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Miksitz

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[54] FEEDING AND PARTICLE SIZE MEASUREMENT OF COMMINUTED SOLIDS

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[21] Appl. No.: **115,051**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 753,505, Aug. 19, 1968, abandoned, which is a continuation-in-part of Ser. No. 547,627, May 4, 1966.

[52] **U.S. Cl.**.................**250/43.5 D**, 198/52, 204/168, 250/83.3 D
[51] **Int. Cl.**...**G01n 23/12**
[58] **Field of Search**.......250/43.5 D, 83.3 D; 198/52; 222/371; 204/168

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[57] **ABSTRACT**

This invention relates to the feeding and analysis of particulate material and in particular to (1) the feeding of such materials at controlled rates, (2) the continuous dynamic measurement of particle size and other properties of the material being conveyed and (3) the provision of a chemical processing environment through which the material is conveyed under controlled conditions.

12 Claims, 13 Drawing Figures

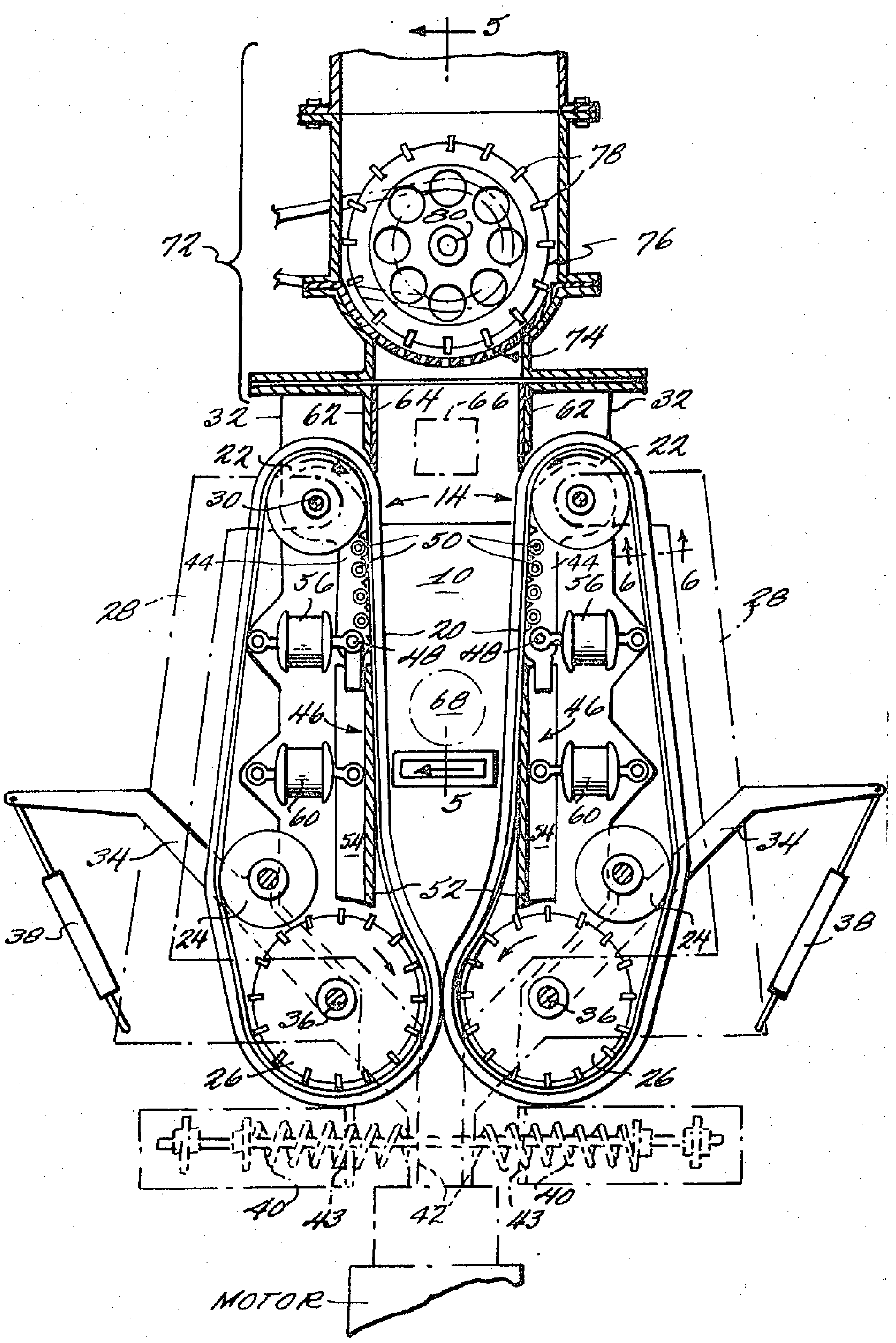
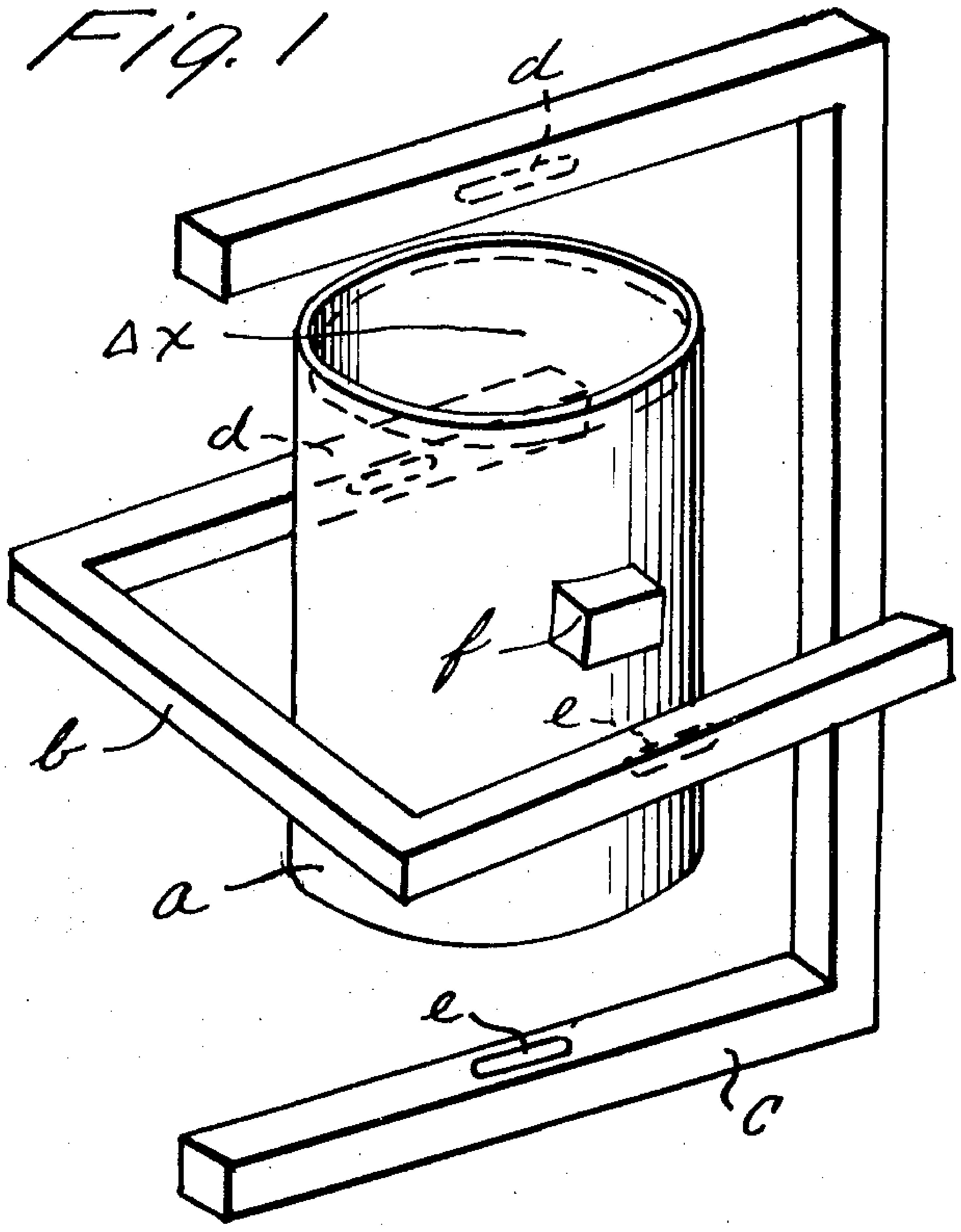


