

# COMMENTS ON THE OPERATION OF A WILSON EXPANSION CLOUD CHAMBER

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## **Abstract**

Comments are made concerning the practical operation of a Wilson expansion cloud chamber for experimental research in heterogeneous and homogenous nucleation. Topics covered are the general operation of the chamber, the detection of cloud droplets, the cleaning of the chamber and the interpretation of nucleation data. The comments include successful and unsuccessful experimental techniques.

## **1. INTRODUCTION**

The main experimental apparatus proposed for the CLOUDS investigation is a Wilson expansion cloud chamber. The following comments are intended to provide guidance in the operation of that chamber by examining what has been done while operating an expansion chamber at the Cloud and Aerosol Sciences Laboratory at the University of Missouri-Rolla. The comments are based on about 25 years experience by the author operating a chamber (designed for homogeneous nucleation experiments). This article is intended to supplement Refs. [1, 2] by the author and other publications, e. g. Refs. [3, 4]. Reference [1] is a description of the cloud chamber as constructed and used by the author. While the basic features of that chamber have not changed, this article does address some of the evolutionary changes that have taken place since it was constructed. Reference [2] describes a Wilson cloud chamber, the UMR absolute Aitken nucleus counter, that was specifically built to detect particles that nucleate from near 100% Relative Humidity to beyond the ion limit. That chamber no longer exists. Reference [3] is a review paper that addresses the “Wilson Cloud Chamber and Its Applications in Physics” circa 1946 and still contains much valuable information. Reference [4] is a book by J. G. Wilson (not C. T. R. Wilson) which reviews the Wilson cloud chamber circa 1951. The following comments include improvements, attempted improvements, suggestions, speculations and failures. Again this article primarily addresses experiments with the author’s apparatus, and therefore the references and anecdotal evidence are greatly skewed towards work done at high supersaturation with that device.

## **2. GENERAL OPERATION**

### **2.1 Chamber principles**

The physical operating principle of the expansion chamber is that if a gas, containing a condensable vapor at equilibrium, is “suddenly” expanded, the temperature of the gas will adiabatically decrease. In the following, the background carrier gas in the chamber will be referred to as the gas and the condensable vapor as the vapor. At the lower, expanded, temperature the equilibrium vapor pressure of the vapor is much lower and since the vapor has not had time to diffuse, it is present at a higher concentration than equilibrium, i. e. supersaturated. Thus the expansion chamber is a device that produces a supersaturation upon demand (expansion). Formally, supersaturation ratio is the ratio of the actual vapor pressure in the chamber divided by its equilibrium vapor pressure at the given temperature but will be referred to in the following as only supersaturation. The length of time for which one knows, to the required accuracy, the physical conditions, temperature and vapor content, in the central volume of the

chamber during and after the expansion, is controlled primarily by the transit (time) of heat and vapor from the walls.

The material or substance in the liquid pool in the case of homogenous nucleation is determined by the experiment. For atmospheric simulation water would be the material of choice. For ion nucleation, the classical mixture, used to detect ion tracks for nuclear physics, is about 1 part water and 2 parts ethyl alcohol, Ref. [3] pg. 237, which produces the smallest expansion ratio for the mixture to nucleate on ions.

## **2.2 Physical parameters in the chamber**

Initial conditions in the chamber are temperature, pressure and vapor content of the gas. Temperature and pressure are measured by sensors and the vapor content of the carrier gas is known from the equilibrium vapor pressure of the liquid pool or by flushing with gas of known temperature and vapor content Ref. [5]. The conditions during and after the expansion are calculated from initial temperature and pressure, the expanded pressure and the thermodynamic properties of the gas and the vapor. Pressure equilibrates at the speed of sound, however note that the speed of sound is not constant, thus pressure can be a valid parameter to describe the conditions in the experimental volume of the chamber. Direct measurement of the temperature in the experimental volume is very difficult since a sensor larger than molecular size in the central volume will probably induce heterogeneous nucleation, along with latent heat release. Laser spectroscopy of a carefully selected molecule has been suggested as method of temperature measurement Ref. [6] but this suggestion has not been implemented. Problems lie in the areas of isolating and measuring molecules only in the central experimental volume and finding a molecule that not only has the desired temperature range and sufficient sensitivity to measure temperature to 0.1 C but also will not interact with the desired nucleation. However, such a molecule could be present in large numbers and this application of laser spectroscopy does not have the same problem as attempting to apply laser spectroscopy to nucleation embryos that are present in very low concentrations. A typical temperature calculation ranges from simple, for an adiabatic expansion in a perfect gas with a minor nearly ideal vapor component (the calculation primarily is the integration of specific heat as a function of temperature), to complex, for a real gas with a significant pressure contribution from real vapor. Argon works well for the gas: it is ideal and it does not leak through seals easily. Helium leaks easily, has a high heat conductivity and new gas cylinders of helium often produces alpha particle tracks Ref. [7]. Air is not an ideal gas but would be needed for simulating the atmosphere. Additional complexity is added if heat and vapor from the chamber walls reach the experimental volume during the experiment and droplet growth, with attendant latent heat release and vapor depletion, occurs. In each case accurate thermodynamic data for the gas and vapor is essential. If one considers the best case of an ideal gas and a low vapor pressure vapor, the gas mixture is very close to ideal since the contribution to the specific heat by the vapor is small. This also means that the thermodynamic data for the vapor can be uncertain since its contribution is small. In addition, the mixture will produce a maximum temperature change on expansion.

