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United States Patent

[11] 3,566,224

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[33] Italy
[31] 26409/64
Continuation-in-part of Ser. No. 492,663, Oct. 4, 1965, now abandoned.

[54] **LINEAR ELECTROMAGNETIC MOTOR**
2 Claims, 7 Drawing Figs.

[52] U.S. Cl. 318/135, 310/14
[51] Int. Cl. H02k 41/02
[50] Field of Search .... 310/12—14; 318/135

[56] References Cited
UNITED STATES PATENTS

3,162,796	12/1964	Schreiber et al.	310/12X
3,185,909	5/1965	Jahn	310/12X
3,219,853	11/1965	Schreiber	310/14

Primary Examiner—Donovan F. Duggan
Attorney—Sughrue, Rothwell, Mion, Zinn and MacPeak

ABSTRACT: A linear electromagnetic motor having a plurality of similar annular, coaxial and uniformly spaced coils or electromagnets, an elongated core of ferromagnetic material coaxially arranged with said coils, and a plurality of similar, annular projections, equally spaced along the core. The length L of the coil row is related to the pitch of the coils P and to the pitch of the projections p by the following equations:

$$L=np$$
$$L=(n\pm 1)P,$$

the length of the row of coils being greater than that of the row of projections.

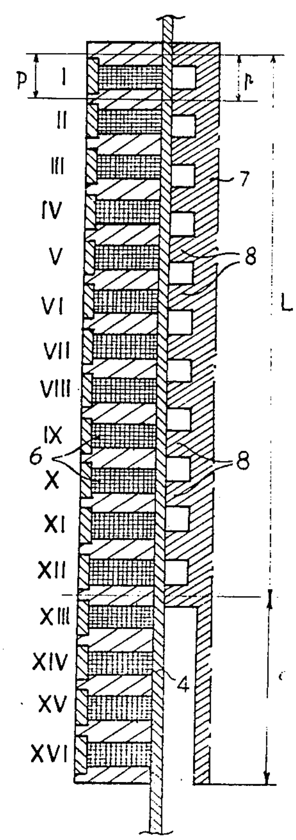

Fig. 1

PRIOR ART

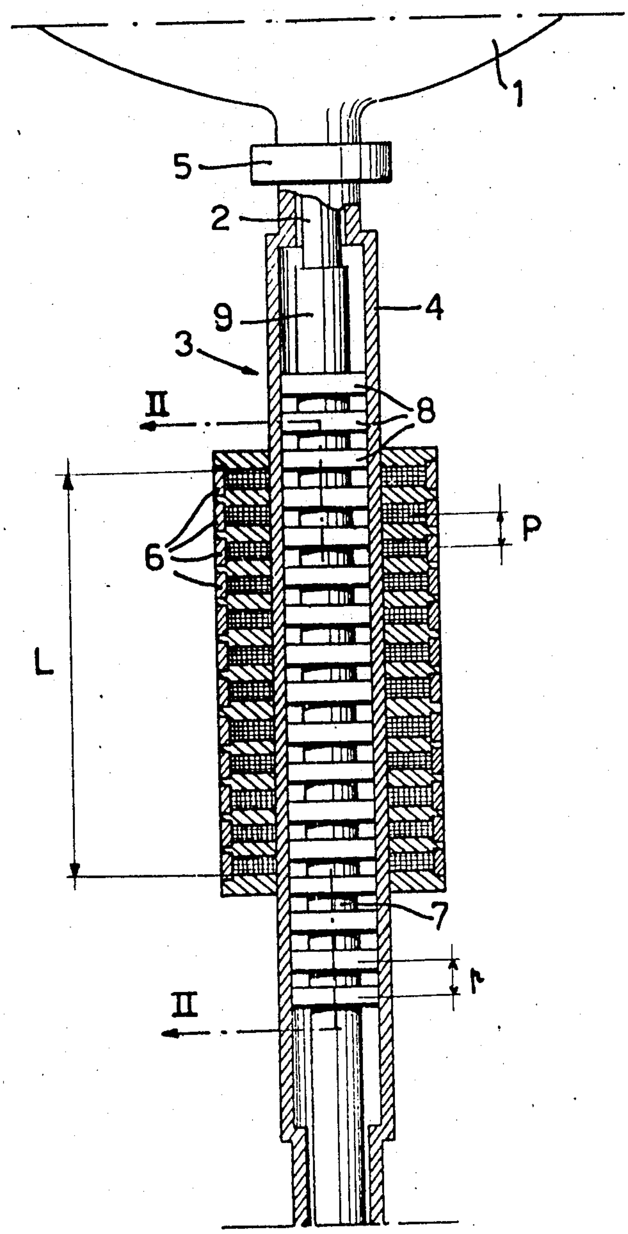

Fig 2

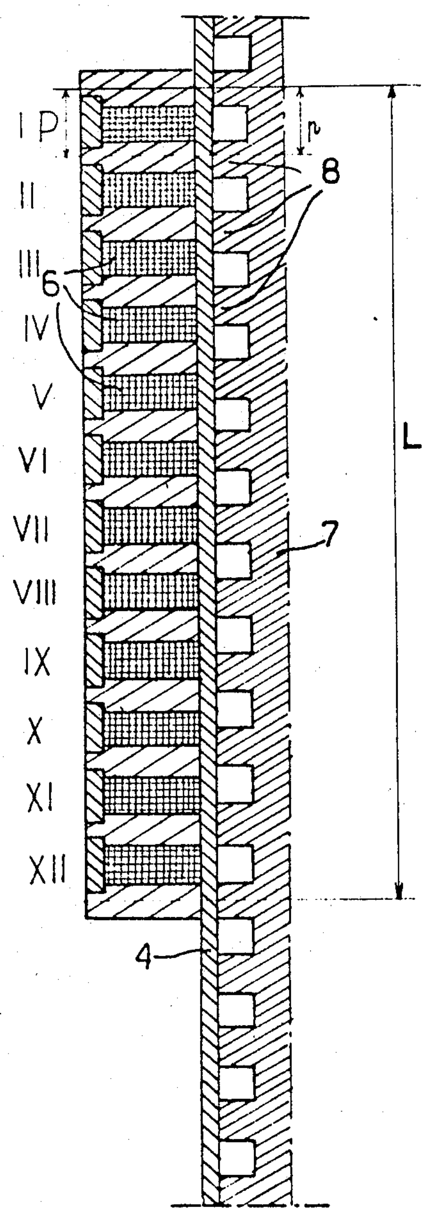
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Fig 3

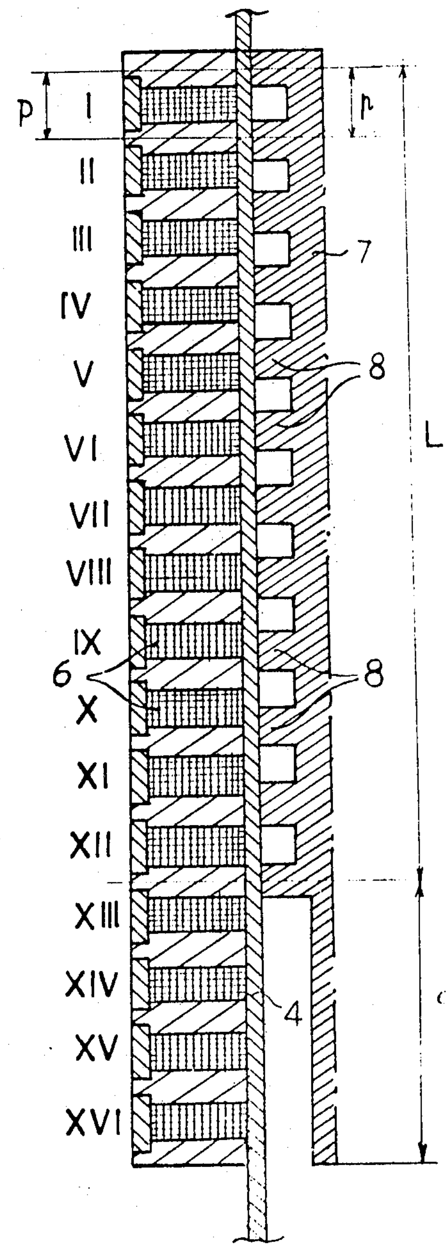
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Fig. 4

