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1. Introduction

If results of investigations on evapotranspiration under special circumstances of soil and crop have to be transferred to practical conditions, the laws governing the influence of soils and crops on evapotranspiration should be known.

Which data are required to describe how the various properties contribute to the final value of evapotranspiration and what level of accuracy in measurement should suffice, follows from the process of evaporation. A model of this process was developed by VISSER (1962).

The data needed to verify the working hypothesis embodied in the formulae evolved in that paper, include a direct measurement of actual evapotranspiration from soil and crop. It should be determined daily, if not hourly, and with a high accuracy. Weighing of soil blocks is then the only procedure possible.

For this purpose a weighing machine has been constructed which is capable of continuously indicating the changes in weight, due to evapotranspiration or rainfall, of rather large soil blocks. The mechanism is described and preliminary experiments with a prototype are discussed in this paper.

2. Design requirements

The weighing machine was to be made for a lysimeter, of which in our case two are situated on either side of a narrow corridor in a brickwork cellar. The containers are of armed concrete and have inside dimensions of 120 x 140 cm and a depth of 175 cm; the wall thickness is 6 cm. They are filled with different soils and the groundwater depth can be fixed at will. According to the moisture depletion curve of the soils, the maximum weight of the filled containers at practical groundwater levels could be estimated to be 7.5 tons.

The machine is to indicate continuously with a high sensitivity and accuracy the changes in weight of such a container. It was assumed that a weighing error of 0.1 surface millimeters of water - or 168 grams - would be acceptable.

The containers are sunk into the cellar to such an extent that the soil in them is level with the soil surface of the field. To exclude as far as possible any discontinuity in the vegetation, the weighing mechanism should be placed under the container. It then must be assembled on the spot because the containers can only be lifted a few inches by means of four jacks. The mechanism should be compact in vertical direction, since between the floor of the cellar and the bottom of the containers only 60 cm was available. Some working space should remain below the mechanism to give access for repairs.

The indicating or registrating mechanism could be situated in the working corridor, this also making an easy observation possible.

The possibility of adapting the design of MORRIS (1959) was rejected, mainly because of the high costs that then would be involved.

3. Description of the machine

3.1 General principle

When balancing a variable weight and registrating the changes with a high order of sensitivity and accuracy, the frictions in the transmission devices are the most difficult to deal with. It was decided that a hydraulic device would have the most favourable properties to eliminate the moving parts of a transmission.

The most essential part of the mechanism is a hydraulic jack of a particular type. It is a steel pressure-cell of which three are supporting the container on membranes that are protected by steel lids. The pressure-cell is filled with oil that can be put under such a pressure that it is possible to lift the lid clear from the contact it has with the other steel parts of the cell, making then the membranes the only surfaces supporting the container. This pressure can be read from a manometer. When the supporting area of the membrane is known, the weight of the container can be calculated.

3.2 The weighing part of the mechanism

3.2.1 Design of the hydraulic pressure cell

The pressure cell is circular, a cross section is shown in fig. 1. In the steel bottom plate, a wide and shallow pressure chamber was turned that has a connection with a pressure pipe. At the top the chamber is closed off by a membrane of 0.05 mm Melinex, a polyester film. Over it is a sheet of 0.2 mm teflon coated glass fabric to give strength to the membrane. The two films are glued together and are clamped to the bottom plate with a tapered steel ring. Use of a rubber O-ring guarantees a perfect sealing. On the membrane and fitting in the tapered ring rests the lid, a tapered steel plate. A third plate is covering the tapered ring and plate, and supports the container. Fig. 2 gives a view of the constituent parts of the cell. Some important details of the pressure cell, when not in use, are shown in fig. 3. Between the tapered plate within the ring and the plate covering it is a tolerance of 0.3 mm. The covering plate (f) is supported by the ring (c). The tapered plate (e) is cylindrical to a height of 1.1 mm from its bottom. This part is projecting below the base of the tapered ring (c). There is a difference of 0.1 mm between the radius of the cylindrical part of the tapered plate (e) and the smallest inside radius of the tapered ring (c).

