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ABSTRACT

The EBR-II rotating plug seals require frequent cleaning and maintenance to keep the plugs from sticking during fuel handling. Time consuming cleaning on the cover gas and air sides of the dip ring seal is required to remove oxidation and sodium reaction products that accumulate and stop plug rotation. Despite severely limited access, effective seal cleaning techniques have removed 12 920 lb (5860 kg) of deposits from the seals since 1964. Temperature control modifications and repairs have also required major maintenance work. Suggested seal design recommendations could significantly reduce maintenance on future similar seals.

INTRODUCTION

The Experimental Breeder Reactor II (EBR-II) rotating plug cover gas seals have been a source of continual maintenance activity since their first use in 1962. Although the seals have successfully met the original design requirements of providing a reactor cover gas mechanical seal during reactor operation and fuel handling, they have been plagued by unforeseen difficulties.

The predominant symptom of seal problems has been difficult plug rotation during fuel handling operations and the major cause of problems has been the undesired reaction of the seal material with its local environment. The resultant corrective maintenance efforts have been hampered by severely limited access to the problem sites, uncertainty in the causes of the seal problems, the need to prevent air from entering the reactor cover gas, and precautionary measures required to protect personnel from radioactively contaminated gases.

This paper will briefly discuss the physical configuration of the rotating plugs and seals, the major maintenance work that has been done, and recommended design improvements to minimize maintenance needed on similar future seals.

PHYSICAL DESCRIPTION

EBR-II is a pool-type sodium cooled nuclear reactor. Two rotating plugs, called the large and small plugs, penetrate the top of the primary tank, as shown in Figure 1, and are rotated to position fuel handling equipment over the reactor core subassemblies. Because the rotating plugs penetrate the top of the primary tank, they are fitted with seals that contain the argon cover gas within the tank during reactor operation and fuel handling.

Each of the plug seals is composed of three parts: a dip ring attached to the periphery of the rotating plug, a seal trough surrounding each dip ring, and a tin-bismuth (SnBi) eutectic alloy filling the trough, as shown in Figure 2. Electric heaters are embedded in each dip ring to melt the seal alloy for rotation of the plugs. The heater output is controlled to maintain the top half of the seal alloy in a solid condition during reactor operation (half-molten mode) and to fully melt the alloy (full-molten mode) for plug rotation during fuel handling. No access was originally provided to view or maintain the seal trough or dip ring on either rotating plug.

The dip ring for each plug is made of an upper and lower ring integrally attached to the circumference of each rotating plug and penetrated by heater and thermocouple holes. Except for their dimensions, the large and small plug dip rings are identical. Electrical resistance heaters are equally spaced within each dip ring to melt the seal alloy for plug rotation. As originally designed, the upper rings were made of Type 304 stainless steel and the lower rings were made of copper to improve the heat transfer from the dip ring to the seal alloy. The present upper and lower dip rings are made of Type 304 stainless steel.

The seal troughs were designed to fit around each dip ring with a uniform gap on each side to contain the tin-bismuth alloy. The large plug seal trough is attached to the structural "Z" ring on the primary tank cover so that it remains stationary when the large plug is rotated. The small plug seal trough is attached to the large plug so that the trough rotates with the large plug but remains stationary relative to the small plug.

The seal liquid is an eutectic alloy of 42 wt % tin (Sn) and 58 wt % bismuth (Bi) with a melting point of 281°F (138°C) which has functioned satisfactorily as designed. Three significant problems with the SnBi alloy are that it corrodes copper, oxidizes into a fine black powdery dross that can become a hard crust, and that it reacts exothermically with sodium to produce high melting point intermetallic compounds. Despite these problems, no suitable alternate seal material has been found to replace the SnBi alloy.

