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Performance Recovery of the TRISTAN Superconducting RF Cavities

K. Asano, T. Furuya, S. Mitsunobu, T. Tajima and T. Takahashi

KEK, National Laboratory for High Energy Physics

1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan

The superconducting RF cavities have been operated in TRISTAN Main Ring (MR) since 1988. In the early stage of the operation, the teflon backup disk on the atmospheric side of the ceramic window for the MR-6b input coupler was burnt down seriously, and the ceramic window was also broken during aging at beam-off at 4.4 K in TRISTAN MR. A lump of green powder consisting of Cu and Nb oxides was observed inside the nearest cavity-cell to the broken input coupler. After surface retreatments, the maximum accelerating gradient, E_{acc}^{max}, of 10 MV/m was obtained for these two 5-cell MR-6 cavities in vertical tests. In TRISTAN MR, the MR-6b cavity was detuned because of low E_{acc}^{max} = 3.0 MV/m in horizontal tests. However, without any surface retreatments, E_{acc}^{max} = 8.4 MV/m was obtained in vertical tests for this MR-6b cavity.

During 5 years operation until the summer shutdown in 1993, 3 pairs of TRISTAN superconducting 5-cell cavities (MR-2, 10, 11) were heavily contaminated with a large amount of leaked cooling water from the input couplers. The main metal contaminations on the inner surfaces of the cavity-cells were Cu and Mo. The cooling water leaked at outer water jackets, especially at the water inlet, of the input coupler ceramic windows because of many local erosion-corrosion pits on 1 mm thick Cu cylinders which were brazed to ceramic disks with Mo wires wound. The inner surfaces of these 8 contaminated cavities were retreated by electropolishing (EP) of about 15 µm and careful rinsing in order to recover the performance.

In the shortest case, it takes 2 months to restore the two 5-cell cavities into TRISTAN MR whose performances were recovered. All the MR-2, 10 and 11 cavities showed E_{acc}^{max} between 11.1 and 5.6 MV/m in vertical tests, and after installation in TRISTAN MR, the MR-10 and 11 cavities showed E_{acc}^{max} between 7.6 and 6.5 MV/m. Now the MR-2 and 6 cavities are set in the test stand outside the tunnel. In this paper, we report the performance recovery after surface retreatments for these 8 contaminated 5-cell cavities in TRISTAN MR.

I. Introduction

The superconducting RF cavities have been operated in TRISTAN Main Ring (MR) for 5 years since the autumn of 1988. The RF performances (Q_0 value, maximum accelerating gradient, electron loading and RF field emission) of the Nb superconducting cavities are very sensitive to the inner surface conditions of the cavity, because the penetration depth of the microwave is several hundreds Å in the superconducting state. The TRISTAN superconducting RF system trips more frequently than the normal conducting RF system where the beam current is relatively high in spite of the good performance without beam. Most of the trips are considered to be triggered by the synchrotron radiation light1). The degradation of the E_{acc}^{max} caused by a large amount of gas burst are also related with the frequent trips during the beam acceleration2). The trips in some cavities are due to the arc by some bad condition at the input coupler2). The crucial reason for the frequent trips has not been able to be confirmed yet. It may be important to investigate the interaction of gas molecules adsorbed on the superconducting Nb surfaces at 4.2 K with synchrotron radiation. The work function for the Nb surface is greatly changed by gas adsorption.

We have been keeping the RF performances and the surface conditions of 32 5-cell Nb superconducting 508 MHz cavities operated in TRISTAN MR and 4 spare cavities. During 5 years operation until the summer shutdown in 1993, 3 pairs of TRISTAN superconducting 5-cell cavities (MR-2, 10, 11) were heavily contaminated with a large amount of leaked cooling water from the input couplers. In the early stage of the operation, the teflon backup disk on the atmospheric side of the ceramic window for the MR-6b input coupler was burnt down seriously and the ceramic window was also broken during aging at beam-off at 4.4 K in the TRISTAN tunnel3). The inner surfaces of these 8 contaminated cavities were retreated by electropolishing (EP) of about 15 μm and careful rinsing in order to recover the cavity performance. Annealing in a Ti box (700°C × 90 min) was also performed for the MR-6 cavities. All the cavities showed E_{acc}^{max} between 11.1 and 5.6 MV/m in the vertical tests after surface retreatments. In this paper, we report the performance recovery after surface retreatments for 8 contaminated 5-cell cavities in TRISTAN MR.

II. Surface Treatments for 8 Contaminated Nb Cavities

A. Vacuum Leaked Cavity

The first 16 superconducting 5-cell cavities were installed in TRISTAN MR in the summer of 1988, and the beam energy was increased from 28 GeV to 30 GeV. The last 16 cavities were installed in the summer shutdown of 1989, and the beam energy was increased to 32 GeV with the beam current of 12 mA in late 1989 using the 200 MV additional accelerating voltage generated by the 28 or 29 operated superconducting cavities.

In this early stage of the operation (January 1989), the teflon backup disk on the atmospheric side of the ceramic window for the MR-6b input coupler was burnt down seriously, and the ceramic window was also broken during aging at beam-off at 4.4 K in TRISTAN MR3). A lump of green powder consisting of Cu and Nb oxides was observed inside the nearest cavity-cell to the broken input coupler. Inside the beam pipe of the broken input coupler side, a lot of white powder whose composition is mainly Nb oxide including small amount of Cu oxide was also observed. Many traces of discharge were found out inside the Nb input port and the outer conductor of the input coupler. Fluorine of the teflon backup disk was detected from the surface to 500 Å depth of the Cu plated inner conductor by Auger electron spectroscopy (AES). Annealing in addition to electropolishing the contaminated cavities was necessary to decompose the C-F bonding of the evaporated teflon on the Nb surfaces. **Fig. 1** shows the photographs of the contaminated area and discharge traces.

The vacuum leak of ceramic windows has happened 6 times. These troubles are reported elsewhere4). In the case of pin-hole vacuum leak of ceramic windows, the cavity performance was recovered by only replacement of input couplers in the TRISTAN tunnel3). Break of the windows has not happened since the arc sensors have been attached to detect discharge near the ceramic windows and switch off input RF power1).

In 1992, the number of operating cavities was decreased to 23 because of many troubles such as vacuum leak at beam pipe indium joints and water leak at outer water jackets of input coupler ceramic windows. We simply reassembled 4 vacuum leaked pairs in a clean room because of only He gas leak. After the tuner was released during warm-up and cool-down, the vacuum leak at indium joints has not happened. The performance for the reassembled cavities was recovered completely.

B. Water leak Cavities

During 5 years operation until the summer shutdown in 1993, 3 pairs of the TRISTAN superconducting 5-cell cavities (MR-2, 10, 11) were heavily contaminated with a large amount of leaked cooling water from the input couplers[4)]. The main metal contaminations on the inner surfaces of the cavity-cells were Cu and Mo. The cooling water leaked at outer water jackets, especially at the water inlet, of the input coupler ceramic windows[4)], because of many local erosion-corrosion pits on 1 mm thick Cu cylinders which were brazed to ceramic disks with Mo wires wound.

