Modern Approach to Liquid Rocket Engine Development for Microsatellite Launchers

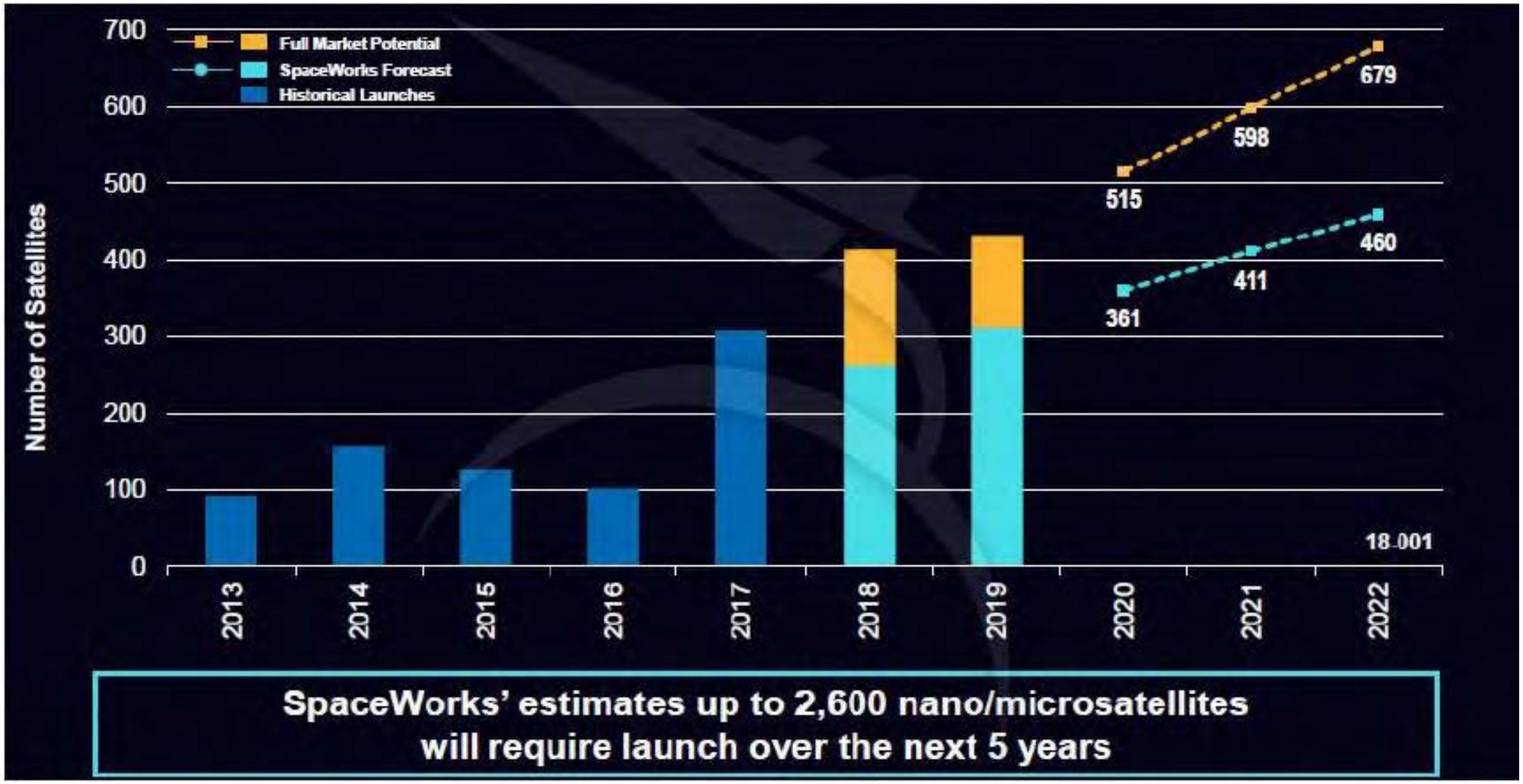
Introduction

Nano/Microsatellite Definition *

- These satellites have been carried to space as secondary payloads aboard larger launchers for many years. However, the secondary payload method does not offer the specificity required for modern day demands such as increasingly sophisticated small satellites that have unique orbital and launch-time requirements.

* 2018 Nano/Microsatellite Market Forecast, 8th Edition, SpaceWorks, 2018

2018 Nano/Microsatellite Launch History & Market Forecast (1-50 kg) *

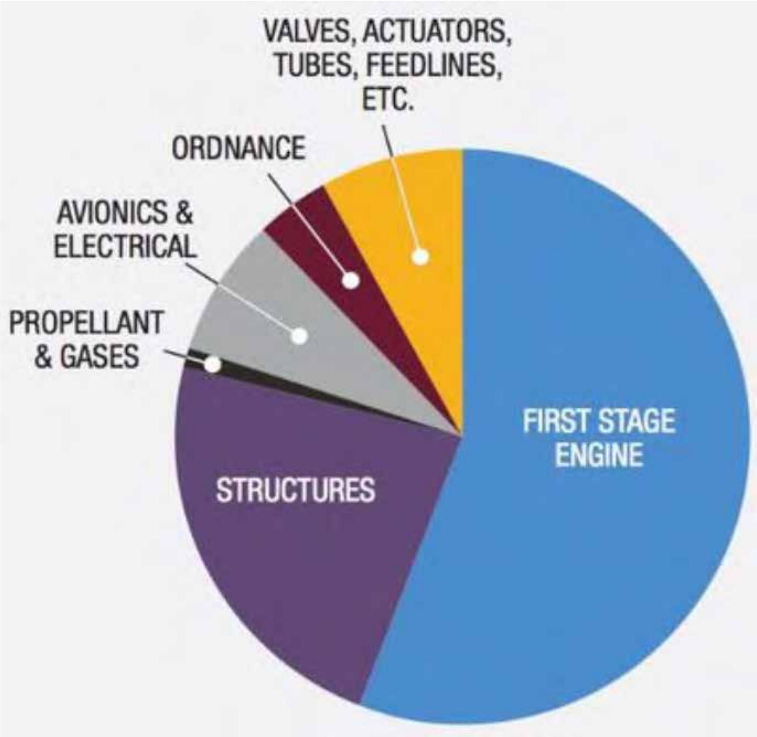


- The competition in the launch industry is getting progressively more aggressive and dynamic
  - SpaceWorks' 2018 forecast predicts 263 nano/microsatellite launches this year
  - 25+ companies are pursuing the development of new small satellite vehicles

* 2018 Nano/Microsatellite Market Forecast, 8th Edition, SpaceWorks, 2018

Launch Vehicle Cost Breakdown by Major Elements*

During the first stage of a launch vehicle's development, the majority of the cost comes from the engine, followed by the structures (as seen below).



