Developing Competitive Liquid Rocket Engines During The Space Gold Rush

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No Capital + No Capability = No Success

- The two biggest obstacles facing commercial space entities are capital and capability as indicated by experts in the industry.

- Jim Cantrell, the CEO of Vector Launch, as well as other executives with experience in the space exploration industry, assert that any space venture needs at least **$100M**, and an experienced team of “seasoned greybeards” or it will not succeed.

How Can We Help?

State of the Rocket Industry

- 100 + startups are currently developing launchers, but how many are actually needed and how many will survive?

- In order to be competitive and attractive to investors in the launch industry, decreased launch cost is a must.

- As a result, the development duration becomes extremely important for minimization of launch costs and for the supply of a specific launcher for a specific need in the shortest possible time. Even a high performance and cost-efficient vehicle may become useless if not manufactured and supplied in time in such a competitive and dynamic market.

So how can we help ?

Through an integrated system that enables:

- Development of reliable, efficient and more cost competitive rocket engines in the short term.

- Utilize the knowledge of **"seasoned greybeards"** to create the design system and keep the knowledge in-house, which allows users to design a highly competitive LRE, even by an entry-level engineer and accumulate all further technical solutions and knowledge.

Universal Goal

Problem: Complexity of the Task

- There are many options for engine designs (single and multichamber engines, variety of turbopump configurations, variety of cycles).
- All engines are different in size and power, and thus require different components.
- Traditional steps to design machinery:
  - Conceptual design
  - Preliminary design
  - Detailed design required years for implementation

Goal

- An affordable method that allows expansion of the configuration options for engine layouts later on.

How?

- Develop a new approach which will automate and streamline overall design process of the engine.

Technology for Engine Design

Key Points to Consider

- SoftInWay, Inc. is working to develop an automated system for engine design based on AxSTREAM.SPACE™.

- Current efforts are devoted to the development of an integrated approach which automatically performs a joint turbopump-engine layout, preliminary geometry generation, and selection of the best engine configuration.

- The Principle of Digital Engineering will be utilized to develop the layout of the rocket engine.

Layout Considerations

During preliminary rocket engine layout creation, it is necessary to determine the location of the components that have maximal mass, and their influence on engine operating behavior.

Generally, interposition of engine components is determined by:

- Engine Purposes
- Number of Chambers
- Required Dimensions of Engine Section
- Structural, Manufacturing and Economic Requirements

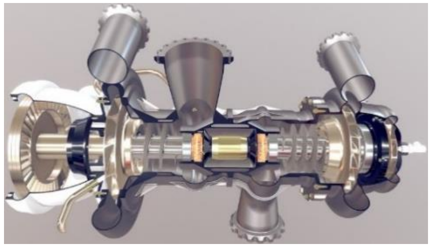
Requirements for Rocket Engine Layout

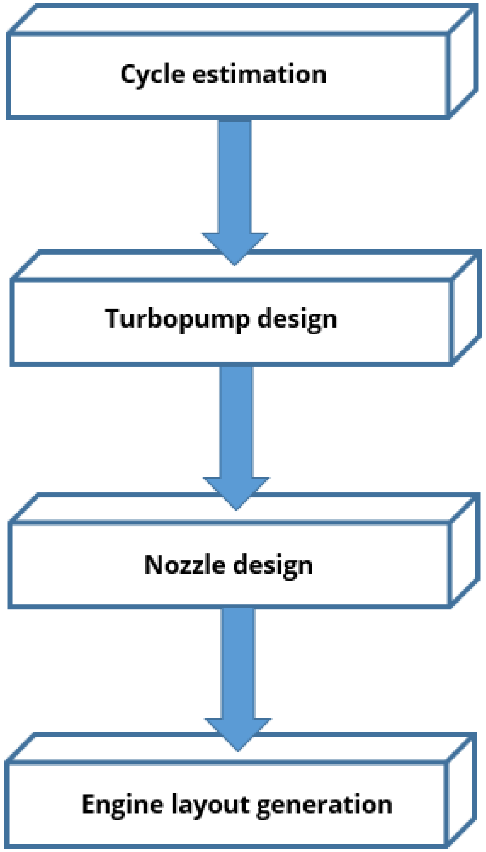
Rocket engine layout is the joint arrangement of its components relative to each other that satisfy the often contradictory requirements:

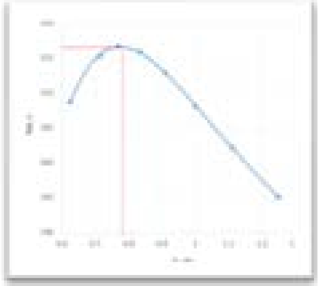
- Compactness and minimum weight of engine
- Minimal hydraulic and heat losses in pipelines
- Static and dynamic strength of engine and its separate components
- Gyroscopic momentum
- Heat fluxes from the combustion chamber and nozzle exit
- Ease of installation and operation of the engine

Digital Engineering for Engine Design

Digital Engineering is the approach that focuses on developing and integrating digital models covering the stages of object design, analysis, testing, and optimization.



