Life Cycle Analysis of Dedicated Nano-Launch Technologies

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Recent technology advancements have enabled the development of small cheap satellites that can perform useful functions in the space environment. Currently, the only low cost option for getting these payloads into orbit is through ride share programs - small satellites awaiting the launch of a larger satellite, and then riding along on the same launcher. As a result, these small satellite customers await primary payload launches and a backlog exists. An alternative option would be dedicated nano-launch systems built and operated to provide more flexible launch services, higher availability, and affordable prices. The potential customer base that would drive requirements or support a business case includes commercial, academia, civil government and defense. Further, NASA technology investments could enable these alternative game changing options.

With this context, in 2013 the Game Changing Development (GCD) program funded a NASA team to investigate the feasibility of dedicated nano-satellite launch systems with a recurring cost of less than $2 million per launch for a 5 kg payload to low Earth orbit. The team products would include potential concepts, technologies and factors for enabling the ambitious cost goal, exploring the nature of the goal itself, and informing the GCD program technology investment decision making process.

This paper provides an overview of the life cycle analysis effort that was conducted in 2013 by an inter-center NASA team. This effort included the development of reference nano-launch system concepts, developing analysis processes and models, establishing a basis for cost estimates (development, manufacturing and launch) suitable to the scale of the systems, and especially, understanding the relationship of potential game changing technologies to life cycle costs, as well as other factors, such as flights per year.

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1. Introduction

In February 2014, shortly after Phase I of the study documented here had concluded, the process began for deploying 28 cubesats from the International Space Station[6]. These satellites from Planet-Labs, a customer of the International Space Station (ISS) NanoRacks CubeSats program, are part of an emerging trend in space systems – small, but capable satellites filling a variety of needs. Private sector commercial business's, academic and scientific needs, as well as government interests, NASA or defense, are discovering the potential of these "nanosats", satellites of less than 10kg mass.

Figure 1: ***The Japanese Kibo robotic arm on the International Space Station deploying Planet-Labs CubeSats***

In the summer of 2013, an inter-center, inter-agency assessment was sponsored by the NASA Space Technology Mission Directorate Game Changing program. The objectives were:

- Identify primary cost drivers for small launch vehicles (nano-small payload class, 5-100 kg)
- Identify technology and concept opportunities to significantly reduce launch cost
- Determine feasibility of achieving goal of < $2 M per launch recurring cost for a dedicated launch capability

The dollar goal was preliminary, a rough target, understanding that the assessment process would have many uncertainties, with the study emphasizing the direction for future technology investments by NASA that could benefit emerging nanolaunchers. These investments could assist the development of capabilities that would benefit NASA needs as well. Other options already exist for getting small satellites to low Earth orbit (LEO), mainly ride share programs, meaning nanosats being carried along as secondary payloads when launching primary payloads. And while current rideshare launch prices are attractive to nanosat customers, the long contract-to-launch times (nominally 18 months) and inherent constraints on orbital destinations are not. This proposed alternative approach is dedicated nano-satellite launch vehicles operated at an affordable price.

2. Related Efforts

One of the first steps in the nanolauncher technology assessment was a review of other related efforts. Many government, private sector and partnered initiatives are underway in this field of nanosats and nanolaunchers. The study was scoped to avoid any single point design, focusing on technology, affordability, and understanding the possibilities and drivers affecting target launch costs; this would distinguish this study from other related efforts.

[6] Largest Flock of Earth-Imaging Satellites Launch into Orbit from Space Station, http://www.nasa.gov/mission_pages/station/research/news/flock_1/ (last visited May 19, 2014).

Related **government** funded nanolauncher efforts (in order of decreasing payload size) include:

- The Super-Strypi program[7] sponsored by the Defense department Operationally Responsive Space (ORS) office seeks to develop a launch system to exploit the 21st century range, including reduced infrastructure, using technology such as Automated Flight Safety Systems (AFSS), Global Positioning System (GPS) metric tracking, space-based telemetry relay, and automated flight planning. Performance goals are for a **300 kilogram** payload to a 475 km orbit at 45 degree inclination. The affordability goal is a $12-15M "fly-away" price as a commercial launch service.

- The Airborne-Launch Assist Space Access (ALASA) program sponsored by the Defense Advanced Research Projects Agency (DARPA): "ALASA seeks to launch satellites on the order of 100 pounds (**45 kilogram**) for less than $1M total, including range support costs, to orbits that are selected specifically for each 100 pound payload[8]." This nanolauncher point design in the trade space of options places special emphasis on moving the launcher away from traditional ground infrastructure, including launch site (especially "range") requirements that have evolved around larger launchers with significantly higher revenue. It would be impossible for a nanolauncher to achieve a price of $1M a launch if payments to the launch site range alone were that amount. Additionally, meeting certain range requirements can create significant costs internal to a launcher organization, regardless of any payment (or reimbursable) to a range. In March 2014, Boeing was selected out of a three-way competition to demonstrate its concept[9].

- The Soldier-Warfighter Operationally Responsive Deployer for Space (SWORDS) program sponsored by the U.S. Army Space and Missile Defense Command (USASMDC): SWORDS is "…an initiative to develop a low cost, responsive and robust space launch system for the U.S. Army to quickly launch and deploy nanosatellites[10]." Eventually the concept would "…launch **25 kilogram** payload to 750-kilometer orbit with 28.5 degrees inclination" for $1M a launch. This nanolauncher point design in the trade space of options lays special emphasis on the factor of manufacturing, parts costs, and systems complexity. "Ultra-low cost is achieved by careful selection and judicious application of commercial-grade materials and components, as opposed to traditional aerospace-grade components." As of this writing, 2014 work is focused on certain ground systems and vehicle engine development.

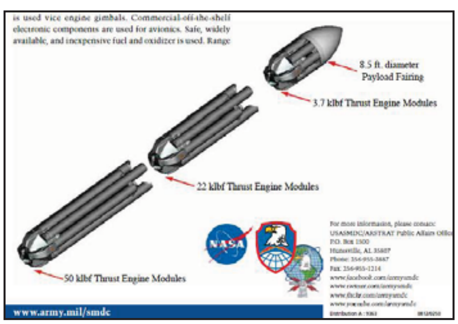

Figure 2: ***A sampling of government funded nanolauncher initiatives – SWORDS (left), ORS/Super-Strypi (right). (Not to relative scales)***

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[7] ORS and Super-Strypi, http://cires.colorado.edu/events/lidarworkshop/LWG/Oct12/presentations/003-ORS Briefing to Lidar Winds Workshop--101612.pptx (last visited May 19, 2014).

[8] ALASA, http://www.darpa.mil/Our_Work/TTO/Programs/Airborne_Launch_Assist_Space_Access_%28ALASA%29.aspx (last visited May 19, 2014).

[9] Boeing Targets 66 Percent Launch Cost Reduction with ALASA, http://www.spacenews.com/article/military-space/40023boeing-targets-66-percent-launch-cost-reduction-with-alasa (last visited May 19, 2014).

[10] SWORDS, http://www.smdc.army.mil/FactSheets/SWORDS.pdf (last visited May 19, 2014).

- NASA is also encouraging the nanolauncher market (supply) by awarding a commercial launch services contract (demand) to Generation Orbit. Generation Orbit Launch Services, Inc. (GO) was selected to launch a group of **three 3U CubeSats** to a 425 km orbit as an initial capability demonstration, potentially leading to additional launch contracts. The launch will "provide a CubeSat-class launch via the NASA Launch Services Enabling eXploration and Technology (NEXT) contract. NEXT is an element of a strategic initiative led by NASA's Launch Services Program (LSP), focused on assuring long-term launch services while also promoting the continued evolution of the U.S. commercial space launch market.[11]"

- The "Nano Launch 1200" program sponsored by NASA Marshall Space Flight Center: The "1200" refers to dollars in thousands. This project is focused on reducing "the cost of launching a small payload or nanosat (**1-10kg**) to space". Partnerships are critical in the approach, including the Air Force Research Laboratory on technology, NASA multi--center groups on avionics, Kennedy Space Center on ground operations and launch, and Goddard Space Flight Center on launch.

There are numerous nanolauncher initiatives in the **private sector** as well (with varying degrees of government support, as a potential customer, or with some form of partnering). Entrants here and some features of their concepts include (in alphabetical order):

US

- Garvey Aerospace -propane/LOX, ground/rail launch
- Interorbital -white fuming nitric acid (WFNA) / turpentine/furfuryl alcohol, ocean/ground (island/non-Range) launch
- Raytheon -solid, 4-stage, air launch, F-15
- Scorpius (spinoff of Microcosm Inc.) -RP/LOX, pressure fed, ground launch
- Space Propulsion Group (SPG) -paraffin/LOX
    - Partnered w. Generation Orbit, air-launch, LearJet
    - Partnered w. Premier Space Systems, air-launch, MIG-21
- Whittinghill Aerospace -rubber/NOX, ground launch

Suppliers

- Orbitec –small liquid engines, provider to Garvey
- Scorpius-composite tank technology
- Ventions –potential avionics and small liquid engine provider

Non-US

- NorthStar Concept/Andoya Range, Norway, hybrid, to polar, in development

Notably, in March 2014 the Interorbital Systems Common Propulsion Module Test Vehicle (CPM TV) launched on its maiden flight, demonstrating its 7,500-lb thrust engine, propelling the 1200-lb rocket to Mach 1+. "The 30-foot long CPM TV rocket is a boiler-plate test version of the identical rocket units that will make up Interorbital's modular orbital launch systems.[12]"

This large and diverse number of private sector initiatives will continue to inform NASA technology investments. The study undertaken in the summer of 2013, however, would address a broad trade space, to understand what truly drives costs and flight rate capability for nanolaunchers, and what technology and approaches, including technology investments and partnerships, could enable the sectors healthy and sustainable growth.

