ICARUS I: AN OPTIMIZED, REAL TIME DETECTOR OF SOLAR NEUTRINOS

by the

ICARUS COLLABORATION
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FOREWORD

The present document is an update of the – by now two years old – original ICARUS proposal. During this time an intense activity of Research and Development has put on solid grounds the technology of the ultra-pure Argon and of the non-destructive read-out of the events. Energy and spatial resolutions of the Liquid Argon detector have been explored and found to be exceedingly good, when compared to other devices operating in the field. Therefore the basic assumptions of the original ICARUS proposal now rest on a firm experimental basis and it is possible to delineate precisely the engineering aspects and the deployment of the detector in the Gran Sasso Laboratory, having in mind direct physics objectives.

The ICARUS research program involves the systematic study of the large variety of different physical phenomena which are made possible by the remarkably good energy and spatial resolutions of the liquid Argon Image Chamber concept. These phenomena cover many orders of magnitude in the energy deposits inside the detector, from the few MeV of the solar neutrino interactions, the ≈ 1 GeV of the proton decay, up to the very high energies of cosmic neutrino interactions and muon bundles. *It is by now clear to us that such a complex and ambitious program cannot be realized with a single, universal detector which is simultaneously optimized for all processes.* For instance, the solar neutrinos and the other low energy (= MeV) events require the highest spatial resolution and an optimal rejection of backgrounds due to natural radioactivity, whilst the event rate is relatively high. Instead, proton decay is completely insensitive to radioactive contaminants, but it demands the largest mass even if at the expense of a relatively coarser spatial resolution.

We have therefore maintained milestones and objectives of the original ICARUS proposal, except that now we propose two separate and successive steps, each one with more specialized goals. The first step called **ICARUS I** is designed to operate in the few MeV energy depositions with the highest spatial resolution (± 1 mm) and the lowest background. It consists of a relatively small (= 200 tons), but ultra sensitive Argon Image Chamber with the highest spatial resolution, built up of carefully selected components of low radioactivity and shielded against neutrons from rocks. The minimum energy deposition to trigger an event is ≈ 3 MeV and the lowest energy deposition which can be meaningfully sensed above the electronic noise after trigger is as low as 25 keV in a volume of few m³.

The second phase of the program, **ICARUS II** will involve the construction and operation of a much larger volume of Argon, (several thousand tons), optimized to study (1) proton decay with very high invariant mass resolution, and (2) neutrino interactions coming from cosmic rays or from space and with energy depositions above
the radioactive noise. In this second device, a slightly worse spatial resolution is accepted in exchange for a much larger detector volume. Less pure and cheaper components can be used for the construction. In order to evaluate the backgrounds for proton decay events and the reconstruction criteria to study neutrino oscillations across the earth's diameter, ICARUS II program must be complemented with a number of neutrino events produced by a neutrino beam of an accelerator. In order to collect this important piece of information, ICARUS I will then be eventually moved near an accelerator beam (CERN).

The present report concentrates on the first phase of deployment of the program. The feasibility of observing low energy electrons in connection with the solar neutrino events are studied both experimentally and with Monte Carlo simulations. Background contributions from a variety of sources are considered. We conclude that a clean signal is recordable, at least in the neutrino-electron scattering channel which has the most spectacular signatures, at the rate of about 100 events/year.

The most relevant sources of background are radioactive contaminants in the materials used for the construction of the Dewar and inside the liquid Argon. Although in the present document most of the radioactive backgrounds have been estimated with calculations, it is imperative to assess the actual signals directly in the underground laboratory. To this effect, we plan to set-up a 2000 liters liquid Argon detector with a dewar already in hand in order to measure the low energy spectrum at the Gran Sasso. These measurements will dictate the correct shielding geometry and the requirements of residual radioactivity of the Argon for the final detector. We are presently testing at CERN a full drift length of 1.50 meters at a drift electric field of 1 kV/cm. Once such tests are successful, we believe that we shall be finally ready to initiate the actual construction of the full scale ICARUS I.

In parallel with the construction of the detector we would like to investigate further both experimentally and with Monte Carlo calculations a number of different issues which must be understood before detecting solar neutrino events and in order to analyze neutrino interactions due to cosmic rays. These are: (i) the effects of small amounts of radioactive contaminants inside the Argon. Their possible presence being identified, appropriate purification schemes must be developed; (ii) the effects of external background radiation, like neutrons from the rocks, photons from the walls of the dewar etc.; (iii) the trigger problem; (iv) the overall energy resolution for complex events especially at the few MeV level; (v) the angular resolution for low energy electrons which can be attained in practice with large length drift gaps; (vi) other possible backgrounds of unsuspected nature.
ISSUES OF STRATEGY

1.— Introduction.

1.1.— General considerations. The ICARUS program foresees the ultimate realization of a multi-kton Argon detector with an analyzing magnetic field. Also the possibility of replacing Argon partially or totally with Methane has been envisaged. As pointed out, such a complex and ambitious program cannot be realized in one step, since it involves the introduction on a large scale of a number of different and highly innovative technologies, which have, so to say to "grow" in scale to the requirements of the experiment.

We have therefore subdivided the original ICARUS program in a series of steps, or phases, with specific milestones and objectives, the final ones being those of the original ICARUS proposal [1.1]. The present report concentrates on the first of such phases of deployment of the ICARUS program, which consists of the construction and operation of a small and mobile ICARUS unit, of a mass of approximately 200 tons dedicated to the solar neutrino puzzle. The goals of this phase are therefore primarily scientific. However ICARUS I is also a necessary intermediate step toward ICARUS II and several technical points cannot be neglected:

i) the verification on an adequate scale of the technologies of purification and of the preservation of the cleanliness of the Argon

ii) the basic technologies in the cryogenics, namely the dewar, the read-out electrodes, the signal and high voltage feed through etc.

iii) the organization of the readout including the operation of a number of amplifiers at low temperature and sometimes even at very high voltages

iv) the credibility of repair schemes based on remotely operated "robots" to disconnect and replace damaged amplifiers etc.

v) the basic safety features of operating liquid Argon in large volumes inside the Gran Sasso laboratory C.

In addition, in order to evaluate the backgrounds for proton decay events and the reconstruction criteria to study neutrino oscillations across the earth's diameter it is important to construct a device capable of collecting a number of neutrino events produced in a neutrino beam near an accelerator in the energy range of the cosmic ray events. The accelerator test has been crucial in the past for the proton decay experiment NUSEX and it is even more crucial in our case if one takes into account the increased ultimate sensitivity goals of the ICARUS program. The identification criteria for \(\tau\)-neutrino events, for which neutrino oscillation data are of considerable interest must be perfected. Since ICARUS I is essentially mobile, we plan to move it eventually near an
accelerator. Finally high energy muon tracks traversing the whole volume will be used to study:

i) delta-ray production in order to detect the direction of travel of the track
ii) the ultimate curvature error due to reconstruction and distortion errors etc., which are crucial in the choice and intensity of the magnetic field for the final detector.

All these considerations are relevant in the choice of the general dimensions and of the design of the dewar for ICARUS I. More specifically:

i) the drift gaps and general geometry of the electrodes must follow very closely those of the final ICARUS. Likewise the basic technical choices on the construction of the dewar, such as materials, insulations etc have to be as close as possible to the final ones

ii) the size of the dewar should be sufficiently small to permit its construction quickly outside the Gran Sasso laboratory and to transport it both to Gran Sasso and eventually to a neutrino beam near an accelerator (CERN)

iii) the volume should be sufficiently large to permit reaching the sensitivity required to collect a small but significant number of solar neutrino events, or at least to assess their potential backgrounds with sufficient statistics and at the appropriate level of sensitivity and to try out methods to remove them

iv) the purifiers and the readout units should be the first units of a modular structure employed for the final detector

v) the software must be upgraded easily to the final device.

1.2.— Physics expectations. As will be discussed in detail the main novelty of this detector is in its excellent spatial resolution, corresponding to a bubble volume of about 3–4 mm$^3$ and a typical calorimetric energy resolution of about 3% for electrons and $\gamma$-rays in the MeV range. Since the detector is a very large volume totally active, it is expected that low energy gamma rays produced well inside the fiducial volume will deliver all their energy in a number of subsequent scatterings. Monte Carlo calculations show that the resultant narrow total energy peak will be only a few percent wide at a few MeV and therefore ICARUS is also an excellent total absorption $\gamma$-ray spectrometer.

From a detector of the size of ICARUS I – which is after all of the order of the detector NUSEX but with a considerably better resolution – we should expect some interesting physics results. They can broadly be classified in two main topics:

i) observation of solar neutrino events in real time with determination of their incident direction and energy spectrum
ii) observation of a significant sample of atmospheric neutrino interactions and of their up/down asymmetry by observing the direction of delta-electrons produced along the track of the muon

These topics are reviewed shortly, keeping however in mind that a more complete discussion can be found in the original ICARUS proposal[1.1] and in the paper by Bahcall et al.[1.2].

The Standard Solar Model (SSM) predicts that 98.5% of the solar energy is generated by a series of nuclear reactions called the proton-proton chain (the remaining 1.5% comes from the CNO cycle)[1.3]. Weakly-interacting neutrinos are emitted by these nuclear reactions and could be used to probe the regions of the Sun completely inaccessible by electromagnetic observation. Two experiments have been carried out which were sufficiently sensitive to measure the predicted flux; their results differ from the expectations of the SSM, although the details have fluctuated. This discrepancy between experiment and theory constitutes the Solar Neutrino Problem (SNP), which is considered one of the fundamental problems in modern physics.

The first experiment was the radio–chemical experiment of Davis et al.[1.4] which has been operating since 1968. The detector, based upon the reaction $^{37}\text{Cl}(\nu,e^-) ^{37}\text{Ar}$, is primarily sensitive to the neutrinos from the decay of $^8\text{B}$ in the Sun. The predicted capture rate for this detector is $7.9(1\pm0.33)_{^{(1)}}$ SNU ($1\text{SNU} = 10^{-36}$ captures/atom/sec), where 6.1 SNU are expected from $^8\text{B}$ neutrinos, and the next largest contribution is from $^7\text{Be}$ (1.1 SNU). The observed event rate is $2.1\pm0.3$ SNU. Assuming this event rate is entirely due to interactions of $^8\text{B}$ neutrinos, this puts a severe limit on the $^8\text{B}$ flux of[1.5]

$$\Phi(8\text{B}) \leq 2 \times 10^6 \text{cm}^{-2}\text{s}^{-1},$$

which is about a factor of 3 times smaller than the SSM prediction ($5.8 \times 10^6 \text{cm}^{-2}\text{s}^{-1})^{(2)}$

Recently the Kamiokande II light water Cerenkov detector, built initially to search for proton decay, has been improved in order to make possible the detection of the high energy tail of the solar neutrino spectrum. They measure the flux of $^8\text{B}$ neutrinos to be

$$\Phi(8\text{B}) = (2.61\pm0.78) \times 10^6 \text{cm}^{-2}\text{s}^{-1},$$

which is 0.45 of the SSM ($\pm 30\%$ error) [1.7].

The SNP has prompted a variety of solutions. One possibility is that something happens to the neutrinos on their way to the earth. The suggestion of neutrino decay[1.8] was ruled out by supernova SN1987A[1.9]. Another suggestion is $\nu$-spin precession due to an anomalous magnetic moment or electric dipole moment[1.10]. In

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(1) This corresponds to a 3 s error

(2) Very recently R. Davis presented a new value of the $^{37}\text{Ar}$ production rate averaged on the measurements done between January 1987 and May 1988 after some modifications of the detector. The new result gives $5 \pm 1$ SNU[1.6], still implying a depletion of observed $^8\text{B}$ neutrinos with respect to the SSM. A possible time dependance of the $^8\text{B}$ flux can be most reliably investigated with real time neutrino experiment.
addition there is the possibility of neutrino oscillations[1.11], and in particular, enhanced oscillations due to the propagation of the neutrinos through matter (MSW effect)[1.12]. Other solutions are those that modify the production of neutrinos from the $^8$B production which is deep in the solar core and very sensitive to the central temperature of the sun. In particular, the existence of new weakly interacting massive particles (WIMPs) has been suggested.

It is clear that new experiments are needed that are able to detect solar neutrinos in real time and to measure their energies and fluxes. These experiments will complement those designed to measure the dominant $pp \Rightarrow H^2 + e^+ + \nu$ process. A liquid argon detector is especially suited for resolving this problem. The high density of argon and the excellent spatial resolution of the proposed LAr image chamber make this type of detector particularly good for the direct observation of solar neutrinos from $^8$B decay.

The important feature of the LAr detector is due to the fact that the higher energy neutrinos from the $^8$B decay can produce both inverse $\beta$—decay absorption ($\nu_e + ^{40}\text{Ar} \Rightarrow ^{40}\text{K}^* + e^-$) and neutrino-electron scattering in the liquid Argon detector[1.2]. The measurement of both the $\nu$-Ar absorption events (CC events) and the $\nu$-e elastic scattering (CC+NC events), which can occur both with $\nu_e$ and possibly with converted neutrinos ($\nu_\mu, \nu_\tau$, but with different cross-sections), allows the complete determination of the solar neutrino flux, energy spectrum and flavor composition. This will provide tests of the SSM, of neutrino oscillations and of the MSW oscillation enhancement mechanism. The $\nu_e$—Ar absorption reaction will be dominated by the superallowed transition to the isotopic analogue state at 4.38 MeV above the ground state of $^{40}\text{K}$ (Fig.1.1). The transition to the ground state is via the emission of gamma rays of characteristic energy (three on average).

![Figure 1.1-- The first excited levels of $^{40}\text{K}$](image)
The absorption events, which are almost isotropically distributed, can be distinguished from background events because the gamma rays emitted by the decay of the 4.38 MeV excited state of $^{40}$K will be associated in space and time with the recoil electron and the probability of accidental $\gamma$–e correlations of the required energies is negligible. The solid curve in Fig. 1.2a shows the energy spectrum of recoil electrons resulting from absorption of neutrinos by $^{40}$Ar evaluated under the hypothesis of the SSM.

In the case of the elastic scattering reaction the electron will be emitted with a small angular deflection from the direction of the $\nu$ (≤16° for a 5 MeV threshold on the recoil electron energy). The solid curve in Fig. 1.2b shows the calculated energy of recoil electrons from $\nu_e$–e$^-$ scattering assuming the SSM. The observation of the electron direction with respect to the expected direction of the neutrino is a powerful tool in order to discriminate events from the background. It is then of great importance to know the resolution that can be obtained in the determination of the angle. Using Monte Carlo simulations of electrons in the chamber we have evaluated that for electrons of energy larger than 5 MeV, more than 80% of the events are reconstructed within a cone of 20° aperture.

![Graph](image)

**Figure 1.2.** The calculated energy spectrum (from SSM) of the recoil electrons from $\nu_e$-Argon absorption(a) and from $\nu_e$-electron scattering(b). The solid curves are calculated assuming the SSM while the dashed curves assume resonant neutrino oscillations (MSW effect) with the parameters $\Delta m^2 = 1 \times 10^{-4}$ eV$^2$ and $\sin^2 2\theta = 1 \times 10^{-2}$.

The fiducial volume of the ICARUS I detector will contain about 200 tons (5.2x10$^{31}$ target electrons) of liquid Argon. Assuming a total flux of 5.8x10$^6$ cm$^{-2}$s$^{-1}$ as predicted by the SSM, our detector will observe about 160 $\nu_e$-Ar absorption events
per year resulting in recoil electrons above 5 MeV and about 180 forward-peaked $\nu_e$-e scattering events with $E_{\text{thresh}} = 5$ MeV. Fig. 1.3a shows the rate as a function of the minimum energy of the recoil electrons associated with neutrino absorption to the isotopic analogue state. In Fig. 1.3b is shown the corresponding rate for the neutrino–electron scattering.

![Graphs showing $\nu_e$-Ar absorption and $\nu_e$-e scattering rates](image)

**Figure 1.3**—The event rate as a function of the minimum energy of the recoil electrons for a fiducial mass of 200 tons, a) $\nu_e$ - Ar absorption, b) $\nu_e$ - e scattering.

The electron recoil energy distribution for elastic scattering and absorption events and their fluxes will provide direct information on $^8$B solar neutrinos:

i) recoil electron energy spectra as expected by the Standard Solar Model for both scattering and absorption but with event rates for both processes lowered in the same proportion could be explained by a suppression of the $^8$B solar neutrino flux due to non standard solar behavior;

ii) experimental value for the ratio $R = \frac{N(\nu + e^- \rightarrow \nu + e^-)}{N(\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*)}$ greater than $1.1 \pm 0.10$ may indicate that there are neutrinos converted through oscillations.

Fig. 1.4 displays the ratio

$$R = \frac{N(\nu_e + e^- \rightarrow \nu_e + e^-) + N(\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-) \cdot \sigma(\nu_{\mu}e^- \rightarrow \nu_{\mu}e^-)}{N(\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*) \cdot \sigma(\nu_e e^- \rightarrow \nu_e e^-)}$$

plotted against the fraction of solar $\nu_e$s converted by oscillation phenomena to $\mu$ or $\tau$ neutrinos, calculated for a threshold on the recoil electron energy of 5 MeV.
iii) dramatically different spectra and fluxes for the recoil electrons could be explained by the hypothesis of resonant neutrino oscillation (MSW effect)[1.12]. The dashed curves in Figs. 1.2a (absorption) and 2b (ν_e-ν_scattering) show the expected energy spectra of the recoil electrons in the presence of MSW oscillations with the parameters Δm^2 = 1×10^{-4} eV^2 and sin^22θ = 1×10^{-2}.

Comparison of the measured recoil electrons spectra and rates for absorption (CC events) and ν-e scattering (CC +NC events) will allow the determination of both the Δm^2 and the mixing angle responsible for the ν oscillations and the MSW effect.

We believe that if appropriate care is taken in using low radioactivity components for the construction of the dewar and if appropriate shielding is used to absorb neutron backgrounds from the neighboring rocks, the signal — at least from the electron scattering events — should be essentially clean and therefore first evidence for the process ν_e + e^- → ν_e + e^- could be given in a live time of the order of one year.

The Kamiokande experiment has reported a rather puzzling result [1.13] in which, whilst the electron-like single prongs are in good agreement with the prediction of a Monte Carlo calculation based on atmospheric neutrino interactions in the detector, the muon-like single prong events are 59±7 % of the predicted number. A possible explanation could be neutrino oscillations occurring in the long pathway from the production to the detector[1.14]. Clearly the event topology in the liquid Argon
chamber should be much cleaner than the observation of the Cerenkov rings used by the Kamiokande group and therefore such an interesting question should be clarified. With their cuts, which are rather severe, they have recorded about 0.1 event/ton/year. In our detector we should expect about 50 events in one year of exposure permitting a statistical error of ± 10 % in two years.

Finally exotic low energy processes could be observed inside the liquid Argon volume. One of them is the neutrino-less double beta decay process, which is being searched for in a number of isotopes of Argon, Xenon and Krypton. It should be stressed that both Xenon and Krypton are present in small amounts in our Argon, since they are not separated during the purification phase starting from air. We estimate that the fiducial volume of the ICARUS I will contain $2.8 \times 10^{25}$ atoms of Xenon, but this amount could be increased by dissolving in the liquid additional gas. Linearity of the effect with respect to the gas dissolved will provide excellent proof of the origin of the effect. For instance Alessandrello et al. [1.15] have reported a limit of $> 1.7 \times 10^{21}$ years for the neutrino-less double beta decay of $^{136}$Xe $\rightarrow^{136}$Cs which has a transition energy of 2470 KeV. At this rate and taking into account that natural Xenon contains 8.86 % of $^{136}$Xe, we would expect in our fiducial volume as many as 1500 events/year in a narrow energy peak. However in order to be interesting, our ultimate sensitivity has to be significantly better than the one quoted above, since for the transition $^{76}$Ge – which has the somewhat smaller energy release of 2040 KeV – the limit given by the Santa Barbara group [1.16] is now already $> 6 \times 10^{23}$ years.

Another interesting process is the excitation of nuclear levels by solar neutrinos interacting with Argon via neutral currents, which are neutrino flavor independent. Hence, differently from all previously discussed methods to study solar neutrinos, these events will determine the true neutrino flux. A process of this type is the deuteron breakup by $\nu$ – capture [1.17].

Raghavan et al. [1.18] have considered the reaction: $^{40}$Ar + $\nu$ $\rightarrow^{40}$Ar + $\nu'$ + $\gamma$

According to shell-model calculations, the main M1 matrix element strength corresponds to the 10.42 MeV level of $^{40}$Ar with some 10% for each of the states at 6.1, 7.8 and 9.6 MeV. The event rates per kiloton per year are estimated to be 11, 4 and 5 for the levels at 6.1, 7.8 and 10.42 MeV. This last level is $n$-unstable and yields a 6.1 MeV $\gamma$–ray by $^{40}$Ar ($n,\gamma$). While the rates are generally too small for a practical measurement, the possibility of (1) observing such events with ICARUS II and (2) the possibility of an anomalous signal can be investigated. The signature will be a narrow total absorption line corresponding to the energy of the levels of $^{40}$Ar. Clearly ICARUS I will provide precious information on the feasibility of such experiments.
1.3. — References


L. Wolfenstein, Phys. Rev. D20 (1979) 2634


MODEL STUDIES OF A ICARUS TYPE DETECTOR

2.— Studies on Argon purification

2.1.— Introduction. A fundamental requirement of our project is that electrons produced by the ionizing particles can travel unperturbed from the point of production to the collecting grids. To this effect impurities in the liquid must be reduced to extraordinarily low levels. In order to ensure the stable performance of the device the purity must be preserved in the dewar for the longest period of time possible. A considerable amount of work has been performed in order to ensure that the required level of purity can be reached and is preserved over extended periods(3). The major impurities in liquid Argon which are of importance for our project are electron attaching compounds such as oxygen and fluorinated or chlorinated compounds (freons). The electron attachment to an impurity S can be described by the following reaction

\[ e^- + S \rightarrow S^- k_s \]

where the rate constant \( k_s \) is given by

\[ k_s = \int v \sigma(v) \cdot f(v) \, dv \]

or, if the cross-section is expressed as a function of energy then

\[ k_s = \int \sigma(E) \cdot f(E) \, dE \]

where \( f(E) \) is the well known Maxwell distribution function.

Under the assumption that the number of electrons \( N_e \) produced by the passage of an ionizing particle is smaller than the impurity concentration \( N_s \) in moles liter \(^{-1}\) the number of electrons lost per time interval is

\[ \frac{dN_e}{dt} = - k_s N_s N_e \]

For hermetically sealed containers which have been properly cleaned before filling with liquid, \( N_s \) remains constant and we obtain

\[ N_e = N_{e0} e^{-t/\tau} \]

where \( \tau \) is the electron lifetime and \( N_{e0} \) is the number of electrons at \( t = 0 \). The lifetime is related to the rate constant and the impurity concentration by

---

(3) A by-product of the extremely high level of purity required for the liquid is that the radioactive contaminants and which could simulate low energy events—for instance due to the solar neutrinos—are also kept at a very low level.
\[ \tau = \frac{1}{k_s N_s} \]

The rate constant is a function of the applied electric field as is shown in Fig. 2.1 for $O_2$, $N_2O$ and $SF_6$[2.1]. For a field of 1 kV/cm the rate constant for reaction with oxygen is $5.5 \times 10^{10}$ liter moles$^{-1}$ s$^{-1}$, for $SF_6$ it is $1.5 \times 10^{14}$ liter moles$^{-1}$ s$^{-1}$ and for $N_2O$ $5.5 \times 10^{11}$ liter moles$^{-1}$ s$^{-1}$.

![Graph](image)

**Figure 2.1.**— The rate constant $k_s$ as a function of the electric field for $O_2$, $N_2O$ and $SF_6$.

Fluorinated and chlorinated hydrocarbons have been investigated in liquid hydrocarbons and extrapolating from the data obtained there to liquid Argon we expect them to react with a high rate constant ( $> 10^{11}$ liter moles$^{-1}$ s$^{-1}$ ) also. The attenuation length $\lambda$ is related to the lifetime by the electron drift velocity $v_d$,

\[ \lambda = v_d \tau \]

An alternative way of expressing this equation is

\[ \lambda = \alpha \frac{E}{\rho} \]

where $E$ is the electric field, $\rho$ is the impurity concentration in ppm and $\alpha$ is the "trapping constant", which for liquid Argon is measured to be $(0.15 \pm 0.03)$ ppm cm$^2$ kV$^{-1}$[2.2]. In Fig. 2.2 is shown the attenuation length as a function of the electron lifetime for a drift field of 1 kV/cm for which $v_d = 2$ mm $\mu$s$^{-1}$. We have demonstrated that it is possible to achieve electron lifetimes in the region of 10 ms, implying an attenuation length of at least 20 meters[2.2].
2.2.— The purification method. A schematic of the purification system used for the lifetime measurements is shown in Fig. 2.3. All metal parts of the system were constructed from stainless steel and were thoroughly cleaned and then baked under vacuum (= $5 \times 10^{-7}$ torr) at 950°C before assembly. The system was evacuated using a turbomolecular pump and a liquid nitrogen cold trap was placed between the pump and the system to prevent back-diffusion of oil from the pump. The whole assembly was baked-out under vacuum at 300°C for 48 hours, the final vacuum achieved on the system was $10^{-7}$ mbar.

The filter consisted of a mixture of molecular sieves 4A and 13X [2.3] plus silica gel and was activated as described in Section 11.2. In the actual measurements of the electron lifetime the Argon purification took place in two stages. The starting material was Argon 60 gas which had an impurity concentration of $\approx 0.1$ ppm of oxygen. The gas was passed through an Oxisorb[2.4] cartridge to remove the oxygen present and a flow meter was used to regulate the speed of the gas flow so as to ensure maximum removal of oxygen. A typical flow rate was 0.35 liters of gas per second. The gas was then liquefied in a clean storage container which was surrounded by a liquid Argon bath. The purpose of this intermediate step was to separate out any fluorinated or chlorinated hydrocarbons that may have been present in the gas bottle from the compressor cycle.

In the second stage the liquid Argon was allowed to boil off and pass through the filter to be liquefied in the chamber. The chamber was also surrounded by a bath of liquid Argon. Open dewars were used for the liquid Argon baths for ease of refilling as the quantities of Argon involved were small.
Figure 2.3.— Schematic of liquid Argon purification system used for the lifetime measurements.
The start of liquefaction in the chamber was indicated by a pressure difference between the filter and the chamber, recorded using the two pressure gauges located as indicated in Fig. 2.3. This pressure difference was kept at 300 mbar during the liquefaction. The end of the liquefaction process was indicated by the equalization of the pressures in the chamber and storage container. The rate of liquefaction into the chamber was \( \approx 1 \) liter of liquid per hour. In both stages the rate of liquefaction was controlled by the extent of the cold surface seen by the gas as well as by the level of the external liquid Argon bath. The rate decreases as the chamber becomes fuller as the incoming gas sees a smaller and smaller cold surface. Hence the rate quoted is an average over the time required to fill the chamber and will be slightly higher at the onset of liquefaction and lower at the end.

2.3. — *Measurements of electron lifetime in liquid Argon.* In order to demonstrate the feasibility of producing ultra-pure liquid Argon we have made measurements of the electron lifetime of the liquid produced by our purification system.

The first measurement of the lifetime was made using a parallel plate ionization chamber with a 5 cm drift space. This yielded a lower limit of the lifetime of 400 \( \mu \text{s} \) at a field of 8 V/cm. More detailed studies were then performed using a gridded ionization chamber with a 15 cm drift space. A schematic of this chamber is shown in Fig. 2.4. The construction was as follows.

The cathode and the anode were made of disks of stainless steel 80 mm in diameter and 3 mm thick. The grid was constructed of a mesh of 50 \( \mu \text{m} \) diameter stainless steel wires with 550 \( \mu \text{m} \) pitch. The cathode-grid distance was 153 mm and the grid-anode distance was 4.5 mm. In order to ensure field uniformity, field-shaping rings were placed at intervals of 9 mm between the cathode and the grid, connected to each other by spacers of insulating material (PTFE). Between each pair of rings was placed a 10 M\( \Omega \) resistor. The resistors had their outer coating of paint removed and their ends had been goldplated to avoid corrosion during their cleaning. The last resistor, placed between the grid and ground, was chosen so that the field between the grid and anode was sufficient to ensure 100% transmission of the electrons through the grid. The grid will be 100% transparent to the drifting electrons if

\[
\frac{E_A}{E_B} > \frac{(1 + x)}{(1 - x)}
\]

where \( E_A \) is the field after the grid, \( E_B \) is the field before the grid and

\[
x = \frac{2\pi r}{y}
\]
Figure 2.4.— Schematic of 15 cm ionization chamber used for the lifetime measurements.
where $r$ is the wire radius and $y$ is the grid pitch [2.5]. With our values for $y$ and $r$ we obtained $E_A > 1.8 E_B$ for 100% transparency. The chamber geometry allowed another 10 MΩ resistor to be used, giving $E_A > 2.6 E_B$. The shielding inefficiency $\sigma$ of the grid is given by

$$\sigma = \frac{y}{2\pi p} \ln \left( \frac{y}{2\pi r} \right)$$

where $p$ is the grid-anode distance. The inefficiency is a function of the chamber geometry only and does not depend on the applied field. The inefficiency of the grid was 4%. It should be noted that the equations above are only exact for a grid of equally spaced parallel wires and hence for a mesh the results are only approximate.

Mounted above and below the main chamber were two parallel plate ionization chambers which served as trigger chambers, providing signals which were put in coincidence to indicate the passage of a cosmic ray muon through the chamber. Each chamber was divided into two 4.5 mm drift gaps by a stainless steel disk of diameter 40 mm. The top plate of the upper gap was a stainless steel disk of the same diameter as the cathode and was grounded. The bottom plate of the lower gap was a grounded cup. This cup also shielded the main chamber from the electric field of the trigger chambers.

The whole assembly was mounted on a DN100 ConFlat [2.6] flange and placed inside a stainless steel container of height 250 mm and diameter 100 mm. The top of the flange contained a single pipe for evacuation and filling of the chamber as well as the four cryogenic feed-throughs for the chamber read-out, trigger chambers and high voltage. The flange was sealed to the container with a copper O-ring and the whole assembly was baked-out under vacuum at 100°C for 24 hours. Typical leak test rates of $2.7 \times 10^{-9}$ mbar liter s$^{-1}$ were achieved.

The passage of a cosmic ray through the chamber leaves a track of uniform ionization in the form of electron-positive ion pairs. The electrons then move under the influence of an applied electric field and pass through the grid and then induce a signal on the anode. The contribution to the current from the positive ions can be neglected as their mobility is orders of magnitude less than the electron mobility.

