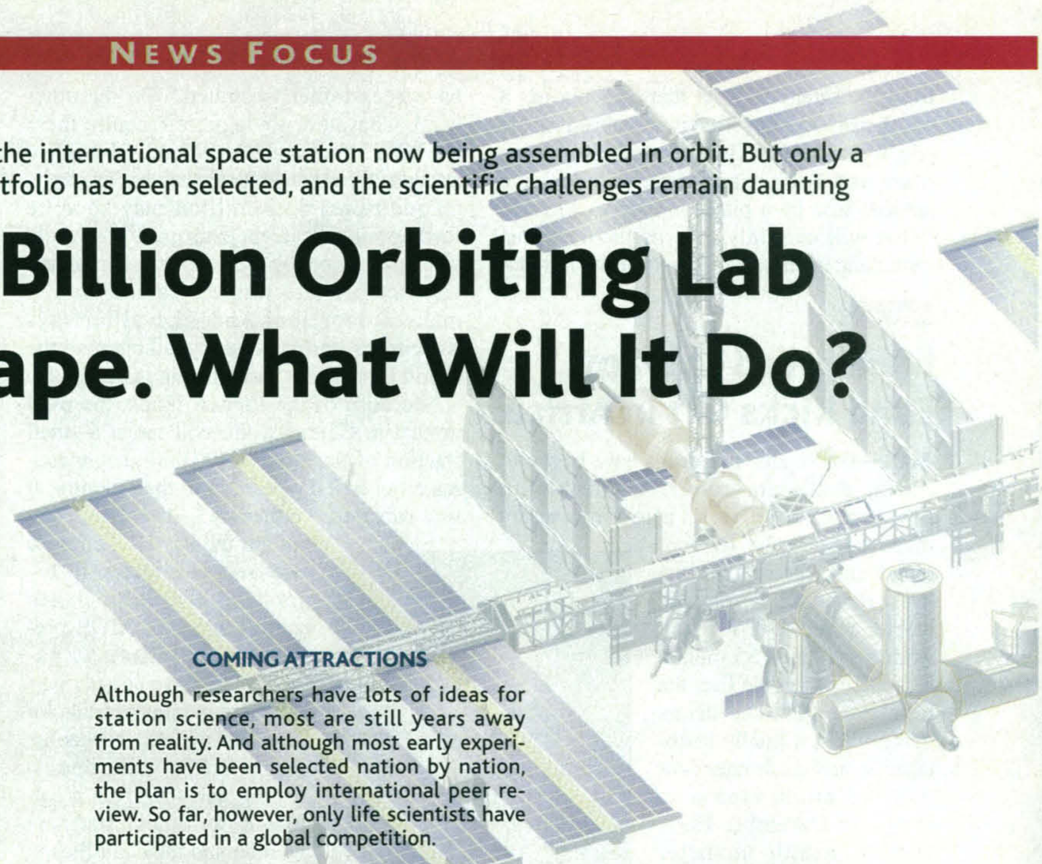
Plans have become reality for the international space station now being assembled in orbit. But only a tiny share of the research portfolio has been selected, and the scientific challenges remain daunting

A $100 Billion Orbiting Lab Takes Shape. What Will It Do?



CREDIT: DOUG STEVENS; SOURCE: NASA/ESA/NASDA

Sometime next spring, if all goes as planned, space shuttle astronauts will deliver a full-sized plastic model of a human head and torso —outfitted with real teeth and bones—to a 10-meter-long orbiting laboratory shaped like a soda can. Known to its creators at NASA's Johnson Space Center in Houston, Texas, as Fred, the mummylike mannequin is already a veteran space traveler; an earlier version flew last year aboard the space shuttle. Nevertheless, Fred's latest trip into space will make history: He'll be the star of the first major scientific exercise aboard the international space station (ISS).

