The Bad News Bearings

Casting and polishing a replacement mirror today would cost an estimated $15 million, so the Palomar staff were understandably reluctant to risk treating the original like a twist-off bottle cap.

by Douglas L. Smith

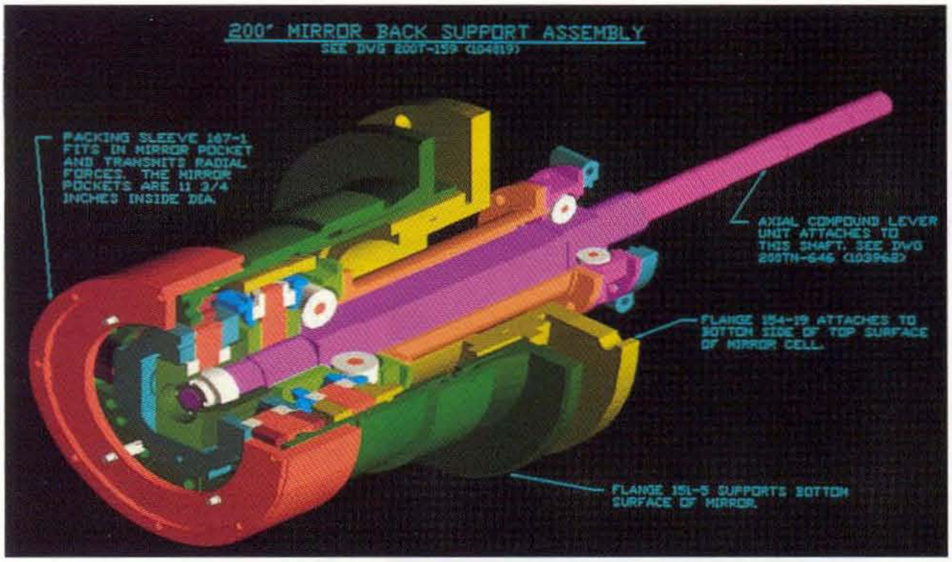
Removing the central gimbal assembly is the tensest part of the process. At 166 pounds, this is the heaviest piece to come out of the mirror and far too heavy to lift by hand. Even though Hal Petrie, Palomar's chief engineer, designed a special hoist for the job, getting the gimbal to ground reminds one of the plight of the fellow holding a bucket of water against the ceiling with a broomstick. Petrie (left) and preventive maintenance mechanic Bruce Baker (right) stabilize the irreplaceable chunk of 1930s engineering bal-anced one false move away from a 14-foot plunge to a concrete floor. Not a sigh of relief, perhaps, but once the assembly is safely down on the forklift, there's certainly a collective letting go of the breath.

Palomar Observatory's 200-inch Hale Telescope—the world's biggest for nearly 30 years, and still one of the most productive—began to show its age recently. Even after 45 years of nonstop use, the telescope remains a premiere scientific instrument, thanks to advanced instruments and aggressive maintenance. But now parts of the sensitive system of supports that maintain the mirror's shape were beginning to stick. And the parts were unreachable—way up inside the mirror itself. In 1947, while the mirror stood balanced on its edge in Caltech's campus optical shop, supported by a giant cradle, the supports had been inserted into pockets cast in the mirror's honeycombed underside. The mirror was then gently tipped into its mounting—a two-foot thick labyrinth of steel members called the mirror cell—on which it lies flat and from which it has never since been removed. Casting and polishing a replacement mirror today would cost an estimated $15 million, so the Palomar staff were understandably reluctant to risk treating the original like a twist-off bottle cap. But everyone, from Observatory Director Gerry Neugebauer on down, agreed that something had to be done.

Says Hal Petrie (BS '68), Palomar Observatory's chief engineer, "For some time, the infrared observers, who use very high magnifications, had been complaining about astigmatic images—images that weren't round, and in some cases were very strongly out of round. What you should see is a round point of light that gets bigger and blurrier as you go out of focus. But as they went out of focus in one direction, they'd see an oval oriented one way; and on the other side of focus, they'd see an oval oriented 90 degrees to the first. And at focus, they basically got the intersection of the two ovals. It looks sort of round, but it's not as sharp as it should be.

