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Special Remote Tooling Developed and Utilized to Tighten TFTR TF Coil Casing Bolts*

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ABSTRACT

Special tooling has been developed and used to tighten toroidal field (TF) coil casing bolts that have loosened from years of Tokamak Fusion Test Reactor (TFTR) operation. Due to their location, many of the TF casing bolts cannot be directly accessed or viewed; their condition was first discovered during unrelated inspections in 1988. Engineering solutions were sought until 1992, when a remotely operated wrench concept was successfully demonstrated on a TF coil mockup. The concept was developed into several working tools that have successfully been applied to tighten several thousand TF casing bolts during recent scheduled outages. This effort has improved the integrity and reliability of the TF coil system in preparing for the final experimental phase of the TFTR. This paper discusses the design and application of this tooling.

I. INTRODUCTION AND BACKGROUND

A. TF Coil System

The Tokamak Fusion Test Reactor (TFTR) has 20 toroidal field (TF) coils (see Fig. 1) consisting of wound copper conductors enclosed in a Nitronic 33 casing [1].

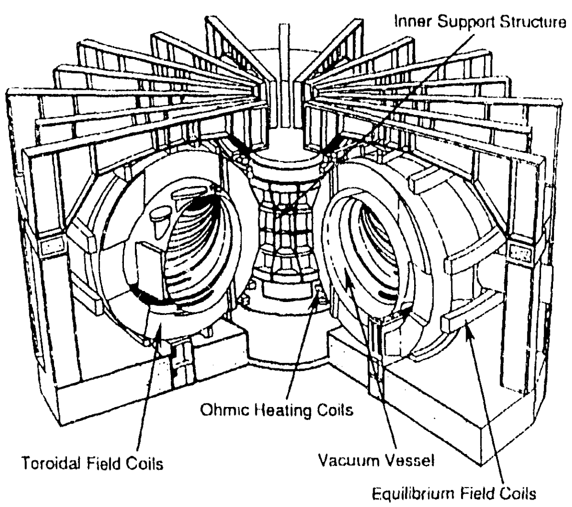

Fig. 1. TFTR magnetic field coils.

Electromechanical forces generated during coil operation are reacted by the casing and transmitted to a system of supports. Each casing assembly is mechanically joined by approximately 1000 bolts distributed around the casing side plates, as shown in Fig. 2. The inner, single row of bolts are 1 in., and the outer, double row are 7/8 in. The bolts are Inconel 718 forgings and were preloaded during initial assembly.

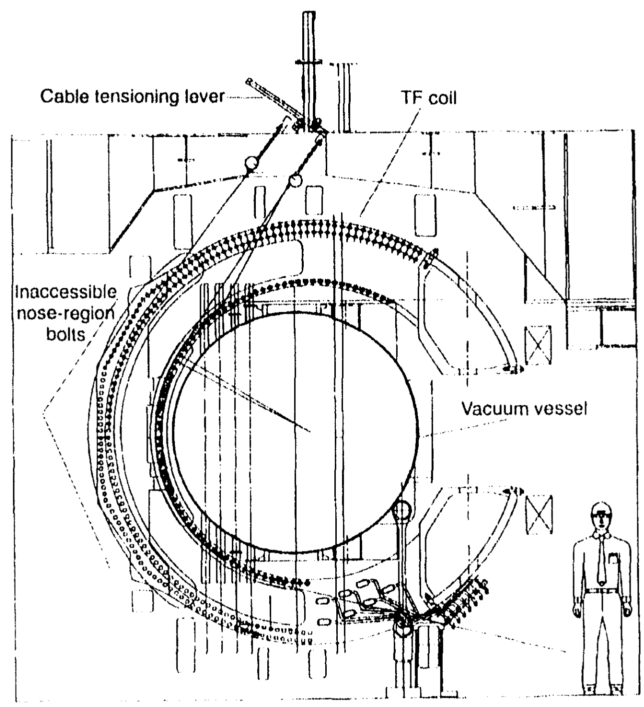

Fig. 2. TF casing elevation view.

B. Problem

In 1988, after 5 years of operation, loose bolts were discovered in certain areas of the coil casings. Many of these bolts were located in the coil nose region, towards the inner support structure at the center of the machine. Unfortunately the nose-region bolts, about 252 per coil, cannot be directly accessed or viewed due to their close proximity to adjacent coils and other obstructions such as the vacuum vessel, diagnostic components, and support structures.

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C. *Implications and Solution*

A thorough study of the problem did not yield any definite solutions to the dilemma. The small, curved access passages leading to the bolts, along with many different component obstructions found on the TFTR and the large number of bolts to be tightened, was very constraining. A bolt-tightening device would have to be very compact, time efficient, and capable of negotiating various obstructions in addition to the small passages.

