

Pumping system for the ICARUS 600 ton detector

P. Benetti, L. Mazzone, C. Montanari, M. Rossella, C. Vignoli

INFN Sez. di Pavia, v. A. Bassi 6, 27100 Pavia, Italy

Abstract

After having analyzed advantages and disadvantages of the possible solutions for the vacuum system for the T600 we estimate in some details the performance a given commercial solution. Pump down times and final vacuum are computed either analytically and with dedicated simulation software. We also estimated the concentration of impurities left in the volume after the cool down and defined some procedures in order to minimize the final contamination of the LAr.

Preliminary considerations

The design of the pumping system for the T600 has to be based on the following basic considerations.

- a) The T600 is actually split in two independent volumes of $\approx 300 \text{ m}^3$ each; the two volumes can be evacuated separately in subsequent times using a single pumping system.
- b) The shape of the basic volume is rather long and narrow and it will contain the readout chambers, which means complicated and long paths for molecules to reach the exit point to the pump; this suggests the use of several pumping points (at least two, if possible 3 or 4) distributed along the structure in order to attain a good and uniform vacuum degree in a reasonable amount of time.
- c) In order to evacuate and degas the interstices that will be present in the internal detector, molecular regime has to be reached in all parts of the volume; to ensure a vacuum of the order of $10^{-2} - 10^{-3}$ mbar in the small holes and in between the faced flat surfaces (cables, mechanical components of the chambers) a pressure of less than $10^{-4} - 10^{-5}$ mbar has to be set in the gross volume.
- d) The evacuation time is not, in our case, a critical parameter; we can easily afford one or two weeks of pumping or whatever reasonable amount of time will be required to attain a good outgassing of the internal surfaces. Therefore the pumping speed is not crucial and the evacuation time will be ultimately limited by the time required to degas the surfaces of the internal detector components. Some heating, obtained for example by injecting hot nitrogen in the cooling serpentines or by injecting hot pure Argon in the internal volume, will help to speedup the procedure much more than using faster pumps.
- e) Due to the large volume to evacuate, the pumping system will have to work for several hours at large pressure; this has to be taken into account when choosing the backing pumps and designing the system layout.

- f) With the exception of what on the previous point, the workload of the system will be rather modest. Each module has to be evacuated only one or two times before filling with LAr and the pumps will be actives only for few weeks per year (assuming that the rate of construction of the T600 modules will be one per year). Robustness is therefore not mandatory even thought the lifetime of the system should extend at least for the construction period of all the T600 modules (≈ 5 years). Maintenance and stocking procedures have to be defined in order to preserve the functionality of the system during the inactivity periods and a routine check (for example by operating the system on the 10 m^3 prototype) has to be foreseen before the installation on a new T600 module.
- g) As usual in our applications, any contamination of the internal volume from the pumping system has to be absolutely avoided; “dirty” pumps (rotary and/or oil diffusion) can be used only in conjunction with an appropriate system of cold traps and fast closing valves to prevent chamber contamination due to oil backstreaming from the pumps.

Table 1: Basic parameters and requirements for the pumping system

Parameter	Value
Volume to be evacuated	$\approx 300 \text{ m}^3 \times 2$
Pumping units	2-4
Final vacuum (target)	$\approx 10^{-5} \text{ mbar}$
Pumping time	$\leq 1 \text{ month}$

Several solutions for the pumping system are currently available on the market, meeting the above requirements. We can identify two basic schemes:

- 1) a “dirty system” using an oil diffusion pump backed by a combination of a roots and a rotary vane pump;
- 2) a “clean system” made of a turbomolecular pump backed by a roots and a dry rotary pump or by a dry scroll pump.

Oil diffusion pumps have been used for a long time in high vacuum applications although they are presently being replaced by turbomolecular pumps, as these are becoming available on the market at relatively low cost and good reliability. Oil diffusion pumps provide high pumping speed at low cost, are most reliable and less delicate. However, according to point g) they can only be operated in conjunction with a cold trap and a set of control systems and fast closing valves which makes the first scheme a bit more complicated than the second one and eventually will make the price difference smaller. Moreover, as the demand is drifting towards turbomolecular pumps, most of the major companies are stopping the production of diffusion pumps eventually with the exception of those with largest speed, so that support and maintenance could be a problem in the long term.

Our personal recommendation goes to the second scheme unless cost is of particular concern. High speed, reliable, turbomolecular pumps as well as dry primary pumps, with good flows, developed for the electronics industry, are presently available on the market at affordable prices. They are easy to install and operate and there is no risk of contamination from oils or greases.

Design of the pumping system

In Figures 1 and 2 we present two possible setups for the installation of the pumps for the two systems above. With the second system, making the primary vacuum directly through the turbo pump could be possible, however, due to the relatively long period in which the system will remain at high pressure, to avoid the overheating of the turbo pump, use of a bypass for the primary vacuum is suggested. In the remaining part of this document we will refer to a specific system made by a turbomolecular pump and a dry scroll pump. Computations and conclusions can be easily extrapolated for other solutions.

We take as an example an integrated system made of a 1000 litres / s turbomolecular pump and a 500 litres / min dry scroll pump which is commercialized by Varian; similar systems are also available from all the major vacuum industries (Alcatel, Balzers - Pfeiffer, Leybold) with eventually some differences about the speed and technique for the primary pump.

