The Space Congress® Proceedings
2003 (40th) Linking the Past to the Future - A Celebration of Space

May 1st, 1:30 PM - 4:30 PM

Paper Session II-B - Legacy and Emergence of Spaceport Technology Development at the Kennedy Space Center

Stanley Starr
Dynacs Inc., Kennedy Space Center

Legacy and Emergence of Spaceport Technology Development at the Kennedy Space Center

Stanley Starr
Dynacs Inc.
Kennedy Space Center, Florida

Kennedy Space Center (KSC) has a long and successful legacy in the checkout and launch of missiles and space vehicles. These operations have become significantly more complex, and their evolution has driven the need for many technology developments. Unanticipated events have also underscored the need for a local, highly responsive technology development and testing capability. This evolution is briefly described, as well as the increasing level of technology capability at KSC. The importance of these technologies in achieving past national space goals suggests that the accomplishment of low-cost and reliable access to space will depend critically upon KSC's future success in developing spaceport technologies. This paper concludes with a description KSC's current organizational approach and major thrust areas in technology development.

The first phase of our historical review focuses on the development and testing of field-deployable short- and intermediate-range ballistic missiles (1953 to 1958). These vehicles are later pressed into service as space launchers. The second phase involves the development of large space lift vehicles culminating in the Saturn V launches (1959 to 1975). The third phase addresses the development and operations of the partially reusable launch vehicle, Space Shuttle (1976 to 2000). In the current era, KSC is teaming with the U.S. Air Force (AF), industry, academia, and other partners to identify and develop Spaceport and Range Technologies necessary to achieve national space goals of safe, low-cost, and more reliable space flight.

Ballistic Missiles (1953 to 1958)

Much of the liquid-fueled missile-firing technology can be traced back to Proof Stand VII at the German missile development center at Peenemunde. This test stand was used extensively for the development and later production testing of the V-2 rocket during World War II. The facility included many of the features of missile test and launch facilities of the 1950s, including a concrete blockhouse, launch gantry, and even a captive firing fixture that permitted verification that the trajectory control systems were functioning properly. Dr. Kurt Debus, Test Engineer for Proof Stand VII, was among the handpicked German engineers who immigrated to the United States with Dr. Wernher von Braun to continue postwar rocketry developments under the sponsorship of the U. S. Army [1]. After moving to Huntsville, Alabama, in 1950, von Braun's team began the development of an improved missile named Redstone. In 1953 a group led by Debus arrived in Cape Canaveral to begin test launches of the new missile. This group became known as the Missile Firing Laboratory (MFL). During the 1950s, the MFL built several launch pads for the Redstone, Jupiter, and Jupiter C missiles. The design responsibility for that equipment rested with groups in Huntsville while Debus's team focused on procedures and operations.

The first launch sites were austere since the missiles were intended to be launched under battlefield conditions from truck convoys, a process called "shoot and scoot." The iterative test launch activity required safer and more sophisticated launch facilities, including a blockhouse and launch gantry. The gantry, a tall movable structure included a crane to erect the missile and provided stairs and access platforms for servicing. The gantry was rolled away prior to ignition, leaving the missile standing alone on the tiny launch stand and flame deflector. The blockhouse, only a few hundred feet away, safely housed the launch team close enough that the switches and indicators on the consoles could directly connect to relays and instruments inside the missile and to ground support equipment. One restored blockhouse and its equipment can be seen today at Complex 5/6 at the USAF Space and Missile Museum. The equipment even includes an industrial scale with a large dial for weighing the rocket during fueling. Like the V-2, the Redstone would simply rise off the umbilical connections between the base of the rocket and the launch stand. Much of the launch equipment developed for missile test purposes can be seen as precursors to space vehicle systems even though the primary emphasis was on developing field-deployable, rugged, and errorproof weapons systems. Later, these missiles and launch sites were pressed into service flying reentry nose cones, the first successful U.S. satellite, and the first American in space.

Large Space Lift Vehicles – Saturn Projects (1959 to 1975)

The Saturn project, initiated in 1958, challenged the Debus team to jump from incrementally improving German legacy systems to creating new technologies capable of handling the checkout, integration, and launch of multistage million-pound rockets [2]. Expansion of NASA and contractor staffing also meant the rapid infusion of a cadre of young engineers, primarily from engineering colleges throughout the Southeast, who would create the spaceport technologies for the Saturn and Space Shuttle.

