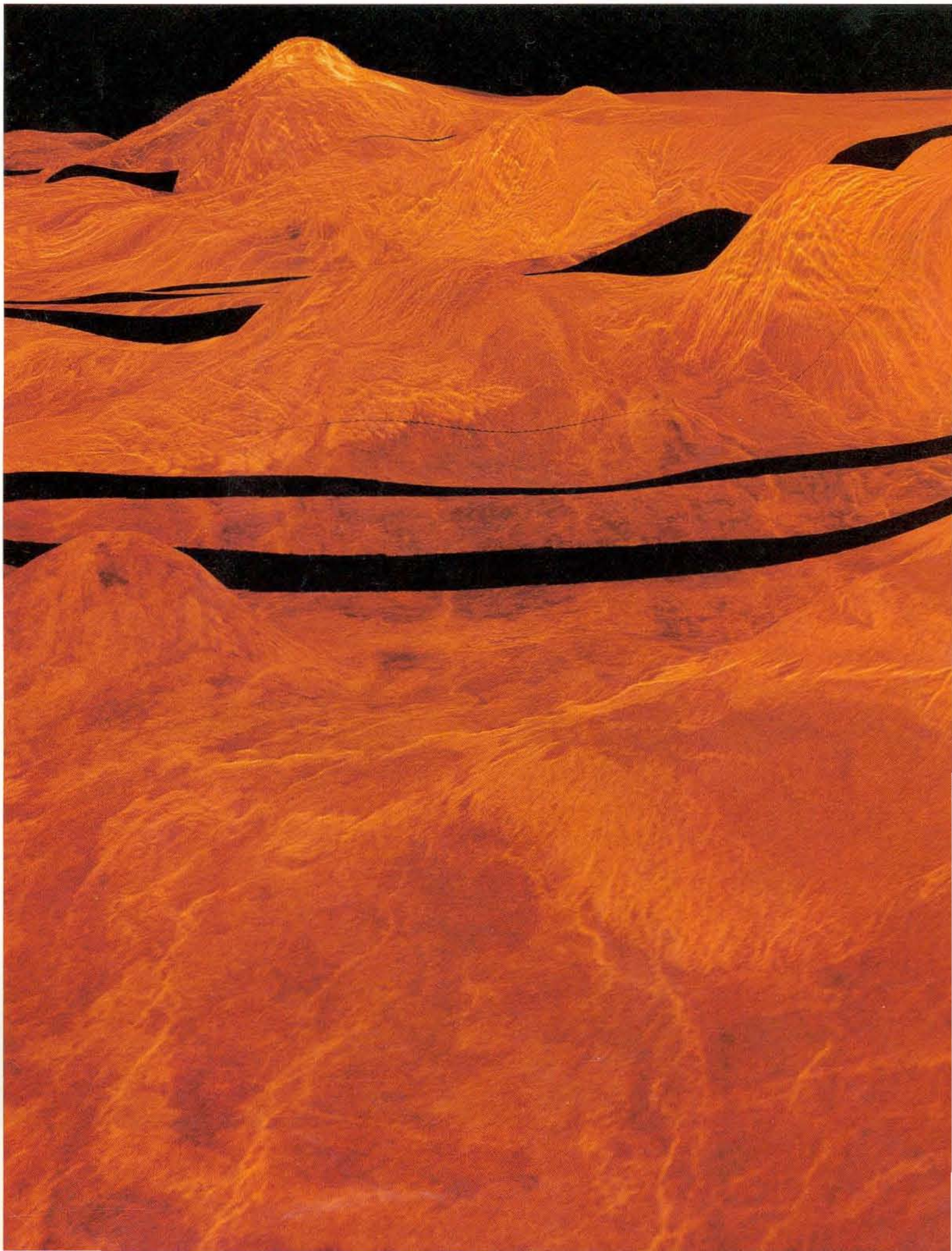
California Institute of Technology

Engineering & Science

Spring 1991

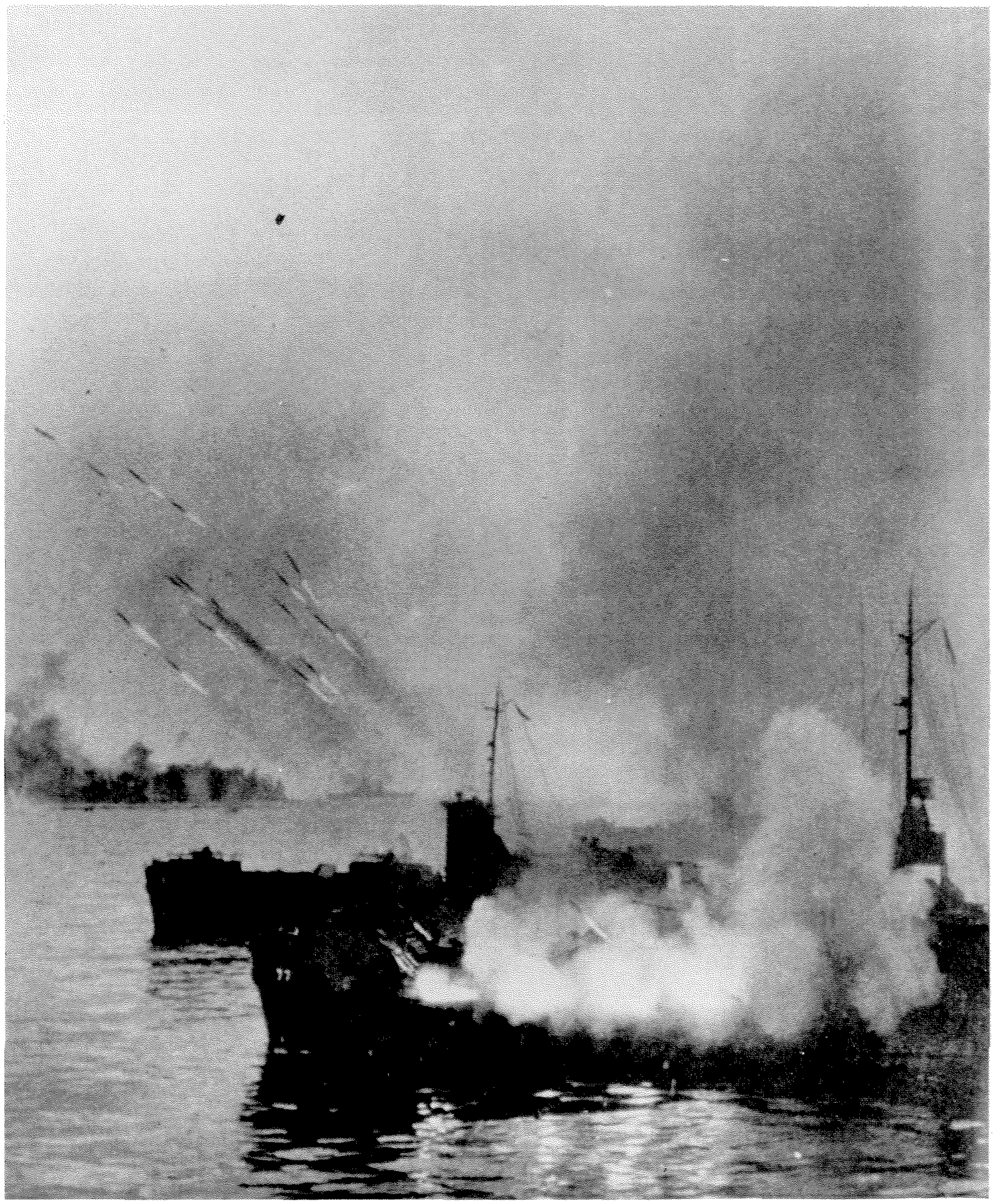


In this issue

Magellan at Venus

Rocket Scientists

Nuclear Power

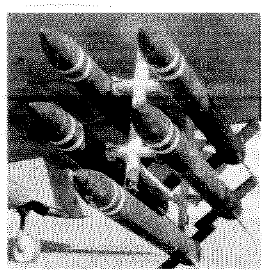


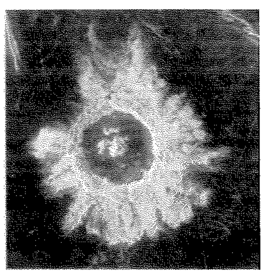
Barrage rockets from Caltech led off every amphibious landing in the World War II Pacific Theater after December 1943.

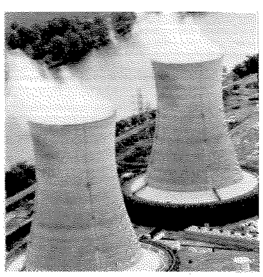
California Institute of Technology

Engineering & Science

Spring 1991
Volume LIV, Number 3



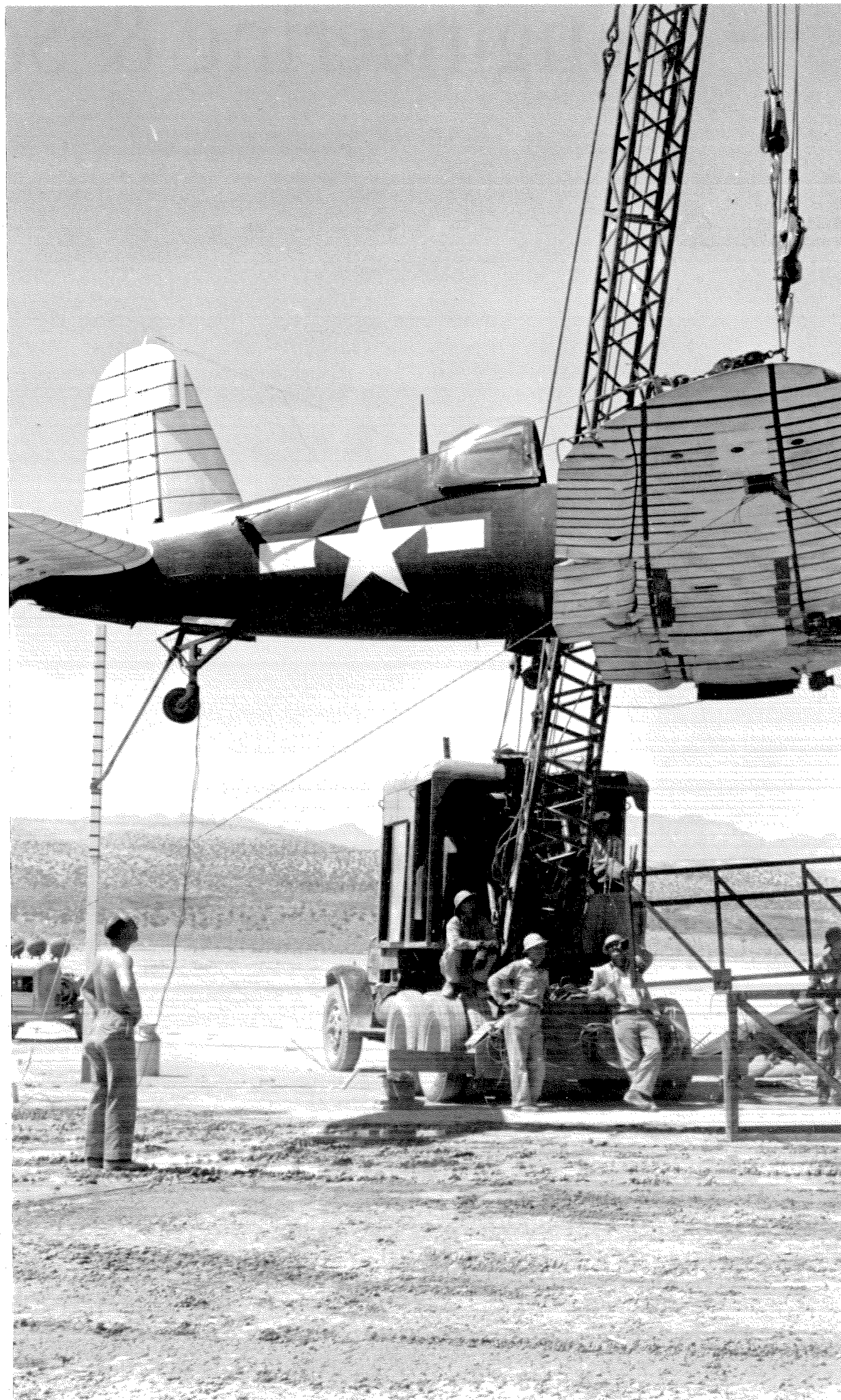




On the cover: A 3-D perspective of the precipitous southern rim and boundary mountains of a Venusian highland called Lakshmi (right horizon). The black ribbons aren't freeways, but swaths of missing data. Such views help scientists interpret Magellan's radar data—for example, the small dome at left is a volcano unnoticed in the normal map-view images. An article describing some early results from the mission begins on page 14.

Engineering & Science (ISSN 0013-7812) is published quarterly, Fall, Winter, Spring, and Summer, at the California Institute of Technology, 1201 East California Boulevard, Pasadena, California 91125. Annual subscription $8.00 domestic; $20.00 foreign air mail; single copies $2.00. Third class postage paid at Pasadena, California. Published by the California Institute of Technology and the Alumni Association. Telephone: 818-356-3630. Postmaster: Send change of address to Caltech 1-71, Pasadena, CA 91125.

PICTURE CREDITS: Cover, inside back cover, 14–17 – NASA, JPL; inside front cover, 2, 9, 11, 13 – U.S. Navy; 6 – Rex Robbins, Albert James, U.S. Marine Corps; 5, 7, 10 – William Fowler; 17 – Soviet Academy of Sciences; 26 – David Senske, James Head; 28, 31, 32, 34 – U.S. Council for Energy Awareness; 37 – Leigh Wiener; 39 – Janet Jenks Plesset; 43 – Douglas Smith.



Caltech's *Other* Rocket Project: Personal Recollections

by Conway W. Snyder

I knew nothing about rockets, but neither did anyone else on the project in the beginning.

At the Naval Ordnance Test Station at Inyokern, members of Caltech's rocket project set up for test-firing Tiny Tim, a large aircraft rocket designed by Tommy Lauritsen. Willy Fowler stands at left. It was September 1944.

Caltech has been identified with American rocket science ever since its first successful experiments with liquid-fueled rockets in 1936, which led to the founding of the Jet Propulsion Laboratory and the launching of the space age. But Caltech carried on another *rocket project in the early 1940s—its contribution to the war effort—which is less well known. Although some of today's air-to-air guided missiles may be direct descendants of the first aircraft rockets developed at Caltech, the Institute's war work ended in 1945, allowing its participants to return to their "real" work.*

According to Archivist Judith Goodstein's forthcoming book on the history of Caltech, Millikan's School, *the project grew from an initial government contract of $200,000 in 1941—three months before Pearl Harbor—into an "$80 million war industry" before it ended. Rocket design and production took over all of the Kellogg Radiation Laboratory and a number of other campus buildings (as well as several hundred subcontractors in the Los Angeles area and scattered testing sites), and exploited the talents of a significant fraction of the Institute's top scientists. According to William Fowler (quoted in Goodstein's book), ". . . the upshot was that a large part of Caltech literally became a branch of the Bureau of Ordnance."*

Conway Snyder joined the project as a grad student in 1942. On the occasion of Caltech's Centennial, he thought it "appropriate to recall a significant episode in its history that began exactly half a century ago and that has been unheard of or forgotten by almost everyone who was not involved in it." Snyder (PhD '48) is now retired from JPL.

At eight o'clock on the morning of June 1, 1942, I walked into Willy Fowler's office in room 203 Kellogg. Most of the research staff of the project—about 15 men at that point—were accustomed to assembling in that place at that time every weekday to discuss the latest developments. As a new Caltech graduate student I found the discussion completely baffling, because I did not even understand the technical meaning of the words being used—*motor, grain, perforation,* and so on.

At the end of the session I had not the remotest idea what the project was about, so I asked my office mate who told me they were developing rocket weapons for the Navy. The word "rocket" had not been mentioned in the meeting. I had no idea what an exciting and stimulating time I was to have in the next three years or that most of the rest of my life would be involved with rockets. I knew nothing about rockets, but neither did anyone else on the project in the beginning.

The Caltech rocket project was officially known as contract OEMsr-418 of Division 3, Section L of the National Defense Research Committee of the Office of Scientific Research and Development. NDRC and OSRD were government-funded agencies that had been set up in 1940 to support and coordinate war-related scientific research. The chairman of NDRC Division A (Armor and Ordnance) was Richard C. Tolman, professor of physical chemistry and mathematical physics, and his deputy was Charles C. Lauritsen (PhD '29), professor of physics.

In the summer of 1941 Lauritsen was sent to England to investigate the British rocket program. He returned with a strong recommendation for an accelerated American rocket program, and he was authorized to set up a project at Caltech.

Artillery rockets had been used by the British in 1814, and modern versions had been under development in the 1930s by the Germans, the British, and the Russians (who had first used them in combat in 1941), but the American military services had shown little or no interest in them until late 1940, primarily because of their assumed low velocity and very poor accuracy as compared to cannon. In the next few months two rocket projectiles were developed by projects on the east coast on contracts with the Ordnance Department of the Army. The most successful was a tiny rocket dubbed the "Bazooka," which depended for its armor-penetrating capability on a shaped explosive charge only 2.36 inches in diameter. Both projectiles were propelled by propellant grains (single pieces of solid propellant) in the shape of cylinders about one inch in diameter, because these were the largest that could be made by the process used in the U.S.

In the summer of 1941 Lauritsen was sent to England to investigate, among other things, the British rocket program. He returned after a couple of months with a strong recommendation for an accelerated American rocket program, and he was authorized to set up a project at Caltech, primarily for the development of a high-altitude antiaircraft rocket. In September 1941 he set up shop in Kellogg Laboratory and recruited, among others, his former student William Fowler (PhD '36), then associate professor of physics (and now Institute Professor of Physics, Emeritus, and Nobel laureate); and his son, Thomas Lauritsen (PhD '39), who was always called Tommy, who later also became a professor of physics at Caltech. Also on the original project scientific staff were physicists Ira Bowen (PhD '26) and Ralph Smythe, chemical engineers William Lacey and Bruce Sage, and Donald Clark, assistant professor of mechanical engineering. Professor of Physics Earnest Watson became the administrative head of the project with the title of official investigator. In his office in Bridge Lab he handled finances, liaison with the government, and similar necessary but unglamorous tasks, so that Lauritsen could concentrate on technical problems.

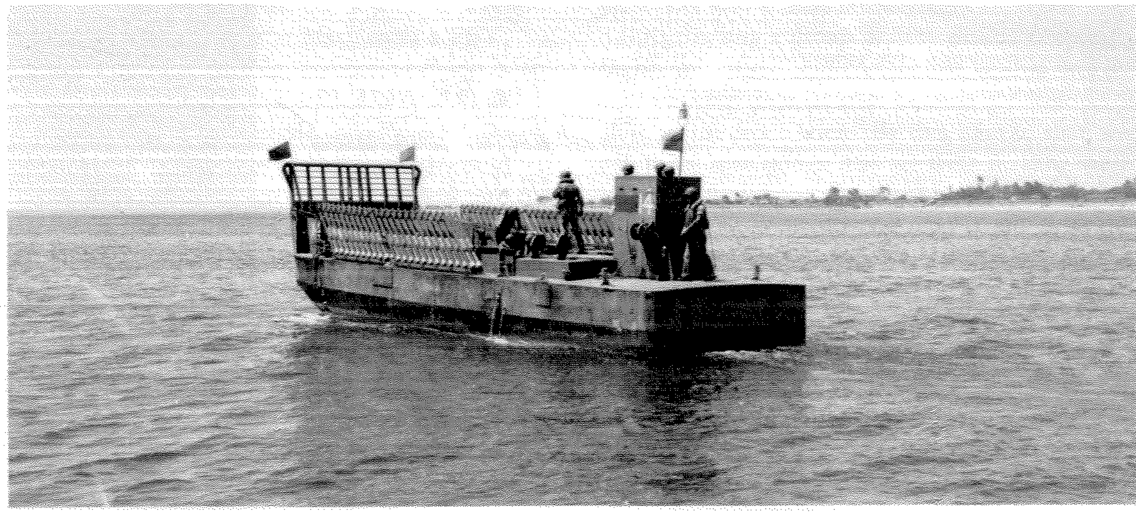
Charles Lauritsen was convinced that the first major problem that needed to be tackled was the production of a suitable propellant. Since rocket motors must be very lightweight, they cannot stand the high pressures that are generated in guns and cannon, and hence require a propellant that will burn evenly and continuously at pressures on the order of 100 atmospheres. An appropriate formulation that was available in the U.S. was a double-base smokeless powder called ballistite, which consisted of about equal parts of nitroglycerine and nitrocellulose. It looked like plastic—black, shiny, and somewhat soft. It was produced in sheets approximately 1 foot by 3 feet by 1/16 inch. The small propellant grains used in the Army rockets were made from the sheets by a process called solvent extrusion, which was not appropriate for larger grains.

Lauritsen had in mind much larger grains, so in the first few weeks of the project, his son put a small extrusion press together out of scrounged parts, mounted it on wheels, hauled it to Eaton Canyon north of Pasadena, and attempted to extrude ballistite without a solvent. According to the project mythology his first product looked rather unpretty, and Tommy thought it might be improved if he evacuated the air from the extrusion cylinder before applying the pressure. It worked, and on November 20, 1941, a good grain 15/16 of an inch in diameter and 30 inches long was extruded. In the next three weeks, Tommy extruded all the ballistite that was readily available into 180 pounds of good-quality grains, and the first major problem was solved. Only later did someone realize that, without the vacuum, the adiabatic compression of air in the chamber could heat it to the combustion temperature of the ballistite and cause an explosion.

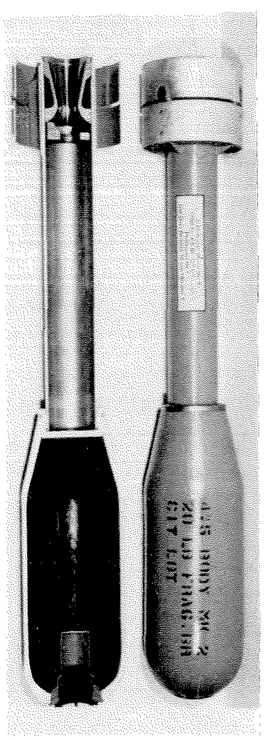
Even as Tommy was building his experimental press, Lacey and Sage were already designing production presses for grains of 1.75- and 2.75-inch diameters, the first step in a project that would ultimately produce hundreds of thousands of grains in various configurations up to a 4.5-inch diameter. These presses were built in Eaton Canyon for the first couple of years, and later at the Naval Ordnance Test Station (NOTS) at Inyokern.

In the early days at Kellogg, procedures were informal. Propellant grains were machined to size in room 106 in Kellogg (now a storage room full of file cabinets), then loaded into the motors (the propulsive units) by whichever staff member was going to conduct the test; the motors were thrown into the back of a station wagon, which was then driven to the test range on Goldstone Dry Lake, 30 miles north of Barstow. The situation changed after March 27, 1942, when a low-level explosion of ballistite in room 106 killed the man working there. Thereafter all handling of ballistite was done at Eaton Canyon, loaded rocket motors were transported in specially equipped vans, and the scientific staff no longer rode along with the rockets.

The first weapon on the project's development schedule was an antisubmarine rocket. In the spring and summer of 1942, we were losing



The 4.5-inch-diameter barrage rocket (below) developed at Caltech was initially used in landing craft such as the one at right with its rockets loaded along the sides, ready to fire. The rocket saw action in every amphibious landing in Europe and in all those in the Pacific beginning with Arawe in December 1943.