For MR-2 cavities, the cooling water (~ 20 *l*) leaked inside the cavity-cells during warm-up from 4.4 K to 300 K in July 1991. In January 1992, 15 *l* and 2 *l* cooling water leaked in MR-10 and 11 cavities, respectively, at room temperature just before cool-down for operation. The dirty marks of leaked cooling water pools were observed in each cell.

C. Surface Treatments for Contaminated Cavities

Table 1 shows the summary of surface treatments for 8 contaminated cavities. After we took these 8 contaminated cavities (MR-2, 6, 10, 11) out of cryostats, we checked carefully the inner surfaces of the cavities with mirror and telescope, and cleaned using bencott with ultrapure water and dilute nitric acid to remove Cu contaminations. The Nb flanges of beam pipes, input, HOM and 15 D monitor ports were polished chemically with HF + HNO_3 + H_3PO_4 solution. The inner surfaces of all the cleaned cavities with bencott were rinsed with demineralized water shower for 10 min. After pre-electropolishing of 3.2 ~ 5.0 μm without circulating the acid, the inner surfaces were rinsed with demineralized water. The used dirty acid for pre-electropolishing was disposed of in a tank, and was not used for next electropolishing. The water leaked cavities were not annealed.

The contaminated cavities were electropolished by 5 ~ 15 μm during circulating the acid from a reservoir in order to recover the cavity performance. Rinsing method including H_2O_2

rinsing is also shown in **Table 1**. By H_2O_2 rinsing, the carbon contamination on Nb surfaces after electropolishing is removed and the stable Nb_2O_5 layers are formed[5]. The clean, stable, dense and thin Nb_2O_5 layers can suppress the electron emission[6] and photon stimulated desorption (PSD) from the Nb surface. The 4.0 eV work function for Nb surfaces is increased to 5.9 eV by oxygen adlayers. How we form the Nb_2O_5 layers on Nb surfaces is important. We will try improved surface treatments for KEK-B factory superconducting cavities.

III. Erosion-Corrosion of Cu Water Jackets

Table 2 shows the analysis results for leaked water in cavities from input couplers, cooling water (used and not used), and final rinsed water after cavity retreatments. A large amount of Mo and Cu contents were included in the leaked water and cooling water for input couplers. Many local erosion-corrosion pits were observed on 1 mm thick Cu cylinders which were brazed to ceramic disks with Mo wires wound.

The corrosion starts at the defect points of the stable protecting films on Cu surfaces and becomes to pitting corrosion. Mo wires are easily corroded by water including air. Mo ions in cooling water accelerate the generation and growth of pitting corrosion on Cu water jackets. The precipitation of molybdate leads to local corrosion of Cu (Deposit Attack).

The corrosion resistant oxide films of Cu are easily peeled off by impingement of air cavitation bubbles in cooling water. The pitting corrosion is generated at the locally peeled off area (Erosion-Corrosion or Impingement Attack). This impingement attack happens at the water inlet (Inlet Attack or Inlet-Tube Corrosion). **Fig. 2** shows the mechanism and photographs of erosion-corrosion of outer water Cu jackets (Inlet-Attack) for input coupler ceramic windows. This trouble will be simply solved by using filters and decreasing the water flow rate and air bubbles in cooling water. But water cooling of outer cylinders was stopped for the moment[4].

IV. Corrosion of SUS 316L Center Connecting Rings in Water Leaked Cavities

TRISTAN superconducting two 5-cell cavities in one cryostat are connected by a SUS 316L center ring and indium ribbon. We found out the brown color corrosion area on the bottom surface of the SUS 316L center connecting ring for water leaked cavities. One of authors observed the corrosion area using Scanning electron microscope (SEM) at KEK. **Fig. 3** shows the typical SEM photographs for the inner and outer surfaces of the SUS 316L ring for water leaked cavities. A large number of pitting corrosion (1 ~ 30 μm) was also observed on the outer surface of a new electropolished ring. The stress corrosion cracking and hydrogen embrittlement were observed only for outer surfaces and inner surfaces, respectively, of the rings for water leaked cavities.

V. Performance Recovery of 8 Contaminated Nb Cavities

Table 3 shows the history of E_{acc}^{max} (MV/m) in vertical tests before and after surface retreatments for 4 pairs of TRISTAN superconducting cavities (MR-2, 6, 10, 11).

The MR-2 (a,b) cavities leaked to about 10^{-3} Torr in precooling by liquid N_2 for vertical tests after surface retreatments due to water trouble. Both cavities showed the break down at 7.9 and 5.6 MV/m in vertical tests respectively. The Q_0 values for both cavities were also lower than those for the 1st measurement. After assembling, MR-2 (a,b) cavities showed E_{acc}^{max} = 7.1 and 4.9 MV/m respectively in the horizontal test7). These cavities are set in the test stand outside the tunnel.

A pair of MR-6 cavities showed E_{acc}^{max} higher than 10 MV/m after surface retreatments. $E_{acc}^{max} > 10.2$ MV/m for the MR-6a cavity was higher than that before the retreatment. The performances for these two cavities were recovered completely in vertical tests. But in horizontal tests, E_{acc}^{max} for the MR-6b cavity was limited to 3.0 MV/m7). In TRISTAN MR, this MR-6b cavity was detuned because of low E_{acc}^{max} 3). We obtained again the high E_{acc}^{max} of 8.4 MV/m in the vertical test for this MR-6b cavity without any surface treatment except for RF processing. We suppose that some dust or micro-particles are introduced into the cavity cells during assembling in a clean room. On the other hand, the MR-6a cavity in TRISTAN MR showed the highest record of E_{acc}^{max} = 9.1 MV/m limited by klystron power7).

The MR-10 cavities also showed E_{acc}^{max} higher than 10 MV/m in vertical tests after surface retreatments. After installation in TRISTAN MR, E_{acc}^{max} = 6.6 (10a) and 6.2 MV/m (10b) were obtained in October 1992⁷⁾. After one year operation, these MR-10 cavities showed E_{acc}^{max} = 7.2 (10a) and 6.5 MV/m (10b) in TRISTAN MR⁷⁾, which were a little higher than before by RF aging.

The MR-11 (a,b) cavities showed the breakdown at 7.0 and 6.2 MV/m respectively in vertical tests after surface retreatments. After installation in TRISTAN MR, E_{acc}^{max} = 6.3 (11a) and 5.0 MV/m (11b) were obtained in October 1992⁷⁾. After one year operation, these cavities showed E_{acc}^{max} = 6.6 (11a) and 7.6 MV/m (11b) in TRISTAN MR⁷⁾. One year operation in TRISTAN MR upgraded both MR-10 and 11 cavities after surface retreatments.

