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DEVELOPMENT OF A LABORATORY SLUG INJECTION MACHINE FOR FABRICATION OF HTGR FUEL RODS

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Summary

A major part of the High-Temperature Gas-Cooled Reactor (HTGR) Fuel Refabrication Development Program at Oak Ridge National Laboratory has involved the development of the slug injection process for remote forming of recycled fuel into fuel rods which can be loaded into graphite fuel elements. The HTGR fuel rod considered here is a 1.27-cm-diameter cylinder approximately 5.08 cm long that is comprised of a mixture of fissile, fertile, and shim particles bonded by a carbonaceous matrix consisting of a mixture of graphite filler in a thermoplastic binder. A laboratory slug injection machine has been developed to perform the major processing steps of fuel particle dispensing, blending, and loading and fuel rod forming.

The laboratory slug injection machine, illustrated diagrammatically in Fig. 1, was developed by applying the principles employed in automated assembly equipment wherein the process is divided into steps which can be performed in sequence at individual operating stations. A rotary indexing table to which 24 stainless steel molds are permanently affixed provides the mechanism by which a fuel rod mold is transferred from one operating station to the next for performance of the required processing steps.

The initial processing step performed by the machine is cleaning and lubrication of a fuel rod mold, which is then indexed to the next operating station where a bottom spool piece is inserted. The mold is

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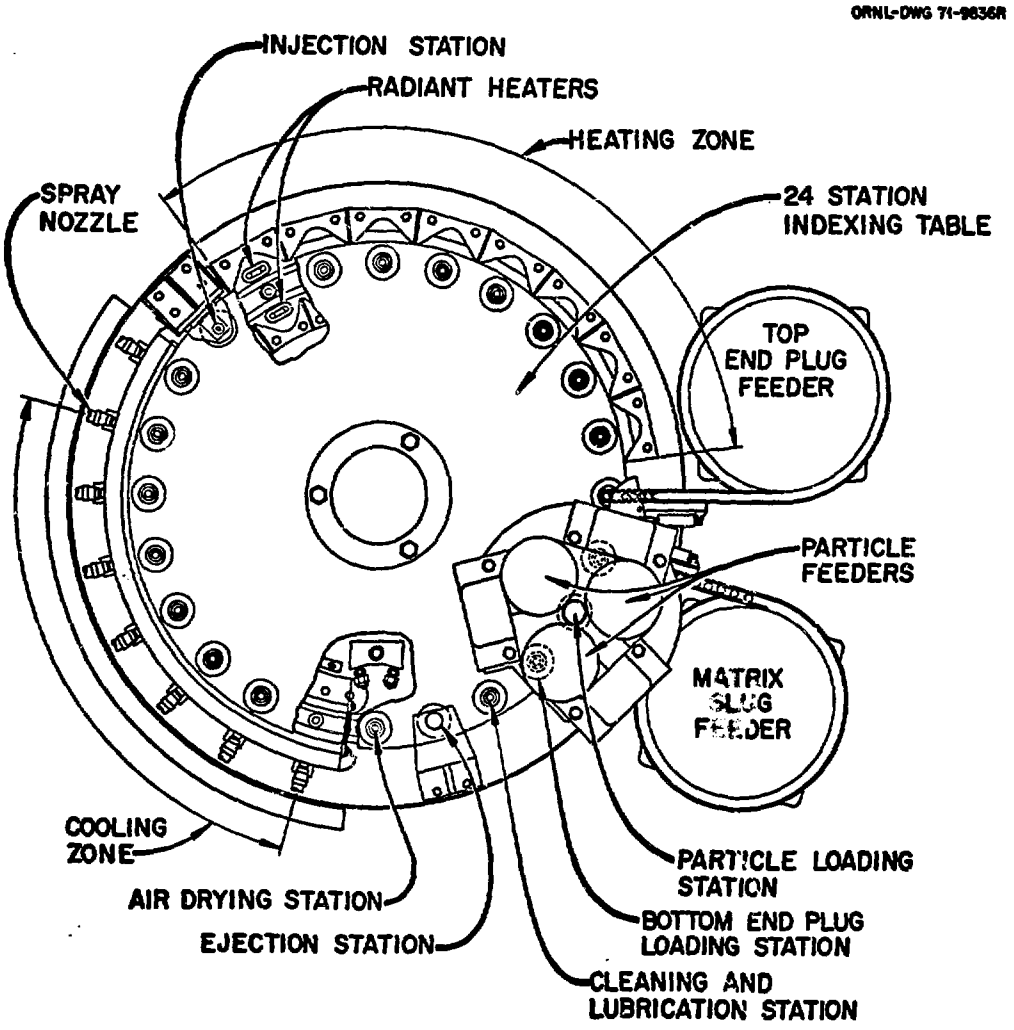