Installation for an Oil Diffusion + Rotary Vane Primary Pump

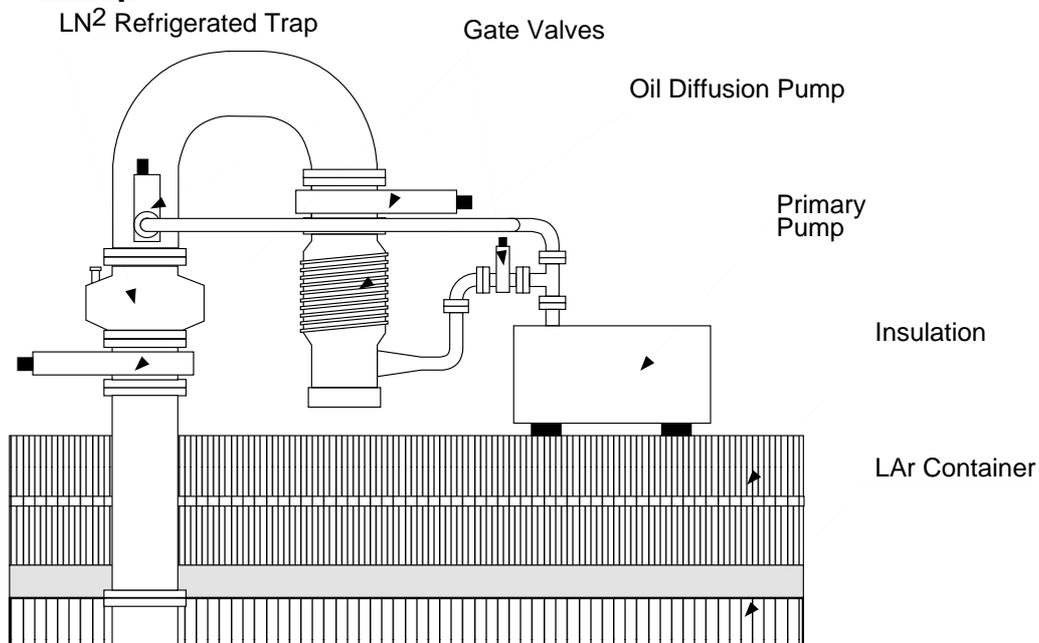


Figure 1: Layout for the installation of a pumping system made of an oil diffusion and a rotary vane pump.

Installation for a Turbomolecular + a Dry Primary Pump

Scheme 1: with bypass for the primary vacuum

Scheme 2: primary vacuum through the turbo pump

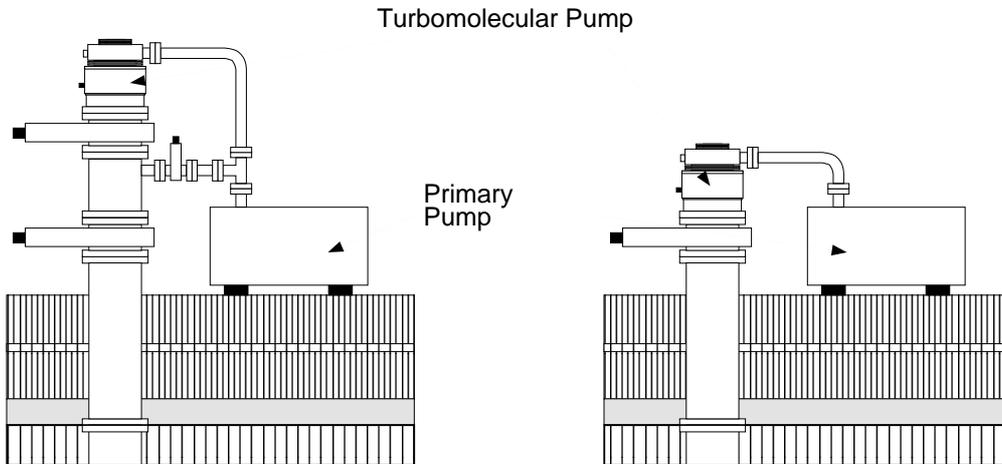


Figure 2: Two possible installation schemes for a *clean pumping system* composed by a turbomolecular pump and a dry primary pump.

For reference we list here the characteristics of the pumping system as they can be found on the data sheet in the Varian catalog [1]. We also assume to have installed a group of 4 of such systems on a half-module.

Looking at the characteristic curves of the primary and the turbo pumps we see that the turbo pump will be effective (larger pumping speed) for pressures below 10^{-1} mbar. We therefore have divided the pressure range in two zones: one above and the other below 10^{-1} mbar. In the first range the primary pump will be effective, while in the second the turbomolecular pump will provide pumping.

Table 2: Primary pump characteristics

Parameter	Value
Pump Type	Dry scroll pump
Free Air Displacement (@50 Hz)	491 litres / min
Pumping Speed	420 litres / min
Ultimate Pressure	$= 10^{-2}$ mbar
Inlet Connection	NW40
Exhaust Connection	NW25
Motor Rating	0.6 kW

Table 3: Turbomolecular pump characteristics

Parameter	Value
Pump Type	Turbomolecular with ceramic bearings and MacroTorr stages

Pumping Speed:	N ₂ , 950 litres / sec He, 870 litres / sec H ₂ , 900 litres / sec
Compression Ratio	N ₂ , > 1 x 10 ¹⁰ He, 2 x 10 ⁷ H ₂ , 1 x 10 ⁶
Base Pressure (with previously quoted primary pump)	1 x 10 ⁻¹⁰ mbar
Inlet Flange	DN 200 CFF
Foreline Flange	NW40 KF
Rotational Speed	38000 RPM
Operating Position	Any
Cooling requirements	Forced air or Water