In the shortest case, it takes 2 months to restore the two 5-cell cavities into the TRISTAN MR whose performances are recovered. Q_0-Eacc curves for MR-2, 6, 10, and 11 are shown in **Fig. 4 ~ Fig. 7**. The performances for simply reassembled cavities (MR-7, 13, 15) due to vacuum leak were recovered completely by RF aging in TRISTAN MR.

VI. Conclusions

We have recovered the performances of water leaked and vacuum leaked cavities, and have restored in TRISTAN MR.

The performances of the water and vacuum leaked superconducting RF cavities were recovered by surface retreatments. Reassembling in a clean room due to vacuum leak at beam pipe indium joints showed no degradation of cavity performances in TRISTAN MR. In the case of pin-hole leak of ceramic windows, the cavity performances were recovered only by replacements of input couplers.

Most of the trips of TRISTAN superconducting cavities are considered to be triggered by the synchrotron radiation light. It is necessary to study the interaction of gas molecules adsorbed on superconducting Nb surfaces with synchrotron radiation light or electron beam such as PSD or surface work function changes due to gas adsorption.

The high quality of thin oxide layers on Nb surfaces will be able to reduce PSD yield and secondary electron or RF field emissions. These studies are important in particular for high current application such as a B-factory.

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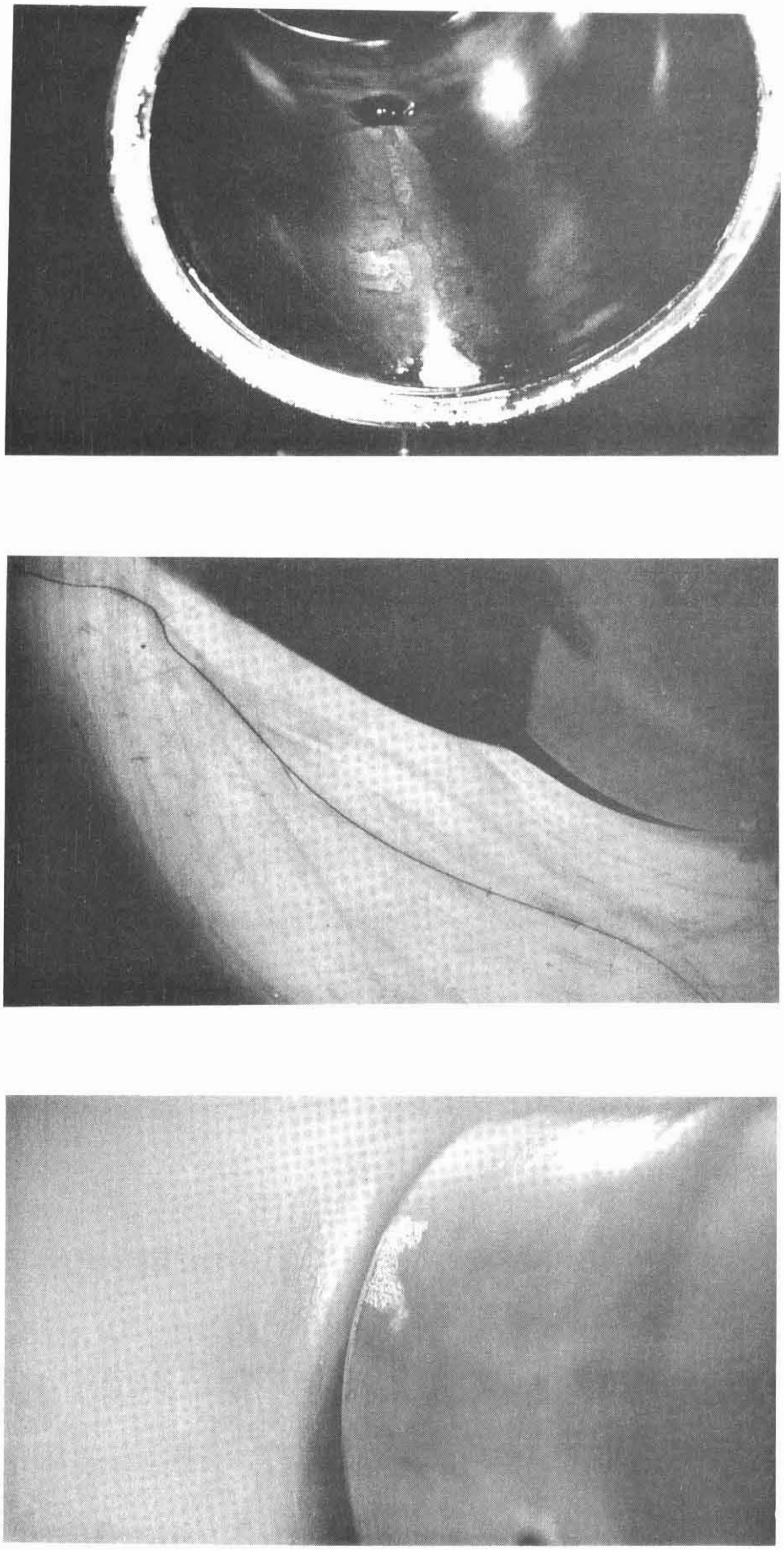


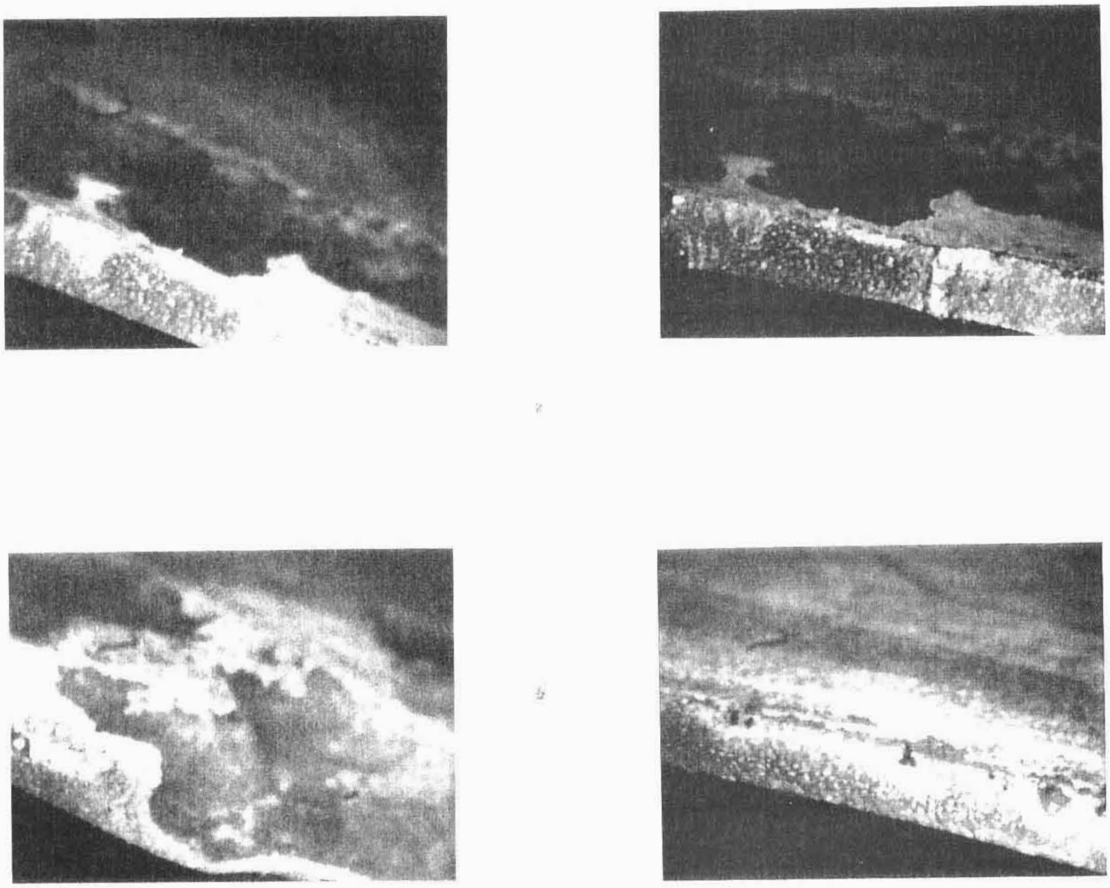
Fig. 1 Photographs of contaminated cavities, broken input coupler ceramic windows, and discharge traces.

