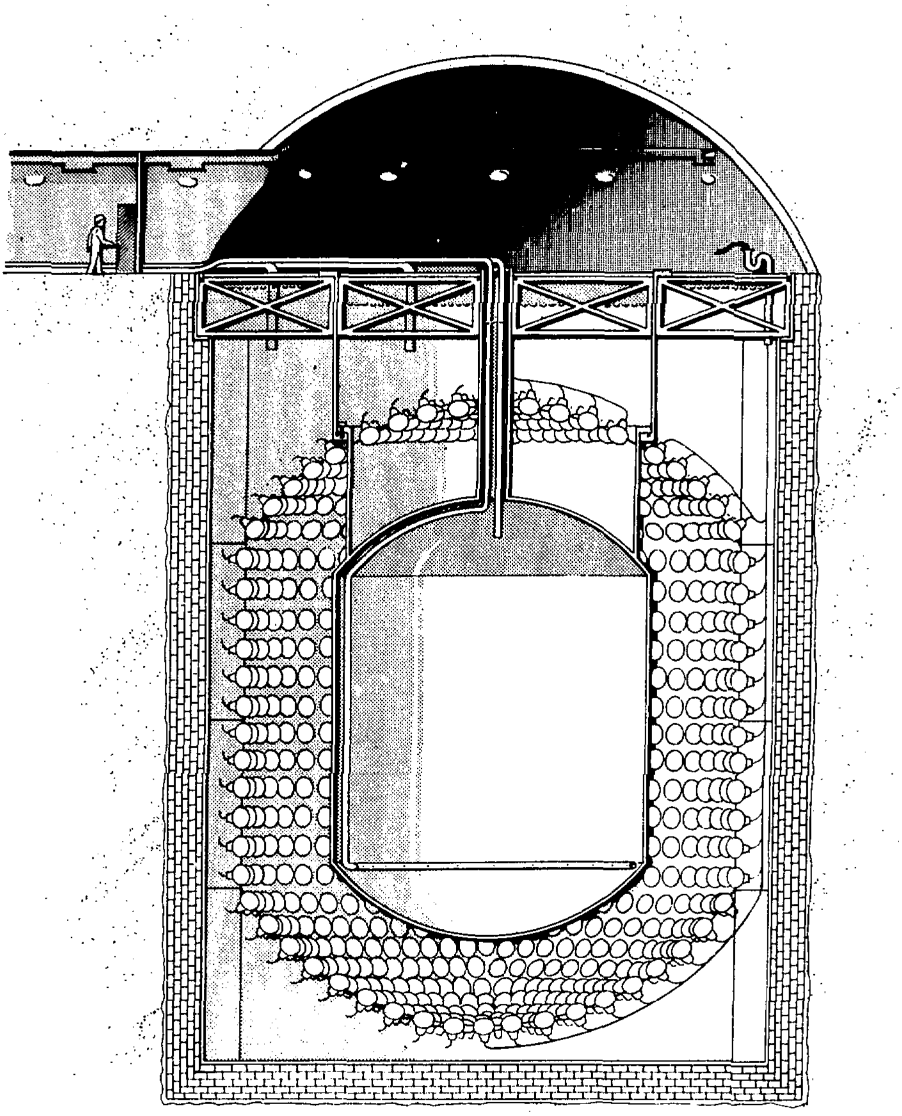
SUDBURY NEUTRINO OBSERVATORY



Participating Institutions

Queen's University
University of California at Irvine
Oxford University
National Research Council of Canada
Chalk River Nuclear Laboratories
University of Guelph
Laurentian University
Princeton University
Carleton University

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THE SUDBURY NEUTRINO OBSERVATORY

A group of Canadian scientists, in collaboration with colleagues from the United States and England, proposes to establish a world class laboratory in INCO's Creighton Mine. The laboratory would be dedicated to the study of neutrinos from the sun and other astrophysical objects to advance our understanding of the physical processes which govern the properties of stars, as well as our understanding of the fundamental properties of matter.

The laboratory would capitalize on two Canadian resources, i.e. access to one of the deepest mines in the western hemisphere and Canada's temporary surplus of heavy water.

The Universe

According to present scientific thinking, the universe we now observe evolved from a violent explosion which occurred about fifteen billion years ago - The Big Bang. This model is consistent with the gross features of the universe we observe - its expanding state, its uniformity, and most importantly with the microwave background radiation which pervades the universe as a remnant of the explosion.

