Commission of the European Communities

technical coal research

IMPROVEMENTS TO COAL TRANSPORT METHODS AND ASSOCIATED SITE RECEPTION AND HANDLING FACILITIES FOR THE INDUSTRIAL USER

Report

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IMPROVEMENTS TO COAL TRANSPORT METHODS AND ASSOCIATED SITE RECEPTION AND HANDLING FACILITIES FOR THE INDUSTRIAL USER

SUMMARY

This ECSC funded project has been aimed at encouraging industrial use of coal by making its transportation, reception, storage and handling more automated, cost effective and environmentally acceptable.

A comprehensive coal handling system, installed at CRE for receiving, storing and supplying coal to a test boilerhouse has shown itself generally reliable and environmentally attractive. The system comprises coal reception by means of a 22 tonne tipping hopper and storage within two silos, one of flat-bottomed concrete stave (250 tonnes) construction and the other of glassed steel (160 tonnes) construction with a hopper bottom. Transfer of coal between these components and boiler feed hoppers is provided by a dense-phase pneumatic conveying system. Minor improvements have been made to prevent coal "hang up" in the tipping hopper and enhance water drainage from the stave silo. As part of the further development of the tipping hopper it has been fitted with an all weather rolling shutter cover to prevent any ingress of rainwater.

In addition to the tipping hopper two further reception systems, containerisation and a wide belt vehicle unloader, have been investigated. Facilities developed to receive, unload and tip standard 20 tonne capacity ISO containers have been installed at a customer trial site. The equipment comprises two tipping frames which permit reception of a loaded container whilst an empty container awaits collection. Coal is automatically discharged from the container and transported away by a mechanical conveyor. The system is operating reliably. A novel coal reception system based on a wide belt lorry unloader and integrated lean phase pneumatic conveyor, has been developed and successfully demonstrated. Up to 22 tonne of coal can be held on the belt allowing rapid turn-around of tipping vehicles. The coal can then be either stored on the belt or fed into the pneumatic conveying system at rates of up to 20 tonne/hr. The unit offers a compact, cost effective reception system for industrial coal grades which, by way of its construction, requires virtually no civil works.

Tests with a 200mm diameter suction nozzle have demonstrated that coal conveying rates of up to 61 tonne/hr can be achieved. Studies have confirmed the importance of using the appropriate conveying velocity for lean phase transport systems in order to minimise coal degradation.

The consequence of long term storage of smalls coal has been investigated during a storage period of 12 months within the concrete stave silo at CRE. Although self-heating caused the temperature of the coal to increase to approximately 30°C above the ambient temperature during the first six months of storage, this did not progress to a fire but subsequently fell and followed seasonal temperature fluctuations. During this period, the carbon monoxide concentrations in the silo headspace underwent considerable daily variation. This was found to be dependent upon atmospheric temperature, pressure and windspeed. Carbon monoxide is used in the UK to detect dangerous self heating and although these variations in carbon monoxide concentration reduce its effectiveness it has been successfully used to detect combustion in silos enabling corrective

measures to be taken which prevented a serious fire. Gas concentrations have been monitored in the headspaces of four further silos at industrial sites and they have shown similar transient variations but no trend of increasing carbon monoxide concentration. Although methane concentrations, measured in the same exercise, have only reached one-eighth of the lower explosion limit, reports of higher concentrations have led to concern. Mathematical models have been developed to improve the understanding of the processes of gas evolution and dissipation within silos and these studies will be continued in a further ECSC funded study.

Coal is extracted from the base of the concrete stave silo at CRE with a rotating auger. Pressures measured on the walls of this silo, using a pressure pad technique, have shown that stresses on the lower parts of the wall are cyclic depending on rotation of the auger, reaching a maximum at a point one quadrant in front of the auger before reducing to a minimum as the auger passes beneath. The maximum pressures resulting from this cyclic behaviour exceed values predicted from the literature and this may be a contributory cause of cracking found on the walls of other coal storage silos of this type within the UK. The quantity of coal extracted from the silo during a complete radial sweep of the auger has been found to increase from approximately 6 tonne per sweep to 26 tonne per sweep as the silo contents were reduced from 234 tonne to 67 tonne. This is considered to be due to changes in the bulk flow characteristics, induced in turn by pressure variations in the vicinity of the auger.

The technical feasibility of using a hydraulic system for removing oversize ash extracted from a fluidised bed by means of an air classifier has been proven using a test unit at CRE. The effect of hydraulic conveying velocity on ash particle velocity has been evaluated. Based on the principles derived from the test unit a hydraulic ash sluicing system has been installed to transport oversize ash extracted from the bed of a 9MWt fluidised bed furnace at an industrial site. Current limited site requirements for use of the furnace have restricted commissioning to periods when the furnace has not been operated.

A low-cost, submerged, rubber belt wet ash extraction system has been installed on a modular boilerhouse which was on test at CRE. This unit has undergone long-term evaluation trials and has been operated successfully during a nine-month trial period. The unit, together with the modular boilerhouse, is to be moved to a customer site and a second unit has been placed on order.

Project No. 7220-ED/802

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CONTENTS

Page No.

SUMMARY

IMPROVEMENTS TO COAL TRANSPORT METHODS AND ASSOCIATED SITE RECEPTION AND HANDLING FACILITIES FOR THE INDUSTRIAL USER

1. GENERAL INTRODUCTION

During the latter part of the seventies and early eighties coal enjoyed a price advantage over its competitors, oil and gas, which led to its re-emergence as a fuel for industry. This led to the development of a new generation of modern coal firing equipment, such as fluidised bed combustion. To complement this improved combustion equipment, a requirement was identified to enhance the amenity of associated coal supply (transport, reception, storage and handling) and ash removal systems. This project has been concerned with such handling equipment for use with coal-fired plant of up to 30 MWt capacity. Special emphasis has been placed on systems which are automatic, convenient and environmentally acceptable. Compactness has been another important aspect as space is at a premium at many industrial sites. The economic viability of coal supply systems has also been important, particularly with the recent improved competitiveness of oil and gas.

UK coal for the industrial market is primarily supplied as one of three grades, "singles" (nominally 12.5mm to 25mm), "smalls" (0 to between 12.5 and 32mm top size), and pulverised fuel. The pulverised fuel market in the UK is currently very small. Use of modern mining techniques tend to generate higher proportions of fines compared to traditional methods and this is leading to an increasing proportion of smalls grade coals being supplied to the industrial market in the UK. The handleability of smalls and singles is very different with singles being a free flowing product and smalls being fairly cohesive and consequently more difficult to handle. Improving the storage and handling facilities available for smalls coal, and hence their acceptability, for industrial use has been an important aspect of this project. The flow characteristics of smalls coals have been investigated under ECSC Project No. 7220-ED/804.

The particular aspects of coal transport, reception, storage and conveying investigated within this study are introduced below, together with a general description of the possible range of handling techniques used at UK sites.

1.1 Scope of Coal Supply and Ash Removal Facilities Investigated

Coal supply systems in the UK (Figure 1) comprise transport and reception to site, storage, retrieval from storage, and a facility for feeding coal into the combustion plant. A more detailed breakdown of these stages within a coal handling system, indicating the range of options available is shown in Figures 2, 3 and 4 with ash handling considered in Figure 5. Within the present project items of equipment from each of the stages of coal and ash handling at industrial sites have been investigated, with new equipment being developed and assessed where particular needs have been identified.

A complete coal handling system (consisting of coal reception by tipping hopper, storage within concrete stave and glassed steel silos and with coal transport provided by dense phase pneumatic conveyors) has been installed at CRE and evaluated in use. In particular, stresses developed on the walls of the concrete stave silo during the storage and discharge of coal has been studied. By chance an incident of spontaneous heating occurred within this silo and this was closely studied. The build up of noxious gases within the silos at CRE and other industrial sites has also been investigated.

Containerisation has been investigated as a convenient method of bulk coal delivery. A mechanical cradle for receiving and tipping standard ISO containers has been developed, in conjunction with a manufacturer, and demonstrated at a customer site. In parallel with this, a new coal reception facility, comprising a wide belt vehicle unloader has been developed as a compact method of receiving smalls. A lean phase pneumatic conveying system based on a suction nozzle[1-3] has been further developed to increase its throughput.

A low cost wet ash removal system comprising a submerged rubber belt has been developed and assessed. Additionally a piped hydraulic ash removal system has been developed to remove large ash extracted from fluidised bed combustors by means of air classifiers.

2. COAL HANDLING AND STORAGE SYSTEM AT CRE

A comprehensive, integrated coal handling system was installed at CRE (Figure 6) towards the end of 1983 and its performance has been monitored whilst supplying fuel to a variety of boilers in a test boilerhouse. Incoming coal, either singles grade (12 - 25mm) or smalls (0 to 12.5 - 32mm) is delivered by tipper lorry to an end-tipping hopper, and then transferred using a dense-phase pneumatic conveying system to either of two silos or directly to boiler feed hoppers within the test boilerhouse. Similar dense phase handling equipment also transfers coal from the silos to the boiler hoppers. Each of these items of equipment is discussed below.

2.1 Tipping Hopper

2.1.1 Description

The tipping hopper (Figure 7) has a nominal capacity of 22 tonne and is capable of receiving and discharging either singles or smalls coal grades. This unit was the prototype for a new design of end tipping hopper which incorporates the best aspects of commercially available tipping hoppers. The unit comprises a mild steel tipping body open at one end to accept a lorry but closed, in the form of a rectangular cross sectional discharge cone, at the other end. The tipping body is supported by a static main support frame (similar to the CRE side-tipping hopper[1-3]) and attached by a pivot at the closed end. A vehicle ramp is included as part of the hopper structure at the open end and a self sealing vibratory bin discharger (Matcon Ltd.) is incorporated into the discharge cone preventing spillage of coal whilst the tipping body is being elevated. By correct setting of the maximum aperture of this self-sealing discharger a degree of screening can be obtained which helps prevent extraneous material from entering and blocking the conveying system. Hydraulic actuating cylinders attached between the supporting frame and the tipping body raise it about the pivot, into its tipping position above the pressure vessel of the dense-phase pneumatic conveyor. Upon reaching the tipping position a limit switch activates the vibratory bin discharger causing coal to flow from the tipped hopper.

2.1.2 Operational Experience

Following commissioning the unit has generally worked well, particularly with UK singles coal (12.5-25mm). The interval between the arrival of a coal lorry on site and its departure is typically 30 minutes and transferring the contents of the tipping hopper to one of the silos takes 90 minutes. The total cycle time is thus a nominal 2 hours to unload 20 tonnes of coal. The time the lorry is actually using the tipping hopper is somewhat less than 30 minutes, but this value includes an allowance for unsheeting and use of a weighbridge. This system could thus handle coal supplies to a boilerhouse with a continuous usage of up to 10 tonnes/h, equivalent to 78 MW (t) with 24 hour per day delivery or 3.3 tonne/h (26 MW(t)) with the more usual UK situation of deliveries limited to 8 hours per day.

As operating experience has increased, however, some difficulties have been identified and overcome. Compaction of U.K. smalls coal (0 to 12.5 - 32mm), around the self-sealing vibrational discharge cone, particularly during wet weather, prevented coal flowing from the hopper into the secondary conveying system. This problem was overcome by lining the discharge faces of the tipping hopper with ultra-high molecular weight polyethylene. Additionally, the four sharp corners of the rectangular discharge cone, in which the coal lodged, were also filled with angled plates. Following these modifications, no further difficulties were experienced with compaction of fine coal.

Occasional problems arose with tramp material finding a path around the self-sealing vibratory discharge cone and into the dense phase blow vessel, of the secondary conveying system. This was overcome by installing a 75mm aperture wire mesh above the blow vessel to collect the tramp material.

Collection of water in the upright hopper during wet weather, particularly if the hopper was used as a buffer coal store, was a further difficulty. Rainfall of 25mm produces an accumulation of approximately $0.5m^3$ of water in the hopper base. This water could easily become transferred to the dense phase blow vessel and hence discharged with the coal. Consequently, water is fed either to the coal storage silos or directly to the day bunkers of the combustion equipment. This problem was resolved by fitting an all-weather rolling shutter cover to the hopper. The roller cover is electrically-operated and incorporates helically wound torsion springs to ensure smooth movement during service. A motor driven shaft is connected to the shutter by means of two continuous drive chains. The cover is constructed from 18 gauge galvanised mild steel curved lath sections. The shutter is operated from a control panel located in the vicinity of the hopper. Use of the shutter was also found to reduce emissions of coal dust during hopper operations in dry weather.

An 18-tonne version of the hopper, installed at a customer site, also operated very successfully during a three-year period.

2.2 Coal Storage Silos at CRE

2.2.1 Steel Silo of prefabricated glassed plates

2.2.1.1 Description

This A.O. Smith silo (Figure 8) has a nominal capacity of 160 tonnes and incorporates a conical discharge hopper (40° included angle). It is fabricated from overlapping mild steel plates which are glass coated on each face, to prevent corrosion and under normal operating conditions to reduce frictional resistance between the silo walls and coal as it flows past during discharge, thus improving the mass flow characteristics. The plates are bolted together, through rubber grommets, along their overlapping faces to form a rigid structure. Mastic is applied to these faces before assembly. A ring beam encircles the silo at the transition between the conical hopper and vertical sections to withstand the high dynamic pressures known to occur on the silo walls in the vicinity of this transition[4]. This particular silo, contrary to standard practice, was lined with Ultra-High Molecular Weight Polyethylene in the cone section as it was felt some of the coals supplied to a Research Establishment could be particularly difficult to handle. The silo has a domed roof fabricated from glass coated mild steel plates in a similar fashion to the walls. Coal is delivered into the silo centrally through the roof by a dense-phase pneumatic conveyor and directed vertically downwards by the conveying pipework. Spent conveying air escapes through a filter unit in the roof. Coal is discharged from the conical hopper section into the pressure vessel of a dense-phase pneumatic conveyor through a rod gate valve and secondary hopper which incorporates a vibratory discharger. The rod gate valve can be shut to prevent discharge of coal should it become necessary to dismantle any of the conveying system for maintenance purposes. The vibratory discharger is automatically sequenced to operate when the pressure vessel of the dense-phase pneumatic conveyor is being filled. A ladder is provided to give access to the silo roof. There are side and roof manways.

2.2.1.2. Operational experience

This silo has generally performed well as a storage system for UK washed singles coal (coals from 8 different sources having been stored at different times). Some initial difficulties were experienced with occasional bridging occurring during discharge through the circular outlet (225mm diameter) despite the presence of a vibrator. Although these difficulties were short lived and have not recurred during the last three years of operation, an outlet diameter of at least 250mm is now recommended for singles coal.

A slide valve fitted at the base of the cone, to isolate it from the dense-phase blow vessel was found to be an unnecessary complexity and was replaced by a manual rod gate valve. This system which consists of a single layer of 16mm rods at 22mm centre to centre spacing, is of low cost and guaranteed operation. It is recommended as a method for coal isolation.

2.2.2 Concrete Stave Silo

2.2.2.1 Description

This silo (Figure 9) of concrete stave construction (Tower Silos), has a nominal capacity of 250 tonnes and is intended for the storage of smalls (0 to 12.5 - 32mm) grades of coal. The staves (measuring 760mm high, 285mm wide and 65mm thick) are held in place by high tensile galvanised steel hoops which encircle the silo and are post-tensioned to withstand the pressures generated on the silo walls by stored coal. After erection, any gaps between staves are pointed and a coating of bitumastic paint applied to the inside surface of the walls to prevent rainwater ingress and air leakage. The latter minimises the risk of spontaneous combustion. The silo has a flat concrete roof and base, both of which were cast insitu. The floor is 3.72 metres above ground level, allowing sufficient space beneath to accommodate a dense-phase conveyor. Coal is delivered into the silo centrally through the roof by a dense-phase pneumatic conveyor and directed vertically downwards by the conveying pipework. Spent conveying air escapes through a vent on the roof via a shaker bag filter unit. Permanently installed ladders provide access on to the silo roof.

Coal is extracted by means of a Parcey Industrial Planetary Extractor (Figure 9) which is a commercially available rotating auger extractor, originally used in agriculture as an aid to discharge of grain from storage silos. This unit comprises a rotating screw auger located 150mm (floor to auger axis) above the silo base. The radial auger arm follows a circular path around the silo base, sweeping coal to a central discharge point. Both the pitch and diameter of the auger flights increase towards its discharge end to promote an even extraction of coal along its length. In operation coal discharges through a central opening (1100mm) in the silo floor and flows into the pressure vessel of a dense-phase pneumatic conveyor via a small conical hopper mounted beneath the silo floor.

The extractor is mechanically supported from a triangular section steel tunnel which passes out through the silo walls and which is in turn secured to two concrete pillars independent of the silo although on the same foundations. This tunnel also allows access to the extractor motor and drive train.

2.2.2.2. Operational Experience

Since its installation in the latter part of 1983, this silo has operated satisfactorily providing an effective storage facility for smalls coal with only the minor difficulties outlined below being experienced.

Water from stored coal (particularly if delivered under wet weather conditions) would drain to the base and into the conveying system. This was overcome by installing a drainage system (Figure 10) into the discharge area. The base of the silo was graded to promote flow of water towards the central coal discharge port where it is now intercepted by an annular trough of triangular cross section fitted around the periphery of the discharge tube. Water entering this trough is collected in two catchment pots. Coal is prevented from entering these vessels by means of horizontal plates located in the trough. This system permits drainage from the silo at all times; washed smalls coal grades generally contain higher proportions of moisture when delivered compared to washed singles because of the presence of fine material which retains water to a greater extent, hence the greater problem with this silo.

On several occasions the auger has 'stalled' in the sense of ceasing to sweep the base of the silo and as a result discharge has been from one sector alone. This is a potentially hazardous condition and recommendations are now made that all extraction equipment of this type has a 'stall' detector. The reason for this stalling is not known, at present, but it occurs when the auger fails to cut into coal in front of it.

Examination of the rotary auger after approximately eighteen months use revealed that it was partly fouled by coal, which had adhered to its shaft and flights (Figure 11). The coal formed a hard compacted well bonded layer on the auger, aided by surface rust of the latter. The extent to which this fouling decreased the rate of volumetric discharge of the auger was unknown. Subsequent examinations confirmed that the amount of fouling did not increase.

Because use of a radially rotating screw extractor is relatively novel, the silo was used as a research facility to study the implications of this method of coal extraction on pressures generated on the silo structure and coalflow within it (Section 5.2). The implications of prolonged storage of smalls coal on spontaneous combustion has also been investigated with a batch of coal being held in storage for a twelve-month period (Section 5.1).

2.3 Dense-phase pneumatic conveying system

2.3.1 Description

Coal is transported from the tipping hopper to either of the two coal storage silos, or directly to feed hoppers in the boiler test house, by a dense-phase pneumatic conveying system (Figure 6); similar equipment is used to transport coal discharged from the two storage silos into these feed hoppers. The conveyor consists of a pressure vessel situated beneath the tipping hopper or silo with an outlet connected to the conveying pipeline and a compressed air inlet (Figure 12). Coal flows by gravity, from the hopper or silo, into the pressure vessel. When full, a pneumatically operated disc or dome valve, located at the entry into the pressure vessel closes through the head of coal and effects an airtight seal. When fully shut a microswitch, incorporated in the valve allows high pressure air to be admitted to the vessel expelling the coal into the pipeline as a plug. The duration of the supply of air is set experimentally during commissioning and is the minimum compatible with propelling the slug through the pipeline to its destination (either of the storage silos or a boiler feed hopper). This optimises consumption of compressed air. The disc valve is then opened allowing further coal to be admitted and the sequence repeated. The conveying system (Figure 6) contains four diverter valves enabling coal to be directed from the tipping hopper into either of the two storage silos, directly into the boiler feed hopper or into the feed hoppers from either of the silos.

2.3.2 Operational Experience

The pneumatic conveying system has worked well as a conveying system for both singles and smalls coal grades.

One problem occurred with the pneumatically operated disc valve and its associated microswitch and there have been difficulties with operation of the diverter valves.

The fault with the disc valve (on the pressure vessel beneath the stave silo) arose when it failed to close properly (it became jammed with coal) and the microswitch failed to detect this (possibly due to coal particles fouling the mechanism). Consequently, conveying air was admitted to the pressure vessel. Because the valve was not completely shut, air escaped around it and ruptured the rubber sleeve connecting the pressure vessel with the silo discharge hopper. The microswitch was re-set and, as a safety measure, a lightweight screen was installed around the rubber sleeve. Since this modification two years ago no further difficulties have been experienced.

The diverter valves operate relatively well if used daily but were prone to seizure if left in one position for long periods. This occurs because the valves have flexible gaskets (some pneumatically operated) which seal the joint, and these gaskets are damaged by compacted and dried coal fines, which almost inevitably seem to accumulate around them. These difficulties have been circumvented (although regrettably not yet overcome) by providing easier access to moving parts of the valve for maintenance. Direction indicators have also been provided to confirm the physical position of valves, should remote indication be faulty.

3. COAL RECEPTION

In addition to the end tipping hopper (Section 2.1) two further reception systems, containerisation and the wide belt vehicle unloader have been developed.

3.1 Containerisation

Containerisation has been investigated as a low cost method of on site delivery. The advantages of containerisation are summarised below:

i) Containers could be filled directly at the colliery washery on a continuous 24-hour per day basis. The contents could be weighed. These containers could rapidly be loaded on to container vehicles as required, avoiding the need for queuing as sometimes occurs at present, when each lorry is filled individually.

ii) In many urban and rural village situations and on certain industrial sites container lorries are considered environmentally more acceptable than coal lorries.

iii) The dispatch of a sealed load of coal from washery to final client in a container reserved exclusively for coal usage, reduces the risk of contamination both from intermediate handling and debris left in open lorries from previous usage (for instance, scrap metal).

iv) The elimination of any double handling of the coal would reduce degradation. This is particularly true for the "export" of coal to many of the islands off the UK mainland.

The technical problems with containerisation have now been overcome as described below. The remaining barrier to implementation on a large scale is the significant capital cost required for container handling equipment at the colliery, client site and the substantial investment already made by the coal distribution trade in conventional tipper vehicles. An attractive route, being pursued, is to encourage other industrialists in the geographical area around the current demonstration site to receive their coal by container.

3.1.1 Development

A standard ISO container (6m x 2.4m x 2.6m) was selected for its flexibility, being suitable for transportation by road, rail or sea. Initially a commercially available portable system for tipping the contents of containers from road vehicles was investigated. The concept originally envisaged by the manufacturer (Telehoist Ltd.) was that, by means of unloading ramps, the portable tipping system (or Tip Kit) would be left at customer sites complete with its container. In practice unloading of the Tip Kit and associated container by means of the ramp was found to require excessive driver skill, particularly in wet weather. The overall height during tipping was greater than desirable (14.5m) and the weight of the Tip Kit adversely affected the coal payload.

In order to overcome these difficulties the Tip Kit was eliminated and the static ramp replaced by a composite framework, which both raises the container clear of the vehicle chassis and tips the contents (Figure 13). Following preliminary proving trials this system was installed at a customer trial site, one tipping frame being installed initially and a second at a later stage.

Figure 14 shows a container at the trial site in its fully-inclined position within the tipping framework. Coal is discharged from the container into a mechanical "en-masse" type elevating conveyor which, in turn, feeds it into a dense-phase pneumatic conveying system for transfer to the boiler service bunker some thirty metres distant. The plant has a design throughput rate of 10 tonne/h and is suitable for singles or smalls coals.

In operation, a skeletal trailer carrying an ISO container, with a nominal payload of twenty tonnes of coal, is reversed into the tipping framework. The vehicle driver connects one of four chains, which are suspended from the frame, to each of the four lower corners of the container, and releases the container. The frame is then raised by automatic control of a hydraulic power pack to lift the container vertically clear of the trailer, which can then be driven away. The time taken for the vehicle to reverse into the frame, demount the container and drive away is about five minutes.

After release of the container rear door clamp, further extension of the hydraulic rams on the tipping frame lifts and subsequently tips the container to allow coal to discharge into the inlet hopper of the elevating conveyor. This hopper has a nominal capacity of three tonnes and subsequent transfer into the dense-phase conveying system is controlled by 'high' and 'low'-level probes within a 0.75 tonne capacity surge hopper located above the dense-phase pressure vessel. The mechanical handling system incorporates a vibrating screen and reject chute to automatically remove oversize material present. Depending upon the coal requirement in the boilerhouse, the pneumatic conveying system will transfer coal in batches at an average rate of ten tonne/h. The discharge time from the container is, therefore, entirely dependent upon boilerhouse coal requirement. When the inlet hopper of the elevating conveyor is empty, the container frame is further tipped, sufficiently to discharge more material until the hopper is full; this operation is repeated as necessary until the container is fully-tipped and emptied. A minimum time to empty a full container is approximately two hours.

The empty container is lowered to a horizontal position such that a trailer can be reversed beneath. Once the trailer is in position, the container is lowered on to the vehicle, the four chains disconnected and the container secured to the trailer before being driven away. A simple painted guide strip is used to assist the driver in this operation. The time for which the vehicle is on site to collect an empty container is about ten minutes.

With the installation of a second tipping frame, alongside the existing unit (Figure 15), a loaded container can be received whilst the empty container awaits collection. The feed section of the mechanical elevating conveyor was extended to accommodate this second tipping frame.

3.1.2 Trial at Customer Site

A trial programme on the plant was completed with 300 tonnes of smalls coal (0 to 12.5 - 32mm) automatically received and transferred successfully using ISO containers. Regular deliveries of coal in containers are now taking place at the customer site and the performance is being monitored under operational conditions.

3.2 Wide Belt Vehicle Unloader

A wide belt vehicle unloader (B and W Conveyors Ltd.) has been investigated for its suitability as a coal reception facility. Wide belt conveyors (Figures 16 and 17) are used extensively as ship loaders, where the conveyor operates as a surge hopper to facilitate fast turn-round of delivery vehicles. The system has been adapted for use as a coal reception facility (Figure 18), and a prototype was manufactured. The unit comprises a 22 tonne nominal capacity belt conveyor to which a lean-phase conveying system is appended. A tramp screen is incorporated at the interface of these systems to protect the pneumatic conveyor and other downstream components of the coal-handling and combustion equipment. The prototype was installed at an outstation of CRE for assessment and as-necessary further development, prior to installation at a customer trial site for commercial evaluation.

3.2.1 Wide Belt Conveyor

The conveyor is based on a chain and slat construction with a conventional rubber-covered belt rivetted to the cross slats, forming a seal such that the whole unit performs as if it were a flat belt conveyor. The belt is driven by an electric motor through a variable speed unit coupled to a gearbox which incorporates a torque limiter to protect the conveyor in the event of a failure. Since the conveyor drive is transmitted completely through side chains, the possibility of belt slip or of tracking problems, common with conventional belt conveyors, is eliminated.

The slat/belt principle enables the conveyor to be constructed such that vehicles may reverse and tip directly onto the belt. No excavation is required and the unit may be located at ground level. The machine will be used as a surge/storage hopper, allowing vehicles to be rapidly unloaded and the coal conveyed away as required. The conveyor is fitted with a weather enclosure to prevent escape of dust and protect the contents from rain.

A feature of the design of this unit is that it is delivered as a complete unit enabling delivery and installation to be completed in one day. Because loadings on the base of the unit are evenly distributed site preparation is minimal simply requiring the provision of a 200mm thick concrete base; site installation costs are, therefore, minimised.

3.2.2 Pneumatic Conveying System

The objective of this work was to produce a smalls handling system, based on lean-phase pneumatic conveying, which would rival the considerably more expensive dense-phase pneumatic option. It was envisaged that the design of the coal entrainment together with the material used in its construction and that of the conveying pipelines were all important.

Coal is discharged from the end of the belt via a tray feeder and tramp screen before being introduced into the 125mm diameter conveying pipeline by a screw entrainment device. This device consists of an enclosed 200mm diameter screw having a 150mm pitch and overall length of

1.2m. This screw configuration provides sufficient sealing against the back pressure in the pneumatic conveying system.

The screw is driven via a variable speed transmission to allow coal to be consistently discharged into the conveying system at any desired rate between 5 tonne/h and 25 tonne/h. The screw flights downstream of the entrainment point are reversed to minimise any built-up of coal in this area. The screw conveyor tube is partially transposed over the conveying pipeline to assist the transfer of coal into the air stream. It was anticipated that this innovation would result in the coal being more evenly discharged into the conveying air and, hence, permit operation at high coal flow rates.

The longest conveying route totalled 51m in length with a 4m rise and four bends, as shown in Figure 19; conveying air pressure was monitored along the conveying route. The conveying air was supplied by a fan. Start-up of this was achieved by means of a novel damper (Figure 20) which only opens when the fan has produced a specific discharge pressure. This was found to reduce starting current by a factor of 20%. A further novel damper (Figure 21) was provided downstream to control air velocity during normal conveying. This unit operated by balancing the pressure produced on a specially shaped vanes, by air flowing past against a counterbalance weight. Such dampers have now been used on a number of lean phase coal conveying installations and the close control of air velocity has reduced coal breakage and pipework erosion. The technique is equally applicable to lean phase ash systems.

3.2.3 Control of the System

Provision was made to operate the system in a manual or in an interlinked automatic mode. In the automatic mode a tipper lorry can reverse up to the conveyor belt and tip. The coal falling on to the belt trips a sensing device, starting the belt and drawing the coal into the weatherproofed housing. Once the coal reaches the surge hopper, the tray feeder is activated, feeding coal through the tramp screen and into the screw hopper. When a minimum quantity of coal has entered the screw hopper the conveying fan and screw drive are started sequentially and will continue to run until the load on the belt has been transferred. The tray feeder starts and stops on receiving signals from respectively low and high level probes located in the screw hopper. The belt starts and stops on receiving low and high level signals respectively from a single ultrasonic level probe located at the top on the surge hopper.

The control philosophy therefore allows for the safe unmanned transfer of the delivered coal from the reception point to the main storage point.

3.2.4 Commissioning

3.2.4.1 Wide Belt Unloader

Pre-commissioning tests (conducted without coal) were satisfactorily completed and the unit was subsequently loaded with 20 tonnes of singles coal (12.5 to 25mm in size) received from a tipper lorry. The vehicle turn-round time was approximately 12 minutes. the coal was then fed (under manual operation) into the tray feeder and screw conveyor at the end of the belt. Sustained operation at high screw speeds (in excess of 125 rpm and corresponding to coal feed rates greater than 14.6 tonne/h) was not possible due to stalling of the screw drive motor. Accordingly, the outlet area of the aperture (feed hopper) above the screw was reduced and the screw drive assembly modified in order to increase the available torque by 12%. By these means, the design throughput of 20 tonne/h was achieved.

A ramp system has been installed in order to ensure that the necessary depth of coal on the belt is achieved during delivery by tipper lorry. the system has a minimum lift of 0.3m, sufficient to accommodate the varying tailgate heights of the lorries.

The unit continued to perform satisfactorily with excellent reliability even on smalls coals with poor handleability. Several cross slats, which loosened during operation, were replaced and attached to the belt in a more secure manner.

The reception end of the unit has also been improved to eliminate any spillage of coal during delivery.

3.2.4.2. Pneumatic Conveyor System

Tests were carried out with three possible pipeline materials, ultrahigh molecular weight polyethylene (UHMWP), steel and reinforced rubber. The coal was washed smalls (0 to 12.5mm). Initial tests employed a single stage fan. This was clearly inadequate and was replaced with a 37kW two-stage version (maximum pressure 3480mm W.G. at 2000m^3/h).

It was found that the reinforced rubber hose would not convey the coal at all and would block almost immediately. Steel pipework would convey the coal at rates up to about 7t/hr but due to the adhesive nature of the coal any slight misalignment of the pipe joints caused a blockage to occur very rapidly. Even if the pipe was aligned correctly, there was a tendency for the coal to adhere to the surface of the steel so reducing the effective diameter of the pipe which in turn produced blockages. The UHMWP pipe was shown to be capable of conveying smalls at rates of up to 17 tonnes/hr. This is due to the very low coefficient of friction between this material and coal. Coal will not stick to the inner surface of the pipe but will slide along. This pipe is currently being evaluated for its long term reliability for conveying smalls grade coal.

