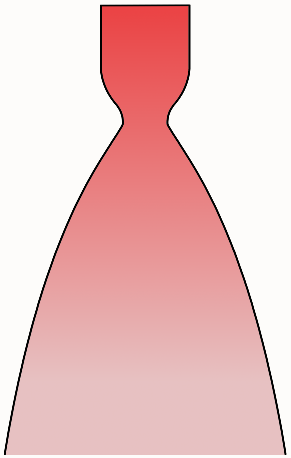
Rocket Propulsion Analysis



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Motivation

RPA is being developed to...

- Provide modern multi-platform tool for prediction of rocket engine performance at the conceptual and preliminary stages of design
- Capture impacts on engine performance due to variation of design parameters
- Assess the parameters of main engine components (thrust chamber, turbopump, gas generator/preburner) to provide better data for detailed analysis/design
- Assist in education of new generation of propulsion engineers

Main features of RPA (1)

- Gibbs free energy minimization approach is used to obtain the combustion composition
- Expandable thermodynamic data library based on NASA Glenn thermodynamic database (also used by CEA)
- Analysis of nozzle performance with shifting and frozen chemical equilibrium
- Optimization of propellant components mixture ratio
- Altitude performance analysis, over-expanded nozzle performance analysis
- Throttled engine performance analysis

Main features of RPA (2)

- Estimation of delivered (actual) nozzle performance
- Determination of combustion chamber size for given thrust, propellant mass flow rate, or throat diameter
- Designing parabolic nozzle contour or truncated ideal nozzle contour (TIC) using two-dimensional (axisymmetric) method of characteristics

Main features of RPA (3)

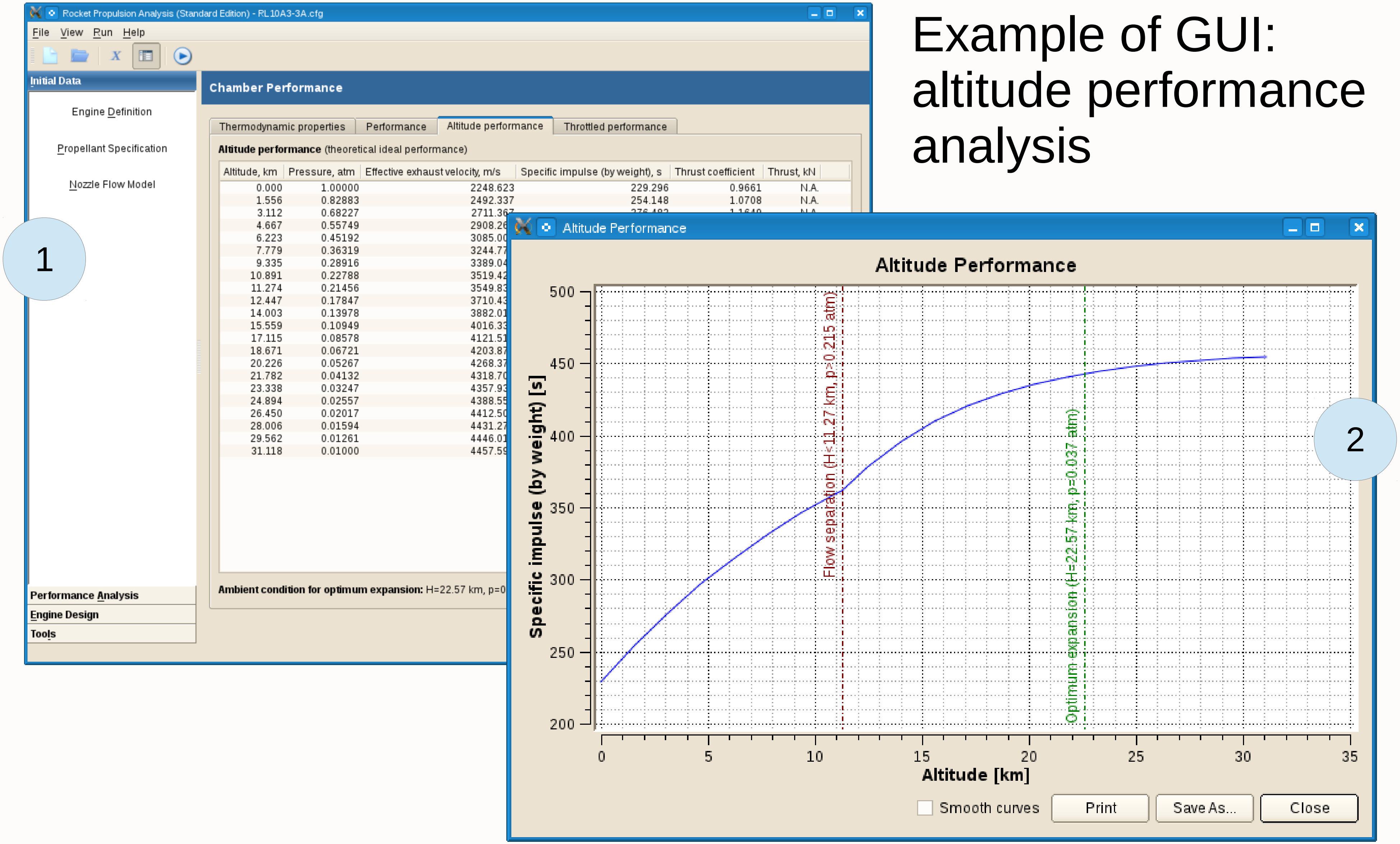
- Thrust chamber thermal analysis
  - Calculation of heat transfer rate distribution (convection and radiation)
  - Film cooling analysis
  - Radiation cooling analysis
  - Regenerative cooling analysis
  - Thermal analysis of thrust chambers with combined cooling: radiation + film + regenerative
  - Estimation of hydraulic losses in the cooling passages
  - Estimation of friction thrust loss

Main features of RPA (4)

- Multi-platform graphical user interface for Microsoft® Windows™, as well as for Apple® Mac OS X and Linux
- Parameters input and results output in SI or U.S. customary units
- Development tools and libraries are available:
  - Scripting Utility
  - C++ Wrapper
  - C++ SDK for development of commercial software

RPA Overview

Example of GUI: altitude performance analysis



How RPA differs from other tools

- Own implementation of thermodynamics analysis, whereas many other tools use CEA
- Availability of development libraries
- Intended for conceptual and preliminary design
  - Steady-state analysis
  - Simplified model initialization with minimum of input parameters
  - Wide usage of semi-empirical relations and coefficients

Areas where RPA is usually used

- Conceptual and preliminary design of rocket engines and propulsion systems
- Education and academic research
- Library for development of commercial software

Rocket engine performance analysis

- Method of minimization of Gibbs free energy is used
  - to obtain the equilibrium product concentrations from combustion of two or more propellant components
  - to obtain the equilibrium product concentrations from decomposition of monopropellant
  - to calculate the isentropic quasi-one-dimensional nozzle flow for both shifting and frozen equilibrium flow models

