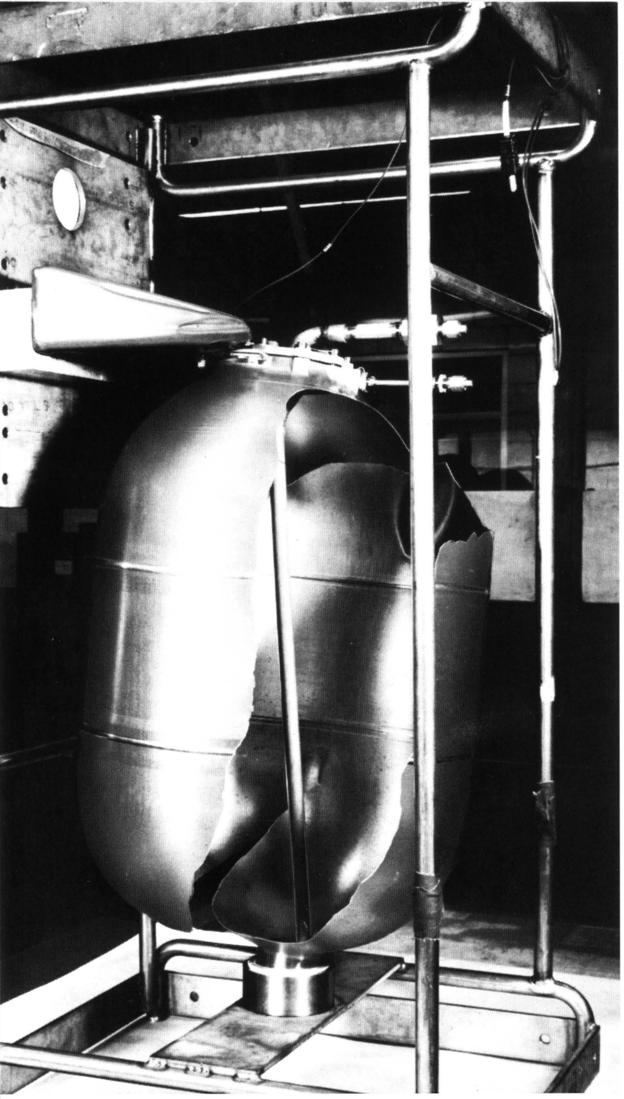


Yet there are times when even the most elaborate precautions on the part of designers and corrosion engineers are swept aside by completely unpredictable events, such as one that occurred at Textron's Bell Aerosystems in Buffalo, N.Y. Bell, under subcontract to North American Rockwell's Space Division, builders of the Apollo command module, is furnishing titanium propellant tanks for the reaction control system.

Trouble Occurs in Tests

A small titanium tank containing nitrogen teteoxide suddenly ruptured in the course of normal test. Other tanks began to burst. The ruptures launched a massive eight-month investigation that called on the highest corrosion talent at Bell Aerosystems, at the NASA Houston headquarters, and at North American Rockwell's Space Division and Los Angeles Division. At stake was the engineering feasibility of scores of other titanium tanks used in the moon venture. At stake was the timetable for landing on the moon.

