Abstract

Scorpius is a Microcosm program to develop an entirely new launch vehicle family with the following objectives:

- Better than 99% reliability
- Launch within 8 hours of payload arrival at the launch site
- Weather and equipment delays comparable to commercial airlines
- Very low initial recurring cost:
  - SR-S Small Sounding Rocket: 220 lbs to 200 km for $95,000
  - SR-1 Sounding Rocket: 900 lbs to 200 km for $275,000
  - SR-3 Micro Lift: 170 lbs to LEO for $700,000
  - Liberty Light Lift: 2,200 lbs to LEO for $1.7 million
  - Exodus Medium Lift: 15,000 lbs to LEO for $7.9 million
  - Extendible to heavy lift
- Total non-recurring development cost for all of the above vehicles through light lift of less than $25 million ($FY94)

The program is funded under multiple contracts with the US Air Force Phillips Laboratory and Microcosm internal IR&D. Microcosm has developed an overall system design and built and fired multiple test engines for the sounding rocket and light lift vehicles. Southwest Research Institute has delivered the prototype avionics system. At present, the program has substantial design margin in all key cost and technical areas.

Scorpius is an R&D program with no guarantee of success. Nonetheless, at each stage the program has been ahead of schedule and done more for the money than called for. It has been through multiple formal reviews with no major show-stoppers identified. We are building major hardware elements at far less than 1/10th the traditional cost. We anticipate more than a factor of 30 fewer parts than a traditional vehicle with almost no machined or tight tolerance components. If funding proceeds, we anticipate being able to reduce total launch costs by a factor of 10 for small payloads within 3 years and for medium payloads within 4 years.
Background

The Scorpius concept for a dramatically lower cost launch system was originally developed over a 12 year period by Edward Keith, currently the Microcosm principal launch system engineer. [1, 2] The original concept has now been extended and further verified with substantial systems engineering work and test hardware development on a total of seven contracts with US Air Force Phillips Laboratory in Albuquerque, NM, and through Microcosm internal IR&D. The current activity was initiated with a Phase I Small Business Innovative Research (SBIR) system study, which began in March, 1993. The SBIR topic came from the Ballistic Missile Defense Organization, but was subsequently transferred to Phillips Laboratory for program oversight. [3]

Phase I was intended purely as a study addressing systems issues for a dramatically reduced cost vehicle. However, it gained substantial support by accomplishing some hardware development as well. Specifically, a 5,000 lb thrust test engine was manufactured under Phase I in three weeks for less than $5,000. This was less than the cost of bringing two engineers to California to explain how to build low cost rocket engines. The end result was that the two engineers did not attend the final review (there was no extra budget available in Phase I) and, instead, sent the finished test engine. This initial test engine was successfully fired in December, 1993, on a private test range east of San Jose, CA.

The initial Scorpius study was oriented toward the government's need for medium and heavy lift. Six subsequent contracts have been awarded by Phillips Laboratory to Microcosm for both systems studies and the development of specific elements of technology. These have focused principally on demonstrating critical hardware elements and on the initial sounding rocket and light-lift applications. Approximately $1.7 million has been spent on the program to date. In addition to other hardware and systems development, we have built a total of five 5,000 lb thrust engines, which is the size appropriate for one and two stage sounding rockets and the Liberty Light-Lift launch vehicle. The average manufacturing cost of the five engines has been less than $5,000 each, excluding the injector. We have now achieved over 100 seconds cumulative burn time on the fifth ablatively-cooled engine with substantial life remaining. Although much engine development remains to be done, the work to date has demonstrated that we can achieve appropriate lifetime, performance, and cost goals to meet our program objectives.
<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (per lb)</th>
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<tbody>
<tr>
<td>Space electronics, on-orbit in GEO</td>
<td>$50,000.00</td>
</tr>
<tr>
<td>RL-10 Centaur Engine (16.5K lb thrust)</td>
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<td>Space Shuttle Main Engine (470K lb thrust)</td>
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<td>Gold</td>
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<tr>
<td>F-1 Saturn Main Engine (1,500K lb thrust)</td>
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<td></td>
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<tr>
<td>Macintosh portable computer</td>
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<td>Silver</td>
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<td>Steak (T-bone)</td>
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<tr>
<td>Kellogg's Corn Flakes</td>
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<tr>
<td>Hamburger (30% fat)</td>
<td>$1.49</td>
</tr>
<tr>
<td>Scorpius Liberty Engine (5K lb thrust)</td>
<td>$150.00</td>
</tr>
<tr>
<td></td>
<td>= $0.90</td>
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</tbody>
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Fig 2. Cost comparisons. See text for discussion.

