GA–A24489

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This is a preprint of a paper presented at the 20th IEEE/NPSS Symposium on Fusion Engineering, San Diego, California, October 14–17, 2003 and to be published in *Fusion Science and Technology.*

Work supported by
the U.S. Department of Energy
under Contract No. DE-AC03-99ER54463

GENERAL ATOMICS PROJECT 30033
MARCH 2004

Fabrication and Repair of Ion Source Components in the 80 keV Neutral Beam Lines for DIII–D

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Abstract. **After eight years of operation, leaks began to develop in critical components of the ion sources of the 80 keV neutral beam lines in DIII–D. Operational adjustments were made that seemed to remedy the problems, but five years later leaks began occurring again, this time with greater frequency. Failures occurred in the stainless steel bellows and molybdenum rails of the grid rail modules as well as in the Langmuir probes. Failure analyses identified several root causes of the leaks and operational adjustments were again made to mitigate the problems, but the rash of failures depleted the program's supply of spare grid rail modules and probes and removed one of the ion sources from regular operation.**

Fifteen years after their original fabrication, the ion source components were no longer commercially available. In 2001 a program was initiated to fabricate new grid rail modules, including new molybdenum grid rails, bellows, and stainless steel grid rail holders, as well as new Langmuir probes. In parallel, components removed from service due to leaks were to be repaired with new rails and bellows and returned to service. An overview of the root causes of the service failures is offered, details of the repair processes are described, and a summary and evaluation of the fabrication procedures for the new molybdenum rails, grid modules, and Langmuir probes are given.

I. INTRODUCTION

The DIII–D neutral beam injection system employs eight 80 kV long pulse sources contained in four beam lines. Each beamline has two ion sources in parallel focussed through a common drift duct. The ion sources were designed by Lawrence Berkeley Laboratory and manufactured by RCA. Installation of the original system onto DIII–D was completed in 1986 [1], [2].

An ion source contains an arc chamber in which a hydrogen or deuterium plasma is generated, and an accelerator that extracts ions from the plasma and forms a high-energy beam (Fig. 1). The accelerator section contains four planar layers of water-cooled, molybdenum grid rails that are energized to different electrostatic voltages during operation. The successive order of these grid arrays through which the ions pass, starting at the exit of the arc chamber, is source, gradient, suppressor and exit. Each planar array of grid rails consists of fourteen rails on each of four adjacent grid rail modules, for a total of 56 rails per array. The grid rails are hollow molybdenum tubes having one of three cross-sectional geometries. The gradient and exit rails are circular in cross section, the source rails are symmetrically diamond-shaped, and the suppressor rails are elongated diamond-shaped. The thermal loading on the molybdenum rails during operation requires that the rails be water-cooled. The bases of the stainless steel structures that support the ends of the rails within a module, known as holders, contain a plenum for cooling water. Water is routed through an inlet-side plenum, through channels bored within the 14 finger-like sections of the holder, then through the inside of the rails via brazed connections between the rails and the tips of the fingers of the holder. Water exits the rails through similar brazed connections to the fingers of the outlet-side holder, through its channels, then to the outlet plenum. A total of 28 braze joints are employed to join the 14 grid rails to the two grid rail holders in each grid module (Fig. 2). The finger-like geometry of the holders is designed to give the holders sufficient flexibility to allow minimally encumbered expansion of

