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The Potential of Centrifugal Casting for the Production of Near Net Shape Uranium Parts

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by

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ABSTRACT

This report was written to provide a detailed summary of a literature survey on the near net shape casting process of centrifugal casting. Centrifugal casting is one potential casting method which could satisfy the requirements of the LANL program titled Near Net Shape Casting of Uranium for Reduced Environmental, Safety and Health Impact. In this report, centrifugal casting techniques are reviewed and an assessment of the ability to achieve the near net shape and waste minimization goals of the LANL program by using these techniques is made. Based upon the literature reviewed, it is concluded that if properly modified for operation within a vacuum, vertical or horizontal centrifugation could be used to safely cast uranium for the production of hollow, cylindrical parts. However, for the production of components of geometries other than hollow tubes, vertical centrifugation could be combined with other casting methods such as semi-permanent mold or investment casting.

I. INTRODUCTION

The purpose of this report is to describe centrifugal casting practices and to determine the viability of using these techniques to achieve near net shape uranium and uranium alloy products which minimize hazardous waste generation. A general description of the centrifugal casting process is given followed by a discussion of the different types of centrifugal casting machines, the product forms most often manufactured by centrifugal casting techniques, some specific advantages of centrifugal casting methods, the combination of centrifugal force with other casting processes, and a summary of research findings on the relationships between various process parameters and final product properties based upon experimentation and validation of models with experimental results. This report is concluded with a section on the potential use of centrifugal casting techniques to achieve near net shapes and subsequent hazardous waste minimization when casting uranium or uranium alloys.

II. PROCESS DEFINITION

Centrifugal casting is a casting process in which molten metal is poured into a rapidly rotating mold. The centrifugal force due to rotation causes the molten metal to be spread over the mold surface such that a hollow, cylindrical type casting is produced after complete solidification. The axis of mold rotation may be either vertical or horizontal. In either case, the centrifugal force causes high pressures to develop in the metal as it freezes with directional solidification, helps in metal feeding and contributes to the removal of non-metallic inclusions and evolved gases toward the inner surface of the hollow casting.

Although the centrifugal technique is used primarily for the production of hollow components, there have been occasions when the use of centrifugal action was used to create solid parts.[1] However, this is most often found when centrifugal force is combined with another casting technique such as investment casting. This specialized use of centrifugal action will be discussed in a later section of this report.

III. CENTRIFUGAL CASTING MACHINES AND THEIR PRODUCT FORMS

A. Flanged Shaft Machine

This type of machine (Fig. 1)[2] supports a mold horizontally on a flange as an overhung load. Horizontal mold orientations are usually used for castings which are sufficiently long, i.e. length/diameter ratios > 1.5. The flanged shaft machine is used to make all forms of flanges, ring-type castings and general cylindrical shapes but is most often used to make short tubes for cylinder liners, bushes, sleeves, tubes to be cut into rings, gear-wheel blanks, piston and bearing cage rings. Casting weight is limited to less than one ton.

B. Horizontal Machine (Roller Type)

This machine (Fig. 2) is used to make tubular castings usually where production quantities are high. It is not the same as the pipe casting machine. The horizontally rotated mold is composed of four parts: 1) the shell, 2) the casting spout (the end of the mold into which the molten metal is poured), 3) the roller tracks and 4) the two end heads. The mold usually lies on four interchangeable carrying rollers which are capable of providing good contact between different sizes of mold diameters and the roller tracks. As the mold is rotated, it is also cooled with a controlled water spray system. With the horizontal centrifugation technique, castings up to 8 m long, 30 tons in weight, up to 1000 mm in diameter, as well as tubes up to 5 m long for all diameters down to 75 mm, in most alloys, have been made.

C. Double-Face Plate Machine

This is another horizontal machine (Fig. 3) which was originally developed to line bearing shells with white metal. In this technique, simple cylindrical molds of steel or cast-iron are clamped between the two face plates and the pouring operation takes place through one of the bearings supporting the face plate. When the casting operation is finished, the cylindrical mold, together with the casting, is removed from the machine for casting extraction.

