SUPERCONDUCTING CAVITIES FROM HIGH THERMAL CONDUCTIVITY NIOBIUM FOR CEBAF*

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ABSTRACT

The Continuous Electron Beam Accelerator Facility (CEBAF) is presently under construction in Newport News, VA. The accelerator consists of approximately 169 meters of 5-cell niobium cavities made from high thermal conductivity niobium with RRR values > 250.

Cavities have been manufactured of material from three different suppliers. The material properties like thermal conductivity, residual resistivity and tensile behavior are compared.

Results on the performance of these cavities in the presence of high rf fields are reported. Q_o values as high as 10^{10} at 2 K and accelerating gradient of E > 14 MV/m have been achieved.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) is presently under construction in Newport News, Virginia. The facility will provide a low emittance electron beam with a current of 200 μA and energies up to 4 GeV for fundamental experimental studies in nuclear physics.

The central part of the facility are two anti-parallel linear accelerators arranged as a race track. They each consist of 160 superconducting niobium cavities of a total length of approximately 160 meters; 18 additional cavities of the same type are used

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in the injector. These cavities are assembled into pairs, which in turn are installed in a single helium vessel forming a cryounit. Four of such cryounits are joined into a cryomodule, which represents the smallest unit that can be independently cooled and installed or removed from the accelerator system.

The 5-cell cavities with an active length of 0.5 m are kept at 2 K by means of a 5 kW refrigerator; they are excited in the accelerating mode at 1497.000 MHz and are operated at an accelerating gradient of at least 5 MV/m. At this gradient, each cavity will dissipate approximately 5.5 Watts of rf power.

In order to achieve these low losses in the cavity walls and the high accelerating gradients, particular care has to be taken during the manufacturing of the niobium material and the cavities.

This paper describes the requirements for the cavity material, measurements of material parameters, the manufacturing process for the cavities and results on cavity performance.

MATERIAL REQUIREMENTS AND PROPERTIES

For a long time, superconducting niobium cavities have been limited in their performance by thermal instabilities in the cavity walls. The systematic use of diagnostic methods, in particular temperature mapping of the outer cavity wall in subcooled helium[1], revealed that microscopic defects are responsible for the increased cavity losses. These microscopic defects include weld imperfections, surface irregularities, foreign material inclusions, residue from chemical surface treatments, dust and debris on the surface are responsible for field breakdown in the cavities at values far below the thermodynamic critical field of the superconducting material. Because of their increased losses, these mircroscopic defects heat up their surroundings in the presence of electromagnetic fields and eventually cause a thermal runaway. Recognition of this situation triggered simulation calculations of breakdown in rf cavities at Stanford[2] and Cornell University.[3] An important result of these investigations is that the thermal conductivity of the cavity material has a significant effect in stabilizing these local defects.[4]

Therefore, high thermal conductivity niobium, with very small amounts of interstitial impurities like H, C, O, and N, has been chosen as the cavity material for areas of high electromagnetic fields in a cavity. In the case of the CEBAF cavity as shown in Figure 1, the thermal conductivity value has been chosen to be > 60 W/mK corresponding to a Residual Resistivity Ratio (RRR) > 240.

Other important parameters for the material include requirements for the grain size, which influences the deep drawing capability of cavity parts and for the tensile properties. Simulation calculations using stress analysis codes on the real cavity shape under realistic load conditions resulted in a requirement of a yield strength > 13500 psi for the waveguide parts of the cavity and > 10700 psi for the cavity cells.[5]

Table I summarizes CEBAF's material requirements as specified in specifications for reactor grade and RRR grade niobium.

Table I

Niobium	Cavity Part	RRR	Grain Size	Yield Strength (psi)	Elong.
Reactor Grade	Couplers	≈40	ASTM >6	>13500	>25%
RRR	Cells	>250	ASTM >5	>10700	>25%

Contracts for high RRR niobium material have been awarded to Fansteel, Heraeus, and Teledyne Wah Chang. Reactor grade niobium for the couplers, flanges, and beam tube extensions is supplied by Cabot, Teledyne, and Fansteel.