The effect of a grid is to shield the anode from the drifting electrons so that charge is only induced on the anode once the electrons have crossed the grid. Each electron drifts the same distance between the grid and the anode before collection so the total charge collected $Q_0$ will be $N_{00}$. Note that the transit time $t_d$ is determined by the cathode-grid distance which is long compared to the grid-anode distance. The charge as a function of time $Q(t)$ measured at the anode is determined by the speed $v_d = d/t_d$ with which the electrons arrive at the grid. This is the case because once the electrons have traversed the grid they come into a region of higher field strength and they cross the
much shorter grid-anode gap in a drift time \( t_d \) which is much less than \( t_d \). The charge collected at time \( t \) namely \( Q(t) \) is given by
\[
Q(t) = \int_{0}^{t} \frac{N_0 e}{d} v_d \, dt
\]
\[
= \frac{N_0 e}{t_d} t
\]
The effect of the lifetime is to reduce the current at time \( t \) by a factor of \( e^{-t/\tau} \). Hence the equation now becomes
\[
Q(t) = \int_{0}^{t} \frac{N_0 e}{d} e^{-t/\tau} \frac{d}{d} dt
\]
\[
= \frac{N_0 e}{t_d} \tau \left( 1 - e^{-t/\tau} \right)
\]
This ideal pulse shape is modified by the electronics chain and this has to be taken into account when fitting the pulse to extract the lifetime. Denoting the response of the electronics at time \( t \) by \( R(t-\theta) \) we can write the charge collected at time \( t \) as
\[
Q(t) = \frac{N_0 e}{t_d} \int_{0}^{t} e^{-\theta/\tau} R(t-\theta) \, d\theta
\]
To avoid introducing uncertainties due to calibration of the electronics and the poor theoretical knowledge of the electron yield at low fields in liquid Argon, we have used the ratio between the charge collected at time \( t \) and the charge at \( t_d \), \( Q(t)/Q(t_d) \), as the quantity to be fitted to determine the electron lifetime. The pulses were fitted for the parameter \( \tau \) using the shape described by the following equation
\[
\frac{Q(t)}{Q(t_d)} = \frac{\int_{0}^{t} e^{-\theta/\tau} R(t-\theta) \, d\theta}{\int_{0}^{t_d} e^{-\theta/\tau} R(t_d-\theta) \, d\theta}
\]
This method is most sensitive if the electron lifetime is less than the transit time across the chamber. Fig.2.5 illustrates the difficulty of distinguishing between different lifetimes once \( \tau \) becomes greater than the transit time. The theoretical pulse shapes for \( Q(t)/Q(t_d) \) are shown for seven different lifetimes \((\tau = 1,3,5,7,10,20,\infty \text{ ms})\), demonstrating that it is possible to distinguish between 1 ms and 3 ms but it becomes harder as \( \tau \) increases beyond the drift time of 2.8 ms. At very low fields the transit time
is sufficiently long that acoustic noise (caused mainly by vibrations of the signal cables which were immersed in the liquid Argon bath) becomes a problem which is difficult to eliminate. Noise superimposed on the pulse can distort the shape leading to a lengthening or shortening of the measured lifetime.

![Diagram showing pulse shapes](image)

**Figure 2.5.**—Theoretical pulse shapes for seven values of $\tau$ at $E = 10$ V/cm demonstrating the difficulty in accurately determining $\tau$ if it is longer than the drift time. The curves are (1) $\tau = 1$ ms, (2) $\tau = 3$ ms, (3) $\tau = 5$ ms, (4) $\tau = 7$ ms, (5) $\tau = 10$ ms, (6) $\tau = 20$ ms, (7) $\tau = \infty$.

Data were taken for a number of electric fields ranging from 3 V/cm to 230 V/cm using cosmic ray muons. For the determination of the lifetime we used the pulses taken at low fields as these are the most sensitive to the effects of electron attachment. We used the data at 5 V/cm to determine the lifetime, using the method described above, and we obtain

$$\tau = 9.2^{+3.4}_{-1.8} \text{ ms (13.2 > } \tau > 7.1 \text{ ms at 95% CL).}$$

We then adopt this value for the lifetime and check that it is consistent with the pulses taken at other fields. We find that a lifetime of 9.2 ms gives a good description of the data at all fields up to 15.2 V/cm as can be seen in Fig. 2.6 where we show four pulses taken at different fields together with the curves for $\tau = 9.2$ ms at each field. The liquid was kept in the chamber for 14 weeks with no recirculation system$^{(4)}$ and we observed no noticeable deterioration in the measured lifetime or the pulse height throughout this time, as is demonstrated in Fig. 2.7.

---

$^{(4)}$ For the final detector dewar we have planned a recirculation scheme and therefore the liquid is continuously renovated. The present results and the consideration that the ratio area/volume is more favorable in the final system may suggest that such recirculation scheme is not strictly necessary.
Figure 2.6.— Averaged pulses for a) 5.03 V/cm, b) 7.6 V/cm, c) 9.93 V/cm and d) 10.23 V/cm together with the curves for τ = 9.2 ms.
Figure 2.7.—The measured pulse height as a function of time.

2.4.—References

[2.6] ConFlat is a trade mark of VARIAN, USA.
3. — Studies on the electron image formed in the liquid Argon

3.1. — Methods for readout. The simplest readout of the electron signals consists of collecting the charge with a set of strips with the periodicity (pitch) which is required by the spatial resolution and signal/noise ratio of the readout. A grid must be located immediately before the plane of collection in order to eliminate the effects of induced, image charges. Unfortunately such method is destructive, although it ensures a very precise recording of the charge. In order to record several "views" of the event, it is necessary to add one or more planes of wires oriented in different directions which are sensitive to the induced charge, and hence are non-destructive. Finally the initial timing of the event, the so-called \( t_0 \) has to be recorded by a set of induction wires distributed uniformly over the whole drift volume. These readout methods which have been carefully optimized with computation of the field and simulation of the signals on the computer, have been extensively tested with a test chamber module with an electron drift of 24 cm and operated in a high energy beam.

3.2. — Details of the 24 cm imaging chamber. The chamber has a two dimensional readout, namely one space co-ordinate plus drift time. A section through the chamber is shown in Fig. 3.1. The body of the chamber was constructed from a cathode plate of 100 \( \times \) 100 mm\(^2\) made of stainless steel. The cathode was joined to the wire plane by a series of 24 field-shaping rings also 100 \( \times \) 100 mm\(^2\) of 3 mm thickness separated by 7 mm spacers of insulating material (PTFE). Each ring was connected to the next by a 60 M\( \Omega \) ceramic resistor. The resistors were cleaned with soap and water and had their coat of varnish removed. The final resistor was connected from the screen grid to ground and it was possible to achieve the required field ratio of 1 : 5 before and after the grid by using another 60 M\( \Omega \) resistor. The grid and sense wires were constructed of 100 \( \mu \)m diameter and 50 \( \mu \)m diameter stainless steel wire respectively and were mounted in a MACOR frame which also supported the stainless steel anode. The distance between the sense wires and the anode was 2 mm.

The high voltage was supplied through the bottom of the chamber via a ceramic feed-through as can be seen in Fig. 3.1. The chamber was contained in a stainless steel vessel 388 mm long with DN160 ConFlat flanges on the top and bottom. The top flange contained a single pipe for the evacuation and filling of the chamber and the four 10-pin feed-throughs for the sense-wire readout. Each feed-through read out eight sense-wires. In addition there were three additional feed-throughs, one for the anode HV and readout, one for the screen-grid HV and one for the sense-grid HV.
Figure 3.1.— A cross-section through the 24 cm drift chamber.
Figure 3.2.—A series of ten pulses taken in induction mode at different drift distances for a) 200 V/cm and b) 500 V/cm. The superimposed curves are the best fits to the pulses using the theoretical pulse shape normalised to the maximum pulse height in number of electrons and including the amplifier response.
These feed-throughs could also be used to supply a test-pulse to the grids and the anode. In the field configuration used it was not necessary to apply any voltage to the grids. The total volume of the chamber was 8.6 liters.

The two flanges were sealed with copper O-rings and the whole assembly was baked-out under vacuum for 48 hours at 100°C in order to avoid damage to the ceramic resistors. After this procedure a typical leak test rate was $5 \times 10^{-9}$ mbar liter s$^{-1}$ and the outgassing rate of the chamber was $1 \times 10^{-13}$ mbar liter s$^{-1}$ cm$^{-2}$. Published values for the outgassing of stainless steel (obtained using different cleaning procedures) range from about $5 \times 10^{-12}$ mbar liter s$^{-1}$ cm$^{-2}$ to $10^{-13}$ mbar liter s$^{-1}$ cm$^{-2}$[3.1].

3.3. — Results on track images. Using the data taken with this chamber we have studied the effects of diffusion on the signal and the production of delta-electrons. There were two methods of operating the chamber, "induction mode" with positive voltage on the anode and "collection mode" with zero volts on the anode. These two modes are described in more detail in chapters 7 and 8. The results described here were obtained from induction mode data.

The effects of diffusion can be seen in pulses taken in induction mode. This effect is explained in section 8.4. Fig. 3.2 shows a series of five pulses taken at 500 V/cm and five taken at 200 V/cm at varying drift distances. The pulse height has been converted into numbers of electrons by using the appropriate calibration. The pulse height can be seen to decrease with increasing drift distance. The superimposed curves are the best fit to the data using the theoretical pulse shape, and including the effect of the amplifier response. The parameters corresponding to these curves are given in Table 3.1.

<table>
<thead>
<tr>
<th>Table 3.1 Parameters used in the calculation of the curves in Fig. 3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric field</td>
</tr>
<tr>
<td>Drift velocity</td>
</tr>
<tr>
<td>Free electron yield</td>
</tr>
<tr>
<td>dE / dx</td>
</tr>
<tr>
<td>Lifetime</td>
</tr>
<tr>
<td>Diffusion coefficient</td>
</tr>
</tbody>
</table>

We fixed all the parameters except the free electron yield. Fitting for this quantity gives 2.5 electrons per 100 eV at 200 V/cm and 2.9 electrons per 100 eV at 500 V/cm.

(5) values from Onsager's theory are 2.4 and 2.6 respectively.
Figure 3.3.— The calculated free electron yield as a function of the electric field for liquid argon using Onsager’s theory.

The field dependence of the electron yield calculated from the Onsager theory[3.2] is shown in Fig. 3.3. For 200 V/cm and 500 V/cm the values are 2.4 and 2.6 electrons per 100 eV respectively. The measured free electron yield depends on the absolute calibration and as this is not precisely known we conclude that the results are consistent with the theoretical expectations. The data have been averaged over many pulses to obtain good statistics.

<table>
<thead>
<tr>
<th>Drift distance (cm)</th>
<th>Number of electrons E = 200 V/cm</th>
<th>Number of electrons E = 500 V/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5510.± 250.</td>
<td>6760.± 190.</td>
</tr>
<tr>
<td>8</td>
<td>5240.± 230.</td>
<td>6490.± 270.</td>
</tr>
<tr>
<td>22</td>
<td>4580.± 160.</td>
<td>5760.± 170.</td>
</tr>
</tbody>
</table>

In Fig.3.4 and Table 3.2 are shown the measured pulse heights in number of electrons as a function of drift distance for 500 V/cm and 200 V/cm. The solid lines are the values obtained from the fits to the pulse shapes at each drift distance. The pulse height at 200 V/cm is less because of the increased recombination of electron-ion pairs, as predicted by the Onsager theory. In addition the data clearly show the effect of
diffusion, there is a 15% loss in pulse height in going from 4 cm to 22 cm drift at 500 V/cm while at 200 V/cm the corresponding loss is 17%. Clearly this effect has to be taken into account when choosing the final wire configuration.

![Graph showing pulse height in electrons as a function of drift distance for 200 V/cm (open circles) and 500 V/cm (full circles). The two solid curves are derived from values of the best fit to each of the pulses in Figure 3.3. The dashed curves are calculated assuming no diffusion.]

**Figure 3.4.** The pulse height in number of electrons as a function of the drift distance for 200 V/cm (open circles) and 500 V/cm (full circles). The two solid curves are derived from values of the best fit to each of the pulses in Figure 3.3. The dashed curves are calculated assuming no diffusion.

### 3.4. Simulation of electron recoils from solar neutrinos.

One of the purposes of the ICARUS experiment is to detect and measure the recoil electrons from the interaction of solar neutrinos within the detector volume and it is therefore important to be able to identify and measure low energy electrons. A particle travelling through matter leaves a trail of electron-ion pairs along its path. If the electrons liberated have sufficient energy then they may form an independent track of their own, creating a further series of electron-ion pairs. These electrons are referred to as "knock-on electrons" or "delta-rays" (a historical name derived from cosmic ray physics). By looking at the delta-rays with energies in the appropriate range, from 5 MeV to 14 MeV, we will be looking at electrons with energies that are the same as those from interactions of $^8$B neutrinos. The delta-ray energy spectrum extends up to the maximum possible energy loss $E_{\text{max}}$, where
\[ E_{\text{max}} = \frac{2m_e \gamma^2 \beta^2}{(1 + 2\gamma(m_e/m) + (m_e/m)^2)} \]

with \( m_e \) = electron rest mass, \( \beta = v/c \) velocity of incident particle, \( m = \) mass of incident particle. For a pion of momentum 5 GeV/c this maximum energy loss is 1 GeV. The number of electrons of energy \( E \ll E_{\text{max}} \) produced per cm is

\[ \frac{d^2N}{dE \, dx} = \frac{1}{2} D \left( \frac{Z_{\text{med}}}{A_{\text{med}}} \right) \left( \frac{Z_{\text{inc}}}{\beta} \right) \rho_{\text{med}} \frac{1}{E^2} \]

where \( D = 0.307 \text{ MeV cm}^2 \text{ g}^{-1} \), \( Z_{\text{med}} \) and \( A_{\text{med}} \) are the atomic number and mass, respectively (which for Argon are 18 and 40), \( \rho_{\text{med}} \) is the density of the medium (1.4 g/cm\(^3\) for Argon) and \( Z_{\text{inc}} \) is the charge of the incident particle. Substituting the constant factors into the equation above gives

\[ \frac{d^2N}{dE \, dx} = 0.097 \frac{1}{E^2} \quad \text{for} \quad E \ll E_{\text{max}} \]

The integral of the equation above gives the number of electrons with energy \( E_{\text{min}} < E < E_{\text{max}} \) produced per cm

\[ \frac{dN}{dx} = 0.097 \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{1}{E^2} \, dE \]

which gives

\[ \frac{dN}{dx} = 0.097 \left( \frac{1}{E_{\text{min}}} - \frac{1}{E_{\text{max}}} \right) \]

In our chamber the distance travelled by the pion through the active volume is 6.2 cm, hence the number of electrons produced per event \( N \) is, from the above equation

\[ N \left( E_{\text{min}} < E < E_{\text{max}} \right) = 0.604 \left( \frac{1}{E_{\text{min}}} - \frac{1}{E_{\text{max}}} \right) \]

In Fig. 3.5 we plot the integral spectrum per event for electron energies from 0.1 MeV to 100 MeV obtained from the equation above.

We note that although we have only one space co-ordinate we can still determine the energy by summing up the pulses contributing to the track but it is difficult to extract any reliable measure of the emission angle of the electron. The initial data sample consisted of 14276 events taken at 500 V/cm and 8 cm drift distance in induction mode. An event was considered to contain a delta-ray candidate if there was a second track, connected to the main track of the pion, with at least two pulses separated from the main track by at least 4 mm.
Figure 3.5.—The integral spectrum per event for delta-rays of energy between 0.1 MeV and 100 MeV

For 500 V/cm the drift velocity is 1.65 mm µs⁻¹ so this separation corresponded to 12 time bins where one time bin was 200 ns. Four typical events selected in this way are shown in Fig. 3.6. The pion track occurs between 70 and 80 µs, as expected for the 8 cm drift distance. The track at 27 µs is a test pulse which indicates the start of drift of the electrons. The delta-rays appear as distinct tracks at an angle to the pion track. The pion travels from wire 31 to wire 1. To obtain the energy of the delta-ray we sum up the energies of the individual pulses satisfying the above criteria. It is often difficult to identify the start of the delta-ray as it may be superimposed on the pion track. Also multiple Coulomb scattering can distort the path of the electron considerably. Hence the requirement on the pulse separation means that we do not reconstruct all the energy deposited by the delta-ray, and this has to be corrected for.

3.5.—Comparing the data with Monte Carlo predictions. To study this energy loss we have used a Monte Carlo to generate events containing delta-rays of a given energy, and hence range and angle, and included the effects of multiple scattering. This program is described in more detail in the section on reconstruction of the electron direction (section 5.2). The events are then passed through a program which simulates the behavior of the tracks in the chamber. Two such events are shown in Fig. 3.7, generated with energies of 10 MeV (Fig. 3.7a) and 15 MeV (Fig. 3.7b) respectively. We then apply the same selection criteria to our Monte Carlo events and compute the visible energy for each event and compare it to the generated energy. This is repeated for many events and the mean visible energy is calculated. Fig. 3.8 shows the curve obtained for generated energies from 1.5 MeV to 23 MeV.
Figure 3.6.—Four typical events containing delta-ray candidates. The track at 27 μs is a test pulse and indicates the start of the drift time. The track between 70 μs and 80 μs is that of the pion and the delta-ray can be clearly seen emerging at an angle from the main track.
Figure 3.7.— Two examples of Monte Carlo events containing delta-rays after simulation of the drift chamber. The track at \(\approx 27 \mu s\) is a test pulse and indicates the start of the drift time. The track at 82 \(\mu s\) is the pion track. The generated energies of the delta-rays are a) 10 MeV and b) 15 MeV.
The percentage of energy seen is not constant but varies from 40% for a generated energy of 5 MeV to 63% for a generated energy of 23 MeV. This curve is then used to correct the data.

Using the Monte Carlo we can also determine the acceptance of the events as a function of electron energy. Several factors contribute to reduce the acceptance to less than 100%. Firstly low energy electrons are difficult to identify as they may only contribute one pulse with more than 4 mm separation from the pion track. Secondly the single wire plane means that for certain angles of emission of the electron it will not be seen as a separate track. Problem configurations are 1) electrons in the same vertical plane as the pion and 2) electrons emitted parallel to the sense wires. In the first case the electron track will be superimposed on that of the pion and in the second case it will deposit all of its charge on one wire. Thirdly due to the limited fiducial volume high energy electrons will exit from the chamber. For this reason we restrict our sample to those events fully contained inside the chamber. In Fig. 3.9 we show the acceptance curve for 4 mm separation. At an electron energy of 5 MeV the acceptance is 37%, falling to 16% at 20 MeV due to electrons leaving the chamber. For energies below 3 MeV the acceptance is less than 1% and between 1.5 MeV and 3 MeV it falls by two orders of magnitude making the acceptance in this region rather uncertain.

The fully corrected data are shown in Fig. 3.10 together with the theoretical prediction (error bars are statistical only). The curve has been obtained, integrating over the chamber diameter and multiplying by the total number of events, $N_{\text{tot}}$. The curve also contains the acceptance as determined from Fig. 3.9. Above 5 MeV the curve gives a good description of the data. In the peak the Monte Carlo predicts less events than are actually observed but it has been noted that the acceptance in this region is falling very fast and is less reliable. In addition there is a systematic error on the energy scale of +10% due to uncertainties in the absolute calibration.

Our final data sample contains 880 events. The expected number of events $N$ can be obtained from the equation below

$$N = N_{\text{tot}} \times 0.604 \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{A(E)}{E^2} dE$$

where $A(E)$ is the acceptance as a function of energy. This gives the expected number of events as 892 for the 4 mm separation, in excellent agreement with the observed number of events.
Figure 3.8.—The visible energy of the delta-rays for a given generated electron energy. Only those electrons producing at least two pulses separated from the main track by at least 4 mm are included in the calculation of the visible energy.

Figure 3.9.—The acceptance curve as a function of the delta-ray energy for the 4 mm separation and at least two pulse produced. The decrease at low energy is due to the requirements on pulse separation and number of pulses. The subsequent decrease at higher energies is due to electrons that are not fully contained in our sensitive volume.
Figure 3.10.—The fully corrected energy spectrum for the delta-rays (error bars are statistical only). The curve is the theoretical prediction after integration over the chamber diameter and including the total number of events $N_{\text{tot}}$ and the acceptance from Figure 3.9.

3.6. — References


4.— Studies on the Calorimetric energy resolution in the liquid Argon

4.1.— General considerations. The cryogenic image chamber has the feature of detecting any ionizing phenomenon occurring within its volume and above a given energy threshold\(^{(6)}\). The drift-time technique and the continuous read-out permit to record the complete electron image produced by the ionizing event. In these respects, this device resembles very much a bubble chamber. The apparent "bubble" size, namely the size of an initial \(\delta\)-function of electrons in the liquid, is ultimately determined by the diffusion of the electrons due to the drift time and to the intrinsic time and space resolution of the read-out\(^{(7)}\). However the cryogenic image chamber, in contrast to the bubble chamber — where ionization measurements are rather inaccurate — is also a superb calorimeter.

The excellent quality of calorimetric measurements in a pure Argon calorimeter has been very extensively investigated, both with Monte Carlo techniques and experimentally. We consider separately the response to high energy \((\geq 100\text{ MeV})\) and low energy ionizing events.

Finally the possibility of measuring continuously the ionization along the track permits the identification of the nature of the particle with the help of the ionization vs. range relationship (Fig. 4.1). Separations between \(K\) and \(\pi\) are entirely trivial. Instead, \(\pi-\mu\) distinction is marginal. However at end range pions and muons behave quite differently. It is worth mentioning that the time delay due to the \(\mu \to e\) decay introduces a significant gap in the track of the decay electron because of the drift velocity effects, namely 2 mm/\(\mu\)s.

4.2.— Response to high energy tracks. The resolution of a few hundred MeV electrons and photons [4.1] is shown in Fig. 4.2 and it is well fitted (see Fig. 4.3) by a formula of the type: \(\sigma/E = 0.0168\ E(\text{GeV})^{-1/2}\), or about a 1.6\% r.m.s. resolution at 1 GeV. Photons and electrons have quite similar behaviors. These predictions are well confirmed experimentally[4.2], as shown in Fig. 4.4. The energy response, as anticipated, is perfectly linear, as shown in Fig. 4.5. Hadrons of significant energy normally undergo additional secondary interactions in the Argon (Fig. 4.6). The energy response to such an hadronic cascade is equally good, as shown in Fig. 4.7. Finally it is possible to determine the angle of emission of a photon or an electron from a weighted average of the energy depositions of the electromagnetic cascade with good resolution, as shown in Fig. 4.8.

\(^{(6)}\) It appears reasonable to set the trigger threshold to about 4.0 to 5.0 MeV equivalent to minimum ionization.

\(^{(7)}\) The resultant "bubble" size is of approximately 1 mm radius, quite similar to the performance of the famous Gargamelle bubble chamber.
Figure 4.1  Energy loss vs. range in liquid argon for different particles. One can see that particle identification can be easily carried out between protons, kaons and pions/muons.

Figure 4.2  Experimental pulse height spectrum of 1 GeV/c electrons from the KEK accelerator in a total absorption pure liquid argon calorimeter [4.2].

Figure 4.3  Expected resolution, according the the EGS Monte Carlo for electrons in the energy range 50 MeV to 1 GeV, from ref. 4.1. The data are well represented by an inverse square root law.

Figure 4.4  Experimental resolution for electrons in liquid argon [4.2]. Results are in qualitative agreement with the Monte Carlo data after subtraction of the electronic noise.
Figure 4.5  Experimental linearity of response of the pure liquid argon calorimeter of ref. 4.2.

Figure 4.6  Attenuation of the hadronic cascade for hadrons (protons) of energy range 1 - 5 GeV, according to Monte Carlo calculations [4.1].

Figure 4.7  Sampling fluctuations for electrons and protons. From ref. 4.1.

Figure 4.8  Angular resolution for photons and electrons, according to Monte Carlo calculations [4.1].

Figure 4.9  Normalized charge collection as a function of the electric field for stopping e, μ and π measured in the KEK beam [4.2].
The relative response [4.2] of the Argon calorimeter to fast tracks is quite independent of the strength of the electric field used to collect the charges (Fig. 4.9). The drop of the collected charge for smaller values of the field is due to the effects of geminate recombination in the liquid.

4.3. — *Response to low energy cascades.* The intrinsic energy resolution of an ionization chamber is governed by the fluctuations in the number of electron-ion pairs produced along the path of a charged particle. In liquid Argon the low value of $W$ (the energy required to create one electron-ion pair) which is measured to be 23.6 eV as compared to the ionization potential which is 15.76 eV indicates that very little energy is lost into undetected excitations. Hence the ultimate resolution obtainable in liquid Argon should be very good. The scale of the fluctuations of the number of electron-ion pairs is characterized by the Fano factor[4.3]. Doke et al[4.4] have calculated the Fano factors for the liquid noble gases Argon, Krypton and Xenon and their results are shown in Table 4.1.

The intrinsic energy resolution $\sigma$ is given by

$$\sigma = \left( \frac{E_0 (\text{MeV})}{F} \times W \ (\text{eV}) \right)^{1/2} \text{ keV}$$

where $E_0$ is the energy of the ionizing radiation, $F$ is the Fano factor. The calculated resolutions obtained from equation 1 for $E_0 = 1$ MeV are given in Table 4.1 for the three liquids and one can see that the expected resolution for liquid Argon is extremely good, with $\sigma(E)/E = 0.16\%$.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>$F$</th>
<th>$\sigma$ (keV)</th>
<th>$\sigma(E)/E$ (%)</th>
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</thead>
<tbody>
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<td>1.60</td>
<td>0.160</td>
</tr>
<tr>
<td>Kr</td>
<td>0.057</td>
<td>1.06</td>
<td>0.106</td>
</tr>
<tr>
<td>Xe</td>
<td>0.041</td>
<td>0.80</td>
<td>0.080</td>
</tr>
</tbody>
</table>

4.4. — *Experimental Results of the energy resolution in the MeV range.* The low energy resolution predictions from Table 4.1 have not yet been realized in practice. The best results obtained so far in liquid Argon are those of Aprile et al [4.6]. They have measured the intrinsic energy resolution for the 976 keV internal conversion
Figure 4.10.—$^{207}$Bi pulse height spectrum in liquid Argon. The drift field strength is $\approx 11$ kV cm$^{-1}$. The energy resolution of the 976 keV electron line is 32 keV (FWHM). The electronic noise contribution is 18.5 keV (FWHM).
electrons from $^{207}$Bi and at an electric field of 11 kV cm$^{-1}$ they find that $\sigma = 11$ keV (26 keV FWHM). A typical pulse spectrum taken at 11 kV cm$^{-1}$ is shown in Fig.4.10.

The 976 keV line is clearly visible and has a width of 32 keV (FWHM) with an electronic noise contribution of 18.5 keV (FWHM). However this value is still an order of magnitude above the predicted value given in Table 4.1.

Several groups have investigated this discrepancy between observation and expectation[4.7,4.8] and have suggested that it is due to the increased recombination of electron-ion pairs along the tracks of low energy delta-electrons produced along the length of the primary electron track. The ionization density along these low energy electron tracks is much higher than for the primary track. Hence at moderate electric fields the recombination is much larger and hence the fluctuations in the number of electrons collected from these tracks will be greater. Using this hypothesis Aprile et al [4.6] have considered the total charge collected $Q_0$ to consist of two parts, one due to the delta-electrons $Q_8$ and the other $Q_0 - Q_8$ due to the primary track. They fitted the charge collected as a function of the electric field using the Jaffe theory of columnar recombination[4.9,4.10] but allowing for the two contributions to $Q_0$

$$Q(E) = \frac{(Q_0 - Q_8)}{(1 + k/E)} + \frac{Q_8}{(1 + k_8/E)}$$

where $Q(E)$ is the charge collected at field $E$, $k$ is the recombination constant for the primary electron track and $k_8$ is the constant for the delta-electron tracks. The values they obtain for the fitted parameters are

$$Q_0 - Q_8 = 5.68 \pm 0.4 \text{ fC} \quad k = 0.2 \pm 0.03 \text{ kV cm}^{-1},$$

$$Q_8 = 1.28 \pm 0.15 \text{ fC} \quad k_8 = 12 \pm 3 \text{ kV cm}^{-1}.$$

![Graph](image)

**Figure 4.11.** — Field dependence of the charge collected for the 976 keV electrons. The line is a fit to the data as described in the text. The values of the fitted parameters are $Q_0 - Q_8 = 5.68 \pm 0.4 \text{ fC}$, $k = 0.2 \pm 0.03 \text{ kV cm}^{-1}$, $Q_8 = 1.28 \pm 0.15 \text{ fC}$ and $k_8 = 12 \pm 3 \text{ kV cm}^{-1}$, and $\chi^2 = 0.2$ per degree of freedom.
The curve obtained using these parameters is compared to the data for the 976 keV electrons in Fig. 4.11 and the agreement is good.

The recombination constant for the delta-electrons is much larger than that for the primary track and at a field of $E = k_5$ the charge collected from the delta-electron tracks is only $0.5 Q_5$. Using these parameters we find that at a field of 1 kV cm$^{-1}$ the charge collected is only $0.1 Q_5$, hence a significant fraction of the charge is lost due to recombination.

One can see from these results that about 20% of the total ionization produced by a 976 keV electron is deposited in the form of delta-electrons. Calculation of the expected number of delta-electrons produced per centimeter with energies in the range $E_5$ to $E_5 + dE_5$ has been performed by Aprile et al.[4.6]. Only delta-electron energies where the recombination is significantly enhanced have been considered in the calculation. Following the suggestion of Ref. [4.8] they choose an energy range between 1 and 20 keV. In this energy range they find that about 200 keV of the primary electron energy is lost into delta-electrons, which agrees well with the 20% obtained from the data.

In determining the energy resolution they have assumed that the fluctuations in the number of electrons along the delta-electron tracks are characterized by a different Fano factor $F_5$ as compared to the primary track. Using this assumption they have fitted the energy resolution (FWHM) as a function of the electric field with an expression of the following form

$$\frac{\Delta E}{E} = 2.35 q_e^{1/2} \left[ \frac{F_0 (1 + k/E)}{Q_0 - Q_5} + \frac{F_5 (1 + k_5/E)}{Q_5} \right]$$

where $Q_5$ is the electron charge and $F_5$ has a value between 1 and 0.11. For fields much

![Graph showing the electric field dependence of the noise subtracted energy resolution of 976 keV electrons in liquid Argon. The curve through the data is the best fit with $F_5 = 0.62$. The upper and lower curves show the predictions for the cases when $F_5 = 1$ and $F_5 = 0.11$ respectively.](image)

**Figure 4.12.** Field dependence of the noise subtracted energy resolution of 976 keV electrons in liquid Argon. The curve through the data is the best fit with $F_5 = 0.62$. The upper and lower curves show the predictions for the cases when $F_5 = 1$ and $F_5 = 0.11$ respectively.
greater than the value given by $k_5$ the fluctuations should be described by $F_5 = F$ whereas for very low fields Poisson statistics should hold ($F_5 = 1$) as most of the electrons are lost through recombination. The results of the fit are shown in Fig. 4.12 where the energy resolution (FWHM) is plotted as a function of the electric field. The curve passing through the points is the best fit with $F_5 = 0.62$. The upper and lower lines are for $F_5 = 1$ (Poisson statistics) and $F_5 = 0.11$ (Fano statistics) respectively. At a field of 1 kV cm$^{-1}$ from Fig. 4.12 we obtain a resolution of 70 keV FWHM or $\sigma(E)/E = 3\%$.

