For large-scale applications, such as superconducting LEP or TRISTAN, cavities made from Nb-Cu composite material offer several advantages over 100% Nb cavities—material cost reduction, defect stabilization, and cryostat simplification through pipe cooling application. Thermal model calculations presented show that if thicknesses less than 0.5 mm can be achieved for the Nb layer, surface defects can tolerate higher power levels. This improves the reliability of achieving target field levels, usually limited by thermal instabilities at defects. Calculations that model pipe cooling copper-backed Nb cavities show that even if coils are spaced as loosely as one every 10 cm, satisfactory cooling of defects can be accomplished. Nb-Cu composite material of good bond quality as well as Nb-Cu cavities have been made. In one S-band cavity, Nb-layer thickness 0.3 mm, Q_e > 2 x 10^9 and E(acc) > 0.5 MV/m were achieved. In this cavity 0.5 mm diameter defects operated at 4.2 MW/m whereas in 100% Nb wall cavities they break down at 3.2 MV/m.

**Introduction**

In this study we report on techniques investigated for superconducting accelerator type cavities from this material. The degree to which defects can be stabilized by reducing the thickness of Nb (and replacing it with Cu) is explored by computer calculations. The performance of a composite cavity is experimentally compared with that of an all Nb cavity when both cavities contain the same artificial defects introduced onto the surface to study breakdown levels. The effect of replacing the liquid helium bath cooling by Cu pipes carrying liquid helium is also investigated by computer calculations.

**Summary**

In an earlier report we have thoroughly explored the thermal behavior of defects in Nb cavities. To study the behavior of defects on Nb-Cu composite cavities we use the same computer program with an altered mesh configuration to correspond to the two layers of different materials.

The expected breakdown field level is plotted in Fig. 1 as a function of defect size. Above 3 mm Nb thickness the presence of a high thermal conductivity Cu backing has little effect on the maximum tolerable field level. As the thickness of the Nb component of the composite is reduced to 0.5 mm and below, the higher heat carrying capability of Cu lowers the temperature of the defect and its neighborhood, and raises the breakdown field level as shown in Fig. 1. As defects get smaller in size the enhancement in power handling capability decreases and the curves tend to converge. Defect stabilization becomes progressively less effective as defects get smaller.

**Thermal Stability Calculations**

There is a limit to the effectiveness of increasing the power tolerance of gross defects by using the composite material. Even though one gross defect can safely dissipate high power, many such defects would provide an intolerably large heat load, or an effectively lower operating Q_e. Another difficulty that arises for large defects is that at high power levels (above ~ 300 mW) the heat flow to the bath immediately below the defect increases towards the film boiling limit. This difficulty can be avoided by increasing the thickness of the Cu layer and spreading the heat flow laterally before it reaches the helium bath, as shown in one example (Fig. 1) for 0.2 Nb-Cu.

**Pipe Cooling Calculations**

To simulate pipe cooling we once again use the program of Ref. 2. One simple possibility is to "braze" the tubing directly on to 2 mm wall Nb cavities. The calculations on pipe cooling show that even at a dense packing of 20 turns per 500 MHz single-cell, the power tolerance of a defect is greatly reduced (~ 60%). On the other hand, pipe cooling looks very promising if a
significant fraction of the Nb is replaced by high conductivity Cu (RRR ≳ 100). Consider, for example, a composite with 1 mm Nb and 2 mm of Cu. We show in Fig. 2 the r.f. surface temperature profiles for a 0.3 mm radius defect at a power level of ~ 80 mW which is close to the maximum that the defect can withstand. Three curves are presented, one for fully immersed 2 mm thick 100% Nb, one for 1 mm Nb plus 2 mm Cu with cooling coils spaced 7 cm apart and one for the same composite with cooling coils spaced 13 cm apart. (A 13 cm coil spacing would allow a 500 MHz cavity to be cooled by as few as four turns per cell.) The curves are barely distinguishable from each other, showing that pipe cooling is as effective as immersion cooling.