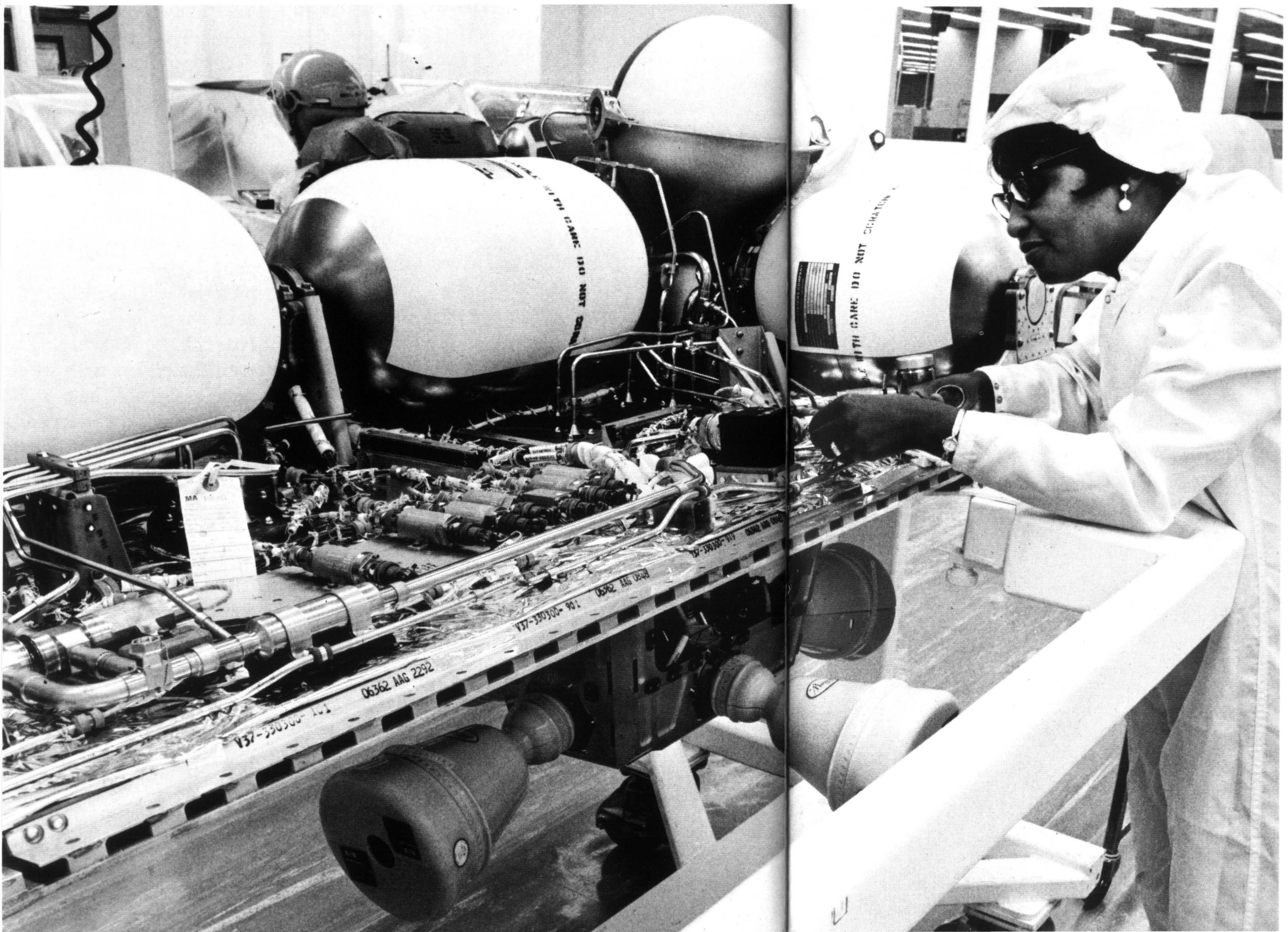
Larry Korb, who headed the tank investigation at Space Division, said, "There are some stress corrosion troubles so subtle that it is almost impossible to duplicate them in a lab test. A microscopic bit of rust on a mill roller could be a threat."

For a time it appeared the titanium tank rupture would be an insuperable problem. A suggestion was made that all the titanium tanks in the moon program be eliminated, and a safer and a more compliant metal be substituted. That would have meant an additional 1500 to 4000 pounds of weight—an impossibility for even the gigantic Saturn V booster.

When the mystery was solved the cause of the rupture was almost stunning in its simplicity. Inadvertently a trace of nitric oxide had been omitted by the propellant manufacturer from the nitrogen tetroxide propellant stored within the offending tanks. That one omission had meant the difference between the acceptance and rejection by the stressed titanium tank of its corrosive inhabitant.

The trace of nitric oxide was returned to the propellant, and the problem was overcome.

Mysterious rupture of Apollo titanium propellant tank, left, launched eight-month stress corrosion investigation by North American Rockwell, Bell Aerosystems, NASA Manned Space Flight Center. Reliable flight operational tanks, bottom, have profited by solution.



The Toughest Weld of All

Half mile of delicately fused metal unites panels of thin-skinned Saturn S-II, second stage of moon vehicle

Coursing like a vast network of arteries throughout the NASA Saturn V rocket's cavernous second stage is nearly a half mile of welded joints; fused metal that unites the S-II as flight loads and tank pressures pound at its structural integrity.

To survive in space, these silver-colored veins must be as strong as the metals they join, surgically clean, and fitted within exacting tolerances down to 13 thousandths of an inch.

Such demanding characteristics, coupled with the stage's enormous size and complexity, have of necessity produced some startlingly advanced welding innovations, and, at least in one instance, forged new technology at Space Division's Seal Beach facility. It was only natural that precedents in welding as well as in other areas of manufacturing would be set during the S-II's fabrication, for nothing even faintly resembling the stage had ever been built before.

Three standard railroad tank cars could stand on end inside the S-II, with enough room left over to lay a caboose sideways atop them. Yet, for space flight, this 81½-foot-tall stage weighs only about 95,000 pounds empty. The three railroad tank cars, by comparison, weigh more than 211,000 pounds dry. The S-II is machined to the preciseness of a fine watch, with construction comparable to an eggshell in efficiency, (the amount of weight and pressure constrained by a thin wall.) It includes two propellant tanks — a large liquid hydrogen one, consisting of six cylinders and three bulkheads, and a smaller liquid oxygen sphere. Fashioned onto these tanks are aft and forward skirts, an aft interstage and a thrust structure which mounts five Rocketdyne-built J-2 engines.

To an outsider, the stage appears to be little more than an oversized hot water tank, and this often raises a natural follow-on question: What's so difficult about putting that together? For the welding engineer, however, there have been blitzkrieging problems from the outset.