When pressure is built up in the cell, the membrane pushes the tapered plate (e) against the upper plate (f). When pressure increases, the plates of the three pressure cells will at a certain moment rise and lift the container from the rings (c). It can be lifted 0.8 mm (1.1 - 0.3), then the base of (e) rises above the top of (a) and the membrane exerts a counter force on the oil and the supporting area may become smaller.

Condition for a friction free lift is that the plates rise in a position which is parallel with the bottom plate and centered in ring (c). To recover a lost centered position, the pressure must be released so the tapered plate will come down, lose contact with the upper plate (f) and center itself in the ring in correct position. Pressure can then be applied again.

To make sure that no contacts whatsoever remain between the lifted plates and the other metal parts of the pressure cell, tell-tale lamps on weak current circuits are used.

3.2.2 Diameter of the hydraulic pressure cell

The diameter of the pressure cell originated from a compromise between the desire to get a sensitivity and an accuracy as high as is needed, and to keep the operating pressure at a level that would not necessitate an excess of technical precautions. The first demands for a small supporting area of the cell and consequently a high pressure; the second item demands a low one.

As will be seen in 3.3 it is possible with a simple device to maintain a high reading accuracy of the changes in the height of the mercury-column which is balancing the weight of the container. For that reason it was decided that a relatively low pressure of about two atmospheres would do. With the container weighing 7.5 tons, this would bring the supporting area of the membranes at about 3750 cm^2. To guarantee a stable position of the container, the weight has to be divided over three supporting cells. This together with a limit to the available sizes of rubber O-rings, fixed the diameter of the supporting area of one membrane at 388 mm. The total supporting area per container is then 3548.52 cm^2. With a load of 7.5 tons this calls for a pressure of up to 2.1 atm.

The overall diameter of the cell made, is 430 mm; the overall height could be limited to 30 mm.

3.2.3 The position of the hydraulic pressure cells

The position of the three identical cells under a container has to be such, that every cell sustains as near as possible a third part of the total weight. These positions are determined by the centres of gravity of three equal volume parts of the container, but they have to be corrected experimentally because the filled container is not a completely homogeneous block.

It is important that the three cells are situated in a horizontal plane, since this facilitates an even distribution of weight. The cells have therefore been put on a supporting frame with an evened horizontal upperside resting on brickwork posts. Since the container can only be lifted 0.8 mm, this means the top plates of the cells have to remain horizontal will the bottom plates rest only on the membranes. To affect this an iron frame identical to the one underneath the cells has been put between the cells and the containers, which have anyway an uneven bottom. In this case the bottom of the frame is even. It is isolated from the upper plates of the cells by a sheet of Pertinax to make it possible to check the cells separately with the mentioned weak current circuit.

Fig. 4 shows the situation of the cells and frames relative to the base of the container. Fig. 5 and 6 give a view of the actual situation in the cellar.

3.3 The registrating part of the mechanism

When the weighing mechanism operates, the pressure that is necessary to keep the container floating on the compressed oil is continuously indicated by open mercury-manometers. Since there is no possibility to divide the variable weight of the container perfectly equally over the three cells and keep it like that, each cell has a manometer. In 3.4 it is explained how pressure differences between cells are being achieved.

The cells are attached to their manometers with flexible plastic pressure tubes with an inside diameter of 6 mm. The manometers are of the U-type. The interesting thing about them is a device to multiply the changes in the height of the mercury-column that is balancing the load on the cell (see fig. 7).

A manometer was made of perspex tubes with an inside diameter of 14 mm. At a point above which the mercury is not expected to rise, the open tube of the manometer changes into a tube with an inside diameter of 2 mm provided with a scale. On the mercury in the open tube a light, slightly coloured oil is poured till an oil-meniscus shows in the narrow tube when a load is balanced. Now a change in the position of the mercury meniscus in the open tube of the manometer will show 49 times enlarged in the changing position of the oil-meniscus. A change in the height of the mercury-column, which balances the weight is enlarged $24\frac{1}{2}$ times.

The capillary tube is inclined to about 10° to the horizontal, to facilitate reading of the oil-meniscus when standing on the floor of the cellar (see fig. 8).

The large factor with which the rise of mercury is multiplicated when it is converted into that of the oil-meniscus may cause the latter to go off the scale. Then the volume of oil on top of the mercury has to be reduced or increased. A three-way tap has therefore been fixed at the lowest point of the inclined tube, making it possible to connect it either with a reservoir for oil or with an outlet pipe, or closing both.

