CENTRIFUGE FOR
RADIOCHEMICAL PROCESSING

MASTER

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Report to
CARBIDE & CARBON CHEMICALS
CORPORATION
DIVISION OF UNION
CARBIDE & CARBON CORPORATION

September 23, 1955

C-59535

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ARTHUR D. LITTLE, INC.

Arthur D. Little, Inc.

THIRTY MEMORIAL DRIVE
CAMBRIDGE 42, MASSACHUSETTS

September 23, 1955

Carbide & Carbon Chemicals Company
Division of Union Carbide & Carbon Corporation
Post Office Box P
Oak Ridge, Tennessee

Subject: Subcontract No. 587 under W7405 eng-26

Gentlemen:

C-59535

In accordance with the terms of the subject contract, we submit herewith a technical report of the work performed by Arthur D. Little, Inc., in cooperation with the Merco Centrifugal Company, on the feasibility of designing and developing a canned centrifuge for radiochemical processing.

Respectfully submitted,

Arthur D. Little, Inc.

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Report to
Carbide and Carbon Chemicals Co.

Subcontract No. 587
Under Contract W7405 eng-26

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I. SUMMARY

A. INTRODUCTION

The purpose of this study was to determine the feasibility of designing and developing a canned centrifuge capable of operating for extended periods of time in a highly radioactive area. The study as applied to the separation of radioactive particles from a highly corrosive process slurry at high pressures and temperatures presents the severest limitations on operational characteristics and materials of construction.

B. CONCLUSIONS

1. The design and development of a canned centrifuge for radiochemical processing is feasible.
2. For the particular process studied a disc-type centrifuge is considered best for accomplishing the desired separation.
3. A prototype unit could be designed and developed in about 18 months at an estimated cost of \$90,000, and additional units are expected to cost between \$18,000 and \$25,000.

C. RECOMMENDATIONS

The following features should be incorporated in the design of the canned centrifuge:

1. Direct-drive, low-voltage, variable-frequency electric motor
2. Water-cooled stator winding
3. Inorganic electrical insulation
4. Fluid piston bearings
5. Stainless steel construction with titanium inserts at points subject to erosion
6. Canned rotor and stator

II. INTRODUCTION

Centrifuges have not been widely used in radiochemical processes because (1) frequent maintenance is normally required, (2) the ambient atmosphere is seriously contaminated by the mist which is generated by the centrifuge discharge, and (3) present commercial centrifuges have not worked at pressures considerably above atmospheric because of the limitations of complex mechanical seals which are required on the spindle drive. For radiochemical processing, equipment must be maintenance-free and leak-tight. The technical personnel at Oak Ridge believed that the canned-rotor drive and hydraulic bearings which have proved successful for centrifugal pumps would also be applicable for centrifuge operation.

Since the design and development of a canned centrifuge would not only be expensive but also would involve considerable time, it was considered desirable to conduct a feasibility study as the first phase of the program. This study would determine whether or not the techniques applied to canned-rotor design would also be applicable to centrifuge design.

The feasibility study, in order to be of value, would have to be made with a realistic set of design conditions. Therefore, the personnel at Oak Ridge selected an application which involves the treatment of extremely radioactive fluids that must be processed at a temperature of 300°C and at a pressure of 2000 psi. (See Figure 1.)

The high levels of radioactivity require that the equipment be enclosed in a concrete radiation shield 6 to 8 feet thick. Therefore, the operation must be remote, and maintenance or servicing of the equipment requiring access to mechanical parts would be prohibitive in expense and in down time. In an attempt to be realistic, a goal of 3000 hours of continuous operation without servicing has been specified. The use of organic materials either as a lubricant, as gasketing material, or as electrical insulation is generally denied because these materials are susceptible to radiation damage. The materials of construction would have to have good chemical resistance as well as resistance to erosion since the fluid being

FIG. 1

CANNED CENTRIFUGE INSTALLATION

handled would be highly corrosive and would contain particles which are assumed to be abrasive. The solids in the fluid are expected to generate heat spontaneously by radioactive decay; therefore, it will be necessary to provide for dissipation of any heat generated, and also to design to eliminate points where solids would be collected.