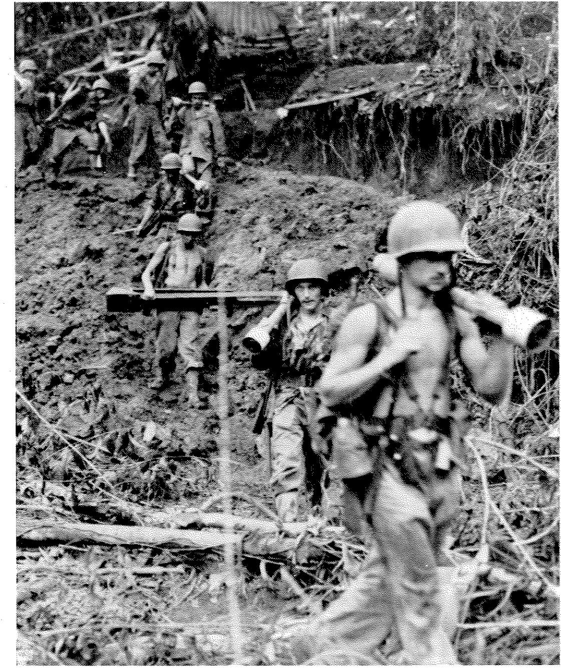
about 20 ships per week to German submarines in the Atlantic and the Caribbean. The Allies had sonar to detect the submarines; the tactics available were to position the ship over the sub and drop depth charges over the side. If they missed the sub, they roiled up the water so much that sonar contact could not be reestablished for some time. Consequently, the success rate in engagements was only about 5 percent. What the Navy wanted was a small rocket that could deliver about 300 yards ahead of the ship a small bomb that was fused so as to explode on contact with the sub; thus, if no hits were made, the sonar could maintain contact.

The Antisubmarine Rocket (ASR), which was nicknamed the "Mousetrap," was already being tested when I arrived on the project; a few rounds had been fired at a towed target off San Diego on March 30. One of my first jobs was to take some of them to the firing range on Goldstone Lake to test their range and dispersion at various temperatures. No explosives were ever allowed at the range; the rocket heads (payloads) were filled with a plaster mixture adjusted to the same density as TNT. The ASR was 35 inches long, weighed 65 pounds, and had a head 7.2 inches in diameter. The motor, which was threaded into the rear of the head, was a steel tube 2.25 inches in diameter and 16 inches long, with a fin at the rear the same diameter as the head. The ballistite grain weighed 1.55 pounds, burned for between .3 and .7 seconds, depending on the temperature, and gave the rocket a velocity of about 175 feet per second and a maximum range of about 290 yards. The warhead's fuse, called the HIR (hydrostatic impact rocket) because it was armed by water pressure and detonated by contact with the sub, was developed by a small project group headed by Robert King, a staff member at the Mount Wilson Observatory. Both the rocket and its fuse were soon in quantity production. By the fall of 1942 they were in extensive use in the Atlantic and the Caribbean, and by early 1943 in the Pacific as well.

Shortly after my arrival, the project began development of its second weapon, the 4.5-inch Barrage Rocket (BR), and I was soon firing these at Goldstone. Whereas my tests of the ASR usually involved a dozen rounds or less, I often fired a hundred BRs in a day. The weapon went into quantity production very quickly, first by the project and soon in factories under contract to the Navy Bureau of Ordnance, and a certain fraction of every production lot had to be fired for proof testing to assure that they met specifications.

The need for the BR to be launched from small landing craft was first suggested to Lauritsen in mid-June by the commander of the amphibious forces in the Pacific. The Navy requested the weapon in September, but Charlie did not wait for that formal authorization, and the BR first saw action in the assault on Casablanca on November 8. It used the same motor as the ASR, with different tail fins to match the 4.5-inch diameter of the head—a 21-pound bomb containing 6.5 pounds of TNT. Its burn velocity of 355 ft/sec gave it a maximum range of 1,130 yards. About 1,600,000 of them were

The BR was so useful and used in such quantities that the Bureau of Ordnance dubbed it "Old Faithful."

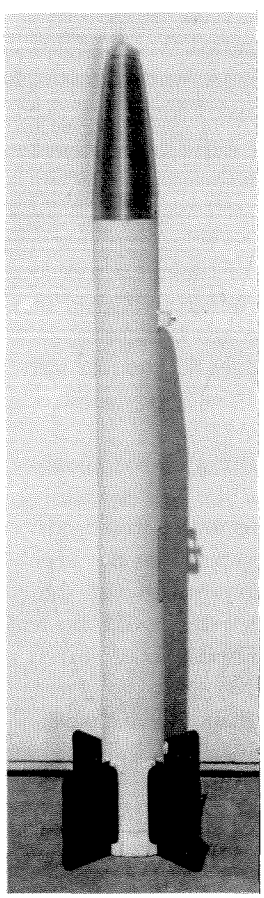


manufactured during the war, and they were installed on hundreds of landing craft and patrol boats and also on some larger ships. They saw action in every amphibious landing in the European Theater and in all those in the Pacific beginning with Arawe in December 1943. They were launched by the thousand onto the beaches in the few minutes prior to the landing, producing the most concentrated bombardment up to that time. Any movie of the war is almost certain to show their flame trails streaking out ahead of the landing craft. I remember well an admiral's coming to Kellogg to report to us on the Arawe landing. He said that the first wave of assault troops in earlier campaigns had always sustained heavy casualties. At Arawe any defenders close to the beach who were not killed were so dazed that they were unable to function for some time, and the first wave was not even shot at. Now, he said, every Marine wants to go in on the first wave.

Various launchers for this rocket were designed by the project and later by the Bureau of Ordnance. Other project groups designed fuses, and some staff members traveled to distant places to instruct the troops on using the weapons. They were soon being mounted on jeeps and trucks and carried into the jungle by hand. The BR was so useful and used in such quantities that the Bureau of Ordnance dubbed it "Old Faithful."

Losses from German submarine attacks continued to increase. (In fact, they did not reach their peak until April 1943.) The best countermeasure appeared to be aircraft, which could

The Caltech barrage rockets were mounted on jeeps and carried by hand. Because they were mobile, the rocket units could use hit-and-run tactics to escape enemy counterfire. At far left, Marines launch rockets at Japanese emplacements on Iwo Jima. Near left: Members of a Marine rocket platoon tote their equipment to the front lines on Bougainville.



scout large areas of ocean, but a suitable weapon was not available. So the Navy took a PBY, called the Catalina (a big, lumbering flying boat with landing wheels) and equipped it with a newly developed instrument called the Magnetic Antisubmarine Detector (MAD), which could signal the moment when the aircraft was directly over the sub. The project designed and attached under each wing of the aircraft a number of launching rails for the ASR. The idea was that the aircraft would fly at precisely the velocity of the rockets, and, when triggered by the MAD, a salvo of ASRs would be launched backward so that they fell vertically down on the sub. As higher velocities were required to match the speeds of various aircraft (up to 400 ft/sec), larger motors, 3.25 inches in diameter, were designed for the "retro" ASRs.

On July 3, 1942, the first test of the system was made at Goldstone—the first time that any rocket had been launched from an American airplane. Somewhat later, I was given the task of designing a submarine to provide a realistic test of the system. My sub did not have to resemble a real one except in one respect—its magnetic field. So we erected two telephone poles about 40 feet apart in the middle of the dry lake, and on them we strung a rectangular multiturn coil of heavy insulated wire, with the bottom side on the ground and the top side at the height of the poles. I connected a set of automobile storage batteries in a series-parallel arrangement to match the voltage of a big old DC generator that we scrounged from somewhere. (It may perhaps once have powered Carl Anderson's cloud chamber.) As the Catalina approached, I would throw a big knife switch to discharge the batteries through the coil and run to get out of the way. Between passes, I would recharge the batteries through another switch. There were perhaps half a dozen passes during the day, and the last planned pass, as dusk was approaching, dropped one ASR squarely on the center of the top run of the coil, effectively ending that test forever.

In the spring of 1943 two squadrons were equipped with the retrorockets; one went to the Pacific, where few submarines were found, and the other went to the Straits of Gibraltar, where it enjoyed some success, although a single squadron could hardly have a significant impact on the war. The rocket is given credit for the last German submarine killed in the war, off the French coast on April 30, 1945.

By sometime in 1943, Caltech's rocket project was up to full strength, with a staff of more than 250 scientific, technical, and administrative personnel and a total employment of about 3,000. It was a group of very skilled people, highly motivated and compatible, and it was a very exciting time, in part because we were so close to the front lines. By this I mean that we could see that things that we were making were being used to great effect by the troops, sometimes within weeks or even days of the time they left our hands.

In three adjacent offices on the second floor of Kellogg were Charlie, Willy, and Tommy, respectively the project director, the deputy director and supervisor of design and development (Section 1), and the Projectile Group supervisor. The organization was rather fluid, and some people changed jobs as conditions changed. Physicists, chemists, biologists, and astronomers did all kinds of things (often including manual labor) that they would not normally be expected to do.

Willy's Section 1 included the Projectile Group under Tommy; the Fuse Group under Bob King; the Theoretical Research Group headed by Leverett Davis (PhD '41), later professor of theoretical physics; the Land and Amphibious Launcher Group; and the Interior Ballistics Research Group under biologist Emory Ellis (PhD '34) and astronomer Franklin Roach (not from Caltech). Section 2, Aircraft and Ballistics, headed by Carl Anderson (PhD '30, professor of physics and already a Nobel laureate), was concerned with launchers and tactics for aircraft rockets, and Ira ("Ike") Bowen, who became director of the Hale Observatories after the war, headed Section 3, Photographic Measurements and Exterior Ballistics. Bowen invented the high-speed movie cameras that were used to measure the velocities and accelerations of the rockets during testing. Joseph Foladare (BS '30) headed the Editorial Section that produced reports and catalogs and kept track of the multitude of statistics on the proliferating number of different rocket models.

Section 5, Propellants and Interior Ballistics, was a very big section with three supervisors—Sage, Clark, and Lacey. It was customarily referred to as "Sage's boys," and he certainly was its vigorous and visible head. Its facilities were located in Eaton Canyon. Among the approximately 20 group supervisors in that section was William Corcoran, who was often the one who had charge of propellant loading for batches of rockets that I then tested. He later became professor of chemical engineering and vice president for Institute relations.

The Development Engineering Section, with headquarters in fancy buildings at 960 E. Green Street, handled the production of metal parts of

Willy spent March and April 1944 touring the Pacific theater, advising the naval officers about rockets and quizzing them about what more Caltech could do for them. Their answer was "more and more rockets."

all kinds, and by war's end it had produced more than a million rocket components through contacts with most of the small machine shops in southern California.

There were two experimental groups that built and used facilities at the lake formed in San Gabriel Canyon by Morris Dam north of Azusa. They were Section 4, Underwater Properties of Projectiles, supervised by Max Mason, chairman of the Observatory Council, and Section 7, Torpedo Launching, headed by Fred Lindvall (PhD '28), professor of electrical and mechanical engineering, who earlier had directed the rocket launcher section.

Charlie mostly stayed in his office, thinking, planning, designing new rockets, and conferring with generals, admirals, and Washington brass like Tolman, so Willy handled the day-to-day direction of the project (i.e., giving orders, conducting staff meetings, etc.). In the early days Tommy "got his hands dirty," but after a few months I realized (to my considerable surprise) that I had become his principal assistant. Often I would sit on a high stool in his office as he explained my next task. Almost always the interview ended with Tommy saying, "If this job was easy, I would do it myself." As a result I think that I got to do as great a variety of unusual and interesting things as anyone on the project.

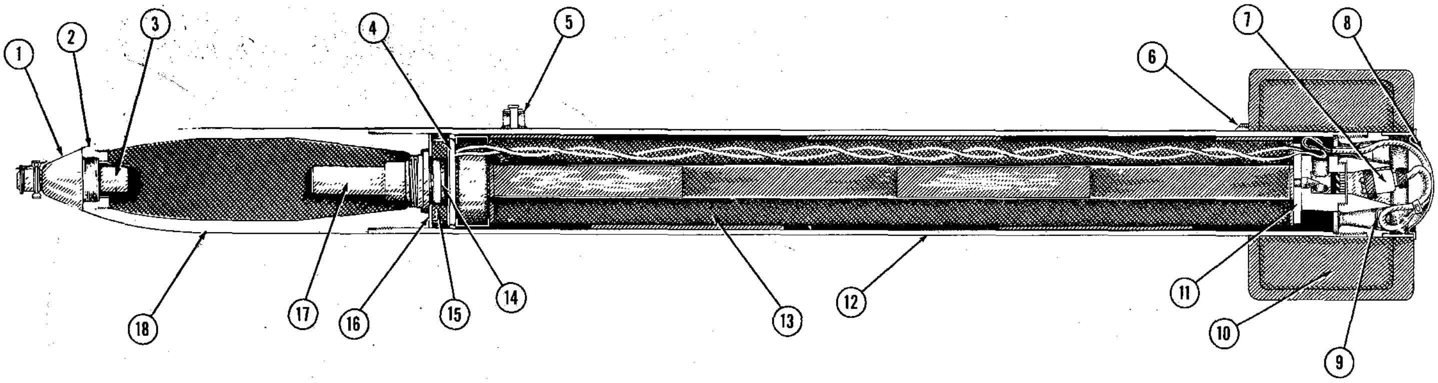
The northeast corner of Kellogg was a big empty room, about 30 by 70 feet in area and four stories high, that had housed the million-volt x-ray tube. As the project began to grow, this room was floored on each level so that the basement floor housed the machine shop (some of which still remains) and the design and drafting group occupied the fourth floor (room 300). I cannot remember who was in room 100, but in room 200 were the desks for the projectile and launcher groups, about 25 people. Members of Sage's group who were not at Eaton Canyon were housed in the old Chemical Engineering Laboratory, and other groups were scattered in various cubbyholes around the campus and in more than 20 other locations in Pasadena.

Meanwhile, by late spring of 1943, the submarine menace was still serious. The subs had begun to change their tactics, choosing to surface and shoot it out with attacking aircraft, over which they had the advantage of greater firepower. Sage's boys had found that the heaviest tubular propellant grain that would function reliably inside a 3.25-inch, 11-gauge, steel tube was only about 6 pounds, so they had developed and begun production of a new "cruciform" design of ballistite grain for our next major product—the 3.5-inch forward-firing aircraft rocket (FFAR). It was patterned after a British rocket that Charlie had seen on his visit in 1940, and which had recently been found effective against subs when fitted with a solid steel head that could penetrate the hull. Our rocket was quite similar to the British one, but with a shorter motor, 45 inches long. With an 8.5-pound propellant grain and fitted with a 20-pound solid steel head 3.5 inches in diameter and four rather large tail fins, it had a velocity of 1,180 ft/sec plus the velocity of the plane that launched it.

Charlie had been given a few of the British rockets, and they were used in the first test of forward firing from an American fighter plane, which took place at Goldstone in July 1943, the month the Allied forces invaded Sicily. The following month, with preliminary testing now completed, aircraft testing with our rocket could begin. These were so successful that the Navy immediately began a crash program of quantity production.

The reason for the notorious inaccuracy of unguided rockets was that their low velocity at the instant of release from the launcher provided insufficient aerodynamic force on the tail fins to stabilize them. When launched forward from aircraft, their velocity at release was already high and the tail fins were effective. Thus their accuracy was about eight times greater than that of ground-fired rockets and quite comparable to cannon. The first AR (aircraft rocket) launchers were about as long as the rocket, to provide stability for the first few feet of travel. It was soon discovered that these were unnecessary, and they were replaced with "zero-length launchers," which guided the rockets only for the first inch of travel and caused much less aerodynamic drag on the aircraft.

I had the fun of conducting all the initial ground testing of these and the later aircraft rockets. When aircraft tests with submerged targets began, it became evident that the steel heads tended to break off on impact with the water. The problem was referred to Ike Bowen, and he and I conducted several tests of aircraft firings into the Haiwee Reservoir in the Owens Valley. Heads of various shapes were tested. It was found that, with a hemispherical nose, the rocket would enter the water and continue in a straight line. However, with a smaller hemisphere at the nose followed by a sort of conical taper back to the full diameter of the head (which provided some lift), the missile would enter the water cleanly, turn upward, and continue along a few feet below the surface until its



The 5-inch high-velocity aircraft rocket was known as Holy Moses. These fins were designed by the author (the Navy eventually abandoned them).
1 fuse
2 fuse liner assembly
3 booster cup
4 igniter
5 lug button
6 suspension mount
7 wire and plug
8 rear seal
9 nozzle seal
10 fin
11 grid
12 motor tube
13 propellant grain
14 front seal
15 felt seal
16 fiber seal
17 base fuse
18 body

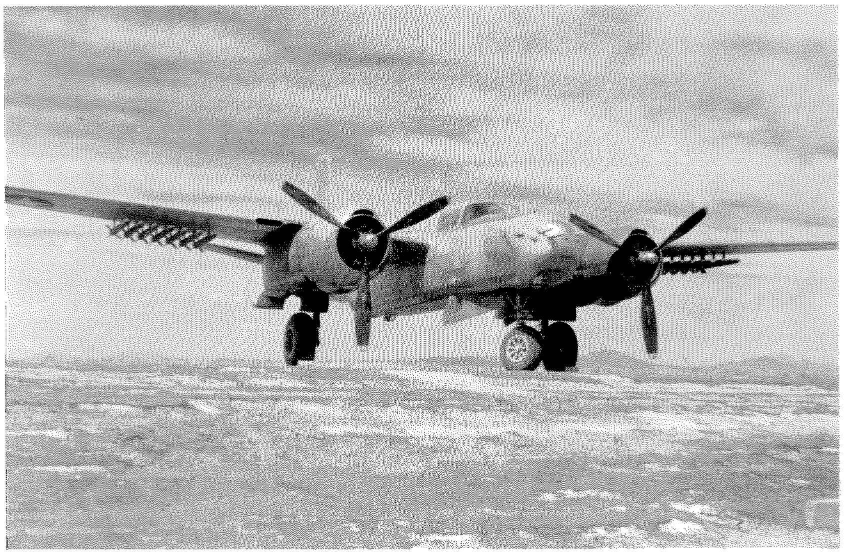
momentum was spent. This performance meant that a submerged submarine would present a target, as seen from the airplane, several times the size of the sub itself.

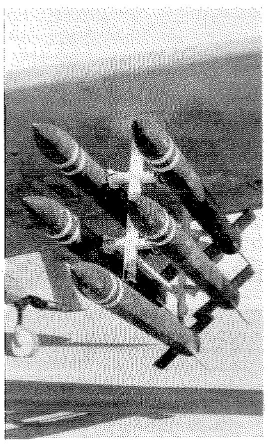
The first confirmed kill with this rocket was on January 11, 1944. It is said that the submarine commander was mystified suddenly to discover two small circular holes in his hull where the rocket had entered and exited, although no projectile had been seen. (I cannot vouch for the truth of this tale.) Submariners were soon to become accustomed to this phenomenon. Their only recourse was to surface and remain exposed to other aircraft and ships with other weapons.

The FFAR motors were soon fitted with explosive heads 5 inches in diameter to produce the 5-inch AR. The increased weight decreased the velocity considerably (to about 700 ft/sec), but they were effective in some circumstances. Willy spent March and April 1944 touring the Pacific theater, advising the naval officers about rockets and quizzing them about what more Caltech could do for them. Their answer was "more and more rockets." The commander in chief of the Pacific requested 100,000 rockets per month. Willy was told that the Marine TBF (torpedo-bomber) squadron using the 5-inch AR had found them to be ineffective against large ships, but that there were plenty of other good targets. They had damaged so many antiaircraft emplacements that those without armored turrets no longer fired against TBFs for fear of revealing their position.

In August 1943 Charlie began scouting around for a suitable site for a Navy rocket testing facility that would gradually be able to take over the project's job and continue the program into peacetime. He settled on a deserted little aircraft landing field east of the inconspicuous village of Inyokern, about 50 miles northwest of Goldstone. The idea and the location were soon accepted by the Navy, and on November 8, the Naval Ordnance Test Station, NOTS Inyokern, was officially established. By December, ARs were being launched on the range, and Sage's group had begun building large extrusion presses nearby. Thereafter, until war's end, the project's test activities were gradually shifted from Goldstone to NOTS.

Tommy assigned occasional small jobs to me in addition to my testing activities. On one occasion the Navy sent a lieutenant from Washington to Pasadena with instructions to launch some rockets underwater. He explained that they wanted to know whether the bubbles produced would be visible from above. We took to Morris Dam a half-dozen rounds of small, so-called subcaliber rockets that were used for training, and a length of steel tubing to use as a launcher. We stationed ourselves near the middle of the lake in a rowboat, lowered the "launcher" on two strings, and touched the igniter wires to a battery. We fired 5 rounds at depths between 4 and 15 feet. The last one emerged from the water about 50 feet from us, and landed on the brush-covered bank. Pleased that we had not started a fire in the dry brush, we left it there and headed home. (Needless to say, the bubbles were clearly visible.) It is a long road from this crude experiment to the





Holy Moses rockets could be mounted under an airplane wing in various configurations.

Navy's submarine-launched Polaris ICBM, but I like to think that I started the development process. Quite possibly this was the first underwater rocket launch in history.

Another morning a phone call from Tommy got me out of bed with a summons to the lab immediately. On the fourth floor was the large steel tank containing Charlie's first Van de Graaff accelerator. Soon some Navy enlisted men brought in on a stretcher a virtually immobile sailor with the bends. He was inserted through the hatch and the tank was pressurized. I spent the day keeping him under observation and gradually reducing the air pressure. By late afternoon he emerged with sore muscles but quite able to function.

Already before the 3.5-inch AR went to war, Tommy had started the design of the 5-inch High-Velocity Aircraft Rocket (HVAR), which would fit the head of the 5-inch AR and give it greater velocity. This was the first rocket development in which I was involved at the outset, and I designed the tail fins. Instead of a large single nozzle, this motor had eight small nozzles in a circle drilled through a steel plate 3.5 inches thick. In the center of the circle was a larger nozzle that was closed by a thin copper shear plate, designed so that it would blow out if the pressure approached the bursting strength of the steel tube, thus lowering the pressure and preventing an explosion. This meant that the rocket could be used safely over a significantly wider range of temperatures than the earlier ones. Its propellant was a larger version of the cruciform grain, weighing 24 pounds.

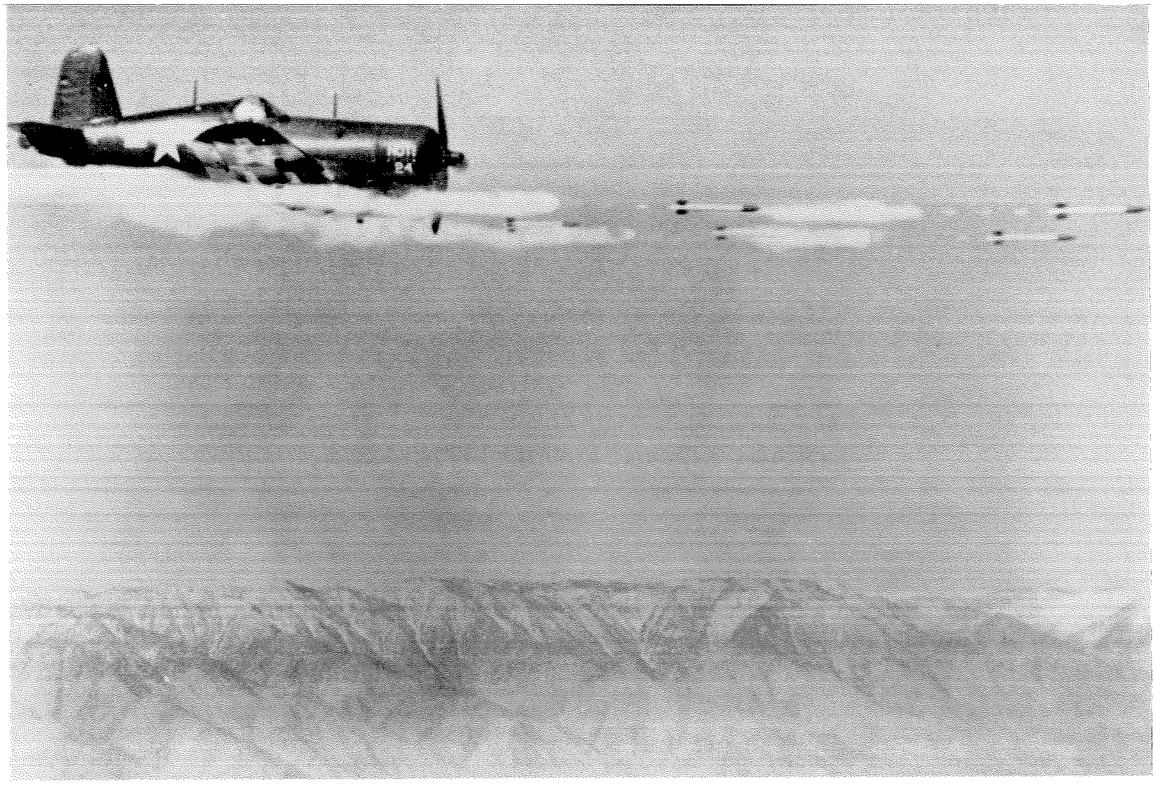
Compared to anything we had seen before, this was an awesome rocket, and on my first ground test at Goldstone (in December 1943, as near as I can remember), I got the idea of giving it the name "Holy Moses," just for the amusement of seeing if the name would catch on. It did—immediately—and the name accompanied the weapon wherever it went. This idea got me my only mention in the history books of the war.