Fig. 1



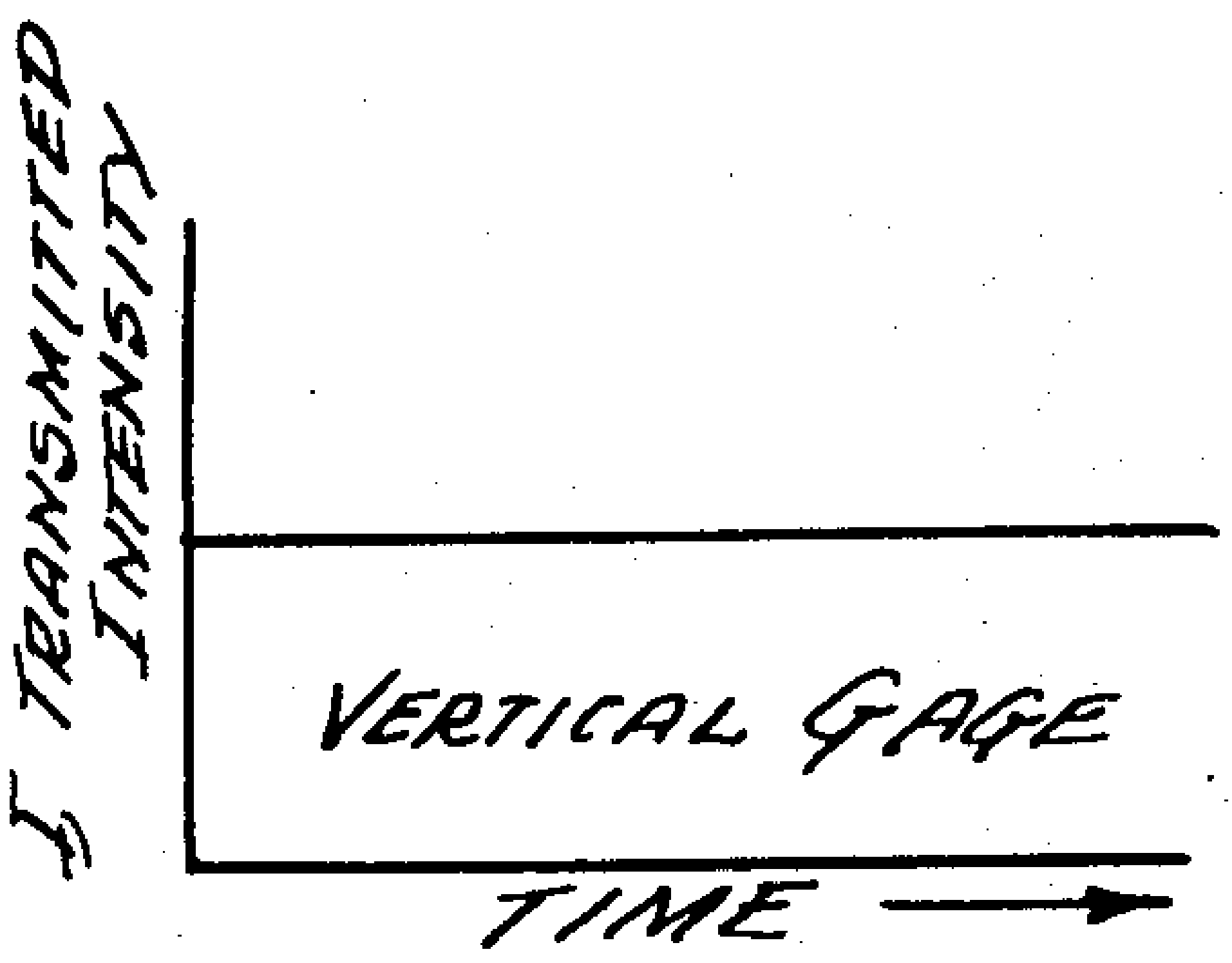


Fig. 2

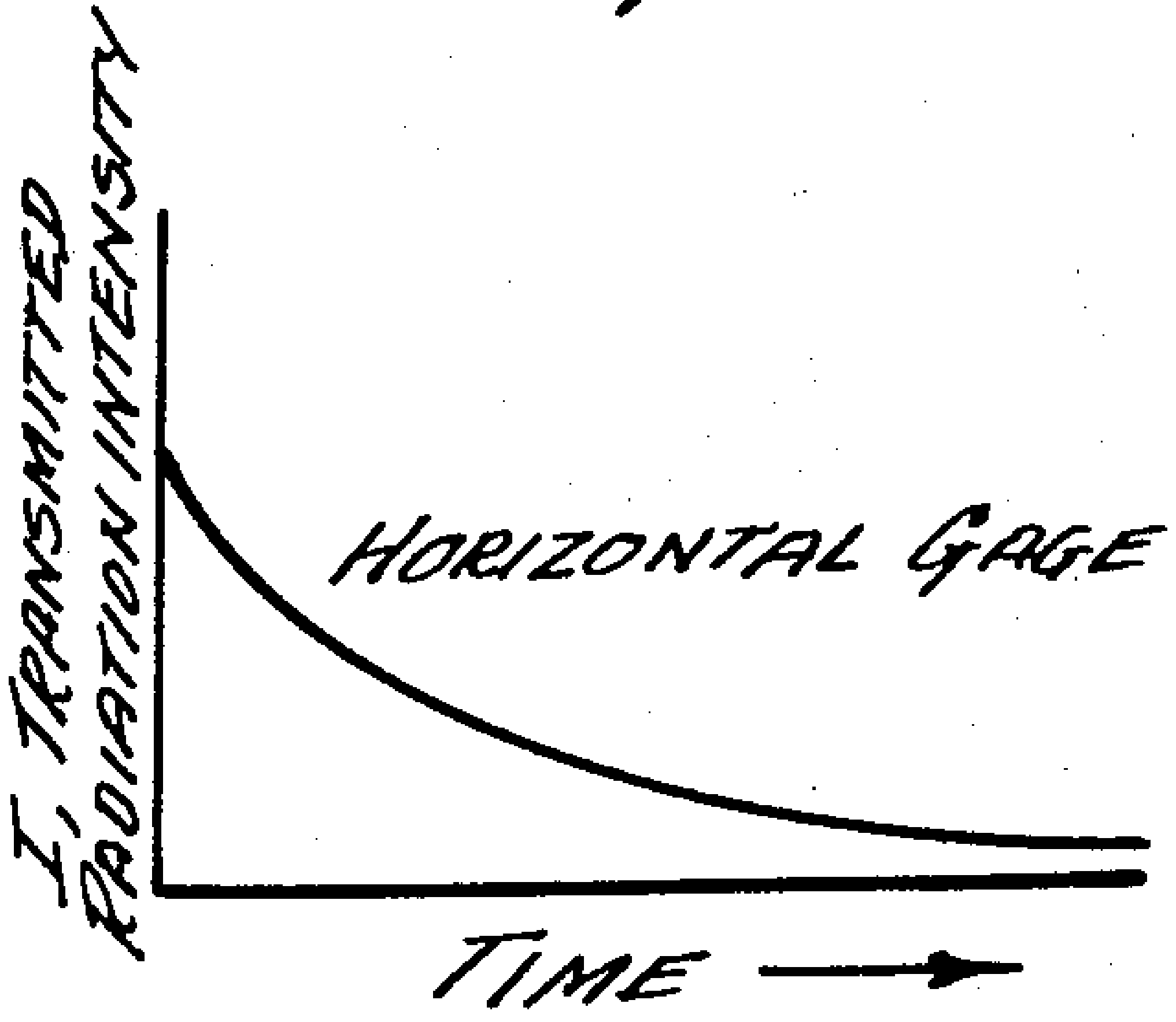


Fig. 3

Fig. 3A

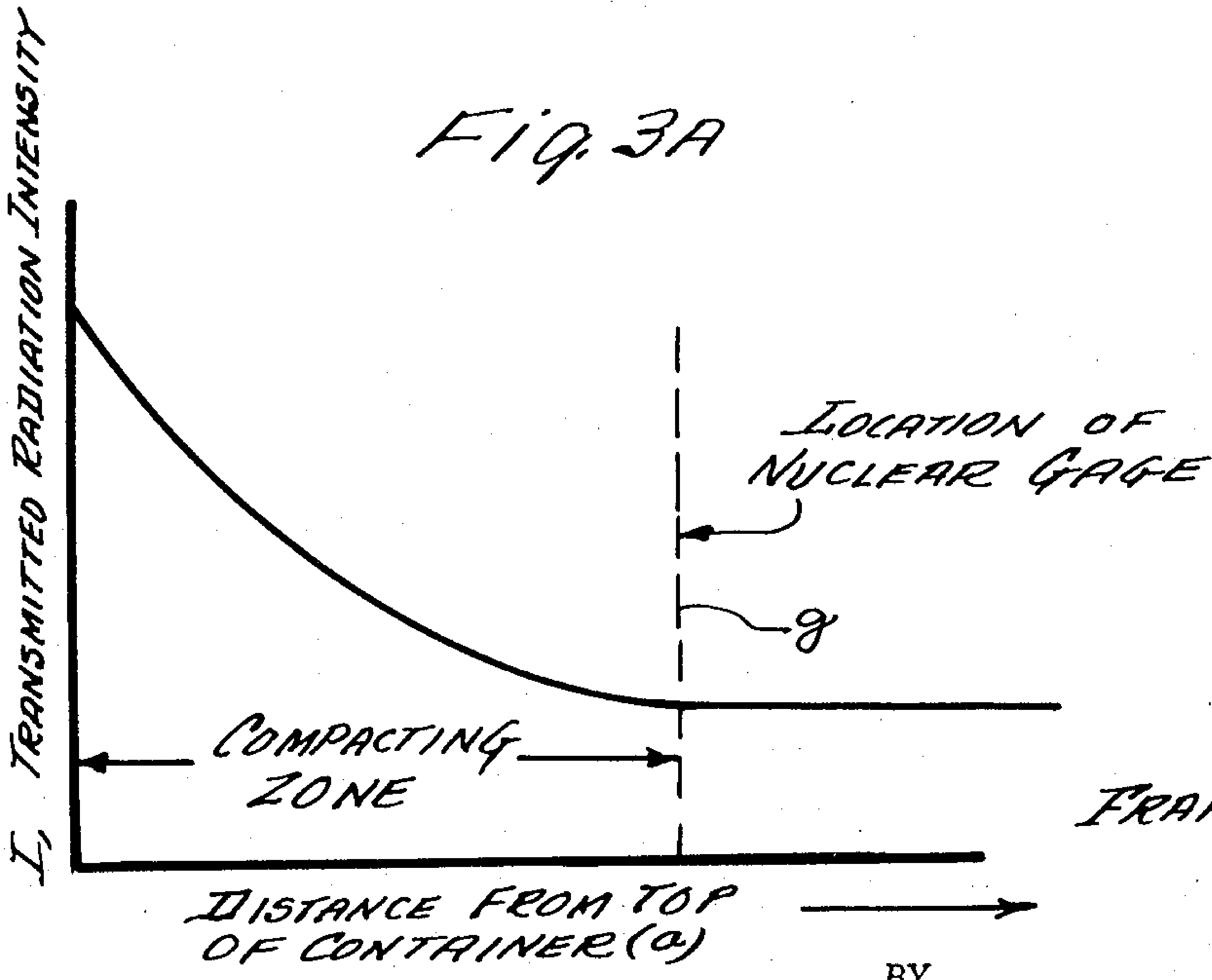


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Fig. 4

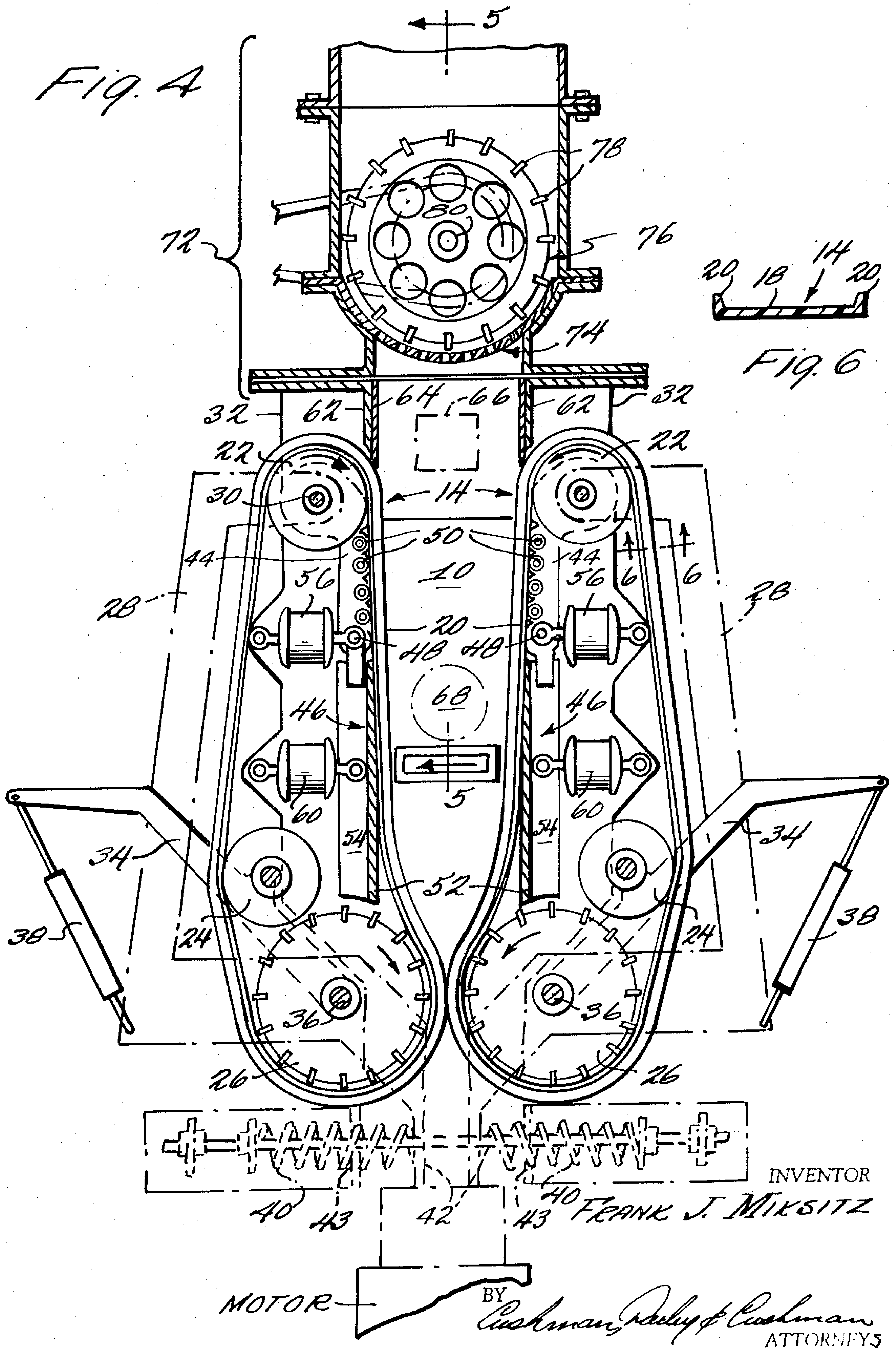

Fig. 6