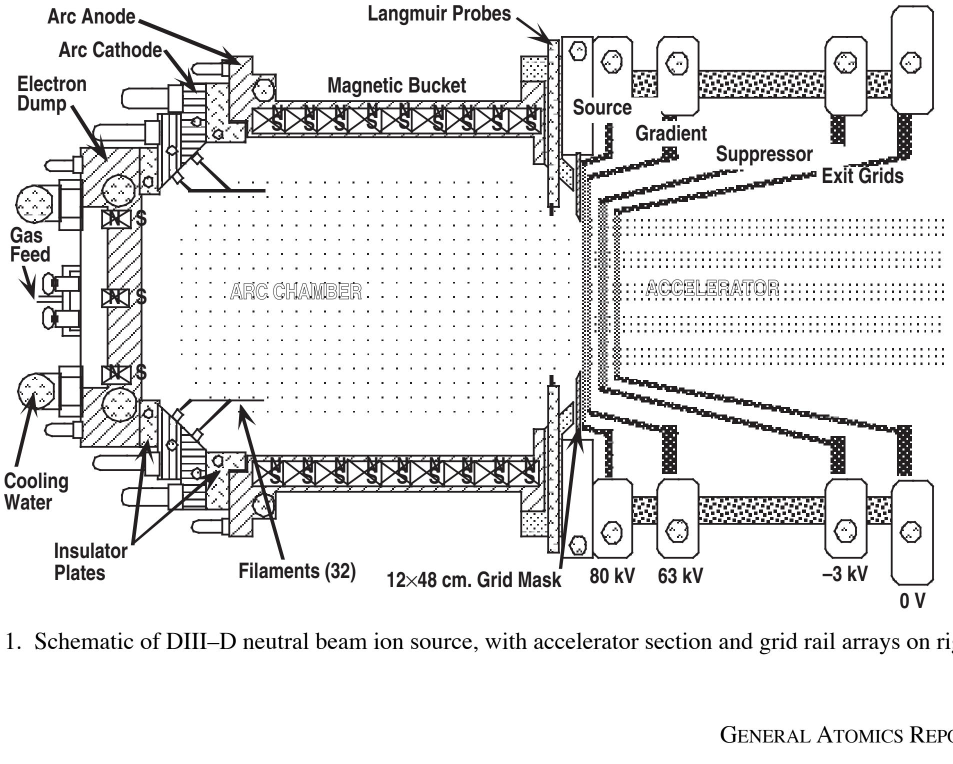

Fig. 1. Schematic of DIII–D neutral beam ion source, with accelerator section and grid rail arrays on right.

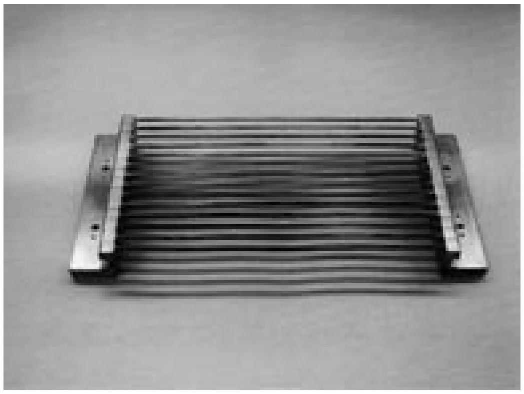

Fig. 2. Ex-service source grid rail module containing 14 molybdenum rails brazed to stainless steel grid rail holders.

individual grid rails as they heat up during operations. The lengths of the fingers on the gradient, suppressor, and exit holders are sufficient to produce the required flexibility. The shorter fingers of the source holders, however, must use thin-walled, stainless steel bellows to transfer water between the plenum and the finger tips and still maintain the required flexibility. Each source grid rail holder, therefore, contains 14 bellows fixed into position by 28 braze joints.

II. SERVICE FAILURES

After eight years of operation, leaks began to develop in the bellows of the source grid modules. Examination of the failed bellows indicated that the leaks might have been caused by flow-induced vibrations. The rate of coolant flow during operations was reduced and no subsequent bellows failures occurred. Five years later, however, leaks began occurring in the molybdenum rails of the grid modules and in the braze joints of the Langmuir probes located near the exit of the arc chamber (Fig. 1). A metallurgical analysis performed on a cracked molybdenum rail (Fig. 3) determined that the failure was caused by corrosion-driven propagation of an original manufacturing crack located on the inside diameter of the rail. Molybdenum-oxide corrosion was found to have removed up to 40% of the wall thickness of the rail due to an abnormally high oxygen content present in the deionized cooling water over a specific operating period of DIII–D. The study suggested that the leak most likely would not have occurred without the original manufacturing crack in the rail wall, but raised concern that the walls of all molybdenum rails in all grid modules in service during the operating period of high water oxygen content would be reduced by 40% of their original thicknesses. Furthermore, examination of other rail sections revealed additional inside diameter cracks thought to be present since their manufacture. Investigation of the failures of the Langmuir probes found that debris in the neutral beam water supply had blocked the tiny channels inside the probes that supplied cooling water to the probe tip and casing.

