Evolution of the Pathfinder Aerial Propellant Transfer Launch System

By

Karl Gallagher

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Prof. Axelband

Karl Gallagher
310-812-0879
karl.gallagher@trw.com

Abstract

Pioneer Rocketplane developed a launch vehicle architecture based on the concept of Aerial Propellant Transfer. This centered on a reusable aircraft-like launch vehicle (the “rocketplane”) which took off with a partial propellant load and took on propellant from a tanker aircraft before taking its payload to orbit. The architecting process went through five design iterations beginning with Air Force feasibility studies and ending with a privately-funded effort focusing on the commercial viability of the concept.

A system “Design Philosophy” guided decisions when quantitative data was unavailable, and other heuristics were applied to produce a sound system architecture. Engineers drew on “rules of thumb” from personal experience and histories of other projects to guide them when decisions needed to be made promptly on subjects too complex to perform a thorough analysis on. The program’s explicit design philosophy focused the team on a specific set of directions to pursue, giving them a common framework for making decisions.

The architecture evolved from a military multi-purpose system to one focused exclusively on performing commercial satellite launches. This required a number of changes to the architecture, including adding an upper stage element and increasing the performance by a factor of four. Most design changes were driven by the need to correct errors found by more detailed analysis in each design iteration. The final architecture was a solid design that could adequately perform its intended mission. Unfortunately, the outside world was changing as the design closed and the profitability of the mission was longer good enough to justify the construction of the system.

Background

Many attractive space projects have proven impractical due to the high cost of placing material in orbit. Much thought has gone into reducing this cost through new launch vehicle technologies or alternate approaches using existing technologies. The federal government has tried to cut costs with the Space Shuttle, NASP, NLS, and other programs, but has wound up relying on the same ICBM-derived boosters for the majority of its launch needs. Other attempts have come from private enterprise—Boeing proposed its RASV concept to the government to try to gain funding, and start-up companies built the Percheron and Conestoga rockets on investor funds. While none of these ventures succeeded they did break trail for other concepts and supported a community of advocates for new launch technology.

One of these advocates was an Air Force captain who developed a new concept for reaching orbit called Aerial Propellant Transfer (fig. 1). The launch vehicle would take off horizontally as an aircraft and rendezvous with a tanker plane carrying propellant. The LV would take on propellant and then boost for orbit, without having to discard any expensive hardware. This concept also avoided the operations costs of delicately integrating separate pieces of hardware for every mission. The great performance benefit was in not having to boost the full propellant load from the ground, saving in wing and engine mass and improving the vehicle mass fraction.

