A 100 H.P. TURBO-SHAFT

FEASIBILITY DESIGN

5 November 2015

- **In response to the AFRL competition per a feasibility study is presented of the competition requirements.**
- **The study expands and covers some gas turbines designs responding to UAV requirements replacing and improving exported piston engines to ISRAEL .**

USAF Offers $ 2M Prize For Lightweight Fuel-Efficient UAV Turbine

The U.S. Air Force Research Laboratory (AFRL) is kicking of f a competition to demonstrate a light weight , fuel-efficient turboshaft engine for unmanned aircraft and other applications with a $2 million prize at stake.

The Air Force Prize seeks a 100-bhp-class powerplant that can achieve the fuel efficiency of an internal-combust ion engine with the power-to-weight ratio of a gas turbine.
The winning engine will have twice the fuel efficiency of a turbine and power-to-weight ratio three times better than a piston engine.

To win, an engine must produce 50-100 bhp with a specific fuel consumption of no more than 0.55 lb./hp/hr. and power-t o-weight ratio of at least 2 hp/lb.
The engine must be a turbine and must run on Jet A fuel.

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ROTAX 914 PISTON ENGINE
0.8 HP/LB

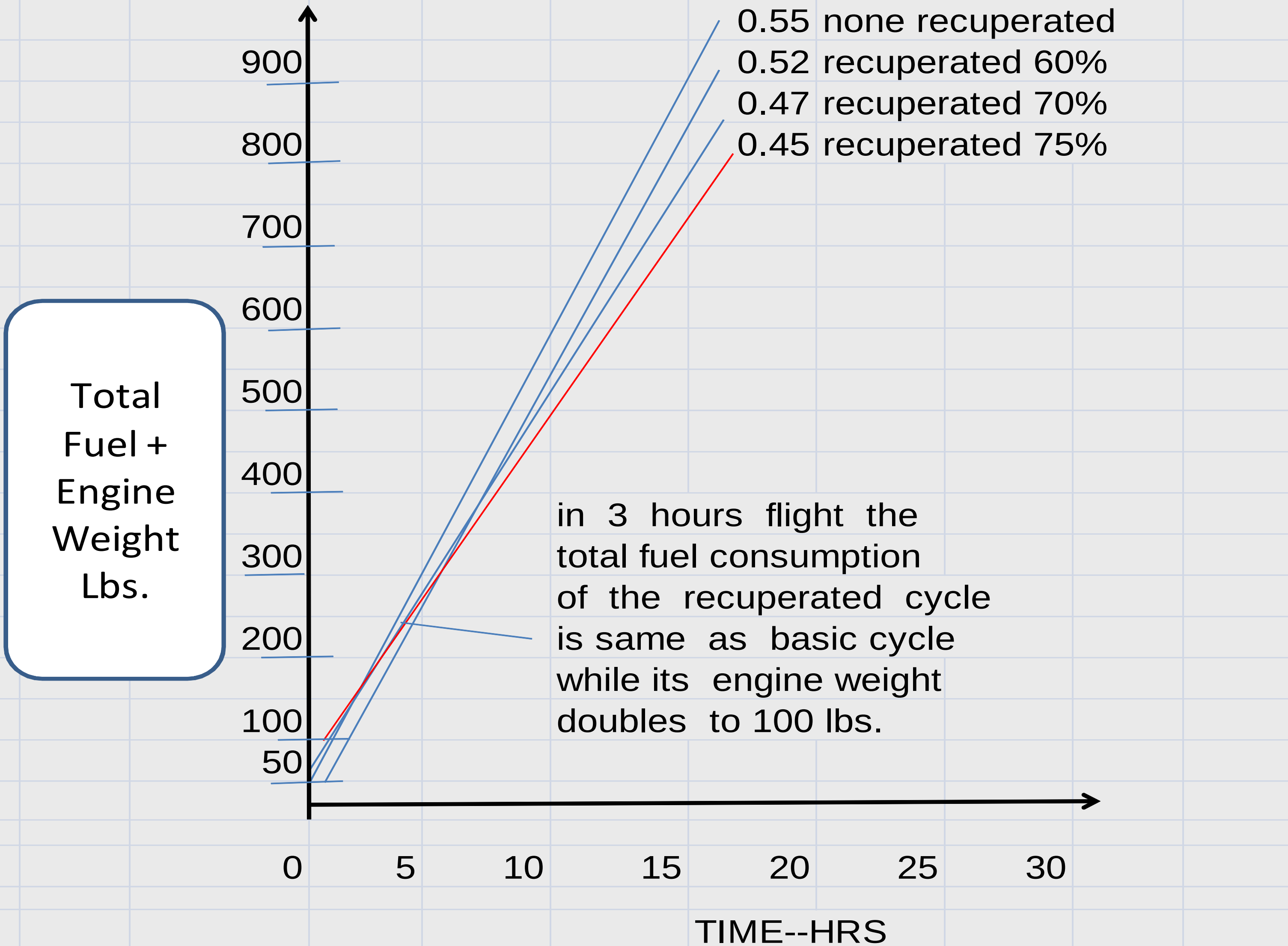
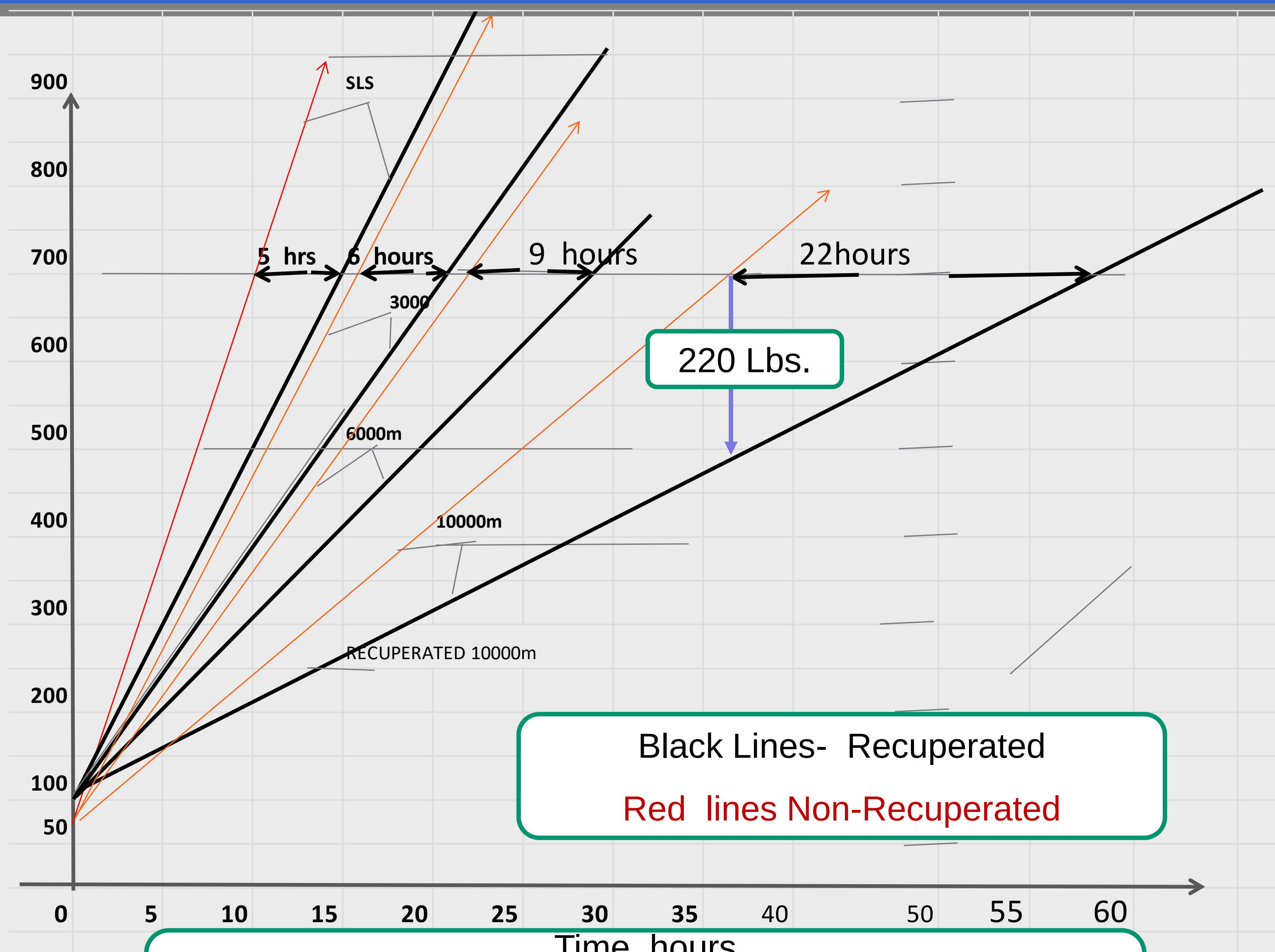