Following the successful transport of about 1500 tonnes of coal, some deterioration in performance has been encountered with those coals that are most adherent. The surface of the pipe appears to have lost some of the initial waxy self-lubricating properties. Pipe wear has not been a problem, even on the bends. Longer term evaluation is continuing.

Subsequent development of the pneumatic conveying system (using UHMWP pipe) was directed towards increasing its throughput from 17 tonne/h to 25 tonne/h thus expanding its range of application to include sites having a larger throughput requirement. This has been achieved by use of a more powerful motor (6.2kW) capable of driving the screw conveyor, which feeds coal into the lean-phase pneumatic conveyor, at a proportionately higher rotational speed.

3.2.4.3. Control

As originally installed the high and low level detectors in the screw feed hopper operated by the ultrasonic principle. These proved unsatisfactory due to false echos generated by the sides of the hopper. This difficulty offered the opportunity to investigate other level probes. There was a reluctance to employ rotary paddle probes as the hopper suffers considerable vibration, transmitted from the vibratory tramp screen. Following an assessment of capacitance probes, which showed them to be unsatisfactory in this application due to false readings resulting from adhering coal, radio frequency probes were fitted. These can tolerate a build up of adhering coal on the probe and have proved very satisfactory.

3.2.5. Conclusions

The prototype wide belt vehicle unloader (and its associated lean-phase pneumatic conveyor) has been successfully demonstrated as a fully automatic reception system for both singles (sized 12-25mm) and smalls (sized 0-12.5mm) coals. The unit has been shown to perform reliably even on smalls coals with poor handling characteristics.

During its development, this unit has been demonstrated to a large number of U.K. coal consumers, resulting in several new sales.

4. COAL CONVEYING

Lean phase pneumatic conveying can provide a low cost but effective alternative to dense phase pneumatic or mechanical conveying systems. A lean-phase conveying system developed in conjunction with the wide belt vehicle unloader for U.K. washed singles or smalls coal has already been described (Section 3.2). Further studies of this mode of conveying have been conducted. A conveying system where coal entrainment in an airstream is by means of a suction nozzle, developed previously with ECSC support[1-3], has been upgraded to operate at higher conveying rates. This development is discussed.

4.1 200mm Suction Nozzle Pneumatic Conveyor

The aim of this development was increasing the range of application of this system, as a means of conveying U.K. singles coal grades, to include larger industrial sites. In order to achieve the desired increased conveying rates, a suction nozzle and conveying pipeline diameter of 200mm was selected compared to the previous maximum diameter of 125mm[1-3]. The experimental conveying system and testwork are described.

4.2 Experimental Conveying System

The experimental system (Figure 22) consists of a suction nozzle assembly connected to conveying pipework of 200mm bore and 35m length, incorporating two 90° bends and two 45° bends. Coal is discharged via a cyclone and rotary valve; conveying air is drawn through the conveying pipework by means of a suction fan positioned downstream from the cyclone. The tip of the suction nozzle is vibrated to aid coal flow at the nozzle tip. The test system offers the additional facility for feeding coal directly on to a belt elevator, which incorporates a weigher. In this way continuous operation of the system could be effected. Provision of a calibrated hopper, during the latter stages of the experimental work, to measure directly the quantity of coal entering the nozzle augmented the weighing system. Pressure tappings were installed at 1m intervals to permit a study of pressure drops across the system under different conditions. A damper arrangement adjacent to the fan allowed variation of conveying air velocities.

4.3 Conveying Tests

Tests were conducted at three nominal conveying velocities, 27, 30 and 34 m/s (34 m/s was the maximum velocity attainable with the 30kW fan used). It was known that the coal conveying rate for a particular air velocity depends critically on the extension of the end of the inner nozzle beyond that of the outer (the nozzle extension). For each velocity, coal flow rates were determined for nozzle extensions from 5mm to 45mm in increments of 5mm. Figure 23 shows the coal throughput rate at the three conveying velocities; a maximum coal throughput rate of 56 tonne/h being achieved at 34 m/s using a nozzle extension of 40mm.

Degradation tests with Gedling washed singles coal (12 - 25mm) were carried out at conveying velocities of 27, 30 and 34 m/s. The data (Table 1) shows that the corresponding increase in the <3.35mm size fractions were 1.4, 4.0 and 12%. These results confirmed the importance of using the appropriate conveying velocity, particularly in situations where degraded coal might have an adverse effect on performance in a combustor.

As a result of the degradation tests, methods of improving the conveying rate at the lower velocity of 27 m/s were investigated. Increased vibration of the nozzle system improved the flow of coal around the nozzle circumference enabling a more consistent conveying rate to be achieved. This permitted the conveying rate, at the "optimum" condition of 27 m/s, to be increased to 61 tonne/h with a nozzle extension of 40mm. The corresponding pressure drop profile (measured at intervals of 1m) is shown together with the pipe layout in Figures 24 and 25. The results show that coal particles were accelerated within a zone over the first 4 metres from the nozzle tip. The average pressure loss downstream from this zone was 33mm WG per metre of straight, horizontal bends did not result in a significantly higher pressure drop.

4.4 Conclusion

The feasibility of pneumatically conveying coal in the lean-phase, using a suction nozzle, at rates of up to 61 tonne/h and with minimal degradation has been demonstrated.

5. COAL STORAGE SILO STUDIES

During the past fifteen years there has been an increasing use of silos as a convenient, space saving and environmentally acceptable means of storing coal on UK industrial sites. Problems have occurred with spontaneous combustion and fears have been expressed regarding the possible build up of dangerous gases, in the headspace above the ensiled coal. These matters have been investigated. The stresses imposed upon the walls and floor of a concrete stave silo, whilst coal was extracted by means of a rotating auger have also been measured.

5.1 Spontaneous Combustion

Surface oxidation of coal occurs even under ambient conditions. In an enclosed situation this can lead to selfheating (typically to about 80°C) which may in turn lead to spontaneous combustion. Coal stockpile fires are well known and the usual procedure is to dig out the affected coal and run a heavy roller over the surrounding area to reduce air ingress.

Detection and prevention of overheating in silos is more difficult. In the UK the recommended method of detecting combustion within a silo is to monitor the concentration of CO in the headspace above the coal surface[5]. The current approach to prevention, adopted in the UK, is to well ventilate silos containing singles coal (12.5 to 25mm), as it is assumed this coal is sufficiently porous to enable the diffusing air to carry away any heat generated. This is achieved with ports in both the bottom and the top of the silos. Silos for smalls coal (0 to 12.5-32mm) are in contrast rigorously sealed at the base and walls to exclude any throughflow air: such silos are allowed to breathe through the top alone.

Several incidents of spontaneous combustion have occurred in coal storage silos within the UK during the past few years. In a recent occurrence (1984) washed singles spontaneously ignited in a 200 tonne reinforced concrete silo of circular cross section erected some eighteen years previously; this was the first recorded incident at the site. Further incidents occurred after intervals of twelve and twenty months. The first was controlled by emptying the silo and spreading the coal on the ground to allow it to cool.

Following this fire, a continuously operating carbon monoxide monitor was installed in the headspace (this monitor had not been fitted previously) and this was successfully interpreted to give warning of the second fire. Figure 26 shows the rapid rise recorded in carbon monoxide from a typical value of 40-50 ppm to over 2000ppm in just four days. Attempts were made to control the combustion by injecting small quantities of inert gases, approximately $20m^3$ of carbon dioxide and $10m^3$ of nitrogen (compared to the volume of the silo $250m^3$). With hindsight, these quantities were clearly insufficient and combustion within the silo continued. Efforts to seal the silo did, however, provide sufficient control to enable the remaining contents to be fed to the boiler plant without major incident. Despite investigation, no clear cause could be identified. These occurrences of spontaneous combustion highlighted the need for an investigation into the factors involved.

5.1.1 Studies with the silos at CRE

5.1.1.1 Carbon Monoxide monitoring

Daily monitoring of the CO levels in the headspace of both the concrete stave and glassed steel silo was initiated midway through 1984. During February 1984 the concrete stave silo had been filled with approximately 200 tonnes of Lindby washed smalls coal and this coal remained undisturbed until the end of the year. In contrast the steel silo had been in regular use throughout the year and contained varying quantities of Lindby washed singles coal.

In both silos the proportion of CO detected above the coal varied with time (Figure 27), the concentration above the smalls (0 to 12.5 - 32mm) coal reaching a maximum of 400ppm whilst that above the singles (12.5 to 25mm) did not exceed 50ppm. Therefore, whilst the record of CO above the singles showed no evidence of any occurrence of spontaneous combustion the initial increase from 50 to 290ppm above the smalls coal during the period 1st - 22nd August (Figure 27) did give cause for concern.

5.1.1.2 Temperature measurement

As a result of these concerns, thermocouples were buried at depths of approximately 1m and 2m beneath the smalls coal surface and temperatures recorded at daily intervals (Figure 28). These temperatures confirmed that spontaneous heating was occurring within the silo, with an initial temperature of 80°C being measured at a depth of 2m beneath the coal surface. However, the temperature within the coal then progressively decreased to about 58°C during the five month test period. This broadly corresponded to that for the ambient temperature over the same period as the exceptionally hot summer of 1984 passed into autumn and winter.

Additionally, temperatures were measured at depths of down to about 4m beneath the coal surface (total depth of ensiled coal being approximately 9m) on the 19th October and 5th December. The temperatures increased slightly with depth (from 70°C and 60°C in October and December) over the uppermost 0.5m before reaching equilibrium values (80-85°C and 65° in October and December). The temperatures in December were generally some 20°C lower than those in October and followed the trend of daily temperatures (Figure 28). The temperature of 80-88°C is very characteristic of freshly stored coal undergoing initial drying and surface oxidation. Site conditions can then either lead to spontaneous combustion or a slow fall in temperature to ambient.

5.1.1.3 Concentrations of Gases Within the Silo

The presence of gases other than CO (CO_2, CH_4, C_2H_6, C_3H_8,nC_4H_{10} and $i\text{-}C_4H_{10}$) were monitored following the discovery of elevated temperatures within the silo and the maximum concentrations detected are given in

Table 2 together with the maximum concentration of CO. For these gases, the respective concentrations (in air) below which they will not propagate a flame (lower explosion limit)[6] is shown together with the recommended occupational exposure limits[7]. The concentrations of all the potentially explosive gases are at least an order of magnitude below those for the lower explosion limit. Accordingly, the principal hazard is to health (arising from the high concentrations of CO and CO_2) should a person enter the silo without breathing apparatus.

The concentration of CO, 0_2, CO_2, CH_4 and C_2H_6 was investigated at depths of up to 4m on the 19th October and 5th December and the results are summarised in Table 3. With the exception of 0_2 the concentrations of these gases are considerably higher within the coal bed compared to the headspace. In particular, the maximum concentration of CO within the coal bed (5.5%) was much higher than was detected in the headspace (0.4%).

5.1.1.4 Injection of Nitrogen into the Concrete Stave Silo

An attempt was made to control the spontaneous heating within the silo during late August and early September by injecting nitrogen into the silo. The nitrogen was injected through a pair of 75mm ports in the silo base and the concentrations of 0_2 and CO monitored above the coal surface (Figure 29). Initially, nitrogen was fed for short periods (1-2 hour durations on 23, 25 and 28 August) and at relatively high flow rates (180 m^3/h compared to the silo volume of 350m^3). There was an associated rapid drop in oxygen concentration above the surface (from 21.5% to between 5% and 11%) and a subsequent increase when the nitrogen was turned off (the oxygen concentration reached 18% after a further three hours). These short periods of injection did not appear to affect the measured CO concentration. In contrast, when nitrogen was injected over a prolonged period (65 hours duration between 3rd and 6th September) and at lower rates (30 - 60 m^3/h) the CO concentration in the headspace fell almost to zero. When the nitrogen was turned off, the CO concentration rapidly rose to 230 ppm during one day. Furthermore, injection of nitrogen at low flow rates had a generally small and non-systematic effect on oxygen concentration.

5.1.1.5 Removal of Coal

The smalls coal was removed from the silo during January 1985, after twelve months storage. The temperature of the coal mass was measured to be 30-34°C after removal by the dense-phase pneumatic conveyor, compared to ambient temperatures of 0°± 3°C during and before emptying. The chemical analysis of the coal, after twelve months storage, is compared with that of the fresh coal in Table 4. These data show that the stored coal had similar calorific values and volatile matter contents compared to the fresh coal but that the proportion of fixed carbon was slightly higher (50-57%) relative to that for the fresh coal (46%). The moisture content of the stored coal ranged from 6% to 16% compared with 16% for the fresh coal.

5.1.1.6 Discussion of CRE silo monitoring exercise

Although the elevated temperatures measured in the silo confirmed the initial warning, given by CO measurements, that spontaneous heating was occurring within the silo during August, conditions within the silo were such that this did not proceed to a fire. This was probably because air leakage rates were sufficiently low for the partial pressure of oxygen within the body of the coal to be significantly reduced, relative to free air (Table 3). The rate of oxidation of coal is clearly related to oxygen partial pressure and within a well sealed silo remains below the level at which spontaneous heating can progress to a fire. The effect of the nitrogen injection is discussed below.

The variations in CO concentration above the surface of the smalls coal (Figure 27) were attributed to changes in atmospheric pressure, temperature and, possibly, wind speed and direction. A reduction in atmospheric pressure may cause gases to be drawn out of the coal bed into the headspace. If it is assumed that gas with a CO concentration of 2.5% is drawn from the bed and mixed instantly with the headspace gases it is estimated that a 4% fall in atmospheric pressure could increase the level of CO concentration by up to 100 ppm. In order to account for the reductions in headspace CO levels it was suggested that there is air leakage (dependent on the wind velocity) into the headspace. This feature would be consistent with the limited success achieved in reducing the oxygen concentration above the coal by the lower rates of nitrogen injection (30 or 60 m^3/h).

The postulation regarding wind speed was generally supported using wind speed data recorded by the UK Meteorological Office at its nearest monitoring station (about 50 miles from CRE) during the relevant time. The daily mean wind speed is compared with the silo headspace CO concentration in Figure 27. This shows that wind speed varies considerably on a daily basis (ranging from 1 to 7.7 m/s during a two-day period in October). Dotted lines have been plotted, in Figure 27, to link wind speed to CO concentration for the twenty-five occasions when a rapid decrease in CO concentration occurred (apart from the time when nitrogen was injected into the silo). Examination of wind speed corresponding to these link-lines shows that, with the exception of two instances (corresponding to occasions 2 and 3), rapid decreases in CO concentration occurred during periods of increasing or high wind speed. These results, whilst not offering conclusive proof, do generally confirm that air leakage dependent on wind speed was an important factor in the rapid changes in headspace CO concentration. Air leakage was considered to occur through the 100mm^3 air vent and the pneumatic conveying air filter (Section 2.2.2).

The study has indicated an inherent difficulty in the use of CO monitoring above the coal surface for detecting the onset of spontaneous combustion.

Although injection of nitrogen appears a promising method of controlling spontaneous combustion there was evidence that use of only two injection ports led to channelling within the coal bed. Even though the CO concentration in the headspace was reduced almost to zero, after prolonged nitrogen injection, it quickly recovered (to 230ppm) when the nitrogen was turned off. This implies channelling of the nitrogen, bypassing a large proportion of the ensiled coal and leaving the gases occupying the voids in the coal unchanged. Therefore, further studies are needed, particularly with respect to ensuring the uniformity of flow distribution within the coal mass. Continued nitrogen injection is however likely to lower oxygen partial pressure and thus control heating.

5.1.2 Build-up of Gases in Silo Headspace

5.1.2.1. Carbon Monoxide and Methane Monitoring

Following the study of gas concentrations in the silos at CRE and reports that high levels of methane had been experienced in particular silos at industrial boiler sites (reaching one-third of the lower explosion limit) methane and carbon monoxide concentrations in four such silos have been monitored. The four sites collectively burn washed singles and washed smalls and an opencast smalls.

Gas sampling and analysis equipment (Figure 30) which records carbon monoxide concentrations and displays methane levels (with alarm facilities) was installed at each of the four sites. Data collected from this equipment during the period July - December 1986 showed that the proportion of CO detected above the coal in each of the silos varied with time. The CO concentration above the singles coal remained below 11 ppm whilst that above the opencast and washed smalls coals did not exceed 34 ppm. No trend of increasing carbon monoxide was detected and this indicated an absence of spontaneous combustion in any of the four silos. The concentration of methane measured in the headspace of silos storing "smalls" coal also showed transient variation but the maximum concentration remained below 1/8 of the lower explosion limit[6]. The transient behaviour of both carbon monoxide and methane concentrations shows general agreement with the studies carried out at CRE.

5.1.2.2. Development of mathematical models

In support of the survey, mathematical models of methane evolution and dissipation in silos have been developed to give an improved theoretical understanding of these processes and to provide predictive data.

As part of the background information for these models, tests were carried out on the concrete stave silo at CRE, when empty, to determine the rate of natural ventilation. The silo was first purged with nitrogen until the oxygen content was reduced from 21% to 10.7%. The nitrogen flow was then stopped and the rate of oxygen recovery recorded. Results (Figure 31) indicate that the rate of air change in the silo is 23.5 m^3/h, equivalent to one air change per 15 hours. The first model, based on previous work by Airey[8], assesses the build up of methane in the silo headspace and takes account of the effect of ventilation on methane concentration. Figure 32 gives results of a simulation for a 650 m^3 capacity silo containing 280 tonnes of coal (30% capacity) with different ventilation rates. The model tacitly assumes that the coal is introduced as a single batch. More realistically, coal is delivered in 20 tonne increments, together with some conveying air if the coal is fed pneumatically. A second model has been developed to simulate the latter situation. Results (Figure 33) show the methane level decreasing to zero as each 20 tonne batch of coal is pneumatically delivered but increasing when deliveries cease.

5.1.3 Conclusions

Although spontaneous combustion can occur within coal storage silos under certain conditions it can be controlled when the silo has been correctly designed, constructed and operated (for smalls coal reasonably sealed to prevent air leakage), even when coal is stored for long periods.

Whilst the monitoring of carbon monoxide remains the recommended method for predicting the onset of spontaneous combustion, these studies have demonstrated potential limitations. Transient variations in daily CO concentration have been explained in terms of changes in atmospheric temperature, pressure and windspeed. A significant degree of spontaneous combustion can, however, be expected to produce a several-fold increase in CO level.

Significant concentrations of methane have been detected in some silo headspaces. Whilst these have been well below the lower explosion limit there remains a cause for concern.

Further studies into the prevention and detection of spontaneous combustion within coal storage silos and methods of preventing high concentrations of methane will be carried out in the forthcoming ECSC contract 7220 EA/822.

5.2 Investigation of Stresses and Coal Flow Within a Silo

In silo design it is necessary to allow for both the static and the dynamic pressures, which the ensiled material applies to the walls and floor during filling and emptying respectively. Theoretical models (supported by experimental testwork)[4,9,10,11] have been established for predicting these pressures in both flat and hopper bottomed silos, discharging to a point nominally central to the base as, for example, employed on the glassed steel silo at CRE. Use of a rotating auger to extract coal from flat-based silos, as used on the concrete stave silo at CRE is, however, a relatively novel technique. Therefore, a study has been conducted into the effect of this method of extraction on wall and floor pressures to confirm the adequacy of existing design formulae to this approach. Since coal flow is another important aspect of silo operation, this was also investigated during coal extraction by the rotating auger.

The discovery of cracked staves within the walls of several UK coal storage silos, of a similar stave construction type (but not including the unit at CRE), has added to the importance of this study. The cracks, which are horizontal, are generally confined to a radial band up to 2m wide extending upwards from the silo floor and appears to be a feature common only to silos using a rotating auger method of coal discharge.

Before embarking on these studies extensive discussions were held with others in this field, notably Rotter of Sydney University, Australia (during a visit to the U.K.), Walker (formerly with the CEGB) and British Coal Civil Engineering Branch. These concerned the most appropriate method of measuring pressures within silos and all warned of the difficulties of obtaining consistent and meaningful pressure measurements for large silos. Pressure pads were, however, installed successfully at the Grange coke ovens in 1961[12] and this method was adopted for this study.

5.2.1 Relevant properties of the coal

The first part of the study was to determine the relevant properties of the Bolsover washed smalls (0 - 25mm) coal to be stored in the concrete stave silo (bulk density, angle of internal friction of the coal and angle of wall friction between the coal and concrete staves). This information was required to enable pressures inside the silo to be predicted using the various models. The bulk density of the coal was 794 kg/m^3. The angles of internal and wall friction were measured using an annular shear cell and necessitated the cutting of an annulus from one of the staves. The tests were carried out at a moisture content of 9.5%, with normal loads on the materials ranging from 2.7 to 14.7 kPa. The angle of wall friction was measured both on the bare concrete surface of the stave and when it was coated with the bitumen, which is applied as a sealant to the inside of this type of silo. The angle of internal friction was 37.4° and the angles of wall friction between the coal and both coated and uncoated stave was 15.5° and 24.4° respectively. During the measurement of the angle of wall friction for the coated stave, coal adhered to the stave surface and consequently gave a result equal to the angle of internal friction of the coal. Furthermore, the bitumen coating became destroyed at the maximum load of 12.1 kPa.

5.2.2. Pressure Pad and Instrumentation.

Because no suitable pressure pad was commercially available and the design of pads used in silos at the Grange coke ovens was no longer available, a pressure pad was developed, specifically for these tests.

Whilst developing the pressure pad careful consideration was given to the diameter and thickness of the pressure sensing membrane. The membrane needed to be large enough not to be affected by individual coal particles (whose maximum size could be up to 25mm), strong enough to withstand the maximum pressures expected within the silo (up to about 60 kPa Walker[4] and DIN[9] 1055) and sensitive enough to provide a reasonable deformation at these pressures. These constraints resulted in a pressure pad (Figure 34) having a membrane with a diameter of 203mm (eight times the maximum particle size) and thickness of 2.5mm being selected. The expected deformation of the membrane, together with both radial and tangential stress distributions, calculated from standard equations[13] and based on the maximum pressures likely in the silo (60 kPa), are reproduced in Figure 35. This figure shows that the deflection at the centre of the membrane (0.33mm) is within that recommended for linearity (up to half the membrane thickness)[13]. Also, the maximum stresses predicted (74 MPa), which occur around the circumference of the membrane, are within the recommended safe value of stress 75 MPa)[13].

Pressures exerted on the pad are measured by four strain gauges bonded to the back of the membrane. Positioning of these gauges was found to be critical. The stress distributions given in Figure 35, which gave a similar form for any pressure, show that negative stresses are produced around the edges of the membrane whilst those in the middle are positive, with null points between them. The four strain gauges were arranged to measure radial stress and positioned as near as possible to the centre of the membrane in order to avoid the band of zero stresses. These gauges, each having nominal resistances of 350 ohm, were bonded firmly to the back of the membrane, to ensure good transmission of strain to the gauge. In addition, four identical gauges were positioned around the circumference, to provide temperature compensation. Because these gauges would be subject solely to thermal strains, they were not bonded to the membrane but to small mild steel plates secured loosely to the membrane. All the strain gauges were connected together to form a bridge circuit (Figure 34). Stresses generated within the membrane, by pressure applied to it, are measured by the out of balance voltage generated across the bridge. Calibration of the pressure pads was carried out by evacuating the space between the membrane and airtight backing plate (Figure 34) to different pressures. A typical calibration chart is reproduced for a wall mounted pressure pad, which was expected to see a maximum pressure of 22 kPa, in Figure 36.

Sixteen of these pads were manufactured for installation. Each pad was cadmium plated to prevent corrosion by acidic or alkaline water in the silo associated with the coal. Twelve were incorporated into hardwood (Iroco) staves which were used to replace existing concrete ones at designated positions in the silo wall (Figure 37). Three pads were set into the concrete floor of the silo flush with its surface. The remaining pad was mounted on the upper face of the transmission tunnel just above the coal extraction auger (Figure 37).

The location of the radial rotating arm of the auger was identified (to within an octant) at any instant by means of a signal generated between a metal plate (attached to the underside of the auger gearbox housing) and eight inductive proximity detectors, positioned on the silo floor beneath the path of this plate.

A mechanical system was installed to measure the level of coal in the silo. A detector was automatically lowered on a wire from the top of the silo sensing contact with the coal; the length of wire fed indicating coal height.

5.2.3. Procedure

Each of the pressure pads was calibrated after installation and immediately before the test programme. The silo was loaded with 234 tonnes of Bolsover washed smalls coal (Table 5) and the charge allowed to stabilise for ten days. In order to assess the coal flow pattern within the silo, labelled, hollow, plastic spheres (12mm diameter) were placed at a depth of 150mm below the levelled coal surface and in two mutually perpendicular horizontal rows (Figure 38). Coal flow was initiated by discharging four 12 tonne increments from the silo, each increment being returned to the silo in order to maintain an approximately constant head of coal. This procedure was repeated for three different charges of coal in the silo (250, 150 and 100 tonnes). The plastic balls were recovered as they emerged.

Stress measurements and proximity detector signals were recorded by a Solatron A data logger. The data were subsequently fed to a microcomputer for recording on magnetic disc and as a printed copy. The information was logged at intervals of one minute (when the silo was being filled or emptied).

At the completion of the test programme each of the pressure pads was recalibrated.

5.2.4. Coal Flow

Analysis of the flow tracer recovery record (Figure 38) shows that about 50% of the spheres were individually detected at the silo outlet during the period over which the silo was emptied. Complete recovery of spheres was not anticipated, as coal was necessarily discharged at intervals and at relatively high mass flow rates; spheres hidden within these batches of coal would not necessarily be readily visible. Those spheres which were detected were recovered after different 'transit times', corresponding to the different total quantities of discharged coal. There was no discernible relationship between the initial location of a sphere and its 'transit time' (Figure 38). These features suggest that the coal flow in the silo is non-uniform. This is in marked contrast to the mass flow discharge anticipated for this silo, prior to this experimental work. Supporting evidence for coal 'hold up' was sought during an examination of the silo interior after discharge. A 1m high pillar of static, compacted coal had formed above the transmission tunnel (Figure 39) and it was concluded that the presence of this coal during the test period could have promoted velocity gradients within the coal mass flowing through the silo.

5.2.5. Coal Extracted per Sweep of Rotating Auger

As part of these studies, the quantity of coal removed by the screw auger as it sweeps across the silo floor has been investigated. These results, expressed as the quantity of coal removed during a complete radial sweep of the screw are shown in Figure 40, together with the remaining contents of the silo. During the first six discharges, after the silo was originally filled with 234 tonnes of coal, the quantities removed by the auger were extremely variable ranging between 5.5 and 22 tonnes per sweep. The rate of discharge per sweep then became reasonably constant at a level of approximately 8 tonnes per sweep until the level of coal in the silo had decreased to 190 tonnes; thereafter, the rate of discharge increased and exceeded 25 tonnes per sweep when the contents of the silo had reduced to 67 tonne.

The axial rotation and radial sweep of the auger is dependent upon a motor driven, planetary differential gear box: the axial rotation of the auger within the coal aids its radial motion. The rate at which the auger progresses will, therefore, depend on the consolidation pressure within the coal and its flow properties (i.e. angle of internal friction, density and size distribution) in the vicinity of the auger. These factors will be further explored and an explanation sought for the increased quantity of coal extracted per sweep, as the silo contents decrease, under the forthcoming ECSC contract "Industrial Coal Silos: Outstanding Problems" (ECSC Contract 7220 EA/822) due to commence in July 1987.

5.2.6 Pressures

Stress measurements relating to the initial filling (static pressures) of the silo and subsequent settlement period are shown in Figures 41 and 42. As expected, increases in horizontal (wall) and vertical (floor) pressures correspond to increases in the quantity of coal present (Figure 41). Fluctuations in pressure during settlement were also evident, although there was no discernible trend with increasing settlement time. Figure 42 shows the measured distribution of horizontal (static) pressure with coal height above the silo floor. Comparison of these results with those predicted according to theories (developed by Walker[4], Janssen[10] and Reimbart[11] and also a method given in the German DIN 1055[9] code) shows that measured (static) pressures exceed the predictions, particularly in the vicinity of the silo base.

Only two of the pressure pads located on the silo base (A and B in Figure 37) produced pressure measurements during filling, the remaining pad and one mounted on the transmission tunnel having ceased functioning during filling (due to damage as coal was discharged directly on to them). Pads A and B ceased functioning when coal was discharged from the silo and this prevented their calibration being checked at the end of the tests. However, since there was no evidence that these two pads behaved abnormally during filling, measurements are presented (also shown in Figure 42). These floor pressures showed reasonable agreement with predictions made from the theories of Walker, Janssen and Reimbart but were much higher than for the DIN 1055 code.

Dynamic stress distributions measured by pressure pads positioned at different heights along a vertical line on the south facing silo wall during coal discharge are shown in Figure 43 with the relative position of the rotating extraction auger, when the silo contents were nominally 230, 200, 150 and 100 tonne. As expected, the stresses were generally greater towards the silo base and when it contained the largest quantity of coal (up to 46 kPa at 1.9m above the floor when the contents were 230 tonnes). An exception to this trend was that stresses measured by the lowest pad (0.4m above the base) were usually somewhat lower (up to 40 kPa) than the pad above (1.9m above the base); this may be due to the presence of the transmission beam in this region of the silo. The most noticeable feature of the pressure distributions is its previously unreported cyclic behaviour. Most of the fluctuations in wall stress measured by the two lower pads, can be explained by relating the position of the auger, as it progresses around the silo floor to the position of the pads. Stresses measured by these lower pads decrease to a minimum as the auger passes beneath and then increase reaching a maximum as it approaches to within approximately a quadrant of the pad. Whilst stresses measured by the intermediate pad (3.4m above the floor) also follow this pattern when the silo contained 230 tonnes, a different pattern emerged when the silo contents were reduced to 200 and 150 tonnes. The fluctuations in stress remained cyclic with the same period as the rotating auger but in contrast were out of phase with the stresses produced by the lower pads. The stress generally increased to a maximum as the auger passed beneath the pad decreasing to a minimum when it reaches the opposite side of the silo.

Stresses measured by the uppermost pad (4.9m above the silo base) fluctuated between 0 and 18 kPa when the contents of the silo were 230 tonne but do not exhibit clear periodicity. When the contents of the silo were reduced to 200 tonnes the pressure measured by this pad generally reduced to zero with occasional pressures (up to 5 kPa) being registered.

Vertical stresses measured by the two functional pads A and B (Figure 37) attached to the silo floor increased from a value of approximately 80 kPa, measured after the silo was initially charged, to 140 kPa after which they appeared to malfunction. Before this occurred the stresses measured exhibited similar cyclic behaviour, associated with auger rotation, as that discussed for wall stresses decreasing to a minimum as the auger passed directly overhead and increasing to a maximum as it approached again. If the levels of dynamic stress measured (140 kPa) are correct they exceeded predicted values (51 kPa and 35 kPa for Walker and DIN 1055 respectively) and also the maximum stress upon which design of the pad was based (Section 4.1.2.), this is considered to have caused their failure. These values are almost twice the simple hydraulic pressures (Figure 42) and must result from local stress concentrations presumably due to arching.

Comparison of the maximum dynamic (flow) stresses on the silo wall (46 kPa) with predicted values (14 kPa and 26 kPa Walker and DIN 1055 respectively) (Figure 44) shows that in common with recorded floor pressures, mentioned above, predicted stresses are exceeded. Since theoretical models (DIN 1055 and Walker) relate vertical and horizontal stresses it is, perhaps, not surprising that if high wall pressures are experienced then high floor pressures can also be expected.