D. Vertical-Axis Centrifugal Casting Machine

In this machine, (Fig. 4)[2] molds are oriented vertically, either attached to a face plate or to the flange of a vertical shaft. The vertical mold orientation is usually used when the diameter of the casting is greater than its length or the length/diameter ratio < 1.5. However, Pfeifer and Moak[4] modified this technique to produce a misch-metal integral liner in the standard 105 mm projectile. Small machines are used at floor level and are used mainly to make gear-wheel blanks, flanges and bushes. For larger and heavier castings (>200 tons), machines are usually placed below floor level. This is the technique most often used for making rolling mill rolls.

IV. FUNCTIONAL DIFFERENCES BETWEEN HORIZONTAL AND VERTICAL CENTRIFUGATION TECHNIQUES

Although both of these casting techniques employ centrifugal force, there are some differences in how the force is applied with respect to the axis of mold rotation and the speed of the molten metal in relation to that of the rotating mold.[2] For example, with a vertical mold axis, the resultant force acting on the liquid is constant. This is not so in the case of a horizontal mold axis where the gravitational component of the resultant force varies by an amount of 2G in one complete rotation (-G at the vertex and +G at the base).

The other difference between the two mold orientations is the speed obtained by the molten metal as it is swirled around the mold. When molten metal is poured into the horizontally rotating mold, considerable slip occurs between the metal and the mold such that the metal does not move as fast as the rotating mold. To overcome this inertia, the metal must be accelerated to reach the mold rotation speed. This is not a problem in the vertical centrifugation process where the molten metal reaches the speed of the mold soon after pouring. However, with a vertical mold axis, there is a tendency for the molten metal to form a parabolic shaped bore due to the competing gravitational and centrifugal forces acting on the molten metal.

V. ADVANTAGES OF THE CENTRIFUGAL CASTING METHODS

The following is a list of advantages of the centrifugal casting process often cited in the literature:[1,3,6,7]

1. The centrifugal action removes unwanted inclusions, dross, and gases thus yielding a cleaner casting.

2. Castings are free from any form of shrinkage because the material that contains the shrinkage is machined away (e.g. boring out the center to make tubes).

3. Mechanical properties are often superior to those of static castings due to the finer grains resulting from the process which are of constant size in circumferential and axial directions.

4. Due to cleanliness and finer grain size, good weldability is achieved.

5. A 100% design factor can be used with the advantages of less metal being required which generates a cost saving.

6. Class I castings can be produced without the need for upgrading and costly weld repairs.

7. The flexibility of the process allows 4 inch to 120 inch diameters to be cast and lengths from a few inches to 16 ft depending on the machine selected. And, with the use of refractory ceramic molds, complex outer part profiles may be

cast.

VI. DEFECTS IN CENTRIFUGAL CASTINGS

The three most common defects observed in centrifugal castings are segregation banding, raining and vibration defects.[6] Segregation banding can occur in both horizontal and vertical centrifugally cast parts, but usually is only found in castings with wall thicknesses greater than 50 to 75 mm (2 to 3 in.). The bands that can occur are annular segregated zones of low melting constituents. Banding is more prevalent in alloys with a wide solidification range and greater solidification shrinkage. Banding has also been associated with a critical level of mold rotation speed as well as with low rotational speeds. However, there are no definitive answers about what factors contribute to banding. Several theories have been proposed to explain this phenomenon which include the effect of vibration, variation in gravitational force, and irregularities in metal flow.

Raining is a phenomenon that occurs in horizontal centrifugal castings. If the mold is rotated at too low a speed or if the metal is poured into the mold too fast, the metal actually rains or falls from the top of the mold to the bottom. Proper process control can eliminate raining and thereby ensure the formation of a casting with a uniform structure.

Vibration can lead to defects in centrifugal castings which manifest themselves as laminations in the castings. This problem can often be overcome by minimizing vibrations affecting the casting equipment; e.g. ensuring proper mounting, careful balancing of the molds, and frequent inspections of other vital parts of the casting machine.