Rocket engine performance analysis

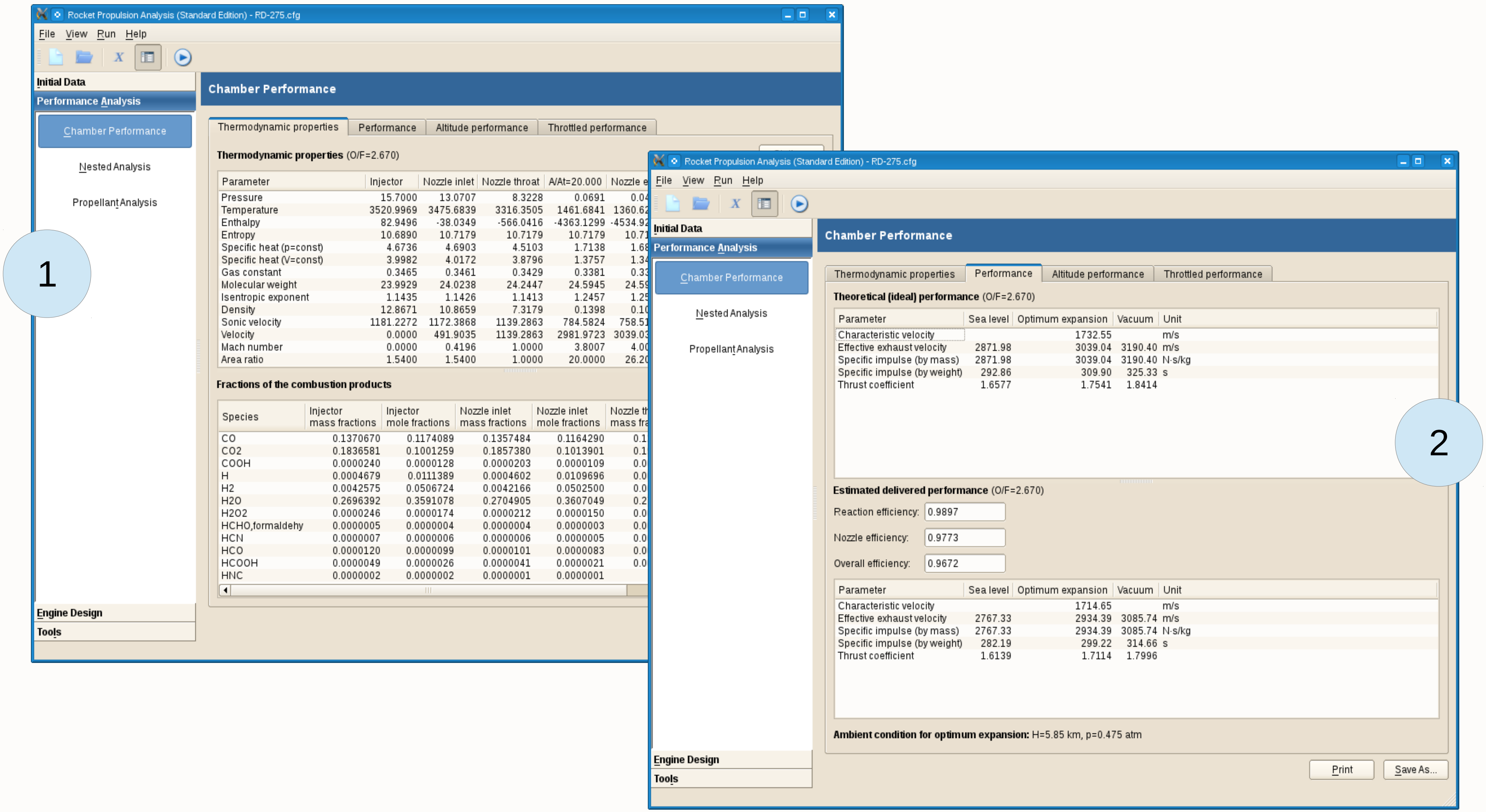
- Expandable thermodynamic data library based on NASA Glenn thermodynamic database
- The library includes data for such propellant components as
  - liquid hydrogen H2(L), liquid methane CH4(L), RP-1, RG-1, Synthine, monomethyl hydrazine (MMH), unsymmetrical dimethyl hydrazine (UDMH)
  - Liquid oxygen O2(L), nitrogen tetra-oxide (N2O4), hydrogen peroxide (H2O2)
- User may define own propellant components with known chemical formula and enthalpy of formation

Rocket engine performance analysis

- Quasi-one-dimensional nozzle flow model
- Semi-empirical relations to obtain performance correction factors, including:
  - Performance loss due finite rate kinetics in combustion chamber and nozzle
  - Divergence loss
  - Performance loss due to finite-area combustion area
  - Multi-phase flow loss
  - Performance change due to nozzle flow separation
  - Performance change due to thrust throttling

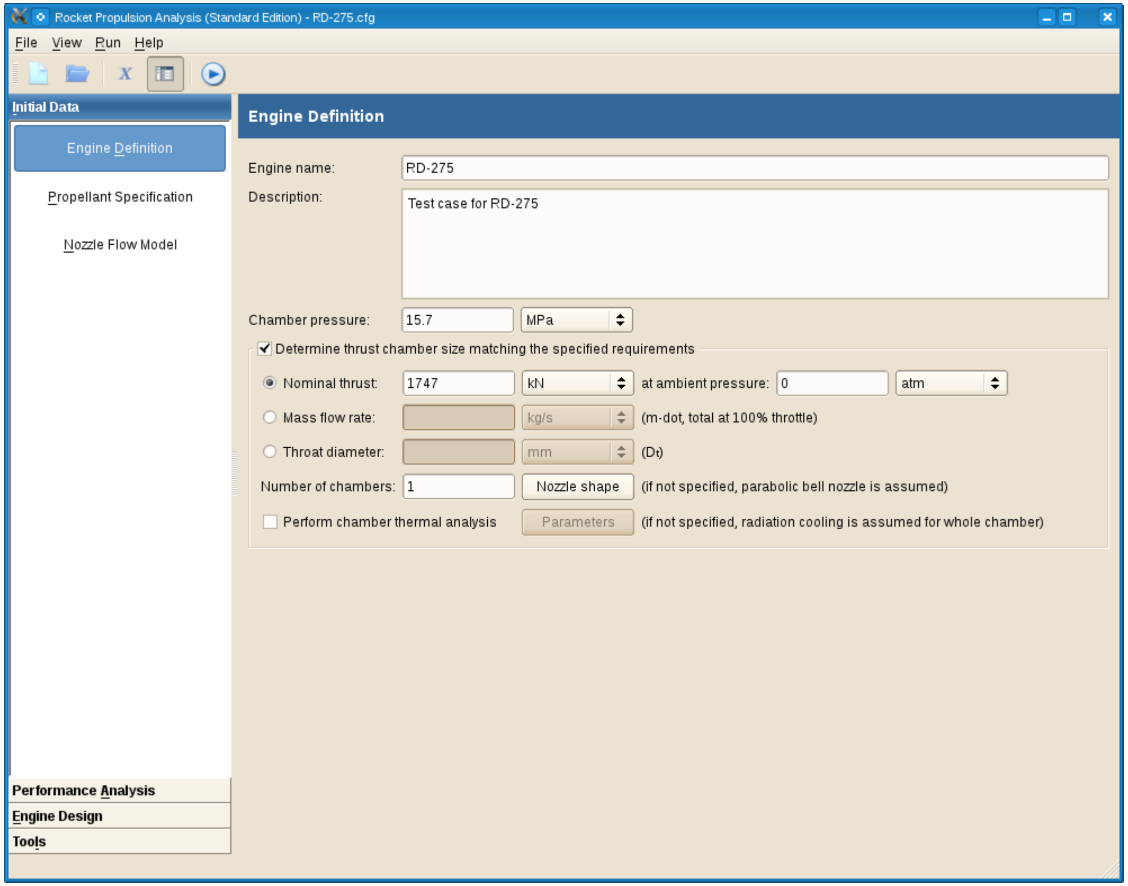
Models and methods used in RPA

Rocket engine performance analysis



Thrust chamber sizing

- Sizing for required thrust level at a specific ambient condition
- Sizing at a specific propellant mass flow rate
- Sizing for a specific throat diameter

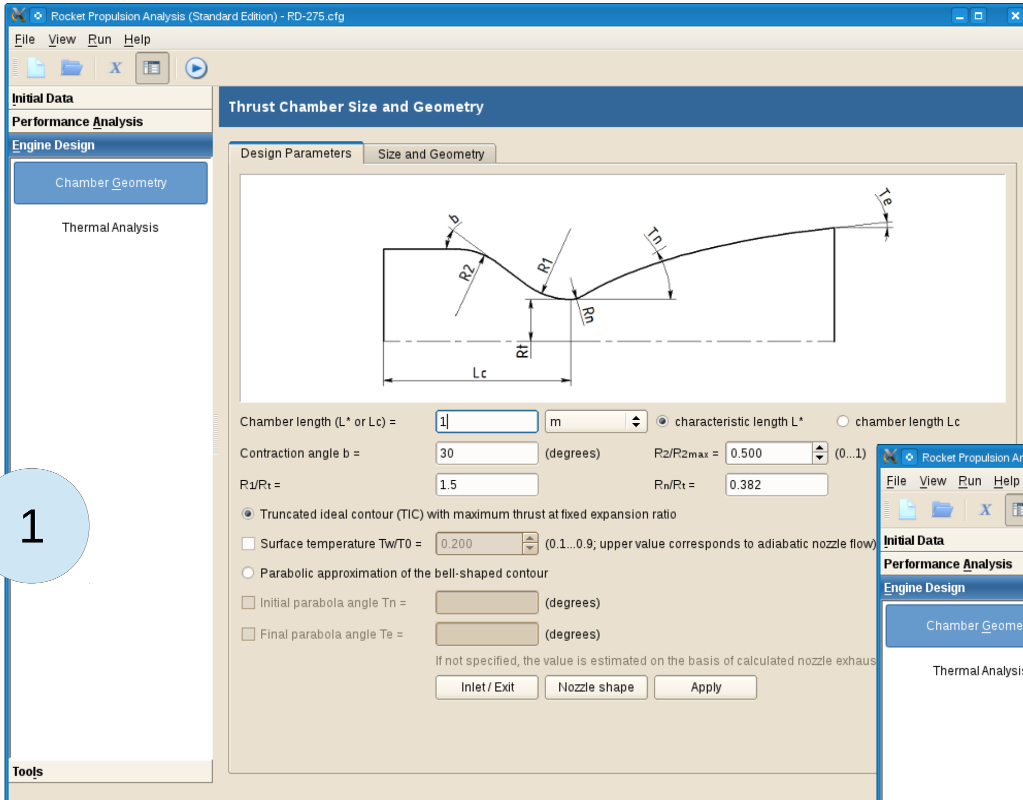


Designing the nozzle contour

- Cone nozzle with a specific exit half-angle
- Parabolic nozzle
- Truncated ideal contour (TIC) with maximum thrust at fixed expansion ratio
- Two-dimensional (axisymmetric) method of characteristics
- Parametric specification of the nozzle inlet geometry
- Export of nozzle contour in DXF (drawing interchange file) format

