MINING & METALS
NUCLEAR, SECURITY & ENVIRONMENTAL
ENERGY
INFRASTRUCTURE & POWER

S. C. (John) Gülen, Bechtel Fellow

Bechtel Infrastructure & Power, Inc.

Gas Turbines

Past, Present & Future (Efficiency Focus)

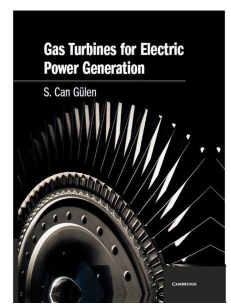
November 10, 2021

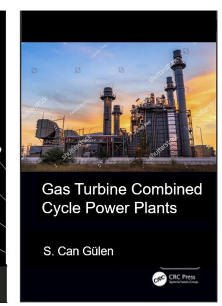
Day 3 in 2021 UTSR Project Review Meeting - Virtual

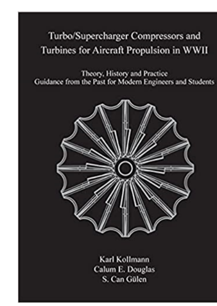
Speaker Background

25 years in gas turbine technology…

- PhD in Mechanical Engineering, Rennselaer Polytechnic University
- ESPC, Inc. (CHAT cycle, 110 MW CAES Plant in McIntosh, Alabama)
- Thermoflow, Inc. (GT PRO/MASTER, THERMOFLEX, PEACE Software)
- General Electric (H-System, 109FB-SS GTCC, Duke Edwardsport 207FB IGCC, Advanced HA Class GTCC)
- Bechtel Fellow
- 50+ Papers & Articles
- Two Book Chapters
- 14 Granted US patents
- Three Books
- ASME Fellow







Bechtel Today – Energy Transition

What we (I) do these days…

Renewable Power Generation

- Solar
  - Thermal
  - Photovoltaic
- Wind
  - Onshore
  - Offshore

Carbon Capture

- Emit
  - Power and Industrial new and upgrades
- Capture
  - Technology assessments
  - Capture and Hubs facilities
- Transport
  - Onshore pipeline and shipping terminals
- Storage

Advanced Fuels

- Renewable
  - Conversions
- Bioenergy
  - Biomass from agriculture
- BioDiesel
  - Animal Fats
  - Vegetable Oil
- Gas to Gasoline

LNG

- LNG Refrigeration
- LNG regasification terminals
- Tanks

Chemicals

- Crude to Chemicals
- Retrofitting plants with steam drives to electric drives to produce renewable power
- Plastic Circularity
- Alternative process routes

Hydrogen

- Technology assessments
  - AMR, ATR, Pox
  - Blue
  - Green
- Logistics
  - Compression
  - Storage
  - Pipeline
  - Distribution
- End Users
  - Fill station networks
  - Ammonia
  - Methanol

Transformational Energy Projects

Some examples…

Keeyask Generating Station, Canada

Role: Project Management, Construction

The Bechtel-led BBE Hydro Constructors Limited Partnership is delivering this new 60 MW powerhouse. As the centerpiece of the Keeyask Generation and Infrastructure Project, its seven turbine units will provide enough renewable energy to power 400K homes. The project involves massive cast-in-place concrete structures – chiefly a spillway and the powerhouse structure – totaling more than 330K m^3

Black Rock Wind Farm, USA

Role: Engineering, Procurement, and Construction

The project will include twenty-three Siemens-Gamesa SG 5.0-145 wind turbines on 107.5-meter tall towers, producing 115 MW of electricity at the point interconnection to the First Energy electrical grid.

Niger Delta Off-Grid Solar

Role: Collaboration with Chevron

Scale-up of an off-grid solar initiative in two remote communities in the Niger Delta. INVEST Project at USAID, Chicago-based Sun Africa, and Tesla are engaged. This program is based on Chevron's "energy in a box" solution.

Ivanpah Solar Electric Generating System, USA

Role: Project Management, EPC, Startup Services

The 377 MW Ivanpah Solar Electric Generating System is the world's largest solar thermal facility. It will produce enough clean, renewable electricity to power 140K homes. Bechtel built and procured the solar field, which includes 173.5K heliostats that follow the sun's trajectory, solar-field- integration software, and solar-receiver steam generators. Ivanpah has nearly doubled the amount of commercial solar thermal energy generated in the USA.

Carbon Capture

Role: Policy Study Contributor

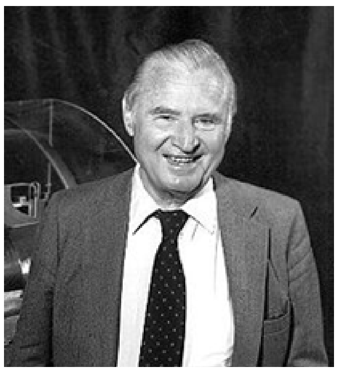
National Petroleum Council Study- assist the Steering Committee in conducting the study and coordinating the work of multiple study teams and subgroups focused on specific subject area

Role: FEED study for Gassnova, Karsto, Norway

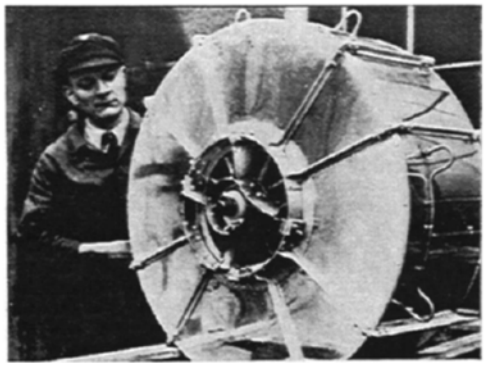
The Kårstø facility was designed to capture 85 percent of the CO_2 emissions from a 420 MW gas-fired power plant in southwest Norway. Kårstø was to be the larges tCO_2 separation facility ever constructed for treatment of gas turbine exhaust gas.

It Began with Hydrogen…

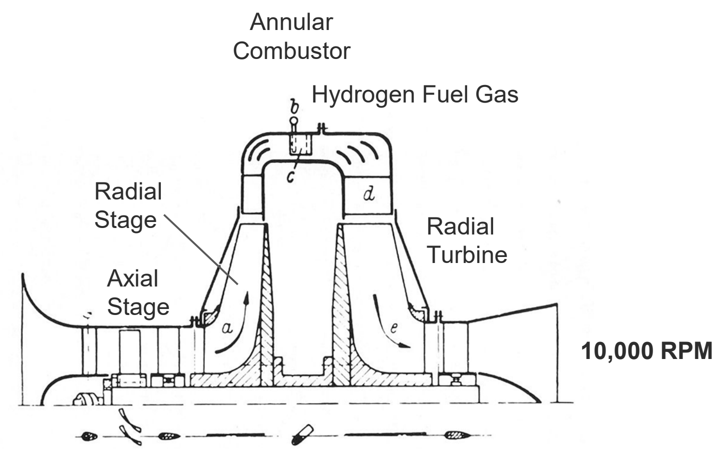
Heinkel HeS (Heinkel Strahltriebwerk) 1



Hans Joachim Pabst von Ohain (1911-1998)



Max Hahn (von Ohain's Chief Mechanic)



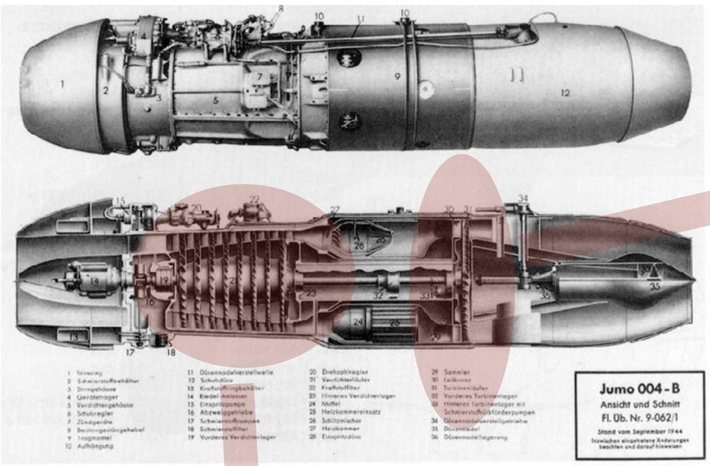
RADIAL TURBOJET (He S-1)
WITH HYDROGEN
(Built in 1936; tested in April 1937)
Radius of rotor - 1'
Thrust - 250#

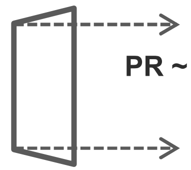
Hydrogen was chosen because of its high flame velocity and wide combustion range. It performed quite well at off-design as well as transient operation (startup and shutdown).