The first aircraft launch of Holy Moses took place at NOTS on March 30, 1944, and I got permission from the pilot to be his passenger. I remember that, after we took off, I began to search my memory for anything that I might have done wrong or failed to do right in the previous ground testing. However, this launch and, to my knowledge, all subsequent ones went very well, and Holy Moses proved to be the best rocket of the war. By the end of the year the Pacific fleet was beginning to get the rockets in quantity and to use them to inflict death blows to Japanese transports, knock out antiaircraft-gun emplacements, and blast away heavy defensive fortifications.

In the autumn of 1943 development of a 3.5-inch, spin-stabilized rocket began. It was believed that it might be more accurate than the fin-stabilized rockets and also, lacking fins, be more compact and easier to handle. A steel plate threaded into the rear of the motor had eight small nozzles in a circle; these were pressed into predrilled holes. They were canted at an angle to impart the spin. Half a dozen rockets were machined in the shop, loaded by Ellis and Roach's group at Eaton Canyon, and sent to Goldstone, where I tested them. It was a fascinating sight. Once off the launcher each rocket began to precess in an ever increasing spiral, giving off a loud whirring noise. Upon landing on the dusty surface of the lake, instead of digging in as other rockets do, it made a neat little circular print in the dust as it continued to spin, and came to rest looking as neat as if it had never been fired.

We knew what the problem was—the rocket was too long (I recall it as being about 3 feet) —but we had no theoretical information to suggest the proper length. So we built another half dozen rockets about four inches shorter, and I took them out to Goldstone the following week with the same result. We repeated this cycle three or four times. Eventually we got the length down to 24 inches, and the rocket performed perfectly. The spin-stabilized rocket (SSR) program was off and running.

At this point a new group in the Projectile Section was formed to handle the "spinners," and



A Corsair fires Holy Moses rockets above Inyokern in February 1945.

I got the idea of giving it the name "Holy Moses," just for the amusement of seeing if the name would catch on. . . . Holy Moses proved to be the best rocket of the war.

I concentrated on the fin-stabilized aircraft rockets. The development and testing of the 3.5-inch SSR were completed, launchers for it were developed and standardized by the launcher group, and the project produced 10,000 rounds, but no quantity procurements resulted because the 5-inch SSR, which was vastly superior, came along shortly. This rocket and several launchers for it were quickly standardized and put into production to supplement the BR in attacking beaches, but at a much longer range (5,000 yards). The combination first proved its worth in the initial landing on Iwo Jima (February 19, 1945), where 12,000 5-inch SSRs and 8,000 4.5-inch BRs were fired, and on Okinawa (April 1, 1945).

Ralph Smythe took on the task of adapting the SSR for aircraft use, because it appeared to have advantages over the HVAR for some applications—greater compactness made for easier handling and might permit launching and reloading from inside an aircraft. The initial trials at Inyokern in October 1944 were disastrous. The rockets precessed even more wildly than the first 3.5-inchers, and the NOTS troops nicknamed them "Willy's Whirling Wockets." In order to determine what was happening, Smythe and Bowen collaborated to design a kind of pinhole movie camera that was installed in the rocket head to produce a record of its orientation during flight. It turned out that, again, the solution was to make the rocket shorter to compensate for the larger aerodynamic force resulting from the initial high velocity.

In the spring of 1944, with the invasion of Normandy approaching, one of the major concerns of the generals was the concrete launching sites for V-2 rockets along the French coast. It was thought in some circles that aircraft rockets might be the best weapon for attacking them. The Army had its 4.5-inch rocket, which had been designed in 1940, somewhat improved since, and manufactured in considerable quantity. It had become clear, however, that the Navy's Holy Moses was a much superior weapon. So on June 19 (D-day was June 6), I had another of my high-stool chats with Tommy and learned that the Army was about to request the shipment by air direct to England of 100 complete Holy Moses rockets per day for an indefinite period beginning as soon as possible.

Once the request was received, Tommy issued a "Confidential" memorandum (virtually all our memos bore this security classification) entitled "Project Moses," which outlined 11 different activities that were required to carry out the project, and designated one or two people to be in charge of each. I was to be the general coordinator, and many of us worked very long days carrying it out for the next three weeks. The first shipment went out on June 22 and the last on July 9. Tommy and Carl Anderson went to England and then to France to assist the Army in getting the rockets into combat and to observe the results.

The typical daily shipment was 100 rocket motors, 100 explosive heads, 100 fuses, and 104 "lug bands" for attaching the rockets to the launching posts under the aircraft wings, although there were some variations in the shipments. In the end, we had dispatched 1,900 rocket motors, 2,000 heads, 1,700 fuses, 1,456 sets of tail fins, 50 sets of launchers, and two boxes of instructions for using the 5-inch HVAR.

A squadron of P-47s, based in England, received the rockets, but by the time they were ready to use, it had been determined that the V-2 launching bunkers had actually been abandoned, so the squadron was diverted to troop support in France, beginning in the Saint-Lô area on July 15. This was just 26 days after we had first heard of the Army's interest. This one squadron destroyed many tanks, armored cars, and pillboxes, and an officer in the Air Technical Service Command characterized the Holy Moses as "the best antitank weapon of the war." The Navy allocated 40 percent of its production to the Army, but the rocket did not see much further action in Europe.

They were found to be most effective against point targets—antiaircraft-gun positions, ammunition and oil-storage dumps, planes in revetments, and shipping. Rocket-fitted planes from the carrier Enterprise *even succeeded in sinking a destroyer.*

The effect of ARs on the naval war in the Pacific was quite different. By early 1945 all carrier-based and twin-engine land-based combat aircraft were being delivered by the contractors fully equipped to fire rockets. To be brief, I will simply note that they were found to be most effective against point targets—antiaircraft-gun positions, ammunition and oil-storage dumps, planes in revetments, and shipping. Everyone involved with them was enthusiastic. Rocket-firing planes from the carrier *Enterprise* even succeeded in sinking a destroyer. At war's end more than a million Holy Moses rockets had been manufactured.

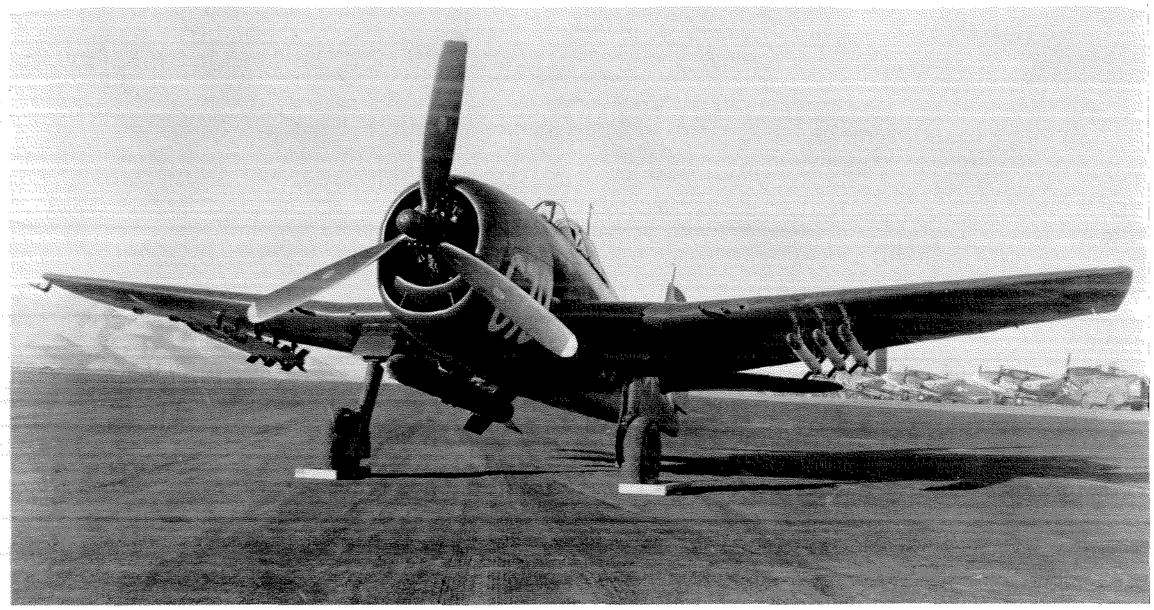
The outstanding success that the Navy was having with Holy Moses against small targets led Charlie to suggest to the Navy that "a really big rocket" should be equally effective against ships heavier than destroyers. Even before the chief of naval operations had directed its development at the highest priority, Tommy had started designing it and had christened it "Tiny Tim." The tentative specifications for the new rocket were agreed upon in a meeting of the Projectile, Propellant, and Production sections on February 24, 1944; the first ground firing at Inyokern occurred on April 26; and the first firing of a pair from a TBF aircraft in flight was on June 22. The size was chosen because the Navy had a standard 590-pound, semi-armor-piercing bomb 11.75 inches in diameter, containing 150 pounds of TNT, and there was a standard oil-well casing of exactly the same size. Unfortunately, nobody was manufacturing oil-well casings in wartime, and so until production could begin, we were reduced to the expedient of salvaging them from abandoned wells.

Far Right: An F6F-5 is loaded with six Holy Moseses under the wings and one Tiny Tim (it could carry two) below the fuselage. Right: A Tiny Tim is launched over Inyokern.

It was not feasible to produce a propellant grain as large as the 11.35-inch internal diameter of the casing, so four of the cruciform grains for the 5-inch rockets were used, separated by an X-shaped steel spacer. Upon ignition, this motor ejected 146 pounds of hot gas in about one second, and its first static firing at Eaton Canyon was a spectacular event. The motor was mounted a few feet outside of the open end of a reinforced-concrete catcher, about the size and shape of a one-car garage, which was intended to trap any pieces of unburnt propellant or hot plastic that might be ejected. At the end of the one-second burning, the roof of the catcher had raised up and the three sidewalls had opened out flat on the ground. Tiny Tim was never again fired at the canyon. In fact, all further tests of it took place at NOTS.

This rocket was just over 10 feet long and weighed 1,385 pounds, and in flight the luminous plume of its exhaust gases was more than 25 times its length and 15 times its diameter. In April Carl Anderson and I conducted the first flight test, launching it from above an airplane wing mounted a few feet off the ground. After observing its flame trail, we were as much surprised as pleased to discover that its effect on the wing had been very slight. The first trial from an airplane in flight (June 22, D-Day plus 16) was a success, but serious problems occurred before the weapon could be certified for use.

Coming as late as it did, Tiny Tim barely made it into combat. As in the case of Holy Moses, Tiny Tim's originally contemplated targets no longer needed attacking. Some aircraft



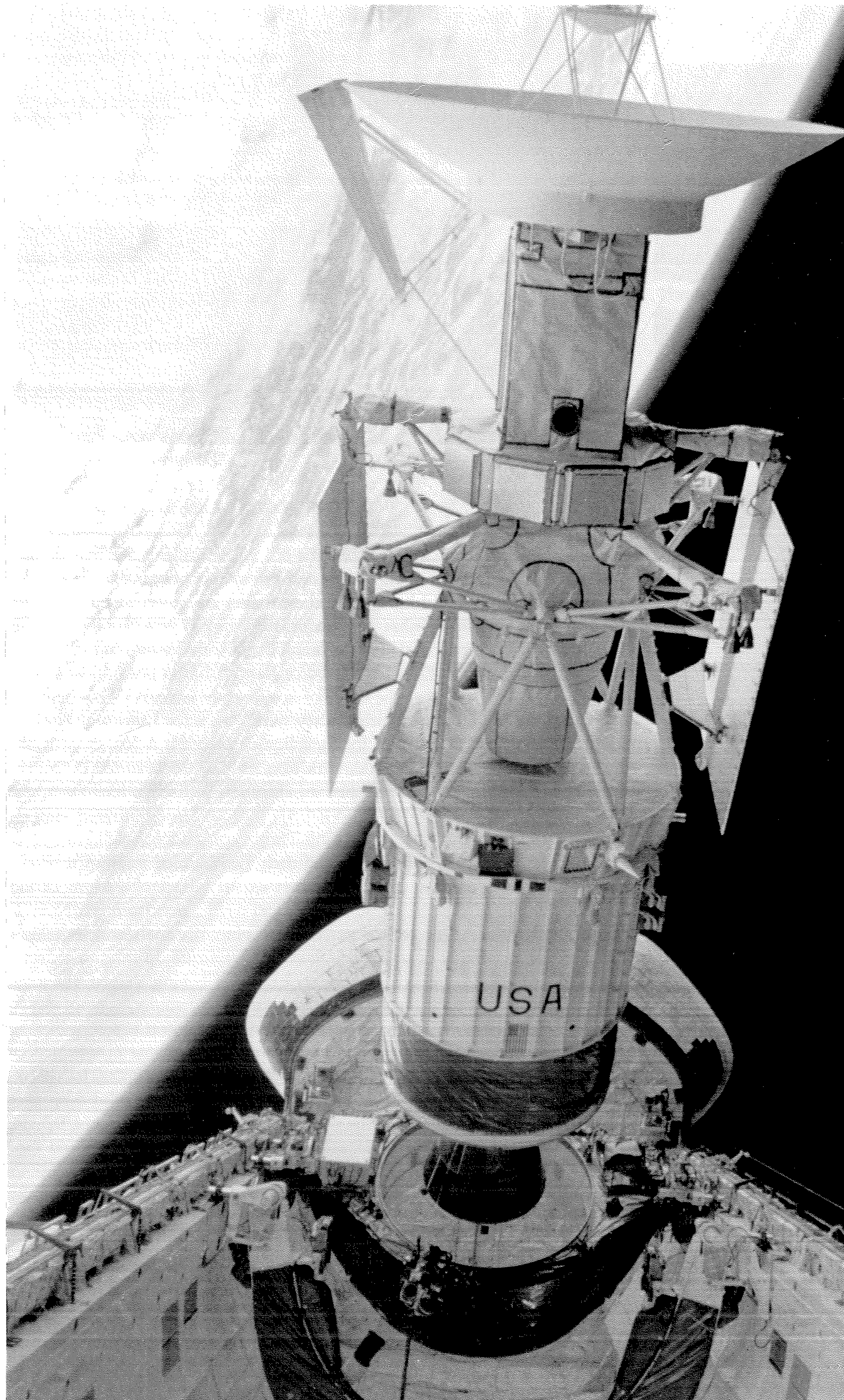
were equipped to carry eight Holy Moseses and two Tiny Tims, a total of 3,800 pounds of potential destruction. Had the war lasted a few weeks longer, they would have made their mark. They did find two noncombat applications. They propelled the rocket sleds at Muroc Dry Lake Test Range (later Edwards Air Force Base) in the Army's early tests of the effect of acceleration (g-forces) on human subjects. They were adopted by JPL as the boosters for their liquid-fueled rocket, the WAC Corporal, which on its first test in October 1945 established an altitude record of more than 40 miles.

As 1944 drew to a close, with Tiny Tim, Holy Moses, the 5-inch spinner, and all their predecessors all in combat, it was clear that we had done about all that we could to arm our troops for this war. Our project was running out of things to do. Many of us became involved with Project Camel (so called to suggest that once Caltech got its nose inside, it would take over the whole tent), which took on a large number and variety of tasks for the Manhattan Project at Los Alamos. But that's another story.

Within a few days of VJ Day, August 15, 1945, nearly everybody except the editorial section left the project, and many of us took up our classwork where we had left off. Because of Charlie's influence, I was able to get fellowships to complete my Caltech degree three years later, and after eight years in the east, I came back to Pasadena to spend 30 years at JPL.

There is a sequel to the story. A few project people moved to NOTS and made a career of rocket development, including Emory Ellis, who became the range supervisor. Several improvements were made on the Holy Moses, incorporating high-tensile tubing and new, more powerful propellants to increase its velocity. In 1967 NOTS was renamed the Naval Weapons Center, and it has remained to this day one of the preeminent naval research and development centers. On the base you can find streets named for Lauritsen, Fowler, Bowen, Sage, and Ellis.

A few months after VJ Day, William McLean (PhD '39) came to the center. He soon had an idea for a heat-seeking guidance system using infrared sensors, and he became the scientific director of the laboratory. He assembled a group to work on his idea, and in the face of continuous indifference and some opposition from the Navy Department, they perfected a complete detection and guidance system that could fit onto a 5-inch rocket motor. Thus the Holy Moses was transformed into the "Sidewinder," one of the earliest and best, and by far the cheapest, air-to-air guided missiles. Since it became operational in 1956, a whole family of Sidewinders has been developed for other applications, and they were adopted by the Navy, the Air Force, NATO, and several countries in the free world. Even the Soviets copied it. The Nationalist Chinese in 1958 were the first to use it in combat, followed by the U.S. against Libyan jets in 1981 and Iraqi jets and other targets in 1991. Although he died in 1976, McLean is still justly remembered in the Navy as the "father of the Sidewinder." I like to think that I have some small claim to being its grandfather. □


USA

Magellan: The Geologic Exploration of Venus

It's been a fantastic voyage, indeed. It's fun to go in every morning, and see new and exciting terrain that no person has ever seen before.

by Steve Saunders

Magellan just before deployment from the Space Shuttle's cargo bay. The bottom third of the spacecraft is a solid-fuel rocket that was jettisoned after boosting the mapper onto the path to Venus. The cone next to the main antenna dish is the radar altimeter. The solar panels that provide electric power are folded flat against the spacecraft's midsection, perpendicular to the camera. Magellan was built by the Martin Marietta Astronautics Group in Denver, Colorado, and the radar was built by the Hughes Aircraft Company of El Segundo, California.

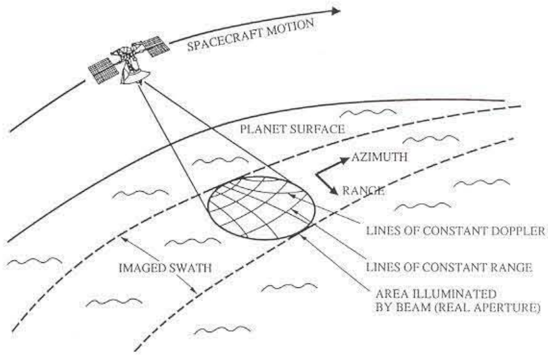
Venus is practically Earth's twin: very nearly Earth's size, just about the same density, and formed at about the same place and time. The two planets should have had a very similar early history, similar internal structure and elemental composition, and similar amounts of interior heat to create volcanoes and build mountains.

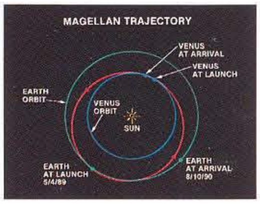
But Venus ended up very different from Earth. At the planetary surface, Venus's atmosphere is nearly 100 times as dense as Earth's, and the temperature of the rocks is nearly 900 degrees Fahrenheit—hot enough to melt lead. The difference is that Venus's atmosphere is about 97 percent carbon dioxide, versus 0.03 percent on Earth. Carbon dioxide traps heat so efficiently that Venus retains much of the heat it receives from the sun. (This "greenhouse effect," on a much reduced scale, keeps Earth warm enough to sustain life.) Venus's carbon dioxide came from its volcanoes. A similar amount has been emitted by Earth's volcanoes, but has been converted into carbonate rocks such as limestone and dolomite. Atmospheric carbon dioxide dissolves into Earth's oceans, where it combines with the eroded mineral products such as calcium that rainfall and rivers have washed out to sea, forming carbonates. The carbonates eventually turn into rocks, locking carbon dioxide into Earth's crust. So, even now, Earth and Venus really aren't as different as they seem. Venus should tell us quite a lot about how our theories of Earth's history might apply to planets in general.

Space scientists need to be very patient people. Magellan was originally approved in one form by the Carter administration in 1980. It was canceled by the Reagan administration about a year later, reinstated in a stripped-down form the year after that, and is now flying under the Bush administration.

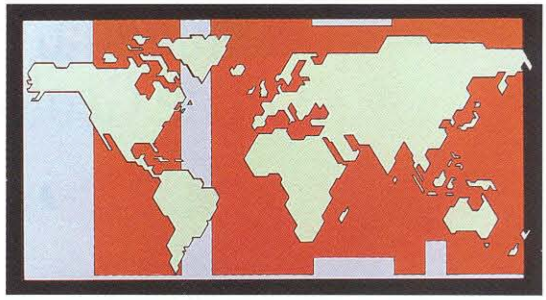
That patience has paid off. As of April 3, 1991, Magellan has achieved the minimum goals for its primary mission—mapping 70 percent of Venus's surface, an area that would stretch from Pasadena eastward to the Bering Straits on Earth. (This took 193 days of mapping, plus a 15-day shutdown during "superior conjunction," when Earth, the sun, and Venus were all in a direct line and data could not be transmitted or received.) The primary mission was a minimum performance goal—we expect to do much more during the extended mission. Magellan has already returned over 100 billion bytes of information, which equals the total amount of data from all other planetary missions to date, including the 12-year Voyager mission. It's been a fantastic voyage, indeed. It's fun to go in every morning, and see new and exciting terrain that no person has ever seen before.

We launched Magellan from Cape Canaveral on May 4, 1989, on board the shuttle *Atlantis*. We took a rather long route to Venus, going around the sun one and one-half times. (We deferred our launch in order to give Galileo the shortest path to Venus for one of the gravity assists that will send that spacecraft on to Jupiter. Otherwise Galileo would have had to wait another two and a half years before the planets got into the right positions again.) Magellan arrived at Venus on August 10, 1990. We got everything working after a few minor problems,

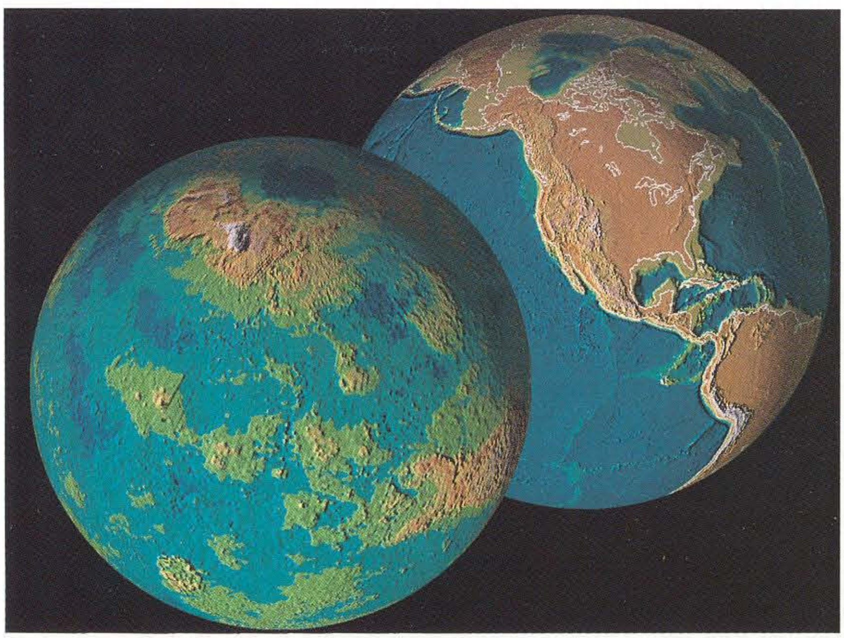




Left: Magellan's trajectory to Venus took 1¼ years—long enough for Venus to orbit the sun twice, while Magellan circled the sun 1½ times. Above: Magellan's mapping radar looks off to the side, collecting image data in two dimensions.



