Performance of the Argonne 12-Foot Bubble Chamber

K. JAEGER

Argonne National Laboratory

Track Sensitive Target Construction and Operating Conditions

H. LEUTZ

CERN

March 1974

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DIS-110-1071

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FOREWORD

This Argonne report consists of two parts. The first half represents a progress report on the 12-foot bubble chamber facility. As such, it is intended as a follow-up to the Argonne Report ANL/HEP 7210 of March 1972. Hence, the present article is in most cases complimentary to the 1972 report.

The second part presents a detailed write-up of a talk given by H. Leutz. The talk was presented at Argonne during a Track Sensitive Target (TST) Workshop in July 1972. During that time, any TST running in the 12-foot bubble chamber was still of speculative nature. In the meantime, a successful TST run has been performed with hydrogen inside and outside the target.

Performance of the Argonne 12-Foot Bubble Chamber

K. JAEGER

Argonne National Laboratory

I. Introduction

This article constitutes the second progress report on the 12-foot bubble chamber. Its purpose is to bring present and potential future users up-to-date on the current status of the facility. In particular, it is aimed at physicists who might be contemplating an experiment with a track sensitive target (TST) or with a polarized proton beam.

The chamber has been in operation for physics runs since September 1970. Since that time, it was subjected to over three million expansions, and it has taken over two million four-view pictures. The picture rate is mainly limited by the particle intensities in the secondary beam lines. Besides its usual running mode of one expansion for each Zero Gradient Synchrotron (ZGS) pulse, the chamber can now be run in the double or triple expansion mode. These expansions can be as close as 150 ms at intervals of two seconds.

Physics pictures have been taken with hydrogen and deuterium. Mixtures of neon-hydrogen are anticipated for 1974. High pressure test runs, required for such mixtures, have already been successfully performed.

Overall, the chamber has maintained its status of being the most productive large hydrogen bubble chamber in the world. With the polarized beam and the TST program, this facility will definitely continue to lead its field in this energy range.

II. Chamber Parameters

During the last three years considerable expertise has been obtained for running this large chamber, either with hydrogen or with deuterium. The following conditions are the ones mostly used:

<u>For H₂:</u>	Vapor Pressure	Between 45 and 60 psia (between 24. 8 and 26. 2 °K)
	Static Pressure	Between 53 and 70 psia (usually 8-10 psia above vapor pressure)
	Expanded Pressure	Between 10 and 16 psia
	Beam Entry	2 ms before P _{min}
	Flash	2-4 ms after P _{min}
	(Track sensitivity has been achieved for temperatures as high as 29 °K.)	
	Track ionization has been observed at vapor pressures of 45 to 55 psia (i. e. between 24. 8 and 25. 5 °K).	
<u>For D₂:</u>	Vapor Pressure	Between 58 and 74 psia (between 29. 3 and 30. 6 °K)
	Static Pressure	Between 80 and 95 psia (usually 20 psi above vapor pressure)
	Expanded Pressure	Between 12 and 20 psia
	Beam Entry	2 ms before P _{min}
	Flash	2-4 ms after P _{min}

No detailed track ionization studies have been made with deuterium.

III. Particle Beams

An overall view of the existing, planned and contemplated beams for the bubble chamber is shown in Fig. 1.

1. **The Main Beam Line:** Resonance extracted protons from the ZGS at energies up to 13.4 GeV/c. This beam line is used mainly for the ν experiments. It has also been utilized for p-p experiments at 12.4 and 8.0 GeV/c. For the future, it will be available for ν experiments, proton as well as polarized proton experiments at ZGS energies.

2. **The K_L^0 Beam:** This beam transports 1.0 GeV/c pions produced by proton interactions with a target inside the ν tunnel. The pions are incident on a liquid H_2 target near the bubble chamber. Decays and interactions from the produced K_L^0 's are then observed within the bubble chamber. The beam has been used for a large K_L^0 exposure and will be available for future use.

3. **The Radio-Frequency-Separated Beam:** This beam has been in operation since March of 1973. Kaon beams can be obtained at 4.6, 6.5 and 8.0 GeV/c. Nearly 200k pictures of K^- at 6.5 GeV/c have already been taken. Protons and pions are available from 2 to 11 GeV/c. The beam line was used extensively for proton experiments at 7.0, 9.0 and 11.0 GeV/c. Anti-proton experiments could be run at momenta between 0.9 and 3.0 GeV/c.

4. The Low Momentum Beam Line: This beam is still under construction. It will use the same line as the RF beam and will make use of two electrostatic separators. Separated π^+ 's, p^+ 's, $\bar{p}^+$'s will be available between 0.6 and 1.5 GeV/c.

5. The Travelling Wave Beam: The line at the downstream end would overlap with the RF beam. This beam could provide K^+ 's and $\bar{p}^+$'s either between 1.5 and 3.0 GeV/c or between 2.5 and 4.0 GeV/c. It would, in fact, be complimentary to the RF beam. No definite installation date has been set.

IV. Experiments for the Chamber

Several experiments have been finished as of this date. The following list represents a short summary.

1. $p + p$ Interactions in Hydrogen at 12.4 GeV/c
110 k pictures taken, Argonne-Illinois Institute of Technology
2. $p + p$ Interactions in Hydrogen at 8.0 GeV/c
30 k pictures taken, Tohoku University in Sendai, Japan
3. $\nu + p$ Interactions in Hydrogen
350 k pictures taken, Argonne
4. $p + p$ Interactions in Hydrogen at 7.0, 9.0, 11.0 GeV/c
300 k pictures taken, Tohoku University in Sendai, Japan
(First experiment to use the RF beam line and to run in the double pulse mode for half of the experiment.)
5. $\nu + d$ Interactions in Deuterium
640 k pictures taken, Argonne
(Approved for another 360 k pictures)
6. K_L^0 Decays and Interactions in Hydrogen
320 k pictures taken, Carnegie-Mellon University-Argonne
7. $K^- + p$ Interactions in Hydrogen at 6.5 GeV/c
200 k pictures taken, Michigan State University-Argonne-Kansas

University-Vrije University, Brussels, Tufts University
(Approved for another 800 k pictures)

