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Whatever the next generation of human space transportation systems look like, human-rating requirements will be a driving force in their development. Follow the discussion on human rating, beginning on page 26.

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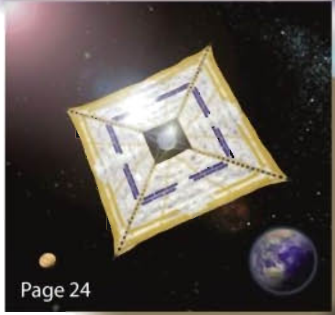

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After a year of refurbishing, Hypervelocity Wind Tunnel Number 9 in White Oak, Md., has emerged from the edge of extinction, serving again as the nation's premier facility for hypersonic testing. It continues a legacy that began, shrouded in mystery, during WW II and lives on today, ensuring that the workforce of the future will be trained in the use of this vital resource and others like it.

Tunnel 9: A national treasure reborn

Hidden in a wooded campus in White Oak, Md., just a few miles north of the Washington, D.C., beltway, the nation's premier high-speed wind tunnel has just emerged from a year-long period of refurbishing and upgrades.

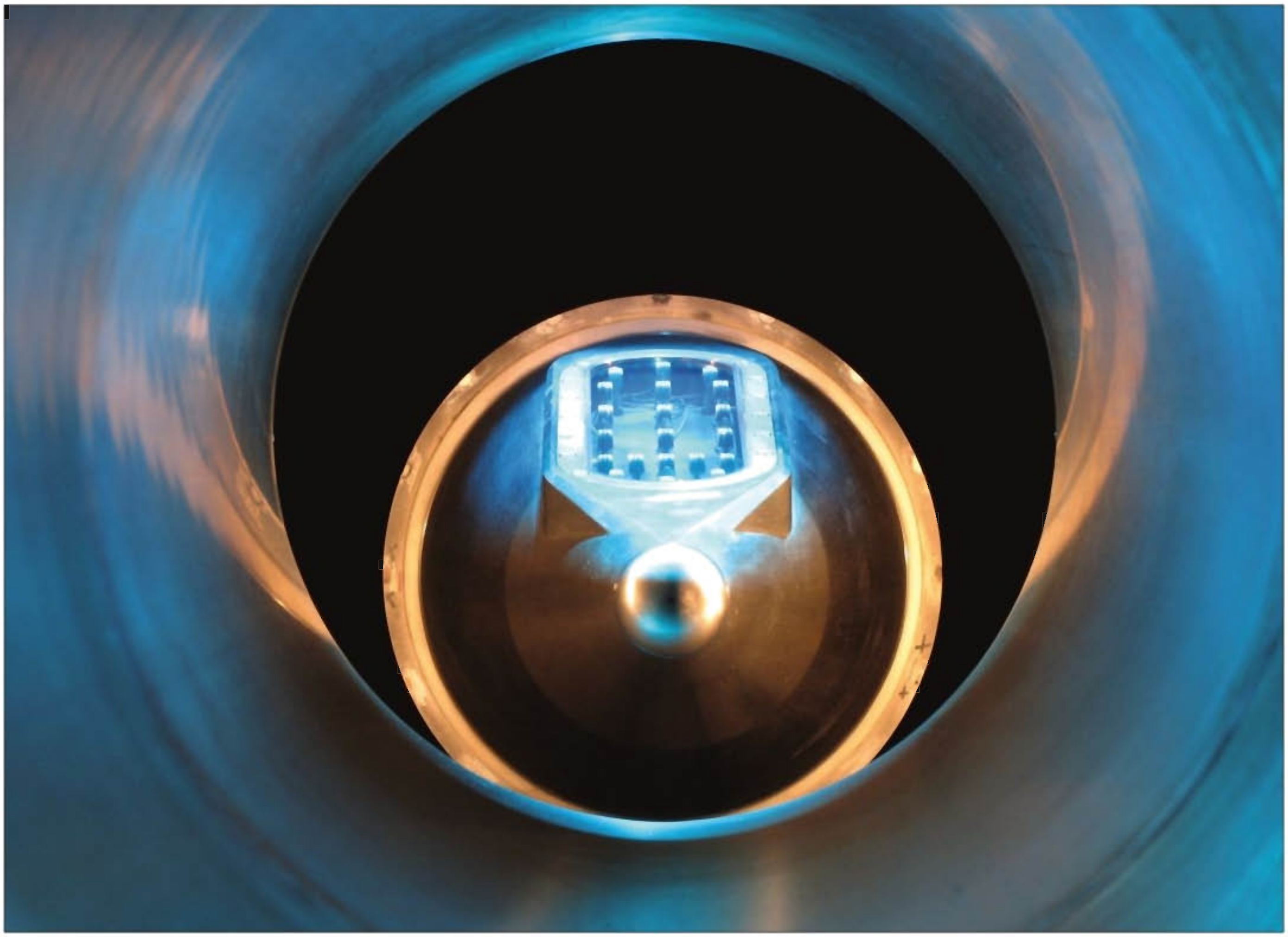
Few even know of its existence. Yet the tunnel, nestled in the middle of the 712-acre former site of the Naval Surface Warfare Center, has been a part of aerospace history for almost 35 years, contributing to nearly every significant U.S. high-speed flight program since the late 1970s.

