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Inertia welds launch Shuttle

Manufacture of the Space Shuttle's main-engine injectors relies on a combination of inertia welding and EDM

WHEN THE SPACE SHUTTLE rose majestically from its launching pad at Cape Canaveral, it ushered in a new era of space flight: launched like a rocket, Columbia, the first true "spaceship" reentered the atmosphere like an airplane and landed smoothly at Edwards Air Force Base so that it may be refurbished and sent aloft again within six months. In fact, according to plan, each Space Shuttle is to have a life of 100 missions!

A key performer in that dramatic and earthshaking blastoff was a cluster of three rocket engines designed, developed, and built for NASA by the Rocketdyne Div of Rockwell International. The Space Shuttle main engines (SSMEs) are the most advanced liquid-propulsion rockets ever developed. To begin with, they are lighter and more efficient and will operate at higher temperatures and pressures than any space-flight engine ever used.

More important, unlike earlier rocket engines, which were used only once, the SSME is designed for 7½ hr of operation over a life span of 55 missions. Maintenance will be performed between flight missions—a little like the routine maintenance used by commercial airlines—to lower the cost per flight.

Recycling the most complex space vehicle ever built is no easy task, and this requirement has had a great influence on the way the vehicle and its systems are constructed. The most visible—and also most publicized—innovation has centered on the controversial tile skin that brought the space craft safely through its searing descent into the atmosphere.

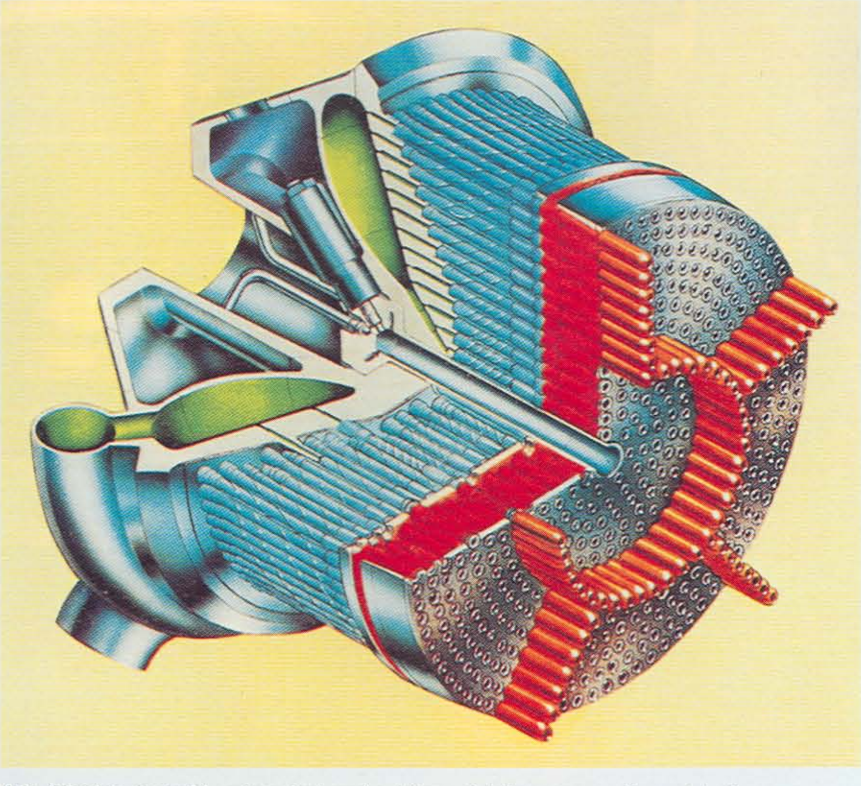
But manufacture of the craft, particularly of the reusable main engines, has also required a great deal of ingenuity and innovation. For example, buried deep inside the fiery throat of each rocket engine is a cluster of fuel-injector posts that have presented some formidable manufacturing problems. The solutions were found with the creative application of inertia welding and electrical-discharge machining (EDM). In fact, this somewhat unusual combination of techniques is the only way the critical main-injector assembly could be produced.

