University Developed Hardware for the Space Shuttle: Strategies for Success

Andrew Peffer
Jackson and Tull/Air Force Research Laboratory
1601 Randolph Rd. SE, Suite 100N
Albuquerque, NM 87106
Andrew.Peffer@kirtland.af.mil, Phone: (505) 853-6322

Mark Kumashiro
Jackson and Tull/Air Force Research Laboratory
1601 Randolph Rd. SE, Suite 100N
Albuquerque, NM 87106
Mark.Kumashiro@kirtland.af.mil, Phone: (505) 853-7878

Lauren Egan
Arizona State University
Mechanical and Aerospace Engineering, Box 87-6106
Tempe, AZ 85287-6106
Lauren.Egan@ASU.edu, Phone: (480) 965-2859

Charles Swenson
Utah State University
4120 Old Main Hill
Logan, Utah 84322-4100
Charles.Swenson@usu.edu, Phone: (435) 797-2958

Abstract. The current trend in space science is for payload developers to minimize program cost and schedule while conducting useful science. One problem with the design, integration, and testing of low-cost missions is that much of the savings results from the assumption of risk. Analyzing lessons learned from high-risk programs is an effective means for increasing success while meeting budget and schedule constraints. University efforts, such as the University Nanosat Program (UNP), are faced with the seemingly contradictory goals of mission success and low cost while designing revolutionary experiments. Currently planned for a shuttle launch, UNP is subject to rigorous qualification requirements resulting from NASA's manned spaceflight safety program. Universities have limited experience with the design, integration, and test of flight hardware for manned spaceflight. The program has identified many areas for improvement. This paper explores the effects of various program and technical approaches--those that worked, and those that didn't. Design, integration and test, configuration management, quality assurance, and safety are considered. Lessons learned from the University Nanosat Program are expected to be the basis for success in launching future university-built technology.

Introduction

A promising way to perform many space missions is to use clusters of microsatellites that operate cooperatively to perform the function of a larger, single satellite. The University Nanosat program (UNP) is a collaborative effort between the AFRL/VS, the Air Force Office of Scientific Research (AFOSR), the Defense Advanced Research Projects Agency (DARPA), the Space Test Program (STP), and NASA/GSFC, to explore this shift in paradigm.

The program consists of multiple nanosatellites (nanosats) designed and built by US universities that are baselined to deploy from the Space Shuttle via the Shuttle Hitchhiker Experiment Launch System (SHELS). The nanosats are being built through university team efforts. Santa Clara University, Stanford and MIT are building the

Emerald and Orion spacecraft. Utah State University, University of Washington, and Virginia Tech are building three nanosats known as ION-F, and Arizona State University, New Mexico State University and the University of Colorado at Boulder have constructed the Three Corner Sat (3CS) nanosats. For both flights, the nanosats are mounted on an AFRL-built integrating structure known as the Multiple Satellite Deployment System (MSDS).

The current UNP flight compliment, dubbed Nanosat-2, consists of the 3CS hardware mounted on the MSDS. Integration and test of Nanosat-2 is completed and the payload is awaiting manifest at AFRL. The Nanosat-2 payload is scheduled to fly on the Space Shuttle in late CY 03. A schematic of the launch scenario is shown in Figure 1, and the flight hardware is shown in Figure 2.