The manometers are placed in a transparant vessel so the mercury columns can be surrounded with water of a constant temperature.

3.4 The operating mechanism

3.4.1 The electric part of the mechanism

It follows from what has been mentioned in 3.2 that there is a minimum as well as a maximum elevation of the containers. The minimum is necessary for a free support of the container by the compressed oil. This is the limit of frictionless weighing. The maximum is attained when the membrane is at the point of bursting and would do so if the oil pressure was increased. This is the limit of membrane strain.

It would be possible that the elevation would go over, respectively drop below these limits. When a load is balanced by the mercury-column in the manometer, there is a certain volume of oil between mercury and membrane. The pressure in this oil is proportional to the balanced load and not to the volume of oil. When this pressure is constant, small losses of oil through leaks in the system would cause a decrease of the elevation at some very slow rate. This would also happen when the loss of oil should exceed the small quantity of oil flowing out of the manometer when the balanced weight is increasing. When there are no losses of oil, an increase in weight would also decrease the elevation because oil is transported from the cell to the manometer. On the other hand would a decrease of balanced weight increase the elevation. In consequence of this and because the weighing is to be continuous, the elevation should be kept automatically within the limits mentioned.

This is accomplished by the use of electric contacts to detect the position of the elevated parts of the cell. Fig. 9 gives a close up of these contacts. Fig. 2, 5 and 6 show how they are attached to the cell.

On the upper plate, and isolated from it, is a central two-sided contact projecting between two one-sided contacts screwed on, and isolated from, the bottom plate. With the two-sided contact they form part of two separate electric circuits.

To prevent the drawing of sparks at the contact points the electric circuits have a current of reduced voltage. In the conditions of the cellar, however, the contacts easily become dirty and contact-boosting is necessary.

The one-sided contacts can be adjusted very accurately with a screw. The lowest one should be adjusted to break circuit when the elevation is just large enough for frictionless weighing. The upper one should close the circuit when the elevation comes to the critical straining limit of 0.8 mm.

In fig. 10 a scheme is shown of the electric circuits governing the hydraulic mechanism. The contacts on the cells activate relay switches. These command solenoid valves which are parts of a hydraulic system. Tell-tale lamps show the action of these valves. The electric- together with the hydraulic part of the mechanism restore the required elevation when the contacts on the cells detect a deviation.

3.4.2 The hydraulic part of the mechanism

A scheme for the hydraulic part of the mechanism is shown in fig. 11. The solenoid valves are connected with the cells by plastic pressure tubing. To each cell with its accessory manometer belong two solenoid valves. An admission valve is connecting the cell and manometer with a pressure cylinder, in which the oil pressure is maintained at a higher level than can be expected to be required in one of the cells. A discharge valve is connecting the cell with an outlet which discharges in a reservoir under atmospheric pressure.

When the admission valve opens, the volume of oil between membrane and mercury-column increases. Because the compression of this oil depends exclusively on the balanced weight, the elevation is bound to increase.

When the discharge valve opens the volume of compressed oil decreases as well as the elevation.

When in the pressure cylinder the pressure drops below a minimum value of about 2.5 atm a pressostat starts the motor driving a gear pump. This pumps oil out of the reservoir through a filter and via a pressure regulator with a by-pass valve and a non-return valve into the pressure cylinder. The pressure in the cylinder is indicated by a manometer.

Between pressure cylinder and admission valves are a main stop valve and three handoperated valves, one to each solenoid valve. The same precautions have been taken between the discharge solenoid valves and the reservoir. They are necessary because contacts and solenoid valves have to be tested without risking an unwanted transport of oil.

Fig. 12 shows the iron case which holds both the electric- and hydraulic parts of the mechanism. The contents of this case are shown in fig. 13. Triple core cords are connecting it with the contact-sets on each of the cells and with the electric main.

