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Decommissioning of Experimental Breeder Reactor-II Complex, Post Sodium Draining

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by

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ABSTRACT

The Experimental Breeder Reactor - II (EBR-II) was shutdown in September 1994 as mandated by the United States Department of Energy. This sodium-cooled reactor had been in service since 1964.

The bulk sodium was drained from the primary and secondary systems and processed. Residual sodium remaining in the systems after draining was converted into sodium bicarbonate using humid carbon dioxide. This technique was tested at Argonne National Laboratory in Illinois under controlled conditions, then demonstrated on a larger scale by treating residual sodium within the EBR-II secondary cooling system, followed by the primary tank. This process, terminated in 2002, was used to place a layer of sodium bicarbonate over all exposed surfaces of sodium. Treatment of the remaining EBR-II sodium is governed by the Resource Conservation and Recovery Act (RCRA). The Idaho Department of Environmental Quality issued a RCRA Operating Permit in 2002, mandating that all hazardous materials be removed from EBR-II within a 10 year period, with the ability to extend the permit and treatment period for another 10 years. A preliminary plan has been formulated to remove the remaining sodium and NaK from the primary and secondary systems using moist carbon dioxide, steam and nitrogen, and a water flush.

The moist carbon dioxide treatment was resumed in May 2004. As of August 2005, approximately 60% of the residual sodium within the EBR-II primary tank had been treated. This process will continue through the end of 2005, when it is forecast that the process will become increasingly ineffective. At that time, subsequent treatment processes will be planned and initiated.

It should be noted that the processes and anticipated costs associated with these processes are preliminary. Detailed engineering has not been performed, and approval for these methods has not been obtained from the regulator or the sponsors.

Introduction

During the EBR-II Plant Closure Project, initial deactivation of residual sodium was performed using humidified carbon dioxide. A different terminology was used at that time, and the deactivation process was referred to as "residual sodium passivation." Since the deactivation process creates a solid carbonate layer on top of the residual sodium, an analogy was made between this "oxide" layer, and the formation of oxide layers on other metals, such as aluminum. In the case of aluminum, for example, the oxide layer that forms on the surface passivates it, and prevents any further reaction of oxygen with the metal underneath. In the case of sodium, the carbonate layer does not prevent any further reaction of humidified carbon dioxide with the residual sodium metal underneath, and so technically does not passivate the residual sodium. It does, however, provide a resistance barrier to gaseous diffusion and would slow the reaction of gaseous reactants with the sodium underneath. Such a resistance barrier would be useful in the case that uncontrolled leakage of moisture occurs into any of the EBR-II sodium systems during the potentially long period of time between the finish of the Plant Closure Project and the resumption of residual sodium deactivation. Placing a thin layer of carbonate on the residual sodium surfaces in the EBR-II sodium systems, the Project was able demonstrate partial deactivation that was acceptable to the Department of Energy in regard to the stored residual sodium, so that the EBR-II sodium systems could be placed in a steady state condition indefinitely while awaiting further resources (i.e., funding, personnel) to resume full sodium deactivation.

Background

The EBR-II was a sodium cooled research reactor located in the southeastern portion of the Idaho National Laboratory. The EBR-II was a 62.5 MW thermal reactor that began operations in July 1964, and when fully operational, produced 19.5 MW of electrical power for the INL electrical grid.

The EBR-II complex, as depicted in Figure 1, consists of the reactor and reactor building, the Sodium Boiler Building, the electrical power plant, reactor cooling towers, water chemistry laboratory support facilities, and the cover gas cleanup system. The EBR-II reactor building is connected, through a below grade tunnel, to the Fuel Conditioning Facility, a large inert atmosphere hot cell facility. The Fuel Conditioning Facility hot cell is used to support sodium bonded fuel treatment and research. The reactor building, a cylindrical structure with a hemispherical domed top, has a steel containment shell with an inner diameter of 24.4 m (80 feet) and a height of 42.4 m (139 feet). The bottom and sides are 2.5 cm (1 inch) thick steel plate and the dome is 1.3 cm (½ inch) thick, lined with a 10.2 cm (4 inch) concrete missile shield.

The reactor was a test facility for fuels development, materials irradiation, system and control theory tests, and hardware development. The EBR-II core and blanket subassemblies were contained within the reactor vessel (Figure 2) prior to defueling. The 1.70 m (67 inch) diameter vessel and its shield were immersed in a sodium pool within the 7.9 m (26 feet) diameter by 7.9 m (26 feet) high primary tank. The sodium contained within this tank represented the primary cooling system for removal of the heat from the reactor core. The primary system contained about 325 m^3 (86,000 gal) of sodium, and transferred heat to the secondary sodium system (which contained about 50 m^3 (13,000 gal) of sodium) through a sodium-to-sodium intermediate heat exchanger that was immersed in the primary sodium. The secondary sodium was circulated in a closed loop through superheaters and steam generators outside of the reactor containment in the Sodium Boiler Building. The high pressure steam produced in the steam generators drove a turbine-generator to produce electric power.