Operational adjustments were made to mitigate the problems that caused the leaks, but the rash of failures depleted the program's supply of spare grid rail modules and probes and removed one of the ion sources from regular operation.

III. REPAIR AND FABRICATION PROGRAM

Fifteen years after their original fabrication, the ion source components were no longer commercially available. In 2001 a program was initiated to fabricate new grid rail modules, including new molybdenum grid rails, bellows, and stainless steel grid rail holders, as well as new Langmuir probes. In parallel, components removed from service due to leaks were to be repaired with new rails and bellows and returned to service.

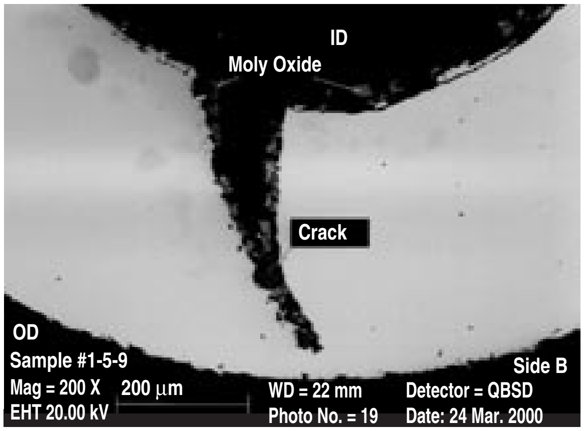

Fig. 3. Photomicrograph of oxide-corroded crack in wall of molybdenum grid rail from ex-service source grid rail module.

A. Molybdenum Rail Fabrication

A study was done to identify potential suppliers of the molybdenum rails for the four grid rail modules. Suppliers were found and contracted to produce replacement rails for the gradient and exit grid modules, which employ 0.125 in. o.d., circular cross section tubes. However, the international search could not identify a supplier of replacement rail stock for the source and suppressor modules, which utilize tubing having diamond-shaped cross sections.

The task was undertaken to develop a facility and procedure to fabricate molybdenum rails for the source and suppressor modules at General Atomics. A machine was designed and built that hydraulically pulled resistively-heated molybdenum tubing of circular cross section between compressive rollers having the desired cross-sectional geometry. Products from this machine and process showed promise. Tubing was fabricated having cross-sectional geometry very close to the original design specifications for the source grid rails and with structural quality and material microstructures suitable for service.

A second, larger machine was subsequently developed that solved several fabrication problems that could not be easily rectified on the smaller unit (Fig. 4). This machine utilizes the same basic fabrication principles as the original unit but was designed to produce rail stock over twice as long as its predecessor. In an argon purge, vertically oriented round stock tubing is hydraulically pulled over compressive rollers while being heated via electrical resistance heating. Early products from the new machine appear promising as cross-sectional geometry has been improved while maintaining tube structural quality and excellent material microstructure (Fig. 5). Further developments to the fabrication procedure will address improving product straightness, consistency in the cross-sectional geometry, and past-fabrication stress relief.

To date, most efforts to roll molybdenum grid rail stock have focussed on the production of source grid rails. Future plans include the production of suppressor grid rail stock. In

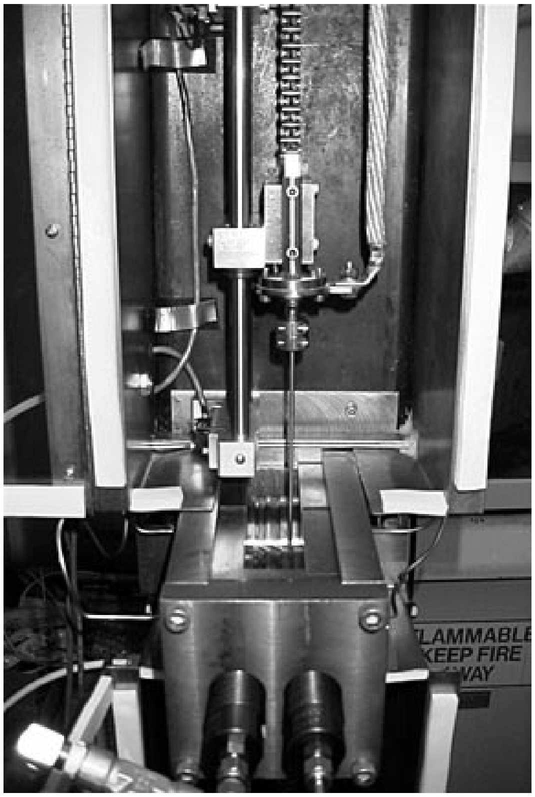

Fig. 4. Molybdenum tube positioned in compressive rollers of new molybdenum grid rail fabricating machine.

the interim, suppressor grid rails have been successfully fabricated using wire electrostatic discharge machining (EDM) techniques.

