A Measuring System to Study LAr Boiling

Danielle Bonhomme
UIC/UIUC
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Abstract

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Abstract

A measurement system to study LAr boiling behavior, as it applies to the application of LAr to HEP calorimetry, has been built and tested. A deep cryostat, carefully shielded to minimize the acoustic and thermal affects of the ambient environment on the samples, has been instrumented with microphones to listen to liquid disturbances. The object is to provide a convenient test and data acquisition system to study subtle boiling phenomena by listening to the bubbles generated. This report describes the design basis and the construction and early test efforts, and ends just as the work of serious data taking is about to begin so the author may return to school.

LAr Study

System Criteria

HEP Calorimetry

Energy Sensing

Collider accelerators are the current forefront of High Energy Physics. Counter rotating beams of accelerated particles (e-, e+, p, pbar) are caused to collide as trains traveling in opposite directions across crossing tracks. The accelerators provide a large number of these "crossings" each second. The collisions occur within the accelerator beam tube rather than in an extracted particle beam at some distant point. A whole new class of detectors that become a part of the accelerator itself are required to exploit the physics opportunities presented by the greater energies and interaction rates of the collider accelerators.

Liquid argon calorimeters are among the competing generic detector types in this race to HEP discovery. The liquid argon functions as the ionization media that does the actual sensing of the particles being measured. The electrons created in the ionization of the argon drift under the influence of a high electric field (1kV/mm) to pads (anodes) that are part of a geometrical array. The electrons are collected and recorded as electrical charge. The main advantages of LAr calorimetry over the competition are intrinsic calibration and high density.

Density, Sampling Fraction

The LAr detector calorimeters use dense metals (Cu, Fe (stainless steel), Pb, and U) to absorb energy. Energy resolution is inversely proportional to the plate thickness of the material between LAr ionization sensing regions. The ratio of the plate to LAr absorption lengths is called the energy sampling fraction.

The lower the sampling fraction the smaller the signal and the greater the accuracy dependence of the energy measurement on the density of the LAr. A higher sampling fraction results in a less dense and compact calorimeter for a detector of a given total absorption length. The value of the LAr density, and thus anything that affects it, is fundamental to the detector measurement accuracy. There are secondary, voltage breakdown, arguments that prefer LAr devoid of GAr (bubbling) as well.

Liquid Argon

Cryogens

Argon is a heavy (A=40, Z=18) noble element that occurs in 0.93% quantities in the atmosphere. Argon gas is available as a byproduct of the air liquefaction that provides liquid nitrogen and oxygen in kiloton quantities to, primarily, the food freezing and steel making industries. These cold liquefied gases are part of a group with 1 atmosphere boiling points less than 150K, called cryogens. The production and use of liquefied gases in applications below 150 K is called cryogenics.

The thermophysical property similarities of the major air constituents; argon, nitrogen, and oxygen (see table 1), clearly suggest that the major features of the boiling phenomena of these liquids will be similar. Nitrogen and oxygen have been studied extensively (ref. A & B), but the data on argon is incidental to binary investigations, limited in range and generally sparse. We will assume we can use boiling data for LN_2 and O_2 to predict the general behavior of LAr and perfect the measuring techniques using liquid nitrogen, and then collect the final results with LAr.

Boiling

The pool boiling phenomenon occurs in three regions: subcooled, nucleate boiling and film boiling. Pool boiling is defined as the boiling that is entirely by natural convection, with depth as a parameter.

When the temperature of the liquid is below the saturation temperature at constant pressure, the liquid is said to be subcooled. Bubbles are created only by relatively large heat fluxes that heat to exceed the subcooling before the liquid moves away by convection. As these bubbles rise toward the surface they cool and collapse in fluids when $\Delta T_{subcool}$ is large and the path long. The transition from the subcooled to saturated nucleate pool boiling region is continuous.

Nucleate boiling is strongly influenced by the condition of the sample surface. Microscopic cavities on the surface initially store air or vapor and can serve as nucleation sites. As the surface is heated some of the air in the cavities is pushed out as bubbles and some is trapped. The bubbles may rise to the surface or they may collapse depending on wall-to-fluid temperature difference $(T_w - T_b) = \Delta T$. As the ΔT is increased, the number of activated sites increase and the bubbles rise all the way to the liquid surface and release vapor. Further increases in ΔT cause the formation of so many bubbles they begin to interfere and coalesce with one another. In that region

Thermophysical Properties

	LAr	LN_2	LO_2
Pressure			
P (atm.)	1	1	1
Temperature			
T (K)	87.16	77.364	90.18
Heat Capacity			
C_p (j/gK)	1.27	2.063	1.695
Heat of Vaporization			
L (j/g)	162.1	198.6	206.0
Liquid Density			
rho_l (g/cc)	1.394	0.8085	1.141
Gas Density			
rho_g (g/cc)x10^{+2}	*0.5705*	*0.461*	*0.4475*
Density Ratio			
rho_l/ rho_g	*244.34*	*175.34*	*254.97*
Thermal Conductivity			
k (mW/cmK)	1.286	1.337	1.384
Thermal Diffusivity			
D (cm^2/s)x10^{+3}	0.72	0.801	0.782
Viscosity			
μ (g/cms)x10^{+6}	2603.7	1515.7	1958.4
Prandtl number			
Pr	2.597	2.339	2.193
Speed of Sound			
u (m/s)	607.6	938.9	903.12
Specific Volume			
v (cc/g)	0.7175	1.237	0.8765
Surface Tension			
sigma (d/cm^2)	13.2	8.27	13.2

Boiling (cont'd)

most of the surface is covered with vapor and the liquid flow over the surface is reduced. The transition region from the nucleate to film boiling is discontinuous. The heat flux at constant temperature drops to a small fraction of its value at the critical nucleate boiling heat flux, or simply the critical point.