"Even in its worst state, it's not a bad shape. Generally the images are better than the seeing. But on nights of good seeing, the mirror's figure can deteriorate the image. And we do get some nights of very good seeing here." The "seeing" is the distortion imparted to the image by turbulence in the atmosphere. With the telescope at zenith, and the support systems working properly, 80 percent of the visible light from a distant source focuses in 0.45 arc seconds, and about 50 percent in $\frac{1}{3}$ arc second. But off zenith, the numbers get about 50 percent worse. Depending on the time of year, the average atmospheric distortion at Palomar is about one arc second, but on good nights it's only half that. In the infrared at two to three microns, it's even better.

Trouble is, like all large telescope mirrors, this one can't support its own weight. It sags out of its optimum light-gathering shape the moment it no longer points straight up. Even though only the top $4\frac{1}{2}$ inches of the 22-inch thick mirror are solid glass—the rest is ribbed into a honeycomb pattern to save weight—it weighs nearly $14\frac{1}{2}$ tons. A 200-inch mirror thick enough to be self-supporting would be impossibly heavy, as is the alternative—a perfectly rigid telescope that could hold a flexible mirror in shape. (The telescope tube weighs 138 tons as it is.) Thus, in a compromise between stiffness and weight, the mirror cell flexes by about a millimeter as the telescope moves from zenith to horizon.



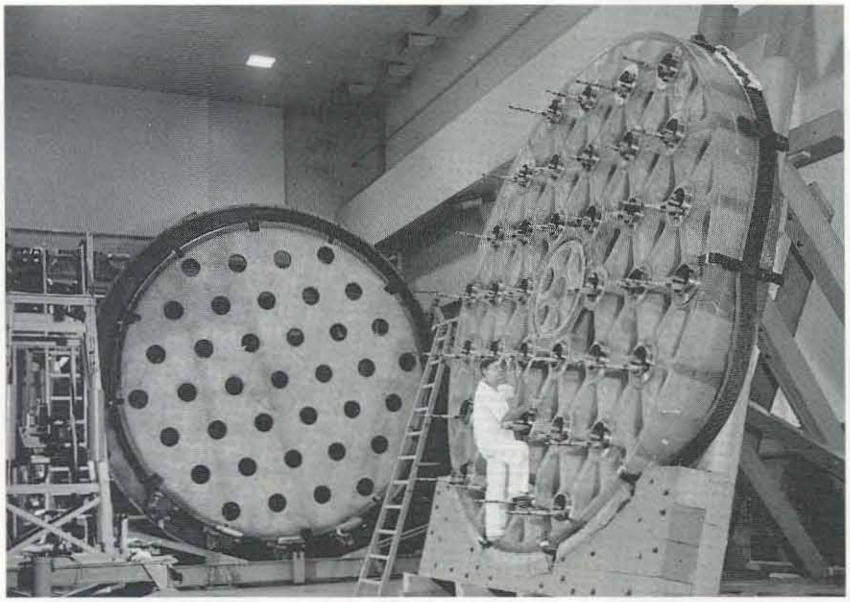
A CAD drawing of the back support, rotated 90° from its vertical position in the mirror. The dark green sleeve fits snugly in the mirror pocket, while the yellow-green flange bolts to the mirror cell. The axial and radial forces needed to keep these two fixed points in their correct relative positions are transmitted through a common shaft (purple). The axial lever unit (not shown) bolts to the lavender casting's bottom and imparts a force to the shaft's exposed end. The force acts via the concentric gray-blue and maroon rings of the upper gimbal assembly on the lime-green sleeve, which is wedded to the dark green sleeve, and hence on the mirror. The radial force is mainly generated by the weight of the axial lever-arm assembly. The white bearings in the salmon pins in the dark blue ring act as a fulcrum for this force, transmitting it through the upper gimbal assembly to the red sleeve, which imparts it to the mirror.