Complex 34 with its single launch stand was completed in 1961. The Saturn stood on a massive ring-shaped launch stand on four legs underneath which a mobile flame defector was positioned. The flame deflector was removed between launches for inspection and refurbishment. The Saturn stages were brought in from barges and aircraft directly to the launch pad, where a huge movable gantry tower, shaped like an inverted U with a bridge crane on top, picked up the stages for erection on the pad. The first Saturn rocket lifted off Complex 34 in October 1961 with a live first stage and a dummy upper stage and nose cone. This huge rocket lifted off the launch stand with no umbilical tower, a picture that strikes us as odd today. The tower was added to service the new S IV hydrogen/oxygen upper stage and required the use of one of the most difficult and troublesome of all spaceport technologies, the swing arm umbilical. The umbilical provides a connection between the ground and the vehicle for propellant loading, command signals, electric power, and other functions. The Saturn first-stage umbilical connections were attached to the launch mount, and the rocket literally rose off the connections. An upper-stage swing arm carries a plate at its vehicle end containing all of these connections. Most umbilicals are required to stay attached until vehicle liftoff in case a problem requires the rocket to be "safed" (i.e., drained of propellants). These are called T-0 umbilicals and must disconnect and swing or retract out of the flight path of the rocket. The Saturn also required these arms to damp wind-induced motions of the vehicle since wind tunnel studies had shown that the vehicle would rock strongly and even fall over in high winds. The length of the arm was based on the possible sideways movement of the vehicle during its slow rise off the pad to ensure that the rocket did not contact the tower.

Another new launch accessory was the holddown system. A single-engine launch vehicle, like a Redstone, simply ignites and rises off the launch stand when the engine thrust exceeds the vehicle's weight. A multiple-engine vehicle must be held down while the engines are started in a timed sequence to avoid water hammer in the propellant feed lines. These holddown arms must release after all of the engines ignite properly and then quickly retract out of the way.

The lessons learned from Complex 34 were reflected in changes to Complex 37, whose single mobile servicing tower and dual launch stands were completed in 1964 to accommodate the increased launch tempo in testing the Apollo/Saturn 1B. The servicing tower used a derrick crane so that large air-conditioned clamshell rooms could be provided to enclose the stages for more extensive on-pad processing. Whereas the small Redstone rockets were transported by truck to the Cape and checked out in a hanger, the Saturn stages were transported by ship or aircraft and taken directly to the launch pad. The extensive integration and checkout requirements, plus the harsh beachside climate, forced the development of these checkout facilities, called white rooms, attached to the service tower.

Many lessons were also learned in the handling of huge quantities of liquid oxygen and liquid hydrogen. Use of cryogenic propellants allows the compression of a large mass of gas into the small volume of the launch vehicle, but with these benefits come the difficulties of handling ultracold, highly flammable liquids. Extensive experience had already been gained with the use of liquid oxygen, but the use of liquid hydrogen drove the need for many new handling technologies. These included leak detectors using mass spectrometers and new types of ultraviolet fire detectors based on radioactive detector technology. The establishment of an in-house applied chemistry and physics capability at KSC to develop new technologies for liquid hydrogen began a significant technology development tradition at KSC. These "offline laboratories" have continued to develop technologies enabling and improving critical ground processing systems and responding to many unforeseen processing events and anomalies.

The Saturn V, the huge rocket that took humans to the moon, required the largest and most complex launch facility to date. The rocket contained so much explosive propellant that locating launch personnel in a nearby blockhouse was no longer safe. This and the complexity of the vehicle, with its three stages and two space vehicles, called for a giant control center located 3 miles away. Many of the launch decisions would require the lightning speed of computers; therefore, the proverbial button to ignite the engines would disappear. The vehicle would be assembled and checked out in one of the largest buildings ever built, the Vehicle Assembly Building (VAB), then transported out to the pad just days before launch. The vehicle was assembled on a Mobile Launcher Platform (MLP), which included two hardened floors filled with special power, hydraulic systems, and instrumentation. It also formed the foundation for the umbilical tower. The entire assembly was named the launch umbilical tower (LUT).