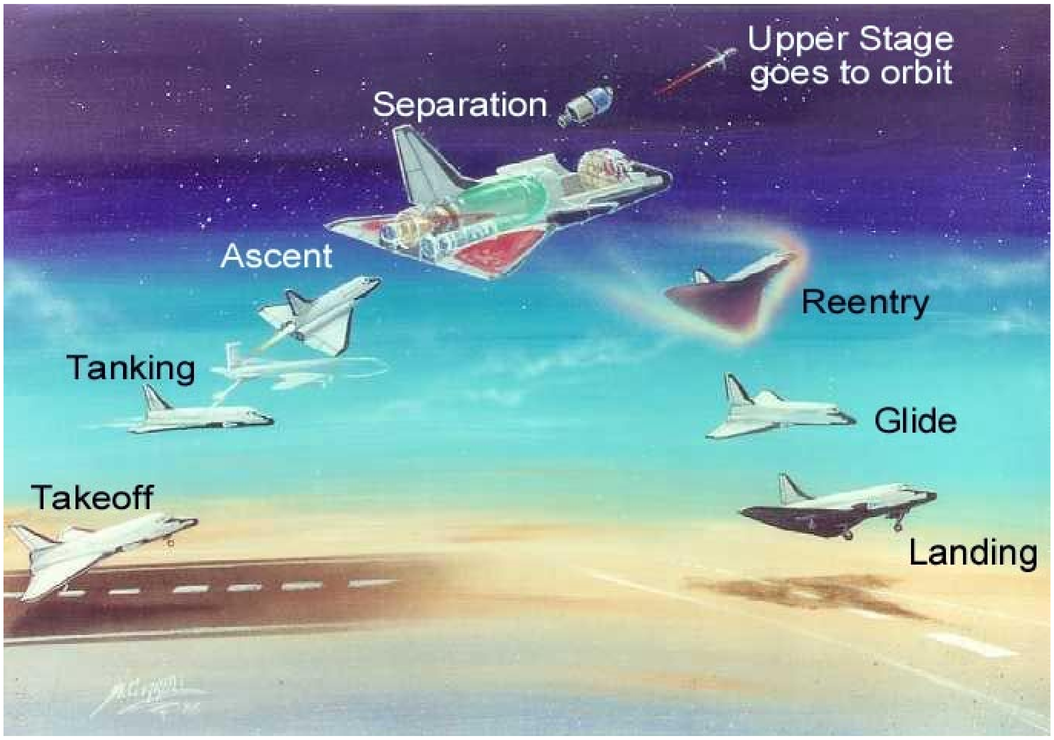

Figure 1. Aerial Propellant Transfer concept, with expendable upper stage

Following some initial investigation by the Air Force (described below), the concept was abandoned and the inventor left the service to found the Pioneer Rocketplane company to develop the vehicle. After another design iteration done with consultants, four more engineers were brought on to bring the architecture to the next level of detail. The design team was very homogenous in background, almost all ex-Air Force MIT graduate pilots. Applicable experience included Air Force flight test operations, development of expendable launch vehicles, and aerospace systems engineering. The author had experience in military space operations and architecting of satellite systems, and was responsible for general system engineering on the project (mission analysis, requirements management, and configuration control).

Statement of Problem

The premise that developing a launcher with lower costs would result in a crowd of new customers appearing to use the service is called the “Field of Dreams” argument in the launch community—“Build it and they will come.” The counterpoint is that the delay time in new customers arriving would most likely be long enough for the new launch company to go bankrupt. To avoid that danger Pioneer focused on an immediate market—the plethora of low earth orbit communications constellations planned in the mid-90s, led by Iridium and Teledesic. Even excluding Teledesic, hundreds of satellite launches were planned for the 2000 to 2005 timeframe, most of them small enough to be launched by Pioneer's vehicle, the Pathfinder. This was a market that could justify developing a new launch vehicle.

The mission statement for the Pathfinder system was kept tightly focused on that market. Payload masses and interface specifications from the potential customers were used to develop system specifications. The launch price of the system would need to be kept low enough to compete with existing launchers and other new launchers under development. US government regulations would have to be complied with, and the system would have to operate safely enough to win approval for operations not covered under existing regulations. And, most important in the investor's point of view, it would have to be profitable enough to justify the risk that investors were taking in supporting this venture. This is a classic example of the "**Success is defined by the beholder, not the architect**" heuristic. The investors owned the company and needed to justify their investment with large returns—the architect would have been content to have a system that enabled new customers to reach space.

The "**Simplify**" heuristic was applied at this point to eliminate missions that might have future potential but could interfere with the focus on the near-term market. Specifically, space tourism and surface-to-surface transport were deliberately excluded from the mission model as their revenue potential was uncertain and their requirements could conflict with those of the satellite launch mission.

Architecting Process

Pioneer used a conventional design iteration process (fig 2). Design alternatives were generated and a baseline selected from them. This baseline would then be analyzed in greater detail than in the previous iteration and specific problems identified (performance shortfalls, requirement conflicts, opportunities for improvement). New design alternatives would then be created to solve those problems and the cycle would continue. Five iterations of this cycle were completed on the rocketplane system architecture.

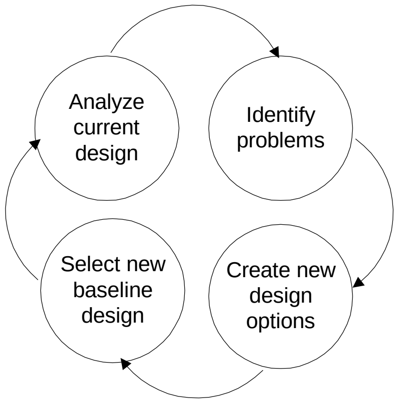

Figure 2. Design Iteration Process

While “heuristics” as such were not used at Pioneer, the team had a “design philosophy” that served many of the same functions:

- **Maximize use of off the shelf technology and existing parts**
- **Use high-criticality components as close as possible to the way they are used now**
- **Design for safety**
  - **Able to abort and recover safely at all flight phases**
  - **All new technologies must be thoroughly and incrementally testable**

Many other heuristics discussed by Richter were used by the engineering team, though not always in the standard phrasing. The architecting team consciously made decisions based on “rules of thumb” and the past experience of the team members and well documented projects, generating their own heuristics. Many decisions on the rocketplane element were driven by a principle of “**Keep it like an airplane**”, enabling the team to draw on the existing funding of aircraft designs, components, and methodologies.