In addition, to the engine work, substantial effort has gone into the guidance, navigation, and control for the vehicle. 3-D and 6-D simulations of the launch profile have been developed and run. Results from these simulations will be presented early next year. [4] The computer and pod electronics for the launch vehicle have been designed and developed for Microcosm by Southwest Research Institute of San Antonio, TX. The prototypes of both units have been delivered and are on display at the Microcosm booth at this conference. The recurring selling price for these units will be substantially less than $10,000 each.

There is, of course, far more to a launch vehicle than simply engines and avionics. Scorpius is a complete system design which addresses the entire problem of low cost launch services, including the vehicle itself, facilities, and operations costs. However, we believe reducing engine costs by more than two orders of magnitude compared to projections based on empirical historical models is indicative of the capacity to make truly dramatic reductions in overall launch costs. Specifically, Fig. 1 shows the projected Scorpius engine recurring cost plotted on an empirically-based model of historical engine costs developed over a period of 30 years by Dietrich Koelle of MBB. [5] Fig. 2 shows similar information presented somewhat differently. While the items in the list are not truly comparable, the figure is intended to give some insight into the scale of the cost reduction. For the Scorpius program, thrust is now cheaper than hamburger. While this certainly does not, by itself, mean that launch vehicle costs will be comparably reduced, we believe that it is a significant positive step.

Fig 3. Scorpius Baseline Configuration
Scorpius Concept Overview

The baseline Scorpius Launch Vehicle configuration consists of 49 engines arranged in seven clusters or pods as shown in Fig. 3. As illustrated in Fig. 4, this provides four horizontal stages plus an optional fifth "upper" stage.

![Diagram of Scorpius Staging Sequence]

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STAGE 3 BURNOUT & SEPARATION

STAGE 2 BURNOUT & SEPARATION

STAGE 1 BURNOUT & SEPARATION

LIFTOFF

Fig 4. Scorpius Staging Sequence.

One of the most important features of Scorpius is that the engines are fixed in the launch vehicle. There are no gimbals, actuators, or APUs. Steering is provided by a combination of off-modulation and thrust vector control via secondary fluid injection. For Scorpius off-modulation (i.e., throttling down some of the engines to provide steering), is far more effective than in a traditional launch vehicle. Because the launch vehicle is wider than normal, off-modulating the outboard engines provides a larger moment arm and, therefore, greater torque than normal. Even more important is the much smaller moments of inertia due to the relatively short, fat design. The vehicle is aerodynamically stable and requires relatively modest control authority. In most Scorpius configurations, off-modulation provides very adequate control. However, early in the design process it became clear that during portions of the flight, particularly fourth stage burn out, the control margins were less than we would have preferred for a robust vehicle. Consequently, steering by thrust vector control via secondary fluid injection was added to the engine design. This somewhat increased the cost and complexity of the engine, but insured that the integration of the vehicle would be easier with looser tolerances. It is the overall launch system cost that we wish to minimize. This robustness, which allows a number of low-cost alternatives for most key functions, provides much of the strength of the Scorpius system design.

Ordinarily, propellants and pressurants are a relatively insignificant part of the cost of a launch vehicle. Because of the overall very low system cost, this is not the case for Scorpius. Consequently, we use kerosene and LOX at approximately $1.36/\text{lb}$ and $4\epsilon/\text{lb}$, respectively. The propellants are pressure-fed using a proprietary mixing gas generator, which is both low cost and environmentally safe. It is the mixing gas generator which allows the vehicle to be scaled to medium and heavy lift launch vehicles. Scorpius does not use high pressure tanks and contains no turbo pumps or complex machinery.