Additional Approved Experiments

1. $\bar{p} + p$ Interactions in Hydrogen at 600-1000 MeV/c
300 k pictures, University of Wisconsin
2. Polarized $p + p$ in Hydrogen at 6.0 and 12.0 GeV/c
150 k pictures at each energy, Case-Western Reserve University-
Carnegie-Mellon University
3. $\pi^+ + p$ Interactions in Hydrogen at 6.0 GeV/c Using a TST
100 k pictures, Rutherford Laboratory-CERN-Argonne
4. $\bar{p} + p$ Interactions in Hydrogen at 600 MeV/c Using a TST
160 k pictures, Tohoku University-Tohoku Gakuin University-Nara
Women's University
5. $\pi^- + p$ Interactions in Hydrogen at 8.0 GeV/c Using a TST
100 k pictures, Notre Dame University
6. $p + p$ Interactions in Hydrogen at 11-12 GeV/c Using a TST
50 k pictures, Illinois Institute of Technology-Argonne

In summary, it should be noted that the 12-foot bubble chamber has taken over 1310 k pictures (four-views) in H_2 and over 640 k pictures in D_2 . Some of these pictures were taken in the double pulse mode using the RF beam line. In terms of backlog, we have the following:

Number of pictures approved in H_2 :	1400 k
Number of pictures approved in D_2 :	360 k
Number of pictures approved in H_2 with TST:	<u>410 k</u>
Total:	2170 k

From the above list of experiments, it is clear that many experimental high energy groups are utilizing the 12-foot chamber, not only for weak interactions, but also for hadron physics. All these groups use the computer programs adapted and modified for this chamber, namely the geometry program TVGP and the fitting program SQUAW.

V. Track Sensitive Target (TST) Program at the 12-Foot Chamber

The Argonne Bubble Chamber Group has committed itself to an experimental program involving a track sensitive target. The purpose is to observe primary interactions either in hydrogen or deuterium within the TST and good gamma conversion efficiency in the surrounding mixture of neon-hydrogen. Because of its large size, the 12-foot chamber lends itself to such physics.

Several limitations have to be taken into account. Since the chamber is completely closed off from the expansion system via the toroidal bellows, the usual entry into the chamber is through one of the five camera ports (Fig. 2). Hence, the width of the target is limited. Furthermore, the target has to be brought into the chamber fully assembled. It has to be lowered vertically through a camera port and then turned horizontally once inside. Therefore, the height of the chamber limits the length of the TST. Together these restrictions allow a single module TST of 200 cm length and 36 cm width, with a height of about 8 to 10 cm. All necessary plumbing, which includes fill and dump lines, cooling loop fill and return lines, sampling tube line, instrumentation lines, etc., are brought inside the chamber via a dummy cartridge set in the center camera port. Since equivalent connections are located in the preassembled target, it only remains to connect these pipes inside the chamber whenever a TST run is scheduled.

A. The First TST Run at the 12-Foot Chamber

The present TST program at Argonne is a joint effort between Argonne, Rutherford, CERN and Tohoku University. The targets are built at CERN. For the first test run, the dimensions were 200 x 36 x (8-10) cm and the material was Plexiglas (Fig. 3). The top and bottom sheets were 0.8 cm thick, which allowed a $\Delta V/V$ of $\sim 1\%$, whereas the sides were 1.2 cm thick. Fig. 2 shows a schematic view of the target after it was positioned in line with the beam window. In Fig. 4, one can observe more details of all plumbing connections, most of which were hidden behind the Scotchlite panels (Fig. 5). This first target was supported at each corner by spring-loaded stainless steel bars. Fiducials were located on the top and bottom surface.

Most of the instrumentation such as strain gauges, position transducers, etc. was supplied and set up by the Rutherford Laboratory. This effort will continue in the future and will include gas sampling and analysis equipment needed for the neon-hydrogen mixtures.

The first TST run commenced in November 1973. Both the chamber and the target were filled with hydrogen. Neon-hydrogen mixture conditions were simulated by running the chamber at fairly high pressures. With reference to Fig. 6, it can be seen that in order to avoid phase separation between neon and hydrogen, one has to stay above the curve shown. We took 6,000 pictures with a 6.0 GeV/c poorly collimated polarized proton beam. The chamber conditions were:

Chamber Vapor Pressure	76.5 psia (27.4°K)
Target Vapor Pressure	70 psia (27.0°K)
Chamber Pressure	87.5 psia
Expanded Pressure	30 psia
Piston Stroke	1.070 inches
Beam Entry	6 ms before $P_{\min}$
Flash	2 ms after $P_{\min}$

These parameters closely simulate the required conditions needed for 30-35% mole neon mixture runs. The photographs presented in Figs. 7, 8 and 9 exhibit the track sensitivity achieved during the runs. One can see beam tracks inside and outside the target. In particular, one should note that tracks passing from inside the TST to the outside clearly show large gaps. These gaps are due to the Plexiglas walls the tracks have to transverse.

Also evident from these photographs is the severe dirt problems that was experienced during this test run. The dirt settled onto the top surface of the TST as well as on the bottom surface of the chamber. Future runs will not be plagued by this dirt. Figs. 10 and 11 indicate schematic views as seen on the film from a nearby and downstream camera.

B. Future Plans

The next step in our TST program concerns itself with neon-hydrogen mixtures. Some pure neon is already available and stored in one of our small existing dewars. It is hoped that by June 1974 enough pure neon will be on hand (~8000 l) in order to perform a 30-35% mole neon mixture run. Such a run is necessary in order to study phase separation and homogeneity problems

with mixtures in large bubble chambers.

The next TST will have a different shape. In order to improve the clarity of the photographs, the sides of the TST will be made transparent and will be slanted towards the nearest camera. Whenever possible, Scotchlite will be used on any support structure. Overall, the picture quality should improve greatly.

It is hoped that by the beginning of 1975, the first actual physics run with a TST and with 30-35% mole neon mixture can be performed. A new TST from CERN will be used which will have all the refinements mentioned above incorporated into its design. In addition, it is hoped to run the TST in a double pulse mode. Fig. 12 shows the displacement of a fiducial on the top surface of the TST during one bubble chamber expansion. The coordinate is down into the chamber along the piston. The indicated curve is a fit of

$$z(t) = \frac{\dot{z}_0}{w_1} e^{-\gamma t} \sin(w_1 t) ,$$

where the fitted parameters are

$$\begin{aligned}\dot{z}_0 &= 33 \text{ cm/sec} \\ w_1 &= 48.3/\text{sec} \\ \gamma &= 12.1/\text{sec} .\end{aligned}$$

The result clearly indicates that after 250 ms, all oscillations have died out, so that double pulsing for a ZGS flattop of 500 ms or greater would cause no difficulty.

