Chapter VI

Skylab: Competition and Cooperation in Human Systems

Like many Marshall people, Wernher von Braun had dreamed of building spacecraft for human flight to the planets since his youth. The dream was so strong that as director of Marshall he sought adventures analogous to space conditions. Funded by a National Science Foundation grant in 1966, von Braun and Ernst Stuhlinger, chief of Marshall's Space Science lab, took Robert Gilruth and Maxime Faget of the Manned Spacecraft Center (MSC) on an expedition to Antarctica. The four space officials experienced the hostile environment, toured scientific installations, and examined equipment, learning lessons that could help NASA. Mixing research and pleasure, NASA's top officials walked around the South Pole, orbiting the earth every five seconds.[1]

The expedition symbolized new directions for Marshall in the late sixties and early seventies, revealing its diversification from rocketry into human spacecraft and its new intimacy with Houston's Manned Space Center. The diversification emerged because Marshall had started work on the Saturn rockets long before NASA had settled Apollo plans and so had a headstart on its part of the lunar landing mission. By the late sixties Marshall needed new challenges. As von Braun told Congress, the Saturns had closed the "missile gap" but now NASA suffered from a "mission gap."[2]

NASA recognized that Marshall needed new work and that Houston was still busy with Apollo. The Apollo fire had delayed Houston's work on the Apollo spacecraft; lunar mission planning and operations continued to be major tasks. Accordingly NASA Headquarters officials, especially George Mueller, head of the Office of Manned Spacecraft Flight, encouraged Marshall to develop America's first Space Station.

Marshall's diversification into human spacecraft engineering, however, led to competition with the MSC. Houston officials worried that in an era of diminishing resources Marshall's gains in new projects would mean Houston's losses. Consequently, *Skylab* planning and preliminary design activities led to considerable controversy and in-fighting. NASA sought an effective division of labor and eventually found beneficial forms of competition and cooperation that helped make *Skylab* a scientific and engineering success. Dramatic accomplishments came when Center personnel helped solve problems with *Skylab*'s defective micrometeoroid shield and effectively managed the workshop's orbital decay.

Diversifying into Human Spacecraft

Skylab emerged from the Marshall Center's quest for post-Apollo work. The Center was, as the official *Skylab* history has suggested, "a tremendous solution looking for a problem."[3] Marshall's search for new business would lead not only to *Skylab* but also to new, sometimes competitive, relationships between the NASA Centers.

Building a Space Station had been an old dream for many at NASA, and Marshall people had envisioned various concepts. Von Braun presented designs for Space Stations in the 1940s and in his *Collier's* articles in 1952. Hermann H. Koelle in 1951 also sketched plans, and in 1959 with Frank Williams helped draft ABMA's Project Horizon report which suggested using a "spent stage" as an orbiting workshop.

The idea of outfitting a spent rocket stage as a Space Station had charmed the Germans since Peenemünde because on an orbital mission, the final rocket stage went into orbit with the payload. From the beginning of the Saturn project, Ernst Stuhlinger recalled, von Braun had talked of the spent stage concept as a preliminary step to a sophisticated Space Station. And of course von Braun and the Center's laboratory chiefs had initially favored the earth orbital rendezvous mode for Apollo in order to develop an "orbital facility" and ensure the race to the Moon led to advanced missions.[4]

The Douglas Aircraft Company, a contractor building the Saturn S–IV stage under Marshall's supervision, shared enthusiasm for a spent-stage station. The company wanted to get into the manned spacecraft business and had built a mock-up spent stage station for the London *Daily Mail* Home Show in 1960. In November 1962 Douglas presented Marshall with an unsolicited plan for such a craft. The Center's Future Projects Office, managed by Koelle and Williams, researched the idea, and a study contract with North American Aviation continued the work. By March 1965 Marshall had begun detailed studies of an empty S–IVB stage workshop.[5]

NASA Headquarters in the early 1960s developed the Apollo Extensions Support Study to investigate how Apollo technology could be used for other purposes. The study incorporated various Space Station concepts proposed by the military and other NASA Centers, including the Langley Research Center's work on the Manned Orbiting Research Laboratory.[6]

But for several reasons NASA's post-Apollo planning was, as one historian has said, "pedestrian, even timid." External problems constrained the Agency. Unlike the Apollo program, no presidential directive defined a follow-up mission. By the mid-sixties, presidents and congressional leaders were preoccupied with war and welfare rather than space. NASA administrators worried that beginning an expensive new project while Apollo was still underway could lead to underfunding of both efforts.[7] Constricted support restrained Agency ambitions for a new project like a Space Station.

Agency politics also inhibited planning. Without an external directive, the Agency had to choose post-Apollo goals. In NASA's decentralized structure, the field Centers had different specialties and interests, but had to agree for plans to proceed. Marshall's plans, however, would realign Center roles. If Marshall converted a spent rocket stage into a manned station, it would encroach on the MSC's turf in manned spacecraft.[8] Marshall managers explicitly recognized that their plans required their entering competition with Houston in this territory.[9] Not surprisingly Houston resented Marshall's intrusion. As Chris Kraft recalled, Houston believed that being "in charge of manned space flight" was their "birthright" and so "whenever Marshall Space Flight Center tried to penetrate that part of manned space flight, I think it was felt as a competitive move." Faget thought they were "always trying to get into our business from the very start."[10]

To overcome Houston's qualms, Marshall needed an influential sponsor in NASA Headquarters and found one in Mueller. As chief of Manned Space Flight, Mueller had several reasons for becoming Marshall's ally. He wanted to use Apollo technology and teams to promote space science, maintain public attention on space flight, and provide a transition between the lunar landings and later missions. He also hoped to help Marshall avoid crippling losses in personnel and keep the Agency's team together through the end of Apollo.[11]

In August 1965 Mueller established the Apollo Applications Program (AAP) Office in the Office of Manned Space Flight (OMSF). The centerpiece of Apollo Applications was Marshall's spent stage. In a classic case of what political scientist Howard McCurdy called "incremental politics," Mueller hoped to use old technology for a new mission and thus avoid controversy and possible rejection in Congress. Leland Belew, manager of the Center's AAP Office after March 1966, said that Mueller wanted a station but knew "it had to be cheap, it had to be salable and such that it didn't impose on the Apollo Program itself." Planners sold the program as an "orbital workshop" or a "spent stage laboratory" because, Belew explained, "you didn't dare call anything a Space Station. It had to be framed right, because there was no way to get a new start." Asking Congress for approval would have been "no-go."[12] As an example of the AAP sales pitch, Stanley Reinartz, Belew's deputy, reassured Congress in 1966 that the spent stage was "not really a program" because it would exploit surplus Saturn IBs. The spent stage thus became the camel's nose under the flap of the Apollo tent. Based on incremental politics, the workshop became, Reinartz later recalled, "an awful lot George Mueller's program. . . . George was a very patient, continuing, ongoing, very bright but patient individual, who would just keep pushing and working and finding a way to keep things moving forward."[13]

After August 1965, planning accelerated on the spent stage workshop. All OMSF Centers, including Houston, participated. Marshall, however, did most of the planning. In December, Mueller made Marshall responsible for development plans and in February gave the Center responsibility for workshop design and integration. The Center's Apollo Applications Office quickly became an auxiliary planning staff for Mueller. Reinartz remembered that one week he and Ludie Richards worked in Mueller's office at Headquarters and phoned changes suggested by Mueller back to Huntsville.[14]

In Apollo Applications planning throughout 1966, NASA concurrently decided technical and managerial issues. Technically, AAP orbital workshops would have several major parts with Marshall overseeing the S–IVB spent stage and Houston an airlock module. Because of the entangled responsibilities, the two Centers were feuding by spring 1966. Kraft complained to Headquarters that Houston was losing its responsibility over manned systems.[15]

To resolve Center disputes and put the AAP Humpty-Dumpty together, the Manned Spacecraft Flight Management Council met in August 1966 at Lake Logan in North Carolina. The agreement reached at Lake Logan, historians have argued, was "perhaps the most fundamental statement of intra-NASA jurisdictional responsibilities since the Marshall Center first became a part of the agency and MSC emerged as a separate field Center."[16] The council confirmed Marshall's role in developing manned spacecraft and proposed handling the new division of labor among Centers with two guiding ideas, the "module concept" and the "lead Center/support Center concept."

The module concept assumed that any spacecraft had several parts or modules. Clean hardware interfaces between modules would allow the Centers to divide labor yet easily integrate the pieces. The Lake Logan agreement established a clear division of labor in some areas, especially by continuing the Apollo pattern with Marshall in charge of propulsion and Houston the "command post" including communication and control systems.