## **2.3 Nucleation pulse technique**

The nucleation “pulse” technique is often used: the chamber is expanded quickly to maximum expansion, is then recompressed slightly and held at a supersaturation lower than the supersaturation at the maximum expansion. Since (homogeneous) nucleation is an exponential process as a function of supersaturation, a slight reduction of supersaturation lowers the nucleation rate by orders of magnitude and thus effectively, when the nucleation rate is integrated over time to calculate the total number of droplets, “all” nucleation occurs very near the maximum supersaturation. (In practice one determines the nucleation rate, droplets/cm<sup>3</sup> sec, from the droplet count, droplets/cm<sup>3</sup>, and the integrated pulse length.) This also limits the nucleation to a known time and length of time. The droplets grow to detectable size only after the slight recompression.

This limits the latent heat release and vapor depletion due to growing droplets to the time after nucleation and thus conditions in the experimental volume are well known during nucleation. The nucleation pulse technique avoids the problems of simultaneous nucleation and growth. However, these effects will have to be included in the models if the experiment requires that nucleation and growth take place simultaneously.

#### **2.4 Supersaturation range and detection of low concentrations**

The expansion chamber can produce a wide range of supersaturation. Water supersaturation in the range from 1.00 (100% Relative Humidity) to 1.05, nucleates on and detects (aerosol) particles, i. e. heterogeneous nucleation. Much higher supersaturation, e.g. 3.5 and up, will nucleate on and detect negative ions and even higher supersaturation will homogeneously nucleate water (examples are for expansions from about 300K, initial chamber temperature). The chamber is capable of detecting by droplet growth, particles from microns in size (particles at the lower limit for easy detection by Mie light scattering and which do not fall out rapidly) to molecules. For example, if one has an molecule, ion, or particle that will nucleate at a lower supersaturation than the homogeneous nucleation of the background vapor, then the chamber is able to nucleate and grow a droplet on that molecule, ion or particle. For reference, a gas at one atmosphere pressure has about  $10^{19}$  atoms or molecules/cm<sup>3</sup>, and one droplet/cm<sup>3</sup> can easily be detected by nucleation in a cloud chamber Ref. [8].

#### **2.5 Low supersaturation expansions**

The expansion chamber was chosen as a detector for CLOUDS because it can produce a wide range of supersaturation. It has been traditionally used at high supersaturation in homogeneous nucleation experiments. One technique to produce low supersaturation is to introduce undersaturated vapor and then expand that mixture, Ref. [5]. If, on the other hand, the equilibrium vapor pressure of the liquid pool is used to provide the vapor, a mixture in the pool can produce (an application of Raoult's Law; one also must know activity coefficients) undersaturation in the vapor. In the case of water, a mixture of tetraethylene glycol and water will initially undersaturate the chamber in water and require large (volume ratio) expansions to produce saturation or supersaturation. Ref. [9].

