"Return, Repair, Refly: Spaceflight Strategies for a Resource-Limited Age"

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While much of the literature on the history aerospace technology focuses on innovation, some of the National Aeronautics and Space Administration's most important technical successes have concerned efforts to repair and reuse existing spacecraft. Creative recycling, though, placed novel demands on flight crews: astronauts who had joined NASA to travel to the Moon instead faced their greatest challenges when forced to maintain and repair spacecraft destined to remain in low Earth orbit.

Winning a used spacesuit in an advertising jingle-writing contest, Kip Russell, the hero of author and former aeronautical engineer Robert Heinlein's 1958 science fiction novel *Have Space Suit—Will Travel*, is simultaneously enthralled with his "marvelous piece of machinery" and disappointed. Seeking a free trip to the Moon, Kip receives, instead, a surplus pressure suit that is full of holes and smells like dirty socks. After writing to Goodyear for patching material and gaskets, though, Kip soon embarks upon the adventure of a lifetime. This was Heinlein's fantasy in a nutshell: that, someday, spacesuits would be as ubiquitous as Colt revolvers were in the Old West or tuxedos were in modern America: an expensive item when purchased new, but one available in large quantities used—for those intrepid enough to repair them. While science fiction has always been motivated by a fascination with innovation, authors have often found amusement in the suggestion that the future will be very much like the present, with the constant repair and reuse of an array of technologies—like the droids from *Star Wars* films—that seem sophisticated now but will, in time, become quite mundane. The real Space Age is as old as Heinlein's novel, but in that time, it has already become as much a story of redesign, reuse, and maintenance as one about invention and exploration.

In a forthcoming NASA study edited by Roger Launius and Howard McCurdy entitled *Seeds of Discovery: Chapters in the Economic History of Innovation*, I explore how inspired recycling allowed creative, but resource-limited aviation pioneers to imagine uses existing vehicles in new ways. Aerospace innovators have rarely had the luxury of unlimited funds or time to build their flying machines. Even during the relatively flush Cold War, when Congress appropriated billions of dollars to projects connected to national security, engineers worked within budgetary limits and schedules that prevented them from fabricating new technologies to fulfill all of their design needs. The first American artificial Earth satellite blasted into orbit atop a vehicle cobbled together from military rocket programs, including the Army's Redstone missile. A later variant of the Redstone launched the first American astronaut into space, and over the next half-decade, Air Force missiles like Atlas, Titan, and Thor launched the bulk of NASA's space vehicles. Spacecraft, too, often saw their capabilities enhanced and extended, were redesigned for greater capability, or simply re-flown. The actual re-use of spacecraft likely began in 1966, when the Air Force re-flew a NASA Project Gemini test capsule to verify new hatch design.

As NASA prepared its costly, technically challenging, and reusable Space Shuttle for flight in the 1970s, it simultaneously demonstrated that surplus Project Apollo hardware built for lunar exploration could be successfully re-engineered to create a space station in Earth orbit: the Skylab Orbital Workshop (OWS). By 1960, engineers in various Army, NASA, and contractor facilities realized almost simultaneously that the large, empty fuel tanks of spent Saturn rocket stages could be vented of remaining propellant by spacesuited astronauts in Earth orbit, resealed, and pressurized with breathable air. Between 1960 and 1969, the constant reengineering of this design to exploit new hardware surpluses enabled NASA to launch Skylab into space in 1973 as a complete, intact space station. The Skylab OWS, though, was a hodge-podge of leftover hardware, including a hatch from a Gemini spacecraft and a telescope originally intended to be mounted on an Apollo Lunar Module. Other Apollo-era hardware was simply reused or minimally upgraded. The Apollo Command and Service Modules (CSM) could ferry astronauts to the station almost without modification, using the same docking assemblies and navigation systems used for the Moon program. Even Skylab's spacesuits were variants of those worn by lunar crews, without the overshoes and backpack used on the Moon's surface.