The seal alloy temperatures are regulated by the seal heaters and controllers. Thermocouples are attached to the air side of each seal trough and others are embedded within each dip ring. Originally, the seal trough thermocouples were used to control the seal alloy temperature but a later

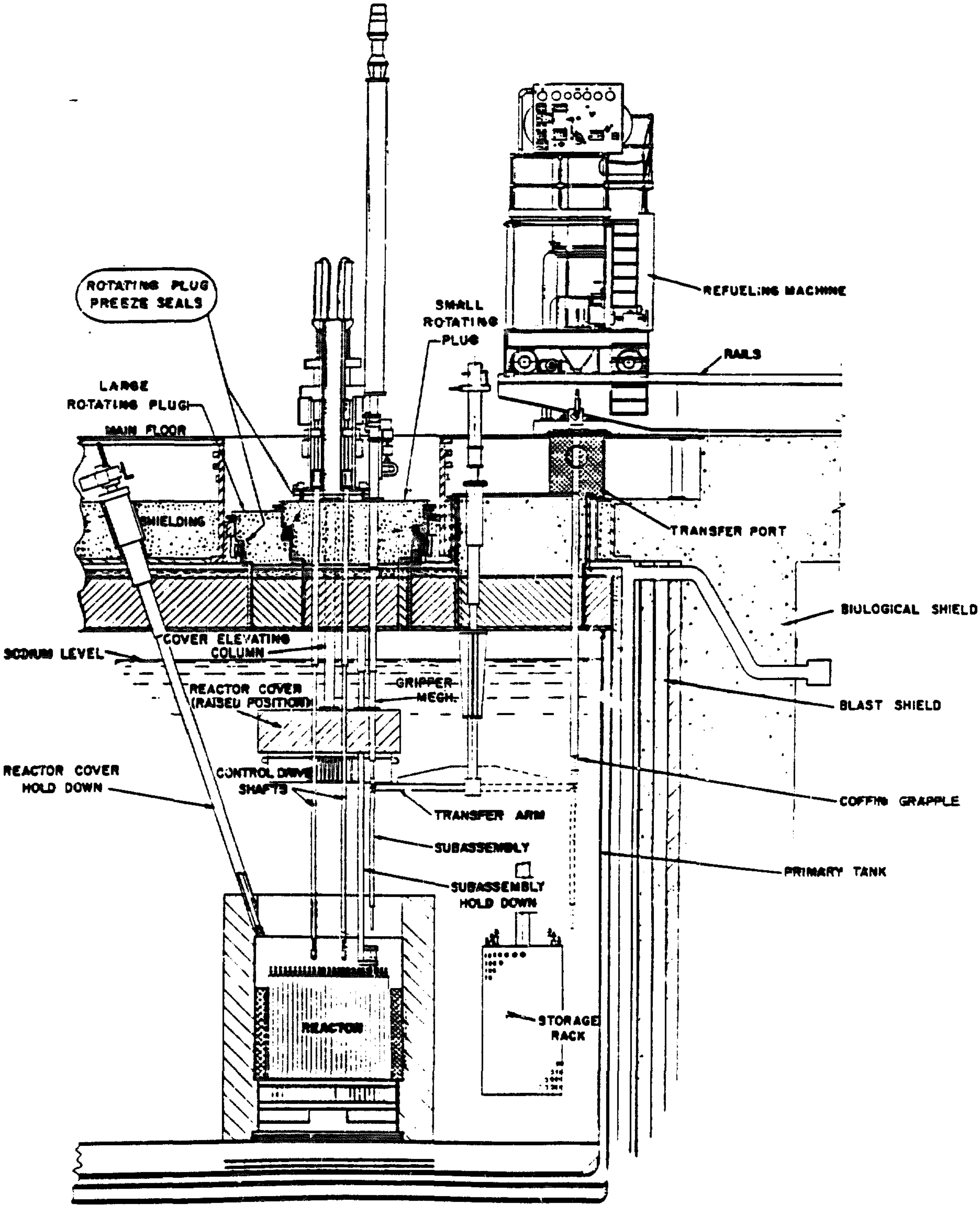

Figure 1: EBR-II Reactor and Fuel Handling System

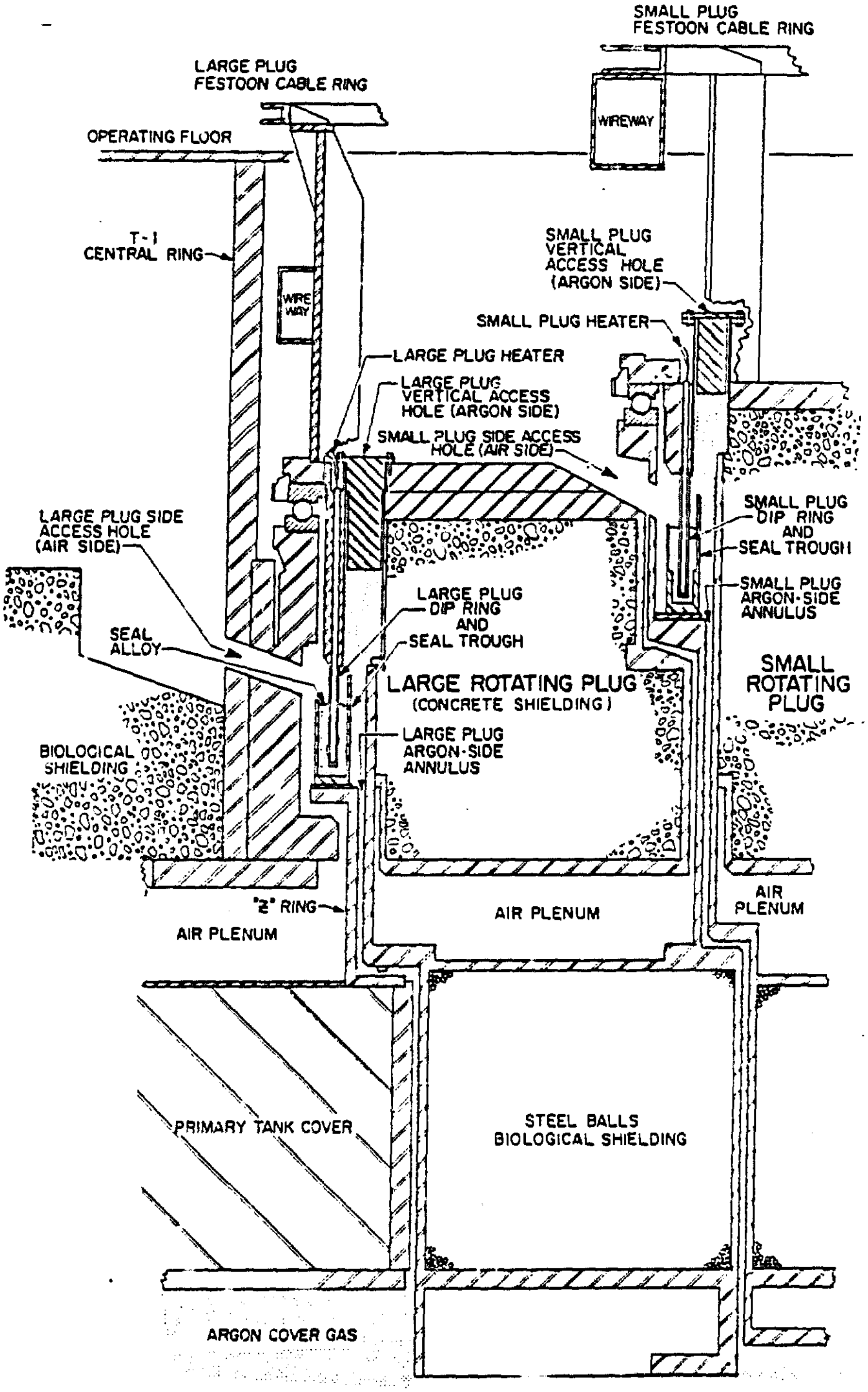

Figure 2: ROTATING PLUG SEALS AND ACCESS HOLES

modification improved the system by using the embedded dip ring thermocouples. The present system operates the upper and lower heaters at "half-molten" mode and at "full-molten" mode power levels that prolong the heater life by minimizing thermal and power cycles.

Each seal trough also has a flow of ambient temperature air over one side of the seal trough designed to cool the top of the seal alloy and to maintain the solid seal during the "half-molten" mode.

MAJOR MAINTENANCE

Since the initial fuel handling system checkout was completed, most seal related maintenance has been performed to improve the temperature control of the seal alloy and to clean, or provide access for cleaning, the air-side and argon-side of the seals. Other actions have been taken, such as modifying the plug drive motors, that will not be discussed here. The items to be discussed have taken a considerable amount of time and could be avoided or minimized through certain initial design changes.