VII. THE COMBINATION OF CENTRIFUGAL FORCE WITH OTHER CASTING METHODS

A. Centrifugal Force and Investment Casting

When the action of centrifugal force is combined with investment casting, the main benefit is an improvement in casting soundness with subsequent improvements in mechanical properties. In an article by Lee and Yun[9], the influence of centrifugal force upon aluminum investment castings was explored. They found that 1) a down-tapered sprue was more effective in eliminating turbulence of the metal stream and non metallic inclusions, 2) surface smoothness and dimensional accuracy of Al-alloy centrifugal castings were much better than the gravity investment castings, but they were much more affected by the fineness of investment material than centrifugal force, and 3) the soundness and mechanical properties were improved with increased centrifugal force.

A more detailed study by Osinskii et al. discusses the importance of the liquidus-solidus interval degree range on solidification in centrifugally cast ivestment mold castings.[10] This work also investigated the quantitative relationships between the "technological production" conditions and the gating system dimensions in relation to final casting soundness in castings of alloys with narrow and wide freezing ranges. Factors which influenced the casting soundness were identified as:

1. ingate diameter, d
2. sprue diameter, D
3. metal pour temperature
4. mold temperature prior to pour
5. mold speed, n
6. spinning period
7. casting weight (expressed as a castings length, l)
8. the number, N, of castings in each ring on the sprue

9. the distance, L, from the axis of rotation to the castings on the sprue (which characterizes the sprue length)
10. the liquidus-solidus interval, I (freezing range)

For a wide freezing range (e.g. 100K, in bronze), the casting soundness was improved by increasing mold speed, ingate diameter and sprue diameter and the product lL of specimen size and sprue length. Mold speed, n, was found to be the most significant variable.

For wide interval alloys, "... optimum conditions are those under which each portion of molten metal newly arriving in the mold cavity should spread out at the appropriate level and freeze on to the solidification front without building up a substantial surplus of molten metal. Thus, the optimum conditions for pouring intricate castings in wide-interval alloys are those which produce layer-by-layer freezing."[10]

Casting soundness decreased as the number of castings at the same level on the sprue increased. "Thus, as fewer castings are made at any given level their density will increase. Increasing the number of ingates surrounding the sprue at the same level probably leads to the development of a hot spot, heat storage round the spot, and departure from the conditions required for layerwise solidification. It is therefore best to assemble the patterns in a helical array on the sprue for the centrifugal casting of intricate castings in wide-interval alloys.[10]

"Density comparisons between castings at the two extreme levels on the sprue have shown that the sprue length has no significant influence on density."[10] For narrow-interval alloys, there is a sprue length effect. Narrow-interval alloys require much greater ingate and sprue cross sections than wide-interval alloys and narrow-interval alloy "castings should invariably be made on short sprues..."[10]

The authors conclude with two summary paragraphs and state that their recommendations have been verified in the production of steel castings with different liquidus-solidus intervals:

> "Narrow-interval alloys require heat accumulation around the sprue and ingates. Sound castings can be made by accumulating surplus molten metal ahead of the solidification front. In this case, the optimum conditions correspond to wide-section ingates and sprues, mold preheating, the use of short sprues and some reduction in the relative rate of molten metal supply to the mold cavities."

> "Intricate castings in wide-interval alloys must be made under conditions which will prevent excessive heat accumulation round the gating system and mold cavities and minimize the volume of molten metal ahead of the solidification front. Sound metal can be ensured by directional solidification. In this case, mold pre-heating, commensurate metal weights and sprue lengths, helical mold assemblies round the sprue and normal ingate and sprue cross sections should lead to a certain 'freezing' action, while rapid mold cavity filling with metal in this condition should lead to layerwise solidification."

