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DESIGN OF A VARIABLE-LENGTH MUON SHIELD IN AREA 1

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ABSTRACT

It is argued that the circumstances of normal operation will exert heavy pressures to operate the neutrino beam in Area 1 at 200 GeV most of the time and that consequently it is very important to try to achieve maximum operating intensity for 200-GeV operation, without sacrificing the 500-GeV capabilities of the area. To accomplish this, a tunnel running about half the length of the 1000-meter dirt shield is proposed which is left open as an extension of the decay region for 200-GeV operation. It is terminated with a hadron dump for the 200-GeV muon beam. For use at 500 GeV, the tunnel is plugged by one of several methods and hadron dump at the front end restores the full 1000-meter shield. The tunnel can be either a pipe into which perchloroethylene is pumped to fill it and from which it can be emptied into a separate reservoir, or else a subway passage that can be plugged by "railway cars" carrying concrete plugs, or with stations into which iron plugs may be moved laterally. More detailed analysis is required to decide among these methods, all of which appear to satisfy the prime requirements. An overall increase in intensity of neutrinos by a factor averaging about 2 is obtained in this way for 200-GeV operation.

I. PROBABLE DEGREE OF USE AT 200 GeV

One prime requirement on Area 1 has dictated essentially all its major features: this is, of course, the stipulation that it provide shielding for operating at or near 500 GeV. This requirement leads to the present design (see Fig. 1) of a 600-m decay path followed by 1000 meters of dirt shield.

The effects of varying both decay path and shield length on the neutrino spectrum and intensity are by now thought to be well understood. Variation of the decay length is much less critical than the shield length; lengths over 600 m cut down low-energy neutrinos somewhat and raise the intensity of the high-energy end.

The neutrino intensity behind the muon shield decreases rapidly with the length of the shield--approximately linearly with the length in the high-energy limit and as the square of the length in the low-energy limit. Thus, especially for low-energy neutrinos, the shortest possible shield for a given proton energy is desirable, hence the desirability of dense shields. Correspondingly, the use of the 500-GeV shield when the proton energy is reduced to 100 or 200 GeV causes a large decrease in overall intensity of neutrinos, especially below 25 GeV, compared to an optimized shield.

Since lower energy accelerators exceed NAL intensities only at energies below about 3 GeV, an auxiliary proton beam, decay path, and iron shield, designed for neutrino production by 100-GeV protons, has been suggested. The cost of such an auxiliary beam is probably in excess of $1 million.

I would like to point out that in all probability the largest portion of the running time for Area 1 will be at 200 GeV, or whatever operating energy in that region is most convenient for Area 2. There is, therefore, a great incentive to optimize the operating efficiency of Area 1 for that energy. The reasons for this statement are as follows:

1. Area 2 will provide 4 or 5 beams and will be at least for some time the major counter experimental area. It will precede Area 1 in operation, and it cannot operate above about 200 GeV. There will consequently be strong pressures to keep Area 2 in continuous and efficient operation. Simultaneous operation of Areas 1 and 2 has been envisaged all along but until recently at the same energy. To operate Area 1 at a higher beam energy, say 400 GeV, requires either

a. Area 2 be shut down. Extended operation in this mode is unlikely.

b. The machine operating cycle include a "front porch" at 200 GeV before carrying the remainder of the beam to 400 GeV; such operation requires either tracking power supplies in the EPB or the ability to set the currents at two successive values within about 1 to 1.5 sec, or

c. Operation of Areas 1 and 2 on different machine pulses.

Either 2 or 3 results in a significant decrease in the duty cycle; 2 reduces the duty cycle of Area 2 by a factor of 4, and 3, at best, reduces each area by a factor of 2. These reductions are sufficiently significant not to be undertaken lightly, and there will be pressure on Area 1 to operate at the same energy as Area 2 so that they can share the same pulses (the design values provide sufficient current for both areas for full efficiency). Accordingly, the duty-cycle problems result in strong pressures for 200-GeV compatible operation.

2. Most of the experiments so far proposed for Area 1 do not require energies above 200 GeV, although higher energies would somewhat extend the range of parameters measured.

3. Improving the efficiency at 200 GeV might remove the necessity for a separate 100-GeV shield.

4. The technical requirements for minimum voltage drop on the 380 KeV power line, and for cooling water, also conspire against 400-GeV operation.