5.2.7. Conclusion

The excessive pressures, together with the cyclic behaviour of wall stresses and the existence of cracked staves within similar silos indicates the need for more extensive studies of pressures within this type of silo, particularly where coal extraction is by means of a rotating auger. These factors will be further explored and explanations sought under the forthcoming ECSC contract "Industrial Coal Silos: Outstanding Problems" (ECSC Contract 7220 EA/822) due to commence in July 1987.

6. ASH REMOVAL

Studies of ash removal have concentrated on wet systems where water is used as a quenching medium. In one application the water is also used to hydraulically transport the ash to a disposal point; the other uses a partially submerged belt conveyor.

6.1 Hydraulic Conveying of Ash

Hydraulic conveying of ash from a combustor to a remote disposal point, (e.g. skip or silo) should offer the physical flexibility of pneumatic conveying with the advantage of robustness to live fire (which may be produced by a combustion plant malfunction), reduced erosion and a simple seal against flue gases.

Initial studies of hydraulic ash sluicing were carried out with a full scale test rig installed in a 0.2MW fluidised bed test boiler at CRE. This handled oversize ash, extracted from the bed, by an air classifier. In this application hydraulic sluicing was considered particularly suitable because of its ability to provide an air seal against a relatively high gas pressure. These studies together with the subsequent installation and initial testing of a hydraulic sluicing system on a 9MW fluidised bed furnace are discussed in the following sections.

6.1.1 Hydraulic Ash Sluice Test Rig.

6.1.1.1. Description of Test Rig

The test unit (Figure 45) was designed to transport up to 3% V/V of ash in water at a water flow rate of 3.5m^3/h yielding a flow velocity of 2 m/s through 75mm bore pipe.

Two ash pick up points were provided in the form of 75mm pipe connected to the conveying line by swept tees (to minimise pressure losses). One of the pick-up points was under the fluidised bed and connected to receive oversize ash extracted by the air classifier and the other downstream of this so that ash could be manually added to ascertain the maximum ash loading and particle size that could be tolerated. The height of water in the vertical legs of the ash collection points was maintained by the constant level water tank. The slurry was drawn through the system by a centrifugal slurry pump and discharged into a 6 m^3 skip. The water was returned from the skip through a filter by another centrifugal pump and hence to the header tank. The flow of water into this tank was controlled by a floating ball-cock. The return pump was sized such that the ball-cock always remained partly open. During operation, any water loss due to evaporation or leakage was made up from a mains supply. To perform tests at a range of water velocities, the slurry pump had a variable speed drive.

6.1.1.2 Results of Testwork

Initial test work was aimed at establishing a controllable circulation of water around the system. Whilst conveying velocities of up to 3.5 m/s could be achieved, there was surging of the water level in the header tank. The problem was overcome by installing high/low level switches in the header tank in order to permit automatic (intermittent) operation of the return pump. These modifications facilitated operation at a range of water flow rates with an approximately constant level in the header tank.

Minimum conveying velocities for batches of four graded sizes of ash (-13.6mm + 9.5mm, -9.5mm + 6.7mm, -6.7mm + 4.4mm, -4.4 + 2.2mm) were determined by introducing them into the conveying line through the ash addition port. The batch transit time between the removal port and the ash collection skip was recorded for different water flow rates. From the determined relationship between the average particle velocity and the water velocity (Figure 46), it was evident that the particle velocity tended not to be affected by ash size above a water velocity of about 1.6 m/s; at a water velocity of less than 1.0 m/s it was not possible to convey the ash. Within these limits, the finer ash could be conveyed at a higher rate. The nominal design velocity of 2 m/s was thus confirmed as suitable for commercial practice.

It was found that, at water velocities of 1.6 m/s and above, there was a substantial risk of air ingress through the ash addition port. This was attributed to the high pressure losses as the return water was accelerated out of the header tank. The problem was overcome by relocating the return line into the header tank such that the nozzle of the return line was co-axial with the header tank outlet port. With the modified system a distance of 150mm between outlet and inlet port was sufficient to maintain a steady flow of water with minimum acceleration. By this means water seals at about 200mm W.G. could be achieved.

Subsequently the performance of the ash sluice rig was assessed using hot ash received from the operating fluidised bed unit. Thirty Kilograms of oversize ash (6mm - 25mm size range) was added to the bed and subsequently discharged into the sluice via an air classifier. At a flow velocity of 1.8 m/s, up to 1.5 kg/minute of ash could be readily transported. The conveying rate was limited by the maximum rate of ash removal from the bed and not by the conveying capacity of the sluice.

6.1.1.3 Hydraulic Sluicing - 9MW Furnace

Following the successful completion of investigations with the test rig a field trial site, consisting of a 9MW fluidised bed fired hot gas furnace, was identified. The furnace burns up to 1.2 tonne/h of untreated smalls coal, having a maximum size of 32mm, in a shallow fluidised bed (150mm deep and with a bed surface area of 9.84 m^2). The system installed on this site, shown schematically in Figure 47, consists of four 100mm diameter air classifier tubes, arranged beneath the bed, each connecting into a common 100mm diameter hydraulic ash sluice pipe which passes beneath the furnace. Air, introduced into the classifier tubes, passes upwards, entraining fine material and carrying it back to the bed, whilst allowing large material to escape and fall into the sluice; water in the sluice pipe ensuring an air seal preventing any escape of classifying air. A pump, capable of accepting large particles (up to 40mm) of ash, continuously circulates water in the sluice, transporting any ash extracted from the bed to a vibrating screen, where the ash is separated from the water. The ash is deposited in a skip for disposal whilst the water is returned via 150mm bore pipeline to a constant level tank, supplying the system. The de-watering screen and ash collection skip are located some 30m from the furnace and this required the dewatering screen to be elevated 3.5m above floor level to overcome pressure losses in the 150mm bore return pipeline.

Site requirements for the use of the furnace have unfortunately restricted commissioning to cold operation. Bed ash (up to 40mm particle size) introduced into the sluice pipe via the four air classifier drop tubes, was successfully conveyed through the slurry pump and along the 30m of 100mm diameter pipework to the vibrating separator and ash collection hopper. The ash particles were conveyed along the pipeline at velocities ranging from 0.5 to 1.0 m/s when the water velocity was 1.8 m/s. Whilst these tests were being conducted the level of water in the constant level tank was 1.09m above the sluice pipe. This enabled water levels in the air classifier tubes to be maintained at levels ranging from 0.88m to 0.75m above the sluice pipe for the tubes nearest to the tank and pump respectively. These water levels were measured in the absence of a fluidised bed. It is predicted that when the fluidised bed was in operation the water levels in the classifier tubes would be reduced by approximately 0.3m as a result of the pressure differential across the fluidised bed (0.15m static depth). Therefore, the classifier tubes would contain a maximum of 0.45m of water and provide an air seal ensuring that classifier air was directed into the fluidised bed.

Negotiations are being held with the furnace owners for it to be recommissioned so that hot trials can commence.

6.1.2 Wet Ash Removal System Employing a Rubber Belt

The modular boiler house is becoming popular in the UK and is frequently fitted with stoker/boiler plant which allows ash to fall from the end of the stoker via a circular exit (drop tube). The simplest design of ash collector is a sealed bin, located beneath the drop tube; the bin being removed periodically. This requires regular manual involvement, typically at 4 to 8 hour intervals at high fire. Alternatively, ash can be crushed and removed by a pneumatic handling system (lean or dense phase) or sluiced by flowing water. Another approach is to discharge the ash into a water bath containing a mechanical or rubber belt conveyor. Traditionally, wet systems of this type have been massively built and of high capital cost and, as such, inappropriate for the modular boiler house. Furthermore, pneumatic systems are economically attractive only in cases where a central air/ash separation and ash storage system serves a number of boilers.

A low cost submerged rubber belt system (Figure 48) was designed and constructed by Vibraflo Ltd. and installed on a 1.2MW boiler in a modular boilerhouse which was under test at CRE. The boiler drop-tube extends below the water surface in a water quench tank, thereby ensuring that the boiler fire tube is sealed to atmosphere. The ash is retained on the smooth belt by means of side guides and the belt speed is suitably low to ensure adequate drainage of the ash before it is discharged. The returning belt is scraped twice to remove the ash. The steelwork is galvanised and the operation of the belt is automatically linked with the stoker drive motor. The quench bath has a large clean-out door to facilitate removal of accumulated ash fines should this be necessary.

The system has undergone long term evaluation trials, operating successfully during a nine-month period. The system has provided a clean and reliable method of ash removal. The careful attention to detail has proved effective and there has been no maintenance requirement, even to remove accumulated fines from the water. The unit together with the modular boilerhouse is to be moved to a customer site. A second unit has been placed on order.

7. REFERENCES

1. ECSC Project No. 6220-EC/8/803, Final Report (September, 1977) EUR.6074 EN.
2. ECSC Project No. 7220-EC/815, Final Report (November, 1980) EUR.7411 EN.
3. ECSC Project No. 7220-EC/821, Final Report (November, 1983) EUR.9396.
4. An approximate theory for pressure and pulsing in hoppers, D.M. Walker, Chem. Eng. Science 21 (1966)
5. Silos for coal storage, British Coal Technical Report, TD.121.
6. Detection and Measurement of Hazardous Gases, Ed. C.F. Cullis and J.G. Firth, Heinemann.
7. Occupational Exposure Limits 1984, Guidance Note EH 40, U.K. Health and Safety Executive.
8. NCB Mining Research Establishment internal report No. 2304, Gas Emissions from broken coal - an experimental and theoretical investigation, E.M. Airey, February 1967.
9. DIN 1055, Design Loads for Buildings, Part 6, Loads in Silo Bins; German Standard, 1964/1977,
10. Janssen, H.A., "Tests on Grain Pressure Silos", Zeitschrift des Veraines deutscher Ingeniere, Band 39, No. 35, 1895.
11. ACI standard 313-77, "Recommended Practice for Design and Construction of Concrete Bins, Silos and Bunkers for Storing Granular Materials" and Commentary. American Concrete Institute, March 1977.
12. Successful failure - stepping lock for a leap forward, H. Wright and W. Thorpe, IPC Business Press Ltd. 1981.
13. Strain Gauges kinds and uses, H.K.P. Neubert, Macmillan.

TABLE 1

Degradation tests performed on Gedling singles using the 200 mm suction nozzle at transport velocities of 27, 30 and 34 m/s

Screen Size (mm)	Percentage retained on Screen			
	Gedling singles	Gedling conveyed at 27 m/s	Gedling conveyed at 30 m/s	Gedling conveyed at 34 m/s
+ 26.5	0.0	0.0	0.0	0.0
+ 19.0	34.6	30.1	24.3	22.5
+ 13.2	50.2	51.0	49.0	41.1
+ 6.7	13.1	14.4	18.1	17.9
+ 3.35	0.2	1.2	2.7	4.4
+ 2.0	0.1	0.5	1.1	2.7
+ 1.0	0.1	0.5	1.1	2.9
+ 0.5	0.4	0.5	1.0	2.8
- 0.5	1.3	1.8	2.7	5.7
% increase in <3.35 mm size	0	1.4	4.0	12.2

TABLE 2

Maximum concentration of gases detected in the headspace above the smalls coal in the stave silo together with their recommended occupational exposure and explosion limits.

Gas	Maximum concentration above the coal ppm	Lower explosion gas concentration limits %	Recommended occupational exposure limited (expressed as time weighted averaged)	
			Long term (8 hours) ppm	Short term (10 minutes) ppm
CO Carbon monoxide	400	12.5	50	400
CO_2 Carbon dioxide	13,500	-	5,000	15,000
CH_4 Methane	164	5.3	Asphyxiant - no specific toxicity	
C_2H_6 Ethane	54	3.0	" " " "	
C_3H_8 Propane	520	2.2	" " " "	
n C_4H_{10} n Butane	50	1.8	600	750
i C_4H_{10} iso-Methyl Propane	310	1.9	Asphyxiant - no specific toxicity	

TABLE : 3

Concentration of gases detected at depths up to 4m beneath the surface of the smalls coal stored in the stave silo at CRE.

Gas	Concentration
O_2	1.6 - 14 percent
CO	1600-5300 ppm
CO_2	3.1-5.4 percent
CH_4	95-635 ppm
C_2H_6	30-150 ppm
$n\text{-}C_4H_{10}$	15-45 ppm
iC_4H_{10}	15-38 ppm

TABLE : 4

Chemical analysis of Lindby washed smalls coal removed from the 250 tonne concrete stave silo at CRE and a typical analysis for the fresh coal.

		Typical fresh coal	Coal after 12-month storage in the silo
Total moisture content	% a.r.	16	6-16
Volatile matter	% a.r.	30	30-34
Fixed carbon	% a.r.	46	50-57
Calorific value	kJ/kg d.b.	30000	2900-33000

TABLE : 5

Chemical analysis and particle size analysis of Bolsover washed smalls coal used during investigation of pressures on concrete stave silo.

SIZE ANALYSIS

mm	%
+ 26.5	1.3
+ 19.0	3.8
+ 13.2	10.3
+ 6.7	23.7
+ 3.35	22.9
+ 2.0	12.9
+ 1.0	13.5
+ 0.5	6.9
- 0.5	4.7

ANALYSIS

Total Moisture (as received) %	9.1
Free Moisture (as received) %	6.1
Inherent Moisture (as received)%	3.2
Ash (dry basis) %	8.1
Fixed Carbon (dry basis) %	58.6
Volatile Matter (dry basis) %	33.3

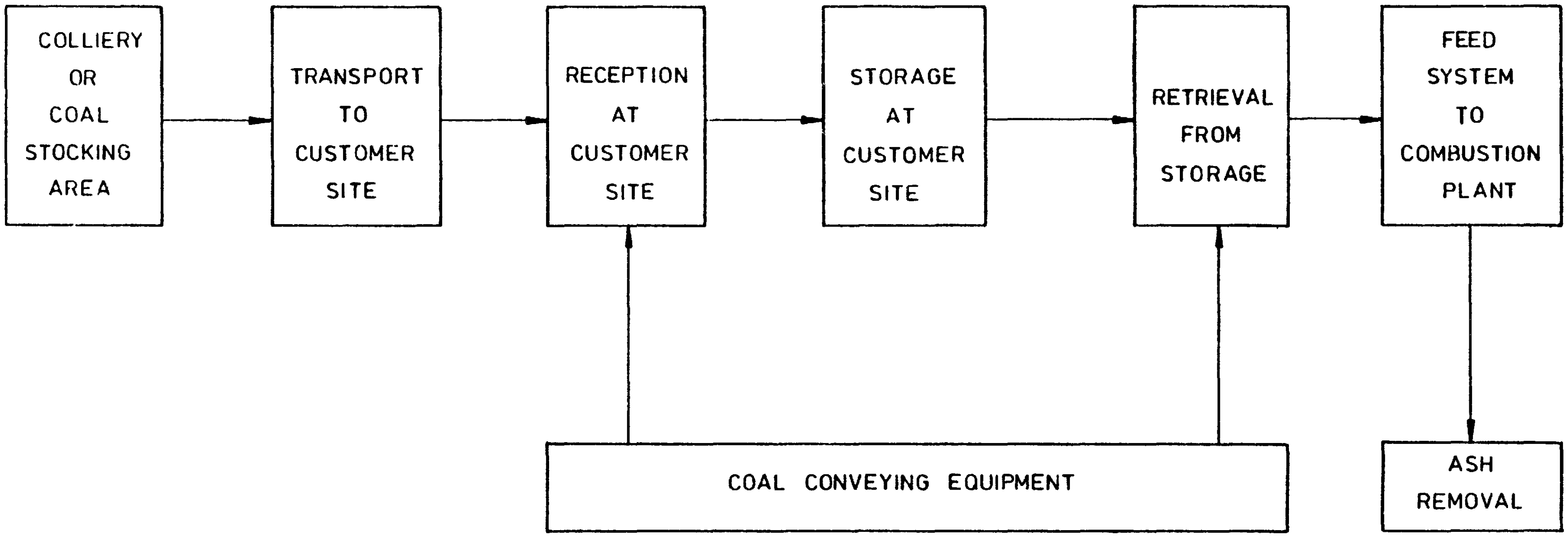

FIGURE 1. ELEMENTS OF A COAL SUPPLY AND ASH REMOVAL SYSTEM FOR AN INDUSTRIAL COMBUSTION PLANT.

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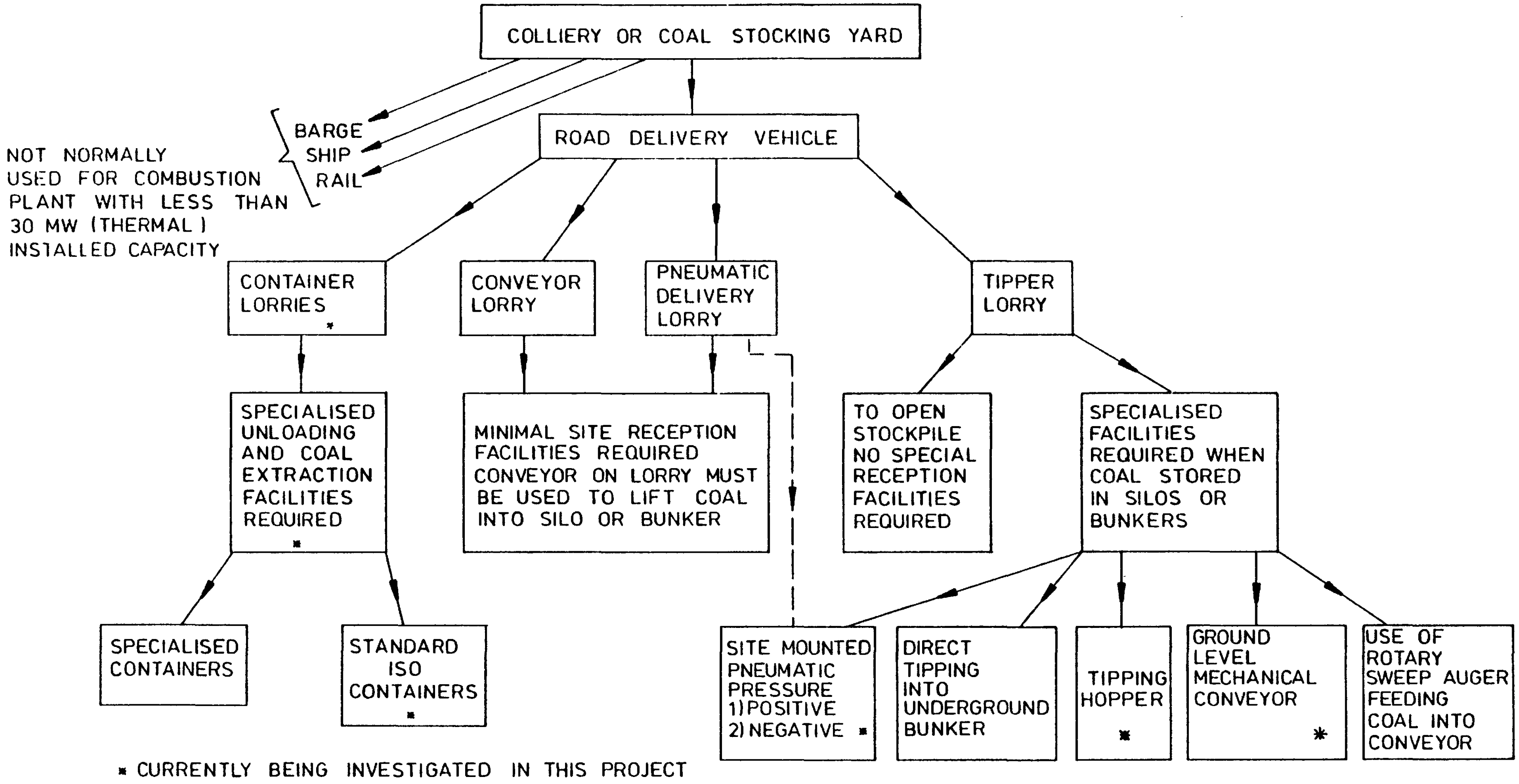
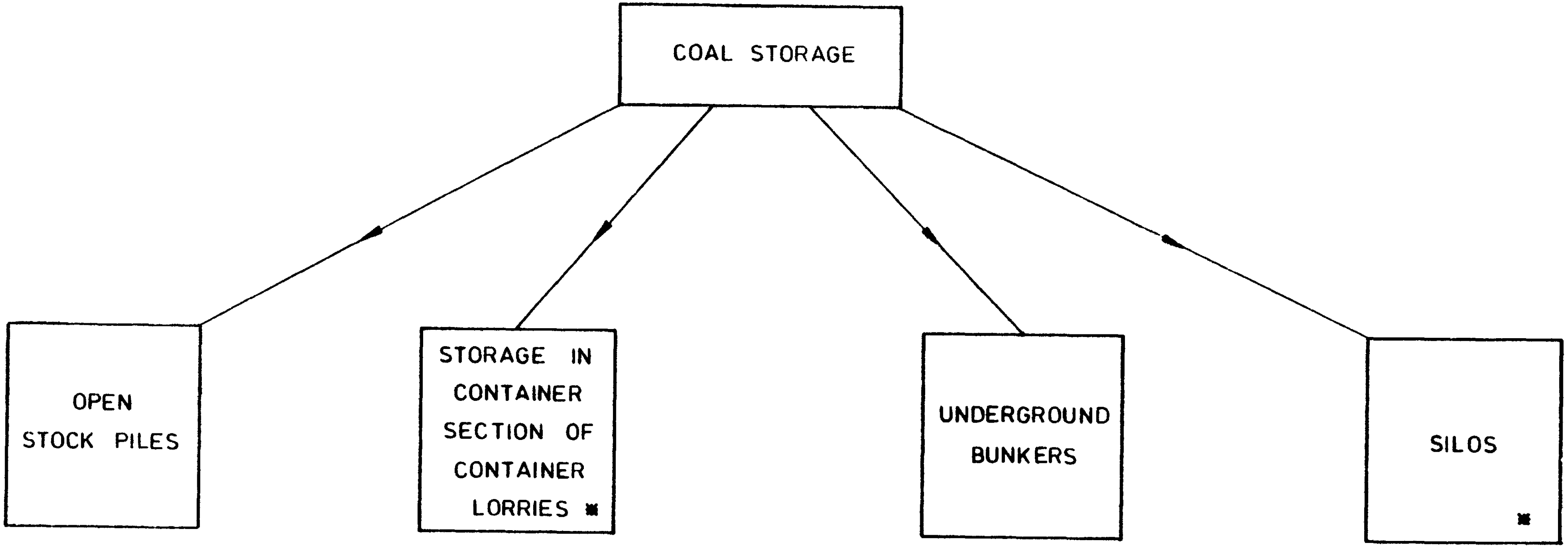


FIGURE 2.

FACILITIES AVAILABLE FOR TRANSPORTATION OF COAL AND ITS RECEPTION AT INDUSTRIAL CUSTOMER SITES



* BEING INVESTIGATED BY THIS PROJECT

FIGURE 3. COAL STORAGE FACILITIES USED BY INDUSTRIAL COAL USERS.

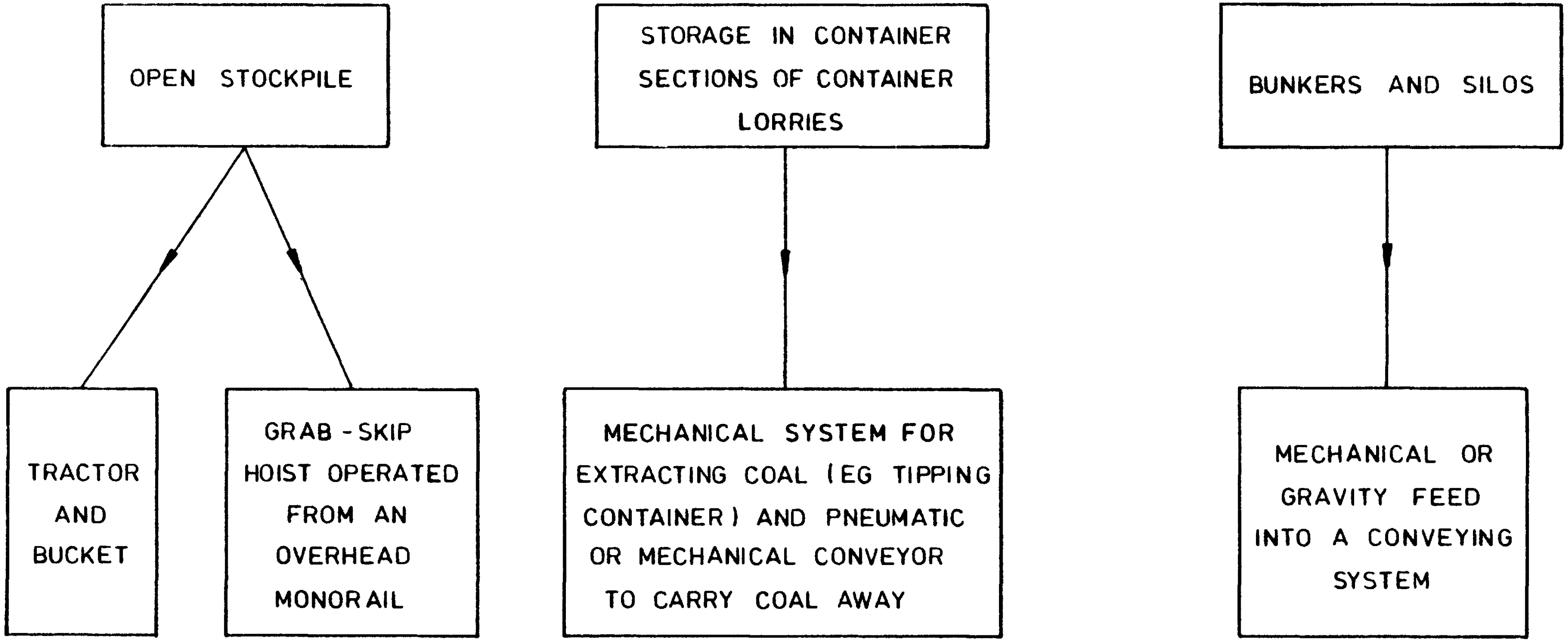
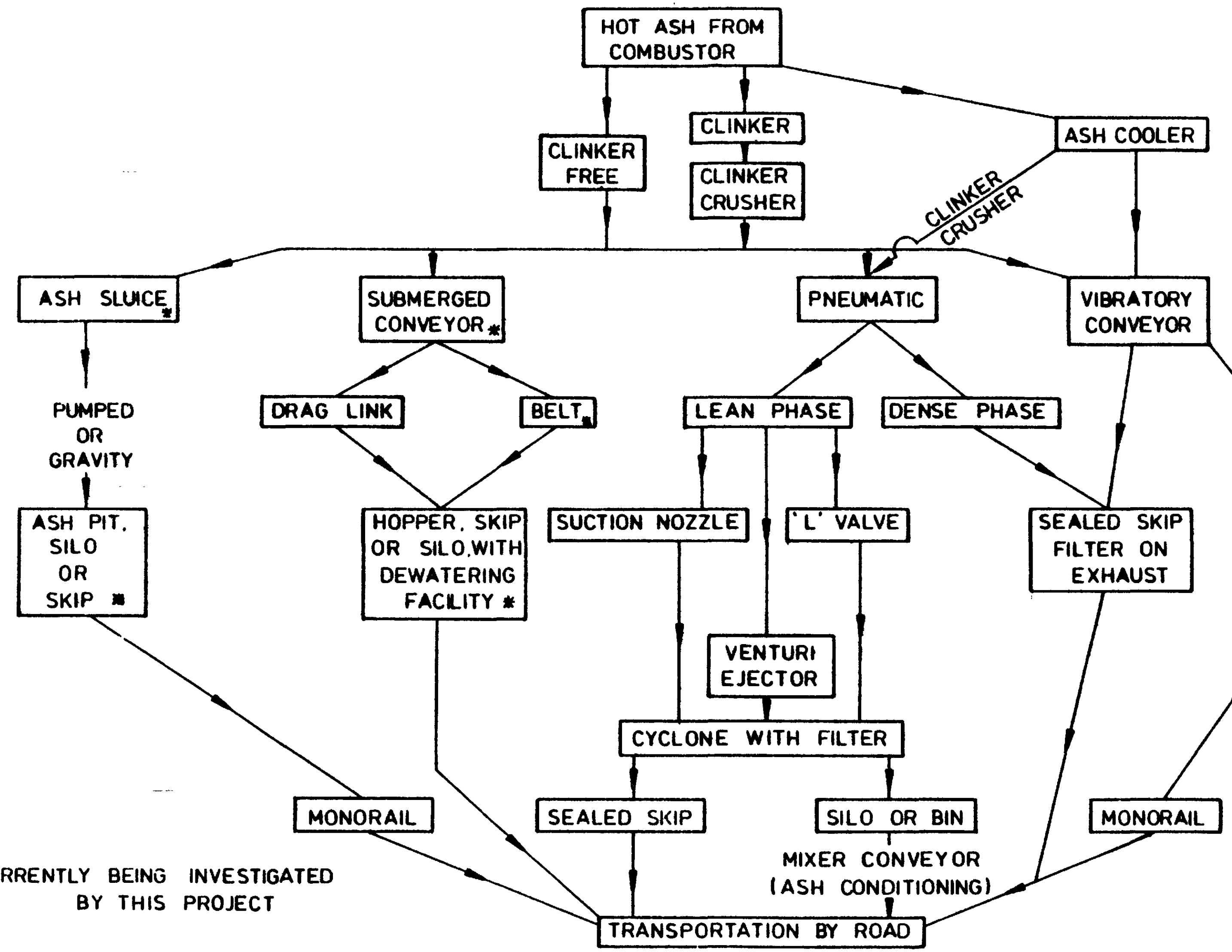


FIGURE 4. RETRIEVAL OF COAL FROM STORAGE AT INDUSTRIAL SITES.



* CURRENTLY BEING INVESTIGATED BY THIS PROJECT

FIGURE 5. CONVEYING, STORAGE AND REMOVAL OF ASH.