A mechanical analysis of the casing condition showed that the coils could be safely operated close to their design limits and that operation could therefore continue. However, some of the loose bolts had backed away from the casing and were impinging on the dielectric insulation between the coil side plates in 4 of the 20 coil interfaces. The 1/8-in.-thick dielectric layer, an epoxy resin glass (G11), electrically divides the TF coil casings into quadrants to prevent electrical currents in the toroidal direction. TFTR operations could be indefinitely interrupted by electrical shorts in these areas, and some bolts had started to penetrate the dielectric material.

Unique remote tools capable of reaching and manipulating the nose-region bolts were successfully developed and demonstrated on a TF coil mockup in 1992. The tools were successfully used during the recent scheduled outages to tighten the 1008 bolts in the dielectric regions of the coils. The tools were then used to tighten the remaining 4032 nose-region bolts to improve the mechanical condition of the entire system.

II. TOOLING DESCRIPTION

Three different tools were developed (see Fig. 3). Each is similar in design and operation and differs primarily in the geometry required for the particular bolt pattern and size, and in the working space in the channel formed between the coil casing and the dielectric insulation. The channel at the outer, double row of 7/8-in. bolts lies between the bolts and is rectangular in cross section, (see Fig. 4). It measures approximately 12 by 37 mm (0.5 by 1.5 in.) at the narrowest location and is 3.1 m (10 ft) long. The channel at the inner, single row of 1-in. bolts lies to the coil side of the bolts, is triangular in cross section and is approximately 12 by 87 mm (0.5 by 3.4 in.) at the narrowest location and is 1.8 m (5.8 ft) long.

A. *Tool Assembly*

Each tool consists of a cable-actuated ratcheting wrench mechanism integrated with a small diameter video probe. The key feature of the tool is the articulated wrench jaw. The jaw is designed to (1) deploy to and ratchet over a bolt head when the cable is extended and (2) grip the bolt to rotate or torque the bolt when the cable is retracted. It provides a positive grip with minimum contact around the circumference of the bolt head, allowing engagement and disengagement in the spatially restricted environment.

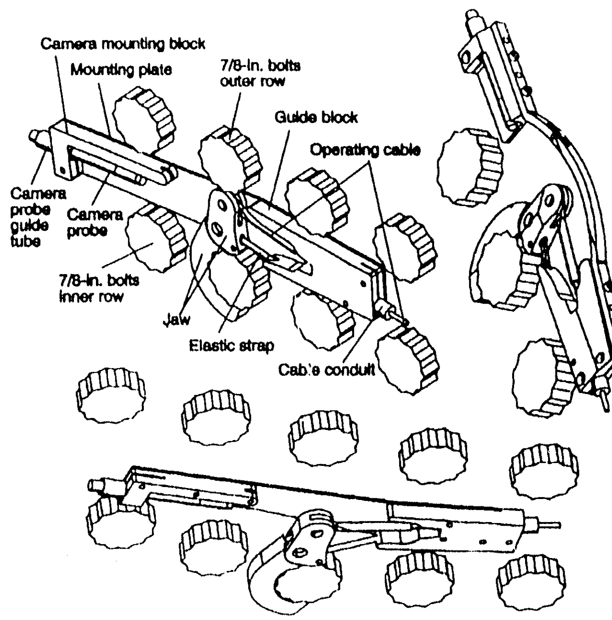

Fig. 3. TF casing bolt tool assemblies: 7/8-in. bolt inner row tool (top left), 7/8-in. bolt outer row tool (bottom), 1-in. bolt tool (top right)

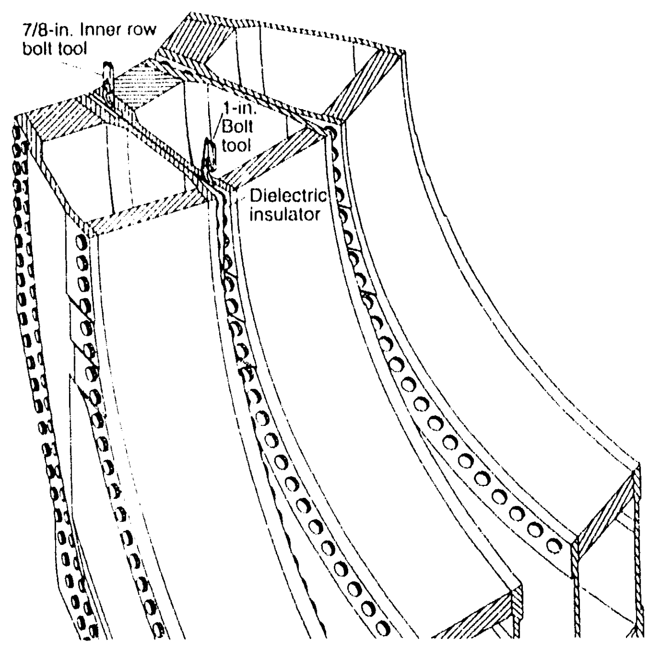

Fig. 4. TF coil casing sectional view.