Composite Fabrication

A. Hot isostatic pressing followed by rolling and annealing. This process has been developed by W. C. Heraeus which supplied us with a 1 m long x 15 cm wide piece. The Nb thickness was 0.5 mm and the Cu thickness 1.5 mm. Details of the procedure are proprietary; however, the general method is as follows. Copper sheets are bonded by hot isostatic pressing to Nb sheets under high pressure in an inert gas environment at an elevated temperature (~ 1000°C). The starting material thicknesses are at least a factor of 2 larger than the final. The thermal conductivity of the OFHC Cu component is ~ 320 W/MK at 4.2 K, and of the Nb component ~ 8 W/MK at 4.2 K. The hot pressed composite is rolled down to the desired thickness and annealed in a vacuum to further improve adhesion. The final adhesion was determined by us to be excellent. A small sample from the plate was repeatedly bent until the base materials fractured by fatigue. Examination of the fractured area under high magnification showed the bond itself had endured the mechanical stress. The interdiffusion of Nb and Cu in the interface region was less than the spatial resolution of the instrument (~ 1 μm). An examination of the entire surface area of the composite sheet with a manually scanned ultrasonic probe showed no detectable cracks or fissures at the interface. Half shells for a 2900 MHz spherical cavity were spun from this material. Both the mechanical workability and the bond quality were found excellent for spinning.

B. Melting a Cu plate onto a Nb plate. At the melting temperature of Cu (~ 1100°C) and in a vacuum, the natural oxide layer on the Nb surface vanishes so that Cu can be deposited on Nb with good adhesion. A 0.4 mm thick sheet of Nb large enough to form a spherical cavity half-shell was formed into a tray by folding up the edges and TIG welding the corners shut. A 2 mm thick OFHC Cu sheet was placed inside the tray. Heating to ~ 1100°C for 5 minutes melted all the Cu onto the Nb to form the composite sheet. Subsequently the sheet was pressed flat, the edges trimmed and the Cu side machined to a uniform thickness before spinning into individual half shells.

Radiation from the bond is excellent. A small sample was fractured by repeated bending. Electron micrograph examination of the bonded region near the fracture showed excellent adhesion (Fig. 3). The bulk thermal conductivity of the material was found to be ~ 150 W/MK at 4.2 K. Half shells for an S-band spherical cavity were spun from this material. Both the mechanical workability and the bond quality were found excellent for spinning.

Test electron beam welds with composite material samples of varieties A and B showed that it is possible to weld the Nb component with partial penetration greater than 50% without melting the Cu layer underneath. The micrograph in Fig. 4 shows weld sections for one type of composite. The welding sequence is described in Fig. 5. It was shown possible to perform the critical inside welds when the Nb layer was as thin as 0.4 mm without risk of a Cu melt. However, increasing the thickness to 0.5 mm considerably eased the welding operations.

C. Dipping Nb into molten Cu followed by electroplating. Another variation of the melted bond technique pursued was to prefabricate a complete cavity out of 0.4 mm Nb material, dip it into a graphite crucible of molten Cu for 5 min and then to withdraw it from the liquid into the vacuum. Fig. 6 shows the experimental setup. A starting layer 50 μm thick was deposited. After the layer of Cu was started, electrodeposition in a standard plating bath was used to increase the Cu thickness to 1.5 mm. The thermal conductivity of the deposited Cu layer was ~ 140 W/MK at 4.2 K corresponding to an RRR value > 100.

Radio Frequency Test Results on Composite Cavities

The dipped/plated cavity gave results comparable to the better of 100% Nb cavities made and tested at CERN.

Fig. 3. SEM photograph of the bond region near a fractured segment of the melted bond material (1400 X).