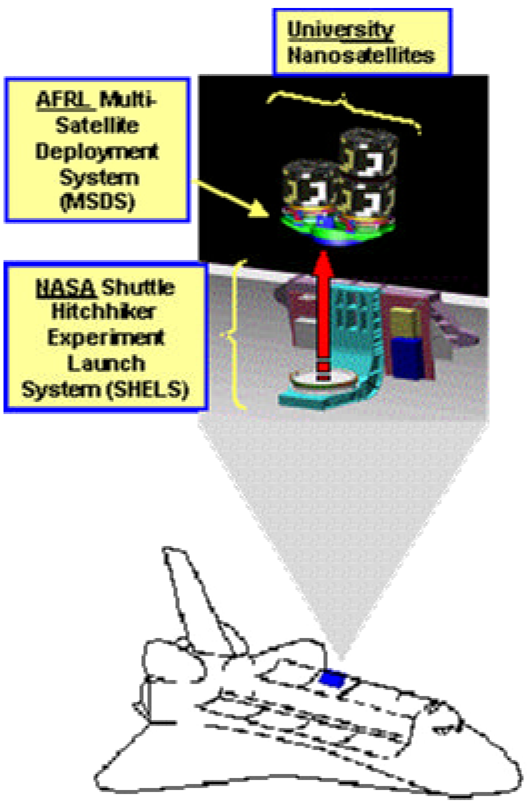

Figure 1. University Nanosat Program Concept

Throughout the program, AFRL has been responsible for program management, preparation of NASA-required documentation including safety documentation, integration and testing of the payload, and evaluation of university designs. From this vantage point, AFRL has accumulated a tremendous amount of experience in working with universities and students, developing and integrating multiple small satellites, and negotiating the NASA manned space flight safety process. This experience has resulted in a valuable list of lessons learned which is documented in this paper, and hopefully can be used by other programs both in the Shuttle and expendable launch vehicle environments. These lessons are summarized in the following sections.

Figure 2. Nanosat-2 Flight Hardware

Safety Documentation

The greatest challenge to the UNP has been navigating and implementing the NASA manned space flight safety process, a procedure being undertaken for the first time by many program participants. Aside from hardware design, build, and test, many lessons learned were generated in the area of required safety documentation. One basic issue is to ensure that the universities understand the quantity of documentation involved. This can by done by providing examples. However two related lessons learned were generated: efficient preparation of documents, and avoiding generation of unnecessary documents.

Before discussing lessons learned, a brief overview of the safety process is warranted. The safety process comprises three phases of safety reviews (Phases 0/1, 2, and 3) conducted by the JSC Payload Safety Review Panel (PSRP). For each phase, documents must be developed that analyze the payload for hazards and detail the means by which safety is verified. Examples of documents are Flight and Ground Safety Data Packages that provide a detailed description and safety analysis of the payload, Structural and Mechanical Verification Plans, a Fracture Control Plan, and a detailed materials list. For each hazardous system identified in the safety analysis, a hazard report, which identifies hazard causes, controls, and means of verifying that the controls are present, must be generated. The verifications are heavily scrutinized by NASA safety and eventually become the checklist of actions that must be satisfied before a payload can fly. Verifications consist of tests, analysis, inspections, reports, and procedures, and are first developed by the payloader as part of their documentation.

The lessons learned in efficiency focused on effective transmittal of information from universities to AFRL. For the UNP, AFRL was the overall preparer of the documents; however, the universities contributed the material relevant to their spacecraft mostly via e-mail. One of the problems encountered in this process was the delay caused by the review and comment cycle between the universities and AFRL. Students had very little experience with technical writing, especially related to safety documentation, and also had a high turnover rate. On the other hand, as the program progressed, AFRL's collective experience with safety documentation increased, with the same personnel working on all of the payload elements. Once the Phase 0/1 review took place for the first flight, a more efficient approach would have been for the AFRL safety engineer to do all of the technical writing based on face-to-face conversations with university engineers and visual inspection of the hardware or prototypes. This would have saved time in review and rewrite cycles with the students, allowed the AFRL side of the program to obtain a better familiarity with the university hardware, and taken the burden off the universities to provide a safety engineer.

Another important lesson focused on control of the scope of requirements imposed by the verifications listed in the hazard reports. This is a subject that provides the connection between payload safety and design and will be discussed in the next section "Design Engineering", as well. The hazard report verifications define a set of requirements that is essentially unique to the payload and can be controlled by the payload organization. The most obvious way to minimize these requirements is simply to design a payload with a minimal number of hazardous systems. However, for those systems where hazard reports must be developed, it is possible for an inexperienced payload organization to inadvertently burden itself with unnecessary documentation requirements. In developing verifications, the payloader must meet safety requirements, but at the same time generate the minimum amount of paper required to prove that the payload is safe.