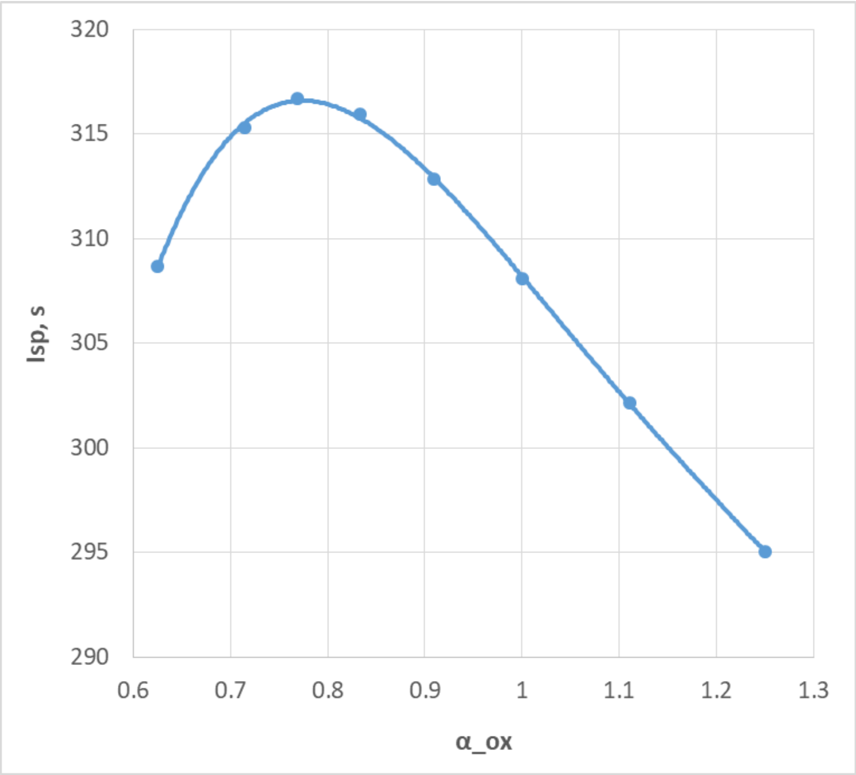




Cycle Estimation

Initial Data:
- Payload
- Orbit

Results:
- Optimal oxidizer excess factor to satisfy maximum Isp
- Fuel components MFRs
- Number of stages
- Preliminary rocket mass
- Pumps and turbine boundary conditions



Establishing Engine Parameters

- Integrated system for the design of the turbopump, nozzle with combustion chamber, and the overall engine using parametric models.

- Enables a previously designed component model to be applied in different boundary conditions/thrust levels without a need for modification.

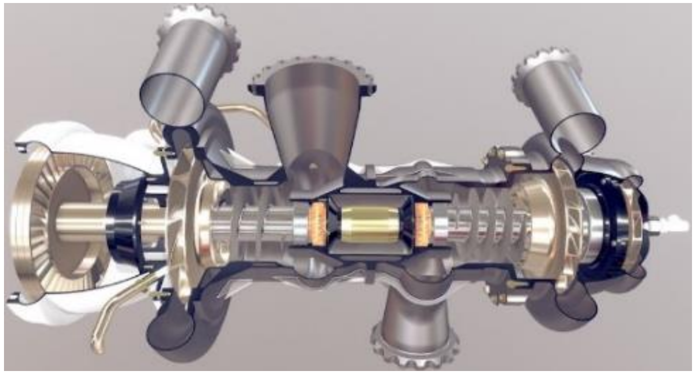
- CAD parameterization combined with implemented algorithms and design rules significantly reduce development time by exchanging manual work with automated work.

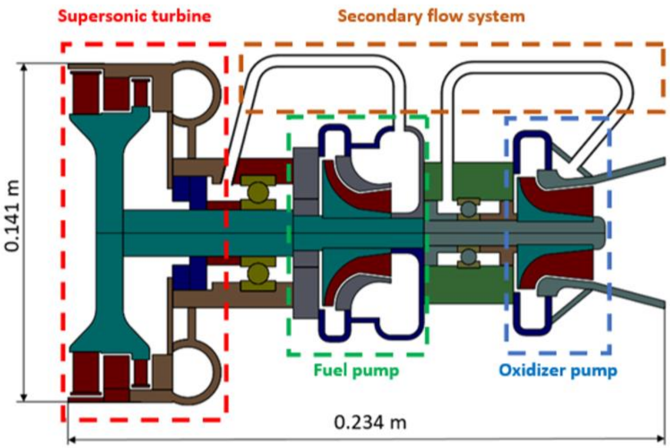
- Parameterized models were created in SolidWorks and integrated into the system via API interface.