Immediately after the Big Bang, all of the matter and energy of the universe was concentrated in a confined space under extremes of temperature which stretch the imagination. Matter appeared in exotic forms, which we can now view fleetingly using particle accelerators, and the fundamental forces of nature produced effects which were quite different from those we now observe in our cold universe. As the expansion proceeded and the temperature fell, the forms of matter we are familiar with appeared. Under the influence of gravity, matter collected into clouds of gas, and sometimes into massive objects such as stars and galaxies. The massive objects themselves evolved, sometimes self-destructing and leaving in their wake dust and gas as raw material for the formation of another generation of stars and more exotic forms of matter such as neutron stars or black holes. The February 23, 1987 supernova in a nearby galaxy is an example of such an explosion.

The Sun

The sun is four or five billion years old and has been formed by the mutual gravitational attraction of recycled material, remnants of the Big Bang and the fiery death of previous stars or supernovae. As gravity forced the constituent particles to occupy an ever-shrinking region of space, the mixture became hotter and hotter, the particles collided with one another with increasing violence and increasing frequency, until the hydrogen nuclei (protons) became energetic enough to sustain a series of fusion reactions in the central region. The energy produced by these reactions, propagating outwards, generated forces to counteract the tendency towards further shrinking under gravity. A state of equilibrium was reached wherein the size and temperature of the sun, and the energy it radiates, are maintained at a steady level.

In astrophysical terms, the sun is not a terribly remarkable star. It is made remarkable only because we are among its by-products. It plays a special role in defining our understanding of stars because it is nearby and therefore uniquely accessible to measurement and observation. It is the natural testing ground for theories of stellar evolution. Sophisticated mathematical theories of stellar evolution have existed for decades and make definite predictions of the properties of the sun which follow from the laws of physics. During the last two decades, a neutrino experiment located in the Homestake Mine in South Dakota has raised fundamental questions about the quality of our understanding of stellar processes.

Neutrinos

Neutrinos are unique particles. As far as we can tell, they have no mass so they travel at the speed of light. They carry no electric charge, they have no size, but they spin around the axis defined by the direction of their motion. As a result of these properties, or more properly, their lack of properties, neutrinos hardly interact with matter at all. The neutrino is also unique in that it interacts only through the so-called Weak Interaction, which is not only weak but active only between consenting particles which come within a range of about a millionth of an atomic diameter. Three different types of neutrino have been identified and these are known as the electron-, muon-, and tau-neutrinos. The fusion furnace at the centre of the sun produces lots of neutrinos which fly out in all directions, including towards earth. In fact, more than 10^{15} solar neutrinos pass through our bodies every second. As matter is largely transparent to them, they carry undistorted information about their birth in the solar interior and about physical conditions there. As they travel at the speed of light the information they carry is only about ten minutes old when they reach the earth. All other forms of energy generated in the solar core take about a million years to reach the solar surface and from there the earth.

Detecting Neutrinos

Since the 1960's, the Homestake Mine experiment has been detecting neutrinos in an enormous (3.8×10^5 litres) vat of cleaning fluid containing chlorine. The neutrinos interact with chlorine-37 atoms to produce argon-37, which is an inert gas. The vat is purged to look for argon periodically. Each argon atom that is found corresponds to the successful detection of a neutrino since the last purging. The experiment has uncovered only a third to a quarter of the expected number of neutrinos, based on theoretical predictions, i.e. 11 per month rather than 48.

This result has puzzled physicists for over a decade as the experiment has accumulated more and more data. The problem could rest in several areas and many experiments and calculations have been carried out to check the validity of input data for the calculations, and the calculations themselves. There have been three broad areas of concern. Do we understand properly the features of the nuclear fusion furnace? Do we understand the energy transport processes in the sun and its temperature profile? Is there something unexpected related to the neutrinos themselves? With respect to the final question, there exist exciting possibilities which are under debate at present. If neutrinos in fact possess a small mass (e.g. 10^{-8} times the electron mass), then they would also take on a split personality, such that on their way through the sun some might undergo a personality change, with the result that two or more different types of neutrino would arrive at the earth, i.e. the electron-neutrino originating in the solar core could change into muon- or tau-neutrinos during their passage through the high electron densities in the sun. Since the Homestake experiment is only sensitive to electron-neutrinos, its "low" result could be explained in terms of these so-called neutrino oscillations. The question is made even more interesting inasmuch as the presence of massive neutrinos (say 10^{-5} times the electron mass) might mean that there is sufficient mass in the universe for gravity to reverse the present expansion and force the universe into a contraction mode, perhaps in the direction of repeating the Big Bang. At the heart of all of these questions is our understanding of the basic forces of nature. A neutrino mass is consistent with grand unification theories which attempt to unify nature's forces into a super force. Experimental proof of a neutrino mass could be the first evidence for the reality of Grand Unification Theories or GUTS.

