- We are involved in tens of European projects an industrial collaborations

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Our skills:

- We develop in house tools for the simulation of complex energy systems
- We commonly use also commercial software like Aspen and Thermoflex for our calculations and for the design of specific components
- We develop optimization algorithm for the design of specific components (S&T HE, axial turbines) and energy system design and management.

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Why we are here:

- We are not material expert but we are currently involved in different projects dealing with coal based power plant:
  - Flexical: is a RFCS project that aims to design a flexible and low carbon emission power system based on USC power plants and CaLooping CCS
  - sCO2 flex: is a H2020 project that aims to design and test a CO2 supercritical cycle more flexible and efficient than state-of-the art USC

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OUR GOAL
Increase USC plant efficiency

How to increase the efficiency of Steam plants?

Looking at the titles of the presentations of this conference…

DP700-Phase 1 Preparation for Commercial Demonstration of 700oC Power Plant — *25 Mins*
by: Peter Barnard (Doosan Babcock Ltd)

United States Advanced Ultra-Supercritical Component Test Facility for 760°C Steam Power Plants — *25 Mins*
by: Horst Hack (Electric Power Research Institute)

DP700-Phase 1 Design by Analysis as Applied to 700C Power Plant — *20 Mins*
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It looks clear that the paradigm nowadays is:

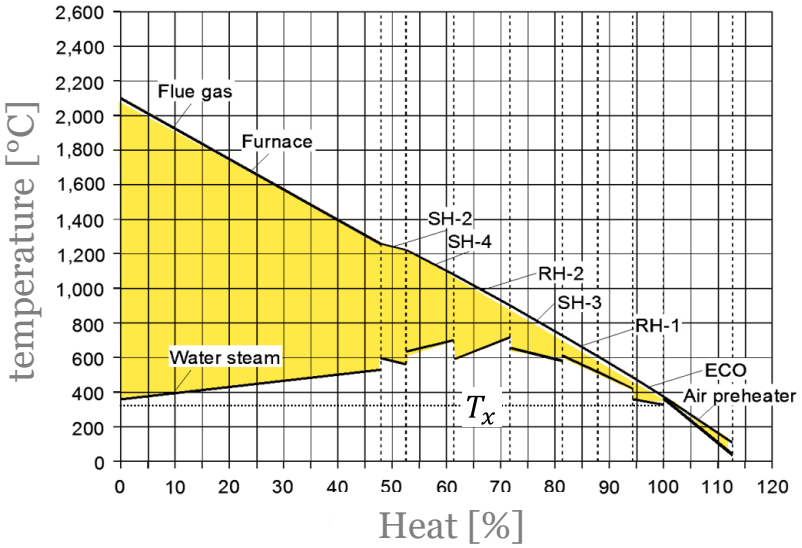
increase
steam power plant efficiency
by increasing both maximum cycle pressure and temperature

Why? The thermodynamic reason

Considering the second law analysis of a common USC plant the main source of efficiency losses are related to:

- Combustion: 23%
- Heat introduction: 18%
- Expansion: 4%
- Heat release: 2%
- Stack losses: 1%

Heat introduction is an irreversible process and the associated power loss is strongly related to the average temperature of the working fluid in the boiler.



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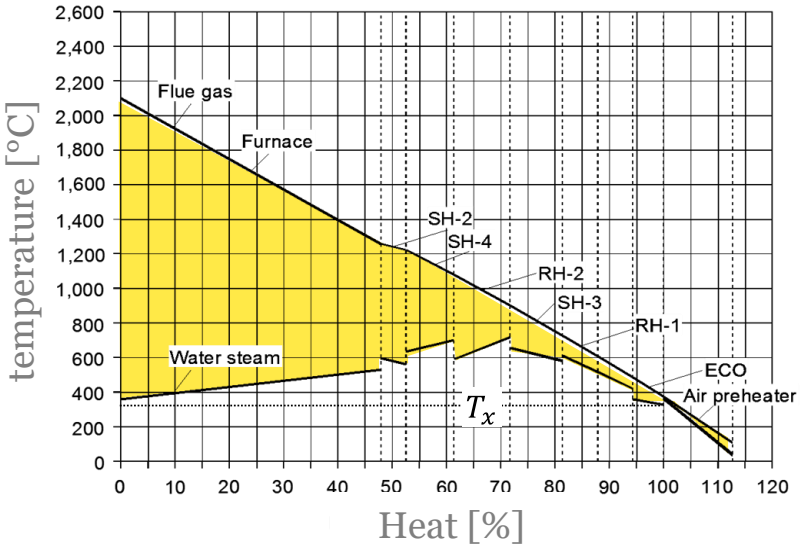

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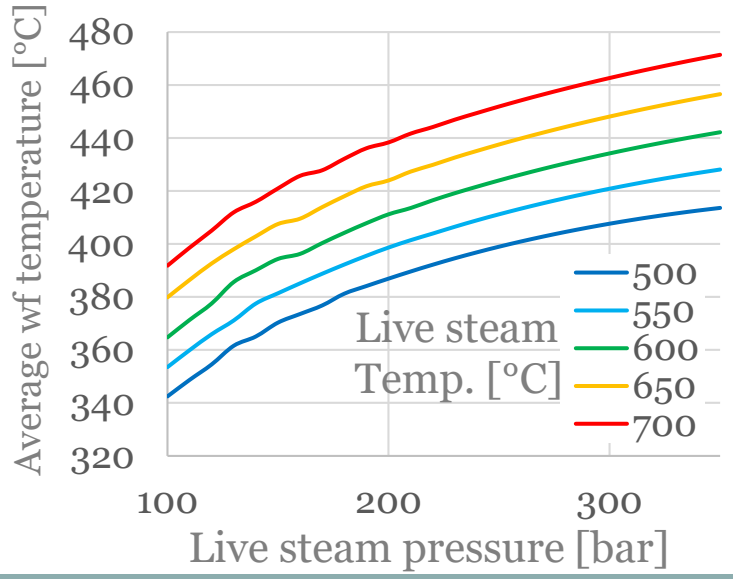
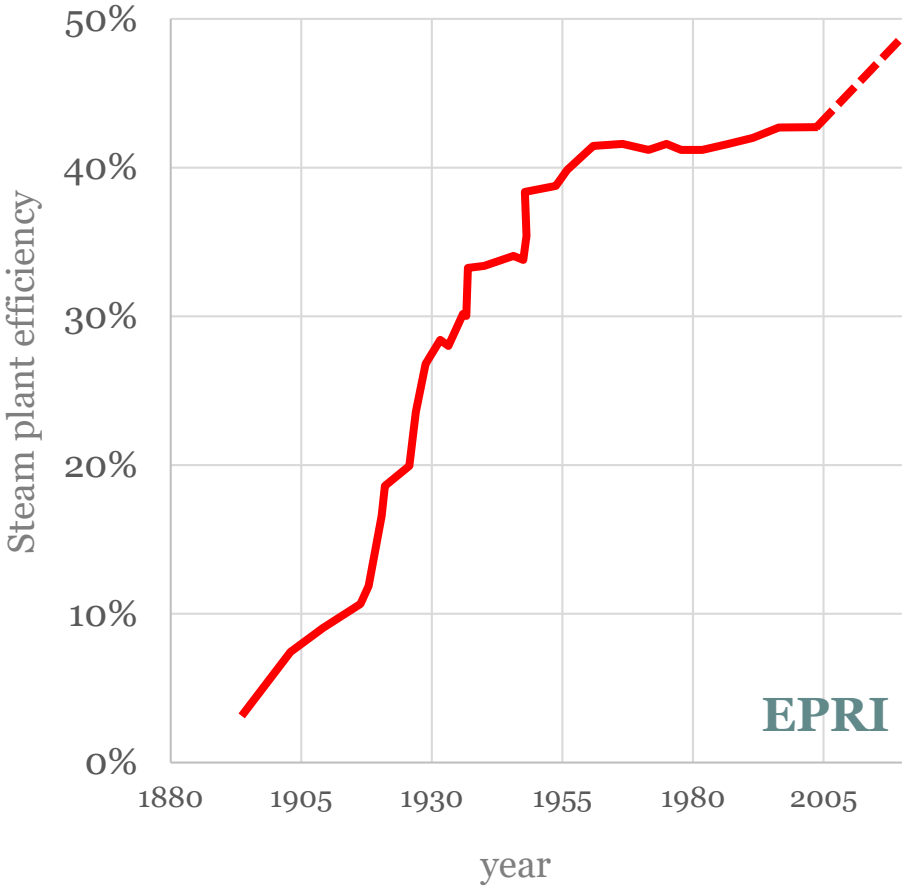
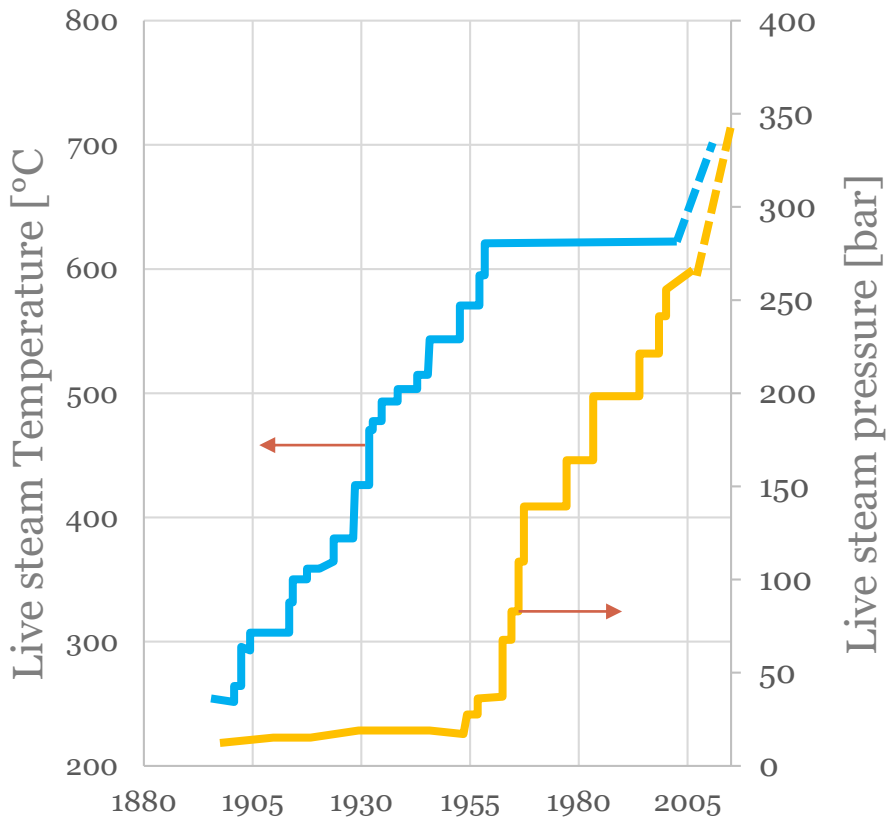
Increasing both live steam pressure and temperature the average fluid temperature is increased with a reduction of the power loss and a jump in efficiency