Turbopump Preliminary Design

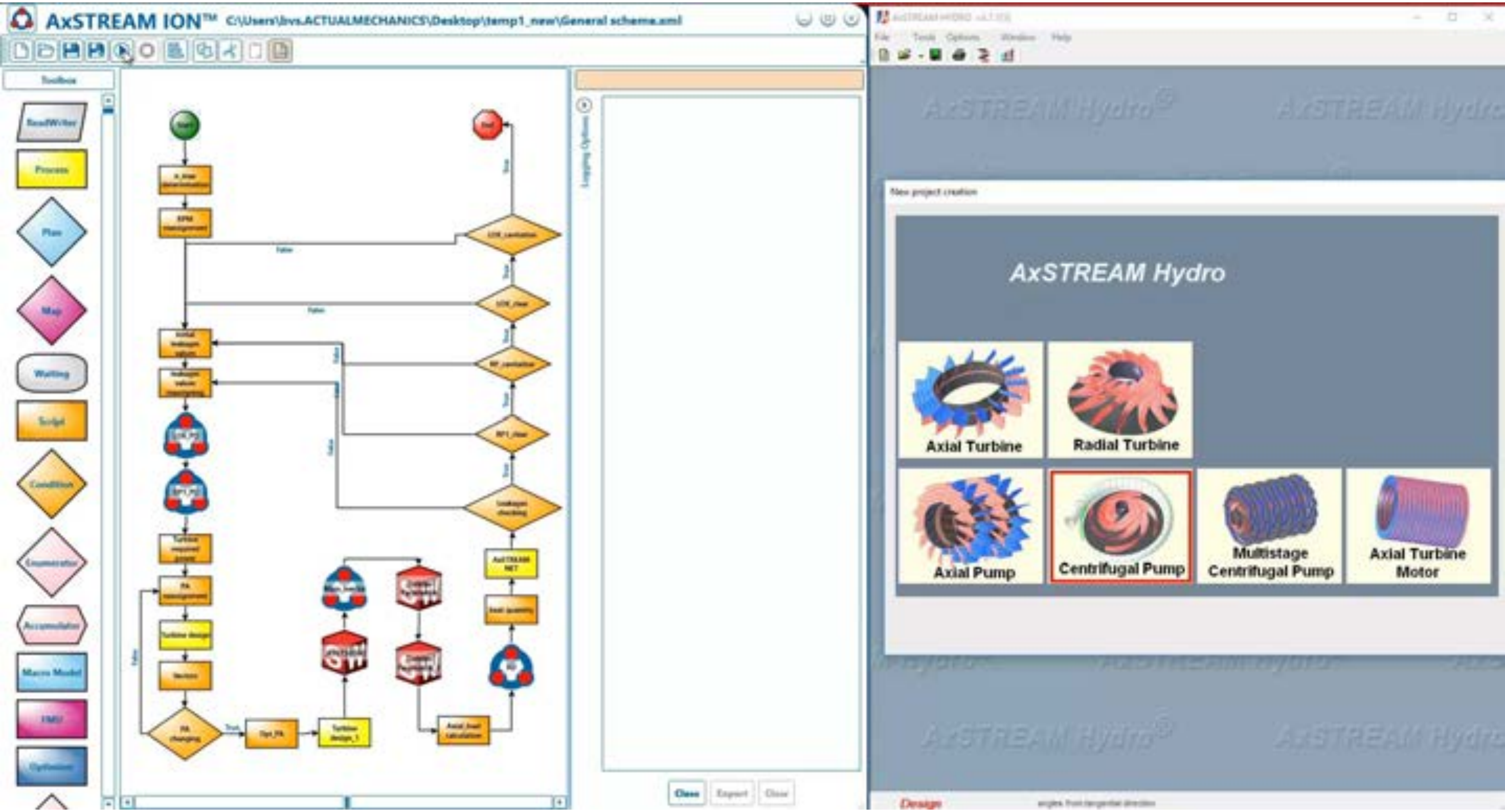
Preliminary Design of the Turbopump Includes:

- Preliminary configuration selection
- 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





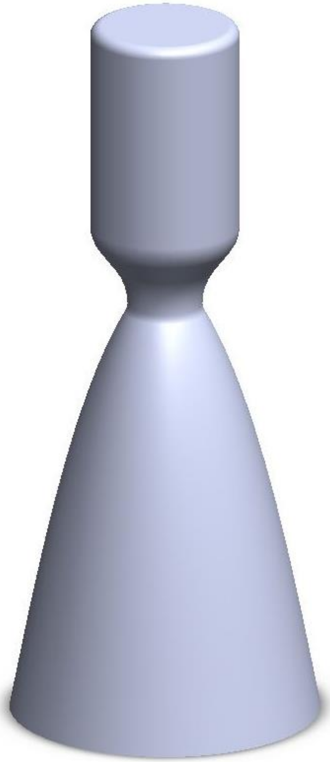
Video Excerpt of Preliminary Design Process



