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Pump Down Rate for SRF Cavities

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INTRODUCTION

The problem presently limiting niobium Superconducting Radio Frequency (SRF) cavities from reaching their potential high Q is electron field emission from the walls. There is strong evidence that this field emission is enhanced by microscopic dust particles deposited on the surface. Clean room techniques are therefore used in the preparation of these cavities. One of these techniques that should be implemented is to avoid aerosols (i.e. particles floating in the air) from being deposited on the cavity inner walls when air is evacuated from the cavity.

The size of aerosols present in clean-room environments vary from atomic (electrons, ions, foreign molecules) to a few microns. The class of a clean room is defined (in the US at least) as the total number of particles per cubic foot greater than 0.5 microns in size. Water molecules in the air and particles $<$ 0.5 microns ("fines") therefore do not count, although such particles can enhance field emission when deposited on the surface.

The adiabatic expansion of the air as it is rapidly pumped out of the cavity causes it to cool condensing water molecules around nucleation sites (particles, fines, ions) causing them not just to grow, becoming countable, but also to stick to the walls. Turbulence is instrumental in depositing them on the surface by speeding up the growth of these water coated particles and increasing their chance of hitting (and therefore sticking to) the wall before they are evacuated out of the cavity.

So control of the pumping speed when evacuating the clean-room air from the cavity is a relevant technique along with other pre-evacuation [1] ones like, dehumidifying the air, using an electrostatic particle precipitator, flushing with dry nitrogen, heating the cavity and perhaps others. Although some of these techniques seem mutually exclusive or reduntant they should be considered independently since in each case the logistics of cleanliness might impose constraints in their use.

This note is about calculations aimed at quantifying adequate pumping speeds of evacuation of normally humid clean-room air from typical SRF cavities. The subject is of high relevance to the semicondutor industry, where the yield of VLSI (Very Large Scale Integration) chip production is affected by micron size particles which may cause fatal defects to their micron and sub-micron features. The recent availability of particle counters capable of operating in vacuum has stimulated measurements at reduced pressures in this subject[2-6].

The two physical phenomena of relevance here are turbulence and condensation, each yielding a limiting value for the pumpdown speed.

TURBULENCE

A fluid is in turbulent flow whenever its Reynolds Number (Re) is larger than 2000 and in laminar flow when Re < 100. The definition of Re is:

$$\mathrm{Re} = \frac{v \cdot D \cdot \mathrm{rho}}{\mathrm{mu}}$$

where:
v = velocity (m/s)
D = characteristic dimension (m)
rho = density (kg/m3)
mu = viscosity (kg/(m.s))

In order to apply this to a cavity being evacuated by manual control of a valve, using a Wallace Tiernam pressure gauge and a watch, we have to write v and rho in terms of the pressure P and temperature T of the air in the cavity as well as time t.

From the equation of state of a perfect gas:

$$P \cdot Vo = n \cdot R \cdot T$$

we obtain

$$\mathrm{rho} = \frac{n \cdot w}{Vo} = \frac{w \cdot P \cdot Vo}{Vo \cdot R \cdot T} = \frac{w \cdot P}{R \cdot T}$$

where:
n = number of moles of air in the cavity
w = molecular weight of air
Vo = volume of the cavity
R = gas constant

The pumping speed $\dot{V} = 0.25 \cdot \mathrm{pi} \cdot D^2 \cdot v$ where pi = 3.14159 is also given by:

$$Vo \cdot \dot{P} = - \dot{V} \cdot P \quad \text{therefore} \quad \dot{V} = - \frac{Vo \cdot \dot{P}}{P} \quad .$$

When treating condensation it will be important to consider the change in temperature. Here we will cosider T constant, which is a good approximation if the pumping speed is low and there is time for the heat flowing from the walls to keep the process isothermal. Therefore

$$v = - \frac{4}{\mathrm{pi} \cdot D^2} \cdot \frac{Vo \cdot \dot{P}}{P} \quad .$$

So in terms of the parameters of the air in the cavity the Reynolds Number can be written as :

$$\mathrm{Re} = - \frac{4 \cdot w \cdot Vo \cdot \dot{P}}{\mathrm{pi} \cdot R \cdot \mathrm{mu} \cdot D \cdot T} \quad .$$

To insure laminar flow evacuation we should keep Re < 100 or

$$|\dot{P}| < \frac{100 \cdot \pi}{4} \cdot R \cdot \frac{\mu}{w} \cdot \frac{D}{V_o} \cdot T$$

Using SI units: R = 8.31 J/(mole.K)
for air: w = .029 kg/mole
mu = 18.2E-6 kg/(m.s) (which holds down to 1 torr)
T = 297 K (a typical room temperature)

$$|\dot{P}| < 122. \frac{D}{V_o} \text{ Pa/s}$$ where D and Vo are in meters and cubic meters respectively

or

$$\boxed{|\dot{P}| < .912 \frac{D}{V_o} \text{ torr/s}} \; .$$

CONDENSATION

Ridding the air of aerosols, via condensation, was a routine process in priming a Wilson cloud chamber for detection of ionizing particle tracks. Of course, then the physicists did not care about the particles sticking to the walls. Next follows a tutorial on humidity.