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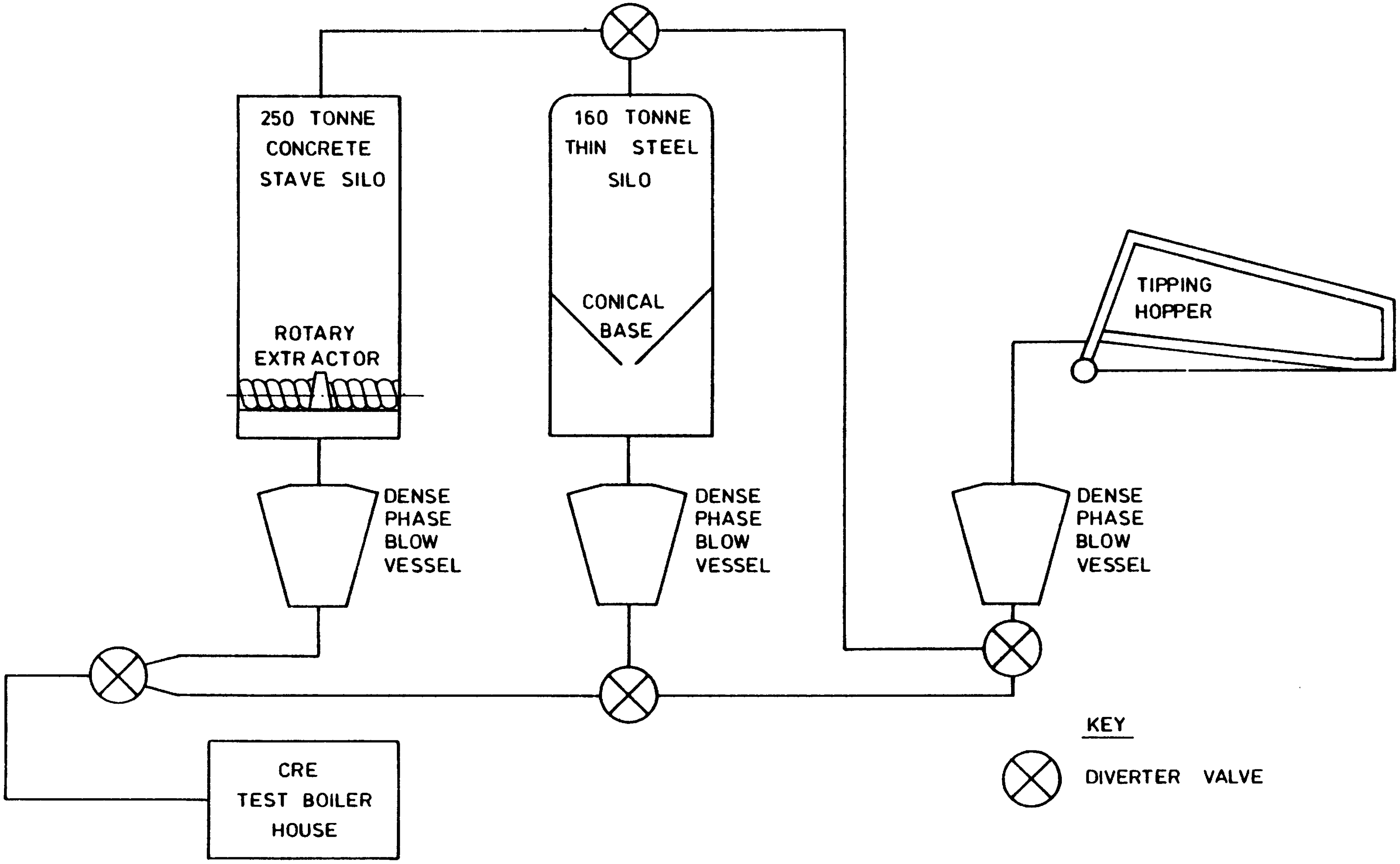

FIGURE 6. SCHEMATIC OF COAL HANDLING SYSTEM AT CRE

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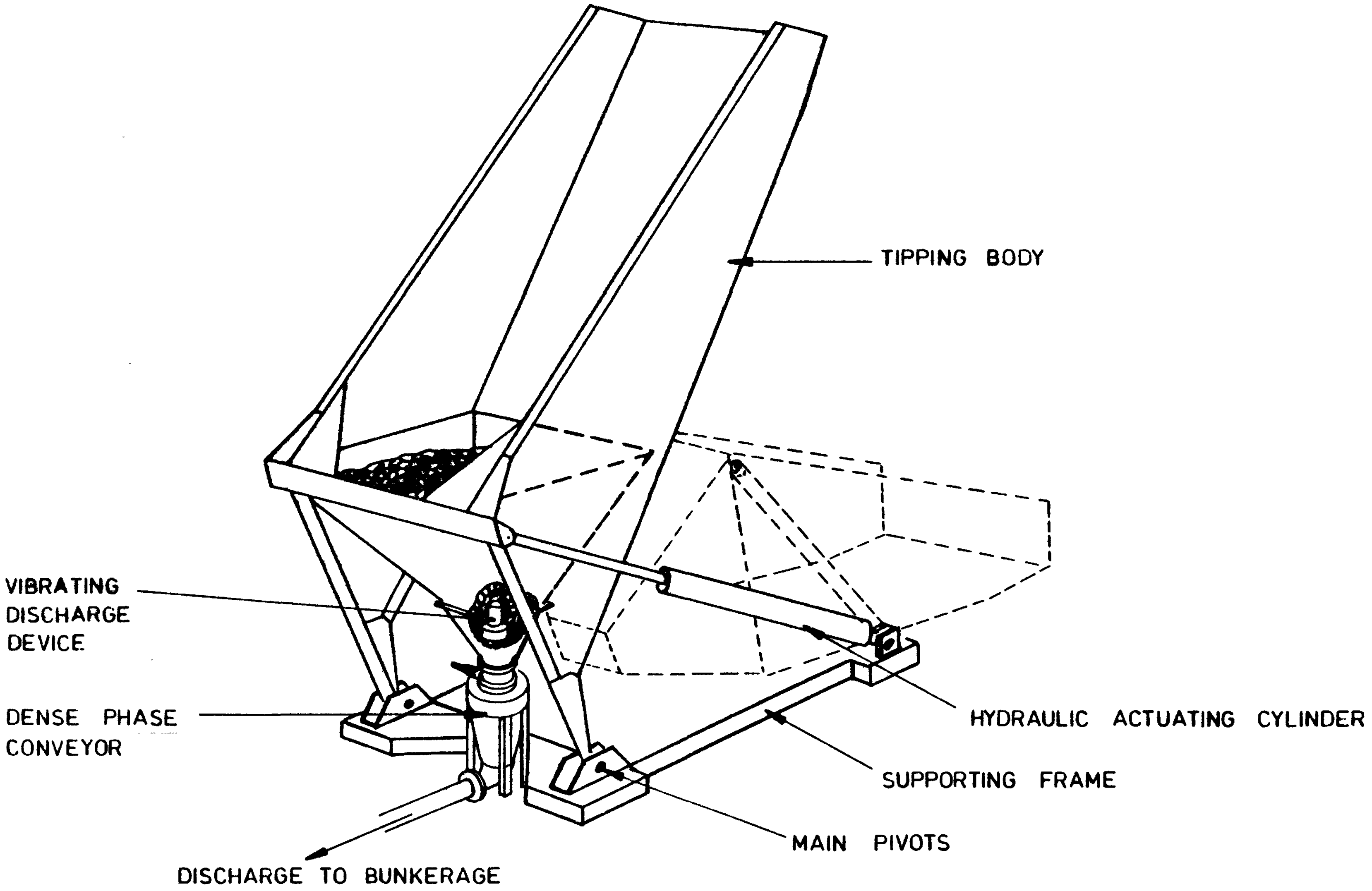

FIGURE 7. TYPICAL ARRANGEMENT - 22 TONNE CAPACITY END TIPPING HOPPER

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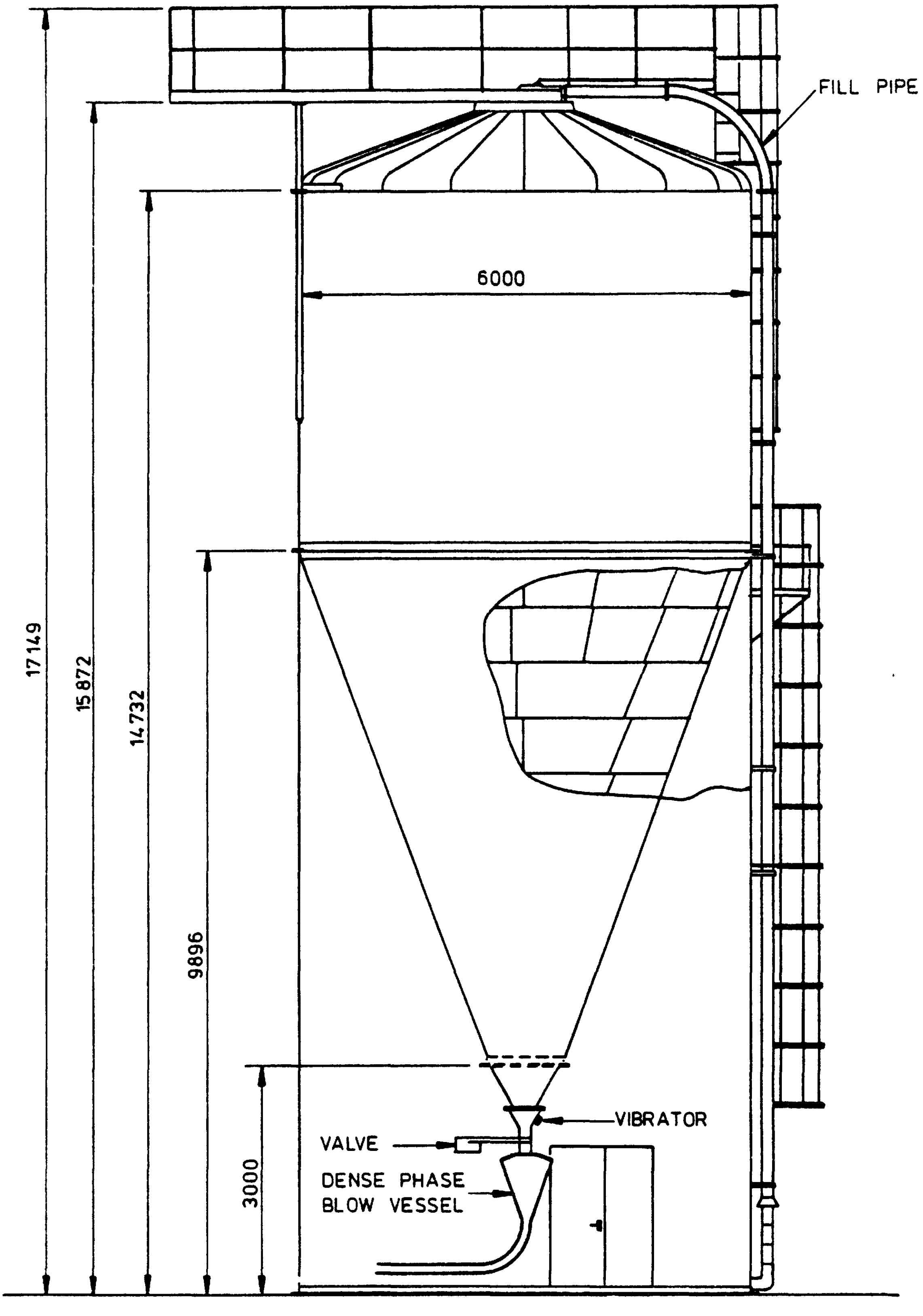

FIGURE 8. 160 TONNE CAPACITY STEEL SILO FORMED FROM GLASSED PLATES

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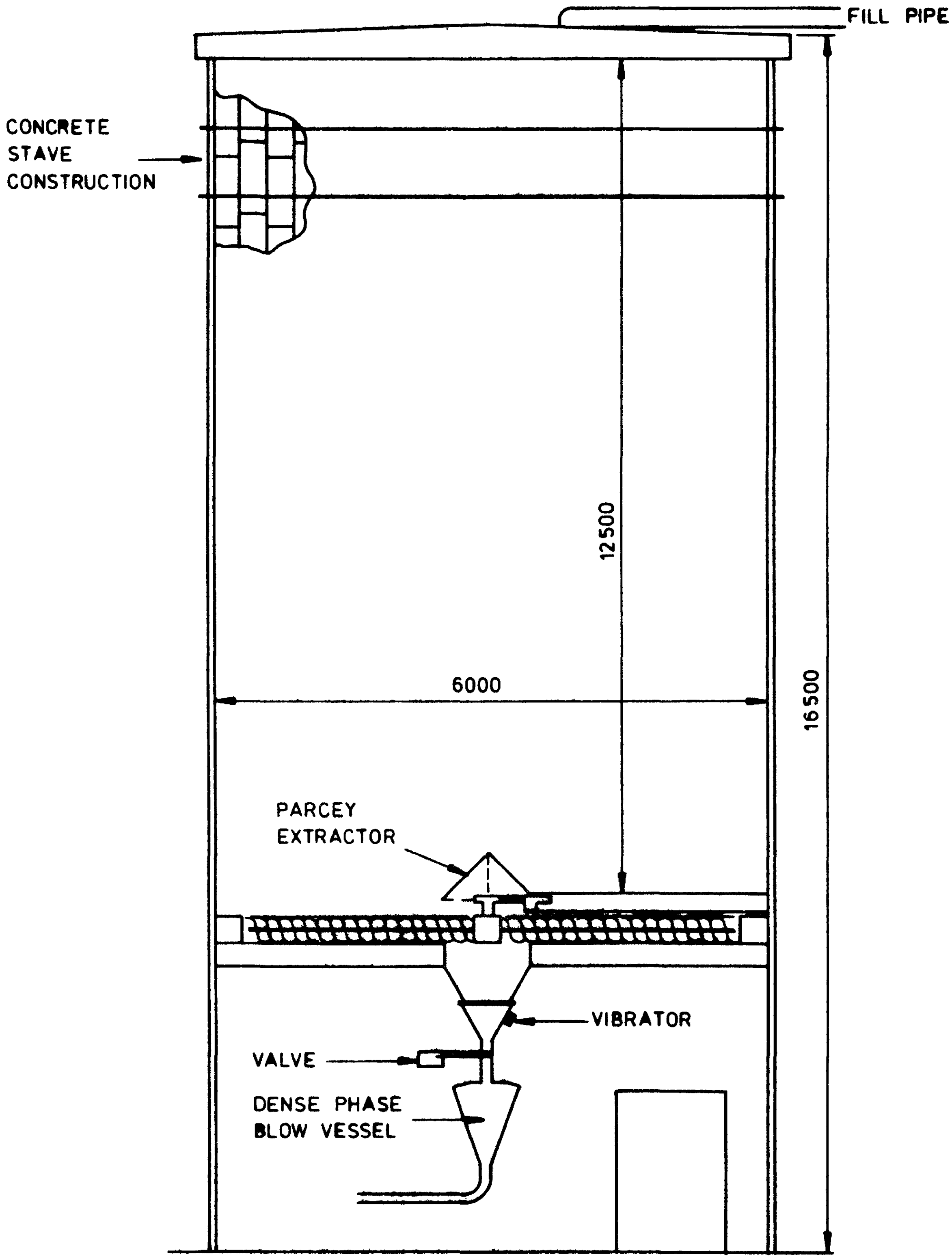


FIGURE 9. 250 TONNE CAPACITY CONCRETE STAVE SILO

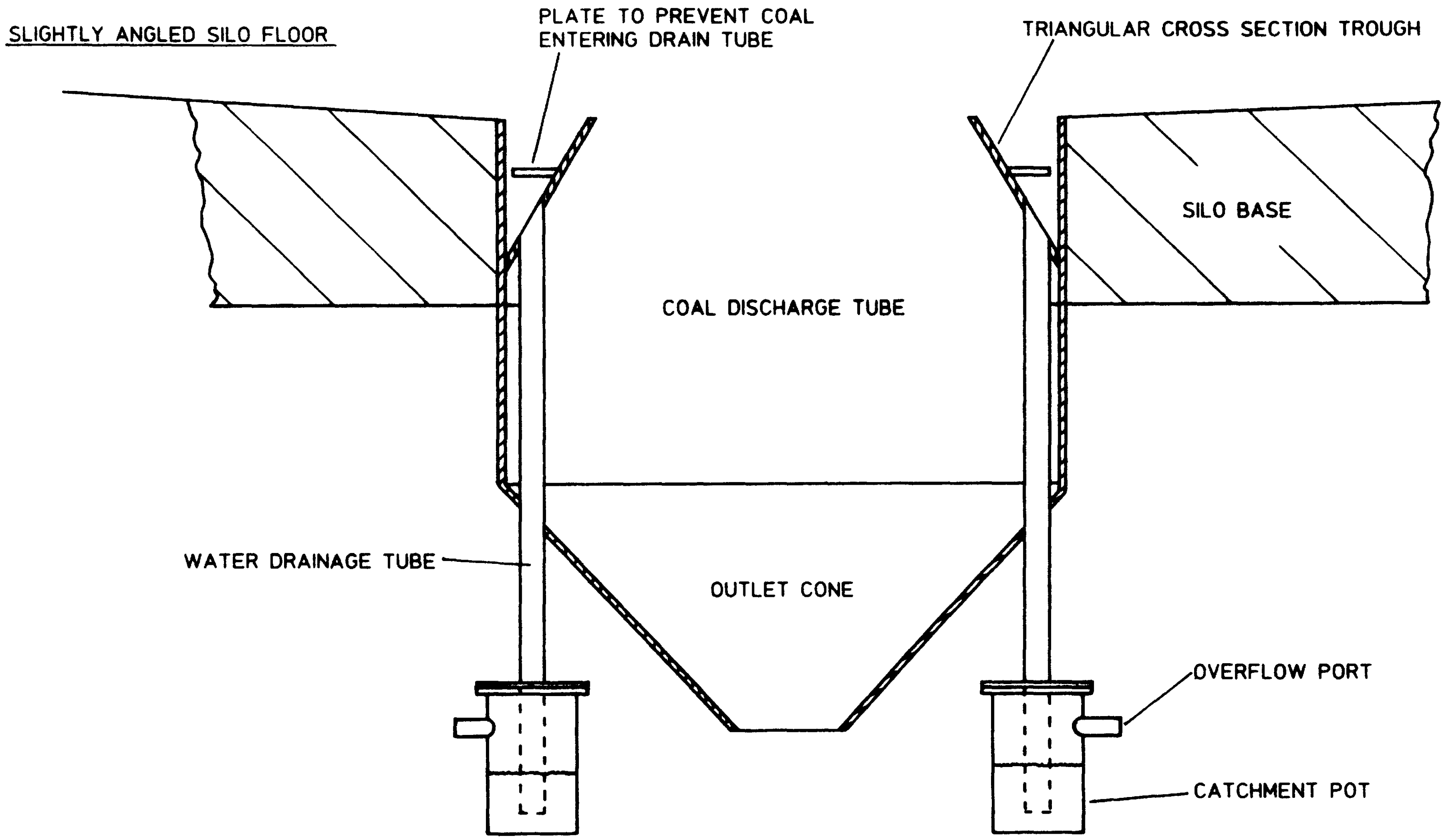


FIGURE 10. DIAGRAM SHOWING DETAILS OF THE NEW DRAINAGE SYSTEM FITTED TO THE CONCRETE STAVE SILO AT CRE

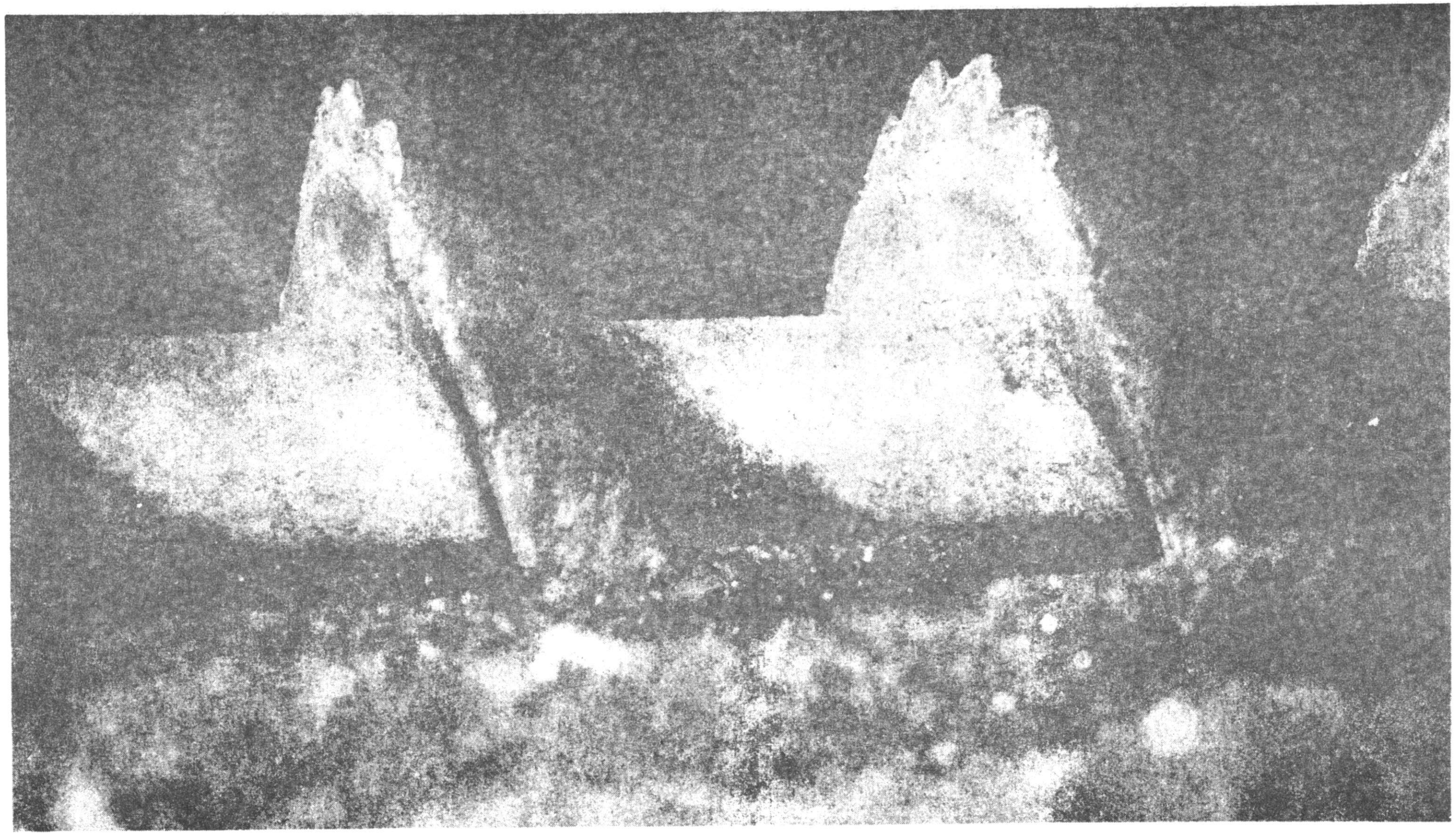


FIGURE 11 FOULING OF ROTARY AUGER USED TO REMOVE COAL FROM THE 250 TONNE CONCRETE STAVE SILO

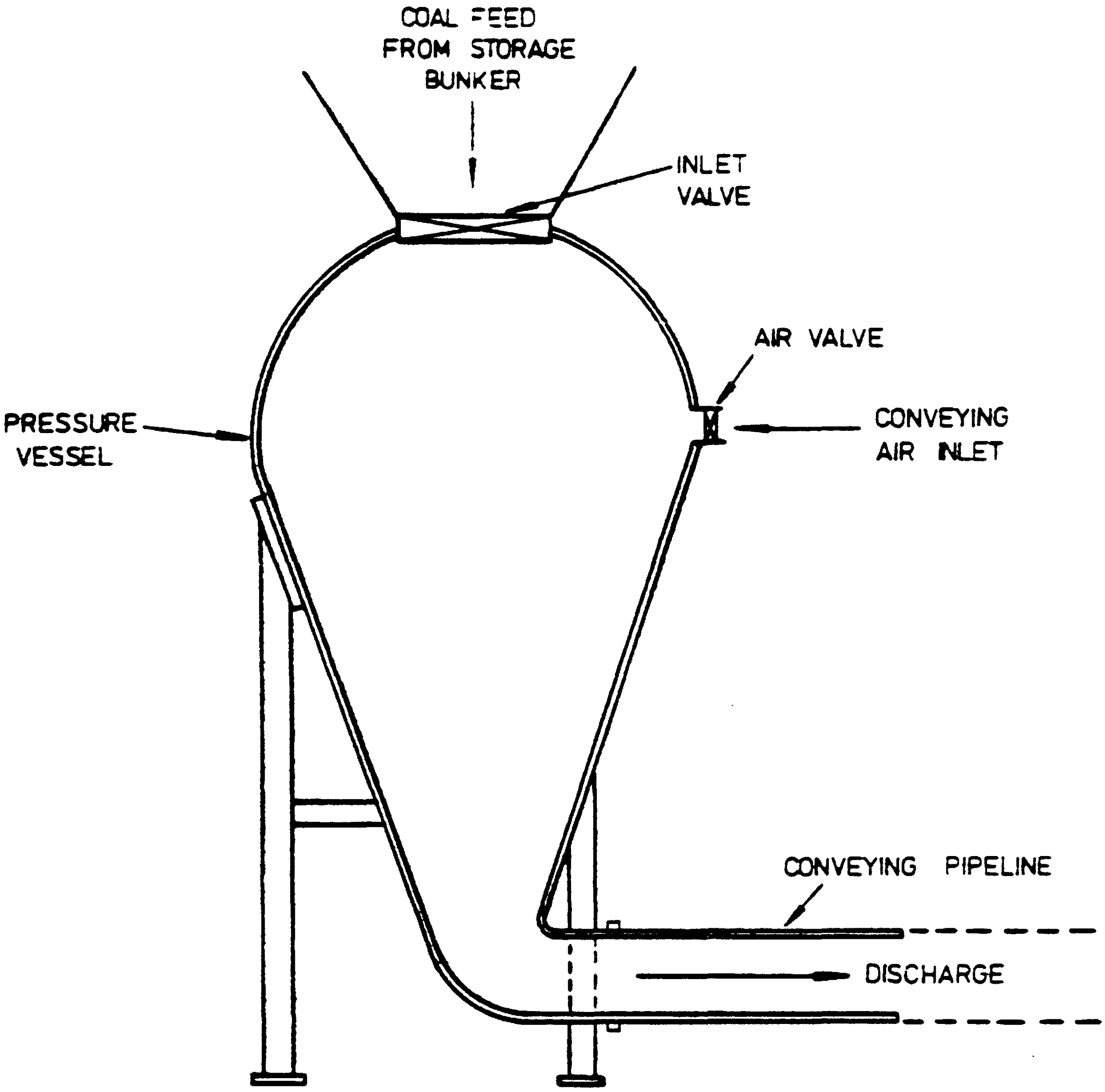
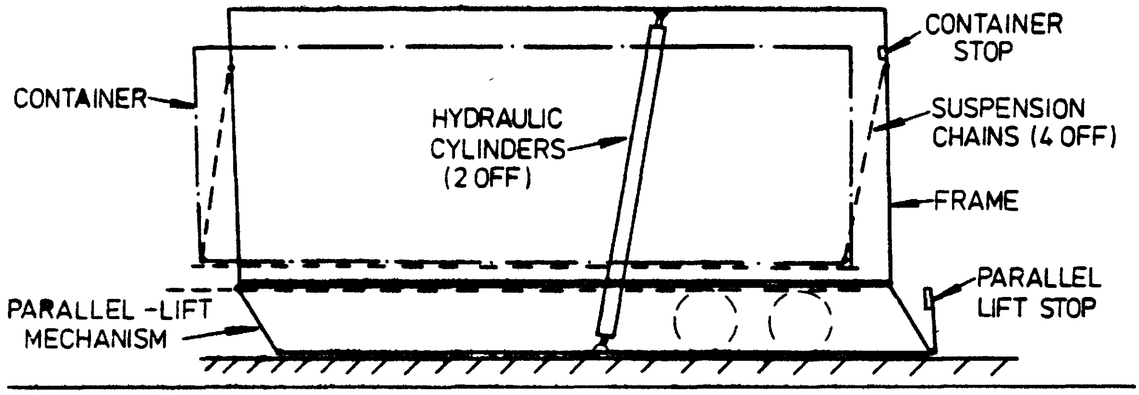


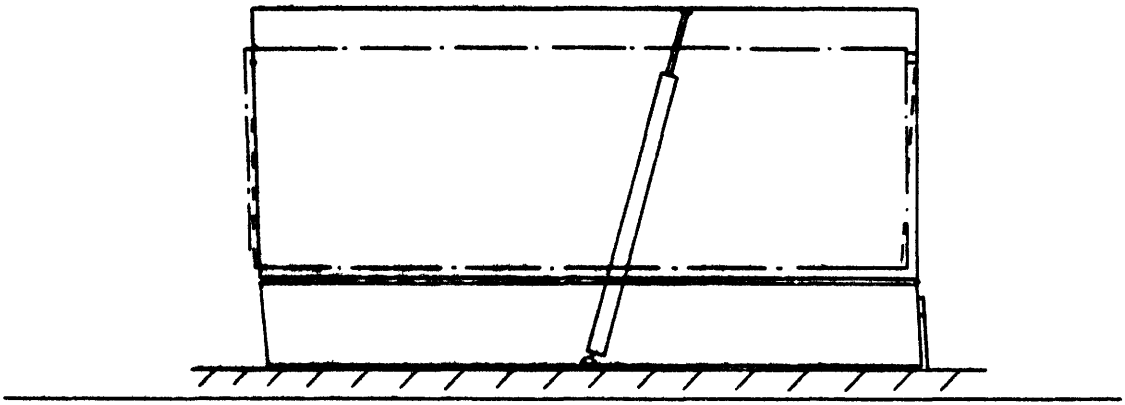
FIGURE 12.

SCHEMATIC DIAGRAM OF DENSE PHASE PNEUMATIC CONVEYOR.