In Less Than Ten Years

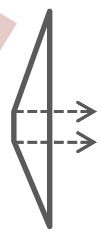
Jumo 004 turbojet engine in Messerschmitt Me 262 (1944-1945)

Same machine 75 years ago…

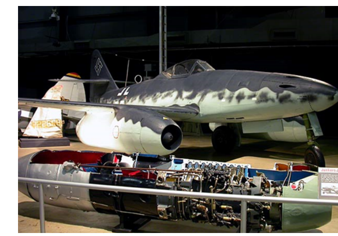




PR ~ 3:1 with single stage – not bad



PR ~ 15:1 with single stage – very bad!

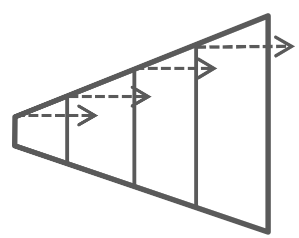


Messerschmitt Me 262
Two Jumo 004 engines

PR ~ 3:1 with 8 stages – bad..

PR > 20:1 with 14 stages – much better..

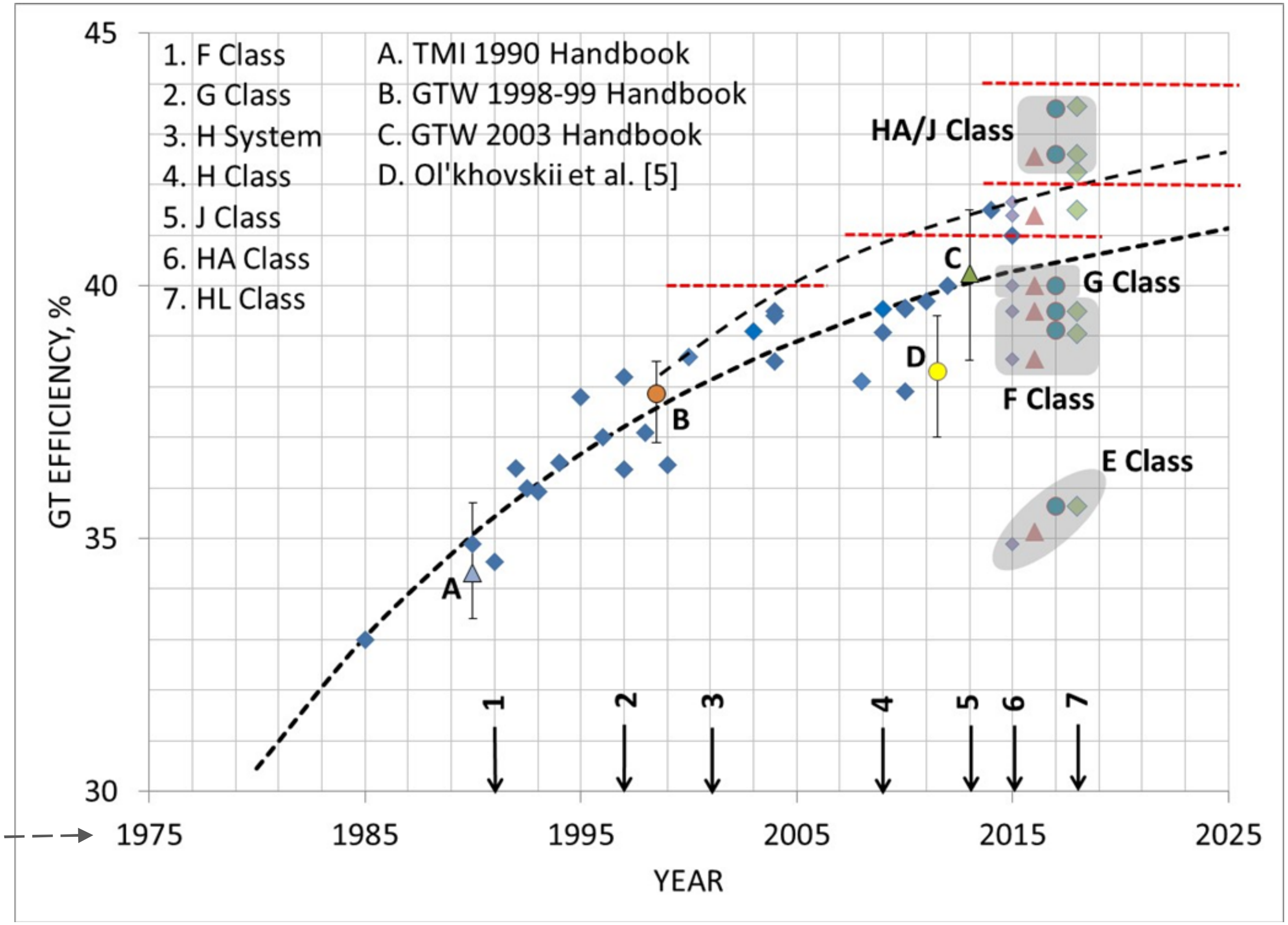
General Electric HA Class

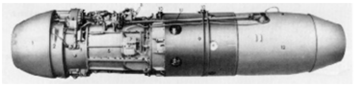


- **3 or 4 stages**
- **High efficiency**

Simple Cycle History 1985-2021

Step change in the last decade…





Jumo-004 1943 (about 14.7%)

Gas Turbine Class Hierarchy

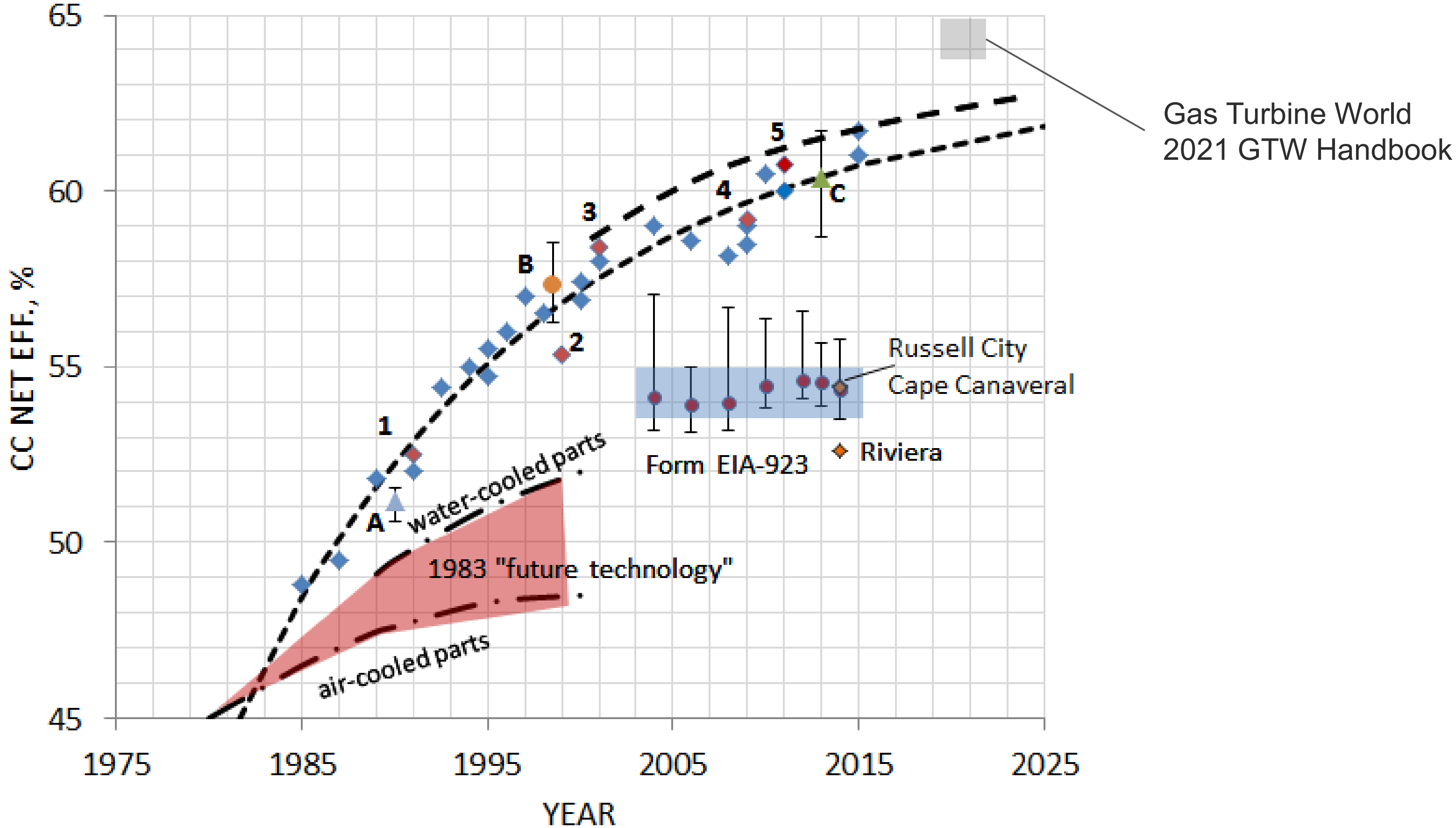
Turbine Inlet Temperature & Cycle Pressure Ratio