If Magellan had been mapping Earth starting from Pasadena, the territory covered during the primary mission would be enclosed by the orange regions. The strip running through Greenland was missed during superior conjunction.

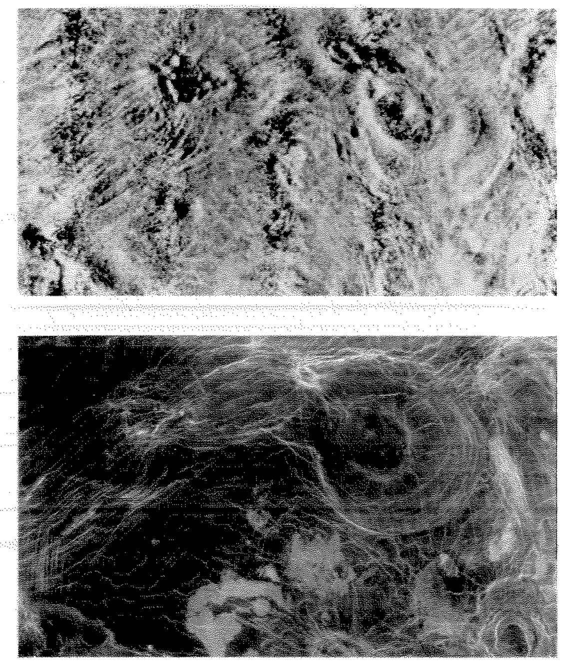


Venus is 95 percent of Earth's size.

and started mapping around September 15. Venus's surface is completely hidden behind thick clouds of sulfuric acid, so we do our mapping by radar, not photography.

Magellan's main antenna, used both for mapping and communicating with Earth, is a leftover Voyager antenna that Ed Stone was kind enough to bequeath to us. (Many components were scavenged from other missions to keep costs down.) Using the one antenna for two functions takes a lot of fancy maneuvering. Magellan's orbit is egg-shaped, with Venus as the yolk. The orbit passes over Venus's poles, while the planet turns below. (Venus rotates slowly, so its day is 243 Earth days.) Every time we go in close around the planet—every three and a quarter hours—we point the antenna at the surface and take a strip of data, slightly overlapping the previous strip, from the north pole down to about 70 degrees south latitude. Then, as we go out to apoapsis—the point in the orbit farthest from the surface—we turn the antenna toward Earth and play back the data. Magellan has a second, smaller antenna on board that serves as an altimeter, recording elevation data as we map. The two radars don't look at the same patch of ground, but we correlate their data later at JPL.

The mapping radar, called a synthetic-aperture radar, uses a very precisely tuned 12.5-centimeter-wavelength radio signal to penetrate the clouds. The signal bounces off the planet's surface, and the time it takes to return to the spacecraft is recorded. The radar looks off to the side, so the signal reflected by the features closest to the spacecraft's flight path comes back first.



Venera image (top) and Magellan image (bottom) of an arachnoid region located on radar-dark plains at 40° north latitude and 18° east longitude. Note the radar-bright lava flows at the bottom of the Magellan image. The flows are crossed by fractures, which must therefore be more recent than the flows. The two large arachnoids in the top half of each image are about 140 miles in diameter. Arachnoids are found only on Venus.

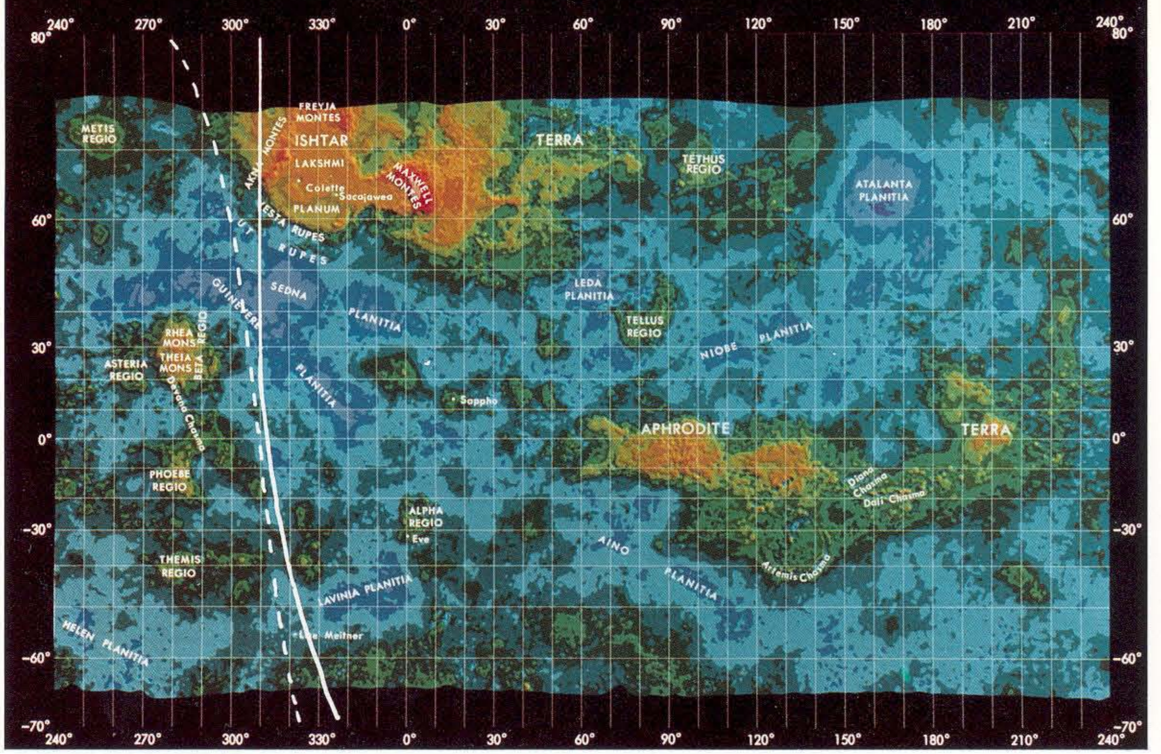
Magellan's 75-meter resolution can make out objects the size of the Rose Bowl.

Simultaneously, features ahead of us—moving toward us along the spacecraft's track—increase the reflected frequency due to the Doppler effect, and features behind us shift the reflection to a lower frequency. We actually see a whole swath of terrain with each radar pulse, because the time delays and the Doppler shifts give us information in two dimensions. We end up with an image that looks pretty much like an aerial photograph, except that the value of each pixel in the image is the ratio, in decibels, of the amount of energy returned from the surface at that location versus the amount of energy we sent. Magellan sends the time-delay and Doppler-shift data back to Earth after an on-board computer, called a block-adaptive quantizer, samples every eight-bit unit and condenses it to two bits. This computer allows us to collect and send a lot more data.

We do all of the image construction here at JPL. We make a wide variety of photo products from the digital data. The basic image strip—one orbit's worth of data—is 12 miles wide by roughly 9,000 miles long. From these, we make a standard series of mosaics. Each mosaic is 7,000 by 8,000 pixels. The first mosaic covers an area of Venus roughly 5 degrees on a side. It's a full-resolution mosaic, so each pixel covers 75 meters, about 82 yards. To make the next size up, we average each 3-by-3 pixel region to make a 225-meter (246-yard) pixel, and produce pictures that cover pieces of Venus 15 degrees square. And so on, up to 2.025-kilometer (1¼-mile) pixels. Six mosaics of pixels that size cover the whole planet. So you can start with the whole planet and then zoom in on the region you wish to study.

There are subtle differences between these images and aerial photographs. The radar illuminates the scene from the left-hand side, so slopes facing toward the radar appear brighter, and slopes facing away are darker. It's as if you were shining a light on the landscape from the left. What you see also depends on the angle of illumination, because many surfaces reflect differently at different angles. Radar also reflects a lot more readily if the surface is rough on the scale of the radar's wavelength, which in this case is a few centimeters to a few meters—terrain covered with small stones up to good-sized boulders. Terrain containing electrically conductive minerals, like iron sulfides such as pyrite or iron oxides such as magnetite, is also very reflective.

In 1984, the Soviet missions Venera 15 and 16 mapped about 25 percent of Venus's northern hemisphere with a resolution of about a mile. Magellan's 75-meter resolution can make out objects the size of the Rose Bowl. Above are Magellan and Venera images of one of the regions we call the arachnoids, because they look like spider bodies connected by weblike fractures. They're actually volcanic features, probably caused by a small "hot spot"—a place where a plume of hot mantle material has made its way up to the surface. We could barely see the bodies in the Soviet data, but the Magellan image even shows details of the web. Magellan was looking sideways at about 35 degrees, and Venera at about 10 degrees. Consequently, a lava flow that's clearly outlined in the Magellan image can't be seen in the other one.



This map of Venus is based on decade-old data from the Pioneer Venus orbiter, which mapped 80 percent of the surface at a resolution of about 30 miles. Elevation data is color-coded, from purple and cool blue lowland plains on up to yellow and red in the mountains. The solid line represents the swath mapped in one orbit, while the dashed line shows what the altimeter sees during that same orbit. The altimeter looks straight down from the spacecraft, so the dashed line shows Magellan's track as well. Magellan began mapping at Venusian longitude 330°. Venus is the only planet in the solar system that rotates from east to west, and Venusian longitude is consequently measured toward the east.

In addition to standardizing descriptive names, the International Astronomical Union has specified the type of being to be associated with each class of Venusian feature. The singular and plural forms of some common features, and their associated females, are:

chasma, chasmata—canyon: goddesses of the hunt or the moon

corona, coronae—ovoid-shaped feature: fertility goddesses

crater, craters (cratera)—crater: famous women

dorsum, dorsa—ridge: sky goddesses

linea, lineae—elongate marking: goddesses of war

mons, montes—mountain: miscellaneous goddesses

patera, paterae—shallow crater with scalloped, complex edge: famous women

planitia, planitiae—low plain: mythological heroines

planum, plana—plateau or high plain: goddesses of prosperity

regio, regiones—region: giantesses and titanesses

rupes, rupēs—scarp: goddesses of hearth and home

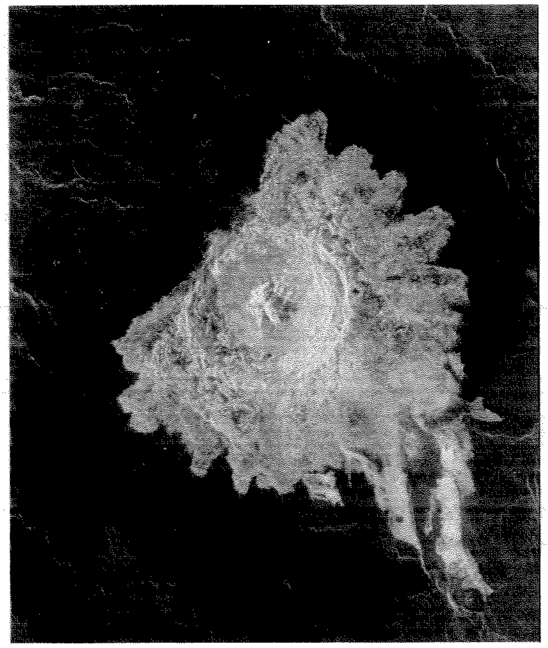
terra, terrae—extensive land mass: goddesses of love

tessera, tesserae—polygonally patterned ground: goddesses of fate or fortune

Suggestions for feature names can be sent to: Venus Names, Magellan Project Office, Mail Code 230-201, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109.

Having mapped features, we name them too. One would expect strange-sounding names on an exotic planet like Venus, but our system is really quite straightforward. We use one set of descriptive names for geographic features on bodies throughout the solar system. (See box.) Each feature gets a particular name that identifies it, plus a descriptive name that says what it looks like. The term *tessera*, in particular, was applied to a number of terrains that looked alike in the low-resolution Venera data, but which are proving to be different at high resolution.

Venus is the Roman goddess of love, so we've chosen our particular names from the ranks of famous females. Most of the large features, terrae in particular, have been named for love goddesses from other cultures. I don't get too involved in this, but some scientists get a real kick out of it, and go to the library and dig out names to use. Most of these names are provisional, and won't become official until they're approved by the International Astronomical Union. That will take some time. The IAU meets in July to consider some of the names proposed up to that time, and then doesn't meet again until 1993. We're open to suggestions, particularly for crater names. We've mapped about 400 craters so far. I expect we'll end up with about 900. You can nominate someone by sending us a note with the name and why the person should be so honored. Nominees must be famous women who've been dead for at least three years. The one exception to the females-only rule is James Clerk Maxwell, whose 19th-century theories about electromagnetism made



Right: Aurelia (20° N, 332° E) is surrounded by a radar-dark halo, as are about half of the craters Magellan has seen to date. The crater floor and the ejecta are very radar-bright, indicating rough terrain. North is to the top in all Magellan images. Far Right: This image, centered at 27° S and 339° E, shows the crater Danilova, its southern neighbor Julia Ward Howe (the author and suffragette), and Aglaonice (an ancient Greek astronomer) to the east. All three craters' interiors are nearly completely flooded by smooth, radar-dark lava. (For comparison, Aurelia is slightly smaller than Howe.) Large flows of very fluid melt issue north from Aglaonice and south from Danilova. The small domes seen in the southeast corner of the image are found all over Venus's plains and number in the hundreds of thousands. A 10- × 12-foot copy of this image, called "The Crater Farm," hangs in the Smithsonian's Air and Space Museum.

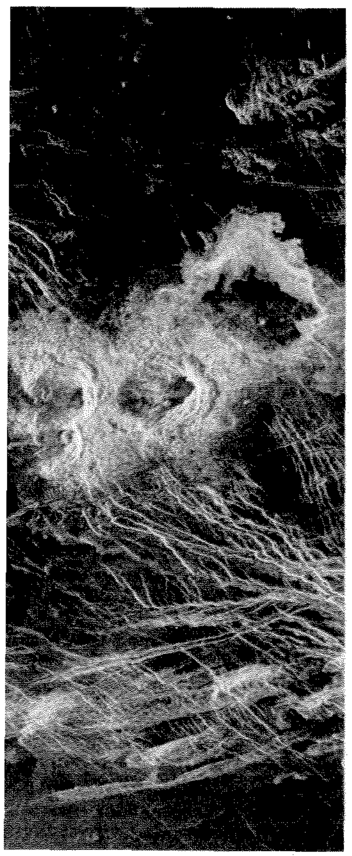
radar possible today. We've honored him with Maxwell Montes, the largest mountain on Venus. At about 36,000 feet, it's higher than Everest.

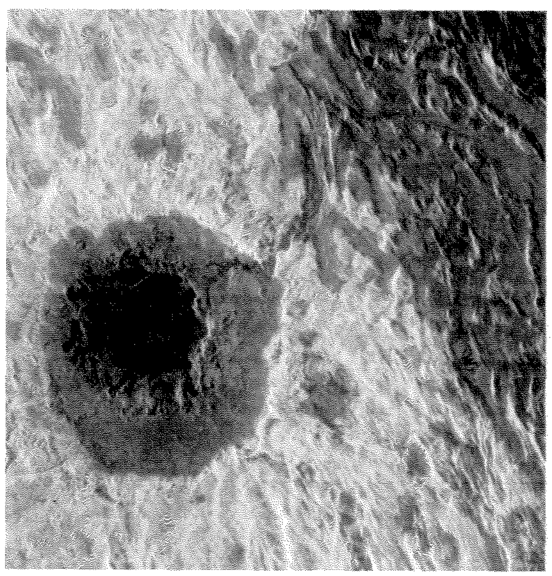
This article will take a quick look at three types of terrain. First, we'll look at impact craters, and see how their features vary with their size. Then we'll look at two highland regions: Ishtar Terra, which includes Maxwell Montes, and Aphrodite Terra. These highlands may help explain how Earth's continents formed. And finally, we'll look at a volcanic province. Throughout our tour, we will see how Venus's high surface temperature—and, to a lesser degree, its thick atmosphere—have affected the processes that shaped its surface.

Venus, like all the planets, has been subjected to meteorite bombardment over the eons—by the rubble of planetary formation, by asteroids jarred loose from the asteroid belt, and by comets. Impactors hit Venus at something like 12 miles per second, and they release a tremendous amount of energy. The impact vaporizes the object and the surrounding crust, blasting out material—ejecta—at very high velocities in all directions, and forming a "transient cavity crater"—a bubble in the crust. The bubble bursts instantaneously, throwing out more ejecta at lower velocities, and folding the adjacent crust's upper layers back over on top of themselves to form the crater's rim. The rim's inner face is very steep and partially collapses under its own weight, forming terraces. Meanwhile, the crater floor rebounds, throwing up the central peak. Impacts can cause volcanism in two ways. The collision creates heat directly. Forming the transient cavity also causes adiabatic heating, by suddenly releasing the pressure on rock that's been at very high pressure miles below the surface. It's like taking the top off a beer bottle. The material expands, releasing heat, and it's pretty hot to start with.

Aurelia (named after Julius Caesar's mother) is a beautiful, 20-mile-diameter crater. It has the central peak, the basin with a rim crest, and a flower-petal-like ejecta pattern around it. The flower-petal pattern is seen only on Venusian craters. It's caused by Venus's atmosphere, which is so thick that ejecta doesn't travel very far. On other bodies, like the moon, ejecta can travel for hundreds of miles. Aurelia also has a little kite tail of what is probably impact melt—rock melted by the heat of the impact—that flowed out into the surrounding plains. We see that in many areas. There are also exterior flows of impact-induced melt from within or beneath the ejecta that look somewhat like lava flows. When the ejecta lands, part of it apparently keeps flowing, probably because the surface is hot enough to keep it liquid. These flows are another feature we see only on Venus. Some craters this size have had their floors at least partially flooded by impact melt, or perhaps later volcanism. Danilova (named for a Russian ballerina) is somewhat larger, about 30 miles in diameter. The central peak has become more complex, and the floor is almost completely flooded. Danilova also has a large lobe of what was probably an extremely low-viscosity melt that behaved very fluidly, flowing around little prominences in its path like a brook flowing

Clockwise from left:
1. Gertrude Stein (30° S, 345° E) is three craters, each 5½ to 8½ miles in diameter, formed by chunks of an object that broke up in the atmosphere. The outflow is probably impact melt.
2. Cleopatra is about 1½ miles deep. The rough ejecta around its rim shows it is an impact crater. Lava breached the rim, flooding the valleys to the northeast.
3. Three dark splotches on a 180-mile span of Lakshmi Planum. One contains a small crater. The other two impactors didn't make it down. Dark streaks at left could be wind-blown splotch material drifting northeast against a ridge.





around rocks lying in its bed.

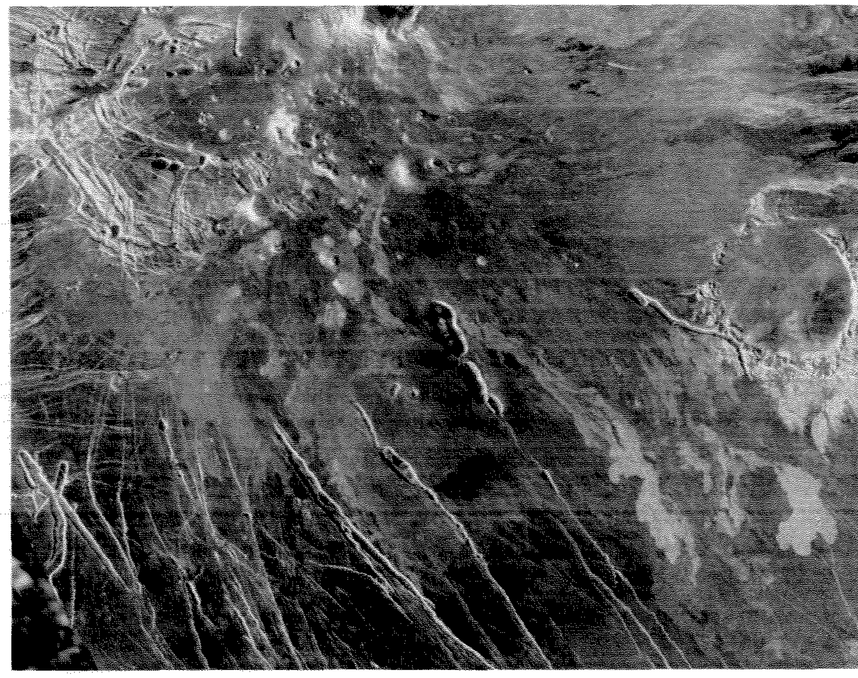
Cleopatra, on the flanks of Maxwell Montes, is a 62-mile-diameter crater surrounded by rugged ejecta. We couldn't tell from Venera data whether Cleopatra was a giant volcano or an impact crater, but it's now clear that it's the latter. Volcanism was either induced by the impact itself, or later volcanism seeped through the crustal fractures that the impact created. The crater's interior is filled with lava, some of which flowed out through a channel and filled in the nearby valleys. Cleopatra's double-ringed crater is typical of the enormous, multi-ringed impact basins that we see on many bodies in the solar system. We believe the rings are part of the surface's hydrodynamic response to an impactor many miles in diameter. The outer ring is roughly the square root of two times the diameter of the inner ring, which may be a relic of the transient cavity. The outer ring might be some kind of later collapse, or a product of the interference pattern between the very intense surface waves and body waves that the impact generates. It may also be the shock wave reflecting off another layer in the interior.

Impactors also interact with the atmosphere in some very curious ways. Objects less than about 100 yards in diameter don't make it all the way through Venus's dense atmosphere. They're pulverized, literally burned up, on the way down. Some make it almost to the surface, and may set up enormous supersonic shock waves and high winds. (Something similar happened over Siberia in the early part of this century. That object didn't hit the ground, but it laid a huge forest waste, flattening trees radially outward for miles in all directions.) We see dark splotches all over Venus. Some of them have a little crater in the middle. Dark lines trailing out radially from the splotches could be wind streaks. We interpret these splotches to be smooth areas, caused perhaps by the deposition of fine material, perhaps by pulverization of the surface by the shock wave that came along with the meteorite. These craters are never smaller than about a couple of miles in diameter. Impact craters can be quite a bit smaller on Earth, because its atmosphere is thinner and smaller objects reach the surface. Venus's atmosphere can break up friable objects half a mile or so in diameter, whose chunks then hit close together to form multiple craters.

In some places, we see what are almost certainly wind streaks where sand is being deposited or scoured away, causing the radar to read the surface texture differently. (Wind streaks are also visible in radar images of Earth.) These

Right: The crater Alcott (60° S, 352° E), 39 miles in diameter and originally about 1300 feet deep, has been almost completely obliterated by bright (rough) and dark (smooth) lava flows emanating from the collapse features at the left of the image. These collapse valleys range from 650 feet to 3 miles wide, and up to 60 miles long. They may have formed when subsurface magma drained away along crustal fractures, allowing the surface to collapse. The complex of intersecting valleys in the lower left-hand corner is informally called Gumby, after the animated character it resembles.