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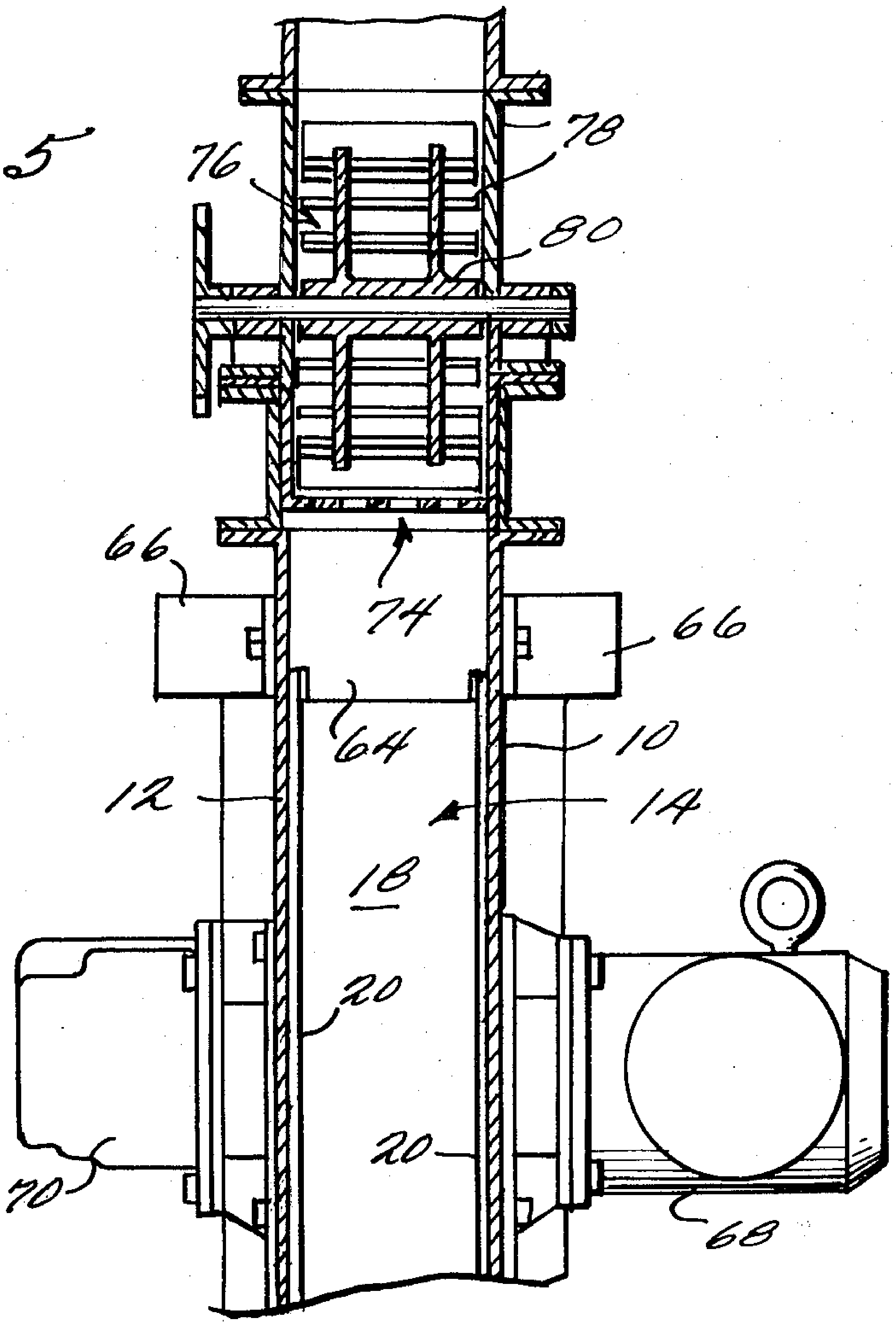

Fig. 5

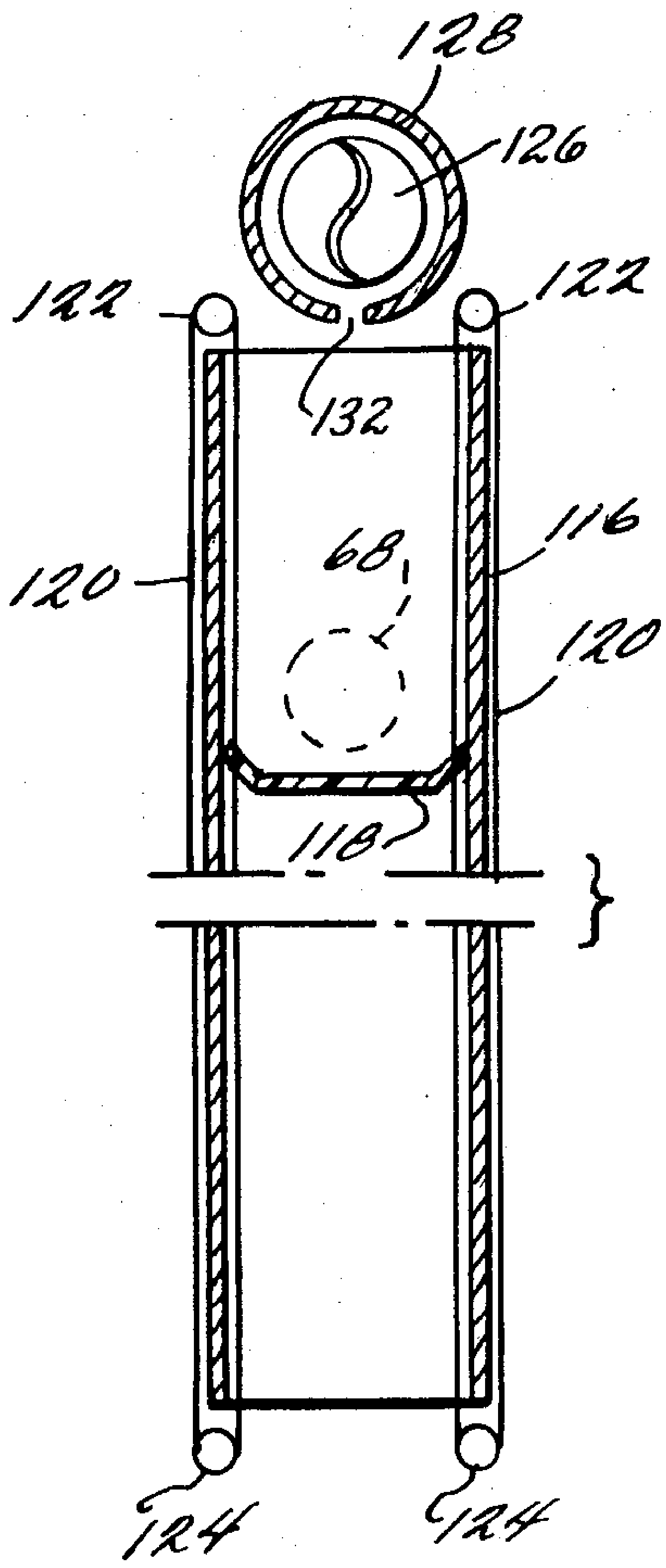

Fig. 12

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Fig. 7

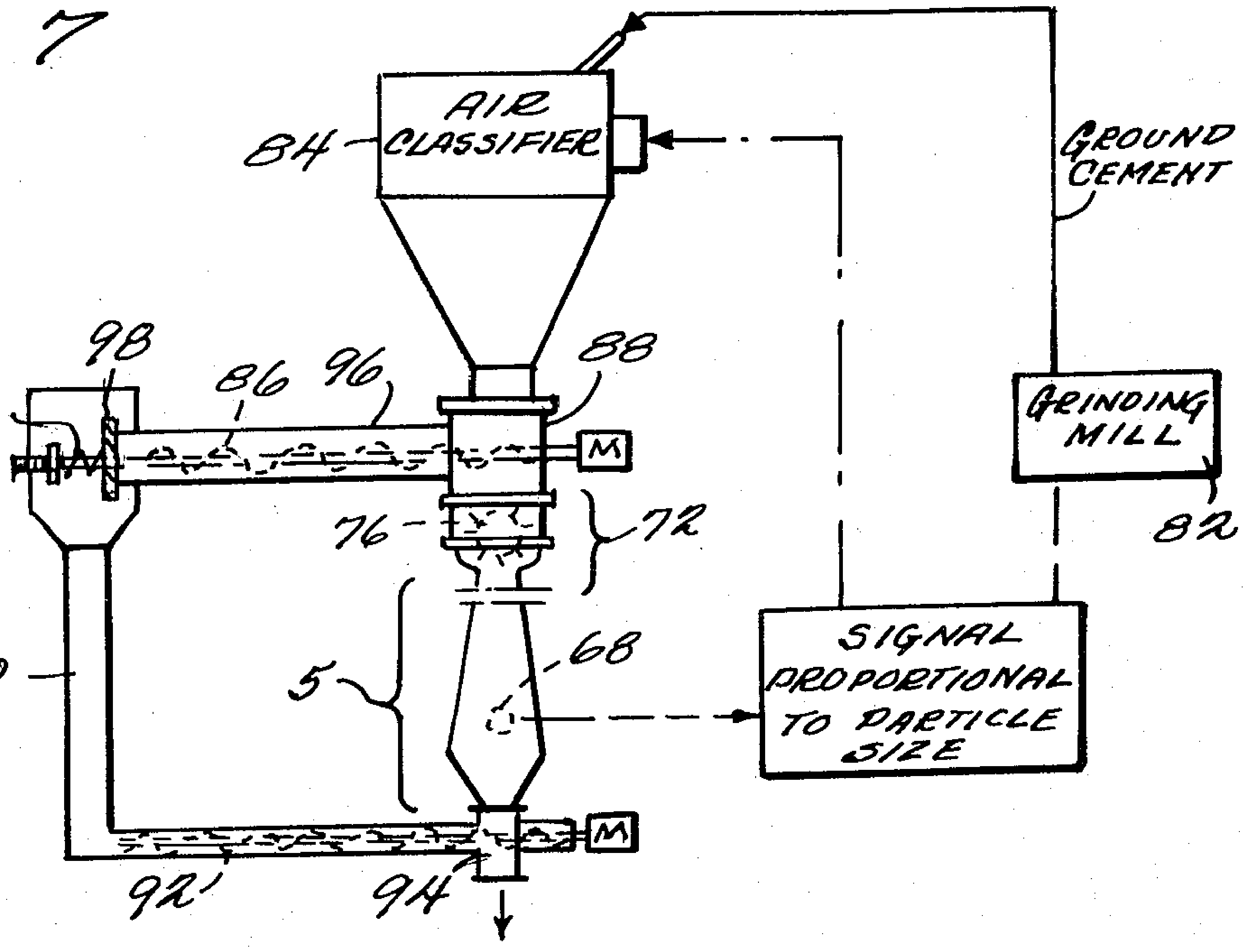
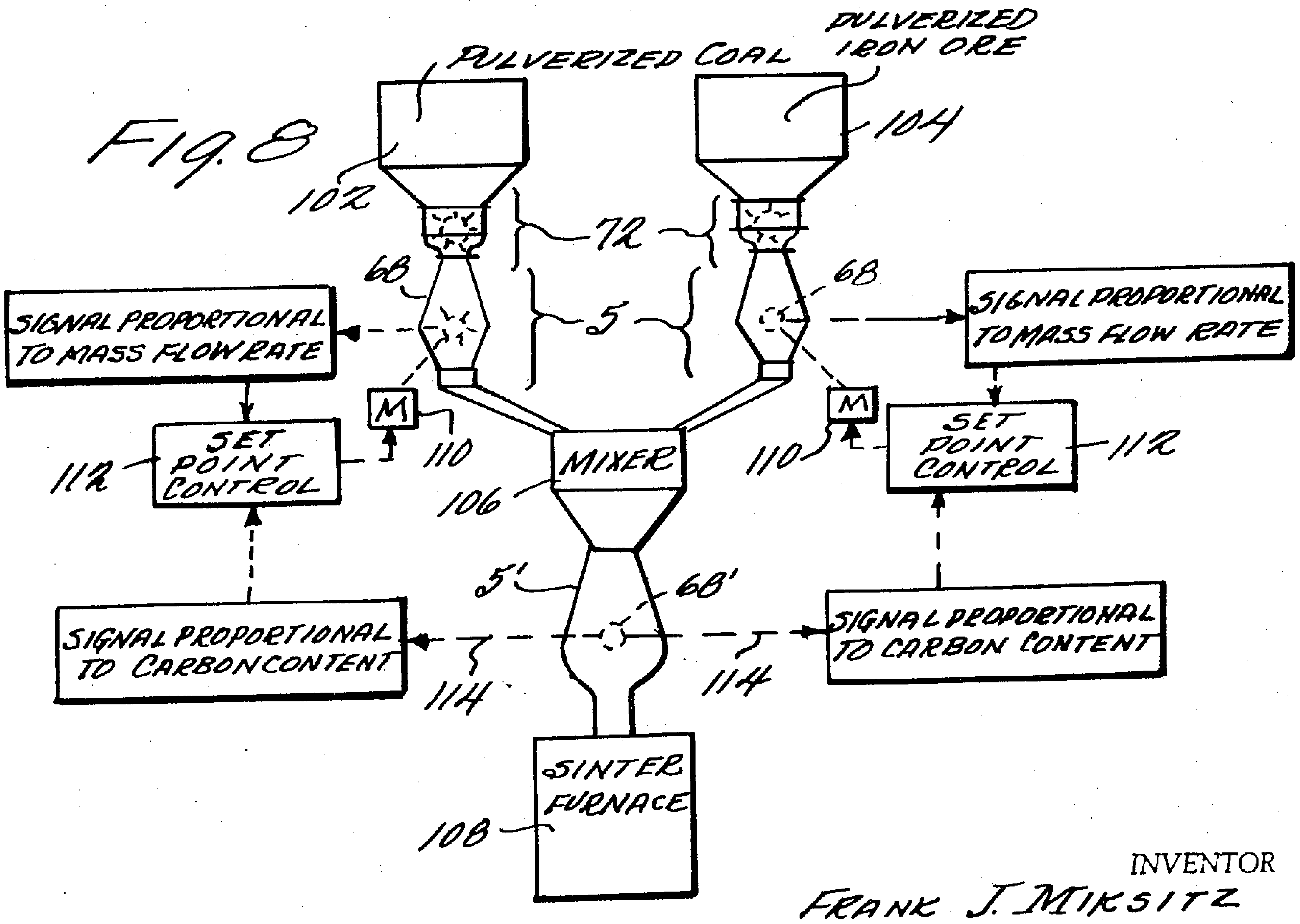