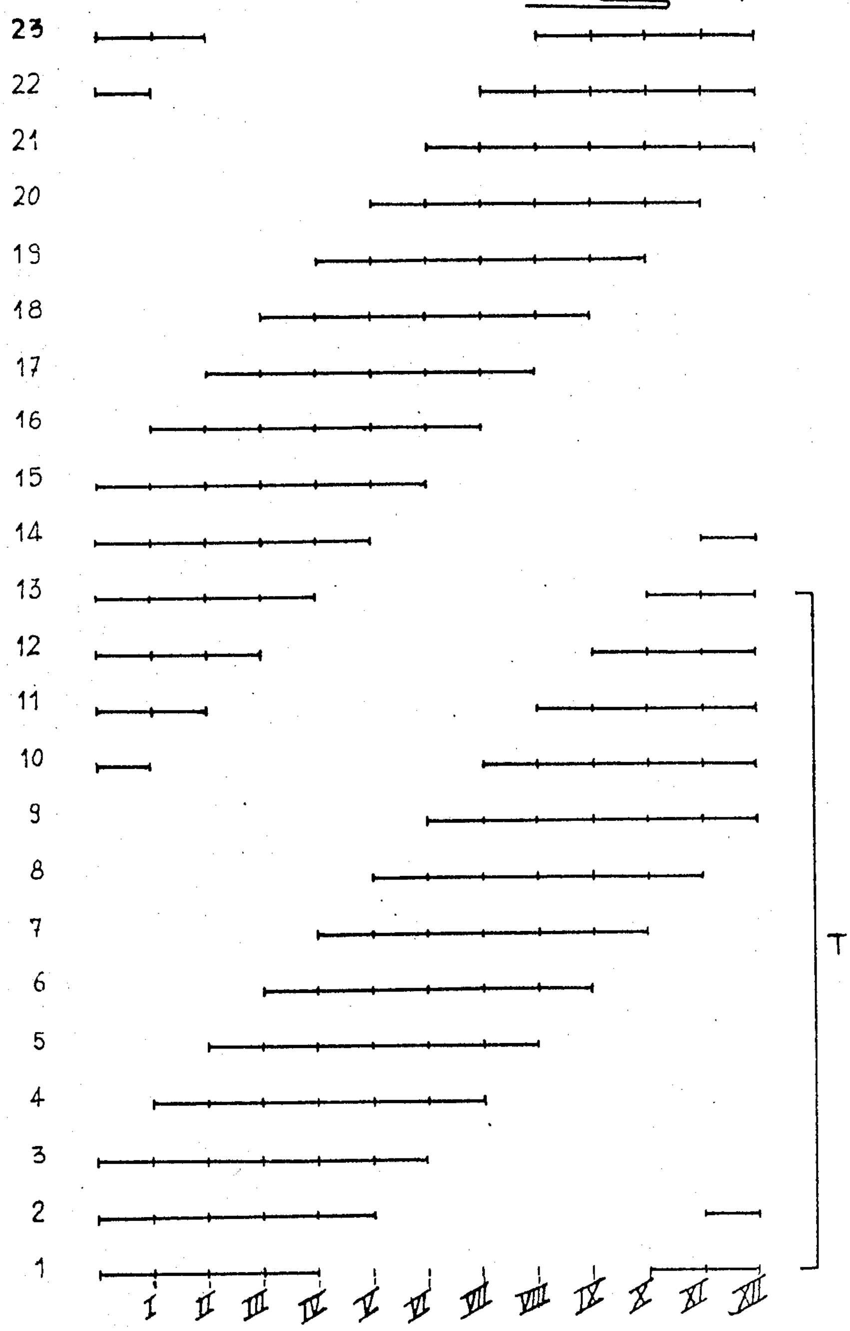
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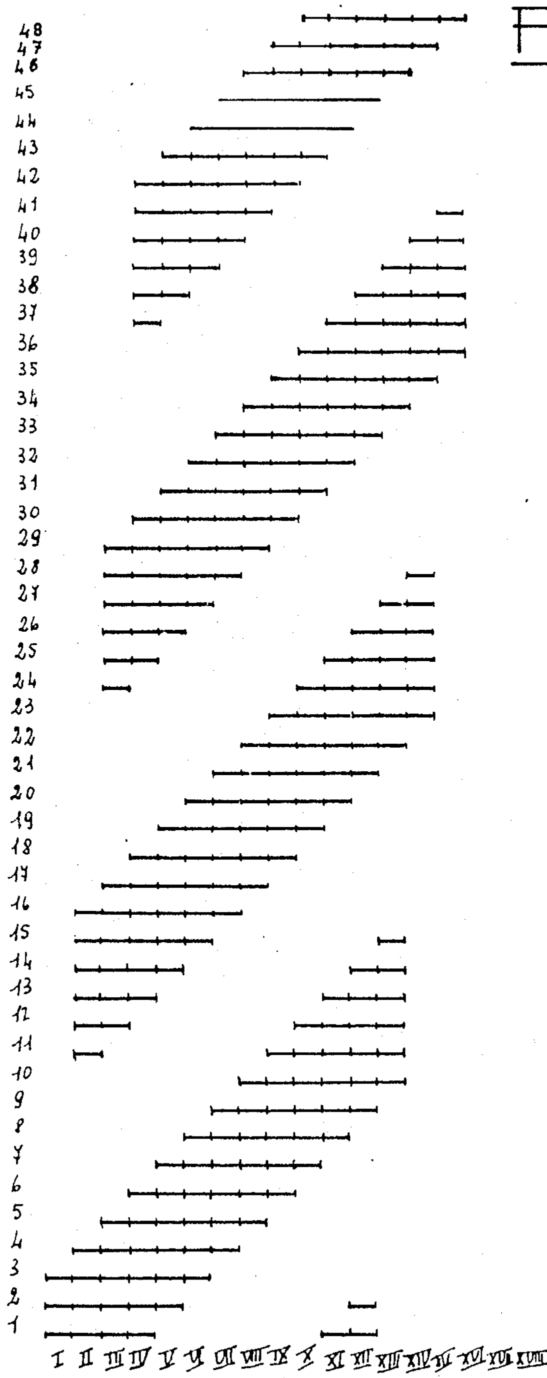