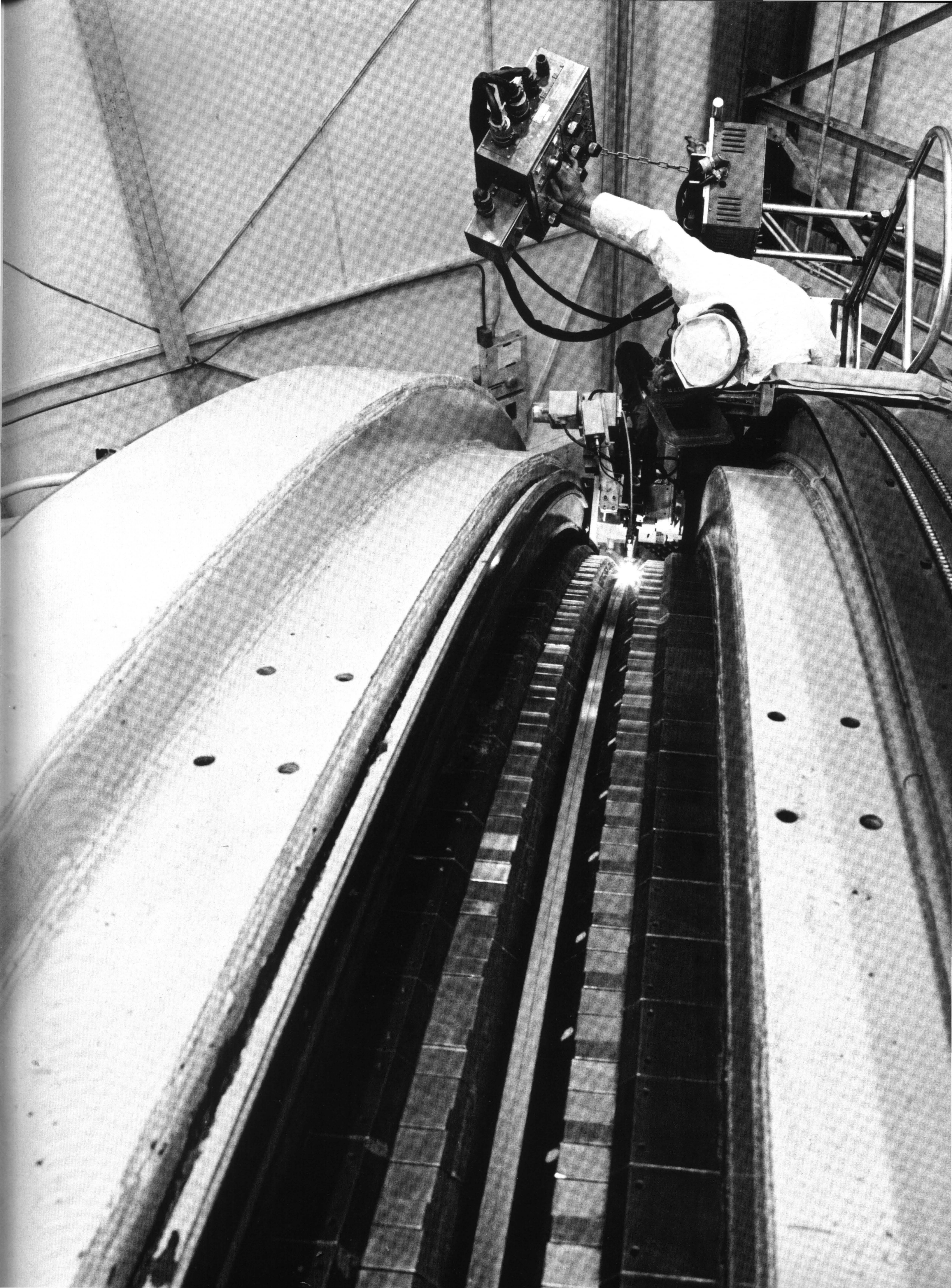
For openers, the S-II's waistline was designed at a diameter of 33 feet, meaning circumferential welds of more than 103 feet around would have to be fused between each cylinder and between cylinders and bulkheads. Anyone with a smattering of mechanical knowledge knows the longer the weld, the tougher it is to maintain quality and hold tolerances. It's one thing to make a three or four foot weld. But at greater lengths the heat input of the torch creates distortion problems on the metal surfaces. A single circumferential weld of 103 feet is enough to cause engineers to think about changing careers.