Below: A portion of the Freyja Montes, with the smooth, dark plains of Lakshmi to the south. Sinuous lava channels are visible in the dark zigzag valleys at the top of the image, indicating that these valleys are at least partially flooded by lava. This image is about 100 × 340 miles.

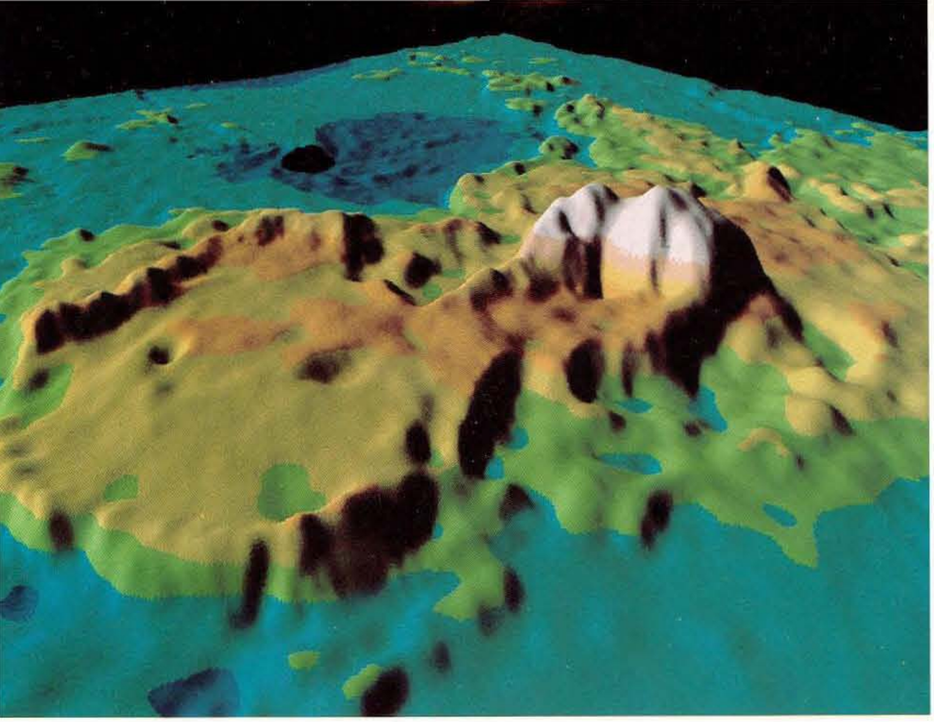


streaks will eventually give us a global map of the wind directions on Venus and hence the weather patterns. I had predicted that downslope winds should dominate, but these wind streaks go in the opposite direction. This may indicate a young, mobile surface, or old wind streaks. The surface winds aren't really very strong. At about 30 miles above the surface, the winds blow east to west at several hundred miles per hour, much faster than Earth's jet stream. But down at the surface, the atmosphere is so thick and sluggish that the wind is no faster than walking speed. This is just enough to move sand grains without giving them much erosive force. In fact, experiments in a Venus-simulation chamber at NASA's Ames Research Center show that the surface rocks are hot enough that windblown sand tends to stick to them. So the wind may be consolidating material rather than eroding it.

Speaking of erosion, when we look at Mars, or the moon, or especially Earth, we see craters of all ages, from ones that look like they formed yesterday, to old, beat-up ones that have practically disappeared. But all the craters on Venus look extremely young. We didn't see any evidence of crater degradation until we found Alcott (for Louisa May), which has been flooded by volcanic material and almost completely obliterated. Only some of the ejecta is still preserved. So it may be that every few hundred million years large regions of Venus get covered by enormous volcanic extrusions that simply erase everything, and the slate starts clean. Very little happens between those episodes of violent, extensive volcanism, except perhaps on the margins to craters that didn't get completely destroyed.

The first highland region we'll look at, Ishtar Terra, dominates Venus's northern hemisphere. (Ishtar is one of the names of the Babylonian universal goddess, the goddess of love—and, incidentally, the "Mother of Battles"—who was identified with the planet Venus.) Ishtar's western half is an elevated plain, the Lakshmi Planum, which stands about a mile above the average elevation of Venus, and is a very smooth highland. (Lakshmi is an Indian goddess of prosperity, a consort of Lord Krishna.) Lakshmi is surrounded on all sides by extremely steep mountains and scarps.

The Freyja Montes, which form Lakshmi's northern rim, are reminiscent of some large mountain ranges on Earth, with visible folds and fractures. (Freyja is the Nordic goddess of fertility and love, who weeps tears of gold as she seeks her lost husband.) I believe the zigzag valleys in the mountains' interior are pull-apart structures caused by gravity slumping. Crustal compression piles these mountains up to such a bulk that their own weight pulls them apart. This is fairly rare on Earth, but on Venus, the rocks are at about half their melting point and they tend to behave plastically. They bend and flow like taffy instead of breaking like peanut brittle. (We do see brittle deformation as well, fracturing that was probably accompanied by Venusquakes.) It's a real puzzle how Venus can have such large mountainous regions unless they're actively maintained. Some of what we see is doubtless very young. On the other hand,



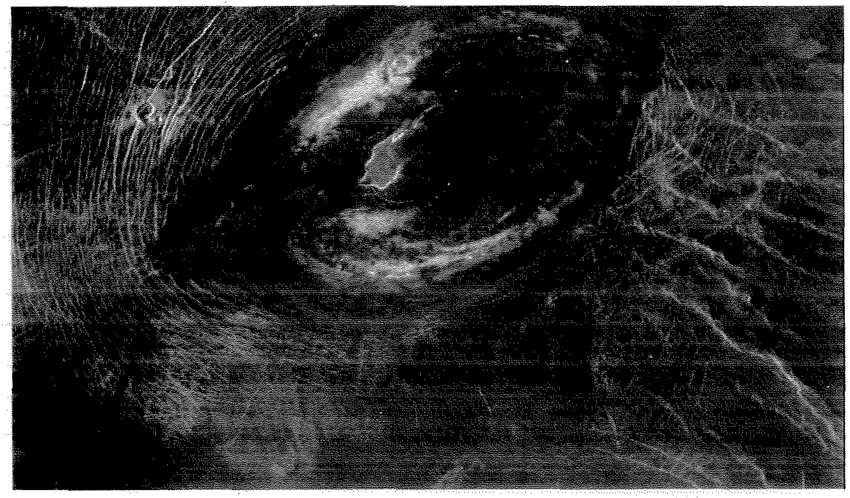
Above: A three-dimensional view of Ishtar Terra, looking northeast across Lakshmi Planum toward Maxwell Montes. The vertical scale is exaggerated. Sacajawea Patera is the rightmost depression on Lakshmi. The rugged highlands beyond Maxwell, called Fortuna Tessera, make up the eastern half of Ishtar. Right: Maxwell Montes. The black vertical bands are strips of missing data. Maxwell covers an area larger than Washington and Oregon, and stands almost 7 miles above the mean planetary radius. Maxwell's western slopes are very steep, while it descends gradually into the highlands of Fortuna Tessera on the east. The linear pull-apart features cover much of Maxwell's western half. Cleopatra is just to the right of center.

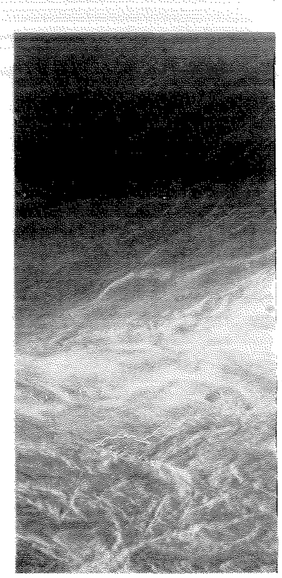
craters the size of Cleopatra don't form frequently, so the odds are good it isn't very young, yet it doesn't appear to be deformed.

To the east, Maxwell Montes is very radar-bright. This may be a mineralogical phenomenon. As altitude increases, temperature and pressure decrease. It may be that a particular mineral assemblage is stable on the mountaintops, but not at the higher temperatures and pressures below. It could be a mineral like pyrite, magnetite, or pyrrhotite—a more complex iron sulfide than pyrite—any of which would be very radar-reflective. Maxwell's margins are steeper than the San Gabriel Mountains north of Pasadena. In places the terrain rises about a mile in a span of less than four miles. Maxwell's flanks also display linear features we think are caused by gravity tectonics. They look very much like what you see if you try stretching an old, dried-out piece of chewing gum.

Lakshmi's southern mountain belt is called the Danu Montes. (Danu was the great goddess of ancient Ireland, ruler of a tribe of ancient divinities who were later demoted to fairies.) Again, the highest regions of these mountains are more reflective than the plains. It looks as though Lakshmi's plains are somewhat folded where they abut the mountains. The plains were formed by lava flows that lapped up against the mountains, so they must have been deformed by compression later on, as if they were carpet being pushed up against a wall.

There are two very large volcanoes on Lakshmi Planum. We've only mapped one so far, called Sacajawea Patera. Sacajawea (named for the Indian woman who guided the Lewis and Clark Expedition) is a caldera—a wide crater caused by a volcanic explosion or collapse—that's about 100 miles from side to side and a bit more than a mile deep. It's surrounded by fractures that form graben. Graben are troughs bounded by vertical faults—long, linear valleys whose floors have sunk, or whose sides have risen. The East African rift valleys are graben, and there are many good examples of graben in Arizona. Sacajawea's graben are concentric rings that record a complicated history of magma withdrawal from below, perhaps accompanied by eruptions on the flanks and the collapse of the central caldera. The result looks somewhat like a multi-ringed basin, but this is a slower process caused by removing support from below, rather than digging a hole from above. Sacajawea resembles some volcanic features on Earth, but is much larger. It's very exciting for volcanologists because of its size, and we're seeing many others like it.





Above: Sacajawea Patera. The fractures that cut across the concentric graben run southeast for nearly 90 miles, and may be a rift zone through which magma drained. A small shield volcano with a prominent central pit sits on one fracture at right.
Upper Right: Smooth, dark Lakshmi Planum ripples against the radar-bright Danu Montes.
Lower Right: The Appalachian Mountains.
Below: Ovda's folded mountains are 5 to 9 miles wide and 20 to 40 miles long. They apparently formed by compression along a north–south axis. The dark plains are lava-filled basins. This image is centered at approximately 1° N, 81° E.

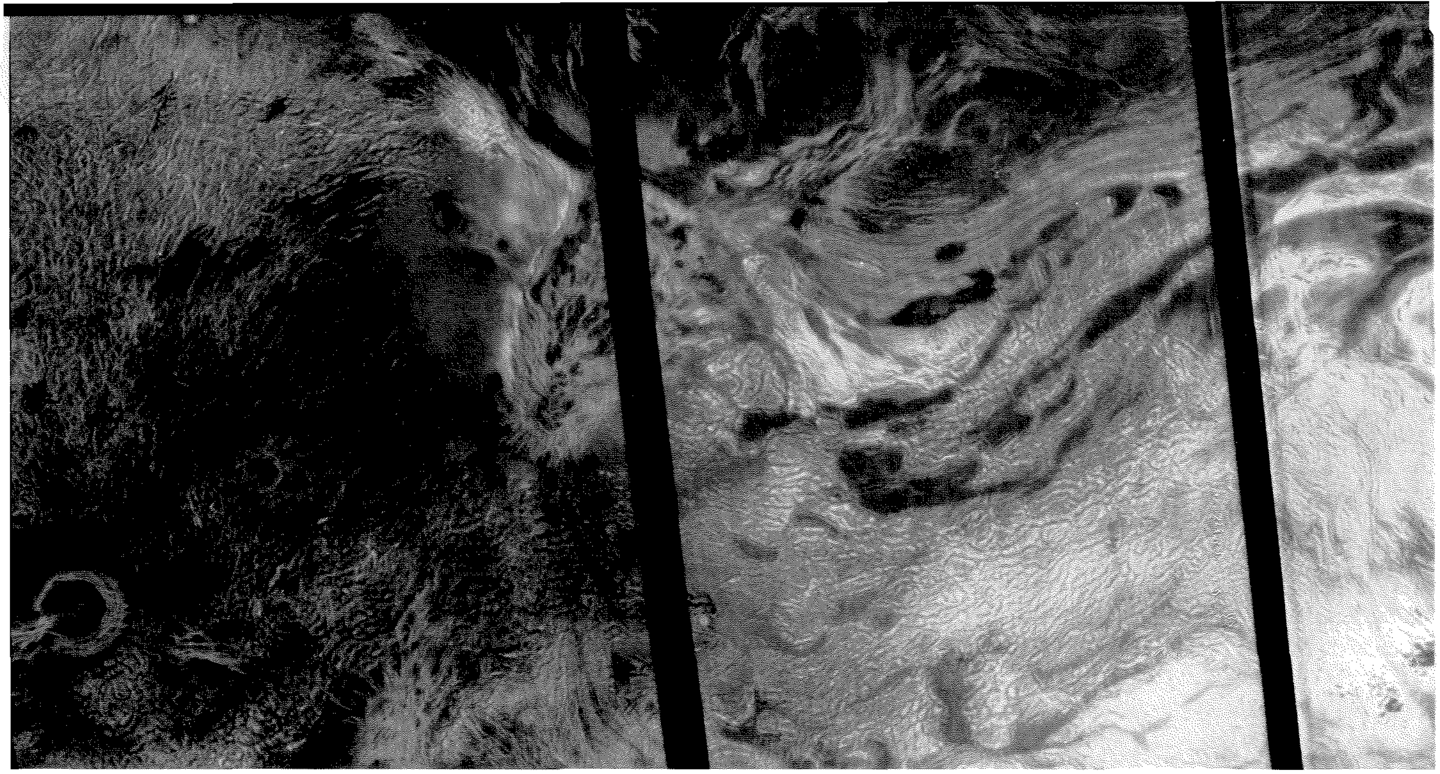
At one point, between the Danu Montes and Maxwell Montes, Lakshmi Planum isn't bounded by mountains. Instead, there's a scarp that just drops off into the plains. There's one feature about 50 miles across that looks a bit like a caldera but is probably a collapse scar. The unsupported margin simply slumped into the valley below, accompanied by fractures.

The second highland region, Aphrodite, extends about halfway around Venus's equator. Aphrodite is shaped a little bit like a scorpion, with claws, a body, legs, and a tail—a string of small volcanoes—that arches back toward the body like a scorpion's stinger. The claws, and the region inside them, may be a highly evolved Lakshmi—a volcanic plain surrounded by mountain belts. If we are seeing similar processes at different stages, it would tell us how these things evolve.

So far, we've mapped only the west end of Aphrodite, but we know already that, geophysically and geologically, it isn't one unit. It changes in its gravity signatures, its topographic signatures, and its geologic aspects. The western part of Aphrodite is called Ovda Regio for a violent, ill-tempered spirit of the Finnish forests who wandered her property naked, her long breasts thrown back over her shoulders, looking for trespassers to tickle to death. The terrain on Ovda's northern margins is very steep, just like the terrain surrounding Lakshmi Planum. The ground drops roughly two miles over a distance of some 50 miles. The plateau has pull-apart basins filled by lava flows.

If we compare Ovda's mountains with a radar image of the Appalachian Mountains, which are also folded, we see that they're superficially similar. In Pennsylvania, alternating beds of sandstones and shales lying deep within Earth have been folded by plastic deformation. Miles-deep erosion has etched away the soft shales, leaving nubbins of resistant sandstones as ridges. That simply hasn't happened on Venus, as we see very little evidence for erosion of any kind. These folds are the original surface of the compressed material, without any modification. So we get similar-looking folding patterns that were probably formed by similar processes, but are revealing themselves by quite different means.

Ovda's interior is tessera terrain. These particular tessera are mountainous massifs, or blocks of rock, that are tens or hundreds of miles on a side. The blocks are roughly equidimensional. The spaces between them are flooded by lavas. The region has clearly undergone a lot of compression, expansion, and folding. It's been there for a long, long time and has really been



This image encompasses most of Ovda Regio. The area shown is roughly 1200 × 600 miles, and spans nearly 30° of longitude. The lava-filled basin in the bottom half of the previous page's image is visible here just to the right of center. (It resembles a recumbent seahorse.) In the lower left corner, a large caldera shows against the background of smooth dark lava. Tessera—bright blocks of rock surrounded by dark lava—extend for hundreds of miles to the caldera's north and east. The bright highlands that resemble Maxwell Montes cover the right half of the image. The very highest elevations, where the terrain turns dark again, are at the edge of the image in the lower right corner. Each pixel in this image covers an area 2215 feet across, a 9× reduction from full resolution. The black bands are missing data.

kicked around quite a bit.

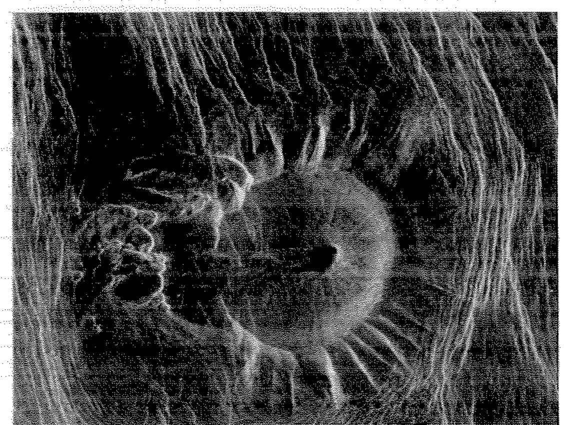
The highest parts of Ovda are similar to Maxwell in that the surface is very radar-bright, but its linear features—Maxwell's pull-aparts—are much more complex. This area has little chevron-like folds, instead of simple linear structures—a product of multiple deformations. Another interesting thing is that the lower region is dark, the middle elevations are bright, and then the very highest areas are dark again. So if we invoke some pressure- or temperature-dependent mineralogical process, it appears to form something that's stable only within a limited range. Other very high massifs in Ovda show this dark-bright-dark pattern, too.

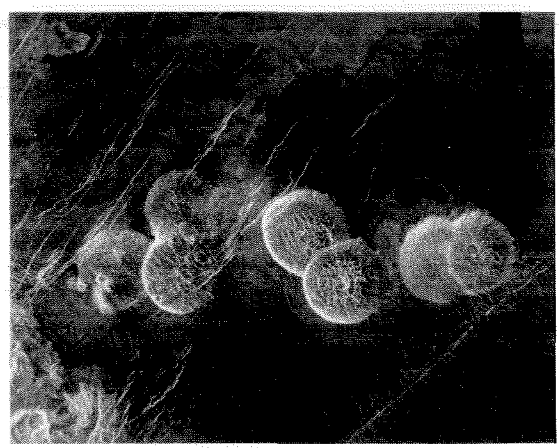
The origin of Venus's highlands is central to the whole idea of where Earth's continents came from and how the tectonics—the crust's motions—interact with what's going on in the interior. There are several models for Aphrodite's genesis. A simple one is that Aphrodite is a piece of ancient continental mass, composed of lighter, lower-density, higher-silica material, like the highlands of the moon. But this begs the question—it just says Aphrodite *is* there because it *was* there.

Another model says that Aphrodite was formed by a process like the seafloor spreading we see in the ocean basins on Earth. Earth's crust and mantle are closely linked, so convection cells in the mantle move pieces of crust like packages on a conveyer belt. New crust forms continuously along lines, called spreading centers, located atop rising sheets of hot mantle material. The fresh crust rides the mantle away from the spreading center. These centers are marked by mid-ocean ridges, which have a very characteristic shape: a main ridge or a trough along the center flanked by lesser, parallel ridges, and the entire ridge system crossed at right angles by parallel fractures marking transform faults along which segments of the central ridge are offset from each other. We can pretty much rule out this model now, because we don't see these features on Aphrodite. It doesn't look like the Mid-Atlantic Ridge, a relatively slow spreading center with a big rift valley down the middle; or the Pacific ridges, which are fairly fast and tend to have little ridges running down their spines.

Yet another model suggests that we're looking at a "hot spot"—a stationary mantle plume that has forced its way up to the surface. A large, long-lived hot spot could dome up a large area. The dome's own weight would cause it to push out sideways from the center, producing mountainous tectonic features on the margins through thrust faulting and crustal thickening. That's still a good possibility. But that model has an opposite twin, called downwelling. If this region of mantle is relatively cold, it would sink, drawing the crust above it in toward the center and thickening the crust into mountains. This could result in very similar surface features. One of these two models is probably the right one, but we haven't yet analyzed the detailed tectonic relationships that would allow us to distinguish between them. This part of Aphrodite is the size of the continental United States, so we're not going to be able to work out its geology in a few days.

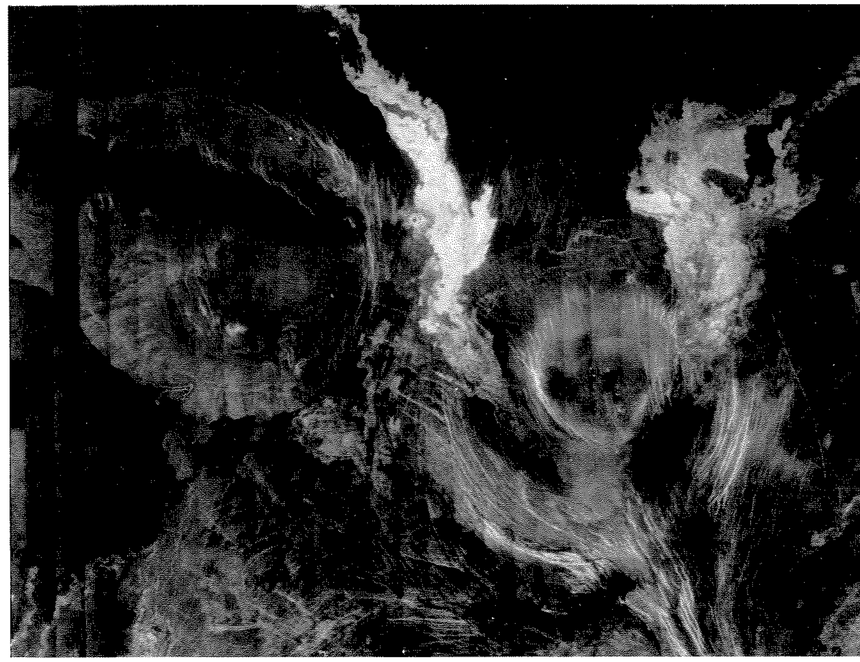
Top: The tick (18° S, 5° E).
Middle: Pancake domes at 30° S, 12° E.
Below: This image of Sif (left) and Gula (right) Montes is centered at 22° N, 358° E. The mountains stand amid layer upon layer of bright and dark lava flows. Fractures run north-northwest from Gula to a low corona skirted by lava flows. The fracture zone running off to the southeast extends to Sappho. Several impact craters are visible, all with bright rings of ejecta, some with flooded floors and lava flows. One crater, southwest of Sif, is surrounded by a prominent dark splotch, while another crater north of Gula lies at the end of a dark streak hundreds of miles long. Dozens of small volcanic domes can be seen on the plains north of Sif, while the onset of tessera terrain is visible at the edge of the image north of Gula. Black bands are missing data.