Primary vacuum: from atmospheric pressure to 0.1 mbar

The time required to attain the primary vacuum can be obtained by integration of the simple relationship:

$$-\frac{dP}{P} = \frac{S(P) \cdot dt}{V} \quad (1)$$

where $S(P)$ is the pumping speed and V is the volume to be evacuated (see Figure 3). For a rough estimate we may assume S constant over the pressure range under consideration with a mean value of $S = 4 \times 400$ litres / min ≈ 96 m³ / hour where, as anticipated, we assumed to have 4 pumps working in parallel. With S constant the integration of the above equation becomes trivial and the pumping time as a function of the final pressure is simply given by the usual logarithmic law:

$$\Delta t = \frac{V}{S} \ln\left(\frac{P_0}{P}\right) \quad (2)$$

Where P_0 is the starting pressure (1 bar). From the formula above we obtain therefore a pumping time of about 30 hours to reach the primary vacuum of 0.1 mbar.

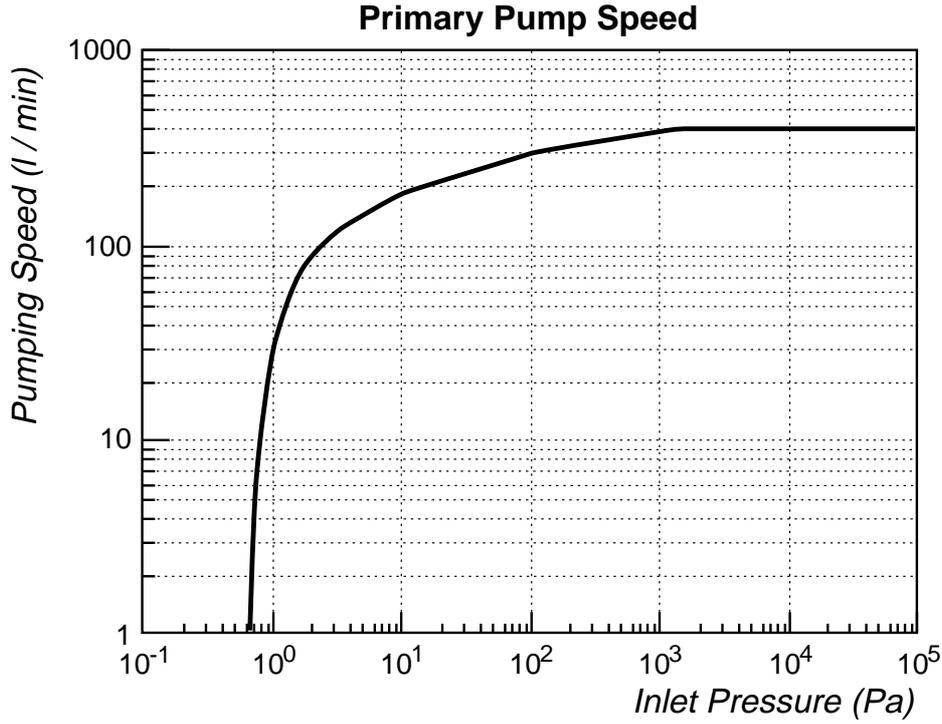


Figure 3: Pumping speed curve of the primary pump (Varian scroll pump model 600D).

High Vacuum: below 0.1 mbar

Below 0.1 mbar the turbomolecular pump becomes effective. Thanks to the high pumping speed we would expect to reach molecular regime ($< 10^{-3}$ mbar), at least in the gross volume, in a relatively short time. From this point on, pressure evolution will be given as the sum of the combined contributions of the output from the pumps and the input from virtual leaks ($L(t)$) (materials outgassing, evacuation of small apertures on the internal detector structures):

$$-\frac{dP}{P} = \frac{S(P) \cdot dt}{V} - \frac{L(t) \cdot dt}{P \cdot V} \quad (3)$$

For constant S and L , the solution of this equation is given by:

$$P(t) = \left(P_0 - \frac{L}{S} \right) e^{-\frac{S}{V}t} + \frac{L}{S} \cong P_0 \cdot e^{-\frac{S}{V}t} + \frac{L}{S} \quad (4)$$

This solution also applies for slowly varying S and L . At regime ($P < 10^{-2}$ mbar) the pumping time constant in the above equation is:

$$\tau = \frac{V}{S} = 75 \text{ sec} \quad (5)$$

to be compared with the typical variation rates of outgassing which, depending on the materials, can extend from few hours to several tens of hours (Figure 5). Therefore, shortly after the efficient operation of the

turbomolecular pumps, pressure evolution will be dominated by the quasi-equilibrium condition where virtual leaks are compensated by output from the pumps:

$$P(t) = \frac{L(t)}{S} \quad (6)$$

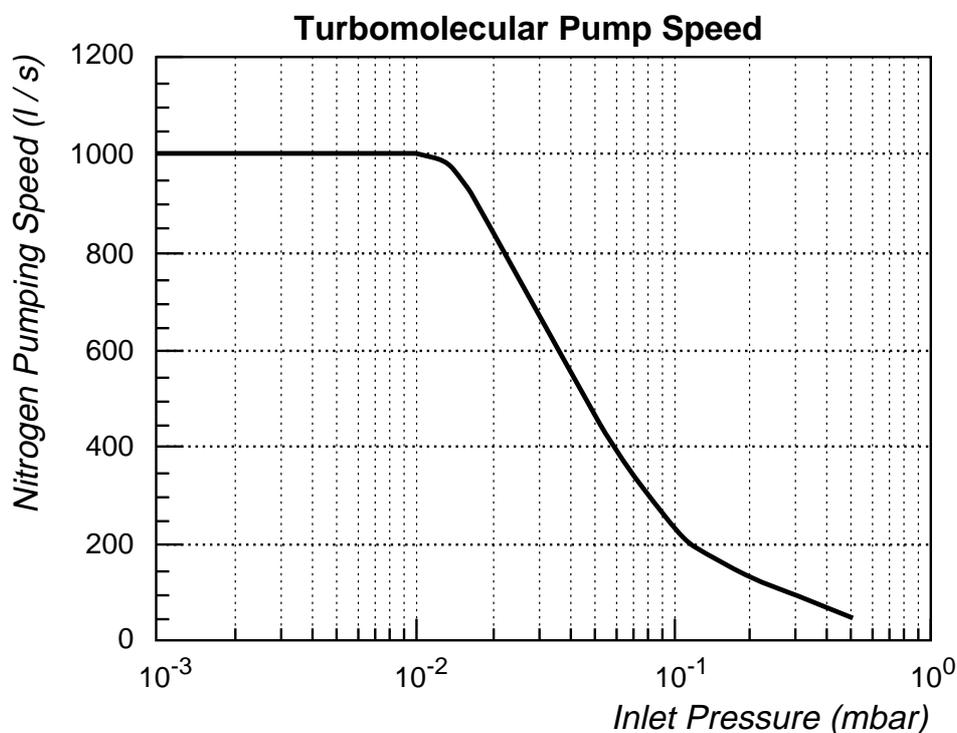


Figure 4: Pumping speed curve of the turbomolecular pump (Varian model Turbo 1000HT).

In table 4 are reported approximate values of the surfaces of the major components of the internal detector and the inner cryostat walls.

Table 4: Surfaces for various items contained in a half-module. Outgassing rates are for clean materials after 100 hours of pumping.

Item	Material	Surface (m ²)	Outgassing Rate (mbar litre s ⁻¹ m ⁻²)
Internal cryostat walls	Aluminum	322	< 10 ⁻⁶
Internal detector mechanical structures	St. Steel AISI 316 L	584	4 x 10 ⁻⁶
Combs & combsí covers	PEEK	24	1.0 x 10 ⁻³
Race Tracks	St. Steel AISI 316 L	561	4 x 10 ⁻⁷
Cathode	St. Steel AISI 316 L	48	4 x 10 ⁻⁷
Race Tracks supports	Vetronite	30	1.5 x 10 ⁻⁵

Cables thin wires ($\phi=0.6$ mm) thick wires ($\phi=0.8$ mm)	Polyolefin	187 250	$< 1.1 \times 10^{-4}$
---	------------	------------	------------------------

Surfaces displayed in Table 4 are computed under the following assumptions:

- 1) For the estimate of the surface of the internal detector structure we based ourselves on the drawings of the test module. Some modifications are foreseen for the definitive structure with practically no changes in the total surface. We also accounted for the surface of a sheet-steel covering the top part of the internal detector (to prevent discharges in GAr) for half of the lateral size of the cryostat.
- 2) Race tracks are made by electropolished hollow pipes with 35 mm diameter with holes for evacuation of the internal volume;
- 3) Cathode is made by a perforated electropolished sheet-steel with 58% transparency;
- 4) Signals are transported by loose twisted pairs cables with a mean length of 1250 mm and 2800 mm for wires with connectors on the top and on the sides of the sustaining frame respectively. Two options are presently considered with thin and thick cables, the difference in diameter (and total surface) being exactly a factor 4/3. The reported value of the outgassing rate, corresponds to the worst of three measurements made by us on samples of cables [2].