Fig. 1. Schematic Diagram of Laboratory Slug Injection Machine.

indexed sequentially to the next three operating stations where a charge of fuel particles, a preformed matrix slug, and a top punch are inserted, one on top of the other. The loaded mold is indexed through six stops where heat is applied by infrared radiant heaters and on to the injection station. At the injection station, pressure is applied to the top punch by an external ram to force the molten matrix slug into the interstices between the fuel particles. Upon completion of the injection operation, the mold is indexed through four stops where it is cooled by water sprays and two stops where excess water is removed by air jets. The mold is then indexed to the ejection station where the bottom spool piece, molded fuel rod, and top punch are ejected. The end pieces are separated and sent to their respective storage hoppers for reuse, the molded fuel rod is directed to the inspection equipment, and the mold is indexed to the cleaning station to begin the next cycle.

The laboratory slug injection machine has a fabrication rate of approximately 4000 fuel rods per day, and it has been used successfully to produce about 20,000 fuel rods for irradiation experiments. The laboratory machine is directly applicable for remote operation, and the operating station components developed for the machine are applicable in larger machines with greater fabrication rates. The laboratory machine will be used to determine the reliability of these components and their maintenance requirements to qualify them for use on a production-scale slug injection machine.

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Abstract

A laboratory model of a machine for fabrication of HTGR fuel rods has been developed at Oak Ridge National Laboratory to demonstrate the feasibility of the slug injection process for remote fabrication of fuel rods from recycled fuel. The design for the laboratory slug injection machine is based on the principles employed in automated assembly equipment, and conventional indexing and parts feeding equipment are used. The laboratory machine is completely automated, and it performs the major processing steps of particle dispensing, blending, loading, and fuel rod forming at a fabrication rate of approximately 4000 fuel rods per day.

Introduction

The recycle of high-temperature gas-cooled reactor (HTGR) fuel requires the development of remotely operable fuel reprocessing and refabrication equipment. A major part of the HTGR Fuel Refabrication Development Program at Oak Ridge National Laboratory has involved the development of a process for bonding coated fuel particles into fuel rods which can be loaded in graphite fuel elements.[1] Since the rods formed with recycled fuel particles must be fabricated in hot cells, the process developed had to be suitable for use with completely automatic, remotely operable equipment. The development of the laboratory model of a machine to fabricate HTGR fuel rods by the slug injection process is described herein.

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The HTGR Fuel Rod

The HTGR fuel rod considered here is a 1.27-cm (1/2-in.)-diameter cylinder about 5.08 cm (2 in.) long that is comprised of a mixture of fissile and fertile fuel particles bonded by a carbonaceous matrix, as illustrated in Fig. 1. The matrix consists of a mixture of 30 to 40 wt % graphite filler in a thermoplastic binder, such as coal tar or petroleum pitch.

To fabricate HTGR fuel rods, the coated fissile and fertile fuel particles must be blended and loaded into a mold in such a manner that a uniform distribution of fissile and fertile particles is obtained. Heated matrix is then injected into the bed of particles to form the fuel rod, which is cooled, ejected from the mold, inspected, and carbonized. The HTGR fuel rods are presently molded from virgin fuel in direct-contact plants by a hot intrusion technique wherein molten matrix is introduced under pressure into the bottom of the mold to fill the voids between the fuel particles.

Slug Injection Process

The slug injection process developed at Oak Ridge National Laboratory over the past several years is well suited for the remotely operable automatic equipment that must be used when HTGR fuel rods are fabricated from recycled fuel. In this process, illustrated in Fig. 2, a stainless steel mold is loaded with a bottom spool piece, coated fuel particles, a preformed matrix slug, and a top punch. The mold and its contents are heated to about 180°C to melt the matrix slug. Pressure is then applied by an external ram acting on the top punch to force the matrix downward through the interstices of the particle bed.

The bottom spool piece has four functions in this process. A 0.25-mm radial clearance between the top of the spool piece and the wall of the mold permits the passage of excess matrix material while preventing the loss of fuel particles. The recessed portion of the bottom spool piece provides a reservoir for excess matrix material, and vertical