- The development duration becomes extremely important in both minimizing launch cost and supplying the launcher when needed.
- Even the highest performing and cost-efficient vehicle can become useless if not supplied on time in such a competitive and dynamic market
- The system design approach applied to rocket engine design is a potential way to reduce development time

* Salvatore T. Bruno, Launch Vehicle Weight and Cost by Major Elements, United Launch Alliance (ULA), 2015

Goal of the Study

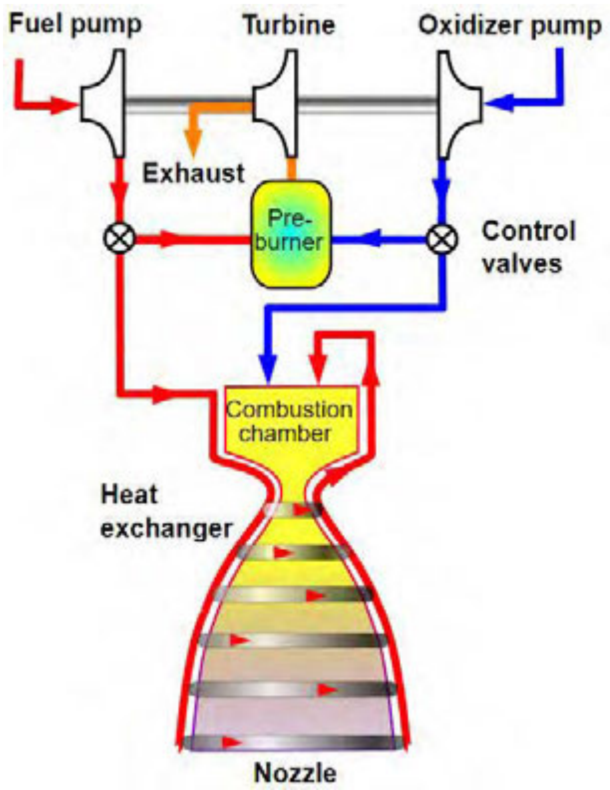
Reduce liquid rocket engine development time by leveraging an automatic system engineering approach focused on preliminary design of the thrust nozzle and turbopump.

Preliminary Engine Specification

Preliminary Engine Specification

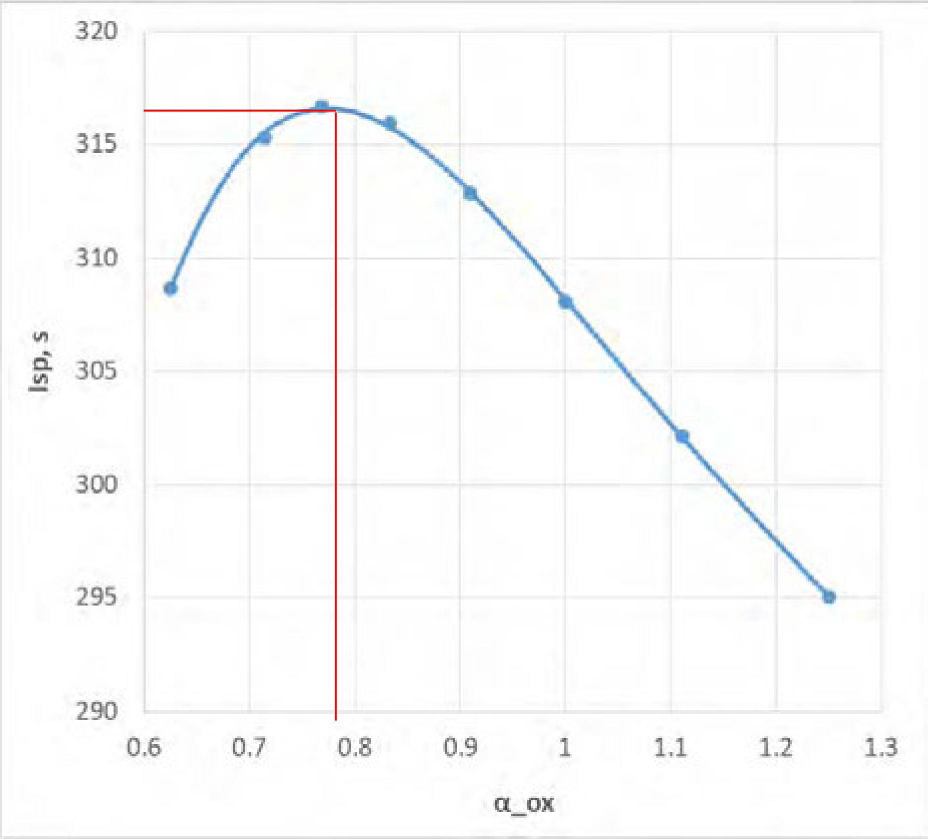
This presentation describes a study for the applicability of the design system for the first stage liquid rocket engine preliminary design for microsatellite application

- Payload to SSO: 100 kg
- Thurst for the first stage: 50 kN
- Gas-generator cycle
- Propellants pair: LOX-kerosene(RP-1)
- Chamber pressure: 8 MPa
- Nozzle exhaust pressure: 0.06 MPa



Gas-generator liquid rocket engine cycle

Optimization of Oxygen Excess Factor at 8 MPa



- Optimum α_ox = 0.774 (O/F = 2.636)
- Thrust chamber Isp = 316.6 m/s

Preliminary Engine Specification Summary

Parameter	Unit	Magnitude
Payload	kg	100
Thrust	kN	50
Ambient pressure	MPa	0.06
Chamber pressure	MPa	8
Isp_thurst_chamber	s	316.59
Total propellants mass flow rate	kg/s	16.10
RP-1 mass flow rate	kg/s	4.43
Oxygen mass flow rate	kg/s	11.68
Fuel tank pressure	MPa	0.3
Oxygen tank pressure	MPa	0.3
Pressure at turbine exhaust	MPa	0.15
Turbine inlet temperature	K	1046.74
Turbine inlet pressure	MPa	6.46
Oxygen pump discharge pressure	MPa	9.4
Fuel pump discharge pressure	MPa	12.6

Design System Description

Design System Description

$$Isp_{\ engine} = \frac{Thrust}{Chamber\ mass\ flow\ rate + \boxed{Turbopump\ mass\ flow\ rate}}$$

In order to design the engine (gas-generator cycle) with the highest possible engine specific impulse, it is necessary to perform a preliminary design of the turbopump with different configurations and select the one with minimum flow mass flow rate.