Complications

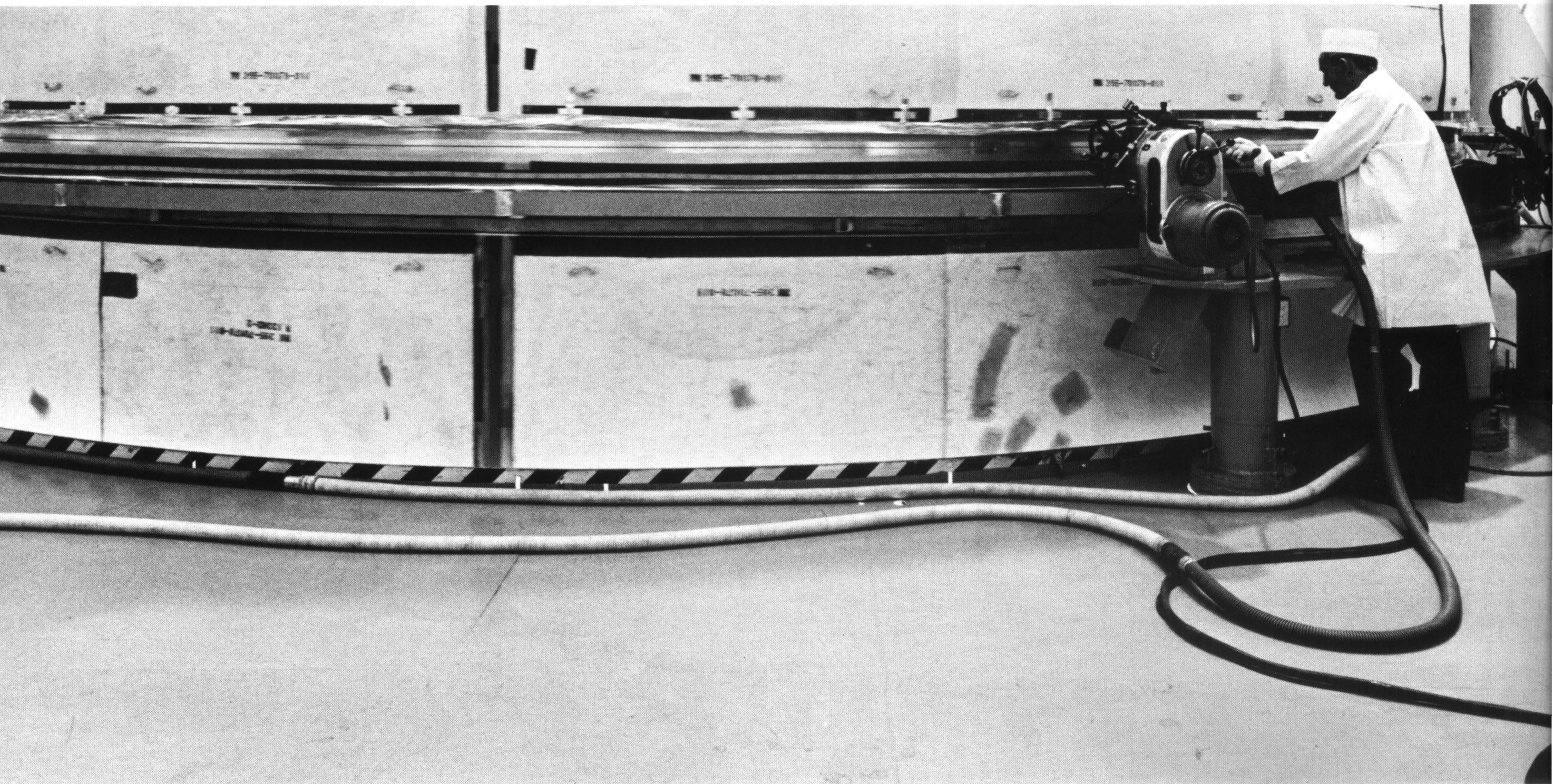
Sheets of metal vary in thickness, size and shape, and one of them is joined in a nearly inaccessible area, further complicating normal welding processes. On one section of the stage, the metal skin tapers from five eighths of an inch down to less than a quarter inch, and then builds back up to a half inch. Such changing thicknesses create hair-pulling complications for the engineer, for weld speeds, arc voltages and other parameters must be changed with each variance. And, quality and tolerance requirements for the fused molten-metal seams binding the S-II are among the most exacting ever imposed on industry. Minute defects that would pass normal industry standards — many not discernible by the human eye — cause rejection at Seal Beach. These include miniscule voids in the weld or below the surface, tiny cracks, or bits of foreign material.

If this were not enough of a challenge, add the fact that cylinders and bulkheads are 2014 T-6 aluminum, selected for its strength under super-cold, cryogenic temperatures. Typical of aluminum alloys, it is susceptible to internal contamination and is crack sensitive. But vastly improved welding equipment and techniques, fostered by stringent aerospace demands, have

Like a miniature locomotive, moving at a precise, geared speed, the welding torch, mounted on skate track, unites Apollo/Saturn V S-II second stage bulkhead panels.




STAINLESS
Helios



given company personnel the capability to confidently employ 2014 T-6 in welds.

Still, on early flight versions of the S-II, welding flaws, and joints far enough out of alignment to cause outright rejection of the product were encountered. But persevering management and line personnel, counseled by a NASA-Space Division team of manufacturing experts, have, over the years, found solutions to even the most elusive developmental problems.

Earlier this year, for instance, workmen finished welding the liquid hydrogen bulkhead for vehicle number nine to cylinder six — one of the toughest welds of all — with no repairs, and with the offset in joint fittings well within design allowances. It marked the first time such a weld had passed acceptance standards without redo on a piece of flight hardware.

"I had very little gray hair when we started," says Norm Wilson, the articulate manager of S-II Manufacturing Engineering at Seal Beach. "But look at me now." (Salt outnumbers pepper three to two.)

Taxed Imagination

"You can't really say our work has been exotic," Wilson says. "But when you consider the sizes, angles, lengths, designs, offset tolerances and overall specifications involved, you have one challenging welding project on your hands. We've had to tap our experience well dry and tax our imagination to come up with the right answers, and it has only been through the combined contributions of many that we have been successful."