More thrust per pound

Space Shuttle main engines burn propellant at high pressure (3264 psi) to provide maximum thrust within a compact engine envelope. Each high-efficiency SSME develops 512,300 lb of thrust, more than twice that of the J-2 engine, which powered the Saturn V launch vehicle to send Apollo astronauts on their historic lunar flight.

To put this awesome power into some more conceivable perspective, consider the following. The energy released by the three Rocketdyne Space Shuttle main engines at full power level is equivalent to the output of 23 Hoover Dams. And, even though the complete SSME weighs only 1/7 as much as one railroad diesel engine, its high-pressure fuel pump delivers as much horsepower as 28 diesel locomotives while its high-pressure oxidizer pump delivers enough power for 11 more. Or, on a more personal level, if one engine could be scaled down to less than 3 lb, it could still develop sufficient thrust to lift a grown person.

The rocket-engine design combines the merits of high-chamber-pressure operation, a high-performance bell-shaped



Main-injector assembly mixes fuel and oxidizer. Oxidizer passes through hollow injector posts while hydrogen is swirled by their spiral-fluted exterior

By George Schaffer, senior editor

nozzle, and a regeneratively cooled thrust chamber for maximum performance and long life. In regenerative cooling, which has been used in all the major high-thrust engines built to date, some of the liquid propellant is flowed through cooling passages in the walls of the thrust chamber and returned to the injector to be burned with the balance of the propellant.

The propellants are liquid hydrogen (the fuel) and liquid oxygen (the oxidizer). Maximum energy is extracted from the propellants through a staged combustion cycle that provides for their total use. Two preburners operate at mixture ratios of less than one part each of oxygen and hydrogen to produce hot exhaust gas, which is actually hydrogen-rich steam. This hot gas drives the turbines to two high-pressure turbopumps required to bring the propellants from tank pressure to operating pressure.

From the turbopumps, the hydrogen-rich steam is transferred by a hot-gas manifold to the main injector, where it is mixed with additional liquid oxygen for combustion in the main combustion chamber. This combustion process is completed at a mixture ratio of six parts of oxygen to one part of hydrogen.

The engine operates at greater temperature extremes than any mechanical system in common use today. The liquid-hydrogen fuel, one of the coldest liquids in existence, is at −423F; when the liquid hydrogen and liquid oxygen are burned, the temperature in the main combustion chamber is 600F, higher than the boiling point of iron.

A forest of injector posts

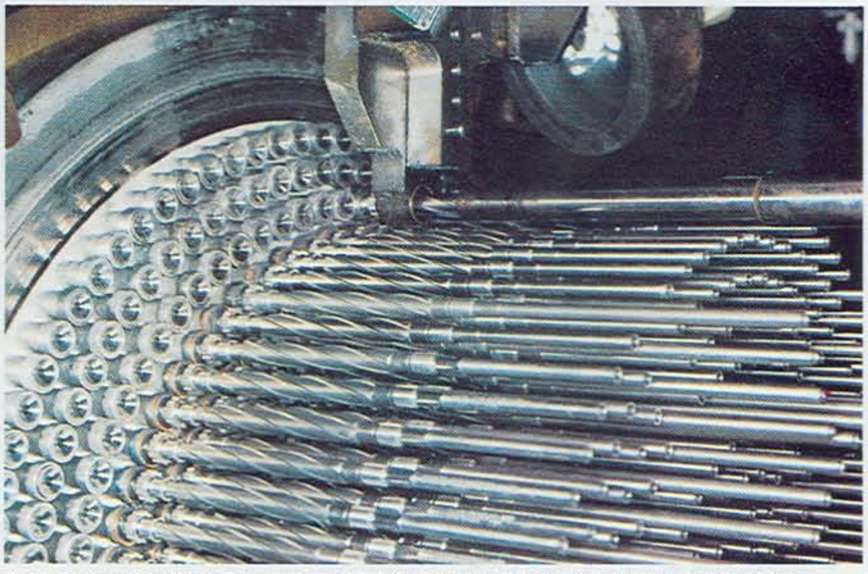
The fuel and oxidizer meet at a faceplate in the main injector after having been mixed by the injector posts: oxidizer passes through the center of the hollow posts while the hydrogen fuel is swirled into the mixture by spiral flutes extending along the exterior of the posts. A forest of 600 injector posts, arranged in a pattern of concentric circles, terminates at the faceplate. The result: a ball of fire.