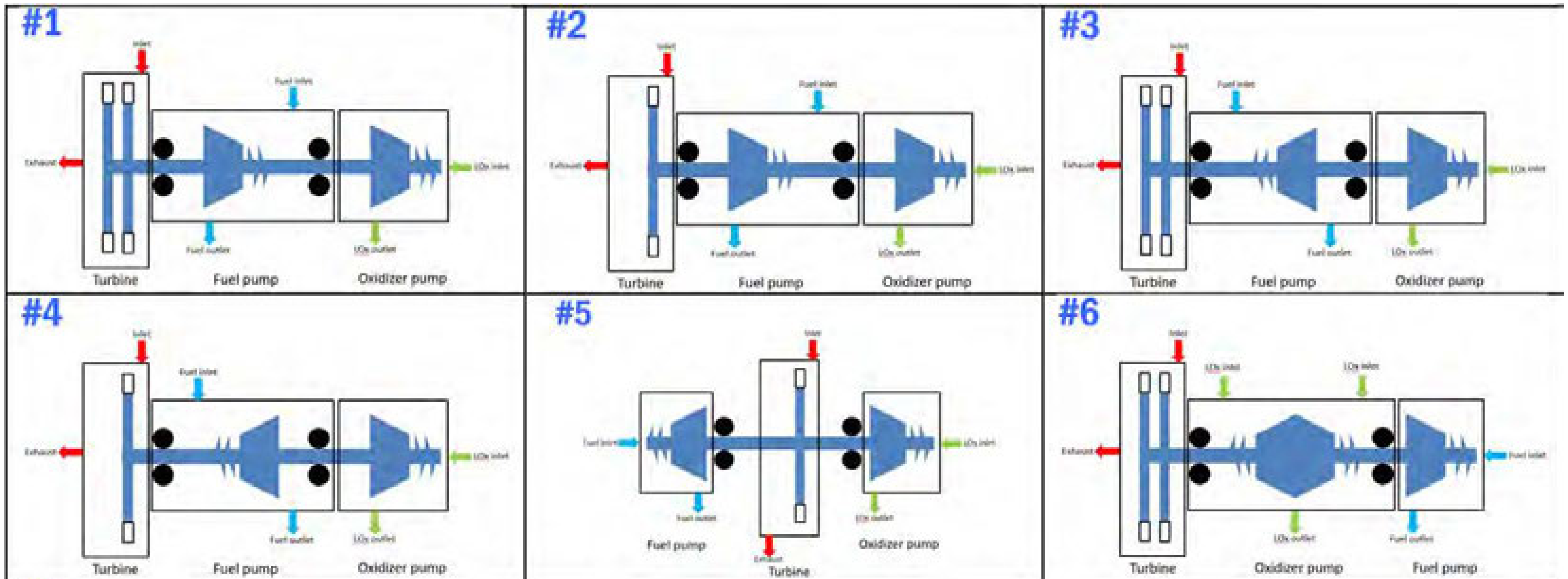
Design System Description

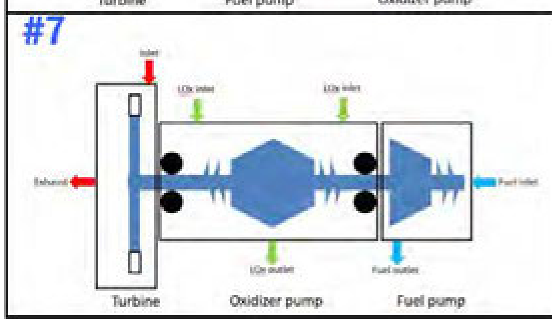
Preliminary design of the turbopump includes the following activities:

- Preliminary selection of the configuration
- Oxidizer pump preliminary design
- Fuel pump preliminary design
- Turbine preliminary design
- Turbopump preliminary layout development
- Rotor mass/inertia parameters preliminary determination
- Estimation of axial and radial forces on bearings, bearings simulation and rotor dynamics analysis
- Secondary flows (leakages) system analysis and determination of the required amount of propellant for each bearing branch
- Preliminary stress analysis of turbomachinery components

Turbopump Configurations

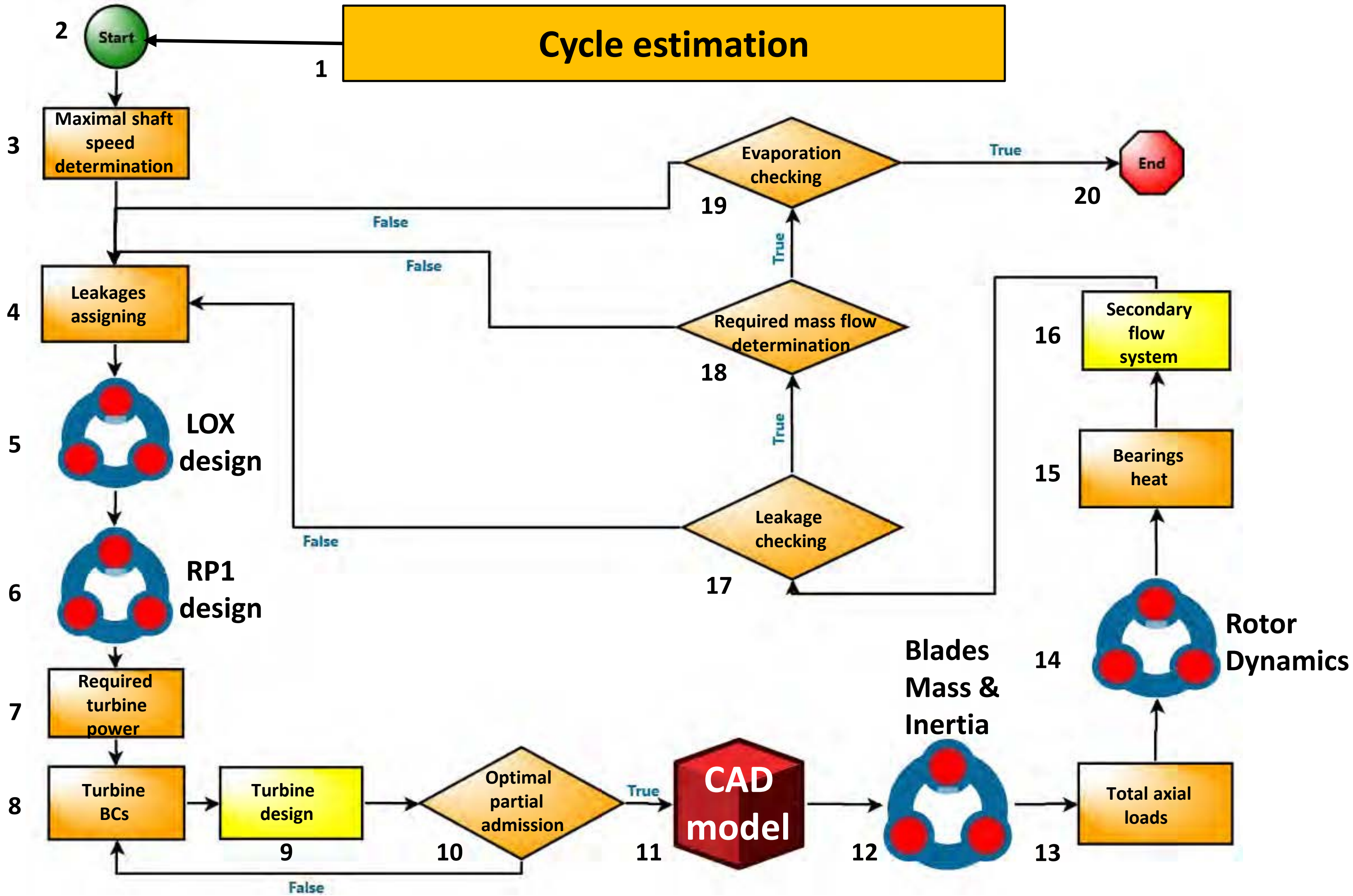
The study includes utilization of 7 turbopump configurations





All configurations have a single rotor, but differently orientated pumps with various types of flow entry, single flow or double flow oxygen pump types, single stage impulse, and a 2-row velocity compound turbine

