On the Conversion of a Large Turbo Fan Engine's Combustor to Be Fueled by Natural Gas

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MY THANKS TO ALL CONTRIBUTORS:

- Dr. Valery Sherbaum, Technion
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- Mr. Nadvany Valery
- Mr. Matan Zakai
- Mr. Ofir Harari, Israel Aircraft industry (IAI)
- Mr. Aviad Brandstein, Israel Aircraft industry (IAI)

Aeroderivative Gas Turbines

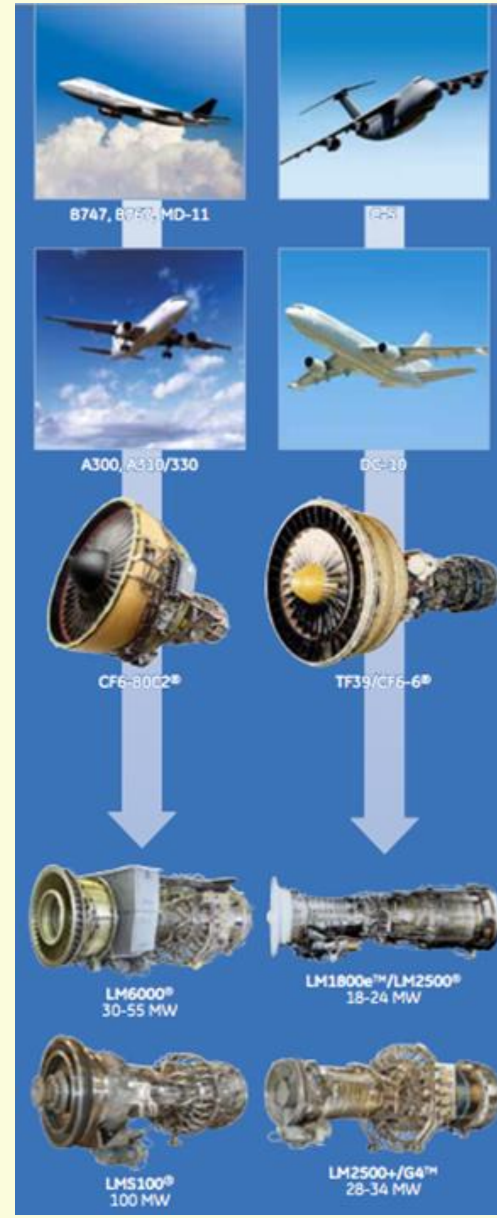
There has been a steady growth in the use of aero-derivative gas turbines, which are stationary variants of aero-engine.

In year 2000

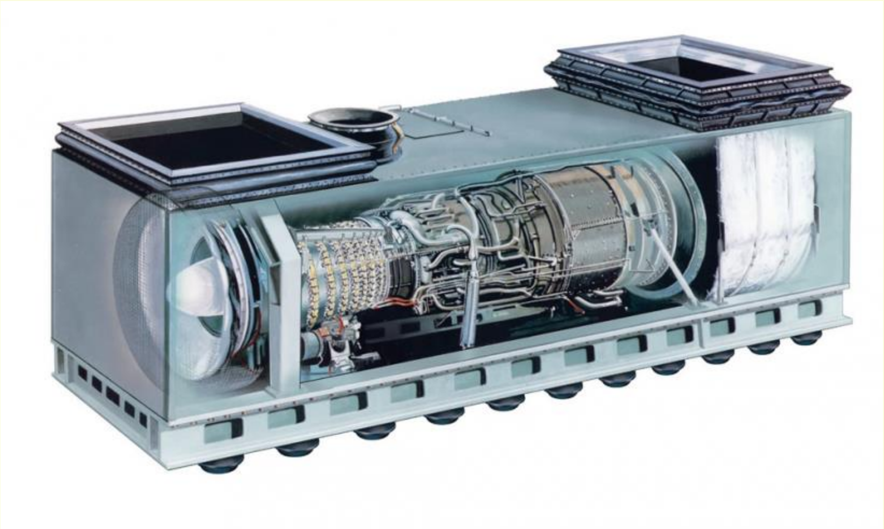
AERO ENGINE		GAS TURBINE	
F404	→	LM1600	150 UNITS
CF6-6	→	LM2500	1130
CF6-80C2	→	LM6000	300

The target:
To convert existing jet engine to stationary electric generator:

1. Reducing fan size and coupling to an electric generator
2. **Converting their fuel from jet fuel to Natural Gas (NG)**

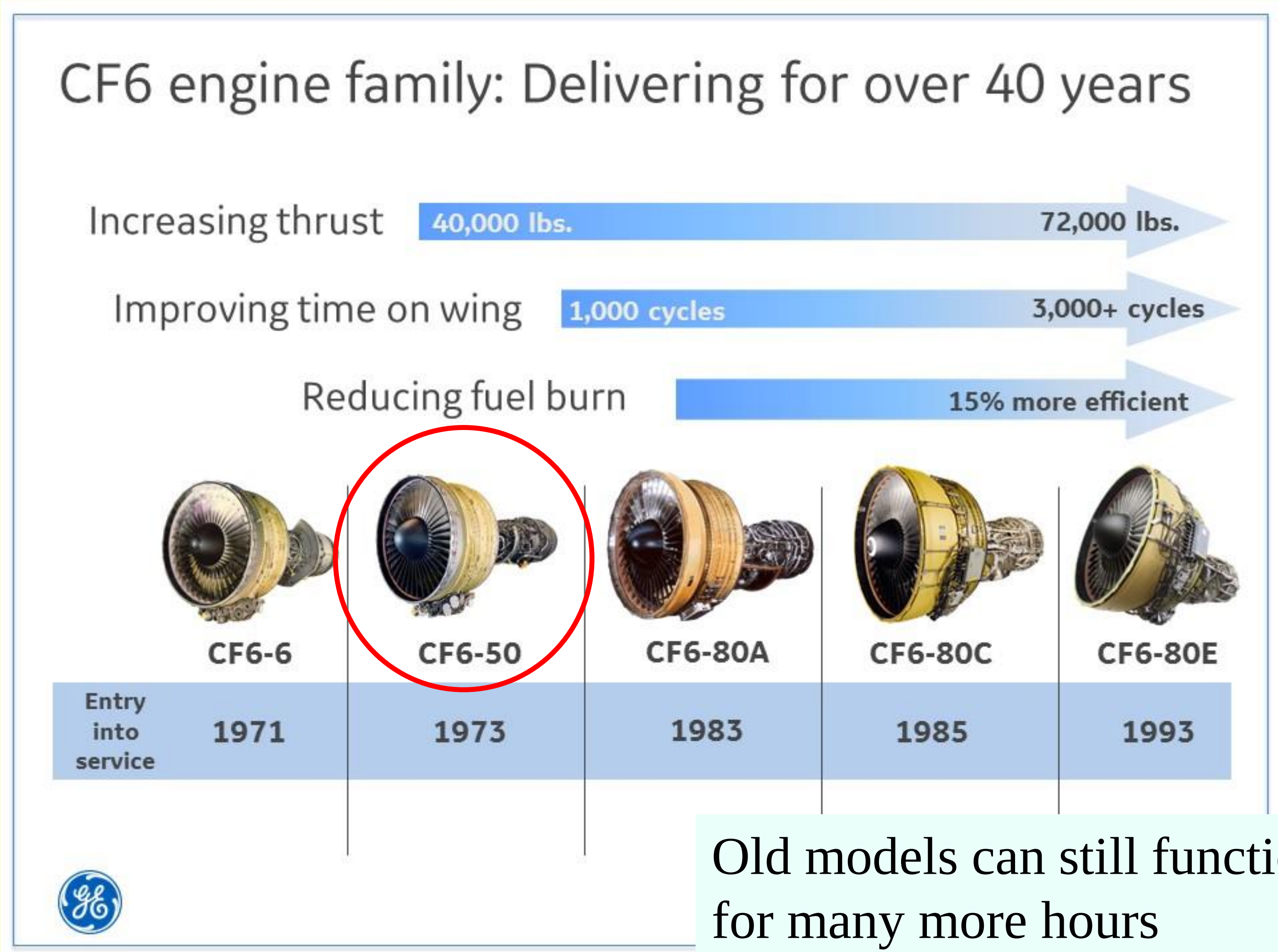


(*) GE Aeroderivative, Gas Turbines – Design and Operating Features
G.H. Badeer, GE IAD, , GE Power SystemsEvendale, OH, GER-3695E



