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Thermodynamic implications on turbines of hydrogen fired turbofan engines

Kennis als Vermogen

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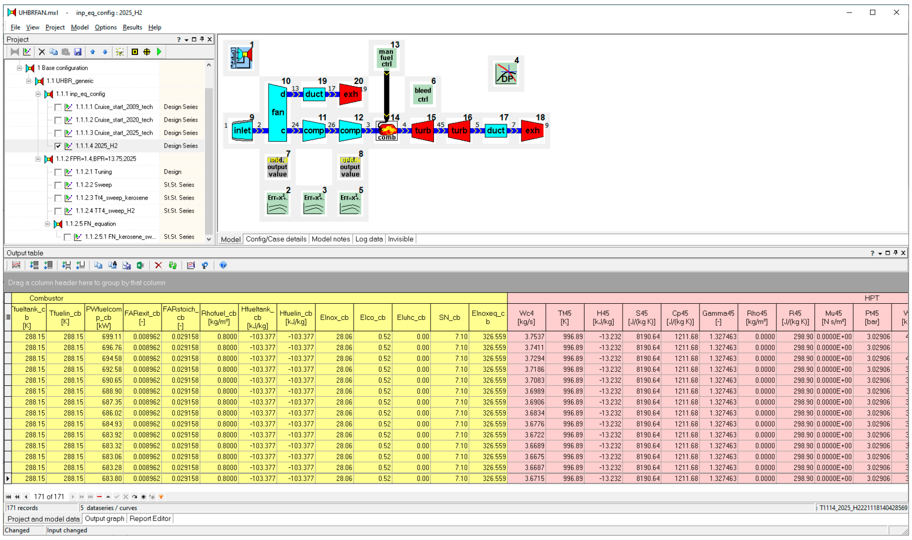
Royal NLR - Netherlands Aerospace Centre

Thermodynamic implications on turbines of hydrogen fired turbofan engines



- 1 Base configuration
  - 1.1 UHBR_generic
    - 1.1.1 inp_eq_config
      - ☐ 1.1.1.1 Cruise_start_2009_tech — Design Series
      - ☐ 1.1.1.2 Cruise_start_2020_tech — Design Series
      - ☐ 1.1.1.3 Cruise_start_2025_tech — Design Series
      - ☑ 1.1.1.4 2025_H2 — Design Series
    - 1.1.2 FPR=1.4;BPR=13.75;2025
      - ☐ 1.1.2.1 Tuning — Design
      - ☐ 1.1.2.2 Sweep — St.St. Series
      - ☐ 1.1.2.3 Tt4_sweep_kerosene — St.St. Series
      - ☐ 1.1.2.4 TT4_sweep_H2 — St.St. Series
      - 1.1.2.5 FN_equation
        - ☐ 1.1.2.5.1 FN_kerosene_sw... — St.St. Series

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Combustor													HPT									
Tfueltank_cb [K]	Tfuelin_cb [K]	PWfuelcomp_cb [kW]	FARexit_cb [-]	FARstoich_cb [-]	Rhofuel_cb [kg/m³]	Hfueltank_cb [kJ/kg]	Hfuelin_cb [kJ/kg]	EInox_cb	EIco_cb	EIuhc_cb	SN_cb	EInoxeq_cb	Wc4 [kg/s]	Tt45 [K]	H45 [kJ/kg]	S45 [J/(kg K)]	Cp45 [J/(kg K)]	Gamma45 [-]	Rho45 [kg/m³]	R45 [J/(kg K)]	Mu45 [N s/m²]	Pt45 [bar]
288.15	288.15	699.11	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.7537	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	696.76	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.7411	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	694.58	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.7294	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	692.58	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.7186	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	690.65	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.7083	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	688.90	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.6989	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	687.35	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.6906	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	686.02	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.6834	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	684.93	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.6776	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	683.92	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.6722	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	683.32	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.6689	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	683.06	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.6675	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	683.28	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.6687	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906
288.15	288.15	683.80	0.008962	0.029158	0.8000	-103.377	-103.377	28.06	0.52	0.00	7.10	326.559	3.6715	996.89	-13.232	8190.64	1211.68	1.327463	0.0000	298.90	0.0000E+00	3.02906

171 records | 5 dataseries / curves | T1114_2025_H2221118140428569

Problem area

Reduced emission goals drive the research for using alternative aviation fuels. Hydrogen is an alternative fuel that is a candidate to be used in aviation (due to the volume, liquid hydrogen is considered a solution for aircraft fuel). The thermodynamic implications have not been well investigated or reported. This study will look into the thermodynamic loading of gas turbines design for hydrogen as well as retrofitting existing hydrocarbon jet fuel designs to be fuelled by hydrogen. Efficient Ultra-High Bypass Ratio (UHBR) turbofan engines having a high propulsive efficiency are used in this study.

Description of work

A generic UHBR turbofan model for NLR's Gas turbine Simulation Program, GSP, (from a previous study in determining the most efficient combination of fan pressure ratio, FPR, and bypass ratio, BPR) is used to calculate various hydrogen and hydrocarbon turbofan designs. An slightly adapted version of the model is used for simulating a retrofit turbofan engine that uses hydrogen as fuel while being designed to run on hydrocarbon jet fuel.

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Turbofan
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Results and conclusions

The simulations show that the optimum design point for a hydrogen design is different (optimum at higher BPR (ByPass Ratio) for given FPR (Fan Pressure Ratio)) than hydrocarbon jet fuel design running on pure hydrogen. The low pressure turbine (LPT) entry and exit temperature are higher for equivalent FPR and BPR values compared to the hydrocarbon jet fuel designs. For a retrofit gas turbine fuelled by hydrogen, the combustor temperature is lower compared to hydrocarbon jet fuel for equivalent thrust performance. For equivalent combustor exit temperature performance, the turbofan spool speeds are higher and may exceed design limits to negatively impact life expectancy. In the retrofit UHBR turbofan, the LPT entry and exit temperature are lower when fuelled by hydrogen compared to hydrocarbon jet fuel, while respecting all engine limits.

It is concluded that pure hydrogen UHBR designs will differ from the current hydrocarbon jet fuel designs as the core has a higher energy density, the optimum BPR is therefore higher for a given FPR. A higher average low pressure turbine temperature is foreseen which may implicate alternative designs (e.g. more cooling or different materials or coatings) to respect current life limits.

Modifying an existing turbofan engine to be fuelled by hydrogen would be possible as the thrust performance can be met at lower combustor exit temperatures while an increase in the life expectancy of the LPT is expected as the average operating temperature is lower compared to hydrocarbon jet fuel.

Applicability

This study gives insight into the implications of using hydrogen designed or hydrogen retrofitted turbofan engines. The results are interesting for after-market component developers that design and sell turbine related components like e.g. seals and blades.

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Summary

Hydrogen is considered to be a sustainable alternative aviation fuel (when produced from renewable energy sources) for the future as an alternative to kerosene (hydrocarbon) jet fuel. However, hydrogen, either liquid or compressed is quite a different fuel with different fuel properties. The thermodynamic implications on turbines for commercial turbofans is investigated in this report using Ultra-High Bypass Ratio (UHBR) turbofan engines.

NLR's Gas turbine Simulation Program (GSP) is perfectly capable to simulate effects of using alternative fuels on new and existing design turbofan engines. The main reasons for this are that the GSP real gas model is derived from the NASA CEA (Chemical Equilibrium and Applications) model and offers the capability of using user-defined fuels. The different fuel properties cause a different thermodynamic profile which requires explorative calculations in GSP with hydrogen as fuel to gain understanding, insight and trust in the calculated results.

The thermodynamic implications in this study are focussed on the turbines when using hydrogen as fuel for a gas turbine designed for hydrogen or for an existing gas turbine designed for kerosene (retrofitting). It should be noted that when retrofitting existing engines for hydrogen, the fuel injection system and the combustor have to be modified.

A generic, configurable GSP gas turbine model of a UHBR turbofan is used for a hydrogen fuelled gas turbine design (exploration of fan pressure ratio, FPR, and bypass ratio, BPR) and a conventional hydrocarbon jet fuel design retrofitted to use hydrogen.

The simulations show that the optimum design point for a hydrogen design is different (optimum at higher BPR (ByPass Ratio) for given FPR (Fan Pressure Ratio)) than hydrocarbon jet fuel design running on pure hydrogen. The low pressure turbine (LPT) entry and exit temperature are higher for equivalent FPR and BPR values compared to the hydrocarbon jet fuel designs. For a retrofit gas turbine fuelled by hydrogen, the combustor temperature is lower compared to hydrocarbon jet fuel for equivalent thrust performance. For equivalent combustor exit temperature performance, the turbofan spool speeds (LP and HP) are higher and may exceed design limits thus negatively impact life expectancy. In the retrofit UHBR turbofan, the LPT entry and exit temperature are lower when fuelled by hydrogen compared to hydrocarbon jet fuel, while respecting all engine limits.

It is concluded that pure hydrogen UHBR designs will differ from the current hydrocarbon jet fuel designs as the core has a higher energy density, the optimum BPR is therefore higher for a given FPR. A higher average low pressure turbine temperature is foreseen which may implicate alternative LPT designs (e.g. more cooling or different materials or coatings) to respect current life limits.

Modifying an existing turbofan engine to be fuelled by hydrogen would be possible as the thrust performance can be met at lower combustor exit temperatures while an increase in the life expectancy of the LPT is expected as the average operating temperature is lower compared to hydrocarbon jet fuel.

Contents

Abbreviations

ACRONYM	DESCRIPTION
3	Subscript used to denote compressor exit (combustor entry) station
4	Subscript used to denote combustor exit (HPT entry) station
45	Subscript used to denote HPT exit (LPT entry) station
5	Subscript used to denote LPT exit station
BPR	ByPass Ratio
DNW	German-Dutch Wind Tunnels
FPR	Fan Pressure Ratio
GSP	NLR’s Gas turbine Simulation Program
HP	High Pressure
HPC	High Pressure Compressor
HPT	High Pressure Turbine (driving the HPC)
MTOW	Maximum Take-Off Weight
N%1	The fan (or low pressure) spool speed
N%2	The core (high pressure) spool speed
NLR	Royal NLR - Netherlands Aerospace Centre
NOx	Nitrogen Oxides emissions
LP	Low Pressure
LPT	Low Pressure Turbine (driving the fan)
OPR	Overall Pressure Ratio
TOC	Top Of Climb
TSFC	Thrust Specific Fuel Consumption
Tt#	Total/Stagnation Temperature for station #
UHBR	Ultra-High Bypass Ratio

1 Introduction

The reduction of fuel burn to reduce carbon footprint requires exploration of different engine layouts. One such path is the increase of the fan bypass ratio (BPR) to lower the thrust specific fuel consumption (TSFC) by increasing the propulsive efficiency (see Figure 1). Large values of BPR (> 12) refer to Ultra-High Bypass Ratio engines (or UHBR engines). Optimising the engine layout for increased BPR requires altering other design parameters like changing the fan pressure ratio, the overall pressure ratio (OPR) and the combustor exit temperature (or high pressure turbine entry temperature Tt4), cooling technology and component efficiencies.

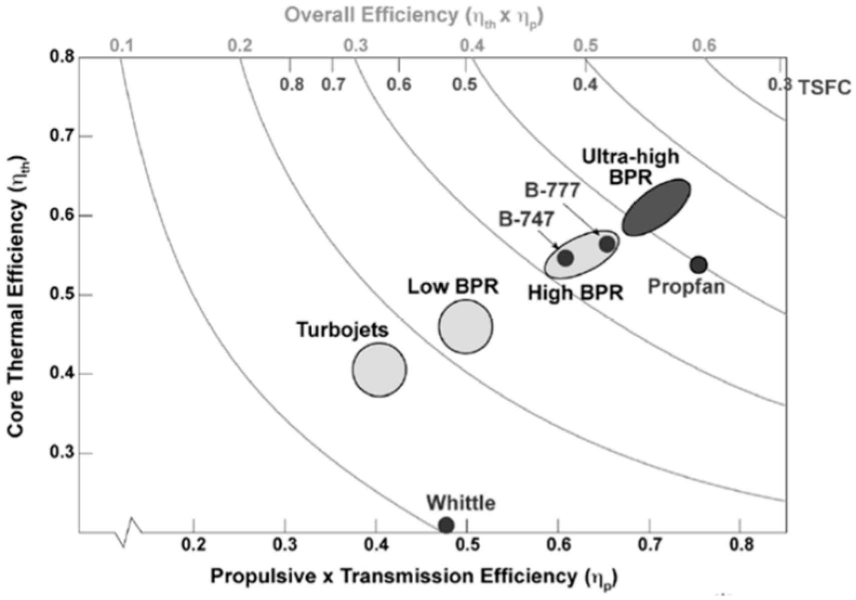


Figure 1 - The link of SFC and overall efficiency with thermal efficiency and propulsive efficiency [ref. Epstein]

Hydrogen is considered to be a sustainable alternative aviation fuel for the future as an alternative to kerosene reducing the carbon footprint further (although hydrogen doesn’t contain carbon, it is possible that it may have been used in the production or transportation, this study focusses on the use of the fuel in the aircraft). However, hydrogen, either liquid or compressed is quite a different fuel with different fuel properties (e.g. specific volume, temperature of liquid state, heating value, etc.). The use of this fuel may have implications on turbine loading for commercial turbofans. This is investigated for the aforementioned Ultra-High Bypass Ratio (UHBR) turbofan engine.

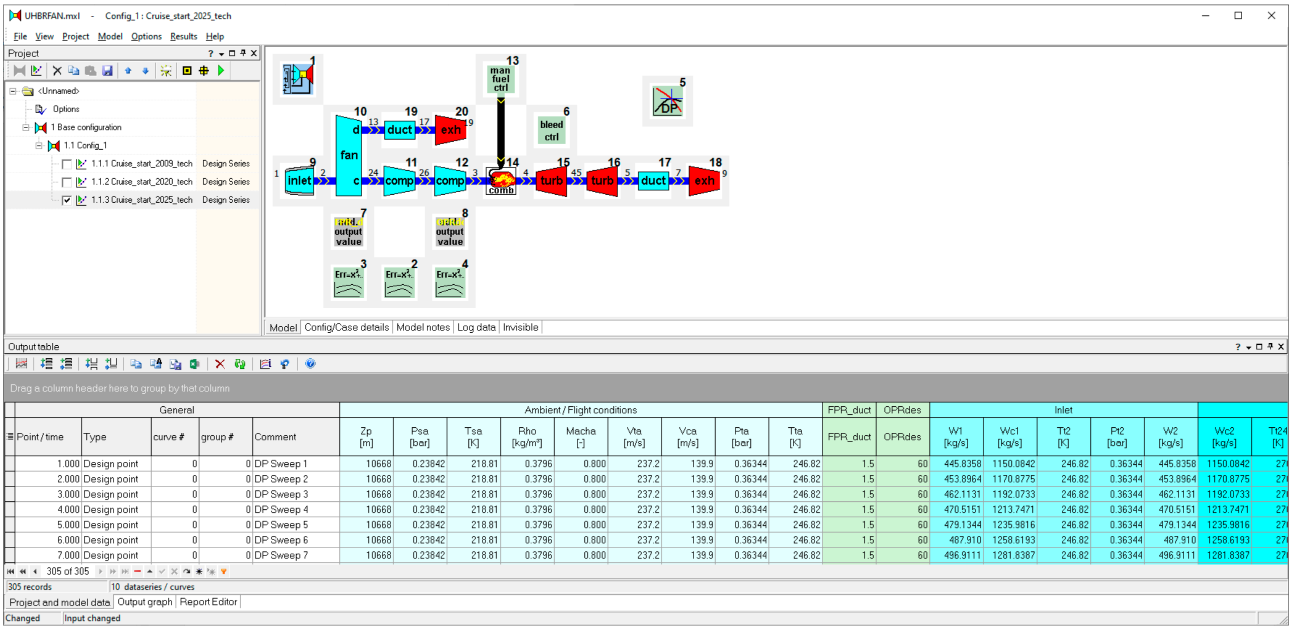
NLR’s Gas turbine Simulation Program (GSP) is perfectly capable to simulate effects of using alternative fuels on new and existing design turbofan engines. The main reasons for this are that the GSP real gas model is derived from the NASA CEA (Chemical Equilibrium and Applications) model and offers the capability of using user-defined fuels. Note that this study focusses on the thermodynamic effects on the turbine, the effects of the production of nitrogen oxides (NOx) is not considered as this is highly depending on the geometry of the combustor and the premixing of the fuel.

1.1 Engine model

This study uses a model (see Figure 2), developed with NLR's Gas turbine Simulation Program, that is inspired by the study of Dr. Nicholas Cumpsty [ref. Cumpsty]. The generic UHBR model is intended to be used for calculating the specific fuel consumption based on varying:

- Fan bypass ratio (BPR)
- Fan pressure ratio (FPR)
- Overall cycle pressure ratio (OPR)
- Turbine entry temperature (Tt4)

The (start of the) cruise segment (or top of climb, TOC) is chosen for the analysis. A well-known condition for this reference point is 35,000 feet (10668 m) with a Mach number of 0.8 (these ambient conditions are used in this analysis unless otherwise specified). The engine thrust (net thrust is denoted as FN) range is chosen in the range to power a Boeing 787 having a take-off power of about 340 kN. For start of the cruise segment it implies that the thrust at start of the cruise segment roughly equals FN_{cruise}=MTOW/21 (Maximum Take-Off Weight divided by the optimum lift/drag ratio of 21).