FIG.1--TOTAL FUEL+ENGINE WEIGHT AS FUNCTION OF FLIGHT TIME AT SLS CONDITIONS

Total Fuel + Engine Weight Lbs.



Black Lines- Recuperated

Red lines Non-Recuperated

Fig. 2 – Total Fuel + Engine Weight at Altitudes

1. For an operating time of less than 3 hours the none recuperated cycle is more effective-its total fuel and engine weight is less than the recuperated Cycle.

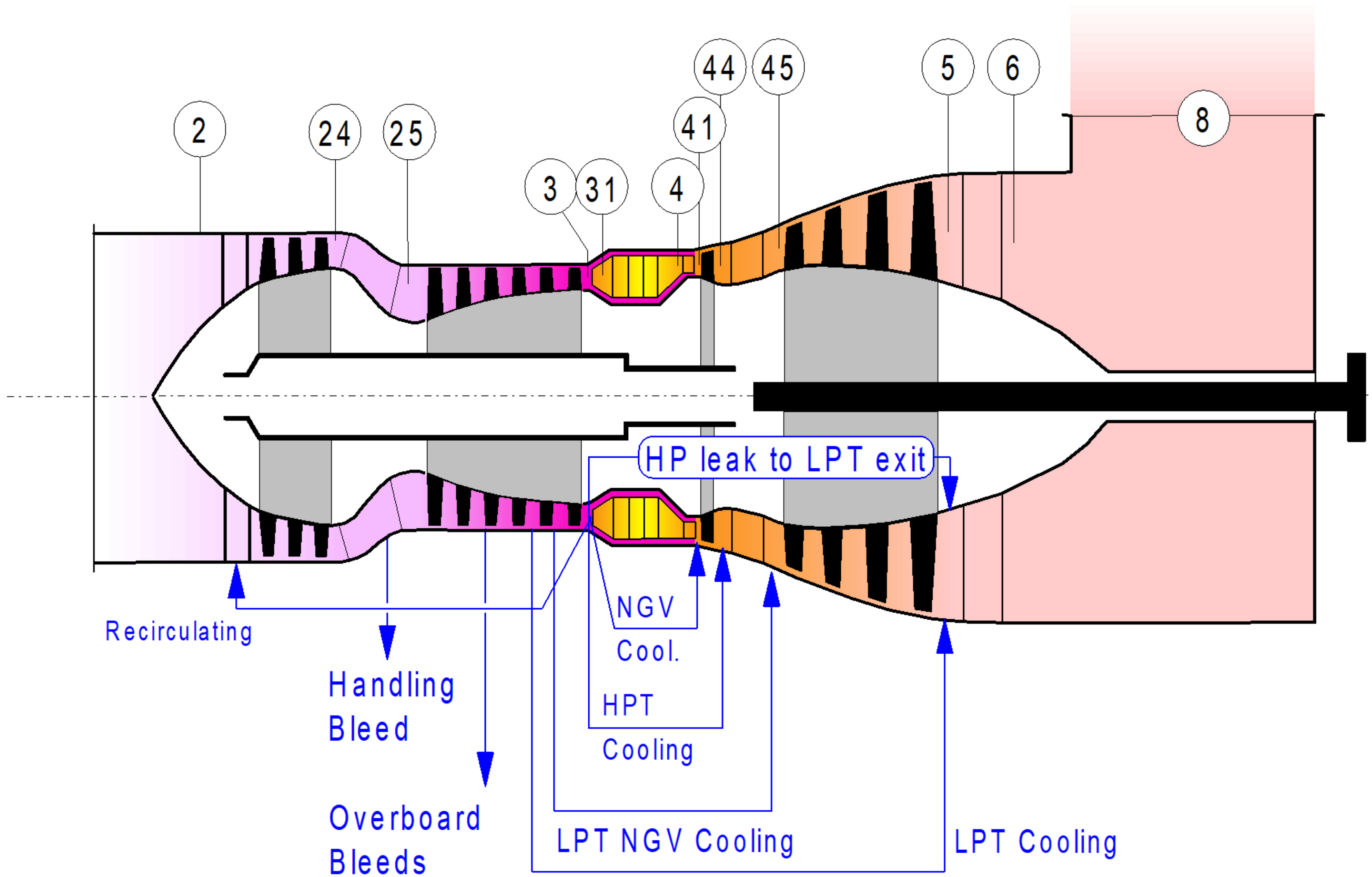
2. For operating time higher than 3 hours the recuperated cycle is more effective-improving with high altitudes