If we admit the necessity, or at least desirability of extended 200-GeV operation of Area 1, we next ask how we can do this most efficiently, still maintaining the 400-500 GeV capability for which we make so heavy an investment in the shield length. The answer to this lies in the concept of a variable-length shield, either with or without a variable decay path.

II. DESIGN OF A VARIABLE-LENGTH MUON SHIELD

The ideal shield would be variable in length and adjusted for the proton energy in use. Since the bubble chamber is practically immovable, the front end of the shield is the variable one, and it can be moved by adjusting the position of the end of the decay channel and the hadron dump. The improvements expected in the neutrino spectrum are shown in Fig. 2.

An approximation to the desired variability can be hypothesized by imagining a tunnel through the shield, of variable length and terminated at several different points by movable hadron dumps, only one of which is in use at any given time. The tunnel must be capable of being filled and emptied by material whose stopping power for muons is at least equal to that of the dirt it replaces. A liquid of density 1.8 to 2.0 is the ideal material for this purpose.

The tunnel, being an extension of the decay path, has the same diameter, 36 in. Once the tunnel has been emptied and used for the proton beam and meson decay channel, it will become extremely radioactive and will no longer be safe to enter. The filling and emptying will thenceforward be done under "hot" conditions. The desirable qualities for the tunnel liquid are:

1. Density 1.8 or more, preferably 2.0. A slightly lower density could be compensated by additional removable iron plugs.

2. Reasonable cost. The cross section of a 36 in. ID pipe is 0.653 m^2. 600 meters of such a pipe has a volume of about 400 m^3 which, when filled with liquid of density 2, holds 800 metric tons. Thus, we need of the order of 800-1000 tons of liquid, accordingly a reasonable upper limit to the cost is probably in the vicinity of $100 to $200 per ton. Many otherwise interesting substances are thereby ruled out.

3. The liquid must be acceptably safe to handle, not highly toxic, and must not dangerously contaminate the environment in case of an accidental spill. The equipment for handling it should be reliable, safe, and preferably already designed.

4. Since almost any material conceivable will become highly radioactive if exposed to the hadron beam in the tunnel, preference should be given to materials sufficiently volatile to leave no residue when pumped out of the tube.

The transfer of liquid into and out of the tube is done only when the energy of the proton beam is being changed. At the same time, the hadron beam dump must also be changed. Consequently, such changes probably will not occur too often, more likely on the scale of months than days.

III. POSSIBLE TUNNEL-PLUGGING MATERIALS

A survey of aqueous solutions of various inorganic salts was made, initially on the basis of density; candidates were then examined as to cost, physical properties such as corrosiveness, toxicity, and potential environmental hazard. Candidates that survive the first test are fairly numerous, but most can be immediately ruled out on the basis of cost; this includes all bromides, iodides, and most heavy metal salts. Ferric sulphate and nitrate are toxic, as is zinc chloride.

Liquid metals are too expensive, and also toxic or dangerous (mercury, gallium, cesium, sodium-potassium alloy). Other liquids considered, which met the cost criterion, included phosphoric acid, sulphuric acid, and tetramethyl lead. All of these are highly toxic, corrosive, and present serious environmental hazards.

Sulphur is non-toxic, insoluble in water, and available in large quantities. Its major difficulty is its melting point of 115° C. Sulphur is mined by melting it with hot water pressure and pumping the liquid up a pipe under pressure. To fill and empty a pipe with sulphur would require a design in which allowance was made for transferring enough heat to melt the thousand or so tons of sulphur in the pipe. Complicating such a design is the requirement that the passage for the hot water must not provide a major muon leak in the shielding; thus, a simple coaxial water-jacketed pipe is not possible. However, a spiral water jacket might be, and a corrugated design might work. As with sulphuric acid, a very extensive technology for sulphur exists. The use of sulphur presents a distinct fire hazard.

Only one commercial liquid met all the requirements: perchloroethylene, $CCl_2:CCl_2$ (or C_2Cl_4), whose major properties are:

Density 1.623; melting point -22.2° C, boiling point 121° C.

Nonflammable, nontoxic, chemically inert.

Major commercial use as degreaser and grease solvent; requires teflon-sealed pumps. No environmental hazard.

The cost is quoted, in drum quantities, as $0.15/lb., which is somewhat high; it might well come down to $0.10/lb. in the quantities wanted.

(575 tons would fill a 500-m pipe 36 in. in diameter.) This would come to just over $100 K. The average density could be brought up to 1.9 by using iron plugs to fill 5 meters in every 100.