Fig. 5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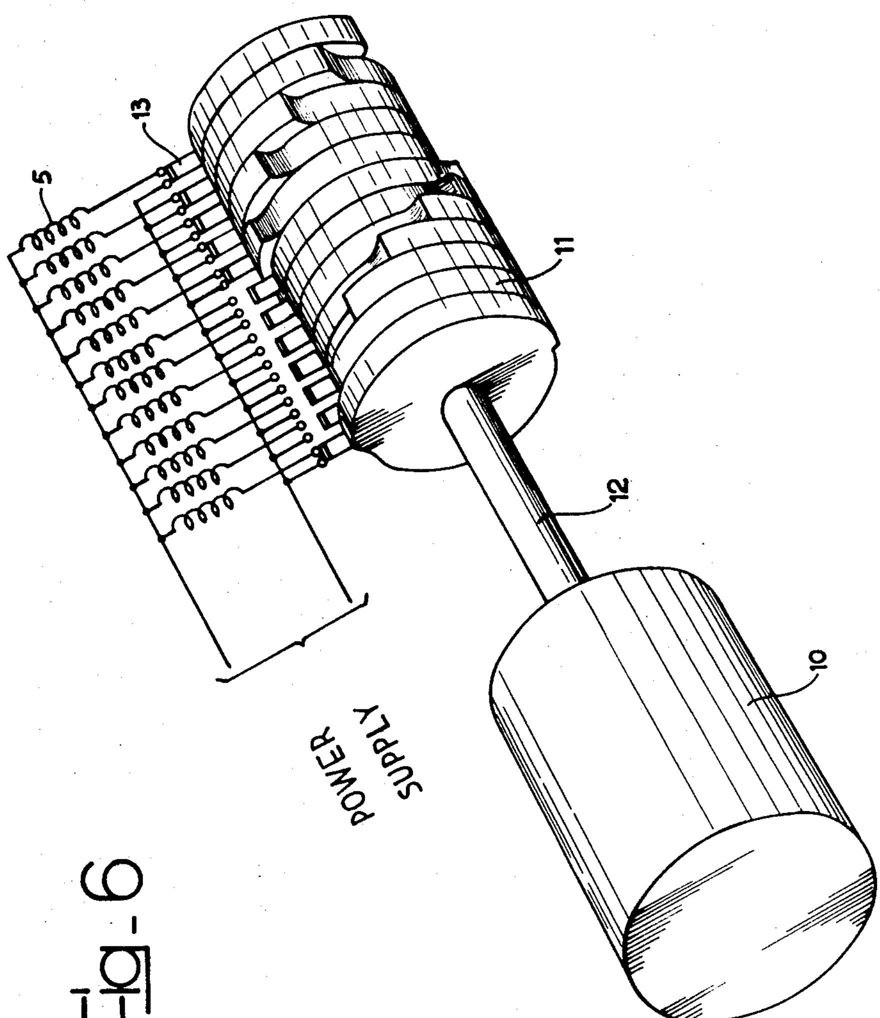