There are 2331 feet of primary structural welds criss-crossing the S-II. Most of them, because of their size and complexity, have to be automatically programmed. The days of the personal, one-man operation, where a goggled welder, sparks flying, did it all, are over. Quality and reliability requirements of the aerospace industry are far beyond the manual control of even the most skilled individual craftsman. Today, every weld must be virtually perfect — 100 per cent penetration without porosity (tiny bubbles), undercut or other defects. The direct current *TIG* (tungsten inert gas) welding method is used. That is, the welding torch, which generates between 3000 and 5000 degree F. heat, uses a tungsten electrode. Inert gas (helium) is used to shield the molten metals being fused from atmospheric contamination.

The Saturn V second stage is made of dozens of panels and frames, which, joined together, become cylinders and bulkheads, and ultimately full-size tanks. Some of the work begins at the Los Angeles Division. Here, intermediate bulkhead panels are welded to thicker, waffled outboard panels, and are sent to Seal Beach. There are a dozen panels for each bulkhead and they are joined, two at a time. Picture sections of an orange that are regrouped and you have a fair idea of how the operation works. Bulkhead panels are called gore sections, and they are clamped vise-like into a fixed position by a clamshell beam. The welding torch is mounted on a skate track on the outside of the structure. Like a miniature locomotive moving at a precise, geared speed, it rides upward, 12 to 20 feet, uniting the two pieces of metal by heating them to a melting temperature that causes fusion. This is called meridian welding. The ingenious skate, which moves vertically or horizontally, on straight lines or around curves, trims, welds and x-rays in sequence as it goes.

Weld engineers developed the precise current, arc voltage, welding speed and skate travel on test panels to produce the required quality. These parameters were then programmed into automatic welding power packs. Document 971-D, the S-II weldor's Bible, defines the parameters necessary to meet design requirements for each weld joint on the stage. There are, in fact, 18 of these weld schedules, each containing over 50 parameters that must be pre-programmed into the machine.

Round and Round

The engineering specifications on the bulkhead panels calls for no more than 10 per cent offset of the material's thickness. Once two sections have been married, they rotate to a new position and the next gore is located under the beam and welded. The process is repeated, until the dozen panels become one.

By design, there is a hole left at the top of each bulkhead after all gores have been joined. The opening is closed out by a round "dollar" section, and it once caused a knotty problem. Early dollars were approximately three feet in diameter, and were welded without difficulty by holding the bulkhead and the dollar in place with vacuum chucks and hard tooling. The vacuum chucks literally suck the aluminum parts into contour. But the re-designed S-II stage number four had a bulkhead dollar with a 111 inch diameter.

"We got about a quarter way around on its weld," Wilson remembers, "and there was a snapping noise. The weld tungsten electrode contacted the material and burned a hole in the bulkhead. This dollar was about $5/8$ths of an inch thick and the excessive heat needed to penetrate caused excessive shrinkage and distortion which forced the dollar to snap loose from vacuum chucks holding it in place."

To circumvent this, engineers devised a way to minimize the torch heat on this particular weld. They did it by linking two opposed nugget welds. Instead of making one weld all the way through, they drove two of them three quarters of the way into the material, first one from the top, and then the other from the bottom — and joined them, like hooking together two croquet wickets. This cuts the heat input.

Once the gore welds cool, they are run through tough, thorough inspection tests. Every inch of each joint is x-rayed. Then a dye penetrant is painted over the weld. This betrays defects or cracks in a fluorescent glow when subjected to ultra-violet light. Next, on bulkhead joints, come helium leak checks. Later, two additional leak tests are run. When the bulkhead has been assembled, a hydrostat tool is used to pump it up with water, and in a pneumostat test, the stage is filled with air.

Near True Circles

Welding the six cylinders to each other is an altogether different task. Cylinders come in four sections — eight feet wide and 27 feet long — and are fashioned at the Los Angeles Division. These are joined, forming near true circles with flat machined mating edges. But structures over 103 feet in circumference, consisting of machined and formed sheet metal parts assembled by many different manufacturing methods, weld-joined, and moved from one location to another, are affected by normal changes due to heat and climate, and are influenced by weight.

Thus, they are actually seldom true circles with flat, even surfaces. Their size and configuration must therefore be allowed for. Because the sections are machined as flat pieces and then are contoured into shape, different stresses are placed on the metal. This can cause problems. On one of the first cylinder-to-cylinder weld attempts, 80 per cent of the joint had been fused when the remaining section ballooned out of shape from the excessive heat buildup.

Left above, checking offset of two welded cylinders with vernier caliper is key operation. Mated cylinders must be matched to tolerances within thousands of an inch.

Brilliant torch light, above right, employs a tungsten electrode, generates temperatures of 3000 to 5000 degrees Fahrenheit.

Under "rotary concept," left, the welding torch remains stationary and cylinders revolve around it, much like a giant phonograph record with weld machine as needle.

Again, engineers had to find the proper parameters — the right speed and tooling — by means of which the weld could be made with a minimum movement due to relief of the metal stresses. A mechanical spokeless wagon wheel tool is used to hold two cylinders in position until they are tack welded every six inches — approximately 200 tacks are made to 25 per cent penetration. A continuous tack weld is then made, followed by the penetration and cover passes. These 100 per cent circumferential welds are made in four steps. Two skate tools operate simultaneously 180 degrees apart, each making half of the 103 foot weld.