The cable is manually operated to grip and snug loose bolts, and is then mechanically tensioned to torque the bolt.

With the tool assembly positioned in the working channel, the operating cable is extended to deploy the jaw from the assembly to the bolt head, as shown in Fig. 5. The elastic strap attached to the jaw and the assembly guide block causes the jaw to pivot towards the bolt as the cable is extended, regardless of the tool's orientation to gravity.

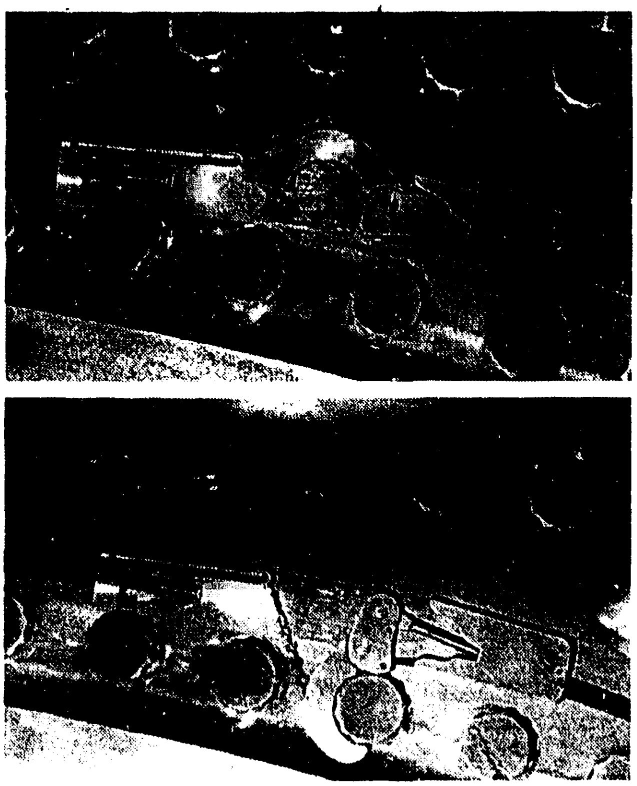

Fig. 5. 7/8-in. inner row bolt tool: jaw retracted for travel in channel (top) and jaw extended to tighten bolt (bottom).

Through a series of short cable extensions and retractions, a loose bolt is snugged against the casing, usually in a matter of seconds. The operating cable is then tensioned to several hundred pounds to torque the bolt. Once torqued, the jaw is moved away from the bolt and retracted into the guide block. In this condition, the assembly is free to move in the channel. The assembly is supported and positioned by the operating cable conduit and/or the video camera guide tube.

A tool is fed and operated from above or below the coil, depending on the bolt configuration and the side of the coil being worked. For example, the right-hand side 1-in. bolts require the tool approach from below, while the left-hand side requires a top-down approach. The video probe is fed from the opposite end of the channel and thus two control areas are involved. Operators coordinate their efforts through radio communication.

B. Operating Cable

A cable drive was the key to the tool's flexibility in negotiating obstructions to the TF coils and the curved paths within the coil channels. Manual operation of the cable was preferred over powered operation because of control simplicity and speed, and the tactile feedback provided to the operator.

The size of the cable was limited by the working space in the channels, as was the length of the jaw lever arm. These, in turn, set the maximum torque that could be produced.

The cable assembly consists of a 2.4-mm (3/32-in.) stainless steel cable housed in a protective conduit, and equipped with high-strength end fittings and a specially designed T-handle, visible in Fig. 6. The tested ultimate strength of this assembly is 500 kg (1100 lb). All assemblies were load tested to 409 kg (900 lb) and operated at 273 kg (600 lb) by procedure to minimize the risk of failure. Cables were occasionally tensioned to the test load to free a jammed bolt. Neglecting friction, the 273- to 409-kg cable tension corresponds to a torque output of 14- to 21 kg-meter (100 to 150 ft-lb), which corresponds well with the torque produced on the TF coil mockup.

