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INVESTIGATIONS FOR THE IMPROVEMENT OF SPACE SHUTTLE MAIN ENGINE ELECTRON BEAM WELDING EQUIPMENT

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Materials and Processes Laboratory
Science and Engineering

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16. ABSTRACT

This report summarizes the progress made in the testing, evaluation, and correction of MSFC's 7.5 kW Electron Research, Incorporated (ERI) Electron Beam Welder in support of Space Shuttle Main Engine component welding at Rocketdyne in Canoga Park, California.

The objective of this project was to locate and correct the deficiencies in MSFC's 7.5 kW ERI electron beam welder and coordinate with Rocketdyne all data that would help to eliminate similar problems with their ERI equipment.

This report describes 17 areas that were deficient in the 7.5 kW ERI welding system, or checkout, and the associated corrective action taken to improve its operational performance.

The areas investigated during this project are not all inclusive but each particular modification or preventive measure provided a definite improvement in system performance. An overall improvement of 20 times the original reliability has been obtained at full rated capacity.

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INTRODUCTION

Prior to May 1976 there were numerous operational problems with the Electron Research, Incorporated (ERI)[1] Electron Beam Welder (EBW) located at Rocketdyne in Canoga Park, California. This unit, which is rated at 30 kW, is used for joining Space Shuttle Main Engine (SSME) components. The George C. Marshall Space Flight Center (MSFC) has a 7.5 kW ERI welding system (Fig. 1). Although MSFC's system is rated 7.5 kW, it is equipped with a 30 kW electron beam gun which is very similar to the Rocketdyne unit. To support ERI EB SSME welding at Rocketdyne, the Materials and Processes Laboratory at MSFC initiated a project to locate and correct deficiencies in the MSFC ERI equipment. This was to be accomplished in close coordination with Rocketdyne to eliminate similar problems with their ERI EB welder.

In attempting to comply with this objective, it was found that the MSFC ERI EB welder was in extremely poor operational order. It was very hard to start. In fact, it often took from 3 to 4 h to raise the weld power level to 45 kV and 125 mA. Then, when reasonable power levels were attained, the nitrogen gas supply required almost constant adjustment to maintain that power output level. There were also very frequent automatic shutdowns of the equipment, due to flashovers, when attempting to operate at weld voltages greater than 45 kV.

THEORY OF OPERATION AND BASIC HARDWARE

Briefly, the ERI/Union Carbide Corporation (UCC) electron beam gun features an indirectly heated tungsten electron emitter which requires no suppression grid for weld current control. This configuration has two distinct

1. ERI was absorbed into the parent organization, the Union Carbide Corporation, in 1973. Although both of these organizations will be referenced within this report, they are now one and the same.