And this is where the sticky supports come in. Between the cell and the mirror are 36 "back supports" that maintain the mirror's figure, or precise optical shape, despite the flexure of the mirror cell. Each support is an elaborate system of weights and levers that exactly balance gravity's force on the mirror no matter where it points. And since both the magnitude and the direction of the compensating force change as the telescope moves all over the sky, the lever systems are masterpieces of subtle mechanical engineering—a pinnacle of 1940s high technology. (See the cutaway drawing above.) Each support counterbalances the force's axial component (which acts along the telescope's length) and radial component (which acts perpendicular to it) with separate sets of weights acting on separate sets of levers with different lever ratios, but then applies both forces to the mirror through the action of a single shaft on two sets of gimbals. (Other telescopes of a similar vintage use two separate sets of simpler lever systems for radial and axial support. And the simpler systems provide radial support only at the mirror's edge, but the Hale's back supports distribute the radial load uniformly over the entire 200-inch mirror, giving it a better figure.) The supports near the center of the mirror balance about 700 pounds' worth of mirror each. Those at the periphery, where the mirror is thicker and the supports are more widely spaced, carry up to 1,100 pounds. Since the lever systems are all floating—"they give you a feeling like a waterbed," says Petrie—three supports at 120° intervals around the mirror's periphery are locked down to "define" the mirror, keeping it parallel to the mirror cell.

When the mirror started to lose its figure—as so many of us do at age 45—the back supports were immediately suspect. After all, there were bearings up in there that hadn't been lubricated in 45 years! But were just a few of them sticking, or all of them? Maps of the mirror's shape, made by a sophisticated wavefront analyzer built especially for the Hale Telescope by Gary Chanan, professor of physics at UC Irvine, were inconclusive. They did show that there was a lot of hysteresis in the mirror—in other words, the changes weren't reproducible. If you mapped the mirror's precise shape when pointed at the zenith, then tilted the telescope as far south as it would go, and then as far north as it would go before bringing it back to the zenith, the figure would change constantly as the telescope moved. But when the telescope was finally brought back upright, the mirror didn't always return to its initial figure.

To ferret out the root of the problem, says Petrie, "during a long series of nights when we were taking lots of engineering data last fall, Keith Matthews [BS '62], a member of the professional staff in physics who has designed many of the infrared instruments for the telescope, actually rode in the Cassegrain cage of the telescope as it was pointed at different places in the sky. [The Cass cage, as it's called for short, bolts onto the back side of the mirror cell, and provides access to instruments mounted at the telescope's Cassegrain focus point.] This was not an easy thing to do, because although the Cass cage has a floor to stand on, the minute you tip the telescope off zenith, the floor tips too. You start sliding around, and the next thing you know, you're standing on instruments or things. But we put a safety belt on him, and gave him a long broomstick. Then we took the telescope from the zenith, where the image was quite good, to a place in the south where we could frequently get a bad image. And when Keith just touched one of the back supports with the broomstick, the back support made a clunking sound and the astigmatism immediately went down by a factor of two. By moving the telescope around and touching every single one of the back supports we determined several things. One was that the mirror's shape could be improved by jiggling the back supports and getting the 'stiction' out of them, but that it never got as good as it was at the zenith. Also, about one-third of the supports went 'clunk' when you touched them, indicating that they had severe stick-slip problems."

How to get to those buried bearings was a real poser. Popping the mirror off the cell was not a



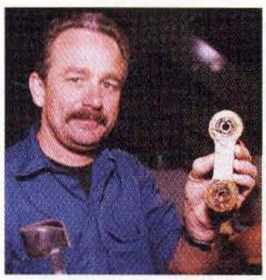
When the mirror stood on its side in the optical shop in the 1940s, getting the back supports out was easy. It's a bit trickier nowadays. From top: Petrie, facilities maintenance mechanic Russ Day, and Baker.