1. CONTAINER ON TRAILER **REVERSED** INTO FRAME. CHAINS ATTACHED TO CONTAINER, CONTAINER RELEASED FROM TRAILER.



2 EXTENSION OF CYLINDERS LIFTS CONTAINER CLEAR OF TRAILER. VEHICLE CAN DRIVE AWAY.



3. FURTHER EXTENSION OF CYLINDERS TIPS FRAME AND CONTAINER.

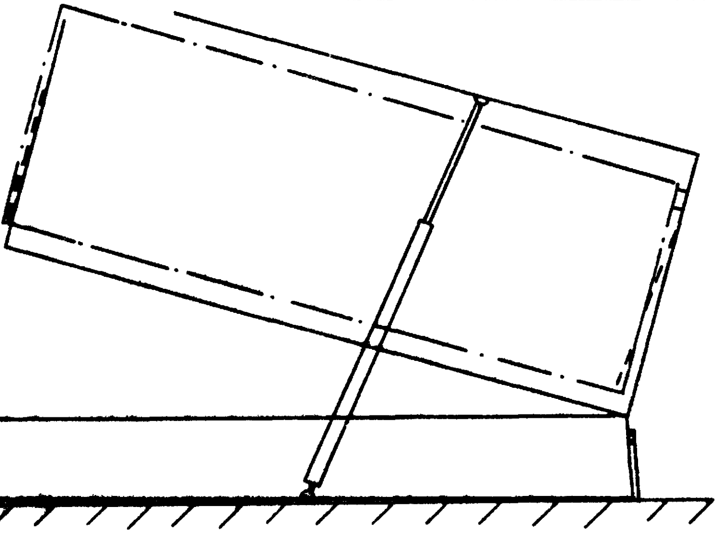


FIGURE 13. COMPOSITE DE-MOUNTING AND TIPPING RIG FOR ISO CONTAINERS

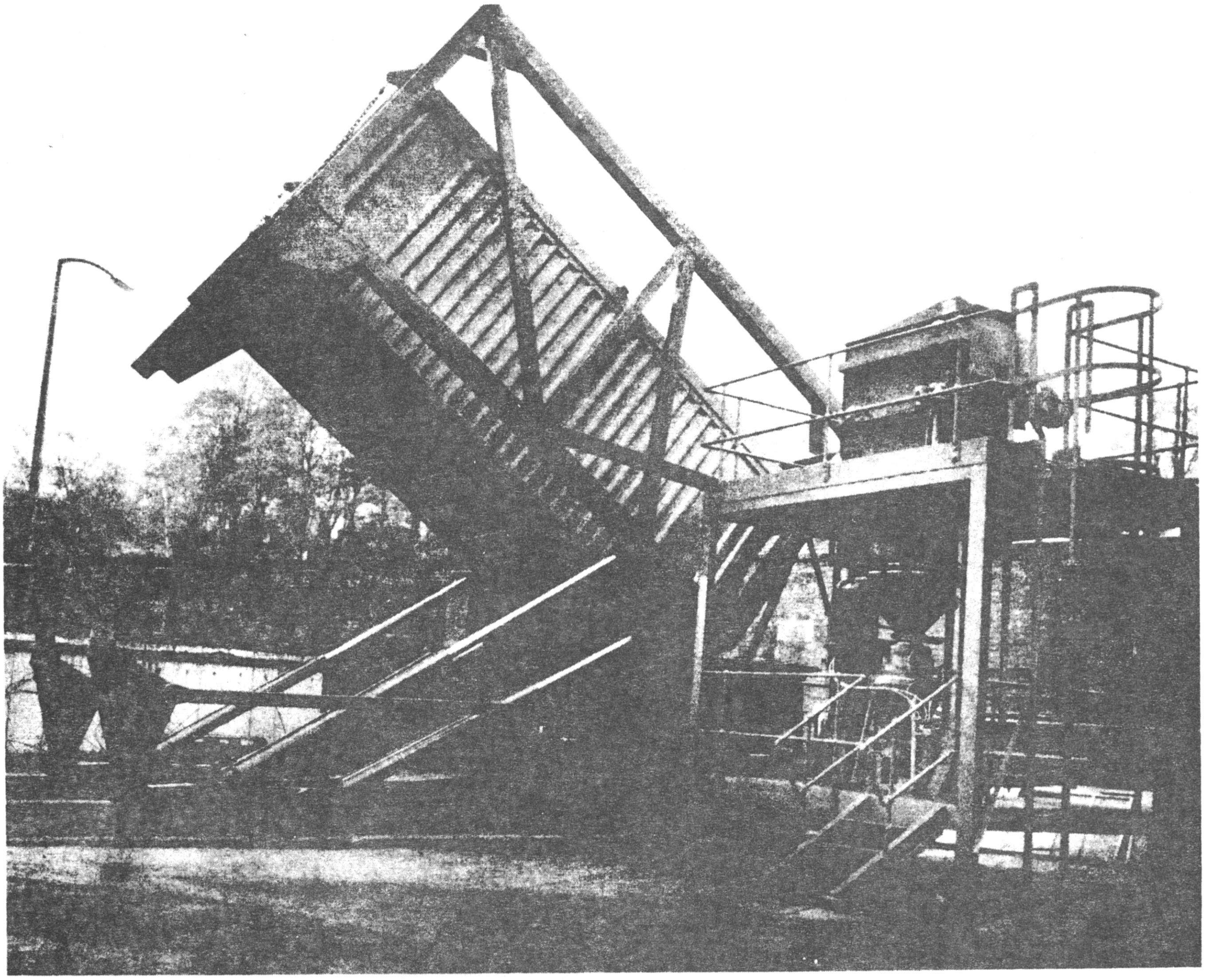


FIGURE 14 SYSTEM FOR RECEPTION,OFF LOADING AND DISCHARGING ISO CONTAINERS

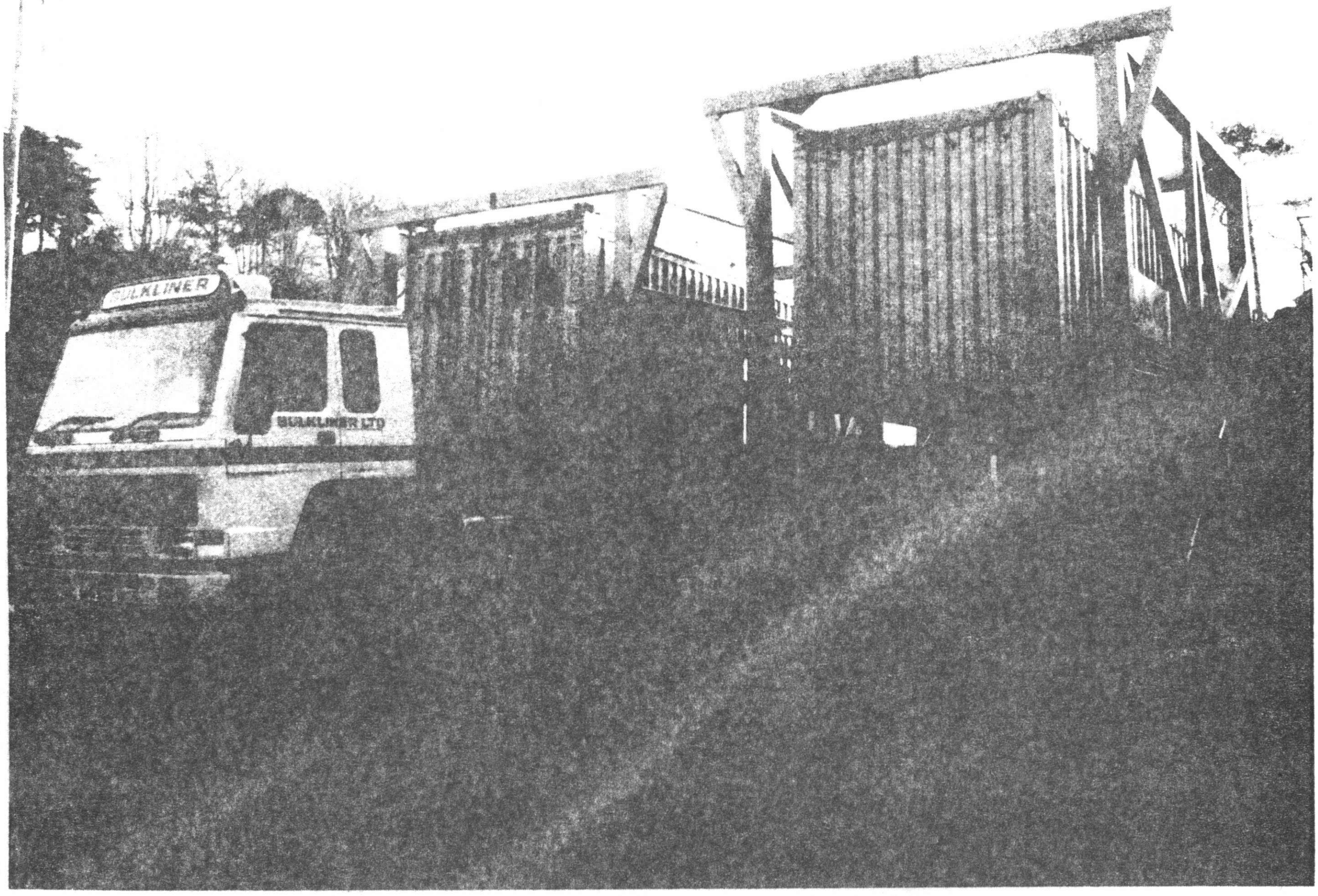


FIGURE 15 TIPPING FRAMES FOR RECEIVING AND EMPTYING 20-TONNE CAPACITY ISO CONTAINERS

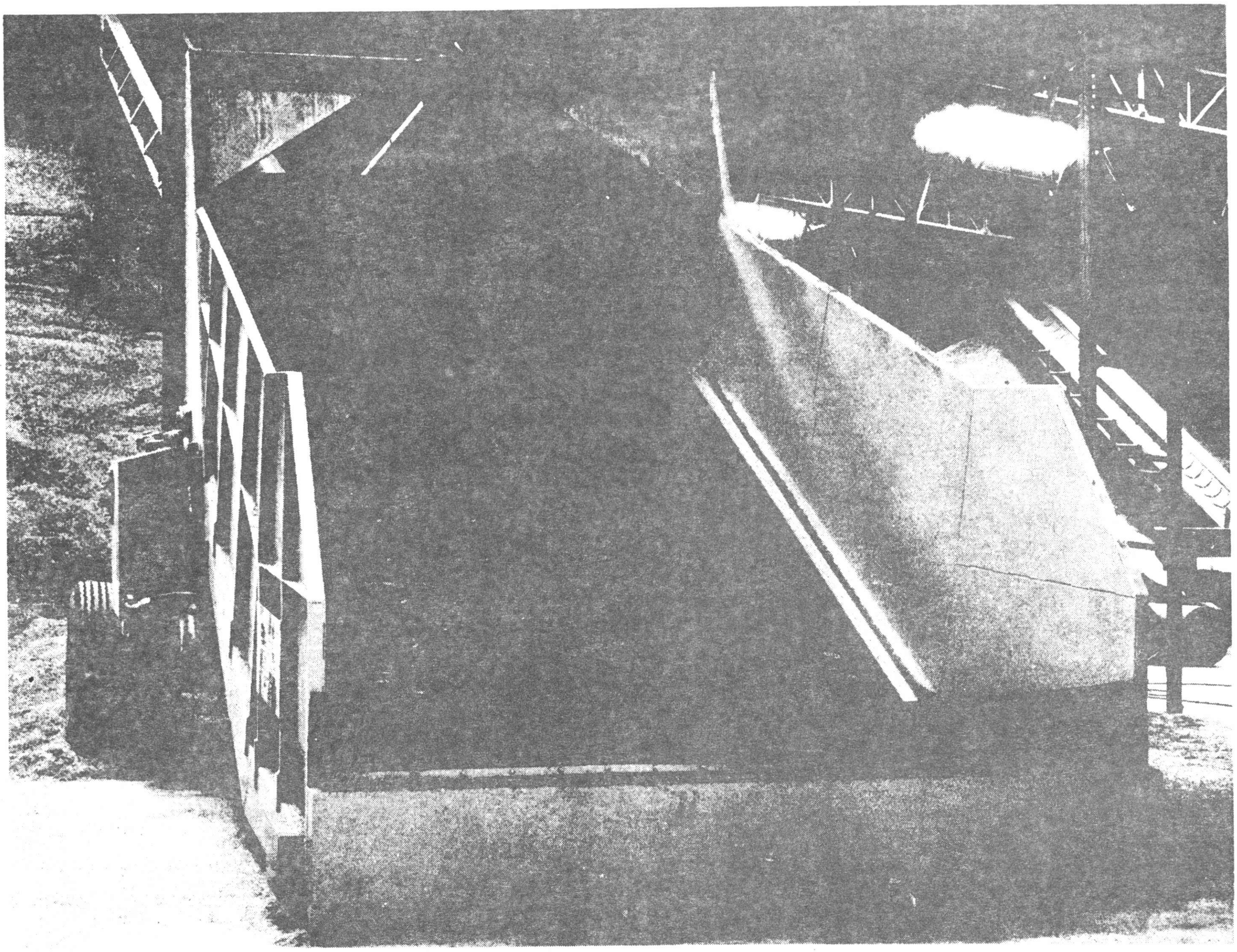


FIGURE 16 WIDE BELT CONVEYOR

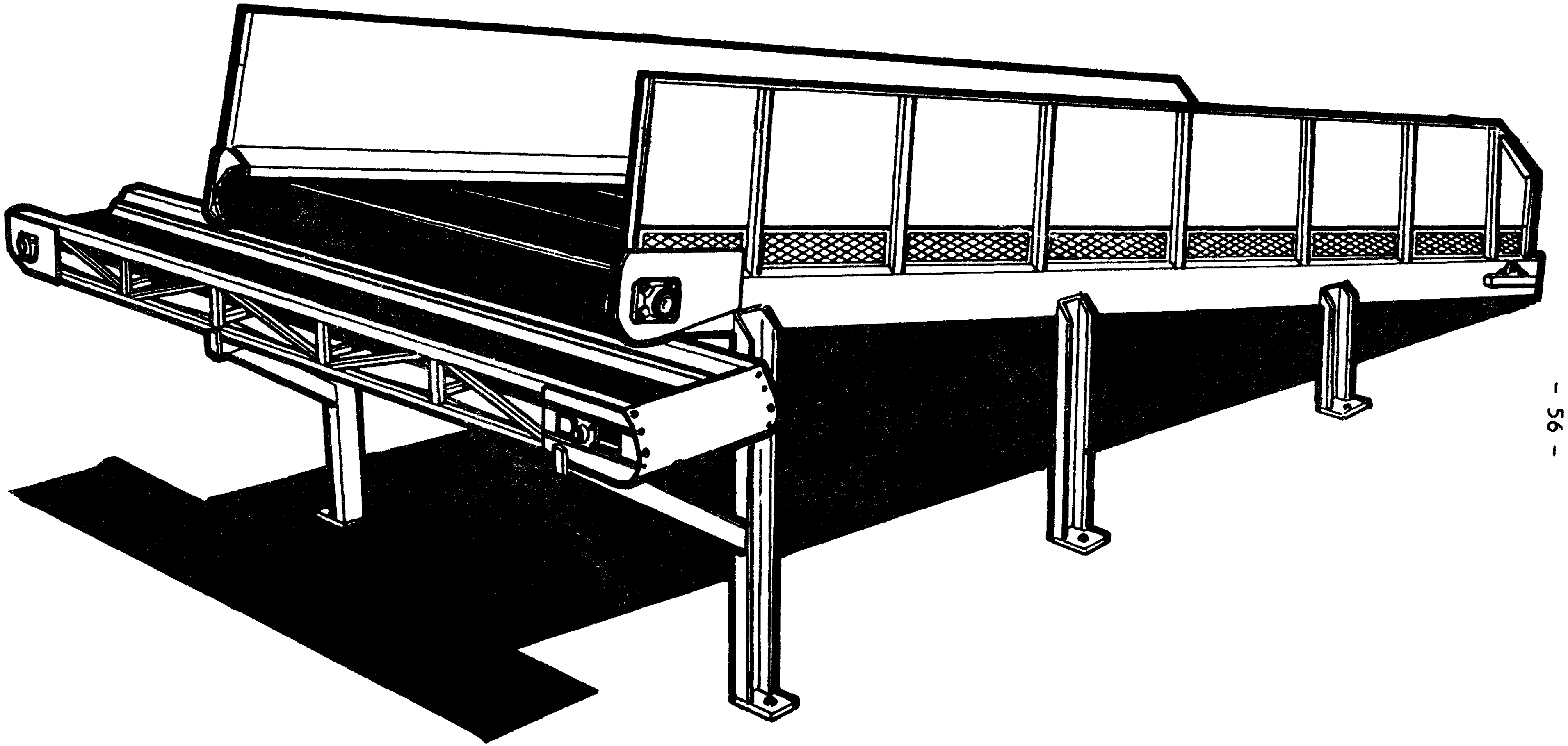


FIGURE 17 WIDE BELT CONVEYOR WITH CROSS FEEDER

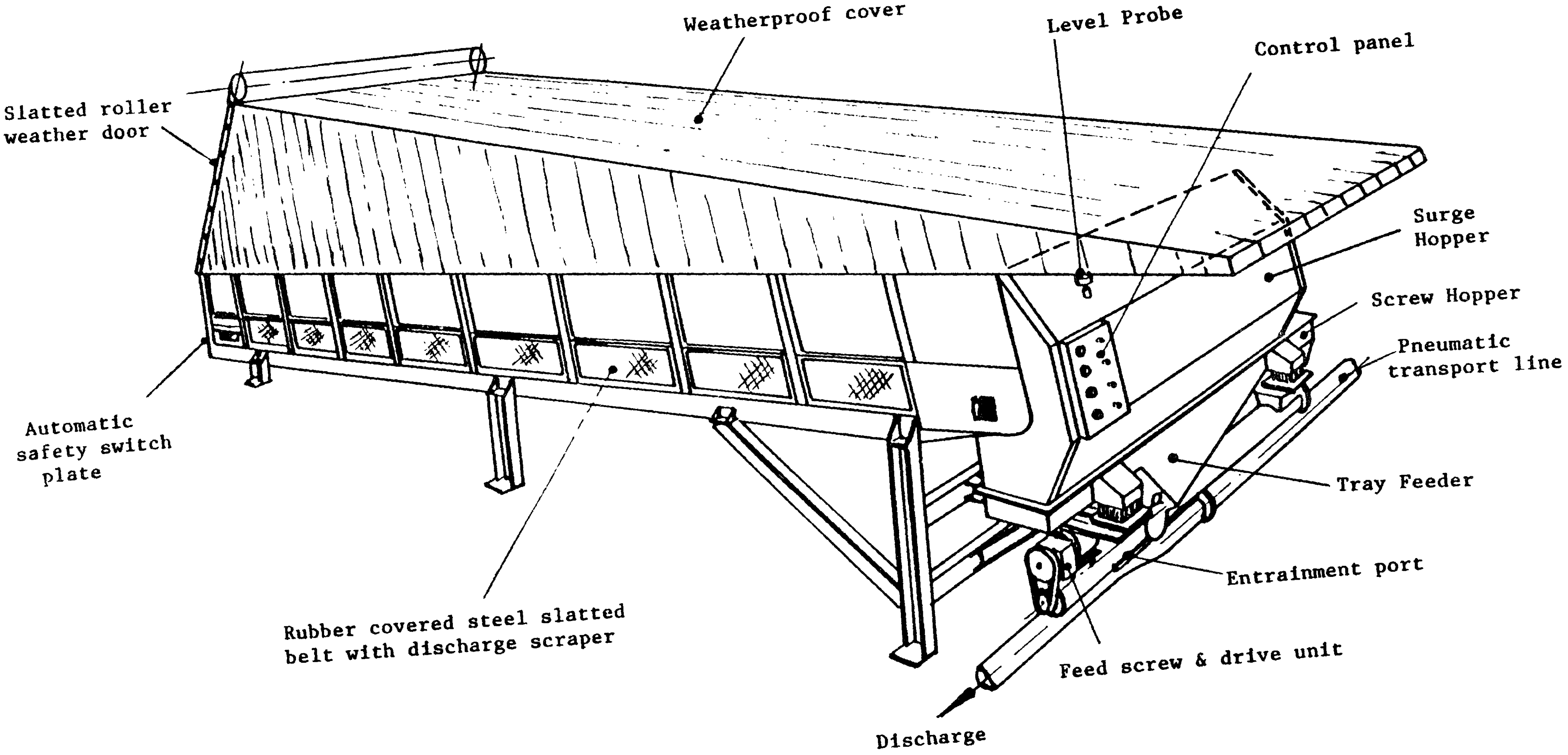


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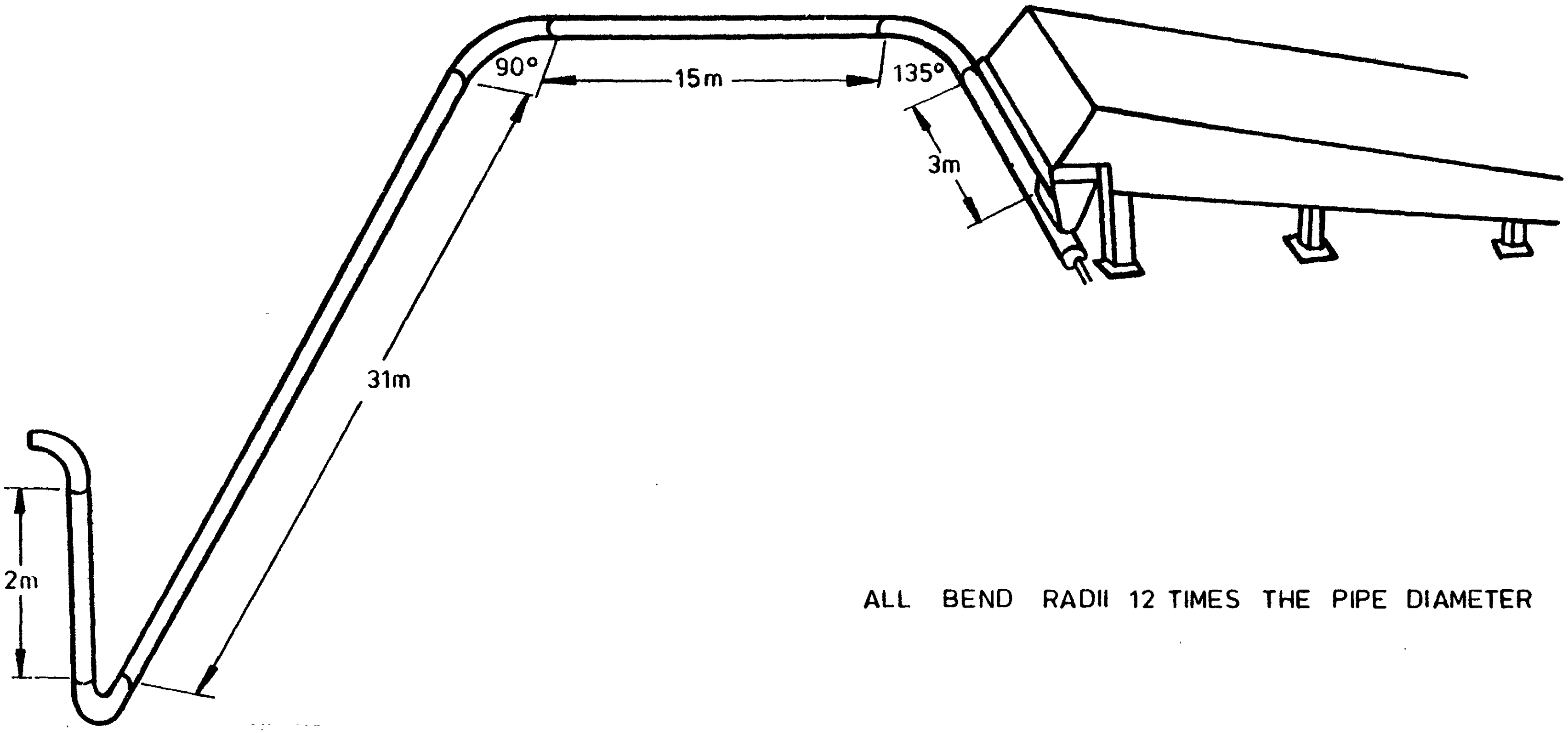
FIGURE 18 : MODIFIED WIDE BELT CONVEYOR



ALL BEND RADII 12 TIMES THE PIPE DIAMETER

FIGURE 19. SKETCH OF CONVEYING LINE AND LORRY UNLOADER ARRANGEMENT DURING INITIAL ASSESSMENT.

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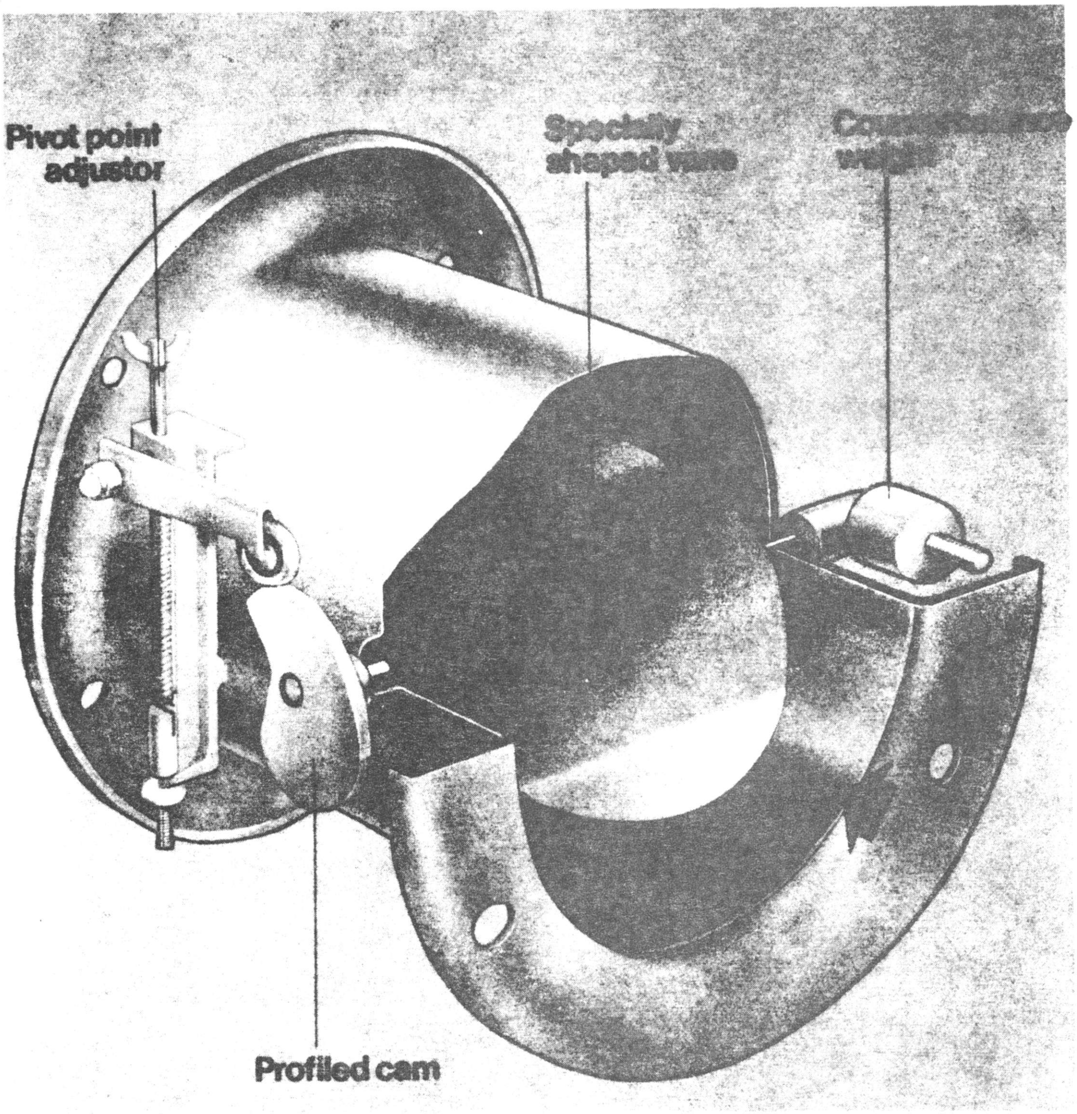