By codifying the design philosophy the team was able to work together more efficiently. Since it was not possible to co-locate the entire architecting team, engineers often had to make decisions without a chance to consult every member. With a set of consensus principles they could make decisions that the other team members would agree with. This also added to the efficiency of face-to-face discussions, as issues could be tackled at the detail level without recurring disputes over the top-level approaches.

Top Level Architecture Definition

The initial architecture concept was proposed to the US Air Force and made the subject of a feasibility study by WJ Schafer in 1993. This fleshed out the “Black Horse” concept (fig. 3)—a single stage to orbit (SSTO) vehicle fueled with kerosene and hydrogen peroxide, loading peroxide from a specialized tanker, and cable of serving a number of roles (satellite launch, on-orbit servicing, reconnaissance, strike, etc.). This was an operationally simple architecture but would have required new technology developments, specifically a high-thrust rocket peroxide/kerosene rocket engine. Meeting the SSTO goal may have also required improvements in structural materials and thermal protection technology. None of the missions were attractive enough to justify the expense of an immediate technology development program.

Fig 3. Black Horse Rocketplane Design—all-rocket propulsion

The aerial propellant transfer concept requires a manned launch vehicle for its execution, as no automated method for performing aerial refueling has been developed yet. This was a factor in making the rocketplane reusable, in addition to the desire to make the reliability higher than that of existing expendable systems. With a reusable vehicle high reliability can be achieved through design and flight test, rather than having to perform extensive (and expensive) inspections of all components. This was the beginning of the "**Keep it like an airplane**" principle—the rocketplane would be designed with the same reliability and safety factors as an aircraft.

The Black Horse architecture had two elements, the tanker and the rocketplane. The tanker would be an existing Air Force KC-135 variant modified to deliver hydrogen peroxide through a rigid boom (using the "**Simplify**" heuristic by taking advantage of existing resources and operations procedures). The rocketplane used only rocket engines for propulsion. Kerosene and hydrogen peroxide were chosen as its propellants because of their high density, which reduced the amount of time needed for tanking and the air drag on the rocketplane.

The problems were addressed in a 1994 Martin Marietta study which generated several design options, including performing the propellant transfer at hypersonic speeds and siamese configurations. The option selected was named "Black Colt", a LOX-kerosene fueled rocketplane with an expendable upper stage (fig. 4). Turbofan engines were added to reduce fuel consumption during the LOX tanking operations. The switch to LOX made tanking operations more complex because of the difficulties in handling cryogens and the upper stage increased the recurring operations cost, but the development costs were considerably reduced which made the program more viable. This was thought of as a "stepping stone" design to support development of the Black Horse vehicle. The upper stage was planned to be an off-the-shelf solid motor-based design to minimize development costs.

Fig 4. Black Colt/Pathfinder Rocketplane 1.0 Design

The new architecture added an element—the expendable upper stage. This added complexity to the overall system but reduced the demands for performance on the rocketplane element. The upper stage/rocketplane interface was the most complex in the system and was carefully managed to minimize system complexity and risk. Using a solid-fuel upper stage was the simplest option available in terms of complexity and development risk and was therefore selected over a higher-performance liquid-fuel stage. A reusable upper stage was considered at points during the program but the effect of that change would have been to reduce recurring cost at the price of increasing development cost. As the system was more limited by raising development funds than by operations costs the expendable element was preferable.

Unfortunately, the Black Colt was still not attractive enough to gain Air Force support for development funding and the inventor left the AF to attempt developing the system in the private sector. The Pioneer Rocketplane Corporation was founded in 1995 by the inventor and the leader of the Martin Marietta study and the military Black Colt design became the civilian "Pathfinder". Pioneer won a NASA study contract for Highly Reusable Space Transportation technologies and continued analysis of the Pathfinder design, along with the upper stage and tanker issues.