Fig-6

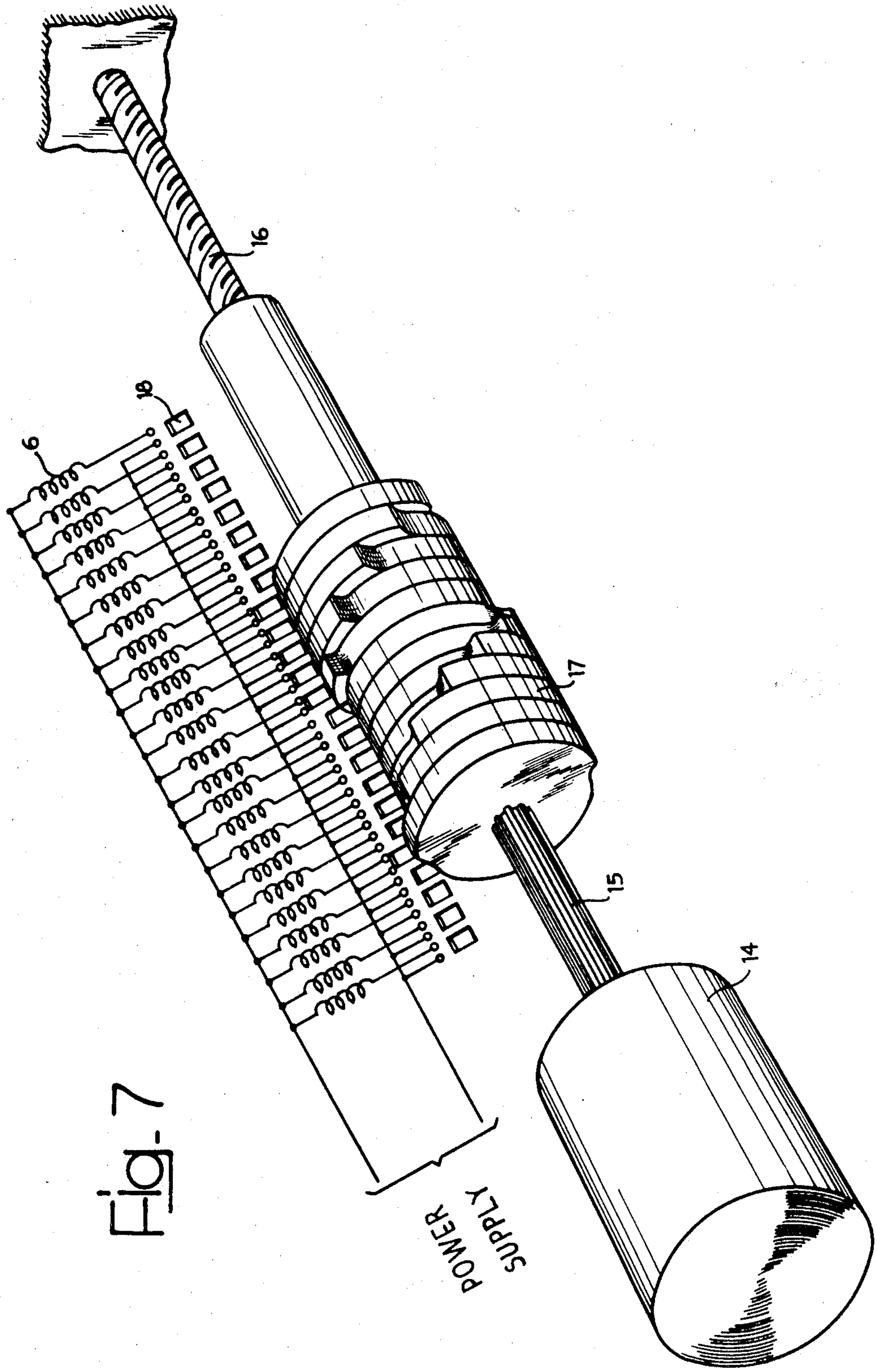

Fig. 7

LINEAR ELECTROMAGNETIC MOTOR

CROSS REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of our prior application Ser. No. 492,663, filed Oct. 4, 1965, now abandoned which in turn claims priority from our Italian application filed Oct. 9, 1964.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to vernier-type linear electromagnetic motors, which may be employed for example for remotely controlling axial movements of members movable within sealed vessels, such as control rods of nuclear reactors.

2. Description of the Prior Art

U.S. Pat. No. 3,162,796 to Schreiber et al. discloses a vernier-type linear electromagnetic motor for moving a rod structure within a sealed vessel of the type including a stationary portion having a stationary supporting casing adapted to be tightly secured to the sealed vessel and a plurality of similar, selectively energizable electromagnets or coils secured to the supporting casing, the electromagnets or coils being equally spaced and extending along the axis of the casing so that the centers of the electromagnets or coils are spaced by a constant pitch, and a movable portion adapted to be connected to said driven member and having an elongated core of ferromagnetic material coaxially movable within the supporting casing, the core having a plurality of similar annular projections or teeth equally spaced so that the centers of the annular projections are spaced by a constant pitch, different from the spacing pitch of the electromagnets, wherein the projections and the electromagnets face each other over an axial section of the supporting casing along a given length wherein said given length is related to the pitch of the projections and to the pitch of the electromagnets according to a predetermined vernier scale ration. In this known structure, the toothed length of the elongated movable core is greater than the length over which extend the electromagnets secured to the stationary supporting casing.

U.S. Pat. No. 3,219,853 to Schreiber shows a similar linear motor wherein, in addition to the above-mentioned feature, several coil groups are used, thereby obtaining a tandem arrangement of a number of motors with a short coil group mounted with correspondingly energized coils in order to multiply the useful force.

Both these known arrangements suffer the drawback that the weight of the movable core increases when its stroke is increased.