A good example was the numerous hazard report verifications which indicated that the program would prepare "inspection procedures and inspection reports" for various steps in the hardware build-up. These documents were specified in some cases for installations that were entered into the build certification logs as standard practice. All of the steps entered into the build log were verified and signed off by a second party. Therefore, in order to establish that the verification had been met, there was little need for development of an inspection report and procedure. In reviewing the hazard report verifications, NASA reviewers are more concerned about safety issues than advising the payload on how to eliminate documentation. Another example occurred wherein universities developed detailed build procedures with sign-out blocks but also completed detailed certification logs for the same processes. Therefore, this was a duplicated effort.

Although these lessons learned apply to documentation, it is probably obvious that design and generation of safety documentation are inter-related because of the need to prove that the payload is safe. Lessons learned related to documentation are summarized in Table 1. The second half of the picture, design and engineering, is discussed in the next section.

Table 1. Summary of Lessons Learned: Safety Documentation

Lessons Learned
Recognize the quantity of required documentation early. Review examples from similar programs.
Generate documentation efficiently. The technical writer should be in direct contact with hardware builders, and know the hardware well.
Limit required documentation by minimizing documentation for hazard report verifications. Provide only what is necessary to prove safety.

Design Engineering

For shuttle projects, working the issues of design and safety in parallel will likely result in time and cost savings. Proving that a design is safe can result in a tremendous cost in document development, tests, and, analysis. The key is to design hardware with the safety requirements in mind and to come up with a design for which safety is easy to prove, i.e. the required tests, analysis, and inspections are within the budget and capability of the university. In other words, as discussed in the previous section, the payload must try to minimize the scope of requirements by minimizing the hazard report verifications. Therefore, from the design standpoint, the basic idea is to design non-hazardous systems with no hazard reports or to design systems with a minimal number of verifications that are easy to accomplish. Lessons learned identify ways in which this approach can be supported and are based on the design review process, understanding how safety problems in design can affect the program as a whole, and use of common designs.

One of the lessons learned early in the UNP program was the need to eliminate potentially troublesome designs prior to the Phase 0/1 safety review. As an example, the UNP program presented a mechanism design to the PSRP at the Phase 0/1 safety review that contained features that were out of the scope of typical aerospace practice. Although there was some concern raised about the designs prior to the review, some of the features in question were not addressed in the NASA safety requirements. At the review, the safety panel was uncomfortable with the design and raised numerous issues including technical questions, quality assurance issues, and simply how to categorize the design within the NASA safety requirements. The program left the review with action items whose resolution consumed a large amount of student time. These efforts involved redesign of the systems, which required resolution of the technical issues, developing a presentation and reconvening with the safety panel to represent the designs, not to mention several review cycles with STP, AFRL, and GSFC prior to the safety review. After the items were finally resolved, AFRL realized that the resolution of the action item consumed too many resources for all parties. AFRL later requested a redesign of several mechanisms that were questionable based on the Phase 0/1 review. The redesigns resulted in greatly simplified mechanisms, elimination of hazard reports, and a few questions from the safety panel.

Successful incorporation of the previous lessons learned obviously relies on the availability of experienced reviewers from numerous disciplines at all levels, such as engineers, technicians, and management. Although there are numerous NASA safety documents, translation of safety requirements into design implementation is not obvious sometimes. In addition, there is very little hardware that is officially "approved" by NASA because the prevailing philosophy is that each design is reviewed for safety on a case-by-case basis. As the UNP program progressed, AFRL had the advantage of reviewing several nanosat designs developed by universities, and of going through the Phase 0/1 safety review. Therefore, the AFRL reviewers developed skills in evaluating designs for safety, and recognizing designs that would likely result in action items or requirements from the PSRP. The following is a list of several of these items:

- When purchasing hardware, especially components that contain non-metallic items, obtain a materials list first and ensure that all materials meet the outgassing requirements listed on the NASA Materials websites.
- Eliminate mechanisms that rely on friction as a means of retention. This could mean

linear screws, crimps, gears, etc. Ensure that the only means of inadvertent release is through failure of a structural, metallic part. Ensure that the part is easy to analyze, i.e. the load path in all environments is clear and that materials properties are well understood.

