INTRODUCTION

My asshole is doing as much to keep me alive as my brain.

—Astronaut Mark Watney, in *The Martian*

IN 2016 NASA ANNOUNCED THE SO-CALLED SPACE POOP CHALLENGE. It delighted children and amused journalists, who flocked to NASA's Johnson Space Center to hear about the competition. The Poop Challenge called for innovative "solutions for fecal, urine, and menstrual management systems to be used in the crew's launch and entry suits over a continuous duration of up to 144 hours." The announcement garnered some five thousand submissions, from which twenty-one finalists were selected. Two of the three eventual winners offered innovative designs for garments, while the third person maintained that laparoscopic surgical techniques were the answer. In a moment of levity about the whole business, NASA added that among the competition's winners were the forty-six currently active astronauts, "who are very relieved."[1]

This competition was more than a playful public relations event. In fact, the problem of waste management has been a central part of the space age from the very beginning. Biological waste is the inevitable flipside of nutrition, and while on Earth the two processes are naturally connected via ecological cycles, in space neither one can be taken for granted. Andy Weir's 2014 novel *The Martian* describes vividly the intimate connection between nutrition and excretion, or food and waste. Weir's astronaut hero Mark Watney is accidentally left behind on Mars and faces the challenge of surviving roughly four years until the next mission is expected to land. Watney has four hundred days' worth of prepacked meals, which are tasty but finite, but also twelve valuable potatoes that were intended for the team's Thanksgiving celebration on Mars. Conveniently, the Mars habitat generates ideal growing conditions for these potatoes, and in a memorable scene in the book (and later film), Watney creates soil to grow his potatoes from a handful of Martian dirt by adding water, bacteria from samples of earth (from Earth), and, finally, his own packaged feces and urine as fertilizers. "My asshole is doing as much to keep me alive as my brain" becomes not only the hero's greatest one-liner but also a succinct description of a core element of twentieth-century space research.[2]

Weir's novel hinged on a necessary reality of humans going beyond the moon, which has been the subject of decades of research in space biology and medicine as well as environmental and systems engineering. From the beginning, both the American and Soviet space programs aimed at going to Mars and beyond. That ambition implied that people would have to spend months or more likely years in space travel, no matter what engine they used or how sleek their rockets were. (One science fiction story of 1940, the first to envisage a generation star ship, imagined a six-hundred-year trip into space.) During these journeys, the inhabitants of the spacecraft would consume considerable amounts of oxygen, food, and water, while at the same time producing proportional quantities of carbon dioxide and various bodily excretions. The two-thousand-person generation ship that Kim Stanley Robinson imagined in his novel *Aurora* (2015) would produce about 315 kilograms of feces per day (150 grams per person per day), or a discomforting 18 million kilograms of human excrement over the course of its 159-year voyage to a neighboring star.[3] Even if this kind of space travel was far beyond the space programs' actual aspirations, the problem reached alarming dimensions fairly quickly when contemplating three-year voyages to Mars, a goal of both Americans and Soviets.

While the problem was simple and obvious, the solution proved difficult to attain. Since it was practically impossible to bring all the necessary food and air for the long journeys from Earth, it would have to be produced on the way. To produce food and air, the space travelers would have to take care of their liquid, gaseous, and solid excretions. The conclusion was that the material cycles had to be closed, as they were on Earth. It was the operating assumption for more than sixty years, in both the United States and the Soviet Union, that long-term life support in space required astronauts to use biological waste to grow their own consumables in meticulously controlled artificial environments. The "waste-processing" component of any life-support system must be equivalent to the "food-processing" component and indeed the "crew itself" (see fig. I.1). How space travelers attempted to make this work is, in part, the subject of this book, which tells the story of how scientists and engineers of the space programs