CF6-6

LM2500



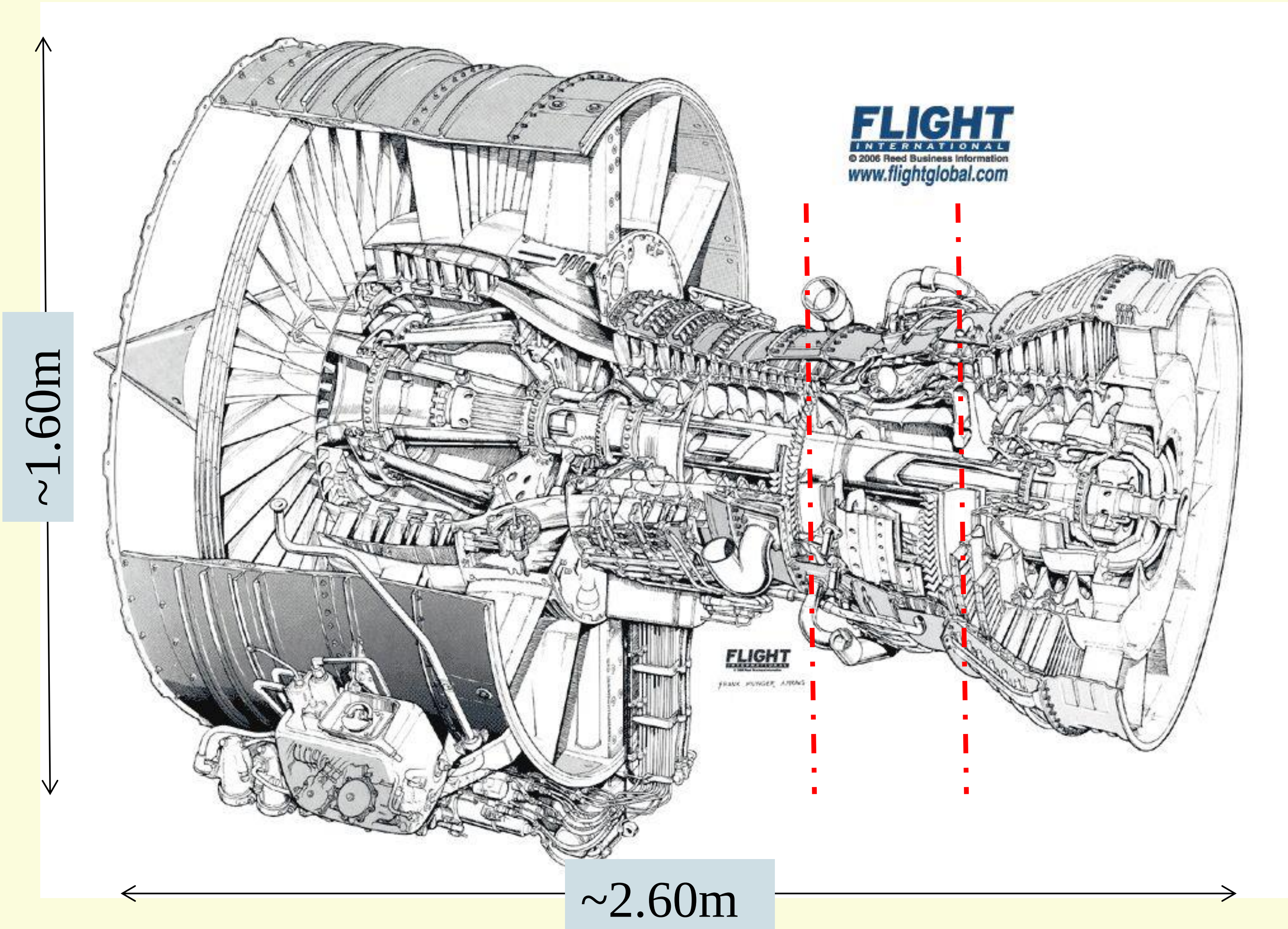
Old models can still function for many more hours

Emission requirement (target):

As for GE LM 1800 e (18 Mwe):

NOx @15% O2, 25 ppm vd
CO @15% O2, 25 ppm vd

(@ 60% relative humidity, Ta 15 deg C)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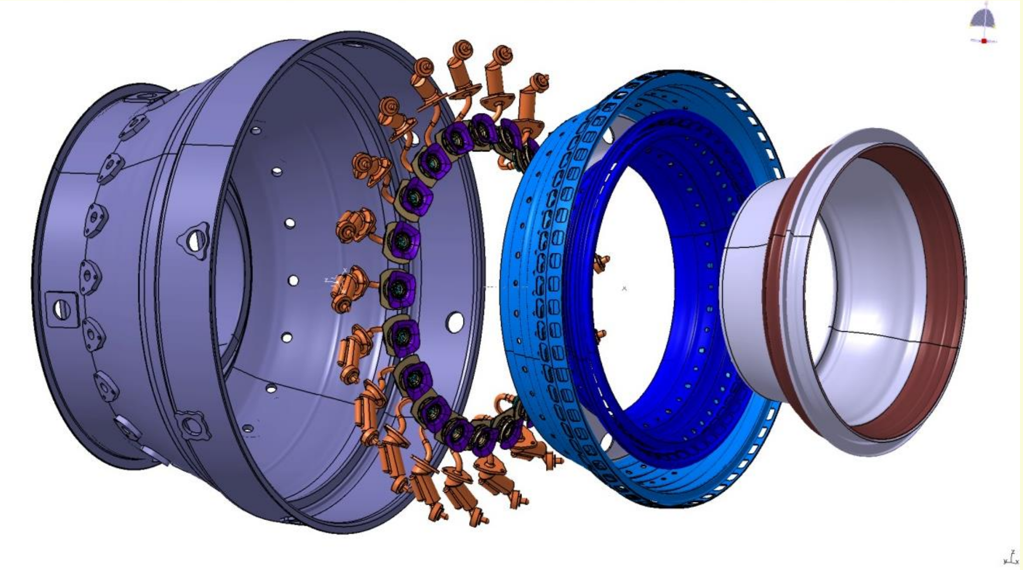


Exploded view of the CAD model of the Combustor

OBJECTIVES

- The conversion of operation of jet engine combustion chamber from liquid jet fuel (JetA1) to natural gas
- The conversion should be done with minimum modifications of the combustion chamber. Ideally, only the fuel nozzle should be changed
- The amount of the NOx and CO emissions of the modified combustion chamber should be minimal and not greater than of the original design.

METHOD:

1. Evaluate performance under normal operating condition using liquid jet fuel (for reference data)
2. Design a NG fuel nozzle and evaluating performance using NG under similar P_{s3} & T_{s3} operating conditions
3. Validation of simulations under laboratory conditions:
   - Design a reduced model of the combustor, operating at atmospheric pressure,
   - Simulate performance at laboratory conditions (kerosene & NG),
   - Compare and calibrate CFD code
4. Optimize fuel nozzle's design

1. Evaluate performance under normal operating condition using jet fuel (for reference data)

NORMAL OPERATING CONDITION

	Corrected data (standard day ISA Conditions)			
	Thrust kgf	Fuel Flow rate, kg/hr	Static Pressure, PS3 bar-a	Static Inlet temperature, T3 deg K
Ground idle	400	350	2	420
Max Continues	10,000	4,000	23	770

CFD Model (Simulation Condition)

Chemical Reaction Model: Non-premixed Combustion (Kerosene & Methane)

For kerosene and methane:

- ***Equilibrium chemistry approximation (minimum Gibs Energy)***; intermediate species are calculated, while there is no need for detailed kinetic data.

Calculated 25 chemical species:
JetA: C12H23 (Jet-A), NCO, O3, C2H4, HNO3, CO2H2, HNO2, HOCO, CH2O, H2CO2, CHO, HCO, C2H6, HONO, H2O2, HO2, OH, CH4, C(s), H2, CO2, H2O, CO, O2, N2

Methane (23 species): CH4, CH3OH, C2H4, O3, HNO3, CO2H2, HNO2, HOCO, CHO, CH2O, H2CO2, HONO, H2O2, C2H6, HO2, OH, CO2, C(s), CO, H2, H2O, O2, N2

For methane (only) also:

- ***Steady Flamelet combustion model*** using the GRI-Mech 3.0 optimized for NG with 325 reactions and 53 species.

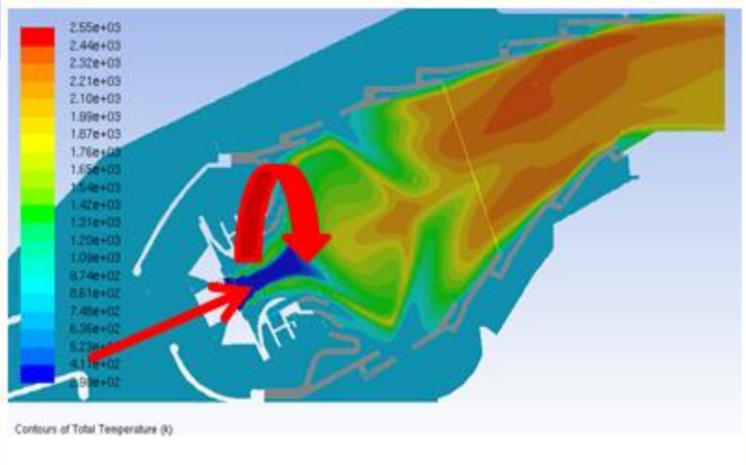
Flamelet and Equilibrium models gave close results.