But the dividing lines between some modules were very fuzzy because Marshall took over some of MSC's traditional responsibilities for manned systems and space science. Marshall and MSC divided responsibility for the "mission module" and "experiment modules." Marshall was in charge of large structures, quarters, laboratories, some power and environmental systems, and the astronomy experiments; the Center was also responsible for workshop and experiment integration. Houston had life support and some power systems on the airlock module, medical research, earth experiments, astronaut activities, and flight operations. But living quarters mingled with medical research, astronomy equipment with crew management, and so on. As Belew recalled, "*Skylab* had no clean interfaces." The fuzzy division of labor produced technical disputes that the Centers could resolve only with careful negotiations.[17]

The Lake Logan agreement proposed the lead/support Center concept as a managerial formula for resolving problems. A lead Center would have overall managerial responsibility and set hardware requirements for the support Center which directly oversaw module development. For Apollo Applications, Marshall would be lead Center for workshop development and MSC lead Center for mission operations. Having two lead Centers was supposed to correspond to the two stages of development and operations, but the two stages were seldom distinct. A mixing of development and operations was natural because the developer would customize hardware to the demands of the operator. In effect this meant that Marshall became a contractor to MSC. As Marshall's Belew said "we structured to meet the requirements of the customer. They were our customer."[18]

After the Lake Logan meeting, Marshall's preliminary planning on what would become *Skylab* would be affected by the interplay of several factors. A design emerged from NASA's quest for a follow-up to Apollo that could get political acceptance, and from technical debates within the agency, especially discussions between Houston and Marshall.

Negotiating a Design

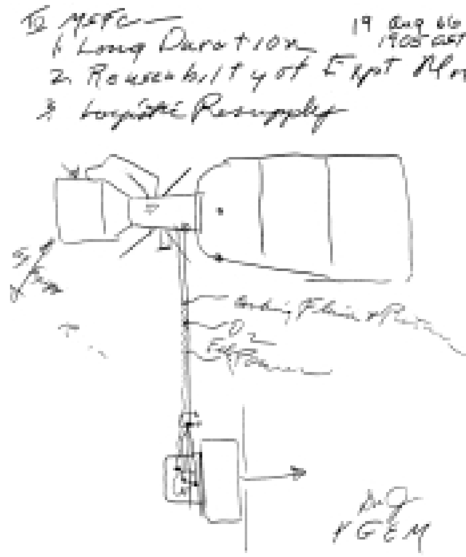
Interchanges among NASA Headquarters and the field Centers shaped the orbital workshop's mission, configuration, and launch system. Marshall contributed to changes in *Skylab*'s design even as the Center and its contractors began development of hardware.

Initial planning for Apollo Applications outlined two missions, the spent stage workshop and the solar science of the Apollo Telescope Mount (ATM). The first Apollo Applications schedule of March 1966 called for three workshops and three ATM missions. The first orbital workshop missions would be very simple, with basic mobility and biomedical experiments, amounting to little more than zero-gravity calisthenics in a pressurized S–IVB tank. The ATM missions were more sophisticated, fulfilling NASA plans dating to the early 1960s to put manually operated solar telescopes in a storage bay of the Apollo service module. In March 1966 the Goddard Space Flight Center, the agency's astronomy specialist, became lead Center for the ATM. By the end of the year, however, the two Earth-orbit missions converged, and NASA decided to reassign the ATM to Marshall and make it part of the workshop.[19]

Politics shaped the decisions. Mueller worked at "selling" the Office of Space Science and Applications on the idea of moving the ATM to Huntsville. Marshall's leaders, especially von Braun and his chief scientist Stuhlinger, also petitioned the agency, pointing out that Marshall had developed scientific payloads for the Explorer and Pegasus satellites. At the same time, NASA Associate Director for Space Sciences John L. Naugle, NASA chief astronomer Nancy Roman, and Mueller began questioning the utility of ATM-service module missions. By the summer of 1966 they realized that mating the ATM to a modified lunar module (LM) would allow for larger instruments and use more Apollo hardware, justifying transfer of the ATM–LM to Marshall because the Center had more experience with complex systems and manned missions than Goddard.[20] A desire to hold the Marshall team together also motivated Mueller.

When a Houston official challenged him for assigning the solar observatory to Marshall partly for political reasons, Mueller replied that his motives "were not partly political but completely political."[21]

Technical factors also influenced the telescope mount decisions. NASA officials realized that ATM–LM missions restricted instrument size, limited observation time, and wasted Saturn lifting capacity. And of course an ATM–LM mission would still be brief. So by the fall of 1966 NASA realized that mating the solar observatory in some way to the orbital workshop would allow for longer missions and larger instruments.[22] Such a configuration also justified giving the telescope mount to Marshall, the lead Center for workshop development, and legitimized the workshop by giving it an important scientific mission.



George Mueller's initial sketch of orbital workshop.

These decisions culminated in the fall of 1966 with the "cluster concept." On a visit to Huntsville in August, Mueller sketched a configuration that had an ATM–LM tethered to the workshop by a power cable. The design looked so bad, Reinartz remembered, that "nobody could figure out what it was, so it got the name of "the kluge." Mueller did not like that name so "in more polite terms it was called "the cluster."[23] Within a few weeks the tether gave way to a new cluster concept in which the ATM would be launched separately. A Marshall-built chamber called the multiple docking adapter (MDA) would anchor the telescope mount and the command module to the workshop.[24]

The observatory decisions proved controversial. Some questioned whether Marshall should build the telescope mount rather than have a contractor do so.[25] Abe Silverstein believed that mating the mount to a lunar module created "a monstrosity" and felt that jury-rigging Apollo hardware for new purposes wasted money. Some on the President's Scientific Advisory Committee wondered whether astronauts could contribute much to space astronomy. Since the ATM would be remotely controlled and not built for repair, astronauts on board the spacecraft could contribute no more than operators on the ground. Moreover, human contamination and motion could impair observations.

Center managers, worrying about the criticism, reminded their personnel that Marshall needed to succeed with scientific payloads. Von Braun declared in October 1966 that the telescope mount was "of particular significance to our Center, as our successful performance in this endeavor will determine MSFC's participation in similar projects."[26] Moreover Center officials defended the ATM choices. They admitted that repairable instruments would be more expensive and were really unnecessary since unmanned satellites had proven reliable, but pointed out that fitting the mount to the workshop allowed for larger, more complex instruments than an unmanned satellite and for photographic film which offered better resolution than electronic telemetry. Astronauts could change film canisters and return them to Earth.[27]

Such discussions were mild compared to quarrels over the spent stage or "wet workshop" idea. The Mueller-Marshall plan called for the first workshops to be launched by a Saturn I–B with a live S–IVB rocket stage. The plan initially assumed that all Saturn Vs would be used for the lunar program, and so a live upper stage was needed to achieve orbit with a I–B. Before reaching orbit, the workshop interior—the inside of the S–IVB fuel tank—would be "wet" with liquid oxygen and hydrogen. Once in orbit, suited astronauts would go on extravehicular activity (EVA), purge leftover fuel, move in the shop, outfit it, pressurize the cabin, and make it habitable.[28]

Marshall's engineers acknowledged problems with the wet workshop. As Eberhard Rees said, problems with habitability and EVA would make it "primitive," but the exercise would be enormously educational in learning about space. Moreover, the use of surplus Apollo hardware would minimize costs and give the wet workshop political advantages. NASA could not move openly for a Space Station because the Apollo Program was expensive and unfinished so expediency dictated "no new starts."[29] "The wet workshop was for us and for von Braun," Stuhlinger recalled, "always only an intermediary step."

Like the Center's preferred step-by-step method of testing rockets, Apollo Application plans called for several increasingly sophisticated wet workshop flights. The long-term goal, however, was a real Space Station, some sort of "dry workshop" that would be fully equipped on the ground. Dating from the first Apollo Applications schedule in March 1966, plans called for a mission with an S–IVB dry workshop launched with a Saturn V. Nevertheless the program from 1966 to 1969 only had enough money for Marshall to develop a wet workshop. The Center's policy until 1969, Stuhlinger said, was that the wet workshop "would be limited, but it could be done" and was worth doing.[30]

As early as 1966 Marshall had begun bending metal for a spent stage station. When engineers discovered structural weaknesses in the dome of the S–IVB, von Braun found money to install a quick-opening hatch large enough to support the dome and accommodate a suited astronaut. Later the laboratories tested interior materials for stress, corrosion, toxicity, and odor. They particularly checked the S–IVB's insulation on the inside of the fuel tank for flammability and outgassing of dangerous fumes. When high-velocity penetration tests showed that a puncture by a micro-meteoroid could cause the insulation to ignite, the Center sealed the insulation with aluminum foil. The labs studied ways of fastening equipment to the thin walls of the rocket. They installed two grid floors to allow for liquid hydrogen flow. The Center also began designing the telescope mount and EVA equipment for activating the workshop.[31]

The laboratories performed most of the EVA research in the Neutral Buoyancy Simulator where the wet workshop really was wet. One of Marshall's unique facilities, the simulator had a 1.5 million gallon water tank that was 75 feet in diameter and 40 feet deep to provide an environment that approximated zero gravity for testing hardware. After being denied Cost of Facilities money, Marshall called the simulator a "tool" and built it using $1 million appropriated for Research and Development. This creative financing led to a GAO audit and reprimand, but became a legendary example of Center resourcefulness.[32]

For workshop efforts, divers submerged mock-ups of the workshop in the simulator. To simulate the weightlessness of space, astronauts had suits and tools weighted to attain "neutral buoyancy," neither rising nor sinking. A team of engineers, psychologists, and human factors specialists monitored the astronauts through windows, television, and physiological displays. By early 1969, the team began to test hardware and devise methods for performing tasks, using tools, installing lights, sealing meteoroid penetrations, and changing ATM film canisters.[33]