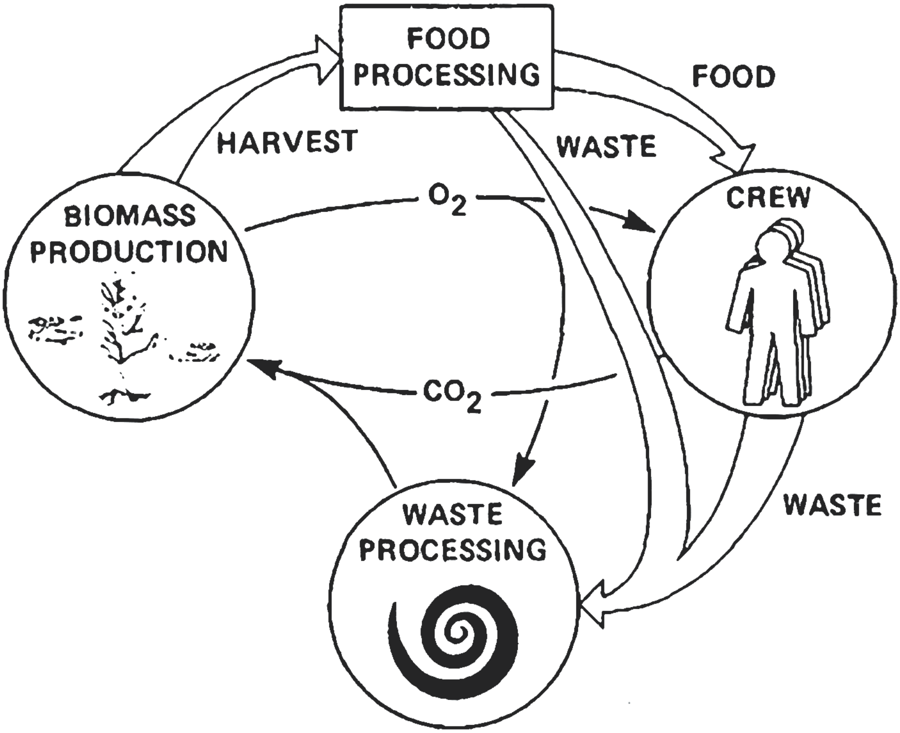

Fig. I.1. "Material cycling within a bioregenerative life support system." From R. D. MacElroy and James Bredt, "Current Concepts and Future Directions of CELSS," in Robert D. MacElroy, David T. Smernoff, and Harold P. Klein, *Controlled Ecological Life Support System: Life Support Systems in Space Travel* (NASA Conference Publication 2378; Washington, D.C.: NASA, 1985), 2.

converted visionary thinking into material reality. The chapters cover the period from the late 1950s until the early 1990s—starting with modest attempts to replace storage devices on board with regenerative algae systems, and ending with the ambitious large-scale projects to replicate whole ecosystems on Earth, such as the BIOS-3 project in the Soviet Union and the Lunar-Mars Life Support Test Project and Biosphere 2 complex in the United States.

Building appropriate environments to sustain humans in space was not considered an unrealistic goal, merely an extremely difficult one. Ever since the late 1950s, the space age sought the science and technology of what we would now call sustainable resource management. It produced a wealth of ecological knowledge of the functioning of closed environments. It also confirmed the insight that a regenerative life-support apparatus was the main factor that determined how long (and how comfortably) anyone could live in space. But the insight itself was not yet the solution. Even today, the quest to build a completely closed artificial environment remains unfulfilled. As the Poop Challenge indicates, space agencies still struggle to create even short-term systems. One of the more successful and promising efforts over the past decades has been the European Space Agency's MELiSSA system, the Micro-Ecological Life Support System Alternative, which used microbes to recycle air, water, and food to astronauts for deep-space missions. In a 2017 interview, its leader, Christophe Lasseur, succinctly explained that the European Space Agency's program and agenda was "to characterize all processes in as much detail as possible as a first step to recreating it, based on the knowledge we acquire." This was the rationale from the start of the space age. In order to make life-support systems work, a comprehensive investigation of all life processes and their interconnection was required and thus NASA and other agencies always promoted large programs in the life sciences and ecology.[4] Yet decades later, even after the first trial runs of the MELiSSA system have been completed, the space age is still far from a fully functional closed life-support system. For all our knowledge of life processes on the molecular level, without understanding the complex interrelations of the components of ecological systems, this task is challenging.

These massive research programs in the construction of artificial environments have not received anything like the attention they deserve. Most historical and popular accounts of the human adventure in space invariably have looked upward and ignored its earthier aspects. This was no coincidence. The space race was a spectacular turn during the heyday of the Cold War, that struggle between distinct ideological visions of society.[5] After 1945 the Soviet Union and the United States vied for international hegemony by becoming military-industrial behemoths with large bureaucracies and secret worlds of security, missiles, and surveillance. By the mid-1950s, however, this rivalry had produced a global power stalemate. The conflict thus evolved into a war of images, rhetoric, and above all grand technological displays, and the space race became its most extraordinary show.[6] Over the next thirty years, it became a competition to see who put the first animal into orbit, then the first person, a landing on the Moon, and eventually who laid the foundations of a permanent human presence in space. "The goals of the [space] program are not scientific goals; they are political," clearly declared the first chairman of the Atomic Energy Commission, David Lilienthal, in 1963. Political leaders on both sides worked to make sure that the correct message was received both by their own people as well as the global community. What was perceived as "correct," however, was very different. It was a vital component of the space race that both sides competed to legitimate their version of events. As historian Asif Siddiqi notes, Russians still see the launch of Sputnik and the later