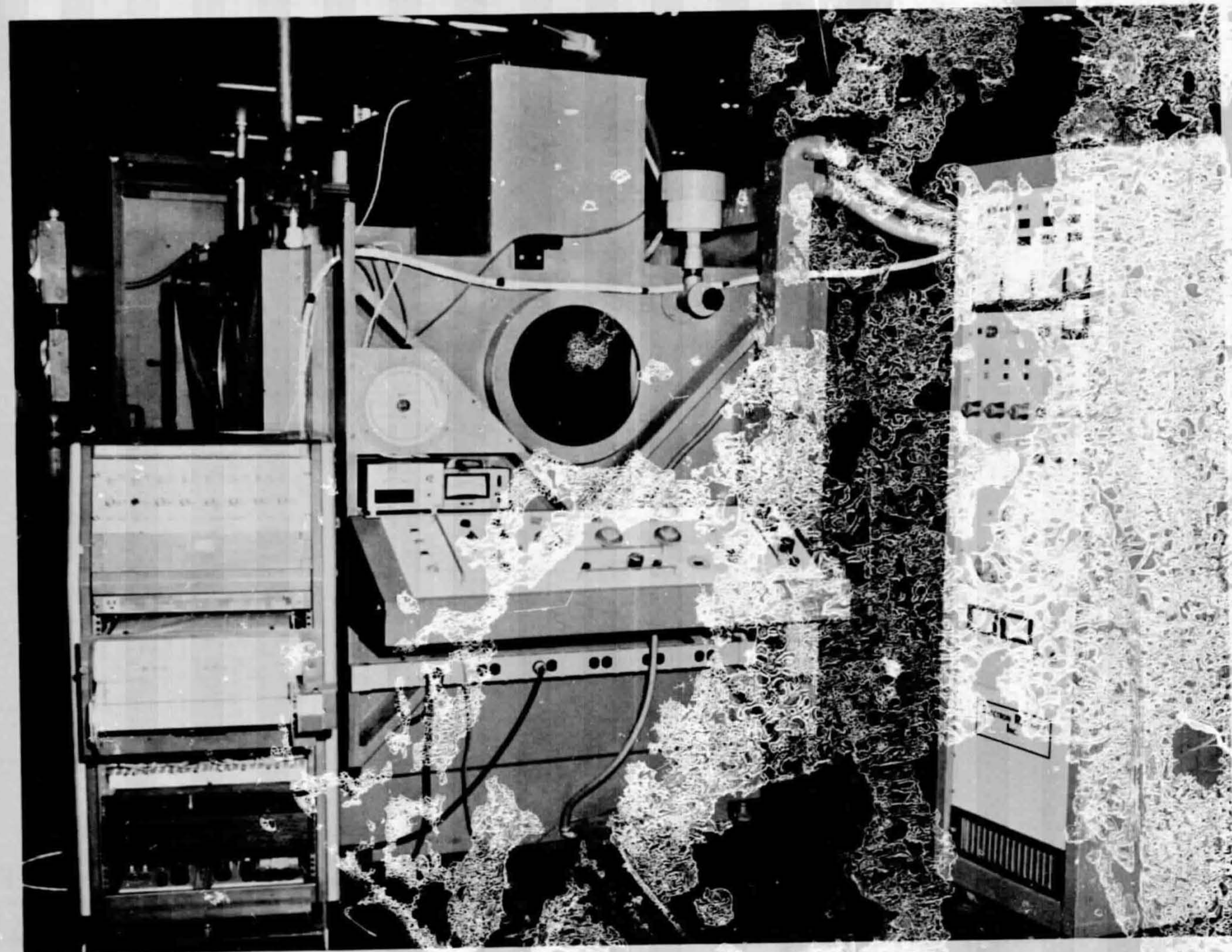


Figure 1. ERL/UCC EB welder, shown instrumented.

advantages over normal EB gun configurations. First, should an EB gun arc (flashover) occur, the ERI system will not momentarily lose control of the beam current and cause overpenetration of the weld. Second, the heated spot on the tungsten weld current emitter is essentially round and, when refocused on the work, will reproduce an almost circular spot at the focal point. Both of these features are highly desirable for quality EB welding.

Indirect heating is accomplished by an ionization beam, referred to as the pilot arc (Fig. 2), which normally operates at a nitrogen ionization pressure of 50 to 150 microns. Nitrogen is fed from an external source through a replaceable 0.0127 mm (0.0005 in.) orifice in the EB gun and into the pilot gun cavity at a nominal rate of 0.5 to 5 SCCM. In the pilot gun cavity, the nitrogen gas interacts with the pilot voltage to create ions and electrons by field emission. These electrons bombard and heat a small spot in the center of the weld current emitter to electron thermionic emission temperature. The ionization gas then exits the pilot arc cavity through two adjustable vents and escapes to the workchamber. Gas flow, therefore, is a function of the source pressure, orifice leakage rate, and gas vent adjustment. Thus, the necessary weld current emitter heat is a function of the ionization gas pressure and the pilot arc voltage. Within the ionization gas pressure range in the pilot arc cavity, the pilot arc voltage is closed-loop, feedback controlled to maintain the required weld current.

Once the weld current electrons are thermally emitted from the anode side of the tungsten weld current emitter, they are electrostatically focused and accelerated by the desired weld voltage of 0 to 60 kV through the anode and impinge on the workpiece. The electron beam is also electromagnetically focused and/or deflected on its way to the work via conventional techniques. The EB gun, focus coils, and beam deflection coils are all normally packaged in a round stainless steel housing which is vented to the workchamber to maintain EB level weld pressures.

The electronic controls for the basic ERI/UCC EB gun are fast acting and moderately complex. In addition to the closed-loop feedback controls for weld current and voltage, the control package features an array of troubleshooting annunciator type circuits. An antiarcout circuit, which is optional, prevents the equipment from shutting down and latching out unless there are three flashovers within 1 s or a sustained overload.