A key problem identified was the impact of reentry on the turbofan engine inlets—the heat of reentry would destroy the engines. Sealing the inlets against the heat and pressure at the leading edge of the wing was a formidable problem, and finding alternative vehicle configurations was more attractive than solving the inlet problem directly. A contract was let to Conceptual Design Corporation, which evaluated a number of options before creating a new configuration ("Pathfinder 2.0") with the turbofans on top of the aircraft, which placed their inlets in a much gentler reentry environment (fig. 5).

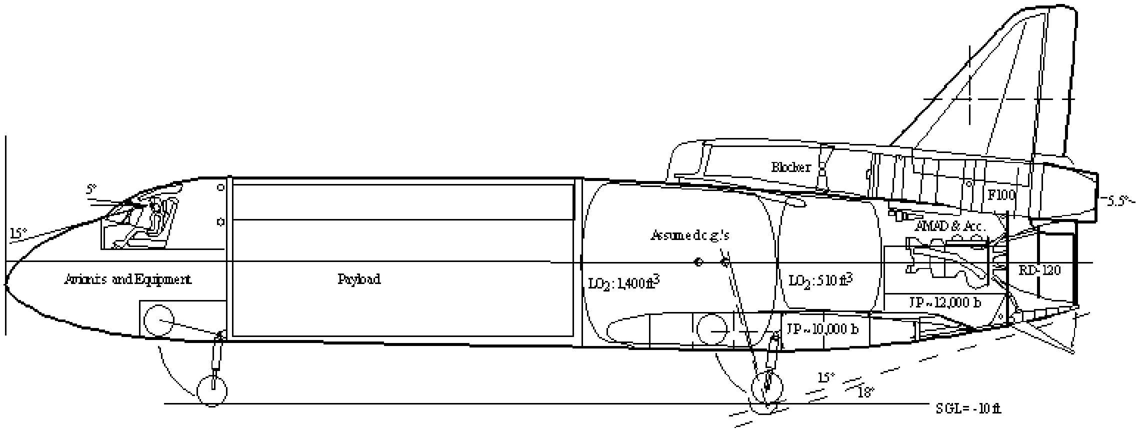

Fig. 5 Pathfinder 2.0 Design

By this point in the development history the top-level system architecture (LOX tanker, rocketplane, upper stage) was fixed. The company had been formed on the basis of that architecture's viability and the investors supporting it were "buying" that concept. It was also being locked in by patent protection (part of company assets) and by publicity establishing the company's comparative advantage against other start-up companies using different launch vehicle architectures. The strength of that architecture decision was showed that in all the following design iterations, at no time was there a problem that would have been more easily solved by changing the top-level architecture. By the standards of the heuristic:

When choices must be made with unavoidably inadequate information, choose the best available and then watch to see whether future solutions appear faster than future problems. If so, the choice was at least adequate. If not, go back and choose again (49)

The Pathfinder system architecture was at least adequate and was certainly shown to be superior to some of the initial architectures of competing companies, which went through multiple top-level changes over the same time period.

System Architecture Definition

At this point Pioneer won a NASA contract for the Bantam low-cost launch vehicle project. By the end of 1997 more engineers were hired to support this effort, completing the design team described above. While government funding was useful in supporting early efforts, it was plain that the Pathfinder system would have to be developed as commercial project through investment dollars. That required a much tighter focus on the problem statement to allow a minimal-cost development effort. The design team reworked the mission in accordance with the heuristic:

Don't assume that the original statement of the problem is necessarily the best, or even the right one (54)

The Pathfinder system was now oriented toward the problem statement discussed above, with alternate missions excluded from design considerations. This approach was possible because of the number of commercial LEO satellite ventures that had sprung up in the past few years, led by Iridium and Teledesic. To gain financial support from private investors the system needed to promise high returns from providing commercial services. System requirements were now driven by the need to provide enough payload capacity for the satellites planned for Teledesic and Motorola's post-Iridium systems, so enough market share could be obtained to justify the investments in the system. This was a four-fold increase in payload delivered to orbit over the original Black Horse concept.