[11] NASA press release, http://www.nasa.gov/centers/kennedy/news/releases/2013/release-20130930.html (last visited May 19, 2014).
[12] Interorbital press release, http://www.interorbital.com/interorbital_03302014_018.htm (last visited May 19, 2014).

3. Nanosat Markets

Having defined broad objectives and reviewed related efforts, a necessary step toward understanding potential nanolaunchers begins with understanding their customers, the market of nanosats of all kinds. Two important factors here appear to be price of entry and flexibility. In launch market parlance, a common metric of cost is "cost per kilogram". While useful in the right contexts, transportation services to space cannot (yet) be procured by the pound. As an analogy, the entire bolt of cloth must be purchased, not just a yard. Nonetheless, team members were aware that smaller launcher size (measured by payload capability) would usually mean higher costs per kilogram.

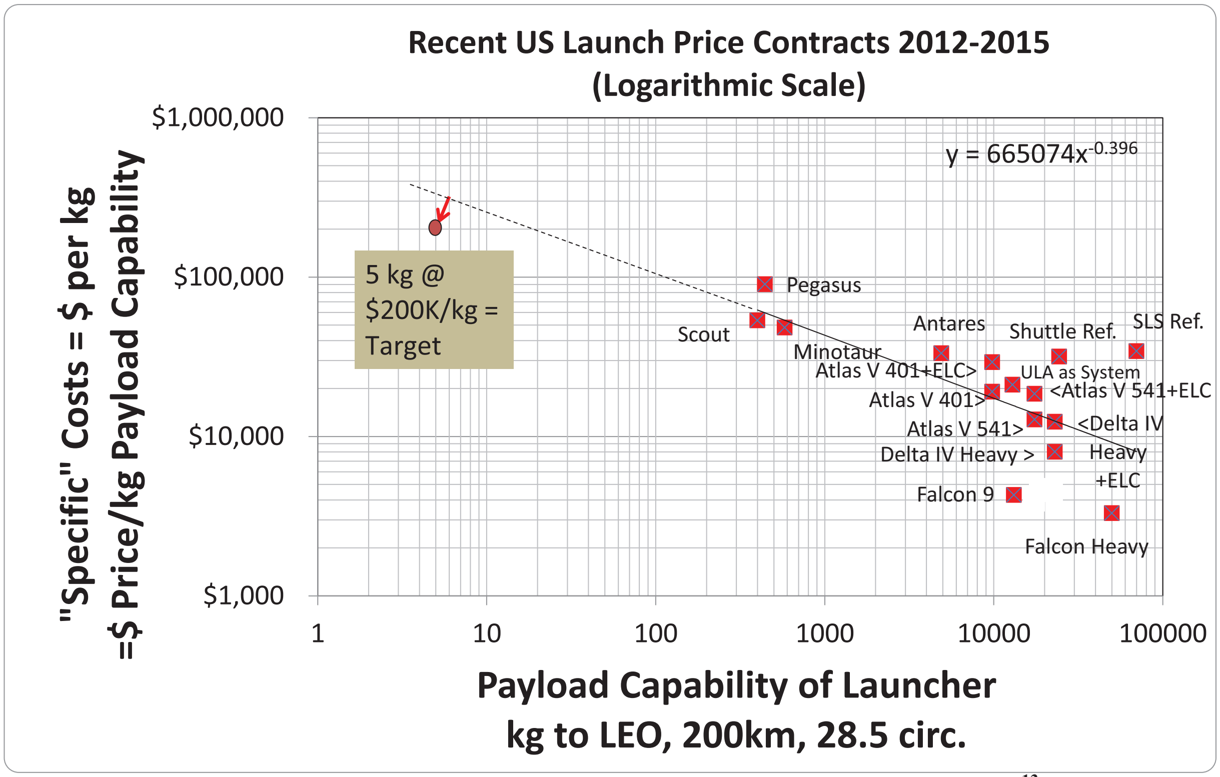

Figure 3: ***A sampling of recent launch prices, from recent contracts of US launchers*[13]*.***

Visualizations of costs vs. scale to observe trends, as in **Figure 3,** are common. When plotting data this way, the nanolauncher cost objective could be taken as asking "does a point exist around 5 kilograms that does not exceed $200,000/kg"? **Figure 3** would seem to indicate that extrapolating beyond Pegasus or Scout rockets would take a 5kg payload into the general area of the cost objective – but improvements moving off the trend-line are required to meet the target costs. There is insufficient data in the very small payload scale range to draw a definite conclusion, or extrapolation, other than to see both potential and challenge.

Similarly, points on **Figure 3** that are well below the trend-line of the rest of the group could be taken as an indication of needed context. More fully "commercial" systems (serving more non-government customers) could end up far lower on a cost per kg intercept at very small payload scales. This big picture view shows both the scope of the challenge and the promise in considering the potential of technology and context for affordable, dedicated nanolaunchers.

[13] The raw data for this figure (Excel format) is available upon request. Contact the author at edgar.zapata-1@nasa.gov.

This leads to specific customers in the market for a launcher (of any kind) for their smallsats. Currently, universities dominate the nanosat/cube-sat field. NASA is a principal player and market maker here, with its Cube-Sat Launch Initiative (CSLI[14]). To date, most CSLI awards have been to universities. The private sector small-sat/cube-sat field is also growing fast and even predicted to soon dominate the market[15]. This is as small-sats continue to offer an increasingly accessible, participatory technology.

Notably, it's impossible to determine the future shape or bounds of a small/nanosat market seeing such innovation and entrepreneurial initiative, while attracting capital reaching into the tens of millions[16,17]. Business cases are innovative as well, for example, where imagery may be a focus, but not the fundamental business case (the case may be analytics[18]).

A key takeaway from the review of the nanosat market information, affecting this study, is the reasonableness of considering flight rates that could assist in achieving price objectives, while also clarifying the question – what's in the cost objective? The objective of $1M-$2M a launch would be a marginal cost then, related to flight rate as follows:

- Cost objective: Amortizing fixed yearly costs (make or launch) over all units for the year plus the variable costs for each unit (make or launch). This will also be referred to as the recurring launch cost.
    - Fixed yearly costs are not considered to be incurred all at once at the start of the year, but may be amortized over the rate of manufacture and launch.
    - Variable costs are those costs incurred directly because of the make or launch of that additional unit.
    - Amortization of upfront costs (e.g., development costs) is not included.

Another market factor informing this study (especially cost objectives) would be the current options for launch available to nanosat customers. A benchmark on prices could be the SpaceX small satellite pricing goals of $200,000-325,000 for a PPOD (a Poly-PicoSatellite Orbital Deployer) and $4-5 million for an ESPA (an ELV (Expendable Launch Vehicle) Secondary Payload Adapter ring (which includes propulsion)[19].

Alternately, companies such as NanoRacks with research platforms permanently installed on the U.S. National Laboratory aboard the International Space Station can charge much less for a launch through orbital delivery service. NanoRacks charges "…by the 1U–a 4 inch by 4 inch by 4 inch educational payload (1U) can be as low as $30,000. A 2U is twice that. A 2U by 1U is three times that. Commercial payloads start at $60,000 per 1U.[20]" Charges are higher for non-US payloads. NanoRacks takes advantage of excess delivery capacity on cargo flights to the station to provide this service. Nonetheless, NanoRacks capability is currently limited by the rate of satellite deployments possible at the station. This gave rise once again to importance of flight rate going in to the study – breaking away from current launch service limitations and constraints – should competitive, dedicated nanolaunchers be realized.

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[14] NASA CubeSat Launch Initiative, http://www.nasa.gov/directorates/heo/home/CubeSats_initiative.html (last visited May 19, 2014).

[15] Dominic DePascuale, John Bradford, "Nano/Microsatellite Market Assessment", February 2013, http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_NanoMicrosat_Market_Feb2013.pdf (last visited May 19, 2014).

[16] Alex Konrad, "Billionaire Yuri Milner Just Poured Millions Into This Whiz Kid Satellite Startup," *Forbes*, December 18, 2013, http://www.forbes.com/sites/alexkonrad/2013/12/18/planet-labs-raises-52-million/ (last visited May 19, 2014).

[17] Peter B de Selding, "Skybox Gets Creative To Raise Capital from Wary Investors", *SpaceNews*, March 26, 2013 http://www.spacenews.com/130326skybox-gets-creative-to-raise-capital-from-wary-investors (last visited May 19, 2014).

[18] Planet Labs advertises it's "analytics platform", appearing to break away from a traditional imagery business case, where a "global sensing and analytics platform unlocks the ability to understand and respond to change at a local and global scale".