- Eliminate structural or mechanical components that are epoxied or glued together, particularly for structures in the primary load path, and in mechanisms for which inadvertent deployment is a hazard.
- Eliminate "soft goods" such as cables, lines, and wires used in structural applications or retention type applications. These items raise many questions regarding structural load path, creep, thermal effects, integrity of connections, (for example, knots or crimps) and rigging procedures for flight.
- Eliminate composites in the primary load path. Composites include aluminum honeycomb, metallic structure that is epoxied or glued together in any way, or traditional composite materials.
- Eliminate items for which safety is highly dependent upon the build or assembly process. One example is composites used in primary load paths. If composites must be used, professionals, not students, should do manufacturing. Also, setting/rigging of complex safety critical mechanisms should be done by the manufacturer.
- Design bolted interfaces with redundant fasteners. Examine use of fasteners in accordance with NASA fracture control and fastener integrity documents. Eliminate single point failure fasteners.
- Consider fracture control in accordance with NASA-STD-5003 from the outset of design. Ensure that there are no fracture-critical components in the design and that it is easy to prove that items are non-fracture critical. Examples are design of structures with redundant load paths, and structures that are built from well-understood, machined metals, with low stresses.
- Incorporate pressure relief devices in high-pressure systems, even when redundant reducing valves are used.
- Incorporate fuses in electrical systems even if the systems will not be energized on the Shuttle.

All of the items on this list presented problems in the UNP program and resulted in cost and schedule impacts; however, many are not thoroughly addressed in the NASA safety requirements. The lesson is that when confronted with a design that is not specifically addressed in the safety requirements or is outside of standard aerospace practice, NASA safety reviewers will recommend very conservative approaches for proof of safety. Note that NASA safety reviewers will not recommend alternative designs if the design presented results in numerous safety requirements. They only review and provide recommendations on what is presented to them. Therefore, if conservative recommendations translate into too many requirements and action items for the payloader's budget, the burden is on the payloader to redesign and re-present to NASA. With this in mind the program management should have the ability to veto potentially troublesome designs early or force the designer to choose only the one or two problematic items that they feel they can best defend.

Another lesson learned related to design was implementation of commonality. Although commonality is almost always a benefit, it is even more so when considered in the light of payload safety. One example concerns the batteries used in the UNP. The UNP made very little effort from the beginning to standardize a battery box design or a cell acceptance test plan even though all of the nanosats and the MSDS were using Sanyo NiCd batteries, and the battery design is an area that is heavily scrutinized by NASA. Therefore, there were four different battery box designs used in the program and all participants purchased batteries from different sources. This resulted in development of separate documentation for each battery because different battery containers had different safety features. Also cell acceptance tests differed from one participant to another. Therefore, it was difficult to present a unified safety picture to NASA. Battery container and battery testing is generally not an area where anyone should expend resources in innovation and this should have been recognized earlier.

Other examples of instances where commonality did help in the UNP were the purchase of all fasteners from GSFC to ensure compatibility with NASA requirements, and standardization on electrical inhibit relays. In the future, standardization could expand to structural buses, flight computers, and power systems. Students can still learn a great deal about aerospace practices by assembling, installing, and testing standard systems, while maintaining more time consuming innovative efforts at a manageable level. Commonality should also apply to program-wide software such as CAD systems and analysis packages.

Other basic design principles take on even more significance when working with the Shuttle safety process. These principles are not necessarily lessons learned but should be considered carefully especially when working with first-time builders:

- Develop prototypes and engineering design units. This will give first-time builders some experience in hands-on build up and will allow qualification tests/fit checks to be done.
- Early identification of areas where additional resources are needed, such as test, safety engineering, software, satellite fabrication guidance, and analysis expertise.
- Keep satellite designs simple: Design based on capabilities and experience of the people who are doing the work.

Lessons learned related to design engineering are summarized in Table 2.