The quality assurance of niobium at CEBAF is ensured via the measurement of the thermal conductivity and mechanical properties. Thermal conductivity is measured between 2 and 20 K. The residual resistance ratio (RRR), a measure of the purity of the niobium, is estimated by multiplying the thermal conductivity value (W/cm K) at 4.2 K with a constant 400.[6] Figure 2 is a typical plot of niobium thermal conductivity as a function of temperature. The estimated RRR from Figure 2 for a sample taken from a recent Fansteel production lot for CEBAF/SURA is 365, which far exceeds the specifications.

The effect of electron beam welding on the RRR of Heraeus niobium has been recently investigated. Figure 3 presents the thermal conductivity of the as received Heraeus material together with the same material electron beam welded at CEBAF and Leybold-Heraeus, Enfield, CT. A degradation in the thermal conductivity by contamination due to poor vacuum conditions is apparent from this figure.

The mechanical properties (viz), yield strength (YS), ultimate tensile strength (TS) and elongation are measured at 295, 77.4 and 4.2 K with a special UTM manufactured by Applied Test Systems, PA. Figures 4, 5, and 6 present the stress-strain curves of Cabot (RRR ≈ 40), Teledyne (RRR >250) and Fansteel (RRR >300) niobium respectively. Table II summarizes the tensile properties of the three niobium samples tested. All the materials meet the specifications. A detailed paper on the physics and tensile properties of high RRR niobium between 295 and 4.2 K will be presented elsewhere. In Figure 7, yield strength of different RRR grade niobium is presented as a function of temperature.

CAVITY FABRICATION AND TEST RESULTS

The CEBAF cavity as shown in Figure 1 was developed at Cornell University. It consists of 5 elliptically shaped cells, a fundamental mode waveguide coupler at one end of the cell assembly, and a Higher Order Mode waveguide coupler at the other end. The cavity cells are manufactured from RRR grade niobium and

Table II
Summary of Tensile Properties

Sample	RRR	Grain Size	295 K YS (KSI)	295 K TS (KSI)	295 K Elongation %	77.4 K YS (KSI)	77.4 K TS (KSI)	77.4 K Elongation %	4.2 K YS (KSI)	4.2 K TS (KSI)	4.2 K Elongation %
Cabot	40	7	21	31	46	92.5	94.2	16.8	-*	165	0.4
Teledyne	>250	8	14.5	23	42	86	88.4	12.1	130	131	>1
Fansteel	>300	6	10.6	19.5	34	82	91	14	110	124.6	>1

* The sample fractured prior to reaching the 0.2% offset

the waveguides and flanges are made out out of reactor grade niobium. CEBAF awarded a manufacturing contract for 360 cavities to Interatom after a competitive bidding process involving 5 qualified manufacturing companies. In addition, several cavities have been built "in-house".

The manufacturing drawings and processes have been developed at Cornell University and have been specified in CEBAF's "Statement of Work". Strict adherence to these procedures together with good workmanship is required to meet CEBAF's cavity specification of a Q_o value of 2.4×10^9 at 2 K and at an accelerating gradient of $E_{acc} \geq 5MV/m$.

The essential manufacturing steps are:

a) Deep drawing and machining of cavity components without deterioration in the quality of the material. (No overheating during machining, no embedding of foreign material into the niobium during the deep drawing process and avoidance of scratches on the niobium surfaces.)

b) QA of the manufactured parts and removal of any kind of visual surface irregularities like scratches, dents, voids.

c) Soaking the manufactured parts in various chemicals to remove possible foreign material embedment and a final cleaning in a solution of hydrofluoric, nitric and phosphoric acids.

d) Electron Beam Welding of the parts with full penetration welds, smooth weld appearance, free of weld splatter and voids, in a vacuum of $< 5 \times 10^{-5}$ torr.

e) Leak checking of the finished cavity, tuning of the cavity to obtain the specified frequency and field profile flatness of the accelerating mode and final machining of the flanges of the cavity to achieve the specified dimensional tolerances.