Science fiction authors of the 1950s recognized that future spacecraft would break and require repair. Though the idea of vehicle maintenance was seldom a featured part of press coverage about NASA's early missions, maintenance of critical space systems became an increasingly important task as American space missions increased in length from minutes in 1961 to months by 1974. Creative recycling placed novel demands on flight crews: astronauts who had joined NASA in the 1960s to travel to the Moon instead faced their greatest challenges when forced to maintain spacecraft in the 1970s, that traced slow circles around the Earth until their oxygen and food ran out. Repairs in space had predated Skylab: Apollo lunar crews had, on a couple of occasions, used duct tape to repair damaged hardware or, in the case of the ill-fated Apollo 13 mission, fashion a device to scrub cabin air of excess carbon dioxide. These episodes, though, were aberrational: regular maintenance duties were not expected for spacecraft that had been rigorously tested and designed to operate for only a few days at a time. Skylab's missions, though, would be long enough to present significant maintenance issues: recharging coolant systems, disinfecting water tanks; removing telescope filters, swapping film magazines. NASA, in fact, expected that "systems management and malfunction procedures" would occupy the bulk of the astronauts' time, and preparations for such work constituted the majority of their training for missions. NASA had intended Skylab to serve as an experimental platform for working scientists, but most of the scientific equipment on the station was semi-automatic and did not require the expertise of trained scientists, whom the agency began recruiting as astronauts in 1965. Sustaining the astronauts' comfort (and even their very lives), though, might prove challenging, and so astronauts were cross-trained in various skills in the event some became incapacitated. NASA's pilot-astronauts were expected to do so little aboard the station that the men trained to serve as dentists—to prepare, they extracted teeth from patients at the Air Force Hospital in San Antonio, Texas. Life aboard the station would likely be very different than that of men who, only one year earlier, were driving dune buggies on the Moon.

The robustness of the Skylab design would be tested on its unpiloted launch, when a failure of the shroud protecting the station damaged the OWS, tearing off its protection against solar heating and micrometeorites and leaving it with most of its solar power panels torn off or folded up. Trying to deploy a stuck solar panel, Skylab 2 astronauts resorted to a “stand-up” spacewalk in which one astronaut, his body half-outside of his Apollo spacecraft, poked at the station with a stick while another held onto his legs to keep him from floating away. A later spacewalk released the stuck panel and restored most of the station’s power, but the explosive release of the panel sent the astronaut flying away from the station, only to be snapped back by a safety tether. The tools for these repairs were clever, but not exotic. Simple cutting tools used by power line workers enabled astronauts to release a large solar array that failed to deploy, while the sun shades installed by the astronauts consisted of gold-coated Mylar sheets stretched over the exterior of the OWS’s habitable compartment. On the Skylab 2 mission, astronauts carried a small, expandable sun shade that could be deployed and unfolded through Skylab’s scientific airlock like an umbrella, without the need to venture outside. A second, larger shade carried by the Skylab 2 astronauts was installed by the Skylab 3 crew.

Though ultimately serving as a “house in space” for three Apollo crews (with the final mission lasting 84 days), Skylab continued to challenge astronauts and ground crews, particularly on the second piloted visit, Skylab 3, when thruster problems with the astronaut’s Apollo ferry vehicle suggested that a rescue mission might be necessary. Within a relatively short period of time, NASA relied on prior planning and assembled a viable rescue craft from its proven Apollo CSM. The Skylab rescue mission, or SL-R, consisted of a conversion kit that launch pad engineers could use to replace the seating on any existing Command Module with five crew couches, accommodating both the two-person SL-R mission crew and the three rescued Skylab astronauts. When the thruster problems appeared on Skylab 3, backup crewmembers Vance Brand and Don Lind immediate began training to recover the potentially stranded crew. Skylab’s multi-month supply or air, food, and water reduced the urgency of the rescue though, and when subsequent work by astronauts and ground engineers determined that malfunctions would not jeopardize the Skylab 3 mission, NASA cancelled the rescue flight. Given the extent of NASA’s preparations, though, the SL-R mission’s success appeared likely.

The third crewed mission, Skylab 4, not only further extended the record for American long-duration spaceflight but demonstrated that isolated astronauts under pressure to perform might rebel against ground controllers if overworked. Throughout the 84-day visit, Skylab’s crew chafed against burdensome schedules and unrealistic performance expectations. Morning routines included daily weighing and the collection and bagging of their urine and feces for later analysis. Determined to exploit Skylab’s longest flight, ground controllers increased the experimental workload, faxing to the astronauts sixty printed feet of paper instructions per day. These experiments usually required little more that set switches and dials, astronaut Ed Gibson recounted; “it never gave you any time to really use your intelligence in how you took data. It was just push the buttons as fast as you can and move on to the next.” Having only enough food aboard the station for 56 days of operations but hoping to extend their visit even longer, the astronauts skipped meals and became irritable. Productive in their work but falling behind an overambitious seven-day-a-week-schedule, the astronauts requested Sundays off, but NASA was reluctant to provide the men with downtime on a multimillion dollar space mission. Possibly in retaliation, the astronauts deactivated their radio, and when they reactivated it, ground controllers reluctantly offered them a day without new instructions to catch up previous assignments and look out the window.