Performance at Max. Continues (jet fuel)

Total Temperature [K]

2550 K

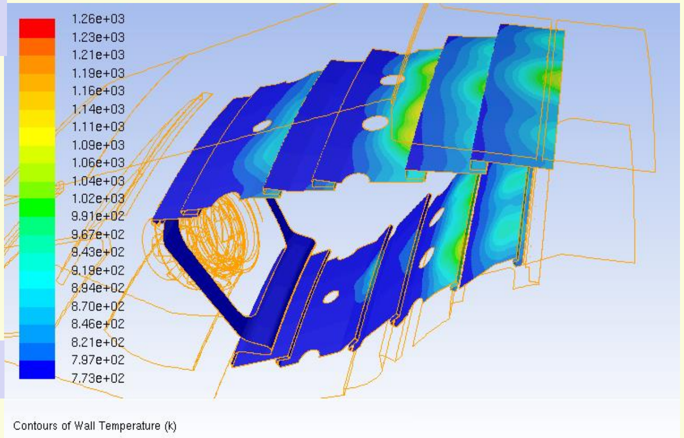
300 K



Liner Wall Temperature [K]

1250 K

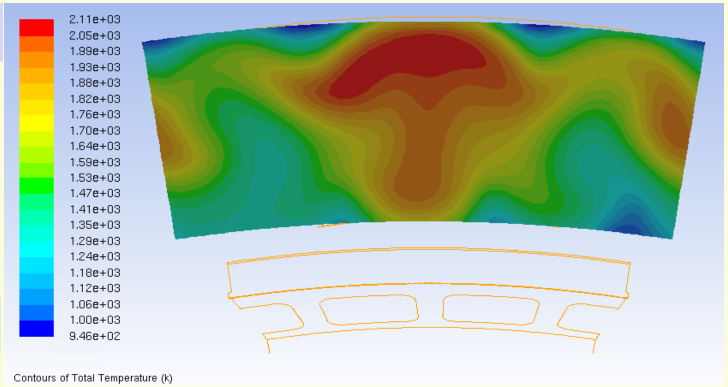
770 K



Exhaust Total Temperature [K]

2100 K

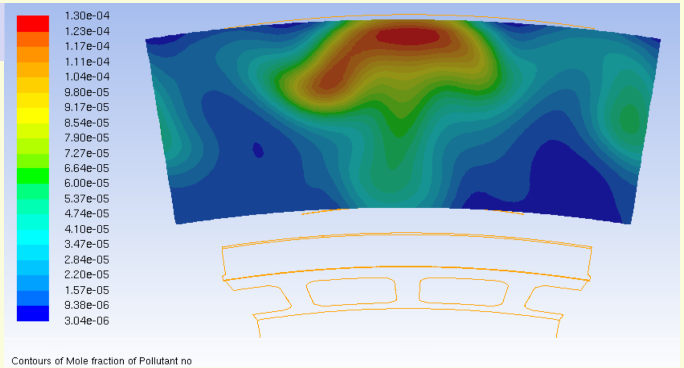
940 K



NOx at exhaust [mole fraction]

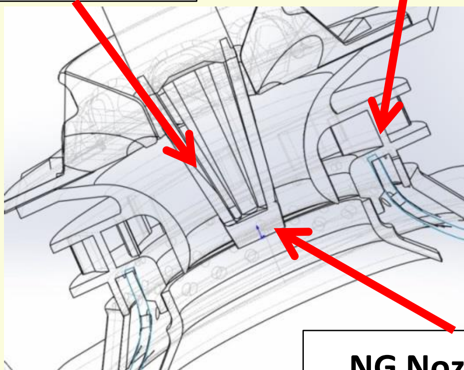
130 ppm

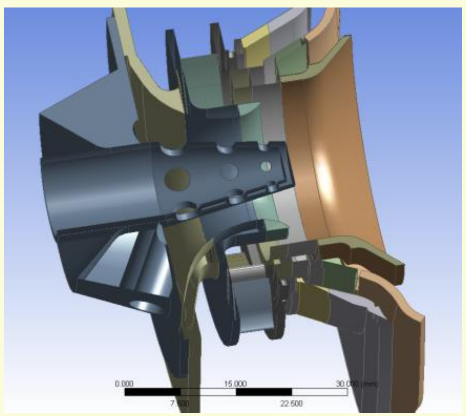
3ppm



2. Design a NG fuel nozzle and evaluating performance using NG under similar P_{s3} & T_{s3} operating conditions.

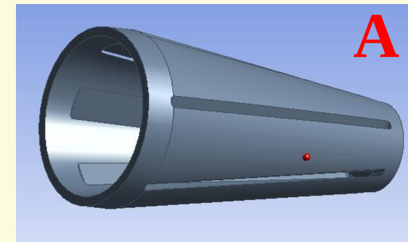
NG Nozzle Optimization



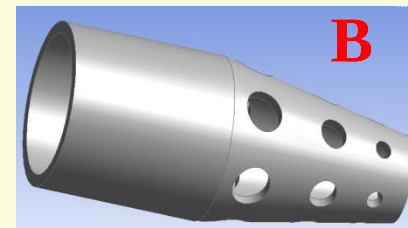


In order to study the effect of gaseous fuel distribution and its velocities, several options of nozzle's designs were investigated:

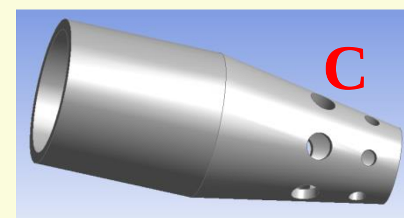
Option A: slots



Option B: 3 rows of circular holes (same area as in A)

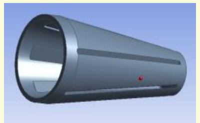


Option C: 2 rows holes (smaller area than in A & B)



Simulation were done using two CFD models:
Flamelet and Equilibrium. Both models gave close results.

NG Nozzles – Simulations Results

		MWA	Max Section	Max Wall	Pattern factor	MWA Unburnt CH4	MWA CO	MWA NOx
		Temperatures [K]				Concentrations [ppm dv] Mole Fraction		
	A	1641	2102	1269	0.53	0.52	426	32
	B	1640	2052	1312	0.48	0.024	188	32
	C	1635	1996	1227	0.42	0.01	42.0	31

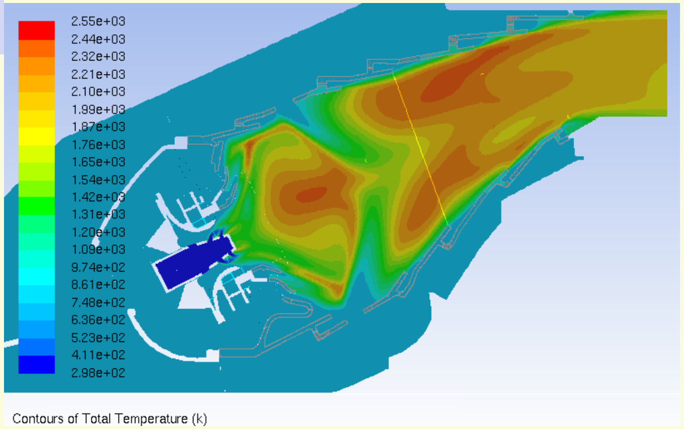
MWA – Mass Weighted Average

$$Pattern\ \ Factor = \frac{T_{\max} - T_{avg}}{T_{avg} - T_{inlet}}$$

Option C (NG) Nozzle Results

Total Temperature [K]

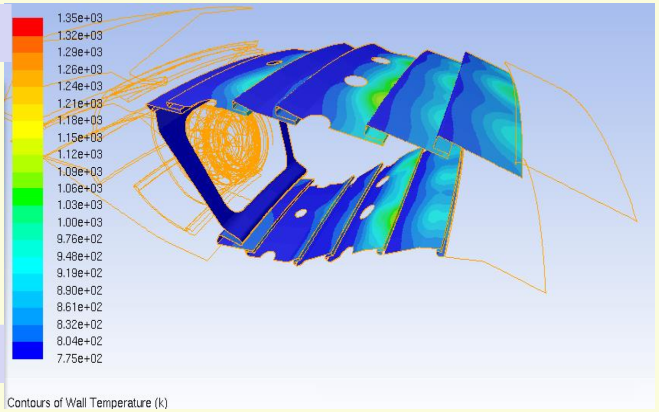
2550 K



300 K

Liner Wall Temperature [K]

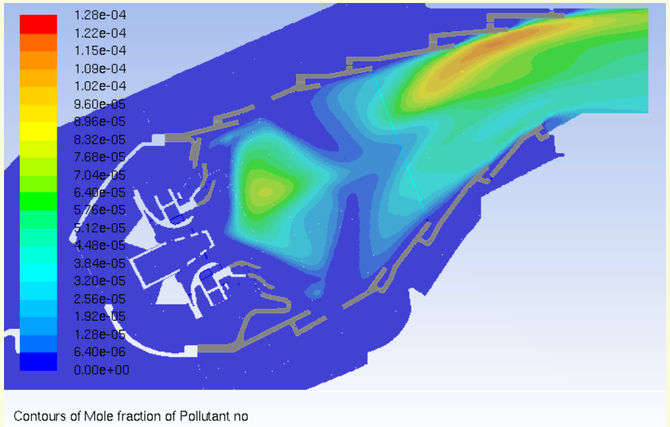
1350 K



770 K

NOx at exhaust [mole fraction]

