Genetic Algorithm Optimization of a Cost Competitive Hybrid Rocket Booster

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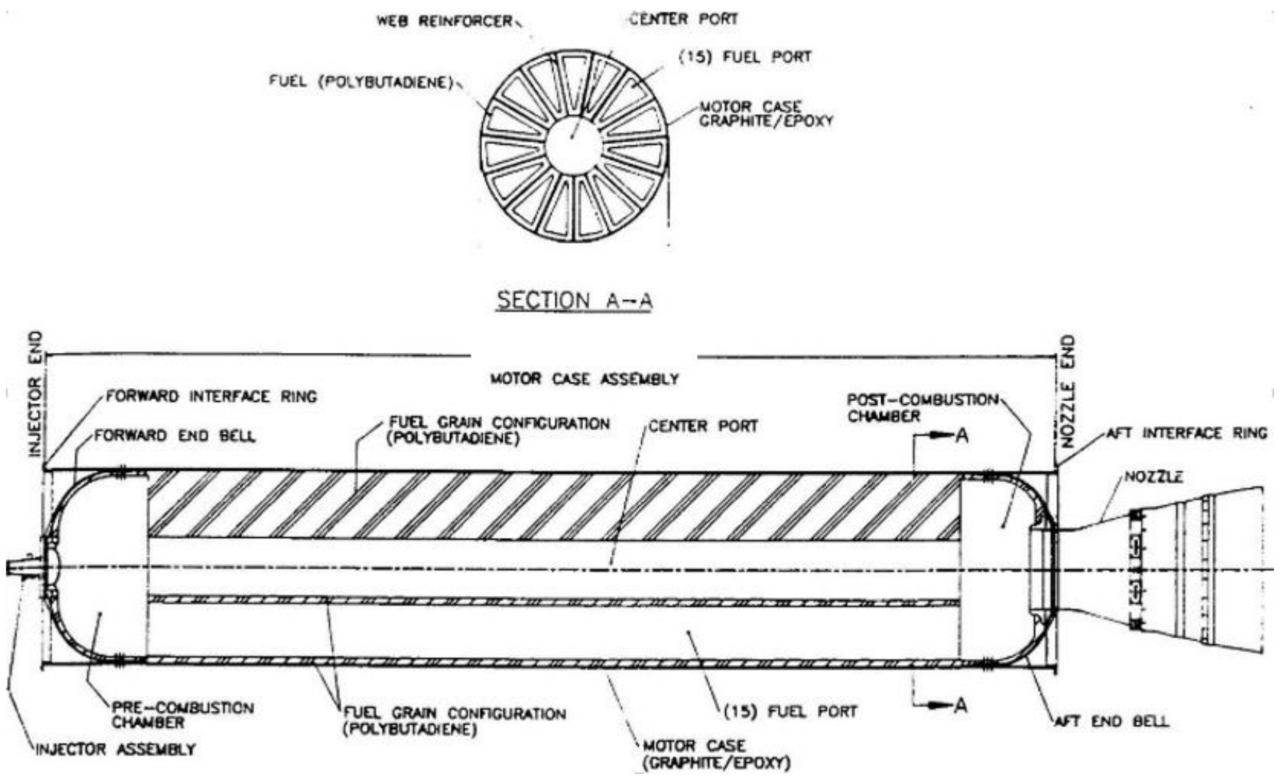
Overview

- Hybrid attributes are typically touted as to why hybrids should be pursued.

  Handling, Operations, Casting, Simplicity, Throttling, Restart, Perfromance and Cost

- Cost has, in the past, been hand waved as being lower than solids and liquids.
- A top level study by Matthias Grosse in 2007, “Design Challenges for a Cost competitive Hybrid Rocket Booster”, indicated that a hybrid rocket booster was more expensive than an equivalent solid rocket booster or a liquid rocket booster.
- That analysis was done using a single point design extrapolated to a much larger size with various weight ratio estimates from solid and liquid systems without optimizing the hybrid system based on cost.
- This paper documents an attempt optimize a booster design based on cost, using the cost indices of functional units from that 2007 study.

AMROC 250K-lb$_f$ Motor Development



Baseline design scaled up in the 2007 study.

Parameter	Burn 1	Burn 2	Burn 3	Burn 4
Thrust (lb$_f$)	216,900	231,900	215,400	214,800
Fuel mdot (lbm/sec)	357	351	339	310
LOX mdot (lbm/sec)	569	600	619	587
ISP (sec)	234	244	225	239
O/F Ratio	1.59	1.71	1.82	1.89
Chamber Press (psia)	412	419	378	369
Nozzle Area Ratio	8.33	8.00	7.61	3.70
Throat Area (in^2)	364	381	402	418
Vac Thrust (lb$_f$)	257,000	272,300	255,800	235,200
Vac Isp (sec)	278	286	267	262

Mass Data of Single Boosters and their Units – Grosse

Fvac/mo=2.6	Liquid	Solid	Hybrid Baseline
Launch Mass(t)	206	292	335
Structural Index	0.0980	0.1596	0.1534
Functional Unit	Mass(t)		
“Structure”	5.1(28%)	5.3(13%)	8.5(19%)
“Equipment”	1.5(8%)	2.0(5%)	2.3(5%)
“Tank”	6.3(34%)	N/A	5.1(12%)
“Motor Case”	N/A	22.9(57%)	14.8(33%)
“Nozzle”	N/A	9.9(25%)	11.6(26%)
“Engine/Lox Feed Unit”	5.5(30%)	N/A	2.1(5%)
Inert Mass	18.4	40.1	44.4

- The solid and liquid rocket reference booster models rely on data from the Ariane 5 solid rocket booster EAP, from the Ariane 5 liquid booster study for the proposed EAL (Etage d' Accélération à ergols Liquides) using kerosene as fuel, and from the Ariane 4 liquid booster L36 and its second stage L33.
- Using scaling factors, Gross made a hybrid design to get the same DeltaV and initial acceleration.