Any centrifuge designed for the specified conditions would probably also be applicable to a number of other separation processes, both in the radiochemical field and in the chemical industry in general. Any applications for processing materials which are not radioactive or not so high in temperature would allow several design simplifications, which would reduce the cost considerably.

Basically, two problems were to be studied:

1. Would a centrifuge give the required separation for the specific example under study; and if so, what type of centrifuge would be best suited to this application?

2. How could the centrifuge be adapted to a canned-rotor drive? (This includes a study of methods of sealing the rotor and the motor, of lubricating the bearings in the sealed system, and also of designing a unit which would stand up under the severe conditions of high temperature and radioactivity.)

The Merco Centrifugal Company was called upon to determine the proper type of centrifuge to be used in the required application and also to prepare a preliminary design of such a centrifuge. Merco conducted several tests, using jeweler's rouge (Fe_2O_3) suspended in water to form a slurry. The personnel of Oak Ridge suggested this material because it is similar to the expected slurry. The specifications for feed and separation requirements indicated that the disc-type centrifuge would be most suitable for the separation. After conducting preliminary tests to determine fluid characteristics, Merco proceeded to make tests on its B-9 centrifuge. The results of these tests allowed Merco to predict the size and power requirements of the centrifuge, and also to predict the separation efficiencies and the operating characteristics of the centrifuge when the slurry was being processed.

We contacted the manufacturers of canned-rotor pumps to obtain information on the latest technological advances in canned-motor design. We held discussions with authorities in the field of materials damage due to radioactivity, both at Oak Ridge and at Argonne National Laboratory. These discussions supplemented a literature survey of both classified and unclassified material pertaining to testing of materials subjected to radioactivity.

Since the best commercially available electrical insulation was found to be unsatisfactory under the prescribed conditions, we conducted a search for a better insulation. We made calculations to show the effect of heating due to the concentration of solid particles, and determined cooling requirements. We considered material stresses due to the high-speed rotation and the effect of high operating temperatures on the creep strength of materials. Finally, we made a preliminary design for the entire unit, including the centrifuge bowl, canned motor, shaft, bearings, and container housing.

III. SPECIFICATIONS

A. REQUIREMENTS OF CENTRIFUGE

The following specifications were chosen by ORNL personnel as posing the most severe limitations on operation of the centrifuge:

Feed: Solids concentration, 0.05 gram/liter

Average solids particle size, approximately 0.5 micron
(0.1-2.5 microns)

Solids considered to be crystalline and generally spherical

Specific gravity of solids, 5.0 - 11.0

Specific gravity of liquid 0.8

Viscosity of liquid, 0.2 centipoise

Feed capacity, 5.0 gpm

Clarified Stream: Maximum solids concentration, 0.02 gram/liter

Concentrate Stream: Solids concentration, approximately 5.0
grams/liter (1.3 - 7.5 grams/liter)

Operating Conditions: Minimum life expectancy of the centrifuge,
3000 hours

Unit to operate at 2000 psig and at 300°C

Unit must be sealed for zero leakage

Maximum bowl diameter limited to 8 inches
because of criticality

Fluid temperatures to be maintained between
270°C and 330°C

Radiation: The solids separated by the centrifuge will spontaneously
generate heat at a rate of 300 watts/gram.

B. DESIGN SPECIFICATIONS

As a result of the tests and bowl design studies carried out by Merco and the design studies conducted by ADL, the following preliminary

specifications are presented for consideration. These specifications may be altered somewhat as more information is obtained on the exact composition of the solids. The proposed centrifuge will be flexible enough in operation to accommodate a wide range of fluid properties.