Fig. 8



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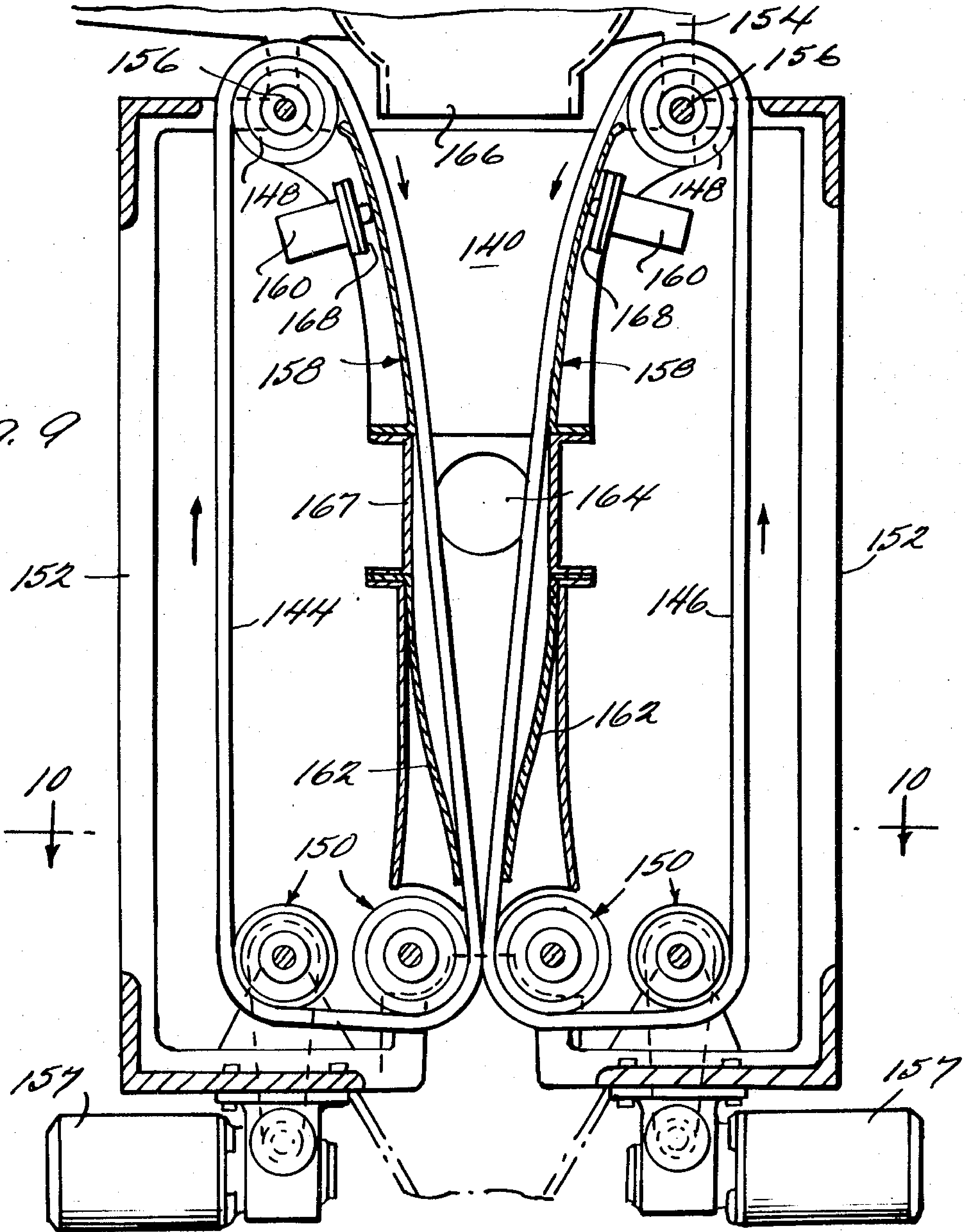