<Unnamed>
- Options
- 1 Base configuration
  - 1.1 Config_1
    - ☐ 1.1.1 Cruise_start_2009_tech — Design Series
    - ☐ 1.1.2 Cruise_start_2020_tech — Design Series
    - ☑ 1.1.3 Cruise_start_2025_tech — Design Series

General					Ambient / Flight conditions									FPR_duct	OPRdes	Inlet						
Point / time	Type	curve #	group #	Comment	Zp [m]	Psa [bar]	Tsa [K]	Rho [kg/m³]	Macha [-]	Vta [m/s]	Vca [m/s]	Pta [bar]	Tta [K]	FPR_duct	OPRdes	W1 [kg/s]	Wc1 [kg/s]	Tt2 [K]	Pt2 [bar]	W2 [kg/s]	Wc2 [kg/s]	Tt24 [K]
1.000	Design point	0	0	DP Sweep 1	10668	0.23842	218.81	0.3796	0.800	237.2	139.9	0.36344	246.82	1.5	60	445.8358	1150.0842	246.82	0.36344	445.8358	1150.0842	27
2.000	Design point	0	0	DP Sweep 2	10668	0.23842	218.81	0.3796	0.800	237.2	139.9	0.36344	246.82	1.5	60	453.8964	1170.8775	246.82	0.36344	453.8964	1170.8775	27
3.000	Design point	0	0	DP Sweep 3	10668	0.23842	218.81	0.3796	0.800	237.2	139.9	0.36344	246.82	1.5	60	462.1131	1192.0733	246.82	0.36344	462.1131	1192.0733	27
4.000	Design point	0	0	DP Sweep 4	10668	0.23842	218.81	0.3796	0.800	237.2	139.9	0.36344	246.82	1.5	60	470.5151	1213.7471	246.82	0.36344	470.5151	1213.7471	27
5.000	Design point	0	0	DP Sweep 5	10668	0.23842	218.81	0.3796	0.800	237.2	139.9	0.36344	246.82	1.5	60	479.1344	1235.9816	246.82	0.36344	479.1344	1235.9816	27
6.000	Design point	0	0	DP Sweep 6	10668	0.23842	218.81	0.3796	0.800	237.2	139.9	0.36344	246.82	1.5	60	487.910	1258.6193	246.82	0.36344	487.910	1258.6193	27
7.000	Design point	0	0	DP Sweep 7	10668	0.23842	218.81	0.3796	0.800	237.2	139.9	0.36344	246.82	1.5	60	496.9111	1281.8387	246.82	0.36344	496.9111	1281.8387	27

305 records | 10 dataseries / curves

Changed | Input changed

Figure 2 - Screenshot of the GSP UHBR turbofan model

The model (see Appendix A for a textual listings of the models) itself consists of some advanced modelling techniques to calculate various designs sequentially by the use of a case control input specification component (to specify series of design point operating points; this is component model marked with a Nr. **1** in the top right corner, see zoomed model in Figure 3). This series control component schedules the *FPR_duct* and the *BPR*. is *FPR_duct* set in component #**7** (by case input controller #**1**) and this value is used in components #**2** and #**3** to set the values of core *FPR* (0.95**FPR_duct*) and duct *FPR* (*FPR_duct*) respectively in the fan module #**10**. Cooling bleed is scheduled using component #**6** (the amount of cooling bleed is based on the maximum turbine inlet temperature; the better the cooling and material technology, the higher the allowable gas temperature and the higher the amount of cooling flow). Furthermore, component #**8** defines the *OPR* of the cycle, from which component #**4** sets the high pressure compressor (HPC) design pressure ratio. Furthermore, a design point iterator (component #**5**) has been added to iterate to a design inlet mass flow for a given design thrust value. The value for cruise thrust in this analysis is 54 kN.

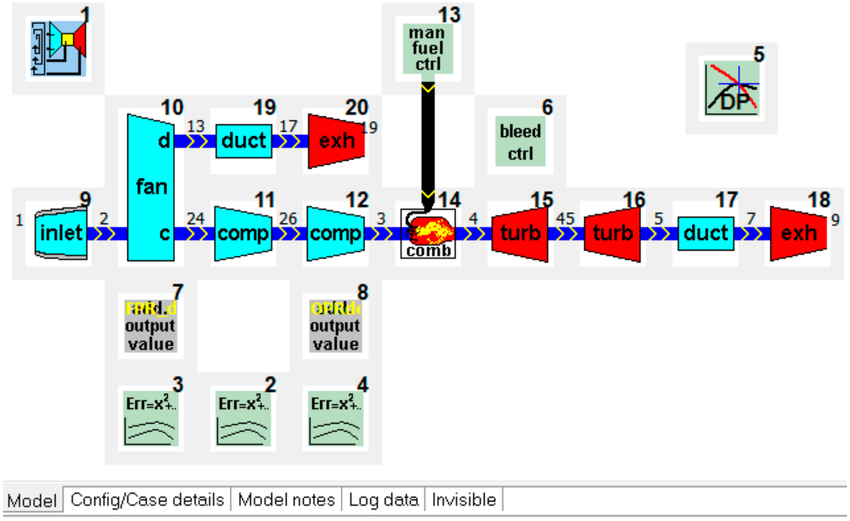


Figure 3 - Close-up of the model consisting of stacked component models

1.2 Hydrogen UHBR turbofan design

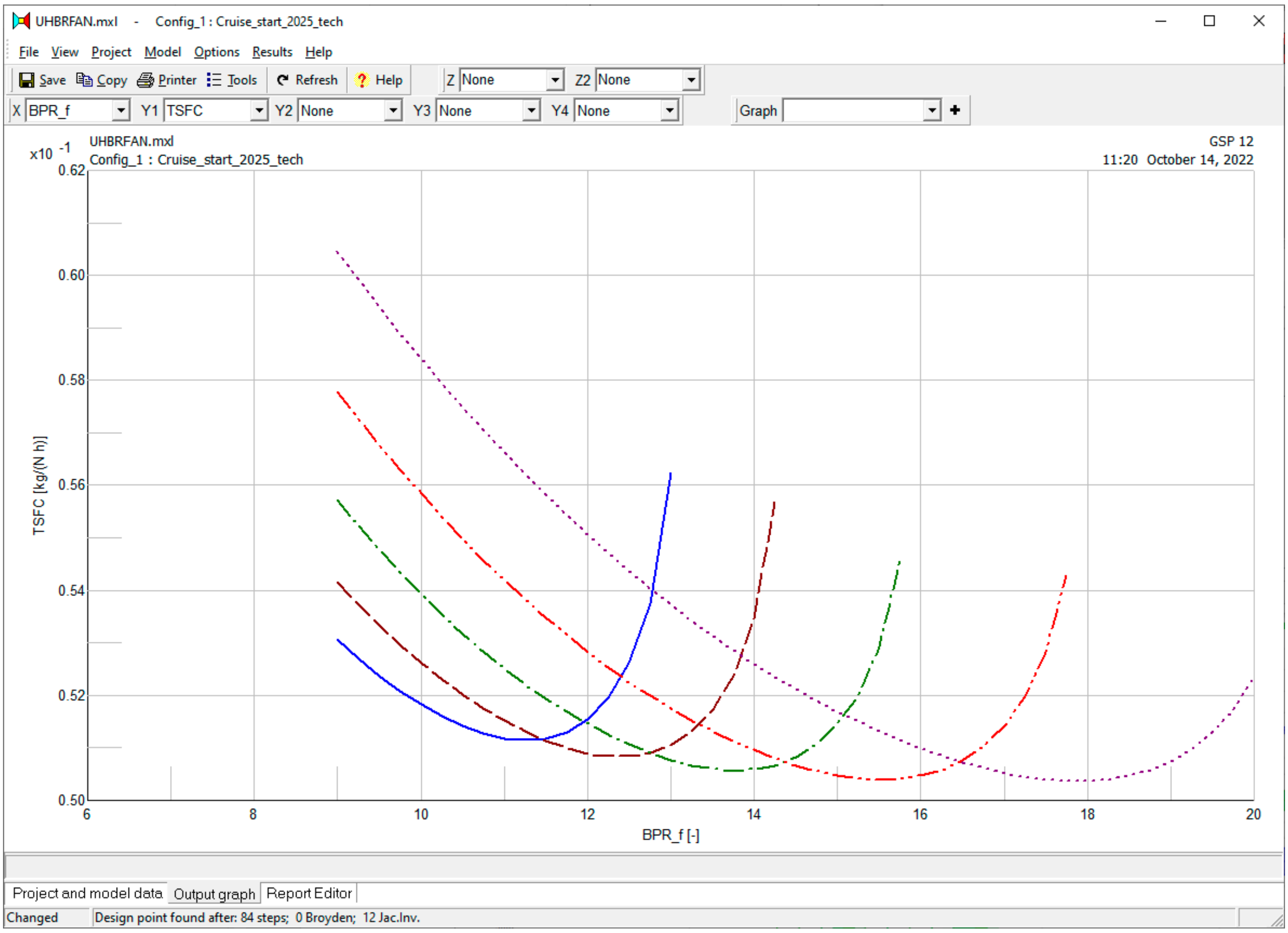
The first analysis (see chapter 2) will consider that the UHBR turbofan is developed/designed to use hydrogen as fuel from scratch (complete new design). These results will be compared to kerosene fuelled UHBR turbofans for exactly the same performance. As design performance point, the end of top of climb will be used for the comparison; the reason for choosing this point is that this is the critical flight phase for the engine design. The resulting thermodynamic properties will be interpreted and compared.

1.3 Retrofitting existing UHBR turbofan

The second analysis (see chapter 3) will consider a kerosene designed UHBR turbofan that is retrofitted with a different combustor to allow using hydrogen as an alternative fuel. The performance at TOC is again considered and will be kept constant, if the engine stays within limits, otherwise the limits are respected. The resulting thermodynamic properties will be interpreted and compared to kerosene results.

2 Analysis of H2 fuelled UHBR turbofan designs

For the analysis of the thermodynamic implications on multiple spool engines, a UHBR turbofan engine with 2025 technology level has been chosen that has a thrust range to power a Boeing 787 (having a take-off power of about 340 kN). With an OPR of 60, a turbine inlet temperature of 1650 Kelvin and an amount of cooling flow of 25 %, we obtain the result as depicted in Figure 4. In this graph the FPR is varied from 1.5 down to 1.3 in steps of 0.05 (5 curves, 1.5 to 1.3 from left to right).


UHBRFAN.mxl - Config_1 : Cruise_start_2025_tech

Z None Z2 None

X BPR_f Y1 TSFC Y2 None Y3 None Y4 None

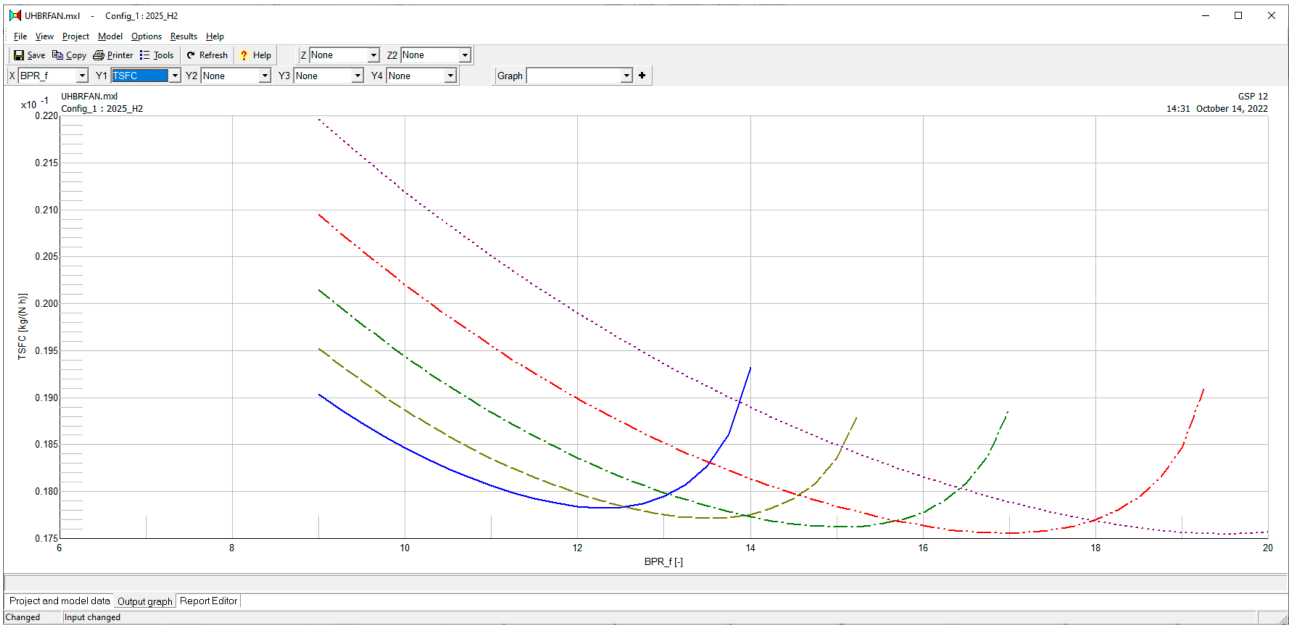
Graph

Changed

Design point found after: 84 steps; 0 Broyden; 12 Jac.Inv.

Figure 4 - Kerosene fuelled UHBR turbofan design sweep performance

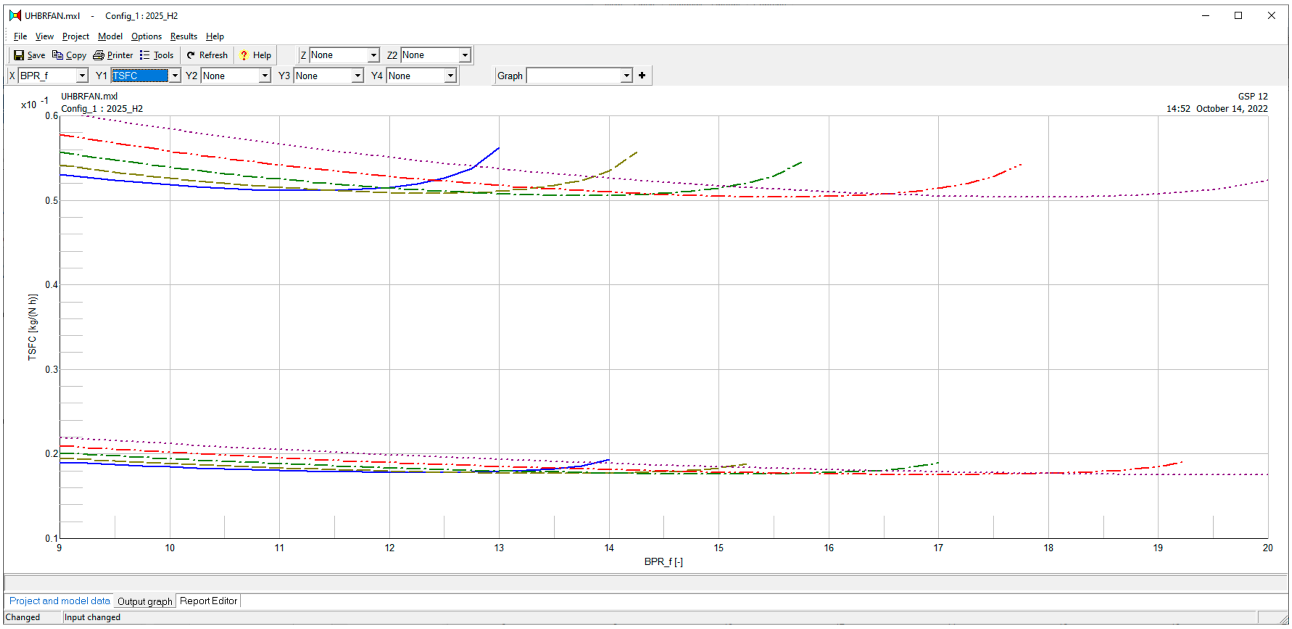
A similar exercise has been performed for the hydrogen fuelled UHBR turbofan, see Figure 5. When combining the 2 figures (Figure 4 and Figure 5) we obtain Figure 6. From this figure we observe that the hydrogen fuelled turbofan results (bottom curves) have a lower thrust specific fuel consumption (TSFC) than the kerosene results (top curves). Furthermore, to show a minimum TSFC for hydrogen fuelled UHBR turbofans we had to increase the BPR to higher values. The minimum values of the hydrogen curves is further to the right than for kerosene. This implies that the core can be designed smaller for hydrogen fuel than for kerosene, hydrogen cores have a higher power to volume density.