The simulator aroused some friction with Houston. The Lake Logan agreement had confirmed MSC's responsibility for the astronauts and their equipment on spacewalks. But Marshall's responsibility for "large structures" and for studies of "EVA equipment and procedures which may be used to carry out . . . operations on large space structures" created ambiguities. Houston's managers resented this crossing into their territorial waters. MSC Director Gilruth believed that Marshall's tank needlessly duplicated Houston's capabilities in order to become "a manned space center." Despite this early jealousy, Marshall's Neutral Buoyancy Simulator immediately became a marvelous agency resource.[34]

Houston officials also objected to the wet workshop concept. No dispute since the lunar mode decision was so controversial. Robert F. Thompson, manager of Houston's Apollo Application's office, said that for the first time two Centers were competing for future work; until the wet workshop idea was abandoned in 1969, Apollo Applications was "not a program" but "a dogfight." Marshall's George McDonough recalled that one intercenter discussion of the wet workshop got so tense that Thompson wanted to take him out and fistfight.[35]

Houston's engineers doubted the technical merit of making a Space Station from a spent stage. They questioned whether suited astronauts in zero gravity could outfit an effective workshop. Because the Mueller-Marshall cluster conglomerated disparate hardware for a new purpose for which it had not been designed, MSC called it a "kluge," or more commonly, a "goddamn kluge." They believed that the wet workshop would waste money, risk failure, and, by perpetuating Apollo technology, prevent progress.[36]

As an alternative, Houston proposed an experiment carrier that would substitute for the lunar module on a Saturn I–B. Kraft recalled that Houston thought this would be "a Space Station, not a kluge." Less than half the size of the S–IVB, the experiment carrier would be "dry," constructed on the ground, and outfitted each time for progressively complex orbital missions. Houston thought it would be superior to a spent-stage station for about the same cost. Marshall Center engineers saw no technical advantages in Houston's carrier, which they derisively called "Max's can" (after Max Faget). They thought Houston was "extremely unrealistic" in expecting Congress to approve new hardware.[37] Most importantly Marshall worried that the experiment carrier could threaten its survival as a major Center. In a July 1966 message, Belew reminded von Braun that unless NASA built an S–IVB station "our allotted funds will be extremely small since our only other orbital station involvement is in the area of experiments." Approval of Houston's cans would mean that "the dollar split . . . [between MSC and Marshall] would tend toward 75%–25% rather than today's 50%–50% split." An S–IVB station, Belew wrote, was necessary "in order to fully utilize the skills that Marshall wants to retain and would insure a substantially more stable resource level for both Marshall internal and contractor operations."[38]

Luckily for Marshall, the rest of NASA also questioned Houston's experiment carrier. Most agency officials felt the S–IVB workshop was feasible, worried about wasting the money and effort already spent on the workshop, and feared delay in turning to new hardware. So in November 1968 NASA rejected the carrier idea.[39] So Houston in the spring of 1969 changed tactics by proposing to launch the S–IVB with a Saturn V rocket as a fully equipped dry workshop.

Although only a recapitulation of the original Marshall plan for an AAP mission, Houston has always claimed full credit for the dry workshop idea. Robert Thompson said, "unquestionably the thrust for the dry workshop came out of this center [Houston]." Kraft argued that by sponsoring a new means to achieve the goals of the Apollo Applications Program, Houston "saved the damn thing."[40]

Marshall engineers resented the implication that the spent stage idea had been bad from the beginning. They responded to MSC's criticism by laboring hard to improve the spent stage and prove that it would succeed. But, Belew said, the Center had all along believed that the wet concept "was never the best notion of doing something if you had an option different." And NASA's original options were limited; since all the Saturn Vs were committed to the lunar mission, a live second I–B stage was needed to achieve orbit.[41]

Moreover, Belew thought Houston's claim to be the inventor of the dry workshop was "only half true." Marshall had formulated the plans to use an S–IVB as a Space Station and helped draft the original AAP plans which had, in the long run, called for Saturn V dry workshops. Stan Reinartz believed Houston could not take full credit for the dry workshop because their preferred alternative was the can; by proposing the experiment carrier, "they tried to kill" the S–IVB station. Houston only warmed to an S–IVB workshop as a last resort.[42]

Marshall's engineers credited Houston, however, with forcing NASA to consider alternatives. Houston's position, Belew recalled, "drove you to a real hard decision of what we really ought to do." In addition, circumstances changed dramatically by the fall of 1968. Declining budgets forced a reconsideration of Apollo Applications, and the agency realized that it lacked resources for several wet and dry workshop missions. Marshall's work on the wet workshop was already behind schedule, with officials complaining they were getting only two-thirds of the money needed to meet deadlines. Moreover, after the success of Apollo 8 in December 1968, NASA concluded that a Saturn V could be used for an Apollo Applications mission. So from the fall of 1968 to the spring of 1969, the agency conducted an exhaustive study of its options.[43]

Marshall had studied the dry workshop before but now Mueller directed a small group at the Center to reassess the concept. Because they were regarded as "pariahs" in Huntsville, McDonough recalled, the dry group operated discreetly and even held a secret poolside meeting with Mueller in a motel at the Cape. After hearing the group's report in early 1969 and recognizing the changed circumstances, von Braun concluded that the wet workshop was no longer the best option.[44]

In May 1969 the Management Council met in Houston and Mueller gave them several options, all of which drastically reduced the number of AAP workshops. Basically the council had a choice of missions involving one wet or one dry workshop. A dry option emerged as their favorite. Von Braun then convinced some of his reluctant lab directors that a ground-outfitted configuration improved the design. In a letter to Mueller on 23 May, he acknowledged that although the wet workshop could meet AAP's scientific objectives on time and on budget, this would "take substantial hard-nosed scrubbing down of some of the current methods." Von Braun thought a dry workshop offered "real and solid advantages over the present program." With the greater lift of the Saturn V, reliability could be improved by using sturdy and redundant hardware and by installing and checking equipment on the ground, and habitability could be improved by eliminating liquid hydrogen.[45]

Gilruth of Houston seconded von Braun, and on 18 July 1969 NASA Acting Administrator Thomas Paine used the success of Apollo 11 as an opportunity to announce plans for the dry workshop. The Apollo Telescope Mount would be launched with the workshop rather than on a separate flight, eliminating the makeshift ATM–LM and a complicated rendezvous with the workshop. The telescope system could be simplified by attaching the instruments to a heavier, specially designed rack and by creating a deployment system; upon reaching orbit, the mount would swing out perpendicular to the workshop. The solar observatory could also duplicate the power, communication, and control systems of the workshop. In addition, by the fall NASA decided to avoid putting all its eggs in one basket by building an identical qualification workshop and equipment that would be used in tests and refurbished to back up the flight model. The competition between the Centers had helped improve the design.[46]

In February 1970 the workshop got a new name. In mid-1968 NASA had held a contest to name the project and an Air Force officer assigned to the agency proposed "*Skylab,*" short for laboratory in the sky. NASA people were initially nonplused by "*Skylab*," Reinartz remembered, but still avoided calling the project a Space Station. Wanting to build a more elaborate station later and fearing that identifying an expensive new project would offend Congress, the agency waited two years to sanction the name officially. *Skylab* became the only NASA project never to get formal congressional approval of a "new start" through the phased planning process.[47] The incremental strategy of Mueller and Marshall was successful and the Center could develop something more than a spent stage station.

Building the Workshop

As Lead Center for *Skylab*, Marshall oversaw diverse, complex development problems. Marshall used ideas from Space Station studies conducted by NASA contractors and Centers, especially the Langley Research Center. During the development phase, Marshall would again work closely with the Manned Spacecraft Center, and their complementary expertise helped solve the technical challenges of the project.

The technical challenges were formidable. No American manned spacecraft had used solar energy to generate all of its electrical power. No manned spacecraft had needed precise pointing control for a solar observatory. No previous manned mission had required equipment and life support systems for nine months. Crew systems had to be not only functional but habitable in order to maintain productivity and morale for long-duration missions.

Other design problems were less novel but still challenging. Onboard and Earth-bound communication and control systems were necessary. The space laboratory and its scientific equipment had to survive a harsh and dynamic environment. The workshop had to withstand changes in inertial loads during launch acceleration, bending forces caused by engine thrust and gimballing, temperature, vibration, and atmospheric and acoustic pressure. In orbit it had to endure vacuum, micrometeoroids, radiation, and docking impacts equivalent to earthquake shocks.[48]

Skylab's designers overcame these complex challenges with a series of systems and structures. The new dry configuration meant that engines and flight hardware could be removed and experiments, life support equipment, and storage units added. For launch the workshop was pressurized with dry nitrogen to maintain rigidity and was vented during ascent to equalize atmospheric loads. Because the orbital configuration could not withstand the pressures of launch, diverse mechanisms deployed the payload shroud, antenna booms, solar observatory, workshop micrometeoroid shield, and solar arrays on the ATM and workshop. Thermal control came from passive systems using insulation and exterior surface coatings and active systems using heaters, coolant pumps, heat exchangers, and radiators. The oxygen and nitrogen laboratory atmosphere required methods for purification, humidity regulation, circulation, and odor removal. Pressure tests guarded against leaks.