Film boiling is the region, beyond the critical point, at which the bubbles coalesce on the surface to completely exclude the liquid. The film layer is characterized by large temperature differences for constant heat fluxes and dramatically smaller heat fluxes for near nucleate boiling temperature differences. Continued increases in the power density cause still larger surface temperature increases, and are limited largely by radiation. If the sample is a heated resistance wire, it typically melts.

The size of the bubbles formed is a function of sample surface cavities and the contact angle between the surface and the bubble. This angle is directly related to the manner in which the liquid wets the surface. The size of a bubble influences the distance it will travel before it may collapse. The largest bubbles travel to the surface before they collapse, while smaller bubbles collapse along the way.

The relationship between the frequency of bubble emission and the bubble diameter is a function of buoyancy, drag forces, and surface tension such that a simple relationship cannot be applied over the entire range of the bubble diameters, see fig. 1 [2].

The rate of bubble formation at a site is given[2] by

$$f = 1/(t_d+t_c) \quad \text{where:}$$

f = Frequency of bubble

t_d = Nucleation and growth time for bubbles on heated surface

t_c = Contact time of cool liquid with heated surface

As the sample depth in a liquid increases, the local pressure and the free convection incipient boiling heat flux increases, see fig. 2a, b, ref. 1. The sample depth is a direct measure of subcooling for liquid at a constant temperature. In this work we have constrained the temperature operating range to 87 to 99 K by designing a cryostat with a working pressure of 3 atmospheres and avoiding subatmospheric operation. Point A, of fig. 3, is the depth limit of stable subcooling at a particular temperature for the cryostat. The maximum limit for quasi-stable overpressure subcooling is bounded by the 3 atmospheres design pressure.

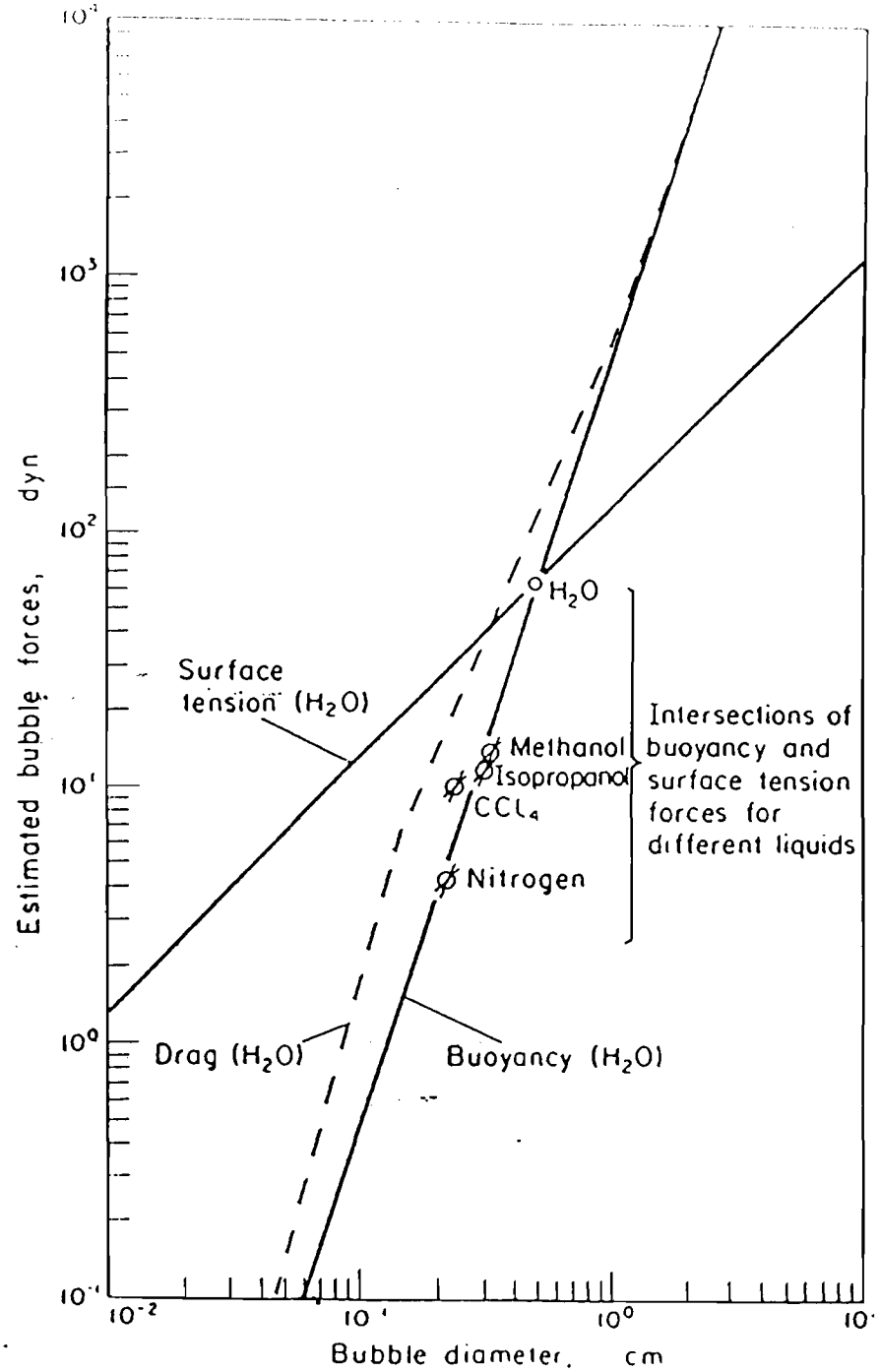


Fig. 1.
Comparison of the absolute magnitudes of surface tension, drag and buoyancy forces for spherical bubbles in water.

