NASA-CR-201117

Lessons Learned

DC-X

The DC-X was conceived and developed specifically to lay the ground work, for develop a data base of "lessons learned", for significantly lowering the cost of space operations. Program content and execution as well as technical solutions were addressed. Additionally, methods and solutions used in the past (50s and 60s) were exercised to expose to a new generation the possibilities of what we now call rapid prototyping. (The first Thor was launched less than a year from contract start. The operational countdown achieved 3 years later was less than 15 minutes.)

In addition to the old lessons, new available technology was implemented, for example in flight controls software development, operations displays, and flight simulations, where matrix X was used to develop the ADA code for a fraction of the cost and schedule of previous programs. Many of these accomplishments have been reported upon in other presentations. In this paper we will concentrate on the system and hardware design elements leading to future payoff.

We should also recognize at the outset that "lessons learned" may be confirmations of approaches as well as unexpected results.

As a further disclaimer, there is a substantial data base of detailed operations items which will be implemented on future programs which will not be discussed here. An example is how day-to-day photography needs to be accomplished at the range.

Lessons Learned, System Design

The system design was based on an initial set of program goals and a finite, limited set of resources. The goal in its simplest terms was to demonstrate vertical landing after rotation of the vehicle from a nose-first to an engines-first attitude. Finite resources actually drove the selection of a robust design to reduce fabrication and preflight testing costs. The result was a system with a large amount of flexibility which allowed expansion of the test goals as the system, and test program, evolved. Several modes of operation and risk reduction were introduced as the program progressed, which were not considered feasible at the start of the program. These included auto climb, auto land, engine out and differential throttling control. Differential throttling greatly increased the control margins for the rotation maneuver in flight #8, and may reduce the gimbal requirements on future vehicles.

The use of the vehicle flight computer interfacing with the ground control system for flight crew training was also not an initial concept. However, by defining an architecture for the system control modes which allowed additions and modifications as learning progressed, the 6 DOF codes used for flight controls software development were transported to the operating system to be used in a simulated flight mode. This was used for crew training as well as code checkout. Additionally, post flight analysis was accomplished by rerunning the flight data through this system and the 6 DOF animated simulation model.

Flight data reduction was also greatly improved as the program progressed, and the data needs and presentation were refined.

The software, avionics hardware, and the FOCC system development proceeded ahead of the vehicle, primarily because most of the hardware elements were existing at the outset of the program. As vehicle elements were completed, at the subsystem and system level, they were tested through the operations control system. There was very little test-unique hardware made, for example, breakout boxes for wiring. System tests proved this to be a valid approach. Later, during the operations period, some unique test hardware was made to perform tests when powering up the whole system was not warranted.

The Built-in-Test (BIT) for avionics and propulsion systems were adequate. Particularly the flight readiness system which verified the vehicle health after engine start and before throttle up for flight. Setting the go/no-go limits for these parameters was a negotiating game, and modifications were made continuously as experience allowed. The lesson here is that there never seems to be enough propulsion instrumentation. We used 6 parameters sampled three times in all four engines. Two values out of tolerance could stop flight. However, the system maintained a reliable pre-flight checkout of all subsystems. Countdown time was controlled by the vehicle fueling rate, limited by the ground system.

Things That Were Done Incorrectly

Mistakes were made which caused assembly and operations delays and impacts. Hopefully, these lessons are learned. At final assembly we discovered that hardware designers and controls software designers used different datum. Configuration control was not implemented early enough. The vehicle was designed with a ventilated engine section to avoid trapping hydrogen. A purge and fan system was used. This system allowed hot gasses to enter the engine section during engine operation and landing which damaged wiring and some low-temperature materials such as insulation on feed lines. Conversion to an all sealed system took considerable effort and was not fully accomplished until the 6th flight.

A closure hood system to protect the ground umbilicals worked well. The vehicle umbilical doors were closed with springs. Considerable development on this system was required to get sufficient initial velocity for this inertia system to work. Both the ground hood and the doors were activated with a lanyard system which worked well.

The hydraulic system has a variable displacement pump on each of the four engines and an accumulator system for backup. The engine control actuators utilized a first-time-ever electronic dynamic pressure feedback system to provide expanded band width. This system provided response rate greater than 30°/sec which saved the day on flight 3 when the vehicle "stumbled" off the flight stand due to H2 in the LO2 feed system (result of a leaking He bubbling valve). Control was maintained until full engine performance could be achieved.