Skylab also had systems for power, communications, and attitude control. Electrical power came from solar cells that provided power during sunlit phases of the orbit and from batteries that discharged during shaded phases. Communications systems could transmit data, hardware commands, video, and voices. The workshop had over 2,000 data sensors and could receive more than 1,000 digital commands. Attitude and pointing control for the 100-ton *Skylab* came from three control moment gyroscopes. The gyros were the first used on a manned spacecraft and were chosen because a gas reaction system would have required too much propellant for the long mission; cold gas thrusters served only as an auxiliary. The control system employed a computer, Sun sensors, a star tracker, and rate gyroscopes to determine position and angular rate.[49]

Marshall divided work on these systems between itself and contractors. As Lead Center for development, the Center was responsible for systems engineering, contractor management, and cluster integration. Boeing helped with systems engineering. McDonnell Douglas modified the S–IVB into a space station in Huntington Beach, California, and built the airlock module that contained power and life support systems in St. Louis. Houston initially monitored the airlock contract, but Marshall soon took it over to simplify project management. TRW built the solar arrays for the workshop and the ATM. Martin Marietta of Denver was responsible for payload and experiment integration; Marshall also assigned the corporation the MDA.[50]

For *Skylab* development, the Center drew on technology and organizational methods from the Saturn era. Its approach to monitoring contractors was essentially the Saturn method. Belew's *Skylab* Program Office established a project office for each major hardware component and for experiments, set up resident manager offices to penetrate contractors, and designated "tiger teams" of specialists to solve crises. The biggest contractor problem came when McDonnell Douglas fell behind schedule in mid-1971 during the enormously complicated final integration of the workshop. The Center's William K. Simmons, project manager of the orbital workshop, organized a 10- to 15-member tiger team that stayed in California until mid-1972. McDonnell Douglas's problem, Simmons believed, was that its management system for manufacturing airplanes was "geared to quantity" and "a lot of their practices weren't compatible with building one-of-a-kind." Particularly, the company managers were isolated from development problems and had not established an integrated schedule for incoming components. The Marshall team imposed order by drawing a master schedule, working alongside McDonnell Douglas's managers, and getting the company president to act as program manager.[51]

Skylab also drew from the remnants of the arsenal system at Marshall. The Center maintained a mock-up *Skylab* in Huntsville to test alternatives and monitor contractor performance. Marshall built two shells of the multiple docking adapter and turned them over to Martin Marietta for final development. Marshall also tested hundreds of components and helped build hardware for many *Skylab* experiments.[52]

The greatest scientific instrument produced by Marshall's arsenal system was the Apollo Telescope Mount. None of the Center's previous scientific payloads had been as sophisticated as the solar observatory. Marshall's experience with vehicle engineering, however, prepared it for payloads. ATM Project Manager Rein Ise said, "once you have applied structures to large vehicles, there is essentially no conversion involved in taking knowledge and designing the structure for a solar telescope."

Teams from the Astrionics, Space Sciences, and Manufacturing Engineering laboratories took on the challenge of the telescope mount. They used components from contractors; Bendix provided the control moment gyroscopes, Perkin-Elmer the pointing system, IBM the computer, and experimenters the instruments. But the Center designed and developed the solar observatory system. To mount the eight solar telescopes, engineers built an octagonal spar 11 feet in diameter and 12 feet long. Their design had subsystems for orbital deployment, communication, electrical power from four solar cell arrays, and attitude and pointing control.

The requirements for the pointing control system were very complex. The telescope needed accuracy within two arc-seconds, which meant an error of no more than the width of a dime at a distance of two kilometers. Yet the accuracy and stability of the telescope system could be affected by the movements of the *Skylab* spacecraft and the astronauts. Moreover large bundles of stiff electrical wires connecting the telescope tub and spacecraft could limit the telescope's pointing motion and accuracy. To solve the wiring problem, an engineering team led by Wilhelm Angele from Marshall's Astrionics Lab developed flat electrical cables that were so flexible that they allowed the telescope mount to move with very little mechanical resistance.

For the pointing system, Marshall chose a design using three control moment gyroscopes, actuators, a computer, photoelectric sun sensors, and a star tracker. The Center tested the system on specially built engineering simulators that used analog devices and computer models. The engineers struggled to simulate the performance of the control moment gyroscopes in microgravity; they compensated for gravity distortion by floating an ATM simulator in a mercury bath. But still ground tests could only prove the accuracy of the pointing system within six arc-seconds. Marshall engineers waited until *Skylab* was in orbit to learn that the system worked well and that astronomers could not measure pointing errors.

Marshall helped solve other technical problems for the solar observatory. When scientists became concerned that the South Atlantic Anomaly, a high radiation area that *Skylab* crossed in orbit, could expose film used in the observatory, Marshall engineers worked with Eastman Kodak to develop special films that could survive in the radiation environment. They devised computer programs that duplicated the anomaly and so could predict the fogging on film. Center personnel also developed crew trainers and operating procedures for the solar observatory. Marshall constructed an ATM checkout facility for final integration and equipped it with automatic monitors and air control equipment that made the whole building a clean room.[53]

Skylab's Apollo Telescope Mount is prepared for Thermal Vacuum Test–1970.

The Center engineers and scientists who worked on the ATM believed that in-house manufacturing accounted for the success of the telescope mount. Dr. Walter Haeussermann, director of the Astrionics Lab and later head of Central Systems Engineering, claimed that the arsenal system allowed for "tremendous flexibility" in inventing new technology. Technicians could build models, allowing designers to execute modifications without making elaborate drawings and wasting time and money. Dr. Tony DeLoach, an experiment scientist for one of the ATM instruments, believed the system centralized management and engineering. When work was done in-house rather than by contractors spread across the country, teams of experts could quickly confer to solve complex problems.[54]

Since the lives of astronauts depended on *Skylab*, Marshall's design incorporated conservative engineering ideas and redundant systems. Marshall set high quality standards and sought to achieve them with heavy structures, existing technology, and extensive testing. Launching *Skylab* with a Saturn V reduced weight problems, allowing for heavy hardware and backup systems. Moreover, using tested ideas and mature technology reduced development time and saved money. The Center, according to Robert G. Eudy, deputy chief of the Structures Division, "relied heavily upon existing technology, available hardware, and hardware concepts" for *Skylab*. Marshall engineering teams used hundreds of components from the Gemini program; recognizing that using proven components could save money and time, the teams tested Gemini technology for its suitability for the longer *Skylab* mission, for example, adopting Gemini hatch latches for the airlock module hatch. Other systems adapted for *Skylab* included a separation system for the payload shroud from the Titan IIIC and a scientific airlock originally designed for the Apollo Command Module hatch. The workshop itself was a modified S–IVB rocket stage with its liquid oxygen tank used for waste disposal, its liquid hydrogen tank used for habitation, and interior structures attached to cylinder rib intersections.[55]

In addition, the workshop had redundant batteries, chargers, electrical circuits, and solar arrays. The ATM controls, Ise said, used "a belt-and-suspenders approach in that we designed redundancy throughout the system" and had three rather than two control moment gyroscopes to change attitude. The gyros were new technology for a manned spacecraft, but Marshall stayed conservative by choosing big, heavy wheels that spun relatively slowly. Moreover, the Center carefully tested equipment; the ATM, for instance, went through functional, vacuum, and vibration tests. And because NASA built prototypes for qualification tests and then refurbished them as spares, the agency had a backup *Skylab*.[56]

Perhaps the greatest Saturn legacy to *Skylab* was relatively liberal funding. To be sure, Marshall experienced budget cuts throughout the late sixties and early seventies and laid off hundreds of Civil Servants. And as the only surviving AAP mission, *Skylab* became the first major NASA program in which budgetary shortfalls caused schedule delays. (*Skylab* was launched in 1973, six years after AAP's target for the first wet workshop.) Nonetheless, compared to later programs, Skylab's budgets allowed for backup hardware and extensive testing. Looking back after almost 20 years, ATM manager Ise saw few funding pressures on *Skylab*. "I am sure that the *Skylab* manager didn't get everything he wanted, but he got almost everything he wanted," he said, "*Skylab* had the money when it needed it."[57]

Marshall's internal management during *Skylab* also continued the same pattern as the Saturn program. During *Skylab* the Center distributed management authority between the project offices, which oversaw budgets, schedules, and contracts, and the laboratories in Science and Engineering, which handled design, development, and testing. Also like the Saturn era, Center managers struggled to find the best division of labor between centralized offices and specialized labs. Their balancing act became more difficult as Marshall diversified from a propulsion specialty and took on more projects. The balance can be seen in relations between the "lead laboratory" system, the project offices, and the Central Systems Engineering Office.