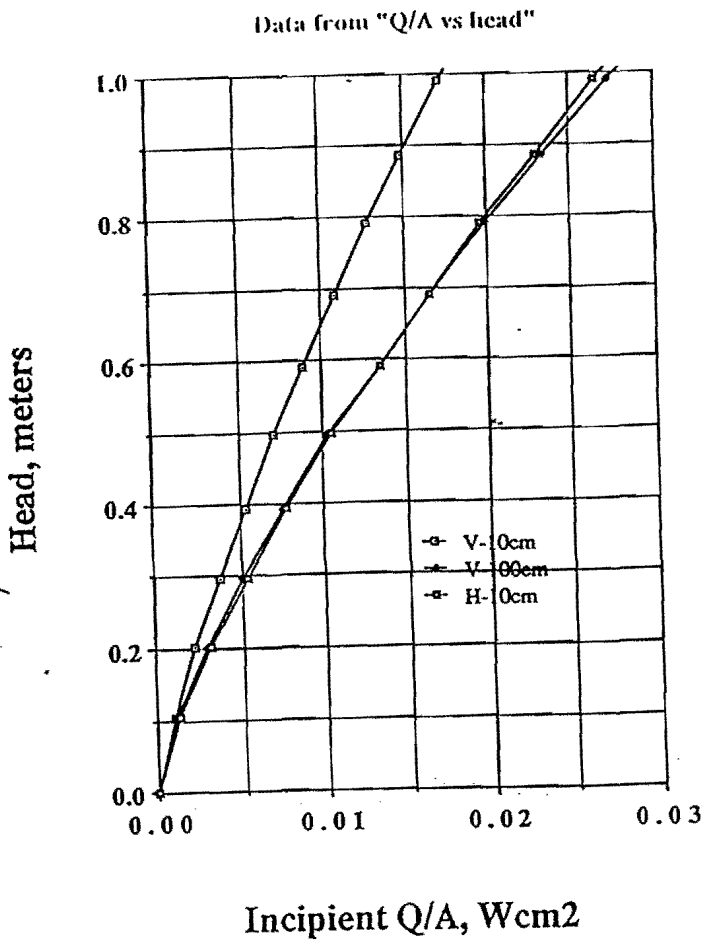


Fig. 2 (a).

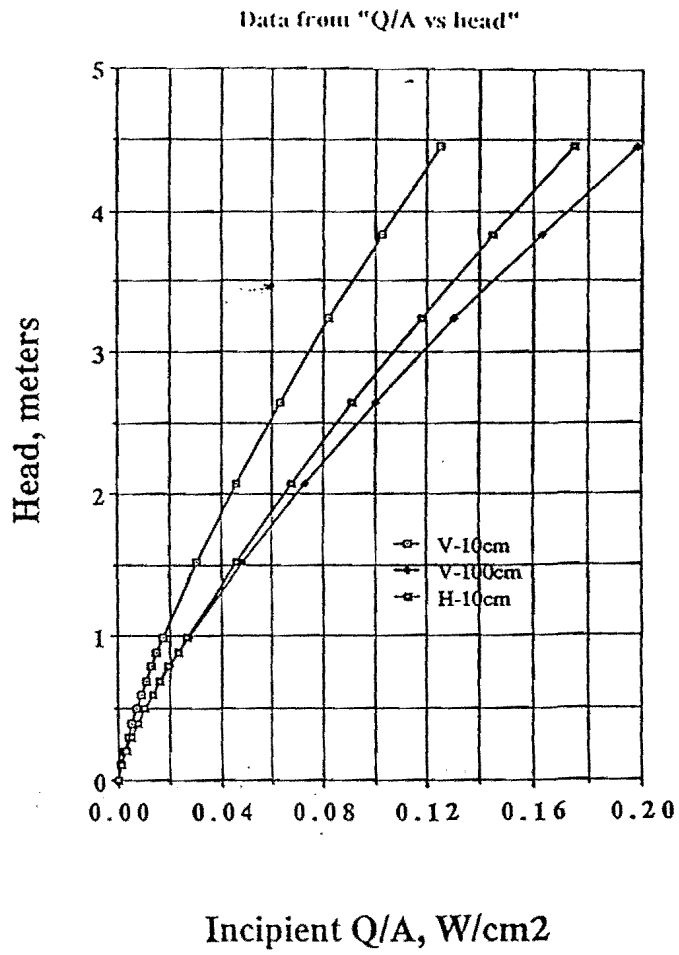


Fig. 2 (b)

Note: The order of magnitude in Fig. 2 (a) is that of this experiment whereas that of Fig. 2 (b) is typical of most practical applications.

Measurement System Parameters

LN_2/LAr Cryostat

The cryostat is designed to completely isolate the working volume from ambient temperature conditions. The working volume is surrounded by a bath of working fluid cryogen to shield and intercept the heat leak into the system. Working volume supports are broken, intercepted, or have specially reduced cross sections and increased lengths to assure the test volume thermal measurements are of sample effects only.

The working volume is a 59 in. deep, 6 in. pipe, the side shield is a coaxial 8 in. pipe with contiguous bottom shield volume, and the top shield and condenser is a 12.5 in. deep, 6 in. OD tube. Flows in and out of the cryostat working volume and shields are controlled by valves and back pressure regulators, protected by reliefs, and monitored by gauges, as shown in fig. 4 [3]. The temperatures of the three volumes; working, shield and condenser, are controlled by high precision back pressure regulators

Sensing Method

The measurement of the boiling phenomena is the size and number of bubbles present in the working volume. Large bubbles can be seen in line of sight, but the visual monitoring of small bubbles on three dimensional samples is a difficult visual task. Jim Hoover, Fermilab, introduced Piezoelectric disc microphones[1] in earlier investigations as a sensitive and effective means of "listening" for bubbles. The advantages of continuous electronic surveillance over photographic and video work through windows into a cryogenic volume for low level, incipient, bubble data taking are apparent. This work used the same Piezo-discs to detect the bubbles, but improved the sensitivity and converted the signals into TTL Logic pulses for automatic data recording. A data acquisition system counts the number of pulses and record the temperatures in the cryostat using RTDs.