Dip Ring Repair

The first seal related problems occurred in 1962 during the fuel-handling system initial checkout before filling the primary tank with sodium. Sticking of the large plug became progressively worse until it was found that parts of the copper lower ring were corroded by the tin-bismuth seal alloy and had fallen off the dip ring into the bottom of the seal trough. Plug rotation wedged the broken dip ring parts between the trough bottom and remaining portions of the dip ring. At a significant cost of time and effort, both the large and small plugs were removed from the primary tank and a major redesign and repair of the dip ring and seal trough was performed. The small plug lower ring had also been corroded but had not yet fallen apart. The copper dip ring parts were replaced with Type 304 stainless steel, the effective heater lengths were changed to compensate for the decreased heat transfer properties, and the seal troughs were slightly modified. The plugs were reinstalled and no subsequent material incompatibilities have been experienced between the seal alloy and the seal trough or dip ring.

Temperature Control Modifications

Early plug rotational resistance was largely thought to be caused by inadequately heated seals. Several modifications have been made to provide a more uniform circumferential temperature distribution and to lower the dip ring temperature needed to melt the seals.

The originally installed seal heater system was electrically connected such that both the large and small plug heaters were turned either on or off together. The temperature controllers were connected such that any extreme high or low temperature in either plug seal trough would deenergize or energize all heaters in both plugs. This arrangement was unsatisfactory because the heaters cycled too frequently and did not respond to the actual conditions in each trough.

This arrangement was changed in 1964 by splitting the heater control into sectors, or groups of heaters, in each plug. One seal trough wall thermocouple from each sector was used for temperature control of a corresponding sector of each dip ring. These changes improved the heater control and allowed lower local seal temperatures, but did not compensate for movement of the heated sector away from the control thermocouple when the plugs were rotated.

In 1968, the trough wall thermocouple control was stopped because dross had accumulated on the thermocouple sheaths and insulated them from the seal alloy. The measured seal temperature was up to 150°F (66°C) higher than the temperature sensed by the control thermocouples so the control function was changed to the thermocouples embedded within the dip rings. This improved control and decreased the operating temperature enough that the "full-molten" seal temperatures were decreased from 400°F (204°C) to 350°F (177°C). The reduced temperature slowed the dross formation rate and increased the heater life. The present system works satisfactorily with periodic calibration of the controllers.

Seal Heater Replacement

Most seal heater maintenance time has been spent replacing individual failed heaters. The large plug has 118 heaters and the small plug has 80 heaters equally spaced within each dip ring. All of the heaters are 350 W cartridge type heaters with a heated length at the bottom end. Except for 20 of the large plug heaters, all heaters are the same diameter with a continuous hollow sheath closed at the heated end and filled with magnesium oxide insulation. The other 20 heaters have flexible sheaths attached to the heater cartridge to allow the heaters to be bent during installation or removal.

Corrosion of the original Type 304 stainless steel heater sheaths was found when the rotating plugs were removed in 1962 and was attributed to contact with the hot seal alloy. All of the heater holes were welded shut at their bottoms to prevent further entry of seal alloy into the heater holes and in 1966 all of the heaters were replaced with Type 405 stainless steel sheath heaters. Most of the heater holes have now seeped small amounts of seal alloy into the heater holes but no corrosive attack of the heaters has been seen.

Removal of the failed rigid heaters is usually done by using a puller tube that attaches a collet to the upper part of the sheath and pulls against the top of the rotating plug. Occasionally, heaters have swollen in place, arced to the heater hole side wall, or been soldered into the hole by solidified seal alloy that has seeped into the heater hole. When that has happened, drilling removal is required at a significantly increased cost in time.

Because the axes of the large and small plugs are offset, the two plug walls come close to the same path in the "tight area" where some small plug components obstruct access to the large plug heaters. Removal of any of the 20 flexible heaters from the tight area is quite difficult because the heaters cannot be reached from directly above. The flexible part of the heaters often breaks off during removal and requires drilling to remove the parts left in the bottom of the heater hole. Drilling in the tight area requires a multi-link drill rig that will bend around the interferences and reach the bottom of the 32 inch (81 cm) deep hole. The hole must be vacuumed to remove drilling debris and inspected with a flexible borescope to verify all of the heater parts are removed. Because heater removal in the tight area may take from 2 to 8 shifts of plant time per heater, the replacement is usually scheduled only when several heaters must be changed in the same area. Physical access is difficult and the work is tediously slow.

Most other maintenance problems have been related to plug rotation difficulties caused by the SnBi seal alloy chemical reactions with air and with sodium aerosols. Removal of the reaction products from the seal area is the only corrective action found to be consistently helpful in reducing rotational resistance. The seal cleaning methods differ on the two sides of the dip ring because of the limited access to the seal surfaces and because of the need to contain the argon cover gas for radiological reasons. The cleaning methods will be discussed in turn as "air-side" and "argon-side" cleaning.