#### **2.6 CLOUD chamber**

The considerable precision with which it is anticipated that the piston of the proposed CERN cloud chamber can be controlled, introduces a capability not found in previous expansion cloud chambers. One now can consider not only experiments where the chamber is expanded once to a high or low supersaturation to nucleate on particles or ions, but also experiments where the position of the piston is accurately controlled with time to attempt to program the Supersaturation (pressure) with time. For example, the chamber is expanded to produce a supersaturation high enough to nucleate on an ion and grow a droplet, the chamber is then compressed to evaporate the droplet and a second expansion is used to detect any re-evaporation nuclei that remain. Experiments of this type have been performed using the UMR simulation chamber Ref. [10]. That chamber has the additional and significant advantage of exact control of the wall temperature with time (up to 10 C/minute rate of change with 0.02 C accuracy). One can match wall temperature to the gas temperature during the experiments. Obviously experiments of this type in the CLOUDS chamber will require good models for the transport of heat and vapor and droplet growth. Finally the motion of the piston in the proposed CLOUDS chamber does not depend upon a difference in pressure across it, to drive an expansion. The hydraulic cylinder and valve system has considerable force and pulls the piston. Therefore, the CLOUDS chamber can be used with very low pressures in the experimental volume (for the simulation of high altitudes). However, one needs to be very careful to model these experiments. For example, accurate calculations for an adiabatic expansion in a low pressure gas that is mostly water vapor at very low

temperatures (the water vapor may be supercooled) and pressures require accurate thermodynamic data. This may be difficult to find or measure.

### **3. DETECTION OF DROPLETS**

#### **3.1 Droplets vs. nucleation embryos**

One detects droplets in the chamber and equates the number of droplets to the number of embryos that were nucleated. This assumption should be valid if the number of embryos is not large enough to coagulate before or during growth or embryos are not destroyed or created (after the nucleation event). All (current) methods of detection do not detect the embryo, perhaps 10 to 50 molecules, directly but depend upon growing it to a size large enough to detect. At present, very small particles have been examined by neutron scattering Ref. [11]. In principle it might be possible to “interrogate” by laser spectroscopy the nucleation embryos or ions, however one must also note that typically one has  $100 \text{ embryos/cm}^3$  in a gas at atmospheric pressure with approximately  $10^{19}$  atoms or molecules/cm<sup>3</sup>. Finally, ion mobility experiments have been anticipated in the CLOUDS chamber by including a field cage in the design.

#### **3.2 Light scattering detection**

The most direct detection methods allow the droplets to grow to about 2 microns (radius) and larger and use visible light to “see” the droplets, e.g. photography and Mie scattering. A straightforward technique is to select droplets using a “sheet” of light 1 cm thick from xenon flash tubes and photograph, from a viewpoint at right angles to the sheet of light, with a high resolution lens and image detector. One calibrates the system by photographing a 1 cm standard grid. A  $1 \text{ cm}^2$  projected area on the detector images a depth in the light sheet of 1 cm and thus one counts droplets in  $1 \text{ cm}^3$ . Most uncertainty in the measurements comes from the “thickness” of the edge of the sheet of light. The basic concept is that the illumination defines the volume that is measured. Images on the detector usually do not measure the size of the droplets but are only a result of the resolution limitations of the film and lens combination. Photographic film has the advantage of very high information content and storage and but also requires handling and processing. The advantages of an electronic detector, e. g. a CCD, are that the image is available very quickly, which is essential in experiments that require interaction, and the image is digital, which can be immediately analyzed by a computer. The disadvantages are that CCD sensors are expensive in the large sizes, e. g. 4000 by 4000 pixels (a 35-mm camera frame can be considered to have approximately 2400 by 3500 pixels for a frame size 24 by 35 mm with 10 micron resolution) and it is difficult to understand what resolution really means for the square or rectangular pixels in a CCD. For example, what is the resolution along the diagonals of the pixels or what can be said about a droplet that images at the intersection of four pixels? An example of a photographic system is a 1500 by 1000 pixel CCD with 9-micron square pixels combined with a camera lens that will resolve 125 line pairs/mm using the sheet of light technique to illuminate the cloud droplets. The lens is used at  $f/4$ , producing a depth of field, i.e. all droplets in acceptable focus, of at least 1 cm (the thickness of the flash tube sheet of light). The CCD detector covers about 25% of the 35-mm film image that it replaced.