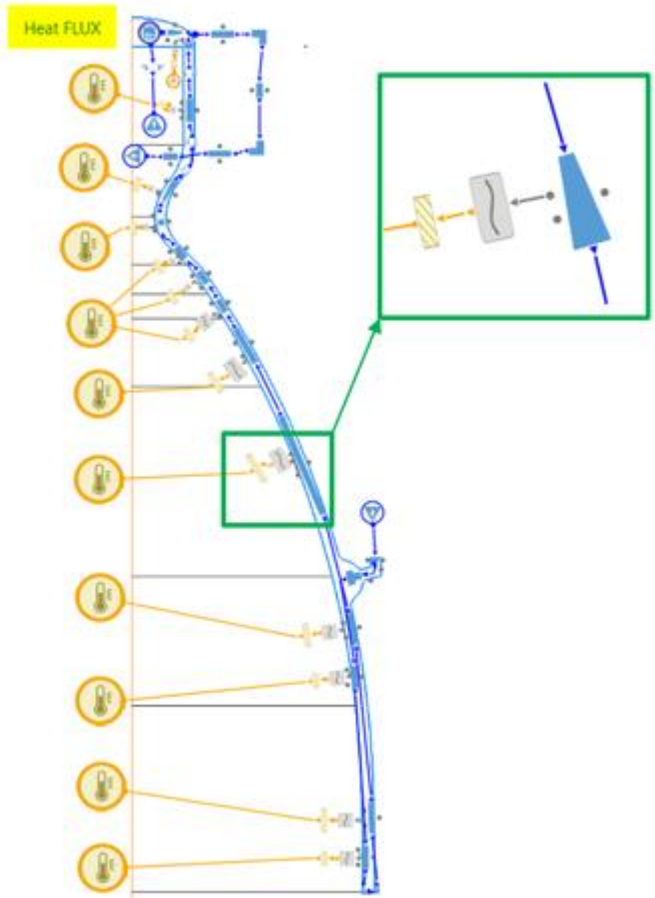
Aerodynamics of Nozzle/Combustion Chamber

Preliminarily designed aerodynamic profile of thrust nozzle with combustion chamber determines:

- Expansion ratio
- Throat radius
- Exhaust radius
- Nozzle length
- Nozzle contour



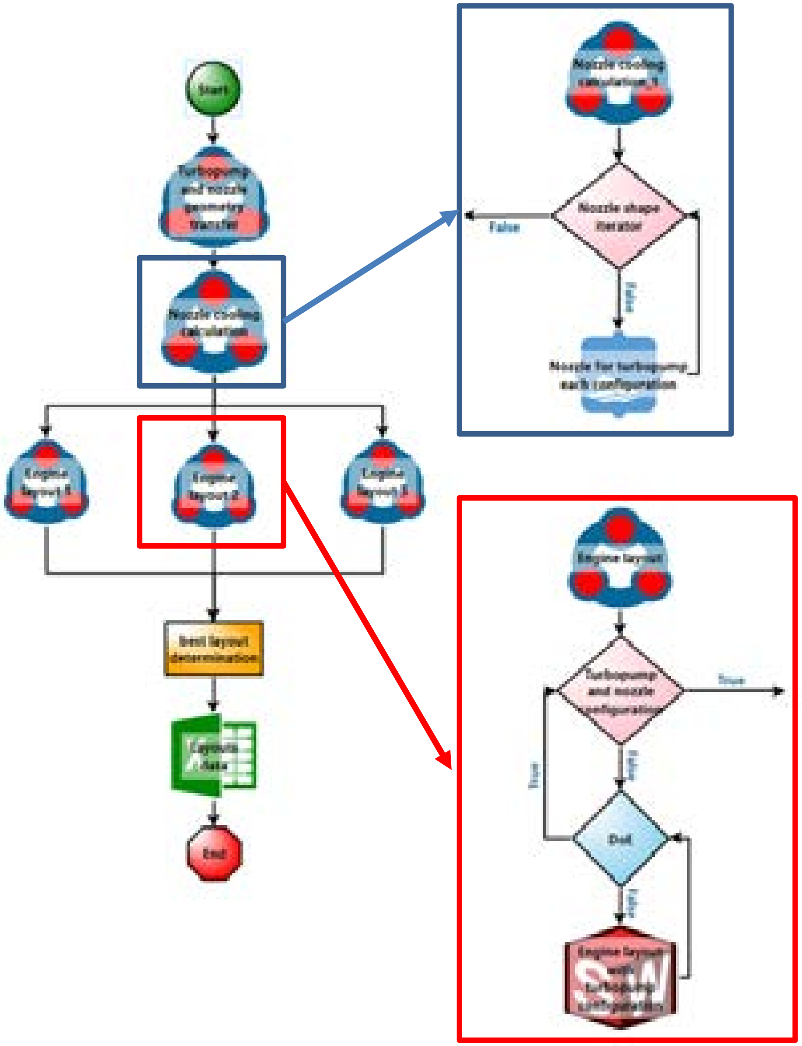
Cooling Simulation: Combustion Chamber/Nozzle



- Calculation of cooling flow temperature distribution along the nozzle and combustion chamber.
- Determination of required dimensions of cooling channels for effective heat removal.
- Determination of required material thermal conductivity for each nozzle and combustion chamber section.
- Nozzle and combustion internal wall temperature calculation.