4.5.— **Complete Monte Carlo simulation of the energy resolution in the MeV range.** In order to determine the energy resolution for electrons and gamma-rays we have carried out a series of Monte Carlo simulations, taking the above effects into account. To generate the electron or gamma-ray we have used the electromagnetic shower Monte Carlo "GEANT"[4.11]. For the gamma-rays we have generated kinetic energies in steps of 1 MeV from $E_{\gamma} = 2 \rightarrow 6$ MeV and for the electrons in steps of 2 MeV from $E_e = 1 \rightarrow 13$ MeV. The Monte Carlo includes all the known electromagnetic processes for photons and electrons. For low energy photons the dominant interaction mechanism is Compton scattering and at very low photon energies the photo-electric effect also contributes. The electrons undergo multiple Coulomb scattering and energy loss by ionization and for the higher energy electrons there is also the possibility of bremsstrahlung.

The particles are tracked through the liquid Argon until they change their identity or their kinetic energy falls below a cut-off value, set to 10 keV due to limitations in the Monte Carlo program. At each tracking step the amount of energy lost in that step is determined and also the $dE/dx$ for that step. A 20 keV electron has a $dE/dx$ of 12 MeV cm$^{-1}$ and we define this to be the cut-off between the normal and increased recombination. If the step has a $dE/dx$ which is less than this value then the deposited energy is simply fluctuated by a gaussian with a width $\sigma = (E_0FW)^{1/2}$ where $E_0$ is now the energy lost per step and $F = 0.11$. If the step has a $dE/dx$ greater than the cut-off then the energy deposited is first reduced to 10% of its value to account for the observed recombination at a field of 1 kV cm$^{-1}$ and then fluctuated as above but with $F = 0.62$. The individual steps are then summed to obtain the total energy deposited.

Initially the volume used was a cube of half-length 3 meters and the electron or gamma-ray was generated at the centre of the volume over $4\pi$ solid angle. The energy resolution $\sigma(E)/E(\%)$ as a function of deposited energy $E$ for this configuration is shown in Fig. 4.13a for gamma-rays and in Fig.4.13b for electrons. For the gamma-rays the resolution is well represented by an inverse square-root law with $\sigma(E)/E(%) = 3.96/\sqrt{E}$ for the range of energies plotted.
Figure 4.13.— Energy resolution $\frac{\sigma(E)}{E}$ (%) as a function of reconstructed energy for a) gamma-rays and b) electrons. The curves are fits to the data of the forms indicated.
The electrons are well described above 3 MeV by $\sigma(E)/E(\%) = 2.61/\sqrt{E} + 0.613$. For a 1 MeV electron we obtain a resolution of 3.03% which is in agreement with the results of Ref. [4.6]. In Fig. 4.14 is plotted the percentage energy loss

$$\frac{\Delta E}{E} \,(\%) = \frac{E_{\text{rec}} - E_{\text{gen}}}{E_{\text{gen}}}$$

where $E_{\text{rec}}$ is the reconstructed energy and $E_{\text{gen}}$ is the generated energy, as a function of $E_{\text{gen}}$ for gamma-rays and for electrons. The percentage energy loss for electrons appears to be essentially independent of energy with a value of around 7.3% while for the gammas there is a slow decrease in the energy loss as the gamma energy increases.

![Graph](image)

Figure 4.14.— Percentage energy loss $-\Delta E / E \,(\%) = (E_{\text{rec}} - E_{\text{gen}}) / E_{\text{gen}}$ as a function of generated electron or gamma-ray energy.

The longitudinal extent of a gamma shower is much larger than that for an electron of the same energy. It is important to know how the resolution for a gamma of a given energy degrades if one does not contain all the energy deposited by the shower. In order to determine this dependence we sum up the energy deposited by the shower in a volume of increasing size. The volume used is a cube of half-length $d = n L_R$ (cm) centered on the gamma-ray vertex, $L_R$ is the radiation length of liquid Argon, equal to 14 cm and $n = 1, 2, \Rightarrow 21$. In Fig. 4.15 we show the resolution $\sigma(E)/E(\%)$ as a function of $d$. As would be expected the size of the volume required to contain the shower and hence obtain the optimum resolution increases as the gamma energy increases. The half-length required to obtain a resolution of 10% is plotted in Fig. 4.16 as a function of the generated gamma energy. This distance increases from $\approx 80$ cm at $E_\gamma = 2$ MeV to $\approx 100$ cm at $E_\gamma = 6$ MeV. This increase is much smaller than the increase in the half-length required to obtain the optimum resolution at each energy.
Figure 4.15.— Energy resolution $\sigma(E) / E$ (%) for energy deposited in a cube as a function of the half-length $d$ of the cube. The cube had a volume of $2d \times 2d \times 2d$ cm$^3$. 
Figure 4.16.— Magnitude of the half-length of the volume for which the energy resolution of the gamma-ray is equal to 10% plotted as a function of the generated gamma-ray energy.

The resolutions obtained here do not take into account the contributions to the resolution from diffusion (this will be small if the collected charge signal is used rather than the induced signal), unfavorable orientations of the tracks with respect to the wire plane or electronic noise, all of which will serve to degrade the resolution. We have measured the energy resolution for the energy deposited by 5 GeV/c pions in 2 mm of liquid Argon using the 24 cm drift chamber (Chapter 3) and we obtain $\sigma(E)/E$ of 6.7%. A 5 GeV/c pion is minimum ionizing and has a $dE/dx$ of 2.11 MeV cm$^{-1}$ so in 2 mm of liquid Argon it will deposit 0.422 MeV of energy. A 5 MeV electron is also minimum ionizing and deposits its charge on approximately 10 wires (2 mm wire separation). Taking $6.7\% / \sqrt{10}$ we obtain a resolution of $\approx 2\%$ for a 5 MeV electron which is in good agreement with the Monte Carlo results.

4.6.— References


DETECTION OF SOLAR NEUTRINO EVENTS

5.— Measurement of the direction of the recoil electron.

5.1.— General considerations. As already pointed out, one of the aims of the ICARUS I experiment is the observation of solar neutrinos emitted in the $^8$B decay through the detection of the elastic scattering reaction

$$\nu + e^- \rightarrow \nu + e^-.$$

The results of the extensive Monte Carlo calculations and the experimental measurements with delta rays described in the previous sections have perfected the simulation of the events in the Argon image chamber to a level where one can simulate realistically the events produced by this process. The visible delta-rays were in the same energy range as the electrons expected from the solar neutrino interactions.

The recoil electron has a kinetic energy less than 14 MeV [5.1]. A threshold energy cut must be imposed for the detection of the electrons in the above reaction in order to remove backgrounds due to various causes such as natural radioactivity, cosmic ray events, etc. As we shall see later on, a reasonable choice for such a cut-off is around 5 MeV. With this condition, the electron emission will be within a cone of a several degrees opening angle ($\leq 16^\circ$ for a 5 MeV cut-off) around the incoming neutrino direction. The observation of the electron direction with respect to the expected direction of the neutrinos is a powerful tool in order to discriminate events from the backgrounds. Fig. 5.1 shows schematically the general geometry of the detection.

5.2.— Simulation of the solar neutrino events. The main uncertainty on the electron direction is due to the multiple scattering in liquid Argon, which has a radiation length of 14.0 cm. For energies from 5 to 14 MeV, the range of the electrons spans from 2 cm to 5 cm — namely from 10 to 25 points on a track. Fig. 5.2 shows the multiple scattering and the range expected for electrons in liquid Argon as a function of the kinetic energy.

The Monte Carlo calculation has taken into account:

i) the path of an electron created with a given direction and energy in liquid Argon,

ii) the drift of the ionization electrons from the track to the detecting system and

iii) the corresponding induced signals on the sense wires.

The electron tracks have been generated step by step taking into account energy loss and multiple scattering contribution [5.2]. The energy loss gives the total number of primary and secondary electrons produced by the ionizing particle.
Figure 5.1— Definition of the angles used in the event reconstruction.
When calculating the total number of ionization electrons reaching the detection system we have taken into account:

(i) the recombination effect (which depends on the electric field in the drift region)
(ii) the removal of electrons by impurities in liquid Argon
(ii) their diffusion.

The last two effects result in distortions of minor importance to the final signal (providing that the electron lifetime is long). Finally we have taken into account the response of the sense-wires and the associated electronics (including the read-out noise).

The results of the program have been checked by comparing the signal shapes, the effective range of the particles and the energy deposited on each wire with the delta-ray tracks recently observed in the 24 cm test prototype chamber.

![Graph](image)

**Figure 5.2.**— Range and multiple scattering over 2 mm of liquid argon as a function of the electron energy. Taken from ref.5.3.

The events generated in this way were then "reconstructed", analysing the signals on each wire. This has been performed by fitting the simulated pulses to calculated signal shapes. For angles smaller than 30° with respect to the wire plane (angle α in Fig. 5.1) the signal shape is approximately triangular, the amplitude decreasing slightly and the width remaining roughly constant. As the dip-angle α increases, the width grows proportionally to the tangent of the angle, while the amplitude remains nearly constant as can be seen on Fig. 5.3a and Fig. 5.3b. This behavior suggests that we have two different ways of measuring the dip-angle at each point. One is to determine the position of two successive pulses and use the known spacing between the corresponding wires. This procedure is appropriate if the track is approximately parallel.
to the wire plane (small dip-angle) because in this case the pulses are narrow and their center well defined. The procedure fails when the dip-angle increases because the signal width grows, introducing an uncertainty on the track position. The second procedure is to use the known relationship (obtained via the study of the electric field configuration of the detector) between the signal width and the slope of the incident electron track. The two methods of measuring the angle are independent and complementary and we have taken a weighted mean of the two. As already pointed out, multiple scattering plays an important role in reducing the information on the original direction of the emitted electron. We follow the technique widely used in a heavy-liquid bubble chamber[5.4], where in the determination of the electron direction successive signals are progressively weighted according to the expected multiple scattering contributions.

![Graphs showing](image)

**Figure 5.3.**—Expected pulse amplitude (a) and pulse width (b) as a function of the angle of the track with respect to the wire plane. The straight line represents a fit to the points beyond 50°; the parameters of the fit are printed on the figure.

5.3.—**Results.** We have generated samples of electron tracks with several initial directions and the energy spectrum of solar electron-neutrino scattering. Following the results of our latest tests, we have also added an electronic noise equivalent to 300 electrons r.m.s.. Fig 5.4 shows for different electron threshold energies the difference $\theta_1 - \theta_2$ between the measured and the real emission angle plotted on a cosine plot (Fig. 5.1). We have chosen this representation because the emission direction of the background events is expected to be isotropically distributed in space, and hence flat in $\cos \theta$. 
Figure 5.4 — Distribution of $\cos \theta$ in neutrino-electron elastic scattering for three values of the cut-off energy. The angle $\theta = \theta_1 - \theta_2$ is the difference between real and measured emission angles. The three sets of curves are given for emission angles $\alpha = 0^\circ, 30^\circ$ and $60^\circ$ respectively with respect to the wire plane. The conventions are those of Figure 5.1.
Figure 5.5 — Fraction of neutrino-electron elastic scattering events accepted as a function of the cone aperture around the neutrino direction. The various symbols refer to different threshold energies. The neutrino angle with respect to the wire-plane is $\alpha = 0^\circ$, $30^\circ$ and $60^\circ$ in (a), (b) and (c) respectively.
We remark that (1) a sharper angular resolution is obtained by raising the energy threshold, since higher energy tracks have lower multiple scattering and more points when reconstructing the initial direction and (2) that the resolution is slightly degraded for larger angles $\alpha$ since the algorithm used has been optimized for electrons parallel to the sense-wire plane.

We show in Fig. 5.5 the fraction of accepted events as a function of the cone aperture around the real emission direction for various energy cut-off and for different angles. For the above mentioned reason we observe a slight worsening of the acceptance as the angle $\alpha$ increases. For a 5 MeV electron energy threshold more than 80% of the events are reconstructed within a cone of 20$^\circ$ aperture.

Finally we have studied the possibility of determining the direction of motion of the electron track from the increase in ionization towards the end of its range. The fraction of events incorrectly reconstructed is plotted in Fig. 5.6 as a function of the electron energy, and is well below 10% for events above the 5 MeV energy threshold.

The reconstruction program is still under improvement. In order to achieve better accuracy in the measurements and to increase the fraction of events clearly recognizable above the background we are presently trying to introduce a criteria to recuperate even those few events where the end- and start-points are inverted. Our present results however indicate that the direction of the recoil electron is a powerful tool in discriminating against spurious effects, when searching for solar neutrino events.

![Graph](image)

**Figure 5.6.**—Fraction of front-to-back inversions of the electron track due to multiple scattering.
5.4.— References.


6.— Low energy backgrounds due to radioactivity, neutrons and the like

6.1 — General considerations. The expected rates for both absorption and neutrino-electron scattering events in our detector (200 tons fiducial volume of liquid Argon) as reported in Table 6.1 for different values of the recoil electron energy, show that the number of events increases considerably by lowering the energy cut-off. It is important to investigate any possible sources of background, in order to increase our statistics by applying the lowest energy cut-off to the data.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>SSM</th>
<th>Davis et al.</th>
</tr>
</thead>
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<td></td>
<td>Abs</td>
<td>Scatt</td>
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</tr>
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<td>246</td>
</tr>
<tr>
<td>5</td>
<td>161</td>
<td>179</td>
</tr>
</tbody>
</table>

There are several sources of background which can produce a single electron with energy above the chosen energy threshold. The most important sources of background in the energy domain of the solar neutrino events are due to:

i) radioactive decays inside the liquid, producing either (1)electrons directly or (2)photons, which then in turn produce Compton electrons. Argon radioactive isotopes could be sources of such backgrounds, as well as other substances dissolved in minute quantities inside our liquid

ii) gamma rays coming from outside the volume, produced by radioactivity of rocks, walls etc. A fiducial volume cut and appropriate shielding should permit us to keep these effects to a manageable level. Therefore this background will not be further discussed

iii) neutrons coming for instance from the spontaneous fission of the Uranium contained in the rock, in the stainless steel and other materials around the liquid. The neutron mean free path in Argon is much longer than the one for gamma rays and therefore—in contrast to case ii)—fiducial cuts are not effective. Their number has to be kept low at production and therefore the choice of the materials for the detector deserves special consideration.

In most cases these background events simulating electrons from the Sun can be identified and hence removed since:
i) neutrino-electron scattering events must point in the direction of the Sun. Instead, the Compton effect has apriori no knowledge of the instantaneous position of the Sun with respect to the detector

ii) the event must be "quiet", namely no appreciable additional energy must be present in the rest of volume in the vicinity of the event. Instead for background events in the final state there is an additional photon, which — in contrast to the neutrino—most of the times interacts again inside the detector with additional energy releases

iii) in the case of the inverse β-decay induced by solar neutrino, the decay of the excited Argon nucleus should give a "calorimetric" line corresponding to the excitation energy of the super-allowed transition.

We now consider in detail these potential sources of background.

6.2.— Argon isotopes. Most of the Argon isotopes (Table 6.2) are radioactive, with very short half-lives (less than a few days), so that they, as well as their decay products, disappear very quickly.

<table>
<thead>
<tr>
<th>Argon isotope</th>
<th>% nat. abund.</th>
<th>( \tau_{1/2} )</th>
<th>decay mode</th>
<th>Last product of the chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>32Ar</td>
<td>75 ms</td>
<td>( \beta^+ )</td>
<td>33S</td>
<td></td>
</tr>
<tr>
<td>33Ar</td>
<td>173 ms</td>
<td>( \beta^+ )</td>
<td>34S</td>
<td></td>
</tr>
<tr>
<td>34Ar</td>
<td>844 ms</td>
<td>( \beta^+ )</td>
<td>35Cl</td>
<td></td>
</tr>
<tr>
<td>35Ar</td>
<td>1.77 s</td>
<td>( \beta^+ )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36Ar</td>
<td>0.347</td>
<td>stable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37Ar</td>
<td>35 d</td>
<td>EC</td>
<td>37Cl</td>
<td></td>
</tr>
<tr>
<td>38Ar</td>
<td>0.063</td>
<td>stable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39Ar</td>
<td>269 y</td>
<td>( \beta^- (0.565 \text{ MeV}) )</td>
<td>39K</td>
<td></td>
</tr>
<tr>
<td>40Ar</td>
<td>99.59</td>
<td>stable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41Ar</td>
<td>1.83 h</td>
<td>( \beta^- (1.2 \text{ MeV}) )</td>
<td>41K</td>
<td></td>
</tr>
<tr>
<td>42Ar</td>
<td>33 y</td>
<td>( \beta^- (3.52 \text{ MeV}) )</td>
<td>42Ca</td>
<td></td>
</tr>
</tbody>
</table>

The exceptions are \(^{39}\text{Ar}\) and \(^{42}\text{Ar}\), which have half lives of 269 and 33 years respectively. \(^{39}\text{Ar}\) decays to \(^{39}\text{K}\) by emitting an electron of 0.565 MeV kinetic energy well below any reasonable threshold level.

The decay of \(^{42}\text{Ar}\) is more important and it deserves serious consideration. Ray Davis at Brookhaven has performed some measurements on the atmospheric Argon and his results [6.1] give \(1.8 \times 10^{10}\) atoms of \(^{42}\text{Ar}\) per ton of Argon, which means \(3.6 \times 10^{12}\) atoms of \(^{42}\text{Ar}\) in our detector. This is due to the atmospheric nuclear explosions
that occurred about 30 years ago, where $^{42}\text{Ar}$ was produced by a double, sequential
capture of neutrons by $^{40}\text{Ar}$: $^{40}\text{Ar} + n \Rightarrow ^{41}\text{Ar} + \gamma$ and $^{41}\text{Ar} + n \Rightarrow ^{42}\text{Ar} + \gamma$. The
total background rate due to $^{42}\text{Ar}$ in our fiducial mass is then found to be the huge rate
of $2.4 \times 10^3$ events sec$^{-1}$. $^{42}\text{Ar}$ $\beta^-$ decays to $^{42}\text{K}$ with maximum kinetic energy of the
electron $Q = 0.6$ MeV[6.2]. From the $Q$ value and the known $J^\Pi$ values of the lowest
three $^{42}\text{K}$ states, one can deduce that the decay should proceed 100% to the $^{42}\text{K}$ ground
state. In turn $^{42}\text{K}$ $\beta^-$ decays to $^{42}\text{Ca}$ with a half-life 12.36 hours and a maximum
kinetic energy of the electron of 3.52 MeV.

![Decay Scheme of $^{42}\text{K}$ Produced by $^{42}\text{Ar}$ Decays](image)

**Figure 6.1.—** Decay scheme of $^{42}\text{K}$ produced by $^{42}\text{Ar}$ decays

As shown in Fig. 6.1, the decay of $^{42}\text{K}$ proceeds 81.2% of the time to the ground
state of $^{42}\text{Ca}$, 18.3% to the 1.52 MeV excited state, and with lower probability to higher
energy excited states (0.07% to the highest energy level of 3.45 MeV). Gamma rays are
then emitted on the transitions to the ground state from the excited energy levels.

The branching ratio for the energy level transitions are indicated, and combining
the two probabilities the gamma intensity can be deduced. In this decay, since the
probability for $^{42}\text{K}$ to proceed to the $^{42}\text{Ca}$ excited state of 1.52 MeV is 18% and the
branching ratio of the transition from this level to the ground state is 100%, we can
deduce that 1.52 MeV gamma's of 18% intensity will be emitted, while the intensity of
the 3.45 MeV gamma ray is $1.4 \times 10^{-3}$ %. Rates inside our fiducial volume are given
in Table 6.3 in terms of number of electrons produced.
Table 6.3—Rates per year and energies for the decay of $^{42}$Ar $\Rightarrow^{42}$K $\Rightarrow^{42}$Ca.

<table>
<thead>
<tr>
<th>$E_e$ (endpoint, MeV)</th>
<th>Electron energy (MeV)</th>
<th>0 &lt; E &lt; 1</th>
<th>1 &lt; E &lt; 2</th>
<th>2 &lt; E &lt; 3</th>
<th>3 &lt; E &lt; 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.52</td>
<td></td>
<td>1.46x10^10</td>
<td>2.86x10^10</td>
<td>1.71x10^10</td>
<td>1.15x10^9</td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td>8.76x10^9</td>
<td>5.09x10^9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.68</td>
<td></td>
<td>2.07x10^8</td>
<td>5.8x10^7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td></td>
<td>3.78x10^7</td>
<td>1.26x10^5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.07</td>
<td></td>
<td>5.30x10^7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_\gamma$ (MeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.32</td>
<td></td>
<td>2.65x10^8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td></td>
<td>2.65x10^7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.03</td>
<td></td>
<td>1.90x10^7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.52</td>
<td></td>
<td>8.96x10^9</td>
<td>5.21x10^9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.93</td>
<td></td>
<td>1.41x10^7</td>
<td>1.74x10^7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.42</td>
<td></td>
<td>5.58x10^6</td>
<td>7.73x10^6</td>
<td>3.75x10^6</td>
<td></td>
</tr>
<tr>
<td>3.45</td>
<td></td>
<td>2.14x10^5</td>
<td>2.30x10^5</td>
<td>3.78x10^5</td>
<td>2.21x10^5</td>
</tr>
</tbody>
</table>

6.3.—Other elements dissolved in the liquid. We have to take into account other noble gases like Radon, Xenon and Krypton that are present in the atmosphere, since they are not rejected by our purification system and most likely follow the same pathway as the Argon during the Argon separation process from air. In spite of their higher boiling point, some residual atoms of these gases would remain dissolved in the liquid Argon, and hence their potential contributions to the backgrounds has to be estimated as well. Xenon and Krypton are present in the air in ppm quantities (see section 11.1 for composition of the atmosphere), while Radon is present only in small traces, on the average one part in $10^21$. We discuss these gases in detail.

i) Radon. Assuming that it is not removed during the separation phase of Argon from the air, we can estimate that the fiducial volume will contain $3 \times 10^{11}$ atoms of this gas. None of the 28 Radon isotopes is stable and they all have very short life-times. The longest living one is $^{222}$Rn ($\tau_{1/2}=3.823$ days) which comes from the $\alpha$ decay of $^{226}$Ra with $\tau_{1/2}=1600$ years. Almost all of the Radon isotopes are $\alpha$ emitters except $^{223}$Rn, $^{224}$Rn, $^{225}$Rn, and $^{226}$Rn which $\beta^-$ decay. We have considered the decay chains for all of them: the gamma rays emitted have a maximum energy of about 2 MeV and for the electrons from the $\beta^-$ decay the end point of the spectrum is about 3 MeV. In Table 6.4 are shown some of the Radon isotopes with their half-lives, the last product of the decay chain, the maximum energy of the gamma-rays emitted in the chain and the maximum $\beta^-$ energy.
Once the Argon is separated from the air and the major source for the Radon production, the Radium, is almost completely eliminated (except for the radium produced in the $^{224}$Rn and $^{226}$Rn $\beta^-$ decays but this is a very small amount), it will be enough to wait several days in order to ensure that the Radon isotopes have decayed together with their products which also have short life times. The stable isotopes, the products at the end of the chain, are in most of the cases isotopes of lead and metal elements in general and they can either be removed by the recirculating purifier or remain in suspension in the liquid.

<table>
<thead>
<tr>
<th>Radon isotopes</th>
<th>$\tau_{1/2}$</th>
<th>decay mode</th>
<th>end of chain</th>
<th>max $E_\gamma$ (MeV)</th>
<th>max $E_e$(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{199}$Rn</td>
<td>0.29 s</td>
<td>$\alpha$</td>
<td>$^{191}$Ir, $^{179}$Hf</td>
<td>1.68</td>
<td></td>
</tr>
<tr>
<td>$^{200}$Rn</td>
<td>1.0 s</td>
<td>$\alpha$</td>
<td>$^{188}$Os, $^{192}$Pt</td>
<td>2.215</td>
<td></td>
</tr>
<tr>
<td>$^{201}$Rn</td>
<td>7.0 s</td>
<td>$\alpha$</td>
<td>$^{193}$Ir</td>
<td>1.58</td>
<td></td>
</tr>
<tr>
<td>$^{202}$Rn</td>
<td>9.85 s</td>
<td>$\alpha$</td>
<td>$^{198}$Hg, $^{194}$Pt</td>
<td>1.469</td>
<td></td>
</tr>
<tr>
<td>$^{220}$Rn</td>
<td>55.6 s</td>
<td>$\alpha$</td>
<td>$^{206}$Pb</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>3.8 d</td>
<td>$\alpha$</td>
<td>$^{206}$Pb</td>
<td>1.764</td>
<td>3.26</td>
</tr>
<tr>
<td>$^{223}$Rn</td>
<td>43 m</td>
<td>$\beta^-$</td>
<td>$^{207}$Pb</td>
<td>&lt;1</td>
<td>1.4</td>
</tr>
<tr>
<td>$^{224}$Rn</td>
<td>1.78 h</td>
<td>$\beta^-$</td>
<td>$^{224}$Ra (3.66 d)</td>
<td>1.341</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{225}$Rn</td>
<td>4.5 m</td>
<td>$\beta^-$</td>
<td>$^{209}$Pb, $^{209}$Bi</td>
<td>1.566</td>
<td>1.8</td>
</tr>
<tr>
<td>$^{226}$Rn</td>
<td>6.0 m</td>
<td>$\beta^-$</td>
<td>$^{226}$Ra (1600 y)</td>
<td>1.3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

ii) Xenon. Xenon is present in the atmosphere to the extent of about one part in 20 million and we estimate that the fiducial volume will contain $1.5 \times 10^{25}$ atoms of this gas. Natural Xenon is composed of 9 stable isotopes. In addition to these the other 27 isotopes have short life-times of a few days maximum. None of these isotopes can produce gamma rays or electrons above our energy threshold. The effect of neutron capture on the (stable) isotopes is discussed in the next paragraph.

iii) Krypton. Krypton is present in the air to the extent of about 1 ppm hence our fiducial volume will contain about $3 \times 10^{26}$ atoms of this gas. It is naturally occurring and contains 6 stable isotopes. The remaining 20 isotopes have short life-times (of the order of few hours maximum) except $^{81}$Kr which has a half life of $2.1 \times 10^5$ years and can produce through electron capture $^{81}$Br, and $^{85}$Kr which has a half life of 10.76 years and $\beta^-$ decays to $^{85}$Rb but with maximum energy of the electron 0.7 MeV ($E_\gamma = 0.514$ MeV). Therefore, no decay can produce electrons with energies above our threshold requirement. (For neutron capture events, see below.)
6.4—*Neutron reactions.* A primary source of background is the radiation induced by $^{238}$U, which is contained in rocks, concrete and stainless steel. Neutrons coming from the spontaneous fission of $^{238}$U may interact with Argon nuclei through inelastic scattering or absorption, emitting gamma rays which in turn produce Compton electrons. These electrons can then simulate solar neutrino events.

The neutron background in the Gran Sasso Laboratory has been measured in the Hall B, and the following fluxes are obtained[6.3]:

\[(5.3 \pm 0.9) \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \quad \text{thermal neutrons} \quad (E_n = 0.025 \text{ eV})\]
\[(3.0 \pm 0.8) \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \quad \text{fast neutrons from fission spectrum}\]

These fluxes correspond respectively to 14.8 sec$^{-1}$ and 8.4 sec$^{-1}$ neutrons traversing the boundaries of a volume of the dimensions of the fiducial volume. However they can be easily shielded for instance using a water wall of some 30 cm thickness reduces the flux by an attenuation factor of at least $10^4$, thus bringing them down to a harmless level. Thus the external background neutrons can be reduced at the detector surface by an appropriate shielding.

A second possible source of neutron background are the dewar and the cryogenic chamber made of stainless steel. All materials used in the construction of the detector retain a small amount of residual radioactivity which must be taken into account. Typical values for several materials are listed in Table 6.5.

![Energy levels of $^{40}$Ar.](figure62.jpg)
### Table 6.5.— Activities in materials used to construct detectors, from Camp et al [6.4]

<table>
<thead>
<tr>
<th>Material</th>
<th>$^{232}$Th</th>
<th>$^{238}$U</th>
<th>$^{40}$K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life (years)</td>
<td>1.41×10$^{10}$</td>
<td>4.5×10$^{9}$</td>
<td>1.26×10$^{9}$</td>
</tr>
<tr>
<td>Branching ratio into fission</td>
<td>&lt; 10$^{-10}$</td>
<td>≈2×10$^{-8}$</td>
<td></td>
</tr>
<tr>
<td>Typical commercial sample Activity (counts/min/gram)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum 6061 (Harshaw)</td>
<td>0.42</td>
<td>0.04</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Aluminum 1100 (Harshaw)</td>
<td>0.24</td>
<td>&lt;0.017</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>Aluminum 1100 (ALCOA)</td>
<td>0.08</td>
<td>&lt;0.026</td>
<td>0.11</td>
</tr>
<tr>
<td>Aluminum 3003 (ALCOA)</td>
<td>0.10</td>
<td>&lt;0.026</td>
<td>0.56</td>
</tr>
<tr>
<td>Stainless Steel 304</td>
<td>&lt;0.006</td>
<td>&lt;0.007</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>Stainless Steel 304L</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Berillium Copper Alloy</td>
<td>&lt;0.02</td>
<td>&lt;0.06</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Copper sheet</td>
<td>&lt;0.05</td>
<td>&lt;0.06</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Pyrex window</td>
<td>0.45</td>
<td>0.27</td>
<td>3.8</td>
</tr>
<tr>
<td>Quartz window</td>
<td>&lt;0.018</td>
<td>&lt;0.018</td>
<td>&lt;0.07</td>
</tr>
<tr>
<td>Neoprene</td>
<td>&lt;0.008</td>
<td>&lt;0.01</td>
<td>0.36</td>
</tr>
<tr>
<td>Epoxy</td>
<td>0.006</td>
<td>&lt;0.01</td>
<td>&lt;0.19</td>
</tr>
</tbody>
</table>

The values given in Table 6.5 are upper limits for a given sample. We expect very large variations in the numbers, depending on the origin of the metals used for construction. We see no alternative to a careful screening of all components to be used for the detector. We have made measurements on a sample of steel which is close to the material we plan to use for the actual construction. We have found that Uranium is the main contaminant, with an activity of 0.003 counts/min/gram, roughly 1/2 of what is given in Table 6.5, corresponding to a $^{238}$U concentration of $1.02 \times 10^{13}$ atoms per gram of stainless steel. By extrapolation there are $2.7 \times 10^{20}$ atoms of $^{238}$U (0.11g) in 26.5 ton of stainless steel of the inner vessel, which will produce approximately $6.77 \times 10^{4}$ neutrons per year (2.5 neutrons/fission), namely a flux entering the detector of $3.8 \times 10^{-10}$ neutrons cm$^{-2}$ s$^{-1}$.