[19] Dustin Doud, Brian Bjelde, Chritain Melbostad, Lauren Dryer, "Secondary Launch Services and Payload Hosting Aboard the Falcon and Dragon Product Lines", August 15, 2012, http://digitalcommons.usu.edu/smallsat/2012/all2012/40/ (last visited May 19, 2014).

[20] NanoRacks, http://nanoracks.com/resources/faq/ (last visited May 19, 2014).

For benchmark purposes, cost objectives of private sector dedicated nanolaunchers efforts (Raytheon[21], Generation Orbit[22]) are at the million-dollar end of the range of prices, while other launchers (Interorbital) would be on the far lower end (as little as $12,500 per 1u cubesat; and selling "by the yard" [23]). All of this would inform the study going forward.

4. Requirements

Having reviewed goals, related government and private sector efforts, emerging nanosat markets, and current nanosat launch options, the study defined more specific requirements (**Figure 4**) for the dedicated nanolauncher trade space. In this short study the values that would be emphasized most would relate to payload (performance of the nanolauncher), costs, and flight rates.

A follow-up study in 2014 will delve into more of the detailed requirements, especially how requirements interact with very specific technology investments, costs and flight rates.

PARAMETER	VALUE / RANGE	NOTE
Target Orbit:	45° Inclination 400 km Altitude	Target values within range of interest 0° - 98° Incl., 350 – 650 km Alt.
Launch Latitude	38°	Wallops; close to target inclination Others: KSC, Vandenberg, Airlaunch
Payload mass on orbit	5 kg	Mass of free-flying, deployed spacecraft (range of 5 – 50 kg)
Insertion accuracy	±75 km orbit altitude ±1° Orbit inclination	Accuracies are not critical for many small and very small spacecraft - Need to understand sensitivity
Spacecraft accommodations	• Separation signal • T-0 trickle charge • Environmental control within fairing • Narrowband telemetry on launch	Desire minimal demands on launch vehicle - Need environment specs - Payload status for rapid calibration
Load/Environment Limits (Payload)	20 g axial acceleration 5 g lateral acceleration	Need to determine limits on payload
Launch cost (recurring)	<$2M/launch <$1M/launch (stretch goal)	Goal Assumes annual flight rate of 12
Responsiveness	<48 hours call-up time <24 hours call-up time (stretch goal)	Goal – Relates to military ops Source: ALASA and SWORDS
Launch Reliability	0.9	Can accept lower reliability due to very low satellite cost

Figure 4: ***Top-level requirements established in the nanolauncher study.***

5. Assumptions

A handful of assumptions were necessary for the study before models, tools and processes could explore the implications of the dedicated nanolauncher cost and payload goal. These assumptions were:

- Payload capabilities would be maintained through vehicle resizing
- Launcher would assume a Poly Picosatellite Orbital Deployer (P-POD) for all cubesat accommodations
    - (These have deployed > 90% of all CubeSats to date; 100% of all CubeSats since 2006)

[21] Turner Brinton, "Raytheon Developing $2M Small Sat Launcher To Fly Under Wing of F-15", *SpaceNews*, August 8, 2011, http://www.spacenews.com/article/raytheon-developing-2m-small-sat-launcher-fly-under-wing-f-15 (last visited May 19, 2014).
[22] NASA press release, http://www.nasa.gov/centers/kennedy/news/releases/2013/release-20130930.html (last visited May 19, 2014).
[23] Interorbital, http://www.interorbital.com/interorbital_03302014_003.htm (last visited May 19, 2014).

- Launcher would assume standard payload accommodations as:
  - No services, no customizing
  - Akin to rideshare accommodations
  - No trickle charging, spot purging or driving cleanliness requirements

6. Assessment Process: Data

The assessment process required adapting existing models and tools, or developing these anew, capable of providing confidence for new concepts at the small scale of nanolaunchers. The process would also research and establish some baseline data for comparative purposes. This assortment of information would eventually include:

- The old Scout rocket, performance, costs, lessons, yearly flight rate experience
- Small solid motor data, performance, prices
- Missile data, performance, prices, size of production lots

The Scout rocket proved particularly useful in lending insight. As a relatively small launcher, the scale was not significantly far from the scale some nanolaunchers may head. Abundant data was available on financials, launches and the technical design, including its evolution over time. Adjusting for inflation **Figure 5** shows how this traditional (business as usual), older system had performed over time. Data points shown are for individual years of operation. As expected, one feature of such data is the way fixed cost and variable cost concepts can be better understood when contrasting total yearly resources against the flight rates actually achieved. Together, total yearly fixed and total yearly variable costs would comprise any marginal cost per launch (total fixed + variable $ divided by flight rate). This would affect prices, capital, etc. in a private sector business case.

A key takeaway would be the need for the study to assure fixed costs were properly addressed, and drivers or causes understood, as fixed cost could be a significant contributor to prices.

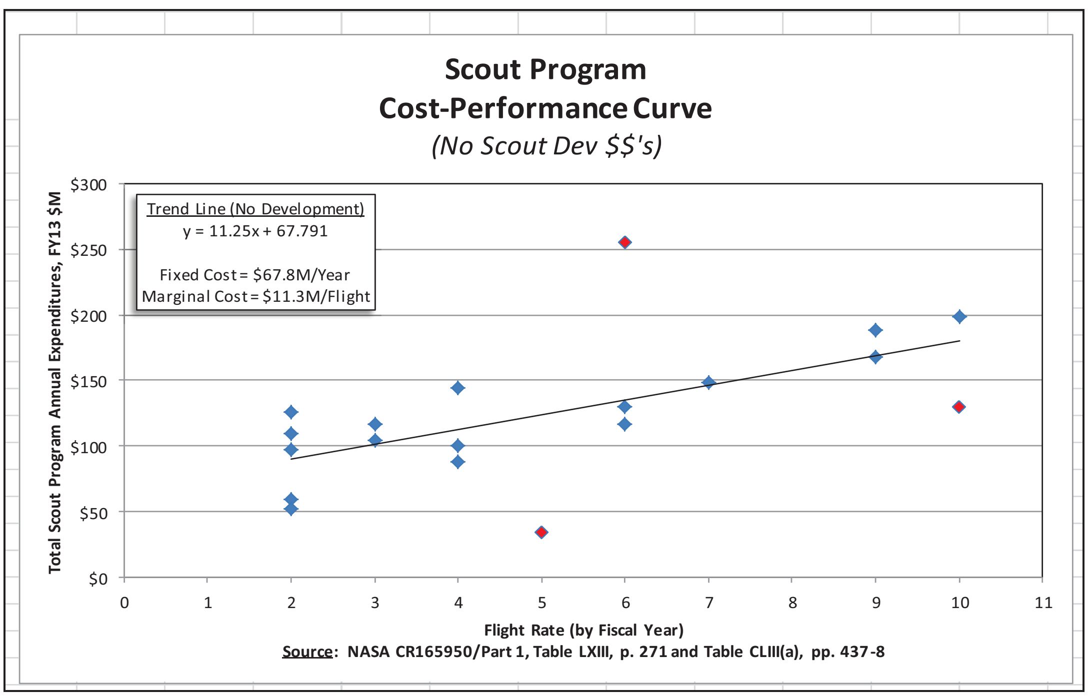


Figure 5: ***Scout rocket cost-performance trend.***

Missiles data also provided somewhat of a sanity check going into the process of analyzing nanolauncher possibilities. As with the Scout data though, a healthy recognition of data shortcomings was required. Data may be old, biased, incomplete, ill-defined as to content, and so on, unless a more rigorous search (and access, such as to contracts) is undertaken. This may represent forward work. Missiles data nonetheless provided useful sanity checks in the nanolauncher assessment process. Asking if a Nano-Launcher can be had for $1M-$2M, to make and launch, is like asking if a solid rocket Surface-to-Air missile (SAM) of the same scale can be had while –

- Avoiding a multi-billion dollar development cost (historical SAM's)
- Costing much less than $3-$4M a unit to manufacture (possibly having to cost significantly less as some SAMs exceed even these amounts).
- Manufacturing in similar lot sizes (100 units)
- Carrying less payload (possibly, vs. SAMs at 60kg)
- Carrying only non-hazardous payloads
- Deleting some requirements (ground based vs. sea-based launchers, storage, etc.)
- Adding other requirements (flight termination systems (FTS) on some stages, etc.)
- Meeting similar precision (but to orbit)
- Breaking up the design/performance; having more stages

For comparison, a missile to scale alongside other launcher and a potential nanolauncher is shown in **Figure 6**. The reader should note that some nanolauncher efforts would fall into the SAM missile scale, while wanting to do so as relatively small businesses, and offering full "fly-away" prices (manufacturing plus operations and launch) well below what missile manufacturers charge only for manufacturing. Again, this informs the scale of the challenge as much as the scale of the systems to be analyzed.