This system had a puzzling pressure cycling for several flights and in the static tests. Outside experts advised that multiple pumps are not used due to this type of problem which was thought to be acoustic resonance. In investigating this phenomena, it was discovered through dynamic modeling analysis of the system that a low-flow pump instability occurs when transients cause the pump swashplate to rotate to a negative angle and cause reverse flow in the pump. A stop was added to the swashplate to terminate the instability. This phenomena had been reported on other systems but never solved in this manner. Developing the solution involved finding methods to test the pumps in the system without engine firing. It was time consuming and once again we suffered from insufficient instrumentation for trouble shooting. Nevertheless, with the above fix, the multiple pump system worked well. This is still an unacceptable system design approach for aircraft.

Landing dynamics for a rocket-powered vehicle was also an area of high learning. The initial design effort evaluated vehicle tipover from lateral motion at touchdown. This is an important issue when landing with significant residual propellant with a LO2 tank forward design. Vehicle height and wind effects are also a concern. The design analysis was performed with 3 DOF and 6 DOF analysis. These analyses indicated that the friction coefficient between the landing gear and the landing surface was a critical factor in stability or tip. Subsequent testing resulted in the application of a lubricant coating on the gear pad, which was adequate for landing on concrete. However, tests on the gypsum surface surrounding the pad showed coefficients high enough to cause tip in certain landing cases. When a successful gypsum landing was achieved on flight 5, the actual coefficient and compliance of the system were backed out of the data. The result was a much lower friction coefficient and higher compliance, which greatly reduced the tip potential. It has been postulated that the surface was blown to a clean hard surface, with possible solidification due to heating, which avoided any plowing. This effect, in conjunction with the contribution of greater compliance has modified the approach to design for future landing systems. As has been reported in previous papers, the blowing gypsum in this landing significantly reduced base heating, which has provided learning for future designs.

Propellant management for the rotation maneuver was very successful. It was accomplished with containment baffles in the LO2 and H2 tanks. This system was designed using a computational fluid dynamic code, flow 3D. The code provided a substantial margin for this maneuver; and as far as we can tell, the system performed as expected. A system to rapidly repressurize the tanks in the event of ullage collapse was never activated. The design of this system provides many lessons learned for future vehicles. The H2 tank baffle was a composite membrane structure. Both baffles utilized controlled venting to avoid gas entrapment while containing the liquid.

There were numerous other specific learning experiences for the DC-X program, many of which have been documented in the flight test reports. The excellent performance of the flight control system and the forgiveness of the vehicle to external events such as the external explosion on flight #5 and the fast landing on flight #8 confirmed many design approaches.

To close, however, the GSE should be discussed. Many issues were overlooked in the initial planning and design, which impacted the operations flexibility of the system.

The shelter is ~~of course~~ the largest and turned out to be the most troublesome. It was designed to be transported to the vehicle on the flight stand to protect it from the environment and allow a sheltered work area. The rolling dollies were extremely cumbersome to operate and required the whole ground operations crew, plus a crane operator whenever it was moved. Additionally, the doors could not be opened or closed in winds greater than 5 mph. Consequently, there were many occasions where the vehicle was left unprotected from the elements. A cantenary was placed over the vehicle on these occasions for lightning protection. It was supported by a crane which was an expensive solution.

The Landing to Launch Transporter (LTLT) had insufficient vertical travel capability to pick up the vehicle if the landing gear honeycomb dampers were crushed as they were on flight #8 and to raise the vehicle high enough for easy installation on the launch mount. In addition, the interaction of the trailer steering and the tug vehicle was very sensitive and transport to the proper location for mounting the vehicle in the launch mount required great skill. Great improvements can be made in these operations for future programs.

The learning from the DC-X program has been exclusive and far broader than originally planned, in vehicle systems and operations. The most significant lesson is that X programs are required to develop knowledge and pass it on.

Continue to be the most efficient [focused] means for developing knowledge that can be passed on for future practical application.

Don — might alternately rephrase — Thanks Bill

Don — good job! Thanks Bill