The energy spectrum of the spontaneous fission neutrons has an average energy of 2 MeV, a most probable energy of 0.72 MeV, and is described by the following empirical expression[6.5]

$$n(E)\,dE = (2/\pi\varepsilon)^{1/2} \, e^{-E} \sinh(2E)^{1/2} \, dE$$

where $E$ is the neutron energy in MeV.

Neutrons are slowed down in Argon by elastic and inelastic collisions and eventually come in thermal equilibrium with their surroundings. For liquid Argon, due to the large difference between the mass of the neutron and the Argon atom, the energy loss per elastic scatter is very small, only 2.5 KeV, and so the neutrons lose very little
energy by this mechanism. For neutrons of energy above 1 MeV inelastic scattering becomes the main mechanism for slowing down the neutrons. A preliminary result from the MCNP Monte Carlo[6.6,6.7] suggests that about 27% of the neutrons actually interact and produce gamma rays, mostly of low energy. The remaining neutrons escape from the active volume before interacting.

The inelastic scattering reaction $^{40}\text{Ar} (n,n'\gamma)^{40}\text{Ar}^*$ produces low energy gammas, up to a few MeV, but for an electron energy threshold of 5 MeV these will not be important. The decay scheme is given in Fig. 6.2. Of much greater importance is the

![Energy levels of $^{41}\text{Ar}$](image)

Figure 6.3— Energy levels of $^{41}\text{Ar}$.

| Table 6.6 — Expected numbers of events for the radiative neutron capture reaction. |
|---------------------------------|----------------|----------------|
| Reaction                        | $E_x$(MeV)    | rate/year     |
| $^{40}\text{Ar} (n,\gamma)^{41}\text{Ar}$ | 3.70           | 33            |
|                                  | 4.74           | 218           |
|                                  | 5.58           | 56            |
radiative capture reaction $^{40}\text{Ar} \ (n, \gamma) \ ^{41}\text{Ar}$. The cross-section for this reaction is 660 mb at thermal energies[6.8] and the Q-value is 6.1 MeV, giving gamma rays of energies up to 5.58 MeV. The $^{41}\text{Ar}$ is also radioactive with a half-life of 1.83 hours (see Fig.6.3).

The main $\beta^-$ branch proceeds to the $^{41}\text{K}$ energy level of 1.293 MeV (99%), and with much weaker branches (0.05%) to 1.67 MeV and (0.8%) to the ground state. The energy of the gamma ray which is then emitted during the transition to the ground state is 1.293 MeV with an intensity of 99.1%. All these energies are sufficiently low to present no problem. The number of $^{40}\text{Ar}$ atoms in our detector (200 tons of Argon in the fiducial volume) is $3 \times 10^{30}$. The expected numbers of events are given in Table 6.6 for the radiative capture reaction.

We have also considered the possible background due to neutron captures on the small amounts of Xenon and Krypton contained in the liquid, since they are the only sizeable impurities which can be accepted because they do not trap electrons. The rates per year of neutron capture events for the stable isotopes of Xenon are summarized in Table 6.7. We conclude that Xenon does not constitute an appreciable source of background.

<table>
<thead>
<tr>
<th>Xenon stable isotopes</th>
<th>Nat. abundance (%)</th>
<th># of atoms</th>
<th>$\sigma_c$ (barn)</th>
<th>rate (events/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{124}\text{Xe}$</td>
<td>0.10</td>
<td>$1.50 \times 10^{22}$</td>
<td>22</td>
<td>$5.30 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{126}\text{Xe}$</td>
<td>0.09</td>
<td>$1.35 \times 10^{22}$</td>
<td>0.26</td>
<td>$5.60 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^{128}\text{Xe}$</td>
<td>1.91</td>
<td>$2.80 \times 10^{23}$</td>
<td>0.36</td>
<td>$1.66 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{129}\text{Xe}$</td>
<td>26.40</td>
<td>$3.96 \times 10^{24}$</td>
<td>18</td>
<td>0.11</td>
</tr>
<tr>
<td>$^{130}\text{Xe}$</td>
<td>4.10</td>
<td>$6.15 \times 10^{23}$</td>
<td>0.42</td>
<td>$4.16 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{131}\text{Xe}$</td>
<td>21.20</td>
<td>$3.18 \times 10^{24}$</td>
<td>90</td>
<td>0.46</td>
</tr>
<tr>
<td>$^{132}\text{Xe}$</td>
<td>26.90</td>
<td>$4.03 \times 10^{24}$</td>
<td>0.025</td>
<td>$1.62 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{134}\text{Xe}$</td>
<td>10.40</td>
<td>$1.56 \times 10^{24}$</td>
<td>0.003</td>
<td>$7.50 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>8.90</td>
<td>$0.16 \times 10^{24}$</td>
<td>0.16</td>
<td>$3.44 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

In Table 6.8 we give the corresponding rates for Krypton. We remark that reaction $^{83}\text{Kr} \ (n, \gamma) \ ^{84}\text{Kr}$ has the highest rate. Gamma-rays emitted during the transition to the ground state of $^{84}\text{Kr}$, starting from the level at 4 MeV have a maximum energy of 2.7 MeV and therefore they are harmless.
6.5.— *Rejection of background events.* The gamma rays produced from the radiative neutron capture have energies of the order of a few MeV. Hence most of their interactions are Compton scatters\(^{(6)}\). Electrons which have energies above our threshold energy, \(E_{\text{thresh}}\), will simulate recoil electrons from the neutrino-electron scatters. However, as pointed out already, these electrons will typically be accompanied by extra energy depositions due to the successive interactions of the photon or to the other gammas emitted in the nuclear cascade process which has generated the initial photon, spread over a relatively large region around the event. In other words, the event will be *"noisy"*. In contrast, the recoil electrons from solar neutrino events will be *"quiet"*, since the neutrino has a negligible probability of secondary interactions. This difference can be used to reject the background events.

In order to make it effective, this technique must pick-up the lowest, additional energy deposition in an extended volume (\(\geq 1\) m\(^3\)) centered around the electron track under consideration. We shall choose as the minimal acceptable energy deposition a signal above a given threshold recorded by two wires, one from each wire plane, coincident in time. The energy deposition must be true, namely the threshold should be set safely above the fluctuations in the electronic noise. The choice of such threshold energy and volume will depend on several parameters:

i) the volume must be large enough to contain as much of the energy of the gamma shower as possible, but taking into account the growing number of channels and the correspondingly increased probability of noise fluctuations as the volume increases

ii) the number of samples in time that are required to be above the threshold (one time sampling is 200 nsec wide). Clearly a physical signal must persist on the wire over several time bins, whereas the most likely noise fluctuation is a single spike in one

\(^{(6)}\) For instance 75% of all interactions are Compton events at 6 MeV, increasing to 99% at 1.0 MeV
Figure 6.4— Scatter plot plus projections of the extra energy deposited in a volume of 1 m$^3$ centred on the recoil electron as a function of the energy of the highest kinetic energy recoil electron from a 4.74 MeV gamma-ray.
bin. We require a chain of five, consecutive time samples above threshold in order to make the signal acceptable. Since to a good approximation the noise fluctuations of the electronic circuits can be represented by a gaussian distribution, we convert the number $n$ of r.m.s. deviations into the equivalent energy deposition inside the volume of Argon $E_n = n \times (r.m.s. \text{ of electronic noise}) \times 0.0236 \text{ keV}$ — where 23.6 eV is the energy loss needed to produce an electron in the conditions of our detector. Taking into account the actual geometry of the detector, we find that the event loss for a volume of 1 m$^3$ is 10% for a threshold $n = 2.4$, falling very fast with $n$, becoming essentially zero for $n \geq 2.5$. Halving the volume does not make a big difference to the choice of threshold.

A typical noise of a single collection sense-wire after appropriate filtering is 400 electrons r.m.s. and the cut $n = 2.5$ corresponds to a minimal energy loss of 23.6 keV in a volume of 1 m$^3$, which is then the lowest energy contribution that our detector is capable of sensing.

The Monte Carlo simulation described in section 4.5 was used to investigate the percentage of Compton events rejected by these cuts. The gamma ray is generated at the centre of one of the drift volumes of the detector. For each event we select the highest energy recoil electron and define the starting point of this track as the origin of the volume in which the extra energy should be contained. The extra energy $E_{\text{add}}$ is the sum of all energies deposited on each wire, excluding the recoil electron. Wire signals simulated by the Monte Carlo were included in this extra energy balance if the pulse height was $n > 2.5$.

**Table 6.9.** Number of background events that survive, as a function of $E_{\text{thresh}}$ for three different gamma ray energies. The volume used is 1 m$^3$. The initial rates are the ones of Table 6.6.

<table>
<thead>
<tr>
<th>$\gamma$ energy (MeV)</th>
<th>Electron energy (MeV)</th>
<th>&gt; 1</th>
<th>&gt; 2</th>
<th>&gt; 3</th>
<th>&gt; 4</th>
<th>&gt; 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.70</td>
<td></td>
<td>5</td>
<td>3</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.74</td>
<td></td>
<td>27</td>
<td>24</td>
<td>17</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>5.58</td>
<td></td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig. 6.4 shows the scatter plot of the extra energy $E_{\text{add}}$ deposited in a volume of 1 m$^3$ around the recoil electron track as a function of the kinetic energy for the highest energy recoil electron from a 4.74 MeV$^7$ gamma-ray. Also shown are the projections

$^7$ This gamma-ray energy is one of the most probable lines in the capture of thermal neutrons by Argon.
of the scatter plot. There is a band of events having extra energy close to zero where most of the energy escapes from the volume.

We give in Table 6.9 and the expected number of neutron induced background events/year(8) that can not be rejected as a function of $E_{\text{thresh}}$ for the recoil electron by requiring that there is an extra energy deposition $E_{\text{add}} \geq E_{\text{n}} = 23.6$ keV.

We note that the events rates given in Table 6.9 are quite low, amounting to a few events /year above 5 MeV threshold, although the large uncertainties of the estimate must be stressed. In these events, the angular requirement has not yet been applied. We expect the recoil electrons from the solar neutrino events to be correlated to the Sun-Earth direction while the electrons from the gamma-rays will be isotropically distributed with respect to the instantaneous orientation of the Sun. As already discussed in section 5, this information is a powerful tool in order to further reduce the number of background events.

6.6. — References.

[6.1] R. Davis, private communication

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(8) The neutron flux has been approximately calculated using the scarce information coming from the measured radioactivity of our steel sample. We must stress the large uncertainties in these figures, which must be eventually determined by measurements on the final detector.
DESCRIPTION OF THE ICARUS I DETECTOR

7. — Mechanical design of the Dewar.

7.1. — General considerations. The cryostat consists of two coaxial horizontal stainless steel vessels, separated by the thermal insulation, made of perlite. The dimensions are governed by the transport requirements of the assembled cryostat with respect to roads and tunnels. The maximum dimensions allowed are: a length of 15 m, a width of 6 m and a height of 4 m.

The simplest, lightest and most economical type of structure for both the internal and external vessels would be a cylinder with a circular cross section. In this case, the outer vessel should have a 4 m diameter and, taking into account the necessary circular stiffeners for both vessels and a minimum reasonable gap for thermal insulation, the inner vessel diameter would be 3.3 m [7.1]. With this geometry, the total internal volume would be 110 m$^3$, the sensitive volume 70 m$^3$ and the maximum drift length 1.30 meters.

In order to increase the sensitive volume and the drift length, an hippodrome shaped cross section has been adopted, with the external dimensions equal to the maximum ones allowed for transportability. To reduce the high bending moments.

Figure 7.1 — Cross section of the 210 m$^3$ ICARUS dewar.
Figure 7.2 — Longitudinal section of the 210 m$^3$ ICARUS dewar.
acting in the transverse plane, the elastic deformations and therefore the weight and the cost of the structure, the internal vessel has been reinforced with a series of columns in the longitudinal symmetry plane, compatible with the geometry of the internal detector [7,2]. Fig. 7.1 shows the cross section of the dewar. Fig. 7.2 shows its longitudinal section.

<table>
<thead>
<tr>
<th>Table 7.1.— Parameter list of the 300 Ton Dewar of ICARUS I</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.-Liquid Argon</td>
</tr>
<tr>
<td>Operating pressure</td>
</tr>
<tr>
<td>Operating temperature</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Total volume</td>
</tr>
<tr>
<td>Total mass</td>
</tr>
<tr>
<td>Sensitive volume</td>
</tr>
<tr>
<td>Sensitive mass</td>
</tr>
<tr>
<td>2.-Inner vessel</td>
</tr>
<tr>
<td>width</td>
</tr>
<tr>
<td>height</td>
</tr>
<tr>
<td>length</td>
</tr>
<tr>
<td>volume</td>
</tr>
<tr>
<td>3.-Outer vessel</td>
</tr>
<tr>
<td>width</td>
</tr>
<tr>
<td>height</td>
</tr>
<tr>
<td>length</td>
</tr>
<tr>
<td>volume</td>
</tr>
<tr>
<td>4.-Access port diameters</td>
</tr>
<tr>
<td>Manhole</td>
</tr>
<tr>
<td>Cable port</td>
</tr>
<tr>
<td>H.V. Connector port</td>
</tr>
<tr>
<td>5.-Design Parameters</td>
</tr>
<tr>
<td>Inner vessel max. Int. overpress.</td>
</tr>
<tr>
<td>Inner vessel max. Ext. overpress.</td>
</tr>
<tr>
<td>Inner vessel Temperature</td>
</tr>
<tr>
<td>Outer vessel max. Int. overpress.</td>
</tr>
<tr>
<td>Outer vessel max. Ext. overpress.</td>
</tr>
<tr>
<td>Outer vessel Temperature</td>
</tr>
<tr>
<td>6.- Materials</td>
</tr>
<tr>
<td>Inner vessel</td>
</tr>
<tr>
<td>Outer vessel</td>
</tr>
<tr>
<td>Supports</td>
</tr>
<tr>
<td>Insulation</td>
</tr>
</tbody>
</table>

For identical reasons, the external vessel is also provided with a special supporting system. The total internal volume of the cryostat becomes 210 m\(^3\) (300 tons of liquid Argon), the sensitive volume 130 m\(^3\) and the maximum drift length about 2.30
m. An external cryogenic expansion vessel of a minimum of 10 m³ is necessary to allow safe and stable operations with the detector cryostat when fully filled with Argon.

<table>
<thead>
<tr>
<th>Suppliers</th>
<th>Others (pipes, entries, etc)</th>
<th>kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative(1)</td>
<td>Perlite, under vacuum.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Perlite, vacuum broken accidentally</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>TOTAL, perlite (under vacuum)</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>TOTAL, perlite (vacuum broken accidentally)</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>Nitrogen consumption, normal oper.</td>
<td>0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Suppliers</th>
<th>Others (pipes, entries, etc)</th>
<th>kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative(2)</td>
<td>Superinsul., under vacuum.</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Superinsul., vacuum broken accidentally</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td>TOTAL, superinsul. (under vacuum)</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>TOTAL, super.(vacuum broken accidentally)</td>
<td>41.2</td>
</tr>
<tr>
<td></td>
<td>Nitrogen consumption, normal oper.</td>
<td>0.034</td>
</tr>
</tbody>
</table>

7.2. — The internal and external vessels. The cryostat's internal vessel is one of the most delicate components of the experimental equipment, because it has to contain the pure liquid Argon. The vessel must withstand two pressure conditions: vacuum during the testing stages, the cleaning and the initial filling and, in addition to hydrostatic pressure, a maximum internal vapor over-pressure of 2 bar, referred to vacuum, at liquid Argon temperature.

The material to be used is a special stainless-steel, chosen for its excellent mechanical and chemical properties at low temperatures. The cylindrical part of the internal vessel is made out of a shell, electro-polished internally, and reinforced externally by welded annular U-type profiles, which also have the function of channelling the liquid Nitrogen of the cooling system. Cooling of the end caps is achieved by circulation of Nitrogen in a special double envelope. One end cap is connected to the cylinder by a bolted flange, provided internally with a lip-joint, to ensure a leak-tight seal. The internal vessel rests on the external vessel by means of two longitudinal vetronite (glass fiber reinforced epoxy resin) supports.

(9) The Physical characteristics of stainless-steel X2CrNiN 1811 UNI 7500 taken from Ref. [7.3] are as follows: C, 0.03%; Mn, 2%; Si, 1%; Cr 17.0 - 19.0%; Ni 9.0 - 12.0%; N₂, 0.12 - 0.25%; P, 0.045; S, 0.03%. The mechanical properties are: tensile stress 55 - 75 kg/mm²; elastic limit 28kg/mm²; elongation 40%; hardness Brinell 210 max; hardness Rockwell 95 max.
The external vessel has two main functions, as a container for the perlite and as a safety container for the Argon, in case of an accidental crack of the internal vessel. For this reason the material chosen for its construction is the same stainless steel used for the internal vessel. Also, this vessel must withstand two pressure conditions: vacuum for better working conditions of the insulation system and an internal maximum over-pressure of 1 bar, referred to atmospheric pressure at liquid Argon temperature. The cylindrical part is a shell, internally reinforced by a range of welded annular T-type profiles, which also provide reinforcement for the supports of the internal vessel.

In addition this vessel has an end cap with a bolted flange and the sealing is guaranteed by an external lip-joint. Fig. 7.3 shows details of construction of the circular stiffener and lip-joint of the two vessels.

**Figure 7.3.**—Details of construction of the circular stiffeners and lip-joint of the two vessels.

Two longitudinal beams, attached to the under-side of the external vessel, provide the supporting system for the entire cryostat. They can be equipped with a system of wheels for transportation. The cryostat is provided with three main entry points on the top: a manhole (1000 mm), a passage for signal cables (600 mm) and one for the high voltage cables (300 mm). A number of other entry points are provided for Argon, Nitrogen, perlite, vacuum pumps, safety valves and control devices.
The volume between the two vessels is filled with expanded perlite, which is a mineral granulate, made out of a volcanic rock, which is ground and expanded under heat.\(^{(10)}\)

It is foreseen to operate this material under vacuum as this vastly improves its insulation properties. In air, at atmospheric pressure, the heat transfer rate is 10 times higher, but still good enough to ensure, in case of a vacuum break-down, the possibility of continuing to run the experiment.

A special annular septum between the two vessels allows the opening of the end cap, for access to the cryostat, without having to remove all the perlite.

Thermal insulation with vacuum and "super-insulation" is also envisaged. The super-insulation consists of aluminium foils separated by glass felt under a vacuum of \(< 5 \times 10^{-4} \text{ torr}\). The aluminium foils reduce considerably the heat transmitted by radiation and the glass felt isolates them thermally. The heat conductivities of the two solutions are given in Table 7.3.

<table>
<thead>
<tr>
<th>Table 7.3 — Heat conductivities of perlite and super-insulation (w / m °K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure</td>
</tr>
<tr>
<td>perlite</td>
</tr>
<tr>
<td>super-insulation</td>
</tr>
</tbody>
</table>

7.3 — The cooling and heating systems. The system, designed to compensate for the heat losses during operation, is also used to cool down the cryostat in a controlled way before filling with Argon, and to warm the cryostat prior to emptying. It is based on the circulation of liquid and/or gaseous Nitrogen, in controlled conditions, inside the annular slots surrounding the inner vessel. The Nitrogen is provided by a storage dewar and a vaporizer produces the gaseous phase. Fig. 7.4 shows the cooling system. During normal operation of the cryostat, the pressurized liquid Nitrogen circulates in the slots and evaporates at a rate which depends on the heat losses. The vapor is released into the atmosphere through a relief valve rated at about 4 bar absolute. In order to avoid large temperature differences, which would cause boiling or freezing of the Argon, and to minimize its convection, the Nitrogen temperature has to be very near to that of the Argon.

\(^{(10)}\) The chemical properties of perlite taken from Ref. [7.4] are as follows: \(\text{SiO}_2\) 75\%; \(\text{Al}_2\text{O}_3\) 15\%; Others 10\% (Na and K oxides + feldspar derivates). It is Non flammable, pH 6 - 8; humidity 0.25\% max; density 70 kg / m\(^3\).
Figure 7.4.— Cryogenic system of the 210 m³ ICARUS dewar.
For this reason, the dimensions of the slots and their relative distances have been optimized and in addition an aluminum sheet is added to envelope the stainless steel wall and increase its thermal conductivity. The system is also used for the operations of filling and/or emptying of the cryostat. In this case, a gaseous Nitrogen flow is used to cool down, or warm up, the internal vessel in controlled conditions, in order to speed up the operations without creating dangerous thermal shocks.

7.4.— Cleaning of the inner surfaces. Cleanliness of the internal vessel is of primary importance in preserving the purity of the liquid Argon. The extremely high level of cleanliness required must be applied to all surfaces in contact with liquid Argon, such as the internal surfaces of the cryostat, all piping, expansion bellows and accessories. They must be clean and free of contamination, especially loose dirt, welding scale, hydrocarbons and all other materials likely to outgas.

The main operations foreseen in order to achieve such a high level of cleanliness in the inner vessel include a series of treatments to be performed on the stainless steel sheet before assembly (degreasing, thermal outgassing, washing, drying, electrochemical polishing, final washing with thermal drying and finally the application of a film protection) and another series of treatments after assembly (smoothing and polishing of welded joints, general cleaning by an anodic treatment, cleaning with Nitrogen, vacuum degassing).

7.5.— Operations. A number of different operations are foreseen in the filling, normal running and emptying of the cryostat.

i) Filling of the cryostat. In order to avoid dangerous thermal shocks in the cryostat during the filling with Argon, the internal vessel has to be cooled down gradually. For this purpose the liquid Nitrogen, coming from the storage dewar, is vaporized in an atmospheric heater and the Nitrogen vapor, at a temperature of about 50 degrees less than the internal vessel's temperature, is sent into the cooling system slots and then vented. When the cryostat temperature reaches of -130 °C, liquid Nitrogen will be sent directly into the slots, in order to accelerate the cooling down process. This operation lasts about three days [7.5].

ii) Normal operation. During the cryostat operation the thermal losses (those through the insulation, the support system, the manholes, the signal and the high voltage cables) will vaporize a quantity of liquid Nitrogen sent from the storage dewar directly into the slots of the cooling system. In these conditions, for the reasons already explained above, the Nitrogen temperature has to be nearly equal to the temperature of the liquid Argon. In these conditions, the Nitrogen must have a temperature of about
91 0K and an absolute pressure of about 3.9 bar. Here also the Nitrogen vapors (about 35 m³/h at ambient conditions) have to be vented.

iii) Emptying of the cryostat. If it is necessary, for any reason, to empty the cryostat, it has to be brought to the ambient temperature with a process exactly opposite to the one applied for the above operation of filling, for the same reason of avoiding thermal shocks. If, for any reason, the inner vessel has to be heated up to 150 0C, an air blower with an electrical heater is provided.

7.6.— Vacuum system. For pumping of the insulation space filled with perlite a mechanical booster pump combined with a rotary pump will be needed. The pumping speed at atmospheric pressure should be of the order of 50 m³/h and the pumping speed at 10⁻² mbar of the order of 200 m³/h. Both pumps will have a liquid Nitrogen cold trap.

For pumping of the insulation space filled with "super-insulation" a diffusion and rotary pump are needed.

The high-vacuum pumping will be carried out using a booster pump combined with a rotary pump for the primary vacuum, followed by liquid helium cryogenic pump to obtain the high vacuum required inside the vessel of about 10⁻⁹ mbar.

7.7.— Safety devices. In case of failure of the Nitrogen cooling system, the liquid Argon will be vented through a rupture disc rated at about 1.5 bar absolute. The argon flow will be about 10 m³/h at 91 0K.

In case of vacuum deterioration the nitrogen flow is increased considerably and the gas produced will be vented through a relief valve rated at 5 bar absolute. The corresponding flow will be 340 l/h liquid Nitrogen in case of perlite insulation and 1230 l/h in case of super-insulation.

In case of a failure of the inner tank a safety device is foreseen in order to exhaust the vapor produced by the liquid entering the vacuum space.

7.8.— Geometry of the inner electrodes. The inner volume of the dewar will be separated into four main parts. The barrel-like volume will be split vertically along its axis to form a left and a right section, each one a mirror image of the other. These in turn will be split in two equal parts roughly half-way along the barrel axis: the for- and aft-sections. A small central part of the volume will be excluded from this quartering because it will be needed as a service area to allow input/output to electronics and high voltage for the detector sections in addition to providing access for general installation and maintenance. Fig. 7.5a, 7.5b show perspective drawings of two adjacent sectors and various cross-sections through them.
Figure 7.5.— (a) Perspective view of two adjacent drift volumes. (b) Schematic cross section showing the $T_0$-wire system and the wire chamber.
Each section will be equipped with an identical wire chamber system. This will be supported by a frame resting on the center of the dewar floor and held vertically in position between two rails. These rails, one on the bottom and the other on the ceiling of the dewar, will be used to slide in the frame and keep it in place in a manner as independent as possible from the cryogenic deformations of the dewar walls (see the engineering description of the dewar, sections 7.1 and 7.2). There will be one such frame support common to two adjacent drift volumes. The frame will ensure a planarity of \( \approx 0.5 \) mm over the entire surface of the chambers. The maximum expected frame deformation under the weight and the tension of the wires is \( \approx 0.1 \) mm.

Each chamber will cover a surface equal to \( 5.5 \times 3.0 \) m\(^2\). The drift volume will be defined by a system of "race-tracks" consisting of 40–50 tubular rings of dimensions \( 5.5 \times 3 \) m spaced \( 5 \) cm apart and \( 20 \) cm from the inner wall of the dewar. The race-track system will be connected to the high-voltage power supply with each individual ring being set at the appropriate voltage by means of a resistor chain contained in the service area. The purpose of the race-track system is to establish a well defined and uniform electric field all over the detection volume so that the electrons may be correctly and efficiently drifted onto the wire plane. Fig. 7.6 shows a schematic of the race-track system.

![Figure 7.6](image)

**Figure 7.6.**—Schematic of the race-track system.

Another constituent of the detector will be the \( T_0 \) grid needed to forewarn the data-acquisition that an event has taken place satisfying the required conditions and that it should be recorded. A further important purpose of this system will be to provide the means (for the off-line analysis programs) for a rough spatial reconstruction of the event origin complementing the information from the wire planes and resolving the possible
pattern-recognition ambiguities which could arise. The components of the $T_0$-system will be steel wires 1—2 mm in diameter and 5.5 meters long stretched parallel to the dewar's longitudinal axis and spaced = 25 cm from each other over the whole detection volume. There will be $= 90$ such wires per drift volume arranged in 8 vertical rows. These wires will be connected to the corresponding race-track rings (this will give the added benefit of an increased field uniformity over the detection volume) and will be supported by the same structure which is used to hold in position the race-track rings. An important requirement of the system is that it must be capable of being easily dismounted to allow access to the chambers in case of adjustments or repairs. The $T_0$ grid system can be seen in Fig. 7.5b.

![Diagram of drift and focusing](image)

**Figure 7.7.** The screening/focussing plane.

7.9. *Geometry of the chamber planes.* Each chamber consists of three planes of wires. Going from outside to inside the first plane will be a screening/focussing grid, followed by an induction-based detection plane and finally a collection-based detection plane. Defining our coordinate system as having the X-axis along the dewar's longitudinal axis and the Y-axis parallel to the vertical direction, these detection planes will measure the projection of the tracks along one or the other coordinate ($X$ or $Y$) plus its time component ($t$). The characteristics of the various planes are as follows.

(a) The screening/focussing plane will be made of a grid of parallel wires =100 $\mu$m in diameter and 3 m long, with a 2 mm spacing and arranged parallel to the $Y$ direction. The purpose of this grid is two-fold. It has to prevent the sense-wires from detecting the drifting electrons until they have crossed the grid. The second function is the focussing of the electric field lines. By an appropriate adjustment of the potential difference between the grid and the sense-wires the field lines will be funnelled through
the narrow space between the sense-wires (500 μm) thus forcing the electrons to pass between the wires. Fig. 7.7 shows a schematic view of the grid.

(b) The first detection plane will consist of a set of sense-wire pairs 500 μm apart, 100 μm in diameter and 3 meters long, interspaced with a 2 mm pitch grid identical to that described above for the screening grid. The purpose of the sense-wires is to detect the signals induced by the electrons while they drift towards them. The presence of the interleaving grid is to insulate the adjacent sense-wires from each other's signals. These wires will be parallel to the vertical axis of the dewar and will measure the "Y-t " component of the track projection. See Fig. 7.8.

![First detection plane (induction)](image)

Figure 7.8.— The induction-mode sense-wire plane.

(c) The second detection plane will be similar to the first except that the electrons will now be collected on the sense-wires. Differently from the "Y-t" planes the sense-wires will be held at a potential such that the electrons are collected on them rather than drifting by. The wire direction will be orthogonal to that of the first detection plane and parallel to the horizontal axis of the dewar. They will be 5.5 meters long, 100 μm in diameter and will measure the "X-t" component of the track projection. See Fig. 7.9.

The three planes described above will be separated from each other by 2 to 4 mm. The exact figure will depend on the result of the study (under way) of the signal optimization. Table 7.4 gives the required voltage setting of the planes for three possible plane separations.
The electric field map of the chamber region has been calculated for the above three different plane separations. These field maps and the method used to obtain them are discussed in more detail in chapter 8.

<table>
<thead>
<tr>
<th>Plane</th>
<th>Function</th>
<th>2 mm</th>
<th>3 mm</th>
<th>4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Screening/focusing</td>
<td>-1250</td>
<td>-1750</td>
<td>-2250</td>
</tr>
<tr>
<td>2</td>
<td>X sense-wires</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>X screening wires</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Y sense-wires</td>
<td>+1400</td>
<td>+2100</td>
<td>+2800</td>
</tr>
<tr>
<td>3</td>
<td>Y screening wires</td>
<td>+1000</td>
<td>+1500</td>
<td>+2000</td>
</tr>
</tbody>
</table>

Each drift volume will have a total of ≈ 10,000 wires for the induction-mode plane of which ≈ 5,400 will be sense-wires (corresponding to 2700 pairs). The collection plane will consist of a total of ≈ 3,000 horizontal wires, of which ≈ 1,500 are sense-wires. The deviation of the wires from their measured position will be minimized by applying a tension of ≈ 200 g per wire. Possible irregularities in the wire construction or in the structure of the holding frames will be corrected by means of regularly spaced combs which will constrain the wire pitch at several critical positions along their length.
The materials planned for the construction of the chambers will be mostly stainless steel (AISI 316 L) and Macor ceramic, their performance and reliability having been checked during earlier extensive operational tests on prototypes in the past few years. In particular, these materials have proven capable of maintaining the extreme cleanliness in the surrounding liquid argon crucial because of the long drift distance for electrons through the detector volume. As a further bonus they are mechanically convenient for the elaborate work needed to achieve the high precision in the positioning of the various elements required for a correct operation at cryogenic temperatures. Finally they guarantee the low content in natural radioactivity contamination which is absolutely essential for the proposed experiment.