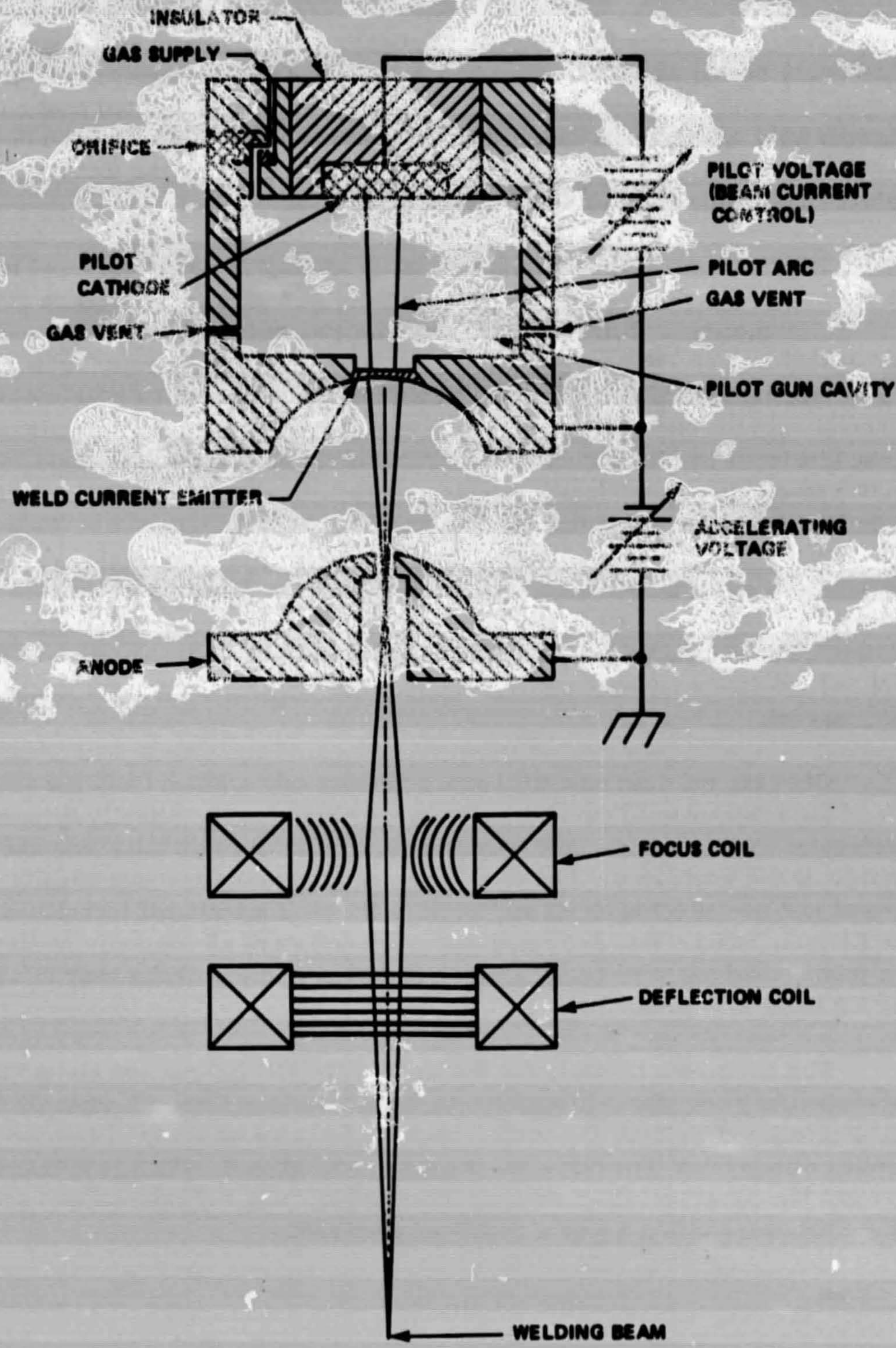


Figure 2. Electron beam gun, simplified diagram.

CORRECTIVE ACTION APPROACH

The first action taken was to instrument the critical electrical and gas parameters on the MSFC ERI EB welder with an 8-channel Brush recorder to simultaneously record weld voltage, weld current, pilot arc voltage, pilot arc relative power (called percent by ERI), pilot arc gas flow rate (0 to 5 SCCM nitrogen), and focus current. EB gun electron losses and secondary electron emission stray losses from the work piece were instrumented as optional measurements. By analysis of the recordings and from prior experience, it was obvious that the following sequence of corrective measures would have to be followed to overcome the poor operation:

1. Pilot arc gas flow problems within the EB gun would have to be corrected to insure reliable EB gun start and operational consistency.

2. The most frequent sources of high voltage flashovers within the EB gun, or associated wiring, would have to be located and eliminated.

3. Electronic controls would have to be analyzed for trouble spots and corrective action taken.

4. Continue with these corrective steps until the equipment runs reliably at full rated power of 60 kV and 125 mA.

Problems that were found and the corrective action taken are explained in the ensuing sections of this report.

PILOT ARC AND PILOT GAS CORRECTIVE MEASURES

When the EB gun (Fig. 3) was disassembled, the pilot arc chamber was found to be severely coated with carbon and aluminum oxide. This indicated excessive impingement of the pilot arc on the electron emitter holder carbon washers and erosion of the pilot arc cold cathode. Relatively thick rings of nonsymmetrically deposited thin film carbon were visible on the aluminum cold cathode, indicating that the pilot arc was not as symmetrical as it should be. Also, streaks of carbon vapor deposition on the back side of the cold cathode insulator at A indicated slight gas leakage around the lead washer seal at B. Other faults in this area of the gun were that the lead seal at C leaked, the compression Viton O-ring at D would not stand the heat causing it to lose