The lead lab system originated in the Center's practice of automatic responsibility. The goal was to empower the technical experts, fuse planning and doing, and keep engineers' hands dirty. Research and Development Operations, the laboratory side of Marshall, assigned technical responsibility for a component or subsystem to one laboratory. For example, the Astrionics Laboratory had responsibility for the telescope mount and the Propulsion and Vehicle Engineering Laboratory had the Multiple Docking Adapter. Each lead lab developed hardware specifications and managed interfaces. Initially project offices for hardware components were decentralized in the laboratories, rather than being centralized under Belew's *Skylab* Program Office.[58]

One of the lead lab's major tasks was soliciting support from other labs. This often meant time-consuming negotiations with other specialists to resolve differences in engineering methods or technical requirements. Indeed von Braun expected the lead lab system to encourage cooperation, Haeussermann recalled, and the lead lab never commanded others. When the system worked well, the lead lab organized a team of experts drawn from other labs that collectively overcame problems in design and development.[59]

Sometimes, however, the system could be frustrating. Decentralized labs often struggled to solve complex problems with multiple specialists and components. Especially troublesome was establishing requirements for a whole system, getting the labs to cooperate, and forming multi-lab teams. For example the Astrionics Lab moved so quickly that ATM design became fixed and not easily changed to meet the needs of labs working on other parts. Ise remembered that the German laboratory directors "had a little bit of this fiefdom philosophy where each one ran their own little kingdom. One laboratory was not very effective in being able to manage other laboratories that also had to participate in a very key way on the whole project." McDonough thought that the boundaries between labs sometimes became "war zones" and to get the support of other labs specialists had to go "up, over, and down" the chain of command. William Lucas, then chief of the Propulsion and Vehicle Engineering Lab, remembered how he struggled to get other labs to commit resources to his tasks. He believed the limitations of the lead lab approach proved the "old Chinese proverb that says, 'If two guys are going to ride on a horse, one has to ride in front.'"[60]

To put somebody in front, Marshall managers sought ways to centralize managerial and engineering authority. Some early centralization for *Skylab* was makeshift and accommodated the labs. James Kingsbury, deputy director of the Astronautics Lab, often worked as ad hoc chief engineer for *Skylab* and helped resolve problems.[61]

Formal mechanisms also existed. A Technical Systems Office in Research and Development Operations, renamed the Systems Engineering Office in July 1967, controlled design requirements, and helped specialists in the labs integrate the many pieces of a scientific space station. Systems engineers became another layer in the Center's hardware hierarchy of lab specialists, chief laboratory engineers, and project managers. Von Braun, recognizing that the Center now had too many projects for him to oversee, strengthened the office in late 1968 and early 1969.[62]

The systems engineering office had its limitations too. Laboratory personnel worried that centralized design and integration, whether in a staff office or a systems engineering contractor, would be ineffective without engineers keeping their hands dirty and maintaining skills. Moreover excessive centralization would weaken the labs. Lucas, answering von Braun's questions about systems engineering and lead labs in November 1968, argued that giving labs responsibility for systems engineering would foster "an entrepreneurial climate" and "let the workers be the master of their own fate." Robert Schwinghamer, head of the lab's Biomedical Experiment Task Team, agreed, worrying that centralized systems engineering would convert technical decisions into financial ones and thereby weaken "the in-depth technical capability of Marshall laboratories." Technical deterioration, he thought, would call into question the need for the Marshall Center because "a purely management function not supported by a strong technical institution could as well be performed in Washington."[63]

Finding the right balance between the labs and project offices was sometimes controversial as well. As *Skylab* progressed, the project office sought more programmatic control over the project engineers in the labs. Chief engineers colocated in both project offices and the labs and answered two bosses—the project manager and the director of Science and Engineering. This change, for instance, meant that the telescope mount project manager more directly supervised the budgets and schedules of the Astrionics Lab.[64]

This quest for greater programmatic control by project managers sometimes annoyed laboratory personnel who feared a loss of technical autonomy. When Belew's project office sought programmatic control over the Propulsion and Vehicle Engineering Lab's development of the biomedical experiments, Schwinghamer resisted. He claimed that greater control by the project office would sabotage the "quick response, economy, and flexibility" necessary to get the experiments done on schedule.[65] Nevertheless, the culture of the labs and their relationship with staff offices remained essentially the same during *Skylab* as during Saturn. New programs started after *Skylab* tended to rely less on the Center's labs and more on contractors.[66]

Because *Skylab* had more complicated technical interfaces and more interaction between Houston and Marshall, its design and development was more controversial than Saturn. The Centers worked together using intercenter panels of lower and middle level officials. Hardware interface and systems panels met regularly to coordinate technical plans in areas of divided authority. Unsolved problems passed on to periodic, face-to-face meetings of upper administrators. Unsolved disputes between Houston and Marshall were passed up to Headquarters.[67] J.R. Thompson, who headed Marshall's Man/Systems Integration Branch and oversaw the Center's interaction with Houston's astronauts and human factors specialists, remembered that the disputes were "good, honest differences of opinion" about "the best technical solution." He explained that usually "Marshall had a stronger engineering solution and Houston had a stronger operational solution. So you tried to find the best of both of them." Marshall, for example, wanted a fireman's pole to extend through the workshop; but Thompson recalled that Houston's astronauts believed this was superfluous and they never deployed the pole.[68] Such technical disputes between Centers became most intense over ATM controls, workshop habitability, and biomedical systems and experiments.

Marshall built the telescope mount controls, but Houston's astronauts would use them. Feuds erupted in 1967 and 1968 when Houston complained that Marshall lacked understanding of crew instrumentation, that the astronauts would have little control over the mechanisms, and that some toggle switches flipped up in the off position and some flipped down. Marshall accepted many of

Houston's recommendations, but Center engineers, who often judged the cost of equipment in terms of luxury cars, joked that the redesign cost "umpteen more Cadillacs." The controls were "probably the most complicated ever flown in a spacecraft" yet worked well during the *Skylab* missions.[69]

Marshall and Houston also struggled to improve "habitability" and make the S–IVB an efficient, comfortable, and pleasant place to live and work for long missions. Center interactions were complicated because NASA never formally defined which one was really in charge of the workshop interior. Headquarters merely divided a list of hardware items, so Marshall had *Skylab* structure while Houston had the habitability experiment—which affected the entire structure.[70]

Making the workshop habitable had been a low priority in Marshall's original planning. Wet workshop designs had been necessarily austere. Center engineers had been mainly concerned about workability, ensuring that equipment functioned properly. Moreover, William Simmons, the workshop project manager, pointed out that Marshall lacked experience with manned systems. "Man-rating a vehicle is one thing," he said, but "making it livable or adaptable for a man is really something else." Reinartz said that emphasis on workability over habitability came because "our guys had been building rockets. We hadn't had people around." He admitted that there was a certain amount of "lack of appreciation by the Marshall people of the concerns for being in these tin cans for up to ninety days." To learn about the problem, Marshall engineers studied designs of ships, submarines, and railway cars and consulted with astronauts.[71]

By 1968 Houston's spacecraft designers, transferring from Apollo spacecraft work, began criticizing Marshall for its lack of concern with workshop habitability. The criticism intensified after the mid-1969 dry workshop decision when Marshall was slow to recognize the new priority for habitability. Recalling an inspection of Marshall's workshop in 1969, Mueller said that "nobody could have lived in that thing for more than two months. They'd have gone stir-crazy." Mueller helped bring in two industrial designers, Caldwell Johnson of MSC's spacecraft division and Raymond Loewy, an internationally renowned industrial design consultant.

Johnson and Loewy thought Marshall's designs lacked creature comforts and aesthetic qualities. They complained that sleeping chambers were too big and living quarters and storage compartments too small. Lighting was random and cold. Loewy said that the color of the workshop was "Sing-Sing green," the same as the death cell at Sing-Sing prison, and the grid floors cast "cage-like" shadows. The interior pattern of cylindrical walls, rectangular equipment, and triangular grid floors was confusing. The workshop lacked a wardroom and a window. Accordingly they recommended changes and received support from NASA Headquarters. Marshall responded by improving the lighting, layout, color scheme, and by adding a window.[72] In 1969 Marshall continued habitability research in "space station analogs," sending an engineer on the Gulf Stream Drift Mission in which a six-person submarine traveled from Florida to Nova Scotia. Marshall also sent personnel to the Tektite II underwater habitat in the Virgin Islands.[73]

Full-scale mock-up of Skylab at Marshall in April 1973.

Despite the improvements, Houston again proposed major changes in the spring of 1970. After a tour of *Skylab* at the Douglas plant, Houston's Kraft argued that workshop habitability was still inadequate, especially in terms of hygiene and waste management. Acknowledging that the contractors and Centers were "all partially to blame," he thought that Marshall and its contractors had relied too much on astronauts who accepted "a make-shift situation on the basis of 'that's the way things have been done in the past.'" But for prolonged *Skylab* missions, a comfortable spacecraft was necessary to maintain crew productivity. Proposed changes included better environmental control, storage, lighting, sleep restraints, and housekeeping devices as well as the addition of an entertainment center and an alternate waste-disposal system.[74]

Kraft's rhetoric prompted Rees, who became Marshall's director on 1 March 1970, to ask his *Skylab* program office to make the changes. Rees remembered how during a research trip to Antarctica "without a shower for six days we really felt rotten." The Center director, however, reversed course after Belew explained that additional changes would put *Skylab* over budget and behind schedule. Moreover Marshall had already improved habitability by expanding the wardroom, rearranging the waste management area, and adding individual sleeping compartments, a window, a food freezer and warming oven, and a trash airlock.[75]

To stay within *Skylab*'s limited resources, Rees decided to oppose Houston's proposals. He argued that for more than three years MSC had gone along with Marshall's designs and then began constantly changing requirements. Houston's habitability proposals had changed *Skylab* from an "experimental astronomy program" to "a very sophisticated and unprecedented medical experiment." By changing the ground rules and upgrading hardware, Rees thought, MSC was threatening the whole program. J. R. Thompson acknowledged that "amenities" were necessary, but contended that Houston wanted to spend money on "interior decorating" rather than on improving equipment. If equipment like *Skylab*'s toilet failed, then he doubted that "any color scheme recommended by any committee would make much difference in improving the habitability of the Waste Management Compartment."[76]