Process Flowchart in AxSTREAM ION™



Maximal Shaft Speed and Axial Load Determination

Maximal allowable shaft rotational speed that satisfies the cavitation absence is determined as:

$$\omega_{\max} = \frac{(C_{CPB})_{\max}\left(\Delta p^*_{CPB} / \rho\right)^{3/4}}{298 \cdot \dot{V}^{1/2}}$$

where

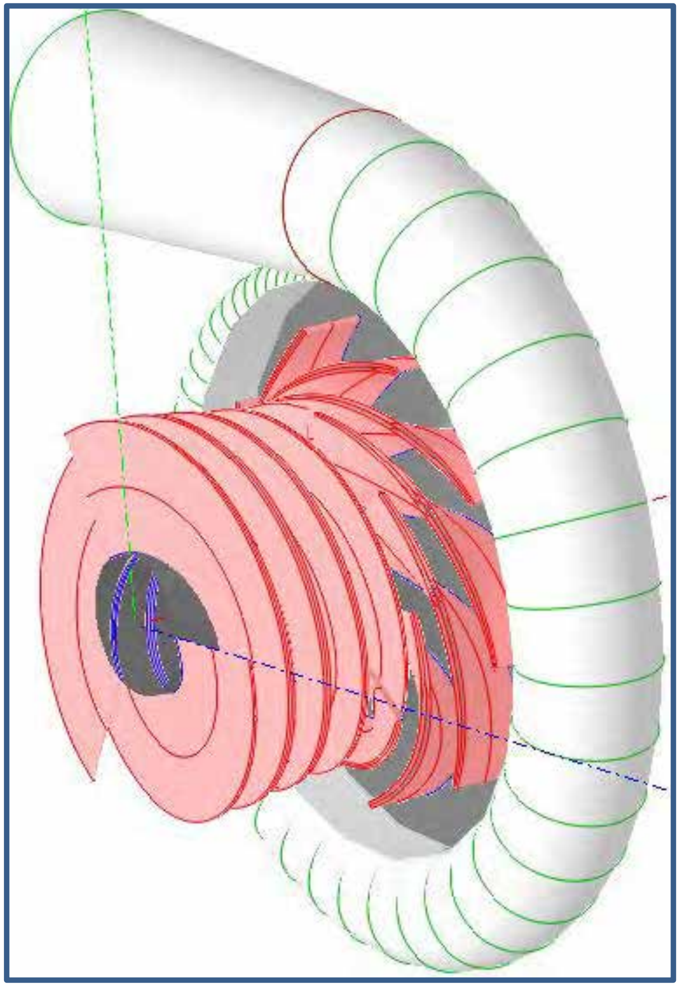
$(C_{CPB})_{max}$ – maximal value of cavitation coefficient of pumps rapidity
$\Delta p^*{}_{CPB}$ – available total pressure drop
ρ – working fluid density
$\dot{V}$ – volumetric flow rate

Turbopump axial load:

$$Ra = \sum Ra_i$$

where Ra_i - is the axial load developed by each component: fuel pump, oxidizer pump, turbine, shaft.

Preliminary Pump Design in AxSTREAM®



Design BCs:

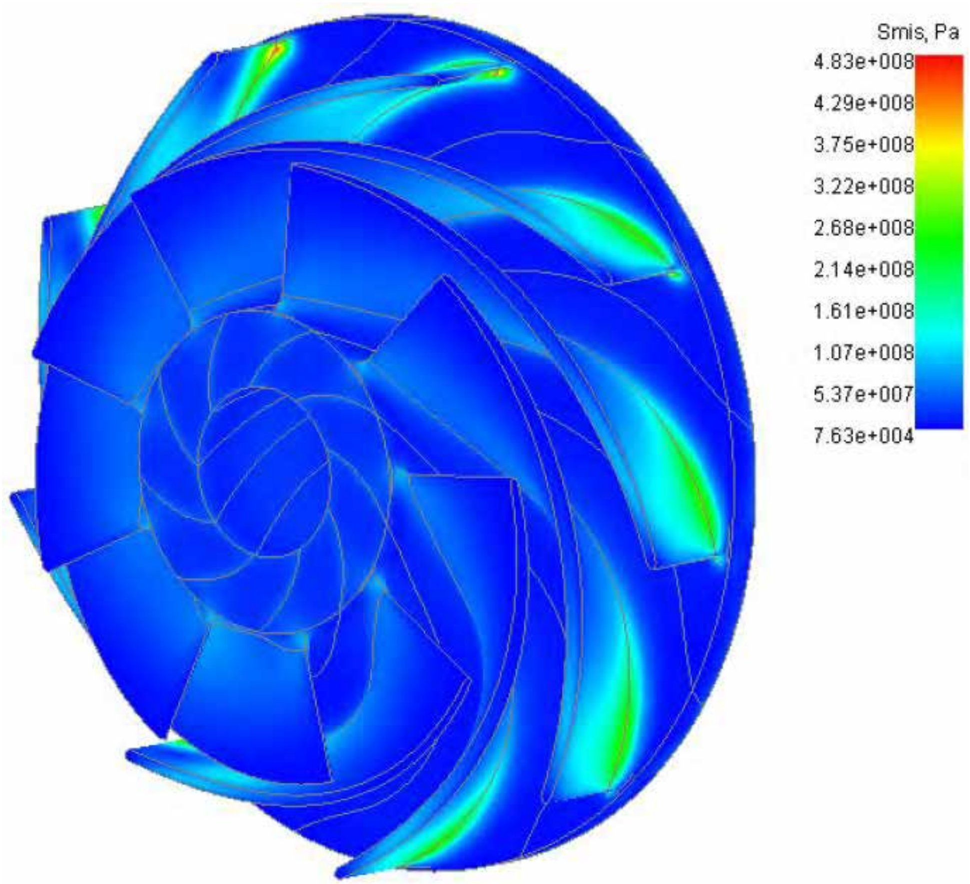
- Mass flow rate
- Pressure and temperature at inlet
- Pressure at outlet

Design requirements:

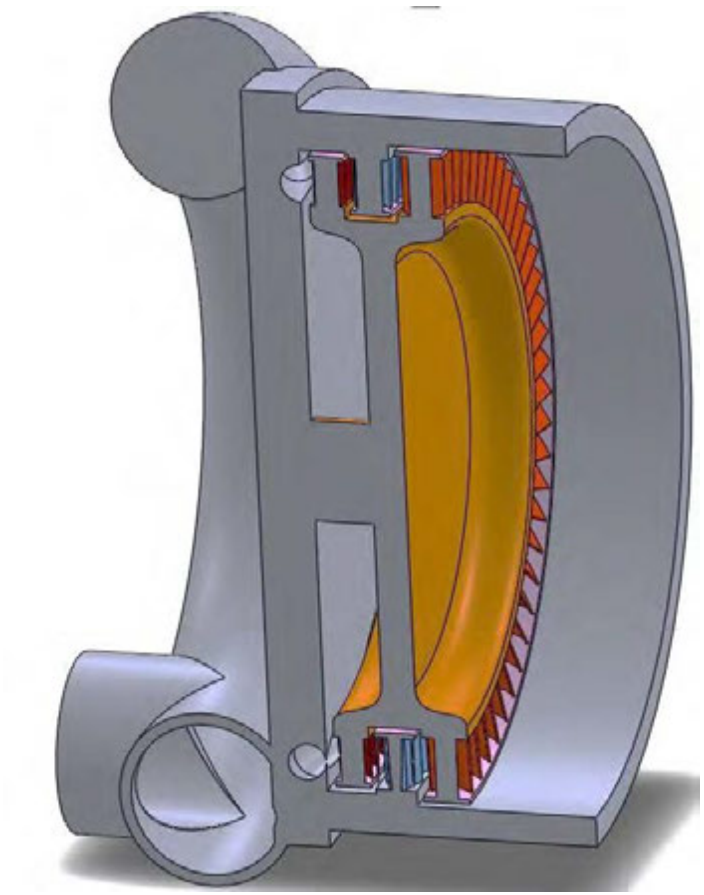
- Maximal efficiency
- Cavitation absence
- Minimal contributed power
- Stress requirements

Stress Calculation in AxSTRESS™

Stress calculations are performed during turbopump design process.