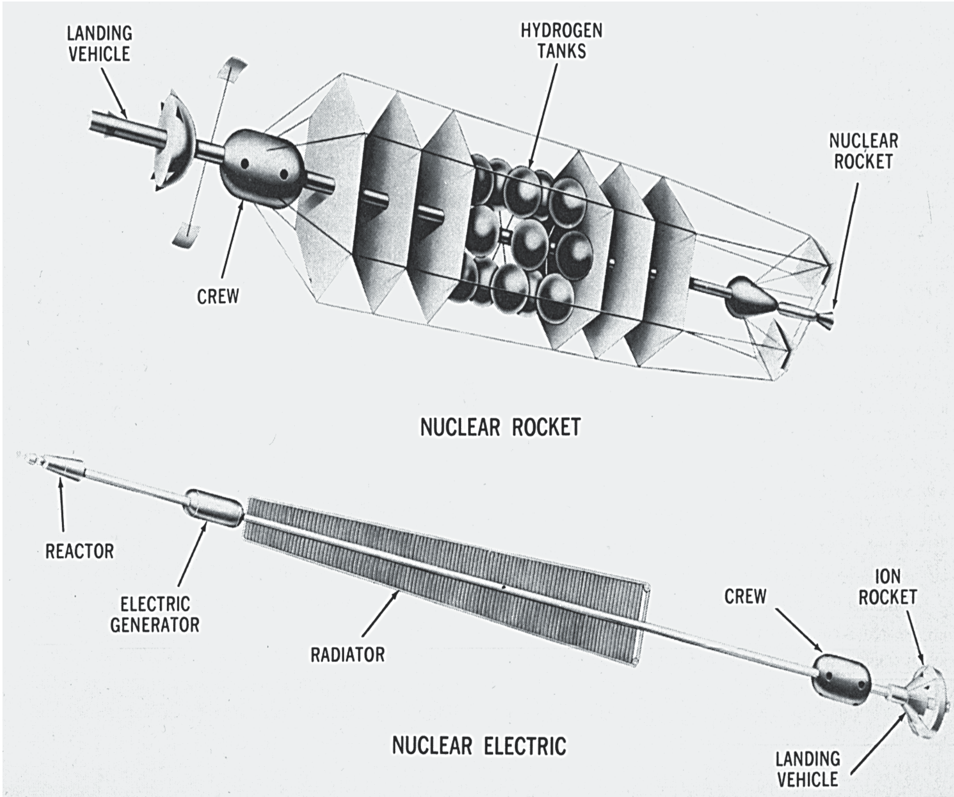

Fig. I.2. "Space Ship Structures." From National Aeronautics and Space Administration, *The Challenge of Space Exploration: A Technical Introduction to Space* (Washington, D.C.: NASA, 1959), 25.

orbit of Yuri Gagarin as the greatest breakthroughs of the century, while the landing on the moon is perceived as only a minor consequence of their earlier triumphs. Americans, of course, see those events in reverse: the landing on the moon is the real feat, while the Soviet accomplishments were just a prelude.[7]

The space race served its political purposes so well because it was a media spectacle covered exhaustively in print and televised everywhere. Countless TV shows, coffee table books, novels, movies, and popular histories parade the splendor of the space programs, with gleaming rockets and movie-star cosmonauts and astronauts next to their Jackie Kennedy–lookalike wives. Their predominant historical narrative stresses stories of engines, heroes, and power, and thus replicates earlier patterns of equally masculine automobiles where horsepower and design had set the tone.[8] Speculation about spacecraft engines was rife, but they were not the entire story, just the most visible part (see fig. I.2). At the same time more socially problematic parts were rendered invisible. The book (and Oscar-winning film) *Hidden Figures*, for example, tells the story of black women computers whose mathematical prowess proved crucial throughout the American space program but remained largely uncelebrated. The working realities of gender and race with a short-lived female astronaut training program and the long-lasting use of black women computers went against how NASA wanted to be perceived.[9]

Our book emphasizes other aspects of the space program that went equally undebated in public but were equally important, specifically ideas about waste and systems to deal with it. Decades in the making, artificial environments were developed—by biologists, social scientists, and environmental engineers—to enable the recycling of waste into consumables. To understand this part of the history, we need to resist being dazzled by rockets and handsome heroes and instead look at the space age from the bottom up, rather than the top down.[10] To live among the stars, ironically, has always meant solving the down-to-earth problem of sustainable waste management.

NASA'S ECOLOGICAL EXPERTISE AVANT LA LETTRE

The first flights into space were so short that the problem of sanitation could be put off. In 1964 Michael G. Del Duca, chief of the biotechnology branch of NASA's Office of Advanced Research and Technology, recounted in his keynote address to a major conference how, "in early manned space flight, much attention was given to space feeding and nutrition, but the problem of waste handling was eliminated by eliminating elimination."[11] As Del Duca noted, adult diapers sufficed for flights of a day or two, while a condom attached to a tube and complemented by a plastic fecal bag permitted flights of up to two weeks. Bags and diapers sufficed for nearly two decades. Incremental progress came in the 1980s, when a space commode was installed in the first space shuttle (employed from 1981 until 2011), and then later in the International Space Station (ISS) since 1998. The commode remains "the most important piece of equipment to master," as astronaut Scott Kelly put it when he arrived at the ISS for a full-year stay in 2015.[12] All these devices work through collection and storage—and the latter to an excessive extent. Solid waste has been returned to Earth throughout humanity's adventure in space (allegedly now sitting in jars on shelves at NASA and elsewhere), while carbon dioxide has been filtered and, until the ISS, urine and condensate expelled. The techniques were considered "well understood, relatively compact, low maintenance," and perfectly sufficient for short-duration