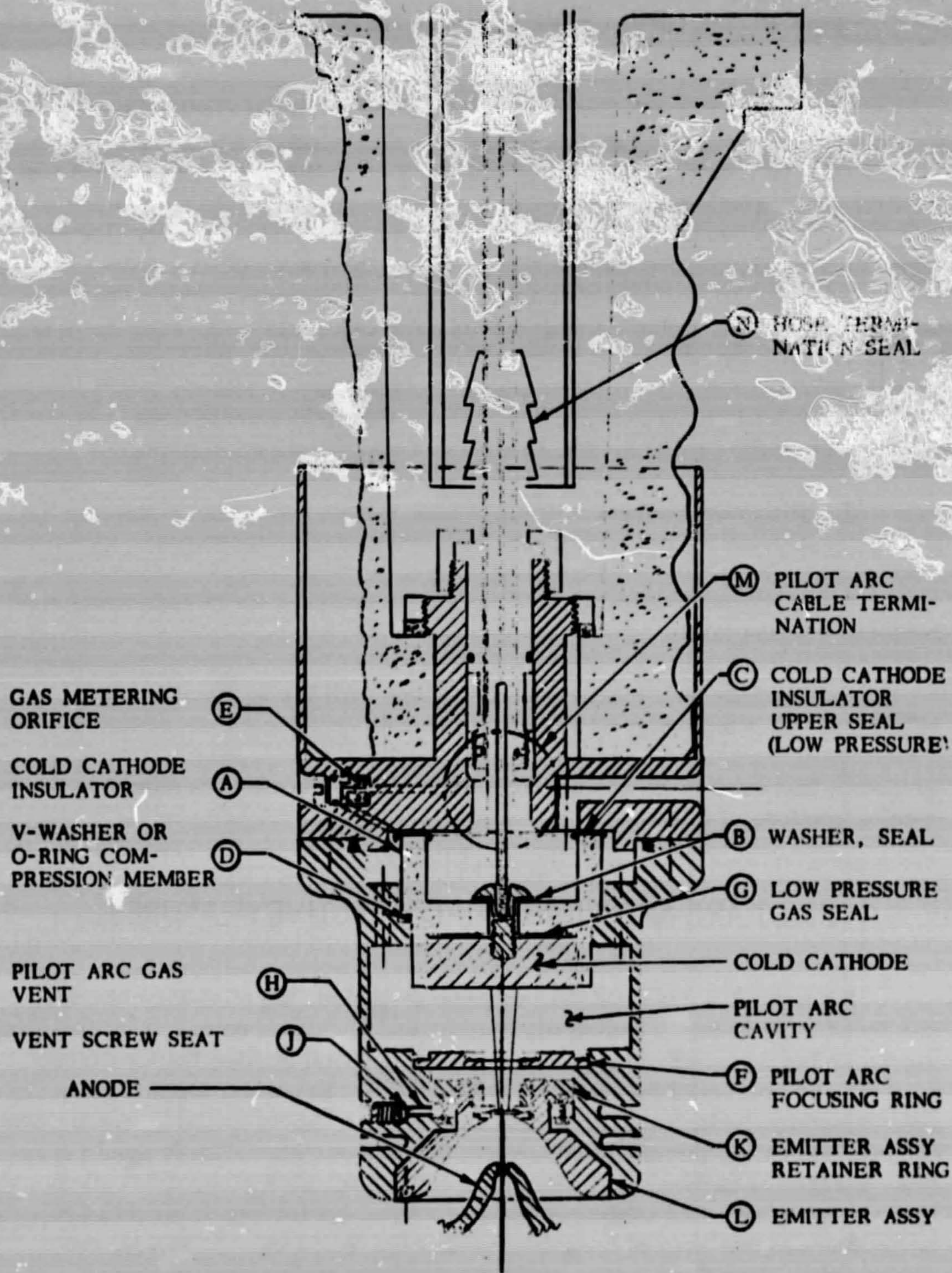


Figure 3. Cross section, EB gun.

resilience, and the 0.0127 mm (0.0005 in.) diameter nitrogen gas metering orifice at E was almost totally clogged with a foreign metallic substance. The orifice required soaking in a solution of nitric acid to remove the restriction but was later replaced with a new orifice disk to meet the flow requirements of 40 to 60 bubbles/min. Modifications to the gun proper are as follows with reference to Figure 3:

1. The pilot arc chamber and focusing ring F were thoroughly cleaned with sodium hydroxide and polished. It was learned that deposits of aluminum oxide on the focusing ring aperture tend to cause defocusing and dissymmetry of the pilot arc. This causes partial impingement of the pilot arc on the carbon tungsten emitter washer rather than totally upon the tungsten emitter. This condition results in poor pilot arc efficiency as evidenced by loss of output weld current and carbon evaporation.

2. Graphoil (A UCC product) seals were used to replace lead washers at B and C to prevent leakage of nitrogen pilot arc gas and resultant erratic gun operation. In the past, the lead seals in these locations were coated with a light coating of vacuum grease prior to installation. However, the Graphoil seals work best installed dry. Also, it has been found that vacuum grease, when heated, offgasses and contaminates the pilot plasma arc causing erratic gun operation. It also drys, flakes, and clogs the 0.0127 mm (0.0005 in.) orifice.

3. All critical dimensions in and about the cold cathode were measured to make certain that there was no adverse buildup of tolerances to cause gas leakage or excessive compression of the cold cathode ceramic insulator.

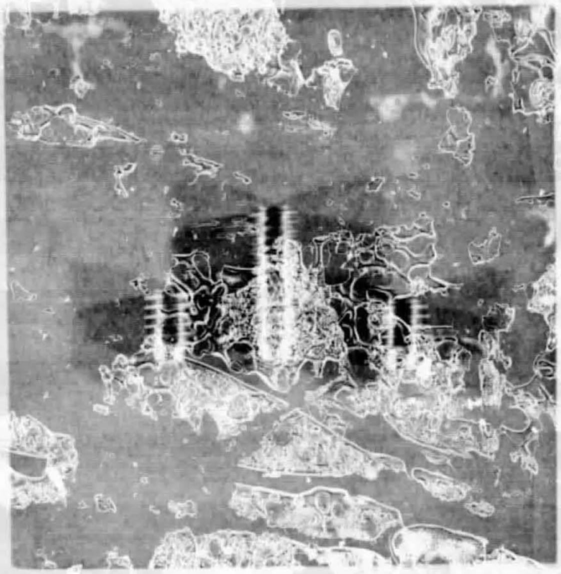
4. An Inconel V-washer (Figure 4a) was used to replace the Viton O-ring at D to maintain sealing pressure at C. Actually, the maintenance of sealing compression at C is one function of the O-ring, or V-ring, at D. The other function is to cushion the cold cathode ceramic insulator.