UHBRFAN.mxl - Config_1 : 2025_H2

X BPR_f Y1 TSFC Y2 None Y3 None Y4 None Z None Z2 None Graph

Figure 5 - Hydrogen fuelled UHBR turbofan design sweep performance

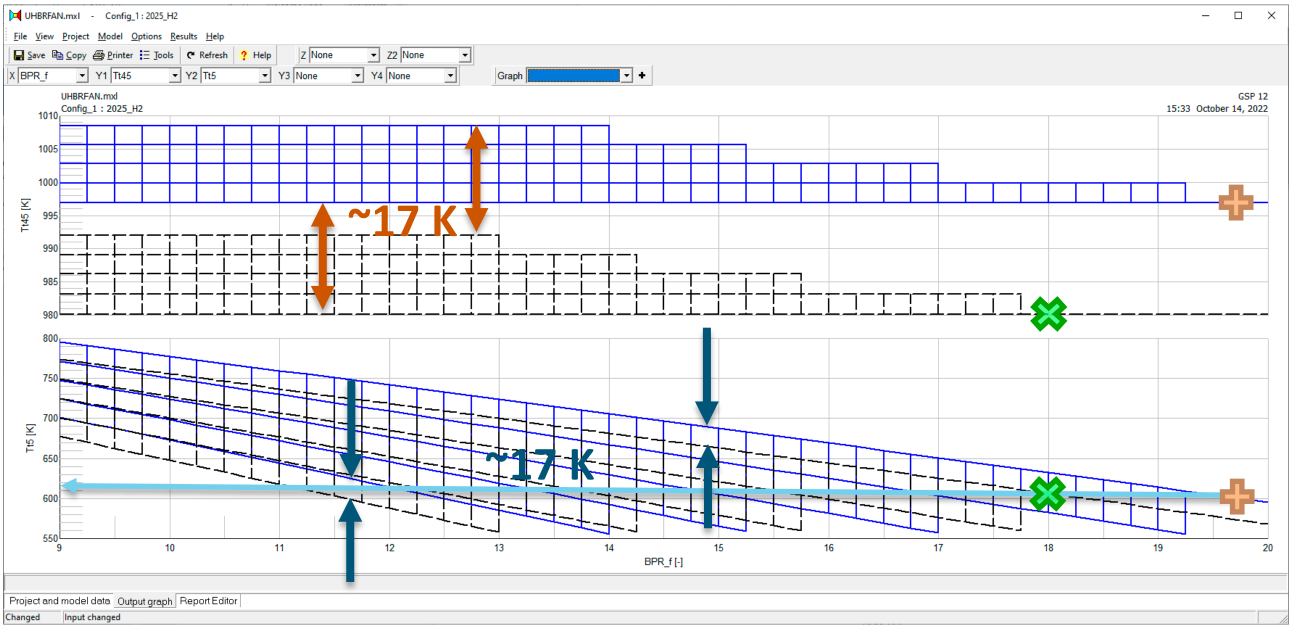


UHBRFAN.mxl - Config_1 : 2025_H2

X BPR_f Y1 TSFC Y2 None Y3 None Y4 None Z None Z2 None Graph

Figure 6 - Hydrogen (lower curves) and kerosene (top curves) fuelled UHBR turbofan design sweep performance

If we focus on the turbine thermodynamics of the UHBR turbofan engines we have to plot the temperatures of the high pressure turbine (HPT; drives the high pressure compressor, HPC) and the low pressure turbine (LPT; drives the fan and booster). Note that since we fixed the combustor exit temperature (per the technology level) the temperature of the exhaust gases entering the HPT is for kerosene and hydrogen exactly the same, so there is no need to plot this temperature known as *Tt4*. Instead, we will plot *Tt45* (HPT exit temperature or LPT entry temperature) and the *Tt5* (LPT exit temperature or exhaust nozzle entry temperature). This is shown in Figure 7.



UHBRFAN.mxl - Config_1 : 2025_H2

Z None

Z2 None

X BPR_f

Y1 Tt45

Y2 Tt5

Y3 None

Y4 None

Figure 7 - UHBR turbofan turbine performance comparison (hydrocarbon jet fuel, black; hydrogen, blue)

Figure 7 shows the turbine temperatures for kerosene (black, dashed) and hydrogen (blue, solid). A remarkable observation from this figure is that the HPT exit temperature (*Tt45*) for hydrogen fuelled turbofan engines is about 17 K higher than for kerosene fuelled UHBR turbofan engines. The LPT (*Tt5*) exit temperature also is about 17 K higher. Note that this is a direct comparison for the same engines based on FPR and BPR. However, when we compare optimized designs (see for reference figures 4 and 5), e.g. the optimum design for a kerosene fuelled UHBR turbofan engine with an FPR value of 1.3 is found at a BPR value of 18 (green cross sign in Figure 7). For the same FPR, the optimum design for a hydrogen fuelled UHBR turbofan the BPR value is 19.5 (orange plus sign in Figure 7). The temperature difference for comparison of optimized designs remains at a value for *ΔTt45* of 17 K (no change), and reduces for *ΔTt5* to a value of -2 K (in favour of hydrogen, this is caused by the distinct constant temperature profile of *Tt45* and diverging profile *Tt5*). This results in a higher average turbine temperature (from inlet to exit) which may have some implications on the life and the design of vanes and blades of the LPT.

3 Analysis of retrofitting a UHBR turbofan design

The previous chapter discussed the development of new designs that incorporate hydrogen as fuel from a design standpoint with the assumption of equivalent performance in terms of thrust compared to a kerosene fuel turbofan. This chapter will focus on retrofitting an existing design (designed for kerosene) to use hydrogen as an alternative fuel. Note that this requires changes to the combustor and fuel system, such changes are not applicable for this analysis as we will not considered. The fuel will be fully burned. Taking combustor design into account would be of interest if the emissions of the turbofan would be analysed; emissions are excluded from this analysis, and hence, the configuration determined by the kerosene (hydrocarbon) jet fuel design can be used to combust hydrogen in off design (steady-state) analyses.

For this analysis a 2025 technology design for kerosene is chosen and used to run on hydrogen in steady state series off design analyses. An FPR of 1.4 and a BPR of 13.75 is chosen for the analysis. We understand that there are more efficient designs (for lower FPR and higher BPR). If the vast amount of effort and costs (when choosing a design with very low FPR and high BPR) to achieve only a small additional increase in overall efficiency is taken into account, such efforts do not justify the increase.

3.1 Flight envelope

The turbofan performance can be mapped from the flight envelope (Mach and Altitude) for various power settings. The chosen power setting for the simulation is combustor exit temperature, this is a technology limitation, which can be applied to both hydrocarbon jet fuel and hydrogen fuelled gas turbines.

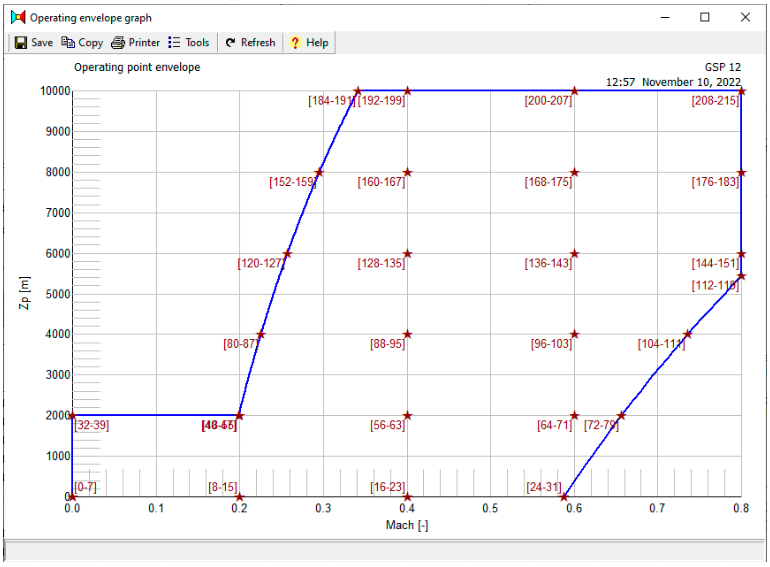


Figure 8 - Flight envelop

Figure 8 shows an example of the used flight envelop; the envelop cut-outs represent areas that are not actual flight conditions where engines cannot or don’t have to provide thrust. The numbers in between square brackets represent the individual simulation number; this flight envelope contains 216 simulations (resulting in well over 1000 simulations as in between each simulation step 5 intermediate steps are used to prevent too large input deviations and thus iteration/non convergence issues).

3.2 UHBR turbofan simulations

Using a different fuel than the fuel the gas turbine is designed for should not affect the performance of the aircraft within the limitations of the engine (control) limits. Two types of analysis can be performed to ensure the performance of the engines is enough to power the aircraft:

1. Analysis respecting the gas turbine design limits, e.g. respecting combustor exit temperature, spool speeds.
2. Analysis calculating fuel requirement for aircraft performance, e.g. calculating the fuel flow or combustor exit temperature for the thrust specification of the aircraft in the flight envelope.

Both analyses yield results that can be used to evaluate if the change in fuel effects the gas turbine integrity or the flight performance. The second analysis requires changes to the UHBR model to calculate free state fuel flow/combustor exit temperature based on the input of a thrust requirement (this requires another equation in the model that generally requires more steps and thus longer simulation times apart from an extra step to generate input and modify the model). This is more complicated than the first type of analysis where the combustor exit temperature is maximized, so that the first type of analysis is explored first. For this analysis it is important to check the thrust generation after the simulation and other engine limits.

Running the various power ratings (maximum combustor exit temperature to a low temperature which corresponds to a high to low fuel flow value, but respecting the allowable material temperatures) for the various flight conditions (Mach or speed and altitude values) yields the thrust performance as depicted in Figure 9.

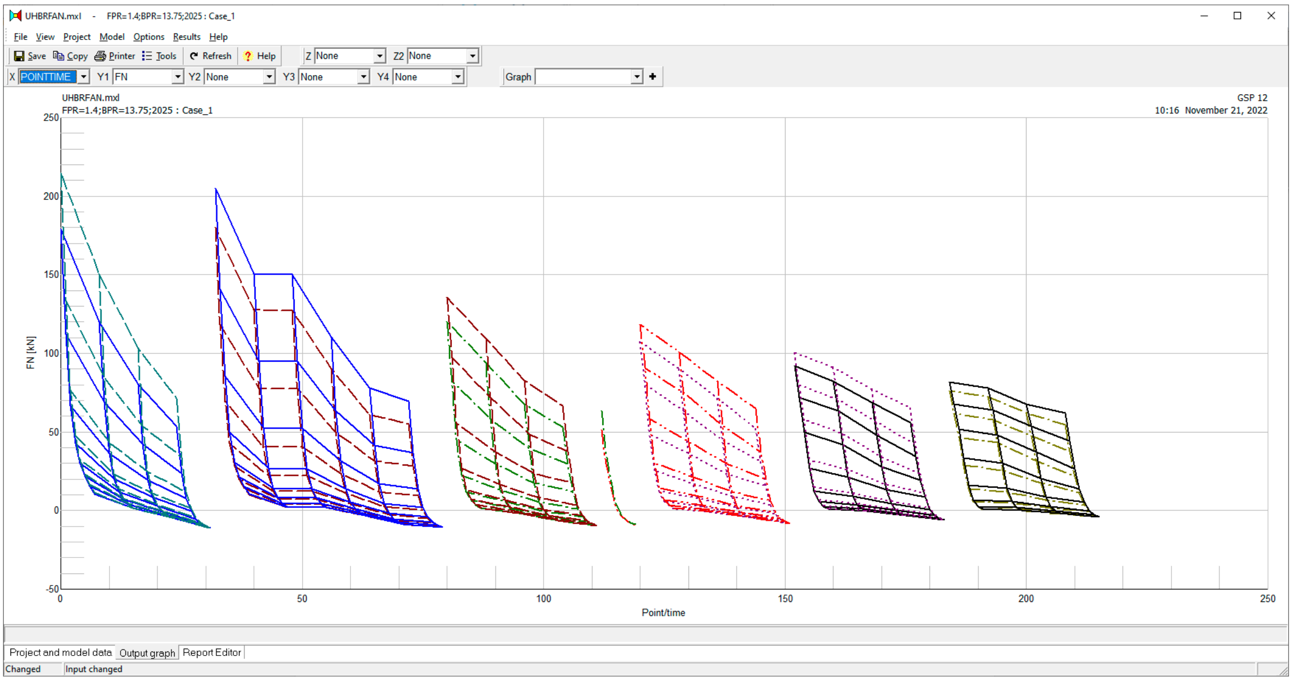
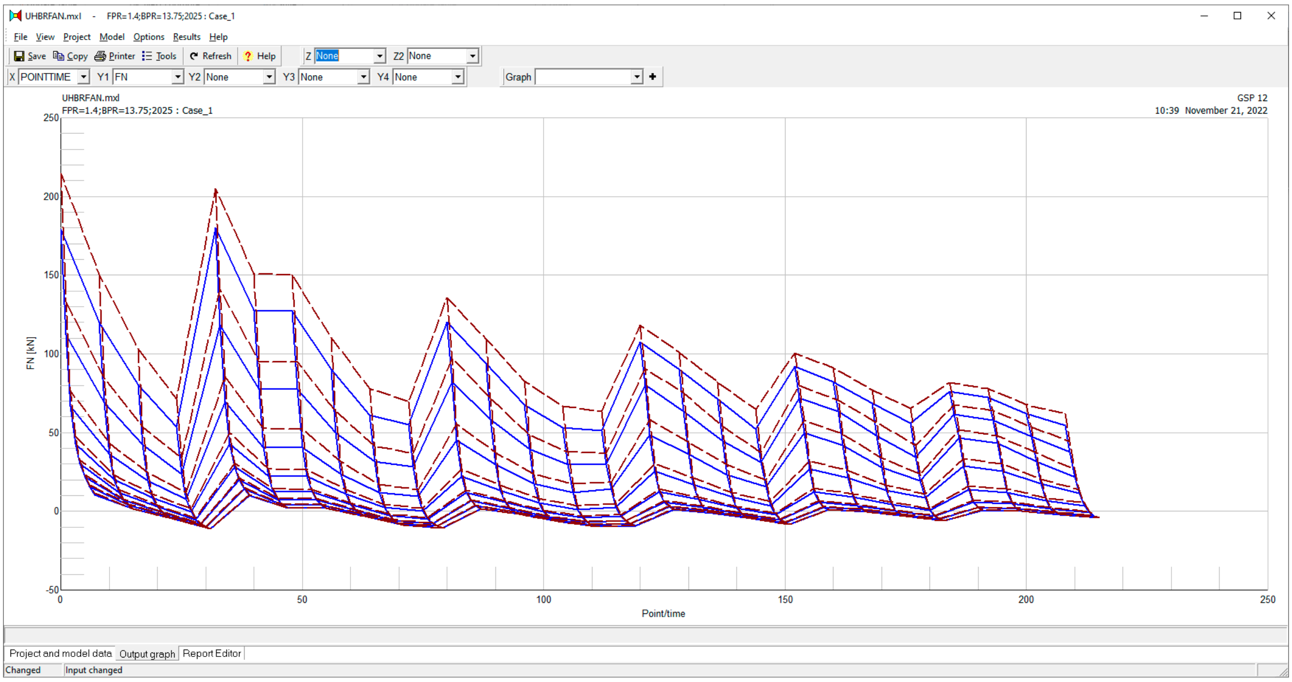


Figure 9 - Flight envelope performance for hydrocarbon jet fuel and Hydrogen

Figure 9 shows carpet plots for hydrocarbon jet fuel and Hydrogen fuel grouped by altitude as shown in Figure 8 (note that simulations 112-119 are a separate flight level) which may be a little difficult to read. Grouping the data for fuel type, we obtain Figure 10.


UHBRFAN.mxl - FPR=1.4;BPR=13.75;2025 : Case_1

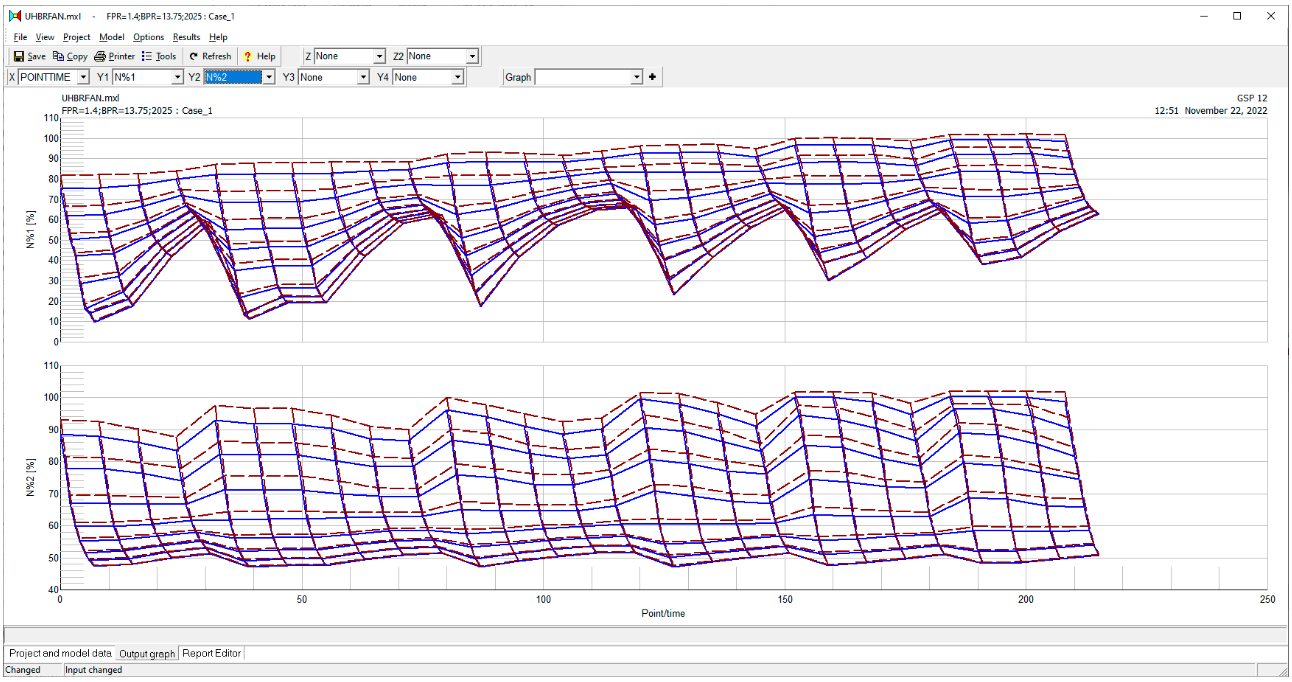
Z None Z2 None

X POINTTIME Y1 FN Y2 None Y3 None Y4 None Graph

Figure 10 - Flight envelope thrust performance grouped by hydrocarbon jet fuel (solid blue) and Hydrogen (dashed brown)

The latter figure, grouped by fuel type shows that the thrust performance of Hydrogen fuel (dashed brown) surpasses the performance for hydrocarbon jet fuel (solid blue) while respecting the engine combustor exit temperature limits. This implies that enough thrust can be generated in a retrofit engine; it even implies that the temperature can be lowered to match the hydrocarbon jet fuel thrust performance. A lower temperature will cause components life to be extended. Other engine limits to check are spool speeds, see Figure 11 and HPC (high pressure compressor) exit pressure, Figure 12. High spool speeds cause high compressor exit pressure and increased stress levels in rotating parts like disks and rotor blades. The fan (or low pressure/LP) spool speed is denoted as N%1 and the core (high pressure/HP) spool speed is denoted as N%2 (see Figure 11).