Meeting this increased performance requirement required one more change to the architecture. The simple solid upper stage was replaced by a liquid-fuel upper stage powered by a Russian D-58 engine, thus providing enough delta-V to place the necessary mass in orbit. The development costs of the system were increased, but not enough to endanger the financing or profitability. The recurring costs were also increased, but this did not have a major impact as the cost per flight was driven by the need to pay off the financing of the system development.

Switching to a liquid-fuelled upper stage added an additional set of interfaces between the rocketplane and upper stage. Acting in accordance with the heuristic "**The greatest dangers are at the interfaces**" they were carefully managed to reduce the system risk. For example, the LOX and kerosene propellant would be loaded onto the upper stage after its integration with the rocketplane, and provisions were needed for dumping the propellants in the event of an anomaly. Separate connections were used for loading and dumping propellant to simplify the interfaces, even though the more complex valves needed to connect both functions at the same interface would have required less weight and volume. The electronic interfaces were kept simple by placing all high-computation tasks on the rocketplane, particularly in-atmosphere trajectory adjustments.

The design effort included developing a complete flight test plan for the tanker, rocketplane, and upper stage. The tanker would have a 10 flight series before beginning operations with the rocketplane. The rocketplane flights included 25 flights taking it through initial airworthiness, formation flying with the tanker, and transfer of gradually increasing amounts of inert fluid and propellant. This followed the flight test procedures for a conventional aircraft ("**Keep it like an aircraft**"). Once the tanking procedures had been proved out the rocketplane would conduct 7 rocket-powered test flights of increasing duration and range. This would not just be a gradual work-up to the full system capability but also prove that the mission could be safely aborted at any time during ascent. The upper stage would have a series of ground tests followed by two test flights (the number limited by the expense of expendable hardware). The testing program was created in parallel with the system design in accordance with the heuristic:

To be tested, a system must be designed to be tested. (144)

The system design philosophy also strongly forced the team into considering testing issues by making a point that the system must be "**Able to abort and recover safely at all flight phases"** and "**All new technologies must be thoroughly and incrementally testable."**

Analysis on all system elements proceeded under the Bantam contract. Problems were found in each element. The tanker's rigid boom transfer system was a carryover from the Air Force study and was found to be hard for a private company to duplicate cheaply due to the need to develop additional control systems for the boom and its operator. A drogue system—trailing a flexible hose behind the tanker into which the rocketplane would insert a probe—could be developed much more quickly and cheaply. An additional cost consideration was that the drogue system could be installed without major structural changes to the aircraft, allowing Pioneer to lease the aircraft (a 707 or equivalent size airliner) rather than having to buy one to install the boom equipment on. This was a shift of complexity from one element to another that led to a simplified interface and lower total system cost. While the rocketplane was already the most complex element, adding responsibility for control during tanking operations was standard for US Navy aircraft and did not violate the "**Keep it like an aircraft**" principle of the rocketplane's design.

The upper stage design was limited by the performance and availability of the D-58 engine. As it appeared the source of the engine would not be able to reliably supply the number needed to sustain the planned flight rate, a new, probably custom-built engine would be needed. In accordance with the design philosophy stated above, Pioneer avoided new technology development. As no off-the-self engine was available that met the requirements, an engine development plan was baselined using technology from the USAF Phillips Lab that had already been used to make a commercial ablative LOX-kerosene engine. The new engine would be a scaled-up version of an already tested engine based on that technology.

The rocketplane was found to have a serious stability problem due to the movement of the center of gravity in the vertical axis during ascent. While main rocket engine was firing fuel drained out of the wings (eliminating mass at the bottom of the vehicle) and when the tanks were dry the CG location was dominated by the turbofan engines at the top of the vehicle. This made the vertical CG motion larger than the horizontal CG motion and, since the main rocket engine was fixed to the body frame, created torques beyond the capability of the attitude control system to handle.

Solving the CG problem by changing the vehicle layout was strongly preferred to increasing the control authority of the attitude control system. A more powerful ACS would probably have reduced performance by adding weight to the rocketplane, and probably would have required developing new components rather than relying on off-the-shelf parts. The system design philosophy ("**Maximize use of off the shelf … existing parts**") pushed the team away from that solution, and a solution was found at the vehicle architecture level.