B. *Repair of Ex-Service Modules*

While parts were under production for fabricating new grid rail modules, the need arose to repair failed ex-service modules and return them to service. Water leaks in either the molybdenum rails in all module types or the stainless steel bellows unique to the source modules constituted the vast majority of service failures.

The braze joints connecting the stainless steel bellows to the source grid rail holders are composed of 37.5 Au-62.5 Cu, having a liquidus temperature of 1005°C. Initial repair efforts attempted to remove the single leaking bellows from a source module and braze in a new replacement bellows using a lower temperature braze material, Palcusil-10 (59 Ag-31 Cu-10 Pd). The vacuum braze successfully produced leak-tight connections of the new bellows to the grid rail holder, but the temperature cycle tended to deplete braze material, either through diffusion or evaporation, from the joints of the original bellows. Frequently, this depletion of the original braze metal opened up one or more new leaks in previously leak-tight bellows connections. This problem was solved by replacing all 28 bellows in any source grid module requiring repair with new bellows and new braze material (Fig. 6). This change in procedure lead to successful source module repairs and currently two repaired modules have been returned to service.

Efforts to repair leaking grid rails were met by both a familiar problem as well as a new problem. Attempts to replace a single leaking grid rail with a new rail using a lower temperature braze material again caused depletion of the braze metal on the untouched joints of the original rails, opening up new leaks. Additional new braze material was added to braze-starved joints, but the new material failed to wet the joint interface and instead migrated to adjacent areas. Contamination of the joint by oxides originating inside the original molybdenum grid rails was suspected and a new step in the repair procedure was added to include a high temperature bakeout to remove oxides from all parts prior to fixturing for the braze run. The addition of a cleaning bakeout prior to brazing yielded improved joint interface wetting and a successful rail replacement braze was achieved on an exit grid module.

C. *Fabrication of New Modules*

Four pairs of grid rail holders for each of the four module types were fabricated to produce sufficient modules to outfit one complete ion source. Successful fabrication of these holders was challenging due to the extremely tight dimensional tolerances on the pitch of the counterbores that fix the position of the ends of each grid rail. Formation of the 14 fingers on each holder requires slitting the stainless steel holders using wire EDM as one of the final stages in the machining process. Residual stresses in the stainless steel caused movement of the ends of the fingers as a result of the slitting process. This movement resulted in discrepancies from the specified counterbore positions that were up to 30 times

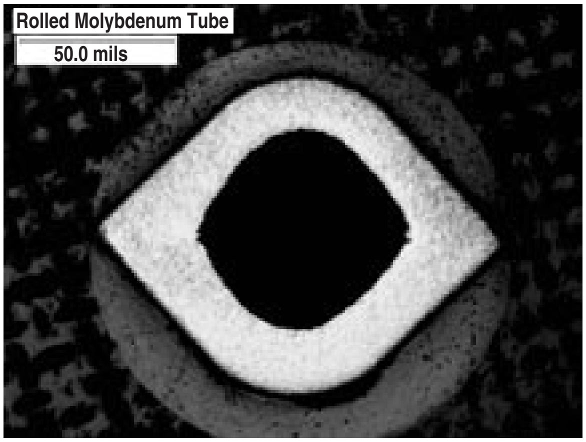

Fig. 5. Photomicrograph of cross section of molybdenum source grid rail produced in new grid rail fabricating machine.

Fig. 6. Successful Palcusil-10 braze of replacement bellows into an ex-service source grid rail module.

greater than the specified limits of tolerance. These discrepancies were successfully brought to within acceptable tolerances by clamping the fingers and their counterbores into their correct positions and performing a vacuum stress relief at 900°C for a 2 h hold period.