The result: the historical trend

This is clearly shown by historical data on cycle maximum efficiency, cycle maximum temperature and cycle maximum pressure





Is this really the only option?

FLASH BACK
Old but gold

BACK TO THE 1929

BACK TO THE 1929

About the facts!

BROOKLYN DAILY EAGLE
And Complete Long Island News
LATE NEWS
★ NEW YORK CITY, THURSDAY, OCTOBER 24, 1929. ★
32 PAGES

WALL ST. IN PANIC AS STOCKS CRASH

Attempt Made to Kill Italy's Crown Prince

ASSASSIN CAUGHT IN BRUSSELS MOB; PRINCE UNHURT

Hollywood Fire Destroys Films Worth Millions

FEAR 52 PERISHED IN LAKE MICHIGAN FERRY IS MISSING

PIECE OF PLANE LIKE DITEMAN'S IS FOUND AT SEA

High Duty Group Gave $700,000 to Coolidge Drive

STOCKS CRASH IN RUSH TO SELL; BILLIONS LOST

CARNEGIE CHARGE OF PAID ATHLETES

HOOVER'S TRAIN HALTED BY AUTO

WARDER SOUGHT TO KEEP SEA TRIP

SOMERS NAMED AS HEAD OF NEW

EDIZIONE SUPPLEMENTO

Il Popolo d'Italia

L'INIZIO DI UNA NUOVA ERA PER L'ITALIA E LA CRISTIANITÀ

Una grande vittoria politica e spirituale del Regime

La "Questione Romana" risolta in modo definitivo con un accordo sanzionato a Roma tra Mussolini ed il Cardinale Gasparri

EMOZIONE IN TUTTO IL MONDO

La firma delle Convenzioni

Sovranità reale e visibile

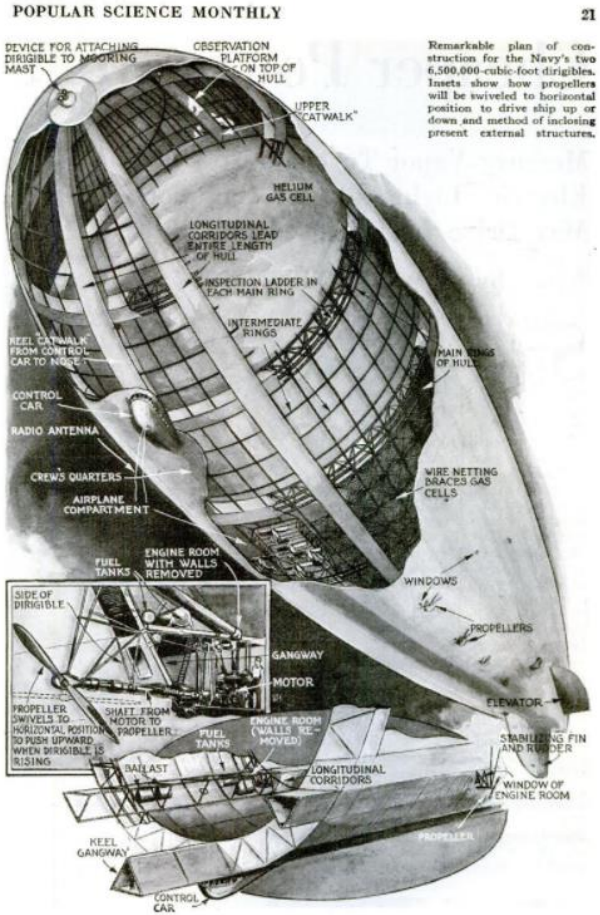
Wall street Stock Market crash
Great depression

Vatican gets independence from Italy

BACK TO THE 1929

About technology!

First car radio was invented by Motorola



Zeppeling was a promising means of transportation

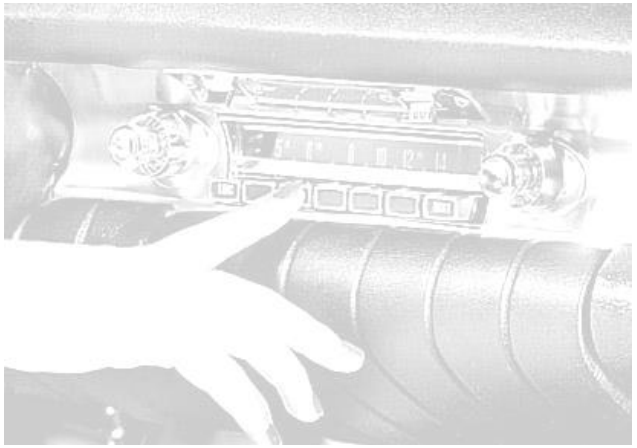
Now—Television in Natural Colors

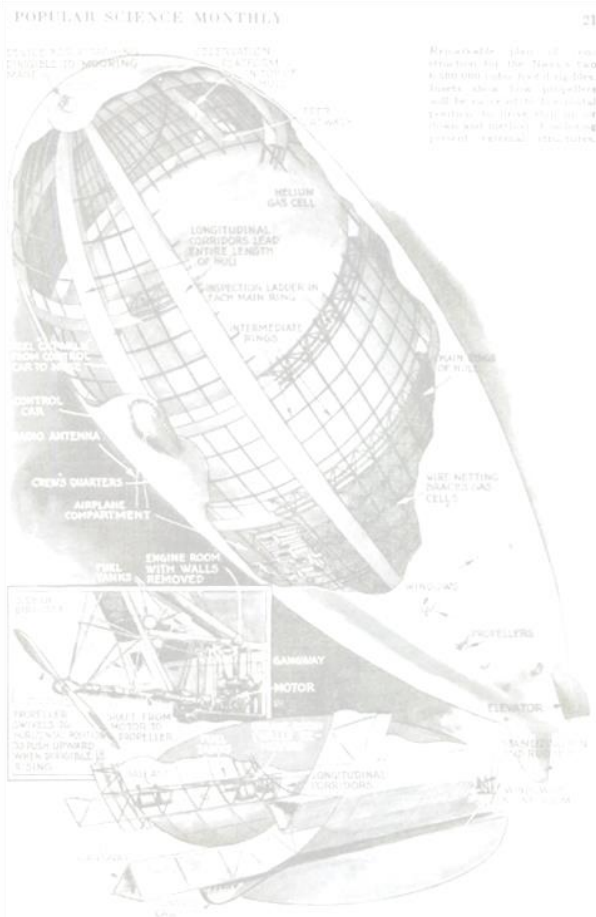
By ALDEN P. ARMAGNAC

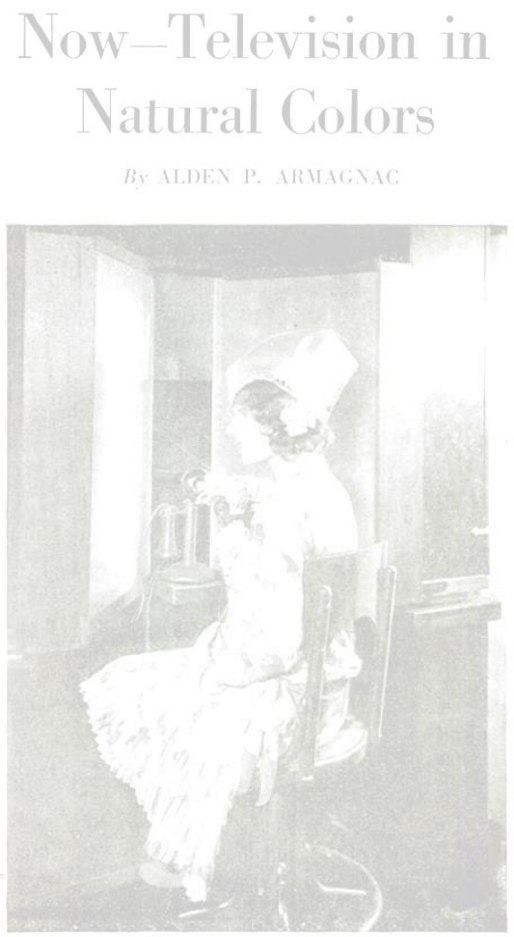
Television was finally in colors

BACK TO THE 1929

About technology!