Preliminary Turbine Design in AxSTREAM®



Design BCs:

- Inlet pressure and temperature
- Pressure at turbine exhaust
- Required power

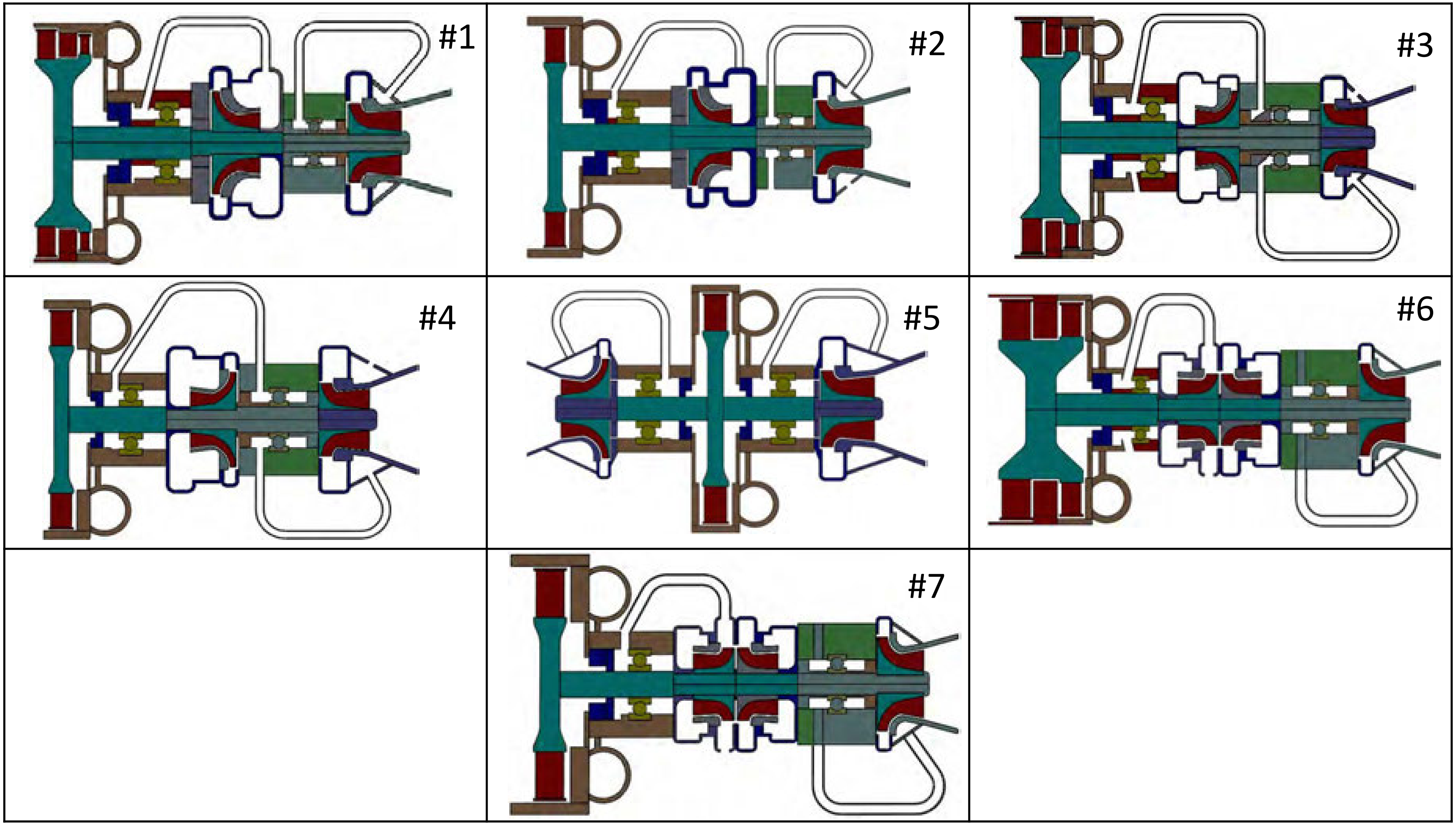
Optimization:

- The optimal partial admission is found during turbine design for each turbopump configuration to get maximal turbine efficiency

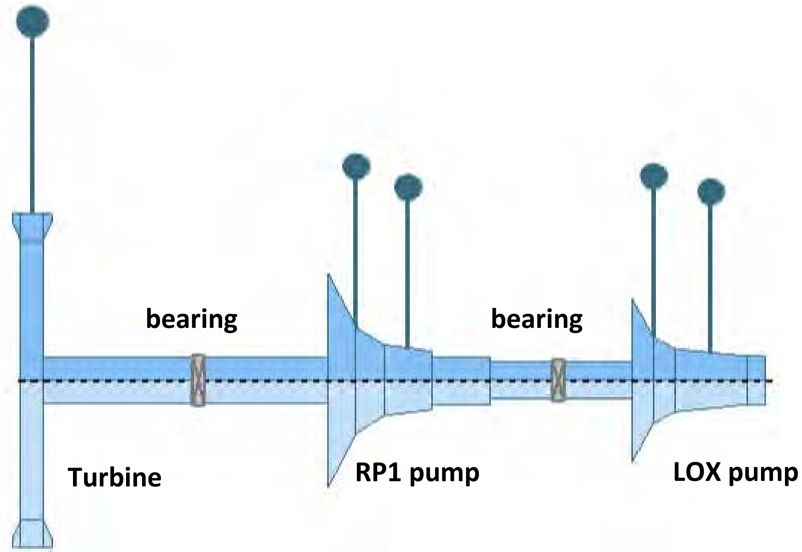
Assumption:

- Pitch turbine diameter to pump impeller diameter ratio is 2.5

Simplified Turbopump Model Parameterization



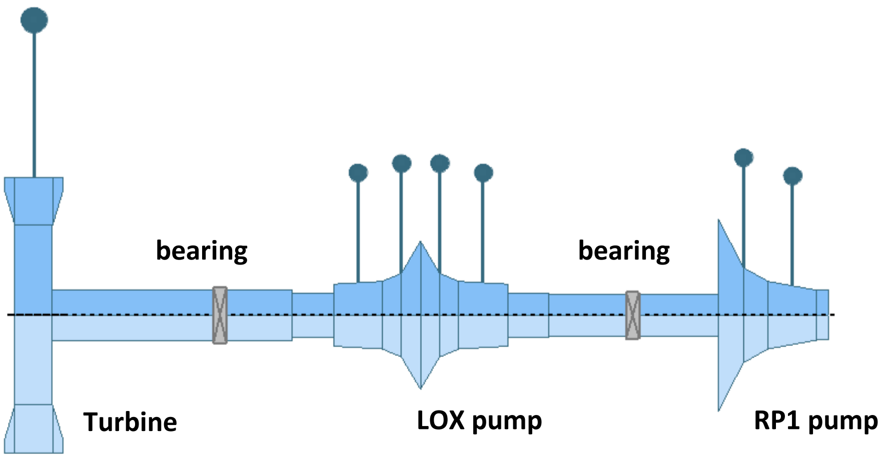
Calculations in AxSTREAM RotorDynamics™



Single flow LOX and RP1 pump

- Rotordynamics analysis is performed to determine bearing radial reaction
- Rotordynamics model was generated for each turbopump configuration
- Geometry of rotor is transferred from the above presented CAD model