The relative humidity of the air (RH) can best be defined in the following way: At a given temperature and pressure a certain mass, mA, of dry air can absorb at most a mass, mWmax, of water vapor without forming droplets regardless of aerosols and turbulence. The ratio mWmax/mA corresponds to saturation of the air or RH = 100 %. For a mass mW < mWmax we have:

$$RH = 100 \frac{mW}{mWmax} \%$$

. It is possible to have mW > mWmax in quiet (non turbulent) and perfectly clean air (no particles, no ions etc). The saturation ratio,

$$S = \frac{mW}{mWmax} ,$$

can have values as large as 8.
The condensation process is called homogeneous when the nucleation sites are clusters of water molecules. The critical saturation ratio, Sc, at which homogeneous condensation occurs has usually values between 3 and 8. Condensation nucleated by positive ions has Sc around 6 and by negative ions around 4. When the nucleating sites are particles of size ranging from 2 nm to larger than .1 microns the process is called heterogeneous condensation and Sc has a value between 1 and 3. The saturation mWmax/mA is a function of temperature, increasing with it. This type of data constitute the so called psychrometric tables.

Since the "rediscovery" paper of Degang Chen and Susan Hackwood[2] most papers related to the semiconductor industry have dealt with this subject with specific goals in mind. One of them, [6], however, provides an algorithm for solving our problem. It is published in a trade magazine (free subscription to practitioners in the business) and it is based on the Ph.D. Thesis in Mechanical Engineering at University of Minnesota of its first author J. Zhao (1990) . Without having read this thesis we limit ourselves

Characterising the geometry of the vacuum chamber, the pumping system, and the gas in it respectively by the parameters ksi, tau and omega, given below, he defines the Zhao's dimensionless number

$$Z = \frac{\text{omega} \cdot \text{tau}}{\text{ksi}}$$

that describes the evolution of the thermodynamic states taken by the system from close to adiabatic (Z = 0) to essentially isothermal (Z = infinite). Properly converted to units used with figure 1 the parameters are:

$$\text{ksi} = 100 \, \frac{Vo}{So} \qquad \text{tau} = Vo/\dot{V} = P/\dot{P} \qquad \text{omega} = (g.\text{alpha}/Pr)^{1/3}$$

where So is the area of the cavity in square meters, g is the gravitational constant, alpha is the air thermal diffusion coefficient at the initial pressure and temperature and Pr is the air Prandtl number. For 760 torr and 293 K the numerical value of omega to be used in these formulas is 6.73 .

The maximum saturation ratio, Smax, that occurs in a pumpdown is a function of RH and Z, and reproduced in figure 1. The algorithm proceeds in the following way: For a given RH figure 1 is used to determine Z for heterogeneous condensation using the Smax = 1 curve. This is the minimum Z that can be used and it leads to the inequality