SUMMARY OF THE INVENTION

The object of this invention is to provide an improved linear motor which is free of the above-mentioned prior art deficiency, and in accordance with this object, the motor includes a stationary portion having a supporting casing adapted to be tightly secured to the sealed vessel; a plurality of similar, selectively energizable electromagnets secured to the supporting casing, said electromagnets being equally spaced and extending along the axis of the casing so that the centers of the electromagnets are spaced by a constant pitch P; and a movable portion adapted to be connected to said driven member and having an elongated core of ferromagnetic material coaxially movable within the supporting casing, said core having a plurality of similar annular projections or teeth equally spaced so that the center of the annular projections or teeth are spaced by a constant pitch *p*, wherein said projections and said electromagnets face each other over an axial section of the supporting casing along a length L, wherein the length L is related to the pitch *p* of the projections and to the pitch P of the electromagnets according to a predetermined vernier scale ratio, and wherein the projections on the movable portion extend over only a length equal to length L, and the electromagnets extend over a length greater than the length L by an extent equaling the stroke over which the movable portion travels.

The advantages of the present invention in which the improved motor has a movable core provided with annular projections extending over a distance which is shorter than the elongated coil group with respect to known motors having a long movable core provided with annular projections which extend over a distance greater than the shorter coil group are as follows:

The weight of a short movable core provided with annular projections is lower than the weight of a long core, the useful lifting power and stroke length being the same.

The weight of the long core increases when longer strokes are required, whereas the weight of the short core provided with annular projections remains unaltered in accordance with the invention.

A motor having a short movable core provided with annular projections has a smaller length of the section L and requires less power with respect to the motors having a long movable core provided with annular projections, both during the operation and the rest condition, the lifting power and the outer diameter of their electromagnets being the same.

The above-mentioned advantages are highly significant for a number of nuclear applications, inasmuch as they are critical from the standpoint of the possibility of employing the motors in question in nuclear reactors.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagrammatical axial sectional view of a linear electromagnetic motor of the known type used in connection with a nuclear reactor;

FIG. 2 is an enlarged sectional view on line II–II of FIG. 1;

FIG. 3 is similar to FIG. 2 and shows an electromagnetic motor according to this invention;

FIG. 4 is a diagram showing the switching cycle of the coils or electromagnets of the motor shown in FIG. 2;

FIG. 5 is a diagram showing the switching cycle of the coils or electromagnets of the motor shown in FIG. 3;

FIG. 6 is a perspective view of an embodiment of the switchover means adapted to realize the switching cycle shown in FIG. 4; and

FIG. 7 is a perspective view of a modified form of the switchover means adapted to realize the switching cycle shown in FIG. 5.

Referring to the prior art motor illustrated in FIGS. 1 and 2, 1 denotes a sealed vessel of a nuclear reactor provided with control rods (not shown), vertically movable in channels in the reactor core, in the vessel 1.

The movements of each control rod into and out of its channel is effected by means of a rod 2 remotely operated by means of an electromagnetic motor 3 comprising a stationary portion fixed to the vessel 1 and a movable portion fixed to the rod 2.

The stationary portion of the motor 3 comprises a vertical supporting casing 4 tightly secured to the vessel 1 by means of a sleeve 5 and a plurality of similar annular coils or electromagnets 6 coaxially secured to the outside of the casing 4. The coils 6 are uniformly spaced along the axis of the casing 4 so that the centers of the coils are spaced by a constant pitch P. The coils 6 are denoted in FIG. 2 by progressive Roman numerals, starting from the topmost coil which is denoted by I.

The movable portion of the motor comprises an elongated ferromagnetic core 7 coaxially movable within the supporting casing 4 and having a plurality of axially spaced similar annular projections or teeth 8, so that the centers of the projections are spaced by a constant pitch *p*.

The magnetic core 7 is secured to the end of the rod 2 to be operated by means of a coupling 9 of known type shown in FIG. 1. This coupling may take one of many known forms for interconnecting a driving and driven member. For instance, it may be a fixed connection or a connection of the Cardan type.

The part of the core 7 provided with the projections 8 and the part of the stationary portion provided with the coils 6 face each other over an axial section of the casing 4 of a length L.

As shown in FIG. 2, the length L equals 11 times the pitch p of the projections 8 and 12 times the pitch P of the coils 6.

The axial length of the part of the core 7 carrying the projections 8 is greater than the length L of the section over which this core portion and the part of the stationary portion carrying the coils 6 face each other. More specifically, the axial length of the part of the core carrying the projections equals the length L increased by the stroke length c of the movable portion with respect to the stationary portion.

If n is the integer which is the number of projections 8 within the length L, then the length L of the axial section of the casing 4 along which the part of the movable portion provided with the projections and the part of the stationary portion provided with the coils face each other is bound to the pitch p of the projections and the pitch P of the coils by the following relations:

$$L = np;$$

$$L = (n+1)P$$

This provides a vernier structure. It will be understood that n is an integer greater than 1.