Throughout 1973 and 1974, NASA engineers and astronauts adapted to Skylab’s deficiencies while extracting from it virtually all of its capabilities in solar astronomy and Earth resources photography. After 1974, NASA continued to explore ways to inexpensively extend the life of Skylab, which remained in orbit and functioning as the shuttle neared completion. During the late-1970s, though, greater-than-expected solar activity expanded Earth’s atmosphere and increased drag on Skylab enough to threaten its orbit. The first shuttle orbiter, *Columbia*, did not fly until 1981, nearly two years after Skylab’s orbit decayed fatally. Despite NASA’s efforts to direct its debris into the Indian Ocean, significant debris struck a sparsely populated region of Western Australia. Skylab’s demise, though, resulted less from astronomical misfortune than a budgetary decision to shift funding from Skylab to NASA’s new spaceflight infrastructure.

In his 2007 book *The Shock of the Old: Technology and Global History since 1900*, David Edgerton writes that despite the excitement surrounding the invention of exotic new technologies, older alternatives tend to persist in regular use far longer than most people would imagine. Rather than representing a failure of the inventive process, this fact demonstrates that much of engineering practice involves the maintenance, reuse, and repurposing of robust older technologies. While not all of NASA’s efforts to operate and extend the life of Skylab were successful, they demonstrated that, eventually, human exploration of space will be a story of maintenance, often using surprisingly rudimentary technologies. In a field punctuated by what Edgerton describes as a false “futurology of the past,” it is technologies that confound our understanding of the “new” that often prove most effective.