Centrifuge: Disc-type, maximum angle of discs, 45°
Developed pressure, 675 psi
Capacity, 5 gpm
Nozzle discharge, 6.47 gpm
Number of nozzles, 8 (each 0.035 inch in diameter)
Power, 10 horsepower
Speed, 10,000 rpm
Cycle time, 5 minutes

Motor: Frequency-controlled, low-voltage canned motor

Insulation: Refrasil - SiO_2 or pure mica

Cooling: 1 gpm water circulated through motor conductors

Bearings: Piston-type, gas lubricated

Material, aluminum oxide

Bearing pressure supplied by centrifugal pump
integral with motor shaft

Construction Material: 310 stainless steel, cold worked

75A titanium tubing and inserts

IV. RESULTS OF TESTS

In order to determine the separation characteristics of the material to be processed, several pilot scale tests had to be conducted. These tests were carried out by the Merco Centrifugal Company in its laboratories. For these tests, the personnel at Oak Ridge suggested that a slurry be made up of jeweler's rouge and water on the belief that this slurry would furnish centrifuge data which could be applied to the separation of the process fluid when its properties are known. Also, the results of these tests could be directly compared with the performance of other equipment being tested at Oak Ridge, and the relative effectiveness of the centrifuge could be readily evaluated. (See Appendix A for description of these tests.)⁽¹¹⁾

The results of the bench examination and pilot-plant tests on the simulated feed material indicate that the solid-liquid separation can be successfully performed in a disc-type centrifuge of the proposed design. An extrapolation from the pilot-plant tests indicates that the capacity of the proposed centrifuge with a maximum diameter limitation of 8 inches will be approximately 5 gallons per minute if the same slurry is processed. The lower viscosity and specific gravity of the process liquid should assist in increasing the capacity beyond that attained in the pilot tests.

The pilot tests indicate that the speed of the centrifuge should be about 10,000 rpm. However, when the prototype centrifuge is constructed and tested, it may be found that lower speeds can be used. The tests also indicate that the power required to drive the centrifuge rotor will be approximately 10 horsepower, and that the temperature rise of the process liquid, which is due to the mechanical work on the fluid by the centrifuge, will not exceed 8°F.

When the feed rate is 5 gallons per minute, the holdup time of the proposed centrifuge was determined to be approximately 5 minutes. In this type of cycle (see Figure 2) the solids are removed from the feed and recycled during a 5-minute interval. Since the clarified liquid is

FIG. 2
CENTRIFUGE DESIGN

continuously discharged, when the feed valve is closed and the underflow valve is open, the total liquid discharge from the centrifuge will contain nearly all the solids which entered the bowl during the interval; and the concentration will be approximately 5 grams per liter as desired. The feed and underflow valves should be either fully open or fully closed, and should be actuated by a simple timing mechanism.

V. SEPARATION CHARACTERISTICS

After a careful consideration of available centrifuge design, (2, 10) the disc type was selected as being the most suited to accomplish the required separation. The discs provide greater separation efficiency; they allow the separation to be made within the 8-inch-diameter limitation posed by the criticality requirements. With this type of centrifuge, continuous separation can be obtained with only a short holdup time. The disc-type continuous centrifuge provides a simple design with no moving parts to wear excessively or to require frequent maintenance.

Tests indicate a high efficiency of separation with iron oxide as the solid material. However, larger solid particles and/or heavier solid particles and/or lower viscosity and density of the liquid medium would greatly improve the separation obtained.

Stoke's Law, covering the settling of solids in a liquid medium, shows the effect of these variables.

$$V = \frac{gD^2 (d_1 - d_2)}{18 u}$$

where

- V = maximum velocity of particle settling
- g = gravitational force or centrifugal force
- D = particle diameter
- d_1 = density of solid particle
- d_2 = density of liquid medium
- u = coefficient of viscosity

In this formula the particle diameter is entered in the second power, and the other factors in the first power. As an example, assume that thorium oxide solids were employed instead of the iron oxide solids used in the tests reported here. The specific gravity of thorium oxide is

10, and that of iron oxide is approximately 5. Further, assume that the thorium oxide particles are 2 microns and the iron oxide particles 0.5 micron. With the other factors remaining the same, the settling velocity of the solids (and the effectiveness of the separation) can be expected to be improved by a factor of 36. Comparative evaluations of various pieces of equipment should be made on the same test medium.