- E Class – 1,300°C TIT (PR = 12:1)
- F Class – 1,400°C TIT (PR = 15:1)
- G Class – 1,500°C TIT (PR = 20:1)
- H System – 1,500°C TIT (PR = 23:1)
- H Class – 1,500°C TIT (PR = 21:1)
- J/JAC Class – 1,600°C TIT (PR = 23:1)
- HA Class – 1,600°C TIT (PR = 23:1)
- HL Class – 1,600°C TIT (PR = 24:1)

PR – Cycle Pressure Ratio
G, J and H System have steam-cooled hot gas path parts
H System is discontinued
TIT values are introductory; HA, J/JAC and HL class are now 1,650+ºC (PR 25:1 for J/JAC)

Combined Cycle History 1985-2015*

Step change in the last decade



(A: TMI 1990 Handbook, B: GTW 1998-99 Handbook, C: GTW 2013 Handbook, 1: Ambarli, Turkey, 2: Tapada do Outerio, Portugal, 3: Mainz Wiesbaden, Germany, 4: Kawasaki, Japan, 5: Irsching, Germany.) Actual U.S. gas-fired GTCC generation data includes duct-fired units.

*: from Gülen, S.C. "Étude on Gas Turbine Combined Cycle Power Plant – Next 20 Years", GT2015-42077 ASME Turbo Expo 2015, June 15-19, 2015, Montréal, Canada

GTW Handbook 2021 Rating Data

Getting close to 65% net LHV in combined cycle…

SIMPLE CYCLE

	60 Hz		50 Hz	
OEM	Output, MW	Efficiency, %	Output, MW	Efficiency, %
A	369	42.3	538	42.8
B	430	43.3	571	44.0
C	435	44.0	574	43.4
D	405	42.6	593	42.8

COMBINED CYCLE

	60 Hz		50 Hz	
OEM	Output, MW	Efficiency, %	Output, MW	Efficiency, %
A	520	62.3	760	62.6
B	647.9	63.9	848	64.1
C	631.8	> 64.0	842.5	> 64.0
D	595	> 63.0	870	> 63.0

“World Record” Holders

Read the “small print”

- Irsching (Siemens 50 Hz H, 2011) 60.75% (small print: 0.6 in. Hg backpressure, cooling water from the Danube)
- Bouchain (GE 50 Hz HA, 2016) 62.22% (small print: old coal plant’s natural-draft cooling tower)
- Nishi Nagoya (GE 60 Hz HA, 2018) 63.08% (small print: gross, once-thru seawater cooling)
- Lausward (Siemens 50 Hz H, 2015) 61.5%

When the Rubber Hits the Road

Real life… it hurts

- From EIA Form 923 Data (Publicly Available)
- 2017 January to September
- H Class Rules But…

	OEM	Class	Config	Generation	Fuel Cons.	Heat Rate	Efficiency	**Efficiency**
				MWh	MMBtu HHV	Btu/kWh HHV	% HHV	**% LHV**
Panda Temple	Siemens	SGT6-5000F	2 (2x2x1)	2,315,620	16,954,109	7,322	46.60%	**51.68%**
Stonewall	Siemens	SGT6-5000F EE	2x2x1	2,159,244	15,275,314	7,074	48.23%	**53.49%**
Wolf Hollow II	GE	7HA.02	2x2x1	2,315,067	16,682,609	7,206	47.35%	**52.51%**
Colorado Bend II	GE	7HA.02	2x2x1	1,983,351	13,060,540	6,585	51.82%	**57.46%**
Riviera Beach	Siemens	SGT6-8000H	3x3x1	5,482,523	36,275,531	6,617	51.57%	**57.19%**
Cape Canaveral	Siemens	SGT6-8000H	3x3x1	5,413,559	36,020,550	6,654	51.28%	**56.87%**

The "Hall of Fame"

Best in class…

- General Electric (GE) HA Class
- Mitsubishi Power (MP) J/JAC Class
- Siemens HL Class
- Ansaldo GT36 (J Class) – *Not Focused in 60-Hz Market*

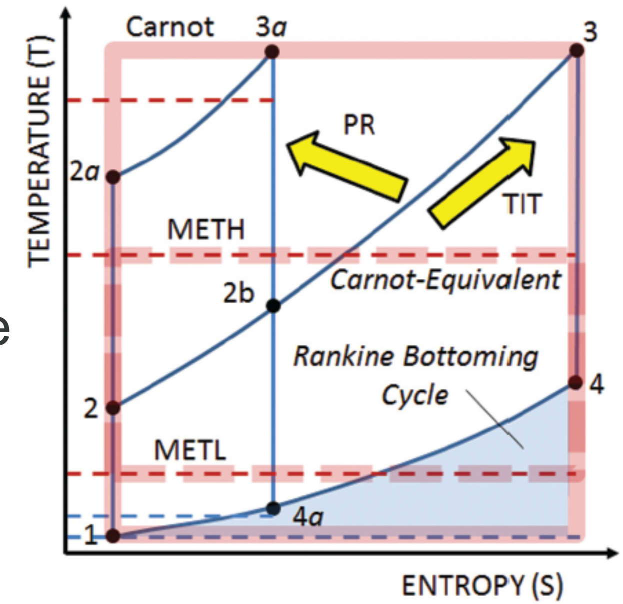
Still Hanging Around…

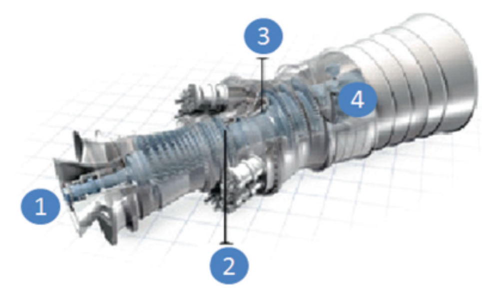
- GT24 (60 Hz) and GT26 (50 Hz) Sequential Combustion
- GT26 HE Package Offered By GE
- GT24 Is Not Offered New

Two Parameters: TIT and PR

Thermodynamics 101

- Biggest Gas Turbine Efficiency Effector is Cycle Pressure Ratio (PR)
- Biggest Gas Turbine Combined Cycle Efficiency Effector is Turbine Inlet Temperature (TIT)
- There Is An Optimum Combination of TIT-PR
- Today's State-of-the-Art is 1,600°C and 23:1
- Next Goal Is 1,700°C and 25:1

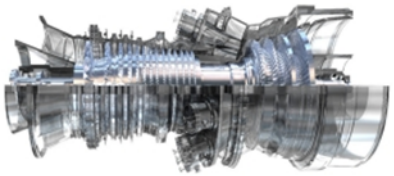




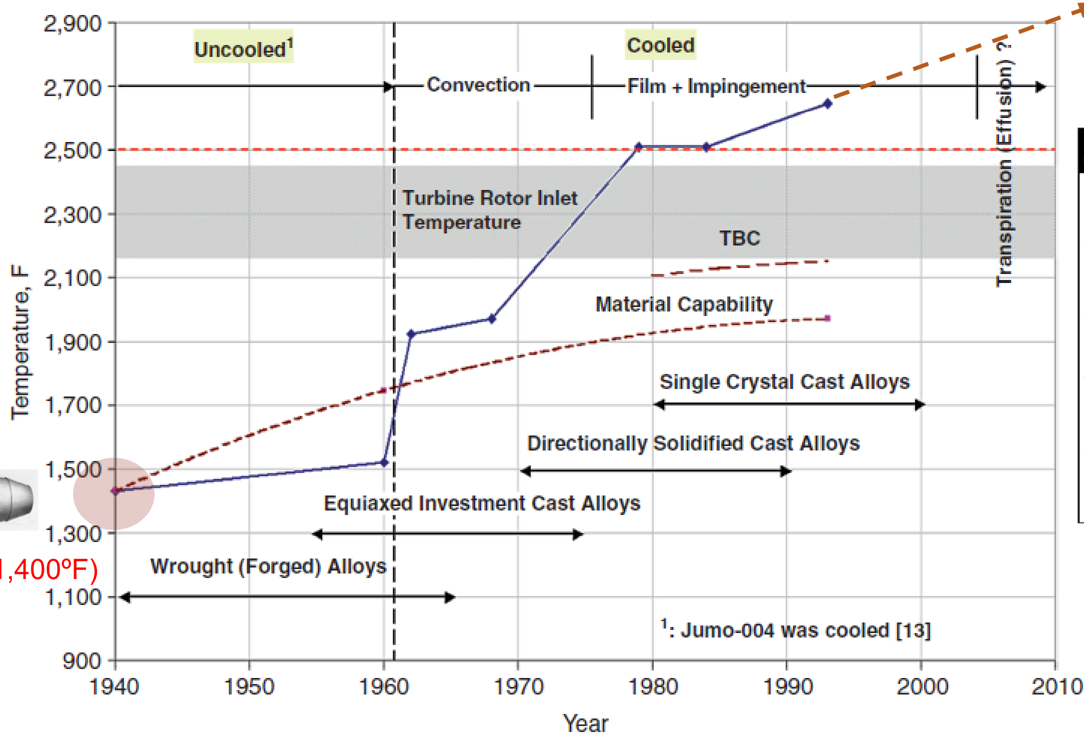
*: Nominal Values!!