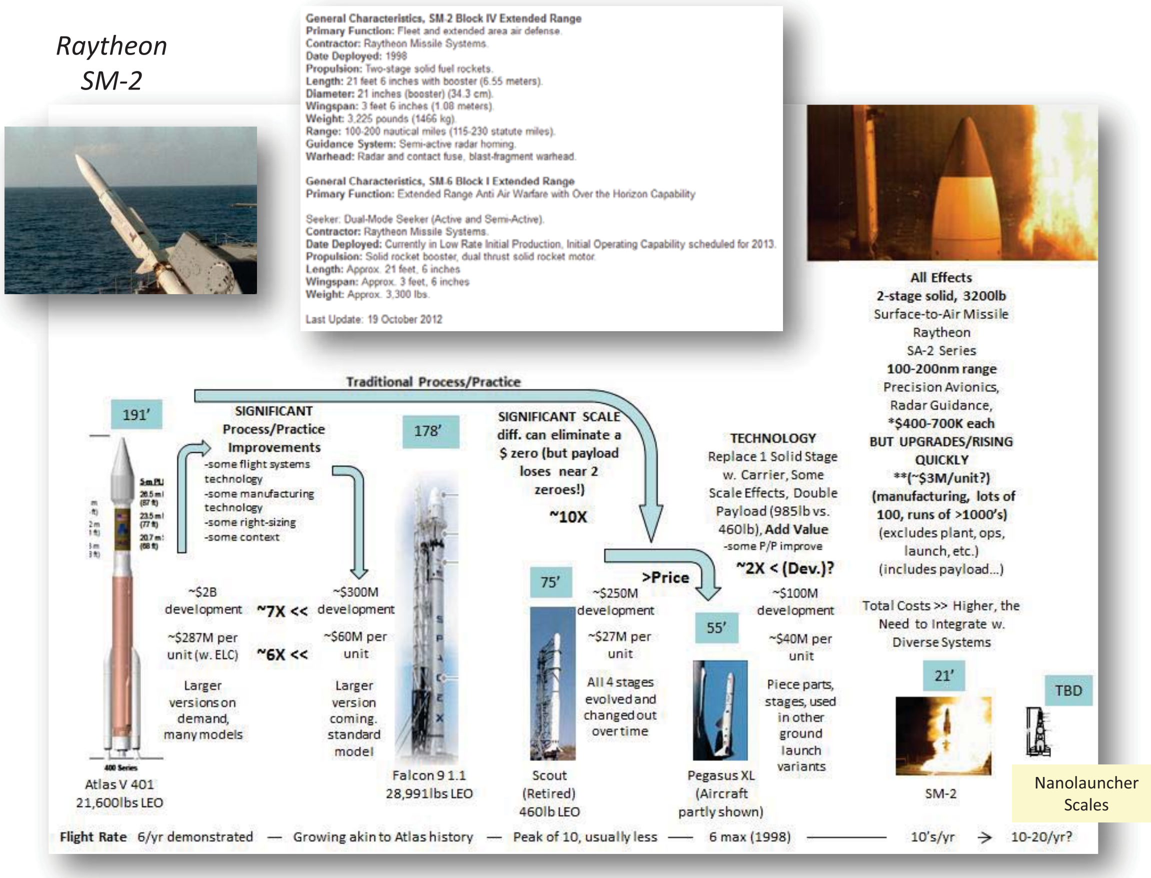


Figure 6: ***A sense of scale for nanolaunchers.***

7. Assessment Process: Models

Performance and cost assessment was accomplished iteratively as well as with some redundancy. Multiple cost models were deployed. This approach would assure that (1) sizing and performance were reasonable, (2) any weakness in any single cost model could be understood when comparing against other models, and (3) any results could be better supported, with more confidence. In its broad strokes, the specific models, process, and results are shown in **Figure 7**. Based on comparisons with historical small launch systems, such as Scout, initial questions that are asked are whether large reductions in recurring launch cost are achievable, while still meeting performance requirements, through a combination of reduced vehicle scale (resulting from payload downsizing) and increased flight rate. The models and tool set are used to answer these questions while also capturing the impacts of alternative technologies.

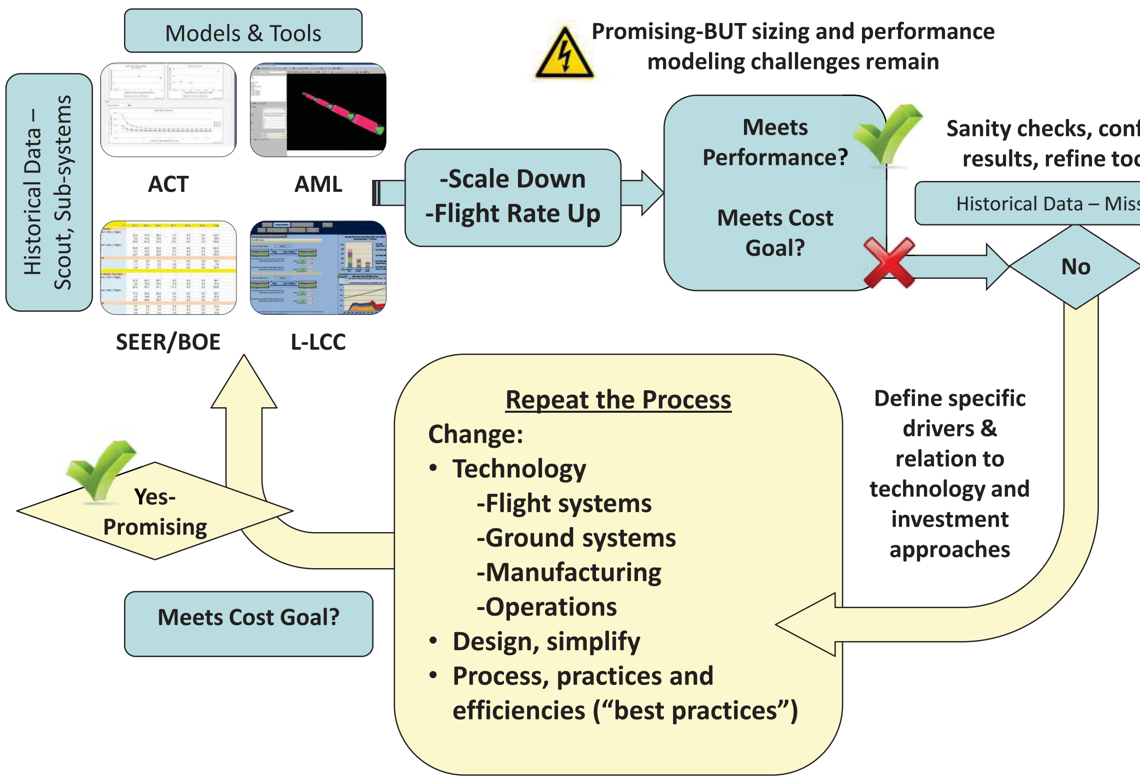


Figure 7: ***ACT, AML, SEER and the L-LCC model would yield some promising results on reference nanolauncher concept performance, but only moving beyond each reference, with the integration of new technology, and other technical and non-technical factors, would it also appear promising that nanolaunchers also reach their low cost, high flight rate goals.***

The models used in the assessment process included (in alphabetical order):

- Affordability Comparison Tool (ACT):

A prototype of the Affordability Comparison Tool (ACT)[24] is able to provide insight into acquisition, operational, and lifecycle affordability for early concept formulation and systems analysis support (**Figure 8**). ACT analyzes different systems or architecture configurations that allows for a comparison of total lifecycle cost, annual affordability, cost per pound, cost per seat, cost per flight (average), and total payload mass throughput. Although ACT is not a deterministic model, it does use characteristics (parametric factors) of the architectures/systems being compared to produce important system outcomes (figures-of-merit) of different system configurations, as well as different business assumptions and system utilization scenarios. The ACT prototype has both spreadsheet and server-based technologies and contains a set of algorithms that processes system configuration and characteristics to a measure of system affordability. Parametric factors are derived from quantifiable data about each system configuration's attributes. An initial algorithm converts quantifiable system configuration and characteristics data into a parametric factor on-the-fly for architecture/system complexity. The next set of ACT algorithms processes the complexity into system affordability figures-of-merit. These algorithms are initialized using known space transportation data to "anchor" embedded values in the algorithms. The algorithms allow the comparison of standard processes embedded with mathematically consistent values. This will not necessarily produce an exact forecast (deterministic cost number), but instead provide consistent figures-of-merit suitable for surfacing more affordable and productive systems and technology alternatives. ACT is scalable in that it can compare architectural design concepts of large scale systems (elements) down to subsystems and their differing technology content. Although the configuration of these systems may be vastly different, ACT can make functional comparisons based on multiple system attributes.