- mass-inertia characteristics of turbine and pumps blades

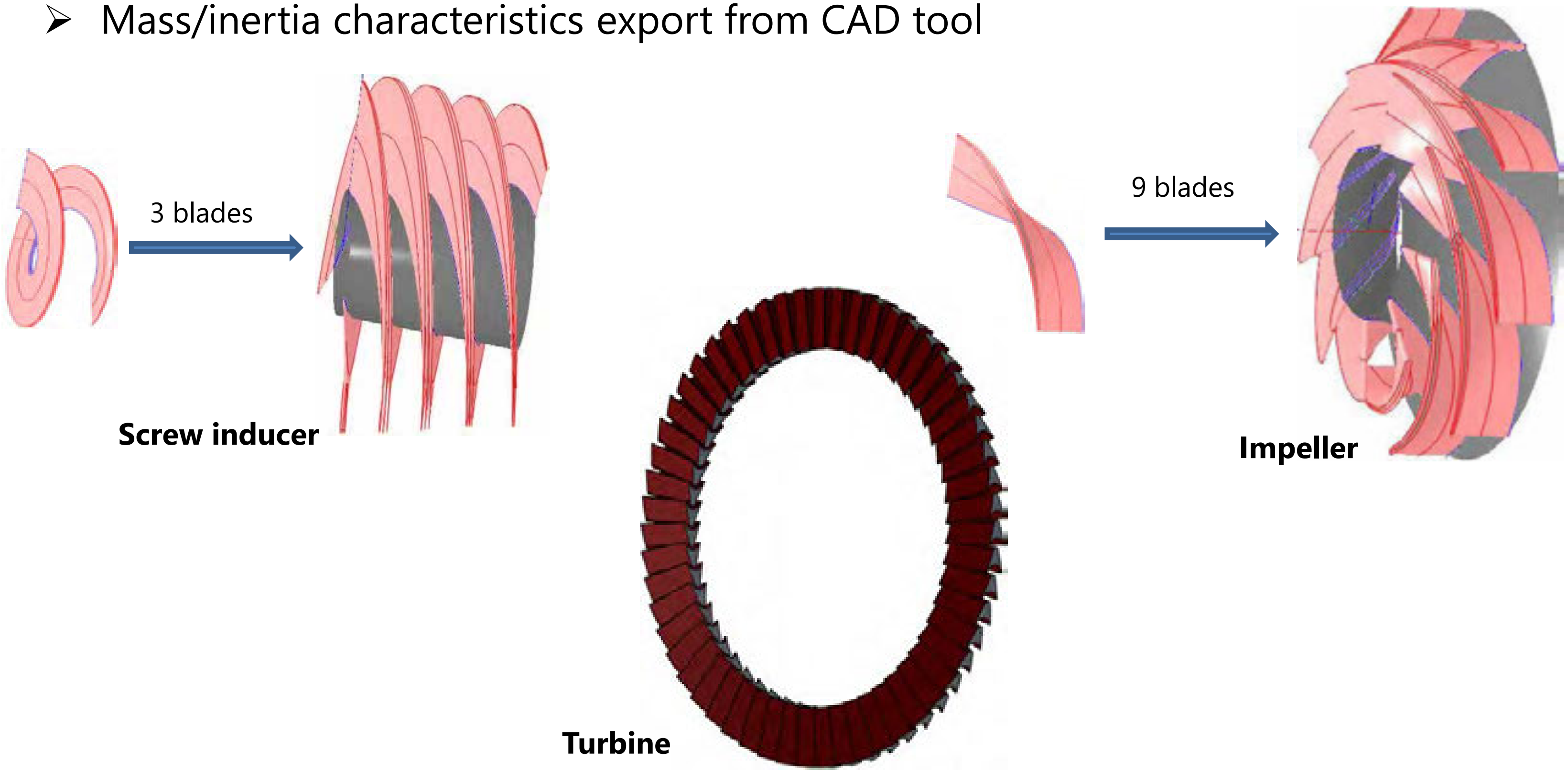


Double flow LOX pump and single flow RP1 pump

Mass/Inertia Characteristics of Blades

To define the mass and inertia momentum values of the entire pump and turbine wheel, the following automatic steps were performed:

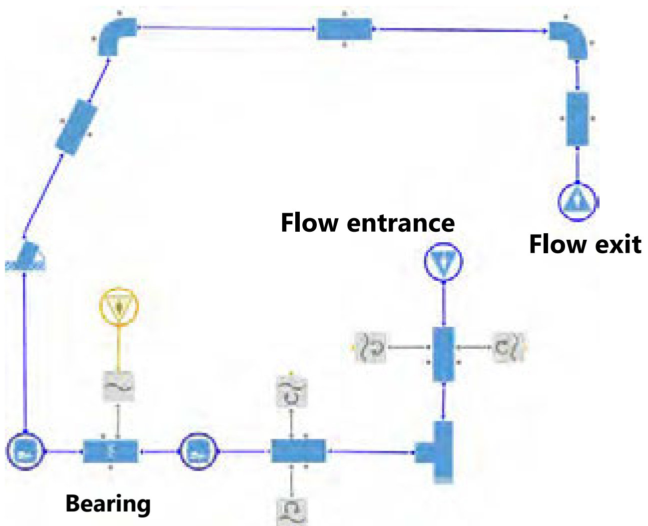
- Export of blades .iges model of designed pump/turbine
- Import of .iges model and blades number to CAD tool
- Mass/inertia characteristics export from CAD tool



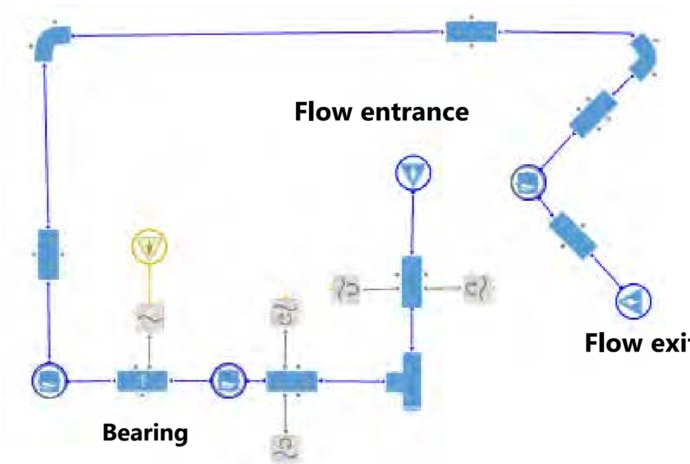
Secondary Flow System in AxSTREAM NET™ Tool

The secondary flow system was modeled for each turbopump configuration to determine the fluid mass flow rate that provides bearing cooling sufficient for its reliable work.

The geometry of the system is transferred from CAD model, BCs from cycle estimation. During the turbopump design process the fluid evaporation absence for each secondary flow path was controlled. The heat quantity due to bearing heating is determined by script calculation.



RP1 secondary flow branch



LOX secondary flow branch

Heat supplying	Surface with rotation	Tube elements
Elbow with recess	Annular channel	Chamber

Bearing Cooling Requirements and Leakage Amount Determination

Friction power of bearings:

$$N_{fr} = f(F, \omega)$$

where

$F = \sqrt{Fa^2 + Fr^2}$ – total bearing load;

Fa – axial load on bearing (from axial loading calculation);

Fr – radial load (from rotordynamics calculation);

ω – shaft rotational speed (maximal available).