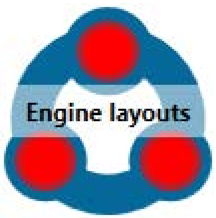
Nozzle and combustion chamber cooling simulation in AxSTREAM.SPACE™

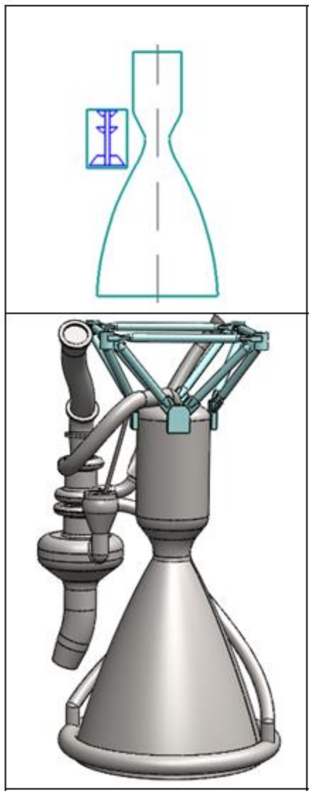
Process Flowchart for LRE Layout



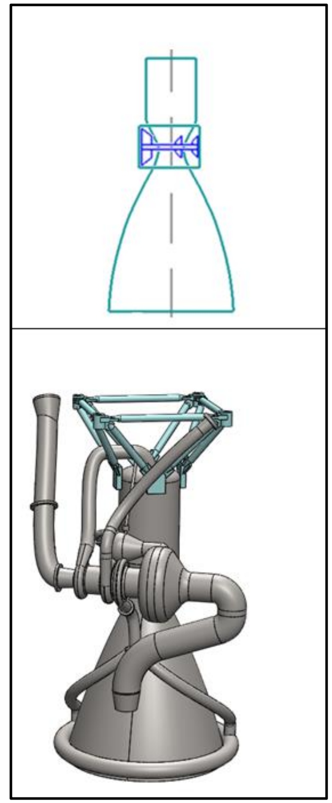
- The algorithm to automatically create the LRE layout was implemented in the integrated environment.
- The turbopump and thrust nozzle with combustion chamber data go to the nozzle cooling calculation procedure (blue rectangle), where the heat fluxes are estimated.
- Each engine layout the procedure of the turbopump optimum interposition determination is performed (red rectangle).
- Optimization algorithm is based on Design of Experiment Theory (DoE).
- The criteria for the best layout and configuration was the minimum mass and maximum compactness. Gyroscopic momentum was also taken into account.

Examples of Implemented Engine Layouts

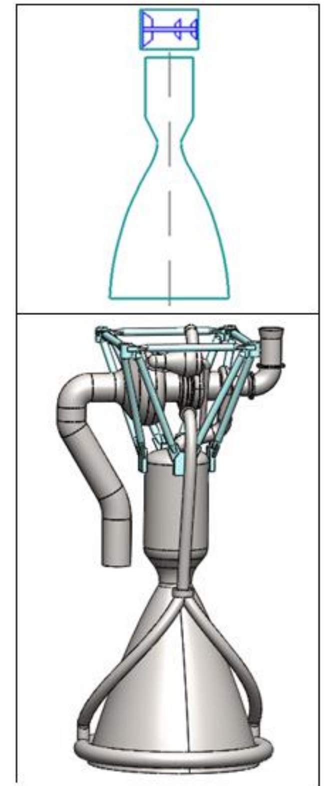




Turbopump on the side of nozzle axis

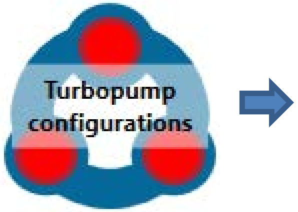


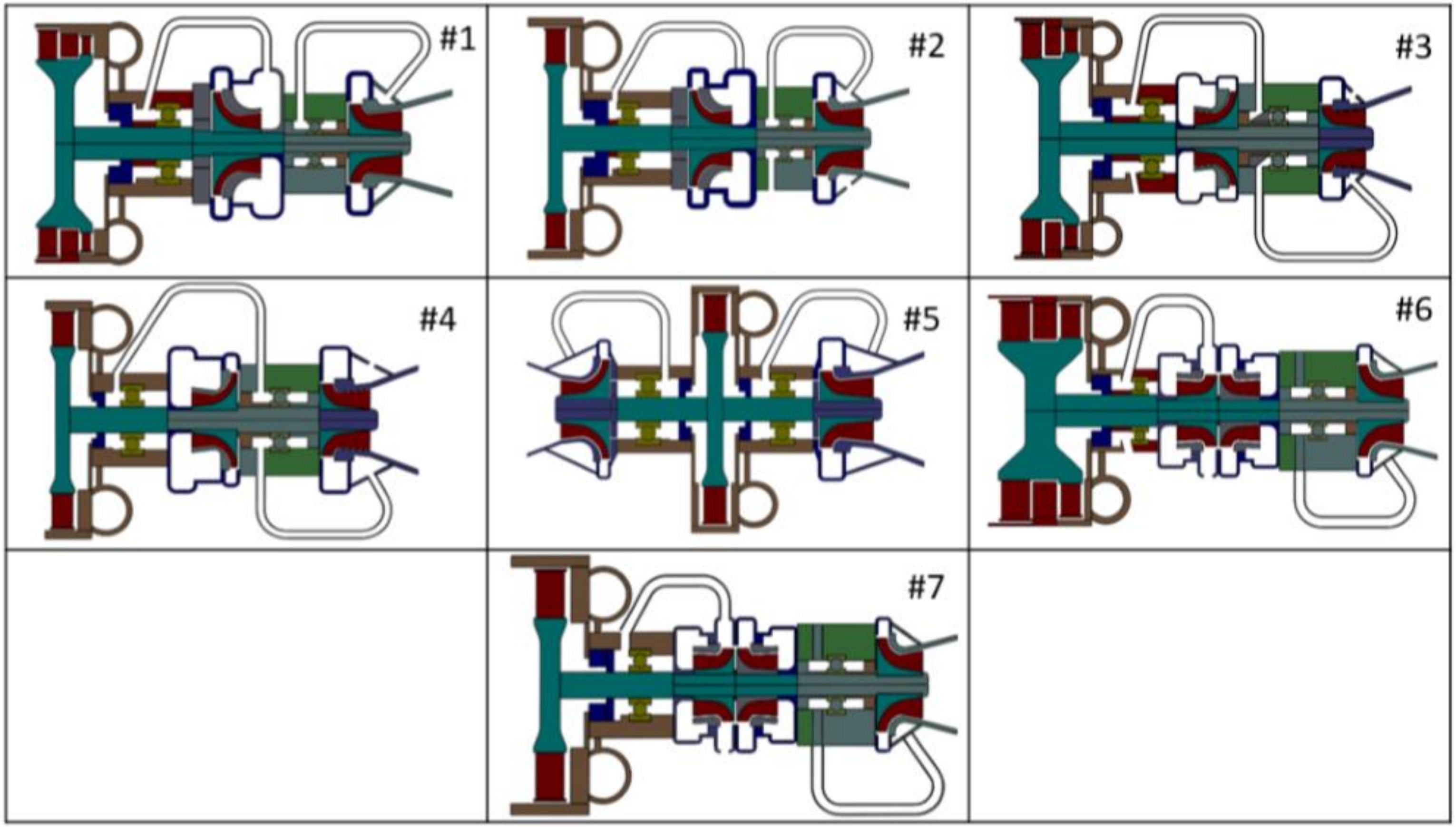
Turbopump with perpendicular orientation