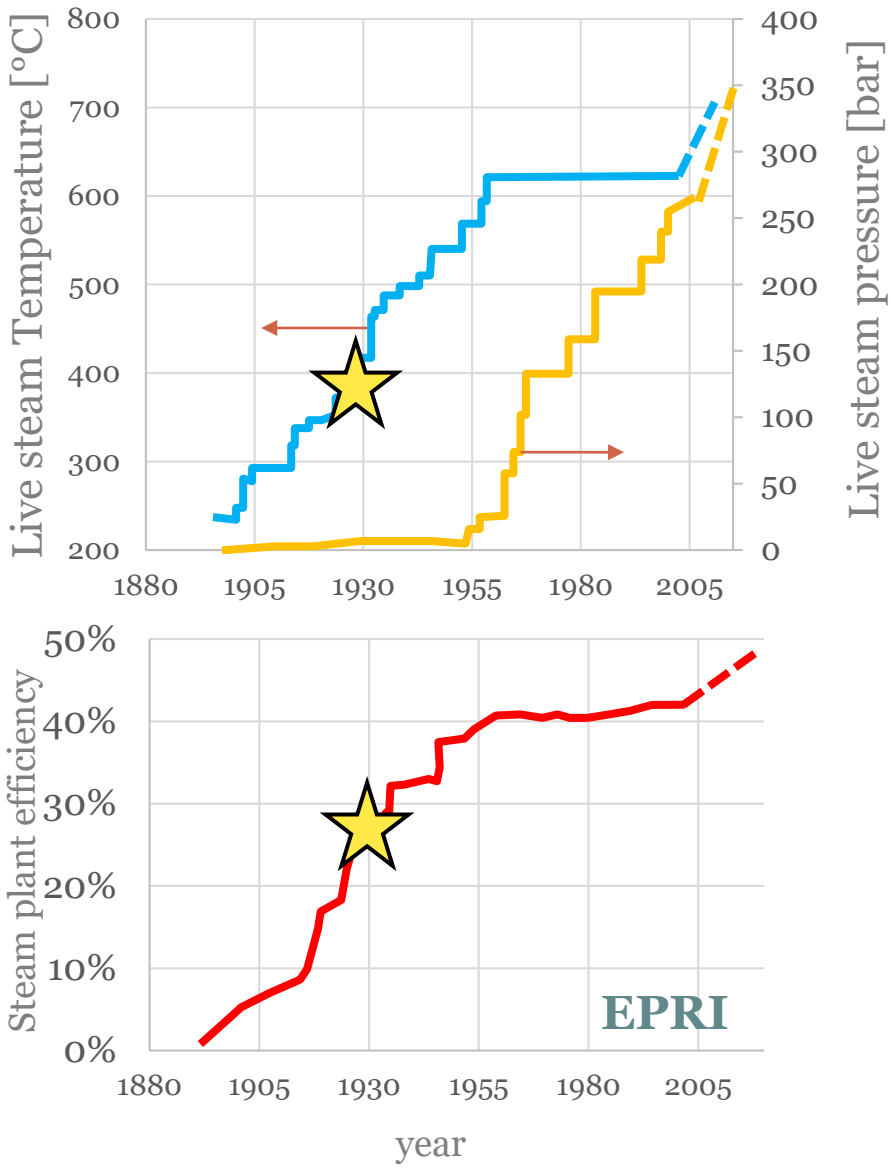


Everything looks very old fashioned and trivial…

The same for steam cycles

- Low temperature: 350-400°C
- Subcritical and superheated
- Low Efficiency: lower than 30%

With the best material available at that time there were no hopes to further increase the efficiency.



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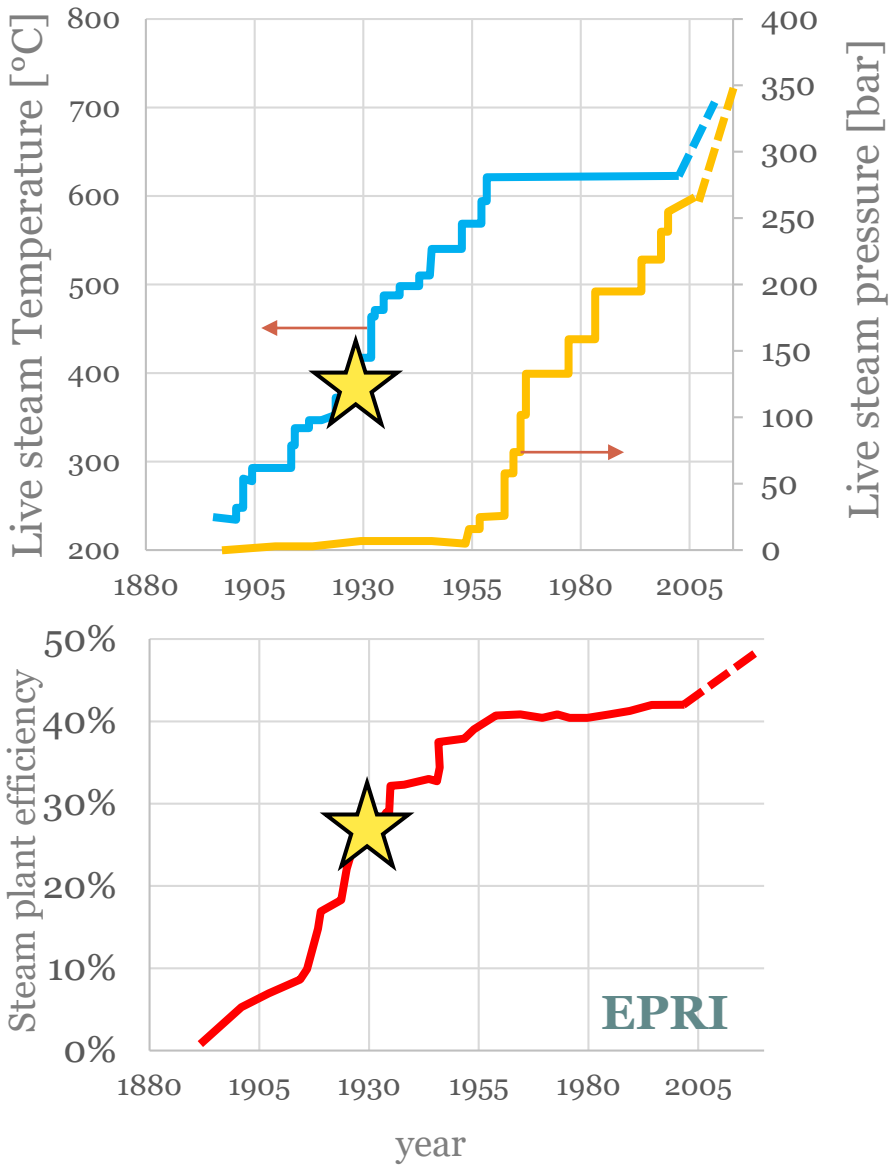
Which options they had in 1929 to increase plant efficiency?

1 The common strategy: Increase live steam thermodynamic condition

2 A new idea



The new idea

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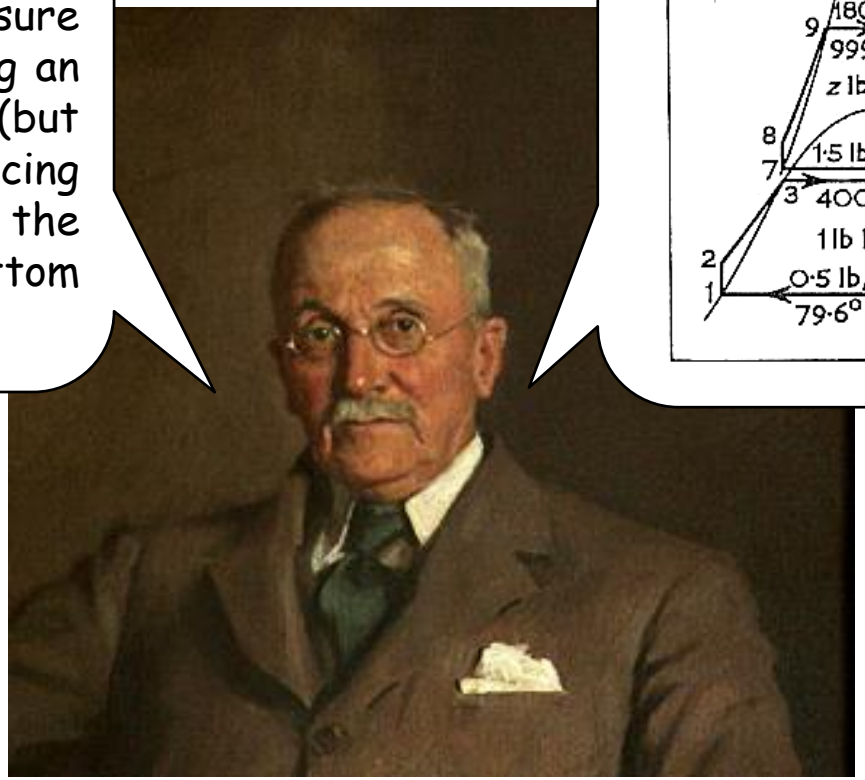
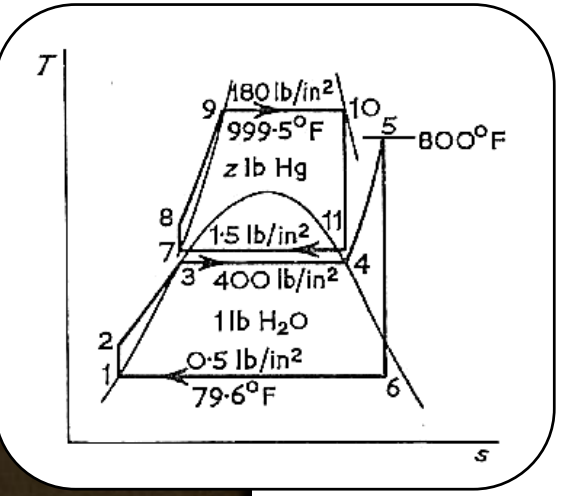
If we cannot further increase steam temperature and pressure we could add a top cycle using an opportune high temperature (but low pressure) fluid producing power and releasing the condensation heat to a bottom steam cycle