The data acquisition system, built around an IBM XT with a 20 MB hard disc, uses DOS to run a Strawberry Tree Data Acquisition and Control system card. For the purpose of this experiment, the programs read the analog inputs from a terminal box, read the digital input from the TTL circuit and displayed all on one screen. Data can be logged on the hard disc and/or printer for later data analysis. The data is loaded on the disc in a format that is compatible with Lotus 1,2,3. The data can be directly spreadsheet analyzed, statistically cut, reorganized, and reformatted for subsequent reporting.

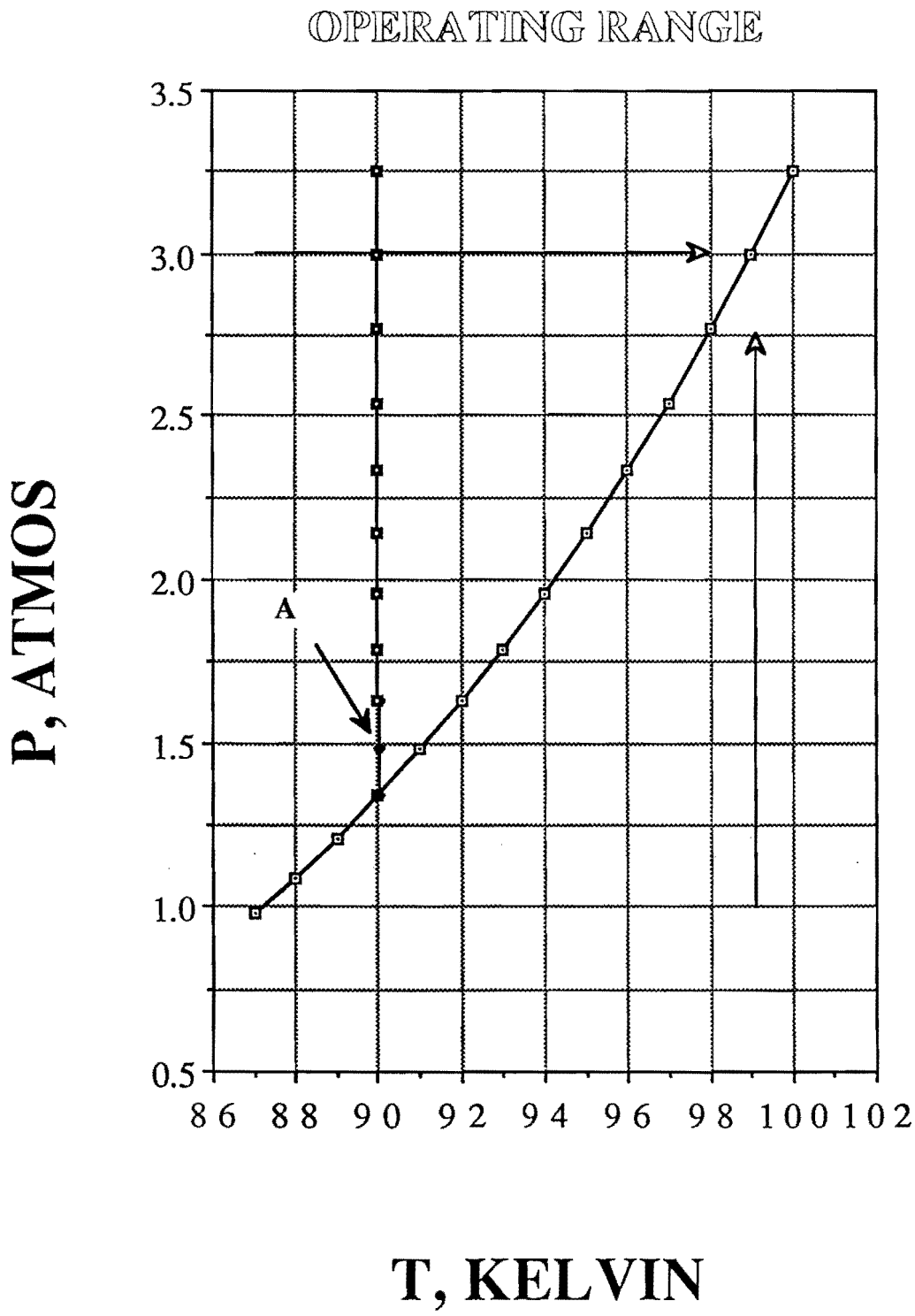
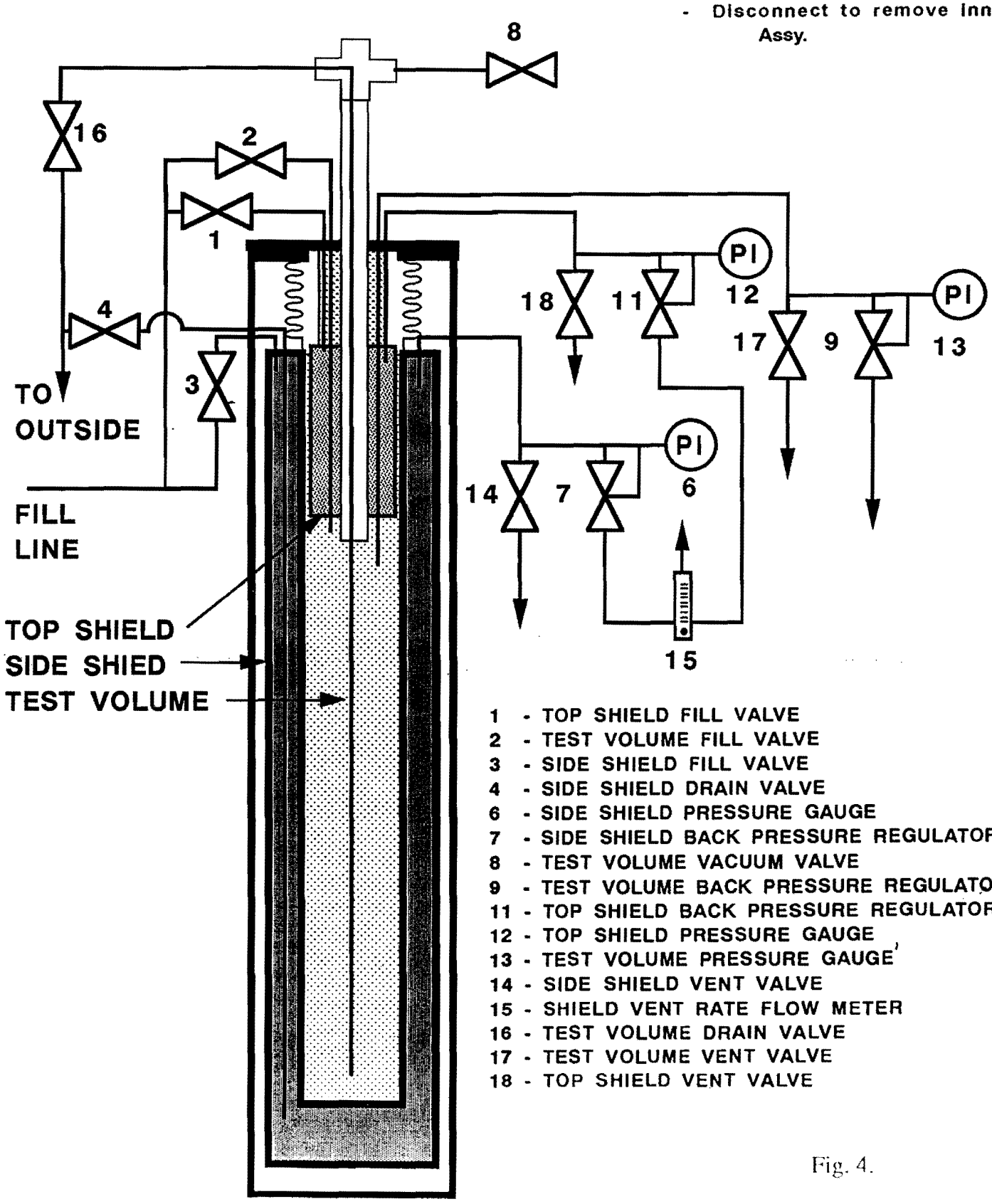