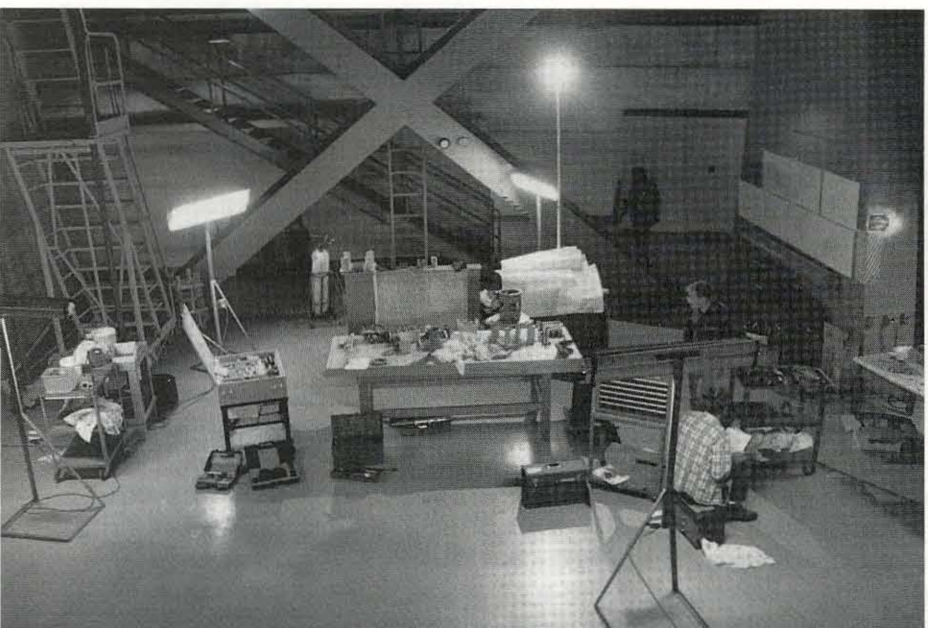
popular option, but nobody knew how much of a back-support assembly was accessible through the holes in the mirror cell below. Petrie explains, "These giants built the telescope, and as they retired and left the scene, not all their knowledge got transferred. Real folklore grew up around this. I go out with my own amateur telescope once a month, and other amateurs come up to me and say, 'Is it true that there are so many thousand parts in there, and nobody alive understands how they work?' In fact, we did know how they worked, although the details of their installation process had been lost. And there *are* a lot of parts, but they're conceptually fairly simple once you get into it.

"So Keith and I looked at the assembly drawings for the back supports, and attempted to understand how the mechanism was put together. We deduced correctly that you can't get the packing-sleeve assembly out, because it's bigger than the hole in the cell. But it wasn't clear that we could get all of the bearings out safely. So I started taking the old machine-shop drawings and converting them into 3-D CAD [computer-aided design] models using a program called AutoCAD." It took Petrie a month to get the drawings into the computer. AutoCAD builds objects by adding and subtracting appropriately sized and oriented "primitives"—simple geometric solids such as spheres, cylinders, and cones—from each other. "These parts are mostly castings, and with all their complex, whittled-out shapes, it often takes some imagination to figure out which primitives should be added and subtracted, and in what order." Petrie initially intended to use the model to see if he could get a fiber-optic camera or a tube full of lubricant up into the works. "Once the model was made, we realized that, in fact, you could get all the stuff apart without removing the mirror from the cell as had been done in the optical shop. We were also concerned that if we got it all out, could we get it back in? But the clearances are fine."

After several weeks of testing their procedures on the computer to assure themselves that they weren't about to do anything irretrievable, they very cautiously removed and inspected one of the worst back supports, unit K_5. Recalls Petrie, "When we took the first one apart on Memorial Day weekend, it was pretty clear that we had a lubricant failure rather than a bearing failure. We didn't have corrosion of the bearings, we didn't have pitting, or cracking, or anything like that." Nor were the individual components deteriorating. All the back-support parts that go inside the mirror are made of Invar, a high-nickel stainless steel whose thermal expansion exactly matches that of the Pyrex mirror. As a bonus, Invar doesn't corrode. (Corrosion could have caused parts to stick together, and perhaps break during disassembly.) The grease, however, had oxidized and polymerized into a tough, rubbery solid that had frozen some bearings outright. Others ran very rough as their balls ground up the dried grease. "We cleaned at least six bearings by hand, with toothbrushes, solvents, and hot, soapy water. A lot of that gunk was very hard to get out, but once we did, the bearings were fine."