Much of Fred's expected supporting cast, however, hasn't even made it to tryouts yet. Although engineers and scientists have spent nearly 2 decades planning the station, and 5 months have passed since spacewalkers mated its first two segments, fewer than 100 experiments—a tiny fraction of the work scientists hope to perform during the station's planned 10-year life—have been fully approved for launch. And the pace isn't likely to pick up anytime soon. Funding cuts have delayed the construction of hardware needed to take advantage of the station's low-gravity environment, and the demands of assembling the station over the next 5 years will leave astronauts with little time for science. In addition, the megaproject's 16 partners are still hammering out a process for collaboratively choosing experiments. Interested researchers also must overcome a thicket of technical obstacles, from vibrations that could wreck sensitive studies to a cloud of contamination floating around the station that may coat and possibly blind sensitive instruments. "There are a whole lot of unanswered questions," concedes Kathryn Clark, NASA's chief scientist for the project.

A debate over the scientific value of the station, which could cost $100 billion to build and operate, has been boiling ever since the idea was first floated (see sidebar on p. 1106). Now that the station is becoming a reality, however, the discussion has shifted to its scientific capabilities, the rationale behind the experiments to be flown, and the nature of the results to be gleaned. And it's not a moment too soon: Next week, the shuttle Discovery is scheduled to carry supplies to the orbiting construction site, and its first science segment—the U.S.-built laboratory Destiny—is due to be bolted on next spring. "For better or worse, this mission is now under way," says astrophysicist Claude Canizares, chair of the National Academy of Sciences' (NAS's) Space Studies advisory board.

COMING ATTRACTIONS

Although researchers have lots of ideas for station science, most are still years away from reality. And although most early experiments have been selected nation by nation, the plan is to employ international peer review. So far, however, only life scientists have participated in a global competition.

WHAT'S IN THE PIPELINE

Field	No. of experiments* U.S.	Europe	Japan
Fluids & combustion science	40	10	5
Life sciences/biotechnology	20	15	18
Materials science	20	NA	18
Earth science	1	1	1
Space science	3	10	1
Technology testing	15	2	NA

* Approved or near approval for flight 2000–04.

Potential payoff

Although it's still far too early to assess the quality of the research scheduled to fly on the station, Fred is as good a place as any to start looking for answers about the station's potential scientific payoff. NASA radiation researcher Gautam Badhwar will be spending the next few months calibrating his equipment as he methodically prepares Fred for flight. Once Fred is aboard, hundreds of sensors encased in the dummy's mock organs, along with several related instruments nearby, will help researchers determine how much harmful cosmic radiation is penetrating the bodies of the station's crew members. Eventually, scientists hope the information will lead to better safeguards for space travelers to Mars and elsewhere.

Fred illustrates both what is right and wrong with station science, which government officials repeatedly cite as the chief rationale for building it. Proponents say that Fred's scheduled 14-week run makes use of one of the station's most valuable assets: time. Whereas researchers using the space shuttle have at best a fortnight to collect data, those using the station can plan experiments lasting months or years. The longer durations will allow Fred, for instance, "to collect far more data than was possible when [he] flew on the shuttle," says Badhwar.

The station also gives scientists a chance to compile larger, more statistically valid data sets by repeating experiments. "You won't have to wait five frustrating years to repeat or retry an experiment," says crystallographer Lawrence DeLucas of the University of Alabama, Birmingham, a veteran of growing protein crystals aboard the shuttle.

Researchers in other fields are also looking forward to extended experimental time aboard the station's six pressurized research modules and dozens of external payload sites. Combustion and materials scientists, for instance, are planning to tinker with burning droplets and solidifying metals in an effort to uncover basic properties, while life scientists will study how people, plants, and even insects react to life in microgravity.

Outside the station, astronomers want to hang instruments that will monitor everything from the sun to x-rays, while earth scientists analyze the planet's atmosphere and land forms. There will also be long-duration tests of new materials and technologies, such as laser-communication systems, that might eventually fly on craft bound for deep space. And although corporate interest is low, station officials are also counting on a host of commercial research payloads, such as Earth-monitoring cameras.

But those who believe ISS science will produce few useful results see Fred as a poster child for the station's limitations as a scientific platform. For example, the station's low orbit means that the mannequin will not record data from further out in space, where Earth's atmosphere provides no protection from radiation. That could make the findings of little help to interplanetary voyagers. The low orbit also makes the station useless to many astronomers, as Earth's upper atmosphere blocks many forms of light and radiation and prevents some kinds of instruments from getting an unobstructed view of distant objects.