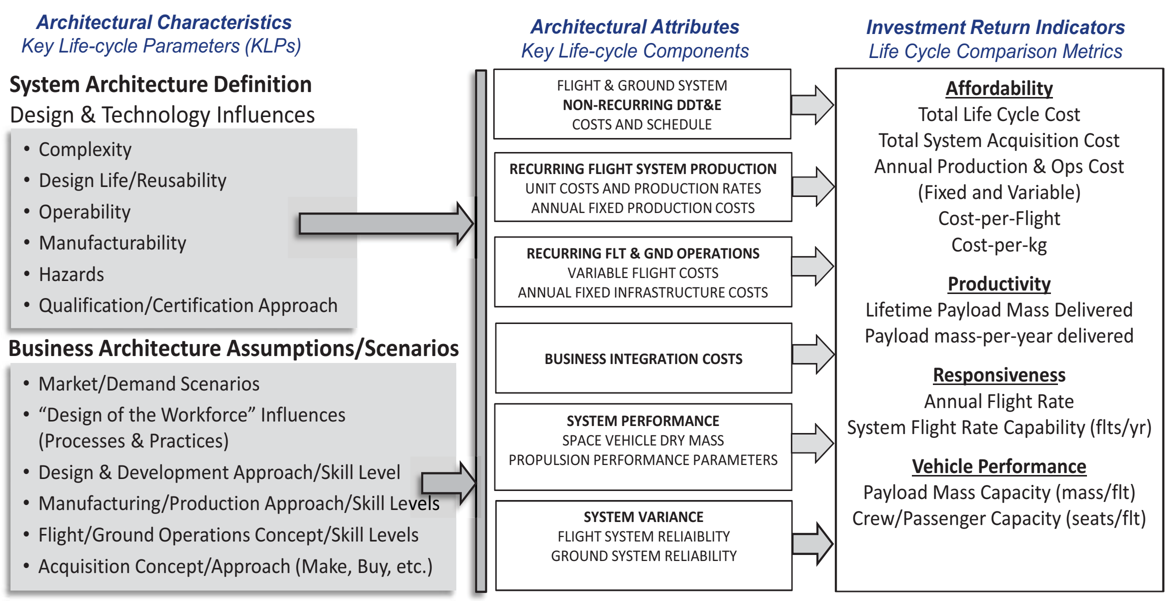


Figure 8: ***Schematic representation of the Affordability Comparison Tool (ACT) prototype.***

[24] Carey McCleskey, Timothy Bollo, Jerry Garcia, "Affordability Comparison Tool (ACT)," *NASA Tech Briefs*, February, 2014.

- IDEA/AML:

IDEA (Integrated Design & Engineering Analysis)[25] is a collaborative environment for parametrically modeling conceptual and preliminary launch vehicle configurations using the Adaptive Modeling Language® (AML™) as the underlying framework. The environment integrates geometry, configuration, propulsion, aerodynamics, aerothermodynamics, trajectory, closure and structural analysis into a generative, parametric, unified computational model where data is shared seamlessly between the different disciplines. IDEA has extensive development heritage and application within NASA Langley Research Center's Vehicle Analysis Branch toward reusable launch vehicle design, and in particular, toward hypersonic air-breathing based systems. Much was leveraged from prior development by AFRL of the IPAT system for the Reusable Military Launch System (RMLS) concept work. For the present application, a new IDEA "class" was derived to enable modeling of expendable multi-stage launch vehicles at this relatively small scale. A number of mass estimating relationships (MERs) were developed that are applicable to this scale. Developing "rubberized" parametric solid motor modeling posed particular challenges. The IDEA environment is particularly well suited for performing system requirements sensitivities and/or technology trades given its parametric nature. IDEA provides the performance related metrics (mass, payload, trajectory, etc.) that are used as input to the life cycle analysis (cost, ops, etc.) predictions that are of ultimate interest.

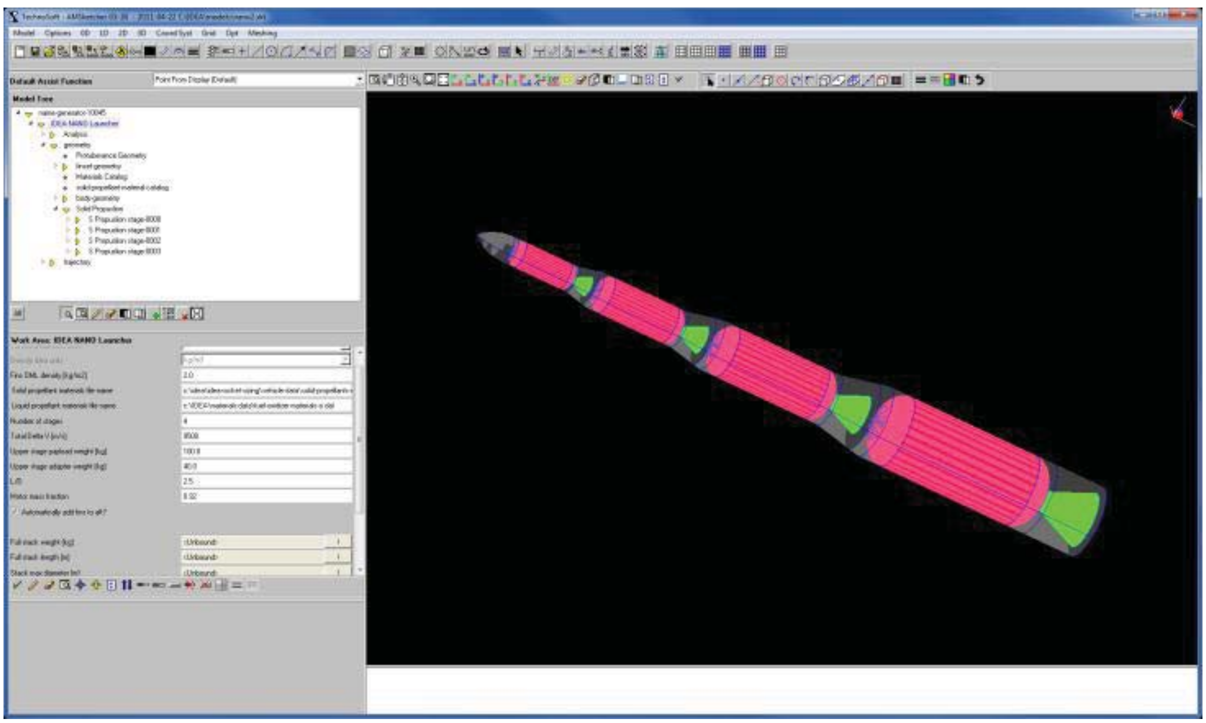


Figure 9: ***Sample screen of the Integrated Design & Engineering Analysis collaborative modeling environment.***

[25] J. Robinson, "An Overview of NASA's Integrated Design and Engineering Analysis (IDEA) Environment (Unclassified)", *AIAA-2011-2392*, April 2011.

- L-LCC:

A new nanolauncher sub-model was created within the already existing ez-Launcher Life Cycle Cost model (L-LCC[26]). The model integrates both technical and non-technical descriptive inputs – that is, the user selects from drop-downs to describe the rocket's design as well as its non-technical context such as industry processes and practices. Development, manufacturing and operations/launch portions of a projects life cycle are all covered. Challenges here included scale as well as the applicability of many model relationships that had been developed originally with larger launch systems in mind.

- SEER-H:

A commercially available cost estimating suite, SEER for Hardware, Electronics & Systems (SEER-H[27]) was also used to develop an alternative costing look at development and production costs within the total life cycle of the nanolauncher design. The tool can be used in early stage development efforts to predict development and production costs, deterministically or probabilistically. Phase I efforts focused on the creation of a Scout-D cost model and a 4-stage solid rocket motor nanolauncher cost model. The intent was to understand rate change effects using this tool and to determine component cost drivers limited to the design/production cost area. An initial Scout model composed of 111 hardware cost elements was created to understand these effects. The 15 element initial 4-stage solid rocket motor nanolauncher cost model serves as a placeholder as more detailed designs evolve, and the framework can guide research and design iterations towards realistic trades and identifying potential cost drivers. The limitation of the SEER-H model, as applied to this study, is a lack of estimation ability on launch operations and ground facility costing, which the other cost models (L-LCC and ACT) can address.