If various pieces of equipment are evaluated on the same material (such as Fe_2O_3) and a centrifuge is proven to be the most effective, it can also be expected to be the most effective on the proposed application.

Any separating equipment should have a high degree of efficiency in removing all the solids on this application. The finer particles will have a great affinity to attach to very small surface irregularities in the process system. In effect, the inefficiency of a separator in removing solids usually denotes classification of the solids into particle sizes. The finer solids remain in the effluent. Recycling these fine solids back to the process equipment, always raises the possibility that they may accumulate in excess of the amount tolerable. This recycling of solids sometimes stabilizes at some level of fine solids concentration, but that level may often be excessively high. Even though some fine solids "grow" or agglomerate in a process, the shearing action of separating equipment also breaks the particles down and may prevent their separation unless the equipment is designed to handle them.

The specifications as presented may change, and the specifications for other applications will differ; however, the proposed centrifuge is designed for flexibility of operation to accommodate a fairly wide range of applications.

VI. CENTRIFUGE DESIGN

The design of the proposed centrifuge, as shown in Figure 3, is similar to that of the tried and proven Merco centrifuge. The large number of discs will provide efficient separation within the limited bowl diameter. All internal rotor surfaces will present a maximum angle of 45° to the direction of the developed gravitational force. The internal surfaces should be brightly polished to provide slippage of solids separated from the liquid phase.

Feed through the bottom of the rotor will provide maximum use of the available rotor space. The top of the rotor will be more available for adoption of a pressurized effluent discharge, which should considerably reduce or eliminate aeration of the effluent. The cyclic sequence of operations of the feed valve and underflow discharge valve will be most easily controlled by a timer.

The centrifuge will have the following characteristics:

Theoretical pressure developed in rotor, 2675 psig;

Pressure inside housing, 2000 psig;

Theoretical nozzle discharge, 0.808 gpm/nozzle;

Total discharge for 8 nozzles, 6.47 gpm; and

Velocity of discharge through 0.035-inch-diameter orifices,
315 ft/sec.

Several nozzle materials have been considered. Some of the more usual tungsten carbides, titanium carbides, sapphires, or ceramics may prove quite satisfactory. The small amount of solids in the feed and the very small size of the particles definitely contribute to good nozzle life. Probably the best way of determining the most acceptable nozzle material would be to operate a centrifuge on a simulated feed material for an accelerated or full-term test, with all of the most favorable nozzle materials made up and installed. Such a test was not considered to be within the scope of this feasibility study, but could be conducted when a prototype unit is built.

FIG. 3

CENTRIFUGE DESIGN OPTIONS

In the proposed design, the amount of nozzle discharge was reduced to a near minimum, in order to reduce nozzle wear. The fewest number of nozzles are used for the size of the rotor which will still provide for a 45° angle of repose on the hoppers between nozzles. The hoppers are necessary to prevent the accumulation of solids between nozzles at the periphery of the rotor. The nozzle orifices are considered to be about the smallest that are practical for continuous operation without plugging. Further experience on a prototype unit, however, may indicate that smaller nozzles can be used. The inner thin shell of pure titanium sheet next to the rotor is designed and attached to the lower-bearing housing so as to assure that any gases given off from the liquid in process will be carried off in the effluent or concentrate streams.

The alternate rotor designs shown in Figure 3 will allow the use of either a 3/4" shaft which will operate above the primary critical speed (option No. 1) or a 2" shaft which will operate below the primary critical speed (option No. 2).

The critical speed of a rotating system is the speed which corresponds to the natural vibrational frequency of the system when at rest. This frequency is a function of shaft stiffness (shaft diameter and material), distance between bearings, rotor weight, and location of center of gravity. At the critical speed, severe vibrations occur, and a system cannot usually be operated at this speed for any length of time without serious damage. It is, however, common practice to operate above the primary critical speed. In this case, the severe vibrations are encountered for only a short interval when the shaft is brought up to speed and when it is slowed down to a stop. We have recommended option No. 2 in this case, because of the difficulty of maintaining proper lubrication during the period the rotor goes through the critical speed, a condition which will occur both during start-up until operating speed is attained as well as during shut-down before the rotor comes to a stop.