Leakage value of MFR is clarified using condition:

$$\frac{2(G_i - G_{i-1})}{G_i + G_{i-1}} < 0.001$$

where

G_i – leakage MFR value at current iteration;

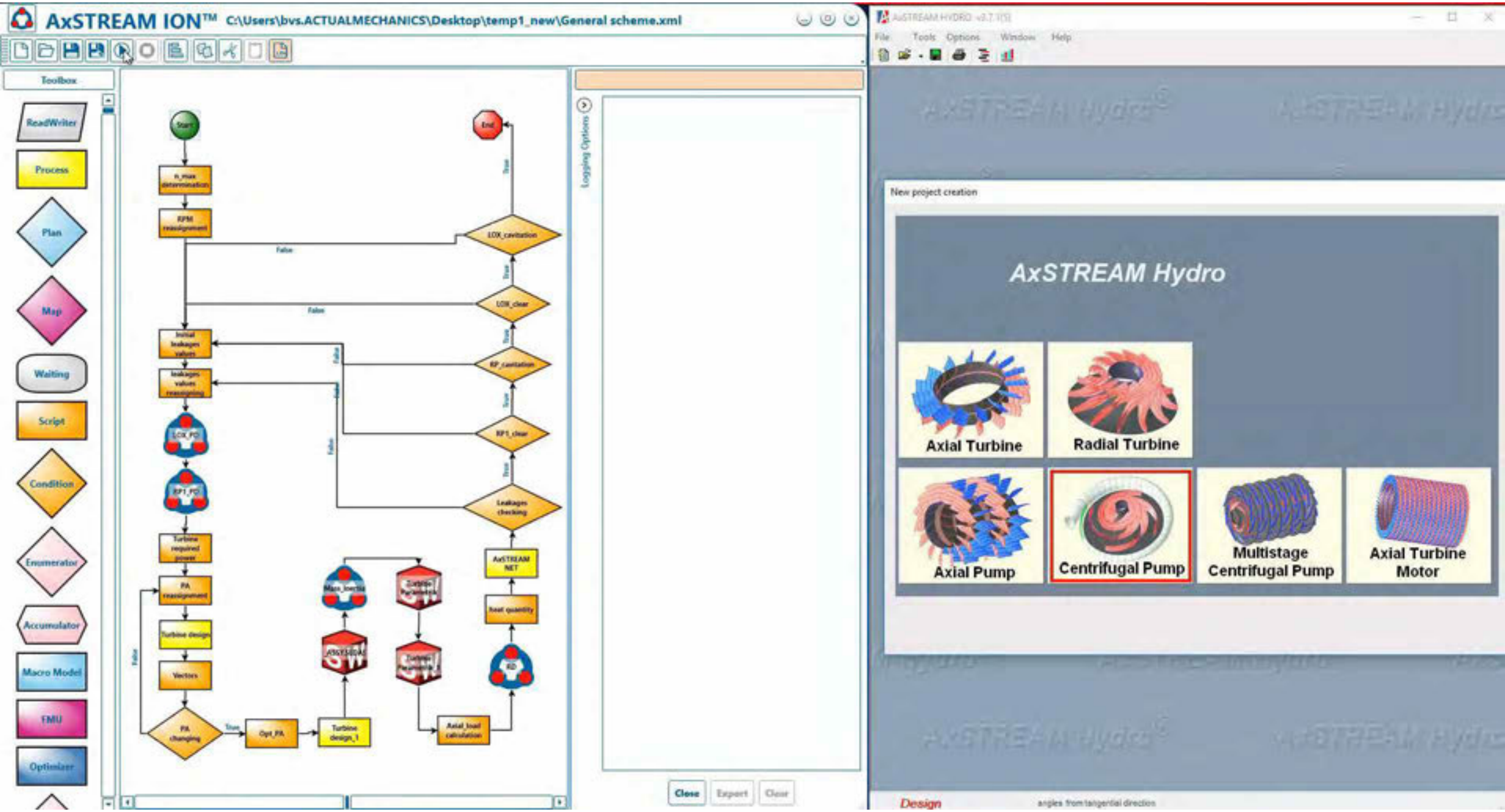
G_{i-1} – leakage MFR value at previous iteration;

For the first iteration the leakage MFR is assigned arbitrarily. The second iteration and its subsequent is determined by secondary flow system calculation.

If the conditional statement is not satisfied the modification of the respective seal is performed and the calculation is being repeated unit convergence.