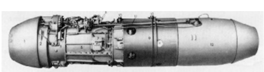
The Key Ingredient

Materials – Ni-Based Superalloys



J,HA





Jumo-004 1943 (1,400ºF)

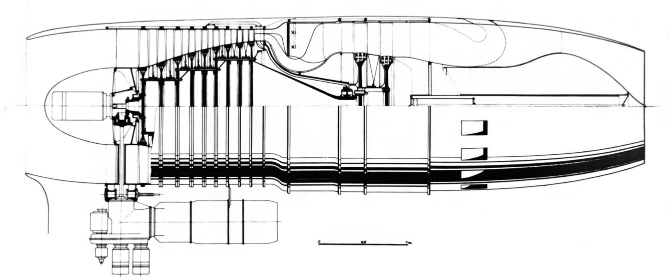
COMPONENT	Cr	Ni	Co	Fe	W	Mo	Ti	Al	Cb	V	C	B	Ta
BUCKETS													
U500	18.5	BAL	18.5	—	—	4	3	3	—	—	0.07	0.006	—
RENE 77 (U700)	15	BAL	17	—	—	5.3	3.35	4.25	—	—	0.07	0.02	—
IN738	16	BAL	8.3	0.2	2.6	1.75	3.4	3.4	0.9	—	0.10	0.001	1.75
GTD111	14	BAL	9.5		3.8	1.5	4.9	3.0	—	—	0.10	0.01	2.8
NOZZLES													
X40	25	10	BAL	1	8	—	—	—	—	—	0.50	0.01	—
X45	25	10	BAL	1	8	—	—	—	—	—	0.25	0.01	—
FSX414	28	10	BAL	1	7	—	—	—	—	—	0.25	0.01	—
N155	21	20	20	BAL	2.5	3	—	—	—	—	0.20	—	—
GTD-222	22.5	BAL	19	—	2.0	2.3	1.2	0.8	—	0.10	0.008	1.00	—
COMBUSTORS													
SS309	23	13	—	BAL	—	—	—	—	—	—	0.10	—	—
HAST X	22	BAL	1.5	1.9	0.7	9	—	—	—	—	0.07	0.005	—
N-263	20	BAL	20	0.4		6	2.1	0.4	—	—	0.06	—	—
HA-188	22	22	BAL	1.5	14.0	—	—	—	—	—	0.05	0.01	—
TURBINE WHEELS													
ALLOY 718	19	BAL	—	18.5	—	3.0	0.9	0.5	5.1	—	0.03	—	—
ALLOY 706	16	BAL	—	37.0	—	—	1.8	—	2.9	—	0.03	—	—
Cr-Mo-V	1	0.5	—	BAL	—	1.25	—	—	—	0.25	0.30	—	—
A286	15	25	—	BAL	—	1.2	2	0.3	—	0.25	0.08	0.006	—
M152	12	2.5	—	BAL	—	1.7	—	—	—	0.3	0.12	—	—
COMPRESSOR BLADES													
AISI 403	12	—	—	BAL	—	—	—	—	—	—	0.11	—	—
AISI 403 + Cb	12	—	—	BAL	—	—	—	—	0.2	—	0.15	—	—
GTD-450	15.5	6.3	—	BAL	—	0.8	—	—	—	—	0.03	—	—

Side benefit of cooling: Hollow blades → Less materials/weight!!

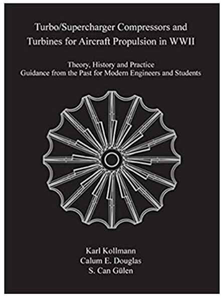
Other Challenges

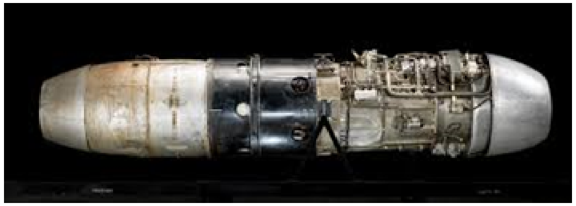
Same as it ever was…

- Higher TIT
  - More NOx
  - More Hot Gas Path Cooling
- Higher PR
  - Higher Air Temperature
  - Bigger Compressor



Daimler-Benz DB 016 1944 (1,562ºF TIT, 7.7:1 PR)
13,000 kg thrust, for "Very Fast Bomber"





Jumo-004 1943 (1,400ºF TIT, PR of about 3:1)

Me-262 with Twin Jumo-004

Everything needed was known from the get-go!!

Remedies

Same as it ever was…

- Materials (Superalloys, CMC)
- Advanced Film Cooling
- Thermal Barrier Coating (TBC)
- Casting (Single Crystal)
- Advanced Manufacturing ⇐ New – Game Changer?
- 3D Aerodynamics
- Advanced Seals
- Tight Clearances
- Model-Based Adaptive Control
- Digital Twin ⇐ New – Game Changer?