Table 2. Summary of Lessons Learned: Design Engineering

Lessons Learned
Work safety and design in parallel to avoid common pitfalls.
Limit hazard report verification requirements (tests, analysis, inspections) through design. Consider the difficulties of proving safety before committing to a design.
Review designs early using experienced reviewers. Be familiar with approaches that make the PSRP uncomfortable. Eliminate questionable designs before Phase 0/1 safety.
Implement commonality wherever possible to limit the variety of safety verifications and present a unified approach to the PSRP.

Configuration Management (CM) and Quality Assurance (QA)

One key element that must be treated early in the program is ensuring that proper hardware fabrication and building techniques are impressed upon students. One critical aspect of satellite construction that students are often unaware of is QA and CM techniques. QA and CM are important for both safety and mission success, and students need to be educated in these areas before hardware build begins. To an extent this was something that was done well by the UNP. Important QA practices were impressed on the universities early, such as two-person build and verification, maintenance of certification logs, and tracking of hardware (fasteners). These practices were documented by AFRL in a detailed CM and QA plan, which was passed on to the students and approved by NASA.

AFRL also conducted a satellite fabrication courses and sent experienced representatives to the universities for configuration management reviews. Unfortunately, although the CM review and fabrication course were effective, they were done too late in the process, after a significant amount of build-up was completed. The reason this occurred was most likely poor communication between the universities and AFRL, wherein AFRL did not know the universities' build schedule. If a representative from AFRL could have visited the universities during some of their early or more critical build up efforts, some problems with CM documentation may have been avoided.

Lessons Learned from CM and QA are summarized in Table 3.

Table 3. Summary of Lessons Learned: Configuration Management and Quality Assurance.

Lessons Learned
Educate students early in CM and QA. Develop a program-wide plan for implementing CM and QA.
Provide direct assistance to students during hardware build-up to verify students' knowledge of basic CM and QA.

Integration and Test

The integration process for UNP, i.e. integration of the University-built satellites with the AFRL-built MSDS went very smoothly, primarily because the interfaces were simple, well-defined, and were communicated to the universities early with few subsequent changes. This allowed easy configuration changes when some difficulties arose during testing. One important lesson learned in the I&T process was related to testing and the need for experienced personnel to review university test setups.

In the UNP program the universities had very little responsibility for testing, as the final payload was to be tested in an integrated state after arrival at AFRL. Most testing conducted at the universities was for mission success/confidence. However, there was a requirement imposed by AFRL that the first mode frequency of the nanosats must be a certain value or greater, such that the integrated payload could meet the Shuttle stiffness requirement. The universities had sine sweep testing conducted by an outside laboratory that resulted in a first mode frequency that was significantly lower than what was expected. When AFRL reviewed the test data and setup, the test configuration, specifically the interface to the vibe table, was immediately suspected. Since at the time the universities were ready to deliver to AFRL, the delivery took place and the system was re-tested at AFRL. The stiffness was significantly higher in the AFRL test with an improved interface fixture. The lesson learned in this case was that AFRL could have assisted with reviewing the university test setup even though the test was conducted by an outside laboratory. A better awareness of the university build and test schedule would have helped with this as well, because AFRL was not aware of the test until after it happened.

Although integration for the UNP generally was not a problem, a few areas were identified wherein the government can and should provide early support. These areas are development and operation of lifting hardware considering all phases of the program, proper design and operation of ground support equipment, and construction of hardware shipping containers. These are subjects that are important but often take a much lower priority than construction of the satellite itself. Government integration and test facilities tend to have personnel with experience with these matters whereas universities do not.

Lessons learned related to integration and test are summarized in Table 4.

Table 4. Summary of Lessons Learned: Integration and Test

Lessons Learned
Define interfaces early.
Review university test set-ups, even if they are performed by professional laboratories.
Provide government support on auxiliary operations such as lifting, transportation, and ground operations.

University Lessons Learned

This section focuses on lessons learned that are particularly relevant to universities' in house efforts on the UNP. Some lessons learned are unique to the universities, and others reflect and support the program-level issues that have been discussed so far.