VII. CANNED MOTOR

The drive for the centrifuge should be a canned induction motor, similar to those used for driving centrifugal pumps in the atomic equipment field (Figure 4). These motors have been developed by the leading manufacturers of electric motors, and have been operating satisfactorily under extreme operating conditions. The canned induction motor can be used in both flooded and gas-atmosphere applications. It is well-suited for applications requiring high system pressures, and has been tested at rotor temperatures of 1000°F. It is generally regarded as a highly dependable machine having a good over-all efficiency.

Canned motors have been built with the stators cooled by the forcing of a gas or liquid through axial or radial passages, or axial or radial-spaced duct work. Motors have also been built with stator windings cooled by conduction with copper wrapping over insulated coil ends.

Since the canned motor usually is designed with an entirely enclosed stator, liquid-cooled hollow conductors can be used. The stator conductors in the liquid-cooled motor are surrounded by an inert gas which contains practically no moisture. The enclosed atmosphere around the stator windings offers ideal conditions, since the moisture-free atmosphere will not allow sweating when the cooled liquid passes through the hollow conductors. The windings are never exposed to dirt or a corrosive atmosphere, nor are the effects of high windage losses realized as they are in a conventional motor. The motor can be designed to occupy a minimum space; it develops a maximum of power at low stator-conductor-insulation temperature. Various techniques have been developed for canning the rotors for applications where the rotor material is not compatible with the surrounding atmosphere. The rotor cans and stator cans are carefully checked for leakage and cracks by both Zyglo and mass-spectrometer tests.

Because of the high temperatures involved in the process, the hollow-conductor cooled winding has been selected as the most feasible for this application. When cooling is applied at the spot where heat is

PRELIMINARY LAYOUT FOR PRESSURIZED CANNED CENTRIFUGE

generated, excessive thermal stresses in the stator can that are due to large thermal gradients will be eliminated. With this type of winding, a low-voltage system can be used thus the possibility of a breakdown of the insulation is minimized. The winding would be cooled by water in a closed circulating system. The water would be purified before it is installed in the system, there should be no danger of plug-up due to scaling. The low-voltage system makes possible the use of an insulation such as Refrasil or pure mica with no organic binder, so that no insulation breakdown due to radioactivity could occur.

A special "pant leg" (Figure 4) of Inconel would be used to seal the motor conductors to the outer housing. Inconel has an electrical resistance which is many times that of copper, and the thin-walled long path produced by the pant leg will provide sufficient resistance to avoid excessive current to ground.

The outer housing of the stator and the stator have been designed to be remotely removable. However, this design is no longer considered necessary, since inorganic insulations which are not affected by heat or radiation are available.

Canned motors for radioactive-material processing have been built by Westinghouse Electric Corp., Allis-Chalmers Mfg. Co., General Electric Co., and others. (5, 7, 19, 24, 28) We discussed the problems involved in the construction of such a motor with these companies and other manufacturers of electrical motors. All of the design techniques described have been tested by one or more of these manufacturers and have been found satisfactory. No problem is insurmountable in the construction of the canned motor.

VIII. BEARINGS

Hydraulic-piston, gas-lubricated bearings have been chosen as the most feasible for the canned centrifuge. This type of bearing is a refinement of special balance pistons which have been used for years to absorb the thrust load on turbines. Bearings have been developed to include the application of the hydraulic-piston principle for radial bearings as well as for double-acting thrust bearings.

The radial bearing consists essentially of three or more pockets or pistons spaced around the circumference of the shaft. Four such pistons are generally used; each piston covers a little less than 90° of arc, so that some space is left between adjacent pistons. Each piston is a shallow rectangular box with an open end facing the shaft. Normal bearing clearance is provided between the journal and the box edges, or piston lips. From a pressurized source, fluid flows into each box through an orifice in the box, and flows out between the lips and the shaft. When the journal is centered in the bearing, about half of the pressure drop takes place through the orifice, and the other half occurs as the fluid passes out between the lips and the shaft.