THE CANADIAN SOLUTION

From its surface, the sun emits electromagnetic radiation whose wavelength extends over a broad spectrum. In other words, the energy of the radiation and its intensity are broad. Our eyes are sensitive only to a limited range of intensities (brightnesses) and to a narrow range of energies, the part we call visible light. Similarly, the neutrinos are emitted with a broad range of energies and intensities. An ideal neutrino detector (eye) should permit the determination of the energy of each neutrino detected, so that the energy spectrum can be constructed from all events. The main shortcomings of the Homestake experiment lie in its inability to determine the energy of the neutrinos, their time of arrival at the detector and their direction.

Heavy Water Detector

A heavy water detector can overcome all of these shortcomings. Heavy water is the same as ordinary water, except that the two hydrogen atoms in the water molecule are heavy hydrogen or deuterium which makes it 10% heavier. Heavy water occurs naturally but only at the level of approximately .015% of ordinary water. For that reason, pure heavy water is expensive. Since it is chemically identical to ordinary water, it is difficult to separate from water. It is primarily used as the moderator in CANDU nuclear reactors. The heavy water for the SNO project must have a very low level of radioactivity. Only unused D_2O is suitable, that is D_2O presently stockpiled for future CANDU reactor sales.

Our interest in heavy water arises from the fact that deuterium has a unique advantage as a neutrino detector. With deuterium it is possible to measure two distinct processes. The first process is sensitive only to the type of neutrinos (electron neutrinos) actually produced in the sun, and will show a low counting rate if they change to another type. The second process detects all neutrinos, independent of their type and would determine the total number of electron neutrinos produced by the sun, even if they had changed to another type before reaching the earth. This unique capability enables the SNO detector to provide direct evidence of the existence of neutrino oscillations (and hence neutrino mass) and, in addition, to provide the most exacting test of our understanding of the sun ever carried out.

In the first process, when an electron neutrino interacts with deuterium an energetic electron is produced whose energy can be measured. From that measurement, the energy of the neutrino and its direction can be determined. In the second process, a neutrino of any type breaks the deuteron into a neutron and a proton. The neutron is then recaptured in another nucleus, producing gamma rays which in turn also produce energetic electrons.

The electrons produced in the D_2O by the incoming neutrinos travel faster than the speed of light in D_2O, resulting in the emission of light. This Cerenkov light is the same blue glow observed in water pools used to store used nuclear reactor fuel bundles which also emit fast electrons or beta particles. The light produced in the D_2O passes through the transparent acrylic walls and is detected by an array of 2 000 photomultiplier tubes (PMTs) surrounding the D_2O vessel. These PMTs are sensitive light detectors and their signals tell us the time of arrival of the neutrino, the direction from which the neutrino came and its energy. The SNO experiment detects neutrinos at a rate that is ten times higher than other experiments and will provide by far the best information on the energy of solar neutrinos.

Why Sudbury?

The rarity of neutrino events in any conceivable detector (10 per day in 1000 tons of D_2O) places very severe constraints on the levels of radioactivity which can be tolerated in the environment of the detector. On the surface of the earth, the radioactivity arising from cosmic rays would completely obscure the neutrino signals from the detector. By mounting the experiment at the 6800 feet level in the Creighton Mine, we can use the overburden as a shield against cosmic rays, reducing their effect about a million times. Even so the radioactivity of the mine environment remains crucial if we are to identify the ten or so events per day which arise from solar neutrinos. Much effort has already gone into determining the radioactive background produced by the norite rock in which the laboratory will be sited. As the detailed detector design proceeds, all components are being tested as potential sources of background. An elaborate design is required if the detector is to be shielded against the natural radioactivity of the surrounding norite. Our aim, quite simply, is to create the lowest background area on earth. It is generally conceded by scientists in this field that the Creighton mine near Sudbury is the best site in North America for such an experiment.