The process of hardware design and build is a balance between meeting program requirements such as safety, mission, and schedule, and allowing students to be educated through design and redesign processes. To help ensure success, it is important to evaluate capabilities and arrive at a feasible conceptual design early in the program. Even having arrived at what appears to be a feasible design, universities should be consistently evaluating progress and have the ability to de-scope if necessary. There are many reasons that even a simple design can become problematic later, for example, unforeseen safety issues, requirements creep, or expected resources that do not materialize. However, the challenges that arise because of design failures or unexpected problems, and the need to evaluate and re-design are part of the education process.

In addition to developing feasible designs, which rely heavily on experience, several additional design-related strategies can help offset inexperience. Students found that purchasing commercial-off-the-shelf (COTS) components where possible instead of building hardware in-house played a large part in minimizing CM and QA requirements. Provided that the product could meet safety issues (materials, structure etc.), the QA was provided by the manufacturer and the manufacturer's Certificate of Compliance met most of the CM needs. Building EDUs is also a helpful strategy both to assure quality and to educate. For example the EDU will reveal a design's strengths and weaknesses and provide the students with experience in hardware build, even if elements of the flight unit are eventually outsourced to a professional manufacturer. Finally, developing CM and QA document templates from the outset of the program will help ensure that documentation is simple and of high quality, and that common formats are available to all program participants.

Because of the complexity and interdisciplinary nature of spacecraft development, the need for dedicated, experienced assistance is of great importance. Both students and professors have highlighted the importance of qualified mentors, particularly those that can be present at critical times. Universities have faculty available in all engineering disciplines, and personnel from all fields must be available to assist. The availability of government personnel to provide hands-on assistance is important as well. As the delivery date for 3CS approached, AFRL did send an experienced technician to assist with final build on three occasions. The students indicated that it was very helpful to have this experienced assistance in making decisions and moving forward when the time schedule was getting tight. However, they also indicated that more visits from qualified individuals would have been helpful throughout the program not only for hardware development but for documentation assistance as well. As stated previously, the students found that the satellite fabrication course offered by AFRL was helpful, but should have been done sooner. In general, face-to-face mentoring is required throughout the program.

Program management issues for universities focus on good communication among university participants, continuity in the workforce, and subdivision of tasks. Communication within the university teams is critical particularly when multiple universities are involved. Students have indicated that the familiarity obtained from face-to-face meetings with students from other participating universities allowed work to proceed more efficiently, and greatly improved teamwork. In addition, in cases where satellite subsystem design is assigned to different universities, an effort should be made to educate all participants in the design and operation of all systems. This will greatly aid in component integration and documentation development. Also subdivision of the program into smaller tasks, whatever the program structure, is important to keep students from being overwhelmed by subjects with which they are not familiar. Universities should also establish a common project website to collect and organize materials such as requirements, designs, datasheets, etc. so that they may be available to everyone. Use of such tools as an organized website, improved teaming through face-to-face meetings, and good program documentation in general will not only help the program run smoothly day-to-day but will help combat issues of continuity in workforce that arise when students graduate, move on to other programs, etc.

One final important issue is motivation. The best means of obtaining of obtaining quality work and maintaining student motivation is simply to pay the students for their work. Students have also indicated that major motivators are the ability to interact with government and industry and thus obtain experience and training after graduation. The opportunity to build and fly space hardware is another motivator. It is important that all participants understand the level of motivation of the student workforce because of the large amount of work involved in a Shuttle flight and the need to recognize where assistance is needed.

University lessons learned are summarized in Table 5.

Table 5. Summary of University Lessons Learned:

Lessons Learned
Assess feasibility of conceptual designs early and have the flexibility to descope if problems are encountered late in the design.
Ensure that students have dedicated, experienced mentors both from the university and government.
Ensure good communication between university team members, through face-to-face meetings and websites.
Subdivide the program into smaller tasks for students so that they can more easily handle unfamiliar areas, such as program management or CM.

Program Management

Program management lessons learned are focused primarily on ensuring success despite university inexperience and managing government/university interaction. The most important part of ensuring success is to have good strategies for university design assessment. Designs must be reviewed regularly and efficiently, not only to identify deficiencies, but also to identify where universities need outside help before problems begin. Another important topic is the need to establish a good government/university interaction in which each party understands the other's goals, mode of operation, and capabilities. These topics are discussed in the next subsections.