IV. SUBSTITUTES FOR LIQUIDS: THE SOLID PLUG SYSTEM

An alternative to the fluid system is a system of movable solid plugs that can be inserted to fill the tunnel and withdrawn to open it. The plugs can be inserted either axially, from the front end, in which case they would be constructed as a sort of railroad train (Fig. 3); or else, if made of dense material like iron, they could be inserted and withdrawn laterally. Iron being four times as dense as soil, only a quarter of the tunnel length would need to be filled with the plugs. The axial plug system could very well utilize ordinary concrete, of density 2. Another possibility is uranium hexafluoride, which is available from the AEC for the cost of transportation only, already canned in cylinders 3 ft. in diameter and 15 ft. long, of density 5. This material is undesirable on the grounds of toxicity and environmental hazard in case of a spill.

If the concrete plug is inserted from the end, it is difficult to avoid long leakage paths along the surface of the plug, which must have some clearance from the tunnel wall. It is possible to avoid these, but expensive; it appears to require either several different siding tunnels for insertion of different portions of the plug, or else eccentric mounts to rotate and misalign sections of the plug after insertion. (See Fig. 4.)

Lateral plug insertion is much easier to design; it requires only a simple sliding mechanism, independently controlling segments of the plug. There must be cavities available into which to withdraw the plugs. This system is illustrated in Fig. 5.

The use of slurries of inert minerals has been looked at and is treated elsewhere; there are more hazards of breakdown with slurries than with homogenous materials.

We are thus left with three apparently satisfactory possibilities which deserve further investigation: one liquid, perchloroethylene, and two solids, concrete and iron.

V. THE IRON-PLUG SYSTEM CONSIDERED AS AN EXPERIMENTAL SETUP

The iron-plug system has one advantage not shared by the other systems. It provides unequaled facilities for measuring and monitoring the muon flux in the shield. It also permits the design of experiments to study the properties of muons up to 500 GeV, including the range-energy relations. It would allow extensive studies on shielding and on the scattering of high-energy muons and might lead to information that would enable more effective shields to be designed.

Plug systems have the advantages of being safe, free from noxious substances and environmental hazards, and straightforward in conception and execution. In addition, the plug materials are not activated by the hadron beam, since they are exposed only to muons and neutrinos and are removed when hadrons are present; they, therefore, avoid the radioactive disposal problem that residues of liquids in the pipe would pose.

VI. SUMMARY

It seems likely that at least one of the above systems can be designed to produce an economical and feasible system to vary the length of the shield. While it is too soon to estimate costs, it does not seem unreasonable to put an upper limit of about \$0.5 million on the cost of a 500-m tunnel and associated equipment. Should magnetic deflection be used to decrease the shield length, the tunnel system on a reduced scale is still applicable to give further length reductions.

Along with the decrease in shield length for 200-GeV operation provided by a tunnel, it may be desirable to consider shortening the decay path by moving the proton target station downstream; some increase in the intensity of low-energy neutrinos would be obtained.

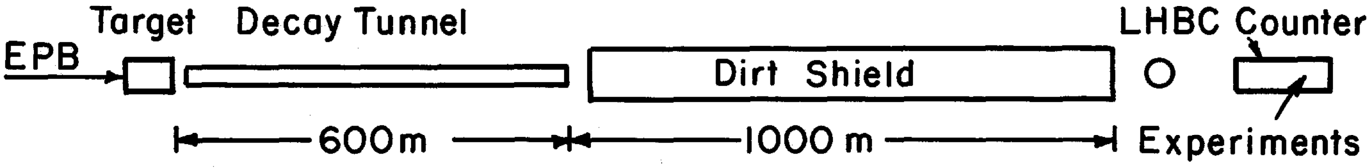

Fig. 1. Area 1 plan as of August 1, 1970.