The Apollo spacecraft command and lunar modules were processed in the new Operations and Checkout (O&C) facility. Unique equipment included two huge altitude chambers, where astronauts would train and check out the spacecraft in a near vacuum, and the extensive computerized Acceptance Checkout Equipment. The limited access provided to the spacecraft through the small egress doors also drove advances in data network technology so that a single cable could carry hundreds of measurements. Encapsulated spacecraft were then transported to the VAB for the final assembly of the giant rocket. The three stages and spacecraft would all be stacked on the LUT and carried by what has become almost symbolic of KSC's spaceport technology, the Crawler Transporter. The Crawler, a giant truck, was adapted from mining steam shovel technology. After some initial problems, the two Crawlers have racked up over 2,500 miles, all at about one mile per hour.

During the Apollo era, the primary design responsibility for specialized launch equipment rested with engineers at the Marshall Space Flight Center (MSFC). General Electric received the contract to design and manufacture the specialized ground support equipment from its locations in Huntsville and Daytona Beach. The umbilical swing arms for example were tested by the Huntsville center and shipped to KSC for installation. KSC engineers were responsible for the design of fixed installations such as the storage and transfer of high-pressure gas and cryogenic fluids. The major facilities were built and activated by the Army Corp of Engineers.

KSC engineering became known for developing top-quality specifications, standards, and processes for designing and producing high-reliability components and systems. As a result, companies throughout the nation benefited from upgrading the quality of their commercial products to conform to the rigorous KSC standards [3]. Many of these standards have become obsolete and have been abandoned as industrial standards have matured. The large number of Apollo-era components, including valves, hydraulic systems, and pneumatic regulators, still in service at the Shuttle launch pads is testament to the excellent design work performed.

The Crawler drove the LUT out to the otherwise bare pad, elevated to contain two floors of electrical connection and other support systems. The Crawler would also bring out another huge girder structure called the Mobile Service Structure. This included clamshell rooms that closed around the spacecraft end of the Saturn V. The first Saturn V launch occurred in November 1967 and generally validated the approach taken to design the launch equipment, although launch blast, heat, and acoustics damage to holddown arms and other equipment was much more severe than expected.

The trend to this point was increased checkout and integration of vehicle stages at KSC. Specialized checkout facilities proliferated in the Apollo-era spaceport technology, and KSC engineers shouldered an increasing responsibility for their development. The conduct of large integrated tests and the wide geographic spread of involved facilities drove the need for extensive data and voice networks. This era saw the creation of two areas of key KSC competency, data networks (video, voice, and timing) and large-scale, computerized checkout and control systems.

Transition to Space Transportation System (1976 to 1981)

The Space Transportation System (STS), a radically different concept and approach to space flight from the expendable Saturn V, required the development of entirely new launch and landing facilities, systems, and equipment. KSC took a leadership role in ground systems development. KSC proposed and implemented innovative designs utilizing as much of the Saturn hardware as possible. For example, the LUTs were dismantled to form the pad Fixed Service Structures and MLPs. The VAB high bay area was rebuilt from four Saturn stacking cells into two Shuttle stacking bays, an External Tank processing area, and the Solid Rocket Booster (SRB) rotation area. Some completely new facilities were also required. An Orbiter Processing Facility (OPF) with two hangar-like bays and a complex system of wraparound platforms was designed and built. To complete the processing cycle, a huge runway and associated equipment, called the Shuttle Landing Facility, was built.

Each of these facilities required unique and complex ground support equipment, including mechanical ground handling fixtures, fluid management, and electrical checkout systems, all customized and directly interfacing with the particular needs of the Shuttle. These systems were designed by NASA and contractor engineers at KSC and built by outside contractors. Each system required extensive testing. Saturn swing arm test equipment was dismantled and relocated from MSFC to KSC in 1974. This equipment was then modified and activated at the Launch Equipment Test Facility (LETF) in 1976 to support testing of the Shuttle Tail Service Masts, Orbiter Accesses Arm, External Tank Vent Arm, and later the GOX Vent Arm. Many of the servicing and launch support systems were classified as safety-critical, requiring extensive reliability analysis and review. Facility designs such as the OPF extensible platform system required the use of, for that time, cutting-edge computer modeling tools used to great effect in ensuring that enclosing structures and extendable platforms did not contact the vehicle.