Table 1 Surface treatments for contaminated 508MHz 5-cell Nb cavities with cooling water in TRISTAN MR

Cavity No.	MR-2 a , b	MR-6 a , b	MR-10 a , b	MR-11 a , b
	Careful check of inner surfaces of cavities with mirror and telescope, cleaning using bencott with ultrapure water and dilute nitric acid, chemical polishing of Nb-input, HOM, and 15D monitor ports flanges Shower rinse with demineralized water for 10min			
pre EP ;	3.3μm	5.0μm	3.3μm	3.2–3.4μm
1st rinse ;	6 times overflow with demineralized water, total 30min			
2nd rinse ;	Shower rinse with demineralized water for 30min			
anneal ;	——	700°C × 90min in a Ti box	——	——
EP ;	15μm	10μm	15μm	5, 10μm
1st rinse ;	6times overflow with demineralized water total 30min			
2nd rinse ;	Shower rinse with demineralized water for 30~60 min , 2kg/cm^2			
10 w% H_2O_2 rinse ;	Rotation (3rpm) with filled H_2O_2 solution for 10min or 40min Immersed in a warm (55°C) ultrasonic bath 28kHz, 600w × 8, 40~70min			
shower ;	Shower rinse with demineralized water for 10~20min			
3rd rinse ;	Overflow with demineralized water in a warm ultrasonic bath			
	220, 186min,	170, 170min,	231, 236 min,	192, 167 min.
4th rinse ;	Overflow with ultrapure water in a warm ultrasonic bath for 5min Rotation (3rpm) for 10min on the EP bed Overflow with ultrapure water for 5min			
final rinse ;	Shower with ultrapure water for 1min Sealed with filtered ultrapure N_2 gas			

Table 2 Analysis for leaked water, cooling water and rinsed water

	leaked water in cavities from input couplers	cooling water for input couplers (not used)	final rinsed water after retreatment (11a)
σ (μS/cm at 25° C)	143	84.0(81.1)	2.00
pH	4.5	4.7(6.28)	5.54
Mo(mg/ℓ)	184	89 (<0.2)	<0.05
Cu	72.9	30.4(<0.05)	<0.2
Zn	0.09	0.11(<0.1)	<0.05
Fe	0.13	0.02(<0.02)	<0.4
Cr	0.04	0.07(<0.01)	<0.2
Ni	8.43	0.74(<0.2)	<0.7
SO_4^{2-}	1.2	0.5(0.01)	0.02
NO_3^-	<0.01	<0.01(<0.01)	0.03



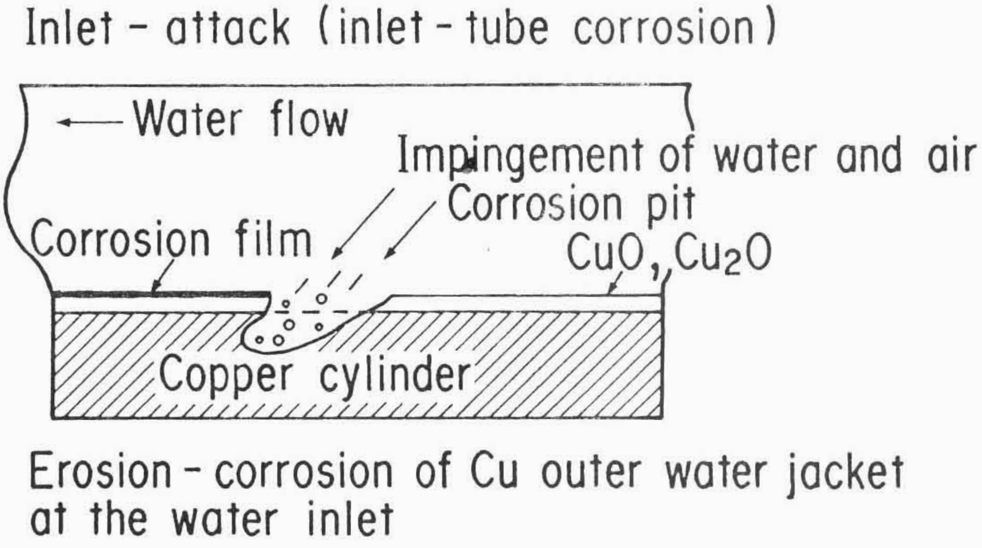
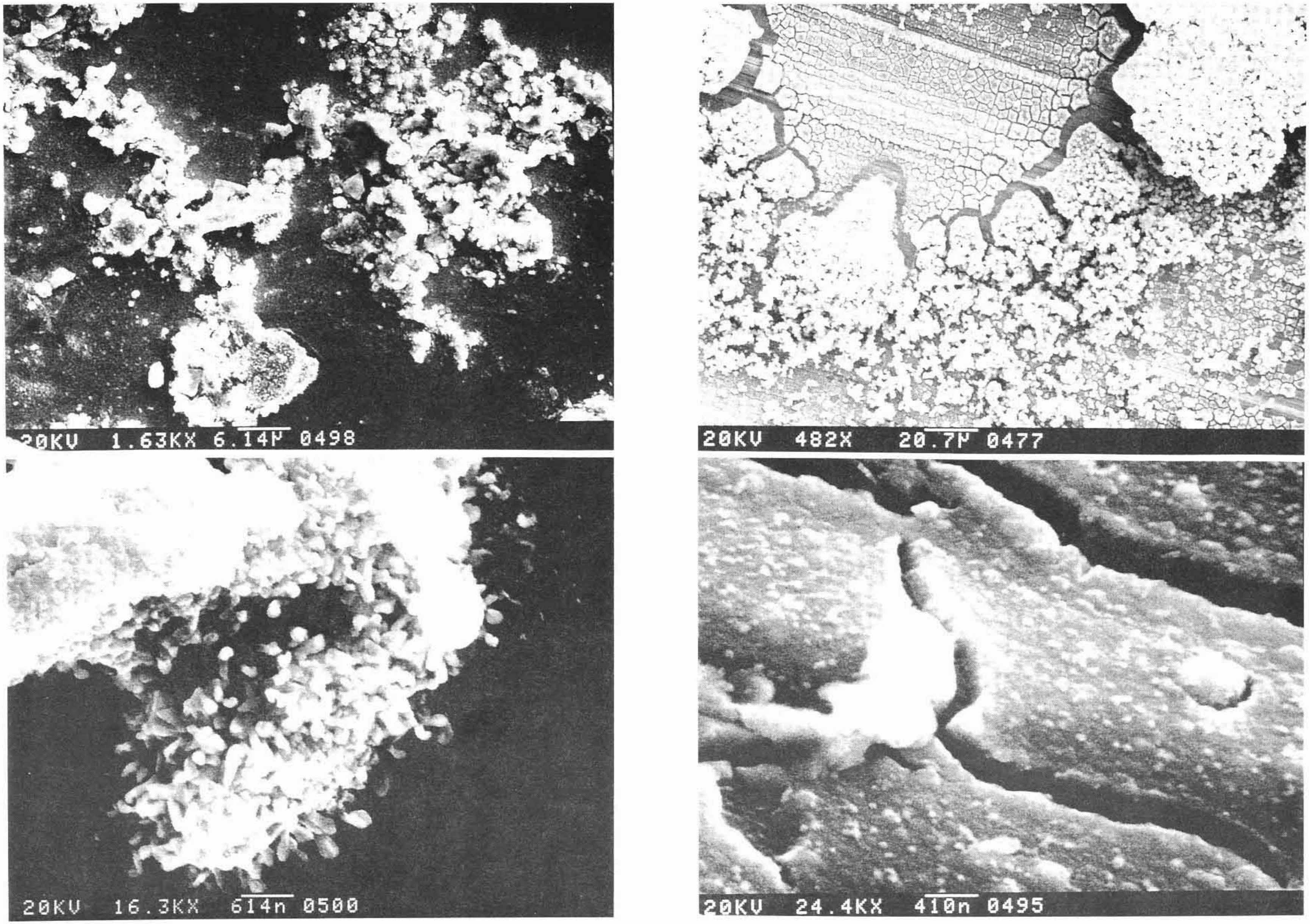