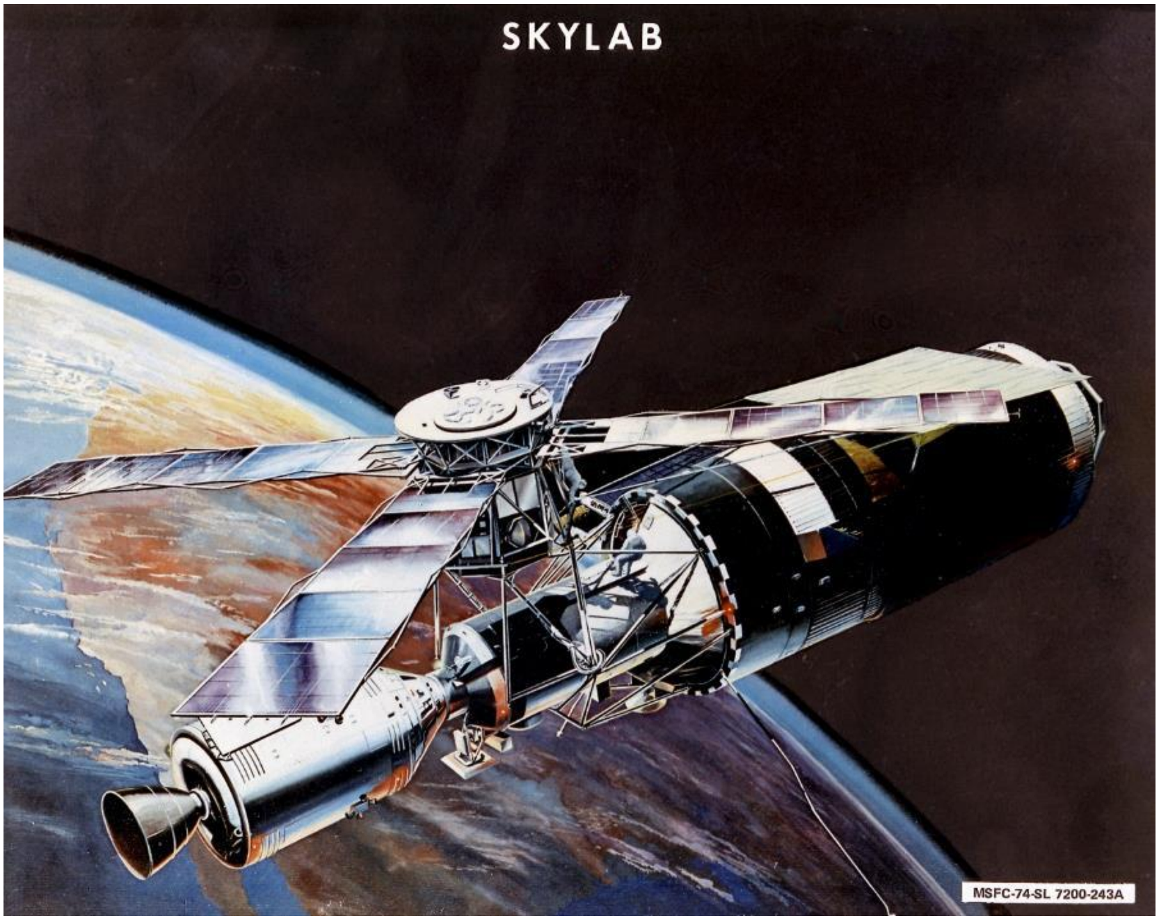

Figure 1. The Skylab Orbital Workshop passes over Baja California in this Marshall Space Flight Center artist's drawing from 1974, depicting the station's actual configuration following the Skylab 3 crew's repairs to the station. Apollo Command and Service Modules are is docked at left, and the Apollo Telescope Mount is visible atop the vehicle. At right, the two sun shades installed by the Skylab 2 and 3 crews are visible, one on top of the other. Photo courtesy of NASA.