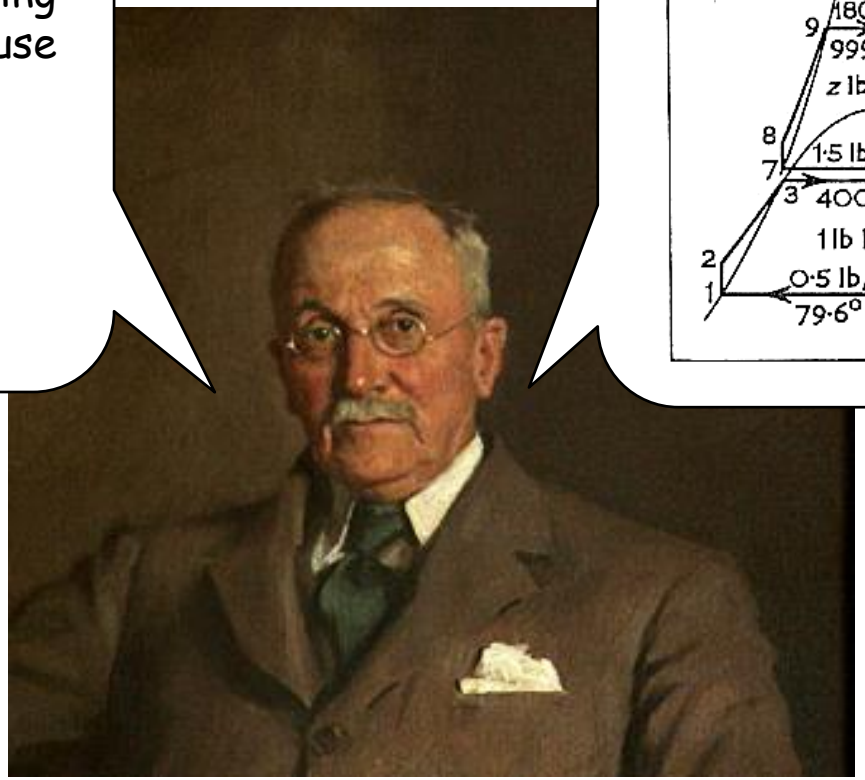


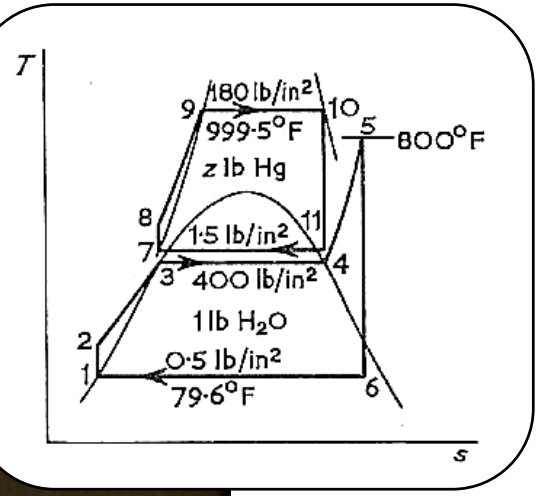
The new idea

In 1914 Mr. William LeRoy Emmet a GE research engineer proposed a paradigm shift introducing the idea of a binary cascade cycle.

I will use Mercury as working fluid for the top cycle because of its:

- high thermal stability
- High critical temperature
- Low critical pressure
- And high molecular mass





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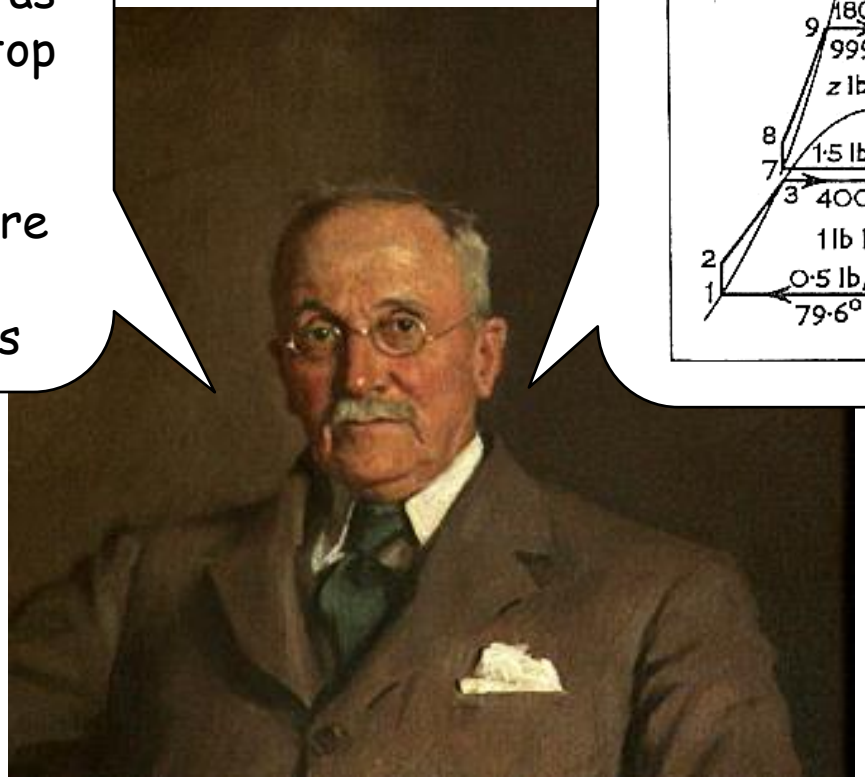
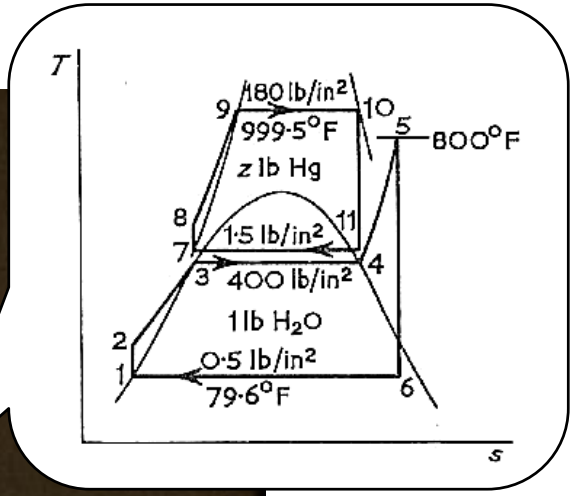




Curiously, the fact that mercury is poisoning was not really an issue at that time!

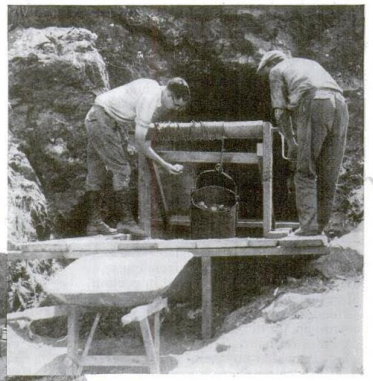
The idea may sound pretty crazy nowadays but…

1928-1929 The first commercial mercury cycle generating unit in the world is installed at Helco's South Meadow Station in Hartford.

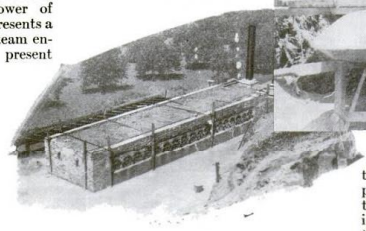
Cheaper Power from Quicksilver

Mercury-Vapor Turbines Now Run Electric Light Plants and Soon May Drive Locomotives and Ships

By GROVER C. MUELLER



A quicksilver mine in southern California. Right: The shaft of the mine. Below: The smelting plant where mercury is extracted from cinnabar, a bright red ore, by heating.



SOON locomotives and ships, as well as thermometers, may be run by quicksilver. Already engineers of an Eastern power plant have put the fluid metal in their boilers and made it generate about 13,000 horsepower of electricity. The mercury boiler presents a powerful potential rival to the steam engine and may revolutionize present methods of producing energy.

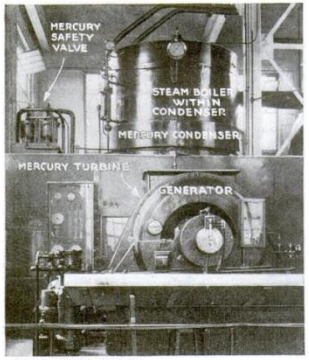
That is the situation described by Alfred D. Flinn, director of the Engineering Foundation, of New York City, in a recent report on actual commercial production of electricity with the "mercury turbine" by a Hartford, Conn., electric light company. Patterned essentially after the familiar steam turbine of commerce, it uses the vapor of mercury instead of steam to drive its whirling blades. Important savings in fuel and money are said to result.