OPERATING RANGE
3.5
3.0
2.5
2.0
1.5
1.0
0.5
P, ATMOS
A
A
86 88 90 92 94 96 98 100 102
T, KELVIN

Fig. 3.

WARNING - Before Draining Vessel Make Sure that End of Drain Line is Placed Outside

- TOP SHIELD SYSTEM
- SIDE SHIELD SYSTEM
- TEST VOLUME SYSTEM

- Connect to Fill/drain; Disconnect to operate.
- Close while operating.
- Disconnect to remove Inner Assy.



1 - TOP SHIELD FILL VALVE
2 - TEST VOLUME FILL VALVE
3 - SIDE SHIELD FILL VALVE
4 - SIDE SHIELD DRAIN VALVE
6 - SIDE SHIELD PRESSURE GAUGE
7 - SIDE SHIELD BACK PRESSURE REGULATOR
8 - TEST VOLUME VACUUM VALVE
9 - TEST VOLUME BACK PRESSURE REGULATOR
11 - TOP SHIELD BACK PRESSURE REGULATOR
12 - TOP SHIELD PRESSURE GAUGE
13 - TEST VOLUME PRESSURE GAUGE
14 - SIDE SHIELD VENT VALVE
15 - SHIELD VENT RATE FLOW METER
16 - TEST VOLUME DRAIN VALVE
17 - TEST VOLUME VENT VALVE
18 - TOP SHIELD VENT VALVE

Fig. 4.

Preliminary Results

Signal, Background

The experiment requires very high gain audio microphone equipment to clearly distinguish the sound of bubble generation. The acoustic noise isolation of the cryostat was overlooked in the original design and the sounds of compressors in the building, passing trucks, people walking by and nearby conversation were readily picked up by the Piezo disk microphones in the cryostat liquid. Large background signals were being counted as more than one bubble and some of the small signals were not counted at all. It was found to be necessary to acoustically isolate the cryostat from the building floor and the service stand to which it was bolted. The cryostat was mounted on a large rubber vacuum cork and laterally stabilized by Tygon tubing tension members tied to a set of support poles secured to the service stand. As the microphone sensitivity was increased the building compressor and nearby welding operations became dominant sources of noise, but these backgrounds can easily be cut from the recorded data because they are sporadic and easily identified.

An audio system with a mixer, amplifier, difference amplifier, and equalizer is used to maximize signal -to-noise performance and provide one TTL pulse per bubble. The mixer output drives monitor headphones, and through auxiliary outputs, the Data Acquisition and Control system, a chart recorder, and an oscilloscope, see fig. 5. The mixer subtracts background noise with the use of a control microphone. The headphones are used to distinguish the bubbles from background noise and the system is tuned to optimize the signal-to-noise ratio. The system can hear, and had to be sound isolated from, the sound of the drops from the cryostat condenser striking the liquid surface. The TTL Logic provides the uniform pulses required by the counter of the DAC system. The storage oscilloscope displays aid the headphone tuning of the equipment. The experiment data is taken at night, when most machines are off and the building is empty, to further enhance the quality of data .