The EBR-II Plant Closure Project's charter was to maintain the facility and complex in an industrially and radiologically safe condition. This was accomplished via the closure plan, contained in the Environmental Assessment (Reference 1) for the Shutdown of Experimental Breeder Reactor - II at Argonne National Laboratory - West. This Environmental Assessment was granted a Finding of No Significant Impact by the United States Department of Energy, documenting that the proposed actions would not constitute a major federal action significantly affecting the quality of the human environment, negating the necessity for the preparation of an Environmental Impact Statement.

Closure of the EBR-II complex was achieved through completion of reactor defueling, primary tank draining, processing of the primary, secondary, and Fermi-1 primary sodium, residual sodium passivation, and system layup.

Reactor defueling consisted of removal of all the fueled assemblies in the 637 core positions and replacing them with non-fueled assemblies of the same configuration. The fueled assemblies were packaged for storage and subsequent treatment.

The primary tank was not originally designed to be drained. A draining system was designed and fabricated using an annular linear induction pump, and operated to drain the primary tank to the secondary storage tank in ~40 m^3 (10,000 gallon) batches. This sodium was then transferred to the Sodium Process Facility through a pipeline and reacted to 70+ wt % sodium hydroxide for disposal. The Sodium Process Facility was designed, constructed, and operated for the processing of the EBR-II primary and secondary sodium, as well as the Fermi 1 primary sodium that was stored at the INL.

Residual Sodium

Test Program

Laboratory experiments were performed at Argonne National Laboratory in Illinois to study the effects of humidified carbon dioxide on samples of sodium metal. The goals of the experiments were to determine the stability of the deactivation process in regard to sudden temperature and pressure changes and changes in the hydrogen generation rate, confirm the chemical composition of the sodium bicarbonate layer, observe the morphology and measure the density of the sodium bicarbonate layer, and determine the deactivation rate as a function of sodium bicarbonate layer thickness and moisture input rates.

In these experiments, samples of sodium metal were placed into a test chamber and exposed to a continuous flow of humidified carbon dioxide. The concentrations of hydrogen and oxygen in the exhaust gas were measured and recorded. The growth of the sodium bicarbonate layer on the samples was observed over time and measurements were taken on the growth rate of the layer versus the consumption rates of the sodium samples. Observations were recorded concerning the morphology of the sodium bicarbonate layer and samples were taken of the layer for chemical analysis. Details of the experimental equipment, procedures, and experimental results and analyses are presented in Reference 2.

These experiments demonstrated that the deactivation of residual sodium metal can be performed safely and in a controlled manner with humidified carbon dioxide. The use of humidified carbon dioxide to deactivate residual sodium results in the transformation of sodium metal into a solid, powdery, white colored material that is primarily composed of sodium bicarbonate. A decreasing sodium reaction rate can be correlated with an increasing thickness of the sodium bicarbonate layer. Expansion of the sodium bicarbonate layer can result in the breakage of glassware and the deformation of sheet metal in confined spaces as was demonstrated under test conditions. For the sample with the longest exposure, a reaction depth of 5.5 cm of sodium was achieved, with demonstrated penetration of water vapor through 21 cm of sodium bicarbonate.

Secondary System

The deactivation of the EBR-II secondary sodium system residual sodium was used to qualify the humidified carbon dioxide deactivation technique on a full-scale system, and to gather safety and performance information so that the technique could be applied to the deactivation of residual sodium within the EBR-II primary cooling system.

The bulk quantities of the secondary sodium were drained into the secondary sodium storage tank and pumped to the Sodium Process Facility for disposition. The secondary sodium system was then modified from its original configuration in order to perform the initial sodium deactivation. First, a carbon dioxide header was installed to channel the flow of carbon dioxide in seven different directions. Modifications were then made to the secondary sodium cooling system to allow for the creation of 14 different gaseous flow paths. The flow paths were not isolated, however, and there was a certain degree of overlap in the flow paths due to the highly interconnected nature of the secondary sodium cooling system components. Also, a vent line was installed at a central location so that all of the exhaust lines could be purged. A hydrogen monitor, an oxygen monitor, and a sample gas-conditioning unit, all identical to the ones used for the laboratory experiments, were installed on the vent line.