Air-Side Cleaning

The molten SnBi seal alloy reacts with air to produce a fine black powdery oxidation product that floats on the surface of the molten alloy. As a powder, the "dross" causes very little rotational resistance. However, during the necessary plug rotations for fuel handling, the dross is mixed near the surface with molten alloy to produce a slurry-like deposit that accumulates between the dip ring and seal trough wall. As the dross thickness increases, the heat transfer from the dip ring heaters to the surface of the dross decreases which allows formation of a solid, or semi-solid, crust on the alloy surface. This crusty dross layer can cause enough rotational resistance to completely prevent plug rotation. Because the seal alloy oxidation rate increases with temperature, raising the seal temperature to melt the crusty dross layer will only contribute to the problem. It has been found that mechanical removal of the accumulated dross is the only effective way to reduce the plug rotational resistance.

Two effective methods have been developed to remove air-side dross: brush cleaning and skimming. A vacuum cleaning technique proved to be ineffective. When the rotating plugs were removed in 1962 for repair of the dip rings, one heater hole in each plug was modified by cutting a "window slot" into the air side of the dip ring. These window slots proved insufficient for removing dross so improved access was made in 1966 by drilling one additional air-side vertical access hole into each plug.

The new access holes were used to vacuum dross from the seals but it was found that some of the deposits adhered tightly to the seal trough wall and the dip ring. The "brush cleaning" technique was discovered in 1966 while trying to remove these oxide deposits from the seal trough thermocouples with a wire brush inserted through the vertical access holes. When the brush was dipped into the molten seal alloy and withdrawn, the dross remained trapped in the bristles but the alloy dripped back into the seal trough. The dross was then easily shaken out of the brush bristles into a convenient container. This technique, using condenser tube cleaning brushes, continues to be an effective way to clean the air-side seals. The brush is dipped into the seal repeatedly at one plug position until molten seal alloy is withdrawn with the dross then the plug is rotated 1/2 to 1 degrees and the process is repeated. Cleaning of the large and small plugs by this method now typically takes 6 shifts of plant time and is required 4 to 6 times per year.

By the end of 1971, approximately 5380 lb (2440 kg) of dross had been removed from the large plug seal trough and 2030 lb (921 kg) had been removed from the small plug trough. Despite these large quantities, the plugs continued to stick, causing delays in fuel handling. Borescopic examinations of the seals after brush cleaning revealed that lumps of crusty dross 1 to 3 inches (2.5 to 7.6 cm) in diameter and thick enough to fill the space between the dip ring and trough wall remained on the seal surface. The deposits could not be removed by the brushes and the trough thermocouple sheaths trapped the lumps between the dip ring and the trough wall contributing to the rotational resistance. In 1972 and 1973 side access holes were drilled through the primary tank support structure and biological shielding into the large and small plug air-side seals (See Figure 2). This was done to allow removal of the lumps of dross that could not be removed by brush cleaning and to allow scraping removal of deposits from the dip rings. Significant time and effort was required to drill a 3 inch (7.6 cm) diameter angled access hole into each seal trough. The relatively small holes allow view, through mirrors, of the seal alloy surface. A new method of cleaning, known as "skimming", was developed for use through the side access holes.

Skimming requires the combined use of the vertical and side access holes. Long handled dippers, small sieves that collect the dross and allow the molten alloy to drain back into the seal trough, were designed to fit through the side access holes to remove dross and lumps from the top surface of the seals. Long handled scraper blades and tongs were developed to remove deposits from the dip rings and to grab larger lumps. Vacuum tools - were found difficult to keep free of the molten alloy. Skimmer tools, designed to fit through the vertical access holes, were made to skim the surface seal deposits toward the side access hole.

The technique requires two people, the various tools, and both the vertical and side access holes. The crusty dross is broken into smaller pieces through the vertical access hole then the plug is slowly rotated toward the side access hole where the dross and deposits are dipped from the alloy surface and discarded into a convenient container. The scraper tools are used to clean the accessible parts of the dip ring as it is rotated past the side access hole. This process is repeated until the entire circumference of the seal is cleaned. The position of the person at the side access hole is awkward and the process is slow but skimming cleans the alloy surface better than brush cleaning. Often, a combination of brush cleaning and skimming is used to clean the seal troughs.