B. Centrifugal Force Combined with Electroslag Casting

A process called centrifugal electroslag casting was developed at the E.O. Paton Welding Institute, Academy of Sciences of the Ukranian SSR, Kiev. In this process, liquid metal from electroslag melting is collected in a lined refractory crucible and poured into a horizontally rotating mold together with slag used for remelting. This method is used for the production of "billets" in the shapes of rings, sleeves or pipes which replace forgings in various components.

The authors set out to determine the optimum casting parameters which would ensure maximum mechanical properties of the centrifugal electroslag blanks. The authors noted that "The amount of information of the CESC process accumulated as a result of theoretical examination, physical modeling and analysis of preliminary experiments was insufficient for considering the effect of the individual technological factors and, in particular, the effect of their interaction on the service properties of the castings."[16] The authors therefore invoked the theory of extreme experiments which "makes it possible to solve the problem of optimising technology and examine the properties of resulting materials even if the data on the process is [sic] incomplete."[16] Based upon this theory, the method of random balance, computer programs which yielded a five-factor regression equation for the CESC process and their experimental results, the authors concluded that the strongest effect on the quality of the castings is exerted by the temperature of the metal poured into the mold and by the rate of metal feed into the mold. They also observed a correlation between the speed of rotation and the mass (wall thickness) of the casting which showed that the effect of the speed of rotation of the mold on the quality of the casting became stronger with the increase of its wall thickness.

VIII. MODELING AND EXPERIMENTAL RESEARCH ON CENTRIFUGAL CASTING

A very early attempt to model the centrifugal casting process was made by S.L. Conner in the early 1930's.[17] An effort was made to model the thermal contours in the casting mold used to produce castings of the gun barrels for the U.S. Army's 75 mm Pack Howitzers. But, in the author's own words, "the results were approximations at best based on assumptions that were not necessarily correct."[17] Although the degree of sophistication involved in this early modeling attempt may have been lacking, it was adequate for its intended purpose. Between 1932 and 1935, this work enabled centrifugal casting to evolve from an experimental technique to a viable manufacturing process for the production of cannon and gun barrels.

In 1970, J. Jezierski performed an experiment aimed at determining the factors which lead to increased centrifugal casting mold life by modeling the temperature gradients in a mold and comparing the results with experimental data. In this study, temperature gradients were determined from thermocouple measurements of the temperatures of the outer and inner mold surfaces during centrifugal casting of cast iron tubing. By gaining a better understanding of the thermal gradients in a mold and the resulting thermal stress states, the degree of mold pre-heating necessary to extend mold life by minimizing thermal shock effects was determined.

In 1983, the thermal aspects of horizontal centrifugal casting were explored at the Research Centre of Pont-a-Mousson S.A. in France using a semi-industrial sized instrumented casting machine. The emphasis of this work was the determination of which casting parameters most influence the temperature history during solidification of a cast tube of a Mn-Ni-Mo-Nb dispersoid steel, or Centrishore V, a weldable high-strength steel with good impact resistance at low temperatures used to manufacture large sized heavy-wall pipes for offshore oil constructions.

This pilot centrifugal spinning machine could be used to measure the temperature inside the rotating mold and on the inner surface of the tube during solidification. This was possible because the mold was equipped with a telemetering device, a balancing system to ensure regular and uniform rotation of the mold, 6 thermocouples placed at different levels in the mold section, a fixed receiving aerial fastened under the machine frame and a receiving set connected to a ketching table to allow for continuous monitoring of the temperature profiles in the mold. In addition, an optical pyrometer was used for measuring the inner tube wall temperature.

Using this set-up, experimental and mathematical studies were performed to examine the influence of various parameters on the thermal behavior of the cast tube and the mold in order to validate a classical model of heat-transfer by conduction. The authors concluded that the parameters directly related to the mold itself had almost no influence on the thermal solidification rate of the steel. From evaluation of the temperature curves of the steel during solidification, the authors determined that the mold thickness, the mold thermal conductivity, the initial temperature of the mold, and the sprinkling flow used to cool the mold had a very small and limited effect such that the metallurgical parameters G/R and G.R were not affected.