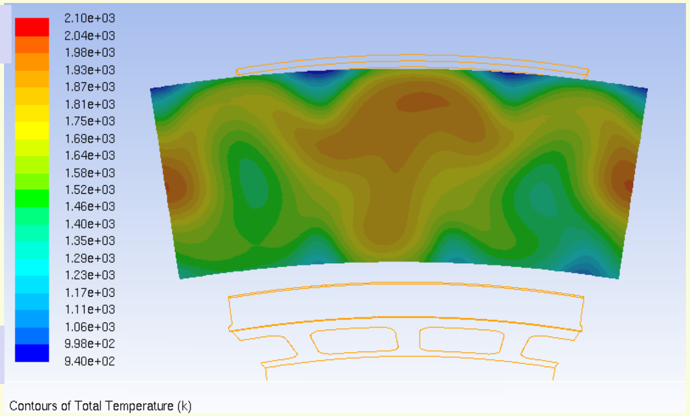
130 ppm



0ppm

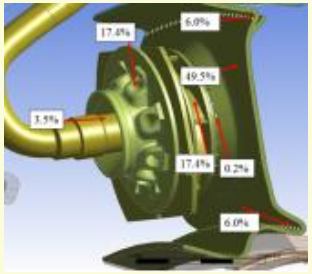
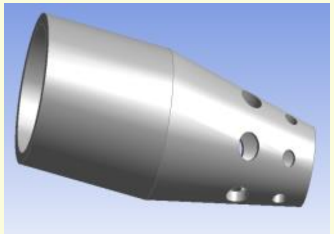
Exhaust Total Temperature [K]

2100 K



940 K

Comparison of the Jet Fuel to NG

	Air & Kerosene	Air & CH4 (Option C)
Design		
CO, ppm	276	42
NOx, ppm	74	33
Pattern factor	0.46	0.42

All values are at entrance to turbine's rotor blades in ppm (dry mass fraction)

$$Pattern\ Factor = \frac{T_{\max} - T_{avg}}{T_{avg} - T_{inlet}}$$

3. Validation of simulations under laboratory conditions:

- Design a reduced model of the combustor, operating at atmospheric pressure,

- Simulate performance at laboratory conditions,

- compare and calibrate CFD code

CFD Simulations for Kerosene – Test Conditions

Considered operating conditions:

Option	Inlet air temperature T_{air}, K	Inlet air velocity, m/s	Air mass flow rate, kg/s (for test rig)	Fuel mass flow rate, g/s (per atomizer)	Required heating power, kW (for test rig)
1	774	130*	0.33	2.5	170 (too high)
2	300	130	0.85	6.5	-
		50.4**	0.33	2.5	-
3	400	130	0.64	4.9	40
		67.2**	0.33	2.5	40

- Assuming stoichiometric conditions in Primary Zone
- Simulations were made for options 2 and 3.
- Three spray models were used: 1) pressure swirl, 2) solid cone, 3) hollow cone
- Only results of option 2 with solid cone are presented

* Taken from CFD simulations

** Parameters evaluated for CFD simulations

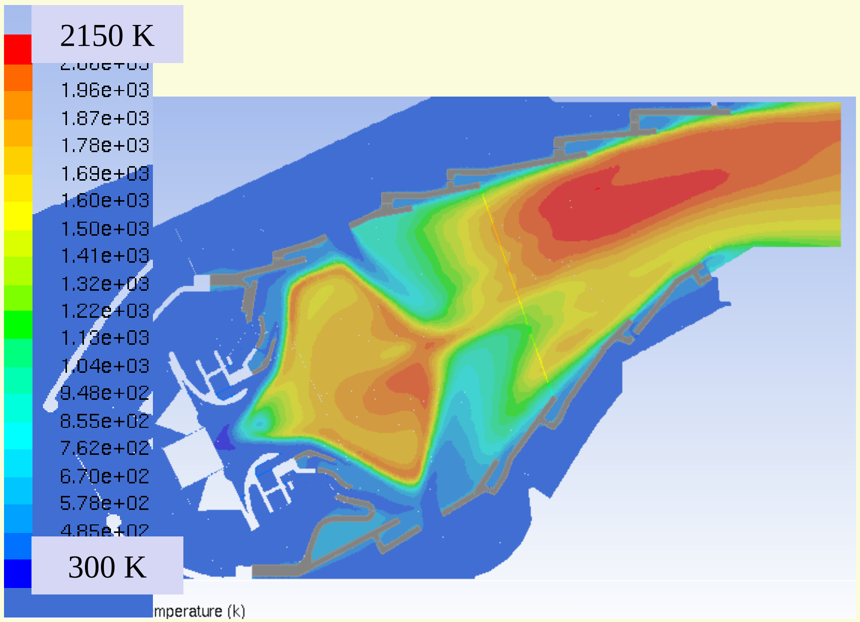
CFD Simulations for Kerosene – Test Rig Conditions

MAIN RESULTS: Effect of initial parameters:

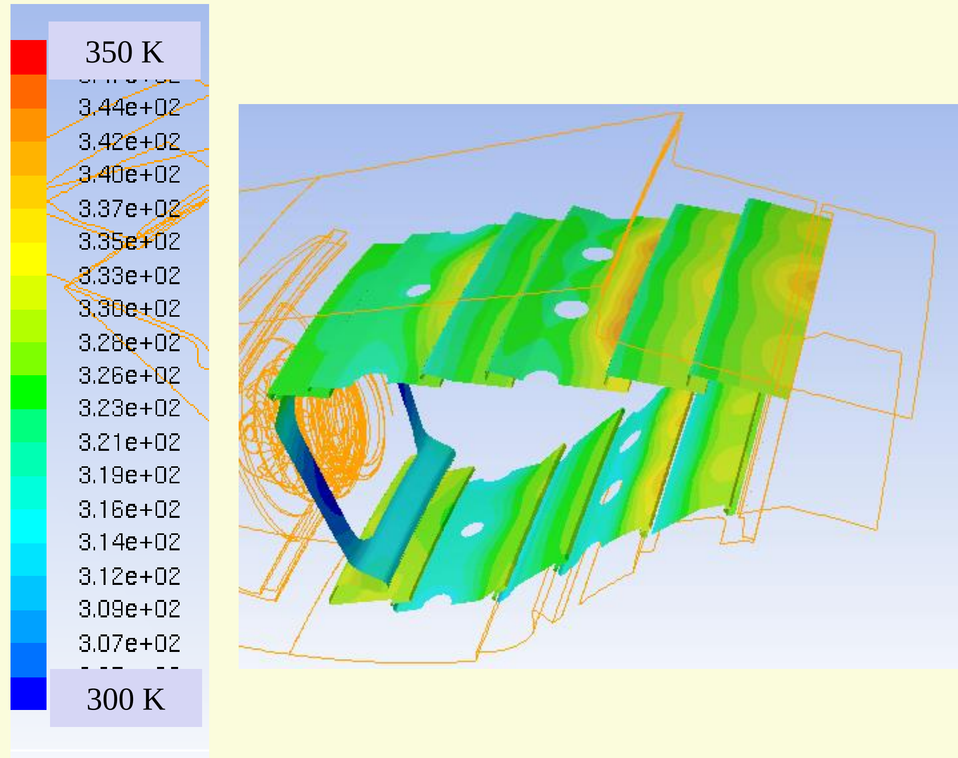
1. Stoichiometric equivalence ratio in combustion primary zone (ϕ=1), $P = 1\ bara\ \ T_{air\_inlet} = 774K$ – not applicable
2. ϕ=1 in primary zone, $T_{air\_inlet} = 300K$- simulations show low combustion efficiency quality under these conditions
3. ϕ=1 in primary zone, $T_{air\_inlet} = 400K$ – simulations show a significant increase in the combustion process quality. Air heater with at least 40kW power is needed.

CFD Simulations for Kerosene – Test Conditions
Solid Cone Atomizer, Pa= 1bar, Ta = 400K

Total Temperature [K]



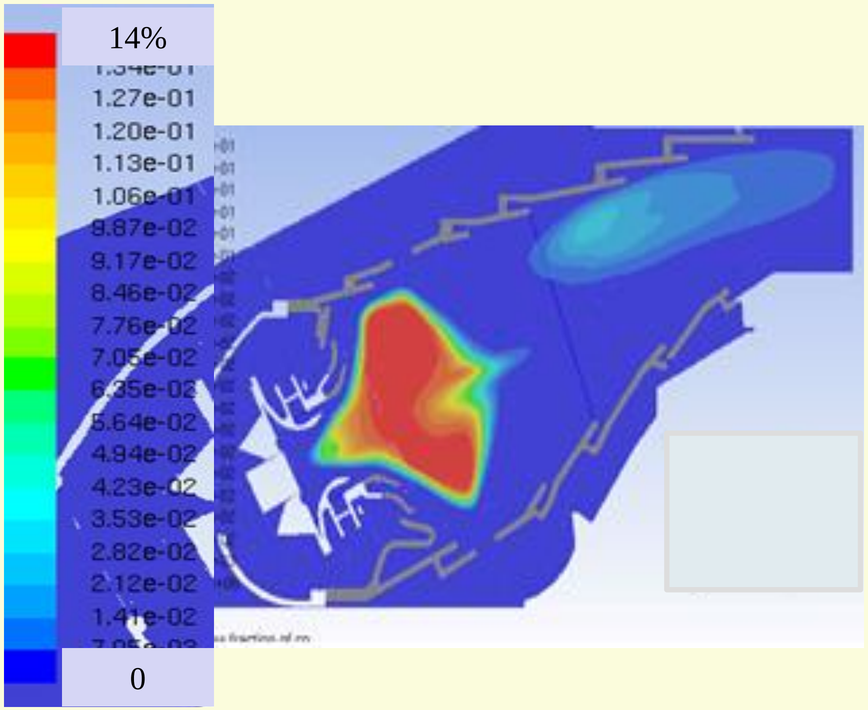
Liner Wall Temperature [K]