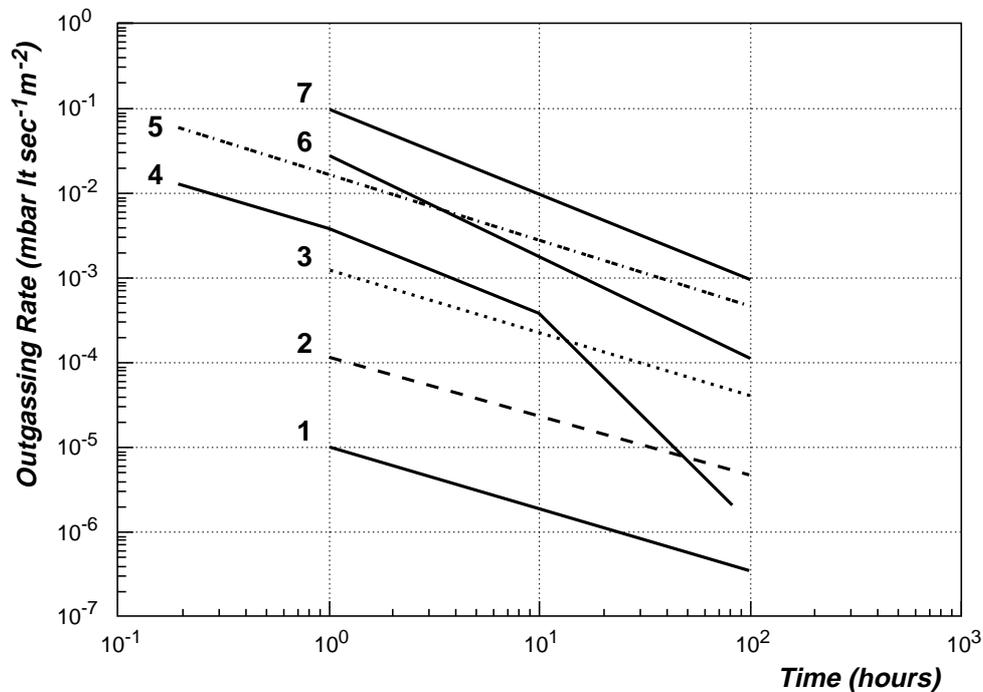


Figure 5: Outgassing rates as a function of the pumping time for several materials: 1 and 2 St. Steel, 3 Cold rolled St. Steel, 4 Aluminum, 5 Teflon, 6 Polyolefin insulated wires, 7 PEEK.

Outgassing rates displayed in Table 4 and Figure 5 have to be taken with some care. Gas desorption from materials surfaces strongly depends on past history of the components (cleaning procedures, exposure to humidity, handling methods). Cleaning procedures for small sized pieces of the ICARUS internal detector and for the cables comprise washing in ultrasounds bath followed by drying in a vacuum oven. Outgassing rates for cables and PEEK components have been directly measured by us under the above mentioned conditions [2,3]. To minimize exposure to air humidity, we suggest that all components will be stored in a dry ambient (by packing them in a bag filled with dry Nitrogen or Argon) until the last moment before their mounting on the internal detector structure.

If they came in contact only with air, most materials would mainly release water vapor; some materials however may exhibit high partial pressures of other gases. A relevant example is aluminum which, due to the increase of hydrogen solubility during the melting of the metal, presents a relevant outgassing of molecular hydrogen which becomes dominant after some hours of pumping. Also St. Steel shows a similar behavior.

It is clear from Table 4 that virtual leaks are largely dominated by the outgassing of plastic components: PEEK supports and cables (thin) both provide an integral outgassing rate of about 2×10^{-2} mbar litres sec^{-1} , while the contribution of all the rest of the surfaces is about a factor of 6 lower. The total amount of virtual leaks, with thin cables after 100 hours of pumping, will be around $L(t) \approx 4.7 \times 10^{-2}$ mbar litres sec^{-1} ; the pressure will be therefore

$$P(100h) = \frac{L(100h)}{S} \approx 1.1 \cdot 10^{-5} \text{ mbar}$$

a value which is just at the lower limit of our target region of 10^{-5} - 10^{-4} mbar. Obviously all these figures should be increased in case thick cables will be used; due to the figures above our strongest recommendation goes to the use of thin cables.

Simulation of pressure evolution during the pump down

To verify the rough estimates reported in the previous paragraph, we implemented a simulation of the T600 vacuum system. We used a commercial simulation package (VACSIM) widely used by vacuum systems designers which is based on the SPICE engine.

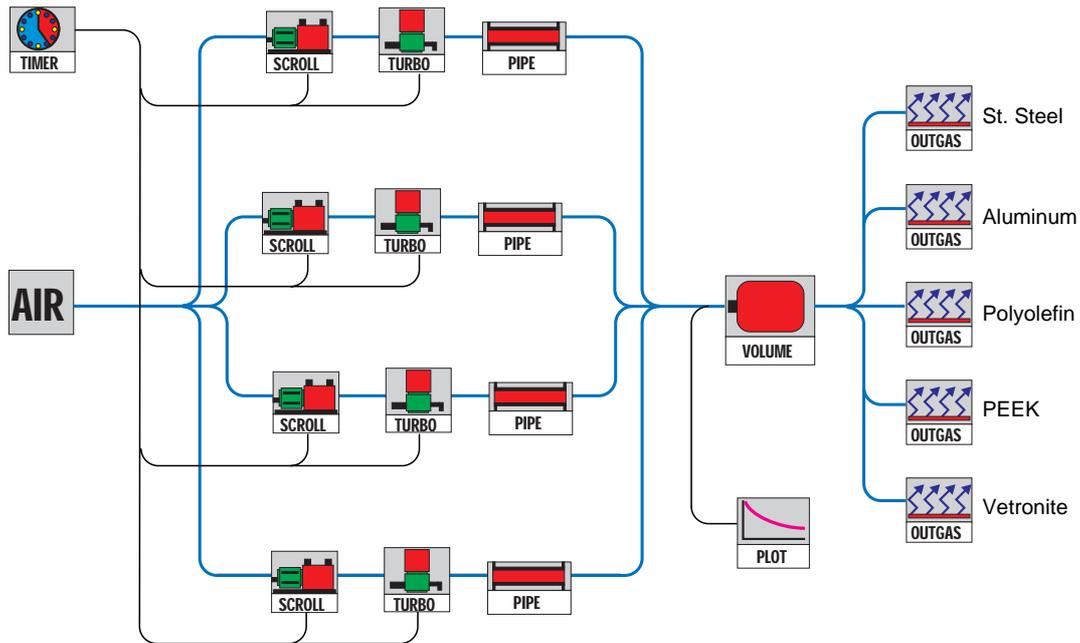


Figure 6: Block diagram of the scheme used to simulate the pressure trend of a half module during the pumping.