Models and methods used in RPA

1



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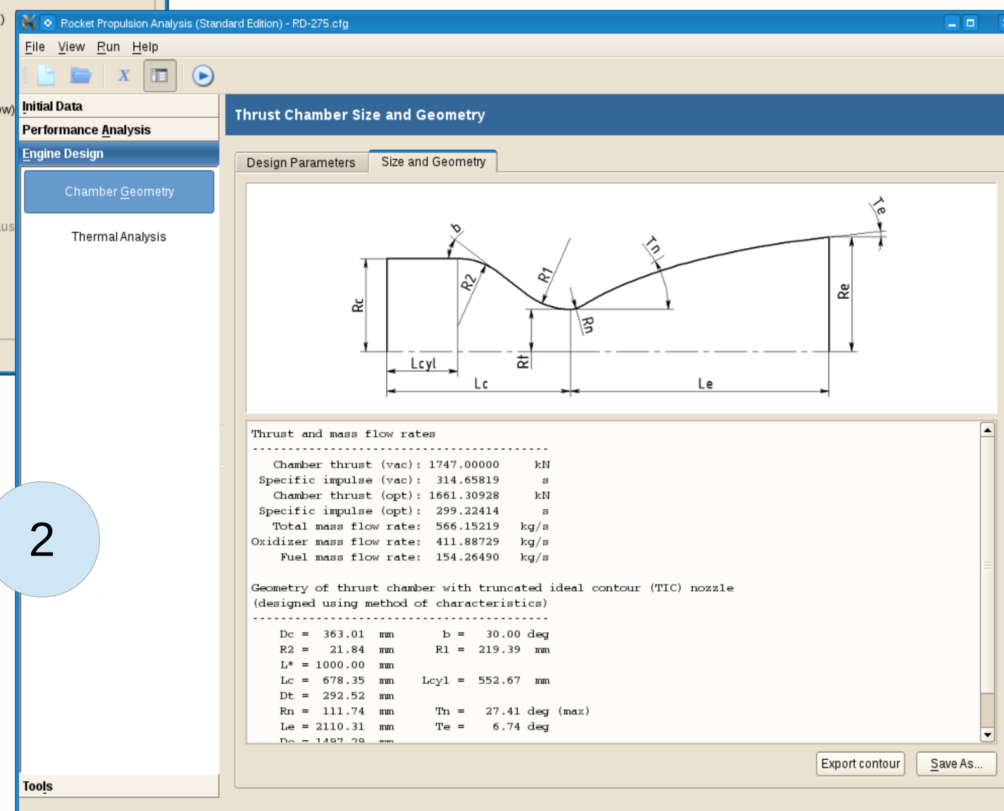


Thrust chamber thermal analysis

- Gas-side heat transfer
  - Convective heat transfer
    - Ievlev method
    - Bartz method
    - Boundary layer and film cooling
  - Loss in specific impulse due to friction in boundary layer
  - Radiation heat transfer
- RPA library for thermodynamic analysis is used to obtain hot gas transport properties

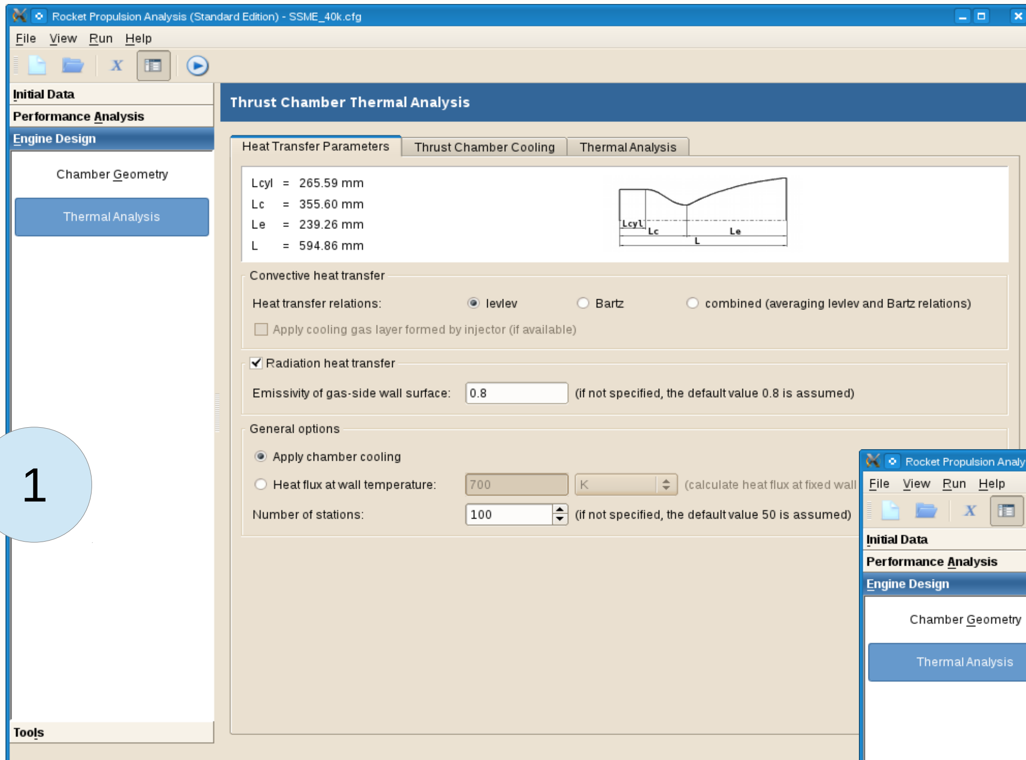
Thrust chamber thermal analysis

- Thrust chamber outer cooling
  - Radiation cooling
  - Regenerative cooling
    - Coaxial-shell thrust chamber design
    - Channel-wall thrust chamber design
    - Tubular-wall thrust chamber Design
    - Pressure loss across cooling passages
    - Coolant properties are interpolated from 2D properties file (can be obtained from REFPROP)
  - Thermal barrier coating layer
  - Balanced heat flux approach