Components Sorting Scheme and cost index for Boosters Data Base -Grosse

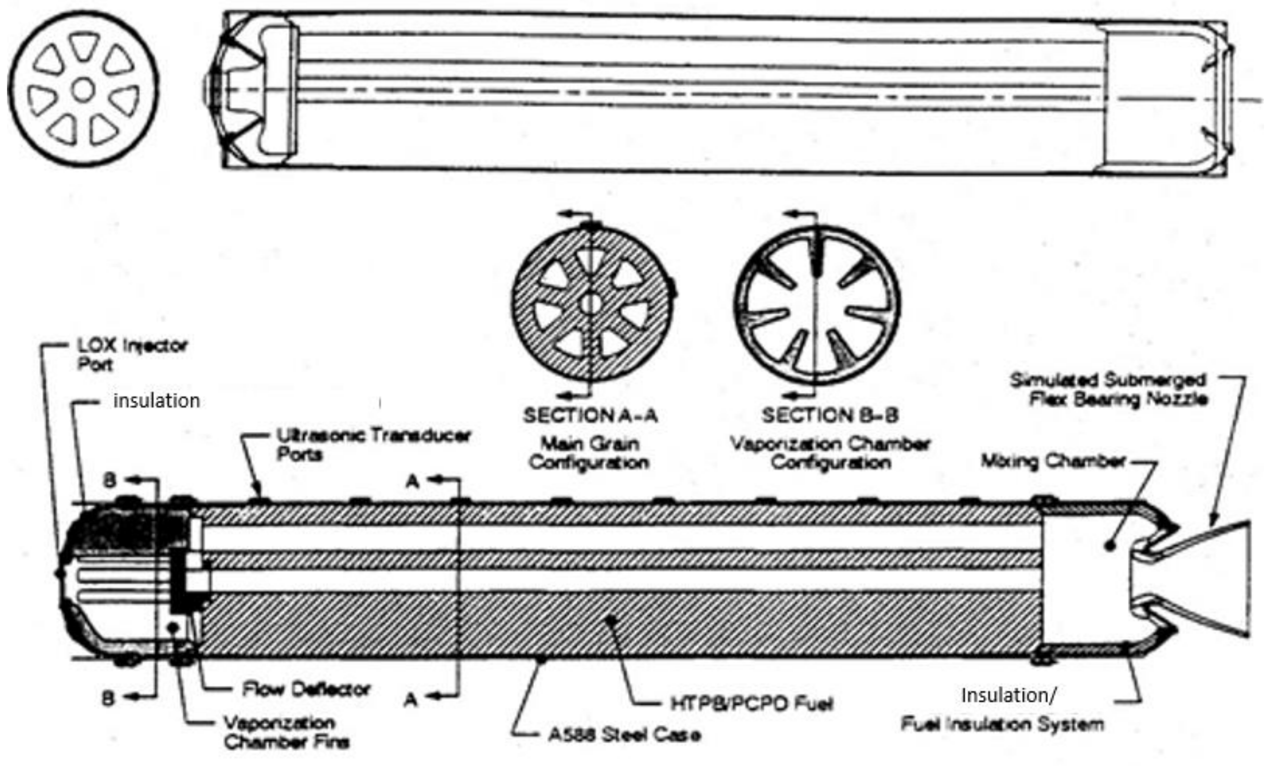
Functional Unit	Related Component	Cost Index (Cost Unit/kg)
"Equipment"	Power supply, harness, instrumentation, telemetry, commando unit, rocket motors for stage separation, pyrotechnics for separation and self-destruction	17
"Tank"	Equipped liquid propellant or oxidizer tank: Tank structure, isolation, propellant pipes, antivortex and -sloshing devices and tank pressurization system (not part of engine or LOX feed unit)	6
"Motor Case"	Rocket motor case incl. insulation, liner and igniter for solid fuel/propellant	1
"Nozzle"	Solid rocket like ablative nozzle with hydraulic actuated thrust vector control unit	4
"Engine" / "LOX Feed Unit"	Liquid rocket engine (incl. Actuation system and control units) or technological comparable "LOX Feed Unit" of the hybrid rocket (turbopump, injector, valves, gas generator and its fuel tank)	20
Solid Propellant		0.1
Hybrid Propellant		0.05

Cost Distribution between Functional Units – Grosse

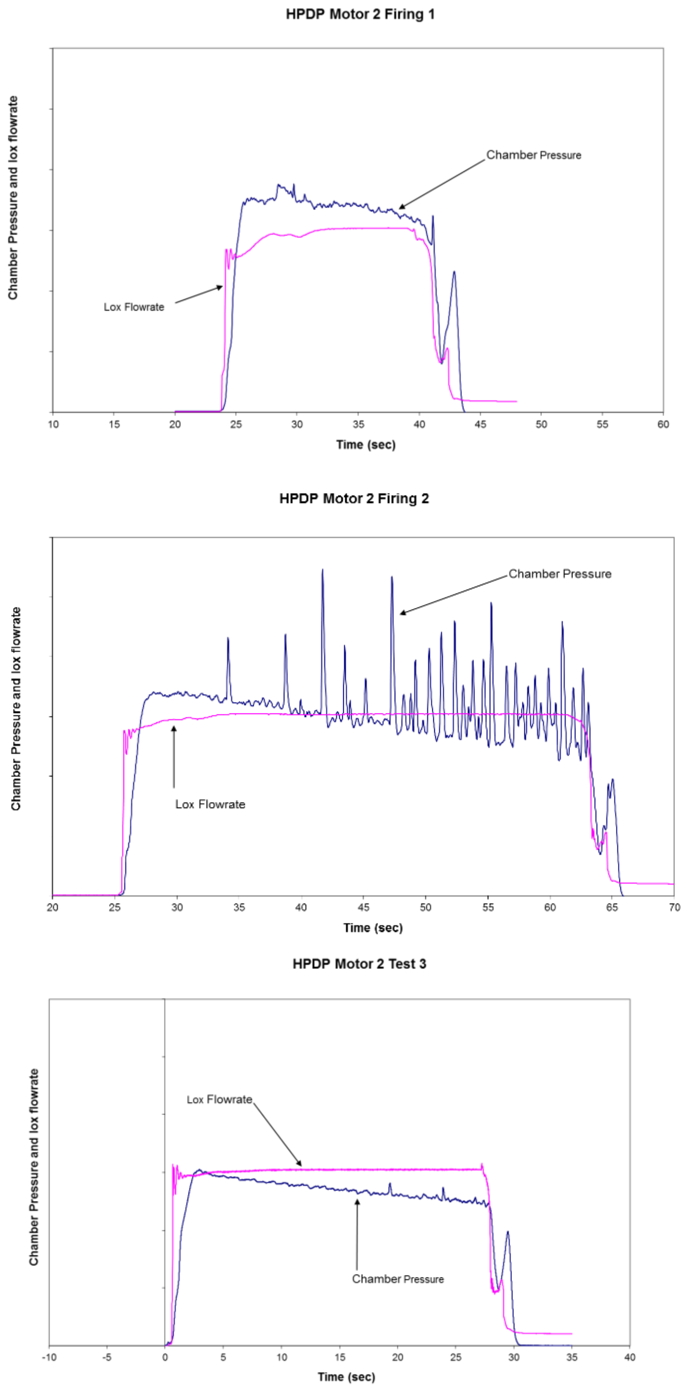
Functional Unit	Liquid	Solid	Hybrid
“Structure”	11%	15%	16%
“Equipment”	13%	23%	19%
“Tank”	19%	N/A	14%
“Motor Case”	N/A	16%	7%
“Nozzle”	N/A	28%	22%
“Engine/Lox Feed Unit”	57%	N/A	20%
Inert Mass	N/A	18%	2%
Total Booster cost (derived)	193.7	142.7	210.5
Total Booster, relative	135%	=100%	149%

- Based on the scale up from the point design, Grosse’s analysis indicated that hybrid rockets were more expensive than liquids or solids.
- This is against the paradigm of hybrids being cheaper and hence the motivation for this paper.