Feasibility designs

The following designs are presented-

1. A none recuperated high compressor pressure ratio cycle
2. A recuperated low compressor pressure ratio
3. A recuperated modified TG40 core engine

A 100 HP NONE RECUPERATED TURBOSHAFT



The conventional 2 spool none - recuperated cycle

- Thermodynamic cycle is presented in Table A
- Aerodynamic design
  - The first spool includes 2 centrifugal compressors and 2 axial turbines with abradable seals for high efficiencies. C.P.R=9.84. Un-cooled turbine rotor blades. T4=1300k. Higher temperatures are restricted due to cooling difficulty of small blades size.
  - The second spool is driving the propeller via a third axial free turbine., thus decreasing transmission size.
  - The components aerodynamic efficiencies have been optimized considering restrictions in size due to a small air mass flow of 0.35 kg/sec.
  - The thermal efficiency is barely 25% which makes the desired value very marginal.

UNRECUPERATED ENGINE STRUCTURAL DESIGN

- Structural design has used the following technologies to meet weight constraints-
- Using aluminum alloys for low pressure compressor and TiAl for high pressure compressor. Ceramics for turbine stators., sheet metal for combustor and casings instead of castings.Ceramic balls for bearings.
- Compact oil system-compact efficient radiator.
- The weight requirement of 50 lbs thus may be achieved.

	Weight Lbs
First spool	22.0
Second spool	8.5
Combustor	4.5
Ducts	4.0
Oil and Fuel system	6.0
Structure	5.0
Total	50

Table A- TG 100 NON-RECUPERATED CYCLE

Station	W (kg/s)	T (K)	P (kPa)	WRstd (kg/s)	
					PWSD = 73.6 kW
amb		287.98	101.325		
1	0.350	288.00	101.350		PSFC = 0.3321 kg/(kW*h)
2	0.350	288.00	101.350	0.350	Therm Eff= 0.25767
24	0.350	408.16	278.712	0.152	Heat Rate= 13971.4 kJ/(kW*h)
25	0.350	408.16	273.138	0.155	P2/P1 = 1.0000
3	0.350	634.58	955.984	0.055	P25/P24 = 0.9800
31	0.350	634.58	955.984		P3/P2 = 9.43
4	0.357	1310.00	917.745	0.084	WF = 0.00678 kg/s
41	0.357	1310.00	917.745	0.084	Loading = 100.00 %
42	0.357	1019.34	266.826		s NOx = 0.26700
43	0.357	1019.34	266.826		
44	0.357	1019.34	266.826		
45	0.357	1019.34	266.826	0.255	P45/P43 = 1.00000
49	0.357	839.19	105.461		
5	0.357	839.19	105.461	0.584	
8	0.357	839.19	103.351	0.596	P7/P6 = 1.00000
Bleed	0.000	634.58	955.980		WBld/W2 = 0.00000
---					P8/Pamb = 1.02000

(Table A- continued)

- Efficiencies:

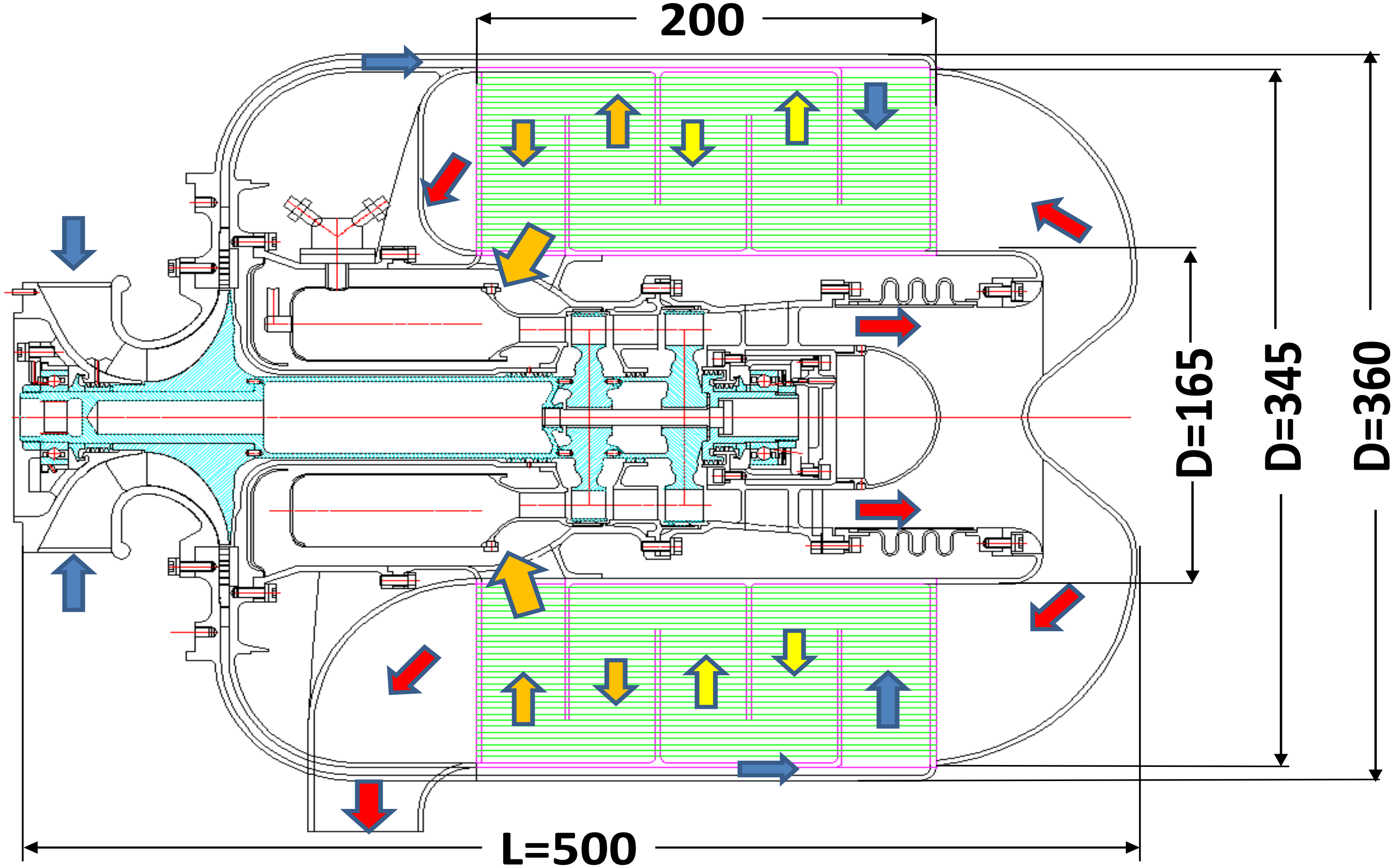
	isentr	polytr	RNI	P/P	
Booster	0.8000	0.8260	1.001	2.750	driven by HPT
Compressor	0.7500	0.7882	1.780	3.500	
Burner	0.9995			0.960	
HPT	0.8700	0.8519	1.539	3.439	
LPT	0.8600	0.8452	0.597	2.530	eta t-s =0.82844