In order to allow even higher neon concentrations, Argonne is purchasing a new high pressure 15,000 gallon dewar. It will allow the storage of up to 100% pure neon. It is anticipated that this dewar will be in operation by the Spring of 1975. The main reason for such a storage facility is the need of ~ 98% mole neon mixtures. Such a mixture concentration is required in order to obtain compatible operating conditions with deuterium in the TST and a mixture surrounding it.

As a final note on the TST project, it should be emphasized that the Argonne program has become a worldwide collaboration. CERN is supplying the targets, Rutherford the gas analysis equipment and TST instrumentation, Tohoku University is buying the initial 8000 l pure neon, and NAL is purifying crude neon and shipping it to Argonne.

VL Summary

In conclusion, it has to be stated that the 12-foot Argonne bubble chamber has become a viable high energy physics tool. Over the last four years, it has proven itself as a reliable, cost-effective facility that continues to lead the field of large hydrogen bubble chambers in terms of productivity and versatility.

Appendix A

History of Chamber

June 1964	Proposal Submitted
May, 1965	Design Started
June, 1966	Construction Started
December, 1968	Superconducting Magnet Tested
August, 1969	First Chamber Cooldown with Liquid Nitrogen
October, 1969	First Chamber Cooldown with Liquid Hydrogen
October, 1969	First Particle Tracks
September, 1970	First Experimental Pictures Taken
November, 1970	First Neutrino Event in Liquid Hydrogen
October, 1971	First Chamber Cooldown with Liquid Deuterium
October, 1971	First Neutrino Event in Liquid Deuterium
March, 1972	1, 000, 000 Physics Pictures Taken
March, 1972	Track Sensitive Expansions in the Double and Triple Pulse Mode at Intervals as close as 150 ms
November, 1973	First Track Sensitive Target (TST) Run with Hydrogen. Track Sensitive Inside and Outside TST at 27.5°K
December, 1973	2, 000, 000 Physics Pictures Taken
December, 1973	Expansion System Reached 3, 000, 000 Pulses with the Same Toroidal Bellows

Appendix B

Publications of Experiments from the 12-Foot Bubble Chamber

1. "Preliminary Results on 12 GeV/c Proton Interactions in the Argonne 12-Foot Hydrogen Bubble Chamber," J. H. Campbell, G. Charlton, K. Jaeger, W. A. Mann and J. Whitmore, ANL/HEP 7124, June 1971.
2. "Study of Inclusive γ and π^0 Production in 12.4 GeV/c pp Interactions," J. H. Campbell, G. Charlton, R. Engelmann, R. G. Glasser, K. Jaeger, W. A. Mann, Y. Oren, P. Peeters, J. Whitmore, C. Fu, H. A. Rubin, D. Swanson and D. Koetke, Phys. Rev. D, 3824 (December 1973).
3. "Inclusive γ Production from 12.4 GeV/c Proton-Proton Interactions in the ANL 12-Foot Bubble Chamber," D. L. Swanson, Ph.D. Thesis, Illinois Institute of Technology, IIT Report No. 122, ANL/HEP 7352.
4. "Study of Inclusive π^0 Spectra and Correlations in 12.4 GeV/c Proton-Proton Interactions," D. Swanson, G. Charlton, C. Fu, R. Glasser, K. Jaeger, D. Koetke, H. Rubin and J. Whitmore, ANL/HEP 7357, Phys. Letters 48B, 479 (1974).
5. "Study of the Reaction $\nu p \rightarrow \mu^- \pi^+ p$," J. Campbell, G. Charlton, Y. Cho, M. Derrick, R. Engelmann, J. Fetkovich, L. Hyman, K. Jaeger, D. Jankowski, A. Mann, U. Mehtani, B. Musgrave, P. Schreiner, T. Wangler, J. Whitmore and H. Yuta, Phys. Rev. Letters 30, 335 (1973).
6. " $\nu p \rightarrow \mu^- \Delta^{++}$: Comparison with Theory," P. A. Schreiner and F. von Hippel, Phys. Rev. Letters 30, 339 (1973).
7. "Neutrino Production of the $\Delta(1236)$," P. A. Schreiner and F. von Hippel, Nucl. Phys. B58, 333 (1973).
8. "Study of the Reaction $\nu + n \rightarrow \mu^- + p$," W. A. Mann, U. Mehtani, B. Musgrave, Y. Oren, P. A. Schreiner, R. Singer, H. Yuta, R. Ammar, S. Barish, Y. Cho, M. Derrick, R. Engelmann and L. G. Hyman, Phys. Rev. Letters 31, 844 (1973).

Fig. 2

Fig. 3

Fig. 4

Fig. 5

FROM: W.B. STREETT and C.H. JONES, JOURNAL
of CHEMICAL PHYSICS, V42, II, 3980 (1965)

Fig. 6

Fig. 7

Fig. 8

Fig. 9

TST SIZE:
205cm x 35cm x 10cm

**TST POSITION AS SEEN
FROM CAMERA 1**

Fig. 10

TST SIZE:
205cm x 35cm x 10cm

**TST POSITION AS SEEN
FROM CAMERA 4**

Fig. 11

Fig. 12

TST Construction and TST Operating Conditions.

H. Leutz, CERN, Geneva

I. Introduction.

Before starting the construction of a track sensitive target(TST), we should always keep in mind what we expect from this device: We want to contain the beam tracks and the beam interaction vertices within hydrogen (or deuterium) and we wish to surround this H_2 (D_2) -region with a heavy liquid. To achieve this goal, we should construct a TST as simply as possible. We should in particular avoid extra optics and an extra expansion device. This requires a completely transparent box for the TST which transmits the pressure reductions via flexible walls from the surrounding heavy liquid to the hydrogen or to the deuterium. In this way the TST works in a completely passive mode of operation. The only transparent material which at the same time has the required optical performance and enough flexibility at liquid hydrogen temperature is PLEXIGLAS or PERSPEX, as they call it in England.