Fig. 6. Manual operation of tool assembly actuating cable during mock-up test operations.

Various mechanical means were used to tension the cable. Special tensioning fixtures and rigging were designed and fabricated for different areas of TFTR. The setup generally consisted of either a lever arm or a chain fall, structural support fixtures, and rigging attached directly to the T-handle with an in-line load cell to indicate tension. Special cable guide blocks were also fabricated and used to control the cable route and position during tensioning.

The location of the operating stations (above and below the machine) were dictated by the space available to operate and secure the cable tensioning equipment. Operating space was very tight, and several cable lengths were usually required to cover the whole length of a channel. For example, 4 to 6 different cable lengths were often required when operating the tool from above the machine. Removing the tool to change cables significantly delayed the operation.

C. Viewing

Remote operation of the tool was monitored with a 6-mm-diam video probe commercially available from Welch Allyn. A 10.7-m (35-ft) articulated Long Steer probe and Model VP 2000 controller were used. The probe utilizes a color CCD camera chip integrated with a fixed lens and iris, and halogen lighting delivered through fiber-optics. Video monitors were located at the two control stations, as shown during mock-up testing in Figs. 6 and 7.

The probe was fed to the tool assembly through a nylon tube attached to the tool assembly from the opposite end as the actuating cable. The tube provided added protection to the probe and allowed it to be independently positioned and controlled from the tool. As previously noted, the video tube and cable conduit were used to move and position the tool assembly in the bolt channel.

Fig. 7. Video probe camera control during mock-up test operations.

D. *Tool Materials*

Nonmagnetic materials were used in the tool assembly since the possibility of lodging a tool between coils could not be eliminated. This precluded the use of tool steels in the jaw, which was fabricated from high-strength alloys, A286, and Inconel. The remaining parts of the assembly consisted of 304 stainless steel, 6061 aluminum, and brass.

III. APPLICATION RESULTS AND STATUS

Two operating crews performed the bolt-tightening operations. Each crew consisted of a (1) tool assembly operator, (2) cable tensioning equipment operator, (3) video operator, and (4) data collection and general support operator. Data collected included the initial and final condition of each bolt in the inaccessible regions. Each crew was equipped with the three different tool assemblies, cable tensioning equipment, and video equipment so that work could be conducted independently.

Bolt-tightening operations were conducted during two scheduled outage periods, which included many maintenance and modification activities in preparation for the TFTR's final experimental phase: dueterium and tritium (DT) fueling. The first session of bolt-tightening operations was initiated in February and continued through April 1993. The second session was in progress in August and September 1993. The crews worked an extended 10-h shift, 6 days per week during these periods.

A. *Dielectric Region Bolts*

The bolts in the dielectric nose regions, 1008 bolts in 24 bolt rows, were all torqued in approximately 6 weeks. Once proficient with the equipment, each crew could typically complete one row of bolts per day. Most of this time was required for equipment setup and cable assembly changes. Although the condition of the bolts varied widely among coil cases, on the average about 30% of the bolts were visibly loose. An additional 25% appeared tight but rotated when torqued, indicating that they were tight to less than 100 ft-lb.

B. *Remaining Casing Bolts*

Completing the dielectric region bolts successfully demonstrated the tooling and completed the original job scope. The decision was then made to apply the tooling to the bolts in the remaining 16 coil interfaces to improve the mechanical condition of the entire system. The ability to tighten bolts in the nondielectric regions had previously been demonstrated on the TF coil mockup. A spacer block was added to the side of each tool assembly in order to span the wider channel.

A total of 4032 bolts exist in the nose regions of the remaining 16 coil interfaces. The 1-in. bolts were addressed first because they had the highest percentage of loose bolts. These were completed in approximately 3 weeks and demonstrated the ability to operate the tooling at every coil interface. Special fixtures and cable-routing techniques were required in some locations due to extensive obstructions. The inner row of 7/8-in. bolts was started near the end of the first outage period and then completed in August. The outer row of 7/8-in. bolts was in progress in September with 17 of the 32 bolt rows completed at the time of this writing.

IV. CONCLUDING REMARKS

The development and application of the remote tooling presented in this paper has helped prepare TFTR for its final phase of operation by improving the structural integrity and reliability of the TF coil system. In addition, these improvements are currently being studied to determine if an increase above the normal TF coil operating current can subsequently be applied to maximize fusion performance during the final stages of DT operation.

ACKNOWLEDGMENTS

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[1] M. Harmsen et al., "Tokamak Fusion Test Reactor System Description, SD-3D, Toroidal Field Coils," Rev. 1, PPPL document, November 1982.

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