Figures 11 and 12 show that when respecting the maximum allowable temperature of the combustor exit flow, the spool speeds and pressure exceed the values for hydrocarbon jet fuel. Whether this is acceptable depends on the construction of the compressor casing and the maximum allowable stress levels in rotating parts (blades and disks), but will certainly decrease component life. This implies that it is imperative to reduce the fuel flow when running on Hydrogen fuel (which should not be a problem since there is more thrust for the same combustor exit temperature).

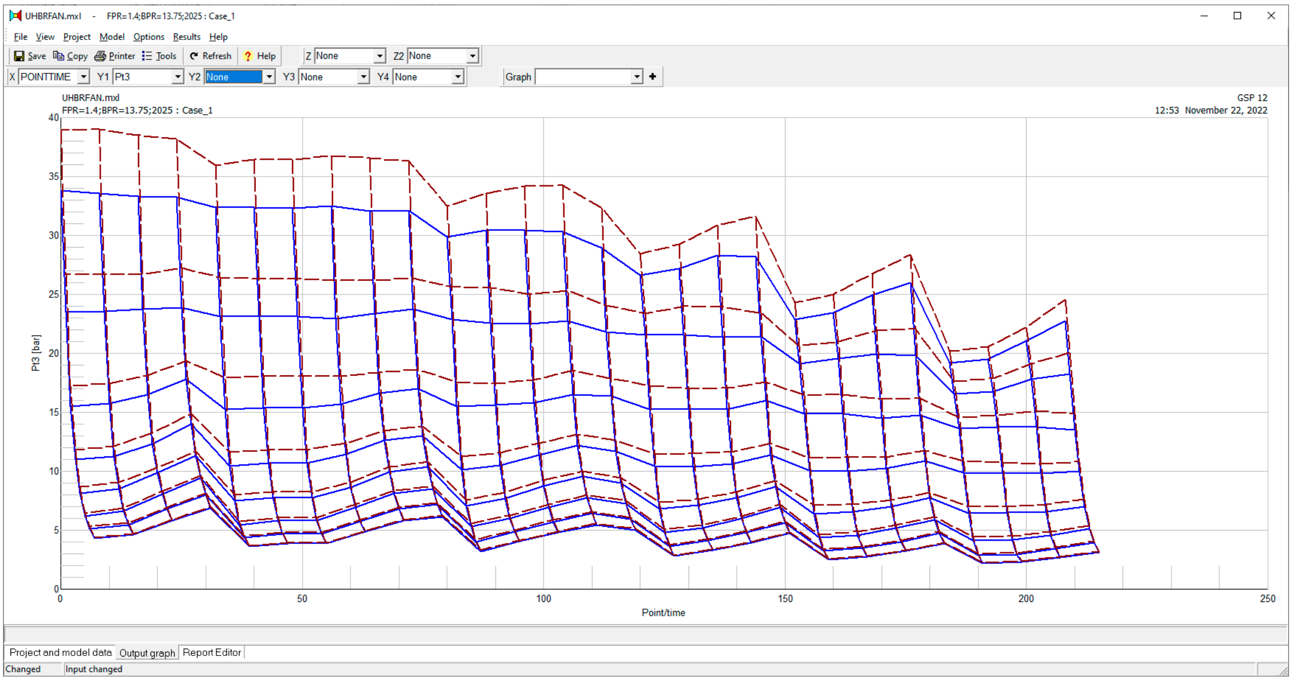


UHBRFAN.mxl - FPR=1.4;BPR=13.75;2025 : Case_1

Z None Z2 None

X POINTTIME Y1 N%1 Y2 N%2 Y3 None Y4 None

Figure 11 - Flight envelope spool speeds, hydrogen fuel (dashed, brown) hydrocarbon jet fuel (solid, blue)



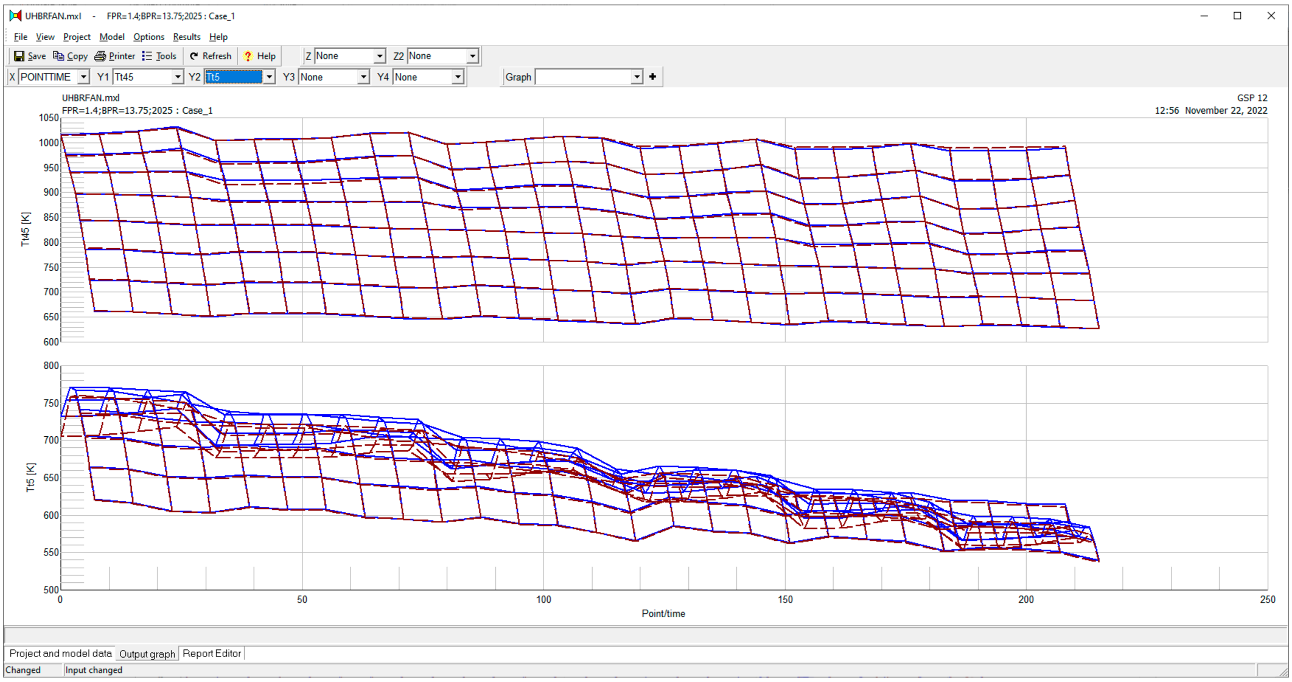
UHBRFAN.mxl - FPR=1.4;BPR=13.75;2025 : Case_1

Z None Z2 None

X POINTTIME Y1 Pt3 Y2 None Y3 None Y4 None

Figure 12 - Flight envelope compressor exit pressure, hydrogen fuel (dashed, brown) hydrocarbon jet fuel (solid, blue)

Further inspection of the low pressure turbine (LPT) inlet (*Tt45*) and exit (*Tt5*) temperature (see Figure 13) shows that the temperatures for hydrogen fuel (dashed, brown) are similar or lower than when running on hydrocarbon jet fuel (solid, blue).


UHBRFAN.mxl - FPR=1.4;BPR=13.75;2025 : Case_1

X POINTTIME
Y1 Tt45
Y2 Tt5
Y3 None
Y4 None
Z None
Z2 None

UHBRFAN.mxl
FPR=1.4;BPR=13.75;2025 : Case_1
GSP 12
12:56 November 22, 2022

Figure 13 - Flight envelope LPT turbine temperatures, hydrogen fuel (dashed, brown) hydrocarbon jet fuel (solid, blue)

Now that several engine limits (spool speeds and HPC exit pressure) are exceeding the values while running on hydrogen with respect to the hydrocarbon jet fuel simulations, it would be best to check whether lowering the fuel flow (to lower the combustor exit temperature and as such lower spool speed and HPC exit pressure) alleviates the limit crossings when the same thrust performance is used for Hydrogen. We can now use the results generated for hydrocarbon jet fuel through a modification of the UHBR engine model by introducing an extra equation (Equation 1) and a free state variable (fuel flow).

$$(\mathrm{F}N_{sim})_{V,alt} - (\mathrm{F}N_{hc})_{V,alt} = 0 \qquad \textit{(Equation 1)}$$

With this addition to the model, the calculated thrust performance (FN_{sim}) is compared to the previous calculated input value for hydrocarbon jet fuel (hydrocarbon thrust, FN_{hc}) for the same flight performance point (flight speed and altitude). The fuel flow is the independent free variable and is perturbated until the resulting error is within the error margin (nearly zero). Simulation convergence for low power settings (low to negative thrust values) is difficult to achieve, therefore, the bottom values of the calculated dataset for equal thrust performance (apple green, dashed line in e.g. Figure 14) are not always present and distort the carpet plot at the bottom of the figures, please ignore this in figures 14 to 17. As can been seen in Figure 14, the net thrust for running on hydrogen equals the net thrust for running on kerosene (except for the low power settings due to convergence issues).

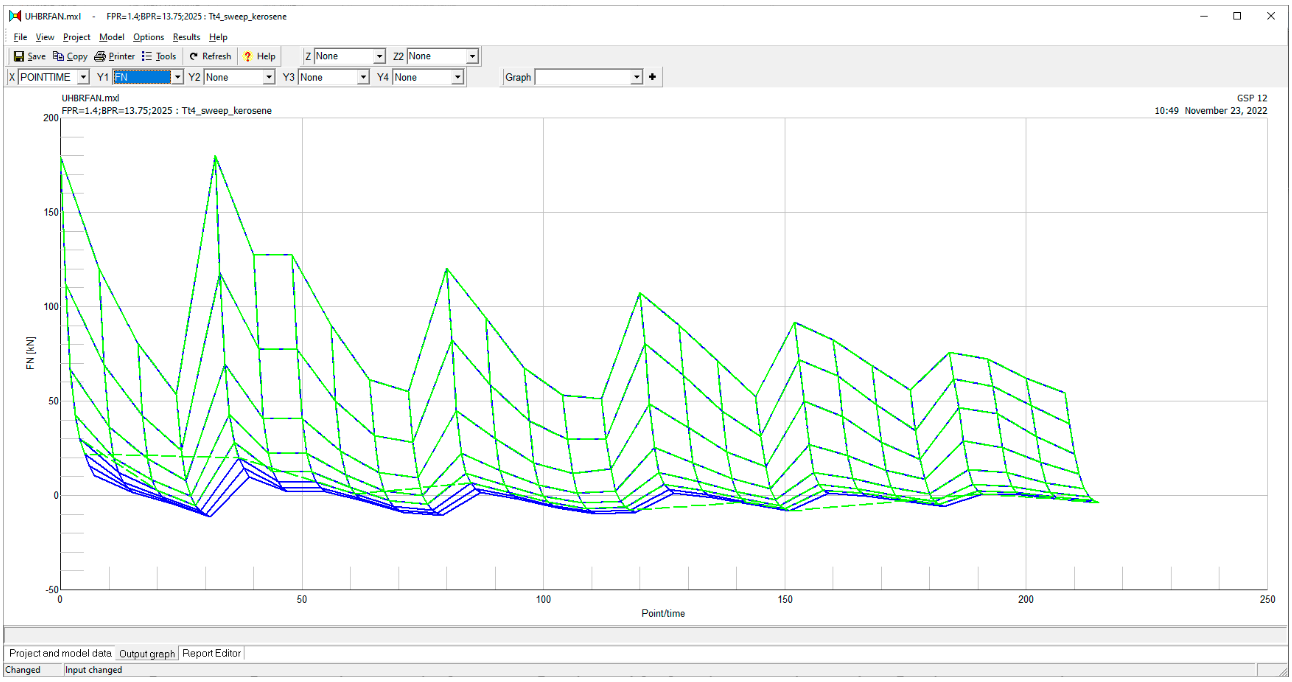


Figure 14 - Flight envelope thrust performance grouped by fuel type, hydrocarbon (solid blue) and hydrogen (dashed green)

The engine limitations for spool speed and HPC exit pressure to confirm the compressor exit pressure drop are revisited in figures 15 and 16. From these figures we see that the limits are respected, the values are equivalent or lower.

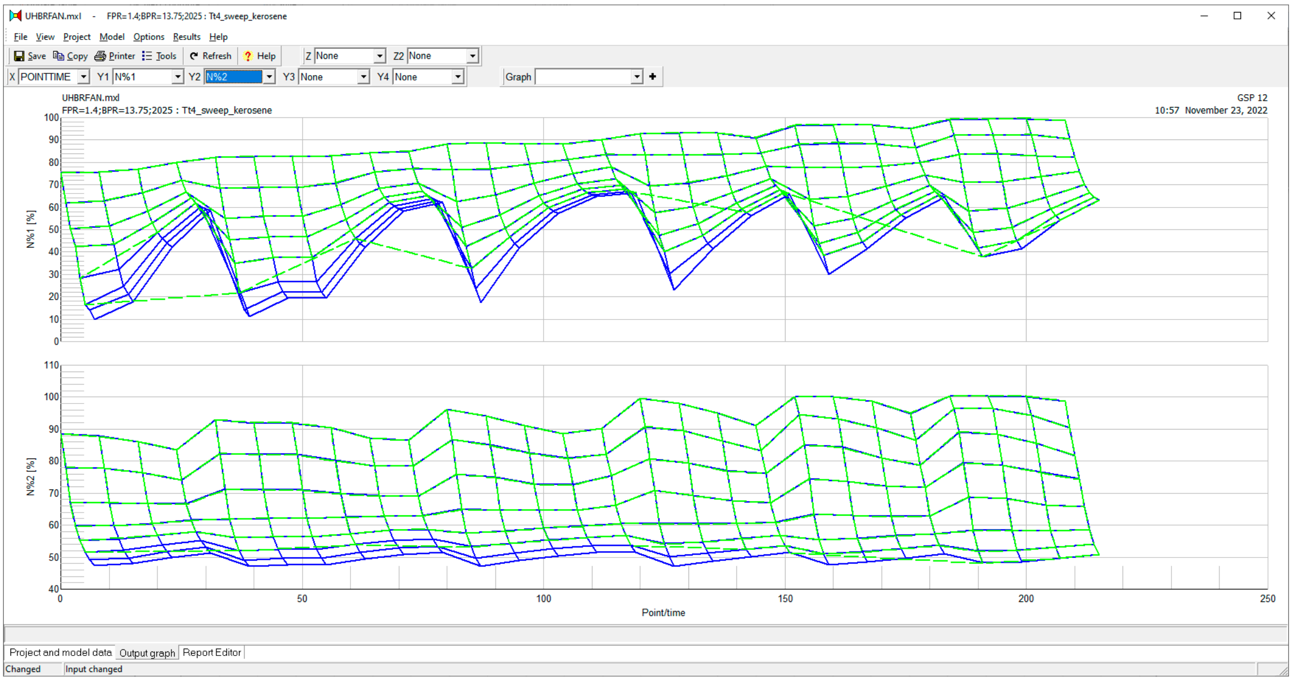


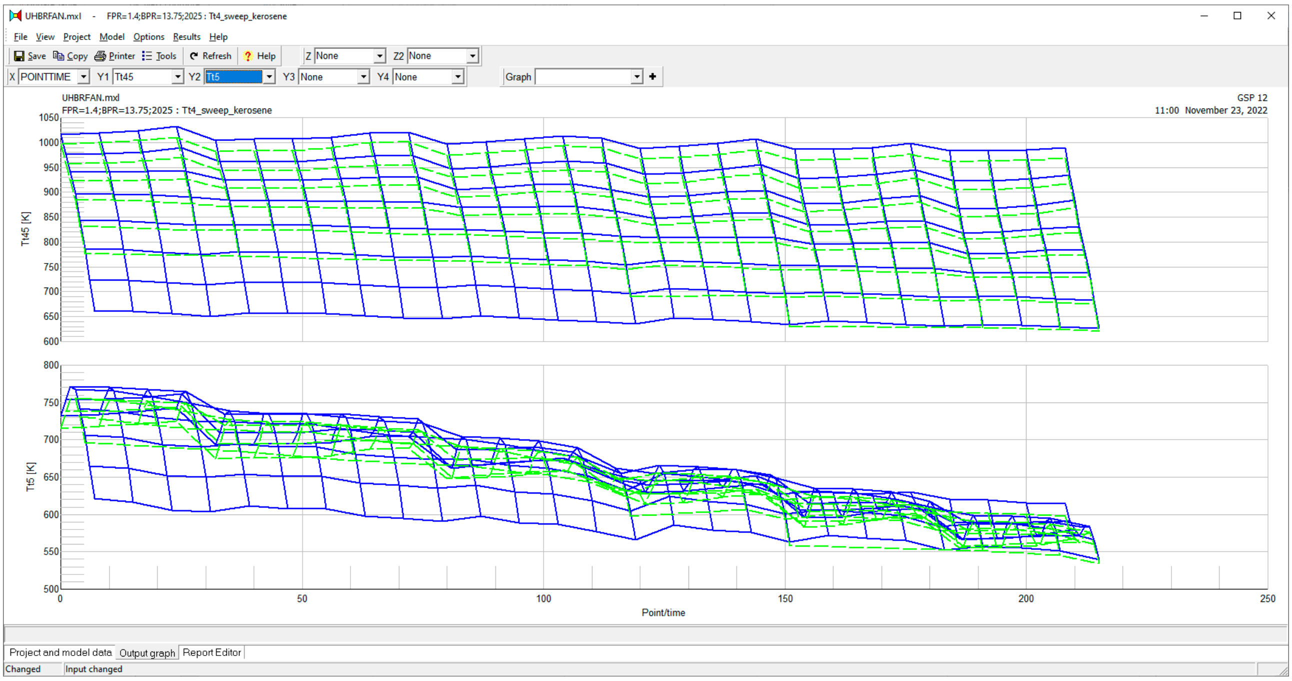
Figure 15 - Flight envelope spool speeds, hydrocarbon (solid blue) and hydrogen (dashed green)

UHBRFAN.mxl - FPR=1.4;BPR=13.75;2025 : Tt4_sweep_kerosene

X POINTTIME Y1 Pt3 Y2 None Y3 None Y4 None Z None Z2 None

Figure 16 - Flight envelope compressor exit pressure, hydrocarbon (solid blue) and hydrogen (dashed green)

The effect of equal thrust performance causes the combustor exit temperature to lower, the effect on the LPT is shown in Figure 17. This figure shows that both entry and exit temperature are lower for a retrofit gas turbine running on Hydrogen fuel.