In order to qualify the cavities for the CEBAF accelerator, their performance has to be measured:

The cavities are chemically polished in a (1:1:1) buffered solution of nitric, hydrofluoric, and phosphoric acids for a duration of several minutes. This chemical polish removes the surface damage layer of $\approx 60\ \mu m$ induced into the surface during the manufacturing processes. Very thorough rinsing of the cavities is carried out with ultrapure water. This step is essential to remove any chemical residue and surface contamination from the cavity surfaces. Finally the cavities are filled with particulate free Methanol to avoid contamination prior to the forthcoming assembly procedures. In a subsequent step, two cavities are assembled into a cavity pair in a class 100 cleanroom and auxiliary parts like Higher Order Mode loads, ceramic rf windows and valve assemblies are attached to the assembly. After establishing a vacuum of $< 10^{-6}$ torr in the hermetically sealed units, they are cryogenically tested at 2 K in a vertical configuration as shown in Figure 8. Variable input couplers for the rf power are part of the test system. They permit the excitation of each individual cavity at minimum reflected power. Typical performance characteristics of a cavity pair are shown in Figure 9. The Q_o value, which is a measure of the losses in the cavity walls, for the upper cavity does not change with increasing field, whereas the lower cavity shows a strong degradation at field gradients above $\approx$ 6 MV/m. This degradation is caused by the onset of field emission loading in the cavity. Electrons, emitted from the material in the presence of electromagnetic fields, are accelerated in these fields and cause bremsstrahlung x-rays and heating when hitting the opposite cavity walls. This loading shows up as additional losses in the cavities. It has been found that the surface conditions on the cold niobium surfaces have a significant influence on the onset of field emission. Clean surfaces show very little loading whereas contaminated surfaces may exhibit pointlike emission sources. In the case of our cavity pairs, we presently think that the typical inferior performance of the lower cavity of a pair is caused by the cooldown conditions in our dewars: the lower cavity gets cold first and most of the residual gases in the pair are frozen out on the lower cavity surface. Improved vacuum conditions in the cavity assembly should provide us with less field emission loading in the lower cavity.

Until now CEBAF has tested 22 cavities out of which 16 are from Interatom and 6 are "in-house" built. The performance of all these cavities is better than CEBAF's design values. An accelerating gradient of up to 14 MV/m, which is nearly 3 times CEBAF's design value, has been measured. Q_o values of up to 2×10^{10} at 5 MV/m and 2 K have been achieved. A summary of all the tests are shown in the histogram of Figure 10, where the peak surface electric fields are plotted. For CEBAF's cavity design, the ratio of peak electric surface field to accelerating field is 2.56. The peak of the distribution is around 20 to 25 MV/m corresponding to an accelerating gradient of 8 - 9 MV/m.

CONCLUSIONS

The niobium producing industry has responded very well to CEBAF's niobium requirements. High purity niobium with RRR values > 250 and a yield strength > 10700 psi, as required by operating conditions for the accelerator, has been produced by three manufacturers. QA measurements on test samples indicate that even higher residual resistivity ratios can be produced. The tensile properties have also been measured at cryogenic tempertures. As the yield strength increases with the lowering of temperature, the elasticity of the material decreases. At helium temperature, the yield strength is $\approx$ 10 times larger than at room temperature and the elongation is below 5%.

CEBAF has successfully assembled and tested several 5-cell niobium cavity pairs fabricated both by industry and "in-house". Accelerating gradients up to 14 MV/m, nearly three times as high as the design value, and Q_o values in excess of

10^{10} have been obtained. As CEBAF enters its production phase, it is challenged to qualify 12 cavities per month in order to stay on schedule.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the help of all the Cavity Production team members both at CEBAF and Interatom.