Sample Behavior and Preparation

Insulating materials submerged in a pool of cryogen exhibit spurious boiling behavior that persists for long time. This effect was found to be the perfect minute bubble generator to test and tune the measurement system. The degree of boiling, or the number of bubbles per unit time, observed is a strong function of the surface conditions of the material, see fig. 6 [6]. A material with the rougher surface finish will form more bubbles. That fact was used to advantage to develop the sensitivity of the measurement system; each gain in sensitivity was tested with more highly polished

Layout of Experimental Setup

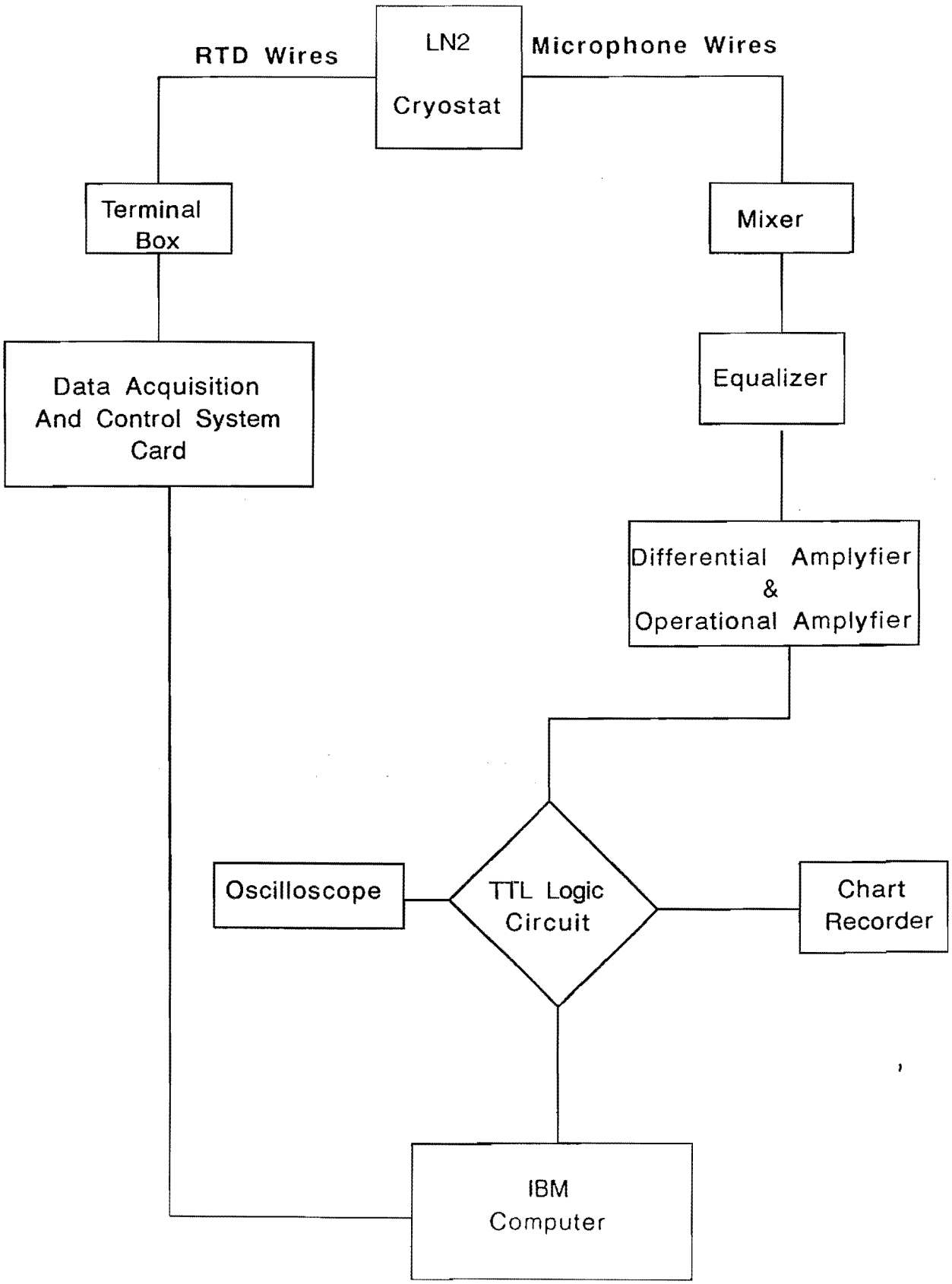
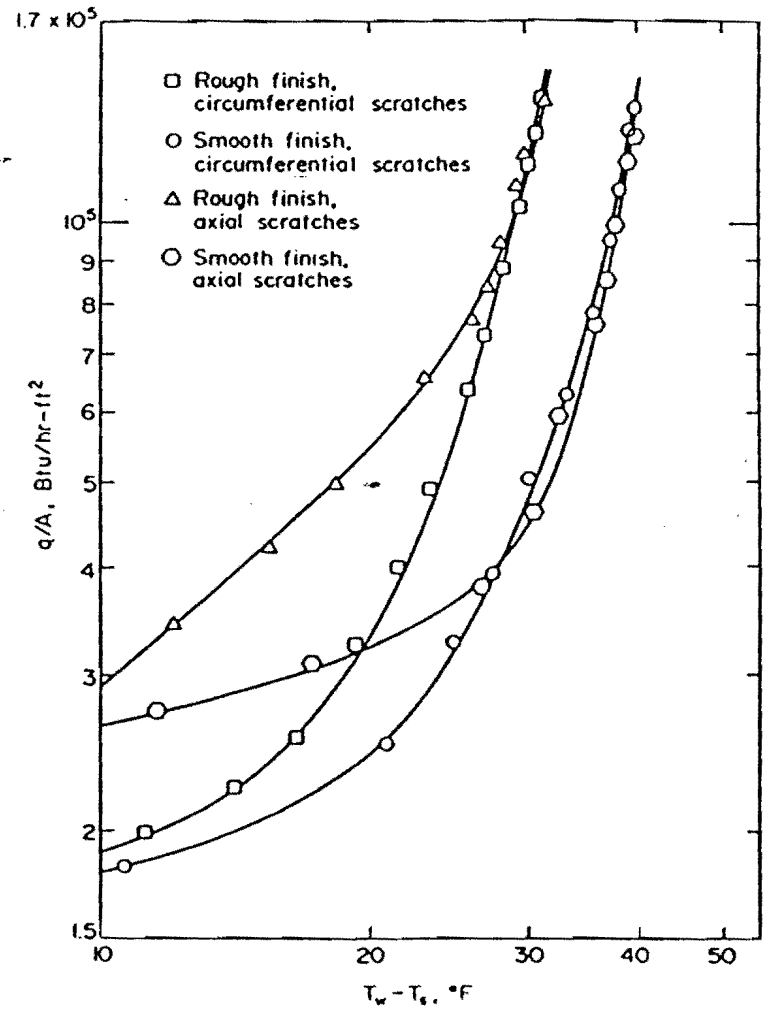