3.5 Some advantages of the design

The mechanism described has some advantages when the design requirements are considered.

a. The weighing mechanism can be assembled on the spot where it will operate. To this effect the container was lifted with jacks of the familiar kind, ~~seen in fig. 5 in the left hand corner~~. The top of the brickwork posts was cut off to such a height that the surface of the soil block in the container was at the same level as the soil surface surrounding it after the mechanism was placed in position. On the posts the lower frame was placed level in wet mortar. When this had hardened, the pressure cells were put into position and after that the upper frame. Then the contacts were installed and the container was lowered on the construction. Connecting the cells with the plastic tubing was the last action to be performed under the container.

b. The flow of the quantities of oil when the balanced weight changes, is very small. Heavy rainfall will cause the quickest changes in weight. In the Netherlands about once a year a rain with an intensity of 1 mm per minute will occur during 5 minutes. During such a shower the weight of a container will change with 1.680 kg per minute. This will cause an increase of the height of the mercury column in each manometer of 0.40 cm and a transport of only 0.03 cc oil per minute. So even in the most extreme circumstances the loss of pressure in the tubing due to friction of the flowing oil can only be of a theoretical significance.

From this point of view the length of the tubing between cells, manometers and operating mechanism is not a factor of importance to the accuracy or sensitivity of the machine. The case holding the operating mechanism, as well as the manometers could therefore be situated anywhere inside or outside the cellar.

c. The mechanism has to be put into operation only once. After gaining a balance between load and mercury-columns, reading is possible at every moment. It only may be necessary to center the tapered plates in the cells by deflating once in a while, but this will not be frequently necessary.

The registering part of the mechanism could and should in time be made self recording.

d. The device can be easily adapted to larger or smaller weights by using cells with a larger or smaller supporting area of the membranes, or by adapting the range of the manometers.

When the ratio between balanced weight and required pressure should become unfavourable for a high sensitivity and accuracy, the ratio between the inside diameter of the mercury tube and the reading tube should be adapted.

4. Operation and calibration

4.1 Operation

To operate the machine, the contacts commanding the admission solenoid valves are closed. The tell-tale lamps, indicating when a free support on the membranes is attained, are connected. The hand-operated admission valves are then opened to admit pressure. When the tell-tale lamps show that the container rests free on the membrane, the particular hand-operated valve is closed again. It costs some time to reach the situation in which all three cells are supporting the container only on their membranes. This is due to the fact that when the pressure in the cells increases there is not at once an even distribution of weight over the cells. Moreover, the position of the oil menisci in the reading tubes has to be adapted to the changes in weight that are to be expected. These positions influence of course the pressures counterbalancing the weight of the container and changing them affects the balance.

Having gained a lasting equilibrium, the contacts on the cells are adjusted. After bringing the cells into operation, the first reading can be made. It is recommendable to adjust the oil menisci in the reading tubes in such a way that they occur in about the same reading interval. This facilitates a quick reading of the three tubes which is of importanc with respect to item b in 4.2. The starting position of the oil menisci will depend on the nature of the experiments that are going to be conduc ed. When for instance a continuous reduction of weight can be expected, this position should be chosen at the upper end of the reading tubes.

Whenever the reading is going off the scale, the volume of oil in the capillaries has to be reduced or increased and readings have to be taker before and after the change.

4.2 Some possible sources of error

There are some possible errors which are of importance due to the high accuracy demands made.

a. When a solenoid valve opens, the pressure between membrane and mercury is no longer dependent on the balanced weight since the pressure on the other side of the valve is propagating towards the cell and its manometer and affects them. This causes the mechanism to be unbalanced during a short time after opening the valve.

It has happened that a truck passing on a small road lying at a distance of some 40 meters caused a quiver strong enough to bring a contact into action. The exceptionnally high sensitivity of the mechanism may then turn into a disadvantage.

b. The container is susceptible to wind. A strong wind blowing into the narrow spaces between the walls of the cellar and the container will rock it, though imperceptable to the eye. This causes small changes in the distribution of the total weight over the three cells and results in an inconstant position of the oil menisci. The tubes should therefore be read as close to simultaneous as possible.

4.3 Calibration

The last paragraph of 4.2 emphasizes the necessity of calibrating the weighing mechanism. Although the equivalence in weight of a change of 1 mm in the position of the oil menisci may be calculated on physical grounds, such calculations start from the assumption that some values used in the calculation are accurate and constant. These assumptions may be false. Calibration accounts for a number of immeasurable details that cannot be implicated in a calculation.