Fig. 2 Photographs and mechanism of erosion-corrosion of outer water Cu jackets for input coupler ceramic windows.



(a) inner surfaces – embrittlement

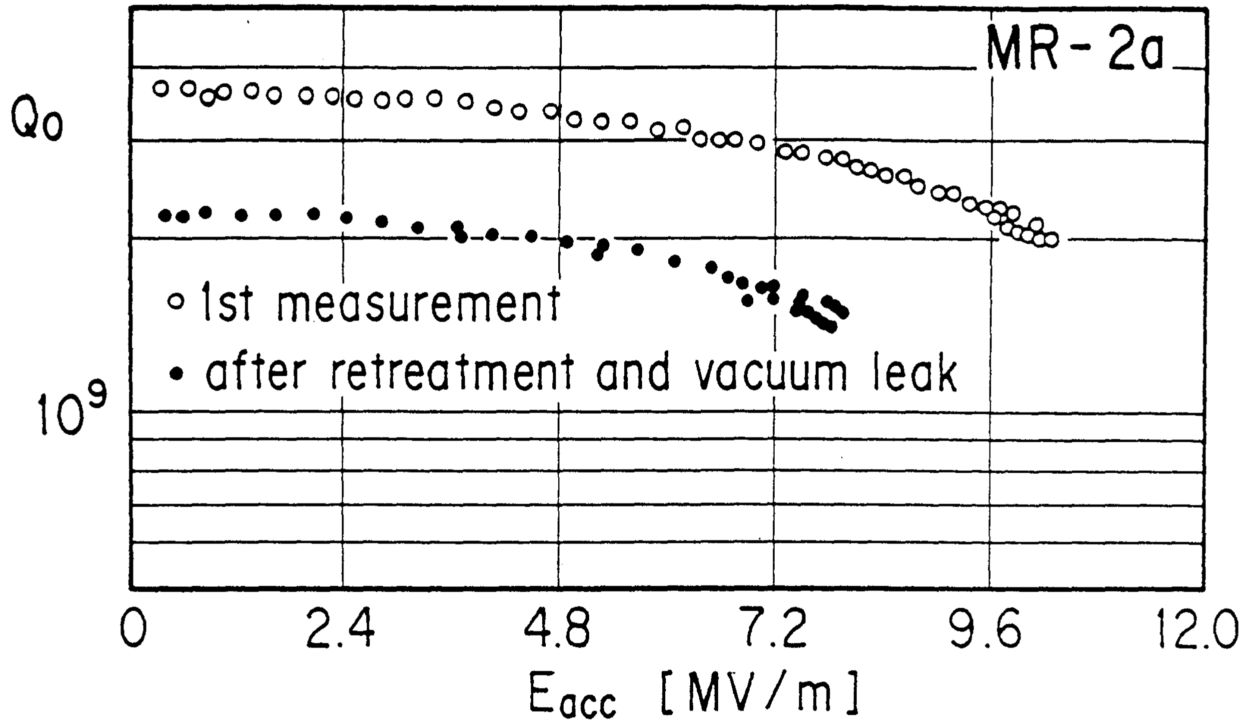
(b) outer surfaces – stress corrosion cracking

Fig. 3 Typical SEM photographs of SUS 316L center connecting ring for water leaked cavities.

Table 3 Changes of E_{acc}^{max} (MV/m) in vertical measurements after surface retreatments for 8 contaminated 508MHz 5-cell Nb cavities with cooling water in TRISTAN MR

Cavity No.	MR-2		MR-6		MR-10		MR-11	
	a	b	a	b	a	b	a	b
1st test	10.2	10.3	2.75↓	10.6	11.7	8.9↓	7.2↓	10.6
2nd test			3.48↓	(after grinding and EP Ⅱ)				
3rd test			7.58↓				(5.0↓ in the horizontal test)	
after retreatment due to degradation							4.7↓	10.4
after retreatment due to water trouble in TRISTAN MR	7.9↓ (vacuum leak)	5.6↓	10.2	10.1 (3.0↓ in the horizontal test)	11.1	10.4	7.0↓	6.2↓
after degradation in TRISTAN MR				8.4↓ (without retreatment)				