The Facility

The Observatory consists of two distinct components.

The first is the Laboratory which must be excavated out of norite rock by INCO. It includes a large cavern to house the Detector, and laboratory space to house ancillary apparatus, technical workspace and the physical plant. It must be set up in accordance with the stringent requirements imposed by the need to achieve radioactive hygiene and optimum detector performance. The creation of this Laboratory, its engineering design, construction, and project management will be carried out by INCOTECH under contract, and at cost.

The Detector consists of several components: one thousand tonnes of heavy water, an acrylic containment vessel, two thousand photo-tubes, concrete shielding, water purification systems, electronics and a data acquisition system. Except for the photo-tubes and the acrylic vessel, all major components are available from Canadian sources. It is possible that the material for the acrylic vessel can be produced in Canada. Management of the Detector construction and commissioning and the heavy water containment and purification systems is at present under study, but may be carried out by Chalk River Nuclear Laboratories under contract.

The attached drawings show the proposed location of the underground neutrino observatory in the Creighton mine and an artist's conception of both the proposed facility at the 6800 foot level and the neutrino detector.

Budget Estimate

The present design of the Observatory, which will be optimized continuously during the next year, involves a total cost of $31M during the five year construction period. The cash flow dictated by the construction schedule and procurement procedures is as follows:

1988/89	$3.1M		
1989/90	6.9M		
1990/91	7.9M		
1991/92	7.9M		
1992/93	5.2M	TOTAL	$31.0M

The breakdown for the major components is as follows:

Laboratory	$15.1M		
Detector	11.1M		
Services	4.8M	TOTAL	$31.0M

The Laboratory figure of $15.1M represents the sum which will go directly into the local economy in Sudbury. The figure for services represents design and engineering costs, management of the Detector construction, and miscellaneous services. In addition, it is customary to add contingency figures of 10 to 30% to estimates at this stage of a design and uncertainty remains over the questions of insurance with respect to the heavy water, and with respect to liability protection for INCO.

Present Status

By October 1, 1987 a detailed proposal for the Observatory, including the scientific case, design, and budget will be submitted for peer review. The proposal will be sent to the Natural Science and Engineering Research Council, National Research Council of Canada, the U.S. Department of Energy, and the British Science Research Council which are the granting bodies charged with the funding of scientific research in Canada, the U.S.A. and Britain. In addition the proposal will be submitted to appropriate ministries of the Government of Ontario and of the Government of Canada.