A number of design options were considered for a new rocketplane configuration. The preferred option would have to:

Handle reentry temperatures and pressures at the inlets
Keep the vehicle center of gravity within limits
Minimize changes to other vehicle subsystems

The selected option was place the turbofan engines under the rocket engine with the inlet in the belly of the rocketplane in the style of an F-16 fighter. The closure mechanism was simple and robust, allowing the inlet to withstand reentry conditions. This became the 3.0 version of the Pathfinder (fig. 6).

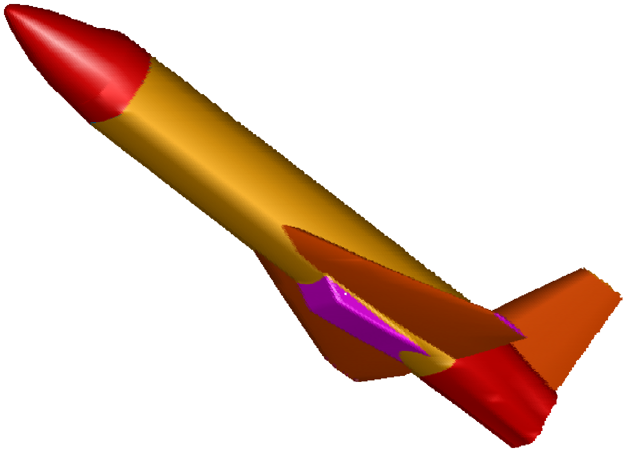

Fig. 6. Pathfinder 3.0 Design—turbofan engine inlets on bottom of vehicle.

In May of 1998 the new architecture of rocketplane 3.0, tanker 2.0 (drogue), and upper stage 3.0 (custom liquid engine) was presented to reviewers at the NASA Marshal Space Flight Center who found it to be a sound design. Unfortunately, even though the Pioneer architecture would have had a lower cost per flight than any of other three Bantam competitors, NASA did not continue the Bantam program with outside contractors.

Pioneer continued its design work with its own funds with additional work being done by subcontractors Scaled Composites and Conceptual Research Corp. The tanker and upper stage designs were found to be sound at that level of analysis and most efforts were concentrated on the rocketplane configuration. Further center of gravity analysis had shown that horizontal movement of the CG could make control during reentry difficult—in particular, a payload-in reentry would not be practical with the 3.0 configuration's aerodynamic controls.

This required revisiting the rocketplane configuration trade that had been done during the Bantam study, as well as conducting a new trade on the layout of the payload back and LOX tanks. To control the horizontal CG movement the LOX tank (previously one tank behind the payload bay) would have to be split into two tanks with one before the payload bay. This moved the payload bay to where it conflicted with the inlet ducts for the turbofans in the 3.0 configuration. This problem was solved by a breakthrough in the method for closing the inlet in a leading edge position by using a deployable mechanism which used a minimum of interior volume, thus fitting between the inlet and the payload bay. This allowed the turbofans and inlets to be moved back to the original configuration 1.0 position without increasing reentry risks.

The configuration issues were also mitigated by a change to the propulsion system. Sensitivity analysis of the vehicle performance showed that additional rocket engine thrust was desirable, but no off the shelf engine was available with less than double the performance (and cost) of the RD-120 engine which had been baselined. However, the RD-120 is normally paired with an RD-8 vernier engine in the Zenit 2nd stage, and the vernier would add 10% more thrust to the vehicle. This kept with the design philosophy principle "**Use high-criticality components as close as possible to the way they are used now**". The RD-8 has four independently-gimbaled thrust chambers and provided significantly more control authority to the attitude control subsystem during ascent then the thrusters previously used. This eased the configuration trade issues by expanding the range of allowable CG positions.

In October of 1998 a System Design Review was held where the new configuration was presented to teams of internal and external reviewers as Pathfinder 4.0 (fig. 7). Further analysis had shown that the center of gravity problem had been decisively solved, as at no moment in flight did the CG go out of the controllable area. All other analysis showed the rocketplane and other system elements to be effective conceptual designs, ready for detailed design when funding was found to support a full-scale design effort.