FIGURE 20 START-UP DAMPER

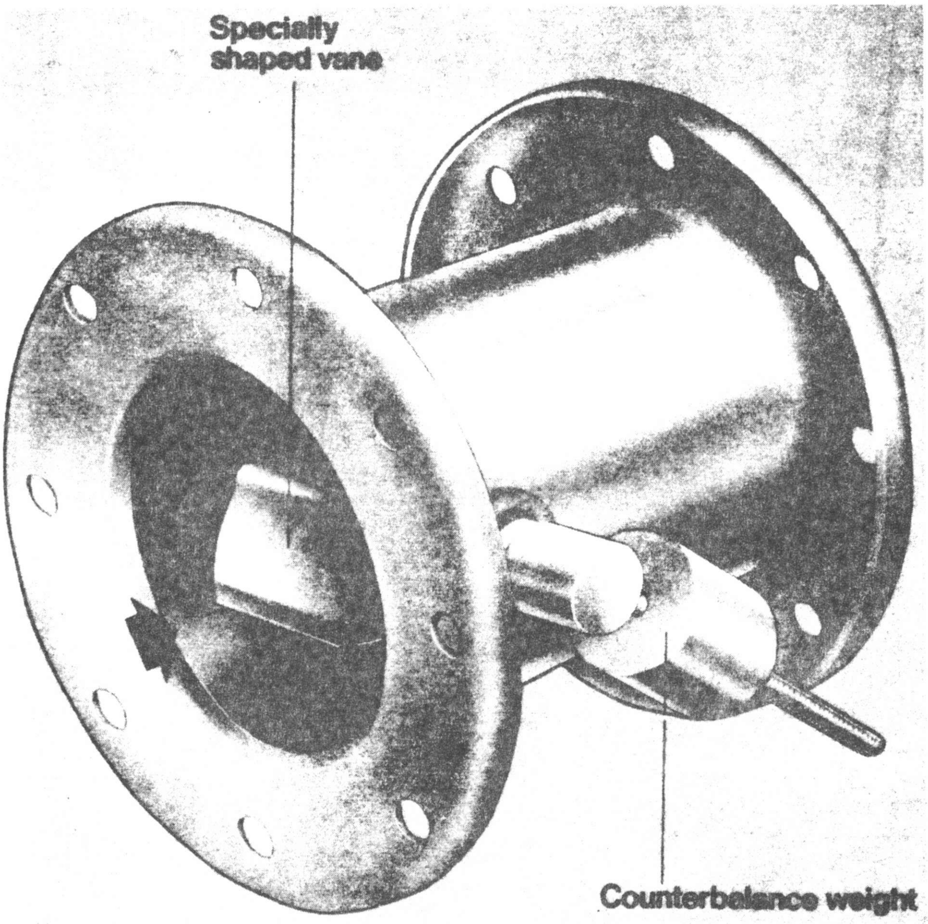

FIGURE 21 CONSTANT VELOCITY DAMPER

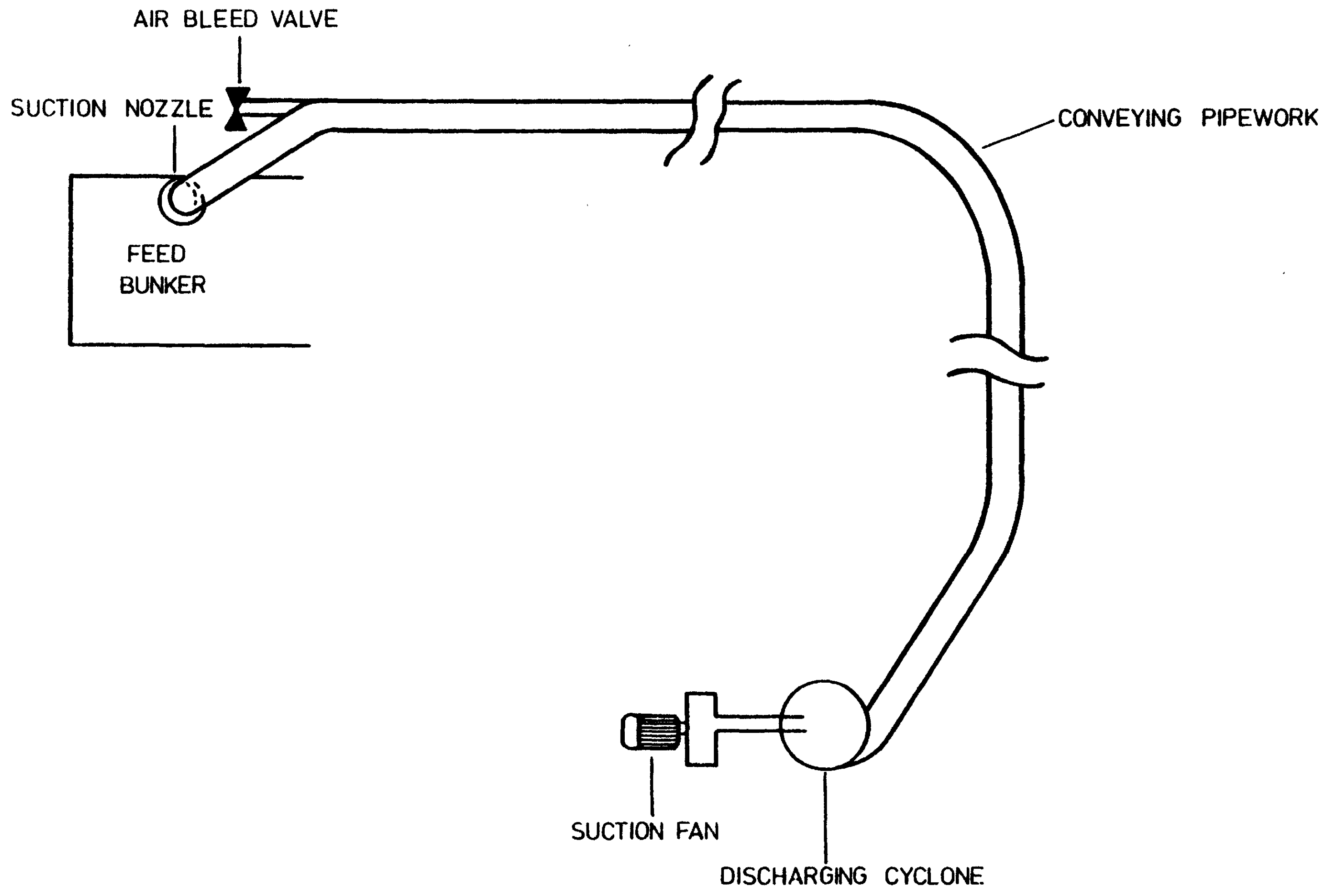

FIGURE 22. PLAN VIEW OF 200mm DIAMETER SUCTION NOZZLE CONVEYING SYSTEM

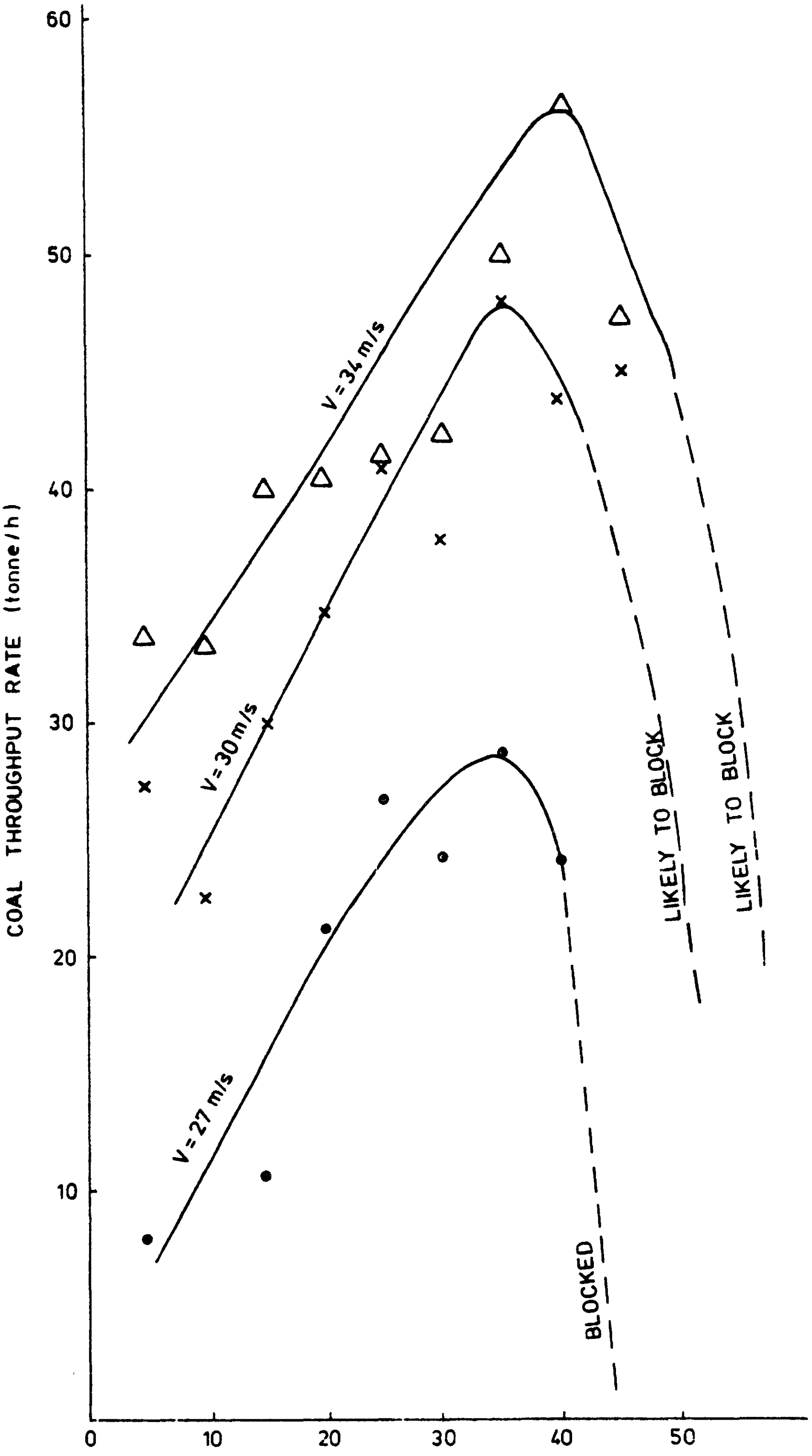

FIGURE 23. COAL THROUGHPUT RATE v. NOZZLE EXTENSION AT DIFFERENT CONVEYING VELOCITIES

7220-ED/802-

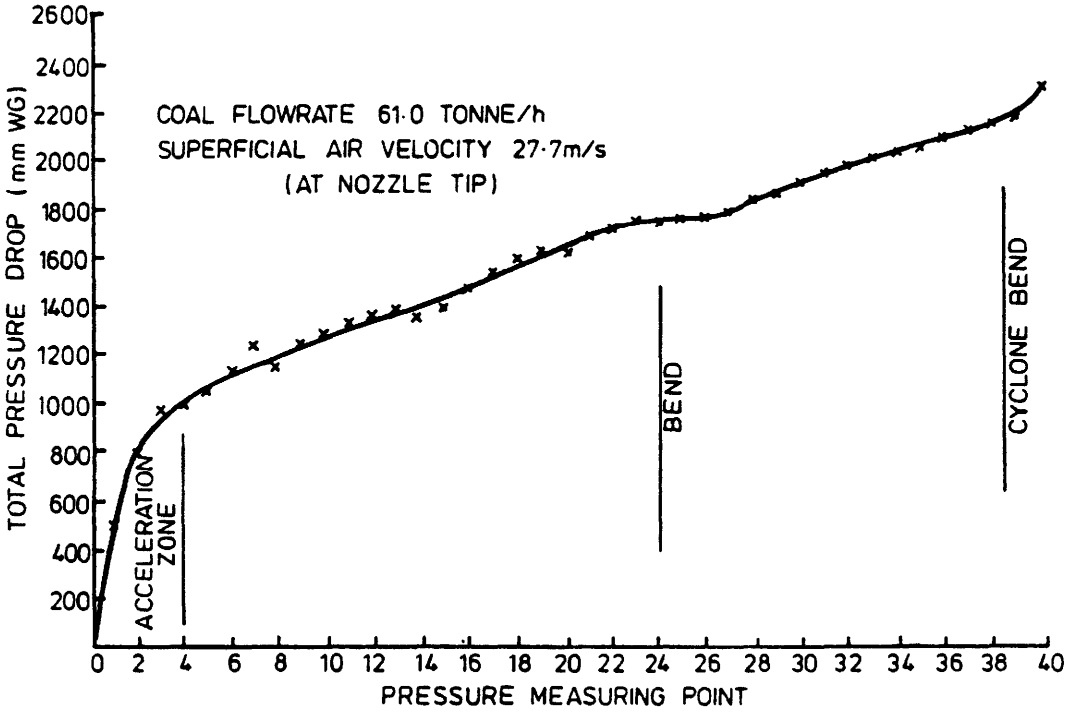

FIGURE 24. 200mm SUCTION NOZZLE PRESSURE DROP PROFILE

7220-ED/802

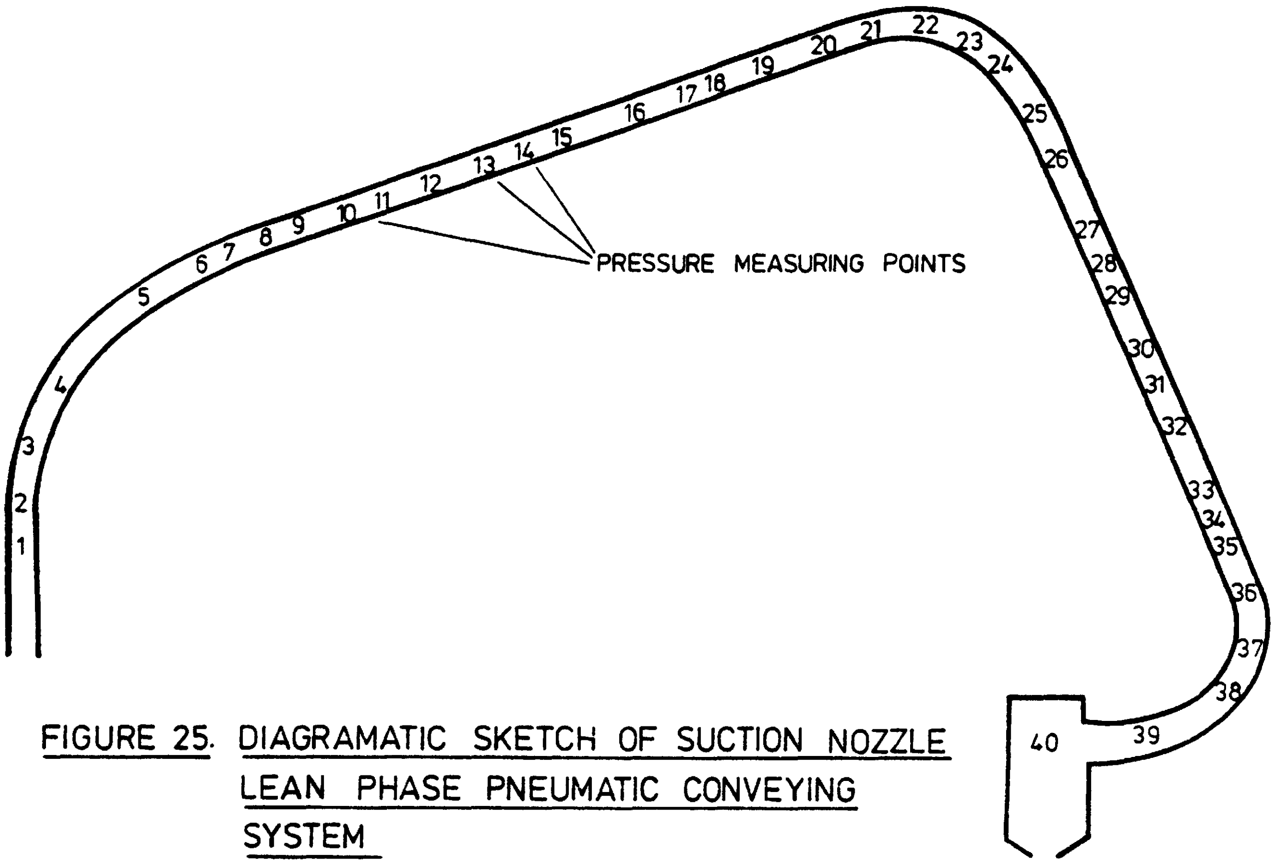

FIGURE 25. DIAGRAMATIC SKETCH OF SUCTION NOZZLE LEAN PHASE PNEUMATIC CONVEYING SYSTEM

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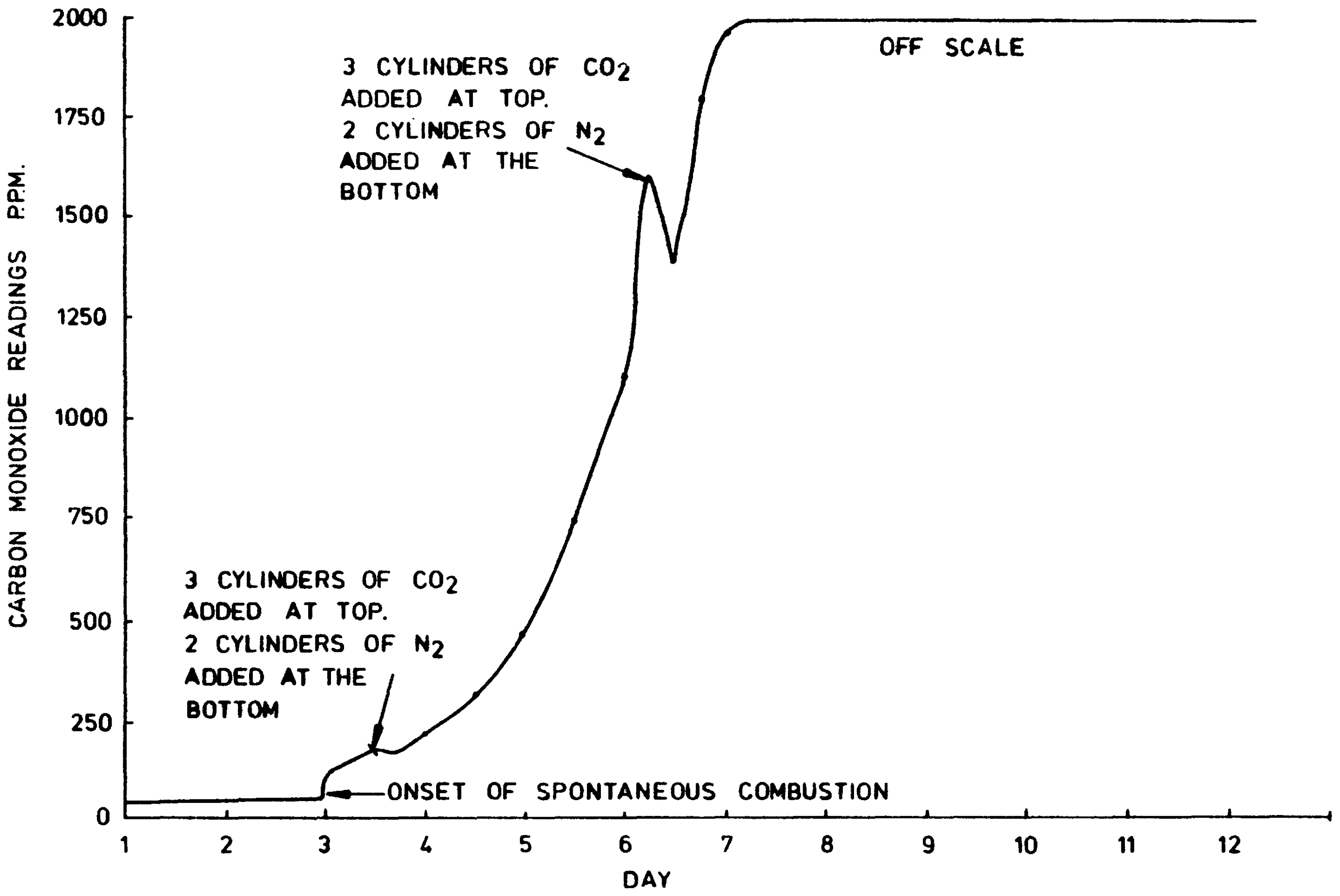

FIGURE 26. CONCENTRATION OF CARBON MONOXIDE IN A CONCRETE SILO SHOWING THE ONSET OF SPONTANEOUS COMBUSTION.

7220-ED/802

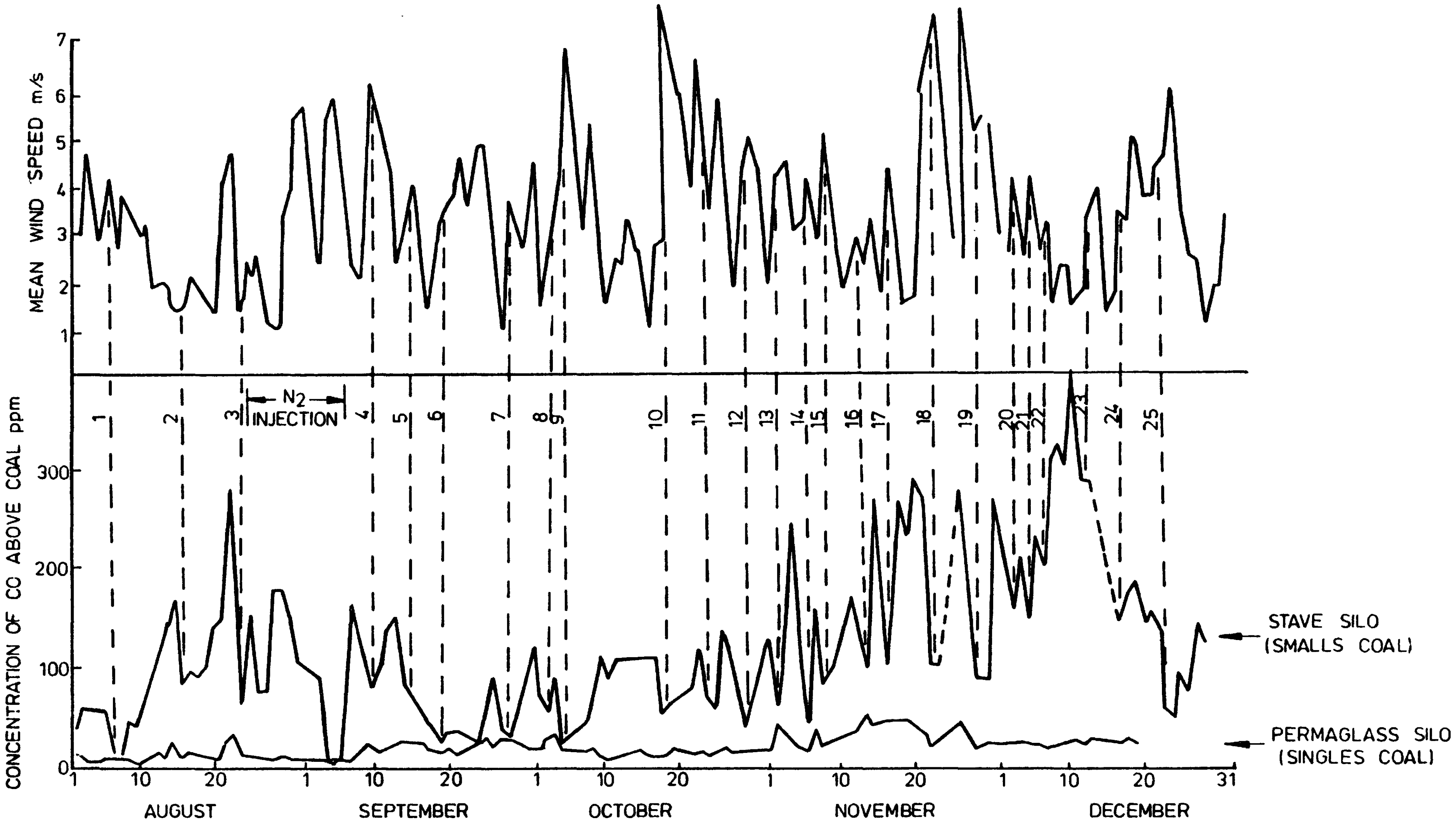

FIGURE 27. DAILY RECORD OF CO CONCENTRATIONS ABOVE THE SINGLES AND SMALLS COALS IN PERMAGLASS AND CONCRETE STAVE SILOS AND AVERAGE WINDSPEED

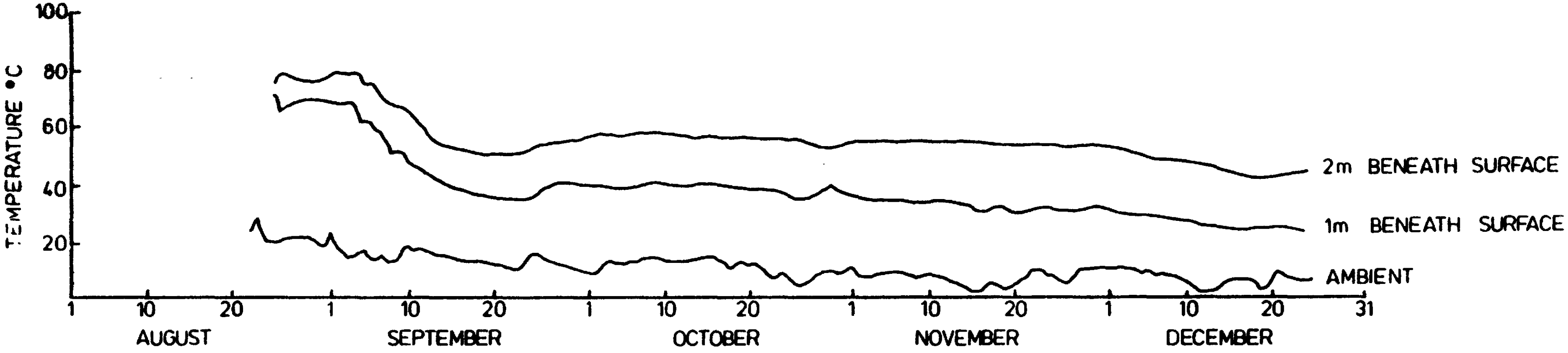

FIGURE 28. DAILY RECORD OF TEMPERATURE WITHIN THE CONCRETE STAVE SILO AND THE AMBIENT TEMPERATURE.

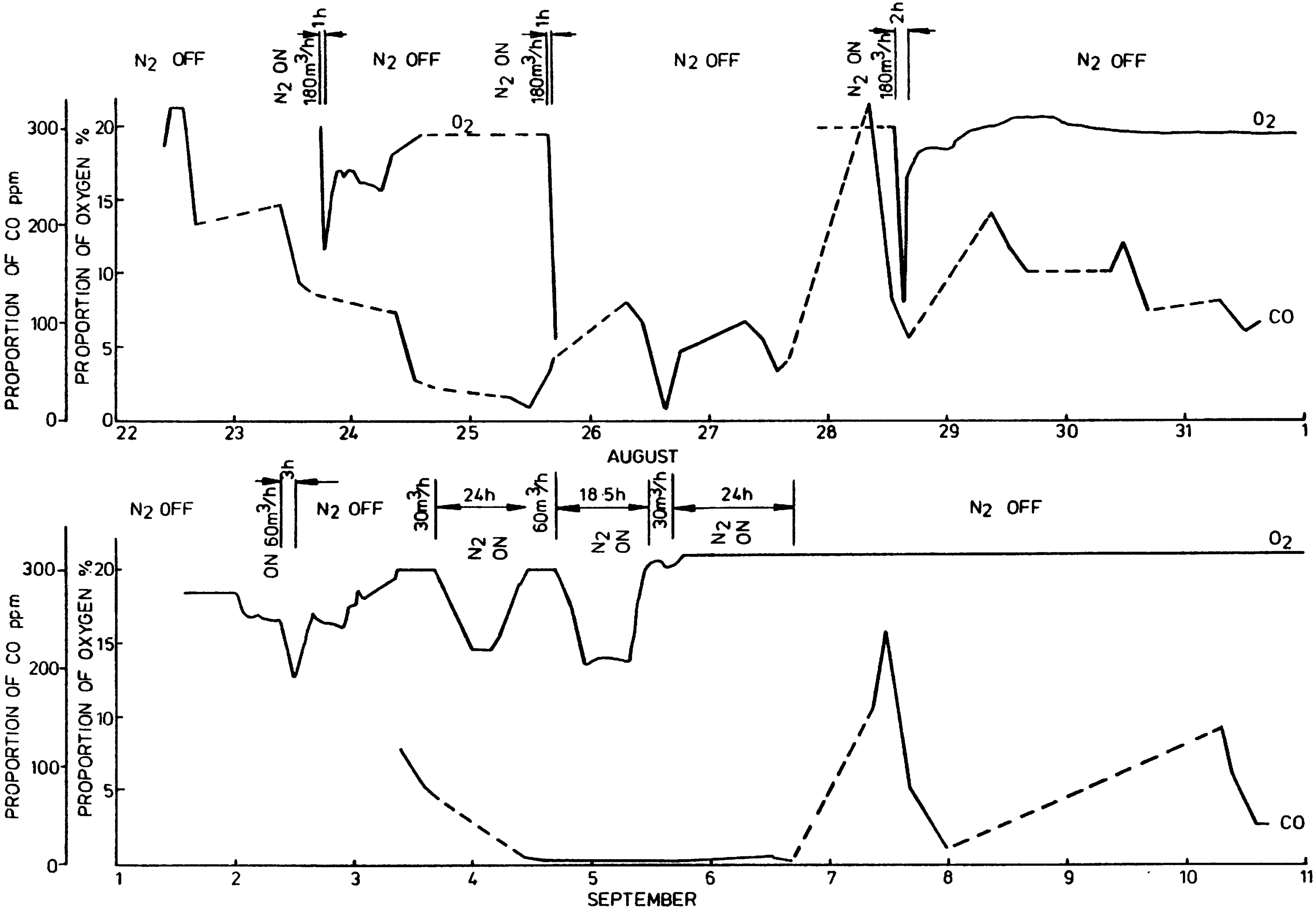

FIGURE 29. PROPORTIONS OF CARBON MONOXIDE AND OXYGEN WHEN NITROGEN BEING INJECTED INTO STAVE SILO

7220-ED/802

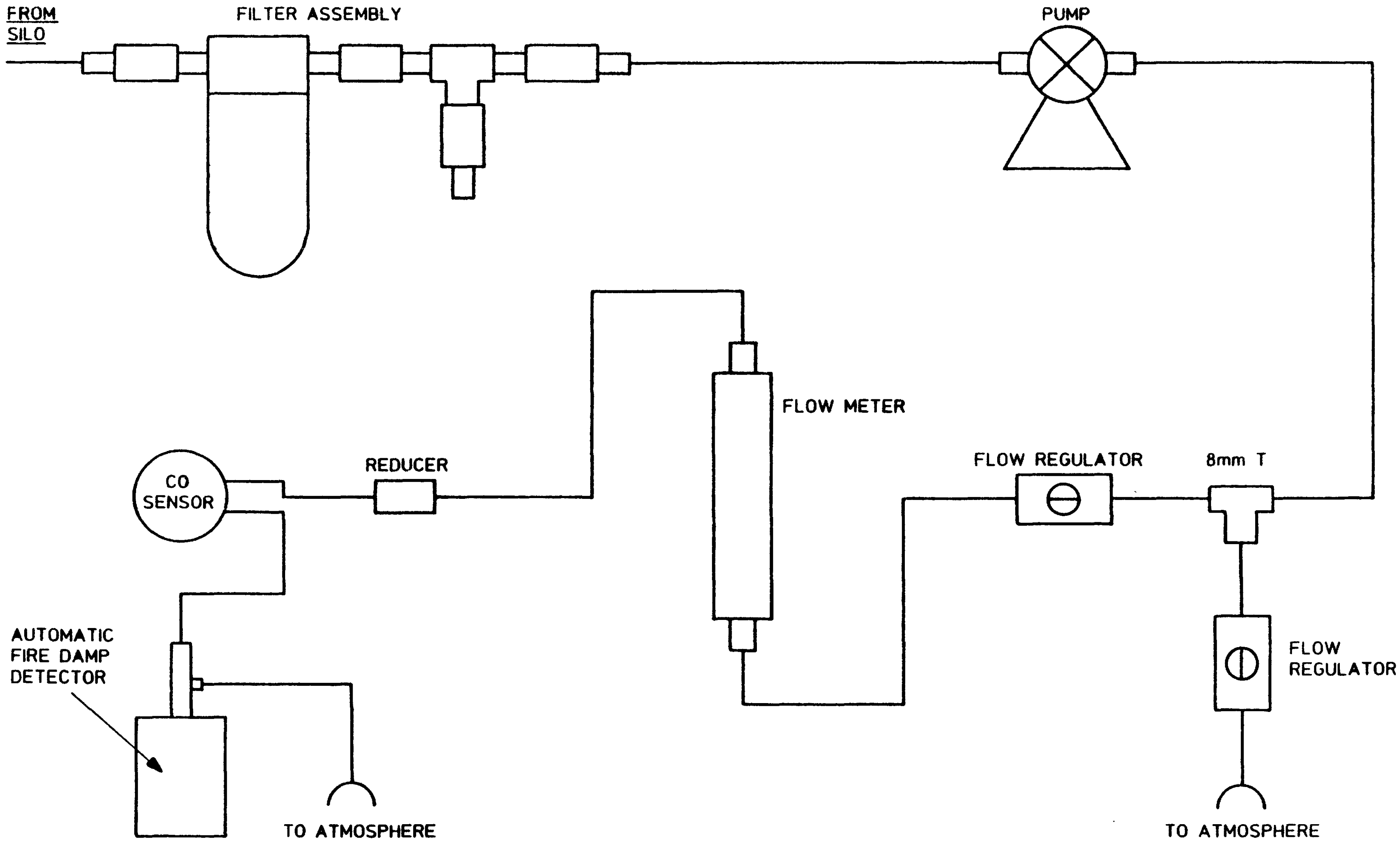

FIGURE 30. SCHEMATIC OF METHANE AND CARBON MONOXIDE CONCENTRATION MONITORING FOR COAL SILOS

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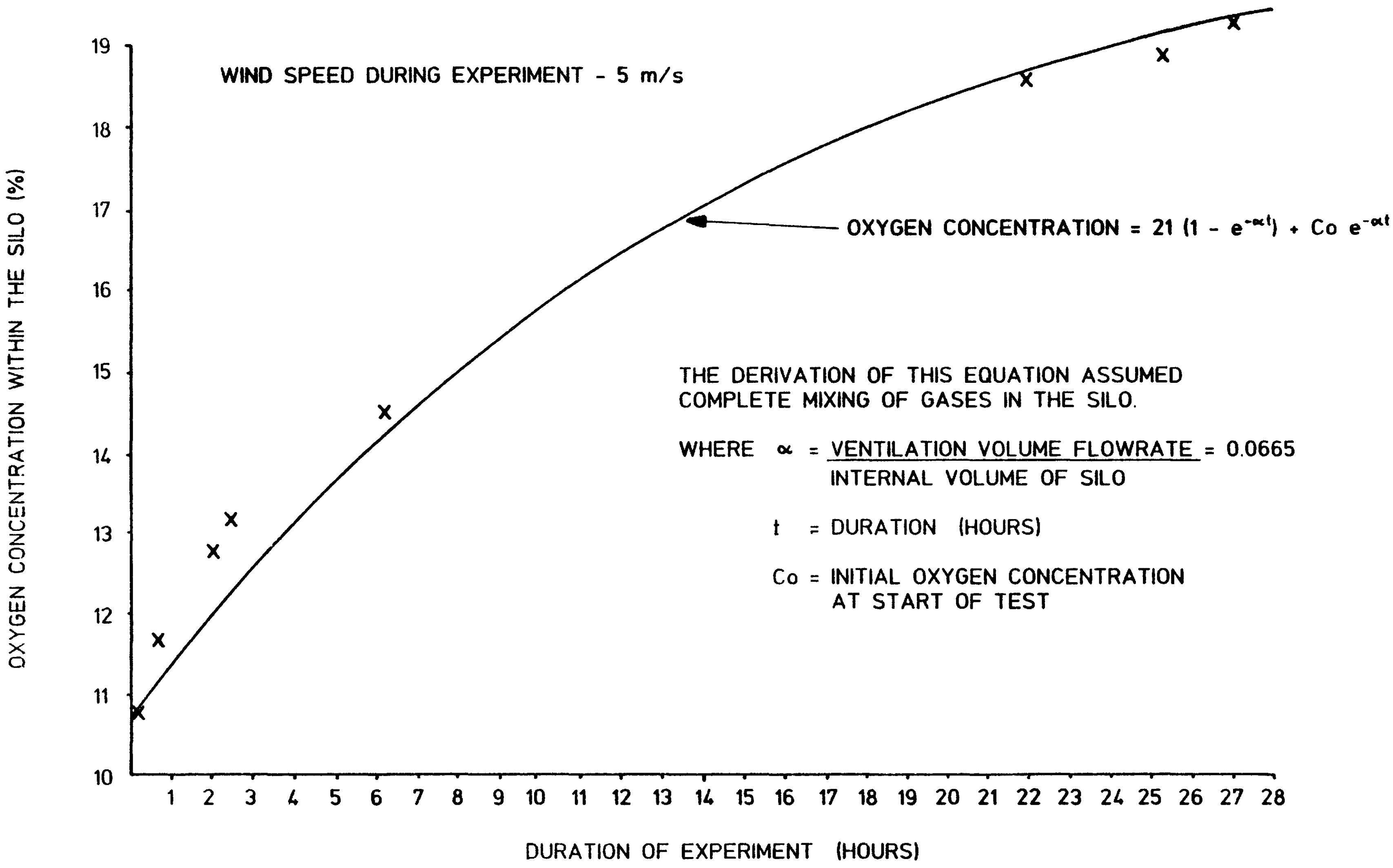
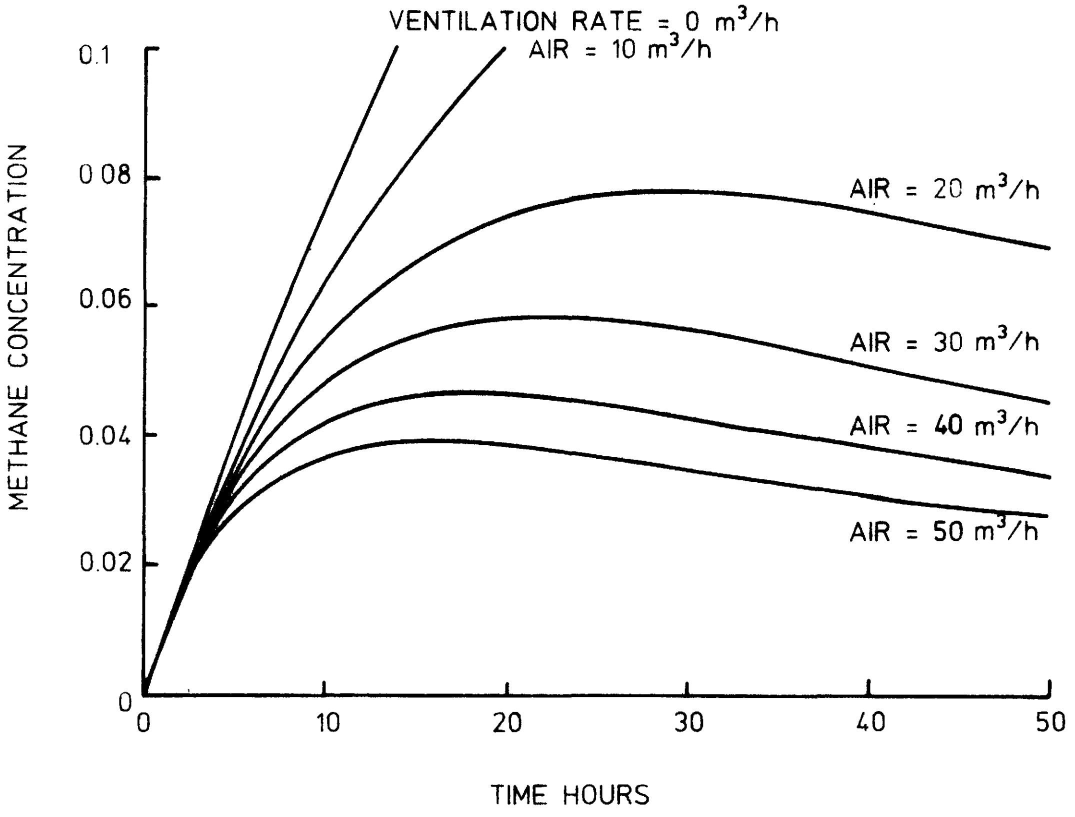