7.10.—The electrostatic configuration. The electric field generated by the race-track and the $T_0$ system has been calculated by the use of the relaxation method [7.6] for different ring positions and dimensions. The best configuration which optimises the field uniformity at the lowest cost in terms of number of shaping rings and simplicity of the installation has been found to be the one in Fig. 7.10.

![Figure 7.10.—Equipotential contours in a drift volume.](image)

This figure represents a transverse section through a drift volume. The ring cross sections are shown by the open circles (2 cm diameter). These are separated from each other by 5 cm and have a gradually increasing distance from the inner wall of the dewar so as to ensure the necessary safety distance against electrical break-down between rings and grounded wall. The bar represents the cathode where the full high-voltage will be applied (225 kV); the distance between cathode and wall will be 25 cm.
The wire plane itself occupies the first 12 cm of the section and is represented by the cross-hatched area. The small full circles are the cross sections of the $T_0$ wires, these are spaced 25 cm from each other and their purpose is fully described in section 8.7. The contour lines represent equipotentials of the electric field in 9 kV steps. The line density between rings and wall shows, when compared to that of the drift volume, that the electric field in this region although quite high ($= 10$ kV/cm) is still very uniform and well below the break-down value (estimated to be in the neighborhood of 50 kV/cm). The maximum drift distance is 225 cm. The active volume (i.e. the part of the volume between rings and chamber) is $= 83\%$ of the total.

7.11.—*The service area.* The space available in the middle of the dewar between the for and aft sections of the detector will be used as a service area. The area is approximately 1.4 meters wide and 3 meters high extending across the full dewar transverse section. There will be three portholes feeding into this region. The largest one is in the middle and allows human access (*the manhole*), two smaller ones are on the side and will serve as input/output for the signals and the high voltage transmission. The following components will be arranged inside this region or close to it.

(a) The high voltage conductors. These are cables and bars transmitting the required 250—300 kV voltage to the race track and the $T_0$ grid. There will be a separate high voltage transmission for each of the four detector sections. Fig. 7.11 shows the high voltage inlet.

![Figure 7.11.— High-voltage inlet.](image)

(b) A flange for the signal transmission. This flange will contain the feed-throughs for the all the sense-wires and whatever special arrangements required for the $T_0$ signals. These feed-throughs will be directly connected to a separate vessel (*the*
Figure 7.12.— Vertical cut along the longitudinal axis of the dewar (we refer to this plane as the X-Y plane).
Figure 7.13.— Horizontal cut along the longitudinal axis of the dewar (we refer to this plane as the X-Z plane; notice that Z in our detector will be given by the drift time, t).
refrigerator box) just outside the service area and standing on top of the dewar. This thermostatically isolated vessel will contain argon gas at 1 bar and at a temperature close to the boiling point.

The front-end amplifiers will be stacked inside this box thereby being at the minimum possible distance from the wires and consequently reducing the capacitive noise of the system to its minimum. Furthermore they will be kept at the optimum temperature needed to achieve the minimum possible noise level from the electronic components. The required temperature will be obtained via heat transfer from the power supply of the circuits themselves (see chapter 9). The amplifiers will transform the signals from the sense- and \( T_0 \)-wires into signals large enough to be transmitted without too much loss or distortion over the larger distances necessary to reach the rest of the electronics chain. The number of feed-throughs on this flange will be of the order of 16,000.

Figure 7.14.— Vertical cut across the longitudinal axis (the Y-Z plane of our coordinate system).

(c) The various systems needed to monitor the argon purity and the liquid level plus all the possible visual controls allowing an external inspection of the detector without having to dismount it. The connection between these system and the outside of the dewar will be ensured by means of cryogenic cables, optical fibers and other feed-throughs needed in particular cases.
(d) A special separate floor arrangement will be mounted at the bottom of the service area stretching over the whole dewar so as to allow easy and protected access to the various detector elements without damaging them.

7.12.—Technicalities. A vast number of detailed drawings of the apparatus have been produced. Here we only show the most relevant which are also useful for a fuller understanding of the simple description given above. Various cuts of the dewar together with its contents are shown on Figs. 7.12 to 7.14.

The rail system holding the frame is shown in three views on Fig. 7.15a,b,c together with parts of the frame.

The chamber mounting and the related support system for the wires is shown on Fig. 7.16. The planes shown here are for the case of the 4 mm plane separation. Fig. 7.17 gives a more detailed views of the wire-supporting and stretching procedure. The structure of the combs is also visible in detail.

7.13.—References.

[7.1] L. Bassi and M. Cicia, "Design and mechanical calculations of a 110 m$^3$ cryostat with a circular cross-section".

[7.2] L. Bassi, M. Cicia and M. Pallotta, "Mechanical calculations for a vessel of hippodrome-shaped cross-section".


[7.5] L. Bassi, M. Cicia and L. Mazzone, "Note on heat transfer problems in 210 m$^3$ ICARUS dewar".

Figure 7.15a.— Details of the rails and the frame.
Figure 7.15b.— Details of the rails and the frame.
Figure 7.15c.— Details of the rails and the frame.
Figure 7.16.— Details of the wire chamber planes and support structure.
Figure 7.17.— Details of the comb system and mounting device.
8.— Detailed analysis of the electrode configurations.

8.1.— Introduction. As we want to reconstruct the events in three dimensions we must record simultaneously all three track coordinates, hence the need for a non destructive read-out.

In the ICARUS detector phase 1 there will be four wire chambers. Each chamber will consist of two parallel read-out planes in the form of grids of sense wires with the wires of one plane arranged at 90° to the other (as shown in Fig. 8.1). In order to ensure the non-destructive read-out only the second sense-wire plane will work in the traditional charge collection mode, the first plane instead will exploit the idea of reading the charge 'induced' by the electrons as they drift towards the sense wires. The wires plus the drift time provide a three-dimensional electron image of tracks produced in the drift volume.

8.2.— The theory of charge induction and the chamber design. The theory of electron imaging of ionization events occurring inside the sensitive volume of a liquid argon TPC and the design of such a chamber was developed by Gatti et al. [8.1]. The basic design consisted of a screen grid of equally spaced parallel wires of pitch $W$ and a sense-wire grid, also of equally spaced parallel wires of pitch ($W$), placed at a distance ($d$) from the screen grid. This arrangement produces a two-dimensional electron image, one coordinate is provided by the position of the hit wires and the other by the drift time. For the three-dimensional read-out a second sense wire grid is placed at 90° to the first. The configuration for an idealised system with two sense-wire grids is shown in Fig. 8.1. The presence of the screen grid means that a signal is not induced on the sense-wires until the drifting electrons cross the grid.

The screening grids will be 100% transparent to the drifting electrons if the following condition is satisfied [8.2]

$$\frac{E_A}{E_B} > \frac{(1 + x)}{(1 - x)}$$

where $E_A$ is the field after the grid, $E_B$ is the field before the grid and

$$x = \frac{2\pi r}{W}$$

where $r$ is the wire radius and $W$ is the grid pitch.

In Fig. 8.2a and 8.2b we show the ideal shapes of the current pulse and charge pulse as a function of time as expected for the configuration in Fig. 8.1. At point A the electrons arrive at the screen grid and the sense-wires start to detect the induced current. As the electrons cross the grid the current remains constant until the electrons
Figure 8.1.— The wire configuration of an idealised system for electron imaging of ionization events.

Figure 8.2.— Idealized shapes for the configuration in Fig. 8.1: (a) the induced current as a function of the drift time expected for the configuration shown in fig. 8.1; the points A, B and C refer to the screen grid, the sense-wire grid and the anode respectively, (b) the induced charge expected for the same configuration, points A, B and C are as above.
reach point B, the sense-wire grid. At this point the current abruptly changes sign as
the electrons drift away from the sense-wires. The current stops flowing when the
electrons arrive at point C, the second sense-wire plane). Integration of this current
pulse to give the induced charge produces a triangular pulse whose width is equal to the
time required for the electrons to cross the distance (2d) between the screen grid and the
second sense-wire plane. Setting the electric field behind the first sense-wire plane to a
value lower than in the region above, results in the termination of the current at point B.
Therefore the charge reaches its maximum at point B and then remains constant (in
reality of course the feedback of the amplifier reading out the wires will cause this
charge to decay). We refer to the situation in Fig. 8.2 as "induction mode" and the case
described above as "collection mode".

The original design of Gatti suffered from two main problems. The first was that
non-negligible signals were induced on one sense-wire from electrons drifting towards
the neighboring sense-wire. One had to move at least three sense-wire gaps away
before this signal became negligible. The second problem was non-uniformity in shape
and magnitude of the induced signals which depended strongly on the lateral position of
the drifting electrons between the sense-wires.

In designing our chamber we have modified the original design to obtain a wire
arrangement that reduces both problems. This is shown schematically in Fig. 8.3. We
have replaced the plane of single sense wires with a plane containing pairs of sense
wires separated by a distance s with an extra wire in between each pair which acts as a
shield between the sense wires. We retain the screen grid as before. The electric fields
in the drift space (above the screening grid), and in the sense-wire region (below the
screening grid) are represented by $E_0$ and $E_1$ respectively. For electric fields in the gap
between the screen grid and the sense wires larger than those in the drift space the field
lines are focussed towards the sense wires. If the electric field between the induction
plane and the collection plane is chosen to be the correct value then the field lines pass
between the sense wires and for the three-dimensional chamber can reach the second
sense wire plane hence realizing the non-destructive readout. We have investigated
different choices of the wire diameters and spacings and our final choice is given below

$$ W = 2 \text{ mm} \quad d = 2 \text{ to } 4 \text{ mm} \quad s = 0.5 \text{ mm} \quad R_{GW} = 50 \mu\text{m} \quad R_{SW} = 50 \mu\text{m} $$

where $R_{GW}$ and $R_{SW}$ are the radii of the grid wires and the sense wires respectively.
These values are a compromise between (a) the spatial and the time resolution which
depend essentially on $W$ and $d$, (b) the simplest electric field configuration, (c) the
maximum induction signal which depends mainly on $R$ and (d) the practicalities of
construction. For these parameters the transparency of the screen grid is 100% if the
ratio of the fields after and before the grid, $E_1/E_0$ is at least 1.4 (as defined by the
equations given at the beginning of section 8.2).
Figure 8.3.— The wire configuration. The dimensions are $W = 2$ mm, $d = 2$ mm, $s = 0.6$ mm; The wire radius is $R = 50 \mu$m.
Figure 8.4.— The electric field for the induction-mode. Also shown are the equipotential lines. The wire configuration is that of Fig. 8.3 with an electric field ratio of $E_E/E_1 = 1/5$. 

Distance along the drift direction (cm)

Distance across the wire plane (cm)
Figure 8.5.— Maximum of the sum of the induced signals on the sense-wires as a function of the lateral position (L) of the electron. Points A, B, C, D, E and F serve as a reference for the Fig. 8.6.

Figure 8.6.— Sum of the induced signal on the sense-wires as a function of time for different positions of the drifting electrons. Points A, B, C, D, E and F are defined in Fig. 8.5.
Figure 8.7.— The equal-induction contour map for a sense-wire pair of the induction plane. The numbers give the fraction of induced charge in percent. The step from curve to curve is 5%.
However, in order to focus the field lines so that the sense wires are 100\% transparent requires that $E_r/E_0 \geq 5$. The field calculations have been made using a drift chamber simulation program that allows us to determine field configurations, expected signal shapes, etc. [8.3]. The procedure is the standard relaxation method applied over the whole drift volume. The calculation generates a full description of the electric field: field-lines, equipotentials, induced signals and wire capacitance.

The best focusing properties and the simplest potential distribution were found when the screen grid alone determined the above field ratios and the sense wires and shielding wires were sitting at the natural potential given by the field itself. The field map is shown in Fig. 8.4 for the geometrical parameters given above. The shielding inefficiency of the screen grid, which is a function of the geometry alone and not of the fields [8.2], is $\approx 10\%$. This inefficiency causes the sense wires to see the drifting electrons before they cross the screen grid and results in a 'small tail' at the beginning of the pulse (i.e. the signal starts with a gentle slope before abruptly increasing denoting the traversal of the screen-grid).

Similar to the case of the Gatti geometry the signal induced on a single sense wire varies according to the lateral position of the drifting electrons. However, for each signal induced on one of the wires there is also a signal induced on the other wire. The sum of the two signals is almost constant, as shown in Fig. 8.5 where the maximum of the sum is plotted as a function of the lateral position of the drifting electrons, for a grid spacing $d = 2\, \text{mm}$. The positions of the electrons generating the signals shown in Fig. 8.6 are indicated. We note that the induced signal never reaches 100\%, the maximum value being $\approx 88\%$ and the mean value $\approx 75\%$. In Fig. 8.6 we show the sum of the signals as a function of drift time for three positions of the drifting electrons, labelled A, B and C. Even though the pairs of sense wires are shielded from each other by the grid wires the shielding is not 100\%. This is illustrated by the curves labelled D, E and F in Fig. 8.5 and 8.6 which represent the signals induced on the sense wire due to the electrons drifting in the neighboring cell. This contribution is $\leq 6\%$ of the total drifting charge. Moving to the next but one cell their contribution is essentially zero. This behavior is quite different from that of the original design.

8.3.— The focussing geometry. Examining in more detail the focussing properties of the system, we have realised that these are exclusively governed by the geometry and potential of the first grid (Fig. 8.4). The screening of the signal appears to be determined only by the geometry of the system and not by the applied voltages. Finally, the transparency of the grid is 100\% when the field ratio exceeds the magic figure of 1.4 [8.2].
The configuration of Fig. 8.4 shows how these features can be combined to achieve, with a simple voltage distribution, good focussing together with a good screening efficiency and a 100% transparency.

Notice that the voltage applied is the same for all the wires of the second grid (sense and interspaced shield) and this voltage is set at the value corresponding to the position of the grid (the "natural" potential) in the constant $E_1$ field. The first grid is at the potential

$$V + \Delta V = (2.0 + 0.3) \text{ kV}$$

required by the fact that the geometry of the grid itself modifies the potential necessary to give the expected electric fields. How this happens is described in ref. 8.2. The voltage producing a field $E_1$ in the sense-wire region over a distance $d$ is not simply given by $V = E_1 d$ but must also take into account the difference between the electric fields before ($E_0$) and after the grid ($E_1$). This has the effect of an additional term $\Delta V = f(E_1 - E_0)$ where $f$ is a function of the wire diameter and pitch of the grid. In our case $f = 0.075$ and, for 1 kV/cm before the grid and 5 kV/cm after, the value of $\Delta V$ turns out to be $\approx 300$ V. When the additional term is taken into account and the potential of the grid accordingly modified, the effective field ratio turns out to be the expected one. Notice that already 1 mm away on either side of the first grid the electric field is uniform to better than 1%.

The signals on the sense-wires for a 2 mm gap between grids are shown in Fig. 8.6 for some of the electron trajectories focussed between the sense-wire pair. The time-spread of the signals is already quite small: the 5 to 1 field ratio here used could be increased if one wished to reduce this spread even further. This is not really necessary when the time spread due to the arrival of the electrons will be already larger than the one shown above.

The slow increase at the beginning of the pulse reflects the shielding inefficiency of the system. Notice that the time corresponding to the first grid crossing is roughly at the point where the signal is $\approx 10\%$ of the total. This effect can be seen better on the voltage equipotential map due to the sense-wires alone (see Fig. 8.7). The contour lines in this figure correspond to constant levels of induced charge and are labelled by the percentage of the total charge seen by the wires. At the crossing position of the first grid the induced signal is between 5 and 10% of the total.

8.4.— *Diffusion effect.* In order to find the optimum spacing ($d$) between the induction plane and the other grids, one has to take into account the spread of the electron cloud due to the diffusion process. This process is governed by the 'agitation energy' of the electrons and by the momentum transfer cross section in liquid argon [8.4].
There are two types of diffusion, lateral and longitudinal. The lateral diffusion is expected to play a minor role here as any movement of electrons towards the adjacent sense-wire cell will be compensated by the electrons moving in the opposite direction. However, the effects due to longitudinal diffusion will have a more marked effect on the electron track. The longitudinal spread is given by

$$\sigma = \sqrt{2Dt}$$

where $D$ is the diffusion coefficient and $t$ is the drift time. For thermal electrons we have the Einstein relationship, namely

$$D = \frac{k_B T}{e} \mu$$

where $\mu$ is the electron mobility, $T$ is the temperature and $e$ is the electron charge. Making the relevant substitutions in equation above with $T = 87^\circ K$ and $\mu = 545 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$ gives $D = 4 \text{ cm}^2 \text{ s}^{-1}$. Electrons in liquid Argon are thermal up to electric fields of $\approx 200 \text{ V/cm}$. At higher fields the electrons gain more energy from the field than they lose in collisions with the Argon atoms, thereby becoming non-thermal. Hence the Einstein relationship no longer applies. However, for fields $\leq 1 \text{ kV cm}^{-1}$ the diffusion coefficient has a constant value of $\approx 4 \text{ cm}^2 \text{ s}^{-1}$ (the low field value) [8.4]. Longitudinal diffusion spreads out the electron track in time; for a track segment which is parallel to the wire plane the electrons no longer arrive all at the same time. This leads to a broadening of the pulse on the sense-wires, hence a reduced pulse height (charge must be conserved). In Fig. 8.8 we show the expected spread in time of the electron track for different drift spaces at 1 kV/cm. Although the time spread is always small, (for a field of 1 kV cm$^{-1}$ and a maximum drift distance of 2.2 metres the time spread will be $\leq 0.5 \mu$s), our signal is very narrow and this small spread has a non-negligible effect. In Fig. 8.9 we have plotted the amplitude attenuation for different drift distances at 1 kV/cm.

The diffusion has the effect of degrading the definition of the track coordinates both in the x-y plane and in the drift direction. This can be reduced if the width of the induction signal is made larger than the typical diffusion spread. This can be done by increasing the space between the grids, this enlarges the signal width because of the increased drift time in the induction region (Fig.s 8.8 and 8.9). On the other hand the spacing cannot be enlarged too much because it has the side effect of reducing the screening efficiency of each 'induction cell' (the charge induced on the adjacent sense-wire pair increases, see Fig. 8.10). A reasonable compromise is a spacing of about 3 mm.
Figure 8.8.— The expected spread (at FWHM) of the induction signal as a function of drift distance. The different symbols refer to different interplane gaps.

Figure 8.9.— The expected amplitude attenuation of the induction signal as a function of drift distance. The different symbols refer to different interplane gaps.
Figure 8.10.— Amount of charge induced by the drifting electrons on the adjacent sense-wire pairs as a function of the spacing between the grids. The line is drawn to guide the eye.

8.5.— The effect of track angle on the induction signal shape. Although the induction signals given by only one electron are nearly independent in shape and amplitude from the starting position of the drifting electron, when we consider an ionizing track a few centimeters long the dip-angle that the track forms with the wire plane can affect both the shape and the amplitude.

This can be easily understood using the following reasoning. When the track is parallel to the wire plane, all the electrons arrive at the same time on the sense wire; the total induction signal will have therefore the same shape as that given by a single electron but the maximum will be proportional to the number of electrons in the track. On the other hand if the track is perpendicular to the wire plane and is long with respect to the grid gap, the signal will behave as follows. Three phases can be distinguished as the track drifts towards the sense-wires.

-When the first electrons of the track cross the screening grid, a charge starts to be detected on the sense-wire pair, this signal keeps increasing and eventually reaches a maximum when the gaps above and below the induction plane are filled with electrons.

-From now on each electron that enters the induction region replaces one that leaves it, therefore the resulting induction signal will be constant in time.

-When the last part of the track crosses the screening grid the number of electrons in the induction gap begins to decrease because there is no more replacement for the charges removed by the collection plane. The induction signal decreases down to zero when all the track is collected.

The dependence of the induction signal on the angle for the intermediate cases is obviously a mixture of the two extreme cases described above, as can be seen in Figs 5.3a and 5.3b. Notice that the signal shape does not change much up to $=45^\circ$ dip angle;
For larger angles there is a linear relation between width of the signal and the tangent of the dip angle, while the amplitude is essentially constant.

8.6.— The detection of the electrons after the first sense-grid. In addition we also want to determine the track coordinate in a direction orthogonal to that of the induction system. As pointed out previously the electrons that have provided induction signals on the sense-wire system described above retain the memory of their initial y-coordinate because the focussing effect has taken place only in the orthogonal direction (x-coordinate). Therefore by collecting the track as in a traditional Time Projection Chamber we can obtain the y-t image of the ionizing event.

The design of the collection plane follows closely the Gatti geometry. It will consist of equally spaced parallel sense-wires of 2 mm pitch and 100 μm diameter, interleaved with an identical grid whose purpose is to insulate the nearby sense-wires from each other's signals. The potential applied to the two coexisting grids are such that the electrons are converged onto the sense-wires (see Fig. 8.11).

An anode (for instance in the form of a mesh) will be put below the collection plane to screen the system from unwanted perturbations originating in the opposite drift volume.

The shape of the signals on the collection sense-wires are shown in Fig. 8.12. Notice that these are the signals without taking into account the decay due to the time constants of the front-end amplifiers.

8.7.— The $T_0$-recording system. The system planned for the ICARUS $T_0$ signal is a parallel wire mesh distributed over the whole drift volume. The purpose of the system is to provide an induction signal from wires in the vicinity of the event origin. The signal thus generated will be used to warn the read-out system that a track of the expected type has been produced somewhere in the active volume of the detector and will soon arrive at the sense-wire plane. A succession of such signals will be generated along the drift path due to the motion of the electron cloud on its way towards the sense-wires. Using the information thus collected (which wires gave which signals and when) we will be able to track the event back to its starting point in space and time. The precision with which the above reconstruction can be made depends of course on the density of wires used. There will be on the average four wires around the event origin which receive the strongest induction signals.
Figure 8.11.— Equipotential contours and electron trajectories for the collection-mode plane.
Figure 8.12.— Signals from a collection-mode sense-wire as a function of the drift time. The various signals refer to different electron trajectories within the 2 mm range of one detection cell.

We shall see that careful use of these signals allows the event position to be pinpointed with a better precision than the mesh size.

The wires will be strung parallel to the cylinder axis and the plane of the sense-wires. The length of the wires will be about 10 m. To ensure the necessary mechanical strength in view of the occasional dismounting, the wires will be made of stainless steel and will have a diameter of several millimeters.

The choice of the wire-spacing is dictated by the following considerations. Too small a spacing would reduce the amount of free drift volume available to the electrons by introducing too much extraneous material; too large a spacing would not allow a sufficiently precise localisation of the event origin. The typical energy of the electrons from the solar-neutrino events which can be detected in the liquid Argon gives a range between 2 and 5 cm. The mesh spacing does not need to be smaller than the above figures. On the other hand the localisation becomes imprecise for a mesh wider than about 30-50 cm. A reasonable mesh spacing turns out to be in the region of 20 cm and the electric field calculations described below have been done for this value.

The presence of the T₀ mesh will be useful in improving the electric field uniformity over the drift volume because the wires must be set to the voltage given by their position (the natural potential). The volume to be covered by the system is approximately cylindrical and has a ~3 m diameter. A full coverage with a 20 cm spacing implies about 200 wires.
Figure 8.13.— Contour lines of equal induction for the $T_0$ system. The selected wire is placed at the origin of the plot. The numbers give the percentage of the charge induced by an electron at the given position. Only the contours up to 30% of induction are plotted. Mesh spacing is 20 cm. The strength of the induction signal due to charges positioned beyond wires contiguous to the selected one is less than approximately 5% of the total charge.

The $T_0$ wire configuration is indicated on Fig. 7.5b. The central plane in the upper sketch represents the central detector, namely the "sense-wire-plus-grids" chamber plane which the electrons will eventually drift to. The lower part of the figure attempts to show the three-dimensional $T_0$ wire-mesh configuration.

The electric field map and signal shapes have been calculated using the program described in ref. 8.3.

The induction map of one wire is shown on Fig. 8.13 (the selected wire is placed at the origin of the plot). The contour lines refer to constant values of the induction signal. The percentage of the induction signal over a given contour is given by the numbers on the plot. The full circles represent the $T_0$ wires. The basic cell is indicated by the dotted lines. Notice that the induced signal is practically negligible beyond 2 basic cells. The rise-time of the signal is proportional to the cell size, which implies that any electronics constraints on the former will reflect itself on the choice of the mesh spacing. Notice that, as long as the wire diameter remains negligible with respect to the cell size, the induction map and the signal shapes will scale linearly with the mesh separation.
The corresponding signals are shown in Fig. 8.14. As illustrated in the same figure, the event origin is defined by two parameters, s and d, representing the lateral separation and the drift distance respectively. The origin of the time scale has been chosen as the time when the electrons reach the wire in question and therefore give the maximum possible induction on that wire. The dips on the curves reflect the shielding effect of the other wires when the electron cloud passes near them.

Notice the strong dependence of the signal shape on the lateral separation. The signal decreases sharply when the separation increases: in the middle of the cell it reaches ≈18%, going down to ≈5% beyond the first cell and below ≈1% beyond the second. This decrease implies that the signal at the moment of the event generation will be well localised within one or two cells.

The range of amplitudes of the induced signals - both in size and shape - may be a source of problems for the event identification. As a possible way to improve the analysis we show what happens if we use the output of two adjacent wires. Fig. 8.15 shows the signals obtained from this sum. The resulting amplitude variation is now seen to be reduced.

The above considerations are a valid description of the effects produced by electrons drifting through our system. On the other hand it should be noticed that the electron generation takes place simultaneously with the creation of an identical number of positive argon ions. These ions drift in the opposite direction from the electrons but will move with a negligible velocity compared to the latter. Therefore their effect will be confined, to all practical purposes, to a static contribution to the induction signals. This contribution has the result that at time zero the net induced signal will be zero. As soon as the electrons separate from the positive ions, measurable signals will appear on the neighboring wires. In particular, all the wires which the electrons drift away from will exhibit a negative signal because the quasi-static positive ions keep inducing a constant negative charge. Furthermore, this signal decreases with time because the electrons progressively fade away. The same but opposite mechanism is valid for the wires towards which the electrons move where the signal will essentially behave as in the earlier description in the absence of positive ions. Figure 8.16 gives a schematic of a solar neutrino event as seen by the T_{0} grid.

As with the sum of the signals from the two wires between which the electrons drift (see Fig. 8.15), we can also exploit the expected shapes described above to further improve the localization of the event origin. With reference to the plot in Fig. 8.17 we notice that the difference of the paired signals from the upstream and downstream wires of the cell surrounding the origin reaches a higher amplitude. this in turn results in an increased signal slope, thereby a better T_{0} definition.
Figure 8.18 illustrates the time-scenario expected from the system after an event has taken place in a cell between wires 0 and 1. The first signal is the difference (S_1-S_0) mentioned above which defines accurately the event origin. The effect of the positive ions is almost nil beyond the first cell, therefore the signals starting from the second wire onwards are only due to the electrons. The plot in Fig. 8.18 shows how successive wire pairs are turned on while the electrons drift by. Only the first such signal (S_2) is still slightly affected by the presence of the ions. It is worth noticing that at any given time there will always be at least one signal with an amplitude larger than ~30% of the total charge.

The capacitance of the wires for different configurations of wire diameters and mesh spacing is given in Table 8.1. The variation of the values is quite small, the typical capacitance being of the order of 10 pF/m. This value of the capacitance directly reflects into the noise of the associated electronics (discussed in chapter 9). Our previous experience has led us to expect that in these conditions the noise level achievable with the electronics will be of the order of 1000 electrons. Our typical event (a 5 MeV electron) is expected to generate in excess of 100,000 electrons thereby assuring that the observed signals will correspond to a charge in the range of 30,000 - 90,000 electrons.

Table 8.1.— Capacitance of the wires in pF/m for different values of the mesh spacing and the wire diameter.

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<thead>
<tr>
<th>Spacing (cm)</th>
<th>10</th>
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<th>40</th>
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<tbody>
<tr>
<td>Diameter (mm)</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>12.1</td>
<td>10.9</td>
<td>9.9</td>
</tr>
<tr>
<td>2</td>
<td>13.7</td>
<td>12.1</td>
<td>10.9</td>
</tr>
</tbody>
</table>

An estimate of the event localisation achievable with this system can be derived as follows. Let us assume that a signal is observable if it is of the same order of magnitude as the noise or larger. Using the wire combinations discussed above the slope of the time dependence of the signal is approximately 500 electrons/µsec, this is equivalent to 2500 electrons/cm at the chosen 1 kV/cm field. If we take an equivalent noise charge from four amplifiers as 2000 electrons (assuming 1000 electrons per amplifier) we will be able to estimate the average track position within one or two centimeters, i.e. well within a distance characteristic of the typical track length.
Figure 8.14.— (a) Schematic illustration of the T₀ single-wire operation. (b) Signal (shape and normalized amplitude) induced on the T₀ wire as a function of the drift time (time = d/v where v is the drift velocity) for different values of the lateral separation (s). The numbers labelling the curves give the values of s in cm. Time = 0 is when the electrons reach the chosen wire.
Figure 8.15.—(a) Schematic illustration of the $T_0$ wire-pair operation. (b) Signal (shape and normalized amplitude) induced on a couple of adjacent $T_0$ wires as a function of the drift time ($\text{time} = \frac{d}{v}$ where $v$ is the drift velocity) for different values of the lateral separation ($s$). The numbers labelling the curves give the values of $s$ in cm. Time = 0 is when the electrons reach the chosen wire.
Figure 8.16.— A solar neutrino event seen by the T$_0$ grid: signals are produced in time sequence during the drift of the electrons from the wires shown as full circles.
Figure 8.17.— Various possible signal combinations from wires surrounding the event origin. The difference \((S_1-S_0)\) of the paired signals from the upstream and downstream wires of the cell gives a better definition of the event origin than any of the other combinations. The drift velocity is 2 mm/\(\mu\)s (at 1 kV/cm).

Figure 8.18.— Time-sequence of the signals as observed on successive wires during the drift of the electrons from the origin towards the detection device (wire-plane chamber). The symbols near the signals refer to the wire combination used to produce that signal.
We note here that in view of the fact that the two systems work on the same principle (induction effects) and have similar values of the wire capacitance, the electronics for both could be essentially the same. The main difference of the T0 system is that the wires will have to be at high voltage (from 10 to 230 kV), hence the need for a decoupling system. The final choice of the mesh spacing will be dictated mainly by electronics and mechanical requirements.

8.8.— References.

[8.3] F. Ragusa, "Electric drift field and signal waveform for the ICARUS detector" (Nov. 1986)
F. Pietropaolo, "Preliminary study of the electrostatic field". Parts I and II. (March 1987) and "Study of the electrostatic field" (April 1987).
9. — The trigger system for ICARUS I

9.1. — General considerations. Clearly, the important function of the trigger system is to limit the event acquisition-rate to a level such that no 'good' events are lost because of the saturation of the buffer memories (the present limit is 4 events per second). In this chapter we discuss the proposed scheme for the trigger system based on the T₀ wires described in chapter 8. We propose to use the induction signals on these wires to determine the z-coordinate (normal to the sense-wire-plane) and the energy of the event occurring inside the drift volume (Fig. 9.1). This volume is naturally divided in slices (parallel to the sense-wires) by the planes formed from the T₀-wires held at the same potential. The aim is to combine the signals of each T₀-wire in such a way as to give an overall signal for each slice which is maximum when an event originates inside the selected slice and negligible when the event occurs outside this slice (this will give the z-coordinate of the track). Furthermore the amplitude of the signal in the selected slice should depend only on the energy of the event generated inside the slice and not on the position of the track within the slice (this will enable us to put a threshold on the energy to select 'good' events from background).