Turbopump over combustion chamber

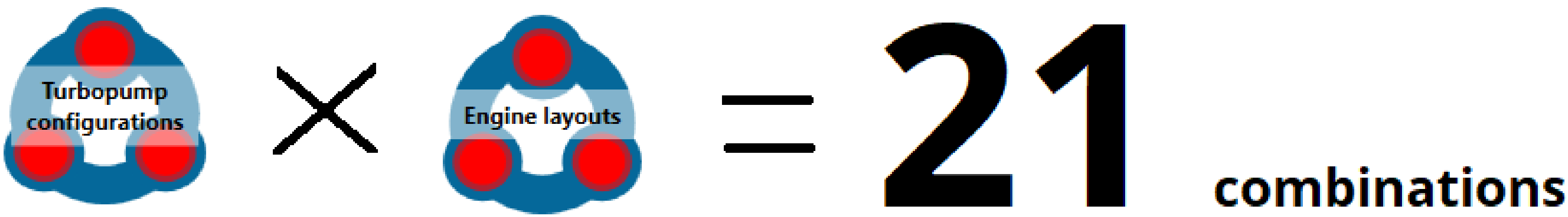
Investigated Turbopump Configurations





Overall Scope of Study

For each of the **three** layout of the rocket engine, **seven** turbopump configurations were used.

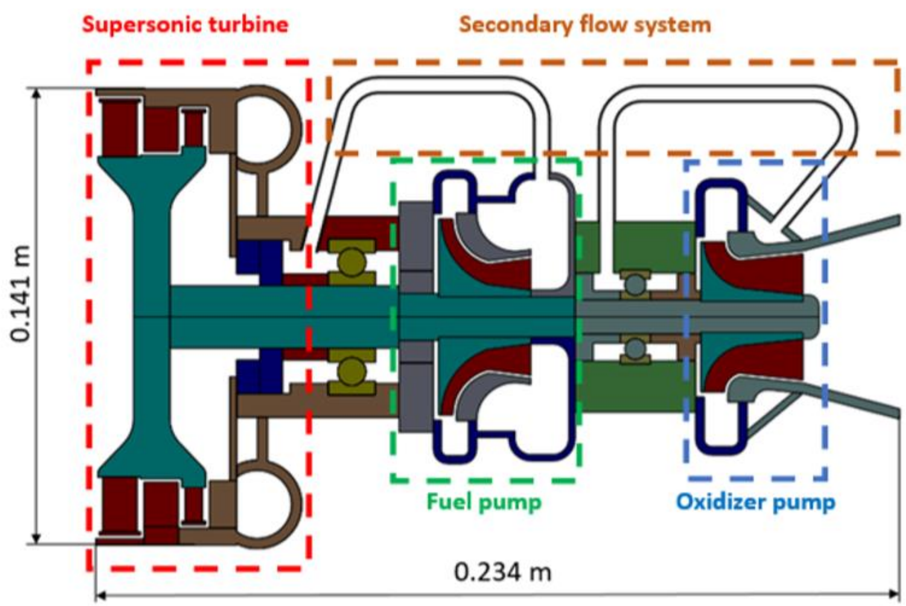


Subsequently, **twenty one joint turbopump and LRE configurations** were investigated.