I also want to show you some strange and wonderful volcanic features. One that we call "the tick" is about 20 miles wide at the summit. It's a bottle-cap-shaped structure, somewhat concave on top, with ridges radiating out from it. On Earth, something like that could form by differential erosion, but, as I remarked before, we see very little evidence of erosion of any kind on Venus. We also see little pancake domes. They're typically less than a mile high, and about 15 miles across, although they come in various sizes. They sometimes overlap each other, like pancakes on a platter. On Earth, these are associated with magma that has a higher than normal silica content, making it a much stickier, thicker, more viscous material. There are pancakes of this type around California's Mono Lake. Those on Venus, however, are much larger than anything we see on Earth. I've seen perhaps a couple of dozen of them scattered over the Venusian surface. They may be a clue as to the distribution of early continental masses—which would have contained a higher percentage of silicates—if it turns out that they formed when later, more basaltic magma penetrated up through the continent and was contaminated by remelting silicates. But you can also make this stuff by differentiation in a purely basaltic magma. Very siliceous magma has a lower freezing point. Since it stays molten longer, it tends to come out later in a volcanic sequence. If you have a big body of subsurface magma, some of which is squirting out through volcanoes while the rest cools slowly, the last stuff to emerge will be highly siliceous. Conversely, if you're melting rock, it's the stuff you'd expect to erupt first.

I'll briefly mention two volcanoes called Sif and Gula. (Sif is the Scandinavian grain goddess, Thor's lover, whose long golden hair is the autumn grass. Gula is an Assyrian "great mother" goddess, sometimes rendered with a dog's head.) Each is a couple of hundred miles in diameter, but stands only one to three miles high—they're rather low features. They look like the Hawaiian volcanoes, which are shield volcanoes caused by a thin, runny lava building a very broad, flattish, gently domed mountain. They, like Hawaii, are probably associated with hot spots. Sif and Gula are linked by a complex of fractures, part of a rift system that extends several hundred miles southeast to another volcano called Sappho, for the poet. Gula is a little bit higher than Sif, getting just up into that zone where the brighter surface starts to form. There are lava flows hundreds of miles long—probably longer than any on Earth—extending out north-



A closeup of the plains north of Gula. The corona—the circular structure between the lava flows—is about 60 miles in diameter. The multiple crater at the end of the dark streak lies on the bright lava flow extending northwest from the corona.

The sulfuric-acid clouds filter out every color but orange. At ground level, the sky is one diffuse light source, sort of like a dark, smoggy day in Los Angeles.

ward from Gula. There's a corona—a dome—surrounded by fractures, with lava flows from its flanks out onto the plains. Coronae appear to be tectonic instead of volcanic features, although they're often associated with lava flows. They're more or less circular rings of what look like low-relief folds. There are probably hundreds of them on Venus. They most likely formed when a blob of hot mantle rock pushed its way up to the surface from its own buoyancy, making a little dome. As the blob cooled, it lost buoyancy and the dome collapsed, leaving behind a ring that looks like a fallen soufflé. This contrasts to paterae, which are caused when subsurface magma migrates, allowing the surface to subside.

On Sif's northern flank, there's a dark streak associated with an impact crater. The streak could be the record of a traveling line of shock, sort of a sonic boom, caused as the impacting object came in at a low angle. There are other dark streaks that suggest that the dark splotches around impact craters are a ground effect and not a shock wave, but this one is certainly continuous over a very long distance—hundreds of miles. The object broke up just before it hit, leaving two main craters that are younger than the lava flows. I'd hoped that Sif and Gula might be active volcanoes that we could come back and look at again during the extended mission. But this lava flow can't be all that young, because of that impact crater sitting on top of it. This is an example of how you deduce a sequence of events from stratigraphy—whatever lies on top is younger than what's below it. As yet, we haven't found any volcanoes that we can say with certainty are active right now.

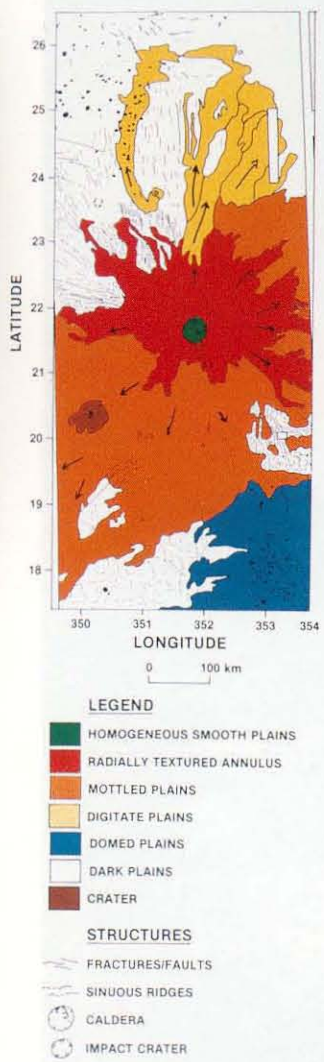
There are also hundreds of thousands of very low domes, little shield volcanoes a mile and a half or two miles across and a few hundred feet high. They tend to have central pits. We see them all over the plains. They're apparently associated with the plains' formation. The plains are a kind of background that covers about 80 percent of Venus. They apparently resulted from a very fluid lava that formed a flat, level surface, like the sea's surface. Venus, having no oceans, has no sea level, so the datum—the elevation defined to zero—is the mean radius of the whole planet. These plains are close to zero elevation.

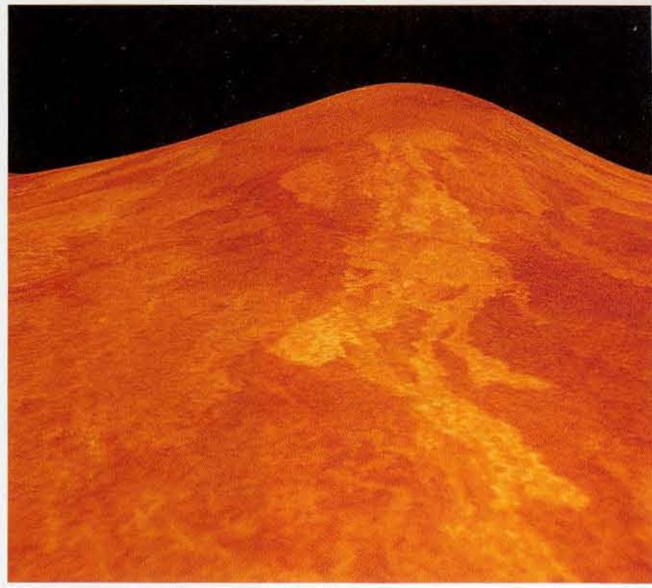
We made a three-dimensional colorized image, showing what an astronaut would see looking at Sif Mons from the north, which served as a key frame in a video we put together. The Soviet landers Veneras 13 and 14 sent back color images from the surface. The landers carried lights on board, because nobody knew if any light made it all the way down. In fact, the sulfuric-acid clouds filter out every color but orange. At ground level, the sky is one diffuse light source, sort of like a dark, smoggy day in Los Angeles.

The video combines topography, derived from Magellan altimeter data, and radar images into a three-dimensional model through which we can "fly" our video camera. The video was produced by a computer at JPL's Digital Image Animation Laboratory. To compose a frame, the computer has to decide whether each pixel in the radar image is visible to the camera or is hidden by intervening terrain. When we first started doing this, a couple of months ago, it took all day to make one frame. The video runs at 60 frames per second, so it would have taken months to create even a few seconds' worth. We've learned how to do better. We can almost do it in real time, now, by using cleverer and more efficient processing algorithms and by running several computers in parallel. We hope to be able to make videos for very large regions of Venus, and actually use them as a tool for visualizing the relationship between topography and geology.

Now that we have achieved our primary mission, we expect to operate for about six more 243-day cycles. We'll finish off the rest of this 243-day cycle, then we'll fill the major gaps in our map—the south polar region and the area we had to miss during superior conjunction. We'll point the radar off to the right instead of the left to get stereo views of the surface, and do interferometry, which will allow us to obtain very high-resolution topography. We'll search for changes. If the wind is moving sand dunes, for example, we'll see it. We'll look for volcanic eruptions. There's an excellent chance that at least one volcano is active at this very moment. We'll eventually attempt to put Magellan into a close circular orbit—still well above the atmosphere—where we can do much better gravity experiments, and some very interesting high-resolution imaging experiments. (We're doing gravity experiments right now, actually—Magellan speeds up and rises a few meters in its orbit whenever it flies over a high-density region, and when it passes over a less dense, low-gravity region, it slows and gets pulled a little closer to the planet's surface. But in order to make a really sensitive gravity map, Magellan has to be closer to the surface and has to keep its antenna pointed at Earth full time.) Circularizing the orbit is a very risky thing to do, so we're saving it for last.

The detailed exploration of our nearest planetary neighbor is now just beginning. Some of our questions are being answered, but, as is always the case in scientific endeavors, more questions have arisen. We haven't yet found evidence for Earthlike plate tectonics, nor have we found any evidence for ancient oceans or running water. However, we see many familiar volcanic and tectonic landforms. It's too early to guess how our explorations will lead to a better understanding of our home planet, but I feel certain that great and valuable insights of relevance to the geological evolution of Earthlike planets will emerge from our detailed study of the Magellan data. □





Left: A stratigraphic map of Sif Mons, showing the interrelationship of various types of terrain. Above: The three-dimensional colorized view of Sif Mons from the north. The vertical scale is exaggerated.

Steve Saunders is the project scientist for the Magellan mission. He is responsible for coordinating the actions of the science team, drawn from JPL and other institutions, and the JPL engineering team that's flying the spacecraft. Saunders earned his BS in geology from the University of Wisconsin-Madison, and his PhD in geology at Brown University. He came to JPL in 1969, just as Mariner 9 became the first spacecraft to orbit Mars, and he made the first geologic map of Mars from Mariner 9 images before turning his attention toward Venus. He joined the Magellan project about 20 years ago, back when it was the Venus Orbiting Imaging Radar, and stuck through its cancellation and eventual reinstatement as the Venus Radar Mapper before it was rechristened Magellan in 1986. Saunders's own specialty is stratigraphy—the analysis of the layering of materials on a planetary surface in order to deduce its history.

The Need for Nuclear Power

by Hans A. Bethe

The "natives," that is, the neutrons, are still friendly if we treat them right.

The Yankee Atomic nuclear plant, a 175-megawatt pressurized-water reactor in Rowe, Massachusetts, began commercial operation in 1961.

The nuclear age started on December 2, 1942, when Enrico Fermi achieved the first chain reaction in Chicago. This was terribly secret at the time, so the boss of the Chicago laboratory couldn't tell it directly to his boss in Washington. Instead he sent a telegram saying: "The Italian navigator has reached the new continent. The natives are friendly." The "natives," that is, the neutrons, are still friendly if we treat them right. But that hasn't always been done, and nuclear power has declined from the popularity it enjoyed in this country in the 1950s and 1960s. I believe it is important to revive nuclear power for three reasons: global warming, pollution from fossil fuels, and dependence on foreign oil.

One sign of the disillusionment with nuclear power in the 1970s and 1980s has been that many of the nuclear power plants ordered before 1973 were stopped, and not a single plant ordered after 1973 ever got completed. Nevertheless, at present nuclear power contributes about 20 percent of the electric power in the United States. In several other countries it contributes more than 50 percent, and in France as much as 75 percent. What are the problems with nuclear power in this country? The three biggest ones are high cost, safety, and waste disposal.

Cost

The cost of nuclear power plants—in dollars per installed kilowatt or millions of dollars per million-kilowatt plant—has increased prodigiously since 1970, when it was $170. By 1983 it had increased to $1,700 on the average, and by 1988 to $5,000. This is not just from inflation; the consumer price index increased by only a factor of 2.2 from 1973 to 1983, and by a factor of 1.2 from then until 1988. It has often been said that the tremendous increase in cost was due to the incompetence of the utilities. It's true that some utilities are incompetent to handle nuclear power. But a very competent utility, for example, which had built many nuclear power plants and did not just accidentally lose its competence after 1970, still had a cost in the late eighties that was 13 times its cost in 1970.

One cause of the increased cost was the lengthening of the construction time, mostly due to changing safety regulations and lawsuits—6 years in 1968 and 12 years for the plants completed in 1980. This has been catastrophic for the cost, because of inflation during construction and because the interest is particularly high before the plant is actually completed. In addition, the utility can't count the incomplete reactor as part of its investment, and because a utility's total investment is considered when the rates are fixed, it ends up with a lot of money tied up with no return on it. This time delay accounted for a factor of three in the cost, and caused several utilities to go bankrupt.

In 1976 most of the cost of a nuclear power plant was in material, and relatively little was in labor. But by 1988 labor cost much more than twice what materials cost. Labor was particularly high because so much of it was highly skilled professional labor—quality-control engineers and design engineers for example. Much of the design and control required by regulation had to be done at the construction site, which is much more expensive than doing it in the factory.

Nuclear power is supervised by the Nuclear Regulatory Commission (NRC), and of course there ought to be such supervision; regulation is necessary in a potentially hazardous industry. Mistakes have been made by the construction people. At the Diablo Canyon plant in California, for example, they built an elaborate earthquake-protection system, but they connected the supports for the left-hand reactor to the right-hand reactor, and vice versa. So the earthquake supports were useless. There has to be somebody who watches out for that sort of thing and doesn't license the operation until such mistakes are corrected. In addition to the NRC there is also an internal industry organization—the Institute for Nuclear Power Operation (INPO). Its purpose is to enable utilities to benefit from the experience of others operating similar reactors, and they tend to listen more easily to each other than to the government.

The NRC has generally done a good job. But tightening the regulations during construction, as they often did, meant that the whole design sometimes had to be changed in midstream. That costs much more than if you start with the new design from the beginning, which anyone who has ever built a house knows very well. And sometimes even successful adaptations to requirements did not end up as a help to the industry. For instance, the NRC required the installation of emergency cooling of the core. Such a system was designed to the NRC's specifications, but when an experiment in Idaho showed that the system worked much better than had been expected by its designers, it was thought that the NRC might then relax some of the requirements. But they didn't do so. Likewise, in the accident at Three Mile Island it was shown that the two most dangerous fission products, iodine and cesium, were retained in the water of the reactor and were never released to the outside. This also might have been expected to lead to a relaxation, but it did not.

France has had a very different experience with nuclear reactors. In France everything is done centrally by the government laboratory: It does the design; it supervises the construction. This made it possible to standardize their reactors, which the French did very early on. They built about eight reactors of one type, which gave them experience, and then they moved on to the next, more powerful type. So theirs was a straightforward development; no changes were made during construction. And they had a standardized design, whereas in this country every nuclear power plant was one of a kind. It still takes the French five or six years for construction—the same as it was here in 1968. By now about 75 percent of French electric power is nuclear, and they also export it to neighboring countries.

Standardization is *possible in this country.*

Standardization *is* possible in this country. Of three new reactor designs in the U.S., sponsored by the Department of Energy and by the Electric Power Research Institute at Stanford (an industry organization), I am particularly interested in one design for a standard pressurized water reactor. It produces power of 600 megawatts, whereas most of the recent power plants are twice as powerful. This is a model we could standardize; we could produce the parts in the factory instead of at the construction site. It's a simpler design than the older reactors; it has larger safety margins; and because of standardization, the company predicts that construction could be done in 5 years instead of the present 12. The designers hope that these reactors will have a lifetime of 60 years, whereas the expected lifetime of present-day reactors is 30 years (although many will go on for 40). And they hope that there will be very few of the small incidents that currently keep a plant available for power production only 65 percent of the time; they're aiming for 85 percent with the new design.

The current cost of production of nuclear plants is about 1.3 cents per kilowatt hour—low because it comes from old power plants constructed when they were cheaper to build, and

The 1979 accident at Three Mile Island in Pennsylvania created a partial meltdown, but the two most dangerous fission products, iodine and cesium, were retained in the water and not released. The release of radioactivity at Chernobyl was a million times greater than that at Three Mile Island.

Compared to the cost of a coal plant, however, the cost of this new generation of nuclear plants is expected to be just about the same.

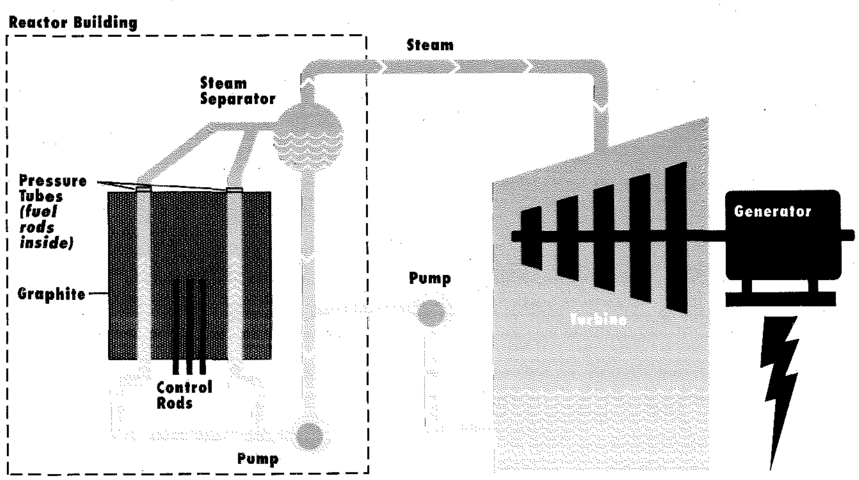
because fuel is relatively cheap. Decommissioning these plants will also be cheap, because it occurs at the end of the plant's life, and the cost can be discounted back over its whole lifetime.

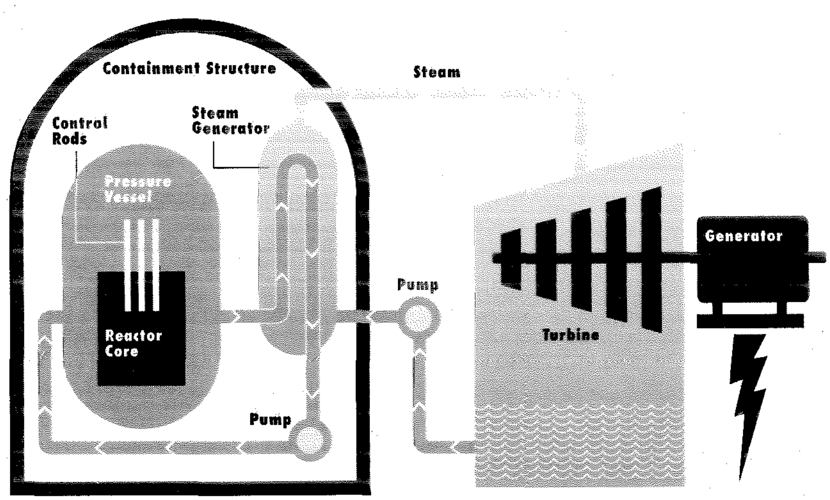
If we compare two pressurized water reactors, one designed on the old ideals of high (1200 megawatts) power, and the other as one of these new, smaller, 600-megawatt reactors, the capital costs are about the same—about 5.6 cents per kilowatt hour—but both are less than even the best figures of recent years. Operation is more expensive in the smaller reactor because you need two of them to get the same amount of power. Compared to the cost of a coal plant, however, the cost of this new generation of nuclear plants is expected to be just about the same. The initial cost of construction is, of course, still much greater for a nuclear than for a coal plant. On the other hand, fuel for a coal plant is much more expensive (and in Europe it would be twice as expensive again). In turn, operation of a coal plant is cheaper than that of a nuclear plant, and decommissioning a coal plant is really cheap. Adding together all the components, the new nuclear plants will be competitive with coal plants, which are already much cheaper than oil or natural gas plants, whose fuel is so expensive.

Safety

As for the safety of nuclear plants, there have been two fairly recent accidents—an absolute disaster at Chernobyl in the Ukraine in 1986 and a major accident at Three Mile Island in Pennsylvania in 1979. An accident such as occurred at Chernobyl *cannot* happen with any reactor in this country, in western Europe, or in Japan. This can be explained in terms of the Chernobyl reactor's design. The reactor is moderated with graphite; that is, the fast neutrons produced by the fission are slowed down to low (thermal) energy in the graphite. This is necessary to control the chain reaction of continued fission. The reactor is cooled by ordinary water, which just begins boiling when it exits the reactor at the top, producing steam to drive a turbine to generate electricity.

If there is excess heat produced, then the water will boil more vigorously, which means that the reactor loses water. In this particular type of reactor, water acts as a "neutron poison," that is, the hydrogen atoms absorb neutrons eagerly. The water does not contribute much to the moderation; that's done by the graphite, which does not absorb neutrons. But when the water absorbs neutrons, that means that fewer of them are available to make fission. So the water actually depresses the energy output in the reactor. But when the water is lost through boiling, fewer neutrons are absorbed and therefore more are available to create fission, thereby increasing the energy output. This means that whenever the heat is greater than that for which the reactor was designed, water will boil and increase the energy output still more. This makes for a very unstable situation: When you have lots of energy, you make more energy. So this reactor has to be controlled constantly by a computer, which keeps it as steady as possible. Why did the Soviets create such a stupid design? They did it because, along with power, they wanted to





Soviet reactors (top) have a graphite moderator (which slows down neutrons to facilitate the chain reaction). Water to cool the reactor begins boiling as it exits at the top, creating steam to drive the turbine. If water, which absorbs neutrons, is lost through boiling, the reaction can run away in a fraction of a second. A western pressurized-water reactor (bottom) uses water as a moderator, which will automatically slow down the reaction if any water is lost.

produce plutonium for weapons. For plutonium production they need excess neutrons and so need a moderator that does not absorb them—hence graphite.

In contrast, western reactors are stable. The moderator is water rather than graphite, so a loss of water means a loss of moderation. This means that power will automatically decrease as soon as any water is lost, because the neutrons have to be slowed down in order for the fission chain reaction to continue.

At Chernobyl there was a total loss of water, which made the reactor "prompt critical." What does that mean? Let's say we have 1,000 fissions occurring. They emit 1,000 neutrons, which are floating around the reactor. After a while a neutron finds a uranium 235 atom, and makes another fission. Now, 995 of these neutrons do this promptly; that is, they need only the time it takes to diffuse around—about a millisecond—in order to get slowed down in the graphite and to find another uranium nucleus. But 5 of those 1,000 neutrons do not act that quickly. These delayed neutrons are emitted between 1 and 50 seconds after the fission. In order to keep the chain reaction self-sustaining from one generation of fissions to the next (a state called "critical"), you have to wait for these delayed neutrons. But if you increase the density of neutrons because they're no longer absorbed by the cooling water, then the chance of a neutron finding another uranium nucleus becomes very high, and the reactor can go critical without waiting for these delayed neutrons. The prompt neutrons can do it themselves in the millisecond that it takes them to find another uranium nucleus. Therefore, once you are prompt critical, the reactor will run away in a fraction of a second—like a bomb.

There were other things wrong with Chernobyl. At the time of the accident the plant was in the charge of an electrical engineer who had no idea whatever about nuclear power. He disregarded all instructions. He pulled out all control rods (which control the reaction by absorbing neutrons); this meant that it was at maximum activity. That's how it got prompt critical. Fortunately, a record was kept of the way the power increased, so we know exactly what happened, although it happened, finally, in a fraction of a second. Because the Soviet reactor design requires frequent reloading of fuel, it had no containment building but was practically open to the air. So when the explosion occurred, radioactivity spread all the way to western Europe. In one of the hardest-hit areas in neighboring Byelorussia, inhabitants will get a lifetime dose of about 40 rem (a unit of radiation equal to a roentgen of x-rays in terms of damage to humans). For comparison, Americans receive from cosmic rays, from radon coming out of the ground, and from diagnostic x-rays, an average radiation dose of about 10 rem over 50 years. Four times that normal dose is likely to be somewhat hazardous, but not terribly so.

The one good outcome of the Chernobyl catastrophe was the application of *glasnost*. The Soviets immediately asked for western help on how to tame their reactors, and that help was willingly given through the International Atomic Energy Agency in Vienna.

A well-known report on safety, known as WASH-1400, or the Rasmussen report, discusses very unlikely combinations of troubles in western reactors and admits that with a combination of enough different and independent malfunctions at the same time, a western reactor could have an accident on the scale of Chernobyl, although due to entirely different causes. But such a combination is exceedingly improbable, and the report concludes that this might happen once in a billion years. Western reactors cannot become prompt critical no matter what we do.