- Generator 1.0000 PW_gen = 73.6 kW

- HP Spool mech. Eff 0.9990 Nom Spd 60,000 rpm
  LP Spool mech. Eff 0.9900 Nom Spd 60,000 rpm
  PT Spool Nom Spd 40,000 rpm

Gas Turbine engine with Recuperator

Power 100 HP, Air flow G=0.46 kg/s, Pressure ratio – 4.5, n=62000 rpm, T*=1285^{o}K, Recuperator Eff=70%, SFC=0.28 kg/kW*h



Cycle ?

Recuperated 2 spool design

- The recuperated 2 spool design cycle is presented in Table
- This cycle has 1 spool with 1 centrifugal compressor driven by an axial turbine and a second spool with a second axial turbine driving the load .
- The first spool is thus lighter than the first cycle-about 10 lbs less.
- A ceramic recuperator is placed between the compressor exit and the combustor heated by the exhaust gases.
- The recuperated weight depends on its heat transfer area and is calculated to be about 18 lbs for getting an effectiveness of 60% .
- The free turbine delivers 79.7 kw and the fuel consumption is 6.61gr/sec resulting in specific fuel consumption of 0.49 lb/hp.hr. which is better by 11% than the design requirements.

Weights – next slide

Recuperated 2 spool design

	Weight Lbs	
First spool	9.0	
Second spool	4.5	
Combustor	4.5	
Recuperator	18.0	
Ducts	5.0	
Oil and Fuel system	5.0	
Structure	4.0	
Total	50	

TABLE B-THE RECUPERATED CYCLE
Recuperator efficiency=60%

Station	W kg/s	T K	P kPa	WRstd kg/s	
					PWSD = **78.9 kW**
amb		287.98	101.325		
1	0.440	288.00	101.350		PSFC = 0.3015 kg/(kW*h)
2	0.440	288.00	99.323	0.450	**Therm Eff= 0.28376**
24	0.440	288.01	99.333	0.450	Heat Rate= 12686.6 kJ/(kW*h)
25	0.440	288.01	99.333	0.450	P2/P1 = 0.9800
3	0.440	486.54	446.998	0.130	P25/P24 = 1.0000
31	0.440	486.54	446.998		P3/P2 = 4.50
35	0.432	787.03	438.058	0.165	P35/P3 = 0.98000
4	0.438	1310.00	420.536	0.225	WF = 0.00661 kg/s
41	0.447	1300.34	420.536	0.229	Loading = 100.00 %
42	0.447	1135.45	216.689		s NOx = 0.42304
43	0.447	1135.45	216.689		
44	0.447	1135.45	216.689		
45	0.447	1135.45	216.689	0.415	P45/P43 = 1.00000
49	0.447	984.86	108.72		
5	0.447	984.86	108.722	0.771	
6	0.447	984.86	106.548		P6/P5 = 0.98000
8	0.447	707.19	103.351	0.687	P7/P6 = 0.97000
Bleed	0.000	486.54	446.997		WBld/W2 = 0.00000
--					P8/Pamb = 1.02000

Table B- The Recuperated Cycle – (continued)

- Efficiencies:

	isentr	polytr	RNI	P/P	A8 =0.00996 m^2
Compressor	0.7700	0.8119	0.981	4.500	
Burner	0.995			0.960	
HP Turbine	0.8700	0.8608	0.712	1.941	
LP Turbine	0.8600	0.8494	0.428	1.993	
Heat Exch.	**0.6000**				

- Generator 1.0000 PW_gen = 78.9 kW

- HP Spool mech. Eff 0.9990 Nom Spd 60,000 rpm
  LP Spool mech. Eff 0.9900 Nom Spd 60,000 rpm

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- Efficiencies:

	isentr	polytr	RNI	P/P	
Compressor	0.7800	0.8202	0.990	4.500	
Burner	0.9950			0.960	
HP Turbine	0.8700	0.8605	0.737	1.967	e444 th = 0.86916
LP Turbine	0.8700	0.8605	0.428	1.918	WHcl/W2 =0.00000
Heat Exch	**0.7000**				
Generator	1.0000				PW_gen = 75.4 kW