Hypervelocity Wind Tunnel Number 9, or Tunnel 9 to its operators and customers, is capable of reproducing flight conditions in excess of Mach 14, well into the regime generally identified as hypersonic—more than five times the speed of sound.

Although several other facilities around the world can reach these flow speeds, Tunnel 9 can produce realistic flight conditions for as long as 15 seconds. That may not seem like much, but it is effectively "forever" in the world of hypersonic flow. In contrast, the vast majority of high-speed wind tunnels provide test times on the order of just a few thousandths of a second.

The office corridors of Tunnel 9 are replete with photographs of its many successes, including early tests of the space shuttle, various missile defense concepts, and most recently the USAF/DARPA Hypersonic Test Vehicle (HTV-2) maneuvering reentry craft, which launched on April 22 of this year but unfortunately was lost. This entire complex was almost abandoned, a victim of the Base Realignment and Closure process of the mid-1990s. That it has survived and prospered as a vital national test asset is a tribute to the foresight of its managers and sponsors. It also serves as

by Mark Lewis
Willis Young Professor,
University of Maryland



A full-scale flight-quality seeker window was tested for the Missile Defense Agency in the Tunnel 9 Mach 7 thermostructural leg to assess the performance and survivability of optical windows under high heating loads.

continuing proof of the value of high-fidelity ground test facilities.

Learning to fly hypersonically

The evolving role of Tunnel 9 has reflected changes in the way ground test facilities are used in developing flight programs. At a time when some believe that wind tunnels are destined to be replaced entirely by computational simulations, this facility and others of its kind continue to provide significant value, and are key players in the international quest for high-speed flight. (See "Wind tunnels: Don't count them out," April, page 38.)

Indeed, the most recent efforts to bring the tunnel into the 21st century have come during what will be a banner year for hypersonics, culminating in several flight programs that would not have been successful without ground test.

Hypersonic flight is not new; the first man-made hypersonic object flew on February 24, 1949, when a WAC Corporal sounding rocket was lofted atop a captured German V-2 missile at White Sands. Since that time, every spacecraft that has reentered Earth's atmosphere, and every probe penetrating another planet's atmosphere, has flown at hypersonic speeds. All have been decelerating craft, slowing down as a result of drag as they enter the atmosphere. In contrast, some of today's most exciting hypersonic projects are exploring high-speed cruisers and accelerators—craft that can fly through the atmosphere, either as gliders or under their own power, for prolonged periods of time.