The model for the vacuum system of a half-module is shown in Figure 6. The four turbomolecular pumps are connected to the main volume (300 m³) by straight DN200 pipes 1500 mm long. The roughing pumps are directly connected to the outlet of the turbomolecular pumps (the bypass was not used to accelerate the convergence of the simulation). The parameters of the pumps models were chosen according to the manufactory specifications (Tables 2 and 3) and slightly adjusted in order to reproduce the speed vs. inlet pressure and gas compression ratio vs. pressure curves found in the Varian catalog. Outgassing of the various components was added to the main volume according to the basic data reported in Table 4; for St. Steel and aluminum we used the internal models preloaded by the simulator. For PEEK and Polyolefin insulated cables we used generic outgassing models with the internal parameters adjusted to reproduce the results of our measurements. To this purpose we set up two other simulation models of the test chambers that we used for the measurements. Finally, for Vetronite, we used the same data of PEEK scaled by a factor 1.5×10^{-2} .

The pumpdown curve obtained by the simulation is shown in Figure 7. We see that the roughing pumps, being boosted by the turbomolecular pumps, reach the lower limit of the primary vacuum in only 18 hours: about 2/3 of the time previously estimated without the contribution of the turbo stages. The sharp falling edge is due to the fast extraction of the turbo pumps and stops abruptly when equilibrium is reached with the internal outgassing. The subsequent behavior of the curve is dominated by the variation rate of the materials outgassing. The transition between desorption and diffusion dominated outgassing at $T \approx 50$ hr is evident. In reality, superposed to the curve there is an oscillating function which, as described in the VACSIM manual, is intrinsic of the mathematical model

used by the program to threat outgassing which tends to accentuate the transition effect.

Accidentally, the agreement between the simulation and our previous estimate of 1.1×10^{-5} mbar around $T = 100$ hr is extremely good; in effect, due to what noted just above, the real behavior of the curve in that region should be a smooth interpolation of the two trends before and after the outgassing transition knee. In any case our estimate is to be considered essentially correct.

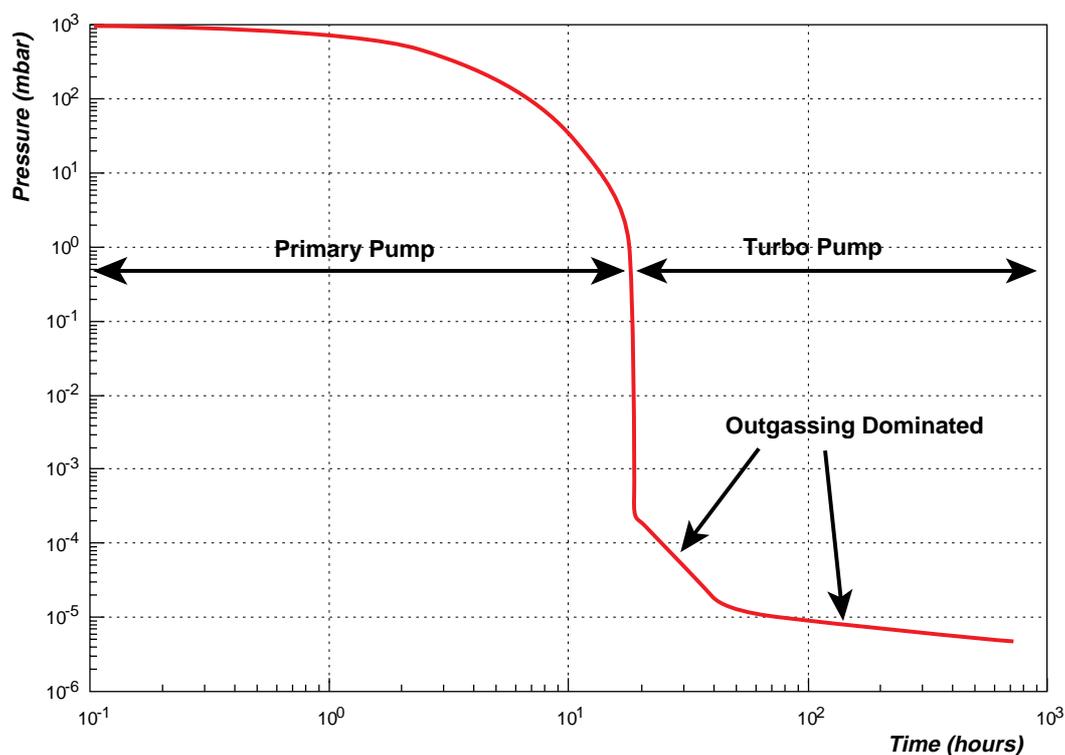


Figure 7: Pumpdown curve obtained with the simulation program.

Procedures

We try to figure out, in this paragraph, a procedural scheme to be applied for the evacuation, cooling and filling of the cryostat in order to estimate the amount of residual impurities that will be left in the volume after its filling with pure LAr. We are conscious that, at present, there is a number of uncertainties which limit our predictive capability to just an order of magnitude guess; also for this reason we will try to define a procedure that will guarantee the best possible result and satisfy our inevitable paranoia.