HP Spool mech. Eff 0.9980 Nom Spd 70,000 rpm WLcl/W2 = 0.00000

PT Spool mech. Eff 0.9900 Nom Spd 40,000 rpm eta t-s = 0.78210

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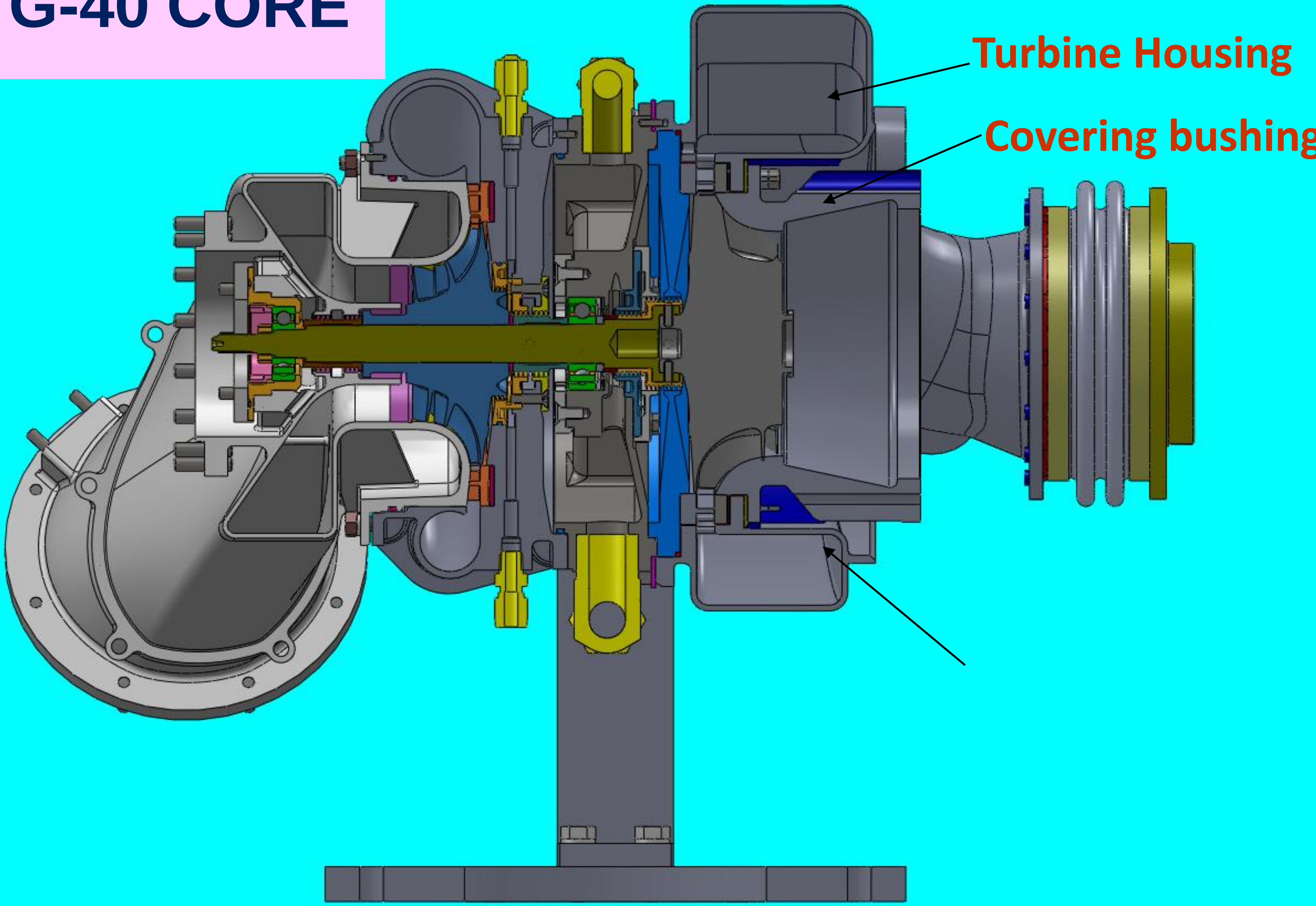
hum [%]	war	FHV	Fuel
0.0	0.00000	42.076	JP-10

A Recuperated modified TG-40 100 HP Core Design

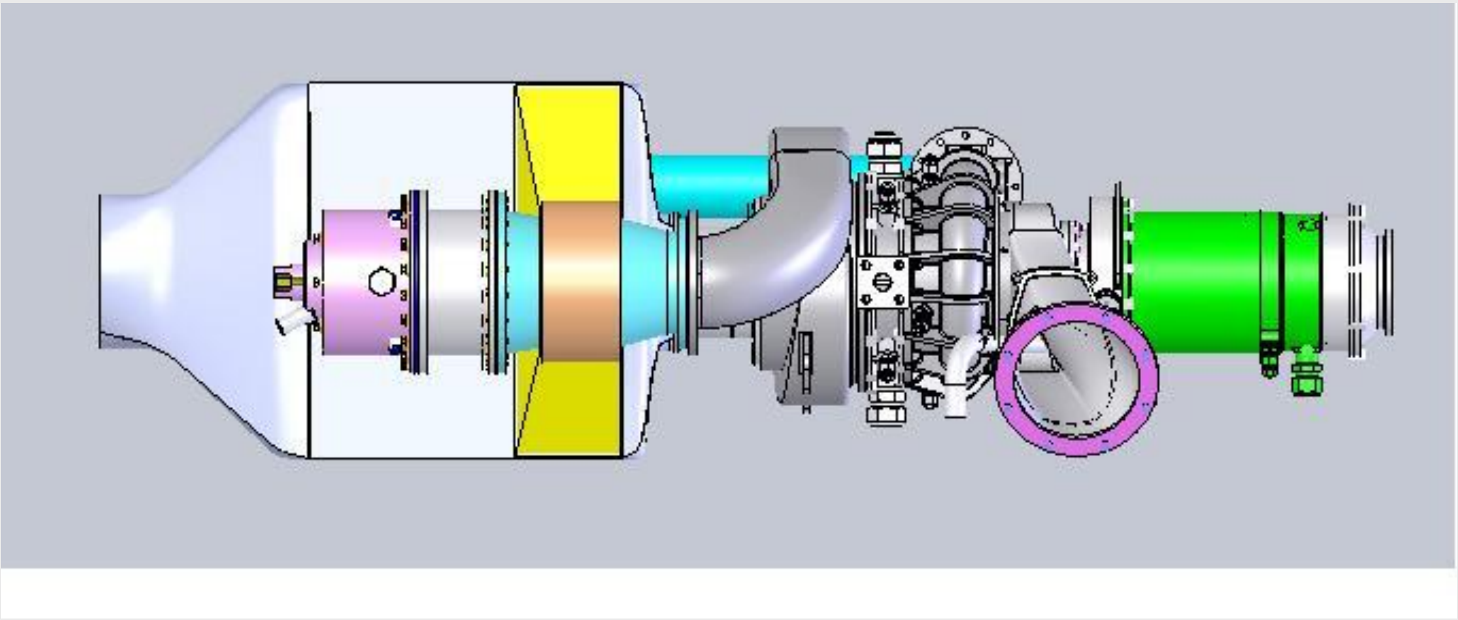
1. The TG-40 is modified as follows:
   - A new first compressor stage is placed before the existing stage raising the C.P.R to 4.6.
   - A fin and plate metallic recuperator is used.
2. The weight is 150 lb -1.5 lb per h.p. -see Table C
3. The fuel consumption-0.4 lb.hp.hr