Altitude is only one of many technical challenges facing researchers. Contrary to its sedate image, for instance, the station will flex and roll like a rubber raft bobbing on a long swell because of atmospheric drag. That movement will make it difficult to operate detectors that need to lock onto a particular patch of Earth or sky. To compensate, the Europeans are building a highly accurate pointing device that will initially be used to allow SAGE III, an instrument analyzing atmospheric chemistry, to stay on target.

The station will also require periodic lifts into a safer orbit to counteract its continuous sinking toward Earth. Those rocket burns, along with frequent shuttle and supply rocket dockings, will cause the station to shake and vibrate, disrupting sensitive experiments, perhaps even those mounted in special vibration-resistant racks. Some experiments will also be vulnerable to "g-jitter," the constant variation in gravitational force in different parts of the station. As a result, researchers will have to consider whether their experiments will work outside the station's "gravitational sweet spot," says Clark.

Instruments hung outside the station, and a special Earth-observing window in the U.S. lab, may face another difficulty: a cloud of contamination that is expected to hover around the station, coating exposed instruments with a potentially troublesome patina. Some of the gunk will come from the station's structure, which will produce gases when it is exposed to the vacuum of space. Another source is the station's 33 exhaust vents, which will also spew gases and water vapor. Visiting rockets will also leave behind a trail of particulates. "It could be like living in Pig Pen's cloud," says one NASA engineer, alluding to a cartoon character perpetually surrounded by a storm of dust. Nonetheless, he predicts such problems "won't be insurmountable." Astronauts, for instance, will be able to periodically remove a shield protecting the window and return it to Earth for cleaning.

Time and money

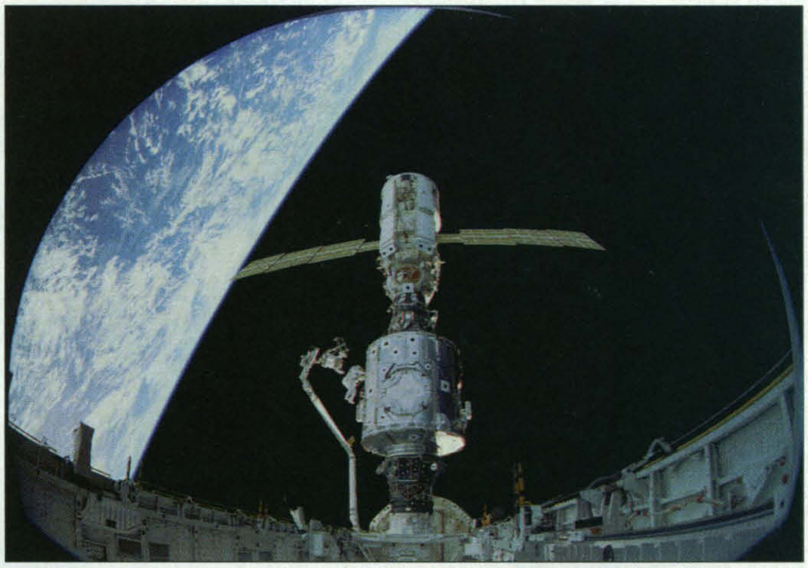
Other challenges involve human, not engineering, issues. It's not yet clear, for instance, whether Russian cosmonauts will fully cooperate in research needing human subjects; some have said they want to be paid extra. It is also unknown how much the astronauts—who will be busy juggling everything from repairs to daily chores—will have leeway to say "no" to ground-based scientists seeking extra help with their experiments. To head off conflicts that sometimes marred researcher-astronaut relations aboard Mir, launched by the Soviet Union in 1986 as the world's first long-duration space station, Clark has jokingly suggested creating a "People for the Ethical Treatment of Astronauts" group. "Researchers can't expect the crew to answer to their beck and call," she says.