UHBRFAN.mxl - FPR=1.4;BPR=13.75;2025 : Tt4_sweep_kerosene

X POINTTIME Y1 Tt45 Y2 Tt5 Y3 None Y4 None Z None Z2 None

Figure 17 - Flight envelope LPT turbine temperatures, hydrocarbon (solid blue) and hydrogen (dashed green)

4 Conclusions

The analyses have shown that GSP is able to calculate the performance of UHBR turbofan engine models for the alternative fuel hydrogen. GSP facilitates the calculation of several engine designs from a single model by clever use of additional equations. The obtained results of the simulation experiments are plausible. When using net thrust (instead of fuel flow or combustor exit temperature) as power setting for the model (so that the model iterates towards the correct fuel flow) it is found that with the current settings the very low and negative thrust values do not correctly converge to a stable fuel flow. It should be investigated if more intermediate steps provide more model stability to iterate towards a valid fuel flow. Nevertheless, these low to negative net thrust values are practically not of use in real aircraft as these power settings are not required for a stable flight condition.

The simulations of chapter 2 show the optimum design point for a hydrogen design is different from a hydrocarbon jet fuel design. The optimum design for running on hydrogen for a given FPR is found at higher BPR values than for hydrocarbon jet fuel. The low pressure turbine (LPT) entry and exit temperature are higher for equivalent FPR and BPR values compared to the hydrocarbon jet fuel designs. It is concluded that pure hydrogen UHBR designs will need a higher BPR to benefit from the higher energy density of the core. A higher average low pressure turbine temperature is foreseen which may implicate alternative LPT designs (e.g. more cooling or different materials or coatings) to respect current life limits.

The simulations of chapter 3 show that for a retrofit UHBR turbofan fuelled by hydrogen, the combustor temperature is lower compared to hydrocarbon jet fuel (for equivalent thrust performance). For equivalent combustor exit temperature performance, the turbofan spool speeds (LP and HP) are higher and may exceed design limits thus negatively impact life expectancy. In the retrofit UHBR turbofan, the LPT entry and exit temperature are lower when fuelled by hydrogen compared to hydrocarbon jet fuel, while respecting all engine limits. Modifying an existing turbofan engine to be fuelled by hydrogen would be possible based on the simulations. The thrust performance can be met at lower combustor exit temperatures. This would increase the life expectancy of the LPT as the average operating temperature is lower compared to engine designs specifically designed/optimized for hydrocarbon jet fuel.

5 References

[1] Epstein A. *A Primer: Aircraft Emission and Environmental Impact. Air Transport Association meeting: Aviation and the Environment*, Washington DC 2008.

[2] Cumpsty, N. A., *PREPARING FOR THE FUTURE: REDUCING GAS TURBINE ENVIRONMENTAL IMPACT*, Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air GT2009 June 8-12, 2009, Orlando, Florida, USA, GT2009-60367.

Appendix A GSP UHBR turbofan models

Appendix A.1 Hydrocarbon 2025 reference design model

UHBRFAN.mxl

```
GSP 12     UHBRFAN.mxl                                  16:56  November 23, 2022
MODEL DATA
================================================================================

Ambient / Flight conditions
================================================================================
Atmosphere model: ISA

Design Conditions:
--------------------------------------------------------------------------------
Pressure Altitude                                     Zpdes = 10668
Deviation from ISA temperature                       dTsdes = 0.00
Static Pressure                                      Ps0des = 0.23842
Static temperature                                   Ts0des = 218.81
Density                                             rho0des = 0.3796
--------------------------------------------------------------------------------

Design Air speed data  (Machdes was specified):
--------------------------------------------------------------------------------
Mach number                                         Machdes = 0.800
True air speed                                        Vtdes = 237.2
Calibrated air speed                                  Vcdes = 139.9
--------------------------------------------------------------------------------

Design Total free stream conditions:
--------------------------------------------------------------------------------
Total pressure                                       Pt0des = 0.36344
Total temperature                                    Tt0des = 246.82
--------------------------------------------------------------------------------

Design Humidity:
--------------------------------------------------------------------------------
Mass percent water                                 Hum [m%] = 0.0000E+00
Vapour volume percent                              Hum [v%] = 0.0000E+00
Relative humidity                               Hum.Res [%] = 0.00
--------------------------------------------------------------------------------

Off-design Conditions:
--------------------------------------------------------------------------------
Pressure Altitude                                        Zp = 10668
Deviation from ISA temperature                          dTs = 0.00
Static Pressure                                         Ps0 = 0.23842
Static temperature                                      Ts0 = 218.81
Density                                                rho0 = 0.3796
--------------------------------------------------------------------------------

Air speed data  (Mach was specified):
--------------------------------------------------------------------------------
Mach number                                            Mach = 0.800
True air speed                                           Vt = 237.2
Calibrated air speed                                     Vc = 139.9
--------------------------------------------------------------------------------

Total free stream conditions:
--------------------------------------------------------------------------------
Total pressure                                          Pt0 = 0.36344
Total temperature                                       Tt0 = 246.82
--------------------------------------------------------------------------------

Humidity:
--------------------------------------------------------------------------------
Mass percent water                                 Hum [m%] = 0.0000E+00
Vapour volume percent                              Hum [v%] = 0.0000E+00
Relative humidity                               Hum.Res [%] = 0.00
================================================================================


Nr. 1 Component: LoopCtrl
================================================================================
General Data:
```

```
--------------------------------------------------------------------------------
Active: Checked

Loop 1 input data:
--------------------------------------------------------------------------------
Component: FPR_duct
Parameter: ScheduleValue
Start value                                                 = 1.5000E+00
End   value                                                 = 1.3000E+00
Incr. value                                                 = -5.0000E-02
List data:
----------
Title 0,1||Title 0,2
          1.5000E+00
          1.4500E+00
          1.4000E+00
          1.3500E+00
          1.3000E+00

Loop 2 input data:
--------------------------------------------------------------------------------
Component: Fan
Parameter: BPRdes
Start value                                                 = 9.000
End   value                                                 = 20.000
Incr. value                                                 = 0.250
List data:
----------
Title 0,1||Title 0,2
               9.000
               9.250
               9.500
               9.750
              10.000
              10.250
              10.500
              10.750
              11.000
              11.250
              11.500
              11.750
              12.000
              12.250
              12.500
              12.750
              13.000
              13.250
              13.500
              13.750
              14.000
              14.250
              14.500
              14.750
              15.000
              15.250
              15.500
              15.750
              16.000
              16.250
              16.500
              16.750
              17.000
              17.250
              17.500
              17.750
              18.000
              18.250
              18.500
              18.750
              19.000
              19.250
              19.500
              19.750
              20.000
--------------------------------------------------------------------------------

Series control input data:
--------------------------
Point   Break   FPR_duct||FPR_duct   Fan||Design BPR
    1    TRUE                  1.5             9.000
    2                          1.5             9.250
    3                          1.5             9.500
    4                          1.5             9.750
    5                          1.5            10.000
    6                          1.5            10.250
    7                          1.5            10.500
    8                          1.5            10.750
```

```
 9                           1.5             11.000
10                           1.5             11.250
11                           1.5             11.500
12                           1.5             11.750
13                           1.5             12.000
14                           1.5             12.250
15                           1.5             12.500
16                           1.5             12.750
17                           1.5             13.000
18    TRUE                  1.45              9.000
19                          1.45              9.250
20                          1.45              9.500
21                          1.45              9.750
22                          1.45             10.000
23                          1.45             10.250
24                          1.45             10.500
25                          1.45             10.750
26                          1.45             11.000
27                          1.45             11.250
28                          1.45             11.500
29                          1.45             11.750
30                          1.45             12.000
31                          1.45             12.250
32                          1.45             12.500
33                          1.45             12.750
34                          1.45             13.000
35                          1.45             13.250
36                          1.45             13.500
37                          1.45             13.750
38                          1.45             14.000
39                          1.45             14.250
40    TRUE                   1.4              9.000
41                           1.4              9.250
42                           1.4              9.500
43                           1.4              9.750
44                           1.4             10.000
45                           1.4             10.250
46                           1.4             10.500
47                           1.4             10.750
48                           1.4             11.000
49                           1.4             11.250
50                           1.4             11.500
51                           1.4             11.750
52                           1.4             12.000
53                           1.4             12.250
54                           1.4             12.500
55                           1.4             12.750
56                           1.4             13.000
57                           1.4             13.250
58                           1.4             13.500
59                           1.4             13.750
60                           1.4             14.000
61                           1.4             14.250
62                           1.4             14.500
63                           1.4             14.750
64                           1.4             15.000
65                           1.4             15.250
66                           1.4             15.500
67                           1.4             15.750
68    TRUE                  1.35              9.000
69                          1.35              9.250
70                          1.35              9.500
71                          1.35              9.750
72                          1.35             10.000
73                          1.35             10.250
74                          1.35             10.500
75                          1.35             10.750
76                          1.35             11.000
77                          1.35             11.250
78                          1.35             11.500
79                          1.35             11.750
80                          1.35             12.000
81                          1.35             12.250
82                          1.35             12.500
83                          1.35             12.750
84                          1.35             13.000
85                          1.35             13.250
86                          1.35             13.500
87                          1.35             13.750
88                          1.35             14.000
89                          1.35             14.250
90                          1.35             14.500
91                          1.35             14.750
92                          1.35             15.000
93                          1.35             15.250
94                          1.35             15.500
95                          1.35             15.750
```

```
   96                         1.35            16.000
   97                         1.35            16.250
   98                         1.35            16.500
   99                         1.35            16.750
  100                         1.35            17.000
  101                         1.35            17.250
  102                         1.35            17.500
  103                         1.35            17.750
  104    TRUE                  1.3             9.000
  105                          1.3             9.250
  106                          1.3             9.500
  107                          1.3             9.750
  108                          1.3            10.000
  109                          1.3            10.250
  110                          1.3            10.500
  111                          1.3            10.750
  112                          1.3            11.000
  113                          1.3            11.250
  114                          1.3            11.500
  115                          1.3            11.750
  116                          1.3            12.000
  117                          1.3            12.250
  118                          1.3            12.500
  119                          1.3            12.750
  120                          1.3            13.000
  121                          1.3            13.250
  122                          1.3            13.500
  123                          1.3            13.750
  124                          1.3            14.000
  125                          1.3            14.250
  126                          1.3            14.500
  127                          1.3            14.750
  128                          1.3            15.000
  129                          1.3            15.250
  130                          1.3            15.500
  131                          1.3            15.750
  132                          1.3            16.000
  133                          1.3            16.250
  134                          1.3            16.500
  135                          1.3            16.750
  136                          1.3            17.000
  137                          1.3            17.250
  138                          1.3            17.500
  139                          1.3            17.750
  140                          1.3            18.000
  141                          1.3            18.250
  142                          1.3            18.500
  143                          1.3            18.750
  144                          1.3            19.000
  145                          1.3            19.250
  146                          1.3            19.500
  147                          1.3            19.750
  148                          1.3            20.000
--------------------------------------------------------------------------------
================================================================================


Nr. 2 Component: FPRduct_sched
================================================================================
General Data:
--------------------------------------------------------------------------------
Input1                                   Expression result = 1.30000000000000004
--------------------------------------------------------------------------------
Active: Checked
Scheduled component property: Fan
DP property: PRdesduct : Double
Expression: FPR_duct
--------------------------------------------------------------------------------
================================================================================


Nr. 3 Component: FPRcore_sched
================================================================================
General Data:
--------------------------------------------------------------------------------
Input1                                   Expression result = 1.23499999999999988
--------------------------------------------------------------------------------
Active: Checked
Scheduled component property: Fan
DP property: PRdescore : Double
Expression: FPR_duct*0.95
--------------------------------------------------------------------------------
================================================================================


Nr. 4 Component: FPRcore_sched1
================================================================================
```

```
General Data:
--------------------------------------------------------------------------------
Input1                                   Expression result = 32.4969872584729131
--------------------------------------------------------------------------------
Active: Checked
Scheduled component property: HPC
DP property: PRdes : Double
Expression: OPRdes/PR_lpc/(FPR_duct*0.95)
--------------------------------------------------------------------------------
================================================================================


Nr. 5 Component: DP Equation Control
================================================================================
General Data:
--------------------------------------------------------------------------------
Input1                                          Name input1 = 0
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
Input1des                                              ->FN =
--------------------------------------------------------------------------------
================================================================================


Nr. 6 Component: Bleed Control
================================================================================
Bleed flow number                                           = 1
General Data:
--------------------------------------------------------------------------------
Input1                                           W fraction = 0.2500
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
Input1des                                        W fraction = 0.2500
--------------------------------------------------------------------------------
================================================================================


Nr. 7 Component: FPR_duct
================================================================================
General Data:
--------------------------------------------------------------------------------
Output parameter name                                       : FPR_duct
Expression: 1.34
Format                                                      :
Comment/Unit                                                :
--------------------------------------------------------------------------------
================================================================================


Nr. 8 Component: OPRdes
================================================================================
General Data:
--------------------------------------------------------------------------------
Output parameter name                                       : OPRdes
Expression: 60
Format                                                      :
Comment/Unit                                                :
--------------------------------------------------------------------------------
================================================================================


Nr. 9 Component: Inlet  Station nrs.: ltOut1: 2
================================================================================
General Data:
--------------------------------------------------------------------------------
MIL standard Ram Recovery
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
inlet front flow cross area               Ainlet front [m²] = 0.0000
inlet exit flow cross area                 Ainlet exit [m²] = 0.0000
Mass flow                                              Wdes = 359.8662
Ram recovery factor                                   RRdes = 1.000
--------------------------------------------------------------------------------
================================================================================


Nr. 10 Component: Fan  Station nrs.: ltIn1: 2  ltOut1: 24  ltOut2: 13
================================================================================
General Data:
```

```
--------------------------------------------------------------------------------
Shaft nr./suffix                                    ShaftID : 1
Free State Rotor speed
Gear ratio                                               GR = 1.000
Fan drive gear box efficiency                    ETAgearbox = 1.000
Correction factor for eff. map flows                     CF = 0.000
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
Design bypass ratio                                  BPRdes = 9.000
Rotor speed                                      Ndes [rpm] = 1500
Core side pressure ratio                       PRdesdesCore = 1.425
Duct side pressure ratio                       PRdesdesDuct = 1.500
Core side isentropic efficiency                  ETAdesCore = 0.900
Duct side isentropic efficiency                  ETAdesDuct = 0.940
--------------------------------------------------------------------------------

Map data:
--------------------------------------------------------------------------------
Core side map text file name                                :
Map design rotor speed                   NcmapdesCore [rpm] = 1.000
Map design Beta value                        BetamapdesCore = 0.571429
Map design rotor speed                         NcmapdesDuct = 1.000
Map design Beta value                        BetamapdesDuct = 0.571429
--------------------------------------------------------------------------------
================================================================================


Nr. 11 Component: Booster  Station nrs.: ltIn1: 24  ltOut1: 26
================================================================================
General Data:
--------------------------------------------------------------------------------
Shaft nr./suffix                                    ShaftID : 1
Free State Rotor speed
Gear ratio                                               GR = 1.000
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Rotor speed                                      Ndes [rpm] = 3390
Design % rotor speed                           Npercdes [%] = 100.00
Design gear ratio                                     GRdes = 1.000
Isentropic efficiency                                 ETAis = 0.900
Design pressure ratio                                 PRdes = 1.495
--------------------------------------------------------------------------------

Map data:
--------------------------------------------------------------------------------
Map design rotor speed                             Ncmapdes = 1.000
Map Design Beta value                            Betamapdes = 0.571429
--------------------------------------------------------------------------------
================================================================================


Nr. 12 Component: HPC  Station nrs.: ltIn1: 26  ltOut1: 3
================================================================================
General Data:
--------------------------------------------------------------------------------
Shaft nr./suffix                                    ShaftID : 2
Free State Rotor speed
Gear ratio                                               GR = 1.000
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Rotor speed                                      Ndes [rpm] = 10300
Design % rotor speed                           Npercdes [%] = 100.00
Design gear ratio                                     GRdes = 1.000
Isentropic efficiency                                 ETAis = 0.900
Design pressure ratio                                 PRdes = 28.1641
--------------------------------------------------------------------------------

Map data:
--------------------------------------------------------------------------------
Map design rotor speed                             Ncmapdes = 1.000
Map Design Beta value                            Betamapdes = 0.60979
--------------------------------------------------------------------------------

Compressor Bleed flows:
--------------------------------------------------------------------------------
Nr   Type   W bleed   Bleed fraction   dH fraction
 1   Externally Controlled     0.000           0.0000              1
================================================================================
```

```
Nr. 13 Component: Manual Fuel Control
================================================================================
General Data:
--------------------------------------------------------------------------------
Input1                                                   Wf = 0.784
Fuel flow                                         Wf [kg/s] = 0.784
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
Input1des                                                Wf = 2.4912
--------------------------------------------------------------------------------
================================================================================


Nr. 14 Component: Combustor  Station nrs.: ltIn1: 3  ltOut1: 4
================================================================================
General Data:
--------------------------------------------------------------------------------
User specified combustion efficiency
Combustion efficiency                                   ETA = 0.9950
Burner duct cross area                               A [m²] = 0.3800

Fuel type: Jet A/A1, JP-8, Avtur

H / C ratio                                           HCrat = 1.9167
O / C ratio                                           OCrat = 0.000
Off design heating value (HV) at TrefHVCpdes            LHV = 43031.000
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitMach                                        Aexit2 Mach = 0.258114
Design Fuel type: Jet A/A1, JP-8, Avtur

Design H / C ratio                                 HCratdes = 1.9167
Design O / C ratio                                 OCratdes = 0.000
Temp. for design lower heating value (HV) spec.TrefHVcpdes [K] = 298.15
Design Lower heating value at TrefHVCpdes            LHVdes = 43031.000

Design exit temperature                          Ttexit [K] = 1650.00
Design combustion efficiency                         ETAdes = 0.9950
Relative total pressure loss                       dPreldes = 0.0400
--------------------------------------------------------------------------------

Pressure Loss Data:
--------------------------------------------------------------------------------
User specified rel. pressure loss                     Dprel = 0.0000
--------------------------------------------------------------------------------

Emission model: Semi-empirical ratio- or direct prediction method
--------------------------------------------------------------------------------
Design point emission indices [g/kg fuel] :
NOx design point emission index                    EInoxdes = 28.060
CO  design point emission index                     EIcodes = 0.520
UHC design point emission index                    EIuhcdes = 0.080
Design point Smoke number                             SNdes = 7.100

Ratio NOx model (relative to design EI) used
================================================================================


Nr. 15 Component: HPT  Station nrs.: ltIn1: 4  ltOut1: 45
================================================================================
General Data:
--------------------------------------------------------------------------------
Shaft nr./suffix                                    ShaftID : 2
Free State Rotor speed
Gear ratio                                               GR = 1.000
Spool inertial moment                      Ispinert [kg m²] = 0.7578
Spool mechanical efficiency                            ETAm = 0.990
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Rotor speed                                      Ndes [rpm] = 10300
Design % rotor speed                           Npercdes [%] = 100.00
Design gear ratio                                     GRdes = 1.000
Isentropic efficiency                                 ETAis = 0.880
design External power off-take                     PTO [kW] = 0.00
design External torque load                        TQ [N m] = 0
--------------------------------------------------------------------------------

Map data:
--------------------------------------------------------------------------------
```

```
Map design rotor speed                             Ncmapdes = 1.000
Map Design Beta value                            Betamapdes = 0.864906
--------------------------------------------------------------------------------
================================================================================


Nr. 16 Component: LPT  Station nrs.: ltIn1: 45  ltOut1: 5
================================================================================
General Data:
--------------------------------------------------------------------------------
Shaft nr./suffix                                    ShaftID : 1
Free State Rotor speed
Gear ratio                                               GR = 1.000
Spool inertial moment                      Ispinert [kg m²] = 0.7578
Spool mechanical efficiency                            ETAm = 0.990
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Rotor speed                                      Ndes [rpm] = 3390
Design % rotor speed                           Npercdes [%] = 100.00
Design gear ratio                                     GRdes = 1.000
Isentropic efficiency                                 ETAis = 0.925
design External power off-take                     PTO [kW] = 0.00
design External torque load                        TQ [N m] = 0
--------------------------------------------------------------------------------

Map data:
--------------------------------------------------------------------------------
Map design rotor speed                             Ncmapdes = 1.000
Map Design Beta value                            Betamapdes = 0.700
--------------------------------------------------------------------------------
================================================================================


Nr. 17 Component: Hot core duct  Station nrs.: ltIn1: 5  ltOut1: 7
================================================================================
General Data:
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Flow 1 rel. tot. pressure loss at design point    dprel1des = 0.010
--------------------------------------------------------------------------------

Pressure Loss Data:
--------------------------------------------------------------------------------
Specified design rel. pressure loss only
Off-des rel. dp is corrected proportional to Wc²
================================================================================


Nr. 18 Component: Hot exhaust nozzle  Station nrs.: ltIn1: 7
================================================================================
General Data:
--------------------------------------------------------------------------------
Velocity coefficient                                     CV = 0.990
Thrust coefficient                                       CX = 1.000
Fixed throat area nozzle
Convergent nozzle
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Design Velocity coefficient                              CV = 0.990
Design Thrust coefficient                                CX = 1.000
Effective nozzle area                             CD throat = 1.000
--------------------------------------------------------------------------------
================================================================================


Nr. 19 Component: Fan bypass duct  Station nrs.: ltIn1: 13  ltOut1: 17
================================================================================
General Data:
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Flow 1 rel. tot. pressure loss at design point    dprel1des = 0.020
--------------------------------------------------------------------------------
```

```
Pressure Loss Data:
--------------------------------------------------------------------------------
Specified design rel. pressure loss only
Off-des rel. dp is corrected proportional to Wc²
================================================================================


Nr. 20 Component: Cold exhaust nozzle  Station nrs.: ltIn1: 17
================================================================================
General Data:
--------------------------------------------------------------------------------
Velocity coefficient                                     CV = 0.990
Thrust coefficient                                       CX = 1.000
Fixed throat area nozzle
Convergent nozzle
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Design Velocity coefficient                              CV = 0.990
Design Thrust coefficient                                CX = 1.000
Effective nozzle area                             CD throat = 1.000
--------------------------------------------------------------------------------
================================================================================
```