Fig. 5.



Influence of surface finish on pool boiling water from the outside of a horizontal tube

Fig. 6.

Sample Behavior and Preparation (cont'd)

samples producing fewer and smaller bubbles.

An unheated 1.5"X1.5" piece of G10 (fiber reinforced epoxy laminate) was used as the sample material. Special care was taken with the more advanced samples to keep their surfaces as smooth as possible after machine cutting. A Piezo disc microphone is spring loaded to one side of the sample, and an RTD placed nearby. A control microphone was symmetrically placed in the cryostat at the same sample depth, but isolated by steel wool to insulate it from the sample bubble audio signals. The carefully milled ends of G10 finally gave way to samples with their edges carefully painted with nail polish to further reduce the spurious boiling.

Preliminary, but carefully recorded, data taken over days indicates the spurious boiling of the G10 samples slowly decreases in time with a time constant of about a day in one test.

Conclusions

This experiment demonstrated:

1. The sensitivity of the electronic system. Experiments were made with and without a bubble generator Data comparison allowed systematic background noise reduction and electronic threashold adjustments. Orders of magnitude signal-to-noise ratio gains have been made.

2. The surface conditions effect, in a preliminary way, on the number of bubbles generated. The results support the expected qualitative performance of a range of insulator surface finishes.

3. Spurious bubbles frequency decreses as a function of time. The data collected seems to agree, but the conclusion should considered preliminary and the experiment repeated to carefully test the conclusion. Care should be taken to assure the volume level of the top shield and the working volume are not factors.

4. Spurious bubbles rates rapidly decrease with the sample depth in the liquid.

5. A controlled environment can be designed that approximates a constant thermal and acoustic conditions. There are questions of cooling volume fill time constants (see (3) above) to be measured and addressed.

Acknowledgements

The author wishes to acknowledge the contributions of co-investigator Mr. Robert Krasa in setting up the experiment, Mr. Jim A. Hoover as a reference for the sensing method used, and Dan Markley and John Urbin for their general support of project.

References

1. J. A. Hoover, Fermilab. Private Communications, 1989

2. H. J. Ivey, " Relationships Between Bubble Frequency, Departure Diameter and Rise Velocity in Nucleate Boiling". International Journal of Heat Transfer, 1967.

3. R. Krasa, "Operating Procedures of LAr Cryostat". Fermi National Accelerator Laboratory, Engineering Note, 1989.

4. T. Peterson, "Depth in Liquid Argon Versus Maximum Convective Heat Flux". Fermilab. Private Communications, 1988.

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6. W. M. Rohsenow, "Handbook of Heat Transfer". McGraw Hill, Inc. 1973.

Appendix 1

Measuring System, Operating Procedures

1. Turn on The computer. The Strawberry Tree Data Acquisition and Control System will automatically start running and the Analog and Digital inputs will be displayed.

2. Press "Esc" to go to the "Display" menu. Select data to be displayed in the Display menu.

3. Press "C" to go to "Setup" menu. In the "setup" menu select data to be setup, change the parameters and return to the menu. The New setup must be saved by pressing "15".

The "Counter Time Interval " setup is found under menu # 16. The time interval must be set up every time the program is booted up.

4. Press "X" to exit from the Data Acquisition and Control Program. You will now enter the "Basic Mode". To go back to the program type "Run "Astart"". To Exit to Dos type "System".

5. Return from DOS to the main program by typing "Basica Astart".

Note: The "Counter" program is added between lines 201 and 2000 in the "adisplay.bas" program. This segment is called by line 15061 , "Go to 201", of the same program. The "time interval Setup " program is added in lines 34000-35000 in the "asetup.bas" program (please refer to the figures on the following pages).