Four calibration tests were performed at moments when no natural evaporation or rainfall could cause a change in weight of the container. In two of these tests the container was supplied in the course of two hours with 5 surface mm of water in a continuous flow. The tubes were read with intervals varying from 1 to 5 minutes, a reading before the flow of water started taken as a zero level. The difference between this zero reading and those during the test, expressed in mm change as a total of the position of the three oil menisci, was plotted against the amount of water supplied up to the moment of the readings. The diagram is shown in fig. 14. There is no significant difference between the two tests. A straight line is easily fitted to the data, according which one millimeter in total change in position of the oil menisci stands for a change in weight of 143 grams.

The two other tests were performed when water was drained off instead of supplied. The diagram in fig. 15 shows that the outcome is a straight line which coincides, with a negative sign, with the one of fig. 14. Evidently it does not affect the mechanism whether the container loses or gains weight.

The calibration tests were performed at a temperature of 8°C. The possible influence of a temperature factor has not yet been tested.

4.4 Magnitude of errors

The figures 14 and 15 show a scatter which means that the movements of the oil menisci are not an absolute indication for a change in weight. An error analysis is therefore necessary.

The mean error of the readings in fig. 14 and 15 can be calculated by $S = \sqrt{\sum x^2/(n-1)}$, where x is the deviation between the readings and thei: accessory value on the regression lines. Since it is a calibrated reservoi: into or out of which the water was flowing, the error on the abscissa may be assumed to be virtually negligible. So x is the vertical distance from the dots to the regression lines.

The mean error amounts to 175 grams or 0.1042 surface millimeters of water. The calibration tests were performed at a temperature of $8^{o}C$. The possible influence of a temperature factor has not yet been tested.

5. Conclusion

It is clearly understood that, however correct the general principle of the device, the mechanical realization must be perfect to get the best results. The major part of the accuracy problem is the reducing of oil losses since this will keep the action of the solenoid valves at a minimum and consequently reduce unnecessary disturbances of the balance.

In the case of the prototype of the weighing machine discussed, leakage is reduced to an extremely low value. As a matter of fact the contacts and solenoid values could be dispensed with for long periods which had, of course, a favourable influence on the accuracy. It is felt that it is possible to incorporate a few mechanical improvements and that a very accurate weighing mechanism will then be available for lysimeter work.

6. Acknowledgements

The idea to use hydraulic pressure cells of the kind described came from ir. W.C. Visser, deputy-director of the Institute for Land and Water Management Research at Wageningen. He also gave aid in the solving of some fundamental problems and with suggestions during the construction of the apparatus.

Thanks are due to Mr. A. van Capelleveen, manager of the Veca Apparatenfabriek at Wageningen and to his staff for working out the drafts, and constructing the mechanism.

7. References

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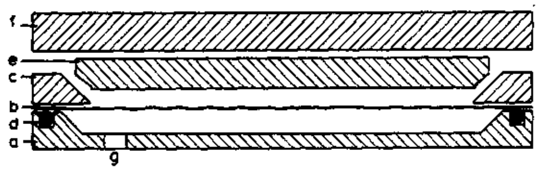

Fig. 1. Cross section of a hydraulic pressure cell.

a. steel bottom plate
b. membrane
c. tapered steel ring
d. rubber O-ring
e. tapered steel plate
f. steel upper plate
g. inlet opening

Fig. 2. View of the constituent parts of the hydraulic pressure cell. The same symbols are used as in fig. 1

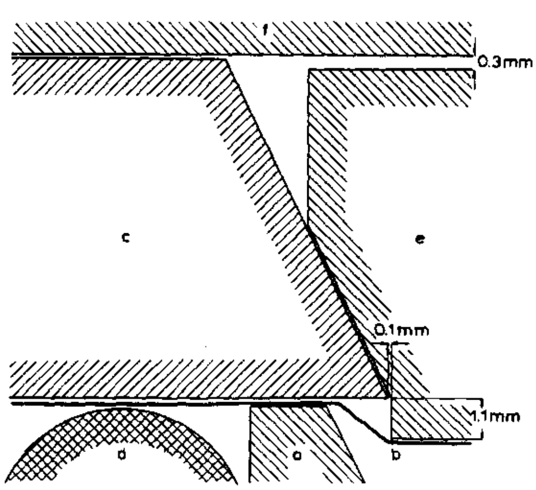

Fig. 3. Detail drawing of the hydraulic pressure cell. The same symbols are used as in fig. 1