Appendix A.2 Hydrogen 2025 design model difference

```
Nr. 1 Component: LoopCtrl
================================================================================
General Data:
--------------------------------------------------------------------------------
Active: Checked

Loop 1 input data:
--------------------------------------------------------------------------------
Component: FPR_duct
Parameter: ScheduleValue
Start value                                                 = 1.5000E+00
End   value                                                 = 1.3000E+00
Incr. value                                                 = -5.0000E-02
List data:
----------
Title 0,1||Title 0,2
          1.5000E+00
          1.4500E+00
          1.4000E+00
          1.3500E+00
          1.3000E+00

Loop 2 input data:
--------------------------------------------------------------------------------
Component: Fan
Parameter: BPRdes
Start value                                                 = 9.000
End   value                                                 = 20.000
Incr. value                                                 = 0.250
List data:
----------
Title 0,1||Title 0,2
               9.000
               9.250
               9.500
               9.750
              10.000
              10.250
              10.500
              10.750
              11.000
              11.250
              11.500
              11.750
              12.000
              12.250
              12.500
              12.750
              13.000
              13.250
              13.500
              13.750
              14.000
```

```
              14.250
              14.500
              14.750
              15.000
              15.250
              15.500
              15.750
              16.000
              16.250
              16.500
              16.750
              17.000
              17.250
              17.500
              17.750
              18.000
              18.250
              18.500
              18.750
              19.000
              19.250
              19.500
              19.750
              20.000
--------------------------------------------------------------------------------

Series control input data:
--------------------------
Point   Break   FPR_duct||FPR_duct   Fan||Design BPR
    1    TRUE                  1.5             9.000
    2                          1.5             9.250
    3                          1.5             9.500
    4                          1.5             9.750
    5                          1.5            10.000
    6                          1.5            10.250
    7                          1.5            10.500
    8                          1.5            10.750
    9                          1.5            11.000
   10                          1.5            11.250
   11                          1.5            11.500
   12                          1.5            11.750
   13                          1.5            12.000
   14                          1.5            12.250
   15                          1.5            12.500
   16                          1.5            12.750
   17                          1.5            13.000
   18                          1.5            13.250
   19                          1.5            13.500
   20                          1.5            13.750
   21                          1.5            14.000
   22    TRUE                 1.45             9.000
   23                         1.45             9.250
   24                         1.45             9.500
   25                         1.45             9.750
   26                         1.45            10.000
   27                         1.45            10.250
   28                         1.45            10.500
   29                         1.45            10.750
   30                         1.45            11.000
   31                         1.45            11.250
   32                         1.45            11.500
   33                         1.45            11.750
   34                         1.45            12.000
   35                         1.45            12.250
   36                         1.45            12.500
   37                         1.45            12.750
   38                         1.45            13.000
   39                         1.45            13.250
   40                         1.45            13.500
   41                         1.45            13.750
   42                         1.45            14.000
   43                         1.45            14.250
   44                         1.45            14.500
   45                         1.45            14.750
   46                         1.45            15.000
   47                         1.45            15.250
   48    TRUE                  1.4             9.000
   49                          1.4             9.250
   50                          1.4             9.500
   51                          1.4             9.750
   52                          1.4            10.000
   53                          1.4            10.250
   54                          1.4            10.500
   55                          1.4            10.750
   56                          1.4            11.000
   57                          1.4            11.250
   58                          1.4            11.500
```

```
 59                        1.4           11.750
 60                        1.4           12.000
 61                        1.4           12.250
 62                        1.4           12.500
 63                        1.4           12.750
 64                        1.4           13.000
 65                        1.4           13.250
 66                        1.4           13.500
 67                        1.4           13.750
 68                        1.4           14.000
 69                        1.4           14.250
 70                        1.4           14.500
 71                        1.4           14.750
 72                        1.4           15.000
 73                        1.4           15.250
 74                        1.4           15.500
 75                        1.4           15.750
 76                        1.4           16.000
 77                        1.4           16.250
 78                        1.4           16.500
 79                        1.4           16.750
 80                        1.4           17.000
 81    TRUE               1.35            9.000
 82                       1.35            9.250
 83                       1.35            9.500
 84                       1.35            9.750
 85                       1.35           10.000
 86                       1.35           10.250
 87                       1.35           10.500
 88                       1.35           10.750
 89                       1.35           11.000
 90                       1.35           11.250
 91                       1.35           11.500
 92                       1.35           11.750
 93                       1.35           12.000
 94                       1.35           12.250
 95                       1.35           12.500
 96                       1.35           12.750
 97                       1.35           13.000
 98                       1.35           13.250
 99                       1.35           13.500
100                       1.35           13.750
101                       1.35           14.000
102                       1.35           14.250
103                       1.35           14.500
104                       1.35           14.750
105                       1.35           15.000
106                       1.35           15.250
107                       1.35           15.500
108                       1.35           15.750
109                       1.35           16.000
110                       1.35           16.250
111                       1.35           16.500
112                       1.35           16.750
113                       1.35           17.000
114                       1.35           17.250
115                       1.35           17.500
116                       1.35           17.750
117                       1.35           18.000
118                       1.35           18.250
119                       1.35           18.500
120                       1.35           18.750
121                       1.35           19.000
122                       1.35           19.250
123    TRUE                1.3            9.000
124                        1.3            9.250
125                        1.3            9.500
126                        1.3            9.750
127                        1.3           10.000
128                        1.3           10.250
129                        1.3           10.500
130                        1.3           10.750
131                        1.3           11.000
132                        1.3           11.250
133                        1.3           11.500
134                        1.3           11.750
135                        1.3           12.000
136                        1.3           12.250
137                        1.3           12.500
138                        1.3           12.750
139                        1.3           13.000
140                        1.3           13.250
141                        1.3           13.500
142                        1.3           13.750
143                        1.3           14.000
144                        1.3           14.250
145                        1.3           14.500
```

```
  146                        1.3          14.750
  147                        1.3          15.000
  148                        1.3          15.250
  149                        1.3          15.500
  150                        1.3          15.750
  151                        1.3          16.000
  152                        1.3          16.250
  153                        1.3          16.500
  154                        1.3          16.750
  155                        1.3          17.000
  156                        1.3          17.250
  157                        1.3          17.500
  158                        1.3          17.750
  159                        1.3          18.000
  160                        1.3          18.250
  161                        1.3          18.500
  162                        1.3          18.750
  163                        1.3          19.000
  164                        1.3          19.250
  165                        1.3          19.500
  166                        1.3          19.750
  167                        1.3          20.000
--------------------------------------------------------------------------------
================================================================================

Nr. 14 Component: Combustor  Station nrs.: ltIn1: 3  ltOut1: 4
================================================================================
General Data:
--------------------------------------------------------------------------------
User specified combustion efficiency
Combustion efficiency                                      ETA = 0.9950
Burner duct cross area                                  A [m²] = 0.3800

Fuel type: H2 (gas)

H / C ratio                                              HCrat = 0.000
O / C ratio                                              OCrat = 0.000
Off design heating value (HV) at TrefHVCpdes               LHV = 120000.000
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitMach                                           Aexit2 Mach = 0.258114
Design Fuel type: H2 (gas)

Design H / C ratio                                    HCratdes = 0.000
Design O / C ratio                                    OCratdes = 0.000
Temp. for design lower heating value (HV) spec.TrefHVCpdes [K] = 298.15
Design Lower heating value at TrefHVCpdes               LHVdes = 120000.000

Design exit temperature                            Ttexit [K] = 1650.00
Design combustion efficiency                           ETAdes = 0.9950
Relative total pressure loss                          dPreldes = 0.0400
--------------------------------------------------------------------------------

Pressure Loss Data:
--------------------------------------------------------------------------------
User specified rel. pressure loss                        Dprel = 0.0000
--------------------------------------------------------------------------------

Emission model: Semi-empirical ratio- or direct prediction method
--------------------------------------------------------------------------------
Design point emission indices [g/kg fuel] :
NOx design point emission index                      EInoxdes = 28.060
CO  design point emission index                       EIcodes = 0.520
UHC design point emission index                      EIuhcdes = 0.080
Design point Smoke number                               SNdes = 7.100

Ratio NOx model (relative to design EI) used
================================================================================
```