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Figure 1 CEBAF superconducting niobium cavity

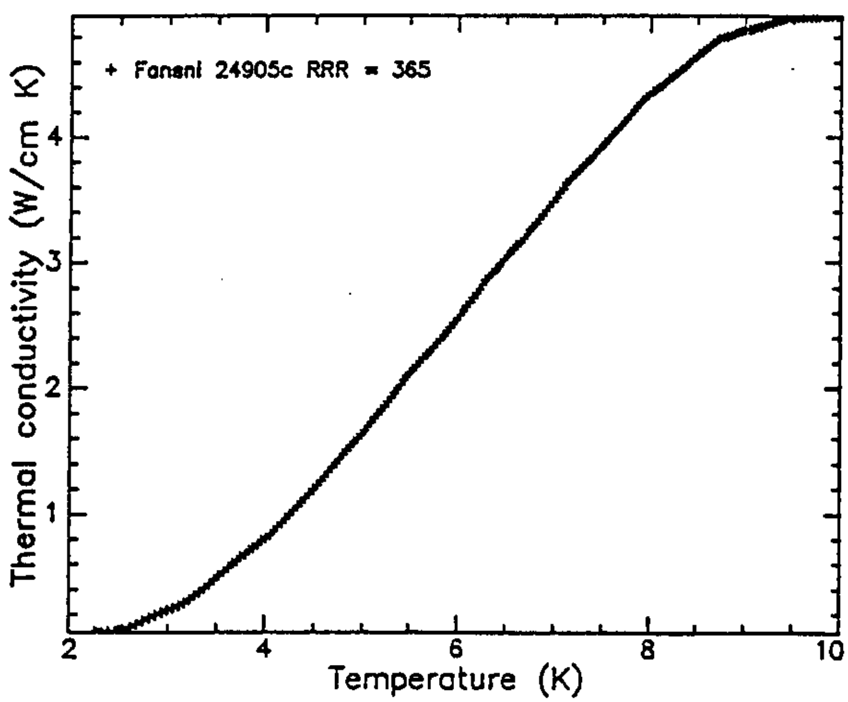

Figure 2 Thermal conductivity of Fansteel niobium

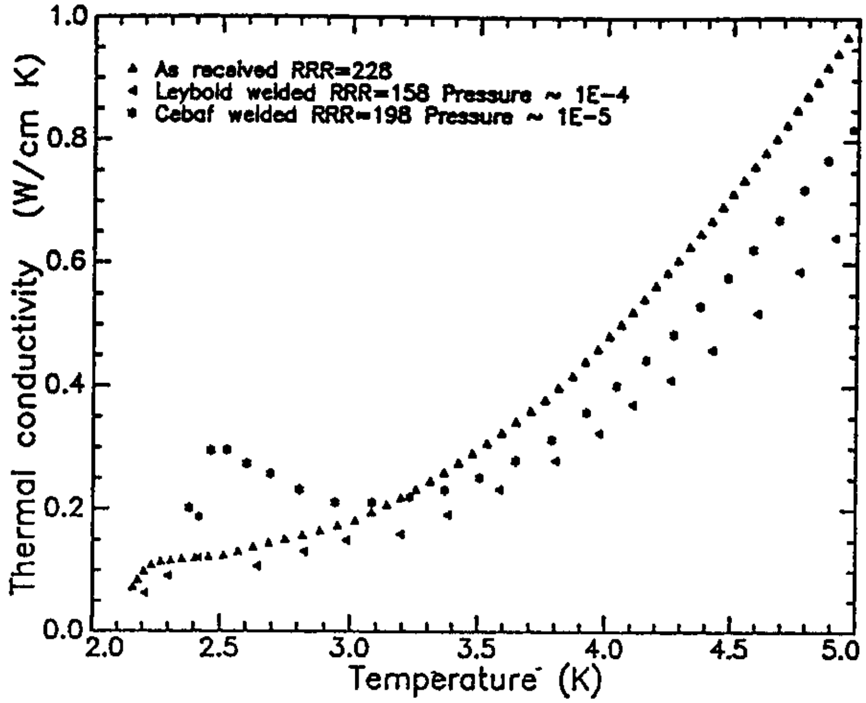