The deactivation of the residual sodium in the secondary cooling system was performed in two phases. During the first phase, each of the 14 flow paths were exposed to humid carbon dioxide for a relatively short period of time (from two days to two weeks) in order to react the most accessible residual sodium. During the second phase, a more concentrated deactivation of the residual sodium within a specific superheater pathway was performed because the superheater was known to contain a deeper pool of residual sodium, and the Project wanted to perform a visual examination of the deep pool after treatment.

During the first phase, approximately 115 liters of water were evaporated from the carbon dioxide humidification cart. In this cart, dry carbon dioxide was bubbled through a height of approximately 1 m of water to humidify the carbon dioxide. This 115 liters of water is sufficient to react up to 145 kg of sodium. Since only 92 kg were reacted according to an integration of the hydrogen concentration data, some water must have been lost from the system through the vent manifold. This water loss was confirmed by the observation that water was frequently collected from the sample gas conditioner unit.

In the second phase, deactivation of the superheater pathway was resumed and treated for an additional 72 days. According to integration of the measured hydrogen data, another 90 kg of sodium metal was consumed. Approximately 110 liters of water were evaporated from the carbon dioxide humidification cart during the conduct of the second phase, which is consistent with the amount of water evaporated from the cart during the first phase for a similar period of time and amount of sodium reacted.

No end point was reached in the treatment process, and residual sodium still remains in the superheater. Treatment was stopped on the superheater because sufficient information had been collected to certify that the treatment process was safe and to verify that the equipment and instrumentation were reliable enough to monitor the treatment process. Further treatment will be needed to fully react all of the residual sodium within the superheater.

Following the shutdown of residual sodium treatment operations in the superheater, three holes were drilled in the side of the superheater near the level of unreacted sodium in the bottom of the superheater. The first hole was drilled 2.5 cm above the sodium level and revealed only white power. The second hole was drilled 2.5 cm below the sodium level and revealed only solid sodium metal. The final hole was drilled at the sodium level and revealed a solid mixture of white powder above sodium metal. These observations confirmed that the carbonate material accumulates on the exposed surface of sodium metal and does not significantly penetrate the sodium layer beneath the surface.

Current State and Future Treatment Options. Since completion of the initial treatment discussed above, the secondary sodium system has been maintained under a dry carbon dioxide blanket maintained at positive pressure. Carbon dioxide is supplied only to counter the leak rate of carbon dioxide from the system. The system is monitored for hydrogen and oxygen, with none detected to date.

Different treatment processes are being recommended for removing the remaining sodium from the secondary system and hence obtaining RCRA closure. The sodium will either be drained, reacted in place, or the component or section containing sodium will be removed from the system and treated elsewhere.

Significant pools of sodium remain in the bottom of the superheaters and evaporators. Drain connections will be welded to these components, the components heated, and the sodium drained to suitable containers. Pools contained in large diameter piping may also be managed using this method.

Narrow pipe sections, dead end pipe legs, and other such parts of the system may require complete removal from the system to reach the residual sodium due to the restrictions to the flow of moist gas. For parts removed, the sections will be cut into manageable pieces and reacted by exposing to a liquid water spray in the INL's Sodium Components Maintenance Shop (SCMS). This facility is equipped with a large reaction chamber that is capable of treating up to 2.3 kg of sodium at a time, in any configuration. The by-product of this treatment process is a caustic solution, which is recycled and used continuously until the concentration level reaches between 5 and 15 wt% hydroxide, at which time it is removed from the system, reacted to carbonate, and solidified in drums for disposal.

The treatment in place will involve further use of humidified carbon dioxide and possibly humidified nitrogen and/or steam-and-nitrogen. This will be decided on a case-by-case basis depending on the configuration of the system. The choice of technique will also depend on factors such as cost and the availability of funding, safety, isolation capabilities, rate of treatment desired, etc.

Following deactivation, all remaining sections will be flushed with liquid water. This flushing operation will be repeated as necessary to react all remaining residual sodium and dissolve all sodium reaction chemical by-products such as sodium hydroxide and sodium bicarbonate. It is expected that this flushing operation will generate up to 60,000 liters of solution for further treatment by methods such as neutralization, evaporation, encapsulation, etc. Instead of directly treating and disposing, the waste solution may be saved and used to flush the EBR-II primary system.

Primary System

Bulk primary sodium has been drained and treated in SPF. Approximately 1.1 m^3 (300 gallons) of liquid sodium remained in the primary tank after draining. In early 2002, moist carbon dioxide was introduced into the tank to produce a sodium carbonate/bicarbonate layer (approximately 2 mm thick). Since completion of this initial carbonation process, a dry carbon dioxide blanket was maintained in the tank until the process was resumed in May 2004.

Proposed Treatment / Disposal

The residual sodium remaining in the tank is currently being treated with wet carbon dioxide and, as of August 2005, approximately 60% of the residual sodium has been treated.