↓ ; Break down



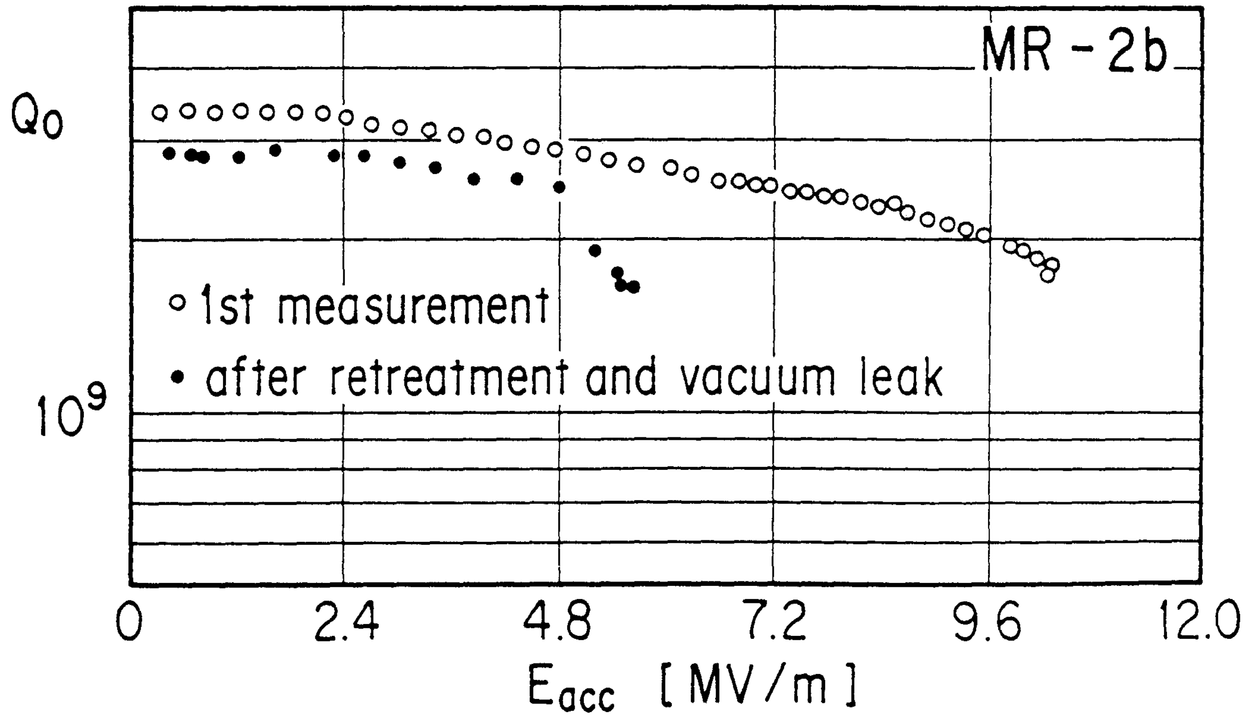
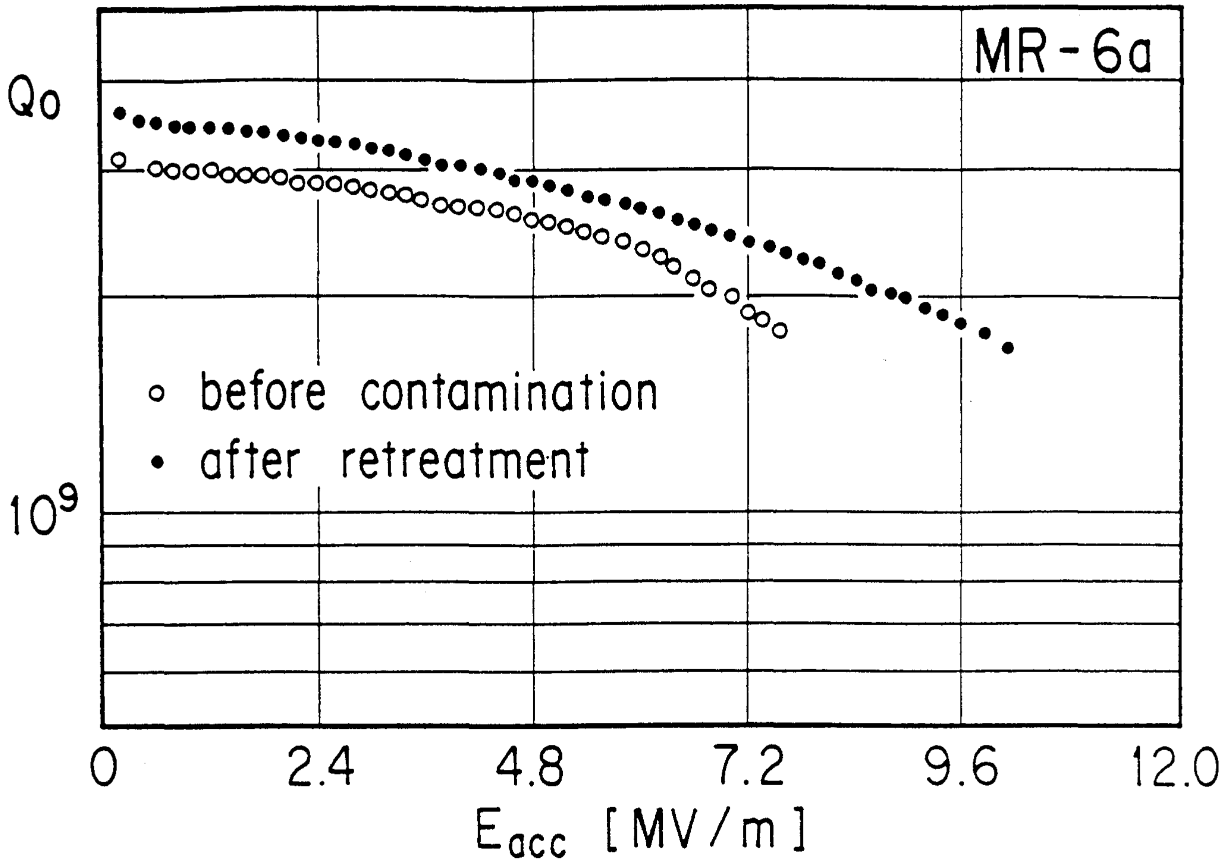


Fig. 4 Q_0-Eacc curves for MR-2 (a,b) cavities.