The bearings had been out of sight all this time, but they hadn't been out of mind. Bruce Rule (BS '32)—Palomar's chief engineer when the mirror was installed, and one of Petrie's "giants"—and colleagues discovered early on that the telescope's performance improved if it was "exercised" periodically by driving it all over the sky for several minutes. This flexed the telescope, working the bearings and freeing them up. If this wasn't sufficient, the levers in one mirror-defining back support would be unlocked and cycled back and forth through their full range of travel a couple of dozen times, rocking the mirror about the axis created by the other two supports. This pushes all the other levers through a much wider arc than they normally move and tends to free up sticky bearings. Says Petrie, "that was done periodically, according to Bruce Rule, to 'break the crust that was forming on the grease.' I don't know if they really knew what was happening, because most of the bearings they were servicing by this process were up inside the mirror, inaccessible. We don't know how often it





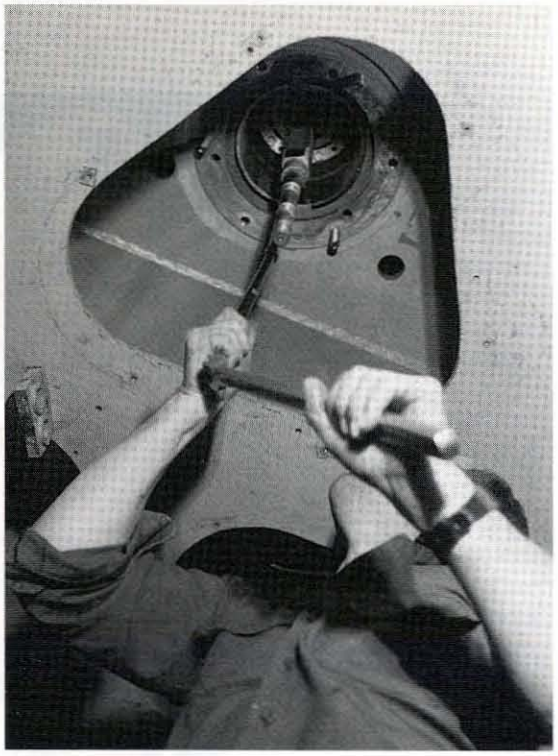
Top: As seen from the dome-level catwalk, the telescope monopolizes the eye, dwarfing the huddle of people and paraphernalia on the hydraulic ram below it. The ram, built into the dome floor to provide access to the mirror cell, becomes the scaffold for most of the removal and reinstallation work, although a mobile scissors lift was needed to reach the outer supports. In order to get to the bearings, the telescope had to be locked at zenith, and the Cass cage unbolted. Once lowered on the ram and shoved out of the way into the lower-left corner of the photo, the cage and its multitudinous electrical outlets became a handy power strip for the work lights on the ram. Middle: Baker shows off the culprit grease. Bottom: The work area, which is out of sight behind the gargantuan steel pier that dominates the right side of the top photo.

was done, either." It is indisputable, however, that the force required to move a lever after exercising it was smaller.