A test braze program is currently underway to establish the precise time-temperature-vacuum level features of the three different braze cycles required to produce the four grid module types. Test specimens featuring identical materials and geometric features to the actual holders and bottom plates were fabricated. Testing will include the braze materials Nicoro (35 Au-62 Cu-3 Ni), 37.5 Au-62.5 Cu, and Palcusil-25 (54 Ag-21 Cu-25 Pd). Braze joints are being evaluated on criteria including helium leak rate for vacuum tightness, hydrostatic acceptability, braze metal penetration through the joint metallurgical bonding of the braze metal with the rail and holder, and satisfactory braze fillet size for structural integrity.

Testing of the molybdenum rail to stainless steel holder joint, using Palcusil-25 braze metal is nearing completion. Fig. 7 shows the mockup holder and molybdenum rails with braze wire and paste packed on the joints just prior to brazing. Fig. 8 shows 100% braze metal penetration with acceptable fillet size on a cross-sectioned rail to holder braze test specimen. Success has been achieved on all evaluation criteria with Palcusil-25 on the rail to holder joints.

D. Future Plans

With a successful completion of the test braze program efforts will commence on completing the final brazing of the 16 new grid rail modules. Assembly will also begin of a modified source grid module that replaces the diamond-cross sectioned rails with appropriately sized circular sectioned rails. Performance testing of this new design will follow the completion of four of the new modules, the number required to outfit one ion source. In a parallel effort, repairs will be completed on the ex-service modules that have begun their repair procedures. All parts necessary to build 25 new Langmuir probes have also been fabricated and brazing of these units will begin as demand requires.

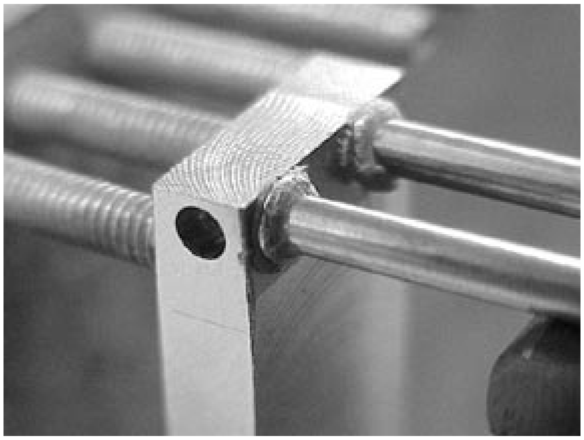

Fig. 7. Grid rail to holder joint packed with Palcusil-25 braze wire and paste prior to braze test.

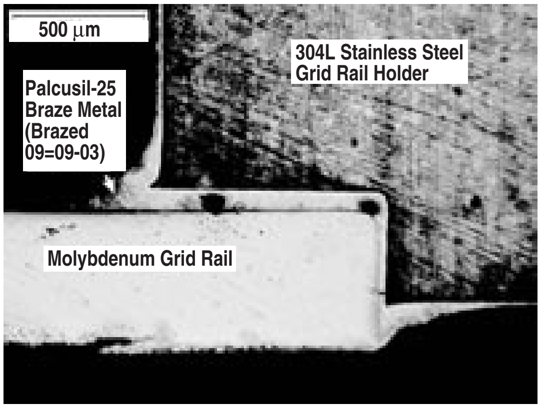

Fig. 8. Photomicrograph of section of joint produced by test braze of molybdenum rail to stainless steel rail holder showing full penetration of Palcusil-25 braze metal.

ACKNOWLEDGMENT

The authors would like to thank Richard Harrington, Jack Knipping, Ward Martin, and Matthew Madruga for their valuable assistance in conducting this program. Work was supported in part by U.S. Department of Energy under Contract No. DE-AC03-99ER54463.

REFERENCES

[1] A.P. Colleraine, *et al.*, “Increased power delivery from the DIII–D neutral beam injection system,” *Proc. of the 13th Symposium on Fusion Engineering*, October 1989.

[2] R. Hong and H.K. Chiu, “Effects of operating parameters on the beam species of DIII–D neutral beam ion sources,” *Proc. of the 19th IEEE/NPSS Symposium on Fusion Engineering*, January 2002.