Clark and other NASA officials also worry that there will not be enough training time to educate the seven-member station crews in the array of experiments they will be operating. Many scientists hope to operate their experiments by remote control from Earth to get around the labor bottleneck. But it's an open question whether the station's communications systems will be up to the task. "Ideally, you automate so that an astronaut doesn't have to be involved," says Clark. Another way to attack the problem, some station planners say, is to run station science in "campaign mode," with each crew specializing in experiments in a particular field, such as fluid physics or materials science. That approach could also help stretch the station's limited supply of electricity by temporarily focusing it on investigations, such as combustion experiments, that require lots of power.

The biggest obstacle to a high-quality scientific payoff, however, may be money. At NASA, science programs have been slowed by construction overruns that have forced agency officials to repeatedly "borrow" money from the station's research accounts. That, in turn, has delayed the completion of science hardware, including fluid physics and animal study facilities (see timeline on p. 1104).

NASA Administrator Dan Goldin has put a positive spin on the cuts, saying the delays will keep the science program "more in phase with" the pace of station construction. Unless Congress adds money to NASA's budget, however, White House forecasts call for the United States' ISS research fund to get $363 million less over the next 6 years than once planned. The cuts mean the science account will grow more slowly than envisioned, from about $350 million this year to $550 million in 2004.

To stretch the dollars, NASA officials are emphasizing experiments that—like Fred—recycle equipment that has already flown and studies using generic facilities that support more than one experimenter. NASA's combustion science program, for instance, is "encouraging proposals that fit existing hardware," says manager Merrill King. The agency's need to stretch funds—and thus maintain an active corps of researchers—has even led it to tilt temporarily toward funding more ground-based projects, which are cheaper to carry out. The agency's Microgravity Research Program,



Under construction. The station's first two segments—Zarya and Unity—were joined late last year. The first science module is scheduled to be bolted on by spring 2000.

CREDIT: NASA

for instance, now funds seven Earth-bound experiments for every one destined for flight, up from a 3:1 ratio in 1991.

Inadequate funding is a much more serious problem in Russia, where economic uncertainty has paralyzed many scientists hoping to place experiments aboard two Russian science modules, tentatively scheduled to be launched in 2004 (*Science*, 20 November 1998, p. 1391). "We have lots of plans but very little money," says earth scientist Vladimir Kuznetsov, deputy director of the Russian Academy of Sciences' Institute of Terrestrial Magnetism in Troitsk. Russia's problems have provided an unexpected bonus to U.S. researchers, however: Last year, in a move to provide the teetering Russian Space Agency with cash, NASA bought hundreds of hours of cosmonaut time to carry out science during the assembly phase (*Science*, 9 October 1998, p. 206).

NASA officials hope Russia's funding crunch will foster greater teamwork by forcing it into the arms of several international working groups trying to coordinate station science. Although leading Russian scientists have urged their government to participate in the joint agenda-setting, the Russian modules have so far remained "a separate world," says Clark. Other NASA officials worry that the war in Kosovo could further fray an already testy relationship.

Outside Russia, however, station planners have been pleasantly surprised by the number of scientists seeking to win funds for station-related research. Japanese scientists have submitted more than 750 proposals to two early, Japan-only funding rounds, with about 50 projects still in the race for a launch spot. In 1997, European researchers offered nearly 100 entries in a continent-wide competition for instruments to hang outside the station. At the same time, the first international call for life science experiments attracted more than 500 proposals from the United States, Canada, Japan, and Europe. Peer reviewers eventually deemed 27 worthy of flight, with more than half of the projects coming from outside the United States.

With plans to use international peer review as the norm for selecting station research, however, scientists are wondering how funding will work. For instance, some ask what will happen if NASA or the European Space Agency (ESA) is unwilling to fund a top-rated project suggested by its scientists. Will lower quality science from a richer agency take its place? Or will the partners create a common fund to pay for the best experiments, regardless of origin? Some U.S. scientists also wonder if their station projects will be competitive with proposals for cheaper, unmanned platforms to be flown on different spacecraft. To avoid that problem, some would like NASA to set aside special funds. But NASA's W. Vernon Jones, who oversees the agency's space science research programs, is against the idea. Earmarking funds for the ISS, he says, "would send the signal that this is lower quality science."