Rocket Engine:
Main Components
& Dimensions

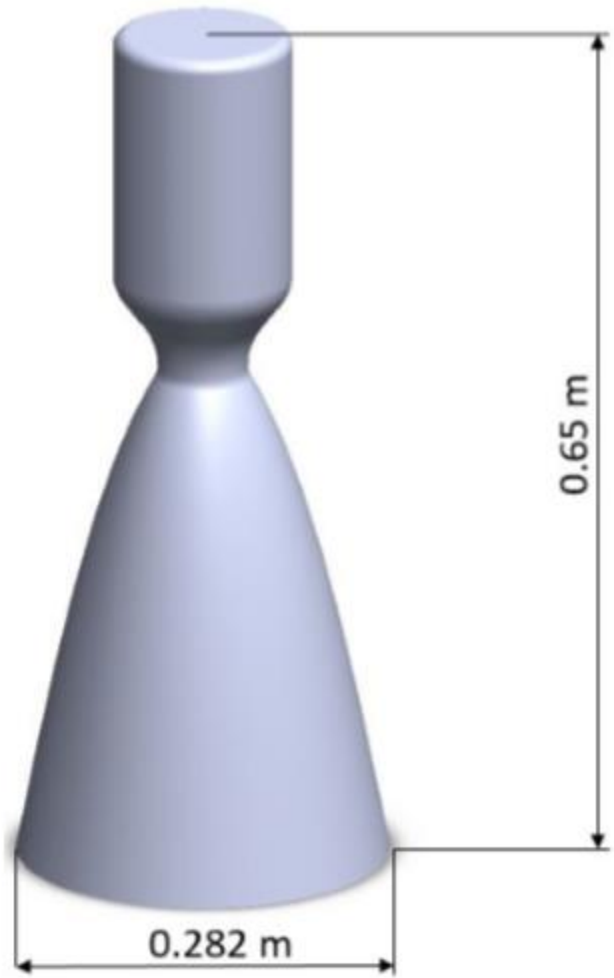
Incoming Data and Dimensions: Turbopump

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



Nozzle and Combustion Chamber Dimensions

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



Results

LRE Layout Selection Results: Part 1

Turbopump layout	parameter	1	2	3	4	5	6	7
Engine Layout 1	Pipes mass, kg	**0.857**	1.071	0.868	1.098	1.250	**1.176**	1.201
	Turbopump mass, kg	**11.97**	11.16	12.25	11.81	11.93	**12.4**	12.15
	Compactness	**0.194**	0.158	0.192	0.157	0.161	**0.191**	0.158
	Gyroscopic momentum, N*m	**$2.2*10^{6}$ Ω**	$2.2*10^{6}$ Ω	$2.2*10^{6}$ Ω	$2.2*10^{6}$ Ω	$2.2*10^{6}$ Ω	**$3.1*10^{6}$ Ω**	$3.1*10^{6}$ Ω
	Total mass, kg	**12.82**	12.23	13.11	12.90	13.18	**13.57**	13.35
	Engine specific impulse, s	**310.69**	309.19	310.54	308.98	308.98	**310.73**	309.23
	Propellants mass to drive TPU, kg	**59.98**	75.26	61.59	77.39	77.39	**59.66**	74.83
	Mass criterion, kg	**72.80**	87.49	74.70	90.29	90.57	**73.23**	88.18
Engine Layout 2	Pipes mass, kg	**0.94**	1.01	0.947	0.99	0.98	**1.34**	1.39
	Turbopump mass, kg	**11.97**	11.16	12.25	11.81	11.93	**12.4**	12.15
	Compactness	**0.182**	0.149	0.179	0.147	0.152	**0.181**	0.173
	Gyroscopic momentum, N*m	**0**	0	0	0	0	**0**	0
	Total mass, kg	**12.91**	12.17	13.19	12.80	12.91	**13.74**	13.54
	Engine specific impulse, s	**310.69**	309.19	310.54	308.98	308.98	**310.73**	309.23
	Propellants mass to drive TPU, kg	**59.98**	75.26	61.59	77.39	77.39	**59.66**	74.83
	Mass criterion, kg	**72.89**	87.43	74.78	90.19	90.3	**73.40**	88.37
Engine Layout 3	Pipes mass, kg	**0.69**	0.77	0.72	0.806	0.88	**1.095**	1.171
	Turbopump mass, kg	**11.97**	11.16	12.25	11.81	11.93	**12.4**	12.15
	Compactness	**0.193**	0.174	0.193	0.173	0.177	**0.193**	0.184
	Gyroscopic momentum, N*m	**0**	0	0	0	0	**0**	0
	Total mass, kg	**12.63**	11.93	12.97	12.61	12.81	**13.49**	13.32
	Engine specific impulse, s	**310.69**	309.19	310.54	308.98	308.98	**310.73**	309.23
	Propellants mass to drive TPU, kg	**59.98**	75.26	61.59	77.39	77.39	**59.66**	74.83
	Mass criterion, kg	**72.61**	87.19	74.56	90	90.2	**73.15**	88.15

LRE Layout Selection Results: Part 2

- Engine layout #1 provides lower values of pipes mass with the maximal compactness value.