Appendix A.3 Retrofit 2025 turbofan model

Appendix A.3.1 Reference hydrocarbon fuel model

```
GSP 12     UHBRFAN.mxl                                 17:09  November 23, 2022
MODEL DATA
```

```
================================================================================

Ambient / Flight conditions
================================================================================
Atmosphere model: ISA

Design Conditions:
--------------------------------------------------------------------------------
Pressure Altitude                                     Zpdes = 10000
Deviation from ISA temperature                       dTsdes = 0.00
Static Pressure                                      Ps0des = 0.23842
Static temperature                                   Ts0des = 218.81
Density                                             rho0des = 0.4127
--------------------------------------------------------------------------------

Design Air speed data  (Machdes was specified):
--------------------------------------------------------------------------------
Mach number                                         Machdes = 0.800
True air speed                                        Vtdes = 237.2
Calibrated air speed                                  Vcdes = 139.9
--------------------------------------------------------------------------------

Design Total free stream conditions:
--------------------------------------------------------------------------------
Total pressure                                       Pt0des = 0.36344
Total temperature                                    Tt0des = 246.82
--------------------------------------------------------------------------------

Design Humidity:
--------------------------------------------------------------------------------
Mass percent water                                 Hum [m%] = 0.0000E+00
Vapour volume percent                              Hum [v%] = 0.0000E+00
Relative humidity                               Hum.Res [%] = 0.00
--------------------------------------------------------------------------------

Off-design Conditions:
--------------------------------------------------------------------------------
Pressure Altitude                                        Zp = 10000
Deviation from ISA temperature                          dTs = 0.00
Static Pressure                                         Ps0 = 0.26436
Static temperature                                      Ts0 = 223.15
Density                                                rho0 = 0.4127
--------------------------------------------------------------------------------

Air speed data  (Mach was specified):
--------------------------------------------------------------------------------
Mach number                                            Mach = 0.800
True air speed                                           Vt = 239.6
Calibrated air speed                                     Vc = 147.0
--------------------------------------------------------------------------------

Total free stream conditions:
--------------------------------------------------------------------------------
Total pressure                                          Pt0 = 0.40298
Total temperature                                       Tt0 = 251.71
--------------------------------------------------------------------------------

Humidity:
--------------------------------------------------------------------------------
Mass percent water                                 Hum [m%] = 0.0000E+00
Vapour volume percent                              Hum [v%] = 0.0000E+00
Relative humidity                               Hum.Res [%] = 0.00
--------------------------------------------------------------------------------

Flight conditions transient input data:
--------------------------------------------------------------------------------
Pnt/Time  Zp  dTs  Ps  Ts  Mach  Vt  Vc  Type
   0.000   0  0.00  1.01325  288.15  0.000  0.0  0.0   ISA
   1.000   0  0.00  1.01325  288.15  0.000  0.0  0.0   ISA
   2.000   0  0.00  1.01325  288.15  0.000  0.0  0.0   ISA
   3.000   0  0.00  1.01325  288.15  0.000  0.0  0.0   ISA
   4.000   0  0.00  1.01325  288.15  0.000  0.0  0.0   ISA
   5.000   0  0.00  1.01325  288.15  0.000  0.0  0.0   ISA
   6.000   0  0.00  1.01325  288.15  0.000  0.0  0.0   ISA
   7.000   0  0.00  1.01325  288.15  0.000  0.0  0.0   ISA
   8.000   0  0.00  1.01325  288.15  0.200  68.1  68.1   ISA
   9.000   0  0.00  1.01325  288.15  0.200  68.1  68.1   ISA
  10.000   0  0.00  1.01325  288.15  0.200  68.1  68.1   ISA
  11.000   0  0.00  1.01325  288.15  0.200  68.1  68.1   ISA
  12.000   0  0.00  1.01325  288.15  0.200  68.1  68.1   ISA
  13.000   0  0.00  1.01325  288.15  0.200  68.1  68.1   ISA
  14.000   0  0.00  1.01325  288.15  0.200  68.1  68.1   ISA
  15.000   0  0.00  1.01325  288.15  0.200  68.1  68.1   ISA
  16.000   0  0.00  1.01325  288.15  0.400  136.1  136.1   ISA
  17.000   0  0.00  1.01325  288.15  0.400  136.1  136.1   ISA
  18.000   0  0.00  1.01325  288.15  0.400  136.1  136.1   ISA
  19.000   0  0.00  1.01325  288.15  0.400  136.1  136.1   ISA
```

```
 20.000   0  0.00  1.01325  288.15  0.400  136.1  136.1   ISA
 21.000   0  0.00  1.01325  288.15  0.400  136.1  136.1   ISA
 22.000   0  0.00  1.01325  288.15  0.400  136.1  136.1   ISA
 23.000   0  0.00  1.01325  288.15  0.400  136.1  136.1   ISA
 24.000   0  0.00  1.01325  288.15  0.587678  200.0  200.0   ISA
 25.000   0  0.00  1.01325  288.15  0.587678  200.0  200.0   ISA
 26.000   0  0.00  1.01325  288.15  0.587678  200.0  200.0   ISA
 27.000   0  0.00  1.01325  288.15  0.587678  200.0  200.0   ISA
 28.000   0  0.00  1.01325  288.15  0.587678  200.0  200.0   ISA
 29.000   0  0.00  1.01325  288.15  0.587678  200.0  200.0   ISA
 30.000   0  0.00  1.01325  288.15  0.587678  200.0  200.0   ISA
 31.000   0  0.00  1.01325  288.15  0.587678  200.0  200.0   ISA
 32.000  2000  0.00  0.79495  275.15  0.000  0.0  0.0   ISA
 33.000  2000  0.00  0.79495  275.15  0.000  0.0  0.0   ISA
 34.000  2000  0.00  0.79495  275.15  0.000  0.0  0.0   ISA
 35.000  2000  0.00  0.79495  275.15  0.000  0.0  0.0   ISA
 36.000  2000  0.00  0.79495  275.15  0.000  0.0  0.0   ISA
 37.000  2000  0.00  0.79495  275.15  0.000  0.0  0.0   ISA
 38.000  2000  0.00  0.79495  275.15  0.000  0.0  0.0   ISA
 39.000  2000  0.00  0.79495  275.15  0.000  0.0  0.0   ISA
 40.000  2000  0.00  0.79495  275.15  0.198834  66.1  60.0   ISA
 41.000  2000  0.00  0.79495  275.15  0.198834  66.1  60.0   ISA
 42.000  2000  0.00  0.79495  275.15  0.198834  66.1  60.0   ISA
 43.000  2000  0.00  0.79495  275.15  0.198834  66.1  60.0   ISA
 44.000  2000  0.00  0.79495  275.15  0.198834  66.1  60.0   ISA
 45.000  2000  0.00  0.79495  275.15  0.198834  66.1  60.0   ISA
 46.000  2000  0.00  0.79495  275.15  0.198834  66.1  60.0   ISA
 47.000  2000  0.00  0.79495  275.15  0.198834  66.1  60.0   ISA
 48.000  2000  0.00  0.79495  275.15  0.200  66.5  60.4   ISA
 49.000  2000  0.00  0.79495  275.15  0.200  66.5  60.4   ISA
 50.000  2000  0.00  0.79495  275.15  0.200  66.5  60.4   ISA
 51.000  2000  0.00  0.79495  275.15  0.200  66.5  60.4   ISA
 52.000  2000  0.00  0.79495  275.15  0.200  66.5  60.4   ISA
 53.000  2000  0.00  0.79495  275.15  0.200  66.5  60.4   ISA
 54.000  2000  0.00  0.79495  275.15  0.200  66.5  60.4   ISA
 55.000  2000  0.00  0.79495  275.15  0.200  66.5  60.4   ISA
 56.000  2000  0.00  0.79495  275.15  0.400  133.0  121.1   ISA
 57.000  2000  0.00  0.79495  275.15  0.400  133.0  121.1   ISA
 58.000  2000  0.00  0.79495  275.15  0.400  133.0  121.1   ISA
 59.000  2000  0.00  0.79495  275.15  0.400  133.0  121.1   ISA
 60.000  2000  0.00  0.79495  275.15  0.400  133.0  121.1   ISA
 61.000  2000  0.00  0.79495  275.15  0.400  133.0  121.1   ISA
 62.000  2000  0.00  0.79495  275.15  0.400  133.0  121.1   ISA
 63.000  2000  0.00  0.79495  275.15  0.400  133.0  121.1   ISA
 64.000  2000  0.00  0.79495  275.15  0.600  199.5  182.5   ISA
 65.000  2000  0.00  0.79495  275.15  0.600  199.5  182.5   ISA
 66.000  2000  0.00  0.79495  275.15  0.600  199.5  182.5   ISA
 67.000  2000  0.00  0.79495  275.15  0.600  199.5  182.5   ISA
 68.000  2000  0.00  0.79495  275.15  0.600  199.5  182.5   ISA
 69.000  2000  0.00  0.79495  275.15  0.600  199.5  182.5   ISA
 70.000  2000  0.00  0.79495  275.15  0.600  199.5  182.5   ISA
 71.000  2000  0.00  0.79495  275.15  0.600  199.5  182.5   ISA
 72.000  2000  0.00  0.79495  275.15  0.656551  218.3  200.0   ISA
 73.000  2000  0.00  0.79495  275.15  0.656551  218.3  200.0   ISA
 74.000  2000  0.00  0.79495  275.15  0.656551  218.3  200.0   ISA
 75.000  2000  0.00  0.79495  275.15  0.656551  218.3  200.0   ISA
 76.000  2000  0.00  0.79495  275.15  0.656551  218.3  200.0   ISA
 77.000  2000  0.00  0.79495  275.15  0.656551  218.3  200.0   ISA
 78.000  2000  0.00  0.79495  275.15  0.656551  218.3  200.0   ISA
 79.000  2000  0.00  0.79495  275.15  0.656551  218.3  200.0   ISA
 80.000  4000  0.00  0.6164  262.15  0.225484  73.2  60.0   ISA
 81.000  4000  0.00  0.6164  262.15  0.225484  73.2  60.0   ISA
 82.000  4000  0.00  0.6164  262.15  0.225484  73.2  60.0   ISA
 83.000  4000  0.00  0.6164  262.15  0.225484  73.2  60.0   ISA
 84.000  4000  0.00  0.6164  262.15  0.225484  73.2  60.0   ISA
 85.000  4000  0.00  0.6164  262.15  0.225484  73.2  60.0   ISA
 86.000  4000  0.00  0.6164  262.15  0.225484  73.2  60.0   ISA
 87.000  4000  0.00  0.6164  262.15  0.225484  73.2  60.0   ISA
 88.000  4000  0.00  0.6164  262.15  0.400  129.8  107.0   ISA
 89.000  4000  0.00  0.6164  262.15  0.400  129.8  107.0   ISA
 90.000  4000  0.00  0.6164  262.15  0.400  129.8  107.0   ISA
 91.000  4000  0.00  0.6164  262.15  0.400  129.8  107.0   ISA
 92.000  4000  0.00  0.6164  262.15  0.400  129.8  107.0   ISA
 93.000  4000  0.00  0.6164  262.15  0.400  129.8  107.0   ISA
 94.000  4000  0.00  0.6164  262.15  0.400  129.8  107.0   ISA
 95.000  4000  0.00  0.6164  262.15  0.400  129.8  107.0   ISA
 96.000  4000  0.00  0.6164  262.15  0.600  194.8  161.9   ISA
 97.000  4000  0.00  0.6164  262.15  0.600  194.8  161.9   ISA
 98.000  4000  0.00  0.6164  262.15  0.600  194.8  161.9   ISA
 99.000  4000  0.00  0.6164  262.15  0.600  194.8  161.9   ISA
100.000  4000  0.00  0.6164  262.15  0.600  194.8  161.9   ISA
101.000  4000  0.00  0.6164  262.15  0.600  194.8  161.9   ISA
102.000  4000  0.00  0.6164  262.15  0.600  194.8  161.9   ISA
103.000  4000  0.00  0.6164  262.15  0.600  194.8  161.9   ISA
104.000  4000  0.00  0.6164  262.15  0.735663  238.8  200.0   ISA
105.000  4000  0.00  0.6164  262.15  0.735663  238.8  200.0   ISA
106.000  4000  0.00  0.6164  262.15  0.735663  238.8  200.0   ISA
```

```
107.000  4000  0.00  0.6164  262.15  0.735663  238.8  200.0   ISA
108.000  4000  0.00  0.6164  262.15  0.735663  238.8  200.0   ISA
109.000  4000  0.00  0.6164  262.15  0.735663  238.8  200.0   ISA
110.000  4000  0.00  0.6164  262.15  0.735663  238.8  200.0   ISA
111.000  4000  0.00  0.6164  262.15  0.735663  238.8  200.0   ISA
112.000  5444  0.00  0.50892  252.76  0.800  255.0  200.0   ISA
113.000  5444  0.00  0.50892  252.76  0.800  255.0  200.0   ISA
114.000  5444  0.00  0.50892  252.76  0.800  255.0  200.0   ISA
115.000  5444  0.00  0.50892  252.76  0.800  255.0  200.0   ISA
116.000  5444  0.00  0.50892  252.76  0.800  255.0  200.0   ISA
117.000  5444  0.00  0.50892  252.76  0.800  255.0  200.0   ISA
118.000  5444  0.00  0.50892  252.76  0.800  255.0  200.0   ISA
119.000  5444  0.00  0.50892  252.76  0.800  255.0  200.0   ISA
120.000  6000  0.00  0.47181  249.15  0.257238  81.4  60.0   ISA
121.000  6000  0.00  0.47181  249.15  0.257238  81.4  60.0   ISA
122.000  6000  0.00  0.47181  249.15  0.257238  81.4  60.0   ISA
123.000  6000  0.00  0.47181  249.15  0.257238  81.4  60.0   ISA
124.000  6000  0.00  0.47181  249.15  0.257238  81.4  60.0   ISA
125.000  6000  0.00  0.47181  249.15  0.257238  81.4  60.0   ISA
126.000  6000  0.00  0.47181  249.15  0.257238  81.4  60.0   ISA
127.000  6000  0.00  0.47181  249.15  0.257238  81.4  60.0   ISA
128.000  6000  0.00  0.47181  249.15  0.400  126.6  93.9   ISA
129.000  6000  0.00  0.47181  249.15  0.400  126.6  93.9   ISA
130.000  6000  0.00  0.47181  249.15  0.400  126.6  93.9   ISA
131.000  6000  0.00  0.47181  249.15  0.400  126.6  93.9   ISA
132.000  6000  0.00  0.47181  249.15  0.400  126.6  93.9   ISA
133.000  6000  0.00  0.47181  249.15  0.400  126.6  93.9   ISA
134.000  6000  0.00  0.47181  249.15  0.400  126.6  93.9   ISA
135.000  6000  0.00  0.47181  249.15  0.400  126.6  93.9   ISA
136.000  6000  0.00  0.47181  249.15  0.600  189.9  142.5   ISA
137.000  6000  0.00  0.47181  249.15  0.600  189.9  142.5   ISA
138.000  6000  0.00  0.47181  249.15  0.600  189.9  142.5   ISA
139.000  6000  0.00  0.47181  249.15  0.600  189.9  142.5   ISA
140.000  6000  0.00  0.47181  249.15  0.600  189.9  142.5   ISA
141.000  6000  0.00  0.47181  249.15  0.600  189.9  142.5   ISA
142.000  6000  0.00  0.47181  249.15  0.600  189.9  142.5   ISA
143.000  6000  0.00  0.47181  249.15  0.600  189.9  142.5   ISA
144.000  6000  0.00  0.47181  249.15  0.800  253.2  193.1   ISA
145.000  6000  0.00  0.47181  249.15  0.800  253.2  193.1   ISA
146.000  6000  0.00  0.47181  249.15  0.800  253.2  193.1   ISA
147.000  6000  0.00  0.47181  249.15  0.800  253.2  193.1   ISA
148.000  6000  0.00  0.47181  249.15  0.800  253.2  193.1   ISA
149.000  6000  0.00  0.47181  249.15  0.800  253.2  193.1   ISA
150.000  6000  0.00  0.47181  249.15  0.800  253.2  193.1   ISA
151.000  6000  0.00  0.47181  249.15  0.800  253.2  193.1   ISA
152.000  8000  0.00  0.356  236.15  0.295363  91.0  60.0   ISA
153.000  8000  0.00  0.356  236.15  0.295363  91.0  60.0   ISA
154.000  8000  0.00  0.356  236.15  0.295363  91.0  60.0   ISA
155.000  8000  0.00  0.356  236.15  0.295363  91.0  60.0   ISA
156.000  8000  0.00  0.356  236.15  0.295363  91.0  60.0   ISA
157.000  8000  0.00  0.356  236.15  0.295363  91.0  60.0   ISA
158.000  8000  0.00  0.356  236.15  0.295363  91.0  60.0   ISA
159.000  8000  0.00  0.356  236.15  0.295363  91.0  60.0   ISA
160.000  8000  0.00  0.356  236.15  0.400  123.2  81.7   ISA
161.000  8000  0.00  0.356  236.15  0.400  123.2  81.7   ISA
162.000  8000  0.00  0.356  236.15  0.400  123.2  81.7   ISA
163.000  8000  0.00  0.356  236.15  0.400  123.2  81.7   ISA
164.000  8000  0.00  0.356  236.15  0.400  123.2  81.7   ISA
165.000  8000  0.00  0.356  236.15  0.400  123.2  81.7   ISA
166.000  8000  0.00  0.356  236.15  0.400  123.2  81.7   ISA
167.000  8000  0.00  0.356  236.15  0.400  123.2  81.7   ISA
168.000  8000  0.00  0.356  236.15  0.600  184.9  124.5   ISA
169.000  8000  0.00  0.356  236.15  0.600  184.9  124.5   ISA
170.000  8000  0.00  0.356  236.15  0.600  184.9  124.5   ISA
171.000  8000  0.00  0.356  236.15  0.600  184.9  124.5   ISA
172.000  8000  0.00  0.356  236.15  0.600  184.9  124.5   ISA
173.000  8000  0.00  0.356  236.15  0.600  184.9  124.5   ISA
174.000  8000  0.00  0.356  236.15  0.600  184.9  124.5   ISA
175.000  8000  0.00  0.356  236.15  0.600  184.9  124.5   ISA
176.000  8000  0.00  0.356  236.15  0.800  246.5  169.3   ISA
177.000  8000  0.00  0.356  236.15  0.800  246.5  169.3   ISA
178.000  8000  0.00  0.356  236.15  0.800  246.5  169.3   ISA
179.000  8000  0.00  0.356  236.15  0.800  246.5  169.3   ISA
180.000  8000  0.00  0.356  236.15  0.800  246.5  169.3   ISA
181.000  8000  0.00  0.356  236.15  0.800  246.5  169.3   ISA
182.000  8000  0.00  0.356  236.15  0.800  246.5  169.3   ISA
183.000  8000  0.00  0.356  236.15  0.800  246.5  169.3   ISA
184.000  10000  0.00  0.26436  223.15  0.341502  102.3  60.0   ISA
185.000  10000  0.00  0.26436  223.15  0.341502  102.3  60.0   ISA
186.000  10000  0.00  0.26436  223.15  0.341502  102.3  60.0   ISA
187.000  10000  0.00  0.26436  223.15  0.341502  102.3  60.0   ISA
188.000  10000  0.00  0.26436  223.15  0.341502  102.3  60.0   ISA
189.000  10000  0.00  0.26436  223.15  0.341502  102.3  60.0   ISA
190.000  10000  0.00  0.26436  223.15  0.341502  102.3  60.0   ISA
191.000  10000  0.00  0.26436  223.15  0.341502  102.3  60.0   ISA
192.000  10000  0.00  0.26436  223.15  0.400  119.8  70.6   ISA
193.000  10000  0.00  0.26436  223.15  0.400  119.8  70.6   ISA
```

```
 194.000  10000  0.00  0.26436  223.15  0.400  119.8  70.6   ISA
 195.000  10000  0.00  0.26436  223.15  0.400  119.8  70.6   ISA
 196.000  10000  0.00  0.26436  223.15  0.400  119.8  70.6   ISA
 197.000  10000  0.00  0.26436  223.15  0.400  119.8  70.6   ISA
 198.000  10000  0.00  0.26436  223.15  0.400  119.8  70.6   ISA
 199.000  10000  0.00  0.26436  223.15  0.400  119.8  70.6   ISA
 200.000  10000  0.00  0.26436  223.15  0.600  179.7  107.7   ISA
 201.000  10000  0.00  0.26436  223.15  0.600  179.7  107.7   ISA
 202.000  10000  0.00  0.26436  223.15  0.600  179.7  107.7   ISA
 203.000  10000  0.00  0.26436  223.15  0.600  179.7  107.7   ISA
 204.000  10000  0.00  0.26436  223.15  0.600  179.7  107.7   ISA
 205.000  10000  0.00  0.26436  223.15  0.600  179.7  107.7   ISA
 206.000  10000  0.00  0.26436  223.15  0.600  179.7  107.7   ISA
 207.000  10000  0.00  0.26436  223.15  0.600  179.7  107.7   ISA
 208.000  10000  0.00  0.26436  223.15  0.800  239.6  147.0   ISA
 209.000  10000  0.00  0.26436  223.15  0.800  239.6  147.0   ISA
 210.000  10000  0.00  0.26436  223.15  0.800  239.6  147.0   ISA
 211.000  10000  0.00  0.26436  223.15  0.800  239.6  147.0   ISA
 212.000  10000  0.00  0.26436  223.15  0.800  239.6  147.0   ISA
 213.000  10000  0.00  0.26436  223.15  0.800  239.6  147.0   ISA
 214.000  10000  0.00  0.26436  223.15  0.800  239.6  147.0   ISA
 215.000  10000  0.00  0.26436  223.15  0.800  239.6  147.0   ISA
================================================================================


Nr. 1 Component: Bleed Control
================================================================================
Bleed flow number                                           = 1
General Data:
--------------------------------------------------------------------------------
Input1                                           W fraction = 0.2500
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
Input1des                                        W fraction = 0.2500
--------------------------------------------------------------------------------
================================================================================


Nr. 2 Component: OperEnvSched
================================================================================
General Data:
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
================================================================================


Nr. 3 Component: Inlet  Station nrs.: ltOut1: 2
================================================================================
General Data:
--------------------------------------------------------------------------------
MIL standard Ram Recovery
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
inlet front flow cross area               Ainlet front [m²] = 0.0000
inlet exit flow cross area                 Ainlet exit [m²] = 0.0000
Mass flow                                              Wdes = 626.6965
Ram recovery factor                                   RRdes = 1.000
--------------------------------------------------------------------------------
================================================================================


Nr. 4 Component: Fan  Station nrs.: ltIn1: 2  ltOut1: 24  ltOut2: 13
================================================================================
General Data:
--------------------------------------------------------------------------------
Shaft nr./suffix                                    ShaftID : 1
Free State Rotor speed
Gear ratio                                               GR = 1.000
Fan drive gear box efficiency                    ETAgearbox = 1.000
Correction factor for eff. map flows                     CF = 0.000
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
Design bypass ratio                                  BPRdes = 13.750
Rotor speed                                      Ndes [rpm] = 1500
Core side pressure ratio                       PRdesdesCore = 1.330
```

```
Duct side pressure ratio                       PRdesdesDuct = 1.400
Core side isentropic efficiency                  ETAdesCore = 0.900
Duct side isentropic efficiency                  ETAdesDuct = 0.940
--------------------------------------------------------------------------------

Map data:
--------------------------------------------------------------------------------
Core side map text file name                                :
Map design rotor speed                   NcmapdesCore [rpm] = 1.000
Map design Beta value                        BetamapdesCore = 0.571429
Map design rotor speed                         NcmapdesDuct = 1.000
Map design Beta value                        BetamapdesDuct = 0.571429
--------------------------------------------------------------------------------
================================================================================


Nr. 5 Component: Booster  Station nrs.: ltIn1: 24  ltOut1: 26
================================================================================
General Data:
--------------------------------------------------------------------------------
Shaft nr./suffix                                    ShaftID : 1
Free State Rotor speed
Gear ratio                                               GR = 1.000
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Rotor speed                                      Ndes [rpm] = 3390
Design % rotor speed                           Npercdes [%] = 100.00
Design gear ratio                                     GRdes = 1.000
Isentropic efficiency                                 ETAis = 0.900
Design pressure ratio                                 PRdes = 1.495
--------------------------------------------------------------------------------

Map data:
--------------------------------------------------------------------------------
Map design rotor speed                             Ncmapdes = 1.000
Map Design Beta value                            Betamapdes = 0.571429
--------------------------------------------------------------------------------
================================================================================


Nr. 6 Component: HPC  Station nrs.: ltIn1: 26  ltOut1: 3
================================================================================
General Data:
--------------------------------------------------------------------------------
Shaft nr./suffix                                    ShaftID : 2
Free State Rotor speed
Gear ratio                                               GR = 1.000
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Rotor speed                                      Ndes [rpm] = 10300
Design % rotor speed                           Npercdes [%] = 100.00
Design gear ratio                                     GRdes = 1.000
Isentropic efficiency                                 ETAis = 0.900
Design pressure ratio                                 PRdes = 30.1758
--------------------------------------------------------------------------------

Map data:
--------------------------------------------------------------------------------
Map design rotor speed                             Ncmapdes = 1.000
Map Design Beta value                            Betamapdes = 0.60979
--------------------------------------------------------------------------------

Compressor Bleed flows:
--------------------------------------------------------------------------------
Nr   Type   W bleed   Bleed fraction   dH fraction
 1   Externally Controlled     0.000           0.0000             1
================================================================================


Nr. 7 Component: Manual Fuel Control
================================================================================
General Data:
--------------------------------------------------------------------------------
Input1                                               Ttexit = 950.00
Exit temp.                                       Ttexit [K] = 950.00
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
Input1des                                            Ttexit = 2.49
--------------------------------------------------------------------------------
```

```
Series control input data:
--------------------------
Point   Ttexit
    0   1650.00
    1   1550.00
    2   1450.00
    3   1350.00
    4   1250.00
    5   1150.00
    6   1050.00
    7   950.00
    8   1650.00
    9   1550.00
   10   1450.00
   11   1350.00
   12   1250.00
   13   1150.00
   14   1050.00
   15   950.00
   16   1650.00
   17   1550.00
   18   1450.00
   19   1350.00
   20   1250.00
   21   1150.00
   22   1050.00
   23   950.00
   24   1650.00
   25   1550.00
   26   1450.00
   27   1350.00
   28   1250.00
   29   1150.00
   30   1050.00
   31   950.00
   32   1650.00
   33   1550.00
   34   1450.00
   35   1350.00
   36   1250.00
   37   1150.00
   38   1050.00
   39   950.00
   40   1650.00
   41   1550.00
   42   1450.00
   43   1350.00
   44   1250.00
   45   1150.00
   46   1050.00
   47   950.00
   48   1650.00
   49   1550.00
   50   1450.00
   51   1350.00
   52   1250.00
   53   1150.00
   54   1050.00
   55   950.00
   56   1650.00
   57   1550.00
   58   1450.00
   59   1350.00
   60   1250.00
   61   1150.00
   62   1050.00
   63   950.00
   64   1650.00
   65   1550.00
   66   1450.00
   67   1350.00
   68   1250.00
   69   1150.00
   70   1050.00
   71   950.00
   72   1650.00
   73   1550.00
   74   1450.00
   75   1350.00
   76   1250.00
   77   1150.00
   78   1050.00
   79   950.00
   80   1650.00
   81   1550.00
   82   1450.00
```

```
 83   1350.00
 84   1250.00
 85   1150.00
 86   1050.00
 87   950.00
 88   1650.00
 89   1550.00
 90   1450.00
 91   1350.00
 92   1250.00
 93   1150.00
 94   1050.00
 95   950.00
 96   1650.00
 97   1550.00
 98   1450.00
 99   1350.00
100   1250.00
101   1150.00
102   1050.00
103   950.00
104   1650.00
105   1550.00
106   1450.00
107   1350.00
108   1250.00
109   1150.00
110   1050.00
111   950.00
112   1650.00
113   1550.00
114   1450.00
115   1350.00
116   1250.00
117   1150.00
118   1050.00
119   950.00
120   1650.00
121   1550.00
122   1450.00
123   1350.00
124   1250.00
125   1150.00
126   1050.00
127   950.00
128   1650.00
129   1550.00
130   1450.00
131   1350.00
132   1250.00
133   1150.00
134   1050.00
135   950.00
136   1650.00
137   1550.00
138   1450.00
139   1350.00
140   1250.00
141   1150.00
142   1050.00
143   950.00
144   1650.00
145   1550.00
146   1450.00
147   1350.00
148   1250.00
149   1150.00
150   1050.00
151   950.00
152   1650.00
153   1550.00
154   1450.00
155   1350.00
156   1250.00
157   1150.00
158   1050.00
159   950.00
160   1650.00
161   1550.00
162   1450.00
163   1350.00
164   1250.00
165   1150.00
166   1050.00
167   950.00
168   1650.00
169   1550.00
```

```
  170   1450.00
  171   1350.00
  172   1250.00
  173   1150.00
  174   1050.00
  175   950.00
  176   1650.00
  177   1550.00
  178   1450.00
  179   1350.00
  180   1250.00
  181   1150.00
  182   1050.00
  183   950.00
  184   1650.00
  185   1550.00
  186   1450.00
  187   1350.00
  188   1250.00
  189   1150.00
  190   1050.00
  191   950.00
  192   1650.00
  193   1550.00
  194   1450.00
  195   1350.00
  196   1250.00
  197   1150.00
  198   1050.00
  199   950.00
  200   1650.00
  201   1550.00
  202   1450.00
  203   1350.00
  204   1250.00
  205   1150.00
  206   1050.00
  207   950.00
  208   1650.00
  209   1550.00
  210   1450.00
  211   1350.00
  212   1250.00
  213   1150.00
  214   1050.00
  215   950.00
--------------------------------------------------------------------------------
================================================================================


Nr. 8 Component: Combustor  Station nrs.: ltIn1: 3  ltOut1: 4
================================================================================
General Data:
--------------------------------------------------------------------------------
User specified combustion efficiency
Combustion efficiency                                     ETA = 0.9950
Burner duct cross area                                 A [m²] = 0.3800

Fuel type: Jet A/A1, JP-8, Avtur

H / C ratio                                             HCrat = 1.9167
O / C ratio                                             OCrat = 0.000
Off design heating value (HV) at TrefHVCpdes              LHV = 43031.000
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitMach                                       Aexit2 Mach = 0.258114
Design Fuel type: Jet A/A1, JP-8, Avtur

Design H / C ratio                                   HCratdes = 1.9167
Design O / C ratio                                   OCratdes = 0.000
Temp. for design lower heating value (HV) spec.TrefHVCpdes [K] = 298.15
Design Lower heating value at TrefHVCpdes              LHVdes = 43031.000

Design exit temperature                          Ttexit [K] = 1650.00
Design combustion efficiency                           ETAdes = 0.9950
Relative total pressure loss                         dPreldes = 0.0400
--------------------------------------------------------------------------------

Pressure Loss Data:
--------------------------------------------------------------------------------
User specified rel. pressure loss                       Dprel = 0.0000
--------------------------------------------------------------------------------

Emission model: Semi-empirical ratio- or direct prediction method
--------------------------------------------------------------------------------
```

```
Design point emission indices [g/kg fuel] :
NOx design point emission index                    EInoxdes = 28.060
CO  design point emission index                     EIcodes = 0.520
UHC design point emission index                    EIuhcdes = 0.080
Design point Smoke number                             SNdes = 7.100

Ratio NOx model (relative to design EI) used
================================================================================


Nr. 9 Component: HPT  Station nrs.: ltIn1: 4  ltOut1: 45
================================================================================
General Data:
--------------------------------------------------------------------------------
Shaft nr./suffix                                    ShaftID : 2
Free State Rotor speed
Gear ratio                                               GR = 1.000
Spool inertial moment                      Ispinert [kg m²] = 0.7578
Spool mechanical efficiency                            ETAm = 0.990
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Rotor speed                                      Ndes [rpm] = 10300
Design % rotor speed                           Npercdes [%] = 100.00
Design gear ratio                                     GRdes = 1.000
Isentropic efficiency                                 ETAis = 0.880
design External power off-take                     PTO [kW] = 0.00
design External torque load                        TQ [N m] = 0
--------------------------------------------------------------------------------

Map data:
--------------------------------------------------------------------------------
Map design rotor speed                             Ncmapdes = 1.000
Map Design Beta value                            Betamapdes = 0.864906
--------------------------------------------------------------------------------
================================================================================


Nr. 10 Component: LPT  Station nrs.: ltIn1: 45  ltOut1: 5
================================================================================
General Data:
--------------------------------------------------------------------------------
Shaft nr./suffix                                    ShaftID : 1
Free State Rotor speed
Gear ratio                                               GR = 1.000
Spool inertial moment                      Ispinert [kg m²] = 0.7578
Spool mechanical efficiency                            ETAm = 0.990
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Rotor speed                                      Ndes [rpm] = 3390
Design % rotor speed                           Npercdes [%] = 100.00
Design gear ratio                                     GRdes = 1.000
Isentropic efficiency                                 ETAis = 0.925
design External power off-take                     PTO [kW] = 0.00
design External torque load                        TQ [N m] = 0
--------------------------------------------------------------------------------

Map data:
--------------------------------------------------------------------------------
Map design rotor speed                             Ncmapdes = 1.000
Map Design Beta value                            Betamapdes = 0.700
--------------------------------------------------------------------------------
================================================================================


Nr. 11 Component: Hot core duct  Station nrs.: ltIn1: 5  ltOut1: 7
================================================================================
General Data:
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Flow 1 rel. tot. pressure loss at design point    dprel1des = 0.010
--------------------------------------------------------------------------------

Pressure Loss Data:
--------------------------------------------------------------------------------
Specified design rel. pressure loss only
Off-des rel. dp is corrected proportional to Wc²
================================================================================
```

```
Nr. 12 Component: Hot exhaust nozzle  Station nrs.: ltIn1: 7
================================================================================
General Data:
--------------------------------------------------------------------------------
Velocity coefficient                                     CV = 0.990
Thrust coefficient                                       CX = 1.000
Fixed throat area nozzle
Convergent nozzle
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Design Velocity coefficient                              CV = 0.990
Design Thrust coefficient                                CX = 1.000
Effective nozzle area                             CD throat = 1.000
--------------------------------------------------------------------------------
================================================================================


Nr. 13 Component: Fan bypass duct  Station nrs.: ltIn1: 13  ltOut1: 17
================================================================================
General Data:
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Flow 1 rel. tot. pressure loss at design point    dprel1des = 0.020
--------------------------------------------------------------------------------

Pressure Loss Data:
--------------------------------------------------------------------------------
Specified design rel. pressure loss only
Off-des rel. dp is corrected proportional to Wc²
================================================================================


Nr. 14 Component: Cold exhaust nozzle  Station nrs.: ltIn1: 17
================================================================================
General Data:
--------------------------------------------------------------------------------
Velocity coefficient                                     CV = 0.990
Thrust coefficient                                       CX = 1.000
Fixed throat area nozzle
Convergent nozzle
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
ExitArea                                        Aexit2 Area = 0.0000
Design Velocity coefficient                              CV = 0.990
Design Thrust coefficient                                CX = 1.000
Effective nozzle area                             CD throat = 1.000
--------------------------------------------------------------------------------
================================================================================
```