Models and methods used in RPA

Thermal analysis: example of input data

1



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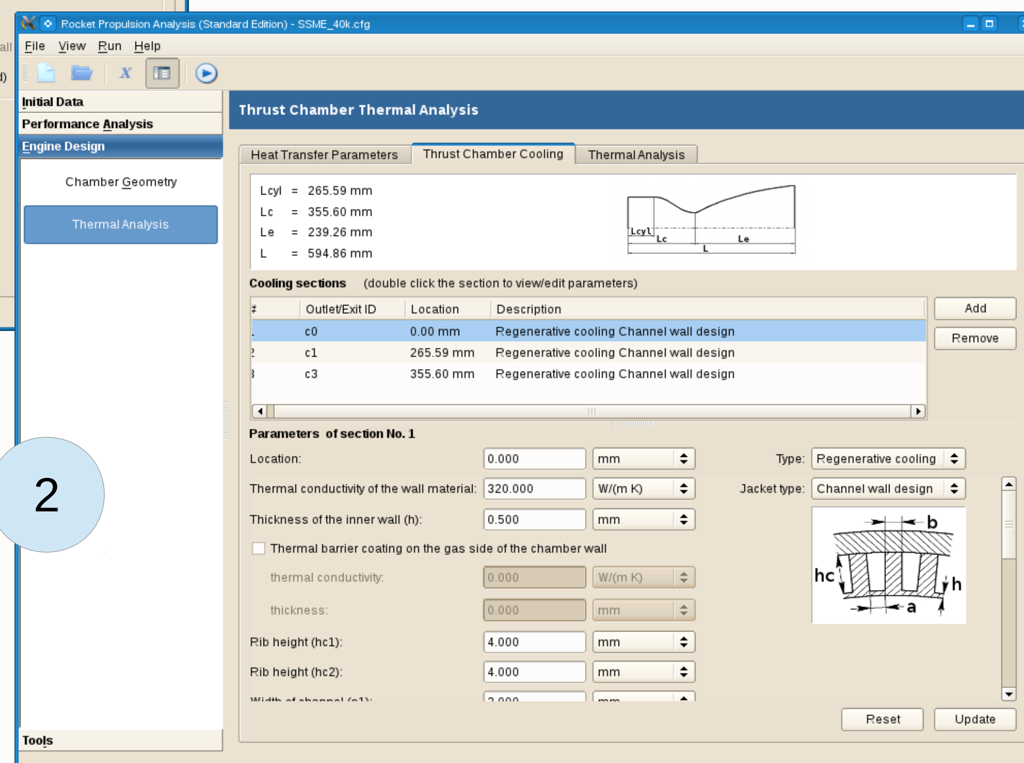
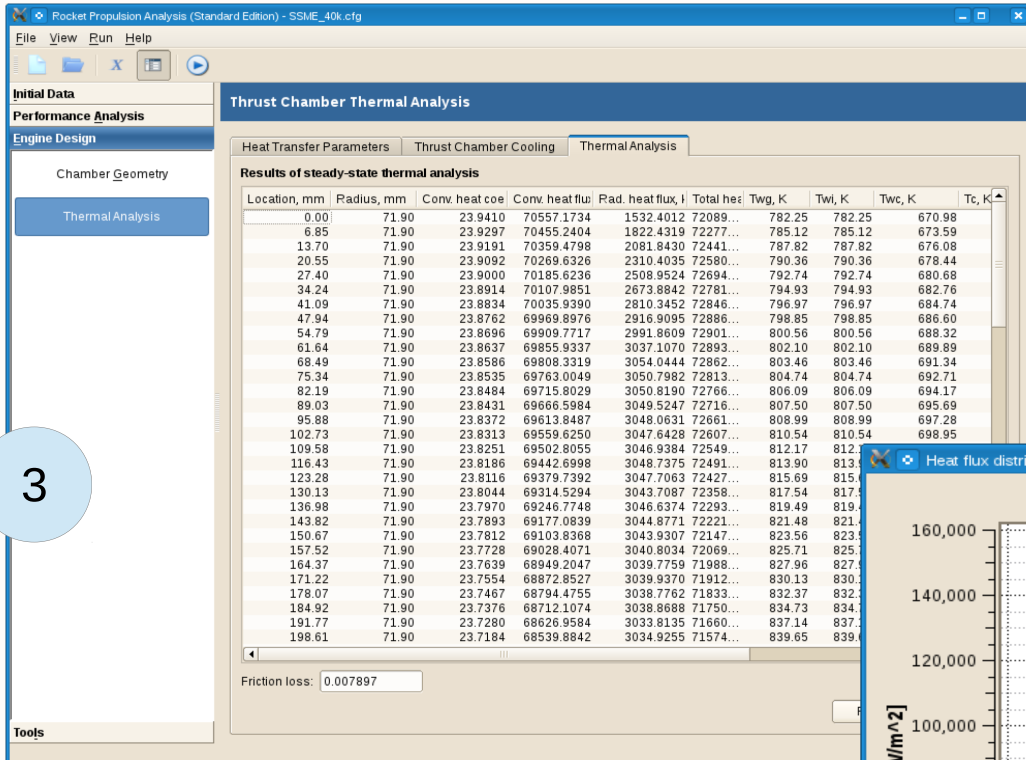


Models and methods used in RPA

Thermal analysis:
example of output data

3



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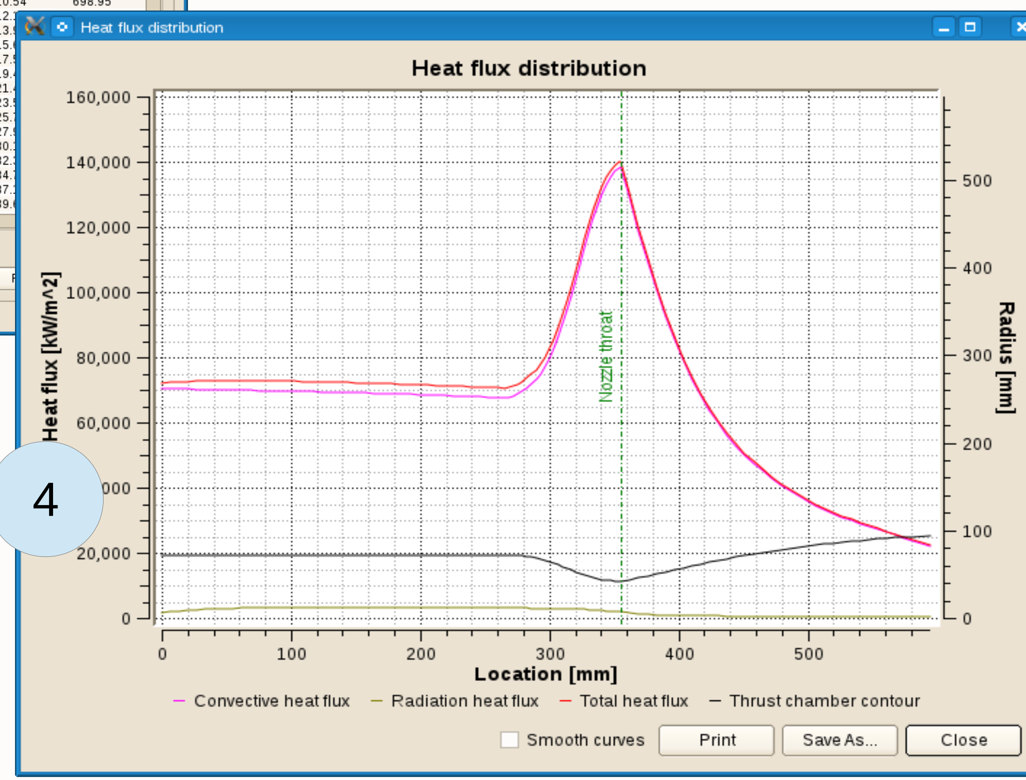


Engine cycle analysis *(to be released)*

- Steady-state analysis
- Variety of cycles:
  - gas generator
  - staged combustion
  - full-flow staged combustion
  - expander
  - tap-off

Engine cycle analysis *(to be released)*

- General input parameters:
  - Number and type of combustion devices (fuel-rich or oxidizer-rich)
  - Maximum turbine inlet temperature
  - Number and flow sequence of turbines
  - Inlet pressure of propellant components
  - Availability of booster pumps and their parameters
  - Type and parameters of turbine of booster pumps
  - Availability of kick pumps and their parameters
  - Availability of bypasses around turbines

Engine cycle analysis *(to be released)*

- Design mode possible input parameters:
  - Thrust chamber pressure, mass flow rate and mixture ratio
  - Pressure drop at valves, junctions, cooling jackets etc
- Design mode possible results:
  - Operational parameters of combustion devices (pressure, mass flow rate and mixture ratio)
  - Operational parameters of turbomachinery (mass flow rate, inlet pressure, discharge pressure, shaft power)
  - Engine overall performance