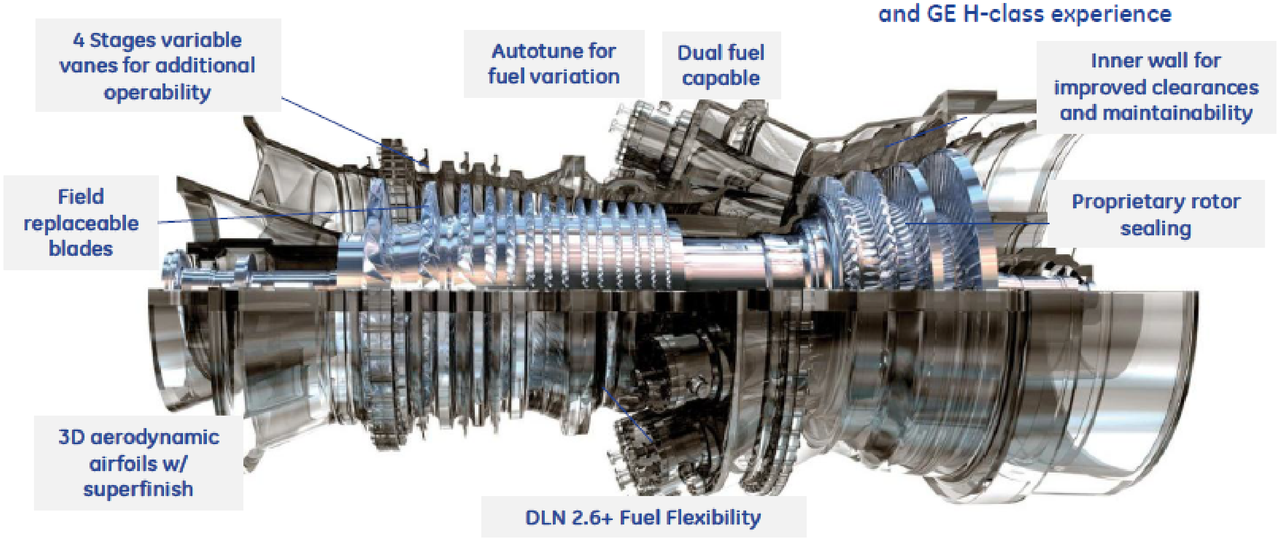
Technology Enablers – I

OEM A

14-stage Compressor
- Proven capability
- 7FA.05 compressor technology

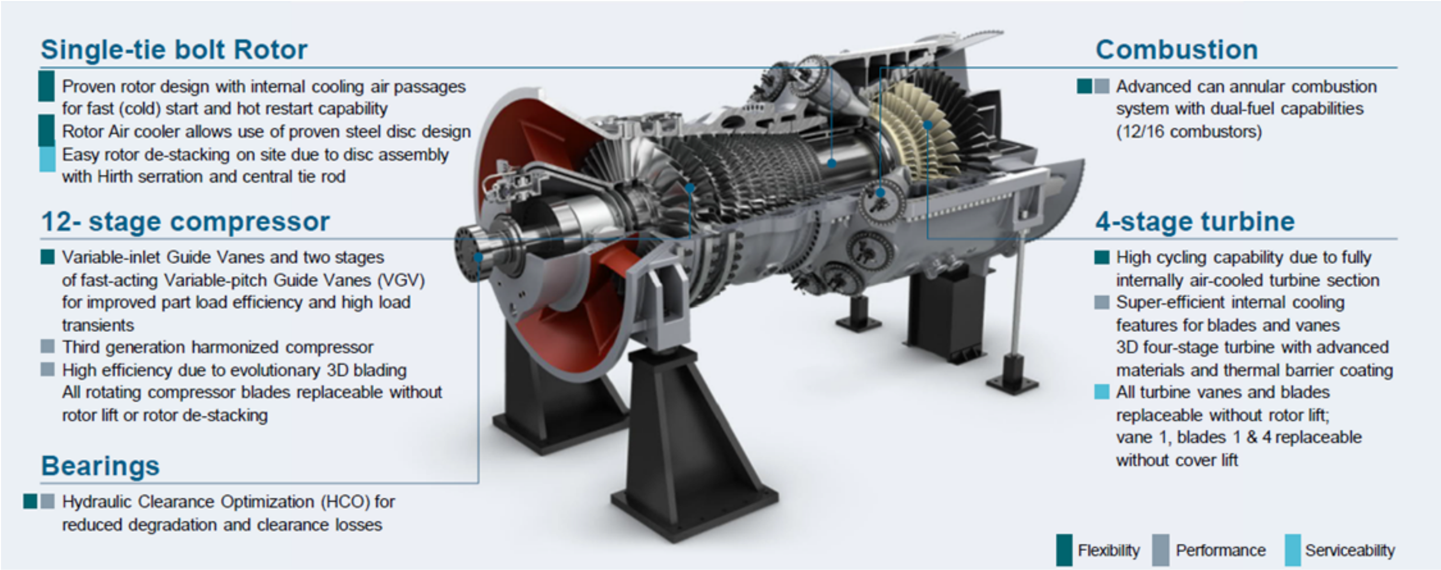
DLN 2.6+ Combustion
- Proven performance
- Increased operability

4-stage Hot Gas Path
- Proven superalloys
- Flow down of aircraft technology and GE H-class experience



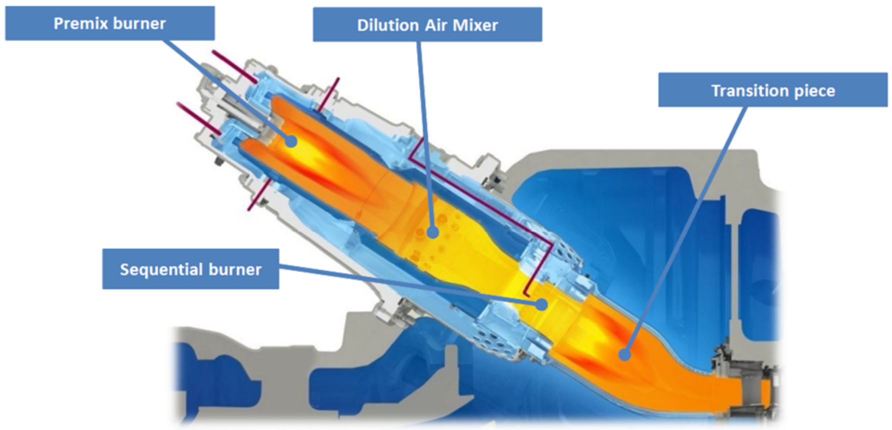
Technology Enablers – II

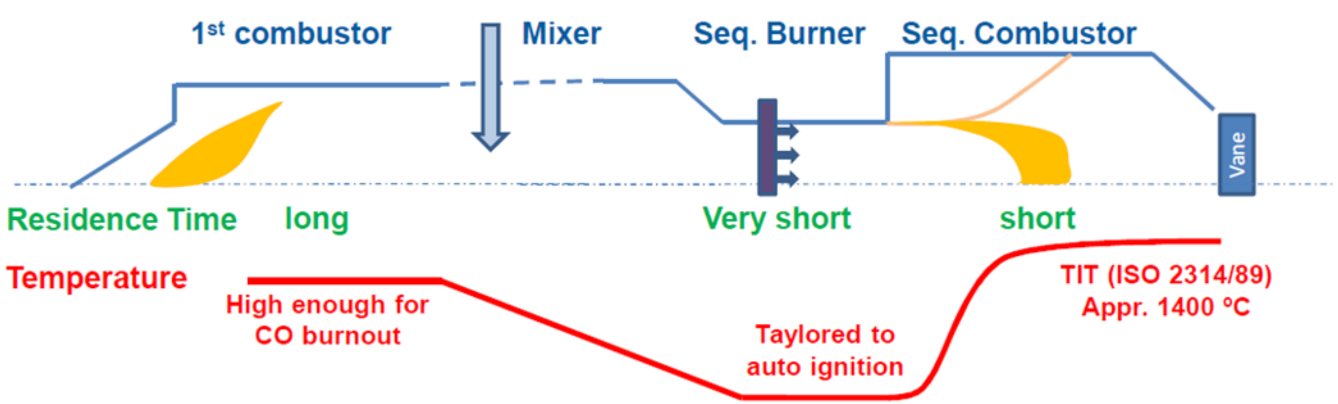
OEM B



Axial Fuel Staging

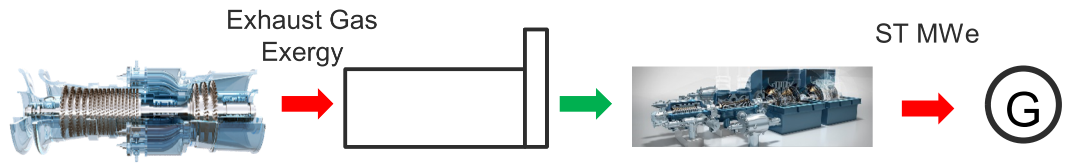
OEM C: Reheat without HP turbine

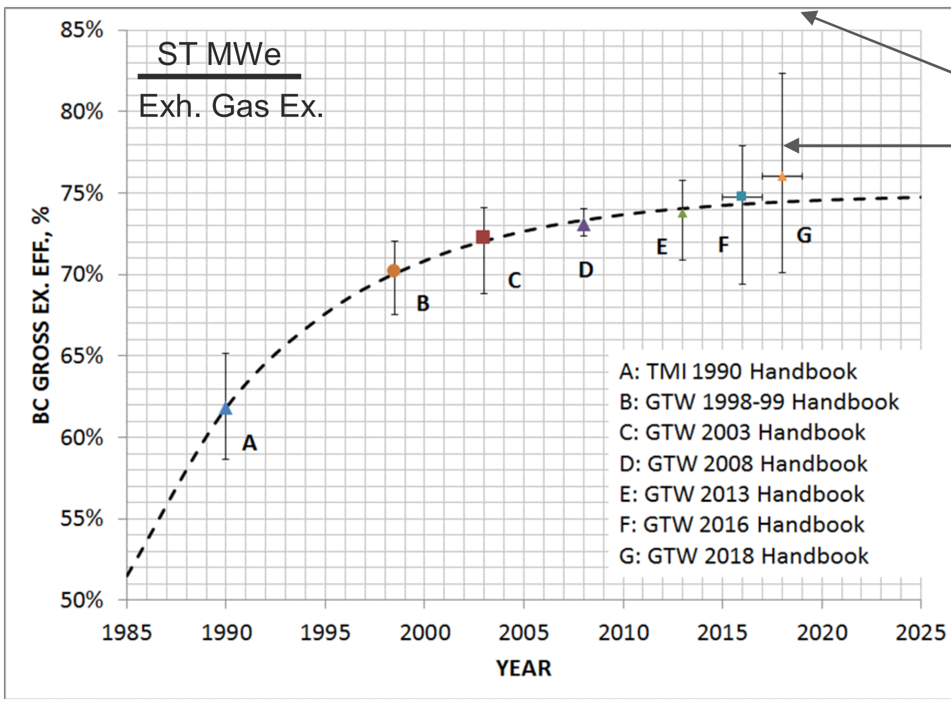




Bottoming Cycle History

One third of GTCC output…but, read the fine print!





~86% (published…)

~78% (my best estimate)

Combined cycle performance ratings undergo thermodynamic reality check

By S. C. Gülen, Bechtel Fellow, ASME Fellow
Bechtel Infrastructure & Power, Inc.

An industry expert calls for "time out" in industry's race to quote 65% plant efficiency, suggesting that OEM data be treated with a healthy dose of skepticism and that ratings be verified for project-specific design conditions

Like many readers of the *Gas Turbine World 2018 Handbook*, the author of this article is often amazed at some of the simple and combined cycle performance data listed by industry's major gas turbine OEMs.

Less than a decade after the 60% combined cycle efficiency benchmark was first achieved by one OEM, and only two years after the 62% barrier was broken by another, two different OEMs are quoting 64% and higher combined cycle efficiencies (presumably from 2x2x1 design configurations with larger and slightly more efficient steam turbines).