5. Pilot arc gas metering orifices with apertures sized to allow 40 to 60 bubbles/min, using the ERI standard bubble test procedure, were found to work best in the 30 kW rated EB gun.

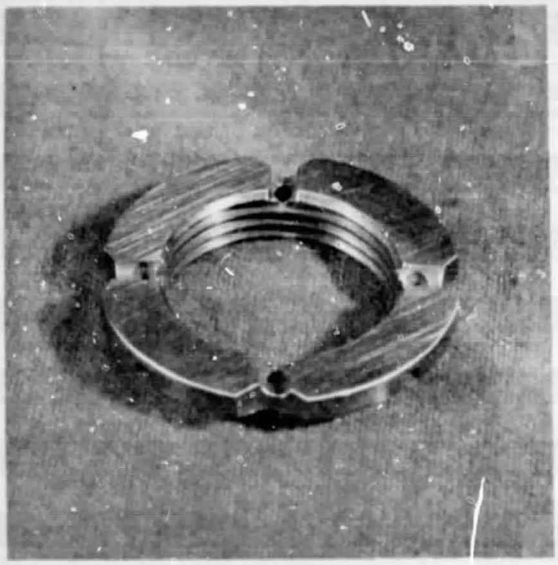
6. For consistent control and finer adjustment of the pilot arc gas vents at J, the following modifications were made:

a. Gas vent ports at H were enlarged to 2.18 mm (0.086 in.) diameter.

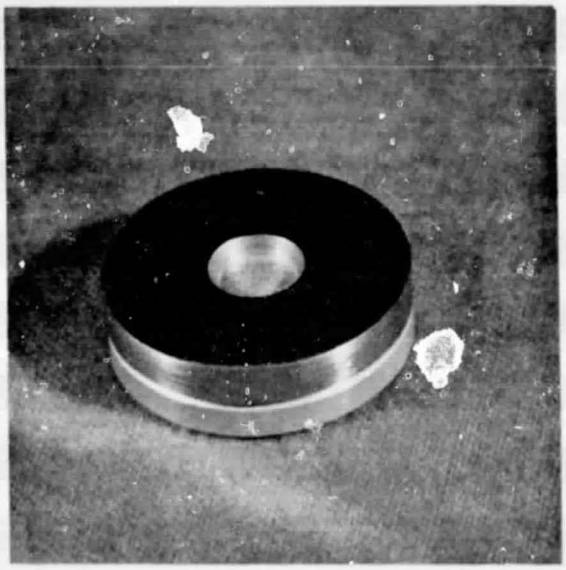
a. Inconel V-Ring



b. Vent screws — Center original design. Cone point new design.



c. Retainer ring — lateral ring grooves shown enlarged



d. Titanium-aluminum cold cathode. Titanium face shown up.

Figure 4. Modified component parts.

b. A cone point was machined on the two vent screws (Fig. 4b), and flat seats were machined into the cathode housing at J for finer adjustment of the gas vents.

c. Enlarged vent grooves were machined in the retainer ring K (Fig. 4c).

7. A special tool was designed per Figure 5 and built to screw into the cathode housing with the hot emitter holder assembly, L, removed. This tool, which is equipped with a thermocouple type vacuum sensor gage, allows technicians to preset the gun at room temperature for a predetermined, nonoperational pilot arc cavity gas pressure. For example, the MSFC 30 kW EB gun has been found to require no further gas adjustment when preset to 240 ± 10 microns pressure under the following conditions:

a. 1 to 3 psig nitrogen pressure upstream of the 0.0127 mm (0.0005 in.) gas metering orifice.

b. 1×10^{-4} to 1×10^{-5} torr external pressure on the gun.

c. 0.75 to 1 SCCM of nitrogen gas flow through the pilot arc cavity in the EB gun.

d. Pilot gas orifice tested for bubble count of 40 to 60 bubbles/min at 23 psig nitrogen pressure.

e. EB gun at room temperature.

This preset calibration technique has proved very successful because it saves considerable time and assures repeatable results. Once the pressure is set, no further adjustment is necessary. From recent operating experience, gas pressure adjustments found necessary at a later date indicate that something internal to the EB gun is wrong and other corrective action is necessary.

HIGH VOLTAGE CABLE AND GUN ASSEMBLY PRESSURE TEST

In addition to the pilot arc gas pressure preset adjustment test previously described, a second relatively easy pressure test is recommended to verify the integrity of the EB gun seals and the high voltage cable assembly on the bench. The purpose of this test is to verify that the gas seals of the pilot

Figure 5. MSFC pilot gas pressure calibration tool.

arc cable at areas M and N (Fig. 3) are free of leaks. Should leaks be present in these locations, excessive gas could enter the gun housing, creating corona and potential flashovers. Evidence of arcing near the base of the high voltage cable, discussed later, is the reason this test is recommended each time the gun is disconnected for preventive maintenance purposes. In brief, the pressure test can be performed as follows:

1. Connect the workchamber feedthrough end of the EB gun cable to a large hose and clamp in place. Take special note that gas must enter the cable through a small opening in the metal rim of the tapered cable connector; therefore, the test hose must slip onto the tapered portion of the cable connector.

2. Connect the large hose to an air or nitrogen gas supply adjustable from 0 to 23 psig.

3. With the EB gun supported vertically, fill the gun's corona cup, which extends approximately 7.6 cm (3 in.) up the high voltage insulator, with pure grain alcohol.