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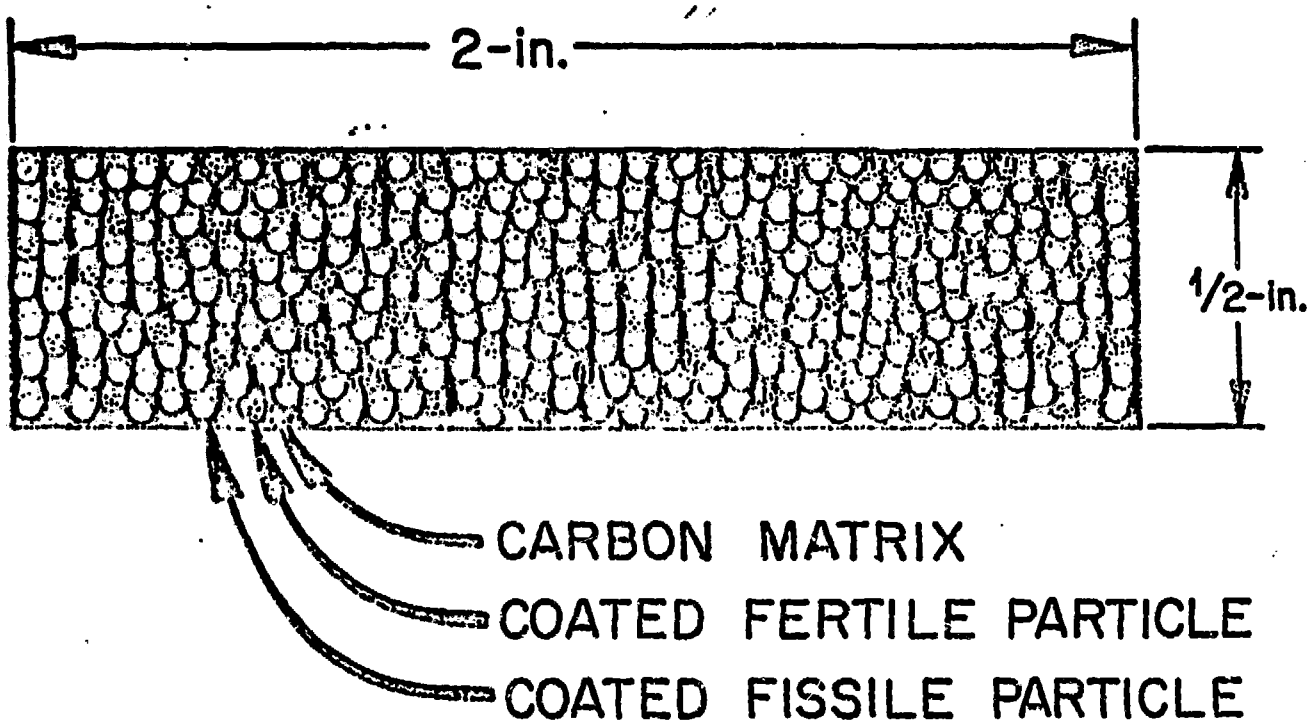

Fig. 1. HTGR Fuel ~~Stick~~ Rod

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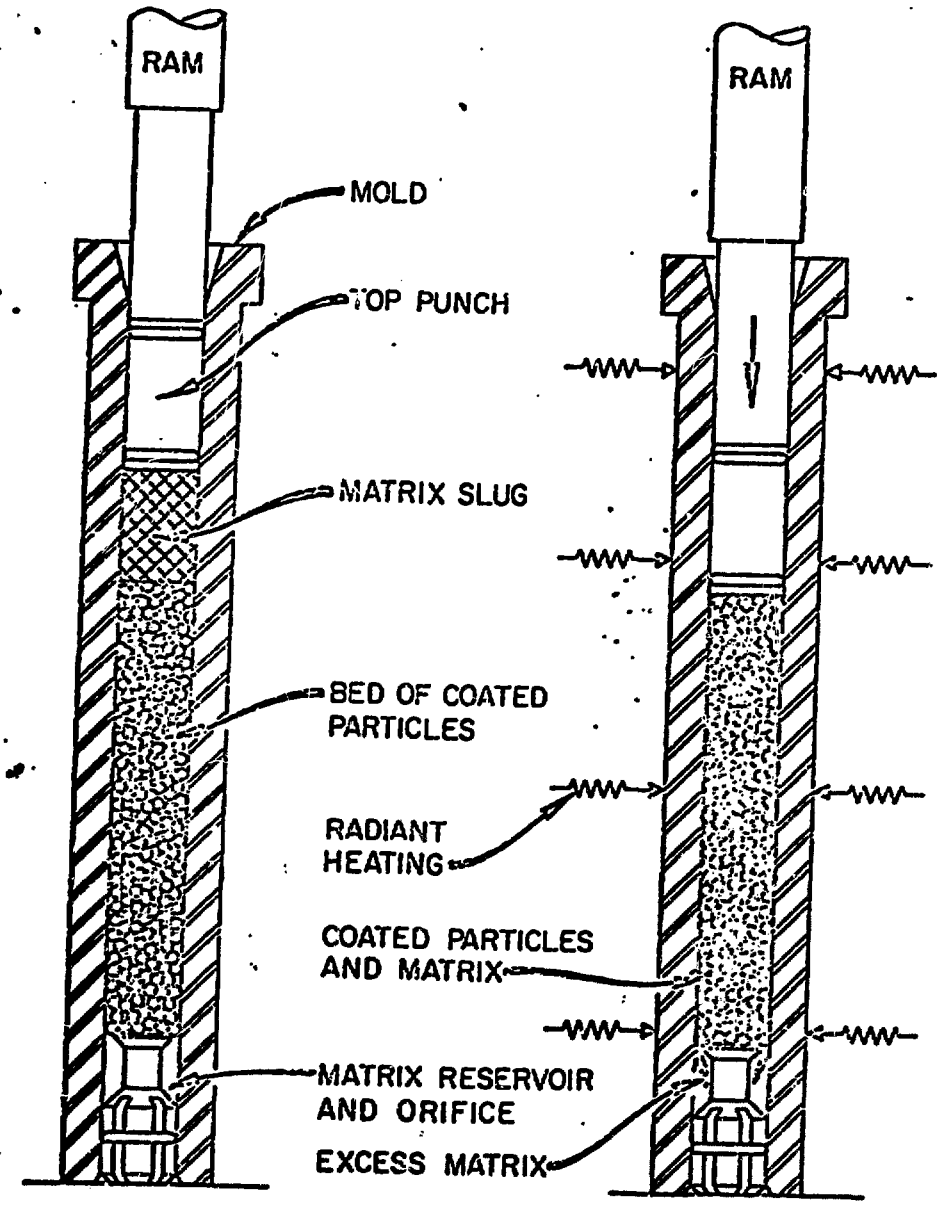