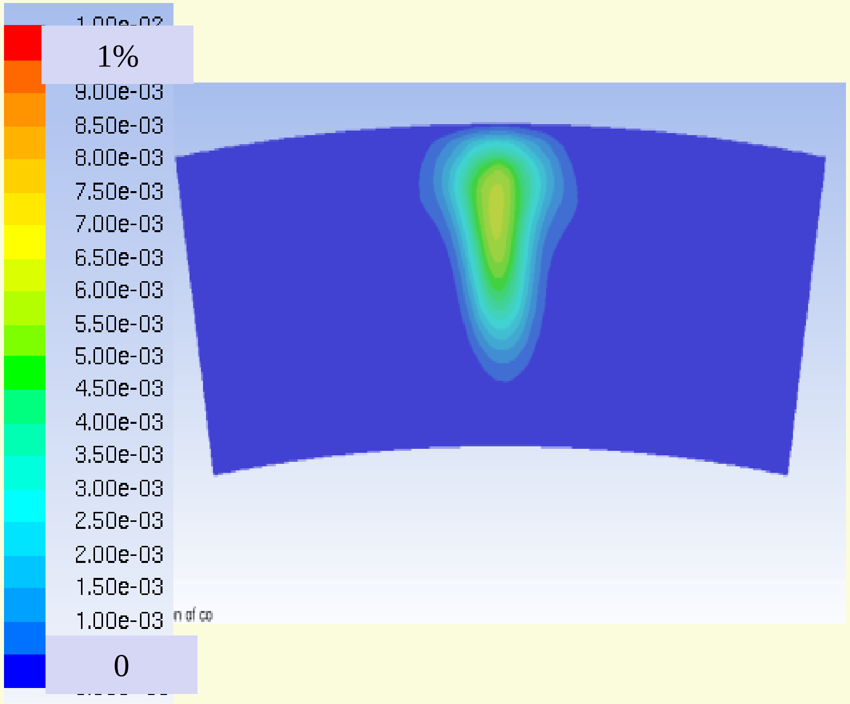


Incomplete reaction process within the combustor !

CFD Simulations for Kerosene – Test Conditions
SOLID CONE ATOMIZER, Ta = 400K

CO Mass Fraction



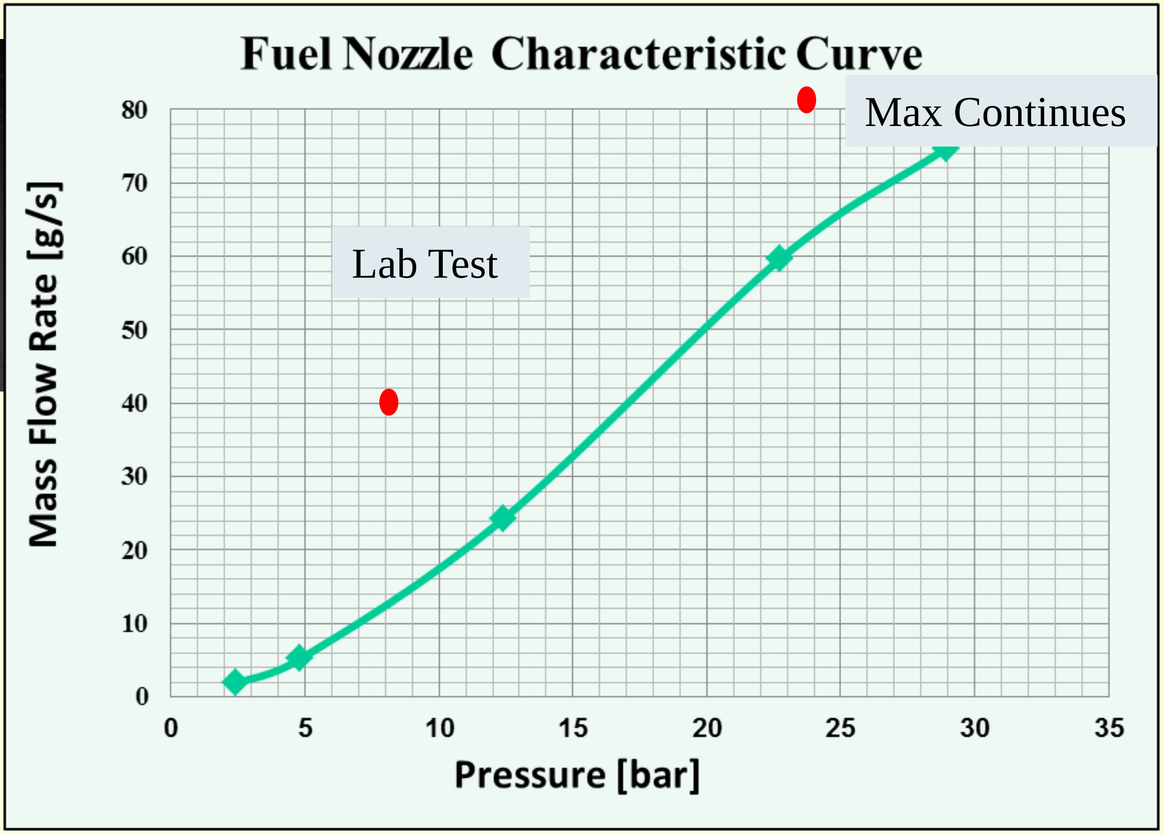


Summary of Jet Fuel Simulations – Test Conditions

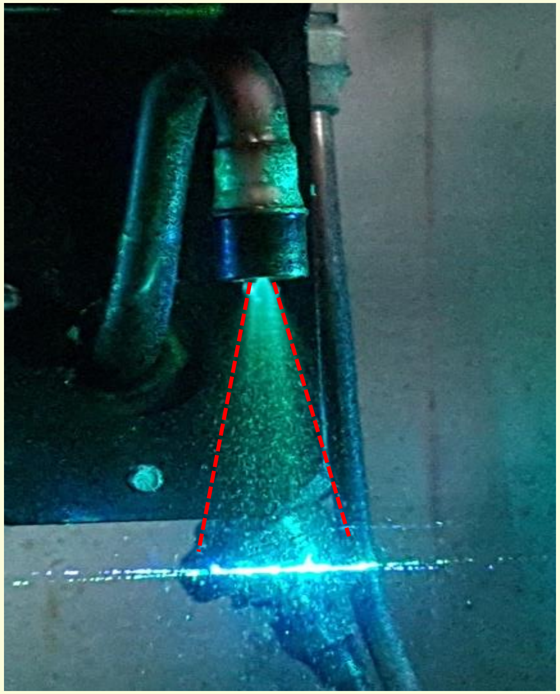
	Temperatures [K]			Velocity [m/s]	Concentrations [ppm] Mass fraction	%
	MWA exit	Max Section #1/#2	Max Wall	MWA	MWA CO	Unburned Fuel
Solid cone atomizer. Vp=5m/s, T_{air}=300K	1250	1999/1653	729	75.7	604	**11**
Solid cone atomizer. Vp=5m/s, Tair=400K.	1325	1993/1670	744	81	321	**9.8**

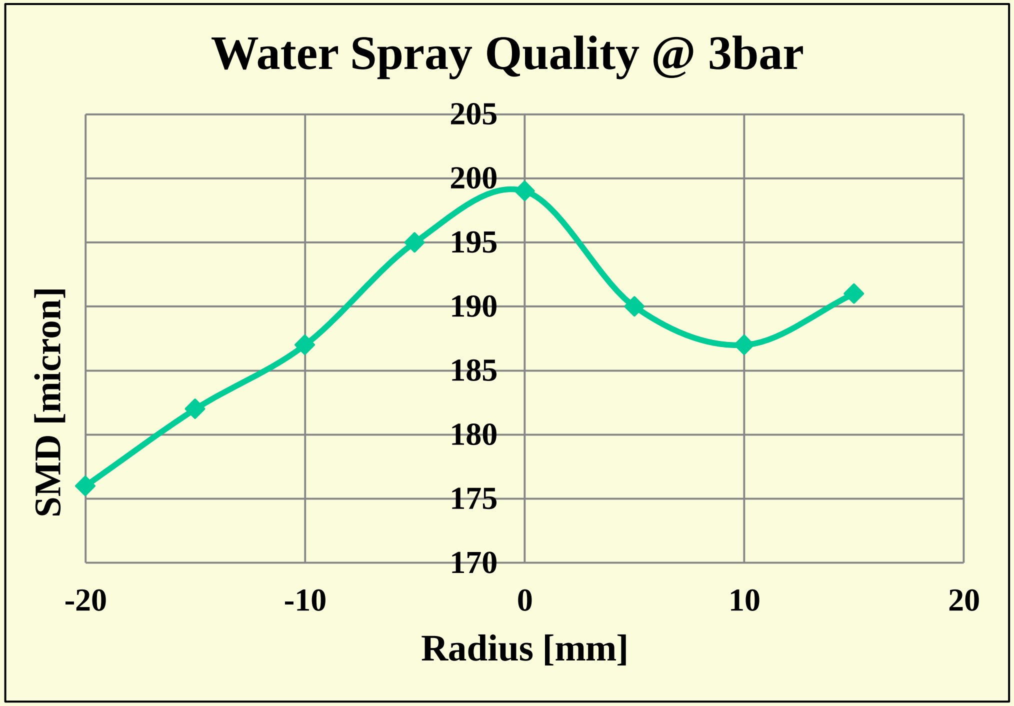
- Too much un-burnt fuel at the exhaust
- Pre - heating to at least 400k is needed !