The combination of fixed engines and no turbo pumps leads to another key element of the design. Scorpius has approximately a factor of 30 fewer parts than a traditional launch vehicle and uses virtually no tight tolerance or precision components. The only moving parts in the launch vehicle are ON/OFF valves.

The basic Scorpius design provides a high level of scalability to both larger and smaller vehicles. Larger vehicles have a similar physical configuration to Liberty. For smaller vehicles, reducing the number of pods and engines provides a variety of sounding rocket and micro lift configurations whose overall
performance is given in the abstract. The SR-S is a single-engine, single-pod configuration which has much the appearance of a traditional sounding rocket. The SR-1 is a single-stage, three-engine, four-pod configuration. The SR-2 uses two stages with a total of six engines in seven pods. It has the appearance of a scaled down Liberty Light-Lift Vehicle. With additional engines and a third (upper) stage, the SR-2 is capable of putting very small payloads in low Earth orbit at an extremely attractive price.

Achieving Dramatically Reduced Cost

Achieving a 10% to 30% percent cost reduction can potentially be done by attacking the principal cost drivers and looking for added simplicity or improved performance in a few key features of the design. Achieving the factor of 10 cost reduction which Scorpius proposes requires building the entire vehicle in a new way. The Scorpius design could not have been built a decade ago. It requires modern advances in low-cost computer technology and low-cost, high strength composite materials. Nonetheless, there is no single breakthrough in technology or new high performance component which results in the low cost. Low recurring cost comes about from designing the vehicle from the outset to be manufactured, not built and assembled by engineers. In this respect it is similar in its approach to the Model T, Volkswagen Bug, or the first personal computers in which optimal performance was given up for the sake of dramatically reduced cost. This closely follows the approach proposed by John London in his extensive study of launch cost reduction [6, 7].

This low cost approach must extend to all facets of the process—including development, manufacturing, test, facilities, and operations. For example, the short, squat Scorpius design provides excellent stability while the vehicle is on the ground. Consequently, no launch gantry or service tower is required, and it is relatively straightforward to design the vehicle such that all servicing is done at ground level. Access to the payload is, of course, at the top of the vehicle. However, for Liberty this is only 30 feet above the ground which is relatively easy to reach by a variety of means.

As the Space Shuttle example has shown, designing a launch system to be low cost is, in many respects, much easier than actually building it with that result. It is the construction and testing of hardware that, in the end, will demonstrate both the cost and performance characteristics. It is in this aspect that we believe Scorpius has been exceptionally successful to date. As indicated above, the first Scorpius test engine was build at extremely low cost. A second test engine, designed for reduced throat erosion, was built at a comparable cost. Both the first and second engines were fabricated and test fired on a private range at total cost of less than $30,000.

This very low cost hardware development and test program is also key to achieving dramatic reductions in non-recurring development costs. When engines cost millions of dollars, then it is important not to damage the engine during testing. This, in turn, adds dramatically to the test preparation and execution cost and reduces the information obtained from the test. With engines at less than $5,000 apiece, it is reasonable to build and test fire a number of engines, even on a very low cost development program. It is also reasonable to destroy engines in the testing process in order to find failure mechanisms and understand the strengths and weaknesses of the design. The testing process itself becomes much lower cost. For example, our first engine tests were conducted in very cold weather. This resulted in condensation freezing in a line such that a LOX line ruptured on the second day of testing with a rather spectacular flame spreading
over the test stand. Fortunately, neither the engine nor test stand were harmed. The line rupture was repaired during the evening, and testing successfully resumed the next day. Consequently, our first test firings took three days rather than two, as we had planned, with only a minor impact on cost.

Our second round of engine testing took place at the Rocket Propulsion Directorate at Edwards Air Force Base, CA, where additional instrumentation and personnel were available. The objective of these tests was to demonstrate that reasonable lifetimes could be achieved in very low cost engines. As shown in Fig. 5, our fifth engine achieved burn durations of 10, 52, and 48 seconds in three test firings on April 24-26, 1995. A video tape of this engine testing is being shown at the Microcosm booth at this conference. After the 110 seconds of firing, engine 5 showed very little erosion either in the throat or thrust chamber. It is clear that there is substantial life left in the engine, indicating that achieving appropriate lifetimes for both sounding rocket and light-lift vehicles can be done with an extremely low cost engine. Engine number 5 had a total of 18 parts, including fasteners, and was fabricated at very low cost consistent with the other test engines and our low cost production approaches.