Referring to FIG. 2, wherein the number n equals 11, supply of direct electric current to each of the $n+1$ coils facing the n projections yields a magnetic force to the coils 6 which is:

upwardly directed and steadily increasing in respect of coils from 1 to $(n+1)/4$ (coils I to III);

upwardly directed and gradually decreasing in respect of coils from $[(n+1)/4+1]$ to $(n+1)/2$ (coils IV to VI);

downwardly directed and steadily increasing in respect of coils $[(n+1)/2+1]$ to $3(n+2)/4$ (coils VII to IX);

downwardly directed and gradually decreasing in respect of coils $[3(n+1)/4+1]$ to $n+1$ (coils from X to XII).

The coils developing a maximum force are:

$(n+1)/4$ and $[(n+1)/4+1]$ (coil III and IV) in an upward direction;

$3(n+1)/4$ and $[3(n+1)/4+11]$(coil IX and X) in a downward direction.

For reasons of symmetry the maximum forces in an upward and downward direction, respectively, are the same.

By simultaneously supplying 5 the $n+1$ coils the same current, the magnetic force acting on the core 7 is nil with all configurations where the transverse plane extending through the center of any projections 8 coincides with a transverse plane extending through the center of a coil 6 or with the middle transverse plane between two consecutive coils; at the intermediate positions the force is small.

In order to supply to the magnetic core 7 a magnetic force of maximum strength, a number m of contiguous coils only should be energized among the $n+1$ coils.

Referring to FIG. 2, the above condition is met when $m = (n+1)/2$, that is when $m = 6$.

Under the above conditions the core 7 biased by the magnetic force and applied load resulting from the weight of the control rod, weight of the rod 2 and the core's own weight, automatically takes a balanced position.

With a magnetic force exceeding the load, the core moves to vary the magnetic resistance or reluctance of the magnetic circuit till the energized coils induce in the core a magnetic force which is equal and contrary to the load.

Assuming for instance the load is nil, that is, the weight of the control rod, rod 2 and core is nil, the core 7 takes a position such that the projections 8 occupy one of the symmetrical configurations with respect to the six energized contiguous coils, so that the total reluctance is lowest.

In the embodiment shown in FIG. 2 one of the said balanced configurations when the applied load is nil is the configuration wherein the coils I, II, III, X, XI and XII are energized.

Where the applied load equals the maximum magnetic force which may be supplied by the coils to the core, the latter moves into a position in which the projections 8 on the core 7 assume with respect to the first energized coil and last nonenergized coil a symmetrical configuration, wherein the total reluctance is highest.

In the embodiment shown in FIG. 2, a balanced configuration with a downwardly applied load of a strength equaling the maximum magnetic force that can be supplied to the core is a configuration wherein the coils I, II, III, IV, V, VI are energized, this configuration representing the condition under which the core is movable in a downward direction without being retained by the magnetic field.

Where the load applied to the core is lower than the maximum magnetic force that can be supplied to the core, the balanced configuration is intermediate the two above described configurations. In the specific embodiment of FIG. 2 balanced configurations in respect of certain increasing values of the applied load are the configurations wherein the coils XI, XII, I, II, III, IV or XII, I, II, III, IV, V are energized.

The core moves by consecutive steps equaling in height $L/(n+1)n$, the switching over in the proper sequence the direct current feeding the coils being accomplished by means of a switchover means of the type shown in FIG. 6 and described below in detail.

Since the possible balanced configurations with which m contiguous coils are supplied is $n+1$, switching over from each of them to the next one is effected by feeding the first nonenergized coil and disenergizing the first fed coil, considered in their order in a direction opposite the one in which the core 7 should be displaced.

FIG. 4 shows a switching diagram for the motor shown in FIGS. 1 and 2.

Referring to FIG. 4, the switching steps are given on the vertical axis of the ordinates and the coil order is given on the horizontal axis of the abscissae.

Each switching over moves the core 7 by one step; since the length of the core 7 equals the length L increased by the stroke length c, the core moves over the whole stroke length c while it is in every position opposite the coils 6 over a length equaling L.

The number of steps required for a stroke of a length c to be accomplished is:

$$c\,33\,n(n+1)/L$$

On each switching over, an increment in magnetic force is applied to the core in the desired direction and is annulled when the core has taken its position wherein the magnetic force equals the applied length.

After $n+1$ switching over operations, grouped by T in FIG. 4, a full cycle of the magnetic configurations is performed in which the core is moved by a pitch p equaling L/n.

Referring to FIG. 2, by changing, by way of example, from the condition in which coils XI, XII, I, II, III and IV are energized to the condition in which the coils XII, I, II, III, IV and V are energized, the core performs an upward movement over a length equal to $L/11 \times 12$ and takes with respect to the energized coils XII, I, II, III, IV and V the same configuration it had before switching over with respect to the coils XI, XII, I, II, III, IV.