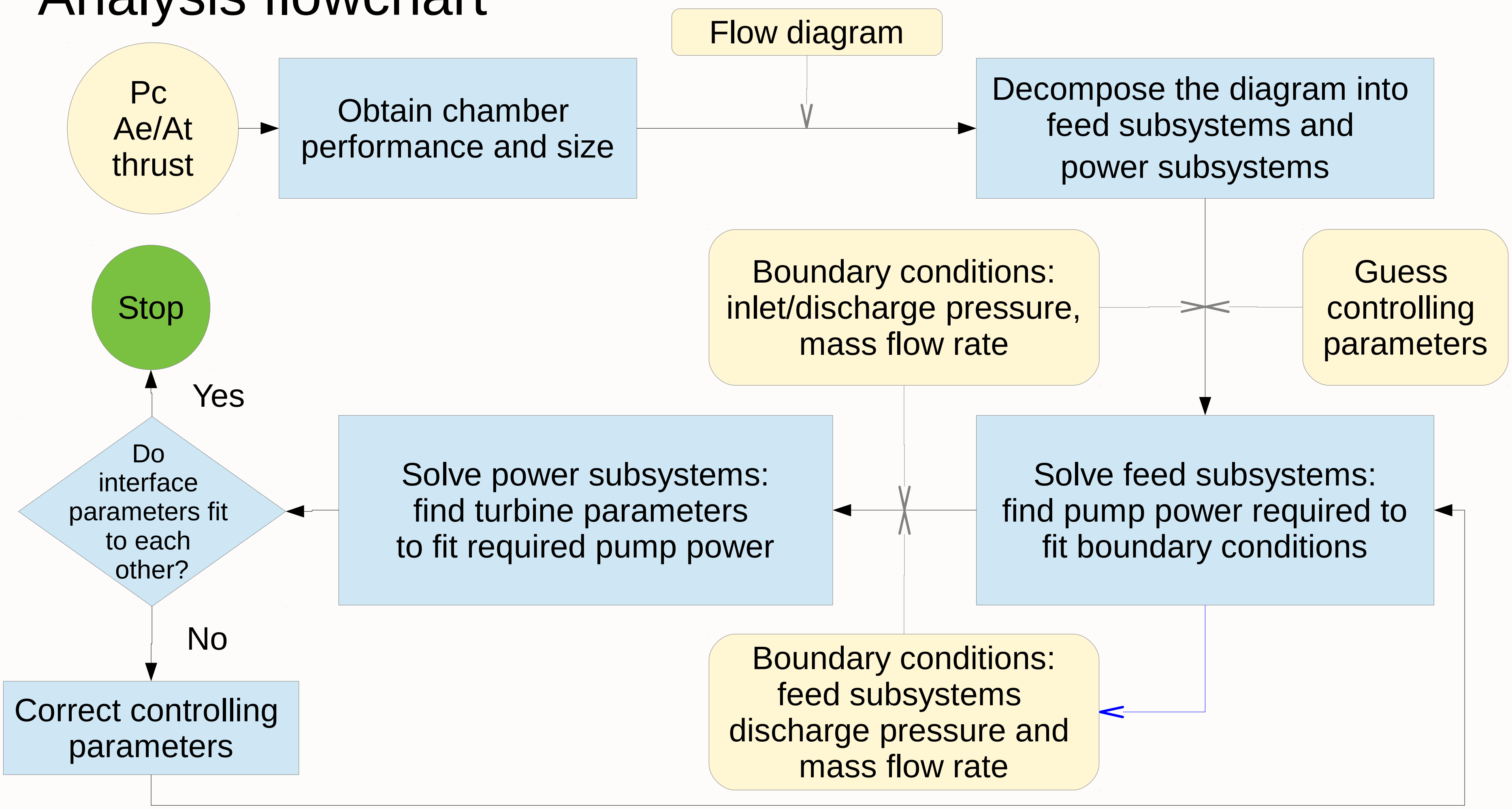
Models and methods used in RPA

Engine cycle analysis *(to be released)*

- Off-design mode possible input parameters:
  - Operational parameters of combustion devices (pressure, mass flow rate and mixture ratio)
  - Operational parameters of turbomachinery (mass flow rate, inlet pressure, discharge pressure, shaft power)
  - Pressure drop at valves, junctions, cooling jackets etc
- Off-design mode possible results:
  - Thrust chamber pressure, mass flow rate and mixture ratio
  - Engine overall performance

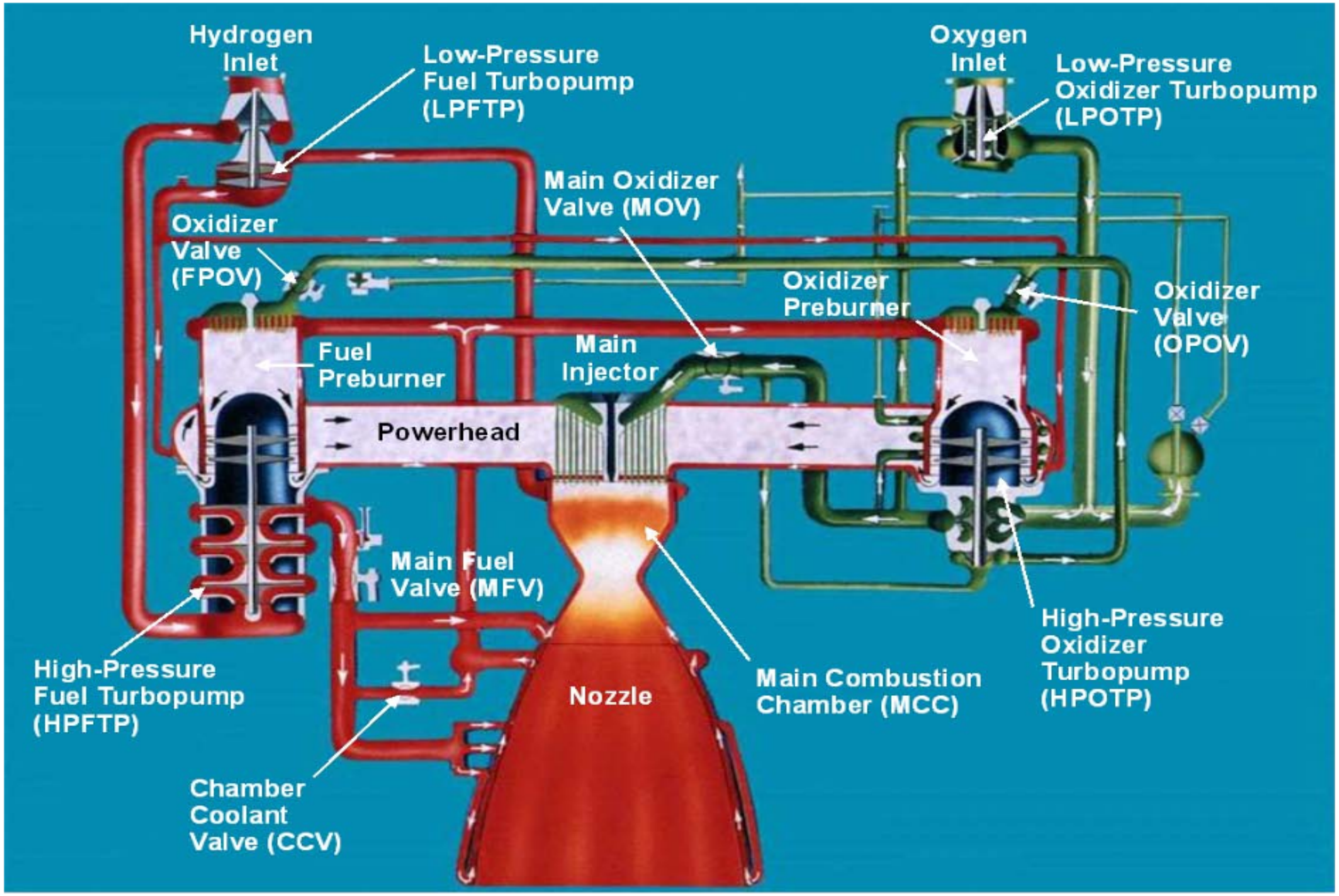
Engine cycle analysis *(to be released)*