Figure 3 Thermal conductivity of Heraeus niobium

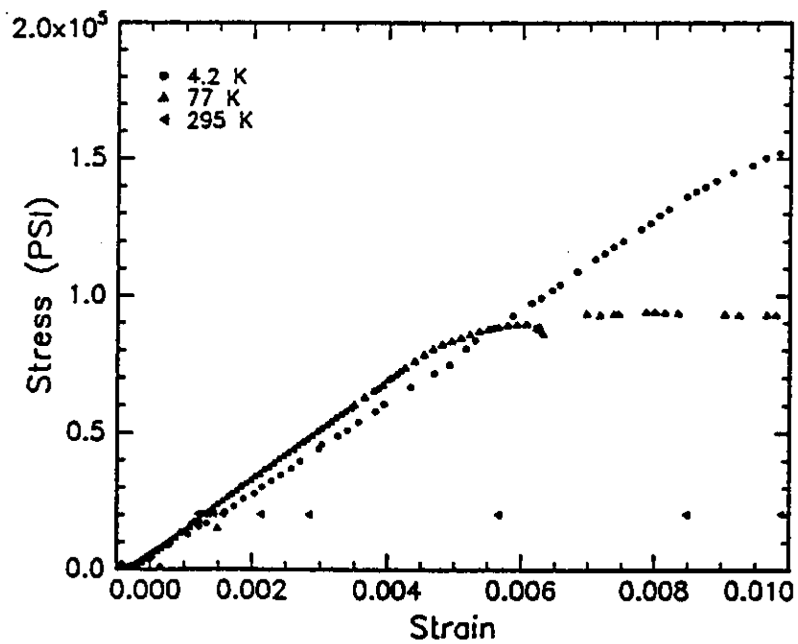

Figure 4 Stress-strain behavior of Cabot niobium

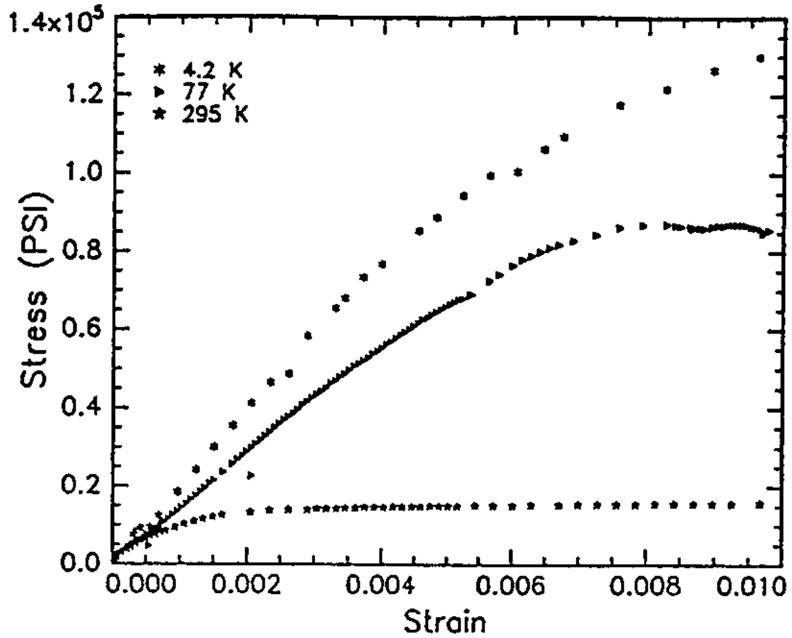

Figure 5 Stress-strain behavior of Teledyne niobium