Skimming usually takes 4 shifts for the small plug and 6 shifts for the large plug and is performed less frequently than brush cleaning. The small plug seal is skim cleaned 2 or 3 times per year, often in conjunction with brush cleaning. Because the large plug side access hole is more difficult to work through, the large plug seal may be skim cleaned only once per year when the accumulated deposits and plug sticking cannot be reduced by brush cleaning.

Argon-Side Cleaning

Cleaning of the argon side of the seals is far more difficult because of the added restrictions necessary to prevent ingress of air into the primary tank and to prevent release of radioactive fission gases. The need for cleaning of the argon-side was not recognized for many years because lack of access prevented observation of the seal condition. In 1975 a 3 inch (7.6 cm) diameter vertical hole was drilled into the large plug on the argon-side of the dip ring. The initial inspection revealed that deposits completely filled the upper annulus, adhered to the trough wall, and that the seal alloy surface was covered with dross similar in appearance to the air-side dross. Because of the large amount of deposits and their assumed effect on the plug rotational resistance, efforts to clean the argon-side annulus and seal were initiated.

A plexiglass glovebox and deposit removal tools were fabricated and used on the vertical access hole in 1976. The first cleaning removed 325 lb (148 kg) of deposits and dross from the argon-side upper annulus and seal trough. Chemical analysis of the deposits indicated a high sodium content suggesting that the sodium aerosols and vapors from the primary tank sodium pool had migrated upward through the annulus and had condensed in the cooler seal trough area. Some of the sodium had chemically reacted with the seal alloy to produce high melting point intermetallic compounds of sodium-tin and sodium-bismuth that had spilled over the trough wall into the annulus area. There was also evidence that some of the seal alloy had been "pumped" over the seal trough wall when the plug and dip ring were rotated past deposits on the alloy surface.

The technique developed for cleaning the argon-side of the seal trough is more time consuming than cleaning the air-side because the argon purged glovebox must be installed and maintained leak tight to prevent ingress of air into the primary tank cover gas. Also, the tools used to reach deposits in the bottom of the upper annulus are more than 5 feet (152 cm) long and require 2 people to operate. The annulus deposits are removed with a clamshell type of device that removes approximately 2 cubic inches (16 cm^3) of material at a time. The seal alloy dross and deposits are removed by skimming or brush cleaning with tools similar to those used for air-side cleaning. All deposits are withdrawn into the glovebox and put into metal cans for later disposal. After sufficient cleaning of the annulus and seal trough in one area, the rotating plug is moved and the process is repeated until the entire circumference has been cleaned. A large plug argon-side annulus cleaning may take from 12 to 24 shifts of plant time to complete, depending on the amount of deposits found, and is not routinely performed.

The large plug rotated freely after the first removal of the argon-side deposits and the annulus cleaning was not again required for 3 years. Air-side cleanings were continued on a more regular basis with a noticeable improvement in plug rotation after each cleaning.

Because the large plug rotated freely after removal of the argon-side deposits, a 3 inch (7.6 cm) diameter vertical access hole was drilled into the small plug argon-side area in 1977. Similar deposits were found in the small plug annulus and seal trough that have not yet been removed. For unclear reasons, the small plug has not had the same sticking frequency or severity experienced by the large plug. Consequently, the small plug seal cleaning urgency has not been as great. Also, the accumulation of deposits in the small plug annulus is thought to have a beneficial effect in retarding the migration of sodium into the seal trough area, so the deposits have been intentionally left in place.

The full impact of the sodium migration into the seal trough area was not immediately recognized because the time between the first argon-side cleanings was acceptably long, being 35 months and 26 months between the first, second, and third cleanings. The time subsequently decreased until there was as little as three months between cleanings in 1984. In addition, the amounts of deposits removed each time decreased from the initial 325 lb (148 kg) to as little as 52 lb (24 kg). Plug rotation improved after each cleaning, but the increased frequency of cleaning and the decreased amounts of deposits capable of stopping plug rotation caused concern that the problem was no longer controlled.

A detailed evaluation of the problem by a group of affected organizations revealed that the predominant problem is the presence of sodium aerosols and vapors in the argon-side of the seal. The corrective actions are severely limited because the only access to the area is through the 3 inch (7.6 cm) diameter vertical access hole. The option of creating other access holes is restricted by the physical configuration of the plugs and by the significant cost of time and effort that would be incurred. Modifying the seal would require removal of the large and small plugs, which is not considered a viable option because of the sodium and radiation controls required.