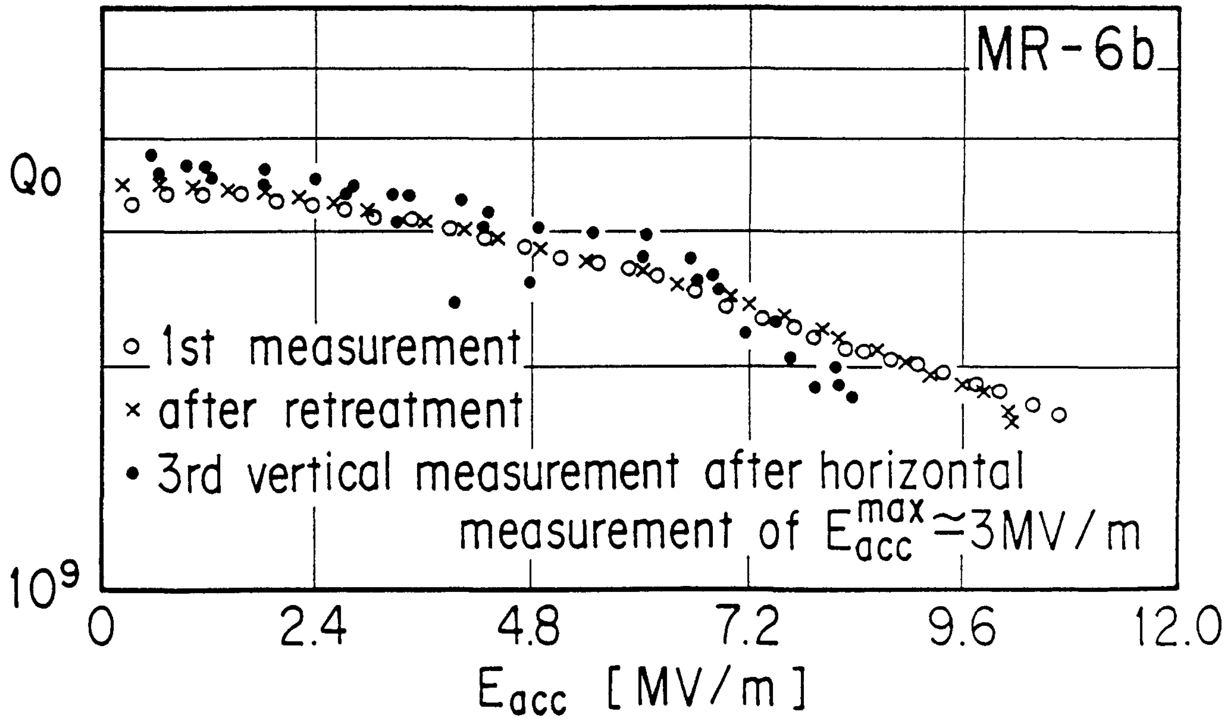
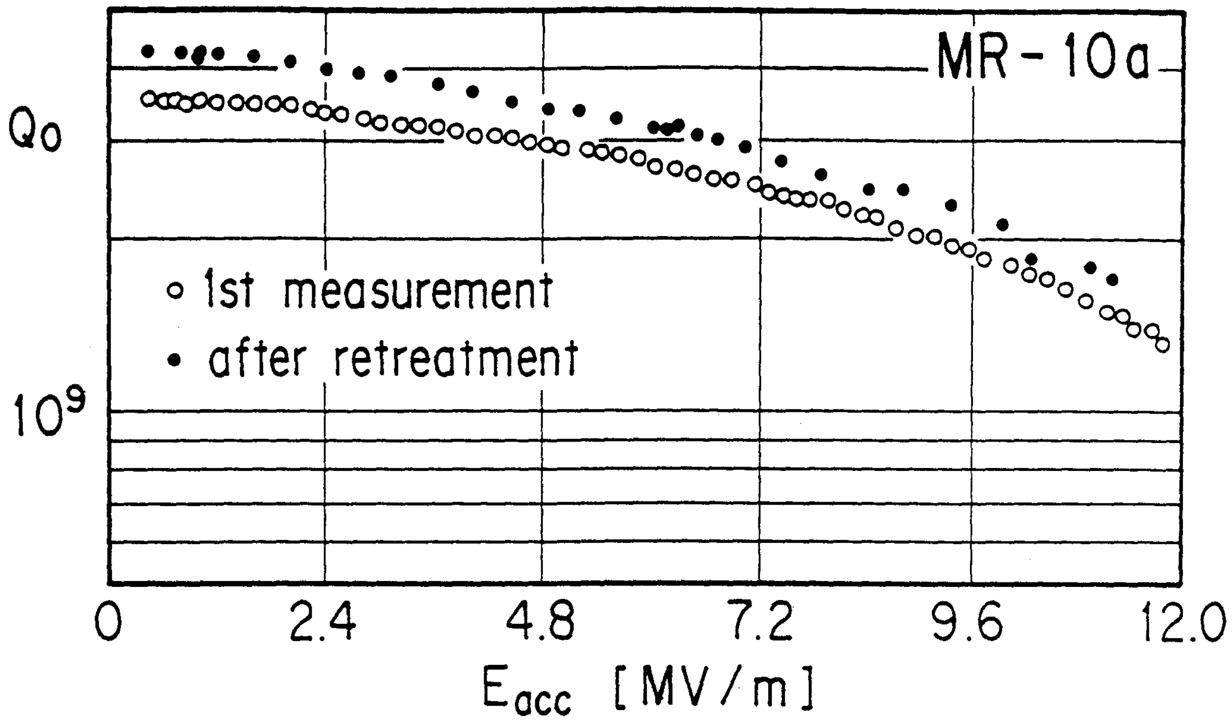


Fig. 5 Q0-Eacc curves for MR-6 (a,b) cavities.