If the shaft were displaced towards one piston, the leakage area out of the piston between the lips and the shaft would be reduced. This condition would result in less flow through the orifice and hence less pressure drop and greater piston pressure. The same displacement would produce reverse results in the piston on the opposite side reducing the piston pressure. This difference of pressure in opposite pistons establishes a restoring force that tends to overcome the displacement of the journal, absorbs the load and causes the journal to remain in running position.

The bearings can be so designed that the shift from the centered position is almost directly proportional to that of the imposed load. Unless this load is close to full bearing capacity, the running clearance will be a large percentage of the centered clearance. This fact demonstrates a fundamental difference between this type of bearing and a sleeve-type bearing, which obtains its capacity from a very thin film

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requiring very close running clearance and almost perfect alignment. It also explains the ability of the fluid-piston bearing to tolerate a considerable amount of foreign particles, which would disable any other type of bearing in a short time.

Fluid, piston-type thrust bearings have also been developed. Their principle of operation is identical with that of the radial bearings. With thrust bearings, the pistons face both sides of a rotating collar. They are also supplied through an orifice; the fluid leaves the piston through the leakage area between the piston lips and the face of the rotating collar. Advantages of the fluid-piston-type bearings apply equally well to both the thrust and radial-type bearings.

In order to make the rotating mechanism self-sustaining, the fluid pressure, in many applications of these bearings, is supplied from an impeller mounted on the same shaft that the bearings support. With this arrangement, metal-to-metal contact of the bearing surfaces, of course, results for a brief interval during each start under a load; but it diminishes rapidly as shaft speed increases. The mechanism attains sufficient speed in a second or two, so that acceleration through 6 to 10 revolutions is enough to obtain sufficient bearing pressure to support the imposed load and to terminate metal-to-metal contact.

Allis-Chalmers has used such bearings in many applications. ^(5, 13)

Because of the high level of radioactivity, the use of any organic materials as lubricants ⁽³²⁾ will be impossible. The bearings will therefore have to be lubricated either with water or gas, or with the process fluid. From Merco's observations on the tests with ferric oxide, the use of the process fluid as a lubricant is probably not feasible, since solid particles would collect on the metal surfaces of the bearing, and a build-up of these particles would present a serious wear problem. The possibility of using the clarified

liquid has been eliminated because this fluid would not be clarified during start-up. The use of pure fresh water requires a separate water-supply system with a circulating pump, which would also have to be a canned unit. For these reasons gas was selected as the most feasible bearing lubricant.

Gas could be used without difficulty if a small rotary pump were provided on the motor shaft. This pump would produce the 100 to 200 pounds of extra pressure needed for lubrication of the bearings.

Provision should be made for pressurizing the bearings from the external supply system during start-up, to eliminate metal-to-metal contact during this period.

The system should be designed to allow operation below the primary critical speed of the shaft. Operation above the critical speed would produce excessive bearing loads during start-up and shutdown, and these loads could conceivably damage the bearings and make them inoperable.

We also considered the use of ball bearings. Merco has had considerable experience with ball bearings at high speeds; however, these bearings have been lubricated. The excessive temperature also presents a problem in the use of ball bearings. Some work has been done on the use of ball bearings at high temperatures with water lubrication, (26, 30, 31) but the results were not entirely satisfactory.

The conventional hydrodynamic bearing has sometimes been used with gas lubrication; but for this application the bearing clearances would be extremely small. Therefore, the hydrodynamic bearing has been eliminated as a possibility.

IX. MATERIALS OF CONSTRUCTION

Because of the strength and corrosion resistance required of the material for the centrifuge rotor, an austenitic stainless steel such as type 310 must be used. Cold working will increase the yield and creep strengths without changing the corrosion resistance and should also increase erosion resistance. The creep strength of this material at 30°C will be entirely satisfactory to withstand the stresses developed. The feed tubing leading into the centrifuge where velocities are high, and the points where the discs discharge to the nozzle pockets, may have to be reinforced with an insert of titanium such as type 75A. This titanium insert may be necessary because of the erosive properties of the slurry. The outer casing, or protective shell, should also be constructed of stainless steel, for corrosion-resistance purposes.