Houston got Headquarters to overcome Marshall's resistance. In July 1970 Charles W. Mathews explained to Rees that the changes were necessary because "*Skylab* may be the only manned missions flown for an uncomfortable number of years between Apollo and early shuttle missions. It is critical that we make the most of this opportunity consistent with our resources." Mathews acknowledged, however, that budgets and schedules had to be kept. Such constraints led the Centers to stabilize habitability designs after the fall of 1970.[77]

Marshall and Houston also cooperated on biomedical experiments that would monitor the effects of microgravity on physiology. Marshall would develop a waste management unit that disposed of urine and feces and preserved samples for return to Earth. In addition, in a meeting at the Cape in 1968, Dr. Charles A. Berry, Houston's chief medical researcher, told von Braun that he was having difficulty getting medical hardware built. Von Braun offered his Center's services for in-house development of an ergonometer with a physiological monitor and a lower-body negative pressure device. Marshall engineers believed biomedical projects would "firmly pave the way for future Marshall missions" and "establish a capability essential to future activities." Houston, while desiring Huntsville's help, also wanted to maintain control over biomedical research and operations.[78]

Consequently by December 1968, the Centers negotiated an agreement that "followed the same general mode of operation as any other contract that MSC has where a contractor is providing flight hardware for medical experiments." Von Braun accepted this agreement as "the best we can get." Nonetheless he worried that the contract's technical requirements would deny Marshall the "leeway" to assist Houston "not only with our hands, but also with our imagination and inventiveness." Von Braun's worries were well grounded because the contract did not prevent the Centers from arguing over the biomedical equipment; the official history of *Skylab* has described the design of the urine collector as "probably the most vigorously contested point in the entire workshop program."[79]

Throughout the multi-year project, Houston's doctors and Marshall's engineers had difficulty communicating. When the doctors "started talking medicine," recalled Henry B. Floyd, head of Marshall's experiment office, "it was just traumatic; it was a whole new language." The doctors were "as much in the dark about engineering language." Schwinghamer, who directed the medical work, said the engineers and doctors acted like "two dogs sniffing at each other" and that "Houston was worried about us getting into their britches."[80]

Marshall's people approached the biomedical equipment as just another engineering problem. To test the fecal management system, the Center installed prototypes in a KC–135 airplane and collected "data points" by having specimens defecate in the half-minute of zero gravity. For the urine collector, Schwinghamer had his people urinate into beakers to determine the appropriate vessel volume, but during tests astronauts sometimes found that their cups runneth over. Schwinghamer expanded its volume to meet conservative engineering standards.

The engineering approach to the urine collector peeved the doctors. Houston pointed out that all medical labs preserved urine by freezing it. Nonetheless Marshall questioned the utility of freezing "urisicles" and believed drying the samples would be simpler, cheaper, and lighter. The stream of invective over the urine collector continued for months with Houston recommending freezing and Marshall drying. Houston's Dr. Berry said "you could not get through to them." Eventually the doctors convinced the Headquarters program director to choose freezing. But Marshall's Simmons insisted "until my dying day I'll always say . . . we should have dried the urine instead of freezing it."[81]

After *Skylab*'s success, participants downplayed design and development controversies and believed that the disagreements had improved the program. Gilruth praised Marshall's engineers, saying "they're a bunch of craftsmen . . . and the stuff turned out well." The chief of MSC's Bio-engineering Systems Division praised "the outstanding performance of the medical experiments hardware" that met its requirements even through extended missions. Caldwell Johnson's final habitability report, while critical of storage and restraint problems, praised many parts of the workshop, including its up-down architecture and ergonometer. Kenneth S. Kleinknecht, MSC's *Skylab* program manager after February 1970, thought the habitability complaints improved the workshop and felt Marshall "welcomed the strong positions we took [because] that helped them with their money."[82]

Marshall's Belew also believed the competition had been healthy and that *Skylab* habitability compared favorably with that eventually built into the Shuttle. The workshop's features were "not slouchy looking things even some twenty years after." Astronaut Jack Lousma went further, saying the waste management hardware was a "no fuss, no muss, no smell system" and the Shuttle system was a "step backwards." Center conflict, Marshall's Haeussermann argued, was mainly restricted to a project's early phases of task division and hardware design; in these periods quarrels arose mainly because of disputes about resources and responsibilities and because working level people had different ideas about what was the best possible system. Disputes were usually set aside during development and operations when the Centers closely collaborated.[83]

An example of this pattern was the planning for *Skylab* operations. As early as 1967 Marshall sought some role in mission operations. No longer just a propulsion specialist, the Center was building a spacecraft and believed the engineers who built it could best operate it. Houston refused to give up its operations monopoly and wanted to use Marshall personnel only if they were subordinate to MSC's managers and part of its organization. Houston should "operate spacecraft developed by MSFC," Gilruth argued, "in the same way that SAC [the Strategic Air Command] flies bombers designed by several contractors."

After heated discussions, the Centers in May 1970 established a flight planning team with a Houston majority and Marshall representatives. Houston would manage daily mission operations and respond to immediate problems but would consult with Huntsville on hardware matters and long-term problems. Sophisticated communication systems linked Houston's Mission Control Center and Huntsville's Operations Support Center (HOSC). Marshall assigned over 400 engineers to 10 mission teams, providing mission support for the systems and experiments it developed. The teams helped with problem analysis and crew training, staffing simulators such as the neutral buoyancy facility and the solar observatory backup unit, as well as developing computer programs for thermal and environmental control, attitude and pointing control, and electrical power. The agreements enabled the Centers to function as one team during *Skylab* missions.[84]

Rescuing *Skylab*

The NASA Centers showed their shared commitment to mission success during *Skylab* operations. Marshall helped rescue, repair, and run the orbital workshop in its three long missions.

Perhaps the most dramatic episode in Marshall's history occurred as it helped to salvage *Skylab* 1, the unmanned orbital workshop, from the damage incurred during launch on 14 May 1973. The Saturn V rocket fired normally, and the launch seemed successful. But 63 seconds into the flight, controllers in the HOSC read telemetry signals showing early deployment of one solar array and the micrometeoroid shield, a thin protective cylinder surrounding the workshop. Designed to provide thermal protection with a pattern of black and white paint, it was supposed to fit the workshop snugly during ascent and then extend five inches in orbit. Although the workshop attained orbit, its solar wings failed to provide electrical current, and temperature readings on its Sun side were off the scale at 200 degrees F. Later investigations determined that the meteoroid shield had ripped away during the launch, taking with it one array and jamming the other.[85]

Skylab was in a crisis. Heating could spoil food and film and cause the S–IVB's insulation to give off poisonous fumes. Lack of electricity would cripple the workshop. Acting quickly, NASA postponed launch of *Skylab* 2, the first crew for the workshop, from 15 May until 25 May. NASA Centers and contractors had 10 days to develop remedies. For Marshall these days were so eventful that Center Director Rocco Petrone said, “We lived through ‘ten years in May,’ not ten days in May.”[86]

Within an hour of the *Skylab* 1 launch, the Center had shifted to a crisis footing. H. Fletcher Kurtz, head of the HOSC’s Mission Operations Office, remembered that he “quickly became a landlord with about a hundred very unhappy guests. The chain of command went out the window as senior managers increasingly moved into key positions in the HOSC, working directly with those most concerned with the rescue.” Petrone appointed a special team headed by Kingsbury of the Astronautics Lab and William Horton of the Astrionics Lab to coordinate trouble-shooting. The director told the team to “keep the vehicle in a mode where we can inhabit it and find out a way to fix it. Whatever you need at the center is yours. This is the one thing we are going to do at the moment.” The team complied and Kingsbury said “we turned on everything and everybody we had who could do anything.”[87]

Contractors, support teams, project offices, and laboratories acted with selfless dedication and spontaneous teamwork. Schwinghamer, who had driven with his wife to the Cape to watch the launch, recalled driving back to Huntsville all night so he could help. People worked long hours, sometimes sleeping in their offices or going for days without sleep. Sometimes their dedication was dangerous since tired people made mistakes. Ludie Richards would walk up to people, hold up a few fingers, and ask “how many?” He sent home those who could not count. “It was long hours,” James Ehl, an engineer in the Manufacturing Engineering lab, said, “but everybody seemed to enjoy it. It was a challenge.” Kingsbury said “we could not drive people away. . . They just did not want to leave. It was their baby and it was in trouble, and they were here to fix it.” And the remarkable thing was “it came right in the middle of a small . . . reduction in force and an announced sizable reduction in force in the coming months. Nobody said, ‘I don’t care. I’m not going to be here next year.’ It was, ‘Let’s get it fixed.’”[88]

Top administrators who had kept their hands clean for years showed up in the labs. Belew remembered that “everyone that had a role was apt to be any place, any time of day or night.” Petrone “was running it. . . . He was there all the time.” Reinartz said that the director, who “was like a bull in a china shop normally,” was even more excited. Petrone worried that the teams were disorganized and would ask "who was in charge?" and when nobody knew "he would just hit the ceiling." To keep the chain of command clear, some began wearing signs saying "I am in charge!"[89]

Marshall's first priority was lowering the temperature and ensuring electrical power in the workshop. George Hopson and Dr. J. Wayne Littles, co-leaders of the HOSC Thermal, Environmental Control and Life Support Team, began changing the workshop's attitude. They performed a delicate balancing act: reducing temperatures required shading the workshop by pointing the MDA end at the Sun and cutting off solar power; increasing power required pointing the ATM's solar arrays at the Sun and heating the workshop. In balancing these goals, Marshall's close involvement with operations paid off because the Center could direct the spacecraft. Hopson said that "one of the things that has been most gratifying to me was the close cooperation between Marshall and JSC. They have been more than helpful, with everybody trying to help the other fellow solve his problems."