In contrast, the factors exerting the strongest influence upon solidification rates and final grain size were the casting temperature and the thickness of the coating material sprayed in the mold. For a high casting temperature, the size of the coarse grain zone and the average grain size were reduced with thinner mold coating thicknesses. For low casting temperatures, a decrease in the mold coating thickness led to a decrease of the average grain size but not to that of the size of the coarse grain zone.

In 1985, Y. Ebisu used different solution methods for thermo-elastic plastic finite element analysis to analyze centrifugal casting molds.[16] The influence of the casting parameters on the stress-strain state of the molds was then analyzed. It was determined that the occurrence of mold warping or bowing decreased considerably by increasing the thermal resistance of the mold coating, by lowering the metal pour temperature and by thickening the mold wall.

IX. CONSIDERATION IN THE APPLICATION OF CENTRIFUGAL CASTING TO URANIUM AND URANIUM ALLOYS

Centrifugal casting, in general, is best suited to the production of hollow, cylindrical parts. If it were desired to produce such a uranium or uranium alloy tube, vertical or horizontal centrifugal casting could be a cost effective production method to achieve this near net shape with the added benefit of reduced machining waste generation and a cost savings. In fact, centrifugal casting of uranium has been performed by the French in 1968.[illegible] It would be interesting and perhaps valuable to have this reference translated into English to learn exactly what has already been done. In the meantime, to consider the application of centrifugal casting to uranium, the following areas would need to be addressed:

1) <u>Selection of a machine with a vertical or horizontal mold rotation axis.</u> This decision should be based on the length to diameter ratio as well as the production capabilities and efficiencies of the chosen machine.

2) <u>Consideration of casting atmosphere.</u> To minimize oxidation effects, the selected centrifugal casting machine would need to be able to operate in a vacuum. This would obviously necessitate the elimination of the usual water sprinkling system used to cool the molds. An alternative mechanism to provide mold cooling could be the back-filling of the vacuum chamber with a circulated inert gas such as argon or helium.

3) <u>Selection of a suitable mold.</u> Material selection and compatibility issues would need to be addressed with emphasis on material reactivity, thermal and mechanical properties. Other considerations would be mold design and mold geometry (e.g. mold thickness, mold coating selection, application and thickness).

4) <u>Determination of metal pour [illegible]ture and mold pre-heat temperature.</u> Experimental researc[illegible] shown that higher pour temperatures result in more dense castings with better mechanical properties. Thus, the optimum temperatures for pouring uranium or its alloys would need to be determined. If mold life is to be considered, determination of the optimum mold pre-heat temperature would be useful to minimize the effects of thermal shock and thermal fatigue.

5) <u>Determination of metal feed rate, optimum mold speed and spinning period.</u> In order to achieve a layered directional solidification effect, the freezing range width must be considered when casting an alloy. If the alloy has a wide freezing range, a faster mold speed and slower metal feed rate will ensure that excessive heat accumulation is avoided and the volume of metal ahead of the solidification front is minimized. If the alloy has a narrow freezing range, a slower mold speed and faster metal pour rate would be needed to ensure that there is sufficient surplus metal ahead of the solidification front.

In conclusion, the determination of which combination of material and casting parameters would provide the best casting soundness and mechanical properties could be a lengthy and costly process if an entirely experimental approach were selected. A more cost-effective and time-effective approach would be to use computer modeling of the casting process (considering such factors as material properties, fluid flow and heat transfer) in conjunction with experimentation to prove the validity of the model. By using such an approach, the potential benefit of applying centrifugal casting techniques to uranium or uranium alloys, the production of near net shape, hollow, cylindrical parts at lower costs associated with less final machining and less hazardous waste generation could be realized. Also, vertical centrifugation could be combined with another casting technique, such as investment casting, to take advantage of centrifugal force when producing parts that are not hollow tubes.

X. ACKNOWLEDGEMENTS

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XI. REFERENCES

1. L.J. Stefan et al, "Research on Refractory Alloys of Tungsten, Tantalum, Molybdenum, and Columbium," Thompson Ramo Wooldridge, Inc., Technical Documentary Report Nr: ML TDR 64-271, (September 1964).