Throughout the evolution of the welding processes at Seal Beach, Aerospace and Systems Group personnel worked closely with their customer counterparts, benefiting in many instances from previous NASA work experience on the S-IC booster stage at the Marshall Space Flight Center in Huntsville, Alabama.

Mismatch Measured

One of the stickiest welds of all joins the forward liquid hydrogen bulkhead to the top cylinder, number six. Here, the aluminum is only about a quarter inch thick at the point where the joints meet, yet there can be no mismatch more than 27 thousands of an inch. And, neither bulkhead or cylinder is perfectly circular until fully fueled — long after fabrication has been completed.

Trouble developed early. In addition to more defects than desired, the offset between bulkhead and cylinder on some stages was above allowable tolerances, and the work had to be rejected. In these instances it necessitated the weld to be cut open, and the time-consuming process of alignment started anew. It began to impact the program, threatening schedules.

It was decided in December 1966 to organize a formal committee — to troubleshoot the problems, and, hopefully, to come up with answers. It was co-chaired by Werner Kuers, Director of MSFC's Manufacturing Engineering Laboratory, and Ralph Ruud, Space Division executive vice president. Other members included Wilson, A. C. Van Leuven, George Lewis, J. Y. Cunningham, Bill Ahern and Bill Long, of North American Rockwell, and Wernher Gengelback, Jim Orr, Jack Franklin, Jim Williams, Joe Hillenbrand, Dick Hopper, Joe Halisky and Angelo D'Agostino, of NASA.

"Our approach on this job," Kuers said at the outset, "is to shoot for a quality goal beyond what is required. In doing this, we will better insure maintaining the necessary standards."

A total assessement of fitting and welding procedures was made. How and where, the committee asked, could improvements be made? Studies were pored over, interviews with welding engineers were held, and a careful examination of the most critical problem areas was made. Suspected trouble causes were isolated, suggested corrective measures weighed, and the ones most applicable were initiated. NASA and Space Division technicians worked side by side.

"We considered a lot of possible solutions," Ruud said, "and some of them sounded pretty far out at the time, but they worked."

For example, welding had previously been done under normal conditions of 50 to 60 per cent humidity, which was the average at Seal Beach. Freshly cleaned surfaces oxidized rapidly. Aluminum oxide has an affinity for moisture and absorbs it like a sponge. Under the heat of welding, this moistured surface oxide film breaks down into hydrogen and oxygen gases, and produces voids or gaseous pockets in the joint. By cutting humidity in the area to an average of 30 per cent, this substantially reduced moisture content in the air and thus lowered, proportionately, the number of these defects.

Humidity control was but one of nearly a dozen separate steps taken to improve on-station conditions. Creating an environmentally controlled clean room atmosphere, something relatively new in large welding operations, was near the top of the list. This wasn't easy, principally due to the enormous size of the work area, which encloses 225,100 cubic feet in the southeast corner of Building S-02. To effectively wall it off, a huge canvas curtain, 57 feet high and 60 feet across, was hung in place. It can be raised or lowered to permit stages in and out.

The only access to this room is through a specially constructed double-door air lock system, which helps maintain a positive pressure in the station so no outside air can get in. The second or inside door cannot be opened until the first one closes. Between the doors in an electric shoe brush machine. Once inside, technicians and engineers must wear white, lint-free smocks and nylon gloves. No smoking or eating is permitted. The epoxy coating on the floor is almost perpetually mopped. Floors and walls were even painted white to help employees "think clean."

Additionally, precise temperature control was maintained. And, during the welding operation, vacuum cleaners suck up chips and dust before they can settle.

Officials realized no one of the cleanliness innovations in itself would be a cure-all. But, they reasoned, the combination of them should have an appreciable effect on the final product.

It was decided, too, to change the actual mode of welding in station 1-A. The standard "skate" style had been used, wherein the tool is moved around the periphery of the stage. Under the newly recommended "rotary" concept, the tool remains stationary and the bulkhead and cylinder revolve around it, much like a giant phonograph record with the weld machine as the needle. NASA had effectively used this method on the Saturn V's S-1C booster stage. The basic advantage gained here is that better control can be maintained, because there is less chance of movement in the trim and weld head. This process is also time saving and easier to handle. Operators can remain in one spot without moving bulky cables around.

To better inspection techniques for joint cleanliness, an ultra-violet "black" light is now used. It can spot things that normally wouldn't have been caught, such as minute particles of lint or dirt.

Next came the vexing problems of offset: how to match the bulkhead and cylinder with unerring precision, perhaps the single most critical step in the entire operation. A split-hair mismatch can cause rejection of the entire job.