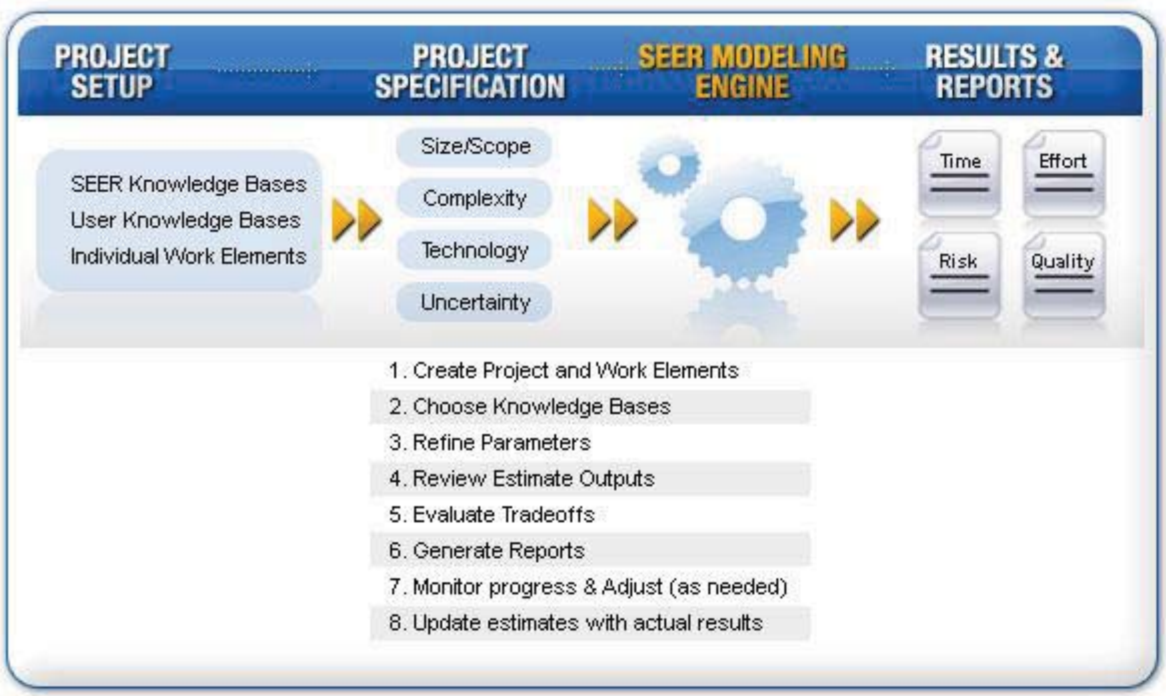
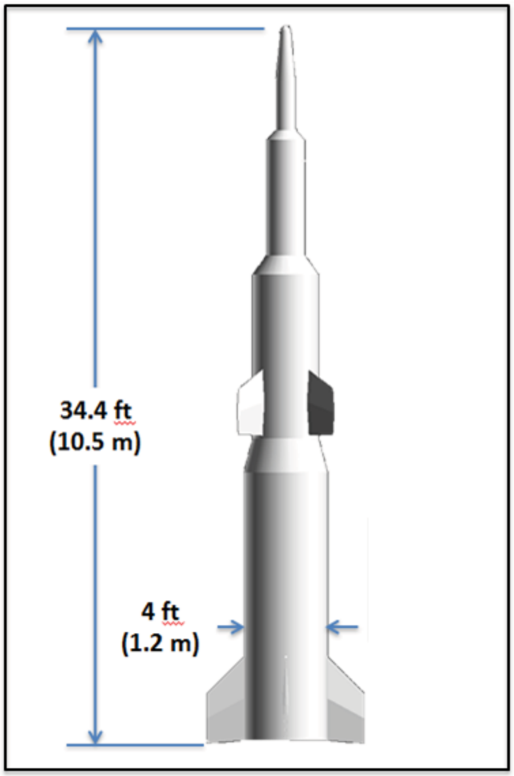


Figure 10: ***A high-level schematic/description of the SEER-H model.***

[26] The ez-Launcher Life Cycle Cost (ez-L-LCC) model (Excel format) is available upon request. Contact the author at edgar.zapata-1@nasa.gov.
[27] SEER-H, http://www.galorath.com (last visited May 19, 2014).

8. Results

The phase I nanolauncher assessment would focus on a 4-stage solid rocket “baseline” as shown in **Figure 11**. A “baseline” would be representative of that type of launch system. Design and technology assumptions were influenced by sounding rocket designs and the desire to baseline existing technologies. Results shown were generated using IDEA and are of a preliminary and conservative nature, with improvements expected as the modeling is matured and refined.



- Baseline Design and Technology Assumptions
  - **Payload Mass:** 10 kg (5 kg target)
  - **Configuration:** 4-Stage, Expendable
  - **Launch Mode:** Rail launch
  - **Propulsion:** All solid
  - **Propellants:** HTPB
  - **Structures:** All composite
  - **Guidance & Cntrl:** Spin/Fin stabilized + ACS
  - **FTS:** Destruct (stages 3 & 4 only)
  - **Vehicle Integration:** Horizontal
  - **Acquisition Concept:** Traditional/Gov.
  - **Manufacturing/Ops/Launch Approach:** Traditional/Business-As-Usual
- Performance Characteristics
  - **Dry Mass:** 630 kg
  - **Gross Mass:** 8130 kg

Figure 11: ***Concept 1 baseline of the nanolauncher technology and life cycle assessment.***

Another nanolauncher “baseline” concept also defined during phase I was an all-liquid two-stage system as shown in **Figure 12**. Beyond the differences due to the liquid propulsion system, the concept had similar assumptions to Concept 1. Sizing for Concept 2 was done with simplified mass fraction techniques rather than the IDEA modeling and is of lower analysis fidelity than Concept 1. Vehicle Sketch Pad was utilized for the configuration layout shown.

There are a number of consequences due to scaling down from EELV scale that affect the design of these very small launch vehicles. These include higher relative drag losses, higher flight loads that drive up structural mass, and increased dispersions from the desired flight profile that the upper stages will have to correct for. Higher drag losses will drive up the required propellant fraction to achieve orbit as compared to larger launch vehicles. Elaborating on some of these issues:

1. Delta velocity losses due to aerodynamic drag increases inversely proportional to vehicle scale. This is due to the fact that drag is proportional to area or scale squared whereas available energy (propellant) is proportional to volume or scale cubed. So if you reduce launch vehicle scale to 10%, your drag loss will be $.1^2/.1^3 = 10$ times original. Typically, for EELV class launch vehicles, the drag loss is about 3%. Therefore for a one tenth scale launch vehicle, the drag loss would be about 30%. This requires increasing relative propellant loading (propellant fraction) or increasing the number of stages.

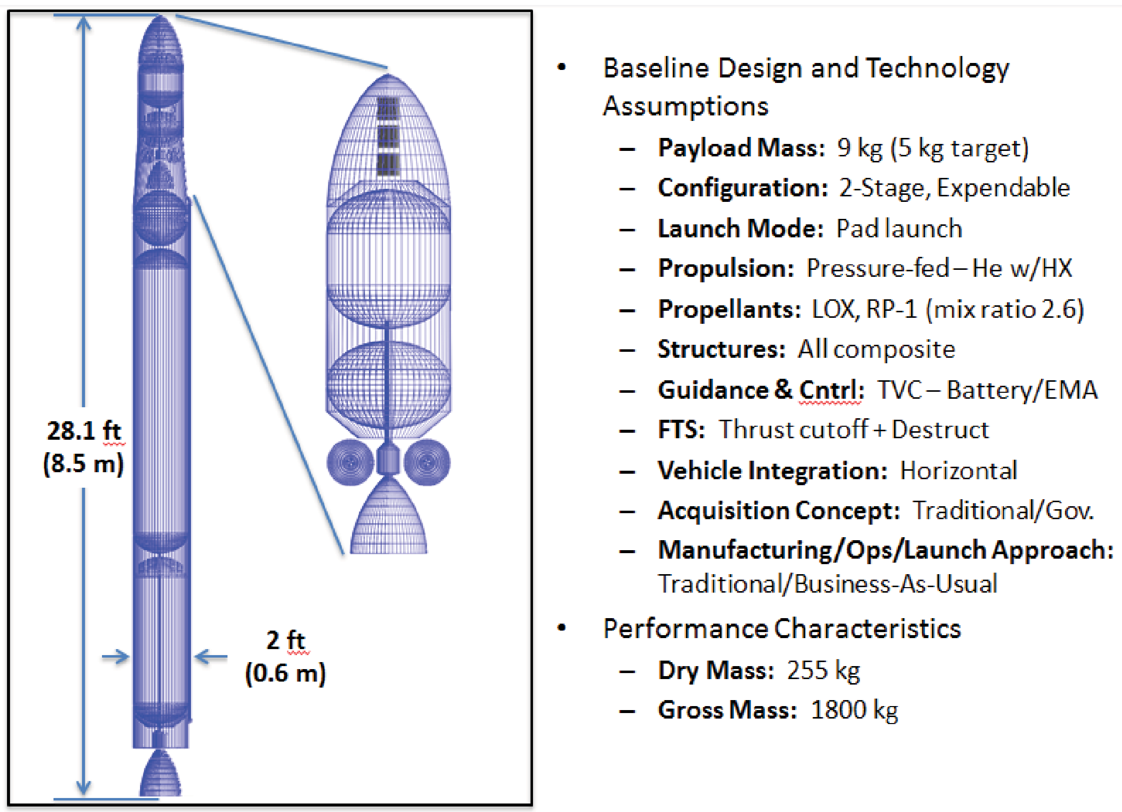


Figure 12: ***Concept 2 baseline of the nanolauncher technology and life cycle assessment.***

2. Normal (lateral) loading during assent also increases inversely proportional to vehicle scale. Given that normal load due to angle of attack or cross winds (winds aloft) are proportional to area or scale squared whereas vehicle mass is proportional to volume or scale cubed, the normal accelerations and therefore responses/loads increases inversely proportional to scale in a similar fashion as drag. This will drive up vehicle bending as well as lateral acceleration inertial loading.

3. Solid rocket motor based vehicles incur additional impacts. Axial acceleration/load and maximum dynamic pressure increases inversely proportional to vehicle scale as well due to the fact that thrust is proportional to propellant burn surface area and vehicle mass is proportional to volume. Burn area is proportional to scale squared assuming the propellant grain pattern is the same. Axial acceleration is a function of thrust divided by vehicle mass. Dynamic pressure profile will essentially increase in proportion to axial acceleration. Dynamic pressure increase compounds the problem given that both drag and normal load is proportional to it, further increasing the propellant loading requirement and structural demands on the launch vehicle. Liquid rocket engine based designs inherently decouple the thruster sizing from the propellant mass allowing the thruster (engine) to be scaled independently and mitigate much of this effect. Typically, solid rocket motor based systems require more stages for these reasons.