The "steamless steam turbine" in the Hartford company's South Meadow power plant looks somewhat like an ordinary steam turbogenerator, but sounds very different. Inside the shell which incloses it, the turbine shaft makes twelve revolutions every second, yet there is scarcely a sound, and vibration is absent. A man standing near it can hardly tell when the turbine is running.

Through the whirling blades of the turbine courses the vapor of mercury, a poisonous cloud heated to 884 degrees F., from boilers fired with pulverized coal on the floor below. Behind the turbine and the electric generator to which it is coupled is a huge cylindrical tank, a condenser that recovers the valuable mercury after it has driven the turbine. Its work is not yet done. It gives up the rest of its heat by turning water into steam, and there is enough power left to run a conventional steam turbine.

There is the secret of the mercury turbine's efficiency. Mercury vapor is so much hotter than steam that its energy can be used over and over again before it cools enough to be useless. In the South Meadow plant, engineers estimate that that means a fuel saving of $200,000 a year.

Credit for the invention of the mercury engine belongs to William LeRoy Emmet, General Electric Company research engineer, who first proposed in 1914 that mercury could be used to drive a turbine wheel and later constructed an experimental machine at the company's Schenectady plant. In 1923 the first mercury-vapor power plant in the world was installed in the Dutch Point plant of the Hartford Electric Light Company. It was an experimental outfit of less than 5,000 horsepower, developing nearly half of its power from a single-wheel mercury turbine and the rest from the by-product steam used in a steam turbine.



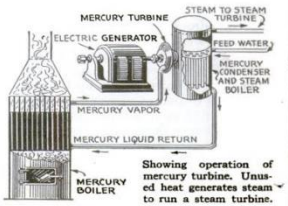
Courtesy Electrical World.

The first installation of a commercial mercury-vapor turbine in power plant of Hartford Electric Light Co.

Years of trial followed, while engineers tested the economy of the novel power plant. Meanwhile, at the General Electric Company, Emmet experimented with improved designs of his turbine. Few took his invention seriously at that time. They said that, even should his machine prove a success, there was not enough mercury in the world to run his turbines. As an answer came the order of the Hartford company for a huge new mercury turbine of 13,000 horsepower for full commercial service, at its South Meadow station. It was completed in November of last year, and gave uninterrupted service until it was recently dismantled for further engineering improvements.

NEARLY seventy tons of mercury are required to run this plant—more than a thousand gallons. With mercury at the current price of about $200 a gallon, a fortune in liquid metal lies within the boiler's tubes. Should a tube leak, $200,000 worth of mercury might trickle away. For that reason, packed joints are out of the question. Arc-welded pipes guard the precious liquid, to avoid its loss and to keep the poisonous fumes from escaping.

So far the mercury turbine has been tried out only in electric power stations. The inventor sees no reason why it should not be applied to locomotives, and to ships, as well.



Showing operation of mercury turbine. Unused heat generates steam to run a steam turbine.

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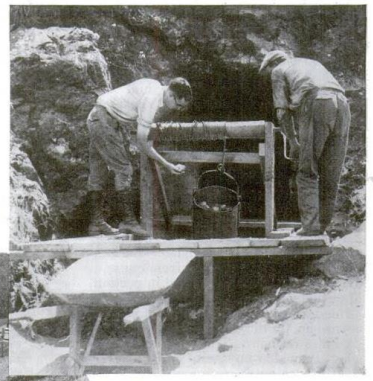

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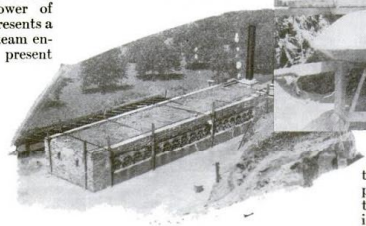

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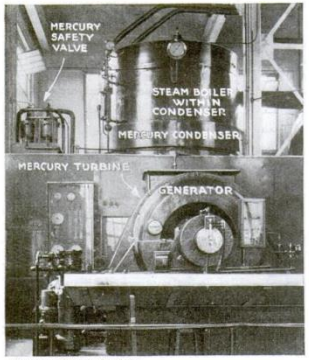

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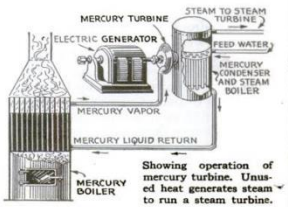

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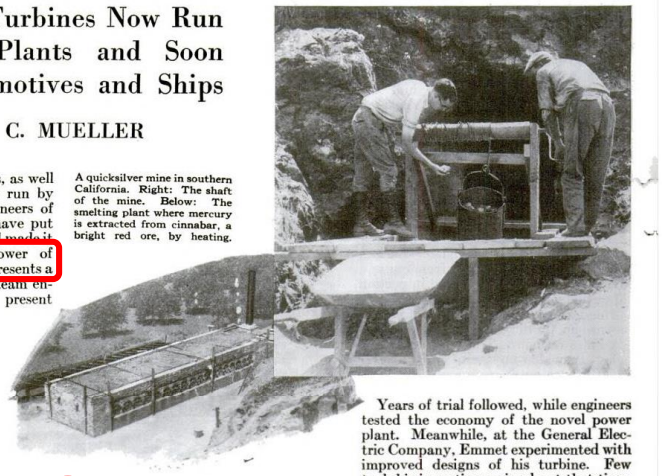

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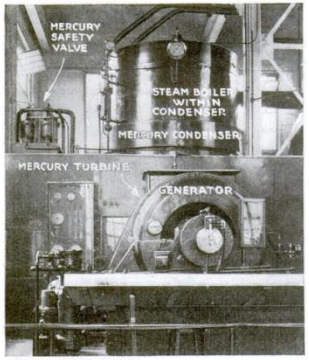

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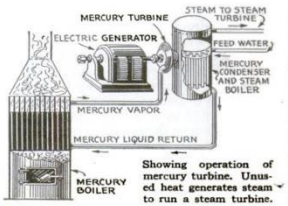

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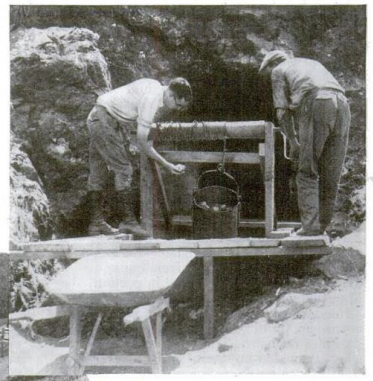

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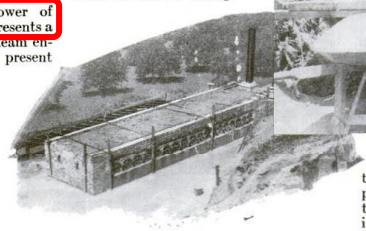

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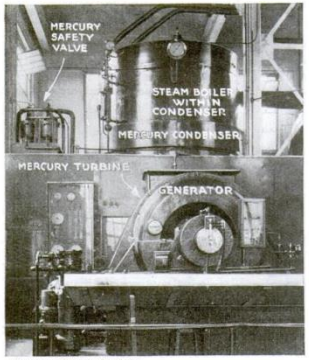

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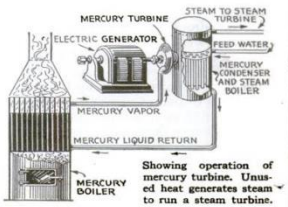

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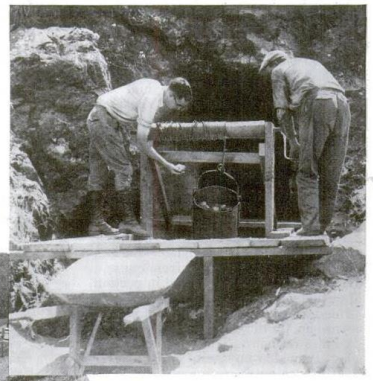

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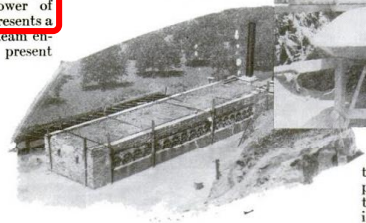

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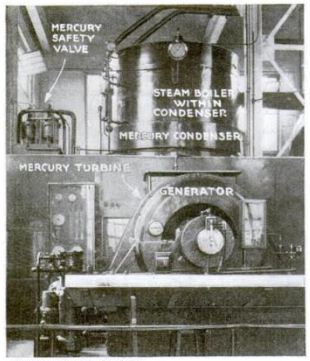

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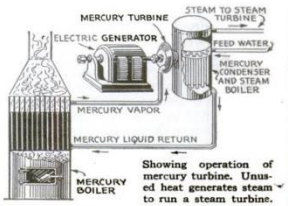

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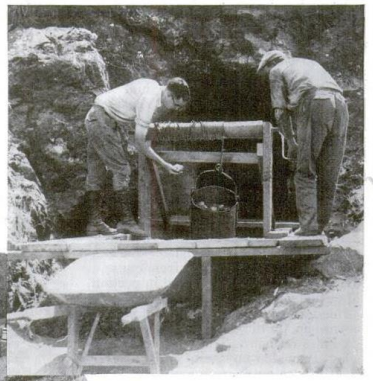

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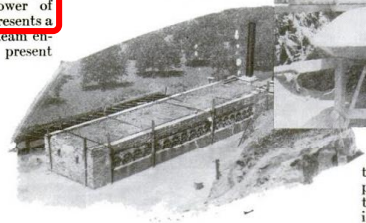