Fig. 2. Slug ~~Technique~~ Injection Process for Making Bonded-Bed Fuel ~~Sticks~~ Rods

slots in the lower portion of the spool piece provide passages for the release of air displaced by the matrix. The spool piece also acts as an end cap that retains the contents of the mold during its transfer from one operating station to the next on the laboratory fuel rod fabrication machine.

The slug injection process was developed on manually operated laboratory equipment, and it has been used to produce fuel rods for irradiation experiments. The main advantage of the slug injection process in remote fuel rod fabrication is attributable to the use of the solid preformed matrix slug rather than a hot liquid matrix. The use of the solid slug permits preparation of the slug with commercial blending and pelletizing equipment outside the hot cell, and it also obviates problems associated with segregation of the filler material within a liquid matrix system.

Laboratory Slug Injection Machine Design Basis

The design for the laboratory slug injection fuel rod molding machine is based on the principles employed in automated assembly equipment wherein the process is divided into individual steps which can be performed in sequence. Ten basic processing steps are required to form a molded fuel rod by the slug injection process. They are

1. cleaning and lubricating the mold;
2. placement of bottom spool piece in mold;
3. dispensing, blending, and loading of fuel particles in mold;
4. placement of matrix slug in mold;
5. placement of top end punch in mold;
6. heating of mold contents;
7. injection of matrix;
8. cooling of mold contents;
9. drying of mold; and
10. ejection of fuel rod.

The design approach followed during the development of the laboratory slug injection machine involved the application of a single processing step to an individual fuel rod mold at each operating station. A rotary indexing table was selected to transfer permanently affixed molds from one operating station to the next. With this type of system, the total machine processing time is determined by the cyclic time required for completion of the longest operation. In this process, the longest single operation is injection of the matrix, and it requires approximately 20 seconds for completion. An increased overall processing rate could be attained by simultaneous injection of a multiple grouping of fuel rod molds at a single station, but this would complicate the equipment and controls as well as the quality assurance requirements. Although heating and cooling of the mold contents require longer cyclic times than matrix injection, these processing steps take place over several indexing stations or stops.

Machine Description

Application of the previously discussed design approach led to the development of the present laboratory slug injection machine, illustrated diagrammatically in Fig. 3, which has a fabrication rate of 4000 fuel rods per 20-hour day. Twenty-four indexes of the rotary table provide stops at eight single-operation stations, adequate heating and cooling stops, and two spare stops for the possible addition of duplicate injection and ejection stations, which would increase the fabrication rate by about 70%.

A standard roller gear drive device was selected as the indexing mechanism. The fuel rod molds are attached to the rotary indexing table so that the bottom of the mold clears a stationary skid ring by about 3.175 mm (1/8 in.). The skid ring provides a surface over which the bottom spool piece slides during the indexing motion. The operating stations are located relative to the fixed skid ring in a manner that will permit alignment of the indexing mechanism stops with the operating stations to be maintained when operating components are removed for maintenance.