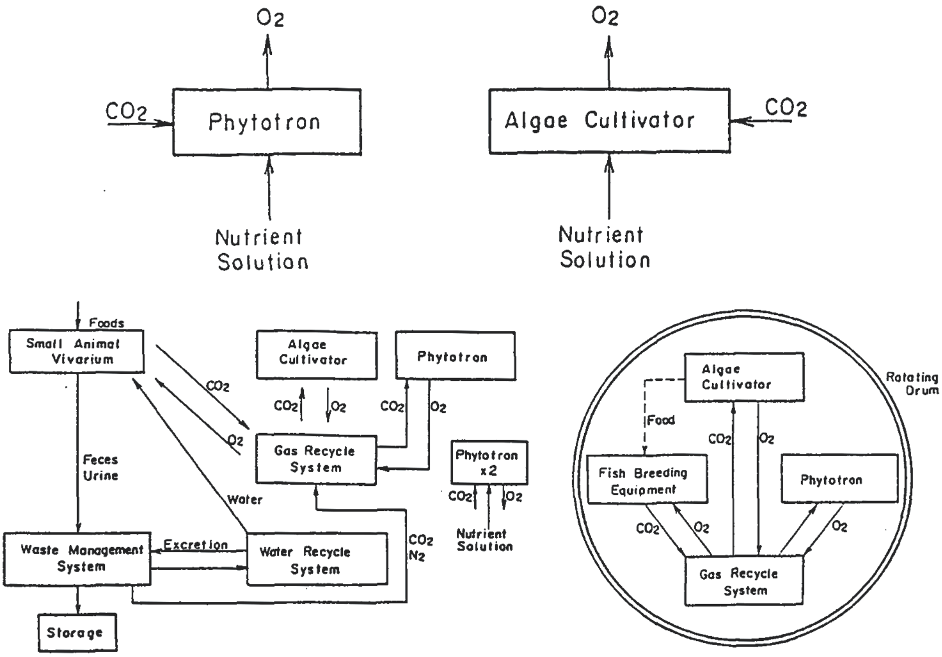

Fig. I.3. "Experimental Concepts." From Haruhiko Ohya, Tairo Oshima, and Keiji Nitta, "Survey of CELSS Concepts and Preliminary Research in Japan," in Robert D. MacElroy, David T. Smernoff, and Harold P. Klein, *Controlled Ecological Life Support System: Life Support Systems in Space Travel* (NASA Conference Publication 2378; Washington, D.C.: NASA, 1985), 14.

flights.[13] But everybody knew that other solutions had to be found for more ambitious endeavors.

From the start, people like Del Duca took it for granted that regenerative systems had to be developed that returned excreted waste to the crew as sustenance. Algae systems were among the space age's favorite alternatives. Norman Bowman's description of the uses of algae for food and waste recycling appeared as early as 1953 in the *Journal of the British Interplanetary Society*, and the notion that this might be the way to go has never faded since. Consequently, many people thought that the space programs had to carefully study algae cultures and acquire profound ecological knowledge if they wanted to conquer space. It was not enough to think of spacecraft as vehicles that were able to travel long distances; one had to envisage them as moving ecosystems. In fact, when NASA planned a new space station in 1985, one discussant, Sharon Skolnick, noted that they were "sending up a new planet, actually a microcosm."[14] Within such microcosms would be interconnected waste management and gas recycling and water recycling systems connecting the crew to their environment through plant growing phytotrons, animal vivariums, fish breeding equipment, and algae cultivators (see fig. I.3).

The ambition on both sides of the Iron Curtain was to create self-contained environments in which people could live for years, perhaps even decades or centuries. Those environments were envisioned as little copies of Earth traveling through space. Indeed, it was an analogy drawn quite early on. Already in 1962, the American sanitation engineers William Oswald and Clarence Golueke noted that their small-scale algae/waste system for space was really "a miniature version of the grand scale terrestrial ecological system of which we are a part." And the image persisted over the next decades: sixteen years later, in 1978, Robert MacElroy and Maurice Averner, two pioneers of NASA's Controlled Environment Life Support System Project, maintained that "an isolated system capable of supporting human life . . . bears a resemblance to the whole terrestrial ecosystem."[15] It was unanimously agreed, throughout the period under study here, that in order to build the former one needed to understand the latter: in order to survive in space one had to investigate how humans survived on Earth, and then try and replicate the conditions—just as Lasseur described the approach of project MELiSSA.

There was, however, no romanticism here. American and Soviet engineers and life scientists did not attempt to reconstitute a fanciful "Edenic Nature" where people would live without labor or concern through recycling waste. Rather, engineering and scientific professionals demanded that to live in space would necessitate a distinct realism for a space station or generation ship to support life. In direct and earthy ways, one popular writer Tom Allen noted in 1965 that any long-term spacecraft would be a "cloacal dwelling place."[16] Such arable biological metaphors contrasted the sterilized futurist "visioneers" of the late 1960s and 1970s, who imagined that humanity's colonization of space would be the opportunity to establish new social arrangements alongside a new architecture. Even in the 2010s the realism of NASA challenged the disinfected assumptions of observers: ethnographer Valerie Olson "sat for months" in meetings listening to life scientists and engineers talk about "waste" "conjoined" with humans and machines. She defined it as "crazy-weird work in cultural terms" but observed that it was "rather matter-of-fact in environmental systems technical terms," betraying her own assumptions about the reality of living in space and the work of NASA.[17]

As this book describes, within the mainstream space programs the entire spacecraft was conceived as an earthy techno-ecological system. The physical challenge was to build such "regenerative" techno-ecological systems into machines that regenerated the fundamental biological and chemical resources of life processes in systematic feedback loops, befitting the cybernetic thinking of the time. A "cybernetic method of thinking," one Soviet space biologist noted in 1965, helped to "find an analogy between the biological phenomenon and the processes which take place in engineering devices" to reveal biological knowledge. This was, to use historian Cyrus Mody's term, square science and technology. Around 1970 a new "groovy science" of the counterculture emerged in distinction to the militarized and mainframe academic culture.[18] However, argued Mody, these divergent directions left out the square middle, scientists and technologists with little sympathy for the counterculture but eager to attack problems such as public transportation, housing, water, and in the case of life scientists at NASA, waste.