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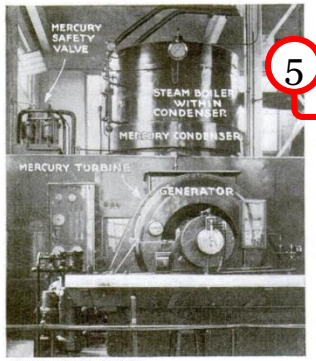

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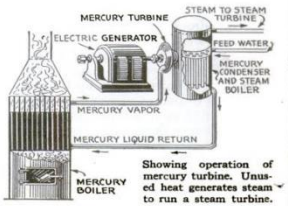

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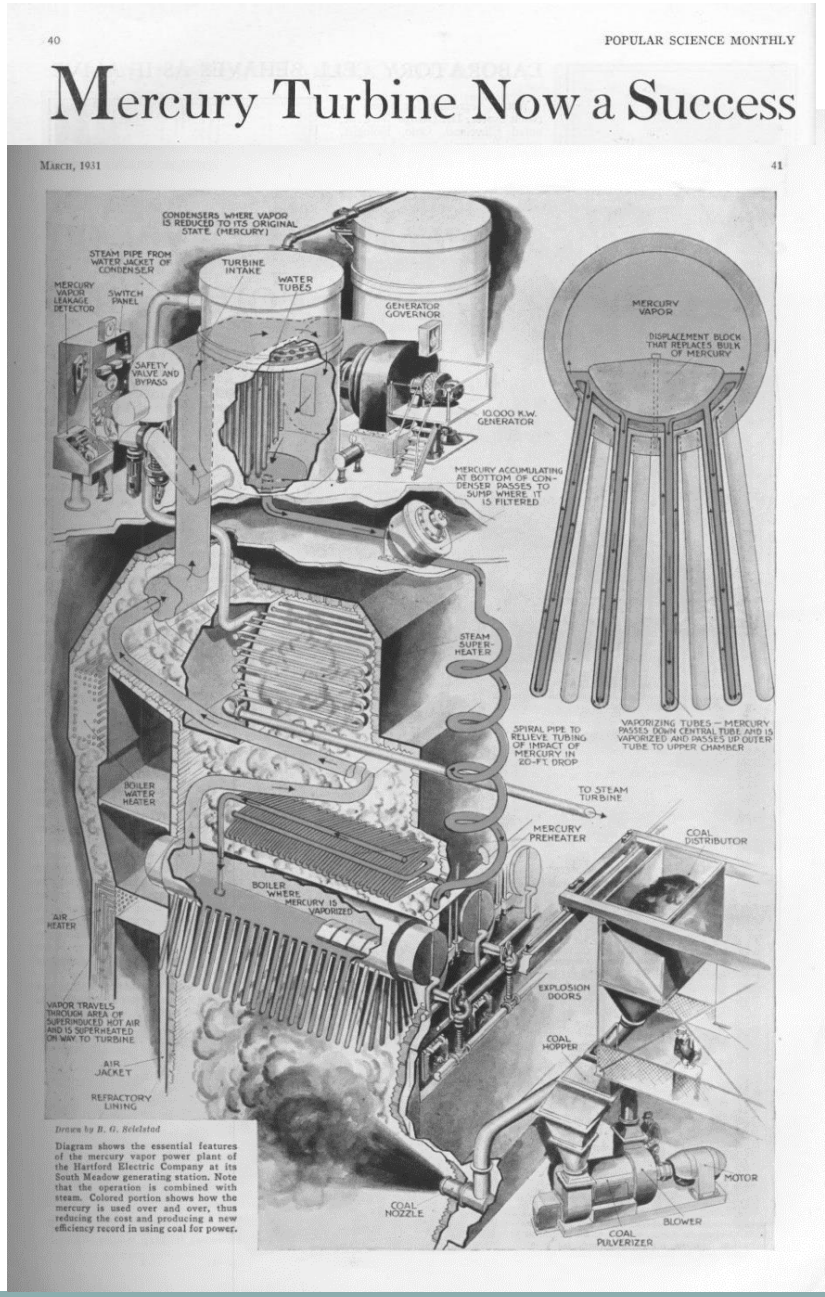

40 POPULAR SCIENCE MONTHLY

Mercury Turbine Now a Success

MARCH, 1931 41

Drawn by B. G. Belelstad

Diagram shows the essential features of the mercury vapor power plant of the Hartford Electric Company at its South Meadow generating station. Note that the operation is combined with steam. Colored portion shows how the mercury is used over and over, thus reducing the cost and producing a new efficiency record in using coal for power.

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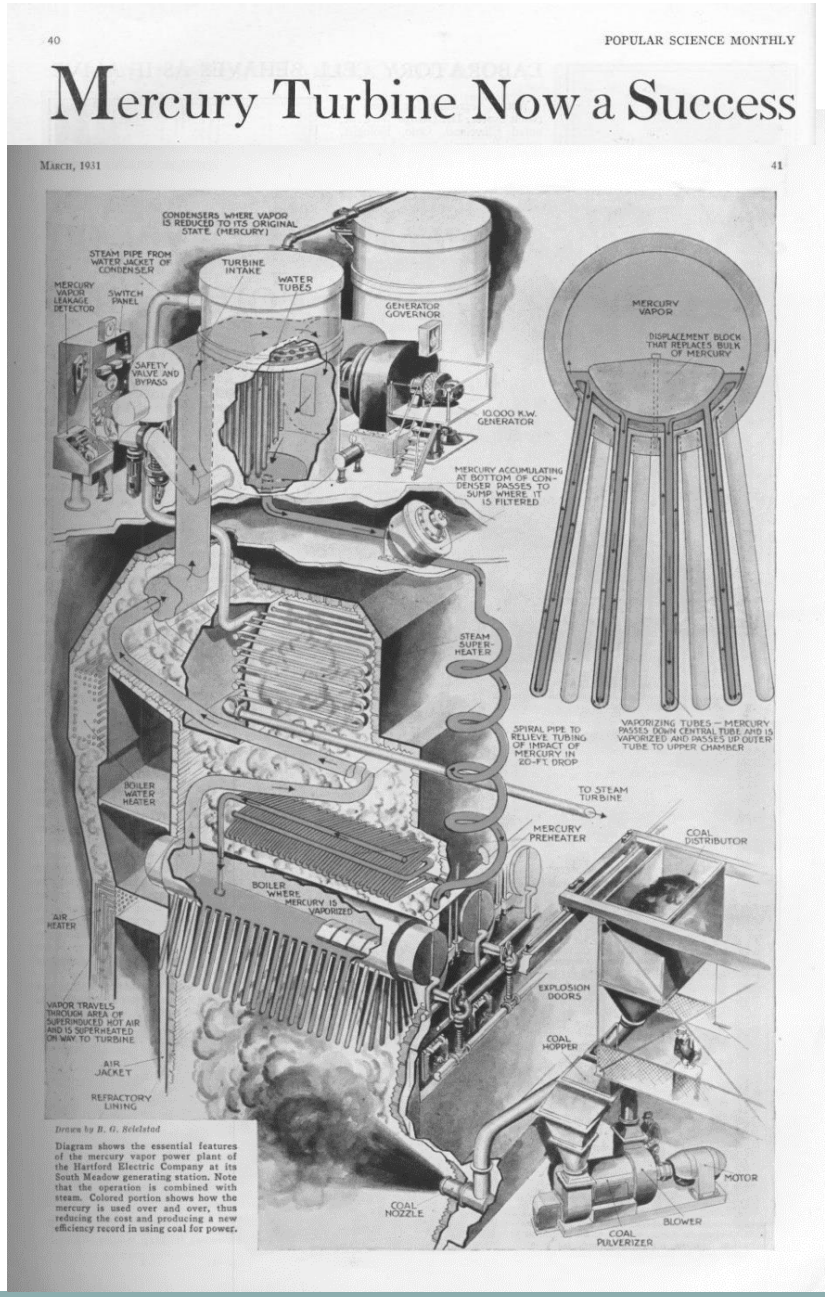
Following steps

- 1931 A General Electric mercury plant is installed at Schenectady, New York State. The mercury turbine output was 20 MW
- 1933 A mercury topping cycle added to existing steam plant at South Kearney, NJ. The mercury turbine output was 20 MW
- 1950 The 40 MW Schiller station goes on load at the Schiller mercury/steam plant at Portsmouth, NH.