Primary vacuum

As soon as the cryostat will be completely closed, primary pumps will be turned on. According to the previous computations, after about 30 hours, a vacuum of the order of 10^{-1} mbar will be reached. At this point we should consider the option of filling the volume with purified argon gas and leave the gas for conditioning the dewar for some time (one or two days). This procedure has been found to produce some benefit by allowing the

argon to saturate the materials surfaces eventually replacing other molecules; also it will reduce the air (oxygen) content of the dewar by simple dilution. A dilution factor of 10^4 will be gained for each emptying / filling cycle. The limiting factor is of course given by the materials outgassing (see § 2) and three cycles seem to be the maximum useful number.

High Vacuum

After having reached 10^{-1} mbar (eventually after two or three fillings with pure GAR), turbomolecular pumps will be switched on. We assume a pumping time of 15 days to attain a good outgassing of the internal surfaces. During this period a helium leak test should be performed on all the flanges, pipes, feedthroughs, etc., directly connected to the cold vessel. According to our specifications, the cold vessel will be independently tested for vacuum tightness before its' delivery by the manufacturing industry, however more than 200 flanges will be then installed on the vessel and all of them have to be tested. The sensitivity on such a large volume cannot be very high, of the order of 10^{-5} mbar litres sec^{-1} at best. We recommend therefore that, whenever possible, the various components (feedthroughs, purifiers, auxiliary dewars for pumps, etc..) will be tested independently. Also, the equilibrium pressure during the pumping will be continuously monitored, so that any significative departure from the $1 / T$ (T = time of pumping) behavior expected from pure internal outgassing will be a signal of some large undetected leak.

Cooling

A relevant difference between the T600 and most of the prototypes operated since now is that, while the latter were cooled under vacuum, the T600 will be filled with argon gas to cool efficiently the internal structures. There will be therefore a period in which the materials will remain at a relatively high temperature, free to desorb impurities. Moreover, the beneficial effect of cryosorption performed by the internal surfaces when they are sufficiently cold, will be lost due to the presence of GAR. It has to be noticed that this effect is efficient mostly for water molecules (and for CO_2 below 150 K).

The total amount of impurities that will be left in the volume is given by integration of the total outgassing rate over the time period needed to cool down and fill the cryostat:

$$I(t_1) = I(t_0) + \int_{t_0}^{t_1} O(t) dt \quad (7)$$

where $I(t_0)$ is the amount of impurities present in the cold vessel when the pumps are excluded.

The outgassing rate of a given type of molecules and a given desorbing material, depends on the temperature T according to the approximate law [4]:

$$O_P(T) = \alpha_P \cdot e^{-\frac{k_P}{R \cdot T}} \quad (8)$$

where k_P is the absorption heat for the considered molecule on the desorbing material. In general k increases with the molecular weight of the desorbed gas; some typical values are: 100 cal mol⁻¹ for molecular hydrogen, 5 - 10 kcal mol⁻¹ for water, 400 - 500 kcal mol⁻¹ for heavy hydrocarbons (oils or greases). We see, for example, that for water ($k \approx 10$ kcal mol⁻¹) the outgassing rate decreases more than 14 orders of magnitude going from room to LAr temperature; already at 200 K the water outgassing rate is more than three orders of magnitude lower than the one at room temperature.

To compute the integral in equation (7) we must take now some positions. We consider the case in which no additional operations are made during the cool down (removal of the “dirty” GAr by pumping or operation of the gas recirculators). This should give the worst estimate. Also we take a uniform temperature decrease during the cool down of 2 degrees per hour. Finally we have to take into account the fact that the upper part of the cables will remain at room temperature: to simplify the computation we assume that 60 cm of cables will remain at room temperature while the remaining part will be cooled in the same way as the cryostat and the internal detector.

With the above assumptions, taking into account equation (8), equation (7) can be rewritten as:

$$I(t_1) = I(0) + O_H(0) \cdot t_1 + \int_0^{t_1} \alpha_{1P} \cdot e^{-\frac{k_{1P}}{R \cdot (300-2t)}} \cdot dt + \int_0^{t_1} \alpha_{2P} \cdot e^{-\frac{k_{2P}}{R \cdot (300-2t)}} \cdot dt + \dots \quad (9)$$

where $O_H(0)$ is the outgassing rate of the *hot* portion of the cables and the integrals represent the various contributions from gas components and materials which are getting cooled. For our estimate we will make the simplification that a single component with an absorption heat of 10 kcal mol⁻¹ (typical of intermediate mass molecules like water and oxygen) is being desorbed. Also implicit is that the outgassing rate in the argon atmosphere is equal to the one under vacuum. This last hypothesis is certainly wrong as the escape probability of the molecules from the surfaces is lowered by the presence of Ar gas layers. The effect is difficult to quantificate and we decided to neglect it; our estimate is probably very conservative.

The contribution of the three terms in equation (9), expressed in mbar at room temperature, is therefore:

$$I(0) = 1.1 \cdot 10^{-5} \text{ mbar}$$

$$O_H(0) \cdot t_1 = 9.3 \cdot 10^{-3} \text{ mbar}$$

$$\int_0^{t_1} \alpha_P \cdot e^{-\frac{k_P}{R(300-2t)}} \cdot dt = 3.8 \cdot 10^{-3} \text{ mbar}$$

As one could have imagined, the dominant contribution comes from the outgassing of the hot portion of the signal cables, the outgassing of the remaining surfaces is concentrated within the first 25 hours of cooling (50 °C of temperature decrease); below 250 K this contribution becomes negligible.