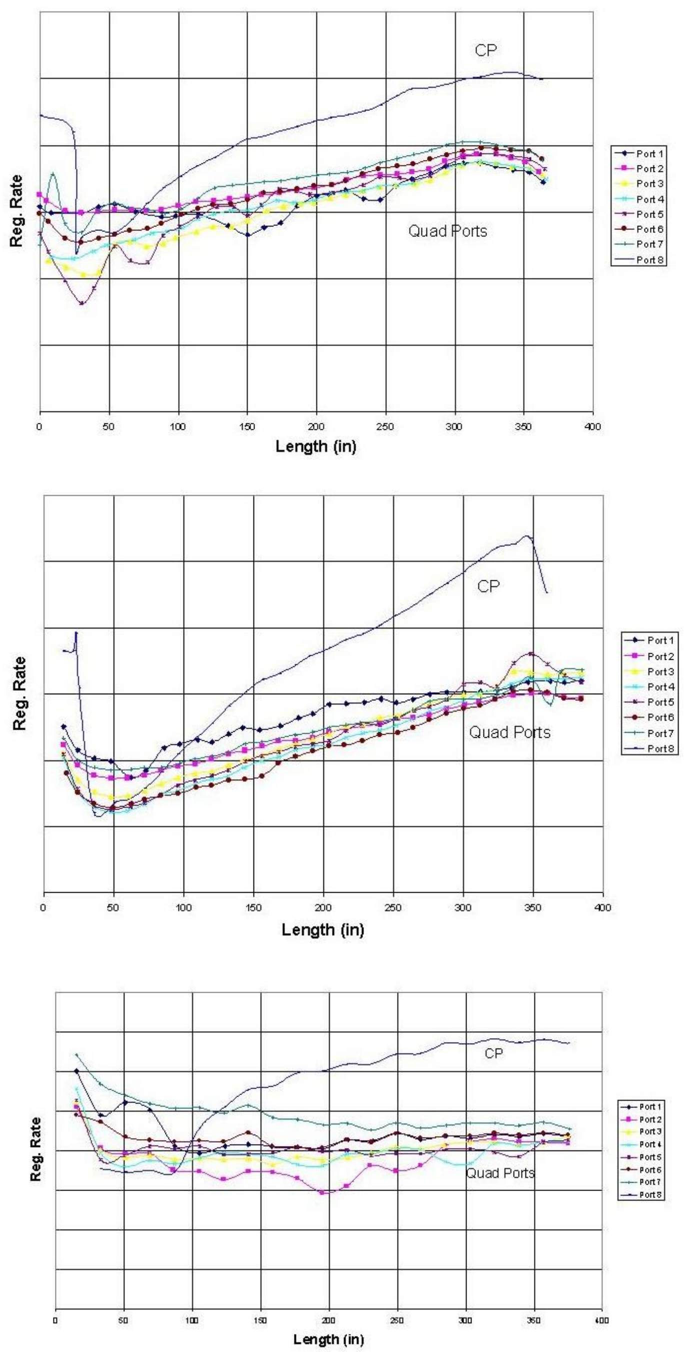
Hybrid Propulsion Demonstration Program 250K-lb$_f$ Hybrid Motor



- Heat addition needed for stability
- Aft end regresses faster than the fwd end
- Scale up from smaller ports to large ports have lower fuel regression