Fig. 9

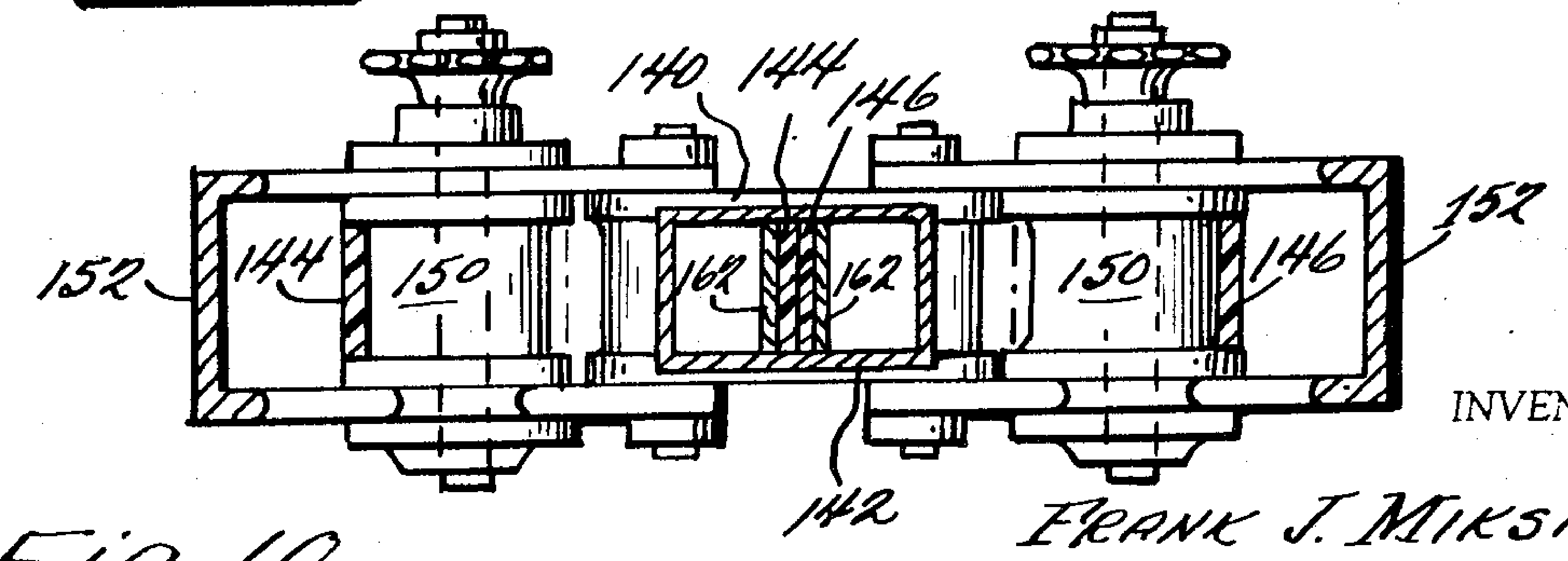

Fig. 10

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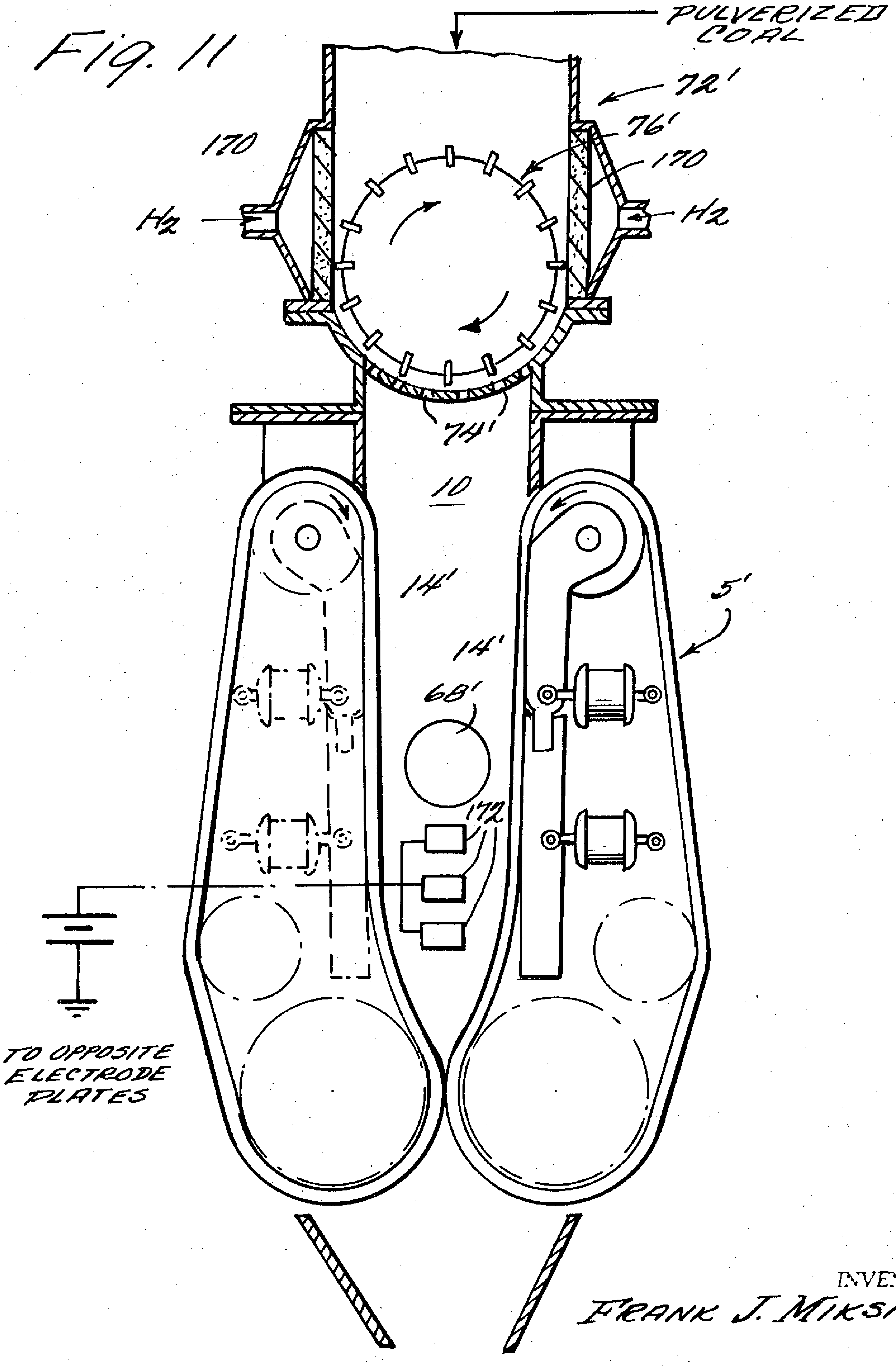
Fig. 11



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FEEDING AND PARTICLE SIZE MEASUREMENT OF COMMINUTED SOLIDS

This is a continuation-in-part of application Ser. No. 753,505 filed Aug. 19, 1968 as a continuation-in-part of application Ser. No. 547,627 filed May 4, 1966.

In the description which follows the term particulate material refers to solid material which is made up of separate particles ranging from fine powder particles, such as ground cement, to relatively large particles, such as coarse sand, aggregate, crushed rock or coal or various natural or synthetic organic particles. While the material need not be dry in an absolute sense its moisture content is always sufficiently low that a slurry is not present.

The handling of bulk particulate material often involves problems of weighing, proportioning, and chemical and physical analysis of the material, and these problems may be quite severe where the material is being processed at high rates measured, for example, in tons per hour or per day. In order to control processes of this kind it becomes increasingly important to be able to measure and control mass flow rates and to analyze the input and/or output materials so that compensating changes can be made in the process variables. In addition, in order to achieve automation of the process it is essential that the various measurements be made continuously and instantaneously on the moving streams of material.

Particulate material is inherently difficult to handle, convey and analyze in a precise manner because during flow of the material, even when particles size is uniform, there are inherent changes in the apparent density of the material due to inherent pressure changes in and on the material. This is true whether the material is being mechanically conveyed, in which case vibration and other mechanical movements of the machine are principally responsible for apparent density changes, or whether the material is being gravity fed, in which case friction and the geometry of the hopper or the like affect the apparent density giving rise to such well-known phenomena as arching and caking. The term apparent density refers to the weight of particulate material per unit volume and is a measure of compactness, or void content of the particulate material, this characteristic being affected by the external variables just referred to and by the properties of the material itself, particularly particle size. Actual density, that is, the weight per unit volume of the solid material itself is not affected by these variables.

These changes in apparent density of a flowing particulate material make it difficult to continuously and accurately measure the mass flow rate of the material under dynamic conditions, primarily because a volumetric measurement although easily obtained has little significance. As a result costly weighing machines of complex structure are often employed for weighing a stream of solids. It has more recently been proposed to obtain the mass flow rate of a stream of solids on a conveyor belt with a so-called nuclear density gage which measures the gamma ray transmittance of the material in a direction transverse to the belt. The nuclear gage includes a source of gamma radiation disposed adjacent one side of the upper run of the conveyor belt and a detector adjacent the other side of the run, the output of the detector being thereby responsive to changes in the mass of the material passing between the source and the detector, assuming that the mass absorption coefficient of the material is constant, so that at constant belt speed the detector output, after appropriate calibration, is a measure of the mass flow rate independent of apparent density. However, this system cannot measure the apparent density of the moving solids, as does the system of the present invention, even though both systems may employ a nuclear density gage.

The most important feature of the present invention lies in the use of a nuclear density gage, or other energy-field type of analyzer, in combination with a specially-prepared, specially-handled stream of particulate material under conditions such that the apparent density of the moving solids is measured accurately and such that variations in the apparent density are meaningful. Broadly, the preparation and handling of stream of particulate material involves continuously moving the material as a void-free plug or column through a tubular zone under quiescent conditions such that no mixing, agitating or relative movement between particles occurs. This is best accomplished by frictionally engaging the material with moving endless members such as belts or chains, and by exerting compacting pressure on the material in a direction transverse to the direction of movement. Under these conditions, as will be fully discussed below, the apparent density of the material moving through the tubular zone is a meaningful variable and can be accurately measured with an energy-field type of analyzer. The measurements are reproducible for a given material and for a given set of operating conditions and can be employed, as hereinafter described, as a continuous direct indication of particle size or mass flow rate, simultaneous indication of particle size and mass flow rate and an indication of the chemical quality of the material. The apparatus, together with the various control functions, may also serve as a reactor for continuous chemical processing.

The invention will be further understood from the following detailed description taken with the drawings in which:

FIG. **1** is a schematic perspective view of a single test apparatus described below in connection with a discussion of the theory of one part of the present invention;

FIGS. **2** and **3** are graphs illustrating the operation of the test apparatus of FIG. **1**;

FIG. **3A** is a graph illustrating the operation of the test apparatus of FIG. **1** modified to operate continuously;

FIG. **4** is a schematic vertical sectional view of a particulate material feeding apparatus embodying the principles of the present invention as they relate to particle size measurement;

FIGS. **5** and **6** are fragmentary sectional views taken on the lines **5—5** and **6—6**, respectively, of FIG. **4**;

FIG. **7** is a schematic elevational view, partly broken away, illustrating the apparatus of FIGS. **4, 5** and **6** employed in a process system for measuring particle size;

FIG. **8** is a schematic elevational view illustrating the apparatus of FIGS. **4, 5** and **6** employed to control the mass flow rate of the particulate material;

FIG. **9** is a schematic vertical sectional view of a modified form of apparatus of the kind shown in FIG. **4**;

FIG. **10** is a sectional view taken on the line **10—10** of FIG. **9**;

FIG. **11** is a schematic elevational view of the apparatus of FIG. **4** modified to function as a chemical reactor; and

FIG. **12** is a schematic vertical sectional view of a modified form of apparatus suitable for particle size measurement.

THEORY AND BASIC PRINCIPLES

Without going too deeply into the discussion of the theory of radiation intensity passing through a given process stream, it can be stated that transmitted radiation is an exponential function of the mass absorption coefficient of the process stream, density of the stream, and the path length through which the radiation passes, Thus

$$I = I_0 e^{-\mu\rho}$$

Where

I is the transmitted radiation intensity

I_0 is the incident radiation intensity

μ is the absorption or attenuation coefficient (cm^2/gm)

ρ is the apparent density of the sample being irradiated (gms/cm^3)

x is the path length cm.

It will now be pointed out why the previously suggested use of a nuclear density gage or its equivalent in conjunction with belt conveyors, vibrating feeders, etc. is limited to continuous weighing only and not applicable to measuring apparent density which is related to average particle size.

First, referring to FIG. **1**, assume that we have a vertical, tubular container *a*and that the container has been filled to the top with a pulverized material and leveled off with a straight edge so that a fixed mass of material resides in the container. The container *a* is then placed between the arms of a horizontal C-frame *b* and between the arms of a vertical C-frame *c*. One arm of each frame carries a gamma ray source *d* and the other arm carries a gamma detector *e*. If the intensity of the transmitted radiation, I, is measured, and at the same time the container and its contents are vibrated as by means of a vibrator *f*, a plot of I versus time for the two nuclear gages will be as shown in FIGS. **2** and **3**. Inspection of FIG. **2** shows that the transmitted radiation in the vertical dimension remains constant even through the surface of the material falls a distance Δx during vibration, due to gravity compaction of the material. This result can be rationalized by the realization that the actual mass of material through which the vertical radiation passes remains constant because the areal density in gm/cm^2 remains constant. The result is also confirmed by the above equation, because when I equals a constant, the expression $I_0 e^{-\mu\rho x}$ does not change even though the apparent density, ρ , increases as x decreases.

On the other hand, an inspection of FIG. **3** produced by the horizontal gamma gage reveals that I decreases as the material surface in the container falls a distance Δx due to gravity compaction created by vibration. The equation again can be used to confirm that I decreases as the apparent density ρ increases when I_0, μ and x of a given material remain constant.

It follows that when a vertical nuclear density gage, or the equivalent is employed in conjunction with a conveyor belt or the like for measuring mass flow rate, the gage output is not a measure of particle size. Since it is possible to apply only the vertical C-frame or transverse type of nuclear gage to belt conveyors, vibrating feeders, etc., as shown by FIG. **2** and not the horizontal C-type frames as shown in FIG. **1**, we can now conclude that the vertical C-frame application is limited to continuous weighing and insensitive to the apparent density. On the other hand, when the horizontal C-frame is used with respect to FIG. **3**, a constant percentage of consolidation due to vibration, with respect to time T_x can be selected for measurement of apparent density. This measurement concept is reproducible.

The present invention employs the horizontal C-frame concept described above, adapted for continuous operation. First, assume that a stream of particulate material is moving at a constant rate downwardly through the tubular container *a* of FIG. **1** and that a substantial constant compaction pressure is simultaneously and continuously applied to the material in a direction transverse to the direction of movement. Now, if the nuclear gage *b* is moved downwardly at the same speed as the stream of material and if the output of the gage is plotted against the longitudinal dimension of the container *a*, the curve shown in FIG. **3A** will result. As the material enters the container *a* the degree of compaction begins to rise as a result of the compacting pressure. Compaction increases with time until a maximum degree of compaction is reached. For a given kind of material moving at a given speed and subjected to a given lateral pressure the graph of FIG. **3A** is reproducible, and maximum compaction occurs at the same distance from the point where compacting began.