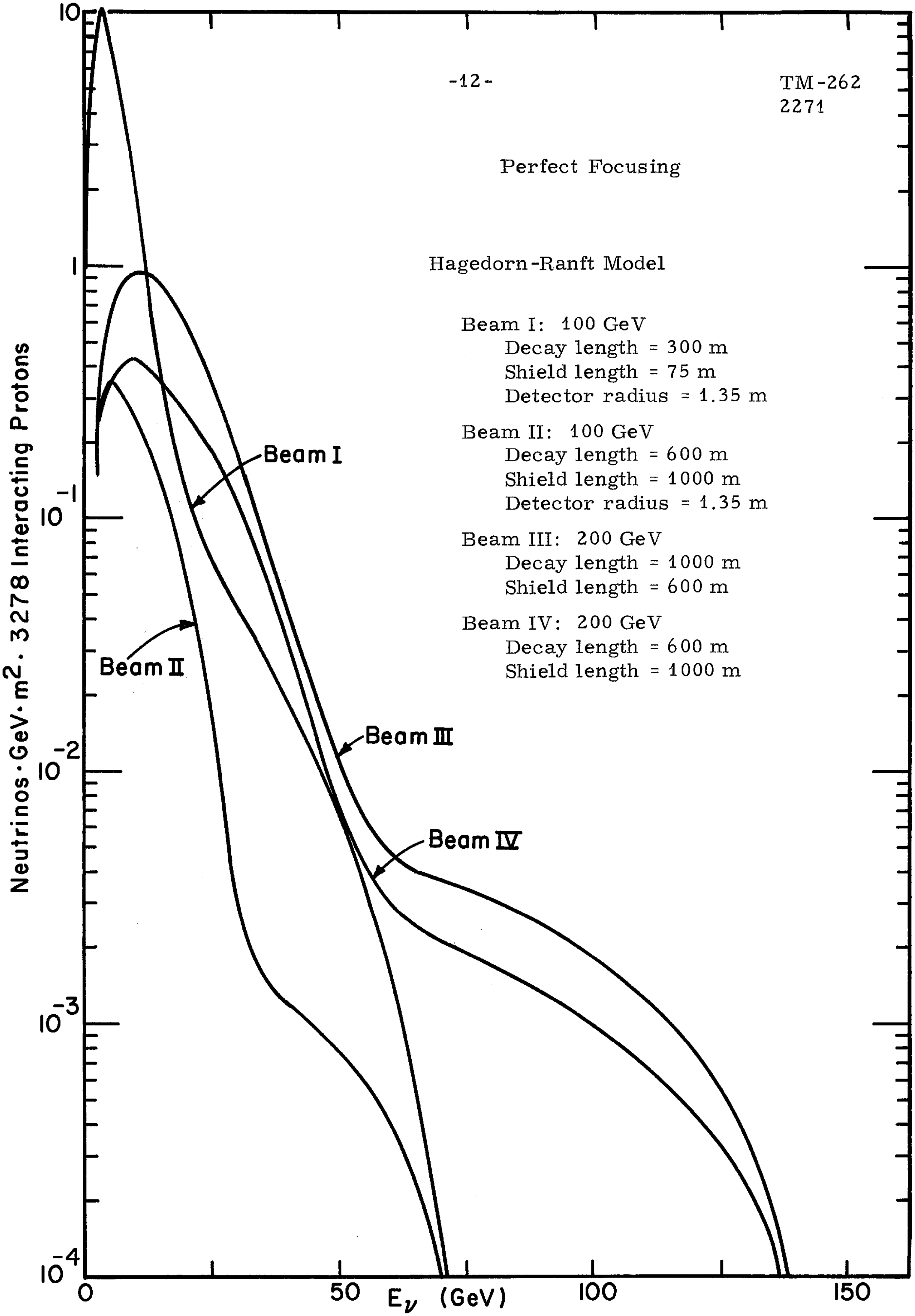
Perfect Focusing
Hagedorn-Ranft Model
Beam I: 100 GeV
Decay length = 300 m
Shield length = 75 m
Detector radius = 1.35 m
Beam II: 100 GeV
Decay length = 600 m
Shield length = 1000 m
Detector radius = 1.35 m
Beam III: 200 GeV
Decay length = 1000 m
Shield length = 600 m
Beam IV: 200 GeV
Decay length = 600 m
Shield length = 1000 m
Beam I
Beam II
Beam III
Beam IV
Neutrinos · GeV · m2 · 3278 Interacting Protons
10
1
10-1
10-2
10-3
10-4
0
50
100
150
Eν (GeV)

Fig. 2

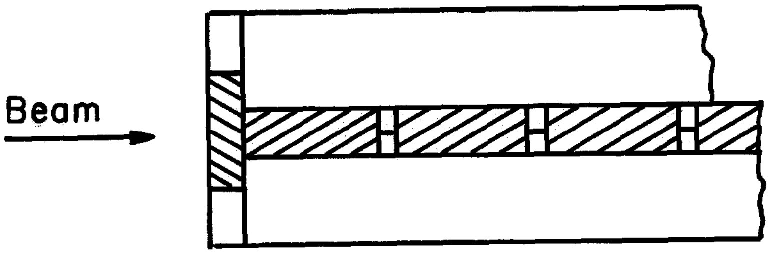

Fig. 3. Concrete plug shield in place in tunnel.