The combined set of models was applied, at times comparing one model's results against another for added insight. The new, baseline concepts were "anchored" (but not limited) by the Scout reference data previously described (**Figure 5**). Knowing what total costs may have been (for historical references) or would have to be (for new concepts) still required seeing assessment results in light of *what kind* of costs arise and *where* these potential costs most arise. As seen in **Figure 13**, it is important that analysis, investments and efforts in this area pay attention to fixed costs, especially in production.

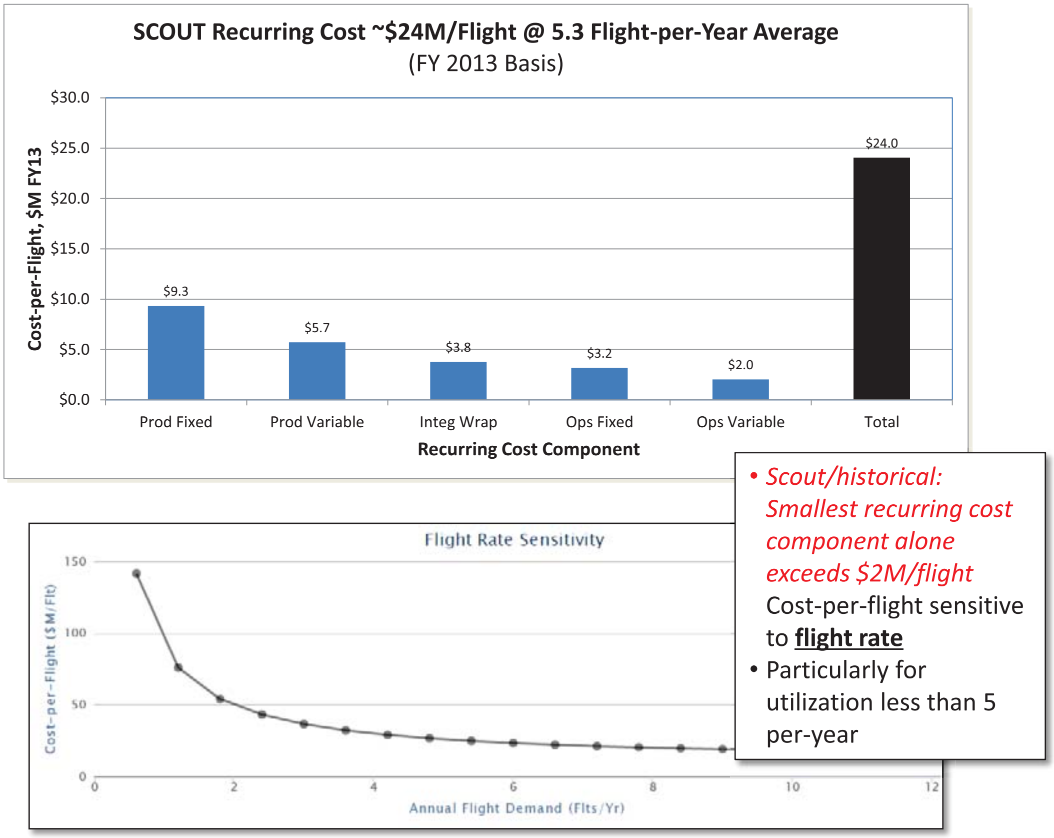


Figure 13: ***What kind of costs (fixed) and where (production) require attention in nanolauncher analysis.***

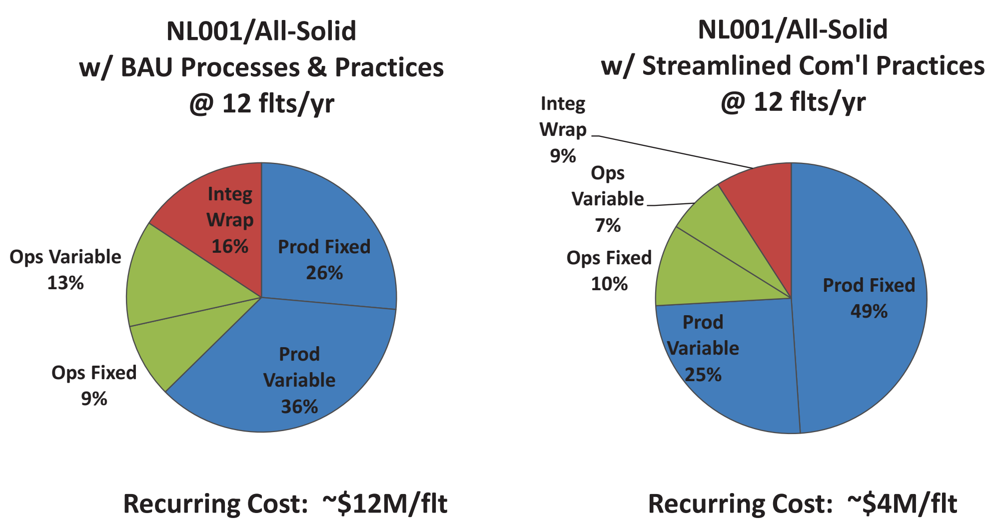


Figure 14: ***Concept 1 (all-solid nanolauncher)*** **breakout of results**

Along these lines, a breakout of results for the baseline, new concepts was derived, as shown in **Figure 14**.

- Majority of recurring costs are accumulated in Nano-Launcher production
- Fixed costs (production and operations together) are substantial
- Streamlined practices reduce costs and can influence any of the recurring cost elements

Within the prior understanding, one of the broader results of the preliminary assessment is shown in **Figure 15**.

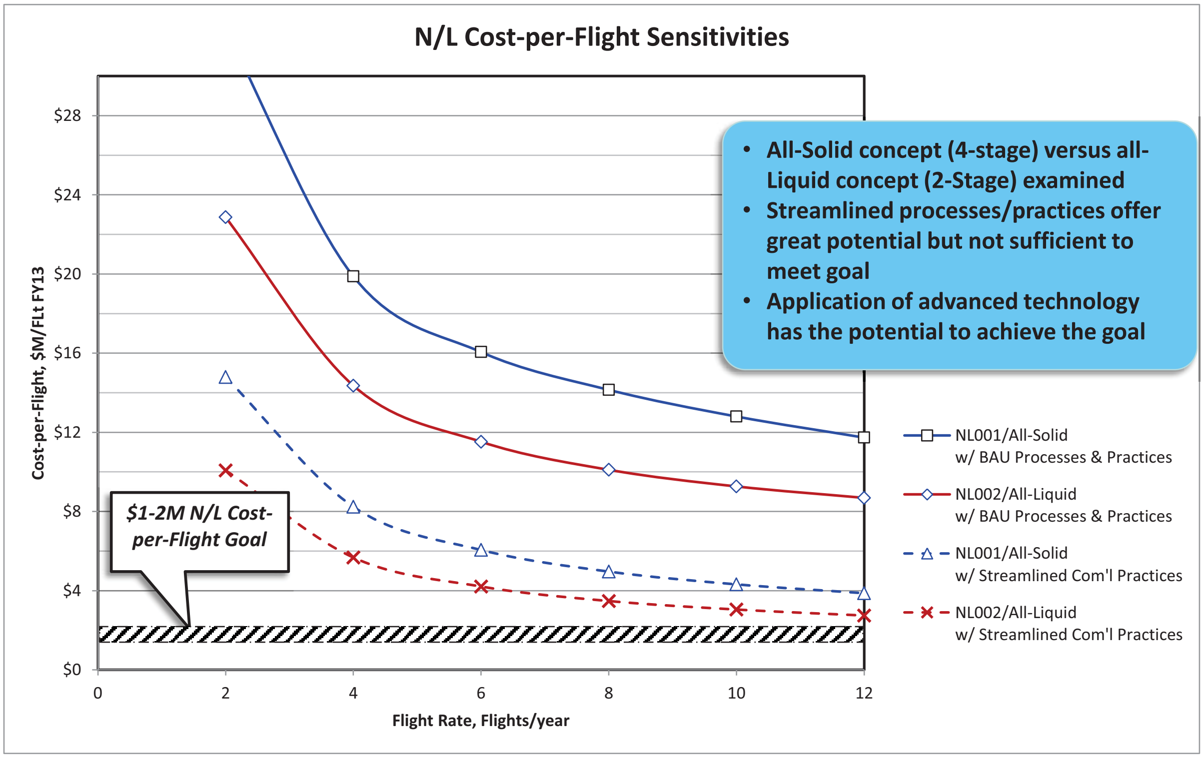


Figure 15: ***Overall results of the preliminary nanolauncher assessment for solid and liquid propulsion options.***

There are some important caveats when thinking about how nanolauncher costs per flight vary with flight rate. The most important thing when reading such charts is to read them asking "if the flight rate were X, then what would approximate costs be per flight". A company wanting to offer certain prices would have to assure enough orders, and an ability to fulfill those orders by producing enough flights, to keep costs per flight well below prices – to even begin to have numbers add up. Other considerations include:

- The size of a company that would be dealing with million dollar launches, in a "what-if" of around 15 launches per year, might be as few as a hundred or so employees. Endless variations around these numbers can be calculated; perhaps more for labor, or less for materials, for labor rates that are average, or lower because of a more supplier driven concept, and so on. Nonetheless, the workforce numbers will hover around the range of this basic "what-if" when dealing with 10's of launches and prices in the low million dollars range.