Accordingly, if the nuclear gage *b* is subsequently fixed at a location at least as far from the beginning of the compaction zone as the point where maximum compaction occurs, then the gage will be in a position to analyze material which will not undergo further compaction due to the operation of the device. Generally it will be desirable to locate the gage *b* at or slightly downstream of the point of maximum compaction, as illustrated by the dashed vertical line *g* in FIG. **3A**. The parameters of the above functions of the apparatus with nuclear gages and/or energy fields are defined by the following basic differential equations:

Since

$$D = M/V \text{ and } V = A \times S;\ D = M/A \times S$$

Where D = Apparent Density — lbs/Ft^3

M = Mass or Weight — lbs

V = Unit Volume — Ft^3

A = Unit Area — Ft^2

S = Unit Length — Ft

Now if $D = M/V$ and $V = A \times S$ is differentiated with respect to time, we have

$$\frac{dD}{dt}=\frac{\frac{DM}{dt}}{\frac{DV}{dt}} \text{ and } \frac{DV}{dt}=\frac{DA}{dt}\times\frac{DS}{dt}$$

Combining these two equations we have Eq. No. 1:

$$\frac{dD}{dt}=\frac{\frac{dM}{dt}}{\frac{dA}{dt}\times\frac{dS}{dt}}$$

Rearranged we have Eq. No. 2:

$$\frac{dM}{dt}=\frac{dD}{dt}\times\frac{dA}{dt}\times\frac{dS}{dt}$$

Where

dM/dt is Mass or Wt. per unit of time

dD/dt is Apparent density per unit of time

dA/dt is Unit area of transverse cross section per unit of time.

dS/dt is Unit length of travel normal to the transverse cross section per unit of time.

dV/dt is Unit of volume of core per unit of time.

Inspection of the parameters for dD/dt of the differential Equation No. 1 for a dynamic average particle size measuring system will reveal that if $dA/dt \times dS/dt$ and dM/dt are constant, then dD/dt is also a constant. On On the other hand, if the product $dA/dt \times dS/dt$ remains a constant value and if dM/dt varies, then dD/dt must also vary proportionally and denotes a change in apparent density or average particle size.

Differential equation No. 1 can be directly applied to the on-line apparatus of the present invention when the object is to obtain a measurement of the average particle size. The stream of material is continuously passed through a zone where it is subjected to a constant compacting action by means of spaced-apart opposed shrouds which are yieldably urged toward one another and through which it is conveyed at a controlled velocity, dS/dt, as a stream having a controlled transverse dimension, dA/dt. Should the packing characteristics of the material change due to a change in particle size, the movable shrouds which are under the influence of constant pressure, will adjust (breathe) accordingly. If the movable shrouds are spreading, then dA/dt is increasing, and the belt speed dS/dt should be decreased proportionally in order to maintain constant volume flow rate dV/dt. Conversely, if the movable shrouds are contracting, then dA/dt is decreasing and the belt speed dS/dt should be increased proportionally in order to again maintain constant volume flow rate dV/dt. The product of $dA/dt \times dS/dt$, which is equal to dV/dt, is always a constant. These parameters must be controlled by an analogue device. Under these conditions the apparent density dD/dt of the material is constant for a given average particle size of a given material. A change in the average particle size results in a change in the degree of packing or void space and this density change dD/dt in turn produces a change in the output signal of the nuclear gage which is installed across a constant dimension of the compacting zone. Preferably the uniform compacting action to which the stream of material is subjected is sufficient to compact the material into a plug which will move as an integral mass, and preferably the plug will be so low in void content that mill room or other vibrations will not change the compaction of the material or affect readings.

Inspection of the parameters for dM/dt of the differential Equation No. 2 for a dynamic constant mass flow rate measuring system will reveal that if the product of $dD/dt \times dA/dt \times dS/dt$ is a constant value, then dM/dt is also a constant value. On the other hand, if dM/dt and dA/dt are held to a constant value and dD/dt (the apparent density of the material) changes, then ds/dt (the rate of material through the system) must also change in inverse proportion in order to have constant mass flow rate dM/dt.

The above differential equation can be directly applied to the on-line apparatus when the object is to feed particulate material of a given composition at a constant mass flow rate dM/dt. The stream moving through the compacting zone is compacted to a constant transverse cross section dA/dt, and the output signal dD/dt of the nuclear gage is employed as a control signal to vary the velocity dS/dt at which the material is caused to pass through the compacting zone. Under conditions of uniform particle size and packing there will be no control signal dD/dt from the detector, and the velocity dS/dt of the stream will be maintained constant. Since the cross section dA/dt of the compacting zone is constant, the volume rate dV/dt of flow will be constant. The density dD/dt of the material will also be constant, because the compaction of the stream to a constant cross section dA/dt effects a constant density dD/dt of the material when the particle size and packing remains constant. Therefore, since volume rate dV/dt of flow and density dD/dt are constant, the mass rate of flow dM/dt will be constant. Upon a change in particle size or packing or both, however, the density dD/dt will change in direct proportion, thereby producing a change in the output signal of the detector. Since the mass flow rate dM/dt has now changed, the detector signal can be employed in any suitable manner, as with a set point controller, to change the velocity dS/dt of the material in order to return the mass flow rate dM/dt to its former value.

Inspection of the parameters for dM/dt of the differential Equation No. 2 for a combination dynamic constant mass flow rate and average particle size measuring system will show that if the quotient

$$\frac{\frac{dM}{dt}}{\frac{dD}{dt}}$$

equals a constant value, then the product $dA/dt \times dS/dt$, or dV/dt, must also equal the same constant value. However, if only one parameter changes or if two or three change simultaneously, then in order to maintain constant mass flow rate the product of all parameters regardless of their individual values must always equal the same constant value of dM/dt. In this measuring system production monitoring may be calculated by feeding the parameters into an analog computer, programmed to integrate Equation No. 2, and to simultaneously control the operation of the dynamic system.

When the object is to feed particulate material of a given composition at a constant mass flow rate dM/dt and simultaneously measure the apparent density dD/dt which is related to the average particle size, the theory presented in the differential Equation No. 1 can also be applied to the on-line apparatus. In this application the stream of material is continuously passed through a zone on the on-line apparatus where it is subjected to a constant compacting action and through which it is conveyed at a measured density dD/dt, at a measured transverse cross section dA/dt and at a measured velocity dS/dt. The product of all the parameters $dD/dt \times dA/dt \times dS/dt$ is equal to a constant value dM/dt, even though each parameter may or may not change individually. For example, a change in the average particle size results in a change in the degree of packing or void space, and this density change dD/dt in turn produces a change in the output signal of the nuclear gage. Transverse cross section dA/dt may also change. Accordingly, for a dynamically operating on-line apparatus these parameters must be instantaneously processed by an analog computer to correct the speed dS/dt of the on-line apparatus in the form of a signal from the computer and to perform the necessary function with the parameters so that the product $dD/dt \times dA/dt \times dS/dt$ is equal to a constant value dM/dt. Another function of the computer is to simultaneously utilize the apparent density signal dD/dt which is related to the average particle size, and integrate the equation in order to obtain a measure of the total production.

The operation of the above on-line apparatus for constant chemical composition rate control can be expressed mathematically in terms of the same parameters that are used by the differential Equation No. 2. The only difference is that an analog computer is used to instantaneously evaluate an additional parameter, dQ/dt, which is a signal from another instrument. $dQ/dt = \% \; DM/dt = \% \; (dD/dt) \; (dA/dt) \; (dS/dt)$ parameters already discussed and make the necessary adjustments to dM/dt so that the on-line apparatus will feed at a constant chemical composition rate. For example with fast neutron activation analysis it is possible to evaluate the percent carbon content of coal in a given

$$(dM/dt) \text{ stream} = dD/dt \times (dA/d) \times (dS/dt)$$

These parameters can be instantly processed by computer and the carbon and hydrogen ratio can be determined to control the feed rate for constant B.T.U. output.

SPECIFIC EMBODIMENTS

Referring now to FIGS. 4, 5 and 6, there is shown in simplified form an apparatus **5** embodying the principles of the present invention and adapted for handling particulate material in several different modes in accordance with the process conditions and the desired operation. Essentially the apparatus is constructed to continuously collect a stream of particulate material (not shown) by peripherally enclosing the stream in a tubular zone as the latter is produced, thereby forming a column of material and to simultaneously convey the column under controlled compaction. The tubular zone in the illustrated embodiment is disposed vertically and is defined by two spaced-apart fixed walls **10** and **12** and by two flexible endless belts **14** disposed with a portion of one belt in spaced-apart opposed relationship to a corresponding portion of the other belt, these opposed portions lying between the fixed walls **10** and **12** so as to straddle and frictionally engage particulate material in the tubular zone. As seen in FIG. **6** each belt **14** includes a central body portion **18** and two edge flanges **20**, the latter being in slidable engagement with the walls **10** and **12** during operation, as seen in FIG. **5**.

The belts **14** are trained over suitable rollers or pulleys such as upper pulleys **22**, idlers **24** and motor-driven, synchronized lower pulleys **26**. The lower pulleys **26** are rotatably carried on the lower end portions of vertically extending arms **28** which are pivoted at their upper ends on shafts **30** for swinging movement in a vertical plane. The shafts **30** are supported by suitable fixed framework **32** of the apparatus. The idlers **24** are rotatably mounted on belt-tensioning arms **34** which are pivoted at their lower ends on the same axles **36** as the driven pulleys **26**. The outer ends of the arms **34** pivotally connect with the upper ends of shock absorbers **38**, the lower ends of which are pivotally connected to the arms **28**.

Belt tension is maintained at a value just sufficient to prevent slippage of the belts **14** on the drive pulleys **26**, this being accomplished by providing weights to the upper ends of the belt-tensioning arms **34** if necessary. This allows the belts **14** to droop, as shown in FIG. **4**, and allows the belt-support arms **28** to sense imminent collapse of the particulate material and take up the slack created by voids in the materials.

The lower ends of the arms **28** together with the lower pulleys **26** are yieldably urged toward one another by spiral springs **40** which press against depending flanges **42** carried by the arms **28** at a location outside the tubular zone. During movement of the belts **14** this feature, together with the fact that the lower pulleys **26** are of relatively large size, applies high compacting pressure to the particulate material passing through the lower end of the tubular zone and thereby forms a dense plug of material which prevents the column of material above the plug from flushing out of the tubular zone. When no material is present in the apparatus, the springs **40** urge the arms to the positions shown in FIG. **4**. When material is conveyed downwardly through the tubular zone by movement of the belts **14**, the arms **28** will swing outwardly against the springs **40** as the material is being compacted into a plug at the lower end of the zone. The plug is continuously discharged from the apparatus through a tubular arrangement formed by the lower ends of the walls **10** and **12** and spaced-apart plates **43**.

It will be recalled that the apparatus is adapted either to apply a controlled transverse compacting force to the column of particulate material moving through the tubular zone or to adjust and fix the transverse cross section of the zone. In the illustrated apparatus these features are obtained with the aid of two vertically-disposed, laterally-adjustable shrouds which are constructed and arranged to bear against the reverse sides of the belts **14**. Each shroud is constructed of upper and lower pieces **44** and **46** hinged together by a horizontal hinge pin **48** or the like. The upper pieces **44** carry a plurality of parallel rollers **50** which extend across the width of the belts **14** and contact the rear faces of the latter. The lower pieces **46** include a flat plate portion **52** having a width about equal to the width of the belts **14** and one or more web portions **54** projecting from the rear face of the plate portion **52**.