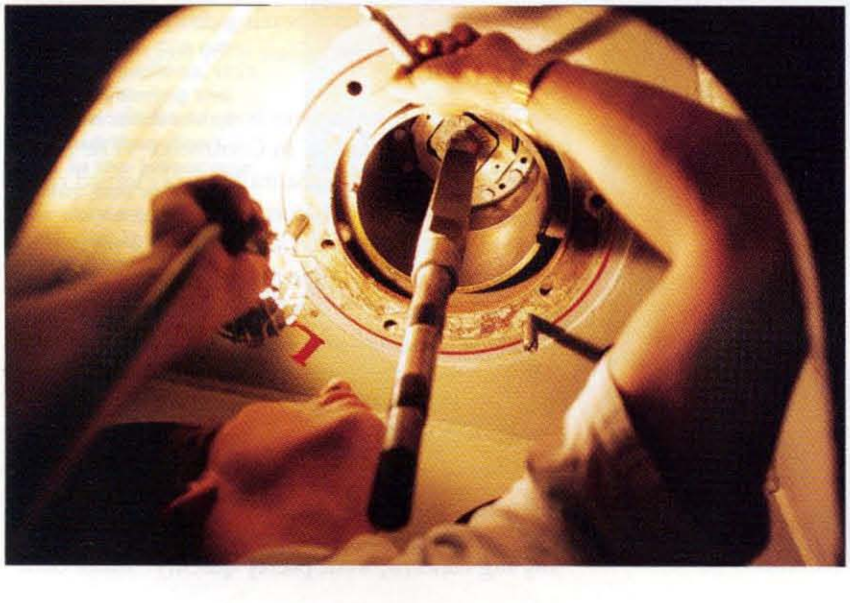
Not all of the grease is 45 years old. The axial assembly, a double-compound-lever system of near-baroque complexity that Rule designed, hangs down into the mirror cell and has accessible grease fittings. "We don't have a good history of how often those were greased, or what they were greased with," Petrie notes. "There are some vague comments in some of the reports about a class of greases, but no brand name or chemistry is given." In 1987, Palomar Superintendent Bob Thicksten flushed a hot silicone-based oil through the grease fittings to clean out whatever could be cleaned. "They saw at least three different kinds of grease come out," Petrie continued. "They saw 'Gargoyle grease,' which is an old, red grease from the Gargoyle Oil Company; and they saw black grease, which is the molybdenum disulfide grease commonly used around here now; and then there was some other, clearer, grease of unknown composition." Once the bearings were flushed until clear fluid came out, silicone grease was injected.

But now they're discovering that the hot oil didn't get all the way through every bearing. "We're still finding mixtures of different kinds of greases," Petrie says. "In some cases, the grease fittings were plugged and no grease got in. So although it helped a lot, and those bearings are in better shape than most of the ones in the mechanism, it wasn't a complete fix. And it only affected the 13 bearings per assembly that are accessible from under the telescope. The other 26 were up inside, getting no attention."

Once computer technology had shown the bearings to be reachable, decisions had to be made: What grease to use? Would a redesigned system be better? The Palomar staff looked into a number of different greases, and considered such exotica as ceramic bearings that never need lubrication. They opted to stick with the existing design, since its mechanical aspects were sound, and put in new bearings lubed with high-performance grease. This grease had to have long-term stability, offer corrosion protection to the bearings, and not absorb water. And finally, the lubricant is periodically exposed to a 10^{-5} torr vacuum every two or three years for five or six hours, when the mirror gets realuminized. Thus the lubricant has to have a low vapor pressure, or it will boil away into the vacuum and contaminate the mirror's reflective aluminum coating. While not quite the void of interplanetary space, this vacuum is equivalent to the rarefied air of Earth's ionosphere some 80 miles up. So Petrie,



Clockwise, from upper left: The axial support unit comes out first, once Baker rotates it in place and removes parts that won't otherwise clear the cell. Baker and engineer Bob Weber lower the 50-pound axial unit out. Once the central gimbal assembly is gone (p. 34), it takes a socket wrench with a four-foot extension to reach the bolts securing the upper gimbal assembly. The orientation of the upper gimbal is marked before it's removed from the cell. The gimbal comes out, its 33-inch shaft dangling within the hollow interior of Petrie's hoist.



armed with a list of NASA contacts provided by astronomy and space-science photographer Roger Ressmeyer, tracked down the spacecraft-bearing experts at JPL and other NASA centers. Several experts recommended their standard flight-certified spacecraft grease, called BrayCote 601. This stuff doesn't oxidize and its vapor pressure is practically nil—10^{-13} torr. It's also a \$100-per-ounce perfluoropolyether that comes in two-ounce syringes.

The first opportunity to fix a lot of bearings came the week of July 26-31. The plan was to service the 10 worst-performing supports—the ones that went "clunk" when Matthews nudged them. The operation would go like an assembly line—supports would be pulled out, dismantled, bearings replaced, reassembled, and reinstalled in a smooth flow.

Each support comes out in several pieces, which are carried to a temporary work area set up beneath the massive horseshoe girder on the telescope's north pier. There, surrounded by a ring of work lights on stands, the units are placed on long tables covered with brown butcher paper. The area could be an operating theater, with small carts instead of gurneys, and tool chests on wheels instead of heart monitors and anesthesiology equipment. The overall effect is as if the surgical team from M*A*S*H had set up a triage station in the *Enterprise's* shuttle bay.