Design Assessment

The subject of early design review has been discussed earlier in the context of avoiding safety problems. Another more basic area that must be assessed is the universities' ability to deliver innovative hardware whether there are safety issues or not. On the university side, there is a need to propose design concepts commensurate with technical capabilities. In order for the government to provide input, design review and evaluation should begin earlier than PDR or Phase 0/1 safety. Making the review process a competition between universities may be an effective tool. For example, rather than evaluating the designs based solely on the quality and quantity of science experiments involved, the ability of the universities to accomplish the proposed design using a student workforce and available resources would be evaluated and factored in the competition as well. Points of evaluation may be: simplicity of the design, ability to pass safety, amount of documentation generated, need for outside special technical capabilities, and/or ability to stay on schedule and within budget. Because of the design and safety issues discussed earlier, it is difficult to produce hardware that is innovative, low budget, and can meet the Shuttle requirements. Therefore, the universities would have to convince the reviewers that they could accomplish both goals, or face elimination from the program.

In addition to simply reviewing design concepts, another benefit of early evaluation is identification of areas in which universities may need help. This can include technical help in such areas as structural and thermal analysis, hardware build, or use of test facilities. Other areas that may be pitfalls are negotiation with other government agencies that may be involved, (providing the universities with experimental hardware), arranging bulk purchases of common equipment, and assisting with administrative issues such as International Trade in Arms Restrictions (ITAR). All of these issues came up in the UNP; some were dealt with successfully and others were not. However, once again universities and government should work together early to anticipate these items.

Of course the need to review design items is continuous throughout the entire project, and this leads to the need for structured review and comment cycles. Readiness for design reviews such as PDR and CDR are often defined in terms of completeness of documentation, such as drawings and analysis. In addition, some of the safety verifications required by NASA were simply reviews of university documents by AFRL representatives. A good document review policy was never established by the UNP; therefore, many design documents were reviewed after the fact, i.e. after the hardware was built. This obviously hindered success in many ways and ties into the need for better communication. Some things that must be considered are prioritizing safety or mission critical review items, generation and review of procedures with time to incorporate changes, and using the level of documentation development as a gauge of program status.

University/Government Interaction

The first lessons learned that will be discussed in this section involve the need for government and universities to have a common understanding of basic program issues. These issues are interrelated and involve communication, scheduling, goals, and developing reasonable expectations of the student workforce. Government engineering programs are inherently different from those of universities especially in the case where students are performing most of the work, i.e. the student work force is different than a government contractor. A university in a low-budget, high-risk situation may not be able to alleviate problems by adding additional funds or experienced personnel. Therefore, although the university PI's should take responsibility for solving management level problems, the program will still rely on a student workforce, and, therefore, all parties must agree on some limitations that come with that workforce.

One of the most basic concepts is the need for the government and universities to account for students' schedules. Students have other obligations and priorities such as exams, class work, and projects, all related to their ability to graduate. The lesson learned is that the government has to have realistic expectations of student work schedules and the universities have to communicate a realistic schedule to the government. For example, if it is not realistic that work will be accomplished over exam periods or scheduled vacations, it is better to simply account for that down time in the schedule. The experience from the UNP was that although there were students working on the program during vacations, usually some key personnel were not available. Recognition of these downtimes is a good way to avoid friction from the outset and will have a positive effect on morale. Early in the program, government personnel would view breaks as times in which the universities could get caught up on work. This was not always true, for obvious reasons such as students' planned vacations, but also because semester breaks were often the point at which student turnover occurred due to graduations and, therefore, new personnel had to be brought up to speed at those times.

Another important item to take into account regarding schedule is the inevitable redesigns that take place due to the difficulty of meeting NASA safety requirements. The university students were often designing spacecraft systems for the first time and most people involved including PI's had minimal experience with NASA safety. As discussed earlier, one of the lessons learned on the UNP program is that the government program management needs to identify and eliminate designs that are potential safety problems early on. However, because of inexperience and low budget, initial student efforts will often incorporate elements that are outside the scope of standard aerospace design and may have problems meeting safety requirements. In these cases the schedule needs to account for redesigns and the government should be prepared to provide technical assistance.