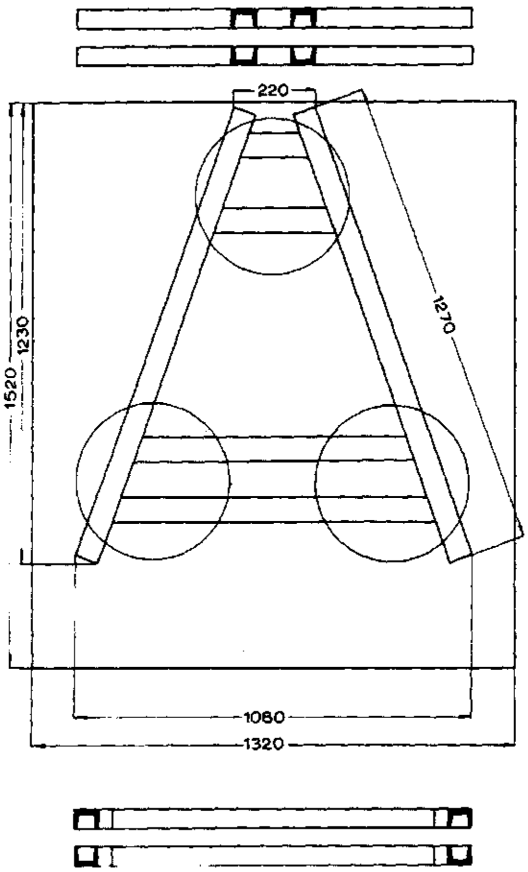

Fig. 4. Situation of the cells and frames relative to the base of a container

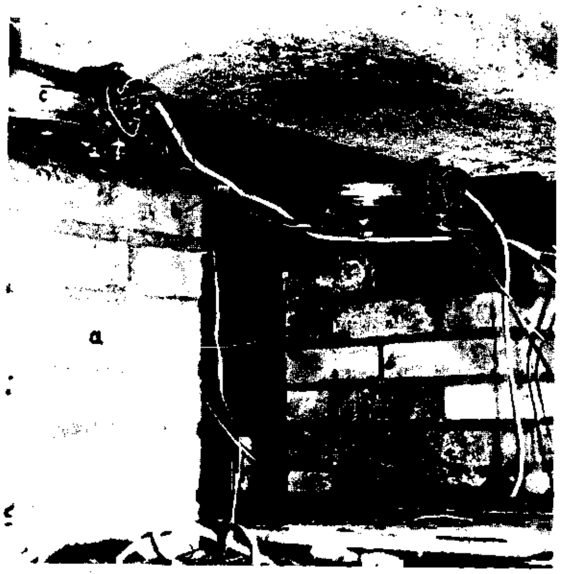

Fig. 5. The front of a container with two of the cells.

a. brickwork post
b. lower frame
c. pressure cell
d. upper frame
e. container

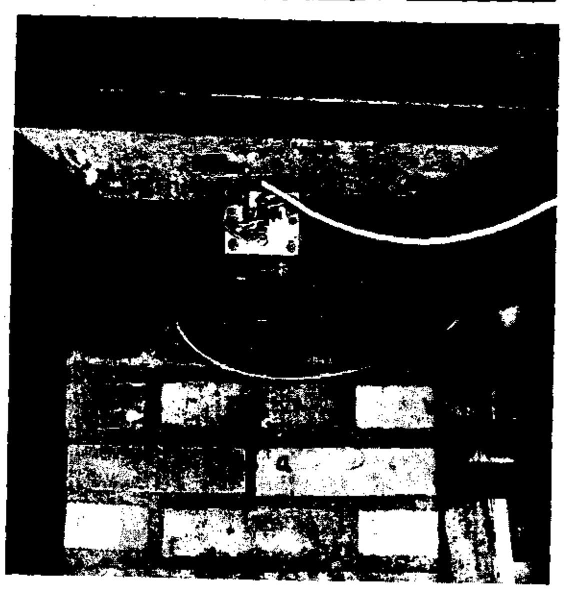

Fig. 6. The third cell at the back.