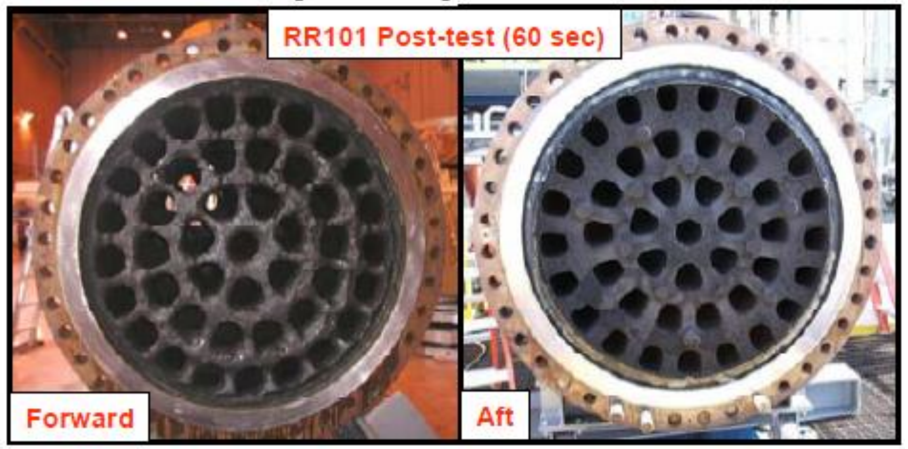


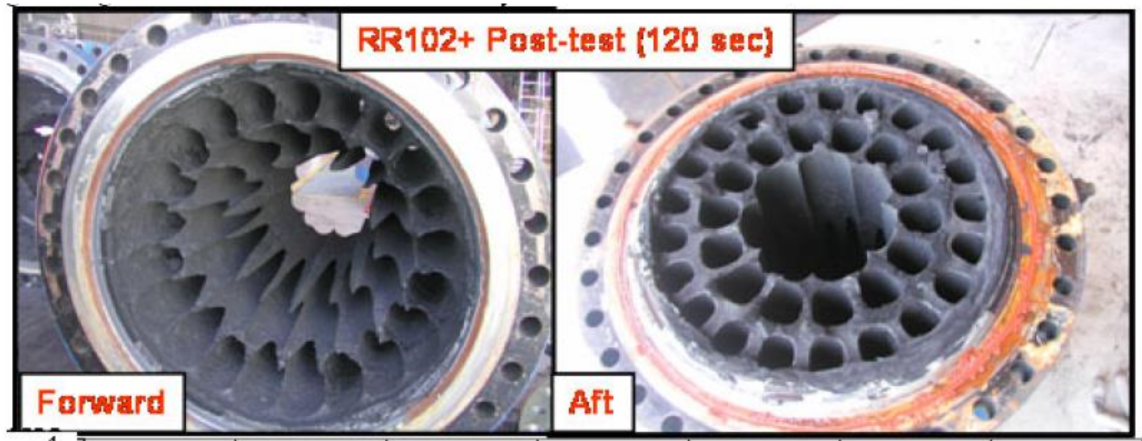
PC and Lox flowrate

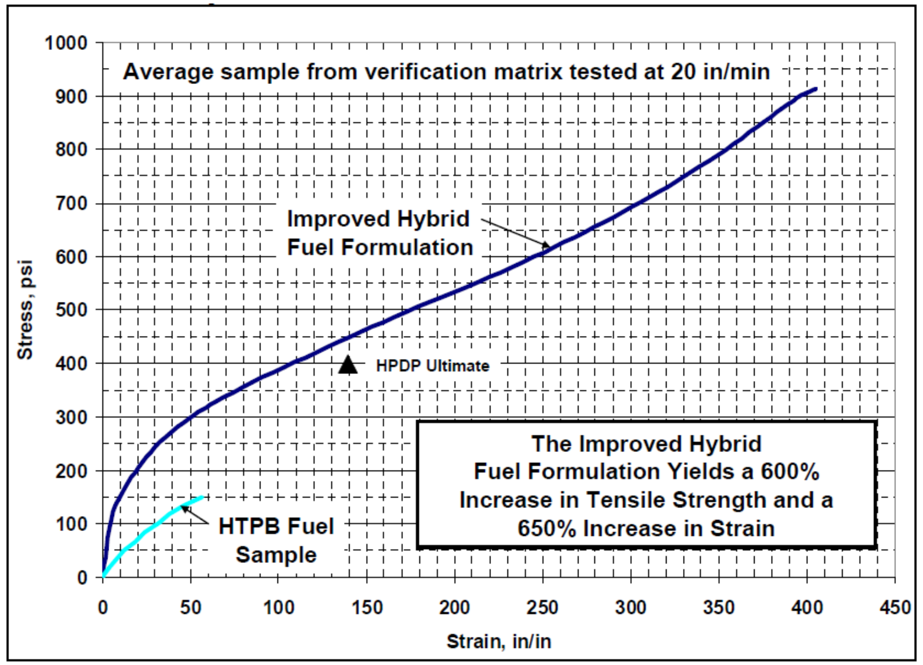


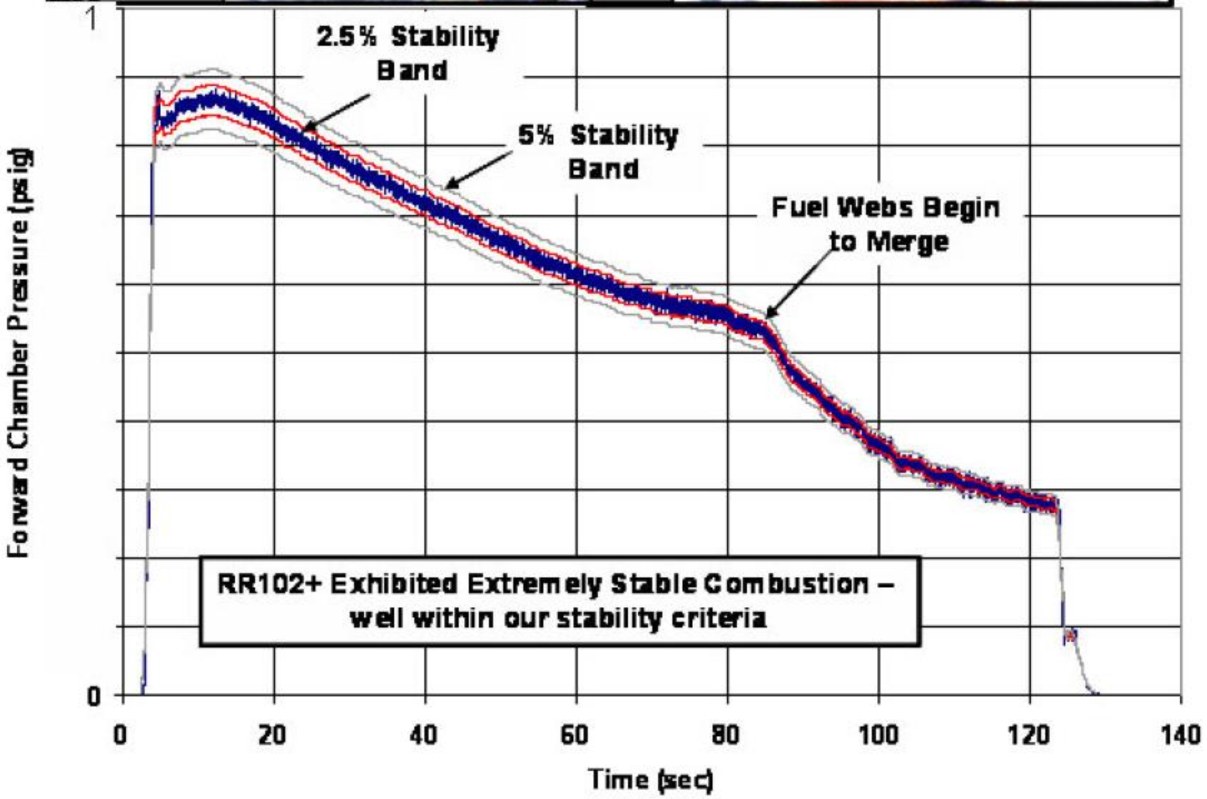
Regression Rate vs length

Lockheed Martin/Darpa Falcon Testing









- Multiport, Multi row
- Fuel Strength
- Web burnout, inside out

Genetic Algorithm

- “Very briefly, a genetic algorithm is a search/optimization technique based on natural selection. Successive generations evolve more fit individuals based on Darwinian survival of the fittest. The genetic algorithm is a computer simulation of such evolution where the user provides the environment (function) in which the population must evolve.”*

- Summary of Code - The genetic algorithm initially makes 50 sets of random zeros and ones. These sets represent the genes in the genetic algorithm. The genes are then interpreted as inputs by the hybrid code, where a few of the characteristics are, for instance, an initial chamber pressure, so these are the characteristics of the hybrid booster being evaluated. The ‘better’ output function characteristics are kept, the lesser ones are discarded. The kept function characteristics are used to generate new pairs of random zeros and ones for the next generation. This is a survival of the fittest concept.