To support rapid Shuttle turnaround schedules, called “flows”, the Cargo Integrated Test Equipment (CITE) was developed to simulate the mechanical, avionics, and electrical interfaces between the Space Shuttle Orbiter and the experiments in the Payload Bay. CITE was used to test and check out numerous payloads in the Vertical Processing Facility (VPF) and Horizontal Processing Facility located in the O&C building, as well as International Space Station elements in the Space Station Processing Facility (SSPF).

Perhaps the crown jewel of the Shuttle transition at KSC was the Launch Processing System (LPS). A real-time control and monitoring system capable of processing and displaying over 10,000 measurements and commands, the LPS not only interfaced with the Shuttle at the launch pad, it was also used to support processing in the OPFs, VAB, and Hypergol Servicing Facilities. Another key electronic system developed during this period was the Digital Operational Intercom System-Digital allowing efficient communications among test team members across KSC as well as Johnson Space Center (JSC), MSFC, and Dryden Flight Research Center.

Early Space Transportation System Operational Period (1981 to 1986)

In 1981, STS-1 was launched. Early Shuttle missions resulted in many lessons learned and drove changes to processing and launch. For example, the much-higher-than-expected overpressures experienced at SRB ignition drove the need for a project called "Grey Streak," which modified the pad sound suppression systems. Also during this period, new facilities were activated to process a growing Shuttle fleet and to support increased flight rates. Work continued to activate Launch Complex 39 Pad B and two more MLPs. Another engineering activity was the analysis of hazards associated with the possibility of inadvertent SRB ignition in the VAB. Extensive analytical work and experiments aimed at estimating how fast an SRB ignition would cause fatal levels of heat and smoke, and new rapid methods of detection and alarm led to the conclusion that the only safe approach was moving people out of the building. The low-tech solution, still with KSC today, is a large modular housing complex (trailers).

KSC engineers were called upon in large numbers to support the Air Force Shuttle systems development at Vandenberg Air Force Base (VAFB) in California. KSC expertise was essential in correcting numerous design problems. Sound suppression, liquid oxygen loading, Environmental Control Systems, umbilicals, hypergolics, hydraulics, Vandenberg LPS, and concern about hydrogen entrapment and detonation were areas where KSC engineers made significant contributions. After overcoming many problems, the Air Force canceled its Shuttle effort and switched to the Titan IV as its launch solution.

KSC's organizational approach to engineering was also significantly changed during the early operational period of the Space Shuttle. A major realignment of the NASA organization and contracts led to the era of "self-sufficiency." Organizations were aligned with major KSC functions to process and launch the Shuttle, perform base operations, and process payloads. Creation of these three major organizations streamlined many aspects of operational management and reflected the decrease in engineering requirements as major facilities and systems transitioned from development to operations. One result was the realignment of the design engineering contractor functions as each operations contractor assumed its own sustaining engineering responsibilities. Thus, the bulk of the engineering talent was transitioned from a single large contractor to the Shuttle Processing Contract, Base Operations Contract, Payload Ground Operations Contract, and their corresponding NASA operational directorates.

There remained a small contingent of developmental scientists and engineers, both contractor and civil service, to support the enhancement of ground support equipment and the resolution of unanticipated problems. This small development group has invented and introduced a number of very useful technologies into the Shuttle processing infrastructure that have improved safety and lowered costs. For example, various pieces of nondestructive examination equipment were developed, including a scanner that automatically maps and classifies defects in the Orbiter external windows. Several generations of mass-spectrometer-based leak detection systems provided adequate warning of cryogenic leaks aboard Orbiters, including early warning of a potentially catastrophic leak on Challenger's first flight (STS-6). Improved ultraviolet hydrogen fire detectors, unique to KSC, informed launch managers of a huge hydrogen fire after the first on-pad abort during STS-10, preventing crew evacuation into the invisible flames. Sensors to detect low part-per-billion concentrations of hypergolic propellant vapors improved personnel protection in processing facilities and at the pad. These and other solutions to such practical problems contributed to KSC's reputation within the Agency for appropriate use of technology development for mission risk avoidance and a demonstrated ability for developing inventions with high potential for spinoff into commercial applications.