Attractive solution compared to ROTAX 914-which has a ratio of 1.65 lb/hp and a fuel consumption of 0.48 lb/hp.hr.

TG-40 CORE



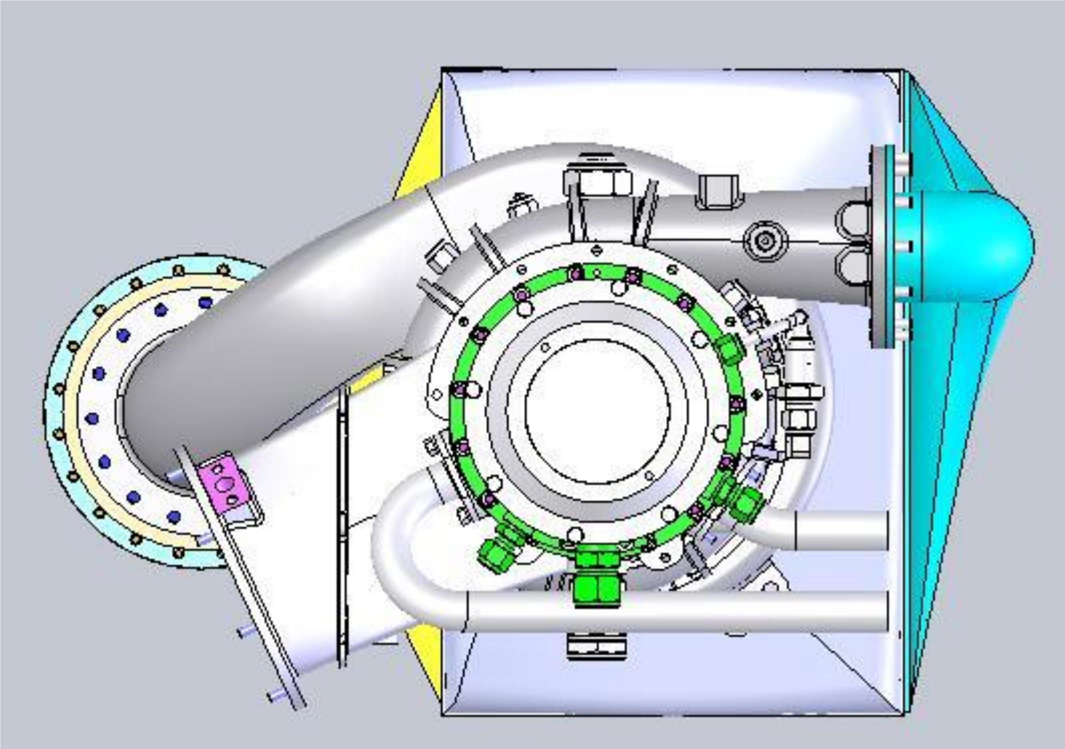
RECUPERATED 100 HP TURBOSHAFT SIDE VIEW



1030 mm

RECUPERATED 100 HP TURBOSHAFT
Rear VIEW

300 mm



460 mm

Recuperated 100 hp-TG-40 core

Station	W kg/s	T K	P kPa	WRstd kg/s			
					PWSD	=	88.1 kW
amb		288.15	101.325				
1	0.445	288.15	101.325		PSFC	=	0.2495 kg/(kW*h)
2	0.445	288.15	100.312	0.450	Therm Eff	=	0.34286
24	0.445	329.41	160.499	0.301	Heat Rate	=	10499.9 kJ/(kW*h)
25	0.445	329.41	160.499	0.301	P2/P1	=	0.9900
3	0.445	479.30	481.496	0.121	P25/P24	=	1.0000
31	0.436	479.30	481.496		P3/P2	=	4.80
35	0.422	820.18	467.051	0.155	P35/P3	=	0.97000
4	0.429	1310.00	448.369	0.207	WF	=	0.00611 kg/s
41	0.442	1296.03	448.369	0.212	Loading	=	100.00 %
42	0.442	1133.00	232.641		s NOx	=	0.51468
43	0.442	1133.00	232.641				
44	0.442	1133.00	230.315				
45	0.442	1133.00	230.315	0.386	P45/P43	=	0.99000
49	0.442	964.03	106.526				
5	0.442	964.03	106.526	0.769			
6	0.442	964.03	105.461		P6/P5	=	0.99000
8	0.442	644.38	103.351	0.648	P7/P6	=	0.98000
Bleed	0.009	479.30	481.496		WBld/W2	=	0.02000

Recuperated 100hp-TG-40 core

- Efficiencies:

	isentr	polytr	RNI	P/P		
					A8 =	0.00939 m²
Booster	1.0000	1.0000	0.990	1.600	driven by HPT	
Compressor	0.8000	0.8277	1.351	3.000	TRQ =	100.0 %
Burner	0.9950			0.960		
HP Turbine	0.8700	0.8609	0.762	1.927		
LP Turbine	0.8700	0.8588	0.456	2.162	eta t-s =	0.82185
Heat Exch	0.7000					