Fig.1 gives an impression of how such a TST would look in a big chamber, e.g. BEBC. The PLEXIGLAS -box starts at the beam entrance window and the beam particles spread over its width W . To achieve track sensitivity inside the TST we need a wall displacement of approximately 1/2 o/o of the box height H on the top- and bottom wall, respectively. To obtain good track quality in hydrogen and simultaneously in the surrounding heavy liquid with such a simple device, asks for almost identical operating conditions of both liquids. In particular, the pressure swing during the

expansion cycle, the static pressure for bubble recompression and the temperatures of both liquids should be the same or very similar.

II. Thermodynamic Considerations.

Let us now consider the feasibility of such a TST -system. Fig.2 shows vapour pressure curves in the range of bubble chamber operation temperatures for hydrogen and deuterium, i.e. between 25.5°K and 32.5°K . The left dotted line represents the parahydrogen vapour pressure, the middle one stands for the normal deuterium vapour pressure and the dotted line at the right shows the vapour pressure for neon. The solid lines indicate the vapour pressures for saturated liquid mixtures of neon and hydrogen. The mixture data are extracted from the paper of W.B. Streett and C.H. Jones¹⁾. Surprisingly enough, up to 80 mole o/o neon, the vapour pressures of neon - hydrogen mixtures are almost identical to the parahydrogen vapour pressure. Above 80 mole o/o neon the vapour pressure drops down with increasing neon fraction. From this figure we learn, that, as far as vapour pressures are concerned, very similar conditions exist for hydrogen and neon - hydrogen mixtures up to about 80 mole o/o neon, and for deuterium and neon - hydrogen mixtures between 90 and 96 mole o/o neon.

Apart from the vapour pressure the feasibility of a TST -system is closely related to the minimum bubble formation energy, which is necessary to create bubbles at all. This minimum formation energy mainly depends on the surface tension, the heat of vapourization, the vapour pressure, and on the expanded pressure of the bubble chamber liquid²⁾. The theory on bubble formation has been extensively reviewed by Ch. Peyrou³⁾ who also gives a set of formulas to estimate the minimum formation energy. Some

uncertainties inherent to the bubble formation theory may be avoided by taking formation energy ratios rather than absolute values. Comparing the formation energies at the mixture operating conditions with those for hydrogen at 26.5° K we find ratios between 5 and 15 for mixtures with neon fractions ranging from 50 to 80 mole o/o. Fortunately enough, these rather high bubble formation energies of the mixtures are counterbalanced by the stopping power for charged particles, which is in the mixtures considerably higher than in hydrogen. Therefore, more energy per pathlength is deposited along the particle tracks in the mixtures. By taking this into account, we obtain ratios of bubble densities from mixtures and hydrogen, which at least in a qualitative manner explain what we find experimentally. Fig. 3 shows these ratios versus the neon molar fraction. The crucial limit for reasonable bubble densities in the mixtures is at a ratio of about 0.4 if we assume a bubble density of $18/\text{cm}$ in hydrogen at 26.5° K. Fig. 3 indicates in general a decreasing ratio of bubble density with an increasing neon fraction in the mixture. This is confirmed by figs. 4 and 5 which show solid tracks in the 45 mole o/o mixture (Fig.4) and gapy ones in 75 mole o/o (Fig.5).

Another item to check the feasibility of the proposed TST -system is the bubble growth. P.R. Williams (RHEL) made some guesses by using the well known Plesset and Zwick formula⁴⁾. The rather surprising conclusion from his analysis is that under the same operating conditions bubbles in the mixture will grow faster than those in the hydrogen by at least a factor of 1.5. This tendency is confirmed by pictures taken with more than 70 mole o/o neon, where the reduced bubble density allows one to look at individual bubbles (see fig.5).

Let me now mention a drawback of neon - hydrogen mixtures, namely the phase separation phenomenon which occurs at temperatures below 29° K.

The area of phase separation is shown in fig.6 . The data are again taken from W.B. Streett and C.H. Jones¹⁾ . Suppose, we work with a mixture of 50 mole o/o neon at 29.5° K. Everything is fine. If we, however, reduce the temperature to 27.5° K we obtain a heavy mixture with about 90 mole o/o neon and on top of it a light mixture with about 35 mole o/o neon.

Now, it would be very convenient if we could get back to a uniform mixture by increasing the temperature to 29.5° K again. However, gravity is against that. The only means to achieve a uniform mixture of 50 mole o/o again is either to empty the chamber and refill it at a temperature above 29° K or to pump the heavy component from bottom to top. Therefore, I would strongly recommend the installation of a cryogenic pump in the chamber in question, which is able to circulate the mixture within some 10 to 30 minutes.

Question: Has anyone actually phaseseparated a mixture, pumped and mixed it up again in the chamber?

Answer: No. It's something in principle you could do, but has'nt been done yet. It is obviously the fastest and most convenient way to achieve uniformity again. It is already clear from many trials that you cannot remix by making deep expansions only.

Another important item is the homogeneity of the neon - hydrogem mixture, because physicists strongly wish to rely on uniform composition, density, and radiation length of the chamber filling throughout the entire visible volume. This morning, Colin Fisher talked already about this point and showed curves on density distributions, obtained via proton range measurements in the 1.5 m RHEL chamber, which demonstrate that in a uniform mixture the density is constant at least within the error margin of 1/2 o/o .

III. TST -Operation in the 1.5 m RHEL Bubble Chamber

Let me now spend some minutes to talk about TST -operation in the 1.5 m chamber at RHEL. Fig. 7 shows the TST going as a thin slice all the way through the beam plane of the chamber. The flexible side walls were of PLEXIGLAS and were contained in a stainless steel frame. At the beam entry port there is the filling valve and a damp valve which in case of pressure differences between TST and chamber in excess of 4 or 5 psia automatically opens by a strain gauge signal. This would, of course, result in a direct connection between TST and chamber, so that the hydrogen would be contaminated with neon and therefore we would be required to empty and refill TST and chamber. Also shown in fig. 7 is a vapour pressure bulb, to measure the hydrogen temperature inside the TST, and a cooling loop. The efficiency of this cooling loop is around 15 W and it would be possible to run the hydrogen in the TST about 1° or even 1.5° cooler than the surrounding mixture. However, with the stainless steel frame this mode of operation is somewhat dangerous because any hydrogen temperature below 29°K could provoke phase separation next to the steel. Therefore we operated with 0.05° temperature difference only. With an all PLEXIGLAS TST we will run at a higher temperature difference without any danger of phase separation.