Fuel Spray Pressure is Too Low …



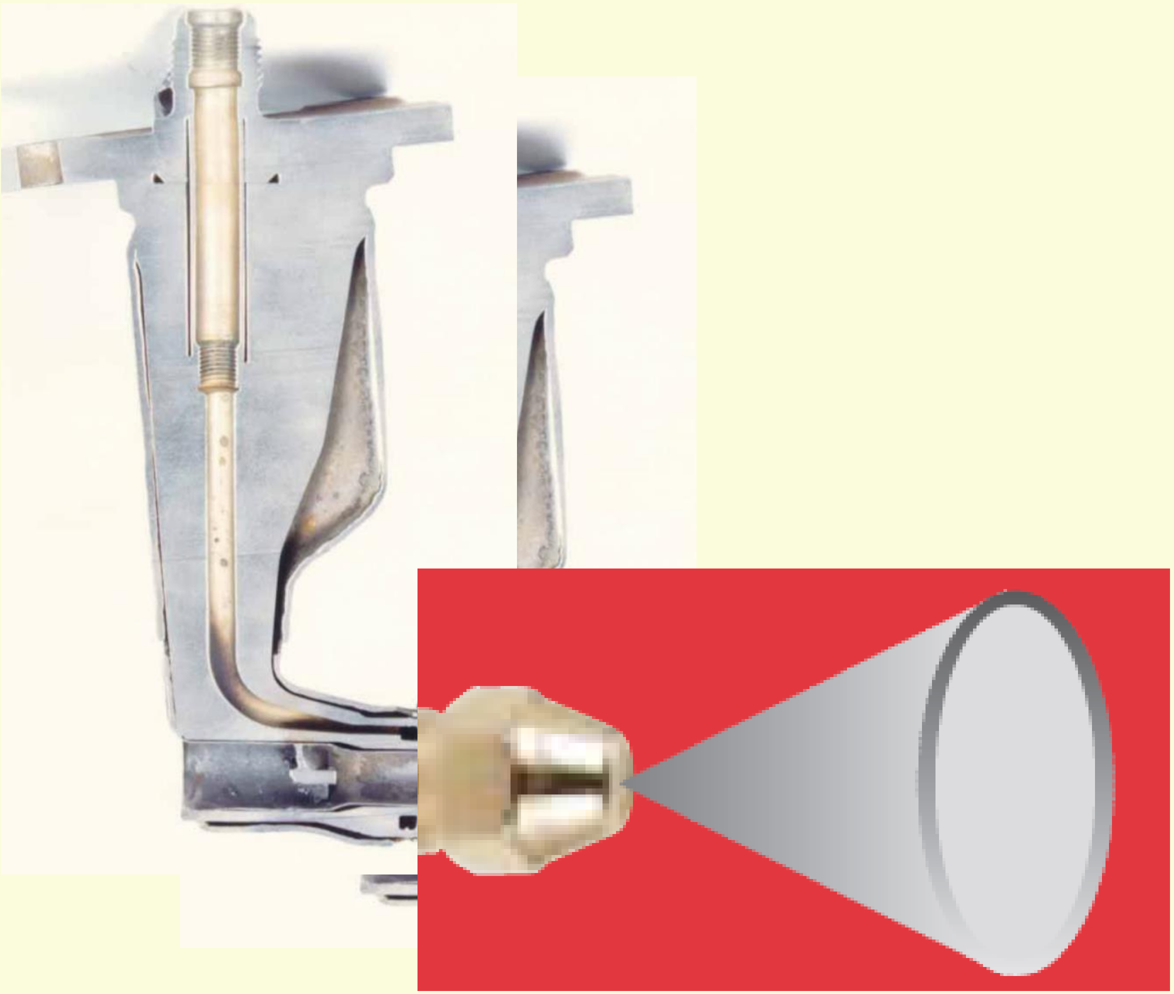
Low Fuel Spray Pressure



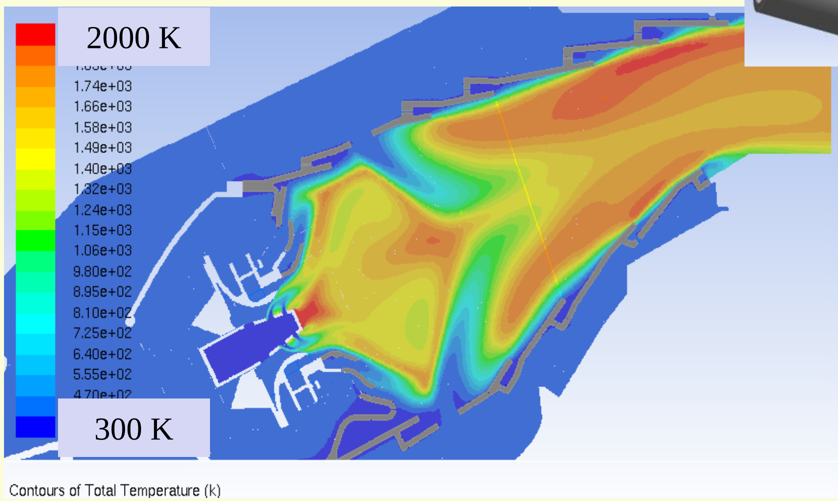


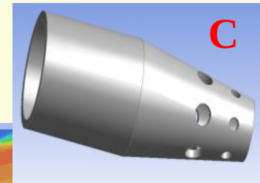
- Narrow spray angle
- Big droplets
- Spray test with the swirling air should be done
- Modifications of the atomizer are needed

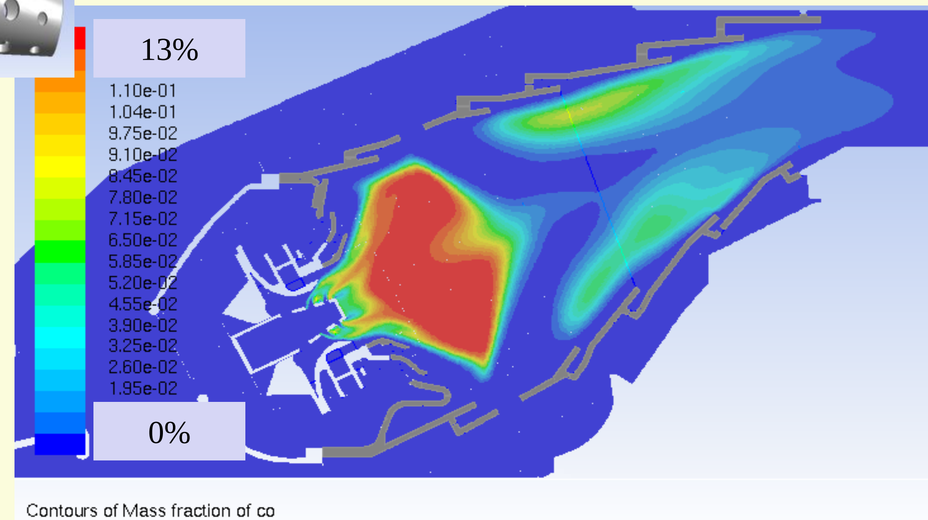
FUEL NOZZLE MODIFICATION



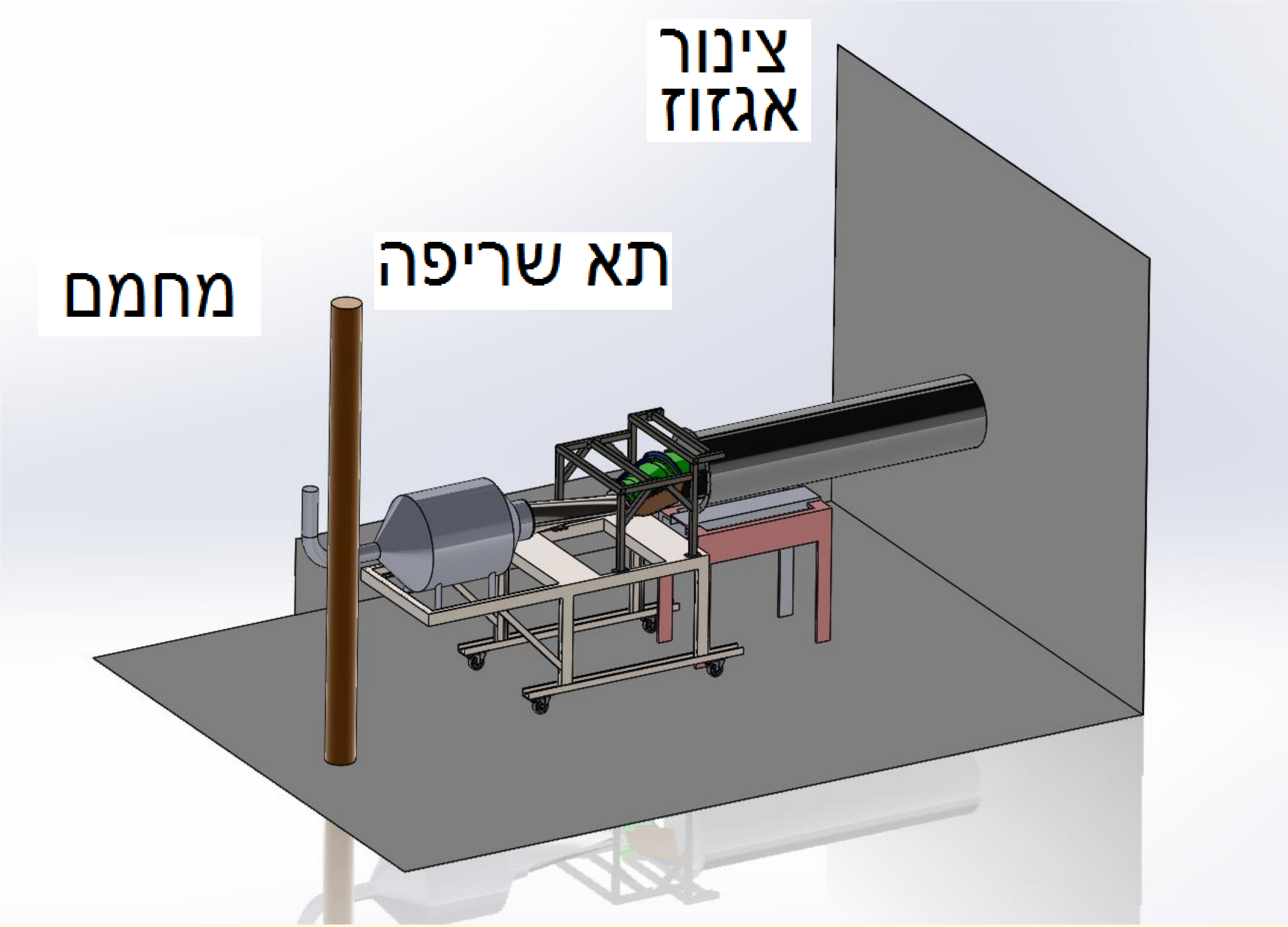
CFD Simulations for Methane – Test Conditions