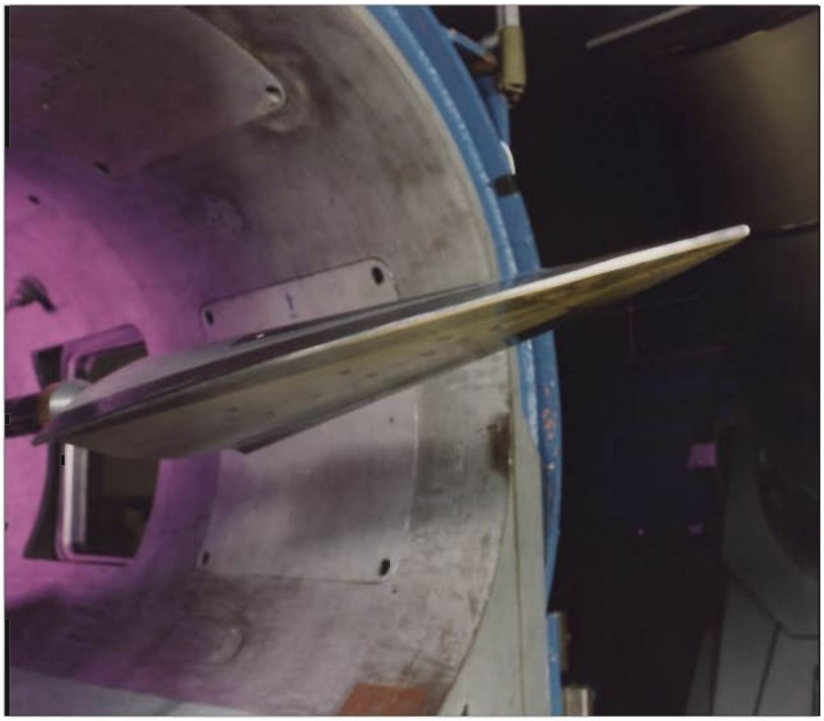
The range of applications for hypersonic craft could profoundly affect military technology, transportation, and civilian access to space. Hypersonic cruise missiles could cover hundreds of miles in a matter of minutes. Hypersonic reconnaissance aircraft could be deployed for rapid sensing in remote areas, possibly filling in for absent space monitoring systems, or providing a closer look at items of interest around the globe. And air-breathing space launchers, using advanced engines to accelerate in the atmosphere on their way to orbit, offer the ultimate promise of airplane-like operations into space.

Despite these promises, efforts to build and fly a hypersonic craft have been mixed at best. Billions of dollars have been spent on failed programs, ranging from the original 1960s AeroSpace Plane to DARPA's recent Blackswift, leading some to question whether hypersonics will ever be practical. Postmortem analyses usually conclude that the programs have been too ambitious, linking unrealistic goals to insufficient funds. The poster child for this is the X-30 National AeroSpace Plane, a mid-to-late-1980s program that was to provide single-stage-to-orbit airplane-like flight.

Regardless of past failures, this is an exciting time in hypersonics. A wide spectrum of flight programs and research activities that will be filling the gaps in our hypersonics knowledge is currently in progress in the U.S. The USAF X-51 program is leading the way this year in flight testing of a Mach-6-class missile-type cruiser powered by conventional jet fuel. The Navy's HyFly program is similarly developing hypersonic missile capabilities, and although it suffered two flight test failures (unrelated to their hypersonic technologies), hopes are high for eventual success.

Even the fundamental research community is having a banner year, with the joint U.S.-Australia HIFiRE program, aimed at delivering a series of hypersonic flight experiments, and the robust basic research efforts jointly sponsored by the Air Force Office of Scientific Research and NASA.

This waverider was collaboratively developed by the University of Maryland, Boeing, and Tunnel 9. The configuration was the first attempt to test a waverider shape designed for good aerodynamics and good volume and packing, with realistic leading-edge bluntness to survive high heat loads.



Test before flight

With so many flight programs in progress, it is tempting to question the need for hypersonic ground test facilities. Indeed, in the days of the NASP program, engineers were predicting that computational tools would soon replace all ground testing, and hypersonic tunnels could all be mothballed. In fact, the reverse has proven to be true.

Program experience has shown more than ever the importance of testing before flight. Some basic issues, such as unsteady shock phenomena, heating rates associated with boundary-layer transition, and the effects of surface gaps and bumps on the flow, are still poorly understood, and only experimental measurements will be directly revealing. In at least one recent case, ground test has proven essential to determining the thermal protection required for a maneuvering reentry test, revealing details computational simulations had completely missed.

Tunnel 9 is unique in hypersonic ground testing. It uses a "blowdown" design, where flow is literally blown from a high-pressure supply into a vacuum. This approach can provide test times long enough to see unsteady effects and other complicated phenomena that may not be captured in shorter duration facilities. Long test times also allow a model to be moved during the course of a single run, so a wide range of angles of attack can be studied in a single experiment. The tunnel also has two separate test sections that can be rolled in and out, and varying the nozzles enables simulation of flight conditions at Mach 7, 8, and 10, in addition to 14.