9.2. — First-level trigger system. The algorithm is based on the fact that the induction current on the wire-plane is negative when the track approaches the wires and is positive when the track is drifting away from the plane. Initially we have tried the following wire geometry and signal combinations:-

i) the wires inside the drift volume form a mesh of 20 cm pitch (much less than the detector dimensions, but larger than the typical track length)

ii) the induction currents flowing into the T₀ wires of the same equipotential plane are summed together. This gives M signals Sᵢ (M is the number of wire planes)

iii) M different combinations (Cᵢ) of these signals are composed as follows (see also Fig. 1)

\[ C_N = \sum_{i=1}^{N-1} S_i - \sum_{i=N}^{M} S_i ; \quad N = 1, M \]

in this way an event occurring in the slice N gives an enhanced signal only on the combination Cₙ.

Fig. 9.2 shows several current signals on the wire combination Cₙ due to events of fixed energy (4 MeV) generated randomly (in space and time) inside the slices N (from 100 to 200 μs) and N-1 (from 0 to 100 μs). The initial induction current (the derivative of these signals, Fig. 9.3) shows more clearly the difference in amplitude
Figure 9.1. — Schematic of the $T_0$ trigger system
Figure 9.2.— Examples of induction current signals on the wire combination $C_N$ for events of energy 4 MeV generated randomly in space and time.

Figure 9.3.— The initial induction current for the events shown in Fig. 9.2.
between the two cases. The high peaks present on some signals at \( t = 100 \mu\text{sec} \) and \( t = 200 \mu\text{sec} \) are due to the fact that the track is drifting very close to a wire, thus enhancing the current variations. Figs 9.4 shows the amplitude distributions of the signals in \( C_N \) for events of fixed energy generated randomly in the slices N and N-1 (shaded histogram). Notice the good separation between the two spectra. The mean value of the initial induction current on the slice N due to a track of 4 MeV generated in the slice N is 1330 electrons/\( \mu\text{sec} \).

We have tested the trigger efficiency using a Monte Carlo simulation of tracks in the detector and the results are summarized in Table 9.1.

| Table 9.1.— Trigger efficiency of the \( T_0 \) wire system for various track energies |
|-----------------------------------------------|-----------|-----------|
| Threshold (MeV) | 3.0       | 4.0       | 5.0       |
| Generated energy (MeV) |           | 3.0       |           |
| Measured energy (MeV) |           | 3.06 ± 0.62 |           |
| Trigger efficiency (%) | 60.2      | 6.1       | 2.2       |
| Generated energy (MeV) |           | 4.0       |           |
| Measured energy (MeV) |           | 4.01 ± 0.79 |           |
| Trigger efficiency (%) | 93.0      | 57.0      | 8.7       |
| Generated energy (MeV) |           | 5.0       |           |
| Measured energy (MeV) |           | 5.05 ± 0.92 |           |
| Trigger efficiency (%) | 98.8      | 88.3      | 61.1      |
| Generated energy (MeV) |           | 6.0       |           |
| Measured energy (MeV) |           | 5.78 ± 0.92 |           |
| Trigger efficiency (%) | 99.2      | 99.2      | 89.8      |

In ICARUS I the main source of background is the \(^{42}\text{Ar} \) beta emission (plus some Compton electrons), the relevant rates for this reaction are summarised in Table 9.2.

| Table 9.2.— \(^{42}\text{Ar} \) background spectrum (\( \beta \) plus Compton electrons) |
|-----------------------------------------------|-----------|
| Total rate in one drift volume (50 tons, ev sec\(^{-1}\)) | 715.4     |
| Energy interval (MeV) | 0 – 1 | 1 – 2 | 2 – 3 | 3 – 4 |
| Rate in one drift volume (sec\(^{-1}\) MeV\(^{-1}\)) | 261 | 310 | 136 | 9 |

In order to estimate the acquisition rate it is therefore important to see how many background events are detected by the trigger system as 'good' events as a function of the applied threshold. Using a simulation method we have evaluated the response of a \( T_0 \) slice to electron tracks generated by the \(^{42}\text{Ar} \) reaction. The results are shown in Table 9.3.
Figure 9.4.— The amplitude distribution of the signals in $C_N$ using $T_0$ wire system for tracks of 4 MeV generated randomly in slice N and slice N-1 (shaded histogram).

<table>
<thead>
<tr>
<th>Threshold (MeV)</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total triggers in 50 tons (sec$^{-1}$)</td>
<td>166.9</td>
<td>124.8</td>
<td>57.8</td>
<td>31.5</td>
<td>23.7</td>
</tr>
</tbody>
</table>

It should be noticed that the final rate is higher than requested (4 events per second) at all the threshold values and that the major contribution is due to the 'anomalous' signals (tracks drifting near a wire). Hence again the need to distinguish them from the real triggers. In any case, with a threshold between 3 and 4 MeV (so as to be sure to collect all the neutrino events), the rate is too high (20 – 50 events per second) even disregarding the 'anomalous' triggers. This means that a second-level trigger that looks in more detail at the event is necessary for an efficient rejection of the background events.
9.3. — Second-level trigger. A possible second level trigger can be designed to exploit:

i) the very precise information given by the $T_0$ system about the 'slice' (i.e. the $z$-coordinate) where the triggering event has happened

ii) the accurate measurement of the track energy given by the signals on the collection wires.

Consider a trigger given by the slice $N$ of the $T_0$ system. After a delay $T_d = (N-1) \times W/v$ (where $W$ is the slice width and $v$ is the electron drift velocity) a time window $T_w = W/v$ is opened during which all the charge deposited on the collection wires is recorded (for example by summing all the collection signals present in the time window). As shown in chapter 4 the 'collection mode' signals will provide us with an excellent energy resolution ($\approx 3\%$ in the MeV region) thus by setting a suitable threshold ($\approx 3.5$ MeV) on the measured energy (charge) we should be able to discard most of the unwanted background events.

All the operations described above can be performed in real time by suitable hardware processors (adders and comparators); this will ensure the feasibility of such a trigger system.

A source of over-estimation of the energy of the triggering event can be the collection on the sense wires of more than one track. Figure 9.8 explains how this can happen: by opening a time window $T_w$ after a delay $T_d$, one records all the tracks generated in the shadowed region of the plot. Assuming the background rate given in Table 9.2 for one drift volume (715.4 Hz) and the energy resolution previously mentioned, we calculated the probability for the collection of more than one event to occur. Taking into account also the spectrum of first level triggers (from the $T_0$ system) we estimate the number of accepted events as a function of the threshold in the second level trigger system. The results are summarized in Table 9.4.

\begin{table}[h]
\centering
\begin{tabular}{lcccc}
\hline
Threshold (MeV) & 2.0 & 2.5 & 3.0 & 3.5 & 4.0 \\
\hline
Total triggers in 50 tons (sec$^{-1}$) & 135.7 & 58.8 & 8.8 & 2.2 & 0.4 \\
\hline
\end{tabular}
\caption{Second level trigger rejection efficiency}
\end{table}

Assuming for instance a first level trigger rate of 50 Hz (see Table 9.3) we find that the overall data acquisition rate goes down to $\approx 2.2$ Hz for a threshold of 3.5 MeV, which is well below the present saturation limit (4 Hz).
Figure 9.8.— Schematic explaining the idea for a second level trigger. The width of the time window is $T_W$ and the delay is $T_d$. 
READ OUT ELECTRONICS FOR ICARUS I

10.— Front end Electronics

10.1.— Introduction. In this Section we describe the design for the front-end electronics. As far as the electronics is concerned, the parameters involved in ICARUS Phase 1 and in the final ICARUS experiment are of the same order of magnitude.

The charge density generated by a typical track is 16000 electrons in the proposed geometry of 2mm spacing between sense wires but falls to 8000 electrons due to various effects like recombination, life time, electronics bandwidth, etc. Since the sense wire capacitance is 30pF/m the total detector capacitance for 5.5m wires becomes 165pF. For a 2mm gap and an electric field of 5kV/cm between the sense wires planes the electron drift velocity is 3mm/µs giving a signal rise time of 666ns. Tracks with dip-angles of 80° will produce a signal of about 4µs length therefore a decay time of at least 50µs is necessary. The maximum potential at which these wires are held is 1.4kV. The major problem to be solved for these amplifiers is the noise level which must be kept to a maximum value of 800 electrons to ensure a minimum signal to noise ratio (SNR) of 9. The total number of channels needed is about 17000.

10.2.— High resolution Amplifiers. The design of very low noise charge amplifiers could be planned in two ways:

The amplifiers as well as all input decoupling components are located outside the detector. Each amplifier is connected to its corresponding sense wire through a coaxial cable. In this case the coaxial cable capacitance must be added to the sense wire intrinsic capacitance. The obvious advantage of this solution is that all the electronic components can be easily substituted in case of damage.

The disadvantages presented by this solution are:

i) noise level increase due to the capacitance of the input coaxial cable
ii) additional noise from the external world: microphonic and EMI noise picked-up by the coaxial cables.

In this situation, taking in account the cable length of up to 7m necessary to connect the external electronic to the sense wires, the parasitic cable capacitance is about twice the wire capacitance of 165pF.

The amplifiers are located inside the detector. The major disadvantages of this configuration are:

i) the electronics is unreachable and therefore not serviceable in case of damage
ii) the presence of exotic materials inside the liquid could affect its purity therefore reducing its lifetime and hence the charge to be collected.

The obvious advantages are:

i) reduction of input capacitance due to the absence of input cables between sense wires and charge amplifiers

ii) the signals at the amplifier input are not affected by any external source of noise since the detector represents a perfect Faraday cage

iii) intrinsic improvement of the signal to noise ratio due to the increase of the input JFET transconductance working at cryogenic liquid temperature. However this condition could be achieved only by using components optimized to work at this temperature[10.1,10.2].

10.3.—Test on a small detector at CERN. The test detector had a drift length of 24cm and one plane with 31 sense wires of 2mm spacing which could be operated either in induction or in collection mode. The sense wire capacitance was 8pF and the minimum charge to be detected was 6000 electrons. The tests have been made in two different situations:

i) electronics outside the detector. The amplifiers used for this test had the following characteristics:
- charge integrator amplifier with feedback
- rise time 1μs
- decay time 50μs
- noise characteristics: 600 electrons at Cin=0pF, slope=5 electrons/pF
- no shaper used

The amplifiers were connected to the sense wires by means of 1.20 meter long coaxial 100pF/m cables. The resulting input capacitance was 140pF. To reduce the induced noise, microphonic and EMI, the amplifiers were mounted in a Faraday cage and the input cables double shielded. Noise measurements made using run data give a noise level of 1300 electrons corresponding to a signal to noise ratio of 4.5.

ii) electronics inside the detector. The amplifier used in the previous configuration could not be used at the liquid argon temperature for many reasons such as size, presence of bipolar transistors and other components not working at low temperature [10.3]. A new type of amplifier was designed for this purpose.

The design constraints were the following:
- minimization of number and kind of components to be put in contact with the liquid Argon to avoid change in characteristics and contamination
- minimization of power consumption to avoid heating of the liquid and subsequent bubble production.
- circuit configuration made in such a way that damage to one channel did not affect the others.

The block diagram is given in Fig. 10.1. The amplifier is made of two sections, the first working in liquid Argon and the other at room temperature. The cable length between the two parts is not critical thus allowing the external part of the amplifier to be put several meters away from the detector without affecting the noise performance of the system.

\[
\text{Qin}=Vt \times \frac{(Cu)(Ct+Cin)}{}
\]

**Figure 10.1.**— 24 cm small scale test chamber front-end electronics schematics.

As far as the signals are concerned, the cold part of the amplifier operates in open loop while a d.c. feedback ensures the correct biasing at any temperature. The charge integration is made on the input capacitance. The remaining part of the circuit acts like a voltage amplifier.

The main characteristics of the two amplifier sections are:
- rise time = 1\(\mu\)s
- decay time = 50\(\mu\)s
- noise characteristics: 300\(\mu\)l at Cin=0pF, slope=12 electrons/pF
- no shaper used.

In this configuration the input capacitance is represented only by the sense wire capacitance equivalent to 8pF. The amplitude of the signals collected during this test
showed that no Argon contamination occurred due to the presence of the amplifier inside the detector. Also, the run data show a signal to noise ratio of 15.5 corresponding to an improvement of a factor 3.5 with respect to the previous setup.

Figure 10.2.— 24 cm small scale test chamber front-end electronics blockdiagram: comparison between electronics inside and outside the cryogenic liquid.

These results were obtained with the JFET inside the liquid Argon, that is at T=87K. However, the technical literature reports that for the device used the optimal working temperature is about 180K. Such a temperature may be reached by putting the JFET in Argon gas instead of liquid. Laboratory tests made in these conditions demonstrate that a further improvement in SNR is possible. Measurements show a 25% noise reduction.

The block diagrams of these setups and respective results are reported in Fig.10.2. This test did not require high voltage input decoupling capacitors due to the fact that the sense wires were held at ground potential. However, laboratory tests made on the same amplifier decoupled at the input by a HV ceramic capacitor at liquid Argon temperature biased at 3kV, prove that, apart from a substantial but expected decrease of the capacitance value, this mode of operation is possible.
10.4.—Design criteria for front-end electronics. The results obtained in the 24 cm test detector at CERN show that it is possible to improve the SNR by operating the amplifiers at very low temperatures and consequently the possibility of putting the amplifiers close to the wires inside the dewar has been studied.

However in such a case the following considerations have to be made:

i) the electronics is completely inaccessible once the dewar is filled with liquid Argon;

ii) the ideal working temperature for commercially available JFETs is generally higher than 87K.

On the other hand, the additional input capacitance introduced by connecting coaxial cables in the case of electronics-outside-the-dewar solution may be drastically reduced by using specially manufactured low capacitance coaxial cables.

In this situation a good compromise seems to be the following. The electronics is put outside the dewar but very close to it in a refrigerated and thermostatic vessel representing a perfect Faraday cage held at the optimal temperature, thus allowing the amplifiers to work in their best condition and with total accessibility. The extra capacitance introduced by the coaxial cables is kept at the same order of magnitude as the intrinsic detector capacitance.

10.5.—Operating JFETs at low temperature. The noise behaviour of JFET's and their dependency on temperature[10.1,10.2,10.4] have been deeply investigated. It appears that three noise sources have to be considered:

i) channel thermal noise, which is due to random thermal scattering of the carriers in the channel. The channel thermal noise power spectrum is frequency independent

ii) carrier density fluctuation due to random emission of electrons and holes in the depletion region of the inversely biased gate-channel junction. The carrier density fluctuation induces a fluctuation in the depletion region width which in turn modulates the channel width. This results in a variation of the channel resistivity. This type of noise is negligible at room temperature (300K) but becomes important as the temperature is lowered.

iii) gate current noise. This type of noise depends on the gate current flowing through the inversely biased gate-channel junction. Its contribution to the overall noise is important when the drain current is of the same order of magnitude as the inverse gate current, that is in the pA-nA range. In charge amplifiers, the drain current of the front end JFET is kept as near as possible to the Idss current (order of magnitude mA) in order to increase the transconductance g_m to its maximum value.

It follows from these considerations that in the working conditions of the front end JFET:
- the carrier density fluctuation noise is negligible at room temperatures
- the inverse gate current gives a fixed contribution to the overall noise level, called the parallel noise, and it does not depend on the amplification mechanism of the JFET. However, in most cases, the parallel noise contribution of the gate resistors is more important than this one, making it negligible.

Hence the channel thermal noise represents the main source of noise.

The channel thermal noise has been evaluated by Van der Ziel[10.5] and may be represented by an equivalent noise resistor $R_{eq}$ whose value is given by the equation:

$$R_{eq} = 0.7 / g_m$$

The noise generated by this equivalent noise resistor is given by the Nyquist formula:

$$\eta^2 = (4kT \times R_{eq} \times B)^{1/2}$$

where $B$ is bandwidth. It follows that

$$\eta^2 = u \times (T/g_m)^{1/2}$$

where $u$ is a filter dependent constant.

It is generally found that as temperature decreases, $g_m$ shows an initial increase followed by a sharp decrease. This can be explained as follows. The transconductance ($g_m$) of an n-channel JFET depends on three factors: the pinch-off potential $V_p$, the free electron concentration in the channel $n_n$, and the mobility of the free carriers $\mu_n$. As the temperature begins to decrease, $V_p$ and $n_n$ remain stable while the mobility $\mu_n$ increases, and therefore $g_m$ increases. As the temperature decreases further, $V_p$ and $n_n$ start to decrease, dominating the increase of $\mu_n$. Finally $V_p$ reaches the applied $Vgs$ voltage value (in the case of the FET working at $Id=Idss$, $V_p$ falls to 0V), the JFET pinches itself off and $g_m$ drops to 0.

At an intermediate value of the temperature, a maximum for $Id$ and $g_m$ is reached. This maximum is found to be situated between 110K and 250K for most of the commercially available JFETs. The temperature at maximum $g_m$ depends on various parameters (channel doping concentration, channel depth and length, etc.) and corresponds to the minimum thermal noise temperature. However, as at low temperatures the carrier density fluctuation noise becomes important, the temperature of minimum overall noise may be higher than the maximum $g_m$ temperature. Fig. 10.3 represents the temperature dependency of $g_m$.

There are two ways of obtaining the most suitable device from these considerations:

i) design and develop an appropriate device, controlling all the parameters like channel doping, width, length, geometry, substrate resistivity, etc. in order to obtain the desired performance at a given temperature
ii) choose from among the commercially available devices the correct JFETs that will satisfy the specifications. In this case, we cannot control parameters like geometry, doping, etc., but can select the device on the basis of two parameters. First, one has to choose an n-type channel JFET (in order to have a greater mobility $\mu_n$ compared with the p-type channel mobility $\mu_p$). Secondly, one has to choose JFETs with a high pinch-off potential value $V_p$ (in order to be sure that the JFET will not pinch itself off if there is a small decrease of the working temperature).

![Graph showing the temperature dependency of transconductance](image)

*Figure 10.3.*—Temperature dependency of transconductance.

The second alternative has been investigated and extensive tests have been carried out on a number of commercial devices, namely 2N4416, 2N3819, 2N4861, 2N5912, U310, 2SK170, SNJ903L, 2SK371.

Transfer characteristics have been measured from 300K to 87K. It is found that the first 5 devices ($V_p < 3V$) show a greater $g_m$ at liquid Argon temperature than at 300K. The U310 has been chosen among these transistors as it has better overall performance. The optimum temperature at which it showed the best SNR has been measured to be about 180K.

The SNJ903L type ($V_p=1V$) works correctly down to 210K while the last two devices (2SK170 and 2SK371 - $V_p=0.6V$) have their best performances at 240K.

These data confirm the previous conclusions about the relation between the optimum working temperature and the pinch-off voltage ($V_p$) magnitude.

### 10.6.— *Parameters of front-end Amplifiers.*

The possibility of operating an amplifier at low temperature, i.e. at temperatures near the cryogenic liquid temperature, in order to obtain a significant reduction of the level of noise, thus achieving the best SNR, is limited by the fact that not all electronic devices continue to work correctly at these temperatures. Some devices like bipolar transistors completely stop working.
while other devices like capacitors suffer a drastic change in value thus preventing their use in circuits in which the correct operation of the circuit depends on a precise value (filters, etc.). For this reason already existing amplifiers like those used in the UA1 Experiment for TMP/Uranium Calorimeter[10.6,10.7] cannot be envisaged due to the presence of such devices.

Considering a capacitance of 20 pF/m using a specially manufactured cable, the total detector capacitances are as follows (Cdet = Csw + Ccoax):

- collection plane: Cdet = 165 pF + 4.5 m x 20 pF/m = 255 pF
- induction plane: Cdet = 90 pF + 7 m x 20 pF/m = 230 pF

The purpose of this new design is to have better SNR at the detector capacitance of about 270 pF than that offered by the already existing amplifiers. It is obvious that the choice of the optimal temperature will play a major role in the improvement of the performance.

The design parameters for the amplifiers are the following:
- best SNR
- detector capacitance 270 pF
- rise time 1 μs
- decay time 50 μs
- compatibility for use in induction and collection mode

10.6.1.— Amplifier design. A very classical solution is adopted using only n-channel JFETs as active components. The number of passive components is minimized. Capacitors of large value are avoided to allow the correct operation at low temperature, easy hybridization and space and cost reduction. The final amplifier schematics is shown in Fig. 10.4.

As a first attempt two JFET types have been tried, namely 2SK371 and U310 as the input device whilst the other JFETs in the circuit were all U310s.

The detector is directly connected to the amplifier. The transformer coupling solution has not been considered in this design due to the well-known disadvantages of this technique at such low detector capacitances[10.6,10.8].

Instead, 4 JFETs have been put in parallel in order to increase the total transconductance g_m and to match the detector capacitance C_d with the amplifier input capacitance C_a thus obtaining the best signal to noise ratio[10.6].

The input impedance of the amplifier may be set by adjusting the value of feedback and load capacitances, thus performing the correct matching with the input coaxial cable characteristic impedance.
Figure 10.4.—Front-end electronics detailed schematics for ICARUS phase 1 detector.

The amplifier is made of two sections: the first section is installed in the thermostatic vessel on the top of the liquid Argon dewar, and performs the integration and preliminary amplification of the charge; the amplified signal is then routed through a coaxial cable to the second section which performs the final amplification and the shaping (if necessary), and outputs a differential signal which will be sent to the Data Acquisition System.

10.6.2.—Noise performances. Calculations are done considering four U310 type JFETs in parallel as the input device. The foreseen detector capacitance value lies in the 140-265 pF range.

The amplifier input capacitance, Ca, is calculated considering all the gate-source capacitances of the front-end devices and those derived from the Miller effect. In this case it results that Ca is 109 pF at 300K and 119 pF at 180K. In this condition a fairly good matching of the detector capacitance Cd to the amplifier input capacitance Ca is achieved.

The output signal is fed into a shaper with transfer function of the type $x^2e^{-x}$ with a shaping time constant of 1μs. Calculations are very straightforward and yield the results reported in Table 10.1. Fig. 10.5 represents measured noise as a function of the detector capacitance.
Figure 10.5.—Measured noise as a function of detector capacitance.

The most interesting step of these calculations concerns the computation of the expected noise reduction due to the correct choice of the working temperature.

The noise reduction due to the different temperatures is given by the ratio of the slopes of the curves of the series noise as a function of detector capacitance $C_d$ (for $C_d >> C_a$) at the temperatures at which this computation has to be done.

The series noise per capacitance unit is given by the equation

$$<\text{ENC}>_s = \frac{(2kT \times R_{eq} \times I_{ser})^{1/2}}{q}$$

and is given in electrons/pF.

In this equation, $k$ is Boltzmann's constant, $T$ is temperature, $R_{eq}$ is the equivalent resistor representing the contribution of the JFET's channel to the noise, $q$ is the elementary charge value and $I_{ser}$ is a filter dependent coefficient.

The noise reduction is expressed by the equations:

$$R = 1 - \frac{<\text{ENC}>_{T1}}{<\text{ENC}>_{T2}}$$

$$R = 1 - \frac{(T1 \times g_{m2} / T2 \times g_{m1})^{1/2}}{}$$

Therefore two factors influence the expected noise reduction: the temperature itself and the forward transconductance of the JFET. In the present case, assuming that $T1=180K$ and $T2=300K$, and knowing from measurements previously done that $g_{m1}=68.7 \text{ mA/V}$ and that $g_{m2}=38.9 \text{ mA/V}$, a reduction factor of 41% is achieved as pointed out in Table 10.1.

At lower detector capacitance values the contribution due to parallel noise $<\text{ENC}>_p$ increases. The final noise, taking in account the amplifier input capacitance $C_a$ alone has the following values: $<\text{ENC}>_{300K}=277\text{ el.}$ and $<\text{ENC}>_{180K}=197\text{ electrons}$. For $C_d=0\text{ pF}$, the noise reduction is therefore 28%:
Table 10.1. — Noise calculations and measurements

<table>
<thead>
<tr>
<th>Temp.</th>
<th>Theor. ENC @ 0pF [el]</th>
<th>Theor. ENC @ 270pF [el]/[pF]</th>
<th>Meas. ENC @ 0pF [el]</th>
<th>Meas. ENC @ 270pF [el]/[pF]</th>
<th>Meas. ENC @ 270pF [el]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300K</td>
<td>277</td>
<td>2.2</td>
<td>845</td>
<td>280</td>
<td>2.73</td>
</tr>
<tr>
<td>180K</td>
<td>197</td>
<td>1.3</td>
<td>521</td>
<td>200</td>
<td>1.86</td>
</tr>
</tbody>
</table>

Therefore from these results, operating the amplifiers at the optimum temperature will give a noise reduction of about 41%. This of course will be the maximum obtainable reduction in the case that $C_d > C_a$, that is in the predominantly series noise region. However even with detector capacitance values involved in this experiment, (namely values around 270pF), calculations show that $<\text{ENC}_{300\text{K}}>=846$ electrons, while $<\text{ENC}_{180\text{K}}>=520$ electrons, giving a noise reduction of about 39% which is not so far from the maximum reduction value obtained above.

Further investigation on other types of JFETs is planned in order to improve the results reported in Table 10.1.

Table 10.2. — Noise levels for various JFETs.

<table>
<thead>
<tr>
<th>JFET type</th>
<th>Opt. Temp.</th>
<th>$&lt;\text{ENC}&gt;<em>{C</em>{det}}$ [el]</th>
<th>Slope [el]/[pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1×SNJ903L</td>
<td>210K</td>
<td>486el</td>
<td>1.06e/pF</td>
</tr>
<tr>
<td>2×2SK170</td>
<td>240K</td>
<td>483el</td>
<td>1.25e/pF</td>
</tr>
<tr>
<td>2×2SK371</td>
<td>240K</td>
<td>583el</td>
<td>1.21e/pF</td>
</tr>
</tbody>
</table>

Theoretical noise calculations done on the same amplifier but using different front-end JFETs give the following reported in Table 10.2.

Finally, it is planned to test a new JFET (SNJ132L - SNJ132H) which has been used by Radeka as a front-end device in cooled amplifiers placed directly in liquid Argon.

10.7. Interconnecting cables. In order to reduce the parasitic capacitance introduced by the long coaxial cables needed to connect each sense wire to its respective amplifier, a very low capacitance coaxial cable will be used. The expected capacitance value is about 20 pF/m considering an external diameter of 3mm and a 80μm diameter internal conductor. The dielectric is expected to be made of TEFLON (PTFE) which has the advantage of not contaminating the pure liquid Argon which the cables will be placed in. A newly developed material named GORE-TEX (expanded PTFE) is also very promising due to the fact that it has a relative dielectric constant of 1.3 thus allowing the
manufacturing of cables with reduced external diameter (reduced weight and volume) and/or increased internal diameter (greater mechanical resistance).

Taking in account the mentioned figures the surfaces necessary to bring out the 17000 channels are the following:
- max surface for induction wires = 230cm² per chamber
- max surface for collection wires = 135cm² per chamber
- max surface for all cables at feed-through input = 1460cm²

However test have to be made in order to verify that the proposed dielectric will not affect the Argon purity.

10.8.— *T₀ Grid amplifiers.*

10.8.1.— *Specifications.* The wires on this grid are held at the natural potential given by the electric field in the drift volume thereby ensuring complete electrostatic transparency. The total charge generated by a typical 3cm length track is about 100000 electrons. Since the wire spacing is 25cm, every wire will sense the total charge drifting in its neighbourhood in induction mode.

If we consider two contiguous wires and a charge drifting between them, the induction efficiency of the image charge will vary from 15% to 100% depending on the distance from the wire at which the charge is drifting. This is explained in more detail in Section 8.7.

The capacitance of these wires is 10 pF/m giving for 5m total length a detector capacitance of 50 pF.

The induced charge has a triangular shape with a 100μs rise and fall time for a drift velocity of 2mm/μs at the nominal 1kV/cm electric field. Therefore the amplifier should sense a minimum charge of 15000 electrons over 50 pF with a decay time of at least 2ms.

The potential at which these wires must be held varies between few kV to 225kV.

10.8.2.— *Solutions.* The main difficulty in designing an amplifier of this type comes from the very high voltage at which it has to operate. Classical solutions like input decoupling capacitors are excluded because of the high capacitance value needed to be operated in an extremely hostile environment, i.e. very high voltage and low temperature.

One possible solution to overcome this problem is to power the amplifier by the mean of photovoltaic cells held at the right potential and illuminated by an external light source. An optical fiber must be used to send the signal to the Data Acquisition System outside the detector[10.9]. This seems to be the best direction to follow.
10.9.— References.


11.— Data Acquisition

11.1.— Introduction. The data acquisition, developed for the test of the Argon image chamber prototype, was based on the readout of few hundred channels using a VME and a μVax setup. The experience with this system has allowed us to study the problems concerning the processing and handling of digital signals, and to tackle all the difficulties for a large scale implementation of such a readout. The main issues for the design of the data acquisition are the following:

a) Data Volume. The readout of the Icarus phase 1 detector involves the processing of the information of 17,000 wires corresponding to more than 100 Mbyte of raw data when all the drift length is recorded. In order to limit the dead time of the experiment and the store only the valuable information, the readout must have a high level of parallelism with autonomous data reduction functions. For example in the case of the 24 cm chamber, the raw data information coming from 40 channels had a size of the order of 100 Kbyte comparable to a UA1 or a LEP event.

b) Trigger and Selective Readout. The trigger system has to provide additional information about the location of the event to measure, in order to reduce the memory area to process for the hit finding.

c) Event Display. The event display is a fundamental tool to monitor the behavior of the apparatus and to drive some steps of the pattern recognition and reconstruction program during the event analysis. Powerful interactive work stations must be attached to this task.

d) Data Link with the counting room. The event data and the control functions are transported to the counting room of the external laboratory by an optic channel data communication system. The system has to provide the fast data transmission and the full remote control of the equipment.

11.2.— Basic Read-Out Unit. The read-out system for the of the Icarus phase 1 experiment consists of four identical units each associated to a sector of the apparatus (Fig. 11.1), a sector corresponding to a semi-cylindrical drift volume with 1500 horizontal and 2750 vertical sense wires. This modular partition will be the basic read-out unit for the extension to the final Icarus experiment as well.