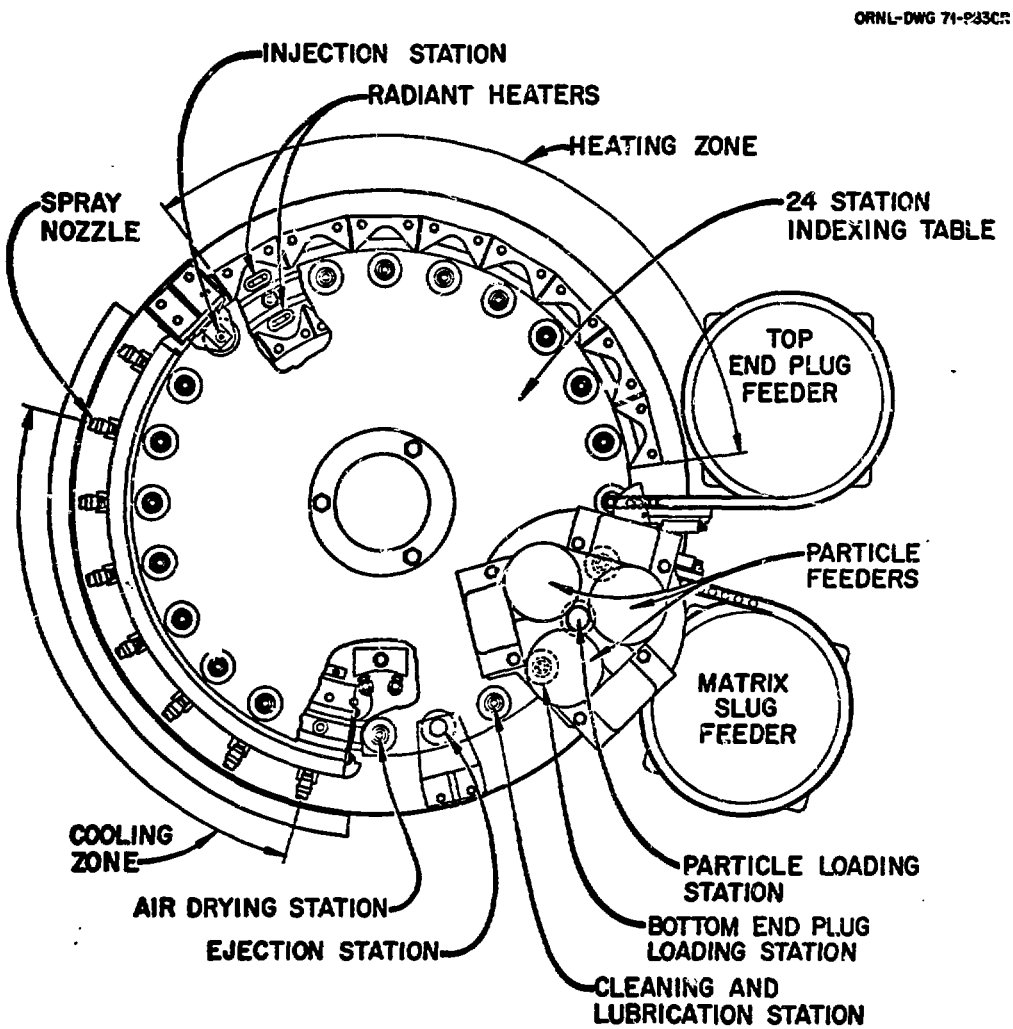

Fig. 3. Schematic Diagram of Laboratory Slug Injection Machine.

The initial processing step performed by the machine is cleaning and lubrication of a fuel rod mold. After this operation, the mold is indexed to the next station where the bottom spool piece is inserted in the mold until it rests on the skid ring below the mold. The mold is then indexed sequentially to the next three operating stations where the fuel particles, matrix slug, and the top end punch are loaded into the mold, one on top of the other. After the mold has been loaded, it is indexed through six stops where heat is applied by infrared radiant heaters and on to the injection station where pressure is applied to the top punch to force the molten matrix slug into the interstices between the fuel particles. Any excess matrix is accumulated in the reservoir within the bottom spool piece. After the injection operation has been completed, the mold is indexed through four stops where it is cooled by water sprays and two stops where the excess water is removed by air jets. The mold is then indexed to the ejection station where the bottom spool piece, molded fuel rod, and top punch are ejected.

Molded fuel rods and end pieces are separated by a device which directs the fuel rods to the inspection equipment and the top punches and bottom spool pieces to their respective storage hoppers for reuse. The mold is indexed to the cleaning station to begin the next cycle. The laboratory model of the slug injection fuel rod molding machine is shown in Fig. 4, and the various operating components and functions of the machine are discussed in the following paragraphs.

Mold Cleaning and Lubrication

Mold cleaning and lubrication is accomplished at one operating station by means of a rotating nylon bristle brush which traverses vertically within the mold. A lubricant is sprayed into the top of the mold on its arrival at the station prior to insertion of the brush from the bottom. No cleaning solvent is required.