Inaccessible Areas

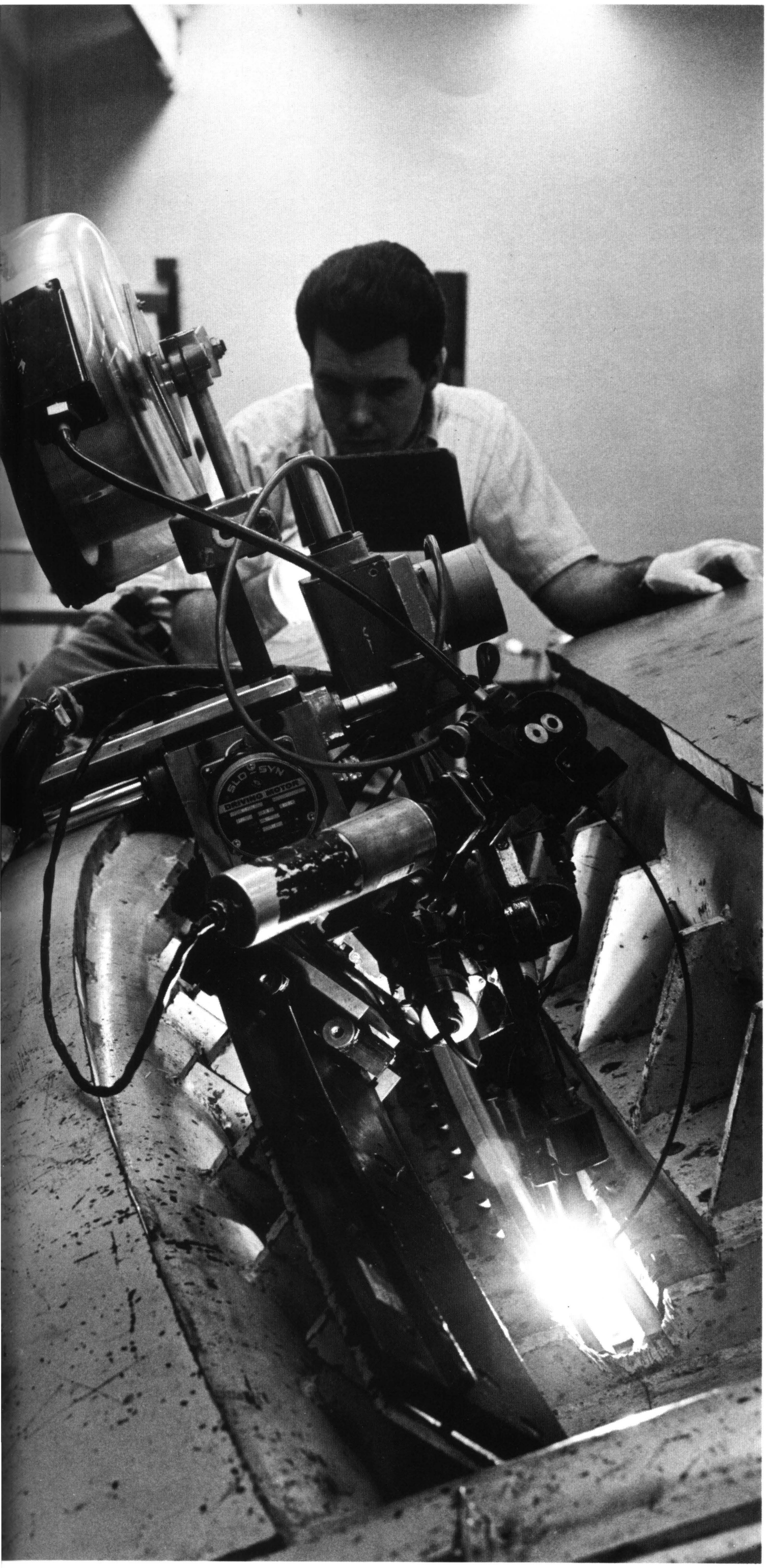
Previously, hand jacks had been used, but alignment adjustments could only be made down to areas about eight inches across. Necessary tooling created inaccessible areas, consequently it was extremely difficult to get an exact fit without excessive mismatch.

The solution? Backup bars which are placed inside the stage during the alignment process were redesigned with individual screws spaced every few inches, thus giving the bars a built-in adjustability. The screws can be alternately tightened or loosened until the bulkhead and cylinder mesh perfectly.

Not only has the offset problem been whipped, but considerable time has been saved too, and in this element of the work, time is of prime importance. Once the stage sections are matched and cleaned,

Intermediate bulkhead panels are welded to thicker, waffled outboard panels, right, at L.A. Division, then sent to Seal Beach.

To match cylinders within thousands of an inch, backup bars, far right, were redesigned with a built-in flexibility. Spaced screws can be alternately tightened or loosened until the cylinders mesh perfectly.