Fig. 7 Pathfinder 4.0 Design

This was the first opportunity for the architecture team to use the "**Pause and Reflect**" heuristic. At the end of 1998 the design was closed, no products were due to NASA or other external agencies, and there was an opportunity to review the architecture and the problem statement. Most efforts at this point were devoted to pursuing investment, but a potential strategic partner pointed out that the market for low earth orbit launches was changing, as various communications companies were changing their designs or schedule. Teledesic was the most notable of these, as it was sharply reducing its number of launches and increasing the weight of its satellites.

Pioneer began a trade study to determine the proper vehicle size working from two directions:

1. The potential market revenue for a particular payload capacity
2. The costs of developing a launch system based on our architecture that would meet different payload capacities

The second path was a wide-ranging study to develop new design options. A variety of possible design changes were identified and analyzed for impact on program performance, cost and risk. Five potential system architectures were developed using combinations of those design options, including replacing the RD-120 main rocket engine with the more powerful NK-33, changing the size of the upper stage to improve the delta-V split between the stages, and increasing the LOX flow rate from the tanker. The largest performance increase came from a massive scale-up of the system elements by 50% (200% for the upper stage). This followed the heuristic:

Explore multiple directions based on partial evidence (54)

Each potential architecture was evaluated against the market model. A "market share" curve determined the amount of the market captured by the Pioneer system for a particular launch price (i.e., the lower the cost compared to competing systems, the higher the percentage of customers that would switch to Pioneer). Given the development and recurring costs for each option, the profitability of the system could be determined at each launch price and an optimum found that would maximize the return to investors (IRR). Trying to build a system that could serve the entire LEO satellite launch market was not the optimum approach, as the revenue to be gained from the additional launches would not justify the higher up front expenses. With every design option, the financial costs of the development funding was always higher than the operational costs of the system, so the financial issues could not be considered independently of the technical design—they were integral to the architecture decision.

This result was extremely sensitive to market model being used. The initial study result favored a rocketplane with the NK-33 engine and minimal other changes. A new report on the planned Teledesic satellite design was received shortly after that, and including that in the market model now favored an architecture that included a 50% larger upper stage in addition to the larger engine. Further reports on satellite weight growth among potential customers drove the preferred system toward a scaled-up design, and further trades were done to find the optimum level of scale-up. At this point the LEO communications satellite market became so unstable that it was no longer practical to have a set market model to design against, and finding an optimized architecture was placed on hold.