Of course, there are always engineering tradeoffs, and the blowdown approach has its challenges compared to shorter duration facilities. Because energy is conserved, as the gas in a blowdown tunnel accelerates through the nozzle, its temperature and pressure drop. By the time it reaches Mach 14, the temperature will have dropped by a factor of 40, and pressure will have decreased by a factor of 400,000. This means the gas must start at extremely high pressures and temperatures or it will condense as it expands in the tunnel. Much of Tunnel 9's technology, therefore, involves the storage of gas at extremely high pressures and temperatures, so that by the time it reaches a model there is still a good match to realistic flight conditions.

This principle depends on having an enormous high-pressure gas reservoir. Buried under the ground at the White Oak campus is a gas supply farm where nitrogen is com-

Building on a legacy

This state-of-the-art tunnel has a history that began with the end of WW II, when Allied forces were evaluating German advances in aeronautics. Theodore von Kármán, one of the top aerodynamicists of the 20th century, led a delegation to postwar Europe to identify critical German researchers and facilities. Working under the instructions of Gen. Henry (Hap) Arnold, head of the Army Air Corps, von Kármán found an aeronautics research and testing complex hidden in a forest on the outskirts of Braunschweig.

As von Kármán later explained, the entire complex had been unknown to the allies during the war. The facility, he said, "was discovered only when the American Army moved into the area. We heard that it was a fantastic place where Germany's ultimate secret weapons were being developed. We went there immediately. There was an airfield which was concealed by means of cover of ash, so it would not present a smooth surface from the air....The whole thing was incredible. Over a thousand people worked there, yet not a whisper of this institute had reached the ears of the Allies."

Fifty-six buildings were identified in the complex, all below tree level and widely spaced so as to be camouflaged. Nearly 3 million documents were recovered, including details on such significant advances as swept wings for high-speed flight. This and other discoveries convinced observers that the U.S. needed its own testing and evaluation centers, especially for the soon-to-be-separate USAF.

A bidding war began among the Allies for captured facilities and equipment and for the scientists who built and ran them. Under Project Paperclip, key individuals in the German military research establishment were brought to the U.S. Among the facilities found were supersonic wind tunnels that Wernher von Braun's team had used in the development of the V-2 missile. The tunnels were crated up for transport to the U.S. They found their way to what was then the newly constructed Naval Ordnance Laboratory at White Oak, Md., but the exact details of how they got there are sketchy. Oral history has it that the tunnels were originally supposed to be sent to the Army, but the Navy wanted them instead. How they wound up in the hands of the Navy is not entirely clear—stories are still told of Navy personnel sneaking into the complex and carrying out crates under cover of darkness. But when the parts arrived at White Oak they were stamped with Army Air Corps labels. Those tunnels became the original "Tunnel 1" and "Tunnel 2," establishing the numbering system that has culminated in "Tunnel 9." About a dozen German engineers also came to White Oak.

Today, parts of the original Tunnel 1 from Peenemünde can be seen on display in the lobby of the complex. Before it was decommissioned, the tunnel was heavily modified, but the test chamber door and an original model of a V-2 derivative rocket still survive as a reminder of Tunnel 9's heritage.

In the two decades following WW II, the laboratory at White Oak added a series of high-speed tunnels, designated 3, 4, 6, 7, 8 (5 was conceived but not built) and finally a modified 8A. They had ever-increasing capabilities, and each played an important role in the development of supersonic flight, both into the atmosphere and beyond. In the early 1960s there was growing recognition that the Navy Submarine-Launched Ballistic Missile Program needed a new facility for the testing of reentry vehicles, and Tunnel 9 was born.

pressed to pressures that are over 1,900 times greater than normal atmospheric pressure; that gas is subsequently heated to temperatures close to 3,500 F on its way through the tunnel and into the test section. Because the heaters cannot survive in oxygen, Tunnel 9 must use only nitrogen, meaning that it cannot simulate combustion conditions.