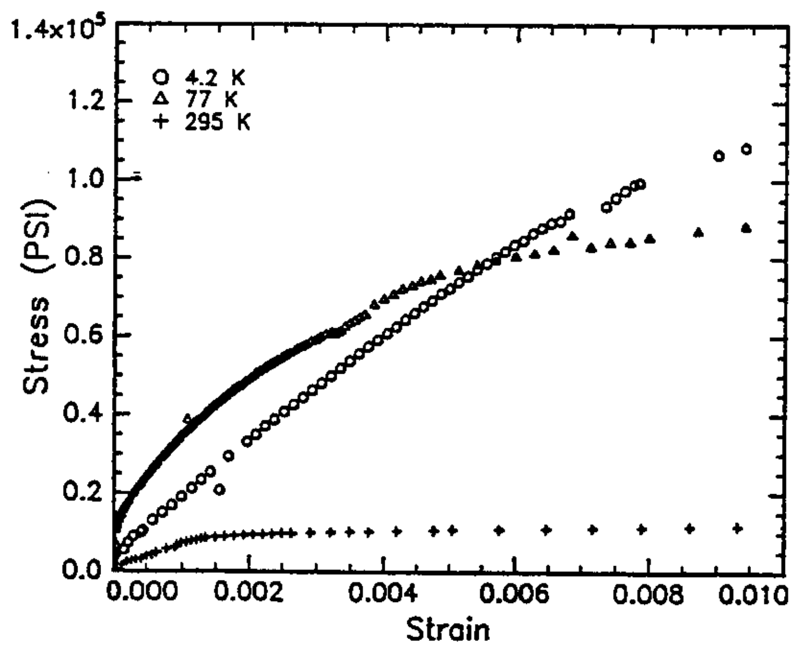

Figure 6 Stress-strain behavior of Fansteel niobium

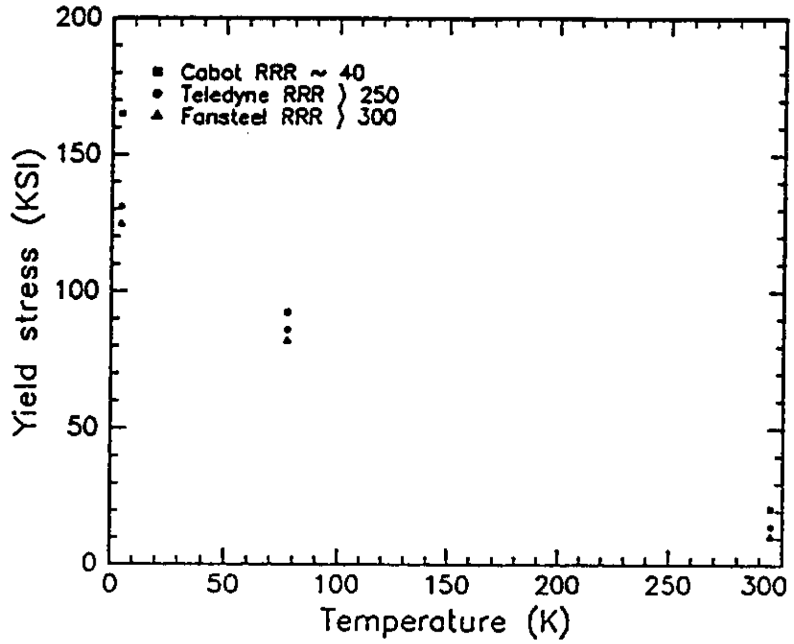

Figure 7 Temperature dependence of niobium yield strength
(Note: Cabot fractured before reaching 0.2% offset)