Optimizing temperature and electrical power was trying because attitude changes would freeze one side and scorch the other. The craft had to be maneuvered continually and judging angle and position was difficult because pointing control instruments had not been set. Slight changes brought tremendous joy or despair. The team worked around the clock and Littles said "that first 'day' for many of us was forty-four hours long." Within 10 days the maneuvering had used almost half of the entire mission supply of nitrogen gas in the control thrusters. Petrone told the team, "you're pouring out liquid gold you know!" Eventually the Center pointed *Skylab* so that its sidewalls were at a 45-degree angle to the Sun which reduced interior temperatures to 122 degrees F but still generated some electrical current.[90]

Center engineers test methods for freeing Skylab's *solar array in the Neutral Buoyancy Simulator in June 1973.*

Meanwhile a group managed by James Splawn and Charles R. Cooper constructed a mock-up of the damaged spacecraft in the Neutral Buoyancy Simulator. They had a good picture of the jammed array from radar images and photographs from Air Force spy satellites. By 19 May, Marshall engineers and Navy divers rigged an underwater model they called "the junk pile." NASA air freighted a mock-up of the Apollo Command Module that the team immersed in the tank to test whether an astronaut could stand in an open hatch and pry the solar wing open with a 10-foot pole. Throughout the crisis, the simulator group tested tools, repair procedures, and workshop shields.[91]

Beginning 17 May, Marshall engineers tested cutting tools for opening the wing, restricting themselves to existing tools to save development time. They even tested the surgical bone saw included in the *Skylab* medical kit. NASA Centers and businesses around the country sent devices. Eventually Section Chief A. P. Warren of the Auxiliary Equipment office got an idea from tree-trimmer shears purchased from a Huntsville hardware store. Working with a manufacturer of electrical cable tools, Marshall helped develop pulley-driven cable cutter and shears and a two-prong universal tool. Each had attachments so five-foot sections of aluminum pole could be added.[92]

Other teams throughout NASA were designing systems to protect the workshop from the Sun. In 10 days the Agency tested hundreds of combinations of designs and materials. In Huntsville, Schwinghamer experimented with spray painting and tried it in a vacuum chamber; he determined that spraying would lower the temperature but could coat ATM lenses.[93]

The solution evolved in discussions between Marshall engineers and the crew of *Skylab* 2. Because the astronauts were in preflight quarantine, Center personnel wore surgical masks, giving the meetings a macabre atmosphere. A 75-person shade team conferred through the night of 16 May, sketching designs on a chalkboard. By the early morning of 17 May, they decided on a method in which astronauts on EVA would attach two telescoping poles to the telescope mount. Then, using lines and pulleys, they could stretch a protective cloth between the poles in much the same way as they would run out a clothesline.[94]

Developing the twin-pole shield was hectic. Henry Ehl found the aluminum sections to make the 55-foot-long booms by calling vice-presidents of aerospace companies in the middle of the night. Marshall flew in two seamstresses from NASA's spacesuit contractor in New Jersey to make the sail by sewing together three-foot-wide strips of cloth. There was even some humor. While Petrone and Thompson watched the sewing, one of the seamstresses pushed the material ahead with her foot. "It just isn't right," Petrone muttered, "You're not supposed to kick flight hardware."[95]

Center Director Rocco Petrone (seated second from left) and Deputy Center Director William R. Lucas (standing) are briefed about twin-pole sunshade.

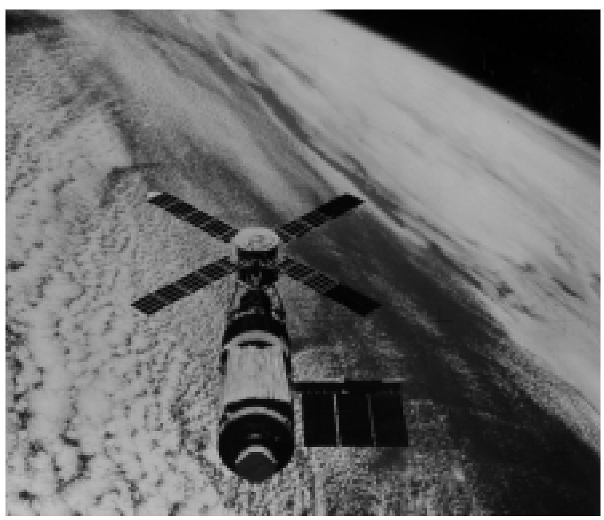
But considering the circumstances, a clear division of labor existed with Schwinghamer and his Materials Division working on sail development, Gustave Krull's Engineering Division designing flight hardware, and J. R. Thompson's Human Factors Branch handling 1-g deployment tests. These engineers tried to remain conservative by using simple materials, testing everything, and following standard development procedures. They made the sail from the same rip-stop nylon used for spacesuits and performed 37 tests on the system in seven days. These included tests on its latex coating to ensure it would not deteriorate in ultraviolet light, and on the deployment system on a *Skylab* mock-up in Building 4619, and on the "junk pile" in the Neutral Buoyancy Simulator. The engineers conducted the normal hardware reviews, although at a

Seamstresses sew Skylab's *solar shield at Marshall.*

rushed pace. Marshall made the first sail on 19 May and tested a mesh mock-up in the simulator on 22 May. At four o'clock on the morning of 23 May, development teams were still working. After final review at six o'clock, Marshall sent the flight article to the Cape. The 112-pound folded sail was vacuum sealed in a breadbox-size container and launched on 25 May.[96]

Testing the twin-pole sunshade at the Skylab *mock-up in Building 4619.*

Marshall's efforts paid off and helped rescue *Skylab*. The Huntsville Operations Support Center changed the workshop atmosphere four times to purge it of any dangerous gases before the astronauts entered. Using the cutting tools and repair procedures developed in the Neutral Buoyancy Simulator, the *Skylab* 2 crew freed the jammed array. Although the astronauts had initially deployed Houston's parasol sunshade, it had not been treated to resist ultraviolet light and began to deteriorate. When temperatures in the workshop began to rise again, the *Skylab* 3 crew deployed the twin-pole shade in a six-hour EVA on 6 August. The workshop temperature quickly dropped to near nominal levels, and *Skylab* became a very successful program. The rescue of



Skylab *in orbit with Marshall's twin-pole sunshade.*

the workshop, J. R. Thompson thought, showed that "NASA functions best when it's flat on its back."[97]

The Agency established a board headed by Bruce T. Lundin, director of NASA's Lewis Research Center, to investigate the sources of *Skylab*'s problems on 22 May. The board visited the major *Skylab* Centers and contractors and quickly determined that the workshop's meteoroid shield had been poorly designed. Marshall and McDonnell Douglas had selected a deployable shield because it was lighter than a fixed shield.[98] But design engineers did not provide enough vents to allow air trapped underneath to escape, and development engineers did not cinch it close enough to the workshop to eliminate air. As *Skylab* gained altitude, the trapped air rose in pressure and eventually peeled off the shield.

Lundin's board decided that the "design deficiencies" had not been caused by improper procedures, limited funding, rushed schedules, or poor workmanship. The fault had been "an absence of sound engineering judgment" at McDonnell Douglas and Marshall. *Skylab* engineers had assumed that the shield was "structurally integral" with the S–IVB hull. Thus the Center and its contractor had failed to assign a systems engineer to the shield and project reviews had failed to discuss aerodynamic stress on the shield during launch. This led to "a serious failure of communications among aerodynamics, structures, manufacturing and assembly personnel, and a breakdown of a systems engineering approach to the shield."

To prevent such failures from recurring, the Lundin report offered two recommendations. First, each hardware project and subsystem should have a chief engineer responsible for "all aspects of analysis, design, fabrication, test and assembly." Second, NASA should encourage direct, hands-on examination of technology and avoid formal, abstract, ivory-tower engineering. Marshall and the rest of NASA implemented the first recommendation, and a chief engineer became a normal part of hardware development.[99] Ironically, however, other NASA policies undercut Marshall's ability to perform dirty hands engineering. Reductions in force and destruction of the arsenal system would increasingly make Center engineers into monitors of contractors rather than builders of hardware and would pressure them to rely on abstract information. Not surprisingly, problems like *Skylab*'s meteoroid shield would happen again.