The injector posts must operate reliably at the heart of this inferno. Originally, the posts were made of 316L stainless steel, but, under extensive testing, some posts succumbed to fatigue failure. Now they are made of Haynes 188 cobalt-base alloy. The posts are mounted to mating hollow stubs protruding from the main-injector base plate, which is made of Inconel 718 material by electrical-discharge machining.

Inertia welding does it

The initial problem encountered by manufacturing engineers was how to

Injector stubs on main-injector base plate are drilled in preparation for welding of injector posts. Note tiered concentric-ring arrangement of the 600 stubs



Drive bar on inertia welder (shown slightly retracted) is steadied by guide bushing. Serrations on post help grip drive bar. Guide rings on stubs will be removed effect the mating of the closely spaced forest of injector posts to the tiered concentric pattern of stubs and arrive at an assembly of sufficient integrity to withstand the grueling service conditions. A welded joint was called for. But how to accomplish welds at the bases of 600 individual closely spaced posts approximately 3/8 in. dia and 8-12 in. long? It would be impossible to direct a welding torch or electrode at these deeply buried locations, no less so to direct the course of the welding action. The solution: inertia welding.

Inertia welding, a form of friction welding, is an autogenous joining process in which the heat for coalescence is produced by direct conversion of mechanical energy to thermal energy at the joint interface. The mechanical energy is generated by the sliding action between rotating or rubbing surfaces at the joint interface. It is actually a solid-state joining process, in which coalescence occurs at a temperature below the melting point of the metals being joined.

In inertia welding, one member of the assembly is held stationary while the other is chucked in a spindle on which is mounted a flywheel of predetermined size. The spindle and flywheel are first rapidly accelerated to a predetermined speed with the parts not in contact. When the rotating assembly reaches that speed, it is disconnected from its drive, and the two pieces are quickly brought together under a heavy and constant axial load.

The kinetic energy stored in the flywheel is thus rapidly converted into frictional heat, and the plastic surfaces that develop are mixed and heavily worked mechanically as the mass smoothly slows to a stop. Coalescence actually occurs before the rotating mass comes to a halt. The remaining flywheel energy then forges the bond and refines the grain structure.

Among the advantages of friction welding particularly suitable to the injector-post-joining project is the fact that it is relatively clean, with little spatter and no arcs, fumes, or scale; and the heat-affected zone is very narrow, with a grain size that is often smaller than that of the base metal.

Fixture aligns stubs

A standard lathe-like inertia-welding machine from Manufacturing Technology Inc (Mishawaka, Ind) was adapted for the task. The main-injector base is held stationary while the individual injector posts are rotated by a drive bar and, after being decoupled from the flywheel, are brought up against their respective stubs to form the weld.

A special fixture provides for alignment of each stub on the base with the fixed drive-bar axis. The headstock-like fixture consists of a cylindrical indexing drum mounted on a vertical adjustment slide. A shot-pin mechanism and 600 accurately spaced and bushed holes on the circumference of the drum are used to manually index the injector base, mounted on the fixture's faceplate, to appropriate angular positions. The vertical slide motion is then used to provide the necessary radial motion for alignment. In addition, a small horizontal slide motion is available for fine adjustment. The entire fixture retracts 12 in. to facilitate loading of the injector base.