Return to Flight (1987 to 1990)

The Challenger accident led to a critical reexamination of the design basis and systems engineering philosophy for all ground systems at KSC. New processes were implemented to ensure critical items were recognized and processes were in place to guarantee that their acceptance criteria remained valid. Significant modifications were made to safety systems throughout the Space Center, and previously declining engineering staff levels were increased. The early Return-to-Flight missions brought new scrutiny and challenges (including hydrogen leaks on STS-35 and STS-38), stimulating significant improvements and innovative technologies for leak detection and location. The extensive hydrogen leak testing work at KSC, which included full-scale mock-ups of the 17-inch disconnect area, resulted in the installation of external purge nozzles on each MLP, the development of the Hydrogen Umbilical Mass Spectrometers, and invention of improved ultrasonic leak locators. These and other issues were a major stimulus to the engineering development capability at KSC. This period also saw the activation of enhanced payload processing facilities and a third OPF high bay. The incorporation of excess VAFB ground equipment into KSC inventories occurred in the outfitting of the third OPF bay.

During this time, the Partial Payload Checkout System (PPCU) was developed as a sophisticated, flexible, and distributed checkout system for Space Shuttle's widely diverse assortment of payloads. PPCU was first installed in 1989 and primarily consists of off-the-shelf hardware and software.

International Space Station (1991 to 1999)

The nature and volume of Shuttle payloads associated with the construction and logistics of the International Space Station (ISS) stimulated a new era of growth in KSC engineering and operational requirements. These included building the Space Station Processing Facility (SSPF) and its myriad specialized ground support systems. The challenge was to process and check out some of the most complex one-of-a-kind systems ever built and ensure they would perform flawlessly when mated on-orbit. The SSPF provides mechanical ground handling and electronic checkout systems that allow component interfaces to be fully explored, characterized, and validated. The Test, Control, and Monitor System, whose architecture was heavily influenced by PPCU, supports the checkout of ISS elements. In addition, many unique access and handling fixtures and fluids management systems were designed and created by KSC engineers. The activation of the SSPF and associated facilities in the later part of the decade represented a major accomplishment for KSC and spoke to the strength of the engineering culture at KSC.

In addition, Space Shuttle logistics support was enhanced through the construction and activation of the NASA Shuttle Logistics Depot and Space Shuttle Main Engine Processing Facility.

KSC's ability to invent unique launch and landing processes and technologies enabled strategic rescoping of KSC Shuttle processing functions without compromising mission safety. Advances in process engineering, innovative tooling, data mining, and computerized process models and tracking systems made it possible to understand flight hardware processing on a new level, enhanced processing capabilities, and provided additional insight tools. These improvements facilitated mandated workforce reductions and allowed NASA personnel to pursue developmental initiatives such as advanced technology concepts for Shuttle and future Reusable Launch Vehicles. This included the JSC-led Integrated Vehicle Health Management (IVHM) system flown on STS-95 and STS-96. KSC provided the integration of IVHM sensors, developed the data acquisition system, and invented two new sensors. It was recognized that economic improvements in reusable space systems depend not only on new vehicle technologies but also on improved processing systems.

Several projects were initiated to replace the functional but antiquated LPS system, the latest a distributed, network-based Checkout and Launch Control System (CLCS). Perhaps the most ambitious development project ever embarked upon at KSC, CLCS was to produce a state-of-the-art critical control and monitoring system with an architecture that allowed incremental upgrades and adaptation as technology created new opportunities, thereby avoiding obsolescence. Work was well underway and a portion of the system had been activated when its cancellation was announced in October 2002. The Shuttle continues to be launched with 1976-era technology although efforts are underway to ensure LPS maintainability and reliability through technology upgrades.

Spaceport Technology Center (2000 to Present)

With plans underway for a single-stage-to-orbit reusable vehicle, X-33, and a hypersonic reusable vehicle, X-34, the Center reorganized in 2000 to ensure that its technology development contributions could be nurtured and operational expertise shared without lessening the focus on flight and ground processing safety. "KSC 2000" resulted in the consolidation of previously dispersed elements of the Center involved in technology development into a directorate named Spaceport Engineering and Technology (SE&T).