a. brickwork post
b. lower frame
c. pressure cell
d. upper frame

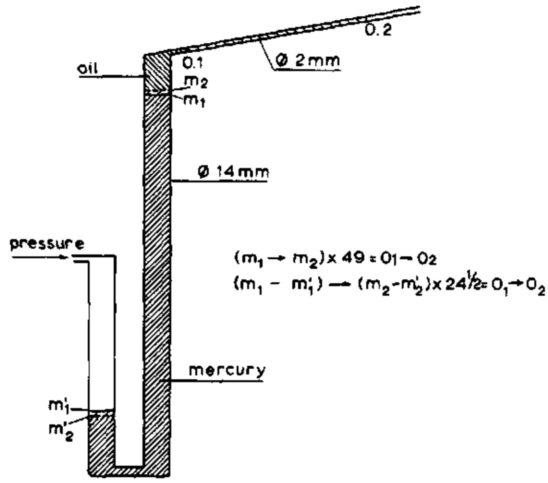

Fig. 7. Schematical drawing of the device to multiply the changes in the height of the mercury column

Fig. 8. View of the upper part of the registrating mechanism.

a. transparant vessel filled with water of a constant temperature, holding the manometers
b. reading tubes with scales
c. three-way taps
d. oil reservoir

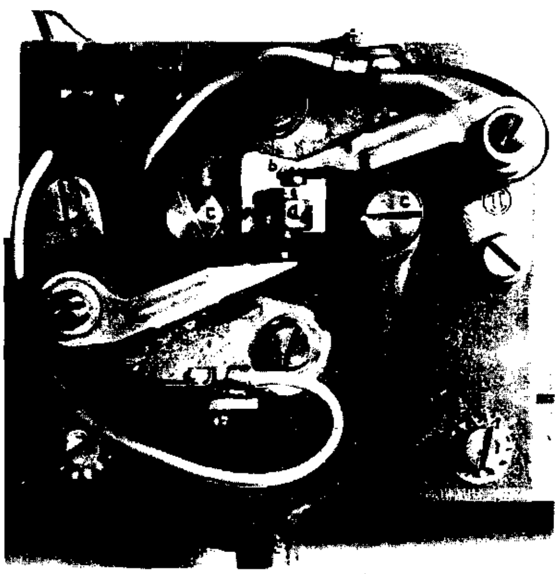

Fig. 9. The contacts on the cells to detect the position of the lifted part.

a. two-sided contact
b. one-sided contact
c. adjusting screws for the one-sided contacts

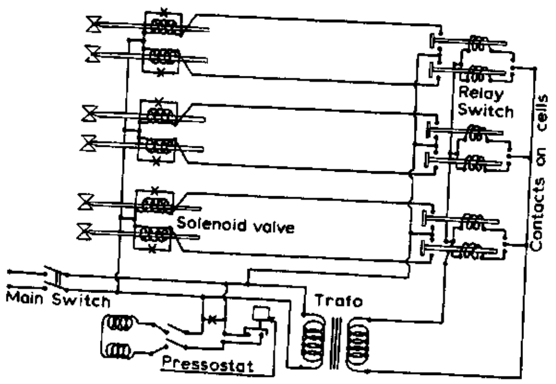

Fig. 10. Scheme of the electronic circuits operating the mechanism

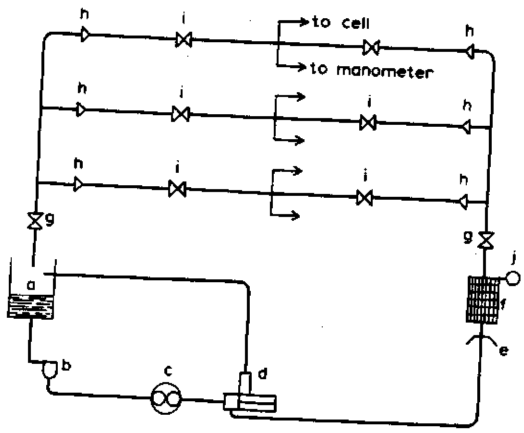

Fig. 11. Scheme for the hydraulic part of the mechanism.
- a. oil reservoir
- b. filter
- c. gear pump
- d. pressure regulator with by-pass
- e. non-return valve
- f. pressure cylinder
- g. main stop valves
- h. hand operated valves
- i. solenoid valves
- j. manometer