2. D.S. Gibson, "Basic Designs of Centrifugal Casting Machines," *Foundry Trade Journal*, **156** (3278), 61-62, (Feb 2, 1984).

3. A. Royer, "The Horizontal Centrifugation: A Technique of Foundry Well Adapted to the Processing of High Reliability Pieces," in *Proceedings of the International Conference on Advanced Casting Technology*, Kalamazoo, MI, 12-14 November 1986. (1987), pp. 1-12.

4. W.H. Pfeifer and D.P. Moak, "Centrifugal Casting of Misch-Metal Liners for the 105 mm Projectile," *Journal of Vacuum Science and Technology, 11* (6), 1072-1083, (Nov/Dec 1974).

5. R.L. Kumar and S.K. Dike, "Experiments on Centrifugal Casting of Aluminum in Horizontal and Vertical Axis Machines," *Indian Foundry Journal*, **28** (1), 9-12, (Jan 1982).

6. P. Nixon, "Advantages of Castings Produced by the Centrispinning Process," *Foundry Trade Journal*, **161** (3352), 557-559, (2 July 1987).

7. B.M. Jones, "Centrifugal Molding and Casting," American Society of Tool and Manufacturing Engineers Technical Paper #SP66-67, (Jan 1966).

8. *Metals Hankbook*, 9th ed., Volume 15, (ASM International, Metals Park, OH, 1988), pp. 297-307.

9. Jong-Nam Lee and Gi-Cheon Yun, "Effect of Centrifugal Force Applied During Investment Casting on the Soundness of Cast Al Alloys," *Journal of the Korean Institute of Metals*, **15** (2), 155-163, (1977).

10. V.I. Osinskii, M.V. Solov'ev, and A.V. Morozov, "Soundness of Intricate Centrifugally Cast Investment-Mold Castings," (Translation) *Soviet Castings Technology*, **7**, 50-54, (1987).

11. V.V. Shakhov and V.L. Shevtsov, "Optimisation of Technological Parameters of Centrifugal Electroslag Casting with the Horizontal Axis of Rotation," *Problemy Spe 'ial'noi Elektormetallurgii*, **3** (4), 35-37, (1987).

12. S.L. Conner, "Operating Report, Centrifugal Casting Equipment," Watertown Arsenal Report No. 613/131, (1 July 1935).

13. J.Jezierski, "Analysis of the State of Thermal Stress in Molds During Centrifugal Casting," *AFS Cast Metals Research Journal*, **6** (2), 75-79, (June 1970).

14. S. Vasseur, R. Roll-Duchanoy, G. Metauer, C. Frantz, and M. Gantois, "Thermal, Metallurgical and Mechanical Aspects of Dispersoid Centrifugally Cast Steels," in *Proceedings of the International Conference on Technology and Applications of HSLA Steels*, Metals Park, OH, 3-6 October 1983, American Society for Metals, pp. 1155-1169.

15. Y. Ebisu, "Solution Methods for Thermo-elastic Plastic FEM and Its Application to Centrifugal Casting Mold," *Transactions ISIJ*, **25**, 30-39, (1985).

16. Y. Ortel and J. Vayra, "Centrifugal Casting of Uranium," Paper from Congres Internat sur les Applications des Techniques du vide a la Metallurgie 1968 Societe Francaise, 94 Nogent/ Marne, 195-198.