#### **3.3 Image analysis**

Analysis of the photograph or image can be done by computer image analysis or by visual counting. Visual image analysis (one looks at the displayed image on a computer screen with a superimposed  $1 \text{ cm}^2$ , scaled, grid and counts the droplets by eye) has the advantage that the eye and brain are very good at distinguishing artifacts and multiple drops. For very low counts,  $1 \text{ drop/cm}^3$ , visual counting can distinguish flaws that if included would greatly skew the drop count. For example, expansions to supersaturations above the ion limit will probably detect cosmic rays. Cosmic rays do not produce the traditional tracks but usually produce “blobs” which are the result of a cosmic ray coming through the chamber from above (perpendicular). One thus sees a

section of the perpendicular track and the blob is produced when the ions in the track diffuse and are detected as ions. For very high counts, 1000 droplets/cm<sup>3</sup>, the eye is good at distinguishing multiple droplets and droplets close together. For experiments visual image analysis is a tedious but straightforward exercise. The error in the drop count is considered to be the square root of the number of drops counted. For concentrations of 1 droplet/cm<sup>3</sup>, one typically must count as many cm<sup>3</sup> as possible on the image. Attempts to count images with computer programs from several sources have produced very mixed results. Some of the results of these attempts: The image of the “droplet” should cover approximately 6 or more pixels so that one can use a measure of the roundness of the image and the number of pixels/droplet to validate a droplet and to distinguish between multiple droplets Ref. [12]. In practice having a droplet cover 6 pixels also limits the CCD camera field of view in the chamber. The photographic system described above has about 1 to 2 pixels/droplet. In general, automatic drop counting systems appear to work well only restricted range of droplets concentrations. Often computer assisted drop counting took longer to do than counting by eye and required careful and constant evaluation for accuracy.

### 3.4 Mie scattering detection

Mie visible light scattering from droplets is another means of detection. At visible wavelengths one begins to detect droplets at about 2 microns in size. Using white light as illumination allows one to use the relationship between scattered intensity and size that is roughly a straight line from 2 to 15 microns. A (Mie) scattering system, for which the calculations were done but which was not constructed, which has the potential to measure to measure size and droplet concentration by scattered intensity, is to use all four strong laser lines (combined) from an argon ion laser as an approximation to white light. This “white” light laser system could be used, to analyze clouds that are polydispersed. This system for counting droplets in real time in the chamber uses a three-mirror scanning system, X, Y and Z, that raster scans a focused (white light) laser beam over 1 cm<sup>3</sup> in the center of the chamber. The focused laser beam isolates the droplets in the desired location. The droplet is detected by the pulse of light scattered as the droplet is scanned by the beam. The intensity of the pulse is proportional to the droplet’s size. The major problem with this system is that while it was concluded that it would work well with a few hundred droplets/cm<sup>3</sup> (each relatively isolated), it would not work well at only 1 droplet/cm<sup>3</sup> (a much larger volume would need to be scanned to obtain good accuracy), and multiple scattering might be a problem in the 1000 droplets/cm<sup>3</sup> range. It however would detect and size each droplet. That information could be used to identify the large droplets that have most of the liquid water content of a cloud.

The detection of size as a function of time can be done with Mie scattering using monochromatic radiation scattered from monodispersed droplets. The CAMS, Constant Angle Mie Scattering, system for the proposed CLOUDS chamber is described in the CLOUDS proposal, Ref. [13]. In general, one uses a collimated polarized laser beam in the chamber and detects the scattered light at a fixed angle. As the droplets in the (monodispersed) cloud grow, the Mie scattering peaks (lobes) move past the detector. The resulting intensity pattern as a function of time is compared to theoretical calculations of size vs. intensity to find size vs. time. The accuracy of the technique is about 0.1 micron. Careful selection of the angle of scattering can greatly simplify data analysis. If one selects, e. g. 30 deg, the intensity vs. time is a pattern that is similar to a sine wave with a D. C. component increasing with time. If the detection of the first peak in the signal is questionable due to noise, it is very difficult to determine which peak corresponds to which size on the theoretical curve. However, if one uses angles near 4 degrees, the scattering pattern is a modulated signal and the modulation allows one to identify Mie peaks easily, even if some of the low intensity peaks are lost in noise. In addition, the scattering pattern changes very rapidly with angle in the 4 to 5 degree range, which allows one to measure a scattering pattern and determine from it the scattering angle experimentally, a great convenience. This system will also measure the number of droplets if scattered light intensity can be directly related to the scattered

light intensity from a single droplet. Note that these detection systems are for clouds with droplets of one size, i. e., monodispersed. A cloud with droplets of many sizes is much more difficult to characterize. For example, the intensity of Mie scattering from a droplet using a monochromatic laser beam varies greatly with very small changes in size and, e.g. a 5.1-micron droplet may scatter much more light than 9.6-micron droplet. This latter property also makes it very difficult to deconvolute the total scattering signal from a cloud and determine the droplet size distribution.