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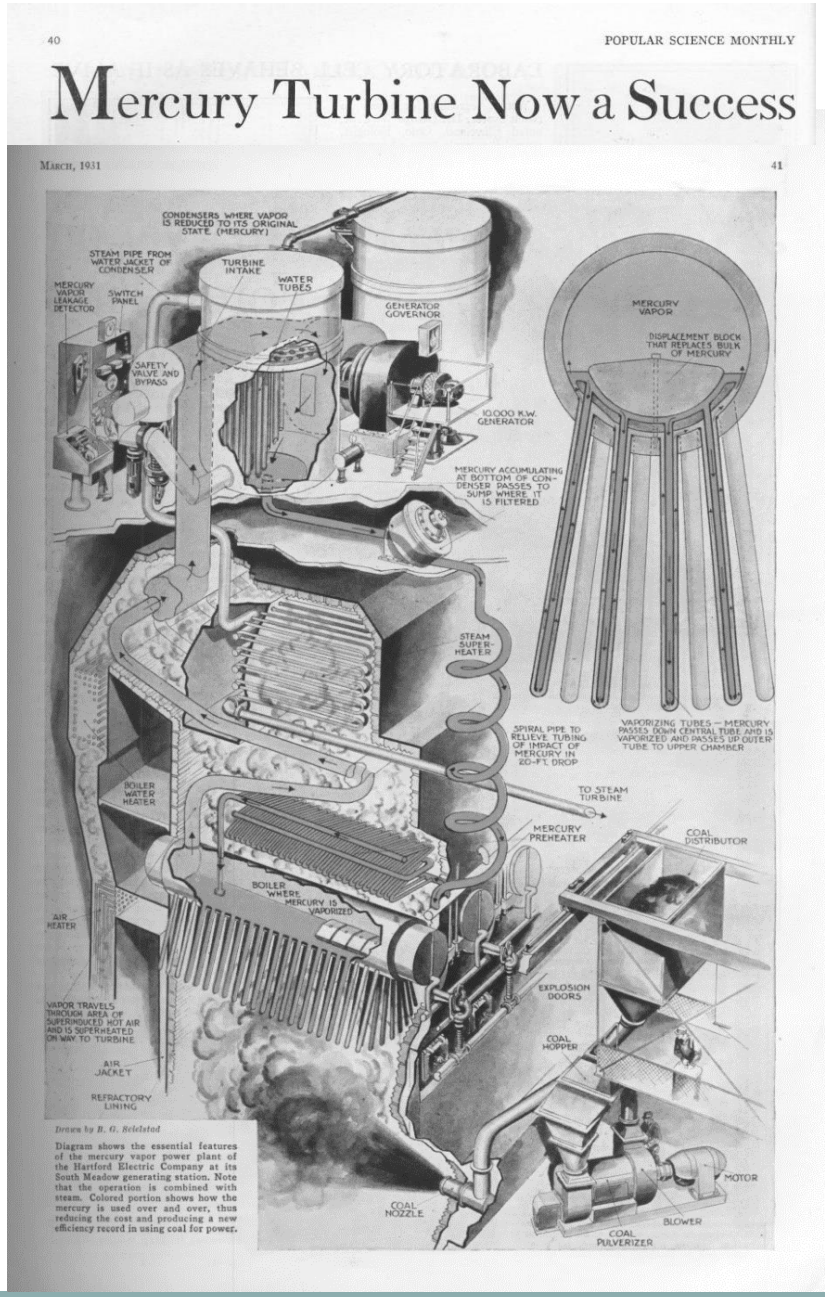
A little success

In spite of the first positive results the concept did not spread around because in the meanwhile the maximum steam temperature rapidly reached 600°C leading to comparable steam plant efficiencies without high environmental risk and low system complexity



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BACK TO THE FUTURE
Our analysis

Is the idea still relevant today?

In our opinion YES!

Is the idea still relevant today?

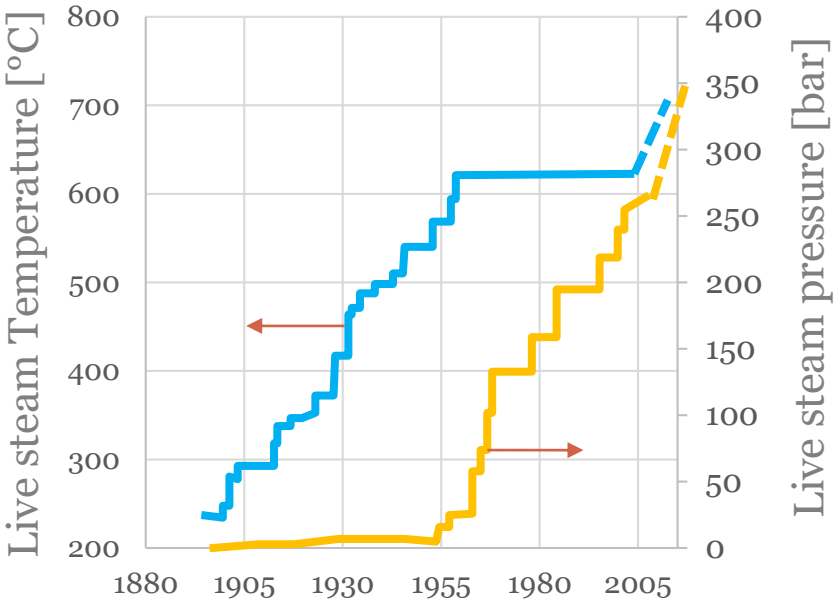
In our opinion ~~YES~~! MAYBE

Consider that:

- The increase of maximum temperature for USC plants is still challenging
- The cost of development and installation of new material is very relevant
- The increase of pressure inside of the boiler lead to safety concerning

As result for many years the maximum temperature remained stable around 600-650°C

A temperature still very far from the temperature of the flue gas



Our study: reference case

We used our in-house code (GS) to simulate the steam plant
This code has been validated on hundreds of benchmark and contains reliable steam turbine efficiency calculation

reference case: **common USC plant**

Boiling feedwater pressure [bar]	320
Boiling feedwater temperature [°C]	307.5
Pressure drop in SH tubes [% inlet pressure]	15.0
Pressure drop in RH tubes [% inlet pressure]	6.25
Pressure drop at SH/RH turbine inlet valve [% inlet pressure]	2
Live steam temperature at SH/RH outlet [°C]	600/620
Live steam pressure at SH/RH outlet [°C]	270/60
SH/RH thermal piping losses [°C]	2
Condensing pressure [bar]	0.048
Number of LP/HP feedwater heaters (incl. deaerator)	4/5
Pressure of steam bled for feedwater heaters [bar]	93.8/64.0/39.2/23.7/14.6/ 6.7/3.5/1.3/0.32
Pressure drop in deaerator/feedwater heaters [bar]	2.0/1.0
Feedwater pump hydraulic efficiency [%]	85.0
Feedwater pump mechanical-electric efficiency [%]	94.0

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benchmark case: **Advanced USC plant**

Boiling feedwater pressure [bar]	**420**
Boiling feedwater temperature [°C]	**340**
Pressure drop in SH tubes [% inlet pressure]	15.0
Pressure drop in RH tubes [% inlet pressure]	6.25
Pressure drop at SH/RH turbine inlet valve [% inlet pressure]	2
Live steam temperature at SH/RH outlet [°C]	**700/720**
Live steam pressure at SH/RH outlet [°C]	**350/70(opt)**
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Number of LP/HP feedwater heaters (incl. deaerator)	4/**6**
Pressure of steam bled for feedwater heaters [bar]	139.5/105.2/74.3/39.5/ 23.7/14.6/6.7/2.6/1.0/0.3
Pressure drop in deaerator/feedwater heaters [bar]	2.0/1.0
Feedwater pump hydraulic efficiency [%]	85.0
Feedwater pump mechanical-electric efficiency [%]	94.0

Our study: the liquid-vapor metal cycle

We added a liquid-vapor metal cycle as topping cycle to the reference case USC.
We selected the working fluids among some candidates:
alkali metals (1st row periodic table)

NASA

	Litium	sodium	potassium	Rubidium	Cesium
MM [kg/kmol]	6,941	22,990	39,0	85,5	132,9
Melting Point [°C]	180,54	97,72	63,40	39,30	28,40
Boiling Point [°C]	1347	883	766	690	670
Tcrit [°C]	2950	2300	1950	1820	1665
Pcrit [Mpa]	67	35	16	16	9

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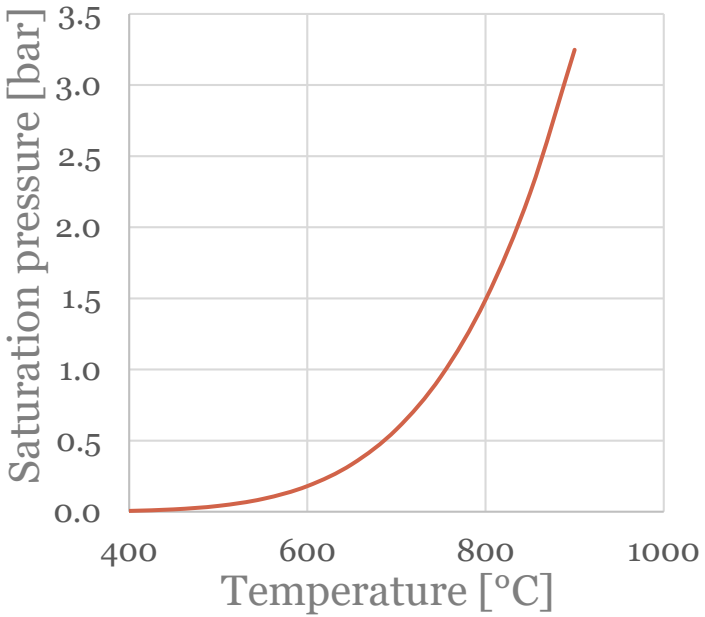
We selected potassium as working fluid because its relatively high MM and a lower critical temperature