FIG. 3 is a detail view of an embodiment of the motor modified with respect to FIG. 2. As shown in FIG. 3, wherein similar reference numerals and letters denote parts common to the motor shown in FIG. 2, the modification comprises making the part of the core 7 carrying the projections 8 equal to L, while the part of the stationary portion carrying the coils 6 is made equal to $L+c$.

The diagram of the switching-over operations in respect of the motor shown in FIG. 3 is shown in FIG. 5 in which the switchover steps are given on the vertical axis of the ordinates and the coil order is given on the horizontal axis.

Referring to FIG. **5**, in order to change, by way of example, from the switchover step denoted by **1**, at which the coils I, II, III, IV, XI and XII are simultaneously energized, to the next step denoted by **2**, switching over should be effected in such manner as to energize in addition to coils I, II, III, and IV also coil V and disenergize coil XI.

It is to be understood the embodiments and constructional details can be varied without departing from the scope of this invention as defined in the appended claims. So, for instance, the number of coils **6** facing over the axial section L of the casing **4** the projections **8** of the magnetic core **7**, can equal $n-1$, n being the number of projections within the length L, n being greater than 2.

The switchover device shown in FIG. **6** comprises a rotary motor **10**, a set of cams **11** rigidly secured to the grooved shaft **12** of the motor **10**, a plurality of switches **13** installed along a generatrix of the cams **11**, the stationary contacts of which are opened and closed by the action of the cams on the respective movable contacts. The cams **11** maintain closed during 180° and open during the following 180° the stationary contacts of the switch associated with each of the coils or electromagnets **6**. The rotation of the motor **10** and cams **11** effects switching of the current at the windings or electromagnets of the motor according to the FIGS. **1** and **2** and according to the switching cycle shown in FIG. **4**.

The device shown in FIG. **7** comprises a rotary motor **14** rotating the grooved shaft **15**, a stationary screw **16**, a set of cams **17** fast with each other and splined on the side of the grooved shaft **15** and coupled by means of a nut and screw on the side of the screw **16**, a plurality of switches **18** installed on a generatrix of the cams, stationary contacts of the said switches being opened and closed by the action of the cams **17** on the respective movable contacts. The cams maintain closed over 180° and open during the following 180°, the stationary contacts of the switches associated with each of the motor windings or electromagnets **6** of the motor shown in FIG. 3.

Rotation of the motor **14** effects through the splined coupling and nut and screw **16**, the spiral movement of the set of cams **17** which are axially displaced on each turn by a pitch of the screw equivalent to the position occupied by one of the switches **18**.

Consequently, the current in the motor windings **6** in FIG. 3 is switched according to the switching cycle shown in FIG. **5**.

We claim:

1. In a linear electromagnetic motor for operating a driven member within a sealed vessel of the type including a stationary portion having a supporting casing adapted to be tightly secured to the sealed vessel and a plurality of similar, selectively energizable electromagnets secured to the supporting casing, said electromagnets being equally spaced and extending along the axis of the casing so that the centers of the electromagnets are spaced by a constant pitch P, and a movable portion adapted to be connected to said driven member and having an elongated core of ferromagnetic material coaxially movable within the supporting casing, said core having a plurality of similar annular projections equally spaced so that the centers of the annular projections are spaced by a constant pitch p, wherein said projections and said electromagnets face each other over an axial section of the supporting casing along a length L wherein the length L is related to the pitch p of the projections and to the pitch P of the electromagnets according to a predetermined vernier scale ratio, the improvement comprising:

a. said projections on the movable portion extending over only a length equal to length L; and

b. said electromagnets extending over a length greater than the length L by an extent equaling the stroke over which the movable portion travels.

2. In a linear electromagnetic motor as defined in claim **1**, wherein the portion of said core having said projections is defined as the toothed portion, and said motor further includes switching means for selectively energizing said electromagnets, the further improvement wherein said switching means comprises:

a. means for simultaneously energizing m contiguous electromagnets of the n electromagnets which face said toothed portion, the end ones of said n electromagnets also being considered as contiguous;

b. means for energizing one of the nonenergized electromagnets which are contiguous to the m energized electromagnets while simultaneously deenergizing the energized electromagnet contiguous to the other one of said nonenergized electromagnets, whereby after a switching operation m contiguous electromagnets are still energized; and

c. means, after energization of an electromagnet k facing the last projection of said toothed portion, for either energizing the electromagnet which is successively arranged in the direction in which said switching operation occurs or energizing the electromagnet preceding electromagnet k by $n-1$ positions in said direction, whereby the energized electromagnets always face said toothed portion.