4. Apply pressure to the cable up to 23 psig maximum and check the alcohol for no bubbles.

5. Remove pressure and alcohol.

6. With the pilot cap assembly removed for access to area M (Fig. 3), invert the corona cup so the pilot voltage cable termination is pointed upward. Fill the small cavity around the electrode with pure grain alcohol and repeat step 4.

7. Remove pressure and alcohol and dry the gun with lint free material.

COLD CATHODE CHANGE

Once all of these changes were incorporated into the gun, start-up problems were resolved. However, it was still apparent that the cold cathode configuration needed improvement. This was evidenced by (1) operational values of pilot arc relative power (percent) greater than factory recommended, (2) excessive carbon and aluminum oxide vapor deposit accumulation in the pilot arc cavity, and (3) suspected arcing from the cold cathode to the gun internal wall. At the suggestion of UCC, a Lanthanum Hexaboride, LaB_6, cold cathode was procured and tried. Before the cold cathode could be tested, UCC discovered a flaw in the design and recommended changing to aluminum-titanium as shown in Figure 4d. UCC provided a cold cathode of aluminum-titanium for test purposes. It was theorized that titanium, being a poorer electron emitter than aluminum at gun operating temperatures, would help prevent arcing between the cold cathode and gun wall. The aluminum disk exposed in the center of the titanium-aluminum cathode is the actual cold cathode emitter material. Pilot arc power for the given beam current range was reduced to UCC recommended levels, and the pilot arc relative power for different electron beam power levels repeated consistently. All indications are that focusing and distribution of the pilot arc are now stable and operate as the gun developer intended. The titanium-aluminum cathode, as received from UCC, proved satisfactory and, therefore, the proposed testing of the LaB_6 cathode was omitted.

60 kV ARC-OUT INVESTIGATION

After stabilization of the gun, the next goal was to locate and eliminate, or at least minimize, sources of flashover (arcing) at the machine's rated voltage of 60 kV. During operation, frequent arcs would occur causing the EBW to shut down. These arcs were very prevalent during the standard 60 kV cleanup procedure. Since the gun housing completely enclosed the gun, visual observations during operation were impossible. To maintain alignment of the cathode and anode, a sturdy "see-through" fixture (Fig. 6) with anode-to-emitter alignment provisions was designed, fabricated, and installed. Provisions were also made to install the focus coils on the new fixture. The screen wire was necessary to maintain a uniform electrical field distribution around the gun. A uniform electrical field prevents corona buildup and an eventual arc. Also, the large round shield at the bottom of the fixture was provided to prevent metal vapors from depositing on the gun's high voltage insulator. Use of this fixture enabled us to determine if most arcs causing machine shutoff were external or internal to the EB gun. Since most flashovers at operating voltages in the 55 to 60 kV range were visually determined to be from the cathode to the copper anode, it was decided to try an anode made from low electron emitting material such as titanium. A drawing of the anode was obtained from UCC, and four titanium anodes were fabricated. It was theorized that titanium, being a nitrogen getter and a poor electron emitter, would absorb nitrogen which is known to leak around the hot tungsten emitter and help prevent small pockets of ionized gas from forming on the anode. As expected, the newly machined titanium anode arced profusely to the cathode during the normal 60 kV cleanup procedure. However, once purged of foreign materials and lightly trapped surface gases, operation