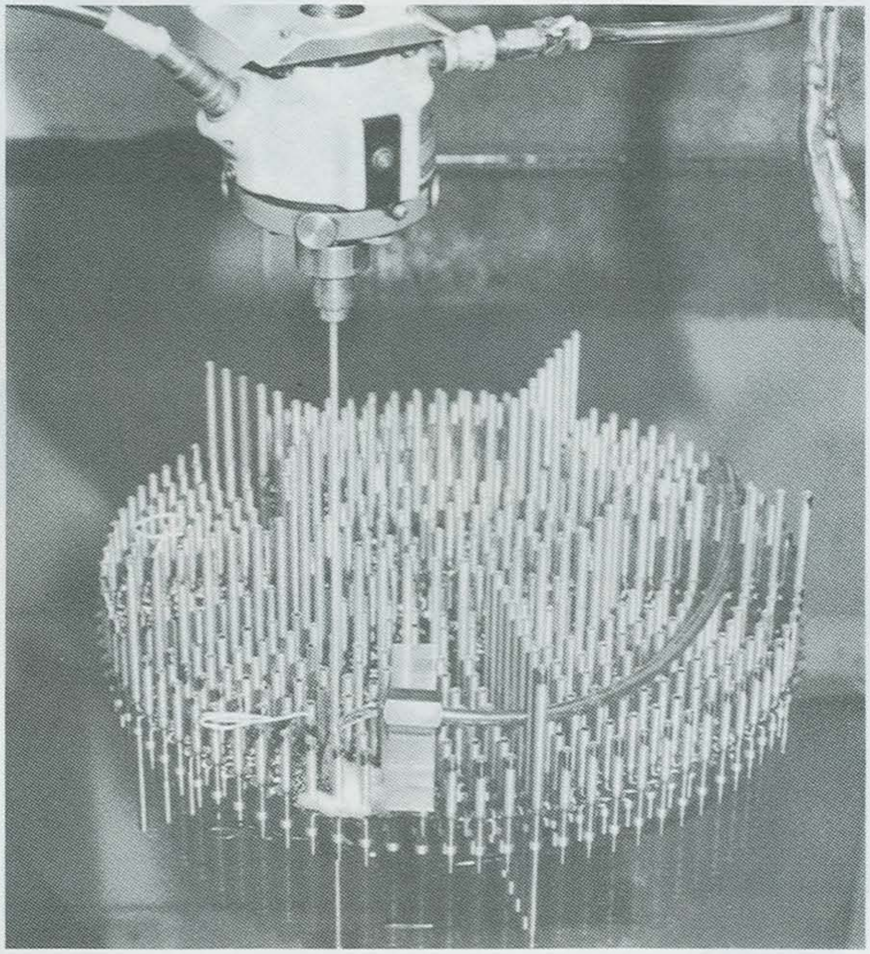
Injector posts are provided with a serrated ring that grips the inside of the relatively long drive bar to transmit rotation. The posts are inserted manually and driven home with a mallet. The drive bar is about 14 in. long, much longer than normally recommended by MTI: a length equal to 1½ times the diameter is usually considered the limit. A special guide bushing helps to overcome the extremely high aspect ratio and stabilizes the long, thin guide tube.