Station partners are also working out

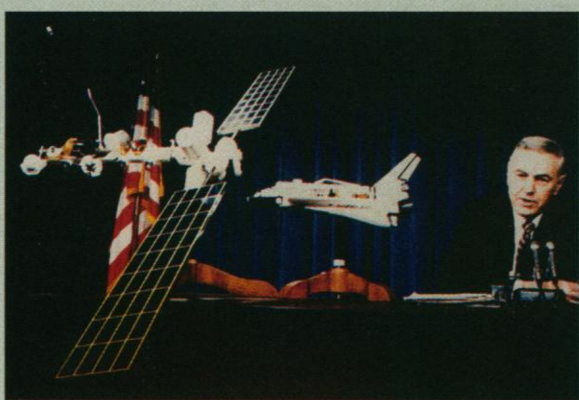
Making a Deal With the Devil

NASA Administrator Jim Beggs knew he faced long odds as he journeyed up a Colorado mountain to a meeting 17 years ago. His job was to explain his vision of a human base in orbit to a dozen eminent researchers from the National Research Council's (NRC's) space sciences board. The astronomers and astrophysicists who dominated the NRC panel were no fans of putting people into space. "We were quite skeptical," confirms Thomas Donahue, then board chair and now professor emeritus of earth and space sciences at the University of Michigan, Ann Arbor. "We didn't want to touch it."

Beggs, a wily former aerospace executive with a folksy manner and a penchant for quoting Shakespeare, had made an international space station his top priority. He had been crisscrossing the globe to assemble a powerful coalition of supporters from government, industry, and academia. The Snowmass, Colorado, meeting in the summer of 1982 was his first major attempt to woo the scientific community.

Despite their misgivings, panel members promised Beggs that they would study the potential scientific benefits of a station. But a few months later, a two-page report made it clear that they hadn't changed their minds. There is "no need for a space station to support missions addressing high priority science missions for the next two decades," declared the report, "Space Science in a Space Station Era." In particular, the astronomers and earth scientists were not impressed with Beggs's plans to enhance research on the station by building robotic servicing facilities and viewing platforms.

However, the scientists did not wholly condemn the project. The report noted that "a manned space station could eventually provide significant opportunities for a number of disciplines in space science" if there were adequate funding. In particular, it noted the "special relationship" between the station and the life sciences, adding that studying humans, animals, and plants in zero gravity would be a prerequisite for long-term space missions.



Boarding the station. Former NASA chief Jim Beggs, shown in 1984 photo, won over the science community with promises of stable funding and a voice in its design.

That opportunity excited a handful of researchers in the nascent fields of space biology and microgravity materials who longed for a permanently inhabited space platform. In May 1983, the board's space biology and medicine committee gave Beggs a four-page summary of the space station's potential that envisioned scientist-astronauts conducting a host of physiological experiments along with fundamental biological research. "We were very much against stretching the station to use it for astronomy or earth sciences," recalls Lou Lanzerotti, a Lucent Technologies physicist and engineer who is a former NRC board chair. "But conducting life and microgravity sciences seemed appropriate."

At the same time, board members chose not to go public with their doubts. "We saw the handwriting on the wall," says Donahue, referring to the growing coalition that Beggs was building among politicians and industrial leaders. A vocal opposition, he says, could have created enemies while denying scientists potential research opportunities. Beggs agrees: "I don't know what good it would have done for [scientists] to have made a big fuss."

That reticence did not extend to the entire community, however, some of whom worked behind the scenes to discredit the idea. The quiet lobbying campaign included former President Ronald Reagan's science adviser, George "Jay" Keyworth, as well as some officers of the National Academy of Sciences (NAS), the NRC's parent body. The resistance proved futile, however, as Rea-

CREDIT: NASA

how to divvy up the station's space. The United States controls the bulk of its power and attached payload sites and, in exchange for launching the European and Japanese science modules, NASA has claimed title to almost half of the space in each. In contrast, Russia has kept 100% control of its two science modules. But the allocations are constantly shifting, as the partners barter space and equipment in what Clark calls "the dance of trading science." ESA, for instance, is building the pointing device, a lab freezer, and other equipment in exchange for the right to place two astronauts and a few experiments aboard the station before its own Columbus Orbiting Facility arrives in 2004.