- The code takes the input and sizes a hybrid motor. The code includes a hybrid ballistics model that runs every iteration and based on the burn out characteristics, updates the web thicknesses so the web thicknesses are equivalent and adjusts the length of the grain so the average O/F is close to the best for that oxidizer fuel combination

*http://www.cuaerospace.com/carroll/ga.html, FORTRAN Genetic Algorithm (GA) Driver, David L. Carroll

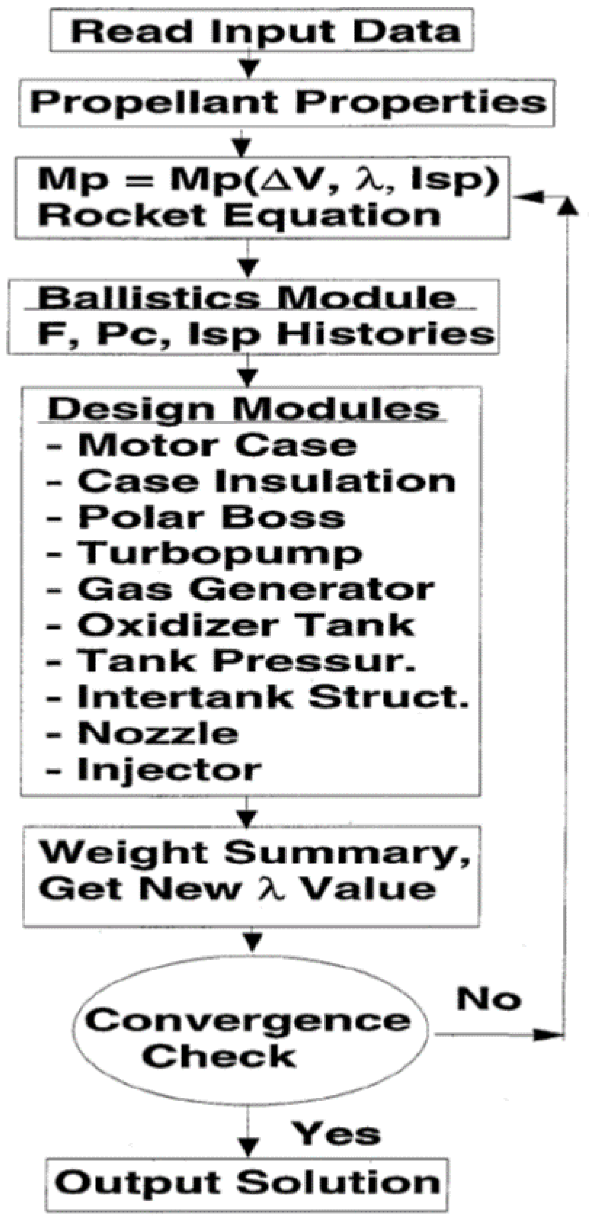
Model Inputs – “genes”

- Fuel type –LOX Polybutadiene combination or a LOX Polybutadiene with Aluminum.
- Number of ports –4 to 9 ports in the multirow configuration.
- Number of rows –originally limited from 1 to 3 rows. It was later expanded to 7 rows.
- Chamber Pressure –300 to 1300 psia.
- Initial Flux –0.4 to 1.0 are allowed.
- Number of heater motors – Based on the concept of canned heater motors from 8 to 22.
- Lox tank pressure - 15 to 165 psi.
- Lox ullage gas temperature
- Burn time –The burn time was varied from 60 to 130 seconds, in 10 second steps.
- Nozzle expansion –fixed to 9 psia.

Details of the booster design

- The program takes the model inputs and generates a hybrid booster design to meet the delta V requirement. The parts are:
  - Hybrid motor grain
  - Forward and aft domes
  - Lox injector nozzle.
  - TVC weight
  - Motor case
  - Pipe/valve/venturi system.
  - Turbopump
  - Hybrid gas generator drives the turbo pump
  - Heat exchanger to flash lox to gox for ullage pressurant
  - Vent valve/line for lox tank filling is sized for the top of the lox tank.
  - Lox tank
  - Heater motors
  - The intertank and aft skirts are based on a representative length to cover the distance and support the weight.
  - Equipment weights

- All weights, except propellants, have a 20% margin added per of AIAA S-120-2006 Standard Mass Properties Control for Space Systems