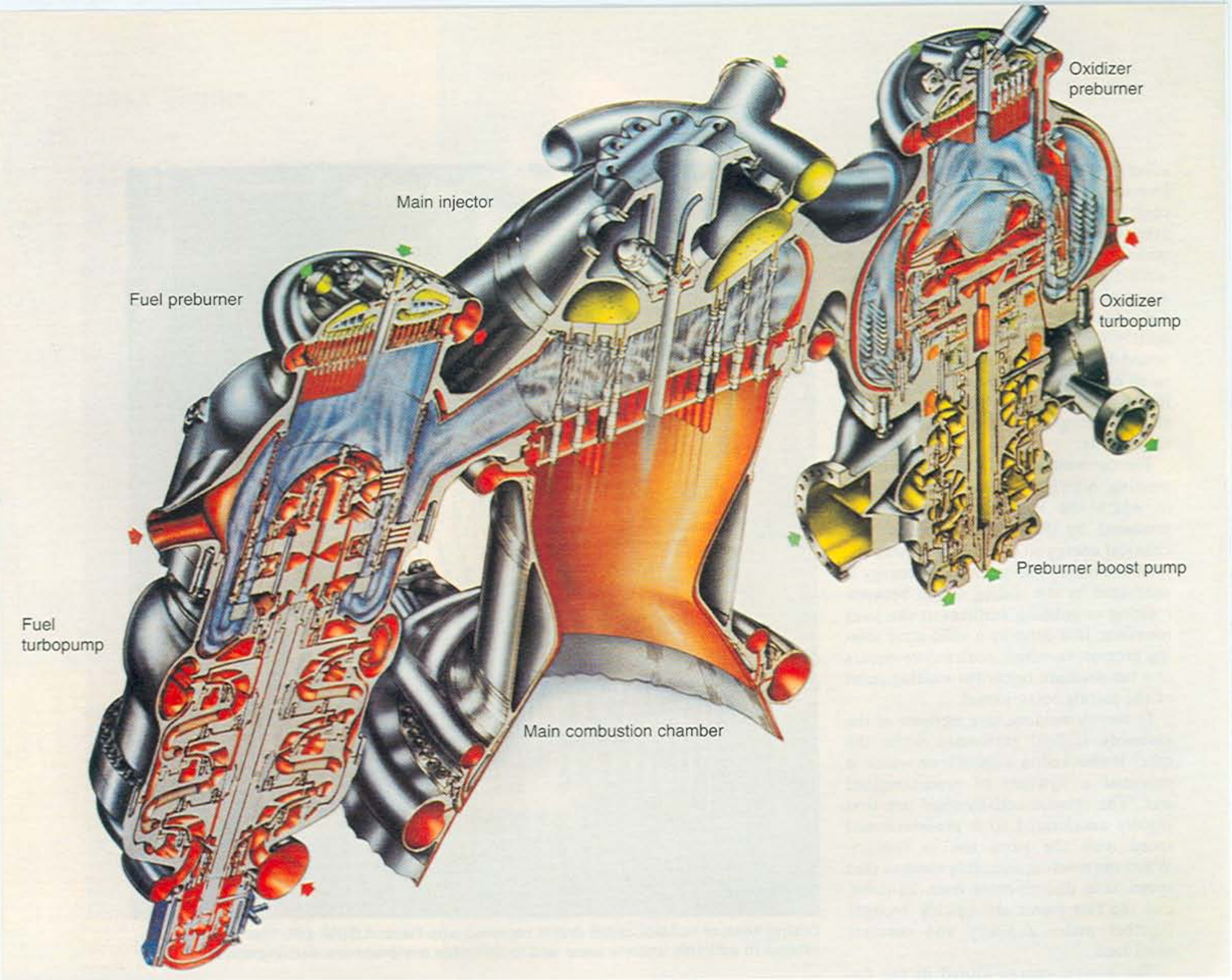
Other modifications of the machine include special instrumentation to record the various machine parameters. These include speed (approximately 3000 rpm), applied axial force, upset dimension (axial), and torque (as a function of deceleration time).

Before welding, each stub is fitted with a special ring to help align the posts, further stabilize the operation, and also limit the expulsion of weld metal during the actual inertia-welding process. These rings are subsequently machined off on a jig borer using a special hollow, long-stemmed facing tool.

Expulsion of weld metal on the inside of the injector posts must also be carefully removed to ensure clear passage of oxidizer during engine operation. This weld flash on the new Haynes 188 posts is extremely hard—the heat of welding brings it above the austenitic temperature—and, therefore, is quite unmachinable by normal metal-removal methods. EDM is the only way.

A Fosdick radial drilling machine has been modified for the purpose. A special


Drilling head of Fosdick radial drill is replaced with Raycon EDM unit. Electrode is rotated to maintain uniform wear and to eliminate any problems with eccentricity



Main injector (center) is welded to hot-gas manifold and flanked by fuel preburner and oxidizer preburner in powerhead assembly. All-welded construction results in high-pressure capability at minimum weight

table was mounted on the base to support a dielectric tank of sufficient size to handle a main injector, and the drilling head was replaced with a Raycon EDM electrode head and power supply. The electrode is a long piece of ordinary, straight, hard-drawn copper tubing that enters the 0.188-in.-dia hole of the posts.