Inconel, which has both high strength and good resistance to corrosion, should be used for the stator and rotor cans. Inconel should also be used for the pant-leg construction between the electrical conductors and the motor housing, since it has a comparatively high electrical resistance.

The bearings should consist of an aluminum oxide liner, such as sintered alumina produced by the Kearfott Co., Inc. (Little Falls, New Jersey) or Norton Co.'s (Worcester, Mass.) Rokide aluminum oxide coating.⁽⁹⁾ Aluminum oxide is an extremely hard, lightweight material having good resistance to acids and oxidation. Its high thermal conductivity combined with low thermal expansion prevents the build-up of thermal stresses. In previous applications of this type,^(5, 7, 19, 24) either Graphitar or Stellite has been used as the bearing material; however, in this case, the excess oxygen would oxidize the Graphitar and make it unsuitable, and the high-temperature corrosive atmosphere would corrode the Stellite.

Because of the high levels of radioactivity, the electrical insulation will have to be an inorganic substance in order for it to remain stable for the required length of time.^(3, 6, 21) Two materials have been found which meet all of the necessary requirements for the insulating material:

the first is Refrasil⁽²³⁾ manufactured by the H. I. Thompson Co.), which is nearly pure silica dioxide and is made into a woven sleeve that surrounds the conductor; and the second is an inorganic mica such as that manufactured by the New England Mica Co. Both of these materials are resistant to high temperatures, and neither is affected to any great extent by exposure to intense radiation. They can be readily applied to conductors for the stator winding and should provide a winding which will last indefinitely.

X. PRESSURIZING FLUID

The housing surrounding the centrifuge rotor and the motor is to be pressurized with oxygen gas. Because of the 2000-psi process fluid, a high-pressure gas must be supplied around the rotor so that the difference in pressure between the inside and the outside of the rotor will be minimized. Oxygen has been selected as the pressurizing gas for two reasons. First, the radioactive decay of the fluid leads to formation of hydrogen and oxygen in a stoichiometric relationship. The mixture thus formed is within the explosive limits for hydrogen and oxygen; addition of oxygen will reduce the hydrogen concentration below the explosive limits, thus eliminating the potential hazard. Second, any gas which is used in the system must be deactivated before it is disposed of; and since there is already a means of deactivating oxygen from other parts of the system, no new deactivation system would have to be added.

The oxygen used to pressurize the housing can also be used as the fluid to supply the bearings. The small pump mounted on the motor shaft will boost the oxygen pressure from 2000 to approximately 2200 psi for use in the bearings.

The windage losses due to the high rotational speeds will be somewhat less if a gas is used in place of a liquid. In any event, the loss due to windage is not as high as would be expected with a conventional motor, since there are no exposed slots or windings to increase the turbulence at high speeds. Windage losses have been calculated and have been found to be a very small percentage of the total power required.

APPENDIX A

CENTRIFUGE TESTS

In order to determine the separation characteristics of the process fluid, several tests were conducted on an iron oxide slurry by the Merco Centrifugal Company.

A. BENCH EVALUATION

A feed sample with the correct concentration of red jeweler's rouge was first prepared by severe agitation in about one quart of water for over one minute in a Waring Blendor.

Under the microscope the individual solid particle size then appeared to be about 0.5 micron in diameter, roughly spherical in shape, and crystalline. Some particles formed small clusters of 1.5 to 3 microns in size. (Considerable Brownian movement of the solids in the liquid was noted.)

Test-tube centrifuge-spinning at 70°F for one minute at 500 g's noticeably clarified and feed sample. The few particles not precipitated from the liquid were under one micron, and most were less than 0.5 micron.

Test-tube centrifuge-spinning at 212°F gave a noticeable improvement in settling of solids. Particles not precipitated were all less than 0.5 micron.