But lesser accidents may still happen if the reactor is overheated and cooling water lost. The loss of water automatically shuts the reactor down so that no further reaction occurs; no Chernobyl can happen. But the reactor still contains lots and lots of fission products—radioactive iodine and others. These will continue to produce heat by radioactive decay, so a meltdown can still happen even after the reactor is shut down.

Three Mile Island had a partial meltdown, which came about because water was lost due to a valve remaining open that ought to have been closed. But it should not be mentioned in the same breath as Chernobyl. For one thing, the release of radioactivity in Chernobyl was more than a million times greater than at Three Mile Island. Second, the accident at Three Mile Island happened over several hours, whereas the Chernobyl accident happened in a fraction of a second.

In the new reactors that I've mentioned, if the reactor overheats, emergency cooling will be provided not by an engineered device that requires the functioning of complicated mechanisms, but automatically by natural convection. Pumps won't be needed for emergency core cooling; rather, the reactor and the water tank high above it are connected by a pipe, and since it's hot at the bottom and cool on top, convection will bring cool water down and hot water up.

Core damage such as happened at Three Mile Island means a tremendous loss to the utility, but it does not endanger the public.

No human interference is needed to get this going; it's independent of engineered devices and of the intelligence of humans. A valve opens as soon as pressure in the reactor goes down due to loss of water. (I presume there are several valves so that you don't have to rely on only one.) The manufacturer's probability risk assessment estimates that core damage such as happened at Three Mile Island will happen in these new reactors once in 800,000 years of operation. I can't guarantee this, of course; such a claim should be looked at by independent people.

Core damage such as happened at Three Mile Island means a tremendous loss to the utility, but it does not endanger the public. For any real danger to happen, the containment has to break, and the chance of a breach in containment, according to the new reactors' manufacturer, is one in 100 million years. So, if you have 1,000 reactors operating, then such a break would happen once in 100,000 years, which is more than 10 times recorded history. This sounds pretty safe to me, but, again, I'm waiting for an independent assessment of that risk.

As for how dangerous nuclear power is, Bernard Cohen in his book, *The Nuclear Energy Option,* gives some nice examples of loss of life expectancy due to various causes. The most dangerous is to smoke, which causes the loss of an average of 2,300 days of life expectancy. But the next most dangerous is to be unmarried, making this a hazardous occupation! Averaged over the U.S. population, regardless of such hazardous exposure, all accidents together give a loss of life expectancy of 400 days; air pollution,

80 days; dam failures, only 1 day.

For comparison, people who live near a nuclear power plant lose 0.4 days of life expectancy due to radioactive releases and possible accidents. If all electricity were nuclear, then the average for the United States population would be somewhere between .04 and 1.5 days. The 1.5 comes from a competent antinuclear organization, the Union of Concerned Scientists, and the .04 comes from the Nuclear Regulatory Commission. But whichever is nearer the mark, it doesn't seem a big threat.

If all electricity were nuclear, then the average loss of life expectancy for the United States population would be somewhere between .04 and 1.5 days.

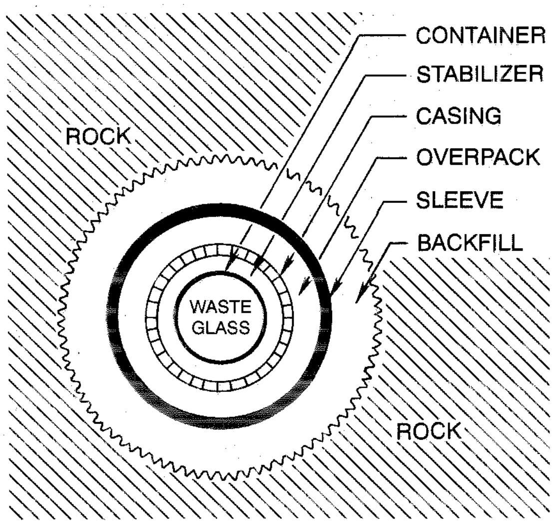
Radioactive Waste Disposal

The fuel remains in a reactor for three years. Every year one-third of the nuclear fuel is unloaded and replaced with fresh fuel. The unloaded fuel elements can be left as they are and encapsulated in borosilicate, a heat- and corrosion-resistant glass. This is how it is currently prescribed in the United States. By this method, the annual spent fuel from one reactor fills 10 cylinders, 10 feet long and 1 foot in diameter. Other countries, France and England for instance, chemically separate the spent fuel into fission products and transuranic elements, such as plutonium and curium, and then convert the separated waste into borosilicate or a similar substance.

The chemical separation is beneficial because the transuranics have a much longer lifetime than the fission products. The longest-lived of the latter, strontium and cesium, have half-lives of about 30 years, while transuranics live thousands of years. (Plutonium, for example, lasts 20,000 years.) Once you separate, the thermal power of a cylinder filled with fission products will decline from about 10 kilowatts after one year to 3 kilowatts after 10 years; after 300 years it's down to about 5 watts—just a flashlight per cylinder. The heat, which is a significant measure of the amount of radioactivity, decays very rapidly. So, if you separate the fission products chemically, the stuff becomes very mild after 300 years and couldn't do much harm anymore. This is important, because the borosilicate and its container will easily last a few hundred years, but they cannot last the tens of thousands of years necessary to contain the transuranic elements of the waste.

But what will we do with these transuranics? With present technology we would bury them separately, preferably in different locations. Precisely because of their long lives, they have very weak radioactivity, and therefore, although this is a great simplification, they will not thermally disturb the surrounding rock. Sometime in the future a much better method will become feasible. We will probably be building breeders to make more fissionable material, and if so, some of the transuranics—plutonium, for example—can actually be used, while others, although not useful, can be burned up. They will undergo fission, which reduces them to fission products with a short life of 30 years.

But if we *don't* separate the transuranics, how are we going to dispose of them? In the proposed system illustrated above, on the inside you have the waste itself, which is in this borosilicate glass surrounded by a container; the container



At Yucca Mountain (left) in Nevada, groundwater must flow 50 km before coming to the surface, which would take 100,000 years. Unseparated nuclear waste could be buried (right) at such a site in borosilicate glass surrounded by a container built to last several centuries. Then comes stabilizer, overpack, and a claylike backfill estimated to last 100,000 years.

can probably be made to last several centuries. Around that is a stabilizer, which is there to stabilize physical and chemical properties. And around this there is another casing—and that is the real safety—made of some very resistant material, such as copper, as has been proposed by the Swedes. Then comes something called "overpack." You now have this cylinder of material, which is let down deep into the earth and shoved into a tunnel.

Around that you then put the backfill, which is the most important of all. This is made of a special claylike material. Clay is impermeable to water, which is a very important property because the only way the waste could come up to the surface and into the biosphere would be through groundwater. So if you protect it carefully from contact with groundwater, then that stuff can sit there for a long time and nothing will ever come to the surface. This clay is not only impermeable to water, but when water touches it, it actually gets stronger—harder, denser, and more impermeable. So reasonable people have estimated that this backfill may easily last 100,000 years, which would certainly be long enough to contain plutonium and other troublesome elements. We can't wait 100,000 years to test it, of course, but experiments have been done on this backfill material to study its properties and determine how it would behave.

Now suppose all this fails—all the lines of defense, including the backfill—and we are exposed to transport by groundwater? Groundwater doesn't flow like a river; it creeps. At a disposal site in Nevada called Yucca Mountain, the Department of Energy has measured the flow of groundwater at 1 millimeter per day. And it has to flow a distance of about 50 kilometers before it comes to the surface, because it generally flows horizontally. With this alone, it takes more than 100,000 years to come to the surface. In addition to that, at Yucca Mountain the waste can be placed about 400 meters below ground, and the groundwater is 600 meters below ground, so the waste won't even touch it. This might change due to geological upheavals, but to start with it's a very good disposal site. And even if the groundwater is flowing 1 millimeter per day, experiments have shown that most dissolved elements take 100 times longer to flow than groundwater; they are constantly adsorbed by the surrounding rock and then put back into solution again. And plutonium, which is the element people are so afraid of, takes 10,000 times longer again to migrate than most elements. In other words, during plutonium's half-life of 20,000 years, you are insured 100,000 times over.

I firmly believe that neutrons are still "friendly" and that the three worries of nuclear power, namely cost, safety, and waste disposal, all have technical solutions. What we need now is public education against the misinformation that has been spread. And we need the political will to go ahead with developing this crucial source of energy. □

Hans Bethe's concern with nuclear power on earth has its roots in his influential work on the ultimate nuclear reactors—stars. His discoveries of how energy is generated in stars by nuclear reactions, work first published in 1938, won him the Nobel Prize in Physics in 1967.

Bethe is the John Wendell Anderson Professor of Physics, Emeritus, at Cornell University, where he has been a member of the faculty since 1935. He received his PhD from the University of Munich in 1928, and left for England in 1933 and the U.S. two years later. From 1943 to 1946 he was director of the Theoretical Physics Division of the Manhattan Project at Los Alamos, and afterward joined other concerned scientists in warning of the potential disaster of nuclear warfare.

A frequent visitor to the Caltech campus, Bethe came as the Lauritsen Lecturer in 1980 and as a Fairchild Distinguished Scholar in 1982 and 1985. During his most recent "unofficial" visit this past winter, he delivered the Watson Lecture from which this article is adapted. Willy Fowler introduced Bethe as "the Isaac Newton of our times. Newton showed how the earth orbits the sun. Bethe showed how the sun shines."

Letters

Editor: It seems that every time I have an article in *E&S* I get into trouble. Last time, I offended Professor Paul Bellan by saying *magnetic confinement* when I meant *magnetic mirror confinement*. This time I've made an even worse error since it is in my own field of expertise.

One of my esteemed colleagues, who prefers not to have his name dragged into this tawdry affair, has written to point out that I said sound waves are *adiabatic*, when I should have said they are *isentropic*. The distinction between adiabatic and isentropic is well known to all readers of *Engineering & Science*, so I should have known better than to try to get away with such sloppy writing.

He goes on to point out that I said sound waves are pushed along by heating and cooling, whereas I should have said in a sound wave, the temperature rises and falls, because there is no heating or cooling involved. (In other words, sound waves are adiabatic.)

Yet another distinguished reader, Dr. Robert Glaser, has written to point out that William Summerlin worked not at the Sloan-Kettering Institute in Minnesota as I said, but rather at the Memorial Sloan-Kettering Cancer Center in New York. He is perfectly correct.

I have carefully considered the significance of these misstatements and decided that, while they do amount to serious scientific error, no misconduct or fraud is involved, and they do not alter the main conclusions of the article. The article therefore does not have to be retracted, and this letter may serve to correct the scientific record (murky as that is).

David L. Goodstein

Editor: David Goodstein's article on scientific fraud laments the growing interference from the sponsor's watchdogs, but fails to give any suggestions for how the scientific establishment might better police itself. Based on the well-known cases of fraud in science and my own experience, I would like to offer the following suggestions for dealing with the problem, which will only grow as the scientific research profession becomes increasingly competitive.

1. Authors relying on experiment or observation should be prepared to make copies of their raw data available for any legitimate request, whether for the purpose of repeating the experiment or for further developing the technique.
2. Incentives should be given for the usually thankless task of verification of the results of others. The disproval of the cold fusion claims is an outstanding example of the importance of verification, but simple verifications are usually not even publishable.
3. To avoid repeating fiascos like the Baltimore affair, senior people must accept responsibility for papers that bear their names and for the honesty of protégés whom they support and sponsor. After all, it is their prestige that provides the edge in winning supporting grants and assures rapid acceptance of results submitted for publication.

Peter Gottlieb (BS '56)

Editor: I just read "First Lights," and really enjoyed it, especially your delightful investigation of what happened on the 100-inch first light night. Firing up a planetarium program and running it for the night of November 2, 1917 (until it crashed my aging computer), I found that Jupiter, the Moon, and Saturn were all near the zenith (or, more correctly, the meridian) soon after sunset that night. So we may assume that Hale and the rest were testing the telescope on near-zenith objects, as is standard practice. (Perhaps as Adams recalled, "the telescope was swung over to the eastward" to see Jupiter, but unless it was still dusk they didn't have to swing it over all that far.) If, then, they returned at 3 a.m. and chose a bright star near the zenith, which star was it? Not Vega, which as you note was below the horizon. *Regulus*, however, was quite close to the Los Angeles zenith at that hour. The visual magnitude of Regulus is -0.3, quite close to the 0.6 mag of the then-subterranean Vega, and its spectral class is B7, close enough to Vega's A0 to make the two indistinguishable in color to all but an experienced visual observer. (Which most professional astronomers are not; indeed, in my experience, many astronomers don't know the sky well enough to find their way out of the woods.)

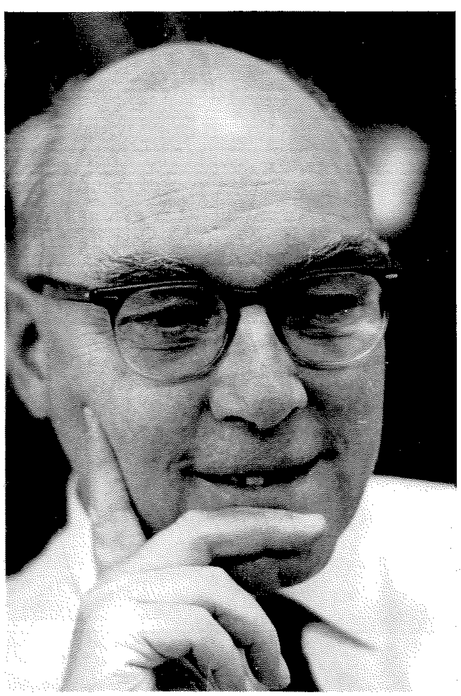
I hypothesize, therefore, 1) that Adams's account of the evening is substantially accurate, except that his memory substituted one blue-white, zenith-achieving, first-magnitude star for another, and 2) that Noyes like the others saw a poor image of Jupiter, but decided (after learning that the telescope worked) to substitute what he *should* have seen for what he actually *did* see. Such prettifying is the stock in trade of clichéd and hackneyed poets, who with "bated breath" as Noyes puts it steadfastly pursue the cosmic yalp as they anticipate it to be, without letting the facts trip them up.

Timothy Ferris

Obituaries

Carl Anderson and his cloud chamber.

Carl D. Anderson 1905–1991



Nobel Laureate Carl D. Anderson, Board of Trustees Professor of Physics, Emeritus, died January 11 after a short illness. He was 85. Discoverer of the positron, the first particle of antimatter shown to exist, Anderson was awarded the Nobel Prize in physics in 1936, when he was only 31 years old. "He lived during the heyday of modern physics," said Gerry Neugebauer, chairman of the Division of Physics, Mathematics and Astronomy, at the February 25 memorial service. "To many of us he epitomized the experimental physicist." He was also "someone whose career epitomized Caltech," added Robert Christy, Institute Professor of Theoretical Physics, Emeritus.

Anderson entered Caltech as an undergraduate in 1923, intending to become an electrical engineer. During the third term of his sophomore year, however, Anderson took Ira Bowen's class in modern physics, a course he found so inspiring that he changed his major to physics. At the memorial service Lee DuBridge, Caltech president emeritus, recalled meeting Anderson in 1926 when Anderson was a senior and DuBridge a young postdoc at Caltech on a National Research Council fellowship. It was Robert Millikan's policy to introduce promising young undergraduates to research by making them research assistants. Millikan offered Anderson to DuBridge. "I thought I'd really made it now that I had a research assistant to help me," said DuBridge, "even though I didn't really need one; the experiments I was doing were very simple indeed."

But the relationship was short-lived. Millikan reassigned Anderson to some work on cosmic rays using a cloud chamber. "So I regretfully said goodbye, and he moved two doors down the hall and started working with the cloud chamber. But I was proud to be at least a forerunner to the experiments that led to the Nobel Prize," said DuBridge. Their friendship resumed when DuBridge returned as president in 1948.

In the meantime Anderson received his BS in 1927 and stayed on as a graduate student, working with Millikan. Millikan was a pioneer in cosmic-ray research and had already measured their enormous penetrating power. What he wanted Anderson to do was to measure the energy of the electrons they produced, and the best way to do that at the time was in a cloud chamber. Anderson designed and built an apparatus consisting of a giant electromagnet wrapped around a cloud chamber. An arc-lighted camera was focused on the chamber's window to record the vapor trails of electrons or other charged particles passing through.

By 1930, when Anderson earned his PhD, scientists had identified only two elementary particles of matter—the electron and the proton. In 1932 Anderson realized that he had found something new when his cloud-chamber photographs showed what appeared to be a positively charged electron. This particle was eventually named the positron, and its discovery was the first confirmation of Paul Dirac's equation for the electron, which predicted its positively charged analog.

By the time he received the Nobel Prize for this work in 1936, Anderson and his first graduate student, Seth Neddermeyer, had identified two more of the fundamental particles of matter, which have variously been called the positive and negative mesons, the mu mesons, or the muons. According to Christy, "Carl was never as impressed by the discovery of the positron as he was by his work with Neddermeyer on the discovery of the mu meson. He felt that the positron discovery was kind of an accident, a stroke of luck, whereas the discovery of the mu meson followed several years of intense work trying to follow one lead after another." Anderson was promoted to assistant professor in 1933, and was named associate professor in 1937 and professor in 1939.

When Anderson discovered the positron, William Fowler (PhD '36), Institute Professor of Physics, Emeritus (and winner of the Nobel Prize for physics in 1983), was an undergraduate in Ohio. Anderson's discovery inspired him to apply for a graduate assistantship at Caltech. Fowler worked in the Kellogg Radiation Laboratory with Charles Lauritsen, who suggested that he talk to Anderson about using a cloud chamber to look at beta rays and gamma rays produced in an accelerator.

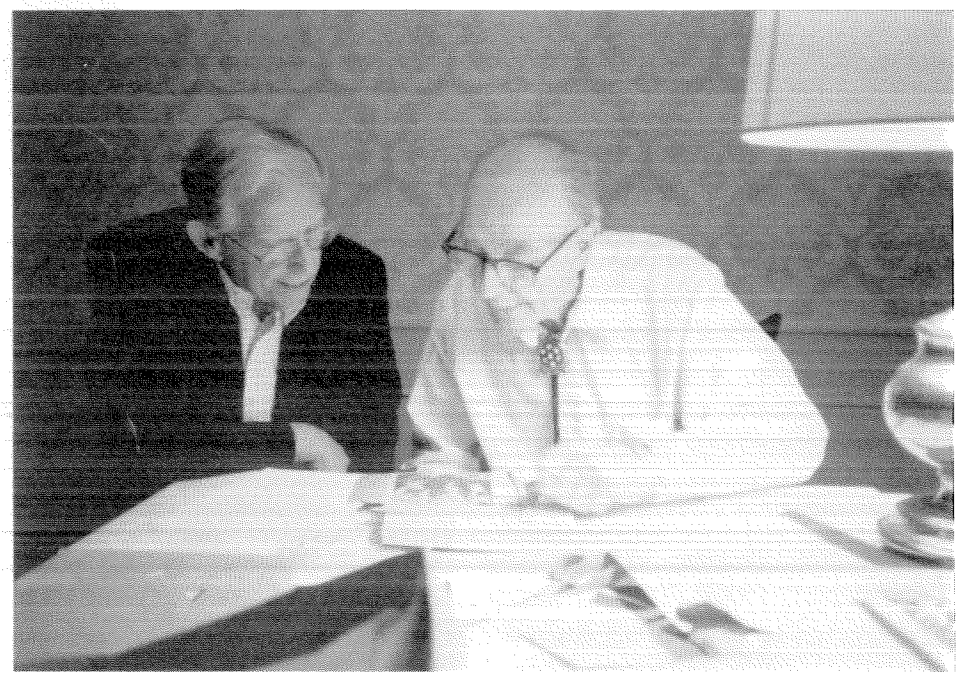
"Anderson showed me his cloud chamber and let me in on the secrets of how to make one operate successfully," recalled Fowler at the memorial service. "I followed his suggestions as well as I could. Although I obtained thousands of cloud chamber exposures, none were ever as clear of background droplets as were Anderson's." Fowler also spoke of his World War II experience with the Caltech group producing land and aircraft rockets, a group that included Lauritsen and Anderson (see story on page 2).

Two of Anderson's former students also spoke at the memorial service—Eugene Cowan, professor of physics, emeritus, who joined Anderson's group as a graduate student in 1945, and Donald Glaser, now professor of physics at UC Berkeley (and winner of the Nobel Prize in 1960), who had Anderson as a thesis adviser from 1947 to 1949. Glaser was measuring the energies of the mu meson. "Whenever I got stuck," said Glaser, "Carl would be more than happy to give me advice and help me, but otherwise he left me strictly alone. I've compared notes with others of his students, and that seems to have been his pattern. The consequence was that he stimulated a great independence in many of us, which I've always been grateful for."

Cowan also recalled "the way of Carl Anderson" with his students. During the early 1950s, when Anderson and his team were looking for new elementary particles, Cowan was scanning photographs of cloud-chamber tracks and discovered "the blob," which he concluded must be evidence of a new particle. When he communicated this to Anderson, "he came immediately to view the blob with an interest that turned to amazement as I showed him the second blob. With growing excitement, we began to see the heavy dark streak and the strange origin of the blob as the possible form of a much sought prize, the magnetic monopole. His next words remain as clear to me now as when he spoke. He said, 'I don't know what this is, but it does look like something new. I want to work with you on this, but I want you to know at the start that this is to be your discovery, and you are to publish it first.'" It was not the magnetic monopole, and though "the discovery was new and interesting, it was unimportant in the basic structure of science." But Cowan never forgot Anderson's generous gesture to a young postdoc.

By the late 1950s Anderson's kind of cosmic-ray studies was beginning to be supplanted by work done on huge high-energy accelerators. "Anderson was trained to be the kind of lone investigator working with a few students and postdocs, and he did not like the idea of becoming one member of a large team," said Christy. Anderson became division chairman in 1962, a position he held until 1970. He retired in 1976.

Fowler eloquently summed up Anderson's contribution: "He was a creative scientist, and he created a new world for all of us—the world of antimatter in the form of positive electrons. Later on, others produced antiprotons, antineutrons, and many other antiparticles, but it was Anderson who took the first step into an enhancement of our knowledge of the physical universe which few other discoveries can match. Anderson stands among the great scientists of all time."□



Longtime friends Milton Plesset (left) and Carl Anderson reminisce at Anderson's home in September 1989.

Milton S. Plesset 1908–1991

Milton S. Plesset, professor of engineering science, emeritus, and an expert on nuclear energy, died February 19 at the age of 83.

After earning his BS (1929) and MS (1930) from the University of Pittsburgh and PhD from Yale in 1932, Plesset came to Caltech as a National Research Council Fellow—just as the positron was in the process of being discovered by Carl Anderson. At that time Plesset was a theoretical elementary particle physicist and an expert on quantum electrodynamics. "The term 'elementary particle physicist' was not yet in vogue and quantum electrodynamics was brand new," said Murray Gell-Mann at the April 2 memorial service. "He was working right at the cutting edge of fundamental physical theory."

Gell-Mann, the Millikan Professor of Theoretical Physics and Nobel laureate, described some of Plesset's early work following Anderson's discovery—first with Robert Oppenheimer, using the Dirac equation and quantum electrodynamics to show how electron–positron pairs were produced. The next year Plesset went to the Bohr Institute in Copenhagen, where some of his important work—on the nature of cosmic rays in collaboration with E. J. Williams—remained unpublished, according to Gell-Mann. Plesset and Williams showed that cosmic-ray collisions took place at energies less than those at which quantum electrodynamics was assumed (wrongly, it turned out) to break down. Therefore, they said, if primary cosmic rays were indeed photons, as Robert Millikan believed, then they would have to behave like photons, which they notoriously failed to do. "Milton told me," said Gell-Mann, "that he and Williams even hinted that the explanation of cosmic-ray phenomena in the atmosphere might somehow involve a heavy version of the electron. If they really said that, then it was an anticipation of the next discovery by Carl Anderson—of the muon. Unfortunately this remarkable work was not published. They sent a version of it as a letter to the great man, Dr. Millikan, who ignored it, since it challenged his pet hypothesis. Perhaps researchers in the history of physics can find that letter in some musty file and see what it actually contains."