The upper shroud pieces **44** are pivoted on the axles **30** for swinging movement in vertical planes, and the lower shroud pieces **46** are similarly movable about the pins **48**. Upper fluid-pressure rams **56** are connected between the pins **48** and a fixed frame member **32**, and lower fluid-pressure rams **60** are connected between a pivot point on the lower shroud pieces **46** and the frame member **32**. The rams **56** and **60** are employed either to apply a constant force to the shroud pieces **44** and **46** or to fix the shroud pieces **44** and **46** in desired positions, depending on the mode of operation of the apparatus. In the first case the rams **56** and **60** may be supplied with constant pneumatic pressure from a suitable supply and control system (not shown) so that a constant force if transmitted to the column of particulate material moving downwardly between the belts, thereby applying a constant compacting action to the material. In this mode of operation the shroud pieces **44** and **46** will move toward and away from each other with changes in the packing characteristics of the particulate material being fed to the belts **14**. In this regard it will be seen in FIG. **4** that feeding of material to the belts is effected by a tubular arrangement which includes the upper end portions of the walls **10** and **12** and two spaced-apart plates **62**. A flexible tubular liner **64** may be provided at this location to prevent spillage. Feeding may also be aided by providing one or more vibrators **66** at this location, as by attaching it to the walls **10** and **12**.

When the shroud pieces **44** and **46** are to be held in fixed positions thereby effecting a constant transverse cross section for the moving column of material, the rams **56** and **60** may be of the hydraulic type provided with a suitable supply and control system (not shown) for hydraulically locking the rams so as to prevent relative movement between their piston and cylinder elements.

A nuclear density gage, which may be of conventional construction, is attached to the apparatus for continuously analyzing the movement column of particulate material. An instrument of this type includes a source **68** of penetrating radiation, such as a source of gamma radiation and a detector **70** for measuring the intensity of the radiation which has passed through the material being analyzed. In the present arrangement the source **68** and detector **70** are mounted on the fixed walls **10** and **12** so that the radiation always traverses a path of constant length. It should be understood, however, that the present invention is not limited to the use of this type of analyzing instrument, although it is necessary that the particulate material be analyzed while it is under compaction as a result of the action of the belts **14** and shroud pieces **44** and **46**.

In operation of the apparatus most if not all of the compacting action will be effected by the upper shroud pieces **44**, while the lower shroud pieces **46** serve mainly to maintain the compaction as the column of material moves past the nuclear gage **68,70**. The degree of compaction at this point will be such that the material is free of voids, moves as an integral mass and is held so firmly that millroom or other machinery vibration will have no additional compacting effect. The bulk material contacts the belts, made of rubber in this embodiment, with static friction which is distinctly greater than the sliding friction between the bulk material and the steel walls **10,12**, and this fact aids in uniformly moving the material through the compacting zone without introducing variations in compaction. That is, the material wants to move with the belts **14** and to slide on the walls **10,12**, thereby avoiding intermittent or stop-and-go movement of the material.

The flanged belts **14** are preferred for finely divided material such as material less than about 100 microns, because the radial forces set up in the compaction zone hold the flanges **20** in contact with the walls **10,12** to prevent escape of material. For coarser material plain, unflanged belts may be employed. For high temperature application flexible metal belts may be used, and for intermediate temperatures combination metal and rubber belts may be used.

Particulate material may be fed to the upper end of the tube defined by the walls **10** and **12** and the plates **62** by any conventional means, such as a gravity flow hopper, either vibrated or static. However, when the particle size is small, for example less than about 100 microns, the operation of the above-described apparatus is sometimes improved by feeding to the tube a supply of material which has been conditioned so as to be continuously available for conversion into the stream moving into and through the tubular compacting zone. In the upper part of FIGS. **4** and **5** there is shown a device **72**, which may be termed a constant head feeder, capable of removing any density variations from whatever bulk supply of finely divided material is employed and offering it to the belts **14** at whatever speed the latter are operating without forcing the material to the belts. It will be appreciated that, if density variations in the finely divided particulate material are not eliminated or avoided before passing it to the belts **14**, these density variations will be carried through into the compacting zone where they will produce spurious nuclear gage readings. Ordinarily, the compacting action of the belts **14** will be sufficiently great to overcome normally occurring density variations in the feed from a hopper or the like.

The constant head feeder **72**, when employed, assures a uniform supply of finely divided particles under a constant gravity head, and in the form illustrated in FIGS. **4** and **5** it includes a perforated member **74** such as a slotted screen, which by itself prevents the material from sifting through by gravity, and means for agitating the material above the screen **74**, such as a motor-driven paddle **76** having a plurality of blades **78** supported on a central hub **80**.

In operation of the feeder **72** rotation of the paddle **76** wipes the blades **78** across the apertures in the screen **74**, breaks up any aggregates of material, prevents arching above the screen **74** and generally agitates the material so that it sifts uniformly through the screen **74** and fills whatever container is disposed below the screen **74** with uniformly loosely-compacted material. If the container becomes full, no more material will pass through the screen **74**, and continued agitation of the material above the screen **74** will have no compacting effect on the material in the container. When the material is continuously drawn away from the bottom of the screen **74** by operation of the belts **14** at any rate less than the rate at which material passes through the screen **74**, the feeder **72** continuously supplies uniformly loosely compacted material to the belts

14. The thickness of the screen **74** is equal to or greater than the width of the slot openings as measured normal to the direction of movement of the blades **78**, because if the screen thickness is less than the slot width, the forces created by the blades **78** would be transferred through the slots and cause erratic compaction of the material below the screen **74**.

Referring to FIG. **7** there is shown a process system in which the apparatus of FIGS. **4, 5** and **6** is employed for continuously measuring the average particle size of the process material under dynamic conditions. For purposes of illustration the process system may be assumed to be that portion of a cement manufacturing plant in which clinker is ground in a mill **82** and conveyed to an air classifier **84** where particles within a desired size range are separated from the incoming material and discharged from the lower end of the classifier **84**. Under normal operating conditions all or substantially all the ground cement from the classifier **84** will be passed through the analyzer **5** so as to be analyzed by the nuclear gage **68,70**.

In the FIG. **7** arrangement the ground cement in the apparatus **5** is subjected to a constant compacting action by applying constant, yielding force to the shroud pieces **44,46** with the rams **56,60** (shown in FIG. **4**), as heretofore described. Under these conditions, once the nuclear gage **68,70** has been calibrated for cement of the same chemical and physical type, the output signal is proportional to the particle size of the cement, as discussed in detail above. The signal may be employed for various purposes and is particularly useful as a control signal for adjusting the operation of the classifier **84** or the operation of the grinding mill **82** or both. The effects of changes in particle size on the properties of cement are well known, and generally it is desirable to operate the classifier and mill so as to obtain a ground product having particles which on the average are within a relatively small range of sizes.

Still referring to FIG. **7** it will be appreciated that the mass flow rate through the classifier **84** is not always uniform. In order to carry off any excess production which exceeds the capacity of the analyzer **5** there is provided a by-pass arrangement which includes a horizontal variable pitch screw **86** disposed with its inlet end within a vertical conduit **88** depending from the classifier **84**. The cement which is by-passed passes downwardly through a vertical conduit **90**, then horizontally to the right under the action of another screw **92** and finally into a discharge conduit **94**. The by-pass arrangement may also be operated to by-pass all the material so as to permit maintenance and calibration of the analyzer **5**.

The discharge end of the housing **96** for the screw **86** is provided with a closure plate **98** which is biased toward a closed position by a spring **100** or an air cylinder. As a result of the back pressure thus created the cement in the housing **96** will be compacted into the form of a plug which presses against the plate **98**. When the compacting pressure exceeds the spring pressure the plate **98** moves away from the end of the housing **96** to permit discharge of cement. The presence of the plug is desirable in this system to prevent air from entering the system due to the partial vacuum generally present in the classifier **84**.

FIG. **8** illustrates schematically a bulk material feeding system employing the analyzer **5** of FIGS. **4, 5** and **6** in a manner to control the mass flow of the bulk material. The illustrated system represents a typical steel industry process wherein pulverized coal and pulverized iron ore from separate sources **102** and **104** are conveyed first to a mixer **106** and then to a sintering furnace **108**. The sources **102** and **104** may be considered simply as hoppers for purposes of illustration. Each source **102,104** is connected to the upper end of an analyzer **5** by means of a constant head feeder **72**. The analyzers **5** are operated to pass their respective materials through a compaction zone of fixed transverse cross section by adjusting the shroud pieces **44,46** to stationary positions as discussed in connection with FIGS. **4, 5** and **6**. Under these conditions the mass of material being analyzed varies with changes in the packing characteristics of the material, and the output signal from the density gage **68,70** is proportional to the mass flow rate of material passing through the analyzer **5**. The variable-speed motors **110** for the analyzers may then be adjusted in accordance with the mass flow rate signals in order to achieve a desired flow rate. Usually it is desired to maintain constant flow and this may be accomplished automatically by conducting the flow rate signal of each analyzer **5** to a set point control system **112** where the flow rate signal is compared with a signal which is adjusted to a desired value indicative of the desired flow rate. The resulting control signal may be employed to control the speed of the motors **110**.

The FIG. **8** system also employs an analyzer **5** in a manner to effect control of the chemical content of the mixture of coal and iron ore. In the type of process illustrated the uniformity of the sintered product depends in part on the amount of carbon in the mixture and it is desirable to maintain the carbon content of the feed to the furnace **108** constant at, for example 7 percent. This may be accomplished by feeding the mixed coal and ore to the furnace **108** with an analyzer **5'** which has been modified to the extent of including a nuclear carbon content gage along with a nuclear density gage **68,70** and by utilizing the output signal **114** of the carbon content gage **68'** to adjust the set point signal in one or both of the control systems **112**. That is, by measuring the carbon content of the mixture and adjusting the mass flow of one or both of the components of the mixture it is possible to control the carbon content in the mixture. The carbon content gage **68'** may be of known construction, one such known instrument operating by irradiating the carbon-containing material with a source of neutrons and by counting the 4.3 mev gamma rays which are produced from the carbon atoms by the inelastic scatter of the neutrons.

FIGS. **9** and **10** illustrates an alternate form of apparent density analyzer and mass flow regulator which embodies the same principles as the apparatus **5** illustrated in FIG. **4**. In this embodiment the tubular zone for enclosing the particulate material includes, as in the FIG. **4** embodiment, a pair of vertical, spaced-apart, fixed walls **140** and **142** and two flexible endless cleated belts **144** and **146**, the latter being disposed with opposed portions lying between the fixed walls **140** and **142** so as to straddle and frictionally engage particulate material in the tubular zone. The belts **144** and **146** are trained over upper and lower sprockets **148** and **150** which are mounted on generally C-shaped side frames **152**. The side frames **152** are suspended below a fixed frame **154** and are pivoted on the fixed axles **156** of the upper sprockets for swinging movement toward and away from each other. The belts **144,146** are driven in synchronization by any suitable means such as motors **157** carried by the side frames **152**.

To achieve compaction of particulate material being conveyed through the tubular zone by the belts **144** and **146**, two vertically-disposed, laterally-adjustable flexible shrouds or blades **158** are arranged to bear resiliently against the reverse sides of those portions of the belts **144,146** which lie between the upper portions of the fixed walls **140,142**. The upper end portions of the resilient blades **158** are curved so as to effect gradual compaction of the material being conveyed. The lower ends of the blades **158** are secured to the upper end of a fixed tubular member **167**. The degree of compaction of the material being conveyed is determined by the force of the resilient blades **158** on the material. This force may be increased by means of extensible rams **160** which are mounted on fixed tie plates **168** so as to bear against the rear surfaces of the plates **158**. The rams **160** may be operated, as in the FIG. **4** embodiment, to apply a constant force against the shrouds or to fix the shrouds **158** in a given position. In the former case, the shrouds **158** can move toward or away from each other with changes in the compaction characteristics of the particulate material, and in the latter case the transverse cross-sectional area of the tubular zone will remain constant.