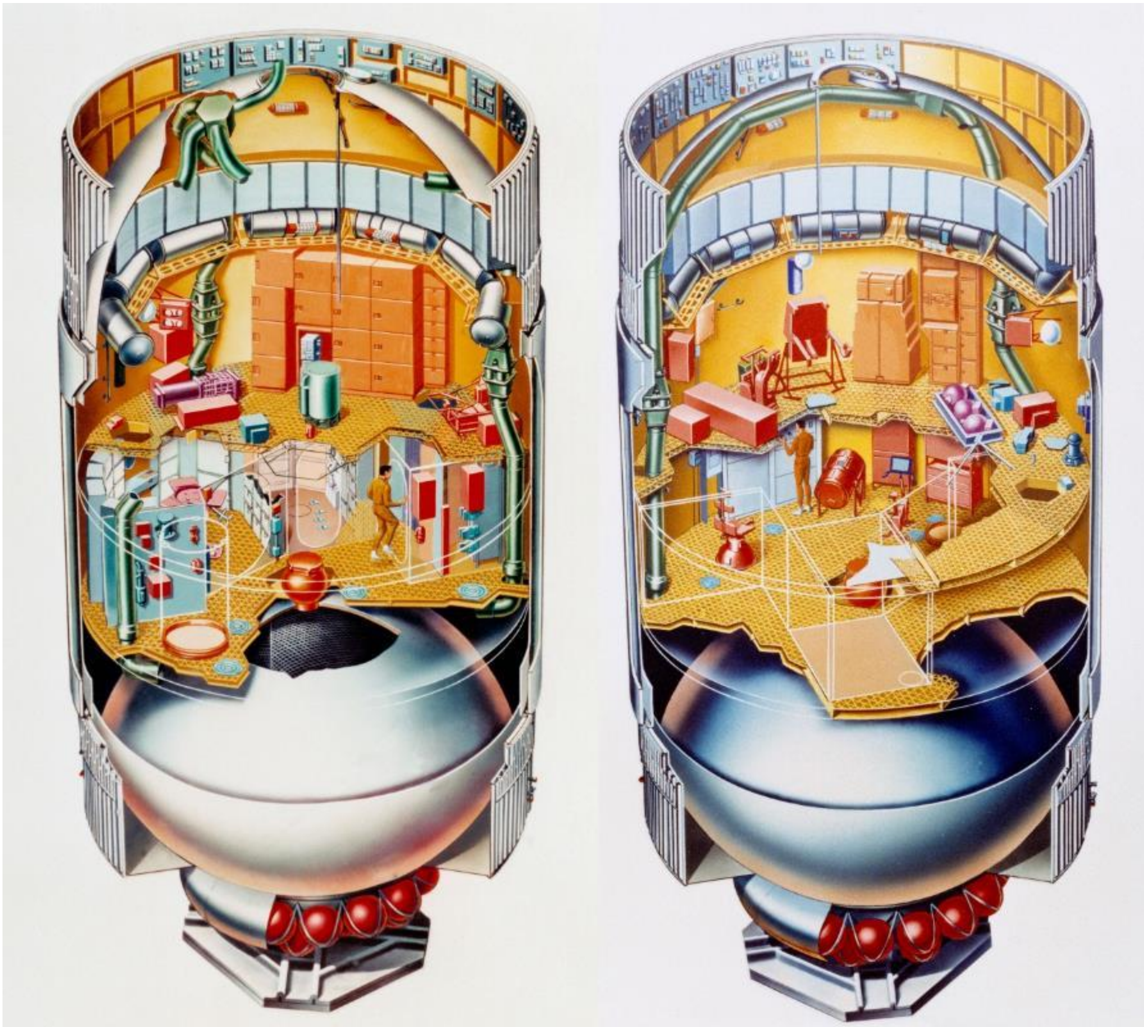

Figure 2. The propellant tanks used to fabricate the Skylab Orbital Workshop are visible in this cutaway schematic of the interior of the station. Photo courtesy of NASA.

Figure 3. Engineers at NASA's Johnson Space Center test a replacement sunshade for Skylab. Note the ice cream vending machine at rear. Courtesy of the NASA Historical Reference Collection, Folder 007575; *see also*, W. David Compton and Charles D. Benson, *Living and Working in Space: A History of Skylab* (Washington, D.C.: NASA, 1983).

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1. PREFLIGHT HISTORY HAS INDICATED PAST RELAY HANG-UPS WHICH HAVE BEEN FREED BY MECHANICALLY SHOCKING THE RELAY.

2. RECOMMENDED PROCEDURE IS TO STRIKE THE CBRM HOUSING AT THE POINT INDICATED BELOW. TESTS INDICATE THAT YOU CANNOT HIT THE CBRM HARD ENOUGH TO DAMAGE IT.

3. DIAGRAM BELOW IS DETAIL OF CBRM. LOCATION WRT CENTER WORK STATION IS SHOWN IN ATM SCHEMATICS BOOK, DIAGRAM 5.9, LOCATION L5.

5. CODE ⊙ = ALLEN HEAD SCREWS ON RAISED PORTION OF CBRM.

✱ = ALLEN HEAD SCREW ON WHICH TO POUND.

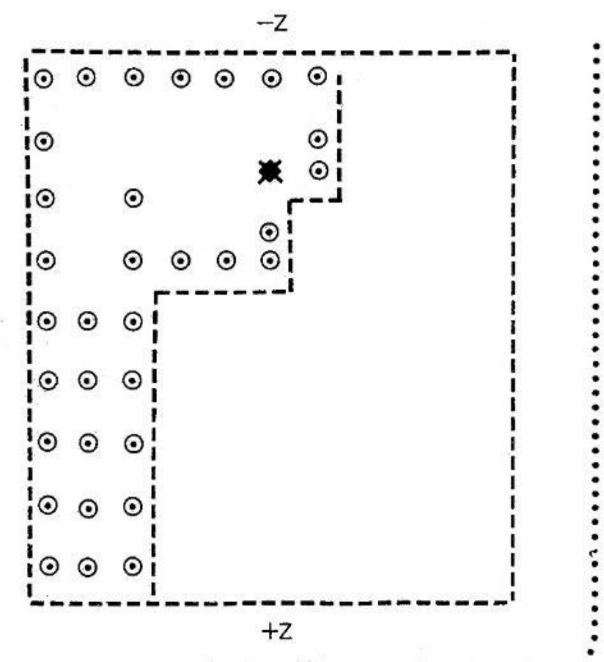

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Figure 4. Instructions for the on-orbit repair of a dead power module, radioed to the Skylab 2 crew and accomplished by mission commander Pete Conrad during a spacewalk. Power was restored after he wailed on the battery housing with a hammer. Courtesy of the NASA Historical Reference Collection, Folder 007575; *see also*, Compton and Benson, *Living and Working in Space.*

Notes:

1. Parts of this paper have been recycled or repaired. It draws from, extends, and compliments research conducted in connection with several other projects, including *Inventing the American Astronaut* (New York: Palgrave Macmillan, 2012), and a contribution to the forthcoming NASA study *Seeds of Discovery: Chapters in the Economic History of Innovation within NASA*, edited by Roger D. Launius and Howard E. McCurdy. I also wish to thank Colin Fries and Elizabeth Suckow at NASA Headquarters in Washington, D.C., for their assistance in utilizing the NASA Historical Reference Collection and the NASA Technical Reports Server.

For Further Viewing:

Skylab: The First 40 Days (NASA, 1973) (https://youtu.be/K3uPuTvFIus).

For Further Reading:

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