Fig. 4. Optical metallograph of a weld section. Partial penetration at the Nb is achieved without melting the underlying Cu.
This cavity was therefore used for a subsequent experiment to test the ability of composite material to withstand artificially introduced defects. The Heraeus material cavity had a consistently lower $Q_0$ ($\approx 5 \times 10^6$). The higher surface resistance could perhaps be due to contamination during hot pressing and/or annealing after rolling. Microhardness, gas analysis, and transition temperature studies on the Nb showed excess of $O_2$ concentration ($\approx 1000$, at ppm $O$ compared to 150-300 at ppm in standard 2 mm sheet Nb). The breakdown location was found not to be at the weld, evidence that the interior welding of the Nb component of the composite was satisfactory up to field levels greater than 4.2 MV/m. The plate-to-plate melting process cavity gave the worst results because of a defect in the weld. This cavity would not withstand more than 1 min of chemical polishing before the defect became unacceptable large.

A technique has been developed to introduce 0.5 ± 0.1 mm diameter defects on the surface of an S-band cavity. A 0.5 mm diameter wire is dipped into silver paint and touched to the clean cavity surface. After the resulting droplet dries, it adheres extremely well. Four silver defects were placed onto the surface of a 2 mm wall 100% Nb cavity in a region where the magnetic field was 0.92% of the peak value. Prior to introducing these defects the cavity was treated with standard surface preparation procedures and tested. A $Q_0$ of $1.9 \times 10^5$ and $E_{\text{max}}$ of 8 MV/m were obtained. After the test, the cavity was demounted from the vacuum system, the defects introduced. Now the $Q_0$ was $3.6 \times 10^5$ and the breakdown field 3.2 MV/m (≤ 120 G at the defect location). All four defects were detectable with the thermometry system. However, one of them gave a much smaller temperature increment than the others. Endoscopic examination after the test showed that this defect was only 0.1 mm and the others were 0.4, 0.4, and 0.5 mm in diameter. The breakdown took place at the 0.5 mm defect.

A parallel series of experiments was carried out for the Nb-Cu cavity (prepared by dipping/plating) with 5 artificial defects. Before introducing the defects the $Q_0$ was 1.7 x $10^6$ and after it was 4.2 x $10^6$. The maximum field level was 6.5 MV/m before and 4.2 MV/m (≤ 160 G) after. Endoscopic examination after the test revealed three defects of 0.6, 0.4, and 0.5 mm and two of 0.2 mm diameter.

From the decrease in $Q_0$ and from the total measured dissipated power, we deduce that the surface resistance of silver defects is $10^{-2}$ $\Omega$, not far from the value ($8 \times 10^{-3}$ $\Omega$) assumed in most of our calculations. The maximum field value measured in the Nb cavity (3.2 MV/m) and the value in the Nb-Cu cavity (4.2 MV/m) were both in remarkably good agreement with our calculations (Fig. 1). Thus we see that an 0.6 mm diameter defect can tolerate 4.2 MV/m on the Nb-Cu surface. An 0.5 mm diameter defect on a Nb surface can support a lower value of 3.2 MV/m.

**Conclusions**

Our calculations and experiments show that if thicknesses less than 0.5 mm can be achieved for the Nb layer, the probability of reliably achieving higher accelerating gradients is improved with Nb-Cu cavities.

We have concentrated our efforts on the melted bond. The bond strength is excellent and easily withstands forces generated during mechanical working.

Large diameter Nb-Cu composite cavities can be effectively cooled by loosely coiled piping instead of immersing them in gigantic helium vessels yielding significant cryostat simplification possibilities. In this application the Nb layer can be relatively thick, e.g., 1 mm. If the additional advantage of stabilization is desired, then the Nb thickness must be 0.5 mm or less and the Cu retained below the weld to stabilize any weld defects. Our work has shown that it is possible to weld composite from the Nb side, without melting the Cu. Further development towards safely increasing the weld penetration as well as weld-free hydroforming techniques would be very useful.

**Acknowledgments**

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**References**

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![Fig. 5. Welding configurations and sequence for Nb-Cu cavities.](image)

![Fig. 6. Experimental layout for dip-plating a Nb cavity with a 50 µm layer of Cu.](image)