- Generator 1.0000 PW_gen = 88.1 kW

HP Spool mech. Eff 0.9950	Nom Spd 60,000 rpm	WHcl/W25 =	0.00000
LP Spool mech Eff 1.0000	Nom Spd 60,000 rpm	WLcl/W25 =	0.00000
PT Spool	Nom Spd 60,000 rpm	WBHD/W2 =	0.00000

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hum [%]	war	FHV	Fuel
60.0	0.00637	42.076	JP-10

Table C

Turbo shaft 100HP design - based on TG-40 core

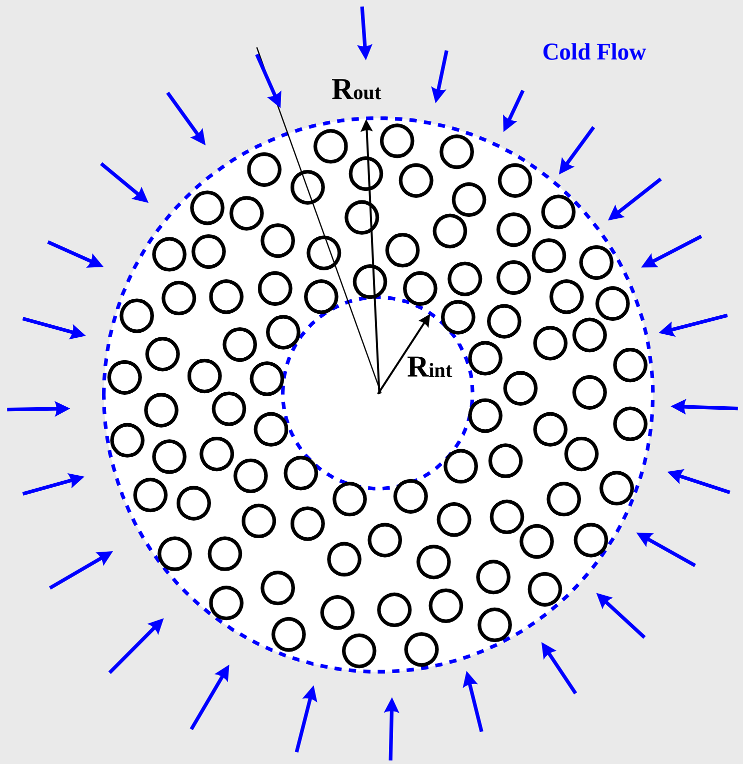
	unit	TG-40-commercial	TG-75-aerospace
Power-SLS	kw	42	75
Thermal efficiency	%	35.5%	31%
Power-6000m Mach=0.35	kw	29	50
Thermal efficiency-6000m Mach=0.35	%	39%	36%
Recuperator weight	kg	60	15
Total weight[without transmission]	kg	95	40
Total weight [with transmission]	kg	120	68
Power/weight	Kw/kg	0.35	0.92
Power/weight-w/o transmission	Kw/kg	0.45	1.85
“	Hp/lb	0.3	1.25
dimensions	mm	930*300*460	1030*300*460

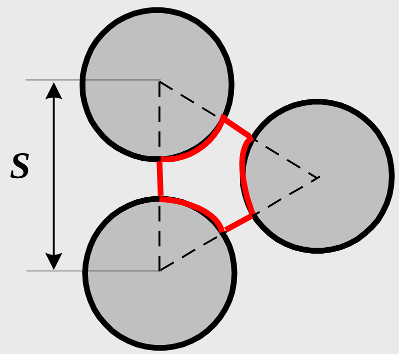
Ceramic tube Heat Exchangers

Hexoloy SA SiC tubes are used in shell and tube heat exchangers in the chemical process industry. Hexoloy's virtually universal corrosion resistance, high thermal conductivity and high strength allow for performance which cannot be equaled by other materials.

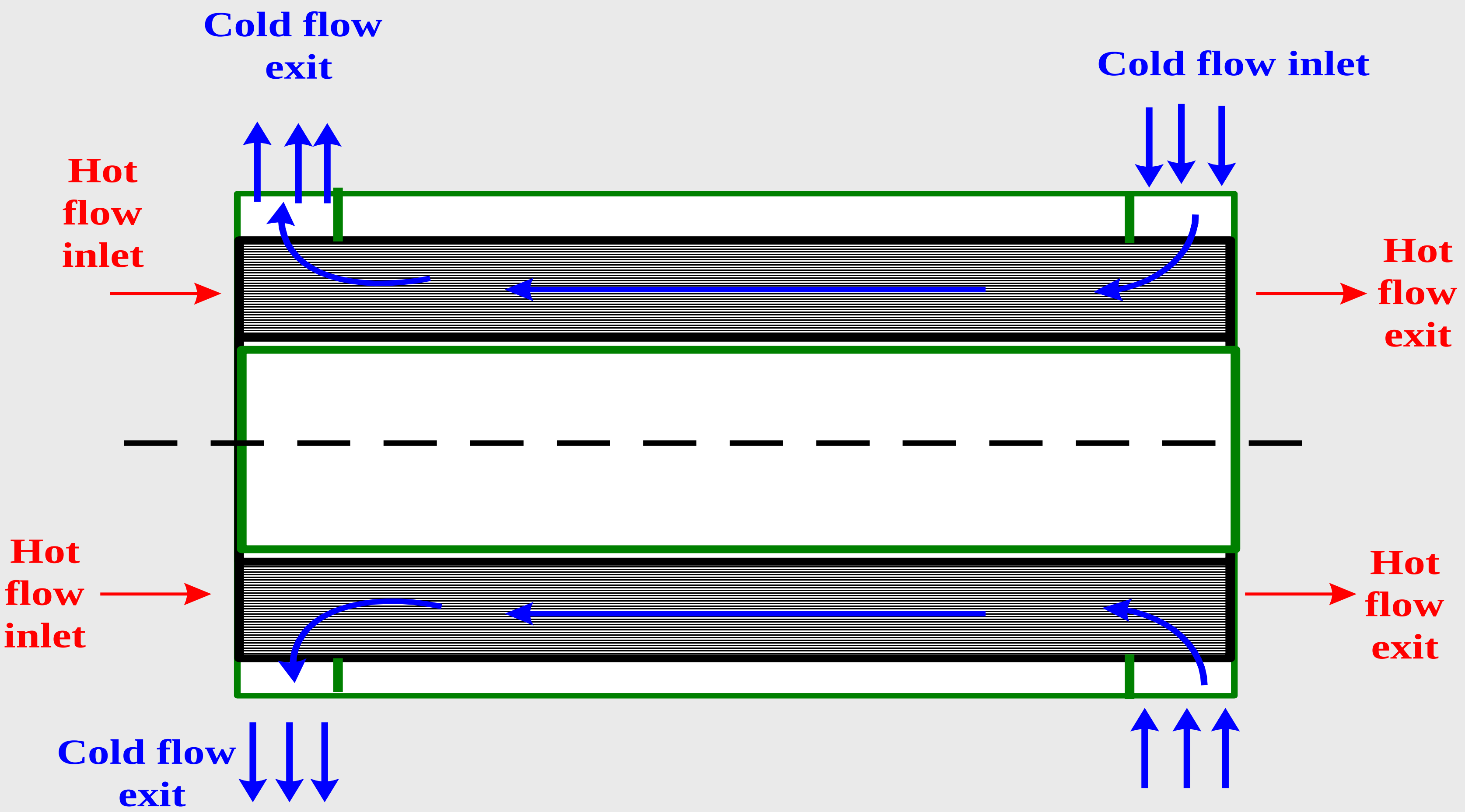
Tubes are available in a variety of diameters and in lengths of up to 14 feet.