Appendix A.3.2 Combustor exit specified

Difference to Appendix A.3.1

```
Nr. 8 Component: Combustor  Station nrs.: ltIn1: 3  ltOut1: 4
================================================================================
General Data:
--------------------------------------------------------------------------------
User specified combustion efficiency
Combustion efficiency                                   ETA = 0.9950
Burner duct cross area                               A [m²] = 0.3800

Fuel type: H2 (gas)

H / C ratio                                           HCrat = 0.000
O / C ratio                                           OCrat = 0.000
Off design heating value (HV) at TrefHVCpdes            LHV = 120000.000
--------------------------------------------------------------------------------
```

Appendix A.3.3 Thrust specified

Difference to Appendix A.3.2

```
Nr. 3 Component: Thrust Control
================================================================================
General Data:
--------------------------------------------------------------------------------
Input1                                                   FN =
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------

Design Point Data:
--------------------------------------------------------------------------------
Input1des                                       Name input1 = 0
--------------------------------------------------------------------------------

Series control input data:
--------------------------
Point   FN
    0   179.373
    1   111.980
    2   66.877
    3   42.704
    4   30.074
    5   21.869
    6   15.651
    7   10.664
    8   120.225
    9   68.986
   10   36.195
   11   20.091
   12   12.080
   13   7.109
   14   3.817
   15   1.449
   16   80.437
   17   42.177
   18   19.518
   19   8.398
   20   2.820
   21   -0.653
   22   -2.908
   23   -4.455
   24   53.463
   25   23.693
   26   7.735
   27   -0.380
   28   -5.278
   29   -8.156
   30   -9.996
   31   -11.194
   32   179.977
   33   118.061
   34   69.462
   35   42.890
   36   28.219
   37   19.880
   38   14.340
   39   9.887
   40   127.482
   41   77.597
   42   40.653
   43   22.295
   44   12.431
   45   7.250
   46   4.080
   47   1.865
   48   127.186
   49   77.413
   50   40.529
   51   22.215
   52   12.373
   53   7.201
   54   4.043
   55   1.835
   56   90.370
   57   49.830
   58   23.515
   59   11.071
   60   4.188
   61   0.663
   62   -1.576
```

```
 63   -3.049
 64   61.264
 65   31.748
 66   11.935
 67   2.370
 68   -2.838
 69   -5.834
 70   -7.662
 71   -8.809
 72   55.138
 73   28.261
 74   9.355
 75   0.137
 76   -4.831
 77   -7.684
 78   -9.397
 79   -10.498
 80   120.153
 81   82.309
 82   44.926
 83   22.362
 84   11.661
 85   6.563
 86   3.519
 87   1.533
 88   94.020
 89   58.488
 90   29.920
 91   13.304
 92   5.556
 93   1.753
 94   -0.501
 95   -1.925
 96   67.568
 97   39.364
 98   17.355
 99   5.491
100   -0.224
101   -3.503
102   -5.354
103   -6.503
104   53.232
105   29.752
106   11.834
107   1.317
108   -3.942
109   -6.931
110   -8.689
111   -9.753
112   51.302
113   29.641
114   14.210
115   2.435
116   -3.178
117   -6.132
118   -7.968
119   -9.037
120   107.373
121   80.279
122   48.261
123   25.554
124   12.184
125   6.012
126   3.043
127   1.239
128   90.141
129   63.645
130   36.071
131   17.218
132   7.431
133   2.671
134   0.366
135   -1.038
136   71.625
137   44.643
138   23.117
139   9.104
140   2.003
141   -1.532
142   -3.486
143   -4.628
144   52.185
145   31.121
146   15.417
147   3.491
148   -2.333
149   -5.367
```

```
  150   -7.209
  151   -8.277
  152   91.817
  153   71.860
  154   49.924
  155   26.789
  156   12.203
  157   5.716
  158   2.702
  159   0.989
  160   82.337
  161   63.446
  162   41.660
  163   21.147
  164   9.060
  165   3.597
  166   1.066
  167   -0.346
  168   68.568
  169   48.112
  170   27.969
  171   13.347
  172   4.231
  173   0.179
  174   -1.976
  175   -3.138
  176   56.010
  177   34.567
  178   19.282
  179   8.429
  180   0.664
  181   -2.941
  182   -4.815
  183   -5.913
  184   75.891
  185   61.757
  186   46.673
  187   28.750
  188   13.839
  189   5.898
  190   2.402
  191   0.800
  192   72.144
  193   57.846
  194   43.340
  195   25.464
  196   12.014
  197   4.835
  198   1.634
  199   0.202
  200   62.141
  201   47.705
  202   31.432
  203   17.404
  204   6.758
  205   1.623
  206   -0.727
  207   -1.957
  208   54.403
  209   37.827
  210   21.883
  211   11.472
  212   3.405
  213   -0.839
  214   -2.901
  215   -4.046
---------------------------------------------------------------------------------
=================================================================================
```

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