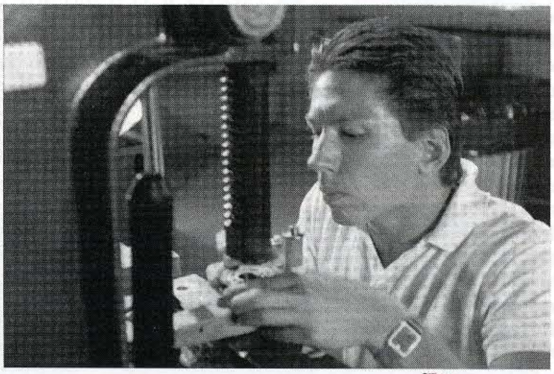
In the operating suite, the disassembly proceeds amidst a clutter of screwdrivers and wrenches, paintbrushes and cleaning rags, and the ubiquitous $2^1/_2$ pound Folger's coffee cans filled with everything imaginable. Dissecting some components is easy, as these things go, but disemboweling the upper gimbal assembly isn't. Most of the pieces that hold it together are hidden within a steel sleeve. "You have to work through the windows," says Petrie. There's a lot of twisting, jimmying, and finagling between removal of successive parts, but eventually, everything yields. Nuts, bolts, washers, and other small stuff are consigned to yellow plastic trays labeled with the assembly's name. The larger pieces lie neatly arranged on the butcher paper, awaiting cleaning with paint thinner to get the old grease off.

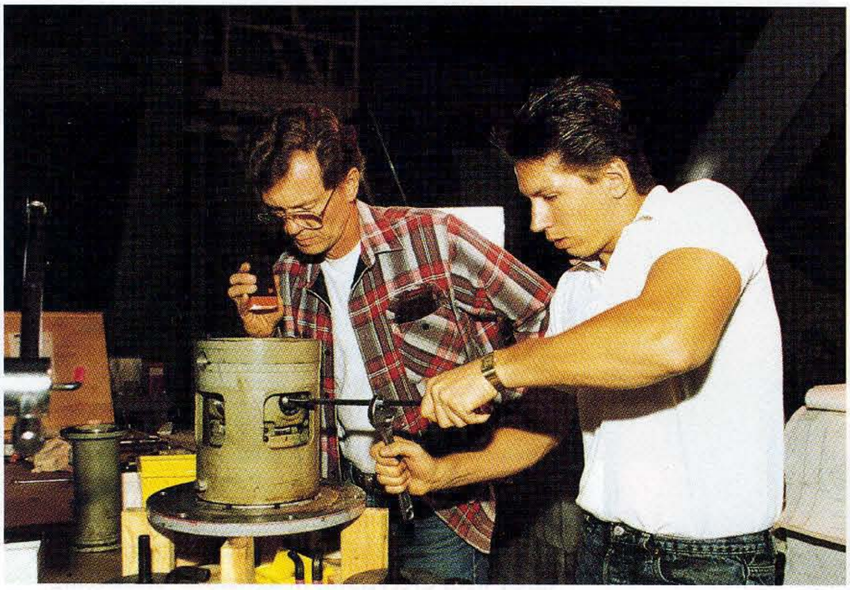
As the old bearings are removed, they're given a cursory examination and tossed into a corrugated cardboard box by the north pier. The bearings themselves are unremarkable. The larger ones wouldn't look out of place in the wheels of a riding lawnmower.

Pulling the old bearings out goes quickly. Not so getting the new ones in. Several people can be dissecting different parts at once, but there's only one arbor press to seat the snug-fitting bearings. As engineer Bob Weber seats a bearing in a connecting rod in the axial assembly, he explains, "If you don't center the bearing in its hole, one side or the other would rub. And, unfortunately, they didn't put a shoulder on the side of the hole to seat the bearing against." When in doubt, improvise. Someone digs out a dime, which Weber puts under the bearing as a spacer. Petrie remarks, "Money plays a very important role in all this. The first one we did, we had to sacrifice a few pennies to get a bearing out. Now we're making a shim out of a dime." Weber produces a micrometer and announces mournfully, "Dime's too thick." (They need a 0.050 inch spacing between the outer bearing race and the surface, and the dime is 0.052 inch thick.) "So I press the bearing down to the dime, measure it, and then adjust it by feel. The dime gets it really close."