$$\boxed{|\dot{P}| < 51.1 \, \frac{So}{Vo \, . \, Z}} \; .$$

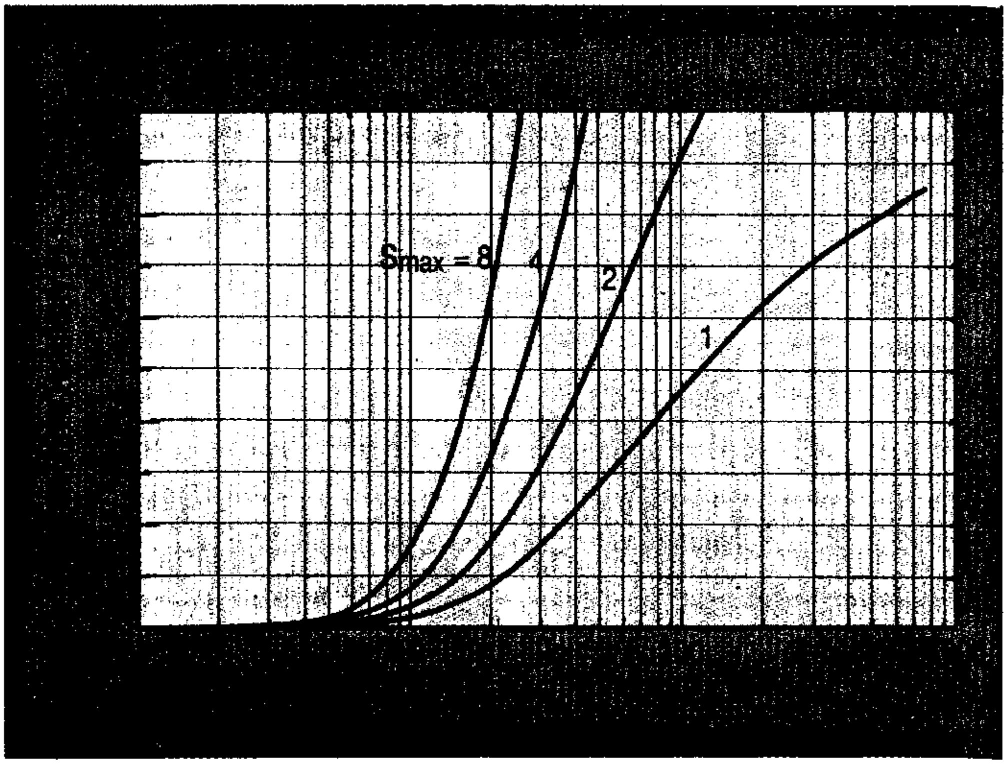

Figure 1. Curves of Smax in the RH vs Z plane

RESULTS

Table I presents rough estimates of parameters for 4 typical cavities and the calculated pumpdown rates that the above formulas yield for laminar flow (1st formula) and Zhao's algorithm for air initially at 293 K, 760 torr and relative humidities of 80% and 20%.

TABLE I:

CAVITY	Cavity Parameters			PUMPING RATE (torr/s)		
	Vo (m3)	So (m2)	D (m)	laminar flow	RH = 80%	RH = 20%
B_Factory (1st test)	91.E-3	2.2	.027	.27	2.2	33.
Mushroom Mark 1	.21E-3	25.E-3	35.E-3	150	11.	170
Mushroom Mark 4	.26E-3	51.E-3	1.2E-3	4.1	18.	280
L Band LE1-28	2.8E-3	.15	.07	23.	5.0	76.

CONCLUSION

The pumping rates calculated above can be readily achieved by manual control and a needle valve bypassing a typical gate valve. The pump rate most demanding on the operator is .27 torr/s. This low value is needed to prevent turbulence near the iris coupling the waveguide to the cavity in the pump out scheme used for the first test of the B_Factory cell.

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$$\boxed{|\dot{P}| < 51.1 \frac{So}{Vo \cdot Z}} \quad .$$

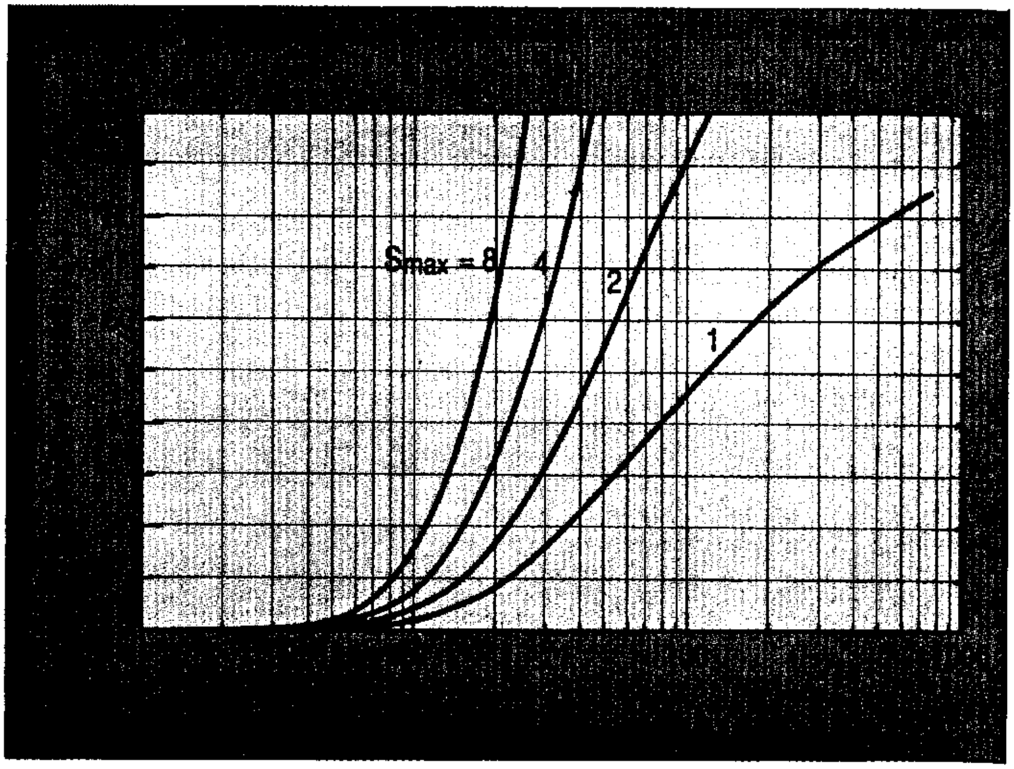

Figure 1. Curves of Smax in the RH vs Z plane