At the beginning of a test, a 72-ft-diam. vacuum tank is pumped down at one end of the facility, and the high-pressure storage tanks are heated at the other. Initially, a set of metal diaphragms is ruptured by gas pressure and the high-temperature compressed nitrogen races down a 40-ft-long nozzle toward a 5-ft-diam. test cell, then out to the vacuum sphere. The test cell has a unique model mount that can pitch through a range of angles, allowing for wide sweep of data in a single run. The pitching mechanism moves at a rate of 80 deg/sec, carrying heavy models smoothly and precisely. Measurement techniques including advanced flow visualization, pressure sensors, temperature sensors, and newly developed temperature-sensitive paints capture the flow physics.

A fast start...and almost a sudden halt

Authorized by Congress in 1966, first run with cold flow in late 1973, and finally calibrated by mid-1975, Tunnel 9 was fully operational by the nation's bicentennial. Within two years of its opening, the tunnel had completed nearly 300 test runs, in support of all three armed services and NASA, in particular the development of the space shuttle. The start of the Strategic Defense Initiative under President Ronald Reagan in the early 1980s saw a new flurry of activity at the facility, where development of optical windows for high-altitude interceptors was a top priority. At White Oak, part of the renamed Naval Surface Warfare

A new, and vital, mission

Perhaps as important as finding a new home with the Air Force, Tunnel 9 found a new mission as a result of the BRAC process in 1997. Rep. Steny Hoyer (D-Md.), who was instrumental in saving the tunnel, offered an important charge to the facility and its staff: Become more closely connected with engineering education, especially reaching out to the nearby University of Maryland campus. This is a responsibility that the tunnel staff has taken very seriously, with extremely positive results.

Almost immediately after Tunnel 9 became an Air Force facility, its staff began an internship and co-op program with the University of Maryland. Students at both the undergraduate and graduate levels have since been involved in nearly every major project at the tunnel. Today, students work directly on tests, help instrument models, work out new capabilities, and use available tunnel results to provide direct comparison to theory and computational solutions. Among the success stories is one of the first students in this program, Inna Kurits, who graduated with a master's degree working at the tunnel and is now employed there as an engineer. And the Tunnel 9 professionals have plans to expand these student opportunities, with the help of the Air Force Research Laboratory.

In part, the motivation for doing so is nothing less than to preserve the very future of ground testing. There is a genuine concern about training the next generation of tunnel engineers. The average age of the contractor workforce at AEDC is nearly 50, and the average time of service approximately 17 years. At Tunnel 9, all but seven of the total 35 employees have worked there less than 20 years, and most will be eligible for retirement within the next decade. To keep the tunnel operating into the future, and to preserve and develop other ground test facilities, AEDC's leadership recognizes the need for fresh blood.

Upgrading the Tunnel 9 facility has confirmed its relevance to the future of hypersonic flight. Focusing on student involvement, research, and education has ensured that it will have the skilled workforce to use this facility, and others like it, for many years to come.

Center, Tunnel 9 was the centerpiece of a Navy operation that covered the range of hypersonic flight technologies.

Then the 1995 Base Realignment and Closure (BRAC) Commission set its sights on the entire Navy organization at White Oak. Tunnel 9 was almost shut down.

The BRAC process was created to reduce the number of military installations in the post-Vietnam era. Recognizing that each military base would have its own constituents (who could thus fight any closure recommendation), the BRAC Commission was established to recommend installations that might be closed or combined with similar facilities; their recommendations were set to go into effect unless Congress were to specifically disapprove the list by joint resolution. When the commission placed the entire Navy installation at White Oak on its list of recommended closings, Tunnel 9's fate was all but sealed.

But recognizing its unique capabilities and its importance to the entire nation, DOD leadership transferred ownership of Tunnel 9 and its support facilities to the Air Force, under the auspices of the Arnold Engineering Development Center (AEDC) in Tullahoma, Tenn. AEDC already operated a list of other world-class hypersonic facilities, each with a unique set of capabilities, including materials testing and high-speed propulsion applications.

On October 1, 1997, Tunnel 9 officially became a part of the USAF; 40 acres are maintained inside the former Naval Surface Warfare campus for the tunnel and its support. The rest of the site is managed by the General Services Administration for the Food and Drug Administration.