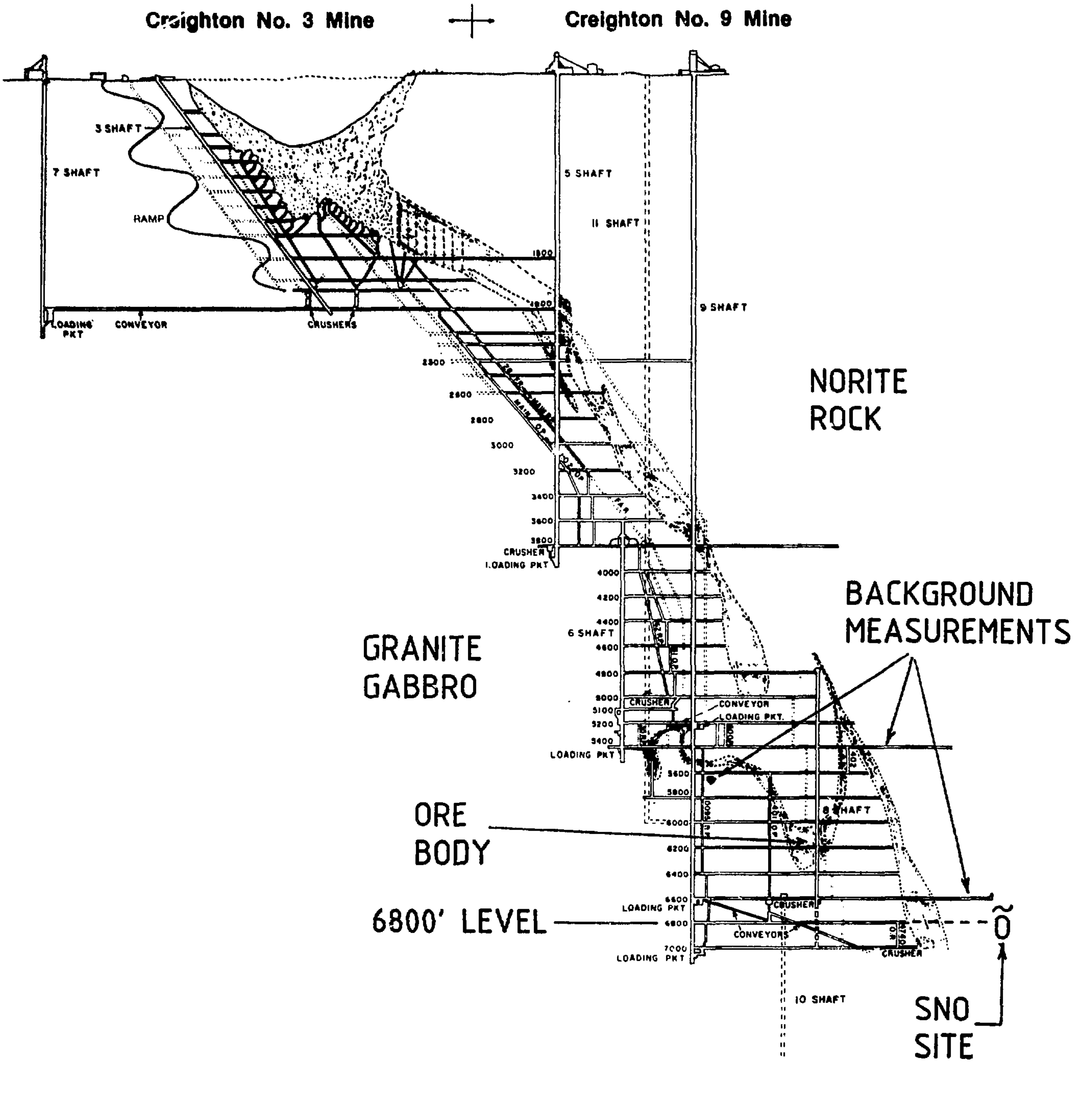
Social and Economic Impact

The Proposal for the Sudbury Neutrino Observatory is driven by our interest in understanding the energy processes that fuel the sun and also by the hope of unifying the laws of physics in one Grand Unified Theory. The peer review process will consider the scientific payoff, the quality of the proposal, and the scientific reputation of the proponents. That is our custom, one which serves excellence. The arguments which follow are offered on the presumption that the proposal will withstand a thorough scientific peer review.

Funding of the Sudbury Neutrino Observatory will create in Northern Ontario a major international centre for underground physics. The Sudbury location provides a city with an airport, an industrial base, and a university. These natural advantages, combined with the unique scientific advantages of the Creighton Mine site, provide a distinct edge over existing and planned centres elsewhere in the world. The location of the facility, in Walden township near Sudbury, is bound to have a positive influence both socially and economically. Over fifteen million dollars would be spent locally during the construction phase, followed by additional monies during the operation of the facility and during possible future modifications. The operation of the facility once it is built will provide about a dozen permanent jobs. Much of the work during the construction phase will be done by the INCO workforce and by local contractors. The project will require the development locally of fabrication facilities for the production of low background Sulfurcrete blocks using dolomite from the Timminco Metals quarry at Haley, Ontario as the aggregate. The low radioactivity of these blocks makes them ideally suited to application in nuclear medicine facilities and other environments where low background conditions are desirable. The high technology base of the data acquisition system, similar to those at the most advanced high energy physics facilities, will introduce and develop in the Sudbury area important skills in fast electronics and computing. These would be important developments for the local educational institutions and for local industry. The creation of the facility will require the development of detection, monitoring, and processing techniques to ensure the maintenance of a radioactivity-free environment. These would be state of the art skills, unique to Sudbury. The technical challenge of creating such an enormous cavern at the 6800 foot level will require INCO to develop mining techniques which may be of benefit to its commercial operation.

The facility will be an important focus of Canadian scientific activity, providing students and scientists with access to a world-class laboratory directed to understanding some of the most fundamental questions about nature: what are the details of the energy generation processes in the stars, can the forces of nature be unified into a single theory and is the universe open or closed? Answering such questions would give Sudbury and Canada a prominent place in future text-books of physics. A functioning laboratory will attract other scientific proposals from scientists in Canada, the United States and beyond, making the laboratory an international centre of excellence in underground physics.