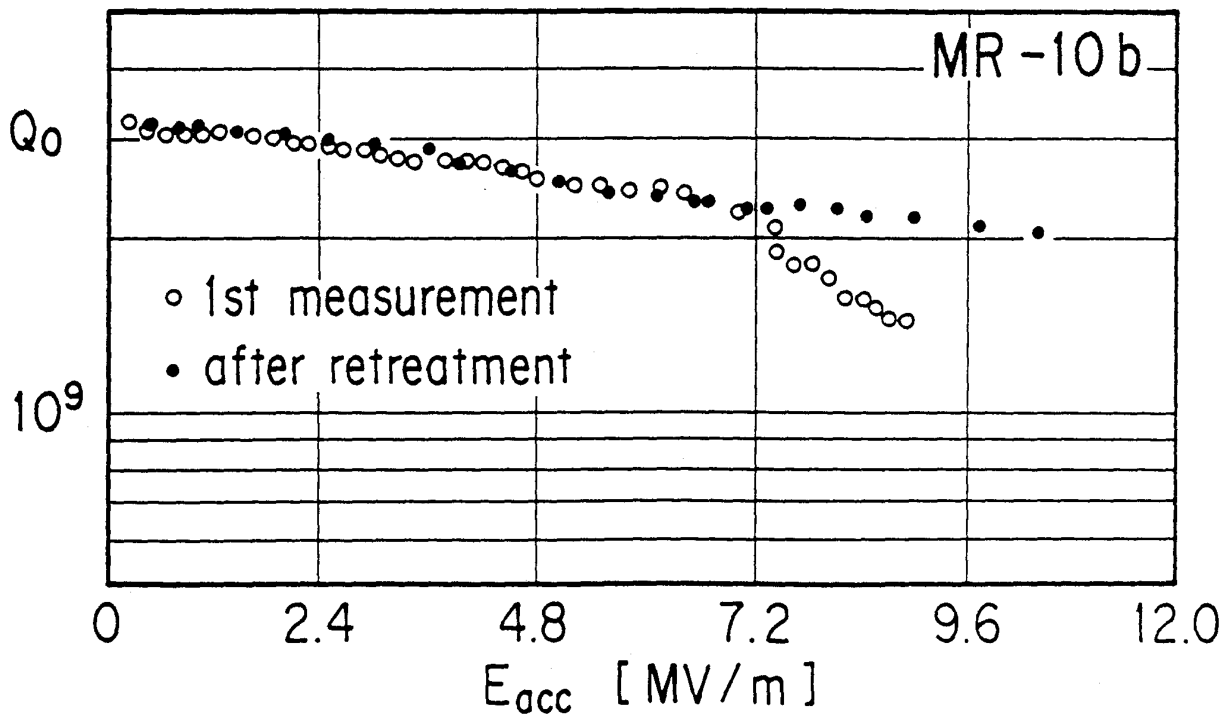
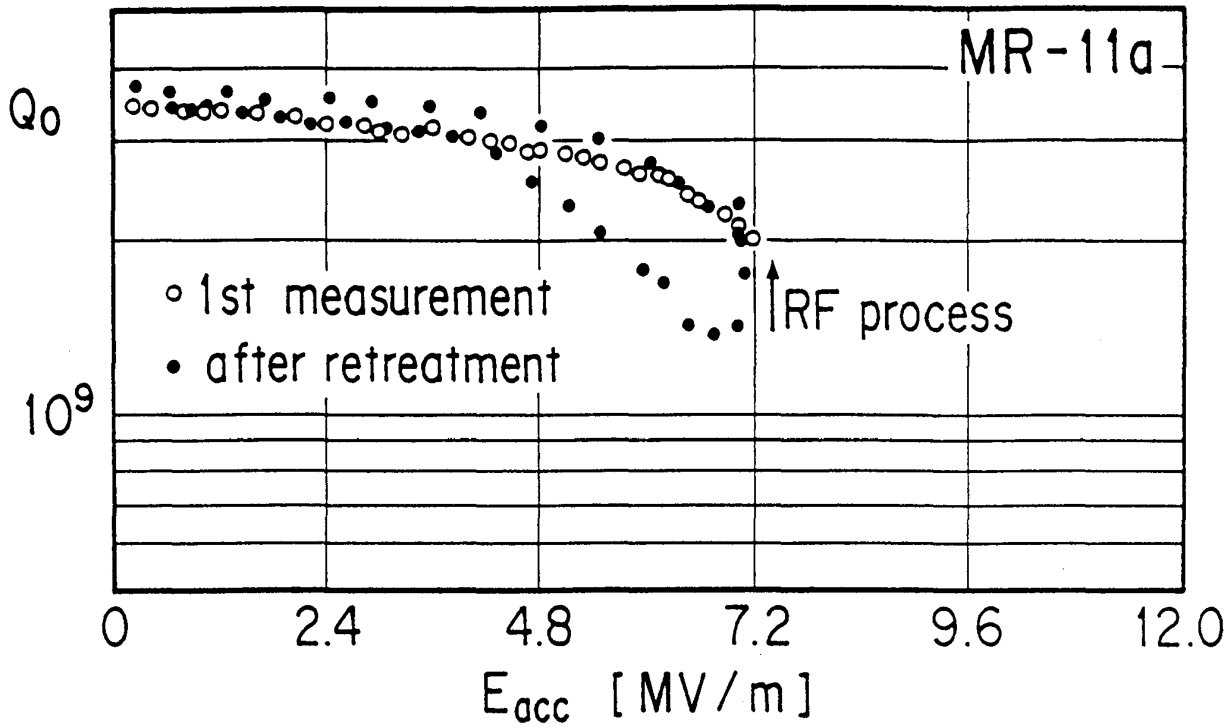


Fig. 6 Q_0-Eacc curves for MR-10 (a,b) cavities.



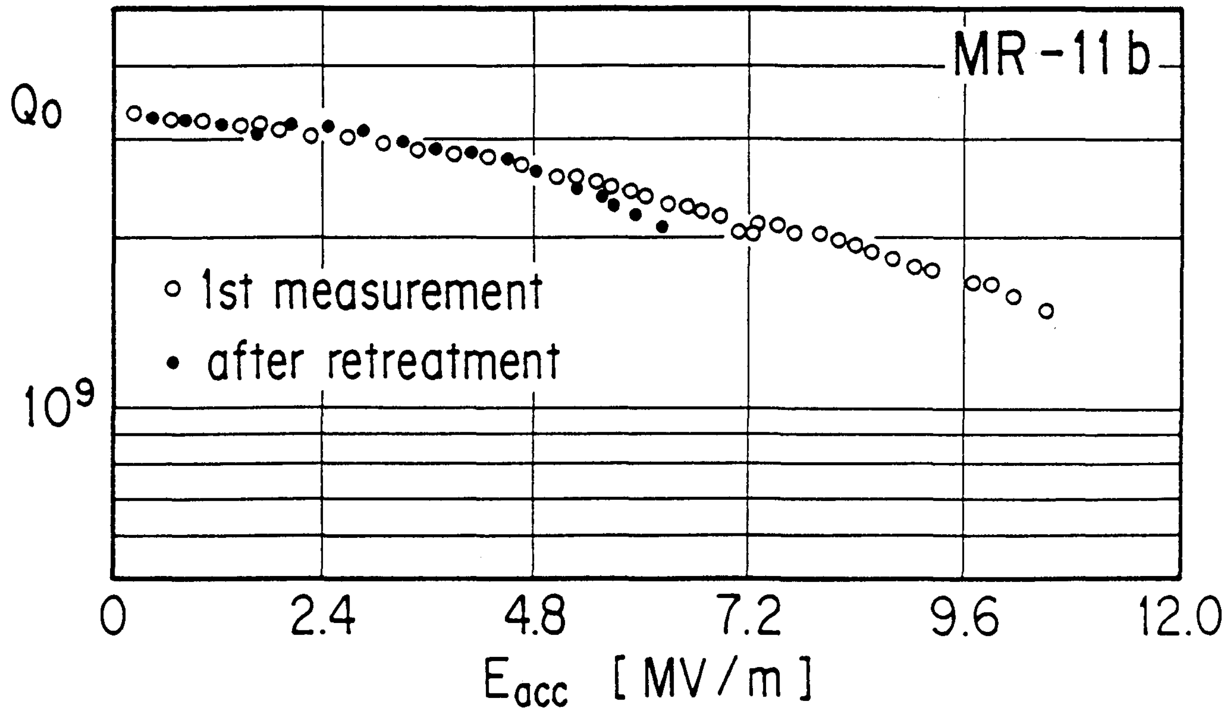


Fig. 7 Q_0-Eacc curves for MR-11 (a,b) cavities.