Counter flow Recuperator





Counter flow Recuperator



COUNTER-FLOW
ARRANGEMENT

Table 2 Calculation Results for the additional run: D_{out} =360 mm, D_{in} =175 mm

Hot flow inlet parameters: $T_{hot,in}$= 941K; m_{hot} = 0.507 kg/s; Inlet pressure $P_{hot,in}$ = 1.076 bar;

Cold flow inlet parameters: $T_{cold,in}$= 480.5K; m_{cold} = 0.481 kg/s; $P_{cold\ ,in}$ = 4.17 bar;

See next slide

Case #	1	2
HX Flow configuration	**Counter Flow** **SiC tubes**	**Counter Flow** **SS316 tubes**
Outer core diameter D_{out} [mm]	360	360
Tube outer diameter, d_{out} [mm]	3.0	3.0
Tube internal diameter, d_0 [mm]	2.6	2.6
Tube relative pitch (distance between centers/d_{out})	1.1	1.1
Total number of parallel tubes, N_{tubes}	8242	8242
Total weight of the tubes: $W_{tubes} = N_{tubes} * W_{1tube}$, [kg]	13.88	33.93
Weight of two end plates and $(N_{pass}-1)$ baffles: $W_{endplates+buffles}$, [kg]	0.61	0.61
Total weight of the heat exchanger core, [kg] $W_{HX\ core} \approx W_{tubes} + W_{endplates}$	14.5	34.54
Internal heat transfer area, $\boldsymbol{A_{hot}}$, [m^2]	20.20	20.20
External heat transfer area, $\boldsymbol{A_{cold}}$, [m^2]	23.30	23.30
Hot flow (within tubes)		
Flow velocity within tubes, [m/s]	24.45	24.45
Reynolds number for flow within tubes: $\boldsymbol{Re_{hot}}$	840.6	840.6
Heat transfer coefficient within tubes: $\boldsymbol{h_{hot}}$, [W/(m^{2}K)]	85.9	85.9
Overall heat exchange coefficient from the hot side: $\boldsymbol{(A_{hot} * h_{hot})}$, [W/^{o}C]	1735.4	1735.4
Cold flow (outside the tubes)		
Cold flow cross sectional area: [m^2]	0.0195	0.0195
Free-flow velocity, (m/s): : $U_m = m_{cold} / (r_{cold} A_{free\text{-}flow\ cold})$, [m/s]	[illegible]1.4	11.4

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Table 2 Calculation Results –(continued)

Hydraulic diameter d_h , [mm]	1.00	1.00
Reynolds number $Re_{d,cold}$ based on the velocity U_m	762.6	762.6
Heat transfer coefficient: h_{cold}, [W/(m^{2}K)]	162.9	162.9
Overall heat exchange coefficient from the cold side: $(A_{cold} * h_{cold})$, [W/^{o}C]	3796	3796
Overall thermal conductance: [W/^{o}C] $(UA) = R_{HX}^{-1} = [(A_{hot} ´ h_{hot})^{-1} + (A_{cold} ´ h_{cold})^{-1}]^{-1}$	1190	1190
Number-Of-Transfer Units: $NTU = (UA)/(m\ Cp)_{hot}$	2.148	2.148
Heat capacity ratio: $R_{hc} = (m´Cp)_{hot} / m´Cp)_{cold}$	1.1608	1.1608
Thermal effectiveness (hot): $e = (T_{hot,in} - T_{hot,exit}) / (T_{hot,in} - T_{cold,in})$	**0.6996**	**0.6996**
Cold thermal effectiveness: ecold = (Tcold,exit –Tcold,in) / (Thot,in –Tcold,in)	0.756	0.756
Exit temperature of the hot flow: $T_{hot,exit}$, [^{o}C]	345.8	345.8
Exit temperature of the cold flow: $T_{cold,exit}$, [^{o}C]	581.4	581.4
Pressure drop in tubes DP_{hot} ,[mbar]	**15.0**	**15.0**
Cold flow Pressure drop: DP_{cold},[mbar]	**28.7**	**28.7**

SUMMARY

The study indicates that the recuperated cycle has 11% more chance to achieve the design goals than the none recuperated cycle provided that its recuperator weight is less than 18 lbs for an effectiveness of 60%.

Another advantage of using the recuperated design is that its fuel consumption decreases significantly with altitude which is not the case for the conventional cycle. <u>This allows us to increase the recuperator solution to 100 lbs and still be more effective in flight Duration above 3 hours.</u>

<u>An alternative attractive recuperated design is presented in which an existing core engine is upgraded Which results in superior performance.</u>

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