Human research first

Such dickering is expected to continue even after the station's science program begins in earnest next spring with the launch of the Human Research Facility (HRF). The HRF, the U.S. hardware that will house Fred, will occupy two of the lab's refrigerator-sized experiment racks. It will bristle with more than a dozen instruments, including an ultrasound imager and a high-tech bathroom scale that can measure a body's mass in microgravity. Astronauts will be able to use the facility to monitor their health, while Earthbound researchers will collect data on one of space travel's most pressing questions: Why does life in low gravity disrupt perception, promote bone loss, and cause other health problems?

"The human studies are in many ways the most defensible science planned for the station, assuming you believe in manned exploration," says one biomedical researcher involved in an NAS review of the program. Other findings that could eventually aid astronauts, he notes, might come from studies of how latent viruses carried by the crew members respond to the stress of life in orbit, and how genes involved in growth and sleep cycles behave in the absence of normal gravity.

Some life science research planned for the station is more controversial, however. In particular, NASA's long-running effort to grow protein crystals in space—slated to get major attention aboard the station starting next year—has generated intense opposition. Last summer, a committee convened by the American Society for Cell Biology (ASCB) called on the space agency to kill the space-based portion of the program, concluding it had made "no serious contributions to knowledge of protein structure or to drug discovery" (*Science*, 24 July 1998, p. 497).

In March, the program attracted more criticism after NASA issued press releases claiming that structural data from space-grown crystals had helped an international team of researchers based at the University of Alabama, Birmingham (UAB), and nearby BioCryst Pharmaceuticals to develop a promising flu drug. The claim infuriated one of the researchers involved, biochemist W. Graeme Laver of the Australian National

gan announced his support for the effort in January 1984. And his underlying reasons—a desire to counteract Soviet advances in space—made irrelevant any debate over its scientific merit, according to NASA and NAS officials. From that moment, says former NAS President Frank Press, it was tough "for scientists to shoot it down [because] the primary issue was not the science but the national goals."

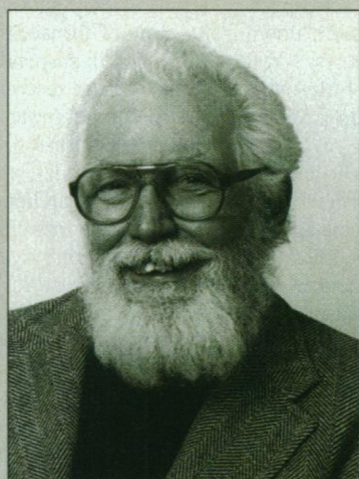
Beggs wasted no time in acting on the president's decision. Within a month he had formed a task force of outside researchers to define the scientific uses of the station. Led by Peter Banks, an earth scientist who is now president of Erim Inc., a remote-sensing company in Michigan, the panel concluded in the summer that the orbiting base would benefit a number of disciplines and that it should include a centrifuge for life sciences research. Although Donahue says disdainfully that the panel "carried water for NASA," Banks believes that the report began the long and grueling process of inculcating scientific values into what was primarily an engineering effort.

"I made a pact with the devil. ... The whole [station] program has been a botched mess."
—Thomas Donahue

Looking to further broaden his base of support among scientists, Beggs invited Donahue to his office shortly after the Banks panel was formed to cement an alliance with the scientific community. The administrator promised to allocate 20% of NASA's overall R&D budget to space science. Beggs also agreed to arrange for "high-level" scientific input into the program, with the Goddard Space Flight Center in Greenbelt, Maryland, and Pasadena, California's Jet Propulsion Laboratory—the two space science–dominated NASA centers—playing a central role in designing the station. In return, Beggs reached a tacit understanding with Donahue not to actively oppose the station.