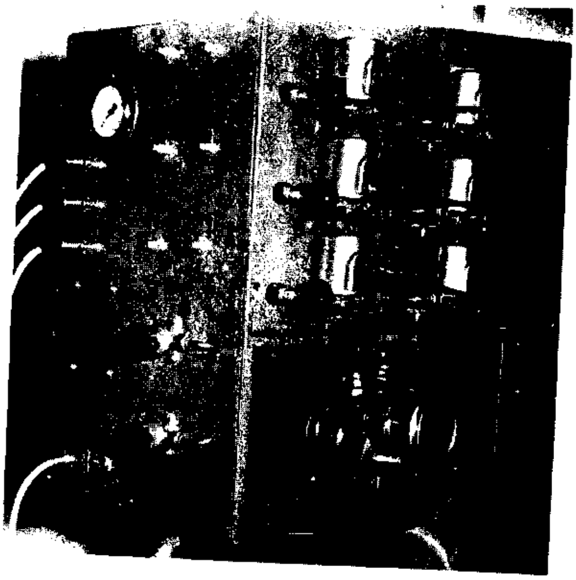

Fig. 12. View of the front of the iron case holding both the electronic and hydraulic parts of the mechanism. For the legend see fig. 11

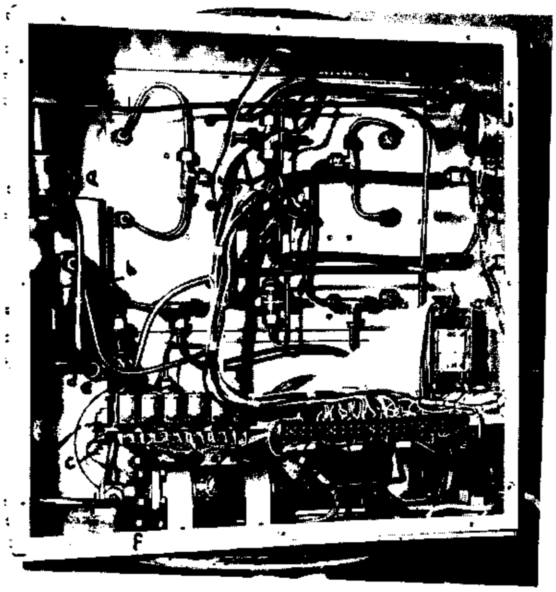

Fig. 13. Close up of the contents of the case shown in fig. 12. For the legend see fig. 11

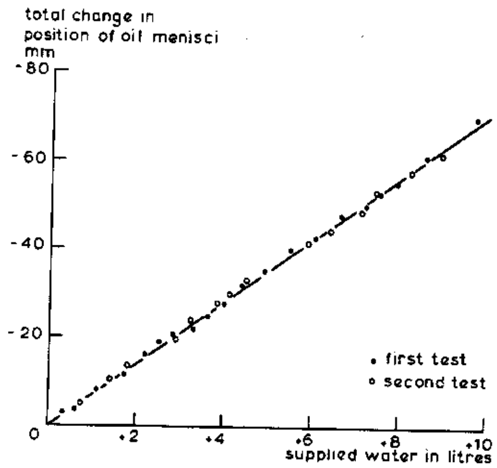

Fig. 14. Results of two calibration tests under conditions of water supply

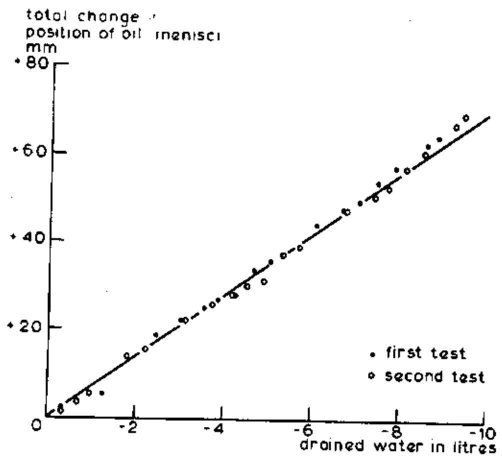

Fig. 15. Results of two calibration tests under conditions of water discharge