The four readout modules can be triggered simultaneously, when a global trigger occurs (e.g. from an external muon detector), or independently one from the other, when the trigger comes from the local T0 grid system. In both cases the event data readout and the transmission to the external counting room will be done by independent optic channels. The event assembly will take place, in the final stage of the readout, according to the trigger pattern and the absolute time clock event information.
Figure 11.1.— Readout Structure

Figure 11.2.— Basic Readout Unit.
The basic read-out unit (Fig. 11.2) consists of a local trigger processing unit, the $T_0$ grid signals, two Fastbus size crates housing the digitizing logic, a VME multiprocessor system for the data compression and formatting and an optic channel linked to a remote global event builder located in the external counting room. The control of the unit is performed locally by a personal computer interfaced to VME, while an optic channel dedicated to the control allows the same functions to be performed from the counting room. All the readout units of the experiment have identical hardware configuration and run the same software tasks.

11.3.— FADC Pulse digitizer. The 4400 channels (1500 vertical, 2750 horizontal and the $T_0$ grid) of a sector of the apparatus are digitized and memorized each 200 ns, using the Flash ADC (FADC) technique similar to that developed for the test of the 24 cm chamber. The digitizing electronics is organized in 36 Fastbus-size boards each processing 128 channels (Fig. 11.3). The wire analog signal is digitized at the rate of 5 MHz by an 8-bit FADC circuit, optimized to service more than one input channel, and the digital information is saved into a memory buffer. The memory buffer is organized in 8 banks of 8 Kbytes each, with dual access capability allowing the readout of a previous event while the current one is being digitized. One event can occupy the full memory bank length corresponding to 1.6 ms of drift time, and the system can store up the 8 subsequent events with a dead time determined by the drift time only.

Since a mega byte of memory corresponds to the maximum size of information accumulated by a single FADC board per event, the total amount of data to be processed by each readout unit (a sector of the apparatus) is 36 Mbytes.

11.4.— VME Sequencer, Hit Finder. Before recording the event, all the null information has to be suppressed and the hit data have to be properly formatted. This function is performed in parallel by 10 VME modules (VME sequencer) under the supervision of a M68020 VME processor dedicated to the optic link as well.

Each sequencer accesses 4 FADC boards by a 32-bit data and 21-bit address parallel bus (Fig. 11.4). The bus allows the random access to the pulse information, at a given delay relative to the stop trigger, and in any event bank of the 4 FADC boards system. The data available on the bus contain the information of 4 consecutive channels at the same time, and an auto-incremental addressing mode permits the scanning of a prefixed drift time domain at the rate of 8 Mbyte/sec. During this scanning, the sequencer compares the 4 channel pulse values with a fixed threshold and saves into a local memory the time at which a threshold crossing occurred for at least one of the 4 channels. For each hit detection the next scanning address is incremented by a given number of steps (e.g. 16 for 3.2 µsec). At the end of this process, the VME supervisor
CPU takes over the control of the crate, and, according to the hit list in each sequencer module, collects the full pulse information by direct access to the FADC data memory through the sequencer bus now used as a transparent port. A number of modes of readout are envisaged:

a) **Raw data readout mode.** For debugging purposes the whole information stored in the FADC buffers is needed. In this case the VME supervisor processor reads directly the FADC memory through the sequencer transparent port, and transfers
the full drift length data of each wire to the remote readout. This operation involves the transfer of up to 36 Mbyte of data.

b) **Full Drift Length readout mode.** When an external trigger occurs or the T₀ information is not usable, then the complete drift length has to be analyzed in order to extract the hit list. This is done in parallel by the 10 VME sequencers each operating on a total of 4 Mbytes at a scanning rate of 8 Mbyte/sec.

c) **T₀ Window selective readout mode.** For those events, localized in a limited region of the chamber and identified by the T₀ grid system (Fig. 11.5), the hit table construction is carried out on a drift segment corresponding to about 1/8 of the maximum drift length, before an analysis of the pulse shape coming from the grid channels. In Table 11.1 the main parameters for the readout of a 100-hit event are reported

<table>
<thead>
<tr>
<th>Readout mode</th>
<th>Raw Data</th>
<th>Full Drift</th>
<th>T₀-Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event Size</td>
<td>36 Mb</td>
<td>~Kbyte</td>
<td>~Kbyte</td>
</tr>
<tr>
<td>Hit Finding</td>
<td>—</td>
<td>500 ms</td>
<td>60 ms</td>
</tr>
<tr>
<td>Event building</td>
<td>15 sec</td>
<td>20 ms</td>
<td>20 ms</td>
</tr>
<tr>
<td>Maximum rate</td>
<td>0.06 Hz</td>
<td>2.0 Hz</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>

11.5. **Event Builder.** The final stage of readout takes place in a VME crate located in the counting room (Fig. 11.6). It consists of the optic data communication link, where the original partition of the system is still maintained, the event buffering and storage, and the standard monitoring and display devices (personal computers or small work stations).

The optic link is driven by the same type of VME M68020 CPU system used in the basic readout unit. The VME crate houses also the monitoring and the event display facilities together with a fast link to a µVAX host processor dedicated to the mass storage and the on-line analysis. The control of the equipment is performed by any active processor unit using a communication network based on the standard Ethernet and multiplexed into the optic channel dedicated to the supervising functions. A summary of the main components of the readout is given in Table 11.2.
Figure 11.5.— Selective Drift Volume Readout

Figure 11.6.— Counting Room Computer System
Table 11.2—Readout Component List

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Component</th>
<th>Quantity</th>
<th>Component</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>VME Crates</td>
<td>6</td>
<td>VME sequencer</td>
<td>40</td>
<td>μVAX link</td>
<td>1</td>
</tr>
<tr>
<td>FADC Crates</td>
<td>8</td>
<td>FADC digitizer</td>
<td>144</td>
<td>MTUs</td>
<td>2</td>
</tr>
<tr>
<td>MAC II</td>
<td>5</td>
<td>M68020+Link</td>
<td>6</td>
<td>Ethernet</td>
<td>6</td>
</tr>
<tr>
<td>μVAX 3</td>
<td>1</td>
<td>VME RAM</td>
<td>10</td>
<td>Graphics</td>
<td>2</td>
</tr>
</tbody>
</table>

**Remarks.** The 24 cm test setup allowed the understanding of several of the mentioned items. Namely the use of a 40-channel FADC digitizer with two event banks of 8 Kbytes, the control of a simplified VME sequencer with FADC transparent port and the handling of several 100 Kbyte events in a VME crate with its link to a μVAX host computer. Experience has also been acquired on the interactive event display data presentation and its implications in the analysis.

11.6.—Optic Data Link. One of the problems of an underground experiment like ICARUS is that a large amount of data must be transferred between the underground tunnel and the external laboratories. The larger the capacity of the data link, the better the access to the experiment and the smaller the amount of data processing that must be implemented in a hostile environment. Ideally, one would like every bit that comes out of the apparatus to be carried to the counting room, 8 Km away. While conventional coaxial cable communication links would make this requirement nearly impossible, the new fiber optic technology promises to solve the problem with ease.

Glass seems to be winning over copper. Recently, fiber optics have gained a definite advantage, at least for high speed, long distance links. This is due to:

a) very high speed

b) electromagnetic noise immunity

c) rapidly increasing system reliability.

Up to now, multi-mode graded index fibers have dominated the market, with limitations of a few Km without repeaters and about 100 MHz bandwidth. With the advent of "single mode" fibers, these limits are exceeded with ease.

A typical mono-mode fiber working in the "second window" (1300 nm) has attenuation better than .5 dB/Km and dispersion of 3.5 ps nm⁻¹ km⁻¹, resulting in a bandwidth of about 1000 GHz Km, or, practically, in connections >30 Km long without repeaters, at every speed that available electronic apparatus can handle. In fact, the real limitation is coming from the transmission electronics, and not from the cable itself.
However, the electronics is rapidly catching up to the new possibilities of this medium. Systems with bandwidths >100 Mbit/sec are commercially available, and Gigabit/sec connections will shortly appear on the market.

What we mean by transmission electronics is not simply transmitters and receivers, but fully developed systems including compatible multiplexers and demultiplexers capable of mixing in a high speed channel a variety of inputs and recovering them at the other end, a few Km away. For example, 64 Kbit/sec channels for voice and low speed (RS 232) data links, LAN bridges running at 10 Mbit/sec, video channels at different speeds, can all be mixed by commercially available instruments. The physical channel can run at different speed, from 2 Mbit/sec to 140 Mbit/sec, depending on economical factors like the total amount of data to be transmitted in a particular implementation. Commercial apparatus typically use a TDM (time division multiplexing) technique to implement these links.

Mono-mode fibers can handle all of the available technologies, with the possibility of immediate upgrade modifying only the end electronics. It must be noted that the price of the electronics equipment at the end of a fiber optic link a few Km long is always much lower that the price of the fiber cable itself, and that the cost of a cable made up of 12 mono-mode fibers is only one third the cost of the cable layout.

What this means is that it is convenient to install high performance fibers, because the difference in price is minimal while it is important to insure the possibility of future expansions. Moreover, it is becoming clear that dedicated channels carrying private data are not as expensive as it may appear at a casual look.

In this framework, we have been moving in several directions. While it is still necessary to keep in contact with the industrial developments, due to the large amount of new hardware which is becoming available, we are also setting up a fiber optic laboratory with the facilities for assembling, connecting and testing fiber systems.

One of the first applications has been to adapt two commercial Tx-Rx pairs to the transmission over a stretch of 10 Km of single mode fiber of an ETHERNET network. The system is now operational in the LNF.

A board using the new AMD TAXI Tx-Rx pairs is being assembled in our laboratory, to test in the field the possibilities of these powerful new chips (125 MHz point-to-point connection with automatic encoding-decoding, error recovery and idle signal generation for continuous synchronization of the line).

A study is being carried on on the relative advantages of the two types of transmitters currently available:

— LED's, with low cost, easy maintenance but low power emission and higher bandwidth spread
laser Diodes, more costly and delicate, but with higher power outputs coupled into single mode fibers and higher transmission speed.

In the meantime, a cable built by Pirelli SpA and containing 100 single mode fibers has been installed under the gallery. The length of the cable is 8.2 Km. The connection of the fibers to a central distribution panel will be completed by the end of March 1988.

The ICARUS connection will be implemented with a set of dedicated fibers carrying TAXI transmission and serving one VME crate each, without sacrificing the VME bus throughput. A pair of fibers will be used for each crate to implement a full duplex connection. A dedicated VME module will support the communication between the two sides of the link, and 8 fibers will be sufficient for the full amount of data.

An additional fiber optic link will also be used for control and service purposes: environmental sensors, alarms, Ethernet networks, etc. A pair of fibers should be enough for every requirement.

The full amount of raw data, as well as the controls and sensors of the installation, can be made available to the experimenters outside the gallery as well. This drastic solution will solve many of the problems, during the experiment test and assembly, associated with work in an uncomfortable environment without sacrificing the possibility to access every detail of the experiment.

<table>
<thead>
<tr>
<th>Fibers</th>
<th>Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single mode</td>
<td>100 single mode fibers</td>
</tr>
<tr>
<td>Second window (1300 nm)</td>
<td>8.2 Km length</td>
</tr>
<tr>
<td>Attenuation &lt;0.45 dB/Km</td>
<td>Installed and maintained by SIP</td>
</tr>
<tr>
<td>Dispersion &lt; 3.5 ps nm⁻¹ km⁻¹</td>
<td></td>
</tr>
<tr>
<td>Transmission Method (TAXI)</td>
<td>Interface</td>
</tr>
<tr>
<td>125 MHz Synchronous Serial Link</td>
<td>140 Mb/s Laser Diode or LED module transmitters</td>
</tr>
<tr>
<td>NRZI 4b-5b encoding</td>
<td>&gt;140 Mb/s PinFet Rx's</td>
</tr>
<tr>
<td>ECL interface</td>
<td></td>
</tr>
<tr>
<td>VME modules</td>
<td></td>
</tr>
</tbody>
</table>
12.1.— Commercial production of liquid Argon. Liquid Argon is the only noble gas for which a real industrial mass production is available worldwide. For instance the yearly production of liquid Argon in Europe is a few hundred thousand tons/year. The cost of 1 liter of liquid Argon delivered to the Gran Sasso Laboratory is of the order of 1000 lire. It is therefore intended to purchase the required liquid commercially and to further purify it locally.

Liquid Argon is obtained as a by-product in the liquefaction and separation of air. The composition of air is shown in Table 12.1[12.1]. As well as these gases, others may be present at the ppb to ppm level, due to the regional variations in atmospheric pollution, such as methane, other hydrocarbons, freons and so on. The three main components of air, namely nitrogen, oxygen and Argon, have rather similar physical properties, especially a narrow range of boiling points.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Formula</th>
<th>Molecular Weight</th>
<th>Conc. by vol. in dry air (%)</th>
<th>Boiling Point (°C)</th>
<th>Density at n.t.p (g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>28.016</td>
<td>78.08 %</td>
<td>-195.80</td>
<td>1.2505</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>32.000</td>
<td>20.95 %</td>
<td>-182.97</td>
<td>1.4290</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>39.944</td>
<td>0.932 %</td>
<td>-185.86</td>
<td>1.7840</td>
</tr>
<tr>
<td>Carbon diox.</td>
<td>CO₂</td>
<td>44.011</td>
<td>0.03 %</td>
<td>-78.45</td>
<td>1.9771</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>20.183</td>
<td>18.21 ppm</td>
<td>-246.06</td>
<td>0.8999</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>4.003</td>
<td>5.24 ppm</td>
<td>-268.94</td>
<td>0.17846</td>
</tr>
<tr>
<td>Krypton</td>
<td>Kr</td>
<td>83.8</td>
<td>1.139 ppm</td>
<td>-153.40</td>
<td>3.745</td>
</tr>
<tr>
<td>Xenon</td>
<td>Xe</td>
<td>131.30</td>
<td>0.086 ppm</td>
<td>-108.12</td>
<td>5.897</td>
</tr>
</tbody>
</table>

The liquefaction process can be divided into four steps
1) Purification of feed air
2) Air cooling and compression in turbines or piston compressors, expansion of the gas
3) Heat exchange between gaseous products and feed air
4) Distillation of air (98 K to 78 K) to separate it into its main components.

Piston compressors work at higher pressure, up to 200 bar, while turbines work at lower pressure, up to 60 bar. Piston compressors need lubrication which is usually provided by synthetic oils or grease. These lubricants may contain fluorocarbons which are electronegative. Turbines on the other hand need much less lubrication and thus are less of a source of dangerous impurities.

<table>
<thead>
<tr>
<th>SUPPLIER</th>
<th>AIRGAZ</th>
<th>AIR LIQUIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impurity</td>
<td>Conc. by volume</td>
<td>Conc. by volume</td>
</tr>
<tr>
<td>N₂</td>
<td>&lt; 2 ppm</td>
<td>&lt; 10 ppm</td>
</tr>
<tr>
<td>H₂</td>
<td>&lt; 0.01 ppm</td>
<td>&lt; 1 ppm</td>
</tr>
<tr>
<td>CH₄</td>
<td>&lt; 0.1 ppm</td>
<td>&lt; 1 ppm</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>&lt; 0.05 ppm</td>
<td>—</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>&lt; 0.05 ppm</td>
<td>—</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>&lt; 0.05 ppm</td>
<td>—</td>
</tr>
<tr>
<td>Total CₐHₙ</td>
<td>&lt; 1 ppm</td>
<td>—</td>
</tr>
<tr>
<td>CO</td>
<td>&lt; 1 ppm</td>
<td>—</td>
</tr>
<tr>
<td>O₂</td>
<td>1 ppm</td>
<td>&lt; 2 ppm</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.1 ppm</td>
<td>&lt; 1 ppm</td>
</tr>
<tr>
<td>H₂O</td>
<td>—</td>
<td>&lt; 3 ppm</td>
</tr>
</tbody>
</table>

A flow diagram of a typical air separation plant is shown in Fig. 12.1[12.1]. Separation of the various components is done in two different fractionating columns one on top of the other (developed originally by Carl von Linde). The columns contain special trays which are perforated by a multitude of small holes. The vapor passes upwards while the liquid flows down over the trays hence providing a good heat exchange between liquid and vapor on each tray. Cooled and partially liquefied air is introduced at the bottom of the lower column. Between the lower column and the upper one there is a condenser-reboiler which allows nitrogen to condense in the lower column. The final separation takes place in the upper column. From the top to the bottom of the upper column there exists a composition gradient from nitrogen to oxygen which can be withdrawn from both ends of the column with a purity greater than 99%. Argon boils at a temperature intermediate between oxygen and nitrogen and hence its concentration is highest in the middle trays of the upper column.
Figure 12.1— Flow diagram of a typical air separation plant

Figure 12.2.— Typical Argon purification system
Gas drawn from this region of the upper column contains 12 to 15% Argon, with the rest being mainly oxygen.

A typical Argon purification system is shown in Fig. 12.2[12.1]. This gas is fed into an Argon column which contains more than 50 trays. Separation produces approximately 98% Argon, 1.5% oxygen and 0.5% nitrogen. The remaining oxygen is removed with a slight excess of hydrogen in a catalytic reactor (usually a palladium-based catalyst). The generated water and part of the carbon dioxide is removed in molecular sieves. The Argon stream now contains approximately 1% hydrogen and 1% nitrogen. In another column the Argon is recondensed with the hydrogen bleeding away at the top of the column. The nitrogen is also removed at the top of the column as vapor while the Argon is liquefied at the bottom. The final product contains Argon with a purity of 99.995% or better, with a few ppm of each of the other gases, oxygen, nitrogen, hydrogen, carbon dioxide, and water. This is illustrated in Table 12.2 where we list the impurities measured at the production plant for two typical suppliers of liquid Argon.

12.2.—Impurities relevant for ICARUS. Not all impurities present in liquid Argon are necessarily detrimental to the experiment. We need to remove only those which may lead to electron trapping and therefore to a decrease in electron lifetime.

As mentioned in Section 2.1, a typical electron trapping impurity is oxygen. Other molecules with similar behavior are those containing atoms of chlorine or fluorine. On the other hand, electron trapping is absent for the alkanes and hydrogen. It is uncertain whether nitrogen traps electrons, however past experience at CERN, using OXISORB and molecular sieves as purifiers (neither of which removes nitrogen) suggests that it does not.

We next consider carbon dioxide, Bakale et al [12.2] have determined an upper limit for the reaction rate constant for \( e^- + CO_2 \rightarrow CO_2^- \) of \( k < 6 \times 10^7 \) liter mole\(^{-1}\) s\(^{-1}\). Although this rate is three orders of magnitude below the one for oxygen it can still limit the electron lifetime if its input concentration is \( \approx 1 \) ppm.

For water, although no direct measurement exists, analysis of the data of ref. 12.2 suggests that the reaction \( e^- + H_2O \rightarrow H_2O^- \) would also proceed, if at all, with a low rate constant, perhaps similar to that of \( e^- + CO_2 \). To summarize, out of the impurities listed in Table 12.2, we need to remove oxygen, carbon dioxide and water.
12.3.—Methods of impurity removal. There are two main methods for removal of impurities, namely chemical adsorption using getters and physical adsorption using molecular sieves. More exotic methods will be discussed briefly at the end.

Molecular sieves are made of synthetically produced crystalline alumino-silicates [12.3] and belong to a class of compounds known as zeolites. Zeolites are crystalline materials which have a precise array of cavities and pores within each crystal. These pores have different dimensions depending on the chemical composition of the sieve. For a pore size of 4 Å the sieve allows the passage of molecules with an effective diameter less than 4 Å, while for 10 Å pores molecules of less than 10 Å are able to pass. Polar molecules are those most strongly adsorbed due mainly to the positive ions that are exposed in the crystal lattice of the sieve material. These positive ions electrostatically attract the negative end of the polar molecule, which then becomes trapped. Polar molecules are typically those which contain O, S, Cl or N atoms and are asymmetric. Non-polar impurities such as CO₂ also enter the sieve pores, but there is no electrostatic attraction. The vapor pressure of CO₂ at room temperature is too high for it to be retained effectively by the sieve. Operating the sieve at -70°C reduces the vapor pressure of CO₂ to about 2 bar and makes the adsorption more effective. In general, the adsorption capacity of molecular sieves depends on the vapor pressure of the impurity at the operating temperature of the filter.

Prior to use, the molecular sieve filters must be prepared or "activated". This is done by heating the sieve to 350°C under vacuum. In Fig. 12.3 is shown a curve of pressure on the filter as a function of pumping time for the activation of the filter described in Section 2.2. Typical final activation pressures are of the order of 5 x 10⁻⁵ mbar with the filter hot, corresponding to about 200 hours of pumping time.

A mixture of molecular sieves 4Å and 13X (this sieve also has pores of 10 Å) activated in this way and operated at -70°C can thus be used to remove water and carbon dioxide. Such a mixture would also remove traces of polar fluorinated or chlorinated hydrocarbons which may be present in the Argon gas below detectable limits (i.e., at levels < 20 ppb) as a remnant of the compressor cycles. However, oxygen is not removed by this method, since it is not polar and it has a high vapor pressure at this temperature. Thus, for oxygen removal we must resort to chemical adsorption using a getter.

OXISORB cartridges are getters built by Messer Griesheim, that operate at room temperature. The filter material is chromium imbedded in a SiO₂ crystal lattice. Oxygen is removed very effectively via the reaction

$$2 \text{Cr} + 3\text{O}_2 \Rightarrow 2\text{CrO}_3$$
Figure 12.3 — Pressure vs. time for a typical filter activation.

Figure 12.4.— Fraction of charge collected as a function of the electron lifetime for a drift time of 1.1 msec, corresponding to a drift distance of 225 cm at 1 kV/cm.
12.4.— *Parameters defining the purification system.* The requirements to be satisfied by the purification system are as follows:

a) It should remove primarily O$_2$, CO$_2$ and H$_2$O, for the reasons discussed above.

b) It should be capable of purifying about 100 liters of liquid Argon per hour, i.e. about 80 m$^3$ of Argon gas per hour.

The electron lifetime can be estimated by using the formula for the charge collected as a function of time for a gridded ionization chamber (Section 2.3). In Fig. 12.4 is plotted the fraction of charge collected Q(t)/Q$_0$ as a function of the electron lifetime $\tau$ for a drift time $t_d$ of 1.1 msec corresponding to a maximum drift distance of 225 cm at a field of 1 kV / cm. If we want to collect $> 80\%$ of the charge then an electron lifetime of $> 2.5$ msec is required. One can see from Fig. 12.4 that increasing the lifetime beyond 2.5 msec does not improve the charge collection efficiency dramatically.

The level of purity consistent with this lifetime can be estimated from the reaction rate constants of e$^-$ + O$_2$ displayed in Fig. 2.1, and that of e$^-$ + CO$_2$ mentioned above (Section 12.2).

An electron lifetime of 2.5 msec determined by the reaction e$^-$ + O$_2$ $\Rightarrow$ O$_2^-$ would demand [O$_2$] $< 0.15$ ppb. If the limiting reaction was that of e$^-$ + CO$_2$ $\Rightarrow$ CO$_2^-$, then a concentration [CO$_2$] $< 0.1$ ppm would be necessary. For reasons already mentioned, the required concentration of water should be similar to that of carbon dioxide.

12.5.— *Design of the purification system.* The purification system will be a modular system, designed using the experience gained with the simple Argon purification system described in Section 2.2, as well as the know-how gained in the UA1 Collaboration in cleaning non-polar room temperature liquids such as tetramethylsilane (TMS) and tetramethylpentane (TMP). With the former, we have already reached electron lifetimes in liquid Argon which are in the range of 10 msec.

The basic purification system is shown schematically in Fig. 12.5. Each of the three purification modules shown in Fig. 12.5 is shown in more detail in Fig. 12.6. The basic purification module (Fig. 12.6) is based on the system pictured in Fig. 2.3, scaled up for the necessary flow and pressure. The OXISORB cartridge for high flow and 10 bars is commercially available from Messer Griesheim and the molecular sieve filters will be built at CERN. A schematic of the molecular sieve filter is shown in Fig. 12.7.

The purifying operation for liquid Argon must be continuous, since there is little or no possibility of storing large amounts of gas during the various phases of purification. This is a potential source of problems, for even with a continuously
Figure 12.5.— Basic Purification System.

Figure 12.6.— Detail of one purification module.
working lifetime counter for electrons in liquid Argon for on line monitoring, the identification of the offending impurities in case of exhaustion of some of the filters remains an open question.

From this point of view, the basic design may not be adequate, because there is a strong possibility that the warning given by a lifetime counter would come too late, after a quantity of contaminated Argon would have already entered the dewar. Moreover, this design leaves little room for deciding whether, in such a situation, the OXISORB or the molecular sieve filter are exhausted. For these reasons the basic design has been improved, adding a second stage that consists of an OXISORB cartridge plus a molecular sieve filter. The schematics of this design is shown in Fig. 12.8. In the improved design, on-line sensors for oxygen and carbon dioxide have been placed between the first and the second stage of the purifier. The oxygen sensor monitors the performance of the OXISORB. The carbon dioxide sensor monitors the performance of the molecular sieve filter since CO$_2$ would be the first impurity to come out of it, provided that the input concentration of water and of carbon dioxide are similar. Since the input concentration of CO$_2$ and O$_2$ should be on the ppm range, the possibility of detecting early enough the exhaustion of the first stage of the purifier, demands detectors capable of sensing traces of CO$_2$ and O$_2$ in the 200 ppb range. Such detectors are commercially available.

![Diagram of molecular sieve filter](image)

**Figure. 12.7.**—Detail of one molecular sieve filter.
Figure. 12.8.— Improved Design of the Purification System.
Complementary to these, a system capable of measuring the electron lifetime in liquid Argon will be installed at the output of the purifier. Such a system is currently being developed at CERN.

Using past experience, we estimate that a minimum of 18 filters, and 14 OXISORB cartridges will be necessary to continuously purify 200,000 liters of liquid Argon. It is almost certain that regeneration of OXISORB cartridges and of molecular sieve filters will be necessary.\(^{(11)}\)

12.6.— *Possible exotic purification schemes.* Since the removal of electron attaching impurities is the main problem one could also think of adding excess electrons in order to allow the scavenging of impurities by these electrons. The following electron sources could be employed and built into a purifier:

1) Discharge between electrodes in liquid Argon
2) Field emission from a tungsten tip in liquid Argon
3) Thermal emission of electrons from a filament in the vapor phase above the liquid Argon
4) Electrodeless discharge in a low pressure Argon stream
5) Irradiation of liquid Argon with \(^{60}\)Co gamma rays.

The main problem is the permanent removal of the negative ions formed by the electron attachment. An electric field is applied and the ions are drawn to the anode. If breakdown of the ion occurs then the impurity may diffuse back into the Argon. Hence the ion has to be permanently fixed and trapped at the anode. Conducting membranes are a possibility, or the use of easily oxidised metals where the negative ion impurity (this only works for oxygen) becomes chemically bound thus creating the appropriate metal oxide. This possibility will be investigated further with an experimental set-up.

12.7.— *References.*


[12.3] Union Carbide Corporation, 4A and 13X Molecular Sieves.

\(^{(11)}\) OXISORB cartridges can be regenerated by the company at a price of about 15% of the cost of a new unit. The molecular sieve filters will be reactivated using a dedicated line.
13.— Introduction

13.1.— General considerations. Referring to the background calculations as reported in chapter 6, we estimate that the smallest scale prototype detector to properly study the anticipated background conditions would be of the size of 1/100 of the ICARUS I mass.

We are going to build a prototype which will have a fiducial mass of two tons of liquid Argon (the total mass of Argon is about three tons) and will then be transported to the Gran Sasso Laboratory, where we will measure the background present in the experimental area where the ICARUS I detector is going to be housed in, the Hall C. To reduce the external background due to neutrons from the walls of the cave we will investigate various forms of shielding. The rate of the internal background due to neutrons from the steel dewar will of course depend on the uranium content of the steel and will probably be different in the final dewar, however the signatures of the events will be identical and therefore can be studied in detail.

A more serious source of background is the liquid Argon itself due to the presence of the isotope $^{42}\text{Ar}$. The rate of activity of the $^{42}\text{Ar}$ will just scale with the volume of the detector therefore the study of this particular process is very important as it is potentially the most dangerous background due to its high rate. As the chamber will contain the wire plane layout planned for the final device, valuable information will be learned from these measurements in terms of the signatures of the possible backgrounds that we expect.

The construction of the ICARUS I detector involves the development of a number of important features such as the operation of large wire planes at cryogenic temperatures, the production of large quantities of high purity liquid Argon, electronics working at low temperatures and readout of a large volume of data. It would obviously be very advantageous to gain as much understanding as possible about these features before proceeding with construction of ICARUS I. As a step in this direction we have studied the purification of liquid Argon on a small scale and have obtained very encouraging results which are described in detail in chapter 2 of this document. We have also studied the behavior of the proposed wire configuration in a small prototype chamber, the results from this chamber are described in detail in chapter 3 and from the electronics point of view in chapter 11. These studies have been invaluable in helping us to decide the design for the final chamber and the large scale prototype, which we are
now ready to construct, will resemble as closely as possible the final ICARUS I detector in terms of wire configuration, electronics and readout.

The construction of the 2 ton prototype will enable us to learn about the problems associated with large wire planes which have to be operated at low temperatures with regard to the types of material that can be used for the frames and so on. We envisage that the electronics and readout will be the first channels of the final scheme for ICARUS I. Likewise the purification system will consist of several modules of the design described in chapter 12. We plan first to test the chamber extensively at CERN, where it is planned to assemble the detector, in order to understand fully the behavior and performance of the system.

In addition to studying the background processes we would clearly like to study the behavior of low energy electrons from $\nu_e - e$ scattering. We are mainly interested on our detector response to the neutrino events, which means a first check of the ability of detecting neutrino events, together with the angular resolution through the measurements of the recoil electron direction. We have carried out extensive Monte Carlo studies to determine this resolution (Chapter 5) which would be useful to be tested in practice. For these measurements we need an intense source of low energy neutrinos. The neutrino beams from most accelerators are of too high an energy for this purpose, being mostly greater than a few GeV. Instead we plan to use an anti-neutrino beam from a nuclear reactor and study $\bar{\nu}_e$-electron scattering. This has the same basic features as neutrino-electron scattering, i.e. forward-peaked scattering events in the few MeV range. The $\nu_e$ from the $^{235}$U fission products in secular equilibrium have a maximum energy of about 11 MeV and the peak value is about 0.5 MeV[13.1]. Although the $\nu_e$ energy spectrum has its peak value at a much lower energy than the neutrinos from the $^8$B cycle (the peak is at 6 MeV) and does not extend as far, it clearly covers the energy range that we are interested in. The direction of the incident $\nu_e$ beam is well known, enabling us to test the validity of our electron direction measurement technique and angular resolution. The precision with which one can reconstruct the incident $\nu_e$ energy spectrum can also be tested. This particular measurement will be important for deciding between the different explanations for the Solar Neutrino Problem.