The electrode is rotated to maintain a uniform wear rate around its terminal end and to eliminate any problems of eccentricity. Suction on the electrode pulls dielectric through its hollow center to provide flushing. Even more important, the suction captures the slug of flash material once it has been released, enabling the operator to account for it. Each of the 600 slugs must be accounted for to ensure that none is lodged where it might subsequently interfere with proper operation of the assembled engine.

In the assembled engine, the main injector is an integral part of the powerhead assembly, which includes the fuel preburner and the oxidizer preburner. The main injector is electron-beam welded to the hot-gas manifold and is straddled by the two preburners, which are also EB-welded to the manifold. Welded construction is used whenever possible on the SSME, to minimize weight (it weighs less than 7000 lb) while maintaining access to the internal areas of the engine for inspection and maintenance. More than 200 major EB welds are required to fabricate an SSME, some more than 1 in. deep.

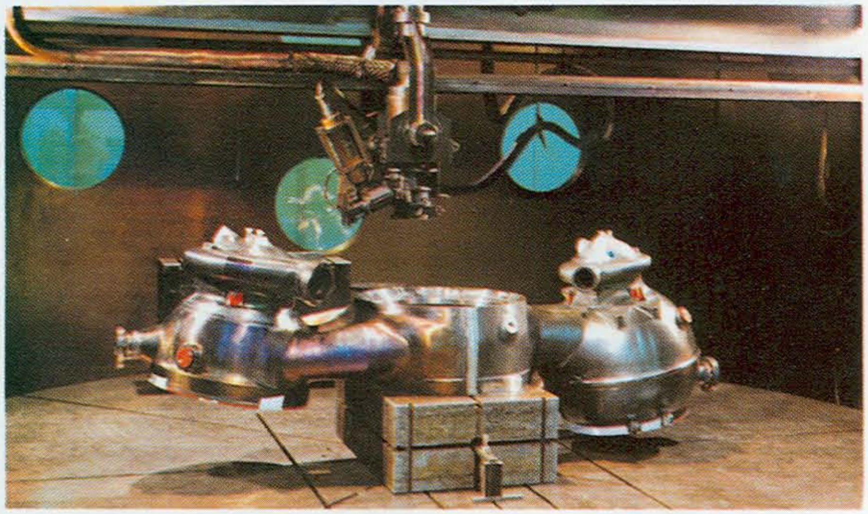
Rework is a problem

Once the main injector has been welded to the powerhead assembly, rework of the injector posts becomes a problem. The complete powerhead assembly cannot fit on the present inertia-welding machine, and it would therefore be necessary to physically remove the injector assembly by burning it away from the manifold with a cutting torch.

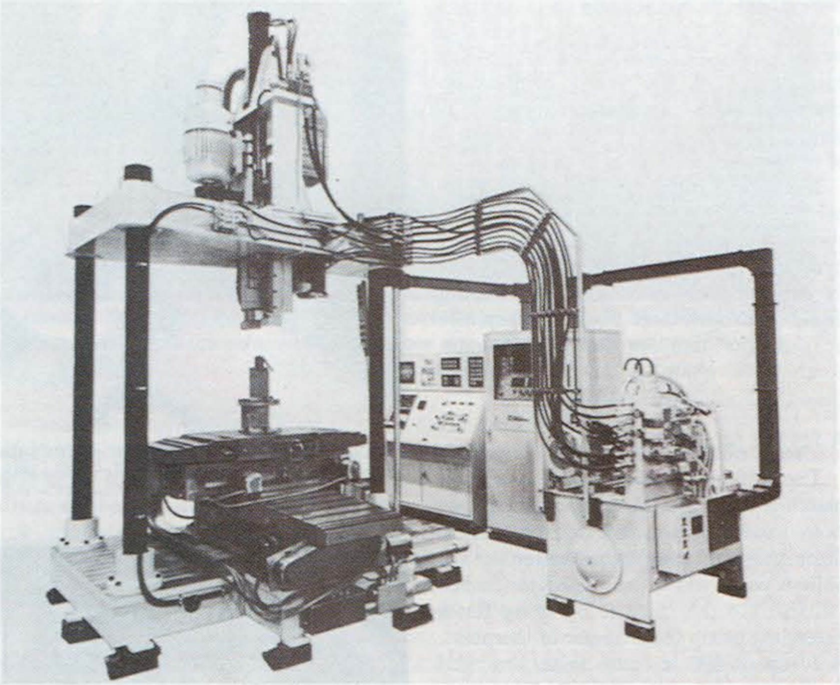
With some 14 completed powerhead assemblies to be reworked for incorporation of the new Haines 188 posts, that approach did not seem practical to Rocketdyne production engineers. Besides, regular overhaul of a SSME engine might also require some reworking of the vulnerable injector posts. For these reasons, Rocketdyne is presently installing a special inertia-welding machine, also built by Manufacturing Technology Inc, that will be able to handle an entire powerhead assembly.