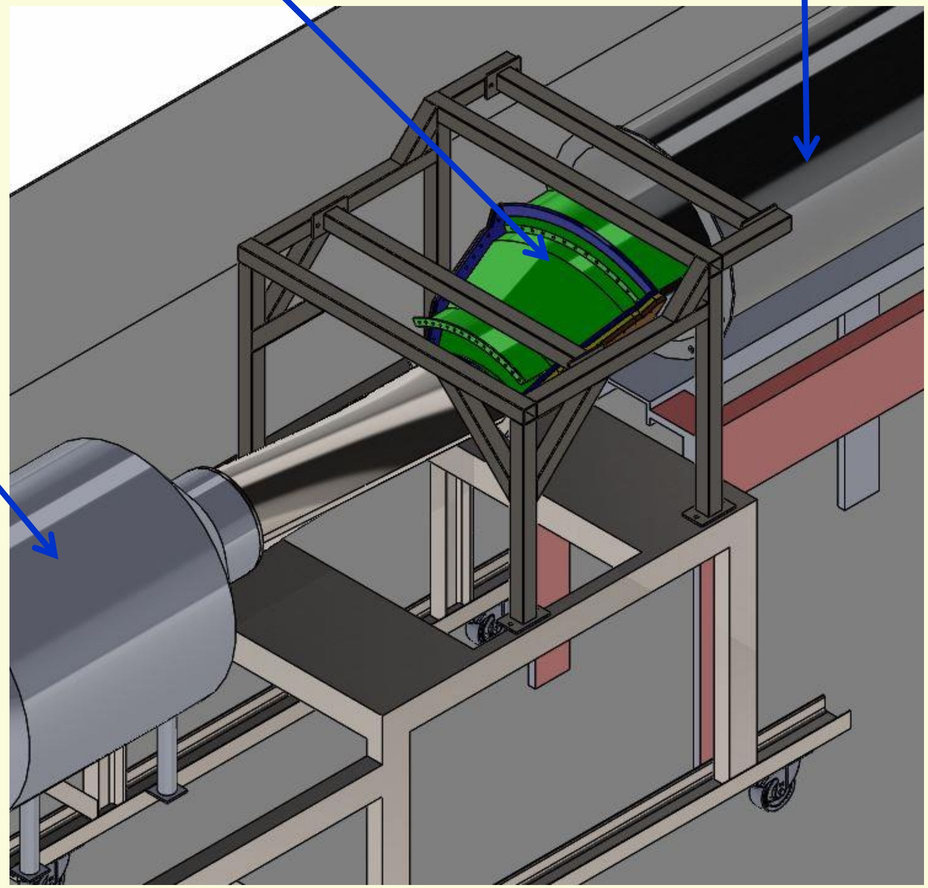


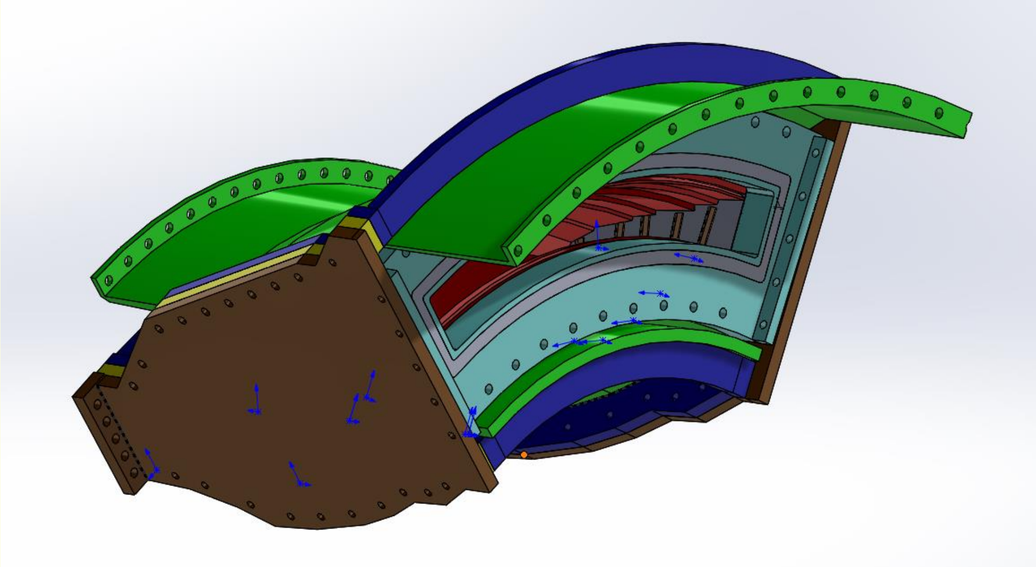


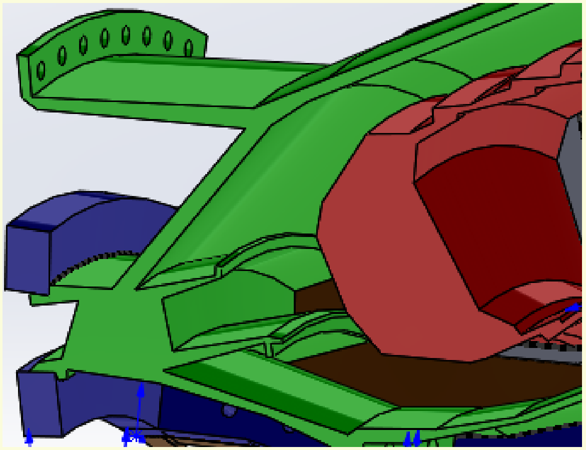


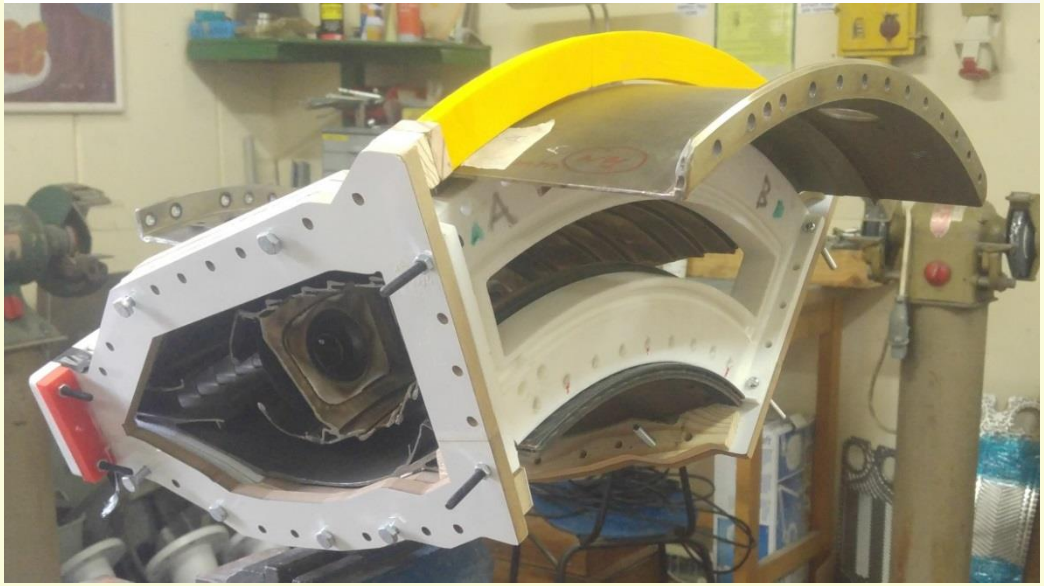
	Temperature, K			Velocity [m/s]	Mass fraction [ppm]		%
Option	**MWA** exit	**Max Liner Wall**	**Max Center Section**	**MWA**	**MWA CO**	**MWA NOx**	**Unburned Fuel**
P= 1 bar **T_{air}=400K**	1259	469	**2202**	79.4	706	0.3	0.8
P=22.6 bar, **T=774K**	1635	1227	**2278**	94.6	42	33	0.5