Turbopump Design Results

Video of the part of the execution process

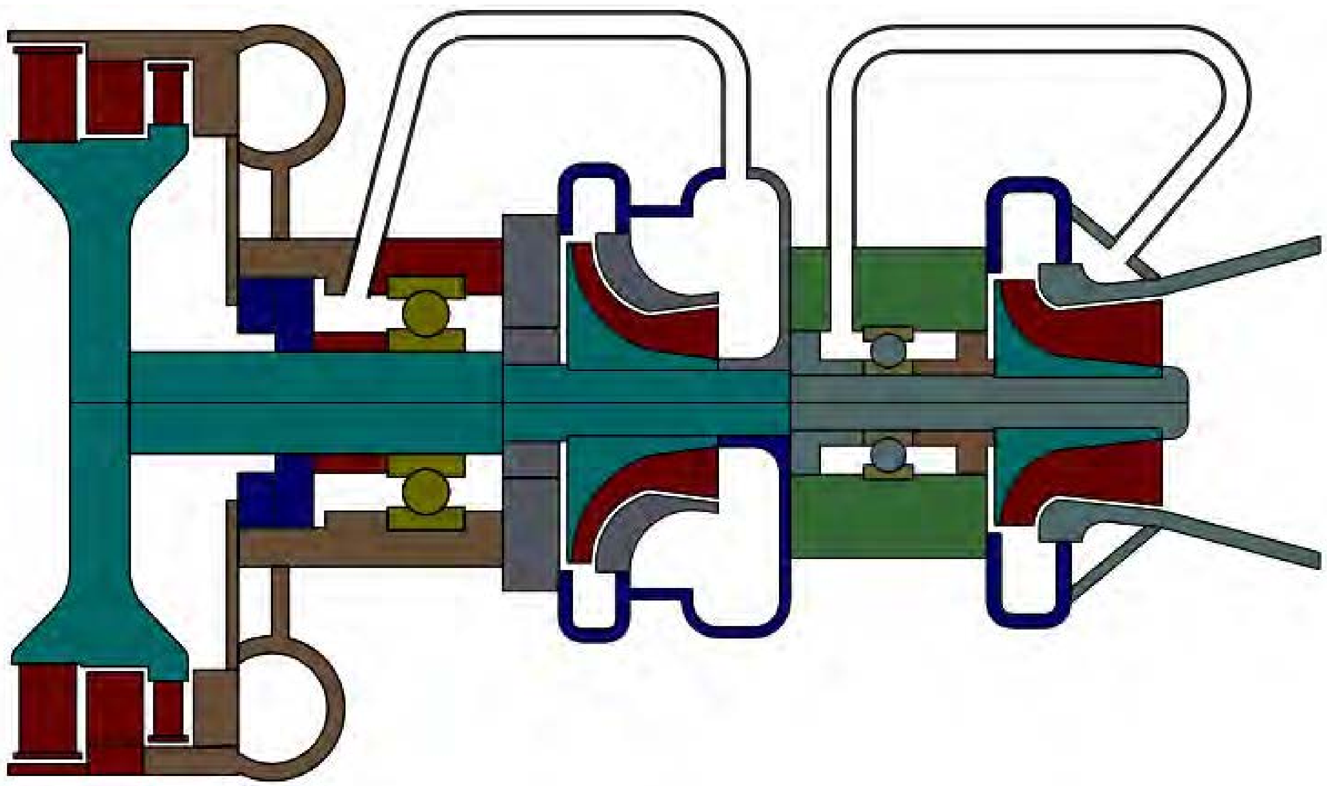


Integral Parameters of Turbopumps

Parameter	Unit	#1	#2	#3	#4	#5	#6	#7
Turbine mass flow rate	kg/s	0.2999	0.3763	0.3080	0.3870	0.3869	0.2983	0.3742
Axial load	N	-14420	-14400	4837	4857	4857	-5406	-5382
Turbopump mass	kg	11.97	11.16	12.25	11.81	11.93	12.40	12.15
Turbopump length	m	0.234	0.226	0.232	0.221	0.217	0.233	0.225
Turbopump diameter	m	0.141	0.138	0.141	0.138	0.138	0.106	0.104
Shaft speed	rpm	52485	52485	52485	52485	52485	74243	74243
Isp_engine	s	310.69	309.19	310.54	308.98	308.98	310.73	309.23

- Maximum Isp_engine was obtained in configuration #6
- Configuration #1 has 0.43 kg lighter TPU comparing to configuration #6
- Assuming 200 s as a single firing duration configuration #1 will require 0.3 kg of total propellants mass more than configuration #6, which is less than the difference in turbopump mass
- Configuration #1 provides a better combination of Isp_engine and turbopump mass
- Utilization of a dual flow oxygen pump enables increased rotational speed and make configurations #6 and #7 compact

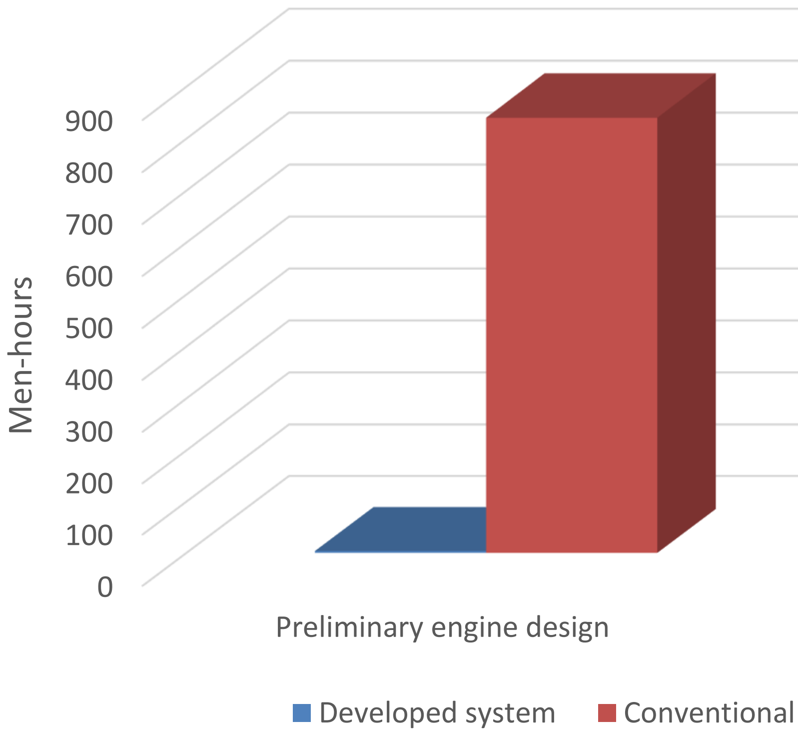
Configuration #1 Turbopump Preliminary Layout



Thrust Nozzle Preliminary Design

Parameter	Unit	Magnitude
Expansion ratio	-	17.3
Throat radius	m	0.034
Exhaust radius	m	0.141
Nozzle length	m	0.65
Nozzle controur	-	90 % bell

Preliminary Design Duration Assessment



- 240 times faster preliminary engine design without compromise in performance
- Dramatic reduction of labor and associated cost
- Shorter duration of engine development and entrance to the market provides substantial financial advantage

Conclusions

Conclusions

1. Taking into account the microsatellite launch trends and launch vehicles market analysis presented earlier in this presentation, we can see that the demand is significant and the state of the industry is becoming progressively more competitive. With this in mind, the development duration becomes extremely important in both minimizing launch costs and supplying the specific launcher quickly, for a specific need. Even the highest performing and cost-efficient vehicle can become useless if not supplied on time in such a competitive and dynamic market.

2. The consideration of launch vehicle breakdown by elements was presented and showed the significant potential for launch cost reduction by shortening the engine development duration which will lead to labor and facilities cost decrease.

3. The system for the design of a liquid rocket engine was developed, which allows automatic iterative execution of rocket engine cycle analysis and turbopump preliminary design, including fuel pump design, oxidizer pump design, turbine design, turbopump preliminary layout development, secondary flows simulation, bearings simulation, rotor dynamics and stress analysis.

Conclusions

4. The proposed design system is easily expandable, which provides the opportunity to perform thrust chamber preliminary design, gas generator design, plumbing routes, turbopump orientation and mounting configuration considerations, and even some more detailed calculations after preliminary design as a part of the presented algorithm which can reduce the duration of the liquid rocket engine detailed design phase as well.

5. The example of the developed system for preliminary design of a rocket engine, considering gas-generator cycle simulation and turbopump preliminary design of 7 different configurations was presented. It was determined that configuration #1 provides a better combination of Isp (310.69 s) and turbopump mass (11.97 kg). The difference between thrust chamber Isp and engine Isp is 1.9 %.

6. The labor time for the preliminary design of the liquid rocket engine was reduced 240 times utilizing the developed approach. This time reduction not only decreases labor time but also decreases the associated facilities cost and enables supply of the engine in a shorter period which is extremely valuable in such a dynamic market.

Future Plans

Future Plans

- The proposed design system is easily expandable.
- It offers the opportunity to perform thrust chamber preliminary design, gas generator design, plumbing routes, turbopump orientation and mounting configurations considerations.
- After preliminary design, more detailed calculations can be performed as a part of the presented algorithm and reduce the duration of liquid rocket engine detailed design phase.
- The authors of the paper are planning to continue work in this direction and present the results in future papers.

Commercial Software Tools Utilized in the Study

Commercial Software Tools Utilized in the Study

- AxSTREAM® for turbomachinery preliminary design
- AxSTREAM NET™ 1D hydraulic network analysis tool was used for leakage flow simulation
- AxSTREAM Rotor Dynamics™ and AxSTREAM Bearing™ were used for rotor dynamics and bearings simulation
- AxSTRESS™ was used for preliminary stress analysis of turbomachinery components
- AxSTREAM ION™ was utilized for the development of the turbopump preliminary design system, including operation flowchart design, optimization, integration of the off-the-shelf and custom software tools, and execution.
- SolidWorks was used for automatic generation of preliminary layout of turbopump and thrust chamber

Thank you for Your Attention