The SE&T organization created "testbeds" or laboratories designated for performing research and available to support industry research and development needs. The Cryogenics Testbed was created from a furniture storage building using a State of Florida loan to Dynacs Inc., the engineering development contractor. This loan was administered by the State's Technological Research and Development Authority under an energy-related economic development program. In the days before the official grand opening, testbed personnel supported the freezing of hydraulic fluids in the Orbiter at the pad to allow for the changeout of a critical component, avoiding a several-month rollback delay. The Corrosion Testbed analyzes new coatings for reinforced concrete, structural steel, and stainless-steel tubing, and also partners with the military to test new metal coatings for ground and airborne structural materials. The assets in the corrosion area include a large fenced compound along the Atlantic Ocean for natural salt spray testing. The newest testbed is working on the difficult problem of rocket acoustics and the tremendous effect it has on the vehicle and launch pad structure. A significant and unsolved problem in making spaceflight practical is the proper acoustic design of a launch facility to minimize sound-induced vibration, manage hot gases, and avoid the potential for the buildup of explosive gas levels in the event of an abort.

The Launch Equipment Test Facility (LETF) has evolved from testing the Shuttle umbilicals and holddown posts to providing mechanism and cryogenic testing for a wide range of customers. The LETF tested the X-33 umbilicals and holddown systems and played a key support role to the Boeing and Lockheed Martin Evolved Expendable Launch Vehicle pad accessories testing, including data acquisition at the launch pads. The Cryogenics Testbed was a spinoff of the LETF. The next spinoff is a new facility under construction at Complex 20 on the Cape Canaveral Air Force Station called Advanced Technology Development Center (ATDC). The ATDC will provide full-flow testing of spare liquid oxygen pumps for the Space Shuttle launch pads. It will then be available to support any other full-scale cryogenics testing, including propellant densification systems and hot fire of cryogenic engines.

The instrumentation and communications laboratories continue to be the major creators of new patents and technologies. Recent products include radio frequency sensor networks, a new instrument based on temperature-corrected laser distance meters to help operators align the External Tank to the SRBs, a pinpoint lightning strike locator for the launch pads, and a spacecraft wire tester that can not only locate wire breaks but also indicate locations of wear. Technology developments have led to numerous patents and commercial agreements in part because of the practical nature of the KSC mission. Corrosion protection coatings, data acquisition, leak detection, lightning location, bearing lubrication, and other applied technology needs form the basis for many critical Spaceport functions yet meet the technology needs of industry and the American public. In fiscal years 2000, 2001, and 2002, KSC led the Agency in Space Act Awards to employees based on new technologies and inventions.

KSC's current strategies continue its primary focus on the safety and cost of Space Shuttle ground operations, the delivery of the best-possible hardware to the ISS, and the successful accomplishment of NASA's Expendable Launch Vehicle missions. In addition, the Center is strengthening developmental capabilities to both improve current operations and to ensure KSC's role and relevance in the upcoming generations of space transportation systems. The Center has entered into partnerships with the State of Florida, universities, and private firms to leverage outside funds and expertise. Projects like the Cryogenics Testbed, Advanced Technology Development Center, and Space Experiment Research and Processing Laboratory will allow KSC to meet Agency science and engineering goals, increase its technology impact within the U.S. economy, and take advantage of its location as the portal through which most U.S. payloads will pass on their way to orbit. KSC has also taken a leadership role in developing working groups involving the Air Force, industry, academia, and other public organizations to develop national technology roadmaps for spaceport and range technologies. Finally, the University-Affiliated Technology Development Contract, a partnership vehicle to involve universities heavily with KSC research and development activities, will go into effect early this year. These partnerships will lay the groundwork for realizing a vision called the Spaceport Technology Center, wherein KSC leverages its intimate knowledge of spaceport operations and its in-house expertise with the resources and expertise of universities, industry and other organizations to create technologies needed to reduce spaceflight costs and provide technology benefits to the public.

Acknowledgements

Versions of this paper were reviewed and valuable inputs made by Jack Fox, Rita Willcoxen, Roelof Schuiling, Dave Shelton, Dick Lyon, Lynn Starr, Mike Sumner, Rick Hurt, Ruth Harrison, Temel Erdogan, Terry Greenfield, Jim Heald, and Debby Doxey.

References

[1] McCleskey, C. and D. Christensen, "Dr. Kurt H. Debus: Launching a Vision," 35th History of Astronautics Symposium, 52nd International Astronautical Congress, Toulouse, FR, 2001.

[2] Benson, C. and W. Faherty, *Moonport: A History of Apollo Launch Facilities and Operations,* NASA SP-4202, U.S. Government Printing Office, Washington, D.C., 1978.

[3] Greenfield, T., "Design Basics," Unpublished draft manual on KSC design practices, 1993.