FIGURE 31. GRAPH SHOWING THE EFFECT OF NATURAL VENTILATION ON OXYGEN CONCENTRATION WITHIN THE CONCRETE STAVE SILO AFTER INITIAL PURGING WITH NITROGEN



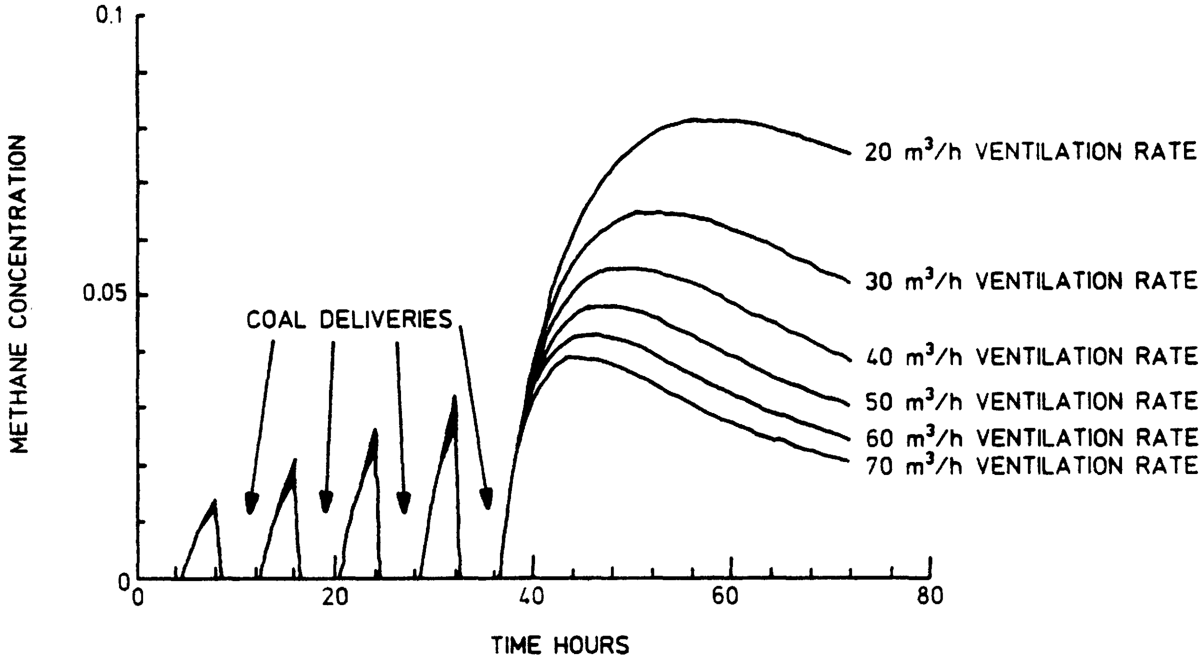
① VOLUME OF SILO = 650 m^3

② MASS OF COAL = 280 TONNES

③ FREE VOLUME = 350 m^3

④ TRAVEL TIME = 48h

FIGURE 32. SIMULATION OF METHANE LEVELS IN A SILO WITH DIFFERENT VENTILATION RATES



1. VOLUME OF SILO = $650 m^3$
2. INITIAL MASS OF COAL = 0
3. SIZE OF LOAD = 40 TONNES
4. TIME TO EMPTY ONE LOAD = 4h
5. TIME BETWEEN LOADS = 4h
6. NUMBER OF LOADS = 5

FIGURE 33. SIMULATION OF METHANE LEVELS IN A SILO WITH DIFFERENT VENTILATION RATES SHOWING EFFECTS OF PNEUMATIC COAL DELIVERY

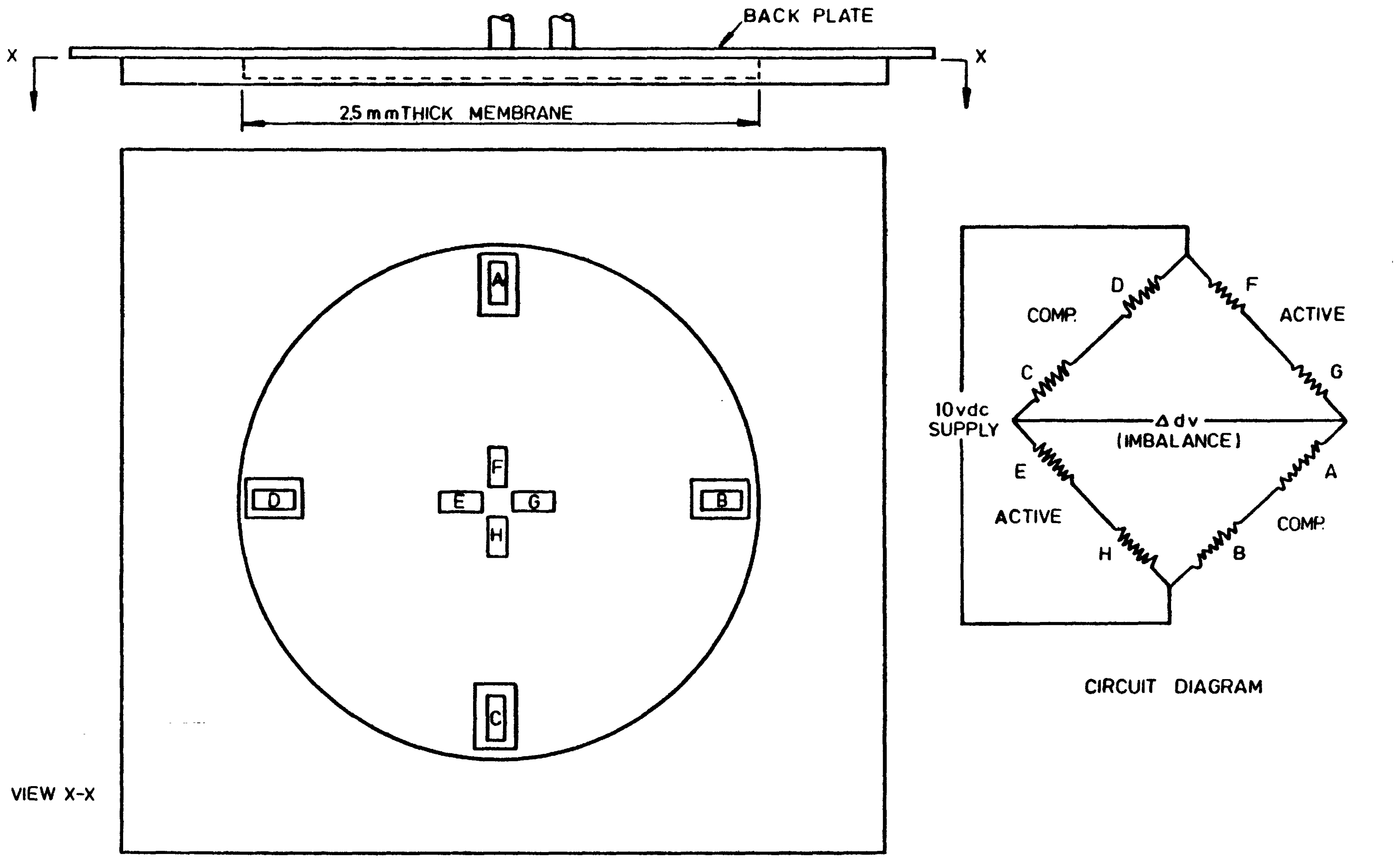
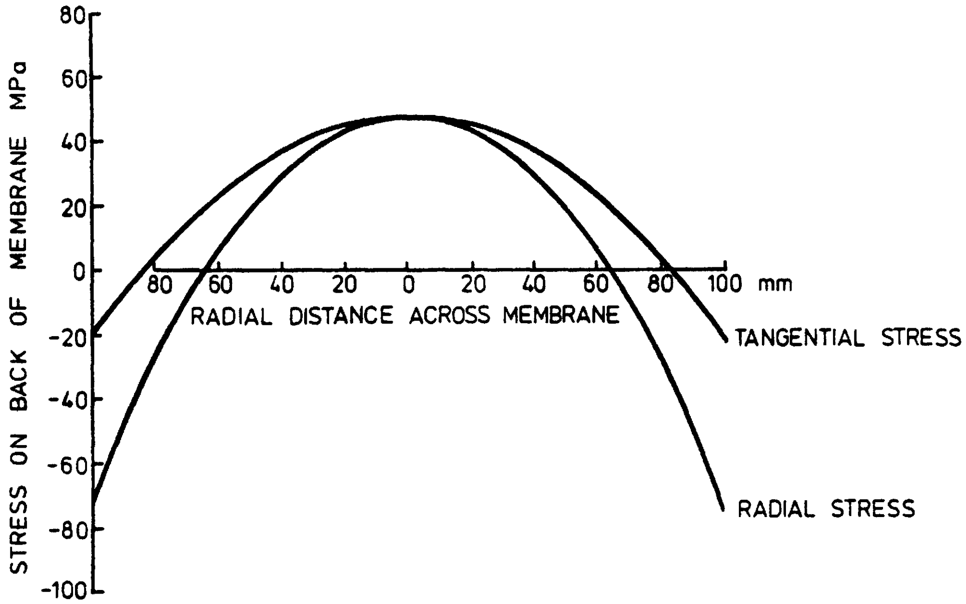
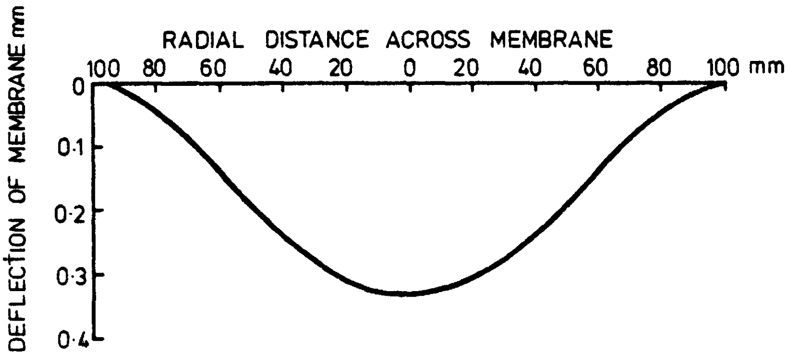


FIGURE 34. CONFIGURATION OF STRAIN GAUGES ON DIAPHRAGM PLATE

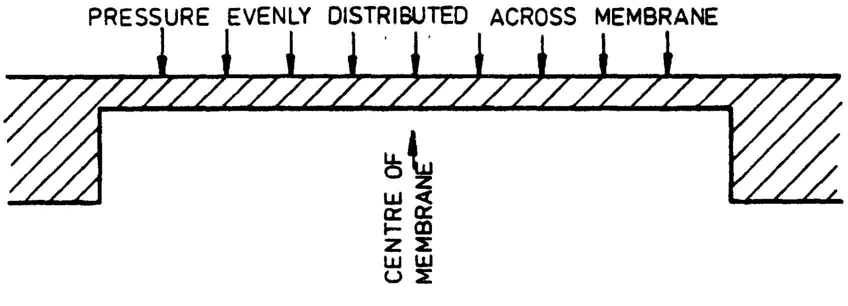
7220-FD/802



a) RADIAL AND TANGENTIAL STRESSES ACROSS MEMBRANE



b) DEFORMATION ACROSS MEMBRANE



c) SECTION THROUGH MEMBRANE

FIGURE 35. EXPECTED DISTRIBUTION OF RADIAL AND TANGENTIAL STRESSES ACROSS THE PRESSURE PAD MEMBRANE AND ITS DEFORMATION WHEN A PRESSURE OF 60KPa IS APPLIED