צינור
אגזוז
תא שריפה
מחמם


COMBUSTOR
MODEL
EXHAUST
HEATER





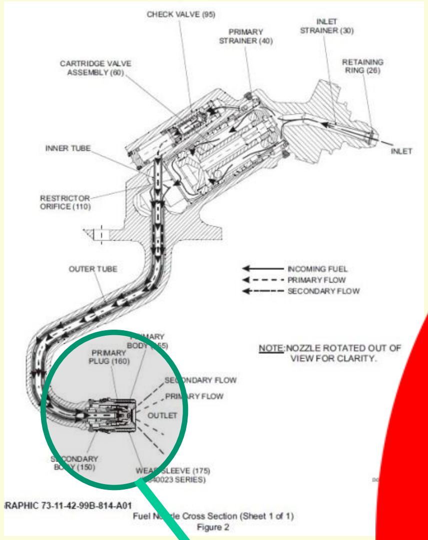


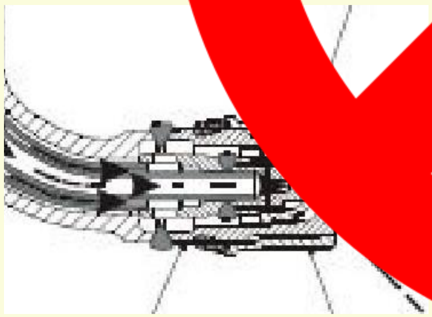
SUMMARY & CONCLUSIONS

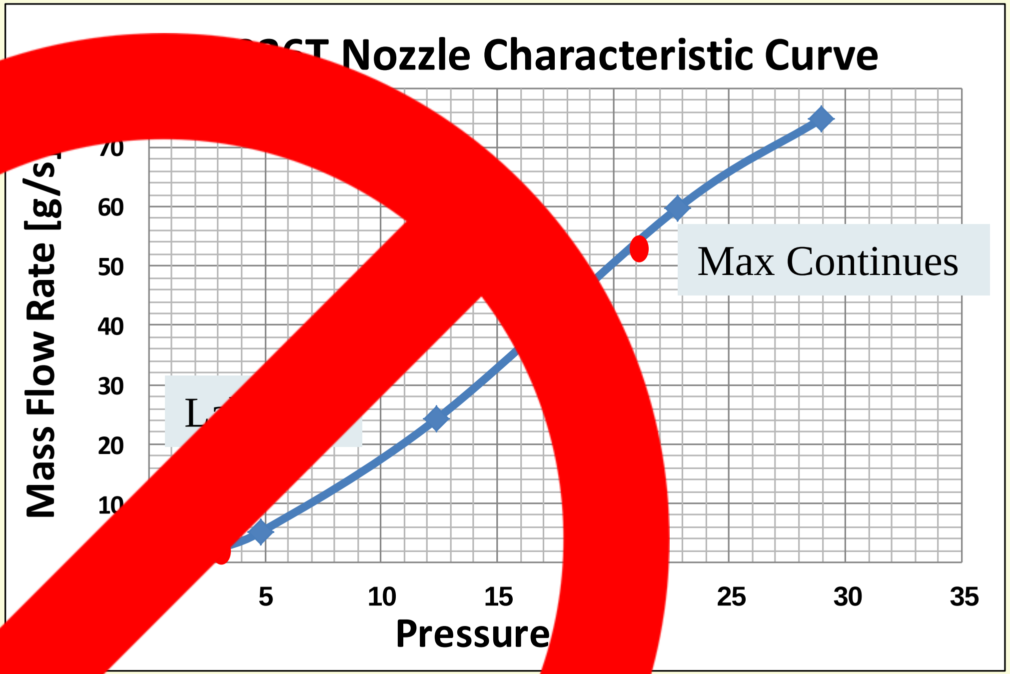
- Reference combustion data were obtained for jet fuel
- Following design iterations, NG fuel nozzles design was obtained with performance confirmed using CFD
- For validation, atmospheric pressure lab scaled model was designed, modeled by CFD and currently being constructed
- Once the model results are confirmed experimentally, we'll consider the full scale simulations as valid and proceed with further optimization using the CFD as part of the design tools.

The End

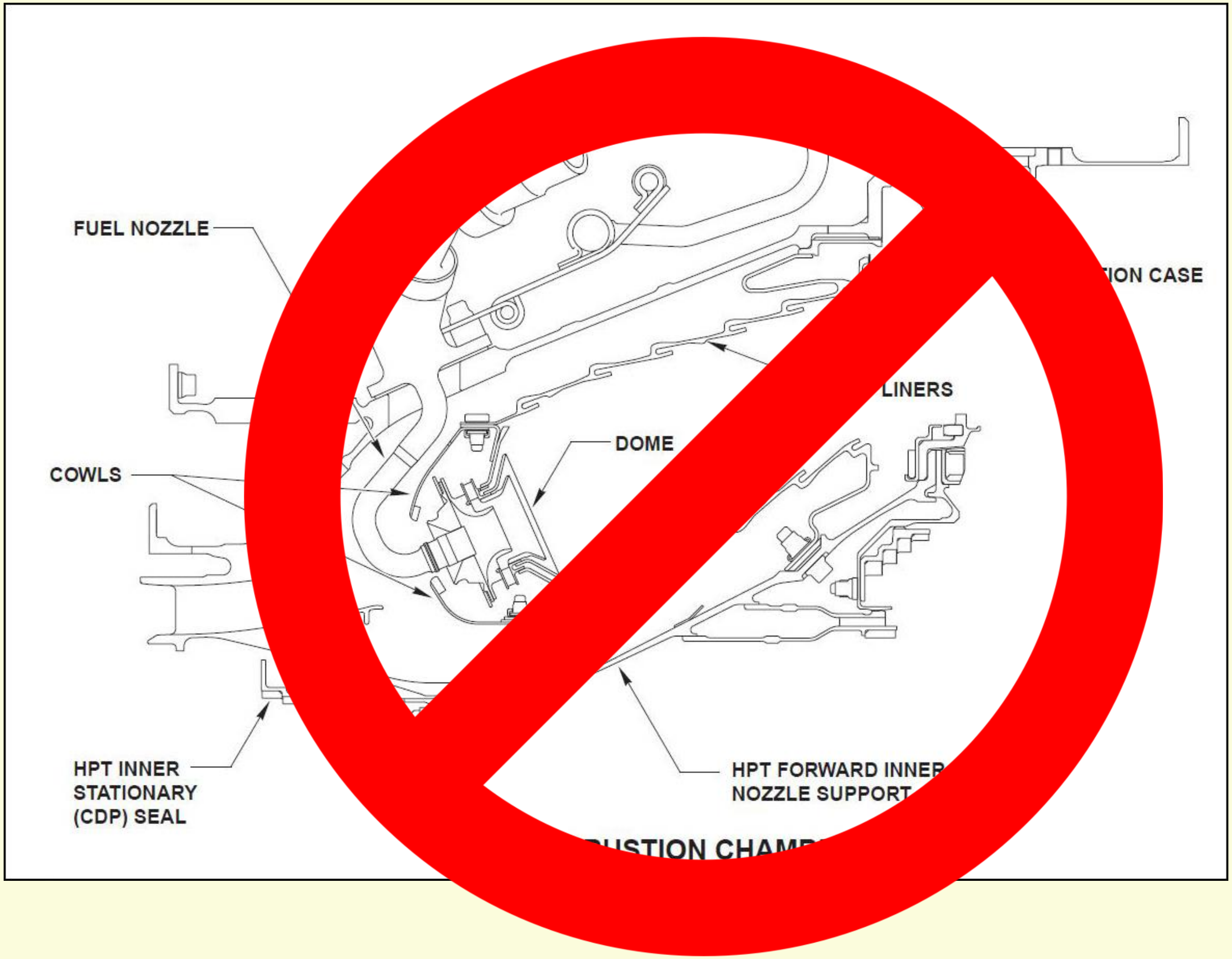
Fuel Spray Pressure is Too Low …



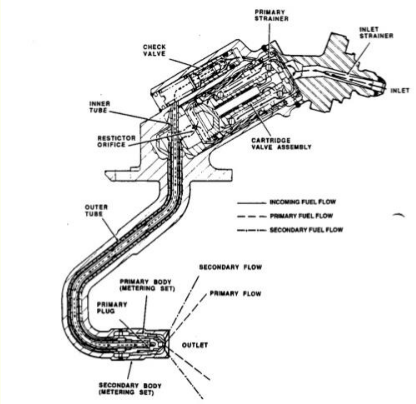




FUEL NOZZLE MODIFICATION


FUEL NOZZLE
LINERS
DOME
COWLS
HPT INNER
STATIONARY
(CDP) SEAL
HPT FORWARD INNER
NOZZLE SUPPORT


Combustion
Chamber



NORMAL OP[illegible]NG CONDITION

	Corrected data (standar[illegible] Conditions)			
	Thr[illegible]	Fuel Flow rate, lb/hr	[illegible] P[illegible]re, PS3 Psia	Static Inlet temperature, T3 deg K
Ground idle	8[illegible]	785.6[illegible]	39.2	418.22
Max Continues	21,[illegible]	[illegible]	328.2	774.2