- Analysis flowchart



Engine cycle analysis *(to be released)*

- Example of flow diagram decomposition



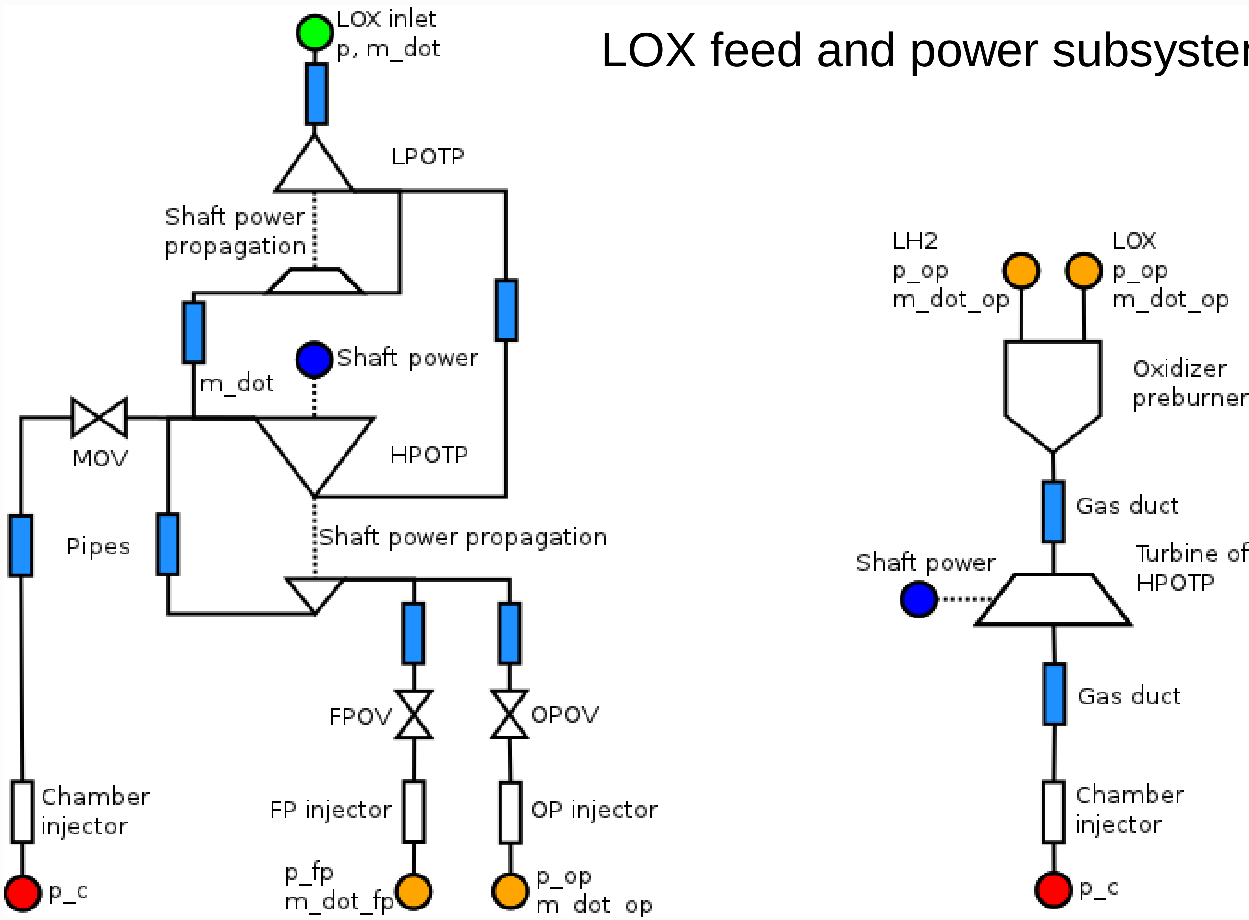
SSME

Models and methods used in RPA

Engine cycle analysis *(to be released)*

- Example of flow diagram decomposition

LOX feed and power subsystems



Solving feed subsystem: find such pump power that the required pressure is achieved at exit port of each branch

Solving power subsystem: find such parameters of combustion device and/or turbine that produced power is equal to required total pump power of the feed subsystem

Models and methods used in RPA

Engine cycle analysis *(to be released)*

- RPA thermodynamics module is used to obtain
  - O/F ratio in combustion device to achieve required combustion temperature
  - Parameters of gas turbine working fluid in all cycles (GG, staged combustion and expander)
- RPA thermal analysis module can be used to obtain
  - Pressure drop in coolant jacket
  - Amount of energy absorbed by the coolant (one of controlling parameters in expander cycle)

Engine weight estimation *(to be released)*

- Based on the set of semi-empirical equations for each major type of engines: gas generator, staged combustion and expander cycles
- Initially developed at Moscow Aviation Institute
- RPA utilizes this method with slightly modified coefficients to better fit the available data on historic engines
- Results of chamber sizing and cycle analysis can be used as an input parameters of engine weight estimation

Chemical equilibrium properties

- Comparison with a NASA equilibrium program CEA has been performed for selected test cases:

Parameter	Case #1	Case #2	Case #3	Case #4	Case #5
Chamber pressure, MPa	10	10	5	1	1
Oxidizer	LOX	LOX	N_2O_4	–	–
Fuel	LH_2	RP-1	UDMH	N_2H_4	H_2O_2 (80%)
O/F	6.0	2.6	2.6	–	–

Chemical equilibrium properties

- Comparison for Case #1 (LOX/LH2):

Mole fractions:

Species	CEA2	RPA	δ, %
H	0.03107	0.03107(22)	0.0
H2	0.24803	0.24802(93)	0.0
H2O	0.67294	0.67294(23)	0.0
H2O2	0.00001	0.00001(26)	0.0
HO2	0.00003	0.00003(28)	0.0
O	0.00285	0.00285(11)	0.0
O2	0.00297	0.00297(14)	0.0
OH	0.04209	0.04208(81)	0.0

Thermodynamic properties:

Parameter	CEA2	RPA	δ, %
Temperature, K	3523.79	3523.79(2)	0.0
Enthalpy, kJ/kg	-986.31	-986.30(8)	0.0
Entropy, kJ/(kg K)	17.613(2)	17.613	0.0
M, 1/n	13.513	13.513	0.0
Cp, kJ/(kg K)	8.2367	8.2367	0.0
γ	1.1425	1.1425	0.0
Sonic velocity, m/s	1574.0	1573.9(50)	0.0
ρ, kg/m^3	4.612	4.612	0.0

Chemical equilibrium properties

- Comparison for Case #2 (LOX/RP-1):

Mole fractions:

Species	CEA2	RPA	δ, %
CO	0.31521	0.31521(14)	0.0
CO2	0.15383	0.15383(04)	0.0
COOH	0.00003	0.00002(73)	0.0
H	0.02686	0.02686(31)	0.0
H2	0.07954	0.07953(53)	0.0
H2O	0.33329	0.33329(25)	0.0
H2O2	0.00002	0.00001(88)	0.0
HCHO	0.00000	0.00000(11)	0.0
HCO	0.00004	0.00003(54)	0.0
HCOOH	0.00000	0.00000(41)	0.0

Thermodynamic properties:

Parameter	CEA2	RPA	δ, %
Temperature, K	3723.63	3723.63(4)	0.0
Enthalpy, kJ/kg	-784.21	-784.2(06)	0.0
Entropy, kJ/(kg K)	11.127(5)	11.127	0.0
M, 1/n	23.603	23.603	0.0
Cp, kJ/(kg K)	6.026(3)	6.026	0.0
γ	1.1392	1.1392	0.0
Sonic velocity, m/s	1222.4	1222.4(29)	0.0
ρ, kg/m^3	7.6236	7.6237	0.001

Chemical equilibrium properties

- Comparison for Case #3 (N2O4/UDMH):

Mole fractions:

Species	CEA2	RPA	δ, %
CO	0.12784	0.12783(55)	0.0
CO2	0.08961	0.08961(06)	0.0
COOH	0.00001	0.00000(56)	0.0
H	0.01602	0.01601(60)	0.0
H2	0.06066	0.06066(30)	0.0
H2O	0.34503	0.34502(96)	0.0
H2O2	0.00001	0.00000(83)	0.0
HCHO	0.00000	0.00000(02)	0.0
HCN	0.00000	0.00000(03)	0.0
HCO	0.00001	0.00000(55)	0.0
HCOOH	0.00000	0.00000(08)	0.0

Thermodynamic properties:

Parameter	CEA2	RPA	δ, %
Temperature, K	3392.31	3392.31(3)	0.0
Enthalpy, kJ/kg	88.271	88.271	0.0
Entropy, kJ/(kg K)	11.149(3)	11.149	0.0
M, 1/n	23.524	23.524	0.0
Cp, kJ/(kg K)	5.2960	5.296	0.0
γ	1.1385	1.1385	0.0
Sonic velocity, m/s	1168.4	1168.3(58)	0.0
ρ, kg/m^3	4.1701	4.1702	0.002

Chemical equilibrium properties

- Comparison for Case #4 (N2H4):

Mole fractions:

Species	CEA2	RPA	δ, %
H_2	0.66274	0.66273(76)	0.0
N_2	0.33255	0.33254(75)	0.0
NH_3	0.00471	0.00471(49)	0.0

Thermodynamic properties:

Parameter	CEA2	RPA	δ, %
Temperature, K	873.49	873.49(3)	0.0
Enthalpy, kJ/kg	1572.16	1572.149	0.0007
Entropy, kJ/(kg K)	15.784(2)	15.784	0.0
M, 1/n	10.732	10.732	0.0
Cp, kJ/(kg K)	3.054(0)	3.054	0.0
γ	1.3642	1.3642	0.0
Sonic velocity, m/s	960.8	960.8(21)	0.0
ρ, kg/m^3	1.4777	1.4777	0.0

Chemical equilibrium properties

- Comparison for Case #5 (H2O2 80%):

Mole fractions:

Species	CEA2	RPA	δ, %
H2O	0.74645	0.74645(36)	0.0
O2	0.25355	0.25354(64)	0.0

Thermodynamic properties:

Parameter	CEA2	RPA	δ, %
Temperature, K	784.47	784.46(7)	0.0
Enthalpy, kJ/kg	-7589.64	-7589.608	0.0004
Entropy, kJ/(kg K)	9.819(7)	9.820	0.0
M, 1/n	21.561	21.561	0.0
Cp, kJ/(kg K)	1.7296	1.7296	0.0
γ	1.2869	1.2869	0.0
Sonic velocity, m/s	624.0	623.9(49)	0.0
ρ, kg/m^3	3.3056	3.3056	0.0