From 1935 to 1940 Plesset was an instructor in theoretical physics at the University of Rochester, lured there by none other than Lee DuBridge, future president of Caltech. DuBridge, who had been invited to start up a new physics department, knew of Plesset's work through Oppenheimer. At the memorial service DuBridge recalled Plesset's time there: "It was the early days of blossoming quantum physics, and Milton helped to put Rochester on the map as a place where modern theoretical physics was being done. Rochester has remained for a long time a leader in both experimental and theoretical physics due to the work that Milton helped start in those days."

His interests, however, gradually shifted to applied science and engineering. After returning to Caltech in 1941, Plesset left again soon afterward to spend the war years with Douglas Aircraft Company as head of the Analytical Group of the Douglas Research Laboratories. He came back to Caltech in 1948 as associate professor of applied mechanics and was named full professor in 1951. During this time his research centered on the theory of cavity flows and bubble dynamics. In 1963 he was appointed professor of engineering science and retired as emeritus professor in 1978. From 1976 he continued to serve as adjunct professor of nuclear engineering at UCLA.

Blaine Parkin (BS '47, MS '48, PhD '52), professor of aerospace engineering, emeritus, at Pennsylvania State University, was one of Plesset's first graduate students after he returned to Caltech in 1948. Parkin stayed at Caltech as a research fellow in hydrodynamics for several years, and at the memorial service recalled his former professor as a man who had "a keen intellect, great generosity, and a wonderful sense of humor, although he could at times be a bit acerbic"—illustrated by calling his students "intellectual provincials" ("but in his smiling, gentle way") when they objected to his assigning a textbook in French for his class in tensor analysis.

Plesset's later reputation was as an authority on the problems and progress of nuclear power. He was a consultant to the Science Division of the RAND Corporation from 1948 to 1972 and to the energy and kinetics department at UCLA. From 1975 to 1982 he served on the Nuclear Regulatory Commission's Advisory Committee for Reactor Safeguards (ACRS) and was its chairman in 1980. Ivan Catton, professor of mechanical, aerospace and nuclear engineering at UCLA, who knew Plesset through his tour of duty with the ACRS, praised his ability to "summarize the most complex ideas in a simple way that all could understand. Although he was a physicist, Milton had more engineering sense than many of the engineers he had to deal with. And his common-sense guidance was invaluable; by example he demonstrated that one should do what is right rather than what is sometimes necessary to get research money."

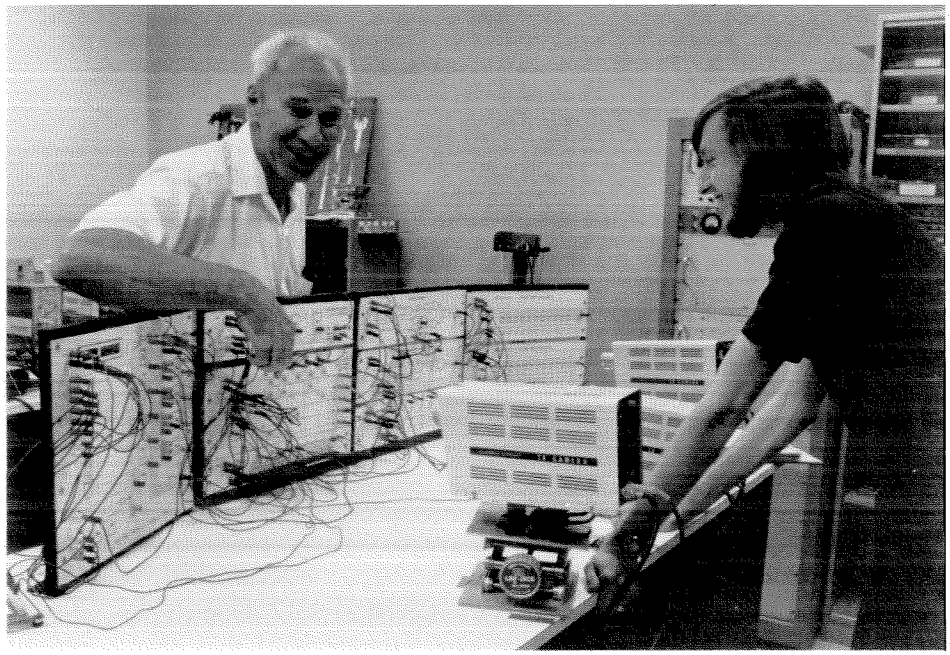
Victor Gilinsky, former commissioner of the U.S. Nuclear Regulatory Commission, noted Plesset's good humor and friendliness as well as his integrity: "He pressed for high standards in conducting nuclear-safety research, and he also pressed for making sure that research was directed at solving real problems and not just building scientific empires. . . . Overall his work for the government was characterized by common sense and a respect for realities. In fact, 'common sense and a respect for realities' describes a lot of what Milton was about. It is sometimes forgotten that these too are graces of the spirit."□

Charles H. Wilts 1920–1991

Charles H. Wilts, professor of electrical engineering and applied physics, emeritus, died March 12, at the age of 71. He was stricken by a heart attack while hiking, one of his favorite activities, along the Sam Merrill Trail in the San Gabriel Mountains.

A native of Los Angeles, Wilts received his BS (1940), MS (1941), and PhD (1948) from Caltech. Like many other Caltech graduate students during World War II, he joined the Navy's rocket project and was assistant supervisor in Aircraft Ballistics, where he worked on retrorockets and on fuses for igniting solid propellant. He joined the faculty as assistant professor of electrical engineering in 1947, and became associate professor in 1952 and professor in 1957. From 1974 until his retirement in 1984, he was professor of electrical engineering and applied physics. In 1970-71 Wilts was vice chairman of the faculty, and from 1972 to 1975 he served as executive officer for electrical engineering.

At a memorial service on April 17, several of his colleagues and former students spoke of Wilts's influence in his field and on their lives. Carver Mead (BS '56, MS '57, PhD '60), the Gordon and Betty Moore Professor of Computer Science, took his first course from Wilts when he was a junior. "Chuck was a wonderful teacher, and he started



Chuck Wilts in his lab in 1977.

me on my way as an electrical engineer," said Mead. When Mead first met him Wilts was working in the Analysis Lab in the basement of Throop Hall, which "had developed a giant analog computer to analyze flutter in aircraft structures. Chuck was amazing because he understood not only all the details of analog computation but also how it applied to this very complex aerodynamic and structural problem. Up till very nearly the present time that kind of analog computation has still outrun our most powerful digital computers in analyzing things like those dynamic problems in aircraft. . . . When I think back on the things I learned from Chuck—the principles behind that kind of computing haven't changed very much. Chuck's insights are still very much with us."

Chris Bajorek (BS '67, MS '68, PhD '72), also first met Wilts as an undergraduate and was persuaded to stay on as a graduate student, the beginning of a long friendship. "He was known as one of the toughest thesis advisers at Caltech," said Bajorek at the memorial service. "But students who had the courage to join him, rapidly found he was very warm, very human but exceptionally demanding of first-class research—research that would advance the understanding of any topic he dealt with in a very basic and unambiguous way." Bajorek noted Wilts's work on ferromagnetic thin films, which are used in memory-storage devices. "He did some of the best work in the world in ferromagnetic films—their synthesis, their structure, their static and dynamic properties, and in instrumentation to characterize such properties."

"In those days Charlie was working on magnetic thin films for computer memories," recalled Thomas McGill (MS '65, PhD '69), the Fletcher Jones Professor of Applied Physics, "but I always felt that he realized that the real memory in the system was in humans." Like Mead, McGill was first a student and then a colleague of Wilts. "Over the last 20 years as a faculty member, I found Charlie to be the colleague I sought out for critical reading of my thoughts on various subjects. With Charlie it was easy to grow accustomed to his absolutely uncompromising sense of fairness and self-discipline, which was wonderfully complemented by a compassionate, sensitive understanding of the human condition."

One of McGill's first recollections of Wilts was "of hearing someone walking along the hall and hitting his hands along the walls of Spalding. I was told that this was Professor Wilts toughening up his hands for his rock climbing." Besides skiing, hiking, and folk dancing, rock climbing was Wilts's avocation, and he claimed considerable fame among California climbers. According to James Campbell, senior electronics engineer at Caltech, "In the golden age of climbing, Chuck was one of the magic names." He had a number of first ascents in Yosemite, and developed a climbing-difficulty classification system, first known as the Sierra-Wilts classification system and later as the Yosemite climbing system. He was the author of the *Climber's Guide to Tahquitz Rock and Suicide Rock*. "He influenced the style and safety of the climbers of his era," said Campbell. "He brought his technological skill to the climbing family and wrote several papers on the strength of ropes, an article on the safety of expansion bolts used for climbing and another on a knife-blade piton that he invented." Campbell learned to climb in the rock-climbing course that Wilts began teaching at Caltech in 1973, which others have taken over in recent years. "He was my best friend, mentor, role model, father figure, my boss (twice), backpacking companion, and rock-climbing partner," said Campbell. "He influenced me more than anyone else in my life."□

Random Walk

Honors and Awards

Charles Barnes, professor of physics, Andrew Cameron, senior research associate in biology, and Mary Kennedy, associate professor of biology, have been elected Fellows of the American Association for the Advancement of Science. Fellows, chosen annually from the organization's 132,000 membership, are AAAS members "whose efforts on behalf of the advancement of science or its applications are scientifically or socially distinguished."

Slobodan Cuk (PhD '77), associate professor of electrical engineering, and David Middlebrook, professor of electrical engineering, have been awarded the Edward Longstreth Medal, presented annually by the Franklin Institute "to honor individuals whose work has made a significant contribution to the way we understand our world, or who have pioneered new technologies in scientific research or engineering."

Professor of Chemical Engineering Richard Flagan has received the 1990 Smoluchowski Award, presented annually by the Gesellschaft für Aerosolforschung (Society for Aerosol Research), in recognition of his "outstanding theoretical and experimental work in the field of aerosol nucleation and reaction chemistry."

Lee Hood (BS '60, PhD '68), Bowles Professor of Biology, has been awarded the Franz Groedel Medal by the American College of Cardiology for his work on genetic research.

George Housner (MS '34, PhD '41), Braun Professor of Engineering, Emeritus, has received the 1991 Alfred E. Alquist Award for Achievement in Earthquake Safety, presented annually by the California Earthquake Safety Foundation to "individuals who have made outstanding contributions or a major impact, past or present, in seismic safety in California."

Gilles Laurent, assistant professor of biology and computation and neural systems, is one of 89 outstanding young scholars to be awarded a 1991 Sloan Research Fellowship by the Alfred P. Sloan Foundation. The Fellowships are presented each year to "highly qualified young scientists on the basis of their exceptional promise to contribute to the advancement of knowledge."

Professor of Chemistry Nathan Lewis (BS and MS '77) has received the American Chemical Society's Award in Pure Chemistry, one of the most prestigious honors in the field, for his work in the development and analysis of a new, highly efficient class of solar cell—a device that produces electrical or chemical energy when exposed to sunlight.

Professor of Biology Elliot Meyerowitz is one of 32 scientists to be awarded a Human Frontier Science Program (HFSP) research grant, established last year by the Economic Summit nations and the European Community to promote "frontier research in brain functions and molecular-level approaches to biological functions." The program supports interdisciplinary research that transcends national boundaries.

Edward Stone, vice president, professor of physics, and director of JPL, has received the 1991 ARCS Foundation Science Man of the Year Award in recognition of his "longstanding contributions to science as project scientist of the Voyager mission to explore the outer planets of the solar system."

Amnon Yariv, Myers Professor of Electrical Engineering and professor of applied physics, was elected late last month to the National Academy of Sciences, one of the highest honors that can be bestowed on an American scientist or engineer. The election of Yariv, who is internationally known for his contributions to both laser technology and integrated optics, brings to 63 the total number of Caltech faculty who are NAS members.

Distinguished Alumni

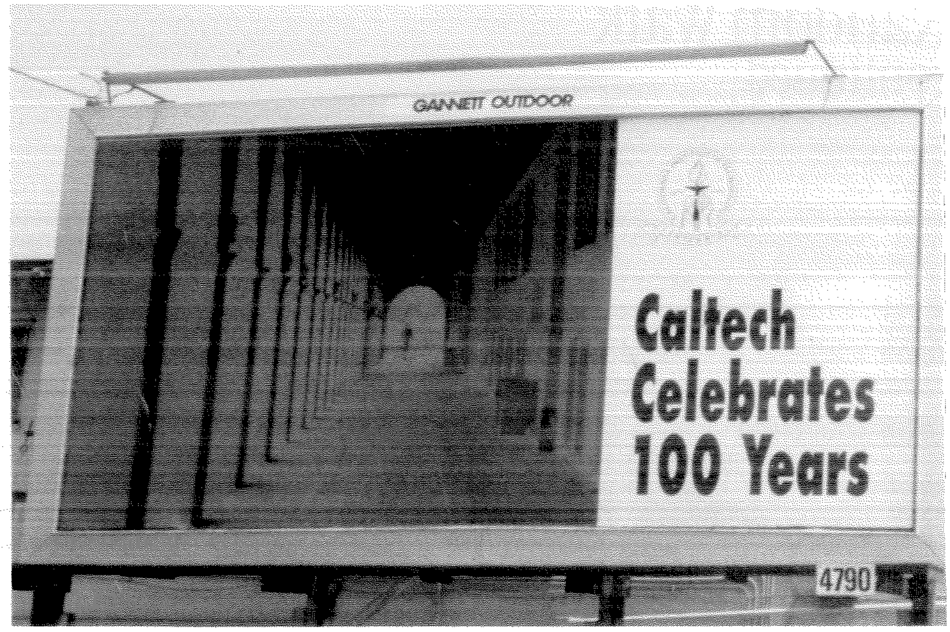
Four alumni received Caltech's highest honor, the Distinguished Alumni Award, during the Centennial Seminar Day on Saturday, May 18. Distinguished Alumni Awards are presented annually in recognition of former undergraduates or graduate students who have gone on to "high achievement in science, engineering, business, industry, or public service." This year's honorees are John P. Andelin, Jr., assistant director for science, information, and natural resources of the Congressional Office of Technology Assessment; Arthur E. Bryson, Jr., Pigott Professor of Engineering at Stanford University; Navin C. Nigam, director of the Indian Institute of Technology in Delhi, India; and George F. Smith, retired senior vice president and director of Hughes Research Laboratories.

Andelin (BS '55, PhD '67) provides direction for national energy policy and has testified to Congress on such wide-ranging issues as air pollution; municipal, toxic, and radioactive wastes; education policy; and new communications technology.

Bryson (MS '49, PhD '51), by his interdisciplinary work in aeronautical and astronautical systems control and optimization, has helped to define a field that didn't even exist when he was a graduate student. He is a former chairman of the National Research Council's Aeronautics and Space Engineering Board, and has been on the faculty of Harvard, MIT, and Stanford.

Nigam (PhD '67) has played a seminal role in fostering engineering education and research at universities in India. His work on random vibration is internationally known, and he has been a key figure in the design of earthquake-resistant structures in India.

Smith (BS '44, MS '48, PhD '52) served as co-director or director of Hughes Research for 25 years, until 1987. His own work included developing the first laser range finder, and research on the first Q-switched laser.



Gannett Outdoor Co. Inc. of Southern California has donated billboard space for a poster commemmorating Caltech's Centennial. The billboard currently adorns the north side of Colorado Boulevard just west of Daisy Avenue, and will appear in three other locations over the course of the Centennial year. The poster was designed by Denton Design Associates of Pasadena, and produced by TM Poster Productions of Montrose, CA.

Electronic Materials to Get Moore Lab Space

Intel Corporation cofounder Gordon E. Moore and his wife, Betty, have pledged $16.8 million for an electronic materials and structures laboratory. The five-story building, which will contain classrooms, laboratories, and offices, will be erected north of Watson. The new building will house materials scientists, applied physicists, electrical engineers, and researchers in related disciplines, working in such areas as computer chips, electro-optical devices that may one day allow computers to "think" with light instead of electrons, micromachines, and new high-performance materials that will lead to improved high-performance information systems.

Moore (PhD '54) cofounded Fairchild Semiconductor Corporation in the late 1950s, and directed Fairchild's research and development during the period when it produced the first commercial integrated circuit. He cofounded Intel, now a multinational computer manufacturer, in 1968. He is a recipient of the Distinguished Alumni Award, and has been a member of the Institute's Board of Trustees since 1983.

Supercomputer Dedicated

On Friday, May 31, the world's fastest, most powerful computer was dedicated at a ceremony in Dabney Gardens. (The computer itself will take up residence in the Booth Computing Center.) The computer, known as Touchstone Delta, was built by Intel Corporation's Supercomputer Systems Division.

Although housed at Caltech, the Touchstone Delta will be operated by the Concurrent Supercomputing Consortium, an organization of more than a dozen prominent research institutions and government agencies. The consortium's members will use the machine's massive computational power to tackle such computation-intensive problems as simulating global climate change, modeling a wide variety of biological and chemical processes on the molecular level, performing complex quantum-dynamic calculations, searching through voluminous radio-telescope data for the faint signatures of binary pulsars, and creating three-dimensional videos from image data returned by the Magellan and Galileo spacecraft (see page 26.)

The Touchstone Delta contains 528 numeric processors working in parallel, coordinated by a custom mesh routing chip developed by Professor of Computer Science Charles Seitz's research group. The computer can perform up to 32 billion floating-point operations per second.

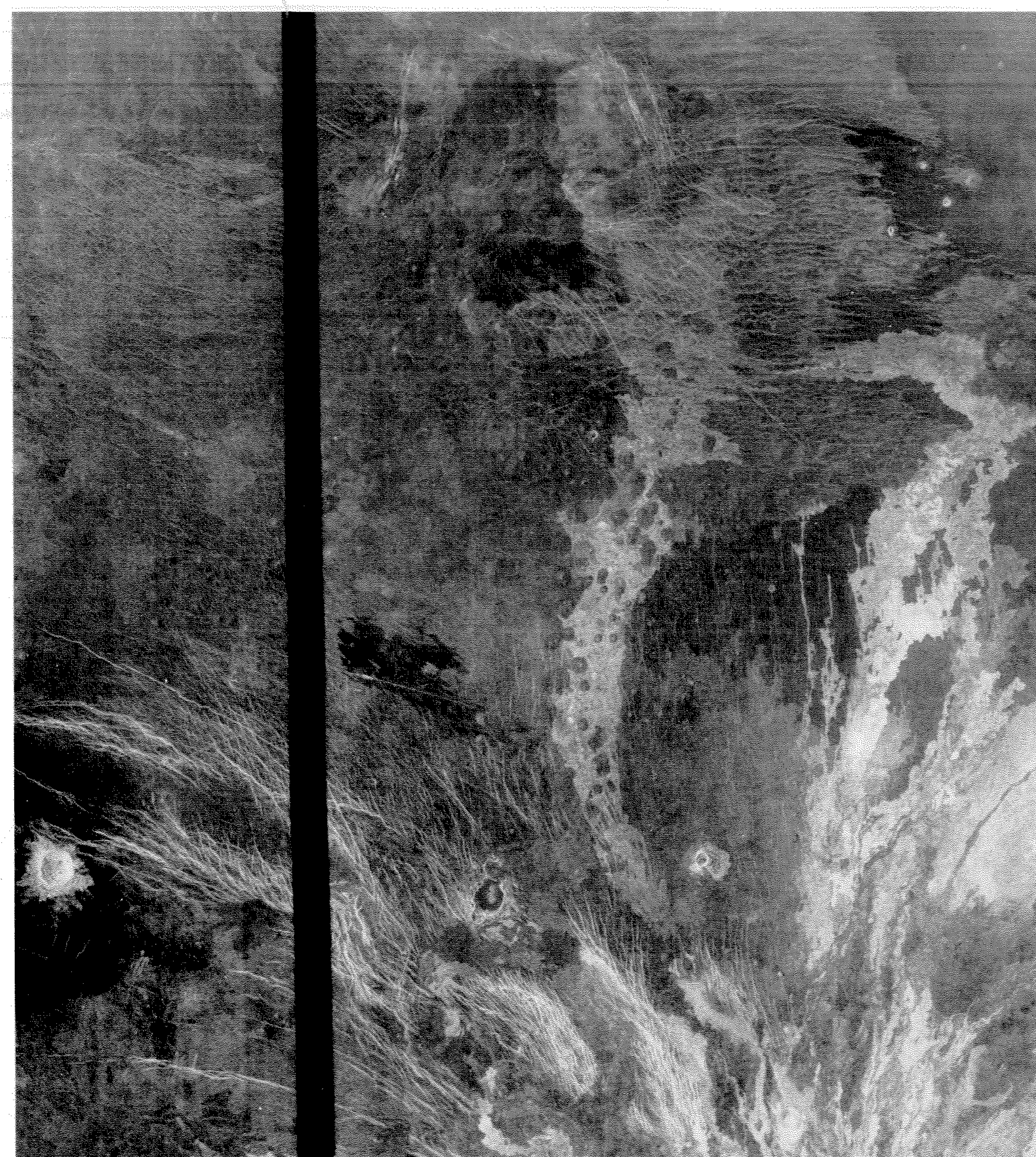
Bush to Speak at Commencement

Commencement will be a little bit different this year. Some 9,000 spectators are expected, and the event has been moved from the Court of Man to the athletic field to accommodate them. The big draw won't be the sight of President Everhart handing out the diplomas, but of that other President—George Bush—giving the Centennial commencement speech. Caltech is one of five universities to be so honored this year. Bush was invited to speak a year in advance, but final approval was not obtained from the White House until this past April. (Bush, of course, retains the option to cancel at the last minute, should affairs of state require his presence elsewhere. If so, D. Allan Bromley, assistant to the President and director of the Office of Science and Technology Policy, will probably speak instead.)

The President, of course, never travels alone. He will be accompanied by his usual retinue of White House staff, press corps, and Secret Service agents. It remains to be seen how the blue-suit-and-reflective-sunglasses crowd, who are not noted for their sense of humor, will get along with Caltech's high-spirited undergrads.

The Biggest Durn Binoculars You Ever *Saw*

The 10-meter Keck Telescope now nearing completion on Mauna Kea, Hawaii, is the biggest optical and infrared telescope in the world. (See *E&S*, Winter 1991.) It won't stand alone in that distinction for long—but then again, it was never meant to. An identical copy of the telescope (known officially as Keck II, but already dubbed "Bride of Keck" by campus wags) will be built by the same team, starting next year. Keck II is scheduled to be completed in 1996. Like Keck I, Keck II is being financed largely by the W. M. Keck Foundation, with the University of California covering the operating costs. Caltech and UC will share the bulk of the two telescopes' observing time. The two together, sited 85 yards apart and connected by tunnel to a common set of observing instruments, will act as an optical interferometer—in effect, forming a single telescope with an 85-meter-diameter (about 280 feet) mirror.



This close-up of Sif Mons's northern flank is roughly 300 miles wide. The radar-bright lava flows reveal much about the topography they flooded. They followed the steepest slope—one flow made a 90° turn before it ponded on the plains. Another flow encircled, but was not deep enough to drown, several small shield volcanoes in its path. And fingers of lava that found a fracture system sluiced along its parallel troughs for dozens of miles. An impact crater associated with a dark splotch can also be seen, at left.