The total number of impurities that will remain in the volume before its filling with LAr is approximately 1.3×10^{-2} mbar (NTP) which would correspond to a concentration in the liquid of about 16 ppb. This value is more than a factor 100 above our final goal of 0.1 ppb (O₂ equiv.), however we must take into account the fact that the impurities left will not all be electronegative: in our tests we always found that oxygen is present in the desorbed gas at the level of few percent; water and nitrogen usually dominate the mixture. Moreover, preconditioning with pure argon will lower the relative amount of other components.

There are several actions that we can take in order to lower the concentration of impurities at the end of the cooling cycle.

The first thing that we can do is to improve the efficiency of GAr conditioning. We can recirculate the argon gas at room temperature in a closed circuit loop through the GAr recirculators or through a dedicated set of filters by using dry gas transfer pumps. We can monitor the purity of the gas before the filters and stop the procedure when the impurities concentration will fall below a given value. Implementation of the hot recirculation system is still under evaluation as it is bound to the existence of vacuum tight dry transfer pumps of adequate speed and prevalence. This procedure will be very helpful in case an inadequate vacuum tightness will be found and therefore the system will have to be maintained overpressurized to avoid that impurities from the outside reach the inner volume.

The second thing that we can certainly do is to re-evacuate the cryostat at a given time during the cooling. All what we need is to provide some heater on the vacuum line to avoid that the primary pumps get frozen by the cold GAr. In this way we will reduce the final concentration of impurities by a factor larger than four.

Finally, before having reached the LAr temperature, we can turn on the gas recirculators to clean up the gas in the volume. Given the recondensation power of the recirculators (50 litres of LAr per hour), within few hours of operation we can recirculate several times the gas in the volume and provide the required purity. Moreover, as the inlet points to the recirculators are located on the connection flanges of the signals

feedthroughs, the impurities will be removed just in the zones (the hot portion of the cables) where they are produced, reducing the contamination of the primary volume. The gas recirculators will be in any case active during all the filling so we can assume that no additional impurities will contaminate the liquid during the LAr filling period.

In order to be able to decide if and when an action has to be taken we have to monitor the purity of the gas during the cool down. We can either use one of our traditional purity monitors installed externally of the main dewar or we can adopt one of the available commercial solutions. Operation of an external traditional purity monitor is rather time consuming and uncomfortable as it requires that the gas is recondensed in the monitor chamber: at least two hours will be required to fill the chamber, make the measurement, empty and heat up the monitor. For measurements on the gas, where a great sensitivity is not required, the use of one of the commercial solutions with fast on-line reading will be more indicated (e.g. devices based on electrochemical reactions from Orbisphere, or based on mass spectrometry from Air Liquide). Installation of an external purity monitor chamber is foreseen in any case.

All the extra handles mentioned before will provide us with a very tight control over the purification process and, taking into account the character extremely conservative of our estimates, we can safely say that the attainment of the required LAr purity will not be a problem. Also in the worst case, given the high recirculation speed of the forced recirculation system ($5 \text{ m}^3 \text{ hr}^{-1}$), recovery of the sub-ppb impurities concentration will require only few days (about 6 days for each factor 10 gain in the impurities concentration).

The complete set of operations is summarized in Table 5 where also the time for each step is reported. We see that, with all the options activated, about 30 days will be required to pump and cool down a half module.

Table 5: Schematics of the operations required to pump and cool down a half-module.

Operation	Start at hour	End at hour	Option
Primary Vacuum	0	24	<i>Required</i>
Pure GAr Conditioning	24	48	Option 1
Primary Vacuum (2nd)	48	72	Option 1
Pure GAr conditioning	72	96	Option 1
Primary Vacuum (3rd)	96	120	Option 1
High Vacuum	120	480	<i>Required</i>
Leak Detection (2 days)	144	192	<i>Required</i>
Pure GAr Conditioning (forced recirculation)	480	600	Option 2
Cooling	600	700	<i>Required</i>
Cold gas extraction (pumping)	650	434	Option 3
Cold GAr recirculation	700	continuous	Option 4
Filling	720	920	<i>Required</i>

Conclusions

We studied the characteristics and performance of the main vacuum system for the ICARUS T600.

We found that the experiment requirements are met using a simple and economical commercial system composed by a set of four medium sized units (1000 lt sec⁻¹ turbomolecular pumps). Using such a system, within 150 hours of pumping, a vacuum of the order of 10⁻⁵ mbar can be reached in the main dewar, the final pressure being dominated by the internal components outgassing.

We also analyzed the procedures required to cool down the cryostat and the internal detector structures, in order to estimate the residual amount of impurities that will be present in the volume before its' filling with liquid argon. We find that, in the most pessimistic case where no additional actions are taken during the cooling and all the outgassing is composed by electronegative molecules, the concentration of electronegative impurities in the liquid will not exceed 10 ppb (O₂ equiv.). This value is already easily handled by using the LAr forced recirculation system.

We also identified several corrective actions that can be performed in order to control and lower the impurities concentration during the transitory phase. These actions comprise pure GAR surfaces preconditioning, removal of the "dirty" cold GAR by pumping before the filling, cold GAR recirculation and purification before the filling. Implementation of all of them will require very little or no additional hardware with respect to the present configuration.

References

- [1] VARIAN Vacuum Products - 1997 / 1998 Catalog.
- [2] C. Montanari et al., ICARUS-TM-98/14
- [3] ICARUS-PV Group internal note on LAr purity measurements in presence of mechanical components of the wires chambers, unpublished.
- [4] M.H. Hablanian, *High Vacuum Technology*, Marcel Dekker Inc., New York and Basel.