Chemical equilibrium properties

- A perfect agreement is obtained between the CEA and PRA programs
- Any percent differences in parameter values are in at least the third decimal place and are negligibles
- The maximum relative difference is 0.002% occurring for Case #3

Liquid propulsion performance analysis

- Comparison with a performance data of selected historic engines has been performed:
  - RD-170
  - RD-253
  - RL10A3-3A
  - SSME

Liquid propulsion performance analysis

- RD-170

Design parameters [1]

Parameter	Value	Unit
Oxidizer	Liquid Oxygen (LOX)	-
Fuel	Kerosine RG-1	-
Components mass ratio	2.63	O/F
Combustion chamber pressure	24.5	MPa
Nozzle inlet contraction area ratio	2.6	A_c/A_t
Nozzle exit area ratio	36.87	A_e/A_t
Frozen equilibrium flow at	1.3*	A_{fr}/A_t

Comparison of actual and calculated engine parameters

Parameter	Actual	RPA	Percent error
Specific impulse (vac), s	337	338	0.3 %
Specific impulse (SL), s	309	309	0.0 %

[1] http://www.rocket-propulsion.info/energomash/RD-170/index.htm

*) Estimated values: $(Afr/At)_{LOX/RP-1}$ < $(Afr/At)_{LOX/LH2}$ < $(Afr/At)_{N2O4/UDMH}$

Liquid propulsion performance analysis

- RD-253

Design parameters [2]

Parameter	Value	Unit
Oxidizer	N2O4(L)	-
Fuel	UDMH	-
Components mass ratio	2.67	O/F
Combustion chamber pressure	15.7	MPa
Nozzle inlet contraction area ratio	2.36	A_c/A_t
Nozzle exit area ratio	26.2	A_e/A_t
Frozen equilibrium flow at	6.0*	A_{fr}/A_t

Comparison of actual and calculated engine parameters

Parameter	Actual	RPA	Percent error
Specific impulse (vac), m/s	3160	3156	0.13 %
Specific impulse (SL), m/s	2890	2832	2.00 %

[2] http://www.rocket-propulsion.info/energomash/RD-253/index.htm

*) Estimated values: $(Afr/At)_{LOX/RP-1} < (Afr/At)_{LOX/LH2} < (Afr/At)_{N2O4/UDMH}$

Liquid propulsion performance analysis

- RL10A3-3A

Design parameters [3]

Parameter	Value	Unit
Oxidizer	Liquid Oxygen (LOX)	-
Fuel	Liquid Hydrogen (LH_2)	-
Components mass ratio	5.5	O/F
Combustion chamber pressure	475	psia
Nozzle inlet contraction area ratio	4.6	A_c/A_t
Nozzle exit area ratio	61.0	A_e/A_t
Frozen equilibrium flow at	3*	A_{fr}/A_t

Comparison of actual and calculated engine parameters

Parameter	Actual	RPA	Percent error
Specific impulse (vac), s	444.4	441.3	0.7 %

[3] http://www.spaceandtech.com/spacedata/engines/rl10_specs.shtml

*) Estimated values: $(Afr/At)_{LOX/RP-1} < (Afr/At)_{LOX/LH2} < (Afr/At)_{N2O4/UDMH}$

Liquid propulsion performance analysis

- SSME

Design parameters [4]

Parameter	Value	Unit
Oxidizer	Liquid Oxygen (LOX)	-
Fuel	Liquid Hydrogen (LH_2)	-
Components mass ratio	6.0	O/F
Combustion chamber pressure	3280	psia
Nozzle inlet contraction area ratio	3.4	A_c/A_t
Nozzle exit area ratio	77.5	A_e/A_t
Frozen equilibrium flow at	3.0*	A_{fr}/A_t

Comparison of actual and calculated engine parameters

Parameter	Actual	RPA	Percent error
Specific impulse (vac), s	454.4	451.95	0.53 %

[4] http://www.spaceandtech.com/spacedata/engines/ssme_specs.shtml
*) Estimated values: $(Afr/At)_{LOX/RP-1} < (Afr/At)_{LOX/LH2} < (Afr/At)_{N2O4/UDMH}$

Liquid propulsion performance analysis

- An excellent agreement is obtained between the actual performance and performance predicted by RPA program
- The maximum relative difference occurring for RD-253
- Comparison of ideal performance calculated by RPA with ideal performance calculated by NASA CEA code (not shown in this presentation) provides an excellent agreement as well

Solid and hybrid propulsion performance analysis

- Comparison with a performance data of selected historic engines has been performed:
  - P80 - first stage engine of VEGA Launcher
  - Hybrid rocket engine for Peregrine sounding rocket

Solid and hybrid propulsion performance analysis

- P80 - first stage engine of VEGA Launcher

Design parameters

Parameter	Value	Unit
Propellant	HTPB 1912 Component / Mass fraction: NH_4ClO_4 0.69 Al 0.19 HTPB 0.12	-
Combustion chamber pressure	9.5	MPa
Nozzle exit area ratio	16.0	A_e/A_t

Comparison of actual and calculated engine parameters

Parameter	Actual	RPA	Percent error
Specific impulse (vac), s	279.5	274.71	1.7 %

Solid and hybrid propulsion performance analysis

- Hybrid rocket engine for Peregrine sounding rocket

Design parameters

Parameter	Value	Unit
Oxidizer	Nitrous oxide (Liquid)	-
Fuel	Wax paraffin	-
Components mass ratio	4.0654	O/F
Combustion chamber pressure	700	psi
Nozzle exit area ratio	8.4	A_e/A_t

Comparison of actual and calculated engine parameters

Parameter	Actual	RPA	Percent error
Specific impulse (vac), s	232	234.3	1.0 %

Solid and hybrid propulsion performance analysis

- RPA obtains the proper combustion composition from any type of solid/hybrid propellants, including metalized
- The obtained agreement between the RPA prediction and referenced data is sufficient for the tool used in conceptual and preliminary design

Thermal analysis

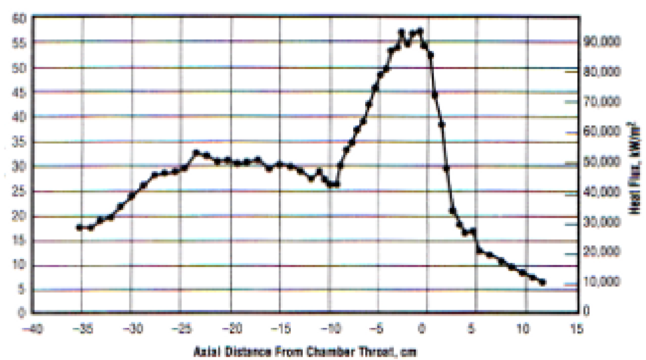
- To verify the accuracy of thermal analysis, the comparison between available reference data and RPA prediction has been performed:
  - SSME 40k [1]
  - Aestus [2]

[1] Scaling Techniques for Design, Development, and Test.
Carol E. Dexter, Mark F. Fisher, James R. Hulka, Konstantin P. Denisov, Alexander A. Shibanov, and Anatoliy F. Agarkov

[2] Simulation and Analysis of Thrust Chamber Flowfields: Storable Propellant Rockets.
Dieter Preclik, Oliver Knab, Denis Estublier, and Dag Wennerberg

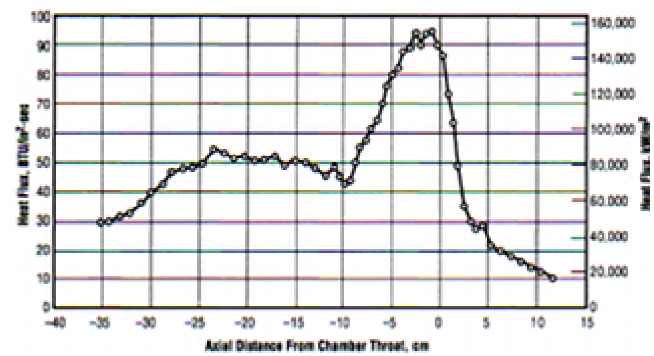
Thermal analysis

- SSME 40k



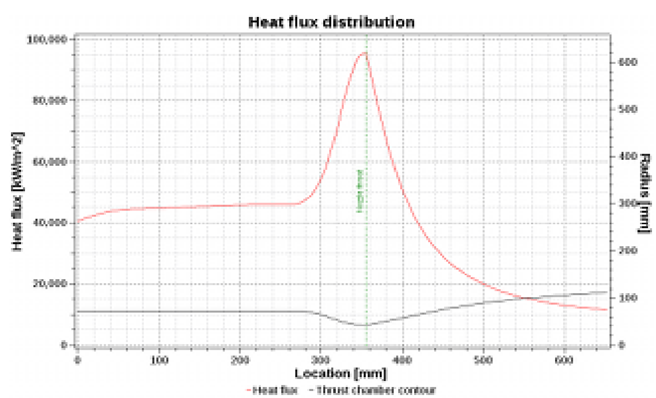
SSME 40 K calorimeter chamber test 024 heat flux profile.