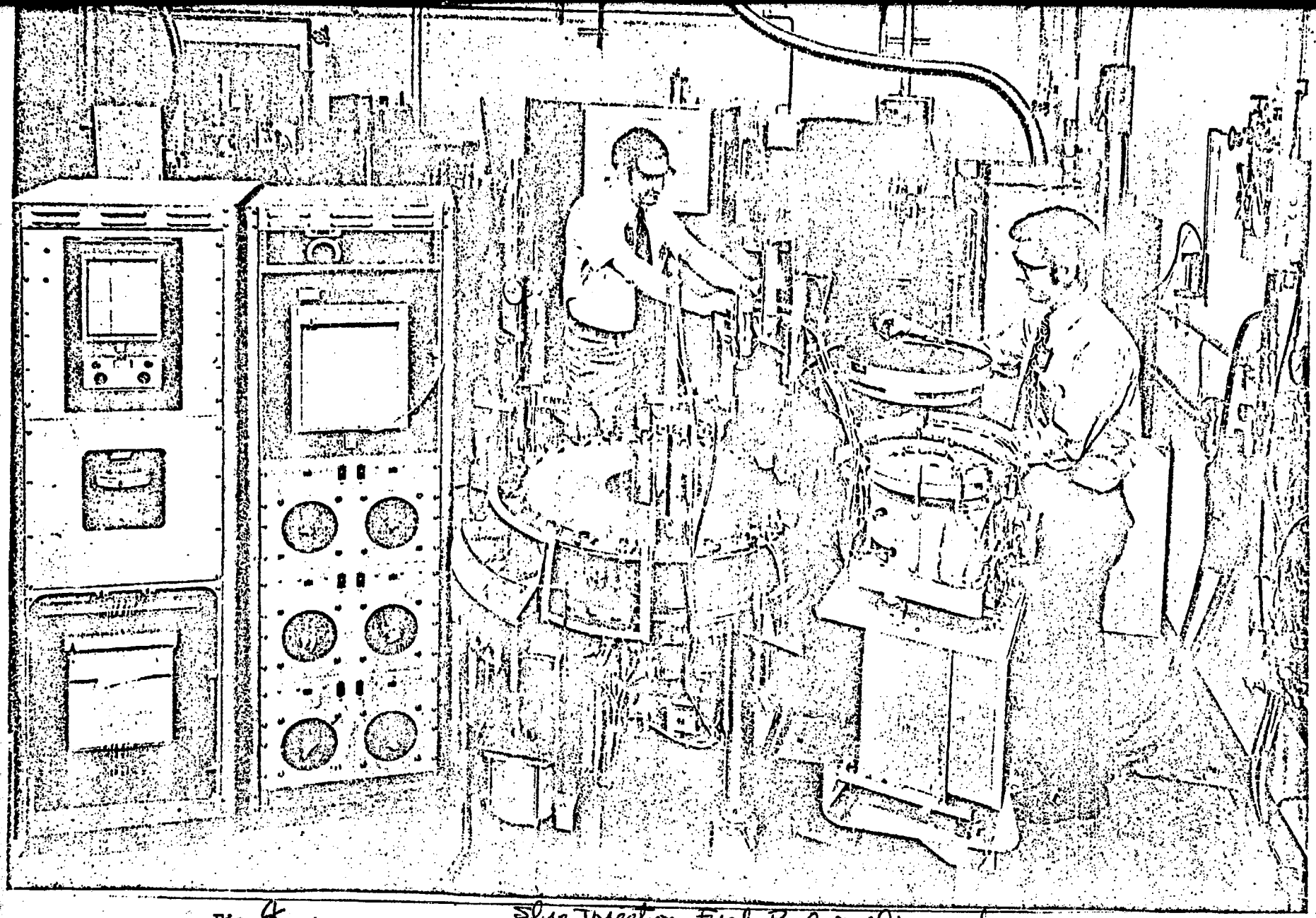

Fig. 4. Automatic Laboratory ~~Fuel Rod Machine~~ Slug Injection Fuel Rod Molding Machine ~~— The major components are identified in Fig. 2. (Capacity approximately 4,000 per day).~~

Parts Feeders

The bottom spool piece, matrix slug, and top punch are each placed within the mold by conventional vibratory parts feeders. Each part feeder is equipped with an external gravity feed tube, a horizontal parts shuttle, and a vertical placing ram. The parts are fed from the parts feeder bowl in a horizontal attitude, and they are reoriented into a vertical attitude in the gravity feed tube. Individual parts are removed from the bottom of the gravity feed tube by the shuttle and deposited in the top of the mold. They free fall into the mold and are positively placed by the placing ram which follows them down into the mold. The bottom spool feeder is equipped with orientation devices to distinguish a preferred end and orient the spool piece properly.

Each parts feeder is controlled by its own individual system which initiates a placing operation upon receipt of a demand signal from the slug injection machine. The feed rates of the parts feeders are limited by the combined cycle time of the shuttle and placement ram at each operating station. The three feeders have feed rates of approximately 40 parts per minute.