These advance class gas turbines are also rated at 44% simple cycle efficiency with about 1,200°F (about 650°C) exhaust gas temperature. Interestingly, one is a 60-Hz 400 MWe machine whereas the other is a larger 50-Hz behemoth with more than 500 MWe gas turbine output.

Their simple cycle and combined cycle performance ratings in both cases are pushing the boundaries of existing technology –meriting deeper analysis and scrutiny to check their limitations.

Ratings reality check

In this article, the author will try to do a forensic analysis of cited performance ratings using fundamental thermodynamic arguments, with the help of a renowned commercial cycle analysis software package to establish some reality check points.

Granted, this article appears in a publication with a professional readership that may not necessarily have the time, inclination, and/or tools to sift through an arcane thermodynamics evaluation. Unfortunately, there is no easy way around this obstacle.

Only high-level results are presented here. For more in-depth theory and analysis, interested readers are pointed to the publications cited at the end of this article. In any event, it is always a good idea to compare and verify performance data from different sources, including OEM catalogs and websites.

As a practical matter, concerned project planners and application engineers are advised to contact gas turbine builders directly as their primary source to verify performance ratings. Many OEMs allow customers and prospects to access in-house performance programs (to a limited extent) through the internet.

Performance evaluations

The focus in this article is on two gas turbines, A and B, being marketed by Gas Turbine OEM suppliers A and B, respectively. There is absolutely no question whatsoever that both designs represent the pinnacle of modern heavy-frame, industrial gas turbine technology.

Said technology includes nickel-based superalloys, thermal barrier coatings (TBC) and advanced casting and machining technologies used to manufacture hot gas path components, advanced film cooling techniques, plus 3D aero design tools to achieve efficient compression in only 14 stages with a cycle pressure ratio (PR) of 23 or higher. Recall that not too long ago, 18 stages were required for cycle PRs of 16.

The ISO base load rating data culled from the *2018 GTW Handbook* for Gas Turbines A and B are summarized in Table 1 for simple cycle plants and Table 2 for combined cycle plants.

Common caveats dealing with the limitations of published performance ratings in general are discussed in pp. 52-54 of the *GTW 2018 Handbook*. More specifically, however, in dealing with Gas Turbine A and B specs, readers should note that:

• no specific information is provided for the fuel gas. However, there is little doubt that it is 100% methane (CH_4) with a lower heating value of 21,503 Btu/lb (at 60°F; plus or minus a few Btu, depending on whatever reference is used by a particular OEM);

• no specific information is provided for the fuel temperature. Nevertheless, it is reasonable to assume that it is 77°F (25°C) for the simple cycle performance (since no external and "free" heating source – practically – is available for performance fuel gas heating). While this value is lower than that commensurate with OEM-required superheat specification, it is commonly used in rating performance calculations;

• both OEMs state that inlet and exhaust losses are included but they are not specified. This is not a big impediment from a heat and mass balance check perspective. However, from simple to combined cycle there

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What Is Reasonable?

Thermodynamics speaks…

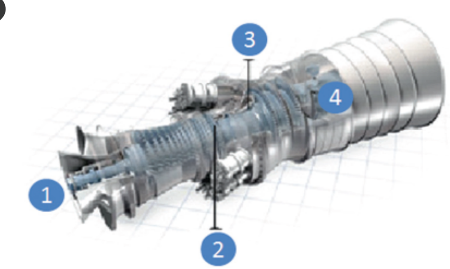
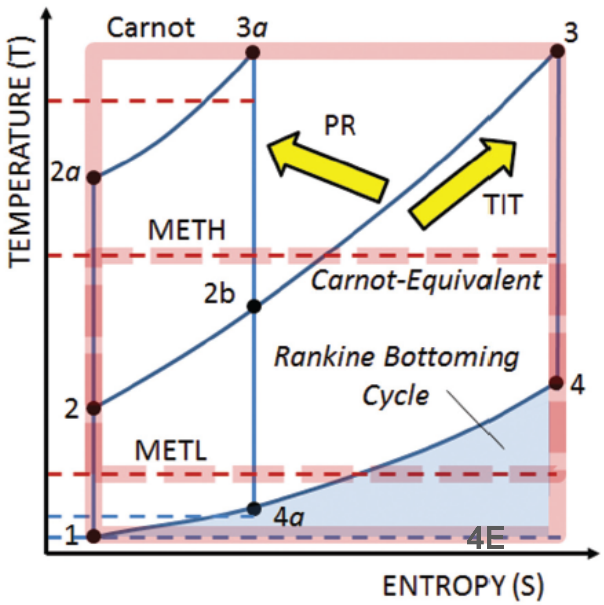


Table: Projected combined cycle efficiencies			
TIT, C	1,500	1,600	1,700
TIT, F	2,732	2,912	3,092
PR	18	22	25
T3/T1	6.15	6.50	6.84
X (see Figure 1)	2.69	2.69	2.73
Carnot	83.7%	84.6%	85.4%
Brayton	56.2%	58.7%	60.1%
Brayton "Enhanced"	74.4%	75.8%	76.8%
Combined Cycle, TF=0.825	61.4%	62.5%	63.4%
Combined Cycle, TF=0.85	63.2%	64.4%	65.3%



Brayton Cycle {1-2-3-4-1}
"Enhanced" Brayton Cycle {1-2-3-4E-1}

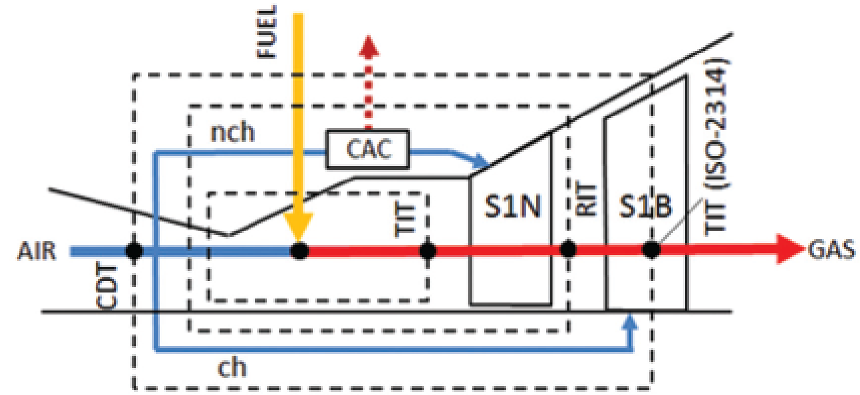
Technology Factor (Gütegrad)
Ratio of Actual Efficiency to Ideal "Carnot" Efficiency
TF = 1 → You built a Carnot engine!!!

Are We There Yet?

65% net LHV, that is... Almost...

OEM B 60 Hz – GTW 2021 Handbook Data
Gas Turbine Heat Balance Analysis

Output, kW		430,000			
Efficiency, %		43.3			
Exhaust Flow, lb/s		1,718			
Exhaust Temperature, °F		1,217			
Cycle Pressure Ratio		23.7			
Chargeable Flows (ch)		12%	12%	10%	10%
Non-chargeable Flows (nch)		12%	10%	10%	9%
TIT	°F	3,110	3,064	3,020	2,999
	°C	1,710	1,685	1,660	1,648
Firing Temperature (RIT)	°F	2,860	2,860	2,824	2,824
	°C	1,571	1,571	1,551	1,551
S1N DT	°F	250	204	196	175
ISO-2314 TIT	°C	1,461	1,461	1,461	1,461
	°F	2,662	2,662	2,662	2,662