The TST cross-section transverse to the beam is shown in fig. 8 with its two PLEXIGLAS walls each 6 mm thick. They were sealed to the steel frame in pressing them against indium wires by inflating the flexible stainless steel tubes shown in the same figure. Because of the differential contraction between the PLEXIGLAS and the steel we allowed the windows to float during the cooldown period. When chamber and TST reached 29°K the PLEXIGLAS windows were clamped in position by inflating the tubes to about 500 psia.

Fig. 9 shows that there are considerable differences in sound velocity between pure hydrogen and neon-hydrogen mixtures. At 29° K the sound velocity decreases from 771 m/sec (hydrogen) to 365 m/sec (55 mole o/o neon fraction) and raises again to 562 m/sec for pure neon⁵⁾. This difference in sound velocity causes phase differences between the pressure waves which, as a result of the expansion stroke, travel vertically through the hydrogen (inside the TST) and through the mixture. These phase differences result in turn in pressure differences horizontally across the PLEXIGLAS walls of the TST, which vary in amplitude and sign along the height of the walls. These pressure differences provoke vertical oscillations of both TST walls. With strain gauges glued on top and bottom centre and on beam entrance and exit centre of both PLEXIGLAS walls and a high speed chart recorder we recorded these oscillations and found frequencies between 60 and 90 Hz depending on the wall thickness. We noticed, that for the first 5 to 10 cycles after the expansion the oscillations showed the same frequency than the oscillations on the pressure time curve (45 Hz). After this short period they switched over^{to} the higher frequency (60 to 90 Hz) and successively increased in amplitude until it became, depending on the PLEXIGLAS wall thickness, some 2 to 15 times larger than the amplitude resulting from the original expansion stroke. After some 20 oscillations the amplitudes started to decrease rather slowly, depending on the shape of the TST. The slightly inflated TST damped the oscillations more efficiently than the deflated one. The stresses induced by these oscillations have been calculated and the result is displayed in fig. 10. At the beginning of our TST runs we worked with PLEXIGLAS wall thicknesses between 2.5 mm and 3mm. From fig. 10 it is obvious, that at this thickness the stress resulting from the normal volume change of 1 o/o is rather low. The hyperbolic curve indicates the stress resulting from the oscillations of the PLEXIGLAS walls. For wall thicknesses between 2.5 and 3 mm this stress is some 15 to 20 times higher than that induced by the normal expansion ratio. At 6 mm wall thickness, however, both stresses are not much different and in fact we used since

November 1971 6 mm walls and in this way avoided the extreme amplitudes of the wall oscillations. All that is, of course, a special case for bubble chambers having perpendicular directions for the magnetic field and the expansion system which consequently results in a TST orientation as shown for the 1.5 m RHEL chamber. In the 12 foot chamber magnetic field and expansion direction coincide and therefore the TST orientation is such that the pressure waves travel along its shortest dimension (height H in fig. 1).

To avoid the stainless steel frame, because it is for several reasons desirable to have an all PLEXIGLAS TST in the chamber, we have the following construction in mind (see cross-section in fig. 11): To the bars on top and on bottom we glue 6 or 8 mm thick PLEXIGLAS walls on either side. To smooth out the stress concentration at the transitions from the bars to the walls we use u-shaped bars. Fig. 12a shows the stress distribution in such a profile, the photograph indicating the stress patterns which appear if polarized light is shone through a PLEXIGLAS sample of appropriate thickness. Fig. 12b shows the stress distribution in a cross-section cut from an old TST with rather sharp bendings. Obviously, the thermal bending of PLEXIGLAS under conditions to conserve the required high optical quality of the TST, resulted in a considerable built in stresses which, in connection with the high stresses induced by the oscillations of the underdesigned 3 mm walls, led to the destruction of the TST.

IV. Optimization of TST Dimensions.

It is very important to define some criteria for the optimization of the TST dimensions - not only physics-wise, but also and firstly from the engineering point of view. Fig. 13 shows the calculated peak stresses in TST walls plotted versus the wall thickness. In this figure this is done for

a constant TST length and width, but for TST heights varying between 10 cm and 20 cm. Two sources of stress are considered: One resulting from the 1 o/o volume change of the TST during the expansion cycle, which rises linearly with wall thickness with a slope depending on the TST width W and on the height H . The other, caused by accidental pressure differences between TST and chamber, which mainly occur during the filling and purging process. In fact, pressure differences of the order of 1 to 2 psia are more or less unavoidable during the filling period. To limit the possible pressure differences we connect at the RHEL the TST with the chamber via a tube, which is separated by a bursting disc at a place outside the chamber, which is easily accessible and at ambient temperature. At a preset level of 1 psia this disc ruptures and the pressures equalize. After this event, two valves installed on either side of the disc can be closed, the disc itself can be replaced and the filling procedure goes on. This tube is of course closed off before the expansions start.

The other dimension which has some effect on the stresses in the TST walls is the width W . Of course, for the 12 foot we don't have much choice in this respect because the TST maximum width is dictated by the diameter of the access hole at the chamber top. But in general we can vary this dimension more easily and fig. 14 shows similar results of stress calculations as fig. 13, this time with a fixed TST height H and different TST widths of 32 cm, 50 cm, and 80 cm. Again, we can predict an optimum wall thickness for the expected expansion ratio and for the tolerable pressure difference pre-set by the bursting disc. Figs. 13 and 14 do not show any stresses due to the oscillations of the TST walls. These oscillations are particularly strong in a gas-expanded chamber, as the 1.5 m in RHEL, which after the expansion cycle acts as a resonating system. The experience with the 1 m CERN model chamber shows, that with a piston expanded chamber these oscillations are much less important.