The new bearings were bought off-the-shelf from King Bearing Co. in Commerce. The Aircraft Bearing Corp. in Santa Monica cleaned the manufacturer's grease from the bearings and packed them with BrayCote 601. "It's very time-consuming to clean bearings by hand," Petrie explains. "But they specialize in doing this—they have a clean room, and machines that blow compressed air and solvent through them. Then they use syringes to inject exactly the right amount of grease."

The original plan was to take out 10 supports, but, says Petrie, "we ended up changing out six units. Removal and installation, which had been my big concern, went pretty quickly. More time





Top: Facilities maintenance mechanic Dana Cuney gets the old grease off with paint thinner. Eventually, rags and paintbrushes give way to a wire toothbrush to clean out all the holes and cutouts. Some of the parts have *a lot* of holes and cutouts. Middle: Weber uses the arbor press to seat a bearing. Bottom: Petrie and Weber dismantle a central gimbal assembly, a process not unlike opening a Chinese puzzle box.

Top: "I got into electronics so I wouldn't have to do this kind of stuff," grouses Superintendent Thicksten, only partly in jest.

Middle: Before the bearings reach journey's end at the telescope, they sojourn in Palomar's machine shop, where they take a spin on the lathe. Impaled 20 at a time on the lathe's spindle, the bearings spin against a rubber squeegee pressed gently against their outer races. "Running in" the bearings this way burnishes the balls against the race, substantially reducing their rolling friction, says Petrie. "In normal applications, this happens during the first few minutes of use, but they don't spin in the telescope —they just rotate a few degrees back and forth—so it would never happen."

Bottom: Sometimes parts need a little encouragement to go back together. Electrician Paul Van Ligten lines 'em up while Weber does the honors.

was spent in disassembly, cleaning, reassembly and adjustment than I had anticipated. The last one went in about dinner time on Friday. Saturday morning before the rotating ring and Cassegrain cage were reinstalled, I exercised the mirror for three minutes at each of two defining points. That night, we did a knife-edge test at prime focus. Neither Thicksten nor I could see any mirror problems. A couple of nights later, I talked to Keith Matthews, who was observing at the 200-inch. He indicated that the mirror was pretty good the first night, but there is still some astigmatism. He did not see any of the severe astigmatism he has sometimes seen in the past.

"It will probably be next year before we get all these bearings out. The observing schedules are set each fall for the next year, and certain blocks of time for engineering are taken out. So we're operating right now on the schedule that was set last October. And we can't just arbitrarily bump people to continue doing this work—they've been counting on their observing time for a year. This run right now involved negotiating with a bunch of observers, shifting them to the Fourth of July weekend, and us here. We've attempted work like this in the past in the dead of winter, when observers are more willing to give up time, but discovered that it's really hard on us." As anyone who has ever tried to change a tire in midwinter in the midwest knows, your skin sticks to everything, but gloves really hinder you.

"We can now pull an assembly out, do a quick inspection of it, and put it back in, in one day," Petrie says. (Disassembling one, putting in new bearings, and centering and readjusting everything takes a bit longer.) "We don't intend to let these things go another 50 years. Especially now that we know how to do it.

"Personally, I see this as the beginning of a project in which we get all of the mechanisms working the way they were supposed to, and then, using the wavefront analyzer, we might be able to get some really good response functions by hanging weights on each individual back support and seeing how it changes the mirror. Then if we have a disfigured mirror, we could identify where we should apply forces to fix it." The ultimate end might be to add small, computer-driven actuators to the lever systems, turning the mirror into an "active mirror" that constantly adjusts itself for optimum focus, just as the large telescopes being built today do. But that would take time, engineering, and money, because such a scheme requires a minimum of 108 actuators—three for each back support. For the moment, the folks at Palomar are happy to bring the venerable Hale into the 21st century with perfect vision. □