Looking back on the shield problem, Center personnel had mixed feelings. Belew believed the Lundin report had been wrong; the design was efficacious. The problem, he thought, had been improper cinching of the shield to the spacecraft. But most Marshall engineers agreed the design was flawed. Kingsbury wondered how the Center had overlooked the flaw. Stuhlinger recalled that the Aeronautics Lab had warned that trapped air had to be vented, but this advice had not been heeded.[100]

Ironically the shield had been unnecessary. Marshall's engineers had incorrectly employed data from the Center's own Pegasus meteoroid detection satellites.[101] Marshall's Space Science Lab had analyzed information from the three Pegasus satellites and had determined that the potential danger of meteoroid hits to spacecraft was negligible. If *Skylab*'s designers had used Pegasus information, they could have deleted the shield because it improved penetration protection only marginally. A coat of paint could have provided thermal protection.[102]

After the rescue, the Marshall Center helped Houston operate *Skylab*'s power, control, and environmental systems and solar instruments.[103] Marshall personnel also provided engineering support for *Skylab* systems. While much of this was routine, Center engineers helped Houston and the astronauts conduct repairs. During the first mission, for example, a solar observatory power conditioner failed and a Marshall team decided that a physical blow to the switch might correct the problem. Working with backup equipment, they determined the location that the astronauts should strike with a hammer. The astronauts carried out Marshall's instructions and the power conditioner resumed functioning, thanks to the big hit. A more complex problem arose with the rate-gyroscope processors used to control the workshop. Several gyros overheated and had drift rates much higher than expected. A Marshall team studied the problem, detecting design flaws which could be corrected. Using the Neutral Buoyancy Simulator, the second *Skylab* crew learned how to make the repairs. They took replacement rate-gyros into orbit and successfully fixed the workshop control system. Repairs like these proved the necessity of linking development teams with operational teams.[104]

Skylab offered many lessons like this and Marshall's *Skylab* Program Office, at the request of Headquarters, compiled a list of "lessons learned." The primary lesson, the program office argued, was that management and engineering must be integrated and all parts of a program should be seen as one system. When many organizations develop "a single hardware entity" from many components, careful attention must be paid to systems engineering and integration. Clear design requirements should be established early in the program, interfaces should be carefully controlled, all changes must be tracked, and many different levels of review should be held. Among the many technical lessons was the necessity of designing hardware for in-flight repair.[105]

With the completion of the manned missions, NASA shut off the workshop's systems and closed down the *Skylab* program offices in March 1974. The next year Marshall helped write the denouement of the Apollo program when the Center provided the Saturn I–B launch vehicle and materials processing experiments for the American and Soviet Apollo-Soyuz Test Project.[106] Apollo was over, but a final chapter remained in Marshall's relationship with *Skylab*.

Managing Reentry

The Center was a principal actor in the story of *Skylab*'s fall to Earth. Marshall studies made during the mission assumed that *Skylab* would remain in orbit long enough for the Agency to complete the Shuttle. The fifth shuttle flight could then carry in its cargo bay a Marshall-built teleoperator retrieval system and propulsion module that could boost *Skylab* into a higher orbit for later reactivation.

The Center miscalculated, however, because solar activity was more intense than the predictive models anticipated. The hotter Sun was heating the Earth's upper atmosphere and increasing drag on *Skylab*. Indeed the Center's predictions were so much more optimistic than Houston's or the National Oceanic and Atmospheric Administration, some journalists and scientists charged that Marshall deliberately ignored the early decay of *Skylab* in order to justify funding for the teleoperator system. Dr. Charles Lundquist, head of the Center's Space Sciences Lab, denied the charges and argued that the different predictions were innocent products of different scientific models. In any event, budget crunches and technical problems were delaying Shuttle development and a possible reboost.

To keep *Skylab* from falling down before the Shuttle could fly up, NASA decided in January 1978 to reactivate the workshop and change its attitude to reduce drag.[107] At the end of February a team of eight—four from Houston and four from Huntsville—went to Bermuda to the only tracking station that could communicate with *Skylab*'s now archaic equipment. Heading the team was Marshall's Herman Thomason, who worked in the Systems Engineering Lab. Dr. Thomason had written his doctoral dissertation in 1969 on *Skylab* control methods. He later joked that he got the job because he "had been griping to management that something had to be done about *Skylab*. I guess I talked too long." His work was made difficult by the fact that many old *Skylab* hands had retired or joined contractors and *Skylab*'s technical documentation was lost or gathering dust.

With radar support from the North American Air Defense Command (NORAD), the Bermuda team made radio contact with *Skylab* on March 6. Initially communication was sporadic because the workshop was tumbling and could only transmit when its solar panels pointed at the Sun. Thomason's team tried switching to *Skylab*'s ATM batteries, but these kept shutting off because of low voltage readings. By April the team recharged the batteries by sending signals every 1.5 milliseconds, ordering the batteries to remain on and receive power from the arrays. Days passed before the batteries recharged. Meanwhile NASA trained more operators and activated four other tracking stations so that *Skylab* could be monitored continuously. Finally on 8 June, *Skylab* had sufficient power to operate the telescope mount's control moment gyros, and Thomason thought to himself, "we are in Fat City." The next day the team turned the workshop about and began a complicated balancing act; for a year they tried to maintain an attitude that minimized drag and fuel expenditure and maximized solar power.[108]

As the work continued through the summer and fall, NASA changed its policy. In December 1978, the Agency decided that the Shuttle would not be ready in time to reboost *Skylab*. Rather than trying to keep the workshop aloft, NASA would manage its reentry. The goal was to reduce risk of damage and avoid anything like the scare caused by the reentry over Canada of a Soviet satellite containing radioactive materials. NASA studies argued that the risk was minimal; *Skylab* was passing over a path that was 75 percent water and where 98 percent of the land had less than one person per acre. A person in the "footprint" had only slightly more chance of being hit by a piece of *Skylab* than by a meteorite. Even more than might have been the case otherwise, in an era of limited funding NASA wanted to avoid any blemishes.[109]

Thomason's team at Marshall played a major role in managing reentry. Officially the same division of labor existed between the Centers, with Houston controlling flight operations and Marshall providing engineering support. But Marshall's 40-person team worked in shifts around the clock in a *Skylab* Control Center and wrote computer programs to adjust attitude. They improvised computer and communication equipment because the original *Skylab* equipment had been scrapped or transferred to other projects. The team continually updated the programs to adjust for increased drag as the workshop fell and sent the programs to Houston where they were relayed to *Skylab*. It was a Marshall program, issued on orders from Headquarters, that on 11 July 1979 caused the workshop to enter its final tumble and end its flight. As a result *Skylab* passed over the east coast of North America and fell harmlessly over the Australian outback and the Indian Ocean.[110]

The Center, however, got little credit. Virtually all the credit went to Houston or to Headquarters. Newspaper reports were datelined from Houston and the official history of the *Skylab* program praised "the Houston team." This slight irritated some at Marshall. One engineer complained that "sure we are part of a team, but even in football the starting line-up has their name announced." Kingsbury, head of the Center's Science and Engineering directorate, said "I guess this is something like the guard or key tackle on a football team. No matter what they do, the camera points at the quarterback."[111] Ironically the Center that had played the largest role initiating *Skylab* got the least mention at its end.

Veterans of *Skylab* remembered the program fondly. Ise, the ATM manager, summarized the views of many by saying that *Skylab* was "the highlight of anybody's career that was associated with it." The project lasted only eight years from beginning to end, and in-house manufacturing created pride in workmanship. "The whole thing was just wrapped up in a nice, neat package with a bow on it. Then you can go back and look at it and say, 'That was it and I was a part of that.' It is something that is not so easy to do today." The difference between *Skylab* and later payload projects, Ise felt, was "the difference between building an Empire State Building and building a bunch of houses."[112]

Skylab indeed closed the Apollo era and helped open the way to a new period in the history of Marshall and NASA. As part of the Apollo era, *Skylab* benefited from arsenal practices, the Saturn V's heavy lift capability, and budgets and schedules which allowed adequate spares and testing. Later programs evolved with more restricted testing, fewer spares, and greater risks. *Skylab* also opened a new era in which Marshall diversified from propulsion to multipurpose engineering. Organizationally, the diversification contributed to a new NASA politics in which Centers competed for control of projects and technical designs.[113] Technically and scientifically, Marshall's diversification helped create a space station of a kind that made splendid contributions to space engineering, Earth observations, astronomy, medicine, and physics.[114]

Unfortunately NASA did not follow up the successes of *Skylab*. As former Houston *Skylab* Program Manager Robert F. Thompson observed at a *Skylab* reunion in 1988, *Skylab* was a "beautiful tactical program" that had "numerous shortcomings" as a "strategic program." *Skylab*, he said, had not been designed for in-flight repair, resupply with air and water, refurbishment with improved technology, revisitation for reboost to a higher orbit, or restructuring as part of a larger station. Consequently it could not, and did not, lead to a strategic, sustained human presence in space. Alternatively, as Marshall's Stuhlinger argued, NASA failed to establish such a long-term presence less because of the workshop's design and more because of the Agency decision not to launch the second *Skylab*.[115]

Even so from the perspective of the design and funding crises over a space station in the 1990s, the success of *Skylab* loomed very large. Many in the Agency wished that *Skylab* was still in orbit, and others, with only a little whimsy, wanted to take the backup workshop on display in the National Air and Space Museum and launch it.[116] Indeed in retrospect *Skylab* came to represent how Marshall and NASA had achieved important successes by imaginative use of existing hardware and pragmatic adaptation to budgetary realities.

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