Presently, a counterflow purge of recycled cover gas in the argon-side of the large plug seal is being tested as a means to suppress sodium migration into the seal trough area. In conjunction with the purge gas, deposits are being intentionally allowed to accumulate in the large plug argon-side annulus to serve as a physical barrier to the upward migration of sodium. Preliminary results show a decrease in the amounts of sodium and deposits in the trough area and significant improvement in plug rotation.

Air-side cleaning of the large and small plug seals continues to be necessary because the dross formation mechanism on the air-side is different than on the argon-side.

Seal Cleaning Summary

Air-side cleaning of the seals has been performed through the available access openings since 1964. To date, more than 8410 lb (3815 kg) and 3500 lb (1588 kg) of air-side dross has been removed from the large and small rotating plug seal troughs, respectively. Argon-side cleaning of the large plug seal has been done since 1976 with more than 1010 lb (458 kg) of dross and annulus deposits removed. About 10 900 lb (4944 kg) and 3880 lb (1760 kg) of new seal alloy has been added to the large and small plug seal troughs, respectively, to make up for the alloy removed as dross and deposits.

Seal Maintenance Impact on Plant Availability

The EBR-II plant operating time is determined by fuel handling requirements, in-core experiment needs, and regularly scheduled equipment maintenance such that the direct impact of seal related activities is difficult to quantify. Seal cleaning, heater repairs, and other seal maintenance activities require an average of 240 hours (30 shifts) of plant time per year, spread out over approximately five maintenance shutdown periods per year. The actual time required has varied widely from 40 hours (5 shifts) per year to 352 hours (44 shifts) per year, depending on the nature of the work required. The seal related work is usually performed in parallel with other required maintenance so that the seals are not the plant controlling maintenance activity. Stuck plugs, however, have repeatedly interrupted fuel handling and have caused enough significant delays in plant recovery to justify the time spent trying to understand and eliminate the causes of plug sticking. The most recent results of using a purge gas in the large plug annulus suggests that the annual seal maintenance time may be considerably reduced by keeping sodium aerosols and vapors out of the annulus area.

Evaluation of the plug sticking problems is always difficult because of the limited access for observation of the seals. Where to direct cleaning efforts, whether on the air-side or the argon-side of the seals, is never a clear choice and is sometimes wrong. Whenever possible, seal cleaning and heater repairs are prescheduled to minimize the plant controlling time, but the plugs sometimes unexpectedly stick during fuel handling and cause delays in plant startup.

RECOMMENDED DESIGN IMPROVEMENTS

Based on the experiences at EBR-II, maintenance on similar rotating plug seals could be significantly reduced through several design changes. The migration of sodium aerosols and vapors into the seal area must be carefully considered and avoided where possible by design of the seals. Sodium vapor flow paths and convection currents in the annular space, between the rotating plug wall and the adjacent stationary structure, should be stopped to keep deposits from accumulating in an area that is very difficult to clean. If physical separation of the seals and the sodium cannot be assured, a well distributed counterflow purge of cover gas could be effective in suppressing the sodium vapors and aerosols. The use of a seal liquid that is non-reactive to sodium and non-oxidizing in air would eliminate reaction product deposits that cause most of the plug sticking problems.

Viewing ports and easy access to all surfaces of the dip ring and seal trough should be a high priority consideration. The viewing ports would allow direct observation of the seal area and its cleanliness condition so that cleaning efforts could be better planned to minimize plant controlling time. Direct and easy access to all seal areas would allow complete and quick cleaning of the surfaces that cause plug sticking

Improved access to all seal heaters would solve some difficult and very time consuming problems with heater replacement. The elimination of seal heaters, through design of the seals or by choice of seal liquid, could significantly simplify maintenance requirements.

CONCLUSIONS

Despite the maintenance problems encountered with the EBR-II rotating plug seals, they have successfully fulfilled their designed function of containing the reactor cover gas and allowing rotation of the plugs during fuel handling. The elimination of sodium aerosols and vapors from the seal alloy area would significantly reduce the amount of seal related problems and the corrective maintenance required. Improved access to all areas of the seals would allow better observation of the seal condition and would significantly reduce the seal cleaning and maintenance time.

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