A longer spinning time (2 minutes at 500 g's) further clarified the liquid above the settled solids, as did a higher-speed spinning developing 8000 g's. At the higher speed, the sample liquid was essentially clear of solids.

The 60° angle on the high-speed centrifuge tubes caused a deposit of solids on the side of the tube; this fact indicated that a lower angle of repose was desirable.

The preliminary bench examinations were considered promising, based on experience with similar-acting materials. Further investigation

was planned with a Westfalia LWA 205 bench pilot centrifuge.

A liquid-liquid separator, disc-type rotor was installed in the LWA set to operate at 12,000 rpm. The heavy liquid discharge orifice was screwed in all the way. A representative feed sample was prepared as above and introduced into the machine at feed rates of 0.5 gpm and later 1.0 gpm. The effluent water appeared brilliantly clear at 0.5 gpm, and nearly the same at 1.0 gpm; thus close to 100 percent removal of solids was indicated. Microscopic examination of the effluent revealed no solids.

The solids accumulated on the vertical surfaces of the rotor, but surfaces with a slope of 40-50° remained essentially clear of solids.

The bench examination on the LWA was considered successful, and pilot tests with the Merco B-9 continuous, disc-type, nozzle-discharge centrifuge were planned.

B. PILOT TEST

For the B-9 tests, a 200-gallon supply of Fe_2O_3 in water at room temperature was prepared as before, with proper dispersion by severe agitation. The feed concentration was made about twice as heavy as specified, since it was anticipated that a considerable amount of solids would be tied up in the centrifuge recycle system during the cycle of operation.

The B-9 was set up to operate at 9000 rpm with eight no. 60 rotor nozzles and twenty-six .050 inch bar-spaced discs with an outside diameter of 6.75 inches; 1/4 inch return tubes were used in the rotor.

The underflow draw-off valve was fully closed during an operating cycle of 1/2 hour. At that time, it was estimated that the liquid in the recycle system would have reached 5 grams/liter solids concentration, based on the concentration of solids introduced with the feed and the feed rate.

The feed rate was set at 5 gpm and later at 7.5, 10, and 12 gpm. Samples of feed and effluent were taken at 10-minute intervals throughout

the cycle to check the separation. Temperature readings of the liquids were also recorded as well as ammeter readings. The effluent at 5 gpm feed was almost brilliantly clear, and at 10 gpm feed it was only slightly more colored. At no time throughout the 9000 rpm tests did the effluent appear as turbid as a control sample made up to 0.02 gram/liter concentration, which is the effluent clarity specified. This test was repeated several times at 10 gpm feed and also at 6900 rpm; at this speed, the effluents at first looked nearly as clear as at 9000 rpm. Later tests with feed rates of 5, 7.5, 10, and 12 gpm at 6650 rpm indicated that between the 7.5- and 10-gpm feed rates, the effluent reached the 0.02 gram/liter turbidity of a prepared control sample.

At 5000 rpm and with a 10-gpm feed rate, there was roughly twice as much solids in the effluent as at 6650 rpm. This determination was made by color (turbidity) comparison; however, with a 5-gpm feed at 5000 rpm the effluents compared closely with those for 5-gpm feeds at the higher speeds.

At the end of a half-hour cycle, the underflow valve was opened wide, and the feed valve was closed. The solids discharged in a concentrated slurry of about 5 grams/liter concentration. This slurry was compared for turbidity with a 5 grams/liter control sample.

After the unit had run dry, the feed valve was opened to the correct capacity, and after approximately 15 seconds, the underflow valve was again closed. This is a sequence of operations which Merco has discovered to give a flushing action within the rotor. The rotor is effectively purged of solids.

At shutdown and disassembly, a thin layer of solids was noted on the 45° angled discs, and heavier accumulations were on the vertical surfaces. It is recommended that all surfaces in the rotor be carefully polished, to prevent excessive solids retention in the rotor. Disc and bowl angles smaller than 45° may be desirable.

APPENDIX B

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