A startling consequence of the space age's square and practical cybernetic thinking was that the human occupants became but one set of components among others. Like algae or machines, humans too processed energy and nutrients and were as replaceable as others. The American science writer Mitchell Sharpe wrote in 1969 that men and machines "cannot be thought of as separate entities" in space. Cosmonaut Yevgeny Shepelev, the first person to live in an enclosed artificial test environment, said in 1965 that "man here is an object to be safeguarded only insofar as he can ensure the normal functioning of the other links in the system." Such views of the comparative values of man and machines challenge the still commonly held assumptions of the entire space age and the centrality of the human to life in space. Olson was equally surprised when she observed in her ethnography that today's NASA as an organization treats the astronaut as an "ecosystemic" rather than a biological entity, but we argue that this has always been the case.[19]

Much of the pertinent work was done at within the Life Sciences Division of NASA's Ames Research Center in Palo Alto, California. Another section of that division was exobiology, which evolved over time into the field now known as astrobiology.[20] The task of exobiology to imagine and pursue ideas about and detection of extraterrestrial life represented only a small fraction of NASA's efforts to create the conditions in a vehicle to move life into space. Within the Life Sciences Division and elsewhere, scientists and engineers at Ames sought to provide values for the rates of cycles, density of organisms, and ranges of tolerances to environmental parameters in order to define the limits of life on Earth and in space, or what is generally known as habitability. Everything about the environment that supports life had to be questioned, since nothing was self-evident in space. Could human beings function in zero gravity, or would they be reduced to spasms of nausea? What about the impact of radiation above the protective atmosphere? How would humans deal with not knowing which way was "down" (in space, there is no up or down), or would their inner ears just keep them spinning? In 1963 NASA's director of its bioscience programs, Orr Reynolds, asked about "the possible occurrence of subtle cellular effects" from a human's mere presence in space, "which might alter basic biological processes." To answer such biological and medical questions, the United States and the Soviet Union cooperated and shared information at international symposia beginning as early as 1962. But forty years later many of the same questions are still being investigated. In 2015 astronaut Scott Kelly and cosmonaut Misha Kornienko spent a year aboard the ISS for test purposes because, as Kelly later explained, "very little is known about what happens [to the human body] after month six" in space. A crucial component of the experiment was that Kelly's twin brother on Earth provided a control to measure space's effects on a body.[21]

Answers to the immediate questions came rapidly—yes, humans were able to function in zero gravity; and, yes, some of them were, in fact, constantly nauseous—but the larger questions were not as easily answered. Public interest in these questions, apparently, was high. A 1963 *Voice of America* broadcast, for example, assured the audience that humans performed normally in space and noted the "reliability of algae" even in the intense magnetic fields. To assemble a life-support system, however, was going to take more than men and algae. As the interviewee said, a critical complication was that the network of environmental factors was so complex it resisted experiment. In 1963 botanist Colin Pittendrigh was called to testify before the U.S. House Committee on Science and Astronautics. He detailed at length that many plant physiologists, space scientists, and engineers had offered ideas about the "environment" of space. Replicating such an environment was still little short of impossible: "Clean questions and clean answers are going to be difficult [because] when we put organisms into space at present and detect deleterious effects, we are simply unable to disentangle the many variables that exist there and decide which has been responsible," Pittendrigh explained. Like many scientists of his generation, Pittendrigh tried to deal with these problems by using controlled facilities, but success remained limited. Even decades later, the challenge has not disappeared: nature remains understood as a highly interconnected system within all space programs, and understanding its dynamics and functions is still regarded as extremely difficult. "Whatever part you describe first, the description cannot be complete without the knowledge of the other parts," the leaders of both the Soviet and American life-support projects concluded in 2003.[22]

It has long been assumed that the space programs pulled such concepts about the environment from emergent ideas in ecology. Prominently, historian Robert

Poole argued that the environmental consciousness of the 1970s could be traced back to the space race, notably as pictures of the Earth as a pale blue dot became widely reproduced. Spaceship Earth—the globally famous metaphor that was coined and distributed by Barbara Ward and Buckminster Fuller and served as a conceptual vision of the Earth as a spaceship traveling through the universe—is often claimed to have raised ecological concerns also among space scientists. As should already be apparent, this narrative requires substantial revision. Rather than ecologists, the American and Soviet space programs relied on plant and animal physiologists, microbiologists, nutritionists, and environmental and sanitary engineers. That ecologists played little role bewildered many: University of Washington ecologist Frieda Taub pointed out as early as 1974 that "sealed ecological systems have been surprisingly unexplored as ecological tools." Taub found that academic ecologists were largely unaware of a vast pool of research from the space sciences into microcosms, regulating mechanisms, and bioregenerative life-support systems, on which the United States had spent an estimated $30 million up to 1966. While it is true that the important ecologists Howard and Eugene Odum proposed a bioregenerative system for the American space program, it was only a theoretical project and had little impact at NASA—indeed, it was prematurely terminated in favor of more realistic endeavors that had been going on for some time already.[23]

The pragmatic environmental sensibility that came out of Stewart Brand's *Whole Earth Catalog* from 1968 to 1972 or paraded at the first Earth Day on April 22, 1970, was much in evidence within 1960s NASA, an organization that was the very antithesis of Brand's small-scale communities and individualized technologies. The practical efforts of NASA to build miniature systems in the 1960s was a parallel, applied strand to the emerging concepts of Spaceship Earth, biosphere, and carrying capacity, which, as historian Sabine Höhler demonstrated, came to dominate the environmentalist movement of the 1970s and 1980s. While ecology became regarded as the "subversive science" because of the work of Rachel Carson and Barry Commoner, the transformation from old-style conservationism to modern environmentalism saw environmentalists of the 1970s push the (allegedly) new and pressing insight that within Spaceship Earth all resources were finite, and thus a sustainable economy and recycling systems were imperative if humans were to survive much longer.[24] However, this was not an entirely new thought. Already during the 1960s, NASA had built life-support systems that fully relied on solar power and had bioregenerative cycles implemented—which could have been, but were not, the foundation for the new and fashionable countercultural ecovillages. On Cape Cod, Massachusetts, John Todd and the countercultural New Alchemist Institute built an eco-village that produced food by means of sustainable agriculture and aquaculture, apparently without any knowledge of the existing research into these very issues by NASA.[25] The Living Machine system built in the Findhorn eco-village in 2003 uses a series of connected barrels with plants and algae as a sewage system, while nobody seems to have been aware that it was almost identical in design to a system built by Boeing aerospace for NASA in 1963.[26]