The $\nu_e$ flux from a typical 1.8 GW reactor is $2.2 \times 10^{13}$ cm$^{-2}$ s$^{-1}$[13.2]. Using the calculated cross-sections for $\nu_e$-electron scattering integrated over the predicted $\nu_e$ energy spectrum[13.3] we obtain predictions for the expected event rate as a function of the distance from the reactor and the energy threshold of the recoil electrons. These rates are given in Table 12.1 for distances of 50 meters and 100 meters and energy thresholds from 1 MeV to 6 MeV. For a threshold of 5 MeV we expect 11 events per day at a distance of 50 meters which is quite reasonable.
### Table 13.1 — The expected event rates for $\nu_e$-electron scattering for antineutrinos from a 1.8 GW nuclear reactor.

<table>
<thead>
<tr>
<th>Electron recoil energy (MeV)</th>
<th>50 meters</th>
<th>100 meters</th>
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<td>1</td>
<td>463</td>
<td>116</td>
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<tr>
<td>2</td>
<td>207</td>
<td>52</td>
</tr>
<tr>
<td>3</td>
<td>85</td>
<td>21</td>
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<td>4</td>
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<td>3</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

### 13.2. — References


14.— Mechanical design of the dewar and electrodes configuration

14.1.— General considerations. The cryostat consists of two coaxial vertical stainless steel (AISI 304L) vessels. The shape of both the internal and external vessels is a cylinder with hemispherical bottom. The two cylinders are connected together by an annular flange on the top of the dewar. Another circular flange closes (vacuum proof) from above the inner volume of the dewar. The outer vessel has a diameter of 1.5 m, a height of 3.3 m and a wall thickness of 3 mm. The inner vessel has a diameter of 1.05 m, a height of 3.08 m and a wall thickness of 3 mm. With this geometry the total internal volume is 2.61 m³ [14.1].

![Diagram of the dewar setup]

Figure 14.1.— Vertical cut along the longitudinal axis of the 2 tons dewar. The following systems are visible on the picture: 'superinsulation' screens, cooling/heating system, detector structure.

The evacuated volume (10⁻³ mbar with a rotary pump) between the two vessels is filled with "super-insulation", consisting of two copper screens surrounding completely
the inner vessel, equally spaced, wrapped with several layers of aluminized mylar sheets and operating under vacuum. The copper foils reduce considerably the heat transmitted by radiation and the mylar insulates them thermally. Fig 13.1 shows the dewar and the systems described above.

The cryogenic system of the chamber has to perform three functions:

i) cool-down of the inner vessel prior to filling with pure liquid Argon

ii) continuous cooling of the liquid Argon during operation of the chamber for extended periods of time

iii) warm-up of the inner vessel prior to emptying the liquid Argon.

The system consists of the following components which are illustrated in Fig. 14.2. The consumption of cooling Argon will be 2 liters per hour or less when the inner vessel is full of pure liquid Argon at 87 K. The cooling of the inner vessel will be performed by liquid Argon circulating in a copper serpentine coiled around the vessel in the vacuum space of the cryostat. The weight of this inner vessel is about 200 kg and 70 liters of liquid Argon will be required to cool it to 87K. The liquid Argon for cooling is supplied by a dump tank of volume 40 liters situated above the cryostat. This tank feeds by gravity the copper serpentine surrounding the cryostat. An Argon storage dewar will fill the dump tank automatically, perhaps once per day. A level indicator coupled with an electromagnetic valve will control the filling of the tank. Filling starts when the level falls below some preset value and stops automatically when the tank is full. Two demountable couplings will disconnect the cryostat from the dump tank without causing deterioration of the vacuum inside the cryostat. In addition there are transfer lines from the storage dewar to the dump tank and from the dump tank to the cryostat.

A number of different modes of operation are foreseen:

i) Circulation of warm air (120 °C) in the serpentine while the couplings are demounted will allow the inner tank to be heated to outgas the inner surface of the walls.

ii) Cooling of the inner tank by circulation of liquid Argon through the copper serpentine.

iii) Injection of pure gaseous Argon into the inner vessel to cool the wire chambers by convection. The quantity of gas will be such that only a few cm$^3$ of liquid are present. This will allow cooling of the wire planes in a uniform and controlled manner.

iv) When the chambers are cold the pure Argon is injected and allowed to condense until the required height. The system is then ready for operation.
Figure 14.2 — The cryogenic system for the prototype 2 ton detector.
v) In order to empty the vessel, warm air will be injected into the transfer line and allowed to circulate in the serpentine and vaporise the liquid. The operation is completed when the outlet pipe unfreezes.

Cleanliness of the internal vessel is of primary importance in preserving the purity of the liquid Argon. The main operations foreseen in order to achieve the required high level of cleanliness in the inner vessel are degreasing, washing with demineralized water (at 90°C), drying and thermal outgassing (at 120°C by means of hot gas circulating in the serpentine as described above).

In order to ensure an impurity concentration < 1ppb of Oxygen equivalent, the dewar has to be kept under vacuum prior to filling with pure liquid Argon. The vacuum required is 10⁻⁶ mbar. This will be obtained by means a pumping system formed by a primary pump and a turbomolecular pump separated from the inner volume by a liquid nitrogen cold trap (pumping phase), and by "baking" the internal surface of the cryostat at 120°C (outgassing phase).

In case of failure of the cooling system, the liquid Argon inside the cryostat will be vented through a rupture disc rated at about 2 bar absolute and eventually through the pumping system previously described.

14.2.— The configuration of the inner electrodes In view of the fact that this prototype should be used also to test the feasibility of the technological solutions to be adopted in ICARUS I, we have decided that the internal configuration of this dewar will follow very closely the one proposed for the 200 ton detector.

The inner volume of the dewar will be split into two independent semicylindrical sections, each one a mirror image of the other, by means of a stainless steel septum put vertically along a diameter of the dewar. This septum will be held in position between two horizontal circular metal plates. These plates, one on the bottom and the other on the top of the dewar, and the central septum will form a solid structure completely independent of the surrounding dewar in which one can insert all the elements necessary to build the drift chambers. This "box" will hang from the upper flange by means of four rods. A small part at the top of the volume will be excluded from this sectioning because it is needed as a service area to allow input/output to electronics and high voltage for the detector sections and to monitor the liquid argon level.

The structure of each drift region will be similar to the one described for the ICARUS I detector. Both sections will be equipped with identical drift chamber systems. Each wire chamber will cover a surface equal to 2.4 × 0.9 m² and will be supported by frames built-in on each side of the central septum. The drift volume will be defined by the chamber itself and a system of "race-tracks" consisting of 10 tubular rings of 2 cm in diameter and a cathode. The "race-track" rings are separated from each
other by 5 cm and have a gradually increasing distance from the inner wall of the dewar so as to ensure the necessary safety distance against electrical break-down between rings and grounded wall. The race-track system will be connected to the high-voltage power supply with each individual ring being set at the appropriate voltage by means of a resistor chain contained in the service area. The purpose of the race-track system is to establish a well defined and uniform electric field all over the detection volume so that the electrons may be correctly and efficiently drifted onto the wire plane. The cathode will be a vertical metal plate, 2 cm thick, 30 cm wide and 2.4 m high, parallel to wire chamber, charged to the negative voltage of maximum 45 kV. With the distance between cathode and wire chamber of 42 cm (maximum drift distance), this voltage yields an electric field of 1 kV/cm in the drift volume. In Figs 14.1, 14.3 and 14.4 different views of the drift chambers structure are presented. Fig. 14.5 represents the electric field configuration (equipotential contours and field lines) in a quarter of an horizontal cross-section of the dewar volume. The wire chamber, the race-track and the cathode are also shown. The total useful volume for signal detection (fiducial value) will be ≈ 1.45 m$^3$ corresponding to ≈ 2.0 tons of liquid argon.

**Figure 14.3.**— Horizontal cross-section of the 2 tons dewar. The inner structure of the detector is indicated.

14.3.— A possible trigger system for the prototype. Unlike ICARUS I the $T_0$ grid will not be used in this prototype. In fact because of the reduced dimensions of the drift volume, a further partitioning of it into smaller regions is unnecessary. Furthermore the $T = 0$ information can be obtained by reading the induction
signal either on the screening/focussing grid or on the race-track rings. The second is preferable because the race-track system has a smaller capacitance (meaning a lower electronic noise). We have investigated the possibility of using the induction signals on the race-track rings to determine the energy of the event occurring inside the drift volume. The z-coordinate (normal to the sense-wire-plane) will be neglected because the small drift distance (42 cm) and the small detector volume (1 ton of liquid argon per drift region) make the background rate so low (14.3 ⁴²Ar electrons per second) that the probability of getting two event above threshold in the same drift time (400 µsec) is practically zero. The idea is to combine the induction signals of each race-track ring in such a way so as to give an overall signal whose amplitude depends only on the energy of the event and not on the position of the track within the drift volume.

The simplest way to exploit the induction current signals on the race-track rings is to sum them all. Unfortunately this method is not precise in reconstructing the energy of the generated track. This can be understood with the help of the equal-induction contour map produced by a test-charge on the race-track shown in Fig. 14.6 where the contours are plotted in steps of 4 % and the induction is maximum near the race-track. As the induction current is the gradient of the induced charge, from Fig. 14.6 it is easily seen that tracks generated in the central part of the drift volume will give a lower induction signal that those produced in the peripheral region. This effect is visible Fig. 14.7a where the initial current amplitude distribution is plotted for tracks generated in the central part of the drift volume with a fixed energy of 5 MeV. The even worse situation of the tracks generated in the peripheral part of the drift region (near the race-track) is shown in fig. 14.7b. A possible solution to make the signal more uniform is to weight the signals of each ring before summing them together. The Green reciprocity theorem suggests the correct weights to assign, resulting in weights that are proportional to the voltage applied to the corresponding rings. Fig. 14.8 shows the corresponding equal-induction contour map. Fig 14.9 shows the resulting induction signals due to tracks of 5 MeV and the initial induction current amplitude distribution is plotted in Fig. 14.10. The results indicate that the induction current is proportional to the track energy as shown in Fig 14.11. The problem is the absolute value of the current which is only 700 electrons/µsec and maybe too small compared to the electronic noise (2500 electrons). This means that one has to wait few microseconds to allow the induction charge signal come out of the noise, the effect of this is a reduction of fiducial volume and a worse definition of the event energy. This is being studied at present.

14.4.— Geometry of the chamber planes. The geometry of the wire chambers will be exactly the one described for ICARUS I (chapter 8). There will be two identical
wire chambers on each side of the central septum. Each chamber consists of three planes of wires. Going from outside to inside the first plane will be a screening/focussing grid, followed by the induction-based detection plane and finally the collection-based detection plane.

Figure 14.4.— Details of the wire chambers.

Because of the much more complex structure of induction-plane and screening grid (four wires needed to form an 'induction cell'), we have decided to strung the wires of these planes vertically, along the shorter side of the chamber frame; thus each drift volume will have a total of \( \approx 1800 \) vertical wires (2.4 m long) of which \( \approx 900 \) will be sense-wires (corresponding to 450 pairs). The collection plane will consist of a total of \( \approx 2400 \) horizontal wires (0.9 m long), of which \( \approx 1200 \) are sense-wires. All the wires will be 100 \( \mu \)m in diameter. The electrostatic deflection and the gravitational sag of the wires will be minimized by applying a tension of \( \approx 400-600 \) g per wire.
Because of the short drift distances the electron diffusion along the drift path should not spread the electron signal too much, thus a separation of 2 mm between the three wire planes should be acceptable. The required voltage setting of the planes for the 2 mm separation is given in Table 7.4. We refer the reader to chapter 8 for a detailed discussion on wire configurations, field maps, electron signals and diffusion effect.

The total number of sense-wires (collection plus induction) for the two drift chambers of the detector will be 3300. Unfortunately the surface available for the corresponding feed-throughs is not enough even with the special design described below. For this reason we have decided to connect electrically together each horizontal sense-wire of one chamber with the corresponding one of the other chamber. The result is a reduced number of feed-throughs (= 2100) that can be placed more easily on the available area. The draw-back of this operation are: increased capacitance of the collection-mode sense-wires, increased difficulty in the event reconstruction. The first

![Electric Field Configuration for the 2000 Litres Dewar](image)

**Figure 14.5.**— One quarter of an horizontal cross-section of the 2 tons dewar showing inner structures of the drift chamber and the electric field configuration (equipotential contours and field lines).
Figure 14.6.— Equal-induction contours produced by a test charge on the race-track.

effect is negligible because of the small length of the collection wires (two wire together are shorter than an induction wire); the second problem will be by-passed by association with the induction-mode signals.

The materials planned for the construction of the chambers will be mostly stainless steel, ceramics and plastics as in ICARUS I because we want to verify on a large scale prototype that the properties of cleanliness, mechanical precision and low natural radioactivity guarantee the feasibility of the 200 tons detector.

14.5.— The service area. The space available at the top of the dewar will be used as a service area (Fig 14.1). In it (a) all the 2100 cable carrying the electron signals will be gathered in bundles, (b) the various systems needed to monitor the argon purity and the liquid level plus the visual controls allowing an external inspection of the detector will be placed, (c) the high voltage conductors (one set for each detector section) feeding the cathodes and the race-track rings will also be installed.

The connection between these elements and the outside of the dewar will be ensured by means suitable feed-throughs placed in the top flange. The flange will also contain the connections for the high voltage power supplies, pressure-meters, vacuum-meters and liquid argon level indicators. Finally the liquid argon inlet/outlet, the vacuum inlet and the safety rupture disks will also be placed on the flange.
Figure 14.7.— The initial current amplitude for tracks of 5 MeV generated in a) the central part of the drift volume, and b) near the race-track.
Figure 14.8.— Weighted equal-induction contours produced by a test charge on the race-track.

Figure 14.9.— Induction current signals on the race-track using the weighting procedure described for tracks of 5 MeV generated randomly in the volume.
Figure 14.10.— Initial induction current amplitude for tracks of 5 MeV generated randomly in the drift volume.

Figure 14.11.— The correlation between induction current and track energy.
Because of all these necessary devices there will be not enough space for all signal feed-throughs on the flange. For this reason we have decided to build a 20 cm high box above the dewar with an upper surface sufficiently wide (1.05 m in diameter) to support the 2100 signal feed-throughs. It will be connected to the flange of the cryostat by means of four pipes through which the signal cables will reach the connectors of the feed-throughs. These will be arranged on 14 small flanges (10 cm in diameter) in groups of 150.

A separate vessel, thermostatically controllable (a refrigerator box), will be mounted directly on top of the structure described above (Fig 14.6). The front-end amplifiers will be stacked inside this box being at the minimum possible distance from the wires and consequently reducing the capacitive noise of the system to its minimum. Furthermore they can be kept at the optimum temperature needed to achieve the minimum possible noise level from the electronic components.

<table>
<thead>
<tr>
<th>Table 14.1 — Design Parameters for the 2 Ton Dewar</th>
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<tbody>
<tr>
<td>Number of drift chambers</td>
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<tr>
<td>Chamber width</td>
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<tr>
<td>Chamber height</td>
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<tr>
<td>Maximum drift distance</td>
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<tr>
<td>Fiducial volume</td>
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<tr>
<td>Fiducial mass (liquid argon)</td>
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<tr>
<td>Total volume of the dewar</td>
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<tr>
<td>Total liquid argon volume</td>
</tr>
<tr>
<td>Total liquid argon mass</td>
</tr>
<tr>
<td>Fiducial volume</td>
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<tr>
<td>Vertical wires (induction plane + screening grid)</td>
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<td>Length of vertical wires</td>
</tr>
<tr>
<td>Horizontal wires (collection plane)</td>
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<tr>
<td>Length of horizontal wires</td>
</tr>
<tr>
<td>Induction-mode signals</td>
</tr>
<tr>
<td>Collection-mode signals</td>
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<tr>
<td>Number of feed-throughs</td>
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<td>Nominal High voltage</td>
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<td>Electric field in the drift regions</td>
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Figure 14.12.— Details of the pre-amplifier box and the structure that brings the signal cables to the pre-amplifiers.
14.6. — References.

[14.1] Technical notes on design, calculations, construction and tests of the dewar DN1000 by E. Zanon s.p.a. Schio (VI) 1986/7
15.— Prototype detector read-out electronics.

15.1.— System description. The general layout of the Read Out Electronics (ROE) is shown in Fig. 15.1. The system consists of a Main Processor (MP), and four 512-wires modules, each one reading 512 sense wires and communicating with the outside world through a VME bus. The MP may either read directly the raw data out of the 512-wires modules, or give them some commands in order to start preprocessing (data compaction, hit list extraction, etc.) on the data.

![Diagram of ROE layout](image)

**Figure 15.1.— General organization of the read-out system.**

Fig. 15.2 shows the block diagram of a 512-wire module. This module contains a Signal Processor Unit (SPU), a Bus Adapter and a group of Signal Digitizer Boards (SDB). Actually there are 4 SDB’s in each 512-wire module. The SPU communicates directly with the MP via the VME bus, and with the SDB’s through a VSB/VMX bus and the Bus Adapter which in turn communicates with the SDB’s via an Internal Bus (IB). It receives commands from the MP and preprocesses the raw data stored in the SDB’s. The SPU acts as a VME slave with respect to the MP and like a VSB/VMX master with respect to the SDB’s. The SDB’s are seen as VMX/VSB slaves by the SPU and as a VME slaves by the MP. The SDB’s contain all the hardware needed to perform the acquisition and storage of the preamplified analog data coming out from the front-end amplifiers located close to the detector.

The Internal Bus is a standard TTL-level read/write 32-bit data, 14-bit address bus. Additional control signal allow the bus to be chained to several SDB’s. The data organization of the 32-bit data bus is explained in the next section. The Bus Adapter
ensures the translation of the Internal Bus signals to any standard local bus protocol such as VMX, VSB or others, together with the interface to the VME bus used as global system bus for control and data acquisition access. This open design approach allows, in the first instance, the development and test of the system using existing standard processor units but will not prevent the improvement of its performances by addition of the latest technology products.

Fig. 15.3 shows the detail of a SDB. It consists of 16 Signal Digitizer Units (SDU) and of three control sections. The 16 SDU’s contain the acquisition and data storage electronics for 128 sense wires. The Main Controller (MC) acts as a master on the SDU’s and controls the access requests to the data storage memory coming both from detector's trigger system and from the external world (i.e. the MP). Accesses to the memory requested by the MC, as well as the refresh operation are controlled by the VDM (Video DRAM Manager) in such a way that, seen from the MC, the memory looks like a static RAM with a variable access time depending on several parameters explained in the next paragraph.

Fig. 15.4 shows the detail of a SDU which contains 8 FADC modules and a VDRAM (Video Dynamic RAM) with a total capacity of 128 KBytes. The SDU receives the analog signals from 8 sense wires which are converted in the FADC modules and the results (bytes) are stored in the VDRAM.

The memory is organized as follows. Analog signals are sampled every 400 nsec on each sense wire. (This operation is performed in the FADC modules). Each sample corresponds to 1 Byte. Eight FADC modules present their byte at their output port. A digital multiplexer operating at 20 MHz opens the output port of each FADC module one at a time every 50 nsec so that 8 samples may be stored in the memory in a time
slice of 400 nsec. To achieve this rate, a particular device called VDRAM has been chosen, which allows, due to its particular architecture, to store serially and at the required rate a stream of bytes through a serial port, while allowing a fully simultaneous random access through a separate random access port. Additional technical information on these devices may be found in [15.1] and [15.2]. The earlier mentioned 128 KBytes total capacity of the memory derives from the following considerations. The VDRAM's are actually nibble-wide devices containing a standard matrix of RAM cells and four 256-bit deep shift registers which are filled in serially and then saved in one row of the RAM matrix. Two of these chips are put in parallel to obtain a byte wide VDRAM, which will be called a "bichip".
During the register to memory transfer, that is during the saving of the data present in the input serial shift register, no additional serial data may be retained. This situation would cause the loss of the samples of data coming during this time. To avoid this loss a second bichip is foreseen (see Fig. 15.5) so that serial data is switched from one bichip to the other every 256 samples of data. As each bichip has a capacity of 64 KBytes, the total memory capacity is 128 KBytes for 8 sense wires, which is equivalent to 16 KBytes dedicated to each sense wire. The data given above are valid when considering a TMS4461 type device [15.1]. Using a TMX44C251 type device [15.2], the overall system performances will be upgraded accordingly.

Fig. 15.6 shows the detail of a FADC module. A differential line receiver is followed by a Flash ADC which converts the analog signal coming from a sense wire into a digital datum which is hold stable for 400 nsec until it has been stored as explained above. The signal fed into the receiver comes from the front-end amplifier-shaper-driver ensemble which has been extensively described in chapter 9 of this document. Three DAC’s are foreseen in this module. The first one controls the gain of the differential receiver so that the system dynamics may be adapted to the range of picked-up signals. The second one can inject an analog signal into the FADC and is used for calibration purposes. The third one can control the FADC’s reference voltage so that pedestals may be set by the MP.
15.2.— *System Operation*. The system can operate in three different modes:  
1) test mode  
2) calibration mode  
3) run mode.  

1) Test Mode. In the test mode, control over the whole system and in particular over the serial input port of the VDRAM’s is given to the MP. In this way the MP can perform all the Read/Write operations on the memories and control and status registers buried in the various modules. In test mode, the MP should be able to test the correct functioning of every step through which data pass in their path from the detector to the MP itself.

Fig. 15.7 shows the path of the data along the acquisition system and 4 points where a test pattern may be injected and/or extracted after having passed all or only one part of the path in order to see if all modules are working correctly. The data injected at TP0 is an analog signal obtained from the MP through a DAC. The data at all other TP’s is a digital signal.

2) Calibration Mode. This mode concerns mainly 2 DAC’s which set the reference voltage and the gain of the receiver-FADC pair (See Fig. 15.6). Dynamic range and biasing voltage levels of the analog section of the data acquisition system can be controlled in this way. It should however be understood that only FADC’s are
interested in this calibration. The calibration of the front-end amplifier is envisaged in the usual way.

iii) Run Mode. In run mode, system operation will be synthesized in the following way. At the occurrence of a trigger all the SPU’s scan the associated SDB memory region selected by the MP, looking for a pulse and building a hit list table into a local memory. A selective trigger can determine a time window where to search. At the end of this phase, whose speed depends on the number of processors and the drift time domain, the MP has to read the hit information directly from the VME link according to the hit list tables. The MP then has to format and save the data into the mass storage system (an high capacity device based on the popular 8mm Video recorder or Audio Digital Tape). The same event data can then be made available to a separate system to perform an event display and other monitoring functions.

The SPU is a VME module with a local access to a set of SDB modules (e.g a MacVEE, a M68020 or any VSB/VMX master unit) whose task is to look for pulses in a given drift time segment according to a pre-programmed algorithm. When an hit is found then the corresponding data is saved into a temporary buffer. The simplest algorithm for pulse searching consists of comparing the pulse samples against a fixed threshold. If necessary more sophisticated checks can be done such as a dynamical evaluation of the channel pedestal and a constraint on the number of consecutive samples above the threshold.

The memory region to be scanned by SPU is selected as follows. First of all, the MP should define the time during which an event has to be recorded. This decision determines how many events can be recorded in the memory for a single wire in order to fill it completely. In the present case using TMS4461 type VDRAM’s, five
possibilities are given (See Table 14.1). The number of events per wire is equal to the number of regions in which the memory will be partitioned. Once this operation is done, the MP should communicate to the MC which regions have to be filled and in which order; conversely the MC has to communicate to the MP which regions have already been filled. This interlocked protocol is realized by means of two FIFO RAM's. A block diagram is shown in Fig. 15.8.

<table>
<thead>
<tr>
<th>Number of events per wire</th>
<th>KBytes per event</th>
<th>Reading time per event (μsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>6553.6</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>3276.8</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1638.4</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>819.2</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>409.6</td>
</tr>
</tbody>
</table>

**Table 15.1.— Memory assignment (Kbytes/event/wire).**

![Diagram](https://via.placeholder.com/150)

**Figure 15.8.— Management of memory regions dedicated to several events.**

A typical sequence may be as follows. The MP fills in FIFO A with the base addresses of memory regions which have to be filled; the MC gets the first base address from FIFO A and starts filling the corresponding region as if it were a circular memory. Once the MC receives a STOP signal, it stops filling the memory, stacks the last address (base + displacement address) in FIFO B and restarts filling the region corresponding to the next base address contained in FIFO A. Once the MP notices an address in FIFO B,
it reads the contents of the corresponding memory region, downloads it if the contents are of interest and notifies the MC that the region is again empty by reloading its base address into FIFO A. The reason why the MP loads only base address in FIFO A while MC loads base + displacement address in FIFO B is that the MC needs to know which memory region has to be filled and the filling starts always from location 0 of that region. On the other hand, when data acquisition stops, i.e. a STOP signal arrives, the MP has to know where to begin the read-out of memory contents, hence the necessity of communicating also the displacement address.

Concerning the priorities with which various memory operations are performed, the highest priority is assigned to register to memory transfer operation. When the input serial shift register of say bichip A is full, the MC switches the flow of serial data to bichip B, terminates the current operation (if there was one) on bichip A, saves the register in the desired row and then allows other operations to be performed. The next priority is assigned to the refresh operation which has to be completed once every 4 msec. The lowest priority is assigned to random Read operation by the MP. This fact explains the variable access time mentioned above.

15.3.— System performances. The Read operation suffers some restrictions which are necessary to speed up the downloading of memory particularly in the pre-processing phase. All data busses are 32 bit wide so that most industry standard VME/VSB/VMX boards may be used. It should however be noticed that although data have a 32 bit word length, they are meaningless unless they are considered as being composed of four adjacent bytes coming out from four adjacent memory modules (SDU's). In this situation, a downloading single CPU which wants to extract the data from a single channel should read 4 bytes of data, mask the three uninteresting ones and keep the fourth. This could be a first phase situation in which the SPU may not exist at all and the pre-processing function is done by the MP itself. Conversely, if maximum speed in the pre-processing and parameter extraction phase is required, the SPU may be composed of 4 CPU's, each one always dedicated to the same byte inside the 32 bit word, and passing their individual results to the MP. In a preliminary phase the first solution may be convenient, but the second solution will eventually be necessary in order to achieve the maximum data processing speed. Table 14.2 gives the expected performances of the system when using different SPU configurations for a 1.6 msec drift time, corresponding to 4 KBytes per wire per event. In this case each event represents 8 MBytes, that is 512 KBytes per SDB. The first line considers the case in which no SPU is used and all the pre-processing is done directly by the MP (a MACII in this case). The three following lines in Table 14.2 consider the case in which 2 SDB's have a dedicated SPU.
Table 15.2.— Expected performances with different signal processor configurations:

<table>
<thead>
<tr>
<th>Processor</th>
<th>#CPU units</th>
<th>Bus</th>
<th>Data size (Mbytes)</th>
<th>Time (sec)</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MacII</td>
<td>1</td>
<td>VME</td>
<td>8</td>
<td>16</td>
<td>0.06</td>
</tr>
<tr>
<td>M68020</td>
<td>8</td>
<td>VSB</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MUPAM(^{(12)})</td>
<td>8</td>
<td>VMX</td>
<td>1</td>
<td>0.12</td>
<td>8</td>
</tr>
<tr>
<td>Sequencer(^{(13)})</td>
<td>8</td>
<td>****</td>
<td>1</td>
<td>0.06</td>
<td>16</td>
</tr>
</tbody>
</table>

15.4.— T0 grid circuit. The schematics of the T0 grid circuit (ladder circuit) is shown in Fig. 15.9. Capacitors C2 represent the parasitic race-track capacitance and its value lies in the range of 25-30 pF. Resistors R1 set the correct voltage partition on the various race-tracks. Resistors R2 are the actual biasing resistors of the race-tracks. Capacitors C2 are decoupling capacitors between adjacent race-tracks. Capacitor C1 must have a larger value than capacitor C2 in order to ensure the transmission of the maximum amount of charge towards the charge integrating amplifier. A laboratory test was made with the following capacitor values:

\[ C_1 = 2.2 \text{ nF} \quad C_2 = 22 \text{ pF} \]

A 10-stage ladder circuit was mounted. A graph of the attenuation factor of the output signal with respect to the injected signal versus test signal injection node is reproduced in Fig. 15.10.

\(^{(12)}\) MUPAM is VME slave VMX master module, developed for the UA1 calorimeter readout. It is an arithmetic processor with a 125ns cycle, fully programmable and with extended pipe line capabilities.

\(^{(13)}\) A sequencer can be a VME module able to read and compare 4 bytes of data from the SDB bus at the maximum read speed of 250ns/transfer.
Figure 15.10.— $V_{in}$ attenuation factor.

Noise measurements done on this circuit lead to two conclusions:
1) there is no difference between high voltage ON or OFF
2) the noise is equal to the noise introduced by an external 220 pF capacitor. In other words only the race-track capacitance has to be taken into account for noise measurement purposes.

15.5.— References.

APPENDICES
A1.— Budget estimates

In Table A2.1 is reported the estimated cost in millions of Italian lira (Mlit) for ICARUS I and in Table A2.2 for the 2 ton prototype detector. The majority of the funding for the experiment is provided by the Istituto Nazionale di Fisica Nucleare.

<table>
<thead>
<tr>
<th>Table A2.1.— Estimated cost in Mlit for ICARUS I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanics</td>
</tr>
<tr>
<td>Dewar and cryogenics</td>
</tr>
<tr>
<td>Purification system</td>
</tr>
<tr>
<td>Read-out electronics</td>
</tr>
<tr>
<td>Argon</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table A2.2.— Estimated cost in Mlit for 2 ton prototype detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research &amp; Development</td>
</tr>
<tr>
<td>Mechanics</td>
</tr>
<tr>
<td>Power supply</td>
</tr>
<tr>
<td>Purification system</td>
</tr>
<tr>
<td>Read-out electronics</td>
</tr>
<tr>
<td>Argon</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>
A2.— Timescale

We estimate that the design of the prototype chamber and of its read-out electronics will be completed by October 1988. We expect that the construction of the chamber will start early next year. The development and testing of the digital read-out will be carried out in parallel and should be completed by April 1989 as well as an improved and more efficient purification system which will be ready about at the same time. The first cosmic ray test of the completed chamber will take place in early summer 1989. When the system is understood we intend to begin our background studies in the Gran Sasso Laboratory. A summary of this timescale is given in Table A2.1.

<table>
<thead>
<tr>
<th>Table A2.1.— Estimated timescale for the 2 ton prototype detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryogenics</td>
</tr>
<tr>
<td>Chamber</td>
</tr>
<tr>
<td>Electronics</td>
</tr>
<tr>
<td>Purification system</td>
</tr>
</tbody>
</table>

After the prototype has been fully tested we will start the construction of the ICARUS I detector. It is expected that the building of the dewar by industry will take about one year. In parallel with this we will construct the wire chambers, the purification system and the read-out electronics (analogue and digital) together with the development of the on-line and off-line software. We estimate that the installation of the wire chambers including the vacuum and cryogenics tests will take about six months. Installation of the read-out is expected to take about three months.
ACKNOWLEDGEMENTS

We wish to acknowledge the contributions of many people and Institutions which have participated in some of the aspects of the work which is the basis of the present proposal and without whose help this proposal would have been impossible.

Several of these individuals are active in the ICARUS II program.


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