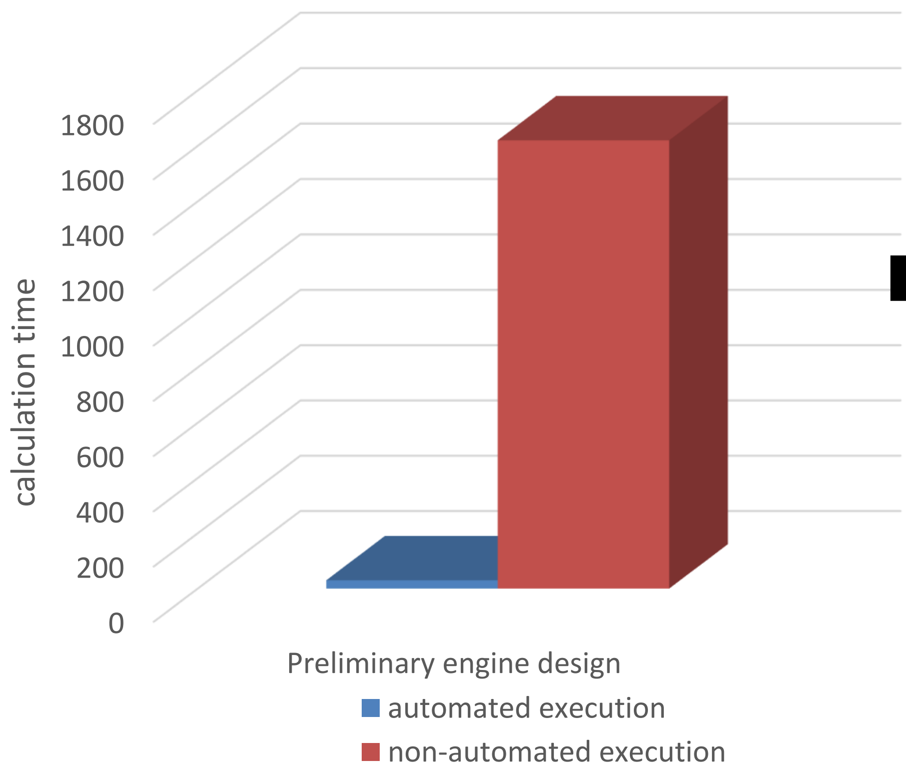
- Engine layout #2 provides maximal pipes mass for the most turbopump configurations.

- Layout #3 shows the slightly lower compactness values, however, provides a minimal mass of connecting pipes. It is seen from the results that utilization of turbopump configuration #1 and engine layout #3 provides the minimal mass of engine including fuel mass required to drive the turbopump.

- The configuration #6 has a maximal value of specific impulse among all of the other ones. The closest by specific impulse configuration is configuration #1. It has 0.04 s lower specific impulse than configuration #6. However, configuration #1 was nevertheless determined as the best one, taking into account the difference in mass of the turbopump and mass of pipes, which are both smaller for configuration #1.

- Specific impulse has the highest impact on the mass creation, but for cases with small differences in specific impulse the consideration of the difference in mass of turbopumps and engine layout optimization, minimizing the pipes mass allow making a more comprehensive selection of the best configuration.

Assessment of Preliminary Design Duration



- **50+** times faster preliminary engine design.
- Number increases to **300** times faster when turbopump and nozzle design is automated.
- Dramatic reduction of labor and associated cost.
- Shorter duration of engine development and entrance into the market provides substantial financial advantage.

Conclusion

Conclusions

- A streamlined approach which automatically performs a joint turbopump-engine layout, preliminary geometry generation, and selection of the best engine configuration while taking into account multiple criteria and constraints was developed.

- Three engine layouts and seven turbopump configurations were considered and the best combination was found.

- Configuration #1 was determined as the best option taking into account the difference in mass of the turbopump (11.97 kg vs 12.40 kg) and mass of pipes (0.69 kg vs 1.095 kg).

- Specific impulse has the highest impact on the mass creation, but for cases with small differences in specific impulse the consideration of the difference in mass of turbopumps and engine layout optimization, minimizing the pipes mass allow making a more comprehensive selection of the best configuration.

Conclusions Cont.

- Generating the engine layout takes approximately 1 minute when utilizing an integrated system while simultaneously checking the best solution:

  - 21 total configurations were analyzed (3 engine layouts applying 7 turbopump configurations to each) in 30 minutes using an automated approach (50 times quicker than if a manual process had been used).

  - This speed increases to 300 times faster if design of both the turbopump **and** nozzle is automated

- Using this approach, the development time and associated costs of preliminary engine design were drastically reduced.

Commercial Software Utilized in the Study

Software Utilized in the Study

- AxSTREAM.SPACE™
  - Turbomachinery component design
  - Nozzle and combustion chamber cooling simulation
  - Rotor dynamics and bearings simulation of the turbopump
  - Preliminary stress analysis of turbomachinery components
  - Development of turbopump and engine design algorithm (operational flowchart design, integration of commercial and custom software tools, and execution)

- SolidWorks was used to create parameterized models of turbopump and overall engine

Thank You!
Questions?

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