We argue that NASA, the epitome of the military-industrial complex, and the Soviet state, were equally unexpected sources of ecological awareness, heralding a holistic conception of life in space and on Earth remarkably earlier than the emerging countercultures that stimulated an environmental movement. The modern ideas of environmentalism have blossomed since 1970, exactly the moment when NASA largely ended its first major research and development effort into waste recycling. Those within the life sciences of the space age were keenly aware of how limited and valuable resources were in a closed system. In fact, in many ways the solutions of the space programs were more radical than those of the countercultures. In 1971 a group of notable Soviet scientists announced their conclusion that life support in a closed system "consists of the members of the system eating each other's metabolites." More startling still, *Time* magazine's science editor was quoted by famed author Arthur C. Clarke as suspecting that in order to ensure complete closure of an artificial environment for long-duration space travel, "cannibalism would be compulsory among interstellar travelers."[27]

Such confronting opinions were public, as was much of the research on closed-environment life-support systems by the military-industrial complex on behalf of NASA. Similarly, the Soviet Union widely advertised their progress toward living in space. In the sharp criticisms of the complex in the late 1960s, however, the knowledge that the highly technocratic space program had developed workable ecological systems to recycle air, food, and waste was largely forgotten (like that shown in fig. I.4). By the 1980s NASA stood very much in the vanguard of ecological thinking. Working on the proposed space station *Freedom* in August 1983, Jesco von Puttkamer from NASA's Office of Space Flight noted that the current United States faced the same situation as any future orbiting habitat, namely a growing population swelling against an "originally pristine environment," "increasing amounts of waste into a finite containment," and the "effluents of industrialization."[28] In other words, the American designers of the future space station were fully aware of the environmental situation of the United States itself, and they used that troubled legacy in their work. It was clear, however, that the results of NASA's work challenged the self-conception of Western society at the time. An astronaut on board a

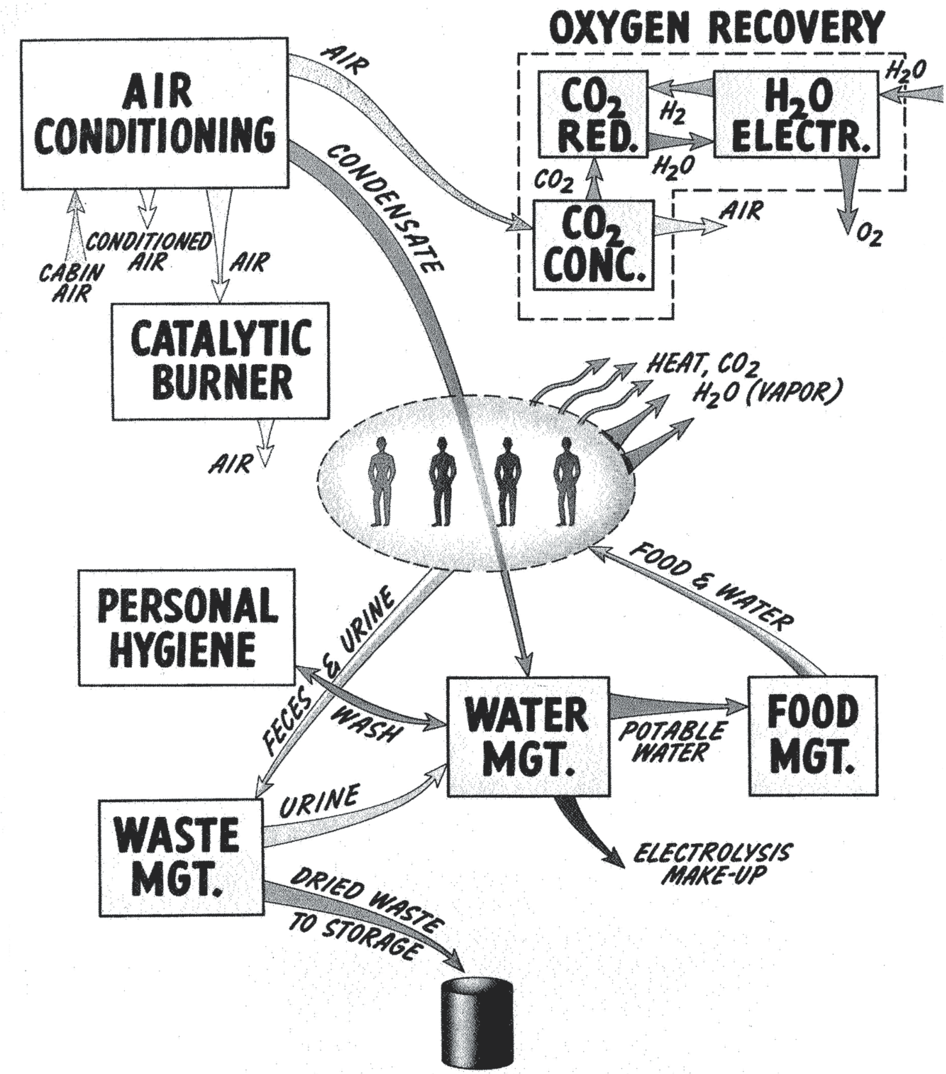

Fig I.4. "Flow diagram of the Integrated Life Support System (ILSS) regenerative process." From Judd R. Wilkins, "Man, His Environment and Microbiological Problems of Long-Term Space Flight," NASA TMX 60422, 1967, 26.

spaceship breathing air recycled from carbon dioxide, drinking water recycled from urine, and eating algae recycled from excrement was shocking to the era's social sensibilities, even though it greatly appealed to the engineer's notions of efficiency and elegance.