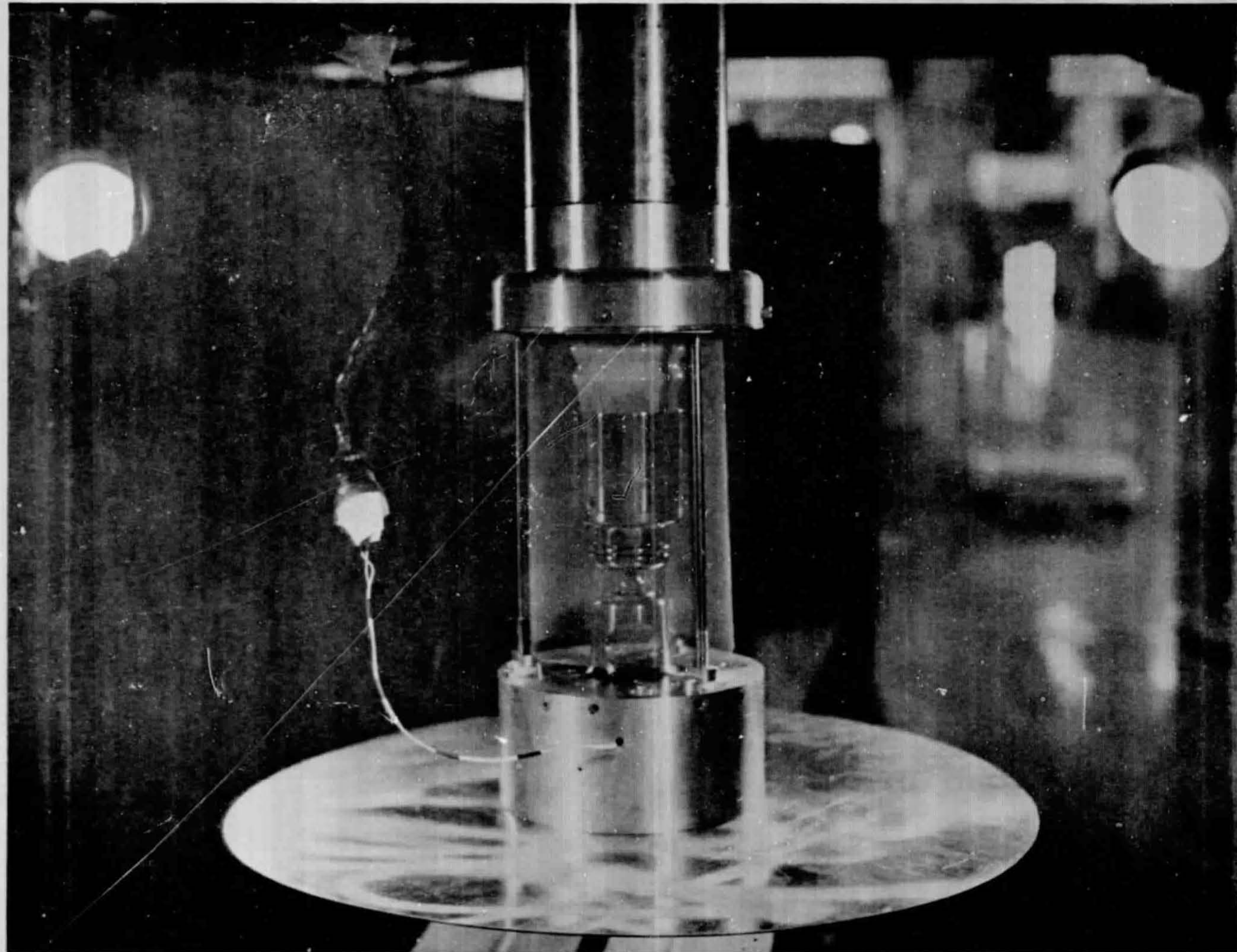


Figure 6. ERI EB gun open, see-through fixture with focus coil.

was excellent and probably superior to copper from the viewpoint of arc suppression. No anode overheating was observed, or evident, and pitting due to arcs was minimal — much less than previously observed with copper anodes. The question of titanium versus copper anodes, though, has not yet been thoroughly tested or evaluated.

While the special fixture was being used, the interior surfaces of the gun housing were honed and lapped to a mirror finish to improve the gun-to-housing dielectric characteristics. In addition, a new, highly polished corona shield was added to the gun. The relatively sharp edges on the new shield, as received from UCC, were rounded and polished to a mirror finish and then satisfactorily tested in the open fixture. To verify if the EB gun would now operate as "arc-free" in the polished standard housing as it did in the open, "see-through" fixture, the gun was reassembled in the newly polished housing and tested. With the gun mounted vertically, ten 2 min runs and twelve shorter duration runs were made within a time span of less than 90 min. A total of 23 min of operation was thus achieved with the gun operating at the power supply full rated power of 60 kV and 125 mA. One arc-out occurred during this 23 min of testing, causing the equipment to shut down normally. This test was repeated a second time with substantially the same results. Thus, operating time between arc-outs at 60 kV tested approximately 20 times better than when the investigation first started. Previously the welder would rarely operate for more than 1 min at 55 to 60 kV without an arc-out. Further testing is planned, but these results indicate that the gun operated in the polished standard 30 kW rated housing essentially equal to its operation in the open fixture with the gun mounted vertically. Orientation is mentioned because horizontal operation of the ERI EB gun is not normally quite as free from arcs as when the gun is mounted vertically.

CONTROLS, POWER SUPPLY, AND HIGH VOLTAGE CABLE

10 kV Pilot Arc Cable

During the investigations, several shorts occurred in the center pilot arc voltage conductor of the EB gun workchamber cable assembly. These shorts were always in the vicinity of M, Figure 3, and were characterized by a significant reduction of beam power and pilot arc voltage. It is postulated that cable failure was due to the inability of the silicone rubber insulated cable to withstand operational temperature levels reached in that area of the gun. Analysis indicates that the silicone rubber cable should be replaced with a special, corona resistant, TFE Teflon insulated cable, or its equal. Such cable is manufactured by W. L. Gore associates, Inc., of Newark, Delaware. Royal Industries of Santa Ana, California, experienced several instances of the same problem and, being pressed for time, used aircraft ignition cable to replace the faulty silicone rubber insulated cable which was supplied by ERI.

EB Gun Power Supply Transformer

While changing transformer oil in the high voltage transformer tank for preventive maintenance purposes, a loose connection was found on the output terminal of one phase of the high voltage three-phase transformer. Fortunately, it was accessible and was repaired. Some evidence of overheating of the terminal was observed, but there was no visual indication of arcing.

Anti-Arc-Out Circuit

The MSFC ERI EB welder is equipped with an antiarcout circuit PC board which, according to UCC, should initiate sequence stop if three pulses of overcurrent (due to flashover) occur in less than 1 s. Otherwise, the circuit should initiate a momentary, millisecond interruption of the high voltage to allow time for the arc to dissipate. Without the antiarcout circuit, any minor flashover could conceivably cause the welder to turn off, and stay off, until purposely restarted.