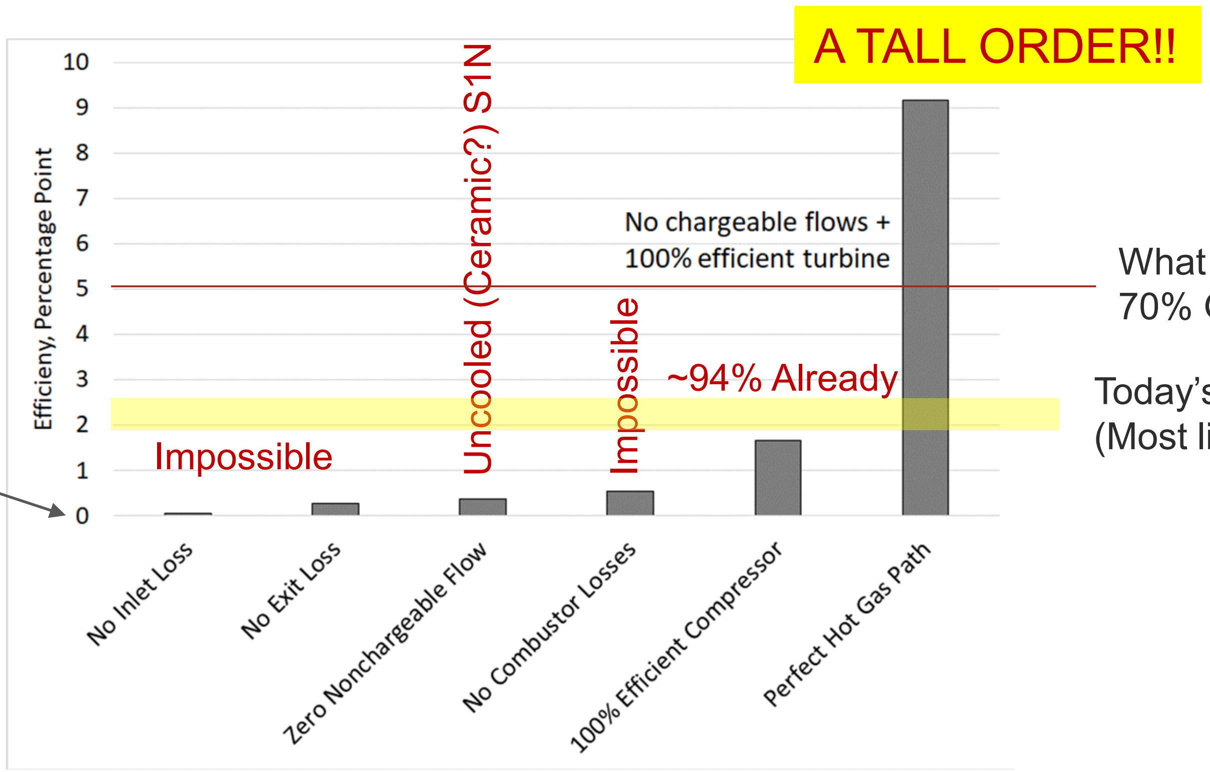
CDT: Compressor Discharge Temperature
TIT: Turbine Inlet Temperature
RIT: Rotor Inlet Temperature
CAC: Cooling Air Cooler
S1N: Stage 1 Nozzle (Vane)
S1B: Stage 1 Bucket (Blade)
ch: Chargeable Cooling Flow
nch: Non-chargeable Cooling Flow

Rated GTCC ISO Base Load Efficiency 63.9%

What Next?

Gas turbine stairsteps to 70% net LHV GTCC efficiency…

Starting Point
- 1,600°C TIT
- PR = 22:1
- 41.4% Efficiency



What is needed for 70% GTCC Efficiency

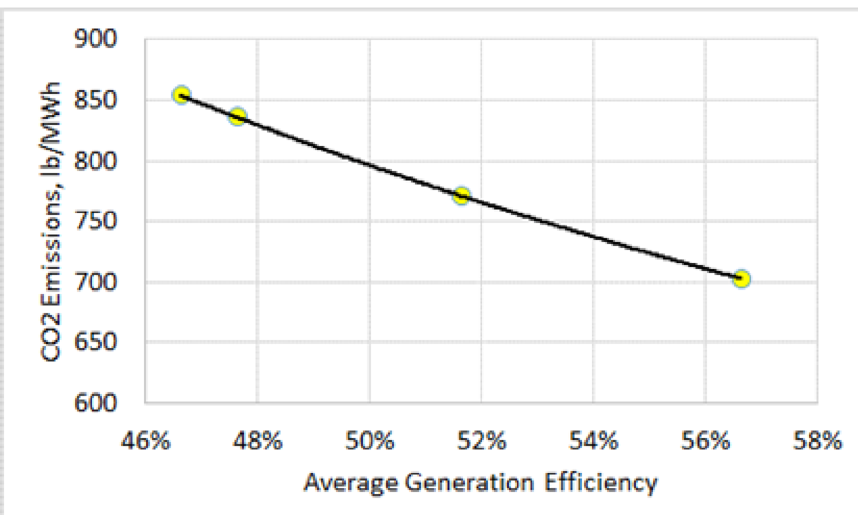
Today's Ratings (Most likely at 1,650°C TIT)

Why Efficiency Is Important – I

Significant reduction in CO_2 emissions…

Year 2019 (US EIA Data)					
	10^6 mt CO_2 per quad Btu	Average Heating Value Btu/cuft, MMBtu/st	Consumption: 10^9 cuft/day, 10^6 st	CO_2, short tons/year	CO_2 per Heating Value, lb/MWh
Natural Gas	52.9	1,035	30.7	677,069,717	398
Coal	96.3	19.149	537.6	1,092,793,028	724
	Average Efficiency	CO2 per MWh Generated, lb/MWh	Generation: 10^6 MWh/day	Generation: 10^6 MWh/year	CO_2, short tons/year
Natural Gas	46.6%	854	4.345	1,586	677,069,879
Coal	32.0%	2,265	2.644	965	1,092,793,289

If average efficiency were higher by one percentage point, 14 million ton less CO_2 would be emitted



Efficiency	CO_2, st/year
46.6%	BASE
47.6%	-2.1%
51.6%	-9.7%
56.6%	-17.7%

Why Efficiency Is Important – II

Hydrogen angle – 60 Hz 1x1x1 GTCC example

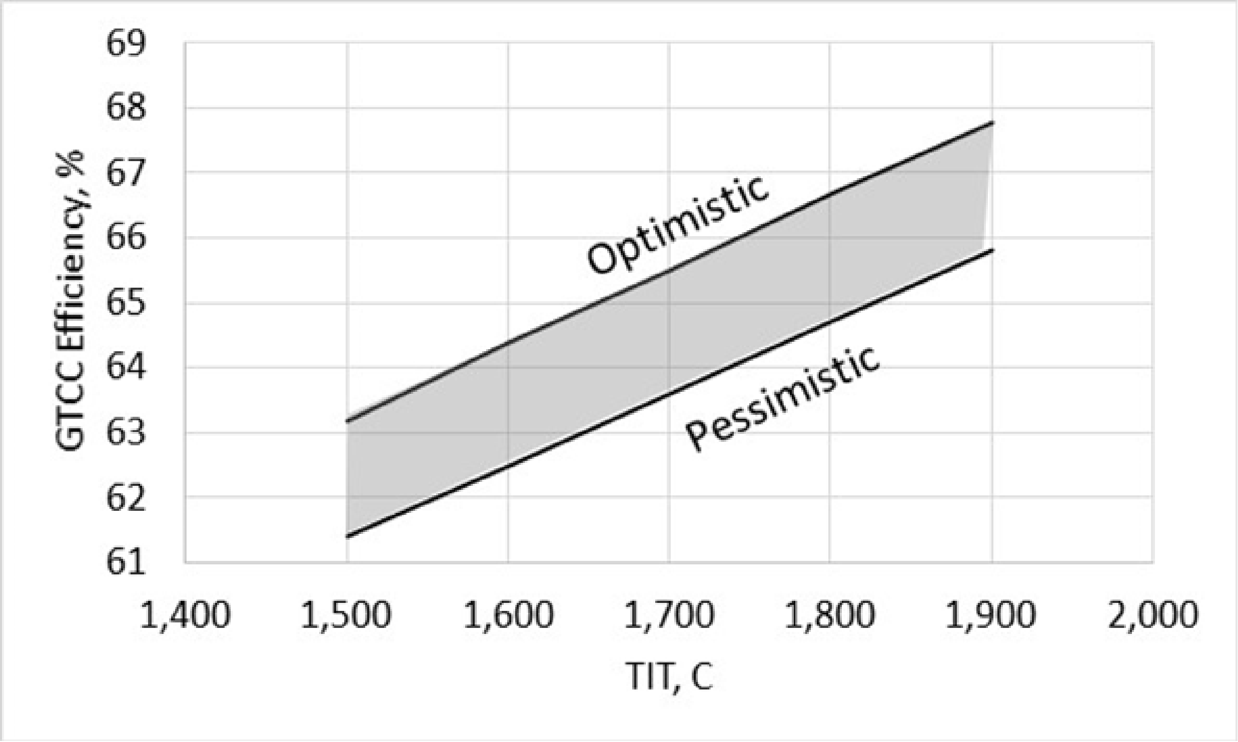
GTCC Output	600	MW
H_2 LHV	119,987	kJ/kg
Electrolysis	55	kWh/kg
SMR	9.2	CO_2/H_2

CC Efficiency	CC Heat Consumption	100% H_2 Fuel Flow		Electrolysis	SMR CO_2
	MWth	kg/s	kg/h	MW	kg/h
60%	1,000	8.33	30,003	1,650	276,031
61%	984	8.20	29,511	1,623	271,505
62%	968	8.07	29,035	1,597	267,126
63%	952	7.94	28,575	1,572	262,886
64%	938	7.81	28,128	1,547	258,779
65%	923	7.69	27,695	1,523	254,797
66%	909	7.58	27,276	1,500	250,937
67%	896	7.46	26,869	1,478	247,192
68%	882	7.35	26,474	1,456	243,556
69%	870	7.25	26,090	1,435	240,027
70%	857	7.14	25,717	1,414	236,598

*: Total wind power generation in USA in 2020 was 338,000 GWh – say, 350,000 GWh
Assuming 5% curtailment, 17,500 GWh can be diverted to H_2 production
This can support about two 600 MW GTCC plants (at η=60%) for 5,000 hours/year or three of them (η=70%) for 4,000 hours/year.