Science North has created a remarkable community awareness of science in Sudbury. The Sudbury Neutrino Observatory would advance that awareness from the realm of spectator interest to that of participation in world-class science.



Creighton Mine Longitudinal

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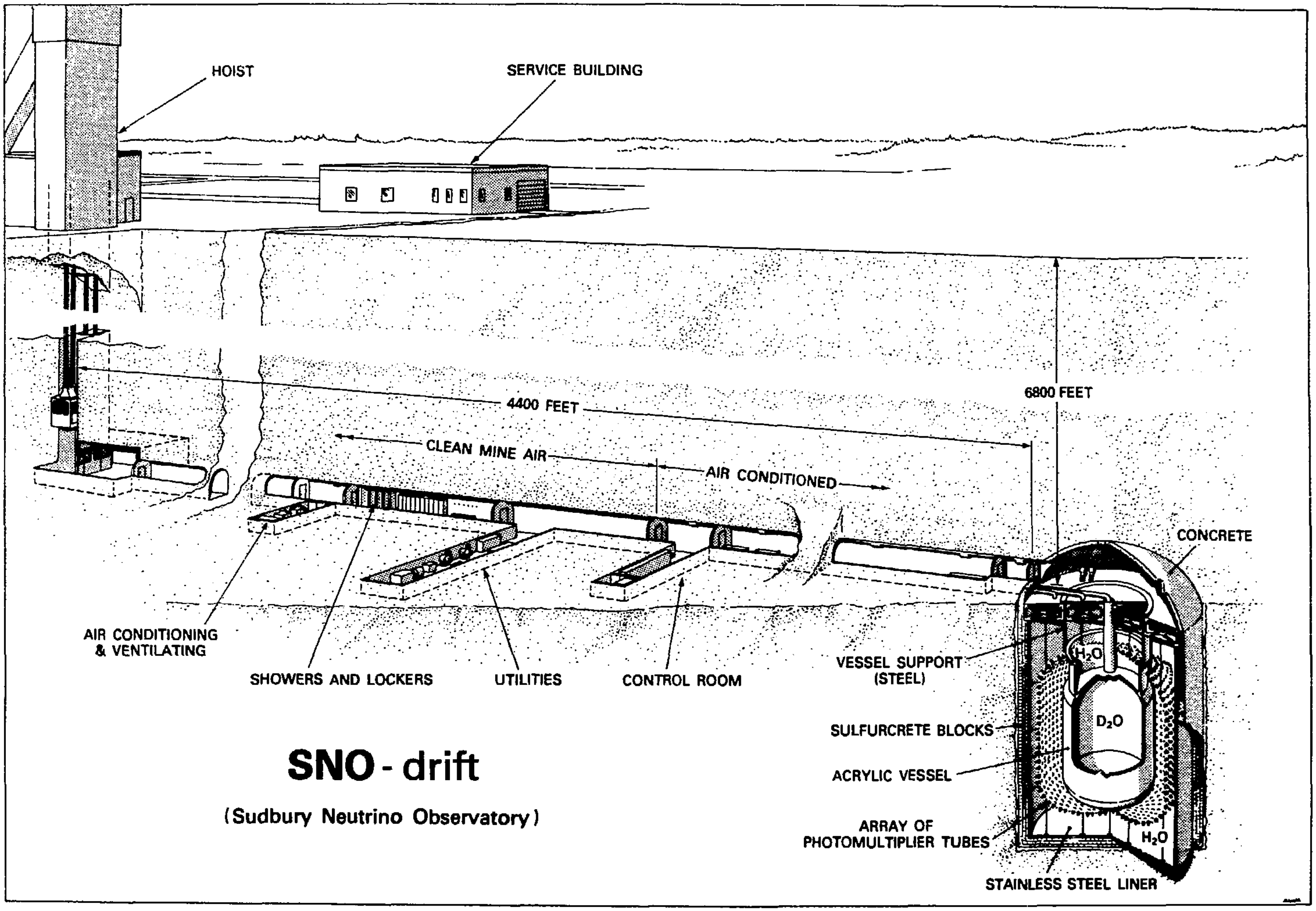
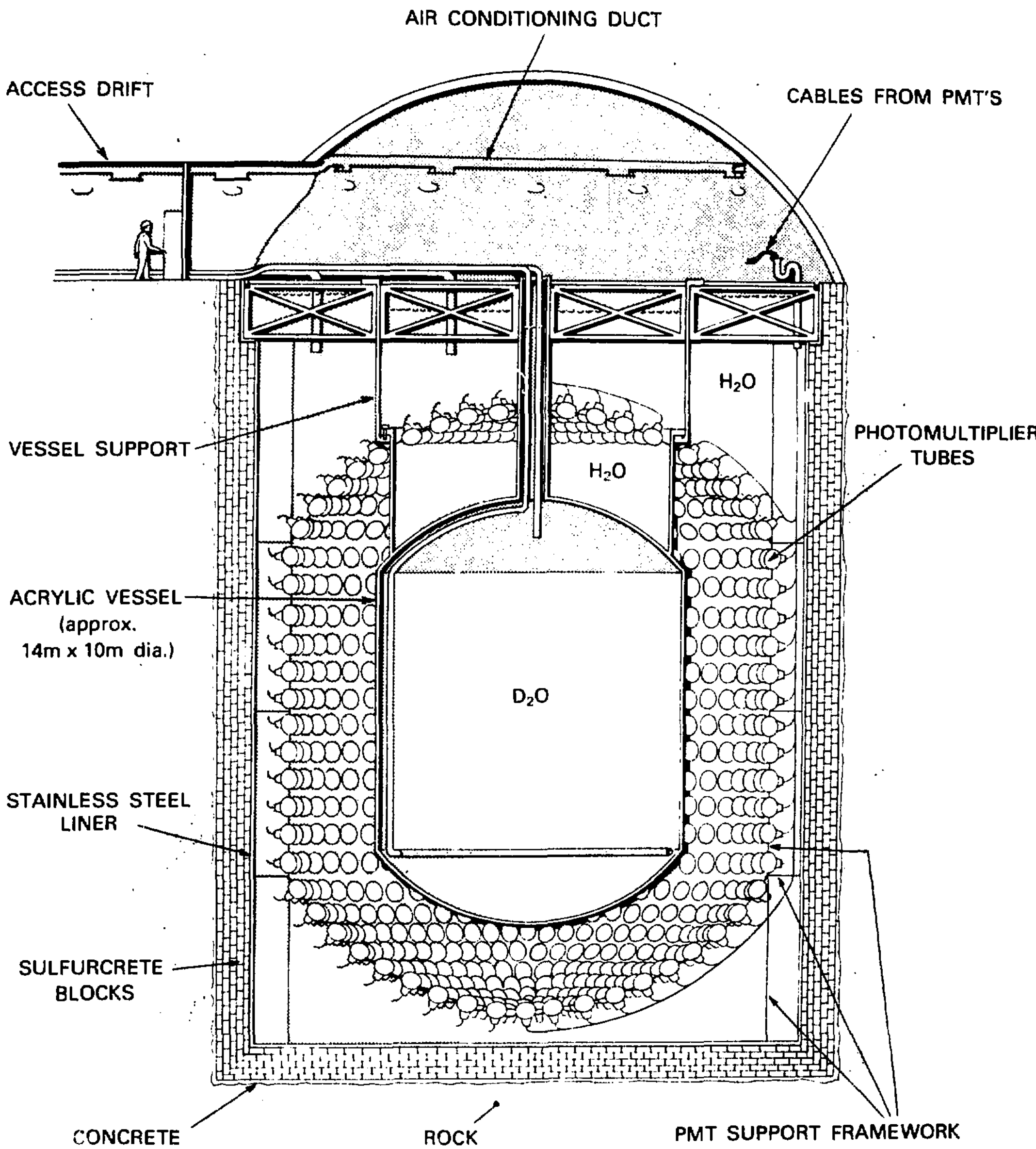

HOIST
SERVICE BUILDING
4400 FEET
6800 FEET
CLEAN MINE AIR
AIR CONDITIONED
CONCRETE
AIR CONDITIONING
& VENTILATING
SHOWERS AND LOCKERS
UTILITIES
CONTROL ROOM
VESSEL SUPPORT
(STEEL)
H_2O
SULFURCRETE BLOCKS
D_2O
ACRYLIC VESSEL
ARRAY OF
PHOTOMULTIPLIER TUBES
H_2O
STAINLESS STEEL LINER
SNO - drift
(Sudbury Neutrino Observatory)

3735-H



CROSS-SECTION OF NEUTRINO DETECTOR

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