SSME 40 K calorimeter chamber heat flux profile (reference).

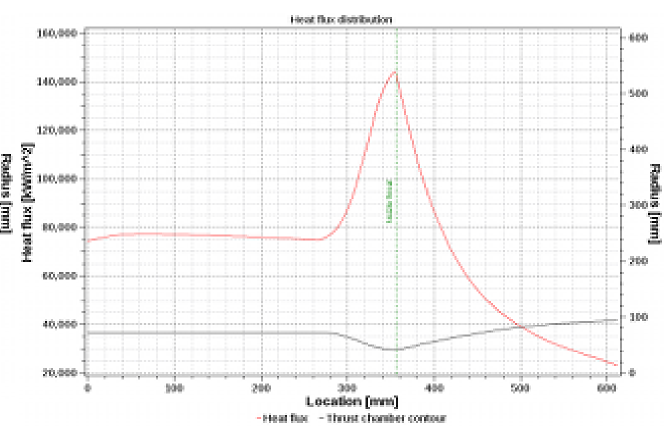


Predicted SSME 40 K regenerative chamber heat flux profile.

SSME 40 K regenerative chamber predicted heat flux profile (reference).



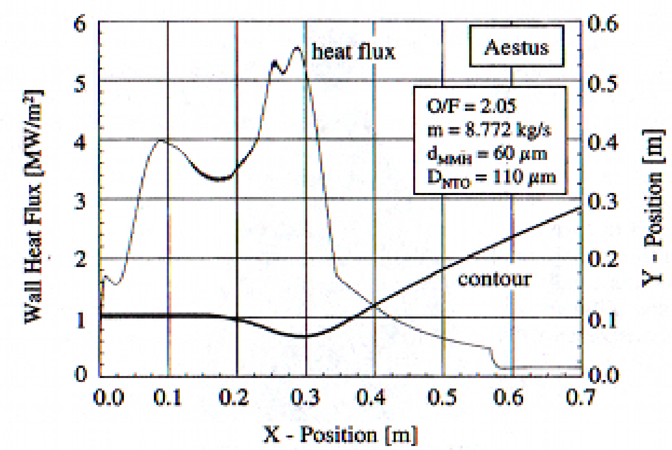
SSME 40 K calorimeter chamber heat flux profile (RPA)



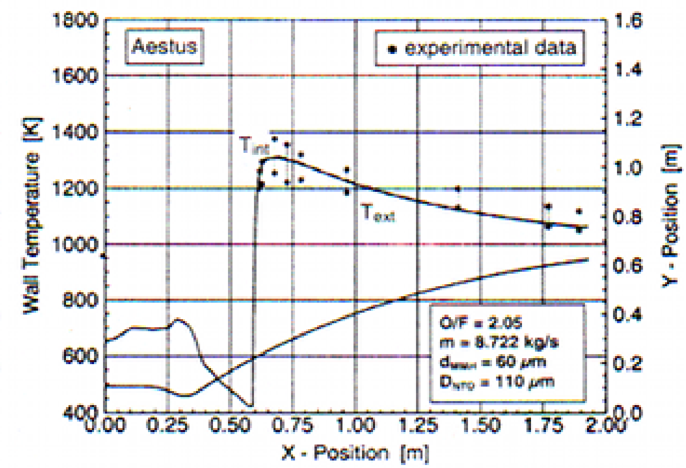
SSME 40 K regenerative chamber heat flux profile (RPA)

Thermal analysis

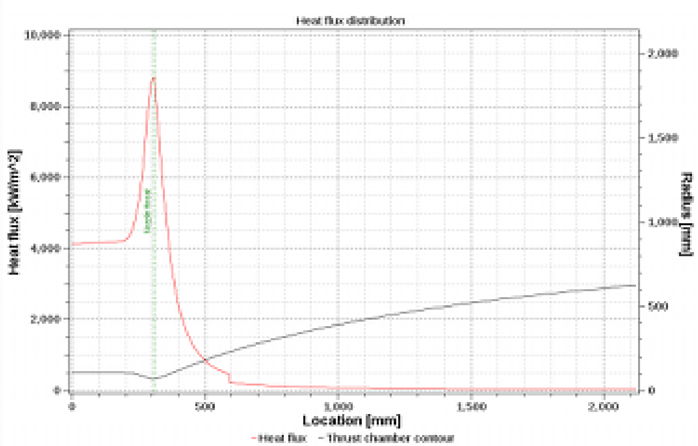
- Aestus



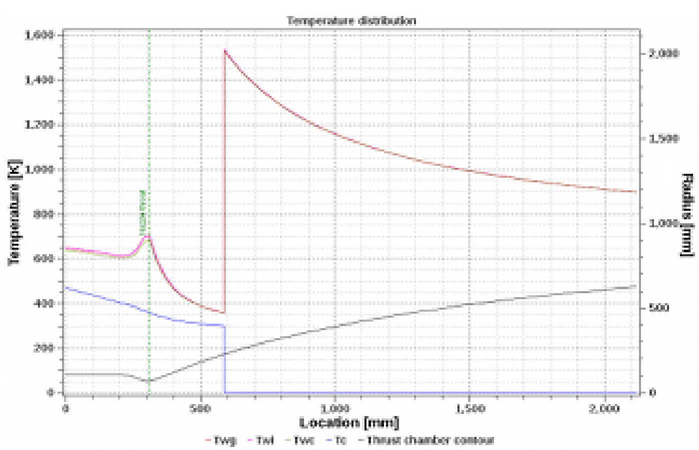
Calculated heat flux distribution (reference)



Temperature distribution (reference)



Calculated heat flux distribution (RPA)



Temperature distribution (RPA)

Thermal analysis

- The obtained agreement between the RPA prediction and referenced data is sufficient for the tool used in conceptual and preliminary design
- Quantitative and qualitative differences in results can be explained by the following:
  - RPA does not simulate fuel atomization and dispersion, as well as droplets burning
  - The hot gas properties for thermal analysis are retrieved from quasi one-dimensional flow model
  - The heat transfer is simulated in RPA using semi-empirical relations

Cycle analysis and weight estimation

- Validation to be performed

Architecture of RPA

- Written in C++
- Can be compiled on MS Windows, Linux and Apple MacOS X
- Shared (Linux/MacOS X) and dynamic (Windows) libraries provide functionality
- Executable file provides GUI and is created with Qt

Architecture of RPA

- Available shared/dynamic libraries:
  - Libutils — Utility classes (exceptions, logging, etc)
  - Libmath — Classes for solving equations, linear systems, etc.
  - Librpa — Thermodynamics
  - Libnozzle — Chamber and nozzle sizing and geometry
  - Libthermo — Thermal analysis
  - Libdesign — Cycle analysis and weight estimation

Architecture of RPA

- Third-party libraries:
  - Qt — Application and GUI framework
    http://qt-project.org
  - Qwt — GUI components for 2D plotting
    http://qwt.sourceforge.net
  - Eigen — C++ template library for linear algebra
    http://eigen.tuxfamily.org
  - Libconfig — C++ library for processing structured configuration files
    http://www.hyperrealm.com/libconfig

Future development

- Release of RPA 2.1 with cycle analysis and weight estimation
- Development of wrapper C++ classes to make the usage of cycle analysis easier and release of the next version RPA SDK
- Solid-propellant grain design
- Design of thrust-optimized nozzle contour (TOC)
- Implement better integration of available RPA libraries

References to RPA reports

- Ponomarenko A. RPA: Tool for Liquid Propellant Rocket Engine Analysis. 2010.
- Ponomarenko A. RPA: Tool for Liquid Propellant Rocket Engine Analysis. Thermal Analysis of Thrust Chambers. 2012.
- Ponomarenko A. RPA: Tool for Liquid Propellant Rocket Engine Analysis. Assessment of Delivered Performance of Thrust Chamber. 2013.
- Ponomarenko A. RPA: Tool for Liquid Propellant Rocket Engine Analysis. Power Balance Analysis and Weight Estimation of Liquid-Propellant Rocket Engine Cycles. 2013. **DRAFT**

Thank you!

Q & A