We want, of course, to survey the shape of the TST during the filling period and during the expansions. In particular, we want to make sure, that the TST walls are parallel during the data taking period. This survey is done via strain gauges which are glued at appropriate places on the TST walls. With these strain gauges connected to some elaborate electronics - balancing for example any zero drift of the amplifier - it is feasible to control volume changes $\Delta V/V$ of the TST within about 10^{-4} .

For the requirements of high energy physics experiments there is an optimization of the TST dimensions possible as well. The length along the beam is best determined by balancing the fraction of neon background events, as the beam leaves the TST, and the precision of curvature measurements on beam particles and on fast charged secondaries against the detection efficiency of forward gammas, which do not emerge from the sides of the TST. FAKE calculations done at 16 GeV/c beam momentum ⁶⁾ indicate an optimum TST length between 200 cm and 300 cm. The TST width W is more or less dictated by the needs for beam sagitta and beam spread.

The TST height H is aligned with the magnetic field lines and with the camera axes of the large chambers (see fig.1). Therefore, spatial resolution and magnetic bending power are rather poor around this direction. But this dimension reflects on the angular precision of charged secondaries and it dominates in the opposite sense the gamma conversion path length in the neon - hydrogen mixture. Fig. 15 shows the gamma conversion efficiency versus the TST height faked for the 16 GeV π^- p -experiment. Fig. 16 shows for the same experiment the dependance of the missing mass resolution for four prongs from the TST height. All this FAKE work is done with BEBC dimensions, but there should be not much difference to the 12 foot. For bare BEBC (filled with hydrogen) we obtain 30 MeV FWHM missing mass resolution,

whereas with a TST of 20 cm height this number worsens to 40 MeV, and for 10 cm height it becomes 48 MeV. The corresponding figure for the 2 m CERN chamber is 55 MeV. Hence, for track reconstruction we make improvements by increasing the TST height H, whereas a shallow TST increases the gamma conversion efficiency. A reasonable compromise for these conflicting requirements is a tapered TST, which starts at the beam entrance with 15 to 20 cm height, to provide sufficient hydrogen in the vertex region, and ends up with 5 cm height to just contain the beam particles still in hydrogen. In addition, such a tapered TST provides a well defined top region where to put the heat exchanger for the hydrogen.

V. Track Reconstruction and Spatial Precision with a TST System.

Another point to discuss concerns track reconstruction from pictures taken in a bubble chamber equipped with a TST and filled with neon - hydrogen. For a large fraction of the picture area there is PLEXIGLAS between the camera and the event or track in question. Therefore, it is important to know the impact of a PLEXIGLAS layer on the light rays. The flat TST causes parallel light ray displacements only. As long as we stay within the normal expansion ratios, any effects due to flexing of the TST walls during the expansion cycle are completely negligible. The parallel displacements can be calculated from the following formula:

$$s = d \sin \gamma \left(1 - \frac{\cos \gamma}{\sqrt{n^2 - \sin^2 \gamma}} \right)$$

d means the thickness of the PLEXIGLAS sheet and γ is the angle subtended by the camera. n is the ratio of the refractive indices for PLEXIGLAS (1.48) and for the liquid (1.10). However, for a tube shaped TST with radius R things become quite different. At a distance A between the camera nodal point and the tube

axis the displacement s becomes:

$$s = \frac{A}{R} d \sin \gamma \left(1 - \sqrt{\frac{(R/A)^2 - \sin^2 \gamma}{(nR/A)^2 - \sin^2 \gamma}} \right)$$

Fig. 17 shows the track displacements s for a flat TST and those for a tube shaped one seen under different azimuth angles α . But in contrast to the flat TST the light rays traversing a Plexiglas tube do not suffer parallel displacements only, they also change direction. This can be seen in fig. 18 which displays the relative change in viewing angle γ and azimuth angle α suffered by a light ray which has traversed once the wall of a PLEXIGLAS tube. The calculations have been done for $A/R = 8$ which is, for example, compatible to a tube diameter of 0.5 m and a camera distance of 2m. Obviously, the large displacements and the additional angular rotations lead for a tube shaped TST to serious reconstruction problems. Therefore, I proposed the breathing TST with parallel walls which makes track reconstruction quite easy and does not need a bellows system to transmit the pressure swing.

What setting error can we expect in a bubble chamber filled with a neon-hydrogen mixture? If we ignore the errors added during the measuring stage, the setting error ϵ in the chamber is composed of the error due to thermal turbulence T and the error O on the optical constants of the chamber:

$$\epsilon^2 = T^2 + O^2$$

Let us first consider the thermal turbulence effect T , which again is the result of different factors⁷⁾:

$$T = f H^{7/8} L^{3/2}$$

where f mainly depends on the size of small liquid volumes (eddies), which

due to slightly different temperatures traverse vertically the chamber volume, and on the refractive index fluctuations of these eddies. H means the heat flux density through the chamber and L is the distance between the camera lens and the object in the chamber space.

In this context it is interesting to look at the temperature dependence of the hydrogen and neon refractive indices⁸⁾ in fig. 19. Both curves cross at 29.2 °K. This means for track reconstruction that no variation of refractive indices between hydrogen and neon-hydrogen has to be taken into account. Moreover, the refractive index varies much less with temperature in neon than in hydrogen. This is the main reason, that the factor f is considerably smaller with neon than with hydrogen:

$$f_{\text{Ne}} / f_{\text{H}_2} = 0.4$$

Now, most of the heat produced in a bubble chamber is due to irreversible work performed during formation and recompression of spurious bubbles (dynamic heat load). We know already, that the minimum bubble formation energy is considerably higher in neon-hydrogen than in hydrogen. For bubbles created along particle tracks this effect is compensated by the higher stopping power of the mixture. Of course, this compensation does not occur for spurious bubbles and therefore the whole difference of the formation energies comes into the game. Basing again on the formulæ to estimate the bubble formation energy given by Ch. Peyrou³⁾ we find:

$$W_{50} / W_{\text{H}_2} \approx 2 \quad \text{and} \quad W_{70} / W_{\text{H}_2} \approx 8 \text{ to } 10$$

if we compare formation energies W for 50 and 70 mole o/o neon in the mixture at 29.7 °K and an expanded pressure of 4.8 atm (70 psia) to the formation energy of hydrogen at 26.5 °K and 2 atm (29 psia) expanded pressure.