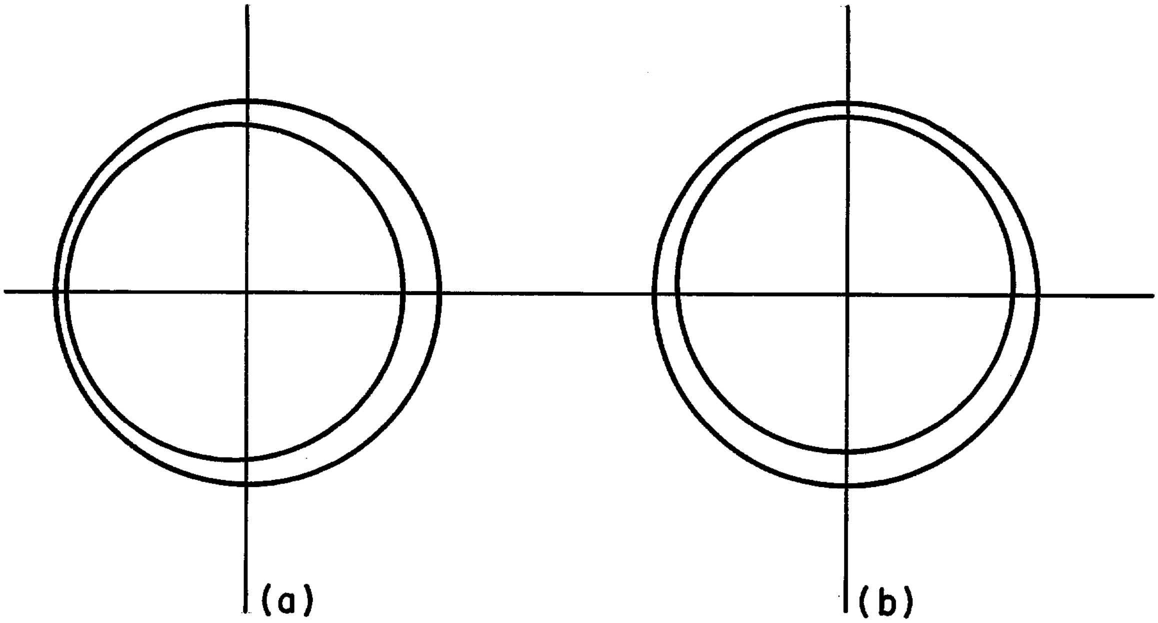

Fig. 4. Nonuniform concrete pipe for tunnel. Successive concrete plugs go into separate pipe sections which are then rotated with respect to each other, as (a) to (b), in order to avoid aligning cracks along plug edges.

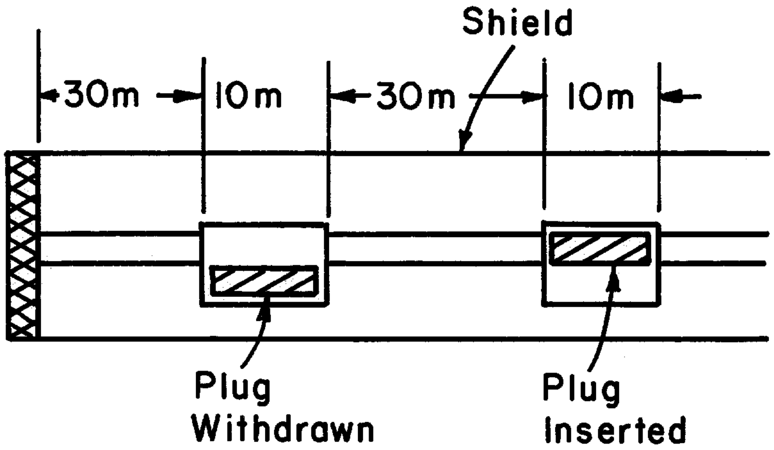

Fig. 5. Iron-plug system showing lateral insertion.