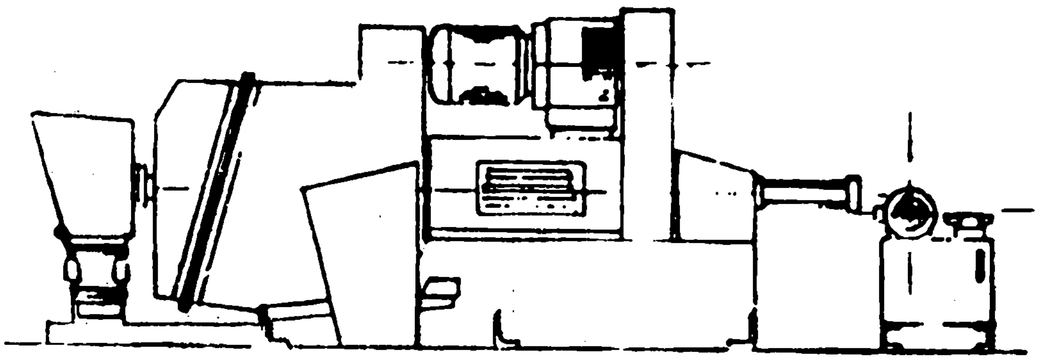

Fig. 1: Flanged shaft centrifugal castir-g machine (ref. 2).

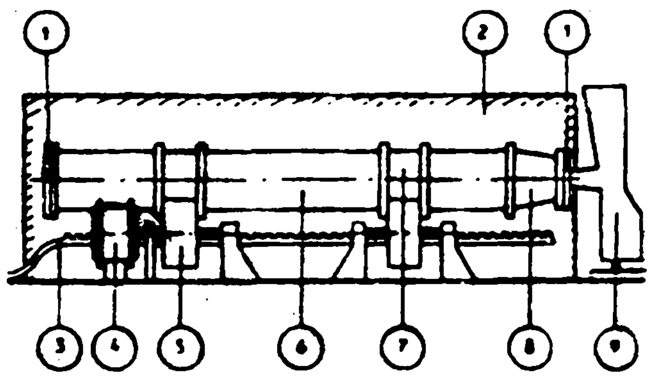

Fig. 2: Horizontal roller centrifugal casting machine (ref. 3).

(1) End heads
(2) Sliding gear case
(3) Cooling track
(4) Motor
(5) Carrying roller
(6) Mold
(7) Roller track
(8) Casting spout
(9) Casting pot

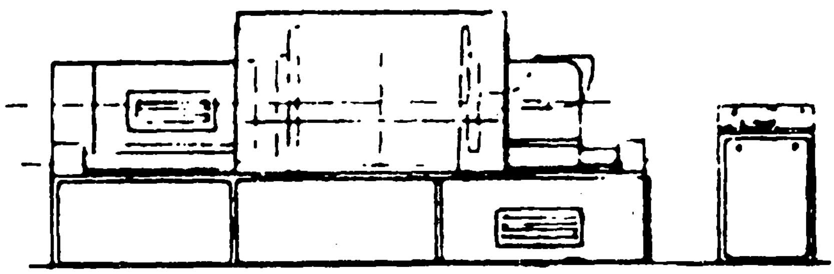

Fig. 3: Double -face plate centrifugal casting machine (ref. 2)

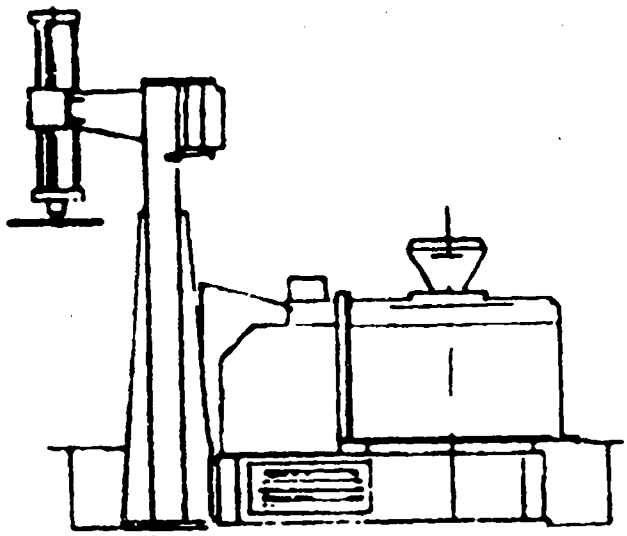

Fig. 4: Vertical-axis centrifugal casting machine (ref. 2).