The MTI machine is a Model V-120 modified to meet Rocketdyne requirements. The vertical-spindle machine is equipped with a coordinate positioning table for handling the complete powerhead assembly. It will, of course, also be capable of handling the separate main-injector body. The machine has an average weld cycle of 3-5 sec and can develop a maximum thrust force of 6000 lb.

A Giddings & Lewis two-axis CNC system is used for point-to-point positioning of the table; a G&L programmable controller coordinates the various control functions of the inertia welder. The machine will be operated in a semiautomatic fashion. After a part has been loaded on the positioning table, the operator initiates automatic positioning of the table to the first position in a 600-step CNC program. Alternatively, the operator can call up any table location by manually selecting a post number at the control panel.



Powerhead is welded in computer-controlled EB welder. More than 200 such welds are required to fabricate an SSME. Main injector will be welded in center section



New inertia welder from MTI will be able to handle entire powerhead assembly on its CNC positioning table. Rocketdyne expects to save $85,000 on reworking each

(This photograph replaces the original sketch of this machine)

Preweld cycle for monitoring

Once the table has positioned, the operator initiates a verification cycle during which the machine spindle lowers until injector post (mounted in the spindle) and injector stub are in visual-alignment range. The operator then increments the spindle down into the alignment collar to verify proper alignment. At this point, manual adjustments of the table can be made to correct for any misalignment.

When proper alignment has been established, the operator initiates a preweld thrust cycle, in which the spindle lowers until injector post and injector stub make contact and thrust is applied without the spindle rotating. The static pressure is monitored to ensure that sufficient pressure is available to effect a proper weld during the actual welding cycle. Also, the measuring system for establishing the upset-length loss is set to zero. If the pressure is not correct, the machine cycle automatically halts, and the fault is displayed on an associated CRT.

Next in the preweld cycle, the spindle backs off slightly and is accelerated to its programmed speed. Again a monitoring cycle checks for proper speed, and the cycle is stopped if that speed is not reached. These parameters are also displayed on the CRT.

Once all the preweld-cycle conditions have been satisfied, the operator initiates the thrust cycle, and automatic welding proceeds. At the end of the thrust cycle, the table indexes to the next programmed location.

The entire procedure, with its manual interventions, is intended to ensure that the welding of the very expensive injector components proceeds without a snag. In addition, all the machine parameters are recorded for future reference.

Two separate recording modes are used. Information displayed on the CRT is printed at the end of the cycle:

- Post position; X, Y location at start of cycle.
- Ram pressure at midpoint of weld cycle.
- Spindle rpm at start of weld cycle.
- Ram oil temperature at start of thrust cycle.
- Upset dimension—difference between thrust contact and end-of-cycle position of the spindle.
- Weld time.
- Preweld thrust (static).
- Part identification number.

A four-channel recorder records analog signals:

- Torque curve, a function of deceleration.
- Ram-pressure curve from part contact to end of weld cycle.
- Upset profile from part contact to end of weld cycle.
- Spindle-speed record from start to finish of weld cycle.

Considering that a main injector is probably worth about $250,000, all this attention to monitoring the process is no extravagance. Neither is the new machine, which Rocketdyne figures should save up to $85,000 per unit for reworking of the posts by eliminating the need to cut the main injector away from the powerhead assembly. It also means a three-month gain in schedule. With a projected six-month turnaround for the shuttle, that, too, is important. ■