Beggs's gambit succeeded. The two men shook hands on the deal and later put it in writing. The arrangement was embraced by Beggs's successor, James Fletcher, who wrote Donahue a few years later that "without a healthy science budget at NASA, the reason for the station's existence is compromised."

The compact has proved remarkably durable, surviving more than a decade of stormy negotiations, lengthy studies, and bitter budget battles in Congress that included attacks by a few scientific societies. But was it the right thing for scientists to do? No, says Margaret Geller, an astronomer at the Harvard-Smithsonian Observatory in Cambridge, Massachusetts, who quit the Banks committee in protest. To her, Banks's committee and Donahue had traded their scientific principles for a slice of station pie. "You don't make Faustian bargains," she says now. "It was obvious to me the station had nothing to do with science. People were jumping on board to get money."



CREDIT: COURTESY UNIVERSITY OF MICHIGAN

In response, Donahue and others, including Lanzerotti and Banks, say the decision to work with rather than against the space station has paid off. Space science funding grew through the 1980s along with NASA's overall budget, creating a flotilla of robotic spacecraft and a flood of new data. And life and microgravity researchers are gearing up to conduct experiments on the orbiting base now being assembled.

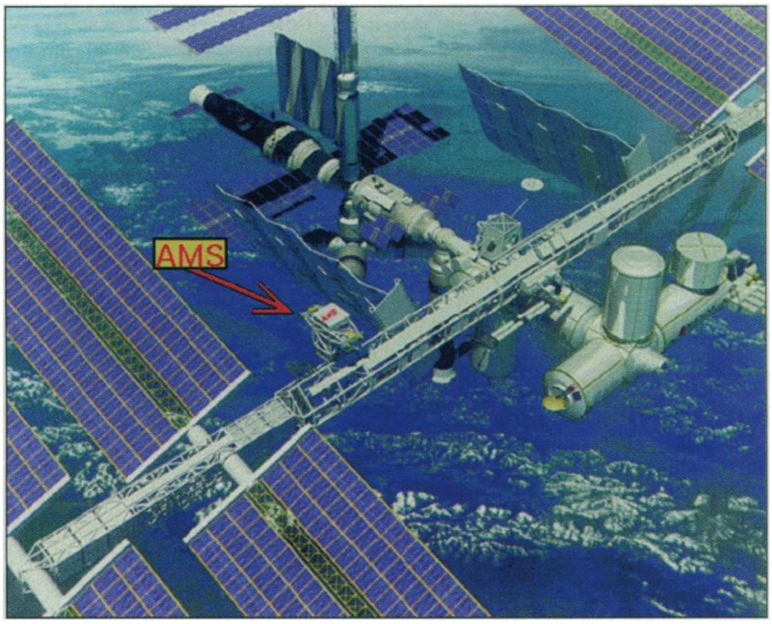
Even so, Donahue acknowledges that the critics have a point and that backing the space station wasn't the scientific community's finest hour. "I made a pact with the devil," he admits. Although space science has benefited, he adds, "the whole [station] program has been a botched mess." —ANDREW LAWLER

University in Canberra. He says his onetime funder inflated the importance of its space-based work in "another pathetic attempt" to boost the crystal program's image. In fact, Laver says, the single space-produced crystal involved in the project was grown aboard Mir without NASA's help. "And it had nothing to do with the drug's development. BioCryst's findings came from crystals I grew on Earth," he adds.

The twin attacks have put UAB crystallographer DeLucas, a former chief scientist for the station and now head of a NASA-funded research center, on the defensive. He says the ASCB report is "dead wrong" and that low gravity has allowed researchers to grow several dozen kinds of crystals that are larger and purer than those produced on Earth, making it easier for crystallographers to deduce their structure. He also notes that the program has been extensively peer reviewed and is currently under the microscope of another NAS review panel, which will deliver its verdict later this year. As for Laver's complaint, DeLucas believes his former colleague has overreacted to an unfortunate bit of NASA hype. In retrospect, agency officials "could have toned down the [press release]," DeLucas says. "You would have to say there was a little overenthusiasm from NASA," adds Charles Bugg, BioCryst's president.