ANALOG INPUTS - DISPLAY MODE

AUG 18 1989 04:30:01 PM

------ Input Name ------	Value	Units
CHAMBER 1A	79.25	Degrees K
CHAMBER 1B	79.35	Degrees K
CHAMBER 2A	79.27	Degrees K
CHAMBER 2B	79.37	Degrees K
LEVEL PROBE	255.392600	Milliamps
TOP CARRIER	79.32	Degrees K
BOTTOM CARRIER	79.31	Degrees K
BOTTOM OF TOP SHIELD	79.17	Degrees K

Reading pulse input

Frequency (Hz) = 6.113433
Count input = 184
Time interval (sec) = 30

Press a menu key or 'Esc' for menu

MAIN MENU - SETUP MODE

```
 1 Parameters setup
 2 Analog input units and ranges setup
 3 Analog input scale factors setup
 4 Maximum / minimum / average setup
 5 Analog input alarms setup
 6 Clock setup
 7 Digital I/O setup
 8 Analog control setup
 9 Digital control setup
10 Analog output setup
11 Graphing setup
12 Picture display setup
13 Data log and reset setup
14 Calibrate
15 Save or load setup on disk
16 Customizeable by programmer
17 Normal display mode - exit setup mode
18 Fast read mode - exit setup mode
19 Exit program - erase setup
Type selection, press ↵
```

OPTIONS: MOVE CURSOR(,End) DELETE(←,Del) ERASE LINE(Home) EXIT(Esc) HELP(?)

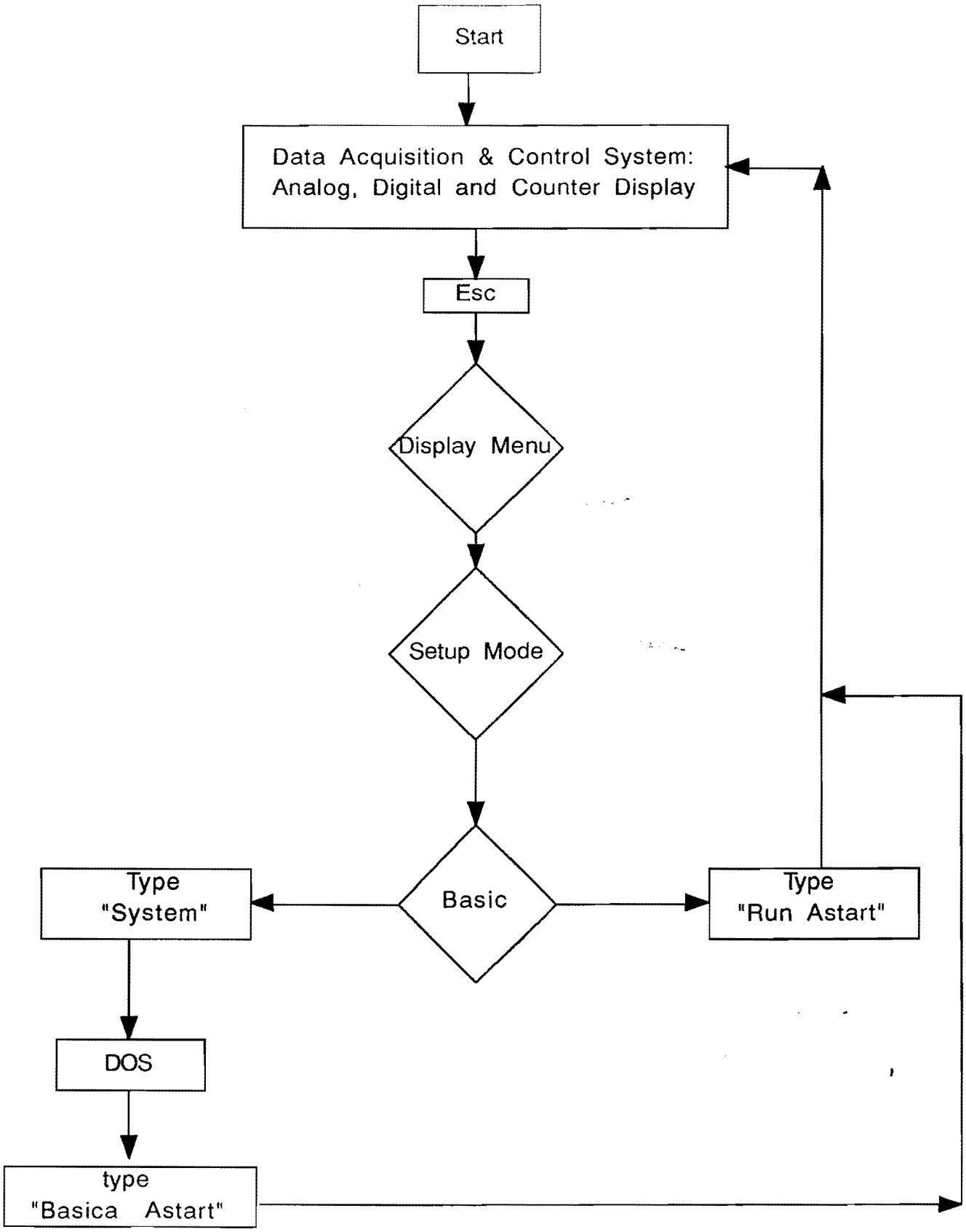
MAIN MENU - DISPLAY MODE

```
 1 Analog inputs display
 2 Maximum / minimum of analog inputs display
 3 Average of analog inputs display
 4 Difference of analog inputs display
 5 Analog alarms display
 6 Digital I/O display
 7 Graphing display
 8 Picture display
 9 No display (fast cycle)

 A Audible alarm signal On/Off
 C Go to setup mode
 D Data log on disk or printer
 G Graphing setup
 O Switch digital outputs
 R Reset maximum / minimum / average / control time lists
 Z Customizeable by programmer
 X Exit program - erase setup

Type selection, press ↵
```

OPTIONS: MOVE CURSOR(,End) DELETE(←,Del) ERASE LINE(Home) EXIT(Esc) HELP(?)


Start
Data Acquisition & Control System:
Analog, Digital and Counter Display
Esc
Display Menu
Setup Mode
Basic
Type
"System"
Type
"Run Astart"
DOS
type
"Basica Astart"