Fuel Particle Dispensing, Blending, and Loading

Fuel particle dispensing, blending, and loading is accomplished in a vertically oriented processing line at the particle loading station. Three storage hoppers located at the top of the vertically arranged processing line contain fissile, fertile, and shim particles. Each of these hoppers is connected directly to a pneumatically operated pinch valve which acts as both a closure valve for the hopper and a volume measuring device. Each pinch valve is mounted above a common dump valve, and each can be adjusted vertically relative to the common dump valve to adjust the volume of particles retained in the tube between the pinch point and the dump valve. The particle flow rate of each measured volume is controlled by the diameter of the outlet orifice to the dump valve. The diameter of each orifice is sized in proportion to the volume of each type of particle to be loaded in a fuel rod mold.

In operation, volumetric measurements are made by simultaneously closing the dump valve and opening the three pinch valves, allowing the particles to flow from the storage hoppers into their respective tubes whose volumes have been predetermined. Restoration of the air supply to the pinch valves locks the particles within each pinch valve, shutting off flow from the hoppers. When the dump valve is opened, the three measured volumes of particles simultaneously flow from their outlet orifices into a conical funnel in which blending occurs.

The particles released by the dump valve and blended in the conical funnel are divided into ten fractions by a decade splitter. The splitter has a cylindrical orifice which directs the particles onto the apex of a cone whose base is divided circumferentially to separate the charge into fractions which are deposited in ten reservoirs within a slide valve. The slide valve permits individual discharge of each reservoir in a programmed order so that the second fraction of particles released was located diametrically opposite the first fraction in the decade splitter. This order of discharge is continued so that each fraction released is followed by that fraction located most nearly diametrically opposite it to assure that any segregation of particles around the decade splitter will be distributed throughout the particle column. After all ten particle fractions have been released, the decade splitter returns to the closed position to await the next particle charge.

Each fraction of particles discharged from the splitter reservoirs falls into a mixing cone beneath the splitter where further blending occurs. The blended particles fall from the cone through a fill probe into the fuel rod mold. The lower end of the fill probe is located within the mold at a point just above the top of the full particle column so that no particles will contact the lubricated sidewall of the mold above the full level of the particle column. Operation of the ten-way splitter slide valve is timed to allow one fraction of particles to come to rest in the mold prior to release of the next fraction. After all ten particle fractions have been loaded in a fuel rod mold, the fill probe retracts to allow the mold to be advanced to the matrix slug and top punch feeders.

Mold Heating

The filled fuel rod mold is indexed through a heating zone comprised of six stops wherein infrared radiant heaters are used to heat the mold and its contents. The heaters are located in an arc on one side of the mold traverse, and aluminum reflectors are located on the opposite side to assure even heating of all mold surfaces and to minimize heat loss. The exterior surface of each mold has a black oxide finish to increase the amount of heat absorbed.

The temperature of the mold is measured by thermocouples which contact the mold at each of the six indexing stops within the heating zone. The mold and its contents reach the desired temperature of 180°C after the fourth stop, and the last two stops serve to assure uniform temperature distribution throughout the particle bed.

Slug Injection

The slug injection station is comprised of an air cylinder with a two-speed injection ram located over the mold stop. With a heated mold in place at the station, the pressing ram is actuated and lowered into the mold to contact the top punch and apply the force necessary to inject the molten matrix into the particle bed.

A radiant heater is located at the slug injection station to maintain the desired temperature of the mold contents during the injection operation. The slug injection station is also equipped with a displacement transducer which can be used to determine the injection rate, when injection has been completed, and the final length of the fuel rod.

Mold Cooling

The fuel rod mold leaving the slug injection station is indexed through a cooling zone to reduce the temperature of the mold contents. Mold cooling is accomplished by water sprays at four indexing stops, and excess water is removed by air jets at two succeeding stops.

Ejection and Separation

The cooled and dried mold is indexed to the ejection station where a pneumatic ram is used to eject the bottom spool piece, molded fuel rod, and top punch from the mold into a separation device. This device separates and removes the spool piece and top punch by rotating them about their interface with the fuel rod. These parts are then directed to their respective storage areas, and the molded fuel rod is routed to the inspection equipment.

Controls

The laboratory slug injection machine is controlled by a relatively simple permissive series controller which allows programmed start-up and shutdown of the machine. Each operating station is equipped with its own controls, and these individual controls are connected in series within the main controlling unit. As the first mold arrives at each operating station, that operation is started. The machine shut-down sequence is similar, with each operation stopping in sequence as the last mold progresses through that station. Molds preceding the first clean mold on machine start-up and molds following the last clean mold on machine shutdown are indexed through the operating stations but no operations are performed on them.