### **3.5 Detection of ice**

The detection of ice in the chamber requires a different technique than the detection of droplets. Light (Mie) scattering calculations are difficult since ice crystals are not spheres. Figure 19 in the CLOUDS proposal, Ref. [13], illustrates photographic detection in our cloud chamber. That illustration shows a cloud of supercooled water droplets, at about - 40 C, in which some droplets have frozen. One observes that the ice particles scatter much more light, appear brighter in the photographs, and thus are easily identified. It is assumed that the ice has a polycrystalline structure because the ice images are all the same intensity, as opposed to, e. g. a needle or a plate, which would reflect light much differently depending upon its orientation with respect to the illumination. No further investigation was made on this assumption and this work is the only work that has been done with our chamber on ice. It is appropriate to mention that the Karlsruhe aerosol chamber discussed at the IACI meeting, Ref. [14], has an ice detection system based on depolarization in the observed backscattering of a polarized laser beam from the ice crystals.

## **4. TEMPERATURE CONTROL**

Accurate control and knowledge of the temperature of the chamber is vital. See Ref. [1] and the CLOUDS proposal, Ref. [13], for chamber temperature control details. In addition, the chamber has been operated with a gradient of typically 0.3 C from top to liquid pool to inhibit convection and the windows are controlled at temperatures slightly higher than the gas and vapor to prevent condensation on them

## **5. CHAMBER CLEANING**

### **5.1 Solvents**

The chamber has been primarily used for homogeneous nucleation experiments and therefore it is essential that it be cleaned as well as possible. Most probably the cleaning technique used on the CLOUDS chamber will depend greatly on the experiment being done. For example, an experiment that routinely admits outside gas will have different requirements than an experiment using ion detection in a sealed system. In addition to the cleaning and the attention paid to the removal of trace contamination of the gas, described in Ref. [1], the chamber walls are now cleaned before experiments by flushing solvents over the walls. Typically the material from the previous experiment is removed by draining, by suction and by evaporation. A fog nozzle is placed in the center of the chamber and, about 10 liters of solvent are forced, using gas from the same system that supplies gas for the experiments, through the fog nozzle to produce a cloud of droplets. The droplets impact on the chamber walls, the resulting liquid runs down the walls and collects in the bottom. Solvents used include water, ethyl alcohol, acetone and some of the material for the next experiments. Water works well in certain experiments, is readily available and easily disposed of. Acetone is very effective for removing hydrocarbons. One also must be careful that the solvents do not introduce contamination. For example, carbon tetrachloride was found to contain a stabilizer that leaves a film behind when it is evaporated. One must also be very careful in using evaporation to remove material. Some materials, such as water, easily develop a surface film that inhibits evaporation very effectively. In addition, homogeneous nucleation can be extremely sensitive to trace molecules and we have found that "high purity"

materials from different chemical suppliers vary widely with respect to nucleation properties in experiments. Materials also will oxidize and thus may change nucleation properties with time in the chamber, if a gas other than argon is used, or improperly stored. One technique for filling the liquid pool in the chamber is to evacuate the chamber and pull the material in from the original bottles. One can flush the bottle with clean nitrogen. Finally, when the operating liquid is put in the chamber, it is wise to use a vacuum and pressure cycle to remove dissolved gas and high vapor pressure impurities from it. If necessary the gas in the chamber can be cleaned by dilution. One can use repeated cycles of using the piston to compress the gas followed by removal by vacuum.

## **5.2 Trace impurities and re-evaporation nuclei**

The chamber is constructed of stainless steel and glass with fluorocarbon seals and was extensively cleaned after its construction to rid it of such pollutants as cutting oil from machining. After it was constructed, it was tested with water nucleation. The new chamber produced homogeneous water nucleation data that was the same as the previous chamber Ref. [15]. This was considered necessary and sufficient evidence that the new chamber was working correctly and furthermore that the experimental technique cleaned, see below, the chamber and removed trace impurities from the liquid, vapor and gas. However, several years later the following experiments were done. The chamber was cycled to produce homogeneous nucleation of water and the droplet growth rates were measured used Mie scattering. The chamber was then cleaned again, this time using about 10 liters of reagent grade acetone that was fogged onto the walls. Finally, the chamber was cycled for water nucleation and the droplet growth rates were measured. They were about a factor of 3 faster. The water nucleation data was the same as before. This was considered evidence that a surface layer, due to trace contamination (hydrocarbons were suspected) was on the droplets in the previous experiments. Subsequent experiments with the UMR simulation chamber showed that a condensation-evaporation-condensation cycle produces considerable changes in the condensation coefficients Ref. [16]. A contaminated surface on the droplet was postulated. It is important to note that the sticking coefficient for a water molecule on the surface of a droplet may greatly differ from the case of a clean water surface to the case of the “dirty” surface the droplet may have in the real atmosphere. This is particularly true if the droplet has been processed through a condensation- evaporation-condensation cycle, e.g. in a cloud.