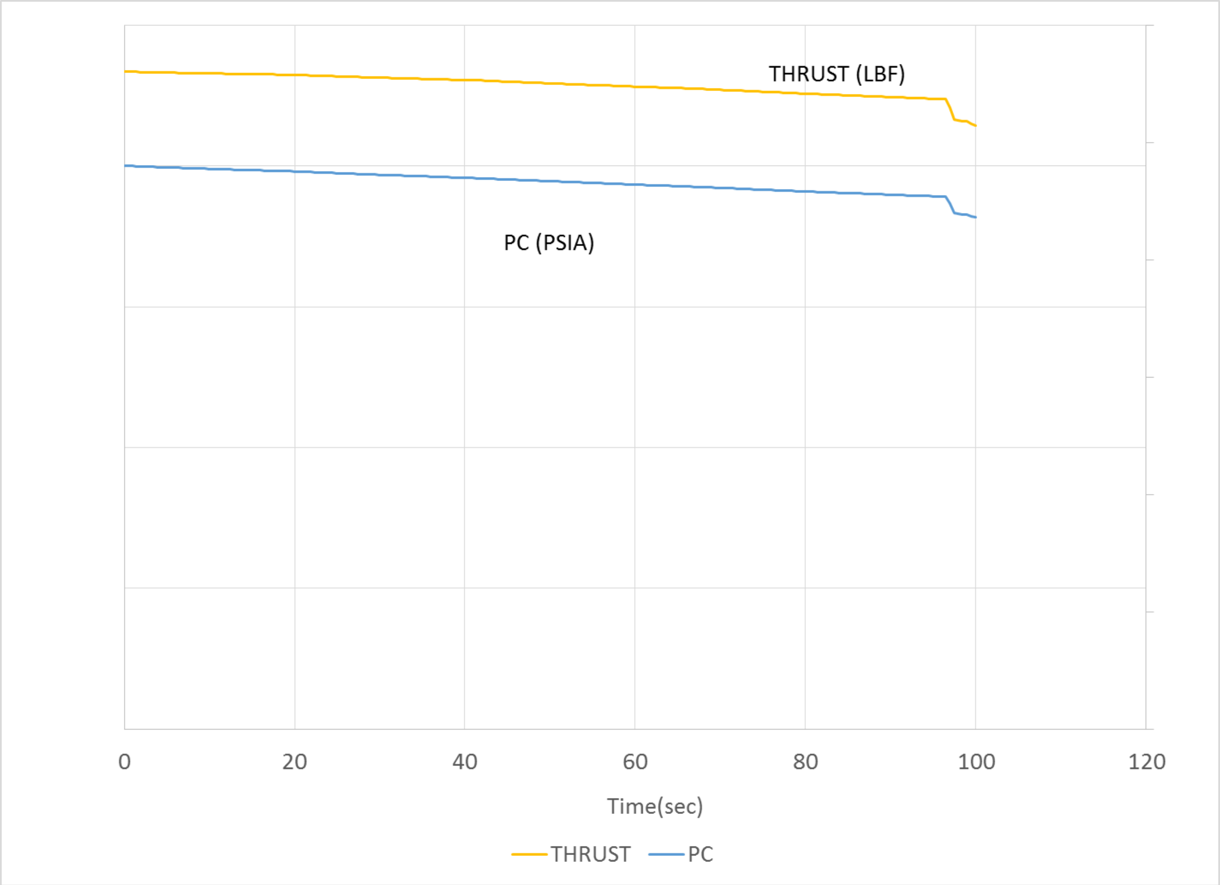


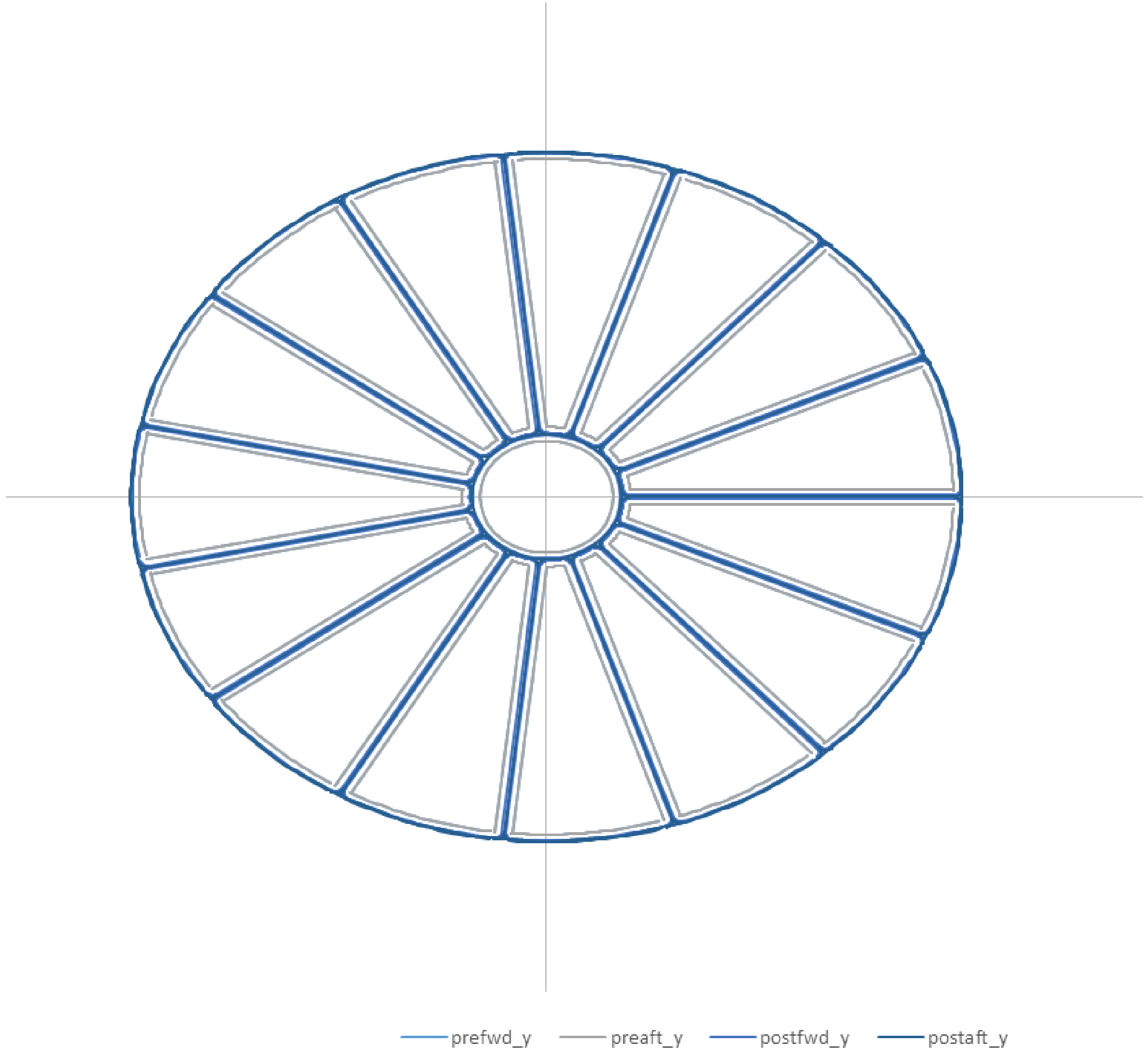
Ariane Solid vs Minimum Cost Booster LOX Polybutadiene with Nsegchk=9

	Solid (P240 Ariane)*	Grosse Hybrid Solution [27]	Hybrid (1 row) Nsegchk=9	Hybrid (1 row) Nsegchk=9 forced to 15 ports AMROC
Ports/Rows			9 P / 1 R	15 P / 1 R
Booster diameter(ft)	10.00		10.6	17.5
Booster length(ft)	103.6		224.7	173.2
Booster gross mass lb	618000	648,256	883248	1,053,740
Booster dry wt (no lox) lb	n/a		368206	461,924
Thrust Lbf (average)	1,140,000		1,849,407	2,287,349
Ave Vac ISP(sec)	275.4	278	283	295
Cost (cost units)	142,700[27]	210,500	117,426	159,205
Residual fuel %			8.5	18.5

*Isakowitz, S.J., Hopkins, J.B., Hopkins, J.P., International Reference Guide to Space Launch Systems, Fourth Edition, AIAA

AMROC 250K scaled to Booster size performance





- Scaled up to a large motor.
- Long fuel webs.