In order to prevent flushing of material out of the lower end of the tubular zone the lower portion of the latter is yieldably restricted in cross section. This is accomplished in the FIG. **9** embodiment by means of two flat, bar-type steel springs **162** which yieldably press against the reverse sides of the belts **144,146**. Other means may be employed to accomplish the same purpose, for example, a tapered elastic rubber sleeve or boot. As shown, each spring **162** is carried by the lower flange of the tubular shroud **167**, this being accomplished by clamping the upper end portion of the respective spring **162** between adjacent flanged portions of the tubular shroud **167**. When no particulate material is present in the apparatus the springs may actually move the belts **144,146** into engagement with each other. When material passes through the device the springs **162** are urged apart by the friction existing between the plug of material and the belts **144,146**.

A nuclear density gage **164** including a radiation source and detector is disposed across the constant transverse dimension determined by the fixed walls **140** and **142** at a location above the anti-flushing springs **162**. The gage **164** and its operation, as well as the overall operation of the remainder of the apparatus illustrated in FIG. **9**, are the same as the operation of the apparatus **5** illustrated in FIG. **4**. It will be understood that particulate material will be fed to the upper ends of the belts **144,146**, for example, through a conduit **166**, in a manner such that variations in compaction during feeding are not carried through into the zone between the belts **144,146**. That is, for finely divided material some means, such as the constant head feeder of FIG. **4**, will be employed to deliver material to the conduit **166**, whereas for coarser material no special feeding mechanism is required.

The nuclear gage **164** may also be employed to measure the change in degree of compaction of the particulate material as the latter moves into and through the compacting zone. To accomplish this the radiation source and the detector are mounted for vertical movement and are moved downwardly at the same speed as the belts **144,146**, from a position adjacent the lower end of the conduit **166** to the lower position illustrated in FIG. **9**.

FIG. **11** illustrates the apparatus of FIG. **4** modified slightly so as to be useful as a chemical reactor, specifically as a reactor for converting pulverized coal to liquid and gaseous hydrocarbon fuels and chemicals by subjecting the coal to atomic hydrogen and methyl radicals produced in a corona-type discharge. As is known, this type of conversion can be carried out at atmospheric pressure by exposing a mixture of pulverized coal and gaseous hydrogen to a corona-type discharge, the latter being characterized by freedom from arcing and by a low current carrying column at a voltage gradient of the order of the electrical break-down strength of the gas. Under these conditions the electrically produced electrons have an energy distribution from just above zero to somewhat above the ionization potential for the gas and in turn cause the production of free radicals. The process is described more in detail in Chemical Engineering Progress, Vol. 60, June 1964, pages 41–44.

In the apparatus of FIG. **11** pulverized coal is first delivered to a mixing device which may be in the form of a constant head feeder **72'** modified to introduce hydrogen gas into the stream of coal. As shown, two opposite sides of the feeder **72'** have been removed and replaced with porous plates **170**, such as porous tile pads, through which hydrogen is forced under pressure so as to flow into the feeder and become thoroughly mixed with the coal.

Upon flowing through the slots **74'** under the action of the agitator **76'** the mixture of coal and hydrogen is engaged and continuously conveyed downwardly by the belts **14'** past the nuclear density gage **68'**. The apparent density or the degree of compaction of a particularly sized coal must be maintained generally constant, and this is accomplished with the gage **68'**, the control functions being related to dA/dt and dS/dt as was discussed previously with respect to mass flow rate. By maintaining a constant specific apparent density the excess hydrogen gas is squeezed out of the coal thereby effecting a desired hydrogen concentration. A plurality of opposed flat electrode plates **172** are spaced in series down along the stationary walls **10,12** of the tubular zone below gamma gage **68'**. The total voltage necessary to initiate coronatype discharge between the plates can be calculated and controlled. Once corona is developed in the void space between the coal particles, the reaction is self-sustaining while the corona power remains on. Since the corona processing of coal is performed on a continuous basis it is possible to perform many different kinds of reactions and create different products as the coal passes through the reactor zone. When the specially prepared coal first enters the reaction zone, rich in hydrogen, a clear liquid is first produced. As the coal proceeds further into the reaction zone and the hydrogen concentration becomes less, a gaseous and tar-like substance is produced. Finally, a stage is reached in the reactor zone in which the electrical conductivity of the remaining coal increases as it reacts until it shorts out the electric field in which corona no longer can be maintained, and the coal is considered processed and is discharged from the lower end of the apparatus 5'. The products of the above-described corona processing of coal are subsequently treated with conventional extraction techniques after the material leaves the apparatus.

It will be apparent from the above that any energy field such as Laser or microwave discharge is applicable for use in conjunction with the on-line apparatus 5' as a chemical reactor for various other chemical and pyro-processing operations.

FIG. **12** illustrates a simplified form of particle size analyzer employing a different type of conveyor system which is suitable under some conditions, such as where the particulate material is inherently free of density variations and where the apparatus is not subjected to vibrations from nearby plant equipment. In the FIG. **12** embodiment particulate material is fed to the upper end of a vertical conduit **116** onto the top of a piston-like structure **118** which is moved downwardly at constant velocity past the nuclear density gage **68**. The piston is suspended between two endless chains **120** which are trained over upper and lower sprockets **122,124**, one set of which is motor driven. The means for feeding the material to the conduit **116** functions in the same manner as the previously described constant head feeder **72** in that the material is made available to the conduit in a uniformly compacted state. In the FIG. **12** embodiment a constant head feeder is constructed in the form of a horizontal screw conveyor, having a screw **126** within a housing **128** disposed above the conduit **116**. The housing **128** has a slot **132** in its wall disposed immediately above the conduit **116** so that the screw wipes the particulate material across the slot in a manner similar to the operation of the blades **78** in FIG. **4**.

In operation of the FIG. **12** device the particulate material is supported on the piston **118** and is urged downwardly by the friction existing between the material and the chains **120**. This prevents arching of the material so that the only density variations present are those due to changes in particle size. These variations are sensed by the gage **68** as a measure of particle size. In this embodiment it will be appreciated that the constant compacting action in the compacting zone, that is, in the conduit **116**, is the force of gravity rather than the belts **14** of the FIG. **4** embodiment. It may be desirable to vibrate the material in the tube, as by attaching a vibrator (not shown) to the upper part of the tube, in order to improve uniformity of compaction.

The various constructions described above have utility in many industrial processes in that they may be employed to measure the particle size of the feed, to measure the particle size of the product and to convey feed or product at desired mass rates and in that these functions may be readily included in an automated system. In addition, the equipment lends itself to combination with known instruments capable of measuring various properties under dynamic conditions.

What is claimed is:

1. A method of treating dry, pourable solids while conveying the same from one point to another at controlled rates and at controlled compaction densities comprising:

disposing a mass of comminuted material immediately adjacent a retaining structure having at least one relatively small downwardly-facing aperture therein;

producing a stream of the material having low, generally uniform compaction; continuously collecting said stream of material under quiescent conditions and without agitation by peripherally enclosing the stream of material as it is produced so as to form a column of material and simultaneously conveying the column along a predetermined path by frictionally engaging a substantial length of the material forming said column between two spaced apart flexible elements and moving said elements along said path, said step of collecting and conveying said column of material including simultaneously compacting said column in a direction transverse to its direction of movement by urging said flexible elements together; and effecting a chemical reaction within said moving column of material by directing an energy field into said column while it is being conveyed by said flexible elements.

2. A method for conveying dry, pourable solids from one point to another at controlled compaction densities and for simultaneously measuring the density of the solids comprising:

continuously delivering a stream of the solids to the end of a tubular zone at a rate which fills the bore of the tubular zone thereby forming a moving column of the solids;

simultaneously moving the column of solids through said zone under quiescent conditions by frictionally contacting and compacting a substantial length of the material in said column between two spaced-apart, flexible elements which extend longitudinally of said zone and moving said elongated elements longitudinally of said zone to urge said material through said zone at the same speed as said elements while maintaining said column free of mechanical agitation;

and continuously measuring changes in the nature of the column by continuously directing an energy field onto said moving column in a direction transverse to the direction of movement of said column and by continuously detecting the effect produced on the energy field by the moving column.

3. A method as in claim **2** wherein said step of moving said column of material includes simultaneously urging said flexible elements toward each other by applying a predetermined constant yieldable force to said flexible elements to cause them to converge in the direction of movement.

4. A method as in claim **3** wherein said step of delivering a stream of solids includes disposing a mass of the solids immediately adjacent a retaining structure having at least one downwardly facing unobstructed aperture and agitating the material only within said retaining structure adjacent the aperture to cause a stream of substantially uniformly compacted material to flow through the aperture into said tubular zone.

5. Apparatus for conveying dry, pourable solids in the form of a continuously moving column which is free of random density variations due to mechanical agitation of the particles, friction and arching tendencies, said apparatus comprising means defining a tubular zone which peripherally engages and encloses and supports the column of solids, said means including two endless looped members which in combination with fixed parallel walls define a tubular zone for receiving at one end a stream of solids, said two endless looped members arranged with a portion of one member disposed in spaced-apart, opposed relationship to a corresponding portion of the other member, said portions converging and extending longitudinally of said zone for frictionally engaging and straddling a mass of solids in said zone; and drive means for smoothly driving said endless members so as to urge the entire column of solids without tumbling or agitation thereof through said zone at the same speed as said members; and feeding means associated with said one end of said zone for delivering loosely compacted material to said one end at a rate sufficient to continuously replenish the column of material in said zone upon continuous movement of said endless members.

6. Apparatus as in claim 5 wherein said feeding means includes means for producing a uniformly loosely compacted, downwardly flowing stream of unagitated solids, said feeding means including a retaining structure having side and bottom walls defining an enclosure for a mass of solids, said bottom wall having at least one unobstructed aperture therethrough in communication with said one end of said tubular zone and agitator means wholly within said retaining structure for agitating the material adjacent said aperture to cause material to flow through said aperture as a uniformly loosely compacted stream free of agitation and free of density variations resulting from movement of said agitator means.

7. Apparatus as in claim 5 further including an analyzer associated with said tubular zone for determining changes in the nature of the moving column, said analyzer including means for directing an energy field onto the moving column and means for detecting the effect produced on the energy field by the moving column.

8. Apparatus as in claim 7 wherein said means for directing an energy field on the moving column includes a source of penetrating radiation and wherein said means for detecting includes a detector for measuring the intensity of said penetrating radiation, said source and said detector being disposed on opposite sides of the moving column so that said detector measures the radiation transmitted through the column, said intensity measurement being a measurement of the particle size of the moving column.

9. Apparatus as in claim 7 wherein said portions of said endless members are mounted for movement toward and away from each other, said apparatus including means for applying a constant yieldable force to said portions to resiliently urge them toward each other.

10. Apparatus as in claim 7 wherein said portions of said endless members are mounted for movement toward and away from each other, said apparatus including means for adjusting said portions to effect a predetermined fixed distance between them.

11. In the method of measuring the particle size of dry particulate solid material by measuring the porosity of the material after compaction and comparing it to the porosity of a standard material which has been subjected to the same compacting and measuring steps, the improvement which comprises: subjecting a mass of the particulate material to a compacting force acting in a given direction while maintaining constant the dimension of said mass in a direction transverse to said given direction thereby reducing the dimension of said mass in said given direction and continuing the compaction until no further compaction of the material occurs; and measuring the degree of compaction in said transverse direction by directing an energy field into the compacted material and measuring the effect produced on the energy field by the moving material.

12. A method as in claim 11 wherein the compacting of the solids is effected by feeding the solids into the space between two spaced-apart driven endless conveyer surfaces and pressing the surfaces toward each other with a constant yieldable force to frictionally engage the surfaces with the solids and move the latter as an integral plug of material, and wherein the energy field is directed into the solids between the surfaces in a direction which is transverse to the direction of movement of the solids.

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