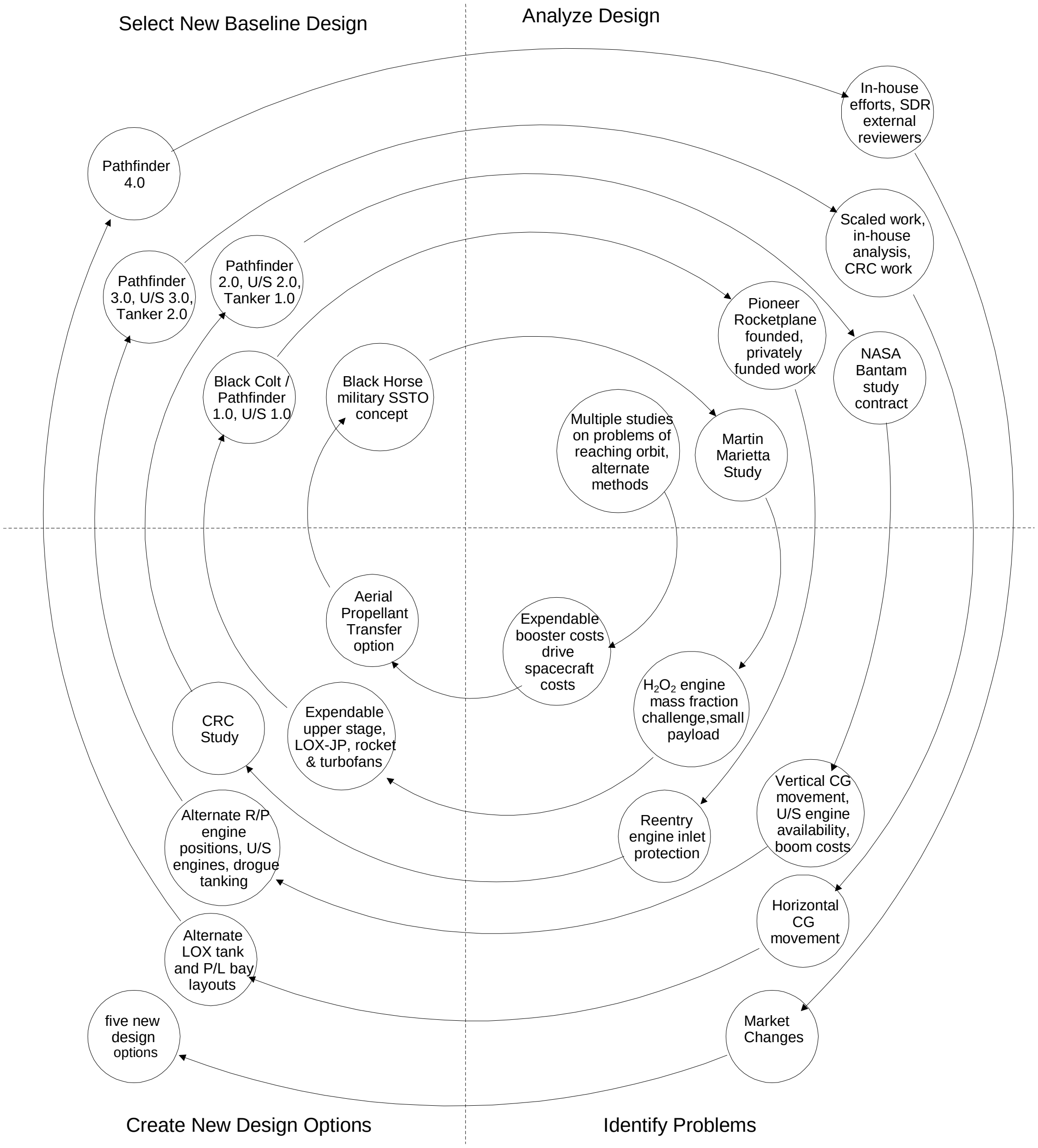

Figure 9. Aerial Propellant Transfer Launch Vehicle Architecture Design Iterations.

At that point (spring 1999) five design iterations had been done on the aerial propellant transfer architecture (fig. 9). The internal drivers of the architecture had been completely addressed. An architecture had been produced that was ready to take to detailed design and development when funding was available. Unfortunately, the external conditions driving the design had changed to the extent that no change to the design would justify the necessary funding.

Architecture Evaluation

The effectiveness of the Pathfinder system can't be proven without actually building and operating it, which is unlikely in the current market climate. However, the extensive analysis and reviews of the system provide confidence that it would be a good candidate for a launch system that launches up to 2.5 tons to low earth orbit and would be operated for over 200 flights in the time needed for the investors' return on the development funding. The system would provide a platform which could be adapted for other civil and military missions as discussed above, and would be a stepping stone for development of more efficient reusable launch vehicles.

Conclusions

Heuristics, while not known as a formal tool, were used extensively in the Pioneer Rocketplane architecting efforts. The short timelines and limited manpower available for attacking some issues required making early decisions and reviewing them later when resources were available. This worked successfully in the entire design process, and more detailed analysis of decisions made by using heuristics usually confirmed them. The issue that caused the most trouble in the architecture process (where to put the turbofans and LOX tanks on the rocketplane) had the initial unworkable designs chosen through analysis, not by heuristics. The rules of thumb used by the design team often matched closely with the documented heuristics and had the same benefit to the design.

Many of the heuristics created by the Pioneer team are specific to the architecture they were working on, but other launch vehicle design teams may benefit from considering them. Designers of horizontal take-off launch vehicles would particularly benefit. The general heuristics that the Pioneer team used would be useful for any launch vehicle team.

Bibliography

Gallagher, Karl. AAS 99-129. “Optimization of Ascent Trajectory and Related Design Issues for an Aerial Propellant Transfer Rocketplane.” AAS Space Flight Dynamics Conference, 1999.

Knapp, Matt. AIAA-99-4932. “Mission Optimization For A Reusable Launch Vehicle System”. AIAA 9th International Space Planes and Hypersonic Systems and Technologies Conference

Rechtin, Eberhardt. (1991). Systems Architecting. Englewood Cliffs, NJ; Prentice Hall.