SLO-SYN
DRIVING MOTOR


MAX. CAP.
450 LBS. INCL.
40 FT. OF CABLE

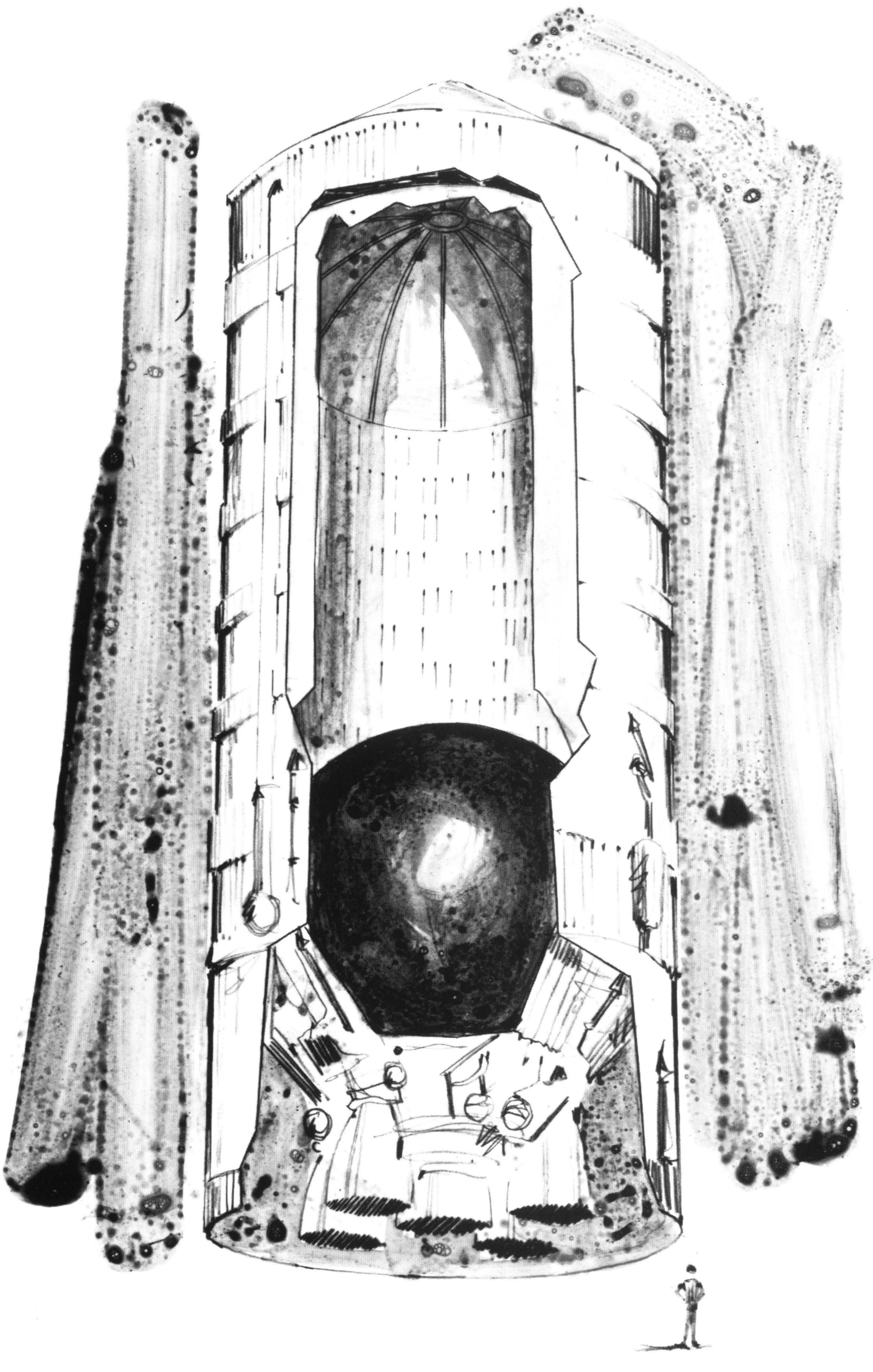
it is essential to weld them as quickly as possible. The longer the time span between cleaning and welding, the longer oxides have a chance to build up on the metal's surface, contributing to eventual defects. By using the new offset method with adjustable backup bars, this time frame has been snipped from 15 to 4 hours.

Once all these corrective steps had been decided upon, a temporary atmospheric control system station was set up — in five days. Its effect was both dramatic and immediate. On the first run-through, of the S-II seven bulkhead to cylinder number six, only four repairs, totaling 12 inches, were needed in the weld. This was reduced to three repairs for nine inches on the S-II eight bulkhead. Next, a test vehicle, the "Mini B," was processed — with zero repairs. Then, in January, came the S-II nine bulkhead. It, too, went through error free and well within the demanding offset tolerances. In fact, at the same time, the 113th cylinder quarter panel weld points were made without repair.

Backed by this proof-of-the-pudding data, it was decided to bring all welding stations up to 1-A's environmental control standards.

"We're getting good results," Ruud says, "because we're paying attention to infinite detail and getting the maximum use of our equipment in these improved stations. But we must maintain this quality. We can't take it for granted. It's too easy to get a latent defect. And, when you reach this quality, corresponding maintenance of schedules and reduction of costs fall into place."

At Seal Beach today, as the final half dozen or so S-II stages are put together, it is not enough to say the weld is better now than it was last month or yesterday. Engineers are striving for the perfectly welded vehicle. If their progress in eliminating errors, reducing offset and improving technology continues at its present pace, they just may do it.



After 12 bulkhead panels have been joined, opening under the canopy, left, called the "dollar section," is then welded into place.

Artist's cutaway drawing of cavernous S-II, right, second stage of Apollo/Saturn V.