By this estimation it is obvious that in the same bubble chamber and under the same dynamic heat load the formation of spurious bubbles would be considerably decreased in a neon-hydrogen mixture as compared to a hydrogen filling.

Most of the spurious bubbles are produced by the piston movement necessary for the expansion ratio which is required to make the chamber liquid track sensitive:

$$-\Delta V/V = \Delta P/\beta$$

ΔP means the pressure reduction during the expansion cycle and β is the isentropic compressibility of the chamber liquid:

$$\beta = - \frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_S$$

In fig.20, β is plotted versus the neon concentration of the mixture⁵⁾. If we compare the volume change ΔV , which corresponds to a certain piston movement, of neon-hydrogen mixtures to that of hydrogen we obtain:

$$\Delta V_{50} = 0.9 \Delta V_{H_2} \quad \text{and} \quad \Delta V_{70} = 0.5 \Delta V_{H_2}$$

We have taken β at 29.5° K for the mixtures and at 26.5° K for hydrogen. All these effects as the increased bubble formation energy, the reduced temperature dependence of the refractive index, and the decrease of the isentropic compressibility give rise to a considerable reduction of the thermal turbulence term T in the expression for the setting error ξ .

The term O , which stands for the optical constants (camera nodal points, orientation of the camera axis, demagnification factor, misalignment of the

fish-eye windows, calibration of lens distortions) can be considerably reduced by a system of fiducial marks on the walls of the TST. Placing fiducials on the chamber body only, involves uncertainties due to undetermined position changes during chamber cool down and expansions. Moreover, they are far from the particle interaction region and near the range limit of focal depth, where the cameras have maximum distortions. On the TST walls, however, the fiducial distances can be measured very precisely ($\pm 20 \mu\text{m}$) at nitrogen or even at hydrogen temperature outside the bubble chamber⁹⁾.

In addition, by using two laser beams which cross the beam plane at an angle of about 90° , we obtain an absolute co-ordinate system for the chamber space. For calibrating the optical constants sufficient visibility of the Rayleigh-scattered laser light ($4880 \text{ \AA}$ and $5145 \text{ \AA}$) may simply be achieved by employing suitable exposure times. According to our experience¹⁰⁾ this requires a continuously working argon laser with a light power between 10 and 100 W.

In connection with the fiducial marks of known distance at the TST walls, such an arrangement allows one to determine the optical constants of the chambers even more precisely than for conventional chambers, where the fiducial system is provided by marks etched at well determined positions on the surfaces of one or two flat glass windows. This is demonstrated by a computer simulation executed by R. Hartmann¹¹⁾. In total, the above described improvements for distortion errors due to thermal turbulence and for calibration errors due to the optical constants, should reduce the setting error in a large chamber equipped with a TST and filled with a neon-hydrogen mixture by a considerable factor.

VI. TST Operation in the Large Bubble Chambers.

The large chambers (12 foot at ANL, BEBC at CERN, 15 foot at NAL, and 7 foot at BNL) have, in contrast to the bath-tub shaped conventional ones, a cylindrical shape with a vertical axis. This necessarily leads to the

configuration, that the magnetic field, provided by Helmholtz coils in annular cryostats around the chamber body, the camera axes, from viewing ports housed at the chamber top, and finally the expansion system, located at the chamber bottom, are all together more or less vertically aligned. This requires a TST orientation as shown in fig.1 , with the PLEXIGLAS box having its largest cross-section transverse to the liquid displacement provoked by the expansion stroke. To avoid liquid turbulence around the TST edges and to reduce the stresses suffered by the PLEXIGLAS at each expansion cycle due to pressure waves hitting the large surfaces, we must care for an appropriate suspension of the TST.

Fig. 21 shows a TST which we built in 1969 for the 1 m BEBC model chamber¹²⁾. It went half way through the beam plane with dimensions of 50 cm (length) x 40 cm (width). This TST was suspended on four edges by springs so that it could follow the liquid movement during the expansion cycles. To measure the TST movement we shone a laser beam through a region, where we had painted black strips on the PLEXIGLAS. By counting the light pulses via a photo multiplier we determined a TST movement between 1.5 and 2mm at each expansion. The filling valve and the release valve were mounted at the support bars of the TST and were connected to the moving PLEXIGLAS box by flexible bellows. I would recommend a similar construction for the 12 foot chamber. TST and bellows did not produce any spurious boiling during the expansions. Both, the TST and the chamber were filled with hydrogen.

To end this talk, I will draw some conclusions with respect to the TST installation in your 12 foot chamber. The main restriction for mounting a TST is the limited access into this chamber. Since you must use one of the optics holes to get a TST into the chamber, this restricts you in TST length to about 2m and in the width to about 38 cm if the height is not more than

12 cm. To achieve larger TST dimensions it would be necessary to operate with TST modules, which could be arranged side by side or one behind the other in order to provide more TST width for a larger beam spread or more TST length to guide the particles within hydrogen through the chamber thus avoiding the background interactions of beam particles in the mixture. However, to begin with TST operations in the 12 foot, I would recommend one module immersed in a rather moderate mixture of about 35 mole o/o neon. This mixture has a phase separation temperature of 27.4°K , so that we could run at about 28°K . We would then have 110 cm radiation length, just the same as in propane. The density would be 0.29 g/cm^3 , this means roughly a factor 5 more than that of hydrogen. The hydrogen in the TST could have a temperature of about 27°K , which is not too far away from your present working temperature.

With such an arrangement the four gamma ($2\pi^0$) -efficiency would be 23 o/o. Based on our experience from the RHEL 4 GeV/c. π^+p -run I would advocate some 7 to 10 beam particles per pulse spread over about 20 to 25 cm. Moreover, the TST should be tapered in order to provide a well defined top region where to put the heat exchanger. It should therefore start with about 10 to 12 cm in height at the beam entrance and go down to about 5 to 6 cm at its end..Fig. 22 shows the beam plane of the 12 foot equipped with a TST 2m long and 38 cm wide.The supporting bars which can be clamped together inside the chamber extend right through the beam plane. A more detailed view of the TST itself is displayed in fig. 23.