Each parts feeder is equipped with its own individual control system which initiates a part placement operation upon receipt of a demand signal from the main controller. After the part placement operation has been completed, the parts feeder control system must send a completion signal to the main controller before the next indexing step can be initiated. If there is a malfunction in a part placement operation, the control system for that parts feeder will stop automatic operation of the molding machine and sound an alarm. However, another placement operation can be initiated manually to permit determination of the cause of the malfunction. The malfunction interlock can be overriden in the

manual operating mode to permit machine unloading prior to maintenance. Integral controls on each parts feeder permit the removal of an entire parts feeding system for maintenance purposes. This feature is advantageous in remote systems where control transducers and mechanical adjustments are required to achieve proper control.

The controls for the radiant heaters are designed to allow shaping of the power distribution in the heater bank. Individual thermocouples contact each mold as it arrives at each indexing stop within the heating zone. Both on-off and power level controls are provided to permit control flexibility in the heating zone.

All operating components that must engage mechanically with the fuel rod molds are equipped with interlocks to prevent further indexing before the operating equipment has been disengaged from the mold. Control transducers which sense abnormalities in the placement of parts, size of particle charges, and length of fuel rods at various operating stations can be coupled with the process controls to provide automatic rejection of abnormal fuel rods.

Developmental History

During the initial bench development of the slug injection process, molds equipped with vented bottom end caps and metal platens for heating were used. However, use of bottom end caps on the molds would have necessitated the inclusion of complex mechanisms on the laboratory machine to remove and replace the caps before and after fuel rod ejection. An attempt was made to completely eliminate the end cap by providing a clearance of about 0.25 mm between the bottom of the mold and the stationary skid ring below and allowing the fuel particles to rest directly on the skid ring. The clearance would allow trapped air to escape during the injection process while preventing the loss of fuel particles during indexing operations. The surface of the skid ring was covered with a teflon compound, and experimental runs were conducted to test the feasibility of this approach. Indexing of the molds with the fuel particle

column sliding over the surface of the skid ring was possible, but problems were encountered after the molten matrix had been injected. Movement of the hot fuel rod prior to cooling caused to lower end to smear on the skid ring. Some consideration was given to chilling the lower end of the fuel rod prior to moving it, but the use of a bottom spool piece appeared to have greater promise. After a few experiments, the proper geometry of a bottom spool piece that would provide the desired results was determined.

Efficient mold heating caused some concern since the size of the heating zone was dependent on the time required to heat a mold. Experiments were conducted in a mock-up of the heating zone in which three different heating methods and two mold materials with different finishes were used. Clamp-on heated platens and infrared radiant heaters raised the temperature at the center line of the particle bed to 180°C in comparable heating times of approximately 130 seconds, while an induction coil reduced this heating time to about 40 seconds. However, use of either a clamp-on platen or a closed induction coil would require the use of actuators to place the heating unit around the mold and remove it. This was further complicated by the fact that heating would still be required at several indexing stops. The geometry of the experimental heating zone was improved for actual machine use, and infrared radiant heaters were selected because their use requires no moving parts, thereby providing fewer control problems.

The characteristics of both stainless steel and aluminum molds were investigated. The aluminum molds used in the experimental investigation had a black hard-coat finish on both the inside and outside surfaces. The hard-coat on the interior surface was intended to serve as a wear surface, while that on the exterior was intended to increase the amount of heat absorbed. Although aluminum is a better conductor of heat than stainless steel, the inner hard-coat nullified any increase in conductivity over that of stainless steel. The result was that aluminum molds offered no advantage over stainless steel molds relative to heating and were less desirable with respect to wear. These investigations led to the selection of hardened stainless steel molds with a black-oxide finish on their outer surfaces.

Considerable effort was expended in the development of a fuel particle dispensing, blending, and loading component. Several concepts of volumetric dispensing were considered, as were several blending techniques. No simple solution to this problem was discovered. The system developed is a combination of components which act together to redistribute any segregation of fuel particles into layers fine enough to provide a uniform mixture along the length of a fuel rod. Although several components are required, each is a relatively simple unit which was developed to perform one of the several functions of the particle loading station required to produce a homogeneous fuel charge.

Summary

The laboratory slug injection fuel rod molding machine has a fabrication rate of approximately 4000 fuel rods per day, and it has been successfully used to produce about 20,000 fuel rods. The laboratory machine is directly applicable for remote operation in a radioactive hot cell. The operating station components developed for the laboratory machine are applicable in larger machines with greater fabrication rates, and the laboratory machine will be used to determine the reliability of these components and their maintenance requirements to qualify them for use on a production-scale slug injection machine.[2]

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2. F. C. Davis, D. D. Cannon, J. D. Sease, and R. A. Bradley, "Production Slug Injection Machine for Fabrication of HTGR Fuel Rods," Proceedings of the Twenty-First Conference on Remote Systems Technology, American Nuclear Society, November 1973.