## **5.3 Chamber self-cleaning**

The above description of how to clean the chamber primarily utilizes solvents to dilute and remove impurities. This may be sufficient for experiments, e.g. with aerosols, at low supersaturation. Only operation of the CLOUDS chamber will answer that question. However, for high supersaturation to detect ions and possible formation of molecular sized nucleation embryos, it is essential to use the self-cleaning properties of the chamber. In fact one may state, with justification, that the reason the Wilson expansion cloud chamber, with its ability to detect 1 ion/cm<sup>3</sup> in a gas at atmospheric pressure, can be used at all is that it is self-cleaning. For a typical data cycle, the basic idea is to expand the chamber to deep expansions that nucleate on impurities, grow droplets, and rain out the droplets. The assumption is that the expansion rains out the impurities and traps them in the liquid pool. A typical experiment, at the time of publication of Ref. [1], was to expand the chamber to a supersaturation slightly lower than the supersaturation needed for the experiment, e.g. homogeneous nucleation, and nucleate on the impurities. The “impurities” includes re-evaporation nuclei, i. e. something left behind when the droplets from the previous data expansion evaporated, Ref. [4], pgs. 2 and 13. A typical experiment included, the first cleaning expansion in which one observed approximately 10 droplets/cm<sup>3</sup>, a 5-minute wait to equilibrate, the second cleaning with 1 droplet/cm<sup>3</sup>, a 5-minute wait, the third expansion with very few droplets visible in the entire chamber, a 5-minute wait and finally the deep data expansion to a higher supersaturation for homogeneous, nucleation. This technique was used to

measure the homogeneous and ion nucleation for water and several other substances. It produced data that was repeatable and internally consistent.

#### **5.4 Homogeneous nucleation data as a lower bound**

Experiments on the nucleation of octane isomers produced results that raised questions about the basic assumptions made about cleaning the chamber by repeated expansions Ref. [17]. It was found that if one used cleaning expansions to a slightly higher supersaturation than the supersaturation reached in the data cycle, that the number of droplets was less, in the subsequent data expansion, than if the cleaning cycles were to slightly lower supersaturation than the data expansion (previous technique). In addition, re-evaporation nuclei were not observed. It was also observed that running the chamber over a long period of time, weeks, in several cases produced dramatic changes in the supersaturation (higher) measured for “homogeneous” nucleation. While this is not yet completely understood, we propose the following model. The high supersaturation expansions nucleate on the trace impurities (as well as homogeneously nucleate a few droplets) and rain out the droplets into the liquid pool. Since many more droplets are formed in the deep expansion, large amounts of impurities are subsequently rained out. However while some of these impurities stay in the liquid pool others have significant vapor pressures and diffuse back into the gas. Since the chamber must come to thermal equilibrium before the next expansion, there is time for re-diffusion of the impurities. In the case of octane we observe no re-evaporation nuclei and thus we can expand to deep expansions without creating additional “impurities” with the nucleation process. Materials, at this time all appear to be hydrogen bonded such as water, that produce re-evaporation nuclei must be investigated with the original technique.

Recent experiments on water, Ref. [18], have produced data that shows fewer droplets at higher supersaturations than the first extensive data set on water Ref. [15]. These experiments were performed with full knowledge of improved cleaning techniques (plus more experience and hindsight). Our general conclusion is that nucleation data is to be represented as a lower bound. The appropriate conclusion to draw from this for the CLOUDS chamber is that, again, a Wilson cloud chamber is an extremely sensitive detector and that trace impurities can and will influence results significantly. The recent water data illustrates, unfortunately, that good data and bad data can look very similar. Particularly when there is no other data.

## **6. SUMMARY**

These comments supplement previous publications, Refs. [1] to [4], on the Wilson expansion cloud chamber. Again they are intended as practical suggestions on how to operate an expansion chamber for nucleation work and incorporate techniques that work suggestions and failures.

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