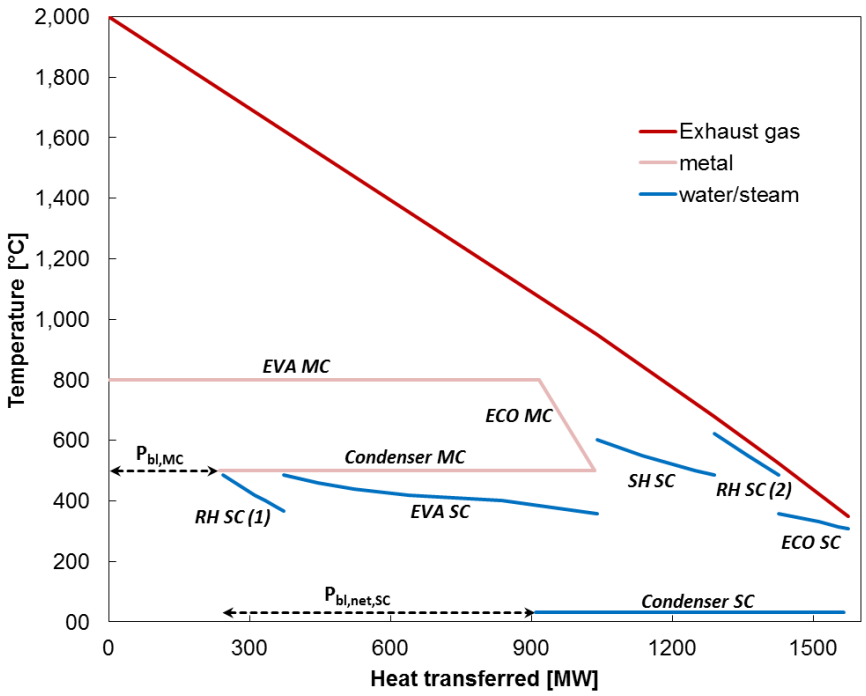
- The cycle is arranged as a subcritical saturated cycle without regenerative preheating
- Two phase turbine efficiency equal to 85%
- Saturation pressure at 900°C is around 3 bar.
- High temperature materials work at low pressure



Our study: system integration

We considered two options:

Single condensation top cycle



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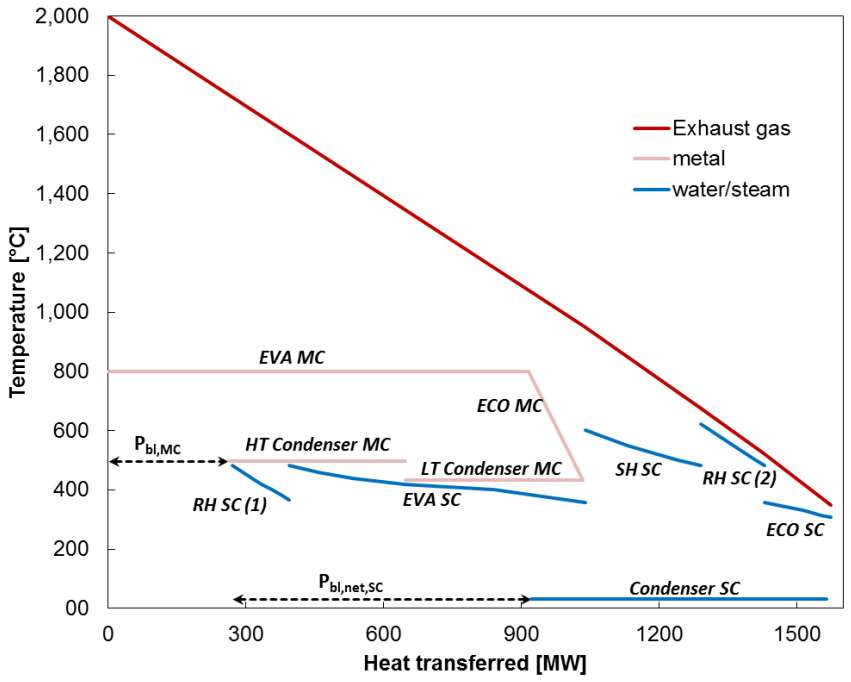

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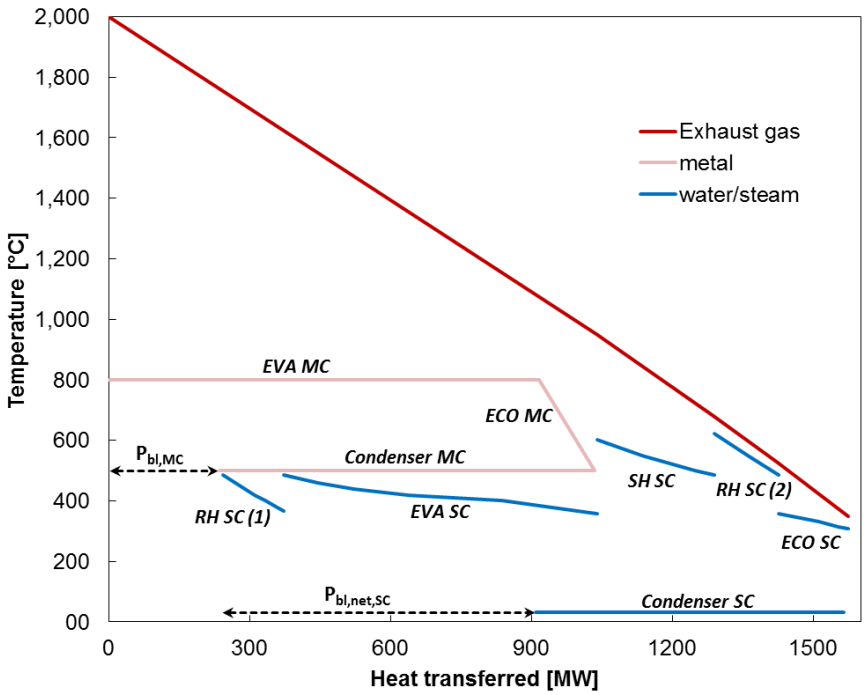

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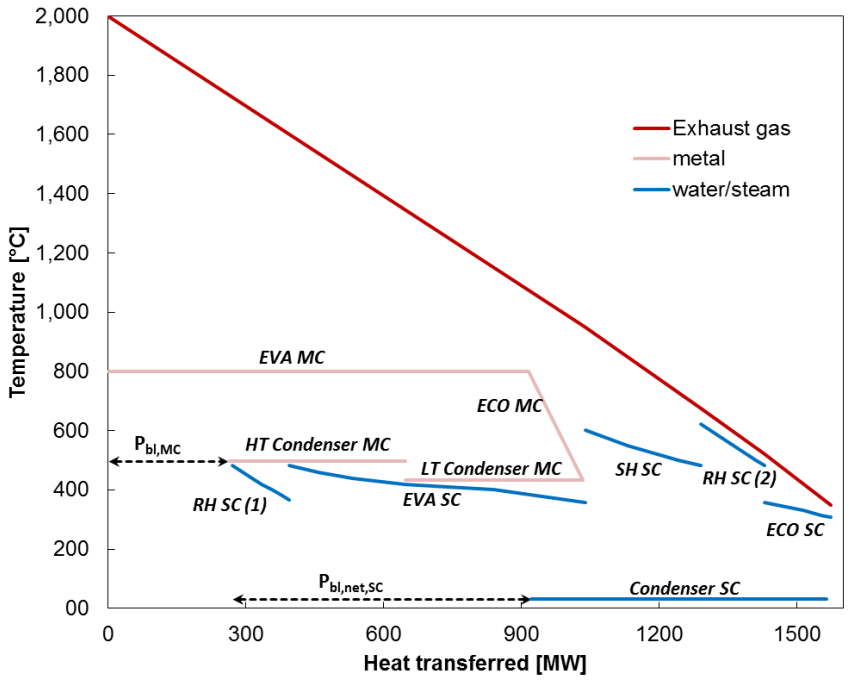

Our study: system optimization

We carried out a sensitivity analysis varying both evaporation and condensation temperature(s) of the top cycle.
Maximum temperature is set at 900°C

Our study: focus on metal turbine

Potassium turbine design is favored by:

1. Large molecular mass leading to low stage loading coefficient
2. Speed of sounds relatively high (around 500 m/s) with the possibility to design reaction stages with subsonic velocity triangles
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On the other side the turbine design is critical because of:

1. Two-phase expansion with blade erosion due to presence of liquid droplets
2. Massively large volume flow rates

1. first issue is commonly faced and solved for both nuclear steam turbines and geothermal turbines with a **continuous moisture removal solution**
2. Second issue is more critical and leads to the necessity of **several large turbines in parallel rotating at low speed** with a soar of the investment cost

Our study: the results

			Binary cycle power plant		
	USC	AUSC	T_{eva}=800°C 1 CL	T_{eva}=800°C 2 CL	T_{eva}=900°C 2 CL
Fuel thermal input [MW_{LHV}]	1657.1				
Steam turbine electric power [MW]	795.5	852.0	673.7	659.0	635.1
Feedwater pump cons. [MW]	25.94	32.74	22.02	21.55	20.78
Condenser pump cons. [MW]	0.63	0.57	0.54	0.53	0.51
Condenser auxiliaries cons. [MW]	6.18	5.78	5.25	5.14	4.95
Metal turbine electric power [MW]	--	--	221.4	248.7	293.4
Coal-based power plant aux. [MW]	21.72				
Net electric power [MW]	741.1	791.2	845.6	858.8	880.6
Net electric efficiency [%]	44.72	47.75	51.03	51.83	53.14

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Conclusions:

- More than 50% of electric efficiency is potentially attainable with the binary steam-potassium cycle proposed, which is well above the performance of future AUSC coal-fired power plants.
- System complexity increases (especially for the potassium turbine) and the reactivity of potassium with water is definitely a safety concern

Is this concept attractive also from a technoeconomic point of view?

Next steps will be focused on:

- Design of the different components of the metal cycle
- Cost evaluation
- Techno economical optimal

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Food for thought and open discussion

- What do you think about this concept? Is it just an academic exercise or do you see any industrial potential?
- Are you aware of studies about compatibility of liquid potassium and metals
- Can you suggest materials for this kind of plant?

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THANKS!