A former NASA scientist who helped get the crystal program going in the 1980s, Bugg says this isn't the first time the agency has hyped the science it supports. Other researchers confirm that a similar controversy once beset a second type of crystal-growing experiment planned for the station. Two decades ago, NASA officials drew heavy flak from scientists for touting its preliminary attempts to grow metallic semiconductor crystals aboard Skylab as the beginning of a new age of space-based manufacturing. "It took decades to stop the talk of factories in space" and to bring the rhetoric more in line with reality, recalls NASA's Michael Wargo, who manages its materials science program. Such hype, however, continues to create "a lot of resentment," says Bugg.

Ironically, some researchers now consider studies of how metals and other materials solidify in microgravity to be one of the station's most intriguing offerings. In particular, there is broad interest in a suite of planned experiments to examine how the complex, fern-shaped metallic crystals called dendrites freeze into shape. The tests, researchers say, will help reveal the basic mechanisms that drive dendrite growth—fundamental information that is obscured on Earth by the tug of gravity. Materials scientists may have to wait years, however, to get into space: A U.S.- and European-built materials science facility—which will include an array of furnaces and freezers, including one that will suspend samples in a magnetic field—will be ready no earlier than 2002.



Wide load. Proponents say the station is perfect for handling large scientific payloads, such as the antimatter-hunting Alpha Magnetic Spectrometer (AMS) due to be launched in 2002.

Researchers interested in using the station as a platform for Earth and space studies face a similar wait. U.S., Japanese, and European researchers have plans for at least a dozen large instruments that will be bolted onto the station's exterior. They include several x-ray observers, a superaccurate atomic clock, a trio of detectors designed to monitor the sun, and a device to scan Earth's surface for forest fires. Although some could orbit on free-flying satellites, researchers say others are too bulky to be launched aboard rockets, or require human tending that only the station can provide.

Perhaps the best known attached payload is the $50 million Alpha Magnetic Spectrometer (AMS), an antimatter hunter proposed by Nobel laureate physicist Sam Ting of the Massachusetts Institute of Technology in Cambridge. NASA eagerly embraced the controversial idea 5 years ago, and an early version of the AMS, funded by the Department of Energy, has already flown aboard the shuttle. An improved model is scheduled to arrive at the station in 2002 and spend 4 years sifting through the rain of cosmic rays for evidence that some are antimatter particles.

Although many physicists are skeptical of the project, station proponents say it exemplifies the station's ability to shoulder bulky payloads. The boxy AMS, for instance, depends on having a large surface area exposed for long periods in the hope of catching rare particles. The same is true of several other instruments proposed to study cosmic rays of different energy levels, including the Extremely Heavy Cosmic-Ray Composition Observatory (ECCO), which could reach the station as early as 2003.

In ECCO's case, the station also offers the opportunity to retrieve data-collecting arrays for analysis on Earth, notes physicist Thomas Gaisser of the University of Delaware, Newark, who heads the NAS's Committee on Cosmic-Ray Physics. Still, Gaisser says there is "an admittedly political aspect" to decisions to place some of the instruments aboard the station. Although some payloads could fly as independent satellites, he compares the station's users to Charles Darwin aboard *The Beagle*: "You seize opportunities as they arise."

That philosophy appears to have taken hold in some researchers. At a recent international conference on space station science,* scientists released a variety of trial balloons. They included one scheme to launch minisatellites that would orbit the station and warn astronauts of potentially dangerous changes in space weather, and another to use it as a base camp to assemble a huge neutrino detector from dozens of flowerlike petals. Launching this giant detector—which would look for high-energy particles difficult to spot on Earth—would be "nearly impossible in a single rocket launch scheme," says Yoshiyuki Takahashi of the University of Alabama, Huntsville. But the station, he says, offers a chance "to think grand thoughts."

It's far too early to know whether such grand ideas, or any of the other science planned for the station, will pan out. But having provided the money, politicians are now looking to scientists to make the best use of the investment. —**DAVID MALAKOFF**

* Conference on International Space Station Utilization, Space Technology & Applications International Forum '99, 31 January–4 February.

CREDIT: CERN