Government organizations and universities should also have a mutual understanding of goals. For the government, the goal of university programs is obviously to access and demonstrate university-developed space technology. The program is also a recruiting and workforce training tool for future scientists and engineers; a benefit for all. For universities and students, education and technology are both goals. However, the government's expectation going into the project should be that student education takes precedence. For example, documentation, presentations, and safety items may be prioritized lower than design and hardware build. This can cause problems early in the process where most of the deliverable items consist of documentation. One solution may simply be more direct support of university document development by the government. Another approach is to only allow simple designs for which the documentation is less complex (particularly for Shuttle safety) so that the paperwork can be accomplished reasonably well by students. In any case the important point is to combine government experience with the universities' ability to conduct advanced research on a low budget.

Good communication between the government and universities is a common theme in the previous paragraphs. The UNP program employed some successful basic communication practices such as regular integration telecons with students, and an FTP site where program documentation of all types could be exchanged between AFRL, NASA, and the universities. There were also some areas that could have been improved. A better knowledge of university schedules on the part of AFRL, such as the hardware build schedule would have been beneficial to both organizations. In addition, universities indicated a desire for AFRL to better indicate the priorities of deliverables such as data, documents, procedures, etc. so they could improve resource management.

Program Management lessons learned are summarized in Table 6.

Table 6. Summary of Lessons Learned: Program Management

Lessons Learned
When planning schedules/events, acknowledge that student schedules vary greatly from industry.
Allow for safety redesigns in program planning.
Government/universities should recognize each other's program goals and plan accordingly.
Universities should prove that they have the capability to deliver hardware.
Identify areas where universities will need outside support early in the program.
Establish a structured document review process.

Summary

The lessons learned discussed in this paper bring out some common themes that can be applied to government/university programs, particularly those that are Shuttle flights. The lessons illustrate the need for mutual understanding of program goals and schedules, the need for early identification of problem areas especially related to safety, and identification of areas where students and universities require government assistance, both technical and non-technical. With these concepts in mind, university satellite build programs can be successful, provided that the designs are within the capabilities of the students. The government participants must have sufficient experience to effectively evaluate university designs so that success is possible, and so that costs and schedule remain within limits. Government and universities also need to communicate effectively so that the more experienced government personnel can provide timely assistance to universities as needed. The UNP has been a success, considering the initial lack of experience on the part of most participants. As a result of the UNP, AFRL has gained a vast amount of experience in university satellite programs that it will apply to follow-on efforts.

Andrew Peffer is a mechanical engineer employed by Jackson and Tull Chartered Engineers, Inc. He is stationed on-site at the Air Force Research Laboratory, Kirtland Air Force Base, NM, in support of the VSSV Advanced Mechanisms Group. Mr. Peffer is the safety

engineer for the University Nanosat Program and also provides technical support for low-shock release mechanisms research. Mr. Peffer received an M.S. in Mechanical Engineering in 1998 from the University of New Mexico.

Mark Kumashiro is a mechanical engineer employed by Jackson and Tull Chartered Engineers, Inc. He is stationed on-site at the Air Force Research Laboratory, Kirtland Air Force Base, NM, in support of the VSSV Advanced Mechanisms Group. Mr. Kumashiro is the systems engineer for the University Nanosat Program. He received a B.S. in Mechanical Engineering from the University of California at Berkeley and an M.S. in Civil Engineering from the University of Texas at Austin.

Lauren Egan is a student studying Chemical Engineering at Arizona State University. She is the Program Manager for Three Corner Satellite, part of the University Nanosat Program and is currently supporting the program as a Space Scholar at the Air Force Research Lab, Kirtland Air Force Base, NM.

Charles Swenson is a Professor in the Department of Computer and Electrical Engineering at Utah State University. He is a Principal Investigator for the University Nanosat Program ION-F team.