WASTE AND ITS MANAGEMENT IN HEAVEN AND ON EARTH

As should be clear by now, the history of artificial environments involves talking a lot about waste, especially biological waste. By centering waste in our history, our project takes up historian Donald Worster's call for excremental histories. Worster claims that historians have not paid enough attention to excrement, bowdlerizing environmental history by focusing on where food comes from and not where the waste goes.[29] In a significant social shift in human history, since the 1950s people in the United States (and elsewhere) got used to the idea that "waste" could just be thrown away. Few comparable studies of waste complement a wealth of studies of Cold War consumption, even as the emergence of the "throw-away" society arguably remains the era's most pernicious legacy.[30] The new lifestyle created all manner of waste, including air pollution, refuses, solid, liquid, and gaseous wastes, from municipal and industrial sources. Their ensuing problems were acknowledged only in the late 1960s.[31] A memorable portrayal of the era's attitude to waste was John Kenneth Galbraith's *The Affluent Society*, in which packaged food and new cars contrast littered streets and polluted streams. Galbraith's take on "American genius" can be seen in the iconic period drama *Mad Men*, when the protagonist Don Draper and his family go for a picnic to a park. At the end of the meal, his wife Betty first checks the cleanliness of her children's hands before shaking off from the picnic blanket the unwanted containers, drink bottles and caps, paper plates and napkins. Leaving the trash all strewn on the grass, everybody walks unconcerned back to the car.[32]

While people have only halfheartedly talked and thought about trash, another form of waste, namely sewage, has been rendered silent, odorless, and invisible throughout the twentieth century.[33] Social historians like Donald Reid, Joel Tarr, and Martin Melosi have described how American and European cities confronted epidemics in the late nineteenth century by beginning to build water and sewage systems, but mostly as patchworks of local facilities. In consequence, those cities pushed their problem literally "downstream"—to the detriment of neighboring towns and villages.[34] At the scale of a house, too, the common household water toilet linked to a sewage system was above all "designed to hide" and carry away human excreta. As we shall see, the containment of the same substances in a fecal bag by early NASA astronauts as a stop-gap solution or in the space commode by later ones operated similarly to flushing (if less efficient in eliminating odor). Both containment and removal rendered the substances invisible, at least to the observing public. Rendered equally invisible in the historiography, the topic of sanitation has not found its way into serious descriptions of the space age or the Cold War life sciences. If it is mentioned at all, the topic is used to entertain children.[35] In colloquial presentations, of course, astronauts have regaled their audiences with stories about defecation in space, consciously playing with the notion that this more than anything demythologizes the glory of space exploration. The larger story of waste management in space, however, is little talked about: how bodily wastes—urine, feces, and sweat—became nutrients (see fig. I.4).

Social inhibition contributed to the fact that the problem of sanitation on Earth or in space was for a long time trivialized and underestimated in the face of political reality. Plant physiologists and agricultural experts had known for a long time that waste forms half of the material cycles in nature: whenever and wherever water, air, and nutrients were absorbed and processed, the remainder was excreted. In nature, it reentered the cycle through fermentation by microorganisms, and nineteenth-century chemists and agriculturalists excitedly discovered that guano (and other forms of biological waste) could be used as fertilizer. But a century later sanitation professionals in the United States noted that their field was critically short on trained manpower and that its research institutes were woefully underfunded, although the growth of new suburbs obviously increased the problem of sewage. In October 1957, when Sputnik had just started to orbit, the leading sanitary engineering department in the United States at the University of California, Berkeley, warned about "the multitude of problems of environmental sanitation" that accompanied "the explosive growth of California's cities and their attendant industry and agriculture on limited land and water resources." In a bold move, President Lyndon Johnson took up the cause of making "America the beautiful" as part of his Great Society vision. With bills addressing air and water pollution, wilderness preservation, and solid-waste disposal, Johnson accomplished an impressive legislative record by the mid-1960s. Major sanitation systems, however, took decades to improve: as late as the 1980s, raw, untreated sewage still flowed directly out of Boston into Boston Harbor, out of New York City into the East River, and out of Los Angeles into the ocean.[36]

The problem of sanitation was also viewed as a problem of pollution and removal rather than of recycling and reuse. Awash in new chemicals with doubtful effects on human health, the early environmental movement of the 1960s focused on specific substances marked as pollutants. The careless disposal of sewage was criticized alongside the spread of pesticides, nuclear waste, and synthetic detergents, without discriminating between substances of biological and nonbiological origin. These clearly were campaigns to reduce the contamination of fields, streams, and cities rather than movements inspired by a rising ecological awareness.[37] That ecological awareness, however, as our book reveals, was very much in place at the space programs—without, of course, being combined with global, politically motivated, anticapitalist aspirations.