During calibration and analysis of the electronic circuits, it was found that the design of the antiarcout circuit could not possibly work as intended. As a result, it was modified to the manufacturer's operational specifications, and a circuit tester was built to check the circuit operation on the bench and while installed in the welder. With reference to ERI/UCC Drawing No. 2022772, the following changes were made to the circuit board:

1. Resistor R8 was changed from 3.3 K to 6.8 K ohms to allow a 20 ms temporary interruption of the weld voltage each time an arc occurred.

2. During testing of the PC board, it was found that R14 was restricting the current drive of Q5. Also, the RC time constant of R14 and C6 did not allow for any adjustment of potentiometer P2. By changing R14 to 27 K ohms, P2 could control the number of 20 ms pulses necessary to produce an arc-out signal from the arc-out circuit.

3. Potentiometer P1 was replaced with a 330 K ohm fixed resistor. This resistor determines the discharge rate (RC time constant) of capacitor C6.

After these changes were made, P2 could be adjusted to produce an output turn-off pulse anytime more than three arc-outs occurred within a 1 s interval.

SUMMARY

It is summarized that the MSFC ERI/UCC EBW is now in significantly better operating condition than when the project was initiated. Most of the steps taken to improve the performance have been coordinated with the manufacturer, Union Carbide, and Facility Engineers at Rocketdyne. Some of these measures have been adapted by Rocketdyne while others, perhaps, will be incorporated as the equipment becomes available for test purposes. The positive steps taken at MSFC, to date, to attain the improved performance are as follows:

1. Provided critical parameter instrumentation for operational verification purposes.

2. Insured that the best available factory-recommended seal materials were installed in the gun to help avoid temperature related gas leaks. Lead seals were discarded.

3. Omitted the use of vacuum grease on seals inside the EB gun. Vacuum grease drys and offgasses causing the release of foreign materials which clog the gas orifice and interfere with the pilot arc.

4. Pressure test the gun and the high-voltage cable assembly prior to use to verify the integrity of line pressure seals in the cable assembly.

5. Provided a fine, reliable, cone point adjustment of the cathode gas vents.

6. Devised means, by use of a micron range vacuum gage, to properly adjust the vent screws and, hence, preset the critical pilot arc operating pressure when installing, or checking, a gun in the workchamber.

7. Changed from an all-aluminum to a titanium/aluminum configuration cold cathode to improve and retain pilot arc performance.

8. Polished to a mirror finish all highly electrically stressed surfaces to reduce the probability of electron accumulation and dielectric breakdown.

9. Rounded to a maximum radius all sharp edges on highly electrically stressed surfaces on the external surface of the EB gun and the internal surface of the gun housing.

10. Changed the anode material from copper to titanium.

11. Corrected the antiarcout circuit configuration.

12. Electrically calibrated the electronic controls to the manufacturer's latest specification.

13. Designed and used a special see-through fixture, for R&D purposes, to test the gun, anode, and focus coil without the presence of the standard gun housing. This was done to check for arcing sources.

14. Determined the need to change the type insulating material of the pilot arc conductor in the EB gun and cable assembly from silicone rubber to a higher temperature rated material.

15. Initiated scheduled preventive maintenance of the high voltage supply and EB gun to insure cleanliness and integrity of the gas seals and electrical circuits by inspection and test. Cleanliness of the EB gun pilot arc cavity is imperative and required scheduled cleaning and polishing.

16. Reduced ionization gas flow rate to as small as practical to minimize the possibility of a pressure buildup inside the EB gun housing. The higher the pressure in the housing, the more likely there is of a dielectric breakdown.

17. Prior to installation, Hy-Pot tested the gun and high voltage cable to their peak operating dc voltage.

An analysis was made of the electronic circuits; however, there was nothing of significance found which would contribute to excessive arcing or inadvertent shutdown except the antiarcout circuit which had to be corrected. In fact, the electronic circuits operated without failure during all of the testing, but some random terminals were found deficient and were corrected.

CONCLUSIONS

It is concluded that the efforts, to date, have been successful in that much of the black art associated with setting up and operating an ERI EBW has been reduced to a more scientific level. It is recommended that all of the items listed in the Summary be given serious consideration by any user of ERI/UCC EB welding equipment. Depending on the vintage of the equipment (the MSFC is a 1972 design), some of the deficiencies may have been corrected by the manufacturer. However, it is believed that only a few have. Use of the vacuum gage fixture to preset the gas flow and vent screws is enthusiastically recommended. The titanium-aluminum cold cathode, which was supplied by UCC for test and evaluation, was found to be a significant improvement. Other measures, which are basic to the EB gun reliability, are to insure that all highly electrically stressed surfaces are well polished and that electrically stressed corners are machined to the maximum radius. Cleanliness of internal working parts, such as the pilot arc cavity, should be assured. Testing for gas leaks is strongly recommended because, in the long run, such steps frequently save money and manhours. Due to insufficient test data and experience, it is not possible to recommend titanium over copper as the better anode material. However, the gun operating at 60 kV did arc less frequently to the titanium anode than it did to the copper anode.

APPROVAL

INVESTIGATIONS FOR THE IMPROVEMENT OF SPACE SHUTTLE MAIN ENGINE ELECTRON BEAM WELDING EQUIPMENT

By R. A. Smock, R. A. Taylor, and W. A. Wall

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

R. J. Schwinghamer

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Director, Materials and Processes Laboratory

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