Rebuilt for a new generation

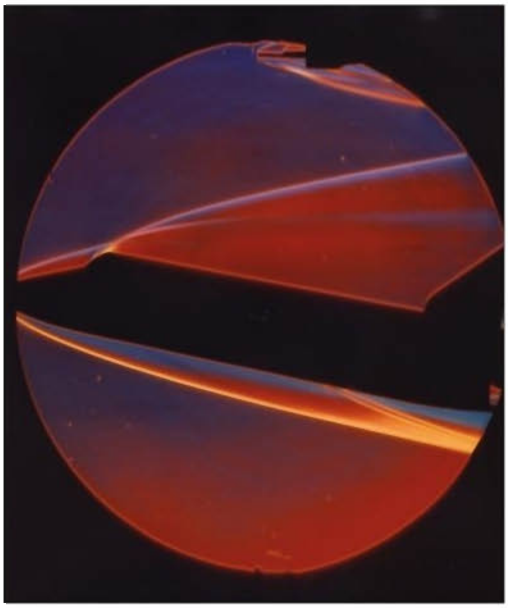
Tunnel 9 received an initial facelift when the Air Force took ownership, but after 10 years it was time for further improvements. Planned FDA construction around the tunnel offered the perfect hiatus for a complete upgrade, including the installation of a state-of-the-art digital control room to replace the old 1970s-era analog system. With a year to plan, engineers readied several experiments and greatly improved instrumentation capabilities in preparation for the tunnel's return to service. March of this year saw the first runs with the new control room and instrumentation, producing significant new results.

In another new approach, the tunnel's technical director, John Lafferty, has successfully coordinated research efforts at Tunnel 9, AFOSR, and universities to perform several experiments simultaneously in the tunnel's vast test section. "By piggy-backing multiple experiments we can maximize the usefulness of the unique conditions provided during each run; this is critical to providing researchers the needed access. Certain challenges in hypersonics cannot make significant advances without access to the salient physics that can be provided by a facility like Tunnel 9," says Lafferty. That approach has already proven extremely successful.

The recent upgrades also reflect a change in the way Tunnel 9 intends to do business in the future. Says Dan Marren, AEDC site director, "Success here will require building partnerships with science and technology activities, inventing test techniques and methods tuned to obtaining important hard-to-measure quantities and providing data in a format that feeds the weaknesses in our computational models." Reflecting the changing nature of ground tests, future tunnel runs will not be isolated data-gathering exercises, conducted only as a precursor to flight. Rather, they will be linked to computation, and some will be done as follow-ups to flight tests.

Marren points out that the first shakedown tests were also an opportunity to include partners in academia, other Air Force organizations, NASA and the Dept. of Energy. That is very much in keeping with the facility's new operating philosophy, integrating more research opportunities into the test and evaluation function of the tunnel.

One researcher who appreciates what Tunnel 9 can do for the research community is Pino Martin, a professor at the University of Maryland and one of the world's foremost authorities on computational simulation of hypersonic flows. As Martin explains, "Tunnel 9 provides the widest range of Mach number and Reynolds number flow conditions in the nation. Using and extending experimental data from Tunnel 9 will allow for the development and validation of new computational tools well beyond the current state of the art."



A series of aerothermal and aerodynamic stability tests of the space shuttle were completed in Tunnel 9 in the late 1970s.

Out of This World: The New Field of Space Architecture

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Brent Sherwood
Syd Mead
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Out of This World: The New Field of Space Architecture

This collaborative book compiles thirty chapters on the theory and practice of designing and building inhabited environments in outer space. Given the highly visual nature of architecture, the book is rich in graphics including diagrams, design drawings, digital renderings, and photographs of models and of executed and operational designs.

Written by the global network of practicing space architects, the book introduces a wealth of ideas and images explaining how humans live in space now, and how they may do so in the near and distant future. It describes the governing constraints of the hostile space environment, outlines key issues involved in designing orbital and planet-surface architecture, surveys the most advanced space architecture of today, and proposes far-ranging designs for an inspiring future. It also addresses earth-based space architecture: space analogue and mission support facilities, and terrestrial uses of space technology.

In addition to surveying the range of space architecture design, from sleeping quarters to live-in rovers to Moon bases and space cities, the book provides a valuable archival reference for professionals. Space enthusiasts, architects, aerospace engineers, and students will find it a fascinating read.

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