Waste management became the subject of well-funded science and engineering projects within the space programs, building on the idea that if sanitary systems could be perfected to fully return waste products as food, water, and air, "humanity could truly and biologically tear ourselves away from the Earth's biosphere." Engineers and scientists looking toward space began to conceive of waste in ways that obviously differed from how it was understood on Earth. The most significant of those new understandings emerged in the late 1950s when space biologists tried to use the waste of one organism as a nutrient for another. They saw success with animals in closed systems, witnessing how mice and algae were able to support each other for weeks on end while closed ecospheres of shrimp and algae in water lived on for years. Ever since, the space sciences have had a radically different notion of waste than that of society at large; there really is no waste in space. As Wendell Mendell of NASA's Mission Science and Technology office said during the planning for Space Station Freedom in 1991, "the term 'waste' becomes an oxymoron [in a closed-loop life-support system] because every atom contributing to organic chemistry is precious." That "waste" might become "nutrients" was by then obvious to NASA's life scientists and environmental engineers but remained a tough concept to accept for even the most liberal environmentalists of the 1970s and 1980s: as Dorian Sagan noted, it "is difficult to wax poetic about medical waste, chlorofluorocarbons, and carbon dioxide. Yet . . . excrement, garbage, trash—all of the most rancid and marginal parts of our anatomy—are one day transmuted into parrots, wine grapes, magnolia trees."[38]

THE SCOPE OF THIS BOOK

Our book claims that research into artificial environments, including the development of regenerative sanitation systems, was an important part of the space age that has been neglected. Furthermore, this book claims that in pursuing this research, space programs on both sides of the Iron Curtain generated profound ecological knowledge about the functioning of interrelated, complex systems. From the early 1960s onward, American and Soviet life scientists and environmental engineers were remarkably informed about sustainable resource management. As the NASA life science division's collection of papers and reports from the Soviet Union's project display, the American and Soviet space programs exchanged considerable information as they worked toward the goal of a permanent habitat in Earth orbit or journey to Mars. Both sides of the Cold War were fully aware of the fact that they had to accommodate all parts of human existence into their life-support systems, and both started to think of human waste, in the sense of all bodily excrements, as being an indispensable component of material cycles. American and Soviet scientists and engineers concerned themselves not only with chrome surfaces, power engines, and combustibles but also with algae cultures, the nutritious value of quail and potatoes, and the composition of feces. And, quite radically for the context, those same scientists and engineers realized that their knowledge about how to live in space could be projected onto Earth as well. From these claims, we suggest that insights from attempts to lead a fully sustainable existence in space are useful to inform more recent attempts to secure our future existence on the planet in the face of the disastrous implications of climate change and other manmade catastrophes.

The story of the creation of life-support system to live in space spans both sides of the Iron Curtain. Our knowledge of the Soviet program is based primarily on sources from NASA, which collected and translated Soviet reports, articles, scientific publications, and popular pieces coming out of all aspects of the Soviet space program.[39] These documents offer initial insights. The challenge of language and other barriers precludes a complete description of the vital Soviet contribution to this story, but we eagerly look forward to future work on the subject.

Chapters 1 and 2 turn to the first twenty years of the space age, from 1957 to 1977, and reveal the major engineering and biological milestones to achieve an artificial self-sustaining environment, complete with material and energy recycling. In chapter 1, we describe how both the American and the Soviet space programs aimed from the start to go to Mars and beyond. The moon landing only was originally proposed by NASA as a stopover on the way to larger and longer missions. As we know, however, once the lunar landings were achieved, American political priorities shifted, and NASA's budget was cut immediately thereafter. Chapter 2 investigates in more detail how scientists and engineers addressed the challenge of sustainable life-support systems in these years—including a particularly instructive and well-documented case: the so-called Algatron, which was developed by sanitary engineers from Berkeley.

Chapters 3 and 4 describe the next twenty years of the space age, from 1977 to 1997. That period saw the first attempts to build a space station, which also—and necessarily—included life-support systems. Longer-term experimentation was needed to prepare these ambitious projects. Chapter 3 describes how the Soviet Union's early *Salyut* and later *Mir* space stations took advantage of the elaborate BIOS-3 facility at Krasnoyarsk, Siberia. In this research station, experts from Moscow's Institute of Biomedical Problems collaborated with the biologists from the Institute of Biophysics to develop appropriate environments. They tested complex life-support systems that accommodated several dozen organisms including wheat, algae, sweet potatoes, and *Homo sapiens*, eventually locked in for yearlong experiments. Chapter 4 begins with the American *Skylab* station as an experimental orbiting habitat, then continues to describe the planning of space station *Freedom*, which was supposed to be the U.S. response to the Soviet successes of the 1970s. By the 1990s, NASA believed itself to be almost there, with a bioregenerative life-support system within reach and a full-scale trial system experimentally proven. Many of its components are now on board the ISS, but complete recycling of material remains elusive. Unexpectedly, as explored in chapter 5, one of the most complete bioregenerative life-support systems came in the form of the Biosphere 2 in Arizona. The two crewed missions that lived inside the closed structure between 1991 and 1994 came closest to experiencing the full range of physiological and psychological pressures of the kinds of long-term space journeys the space age had long dreamed of.

Ultimately, in their attempts to build systems to live in space or on Mars, scientists and engineers gained crucial insights into how humanity may continue to live on Earth. Over the last twenty years, it was a question that haunted the creators of life-support systems. "What kind of knowledge must humanity attain in order to rationally govern the biosphere?" asked Iosef Gitelson and Robert MacElroy, the former leaders of the Soviet and American efforts in the 1990s.[40] There was at least one thing that the quest for life support taught the protagonists of the space age: embracing waste is part of life.