In conclusion,a TST in the 12 foot chamber should be of the breathing type, mounted on springs to follow the liquid displacement. For the first run you should start with one module in 35 mole o/o mixture, which you could run at 28°K . The hydrogen temperature would be at 27°K . Care should be taken for the additional instrumentation necessary to operate with a TST and a mixture. By making use of the experience,gained so far at RHEL,it should be possible to run the 12 foot as well successfully with a TST.

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Figure Captions.

- Fig.1 TST mounted in a large bubble chamber.
- Fig.2 Vapour pressures of para-hydrogen, normal deuterium, neon (dashed lines), and neon-hydrogen mixtures (solid lines).
- Fig.3 Ratio of bubble densities calculated from minimum bubble formation energy and from the stopping power of the liquids.
- Fig.4 Picture taken with a hydrogen TST in a 45 mole o/o mixture. Chamber pressure 7.7 atm (114 psia), mixture temperature 29.3°K , hydrogen temperature 29.25°K , expanded pressure 4.8 atm (70 psia).
- Fig.5 Picture taken with a hydrogen TST in a 75 mole o/o mixture. Chamber pressure 8.1 atm (120 psia), mixture temperature 29.6°K , hydrogen temperature 29.3°K , expanded pressure 5.15 atm (76 psia).
- Fig.6 Area of phase separation.
- Fig.7 Steel frame TST in the 1.5 m RHEL bubble chamber.
- Fig.8 Section through top of TST frame for the 1.5 m RHEL bubble chamber.
- Fig.9 Sound velocities in neon-hydrogen mixtures. Data taken from ref. 5 .
- Fig.10 Stress - thickness characteristic for PLEXIGLAS side walls of TST.
- Fig.11 Section through an all -PLEXIGLAS TST.
- Fig.12 Fringe pattern observed with TST sections placed between crossed polaroids. a shows the unloaded and loaded (200 Kg/cm^2) sections of the new design; b shows built in stresses on the old design.

- Fig.13 Stress -thickness characteristic for PLEXIGLAS side walls of TST with constant width ,different heights, and pressure differences ranging from 40 g (0.6 psia) to 350g (5 psia).
- Fig.14 Stress -thickness characteristic for PLEXIGLAS side walls of TST with different widths and heights of 10 and 20cm.
- Fig.15 Conversion efficiencies for four gammas from two neutral pions. The curves refer to flat TST's in BEBC.
- Fig. 16 Missing mass resolutions of four prong events faked under BEBC conditions.
- Fig.17 Track displacements for a flat TST and those for a tube shaped one seen under different azimuth angles α .
- Fig.18 Relative rotation of angles α and γ for light rays which have traversed once the wall of a tube shaped TST.
- Fig.19 Refraction indices of hydrogen,neon,and neon-hydrogen mixtures. Data taken from ref. 8 .
- Fig.20 Isentropic compressibilities for neon-hydrogen mixtures. Data taken from ref. 5 .
- Fig.21 TST for the 1 m BEBC model chamber.
- Fig.22 Beam plane of the 12 foot equipped with a 2m long and 38cm wide TST.
- Fig.23 Detailed view of the TST envisaged for the 12 foot.

Fig. 1: TST mounted in a large bubble chamber (e.g. BEBC)

Fig.2: Vapour pressures of para-hydrogen, normal deuterium, neon (dashed lines) and neon hydrogen mixtures (solid lines). Mixture data taken from ref.1 .

Fig.3: Ratio of bubble densities calculated from minimum bubble formation energies and from the stopping power of different mixtures. The ratios should be taken as guide lines only, because we have not yet experimental results.

Fig. 4: Picture taken with a hydrogen TST in a 45 mole % neon-hydrogen mixture. $4 \text{ GeV/c } \pi^+p = p\pi^+\pi^0\pi^0$. Chamber pressure 7.7 atm (114 psia), mixture temperature 29.3°K, hydrogen temperature 29.25°K, expanded pressure 4.8 atm (70 psia).

Fig. 5 : Picture taken with a hydrogen TST in a 75 mole o/o neon-hydrogen mixture. $4 \text{ GeV/c } \pi^+ p = p \pi^+ \pi^0 \pi^0$
 Chamber pressure 8.1 atm (120 psia), mixture temperature 29.6 K, hydrogen temperature 29.3 K,
 expanded pressure 5.15 atm (76 psia).

Fig. 6: Area of phase separation.

Fig. 7: Track Sensitive Target for 1.5 M. Bubble Chamber.

Fig. 8: SECTION THROUGH TOP OF TARGET FRAME

Fig. 9: Sound velocities in neon-hydrogen mixtures. Data taken from ref. 5 .

Fig. 10: Stress - thickness characteristic for PLEXIGLAS side walls of TST.

Fig. 11: Section through an all -PLEXIGLAS TST.

unloaded section

Fig. 12a

load: 200 Kg/cm^2

Fig. 12b

unloaded section, showing
stresses built in during the
bending of the PLEXIGLAS

Fig. 13: Stress - thickness characteristic for PLEXIGLAS side walls of TST with constant width, different heights, and pressure differences ranging from 40g (0.6 psia) to 350g (5 psia).

Fig. 14: Stress - thickness characteristics for PLEXIGLAS side walls of TST with different widths and heights of 10 cm and 20cm.

Fig. 15: Conversion efficiencies for four gammas from two neutral pions.
 The curves refer to flat TST's in BEBC.

Fig. 16: Missing mass resolutions of four prong events faked under BEBC conditions.

Fig. 17: Track displacements for a flat TST and those for a tube shaped one seen under different azimuth angles α .

CAMERA FIELD OF VIEW ANGLE γ

Fig. 18: Relative rotations of angles α and γ for light rays which have traversed once the wall of a tube shaped TST.

Fig. 19: Refraction indices of hydrogen, neon, and neon-hydrogen mixtures. Figure taken from ref. 8 .

Fig. 20: Isentropic compressibilities for neon-hydrogen mixtures. Data taken from ref. 5 .

Fig. 21 : TST for the 1 m BEBC model chamber. It is suspended on four edges by springs, so that it can follow the liquid movement during the expansion cycles. The filling valve and the release valve are mounted at the support bars and are connected to the moving TST by flexible bellows.

Fig. 22: Beam plane of the 12 foot equipped with a 2m long and 38cm wide TST .

Fig. 23: Detailed view of the TST envisaged for the 12 foot.