Lox Polybutadiene boosters minimizing on cost

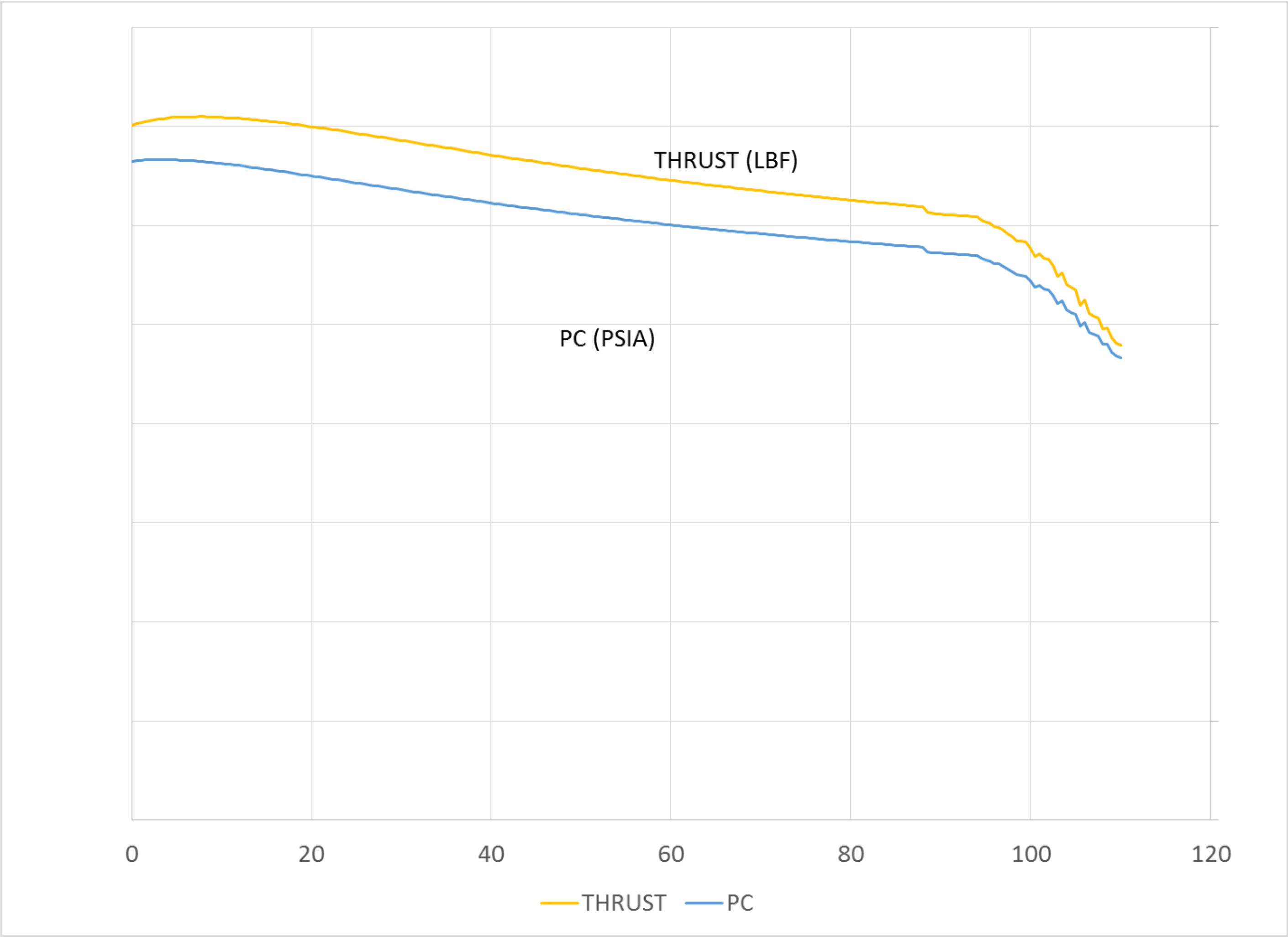
	Solid (P240) Ariane	Grosse Hybrid Solution	Hybrid nsegchk=9	Hybrid nsegchk=5	Hybrid nsegchk=3
Ports/Rows			5 P / 7 R	5 P / 7 R	5 P / 7 R
Booster diameter(ft)	10.00		15	14.2	13.9
Booster length(ft)	103.6		98.6	97.2	98.3
Booster gross mass lb	618,000	648,256	696,731	633,483	625,860
Booster dry wt (no lox) lb	n/a		254,020	227,886	223,873
Thrust Lbf (average)	1,140,000		1,331,564	1,253,613	1,228,307
Ave Vac ISP(sec)	275.4	278	283.5	286.7	283.0
Cost (cost units)	142,700[27]	210,500	98,653	92,820	91,127
Residual fuel %			20.0	14.4	12.6