Recap…

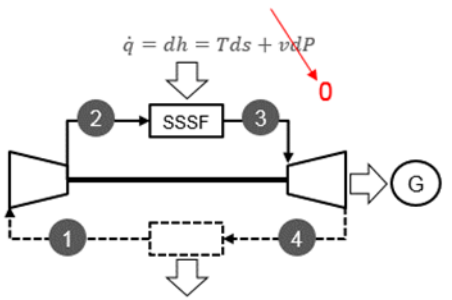
70% GTCC efficiency seems elusive…

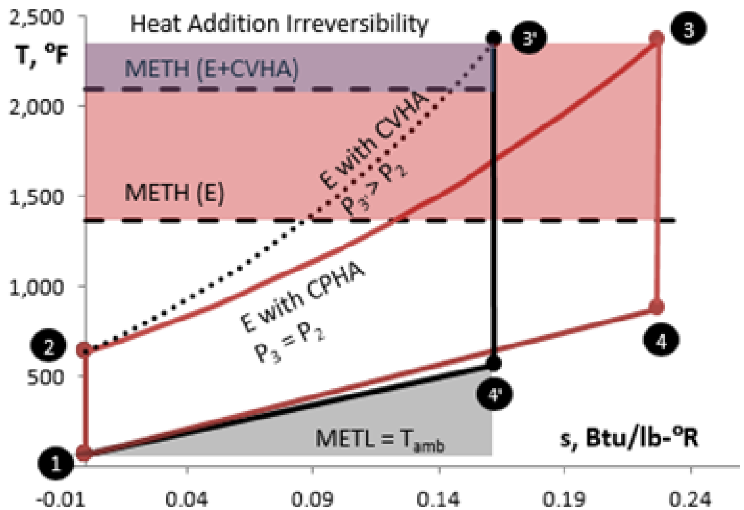


NEED A NEW MOUSE TRAP!!!

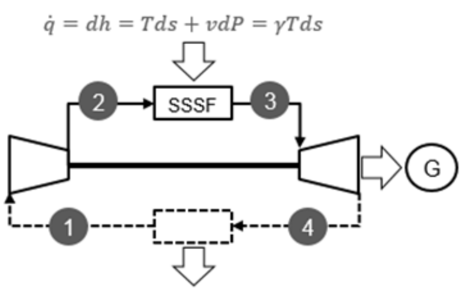
Constant Volume Combustion

A change in gas turbine cycle…





	BASE	PRESSURE GAIN COMBUSTION			
GTG Output, kWe	339,531	438,104	418,721	398,958	405,541
Heat Input, kWth	819,518	892,497	857,284	821,360	848,679
GTG Efficiency	41.43%	49.09%	48.84%	48.57%	47.78%
T_{exh}, °C	629	612	593	573	595
m_{exh}, kg/s	700	702	701	700	701
Precompression PR	NA	13.6	13.6	13.6	11.9
P_2, bara	24.8	13.8	13.8	13.8	12.1
T_2, °C	490	371	371	371	346
PDC PR	NA	1.854	1.810	1.765	1.821
Cycle PR	23.1	25.2	24.6	24.0	21.7
TIP, bara	23.4	25.6	24.9	24.3	22.0
TIT, °C	1,593	1,593	1,538	1,482	1,482
STG Output, kWe	173,722	166,265	156,082	145,705	157,194
CC Gross Output, kWe	513,253	604,369	574,803	544,663	562,735
Plant Aux. Load, kWe	7,912	24,672	23,001	21,330	19,662
CC Net Output, kWe	505,341	579,697	551,802	523,332	543,072
CC Net Efficiency	61.7%	65.0%	64.4%	63.7%	64.0%



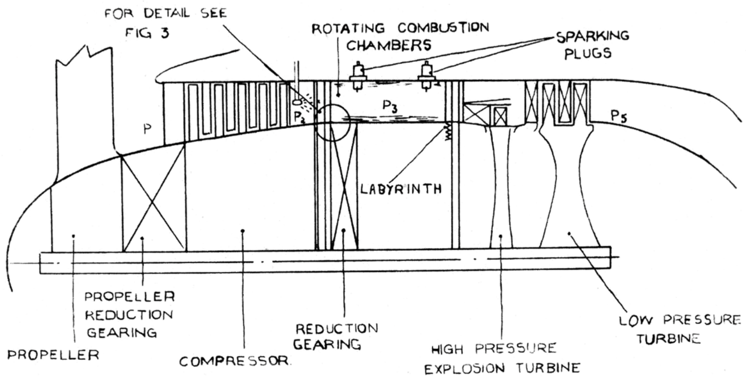
Thermodynamically, a 'no-brainer'!
Practical implementation difficult… (especially in aircraft engines)
Most likely candidate: Detonation combustion

- Pulse(d) Detonation – passé
- Rotating Detonation – current focus

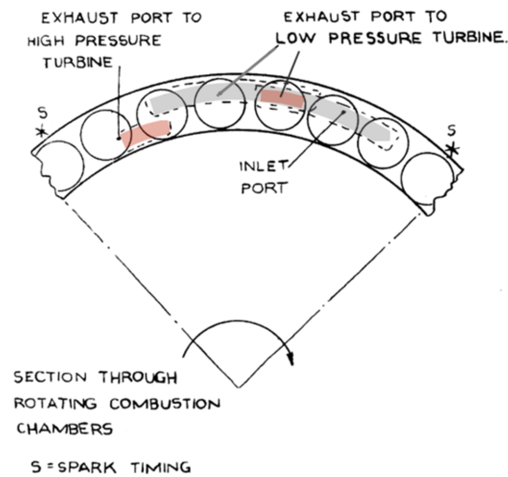
Pressure Gain Combustion Advantage in Land-Based Electric Power Generation, S.C. Gülen, GPPF2017-0006, 1st Global Power and Propulsion Forum, GPPF 2017, Jan 16-18, 2017, Zürich, Switzerland.

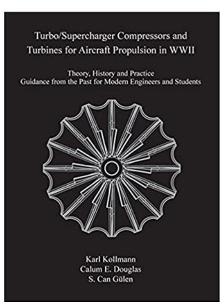
Detonation Combustion

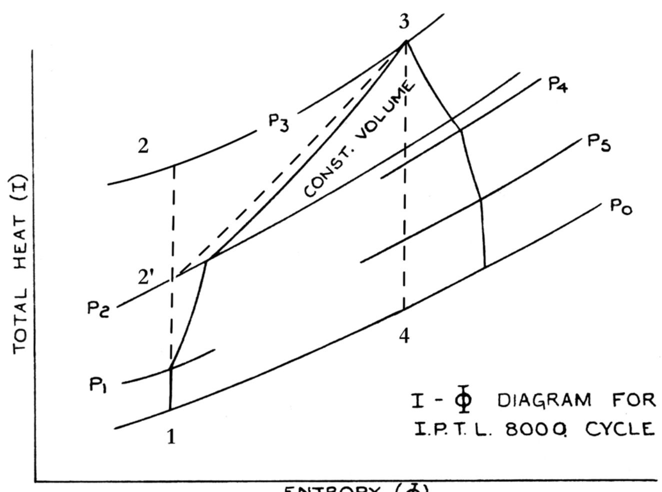
Not a new idea… in 1940s Germans looked at it…

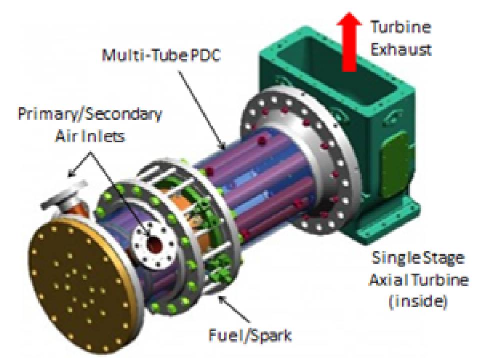


BMW IPTL 8000 – Turboprop engine with detonation combustion









GE-NASA multi-tube pulse detonation combustion turbine rig

Closing Remarks

- Today's GTCC technology is getting close to 65% net LHV (ISO Base Load Rating)
- Actual US NG fleet performance is much lower – barely 47%
- Best in class GTCC field performance is around 57%
- Each percentage point is worth 14 million tons of CO_2
- For a GTCC (60% capacity factor, 100% H_2), each percentage point improvement saves 2,500 metric tons of H_2 annually
- "Constant pressure combustion" Brayton cycle, after 80+ years, is near the end of its technology "S curve"
- For the next "goal post", 70% net LHV (ISO Base Load Rating), a new cycle is needed
- The best candidate is "constant volume combustion" (CVC) cycle
- The best candidate for practical implementation of CVC cycle is detonation combustion