- Fixed costs and variable costs, both of which contribute to marginal costs, are naturally linked to flight rate and the productivity of a workforce. Technology, design, and process steps in manufacturing and operations, will all affect the actual flight rate achievable with a given workforce. **Figure 15** can be read many ways then. *Since the teams cost assessment goal was relatively low, the results show promise for dedicated nanolaunchers if the combination of market (actual demand), flight rate capability (actual productivity), technology improvements, and costs all combine successfully near the lower right.*

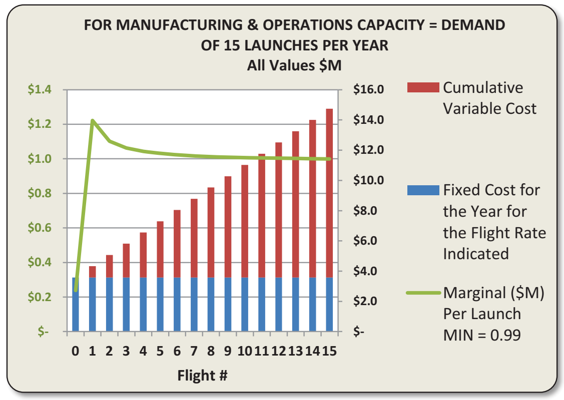
- Fixed costs should not be interpreted here in the traditional sense used in larger aerospace operations. Rather, it is assumed in the scenarios modeled that a company makes a commitment of resources that includes labor, facilities, equipment, materials and supplies, suppliers/relationships, etc. If no launches were produced, what would these costs add up to over a year? This would be akin to fixed costs. Separate these costs from costs that are more specific and additional due to an order for a launch, the variable costs. **Figure 16** shows this separation, where eventually the marginal costs approach the variable costs (the burn rate of fixed costs now being divided, amortized, over so many customers.)

Results
Nano-Launcher Concept 1

- Can Concept 1 meet the Nano-Launcher cost objective?

YES

~$1M/unit
(recurring manufacturing & launch)



- Nano-Scale Concept 1 -
  - 4-stage Solid
  - No Common Stages (Diameter, Length)
  - Composite Case
  - NT RCS
  - Unique Avionics per Stage
  - Low COTS/componentry
  - Low Manufacturing Tooling/Test Automation
  - Standard/~No Payload Services
  - Low Supply Base
  - “Ideal” (Best) industry process/practices (manufacturing + ops efficiencies)

Figure 16: ***One scenario run of many when modeling the costs of potential nanolauncher configurations.***

9. Forward Work

An assortment of forward work remains following this brief phase I nanolauncher technology and life cycle cost assessment. The work to date has delved into some detail in the configuration and performance of a class of nanolaunchers (using solid rocket motors). Work has begun on other classes of configurations (liquids, hybrids, etc.) Certain details of technology, design and technical factors have been related to costs (within certain contexts, factors about business-as-usual vs. new ways of doing business, commercial, etc.)

Forward work in Phase II, based on feedback from sponsors and stakeholders, includes:

- Analyzing the Phase I designs to a higher fidelity.
- Refining life cycle cost methodologies and results.
- Further exploring business case scenarios and market segments.
- Determining the specific sensitivity of potential new technology to cost reductions (vs. no technology or baseline technology). Examples / candidates include:
  - Generic Application
    - Additive Manufacturing
    - Scalable Avionics (ex. Smart Phone-derived)
    - Rapid Robotic Stage Assembly
    - Advanced Work Flow and Supply Chain Technologies

        - Commercial Aircraft-like Certification (vs Flight-by-Flight)
        - Adv Sys Engineering Processes & Tools Applied to Flight Certification Reviews
        - Rapid Mission Planning Tools
        - Autonomous Flight Safety System (AFSS)
        - Low Cost Transporter, Erector Launchers (TELs)
        - Simple Fixed Launch Mounts
        - Rapid, Robotic Nano-Launcher Stage Integration
        - Out-of-Autoclave Composites vs. Conventional
        - Carbon nanotube reinforced tanks
        - Advanced green monopropellants
    - Solid-Propelled Vehicle Application
        - Advanced Solid Propellant Manufacturing & Casting
        - Pre-Segmented, Common Diameter Small Solid Motors
        - Fast Cure Solid Propellant Technologies
        -

Especially, forward work will focus on opportunities for improvements in production/manufacturing that would increase productivity (units per year for a given resource, workforce, etc.) and reduce costs. The framework for more specific technology assessment may follow the basic structure shown in **Figure 17**.

The authors encourage and welcome feedback and ideas on technology candidates as well as a technology assessment framework.

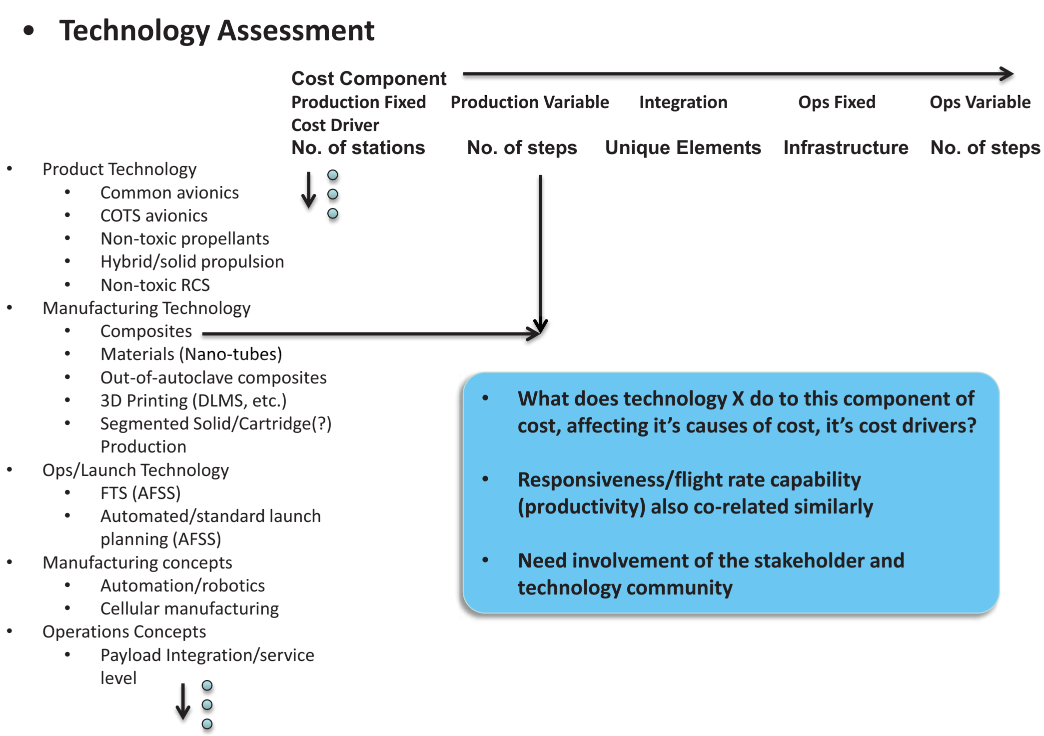


Figure 17: ***Abundant technology options by phase represent potential areas of emphasis for NASA investment and for nanolaunchers pursuing low cost goals.***

10. Preliminary Conclusions

The nanolauncher assessment team was asked "to investigate the feasibility of dedicated nano-satellite launch systems with a recurring cost of less than $2 million per launch for a 5 kg payload to low Earth orbit. The team products would include potential concepts, technologies and factors for enabling the ambitious cost goal, exploring the nature of the goal itself, and informing the GCD program technology investment decision making process."

Preliminary conclusions of this study, addressing the study goals, include -

- There is a limited experience base for this class of launch vehicles; further maturation of performance analysis and design tools is required
- Dedicated nanolaunchers are estimated to cost 10s of $M per launch if following "business-as-usual" approaches
- Launch vehicle scale reductions alone do not enable the goal of < $2M recurring launch cost
- However-
  - Preliminary analysis shows that nanolauncher technology investments can significantly improve dedicated nanolauncher capabilities
  - The combination of technologies and efficient commercial approaches (new ways of doing business) can enable the goal of < $2M recurring launch cost

Forward work as previously described will add more detail, supporting information, and address connections between specific technology, approaches or potential investments and their impacts on nanolaunchers.

11. Acknowledgements

The team gratefully acknowledges the sponsorship and support of Ronald J. Litchford, Principal Investigator in the Game Changing Development (GCD) program.

The authors gratefully acknowledge the support and feedback of the study team and discussion participants who shared their expertise. This included Eddie Santiago and Robert Johnson, from NASA Kennedy Space Center, Greg Moster and Bruce Thieman, from the Air Force Research Laboratory at Wright-Patterson Air Force Base, Roberto Garcia and Jonathon Jones, from NASA Marshall Space Flight Center, Frank Bellinger, from the NASA Wallops Flight Facility, and from NASA Langley Research Center – Brett Starr, Adam Cowling, Janet Ross, Bryce Horvath, Lawrence Taylor, Roland Vause, Mark McMillin, Steven Harris, Jeffrey Robinson, Melvin Lucy, and Robert Fairbairn; also students Jacob Katuin and Alexander Chen.