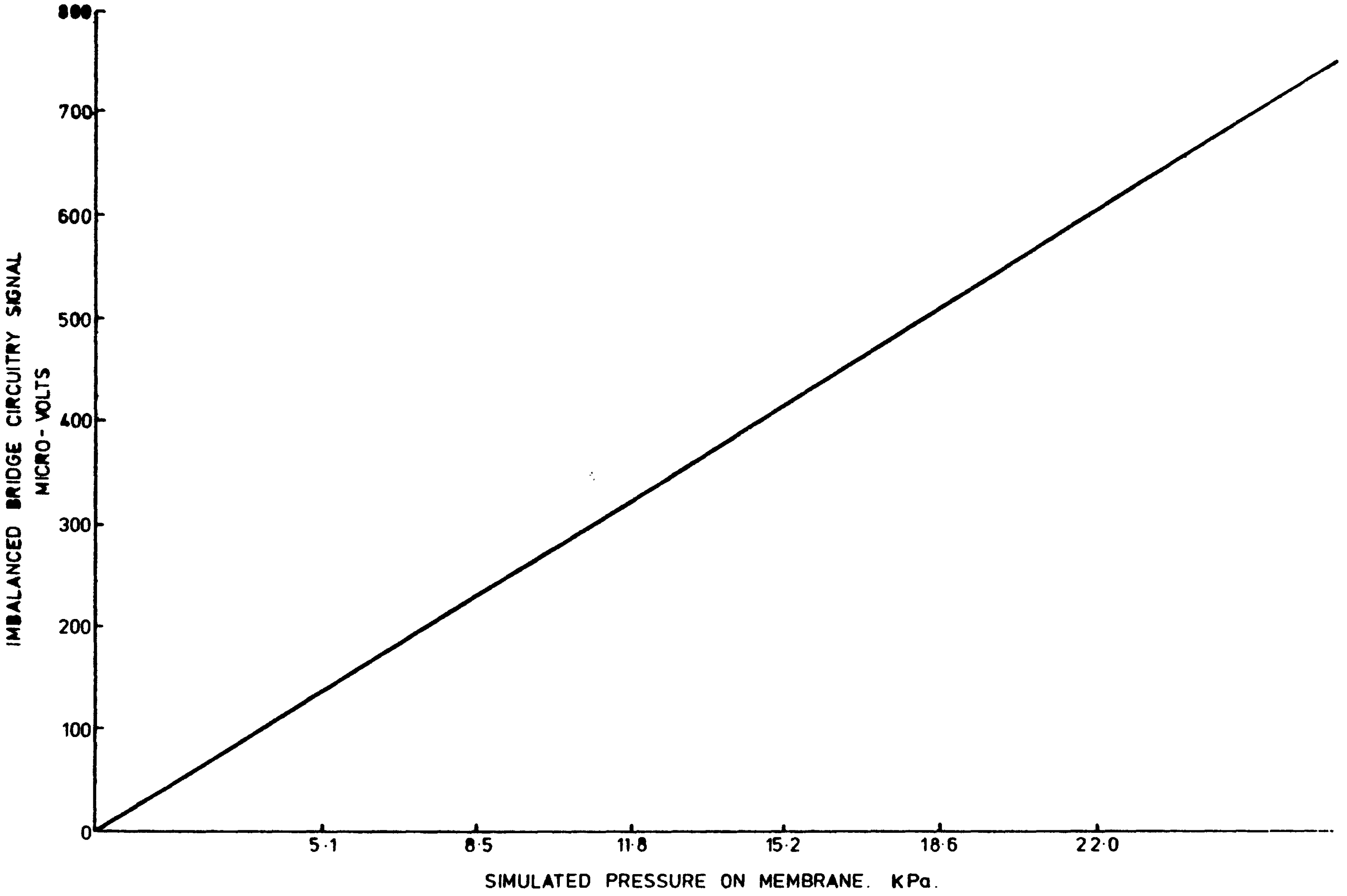


FIGURE 36. TYPICAL WALL MOUNTED PRESSURE PAD CALIBRATION

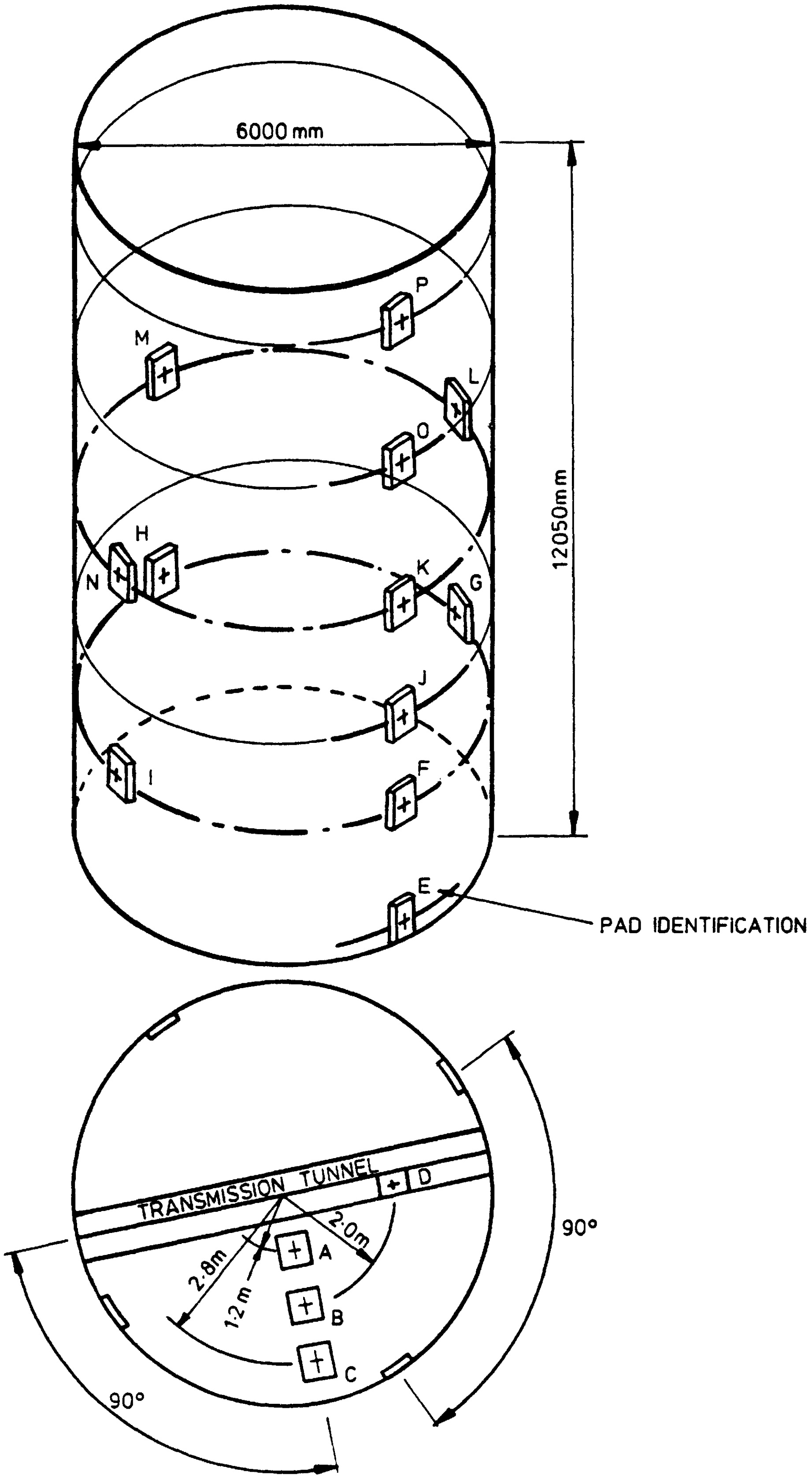


FIGURE 37 POSITIONS OF WALL AND FLOOR MOUNTED PRESSURE PADS WITHIN THE 250 TONNE CONCRETE STAVE SILO AT CRE

7220-ED/802

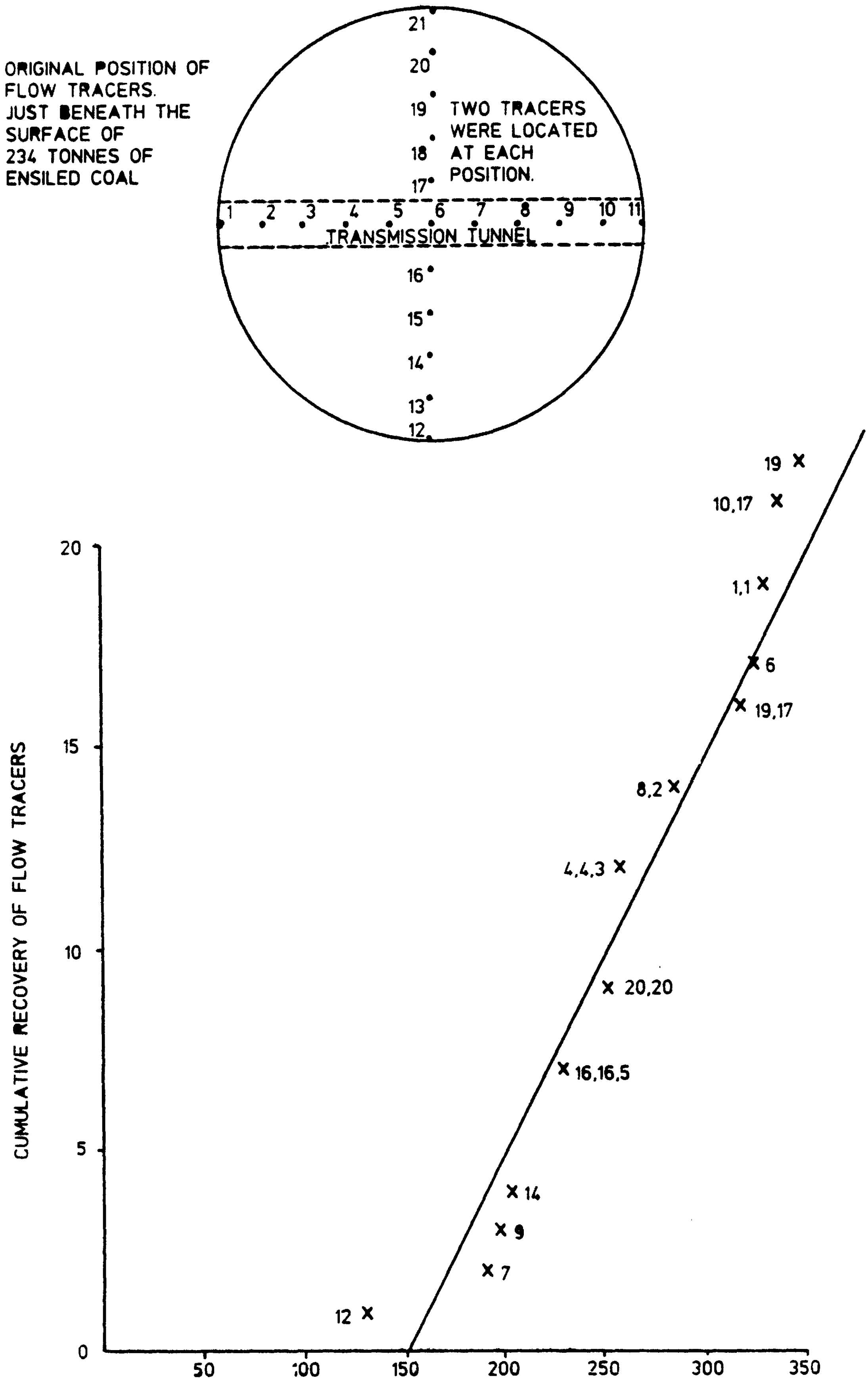


FIGURE 38. FLOW TRACER RECOVERY SEQUENCE WITH THE QUANTITY OF COAL DISCHARGED

7220-ED/802

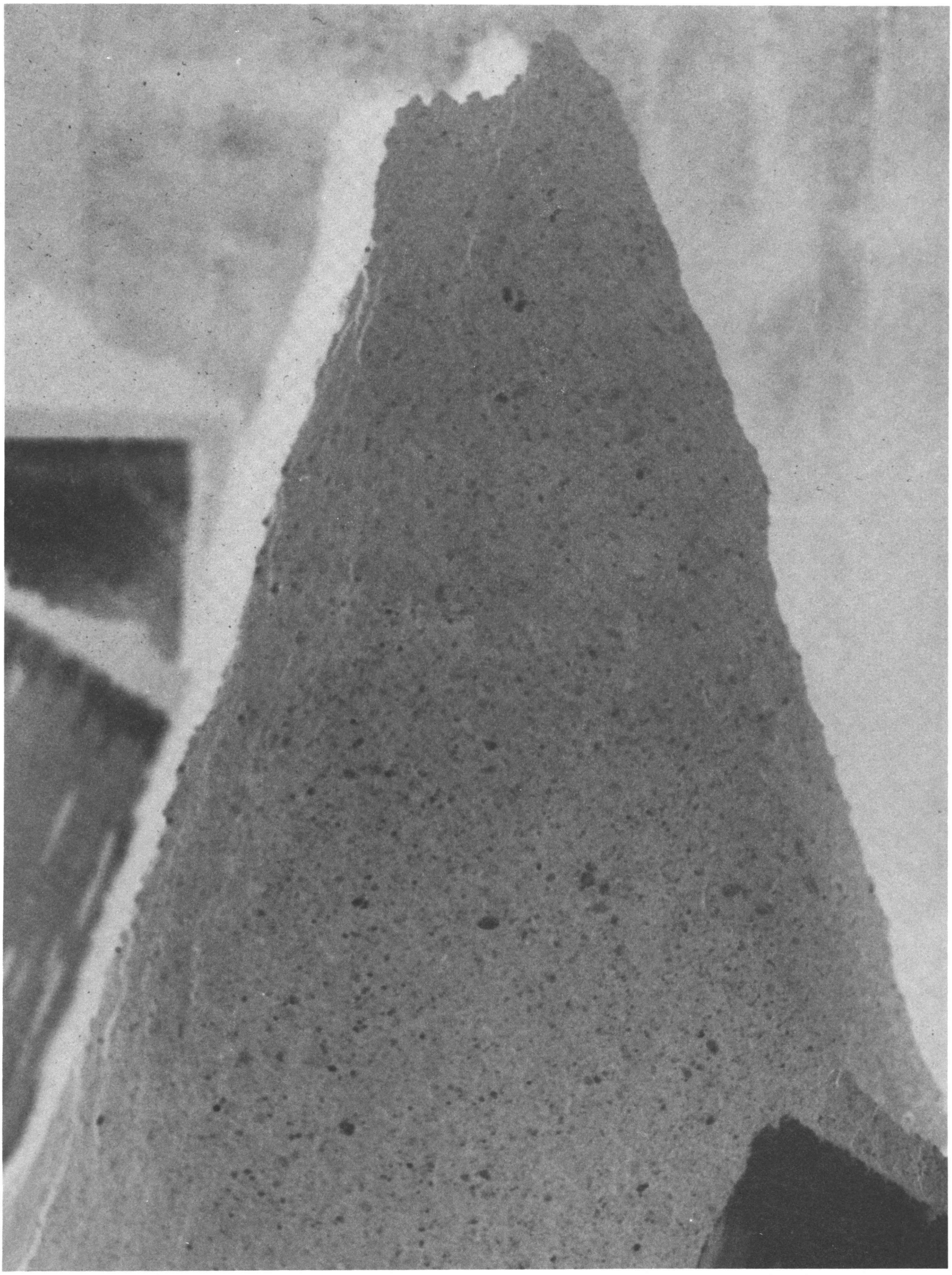


FIGURE 39 COLUMN OF COAL REMAINING IN THE 250 TONNE CONCRETE STAVE SILO AFTER REMOVAL OF CONTENTS

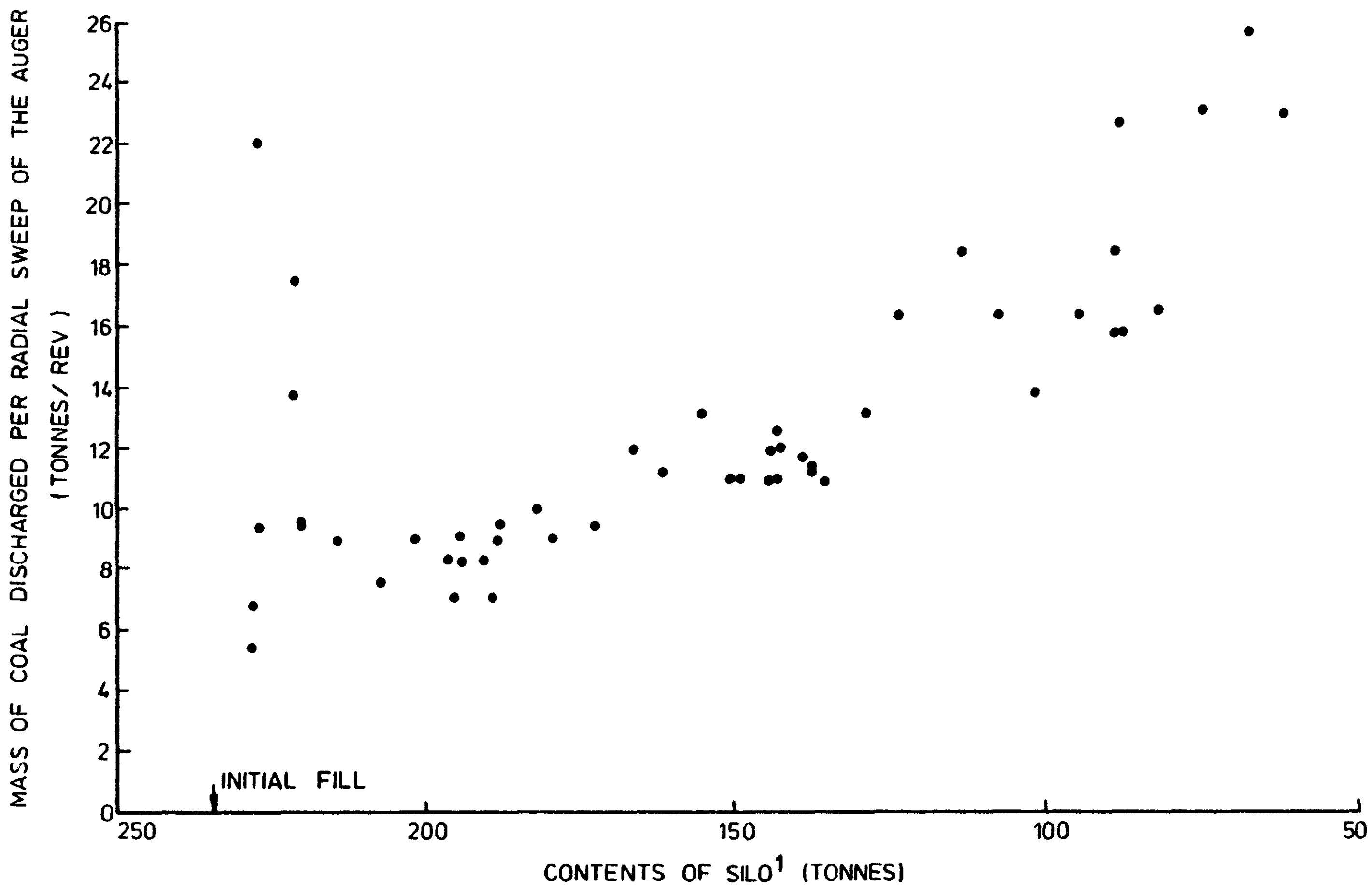


FIGURE 40. THE RELATIONSHIP BETWEEN COAL DISCHARGED AND THE SILO CONTENT

NOTE 1 : COAL WAS RECYCLED DURING THE COURSE OF THE TRIAL

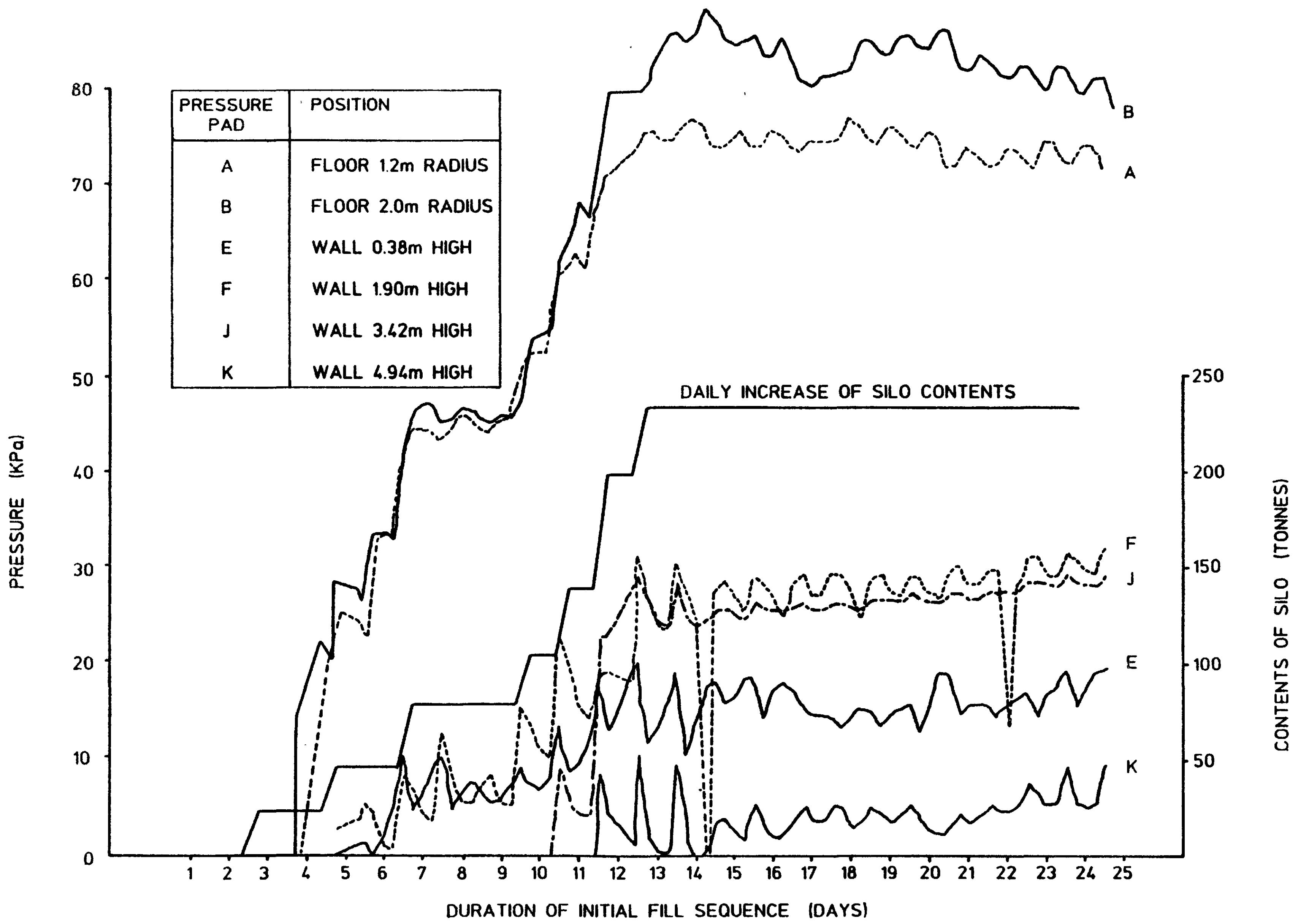


FIGURE 41. INITIAL PRESSURE PAD READINGS WHILE FILLING THE SILO

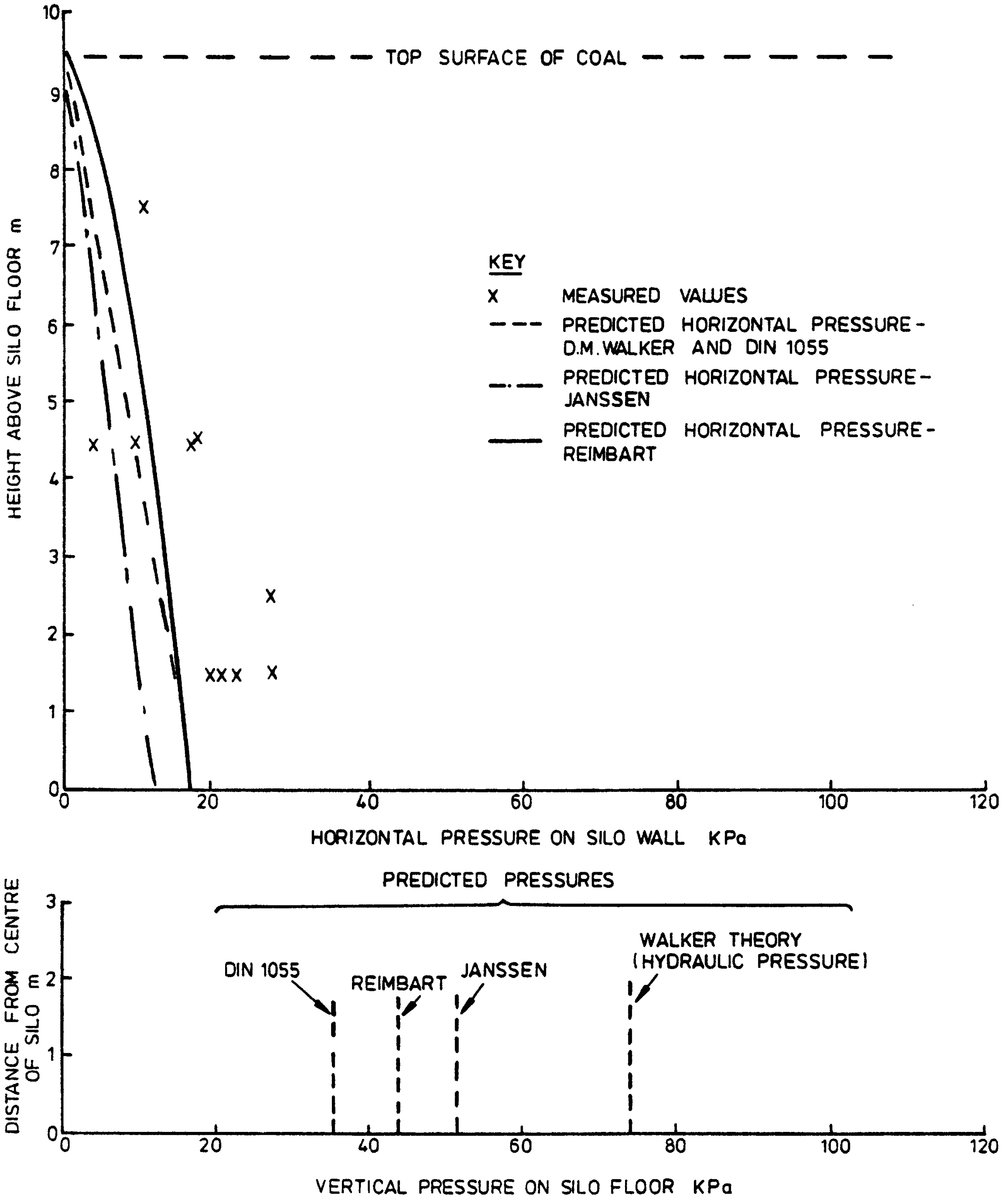
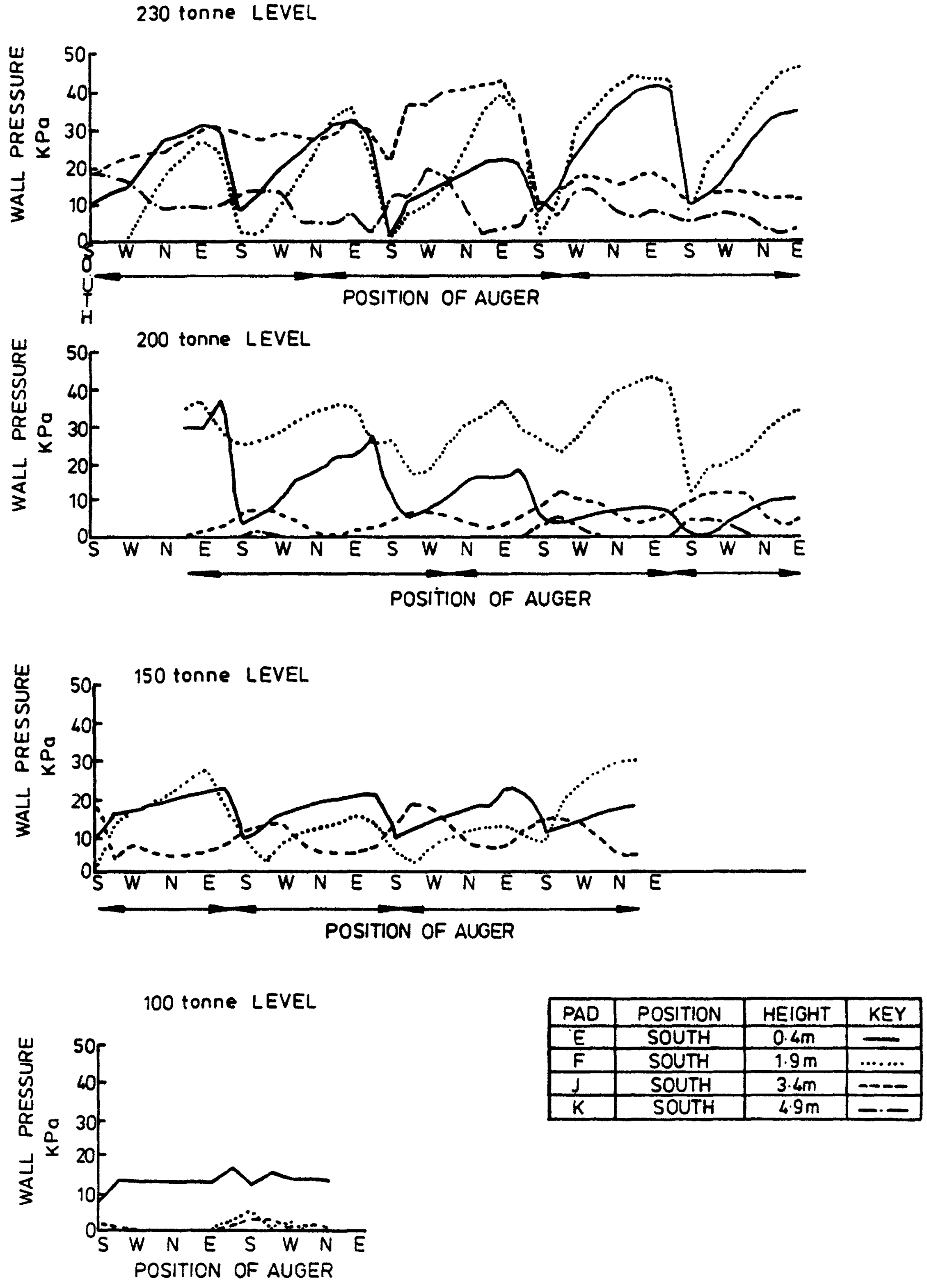


FIGURE 42. PRESSURES ON WALLS AND FLOOR OF CONCRETE STAVE SILO AFTER INITIAL FILLING



PAD	POSITION	HEIGHT	KEY
E	SOUTH	0·4m	——
F	SOUTH	1·9m	....
J	SOUTH	3·4m	----
K	SOUTH	4·9m	—·—

FIGURE 43. THE RELATIONSHIP BETWEEN AUGER POSITION WITH WALL PRESSURES AT VARIOUS HEIGHTS AND VARIOUS LEVELS OF COAL.

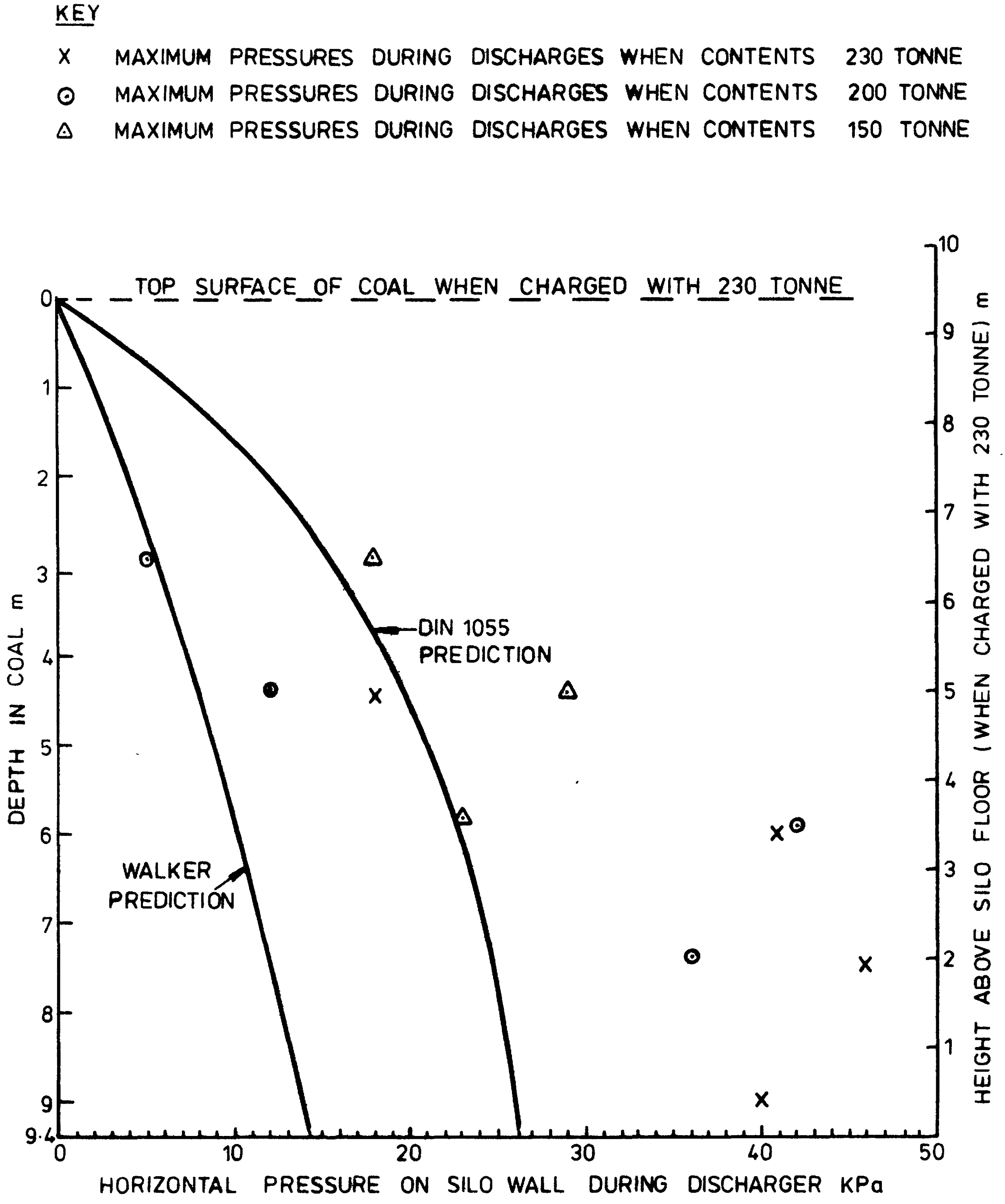


FIGURE 44. MAXIMUM PRESSURES ON WALLS OF CONCRETE STAVE SILO DURING DISCHARGE COMPARED TO PREDICTED PRESSURES.

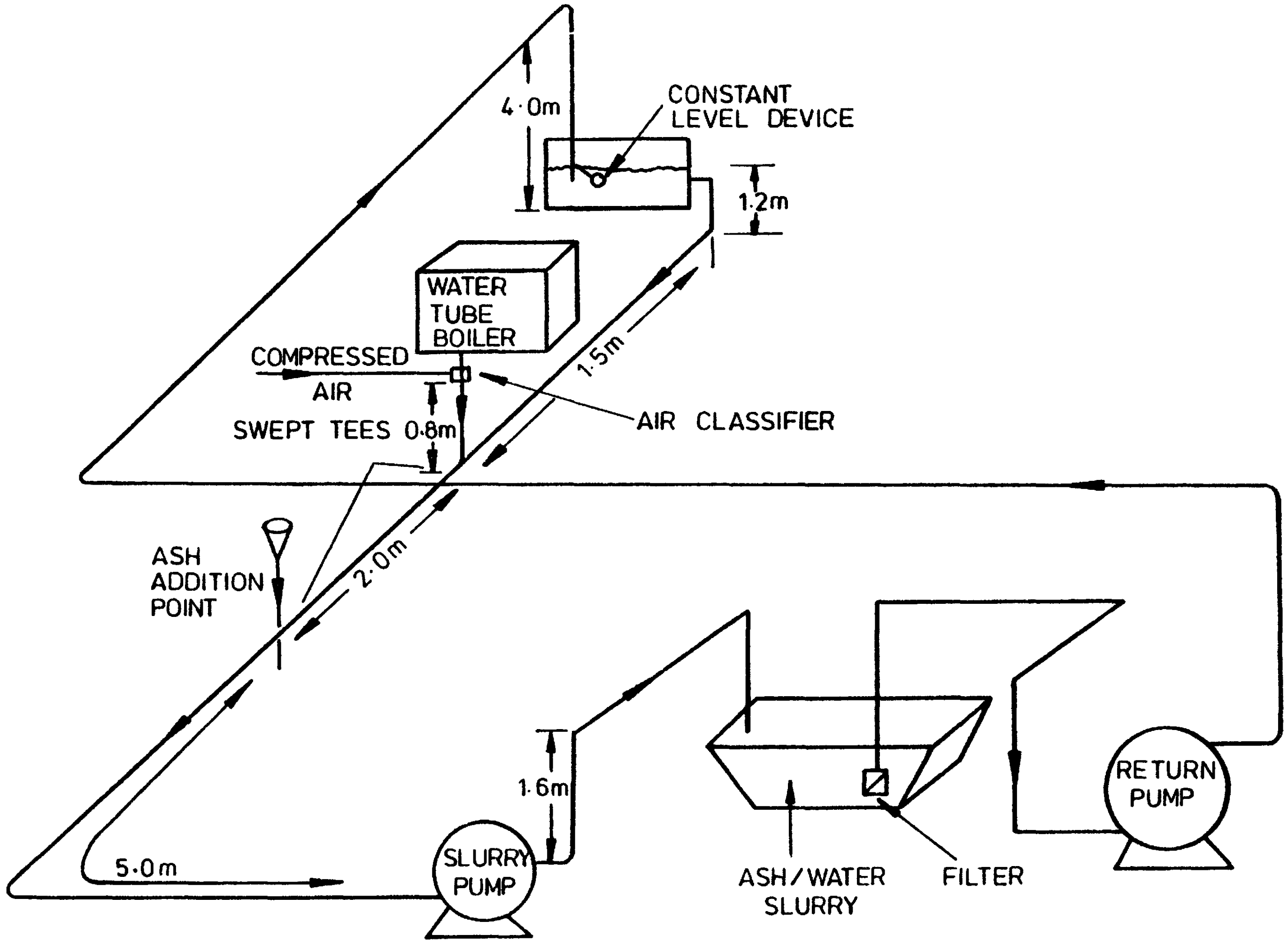


FIGURE 45. ISOMETRIC OF ASH SLUICE TEST RIG INSTALLED AT CRE

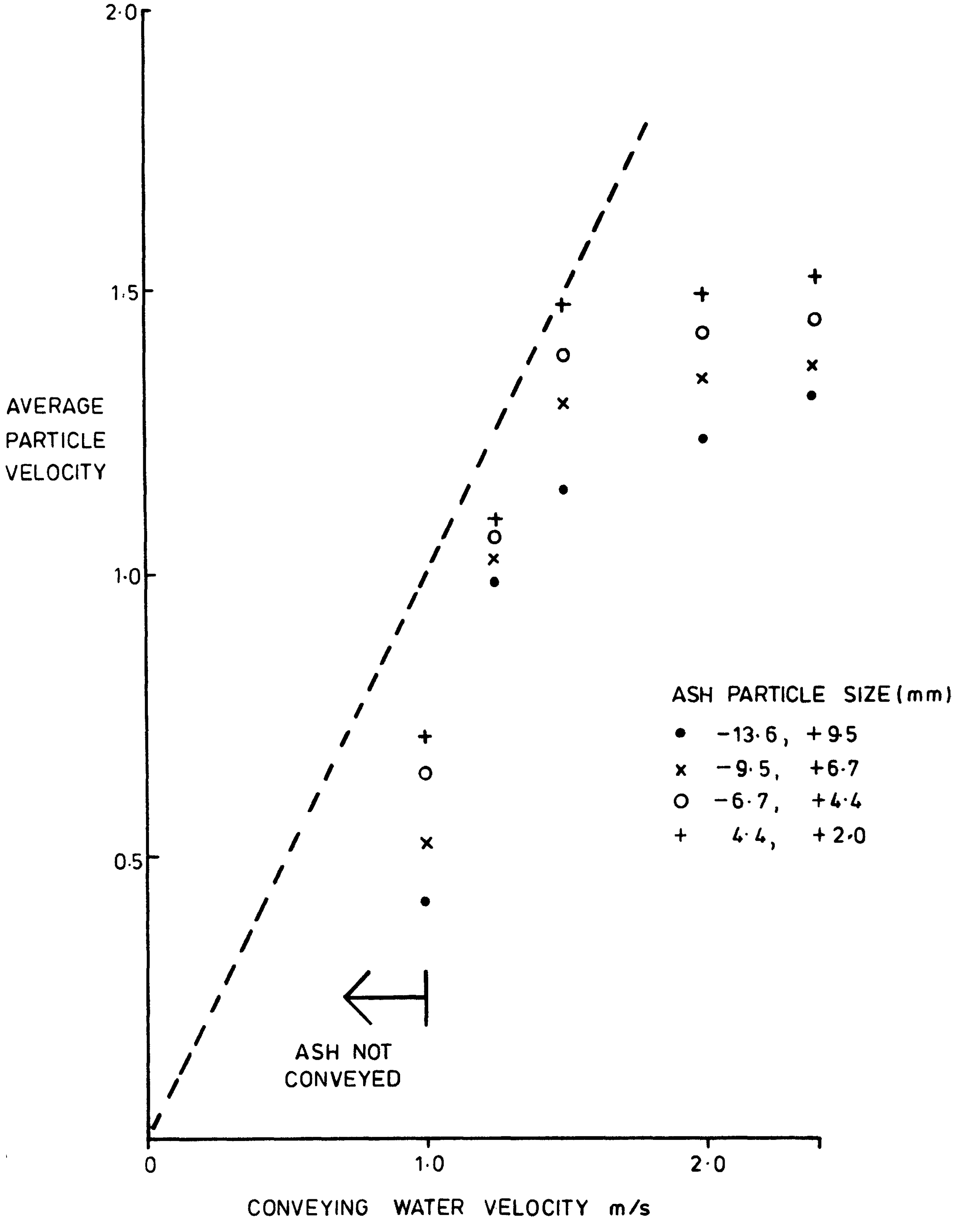


FIGURE 46. GRAPH OF WATER VELOCITY AND AVERAGE VELOCITY OF PARTICLES CONVEYED

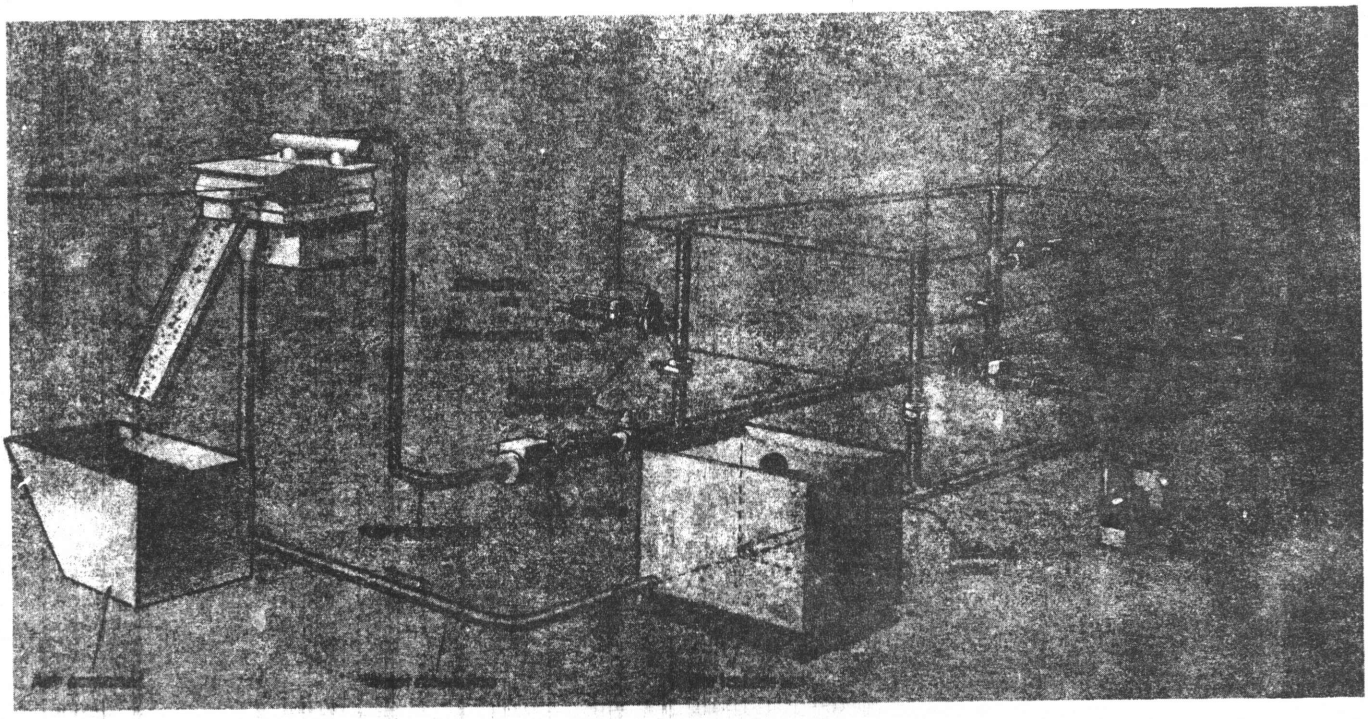


FIGURE 47 HYDRAULIC ASH SLUICE AT CUSTOMER SITE

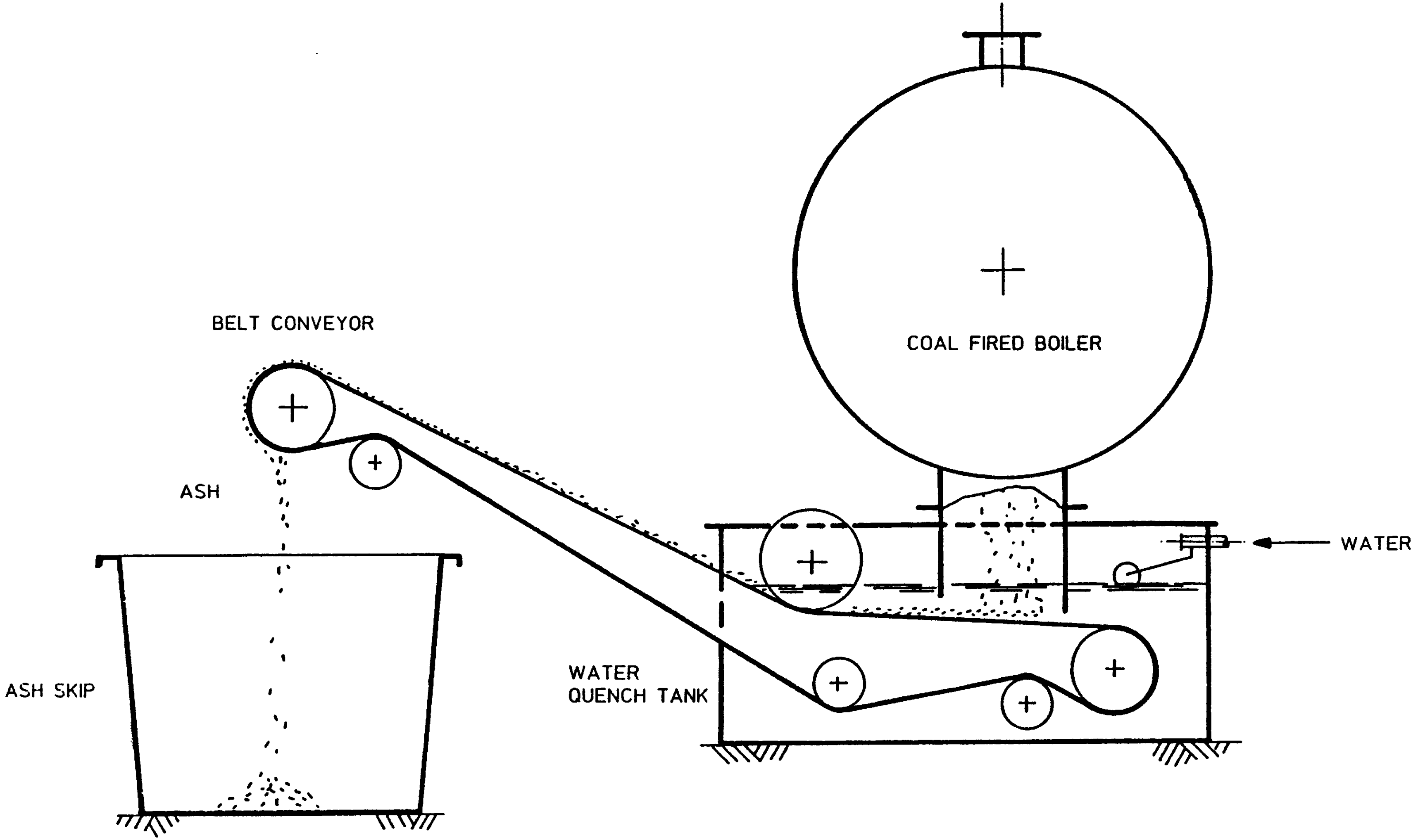


FIGURE 48. ARRANGEMENT OF WET ASH REMOVAL SYSTEM EMPLOYING A RUBBER BELT