A new engine test program is now underway with initial engine firings in late August, 1995, at the Energetic Materials Research Test Center (EMRTC) at New Mexico Tech in Socorro, NM.

In addition to the engine development, other key technology requirements for Scorpius include low cost composite tanks for cryogens and a low-cost, environmentally-safe gas generator. Both of these technologies are being developed under separate contracts from Phillips Laboratory and both are applicable to a variety of launch vehicles and spacecraft. In addition, the system will require low cost avionics. Because the Scorpius avionics will have rather substantial software, a new and significantly lower-cost flight computer was needed. Both the low cost flight

Fig 5. 110 sec test firing of Scorpius 5,000lb thrust test engine on Apr. 24-26, 1995.
computer and associated pod electronics module have been developed for Microcosm by Southwest Research Institute of San Antonio, TX. As shown in Figure 6, prototype units of both the computer and pod electronics have been delivered and are on display at this conference. Like all of the Scorpius hardware, the key characteristics are achieving high reliability and acceptable performance at very low cost. We believe the computer developed by Southwest Research meets these characteristics very well. Both the computer and pod electronics are being offered for sale to the space community for substantially less than $10,000 each, depending on quantity and delivery.

![Fig 6. The SC-2DX Low Cost Flight Computer, built for Microcosm by Southwest Research Institute.](image)

Of course, reducing overall launch cost requires significantly more than low cost, high reliability components. It requires an overall system design and development program which dramatically reduces the non-recurring cost at an acceptable level of technical risk. Microcosm has a system design and development plan to achieve our objectives for a total non-recurring cost of less than $25 million through the Liberty Light Lift Vehicle (including sounding rocket development). We have low-cost alternatives to essentially all of the key components and technologies. Technical problems have arisen, as they will in any development program. However, there is sufficient margin in terms of cost and performance that at the conclusion of each stage we have been ahead of schedule and achieved more than planned. We have had multiple, formal system-level reviews with government, industry, and Aerospace Corporation personnel with no "show stoppers" identified. In addition, we have a group of exceptionally knowledgeable and experienced reviewers, originally very skeptical of the program, who now believe that we have made major progress toward achieving our objectives. Scorpius is a technology development program. Like all such programs, it has potential risk and cannot guarantee success. Nonetheless, many of the key technologies have now been demonstrated, and nearly all technology risks will be evaluated and flight proven early in the program when the cost risk is minimal. Thus, low cost sounding rockets will be used to flight test hardware for light lift vehicles, which, in turn, are the test bed for medium lift.

We emphasize that the substantially reduced cost indicated in the abstract are the initial launch costs in FY94 dollars. These costs can be realized at even a very low launch rate and are not dependent on a launch model requiring a high level of activity. On the contrary, we anticipate that any consequent increase in the number of launches will provide additional reduction in launch costs as economies of scale and learning curve advantages become more relevant.

**Conclusion**

The availability of the key technology required to reduce launch system cost by a factor of 10 has been demonstrated. The United States (both government and commercial) is currently spending $110 million a month on unmanned launches plus an additional $150 million per month for manned flights. In the last five years, the
The approximate average expenditure rate has been:

- Light lift $3 million/month
- Medium lift $72 million/month
- Heavy lift $39 million/month

The technology is available to reduce U.S. launch costs (government and commercial) by approximately $75 million per month with full recovery of the non-recurring investment with approximately one month's savings.

A number of studies have shown, that reducing launch costs will reduce spacecraft costs as well. Consequently, we anticipate a potentially substantial additional savings. The principle issue which will have the strongest impact on overall savings is the timing of a full scale development program. This remains uncertain at present. As has perhaps always been the case, the principle impediments to dramatically reduced cost in space exploration are political and economic, rather than technical.

**References**