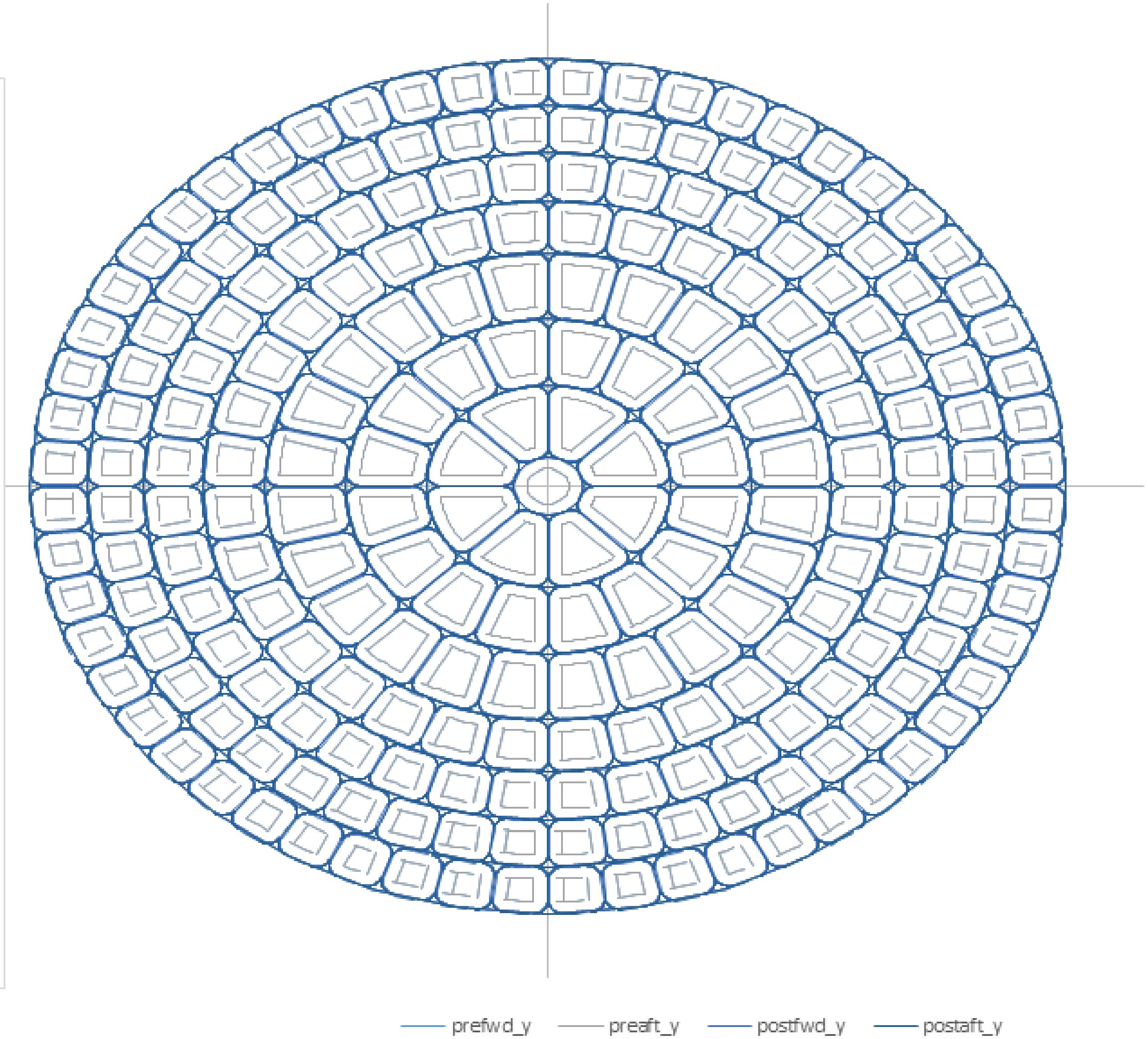
Lox Polybutadiene Minimizing Cost and Booster Length

	Solid (P240 Ariane)	Grosse Hybrid Solution [27]	Hybrid Nsegchk=9	Hybrid Nsegchk=5	Hybrid Nsegchk=3
Ports/Rows	n/a		6 P / 7 R	6 P / 7 R	8 P / 7 R
Booster diameter(ft)	10.00		15.8	14.3	14.6
Booster length(ft)	103.6		97.4	97.3	93.5
Booster gross mass lb	618000	648,256	486,356	658,516	448,667
Booster dry wt (no lox) lb	n/a		260,464	238,607	243,548
Thrust Lbf (average)	1,140,000		1,351,437	1,275,612	1,294,508
Ave Vac ISP(sec)	275.4	278	283.3	281.6	280.9
Cost (cost units)	142,700[27]	210,500	99,553	94,049	93,541
Residual fuel %			19.1	13.8	12.2

Turns out, optimizing on cost and length didn't change the outcome very much, since the length was already short.

Polybutadiene LOX nsegchk=3 min cost and booster length performance





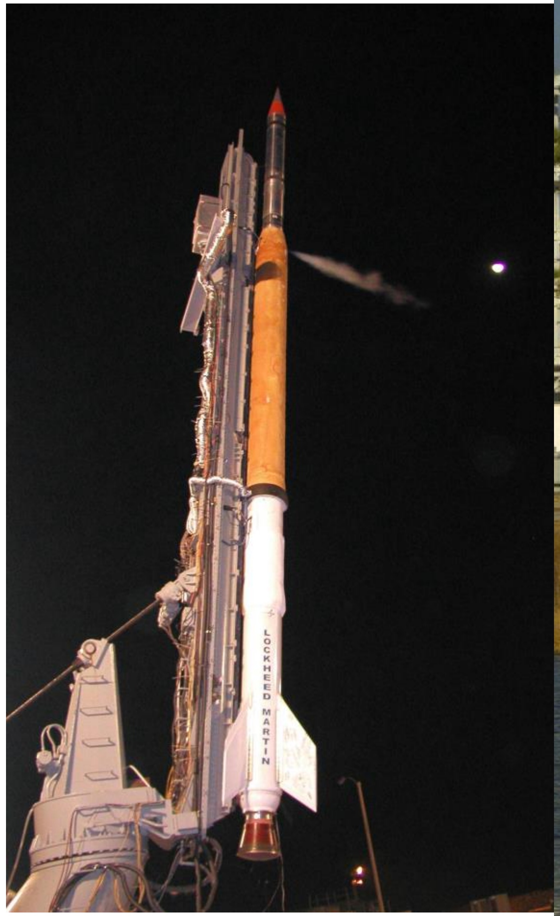
Lox/Polybutadiene/AL Hybrid Booster

- Aluminum loading % wasn't based on any detailed selection process, but just selected to be 25% of the fuel.
- Aluminum increases the density, but also increases the weight of the fuel slivers.
- Modeling slivers after section web burns thru is weak, slivers remain unburning.

	Solid (P240 Ariane)	Grosse Hybrid Solution[27]	Hybrid Nsegchk=9	Hybrid nsegchk=5	Hybrid nsegchk=3
Ports / Rows			5 P / 7 R	4 P / 7 R	8 P / 7 R
Booster diameter(ft)	10.00		17.9	16.2	17.5
Booster length(ft)	103.6		93.1	89.1	86.4
Booster Gross mass lb	618,000	648,256	946,187	808,213	838,604
Booster dry wt (no lox) lb	n/a		420,424	355,133	385,524
Thrust Lbf (average)	1,140,000		1,597,305	1,313,530	1,247,528
Ave Vac ISP(sec)	275.4	278	290.7	286.2	286.9
Cost (cost units)	142,700[27]	210,500	118,321	101,407	100,791
Residual fuel %			25.9	24.5	22.0

SUMMARY AND CONCLUSIONS

- 1) This analysis has shown that, given the assumptions in the analysis, the cost of a hybrid rocket booster for this application is equal to or lower than the cost of a solid or liquid rocket booster. This is different than the results of the Grosse analysis. An explanation for the difference in conclusions is Grosse used the extrapolation of point design to a much larger size.
- 2) A LOX/Polybutadiene hybrid rocket booster is still larger than a solid rocket booster for the same application. Future designs should include requirements based physical limits of the vehicle assembly building, launch vehicle configuration, etc.



Questions?