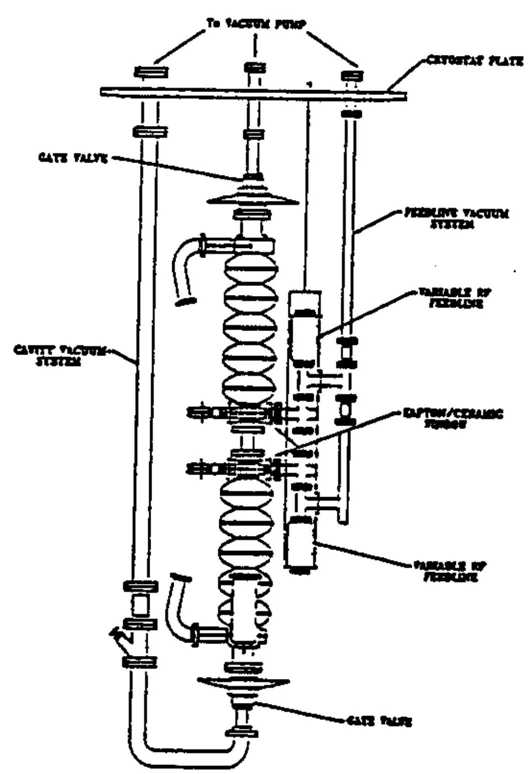

Figure 8 Cavity pair test set-up

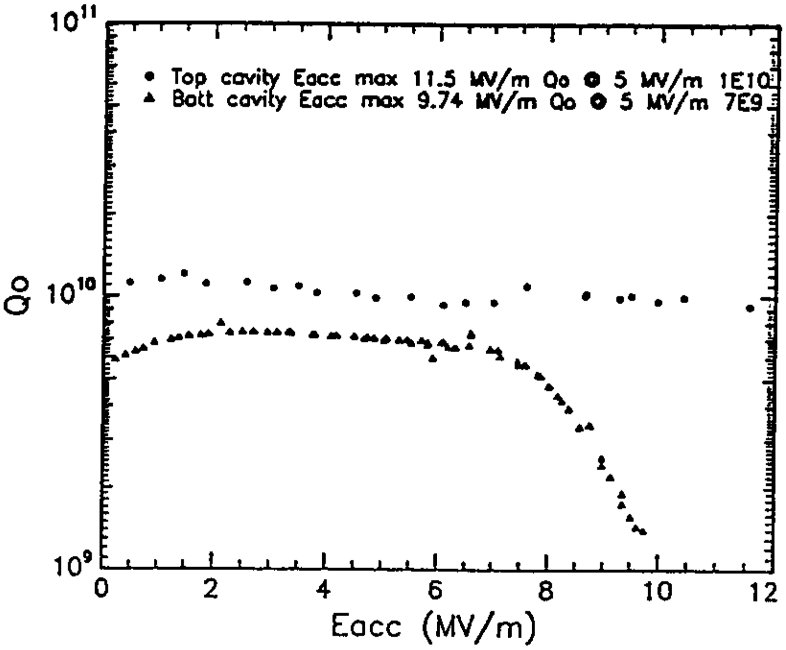

Figure 9 Performance characteristics of cavity pair

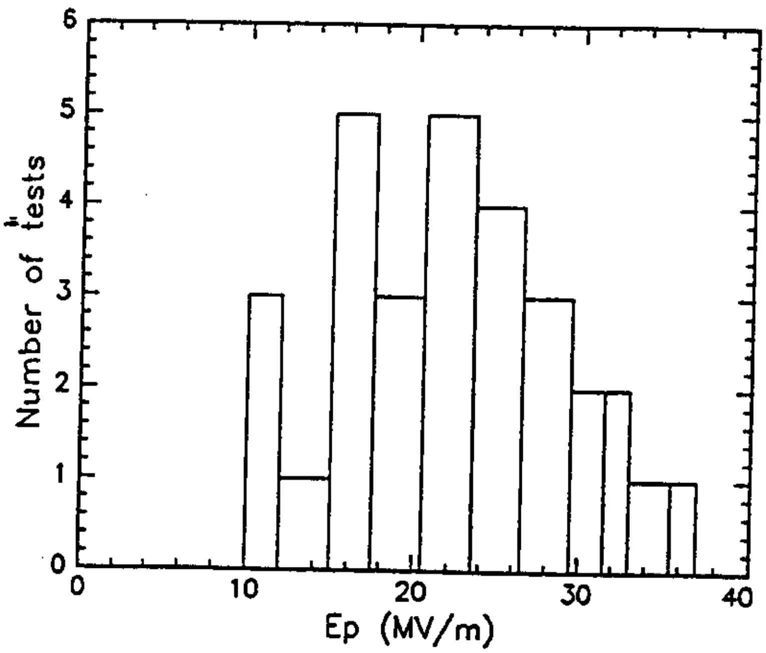

Figure 10 Summary of the cavity test results