Some of the systems/components associated with the primary system contain captivated volumes of sodium isolated from the primary tank. These include the immersion heaters, low pressure plenum throttle valves, primary sodium transfer system, and shutdown cooler bayonets, and will be removed and treated outside the reactor building in SCMS. Some reactor components, including the primary tank-auxiliary heater system, will initially be left in service to assist in residual sodium deactivation.

After treating as much of the residual sodium as possible with moist carbon dioxide, it is anticipated that an intermediate process, using steam and nitrogen, would follow. The primary tank would then be flushed with water to verify that all residual sodium has been deactivated. During flushing of the primary tank, a combination of spraying or heating the water may be used to ensure adequate coverage of the tank and related hardware.

To prepare the primary tank for a water flush, equipment must be installed to provide for introduction and the likely recirculation of the flush water. It is anticipated that this treatment system will also include a means for neutralization of the flush fluid. Sampling and control systems must also be included. In addition, it will probably be necessary to install some form of level indication in the tank to control filling, and limiting the rate of water influx when the water level approaches known pockets of sodium.

Current RCRA regulations require the treatment residuals to be removed from the system. To accommodate this requirement, equipment must be installed in the recirculation system to separate the treatment residuals from the flush water. After the completion of rinsing and meeting RCRA closure performance standards, the treatment water will be removed from the system. It is proposed that the water will be pumped out of the tank and treated in an evaporation / filtration system yet to be designed and constructed. After the treatment water has been removed, the primary tank will be heated to evaporate residual water left in the tank.

Miscellaneous Components/Systems

Reference 3 contains a comprehensive list of the equipment and systems that will require additional action in order to achieve RCRA closure. Included are the primary tank cover gas system, NaK transmitters, secondary sodium purification system, intermediate heat exchanger, rotating plugs, primary tank heaters, primary tank nozzles, fuel handling systems, primary tank cover gas sampling supply system, shutdown coolers, reactor building storage pit and manipulators, cover gas cleanup system, primary purification systems, radioactive sodium chemistry loop, reactor building storage holes, argon purge system, argon cooling system, hydrocarbon analyzer, failed fuel transfer system, fuel element rupture detection, and secondary sodium recirculation system. Preliminary plans for removal, as necessary, and sodium reaction have been formulated as the basis for the cost estimate presented below. Additional engineering will be required in order to establish the basis for funding requests from the Department of Energy.

Preliminary Cost Estimate

A preliminary cost estimate was compiled for achieving RCRA closure on the EBR-II facility. This estimate assumed that the work would be performed within eight years. Assumptions were made without performing detailed engineering analyses or obtaining approval for the proposed actions, leading to uncertainties in the estimates.

Twenty three primary tasks were identified when compiling the cost estimate. For each task, costs were divided into three different categories – materials & supplies (M&S), exempt effort, and non-exempt effort (for the purpose of this paper, the latter two have been combined). Also, the tasks were divided into three separate phases – planning, execution, and treatment/disposal. In addition, a base level of staffing is described that provides the necessary support for all project tasks over the lifespan of the project. The Argonne National Laboratory Pricing Guide was used either directly or indirectly to calculate M&S, effort, and contingency costs that are fully burdened with all applicable divisional and laboratory taxes. Since the project will be completed under Idaho National Laboratory policies and procedures, a different set of pricing guidelines will be implemented for the final estimate. All costs are presented in FY 2004 dollars.

Prior to initiating the efforts, a detailed engineering study will be performed, complete with accurate cost estimates associated with each activity. Once internal approvals are obtained, this study will be submitted to the funding agencies to request budgetary approval for proceeding with the closure activities and the project will be staffed accordingly.

The following cost estimate is based on a series of assumptions and is presented for information only:

Materials and Services	$3,000,000
Labor	$25,000,000
Staffing	$7,000,000
Total w/o Contingency	$35,000,000

Conclusions

The EBR-II reactor and systems are required by law to be removed from the RCRA registers by 2012, with the option to extend the completion by up to 10 additional years. A preliminary plan has been formulated to complete the work required by RCRA in eight years. Additional effort is necessary to finalize this plan and obtain funding for completion of the RCRA required tasks.

References:

1. DOE/EA-1199, Environmental Assessment - Shutdown of Experimental Breeder Reactor - II at Argonne National Laboratory - West, U.S. Department of Energy Chicago Operations Office, September 25, 1997.
2. INL/EXT-05-00280 Rev 0, Technical Information on the Carbonation of the EBR-II Reactor, Steven R. Sherman, April 2005.
3. ANL W7500-xxxx-ES-00 Rev 0, Experimental Breeder Reactor II RCRA Treatment Project Cost Estimate, Argonne National Laboratory – West, September 2004.

Figure 1. EBR-II Complex

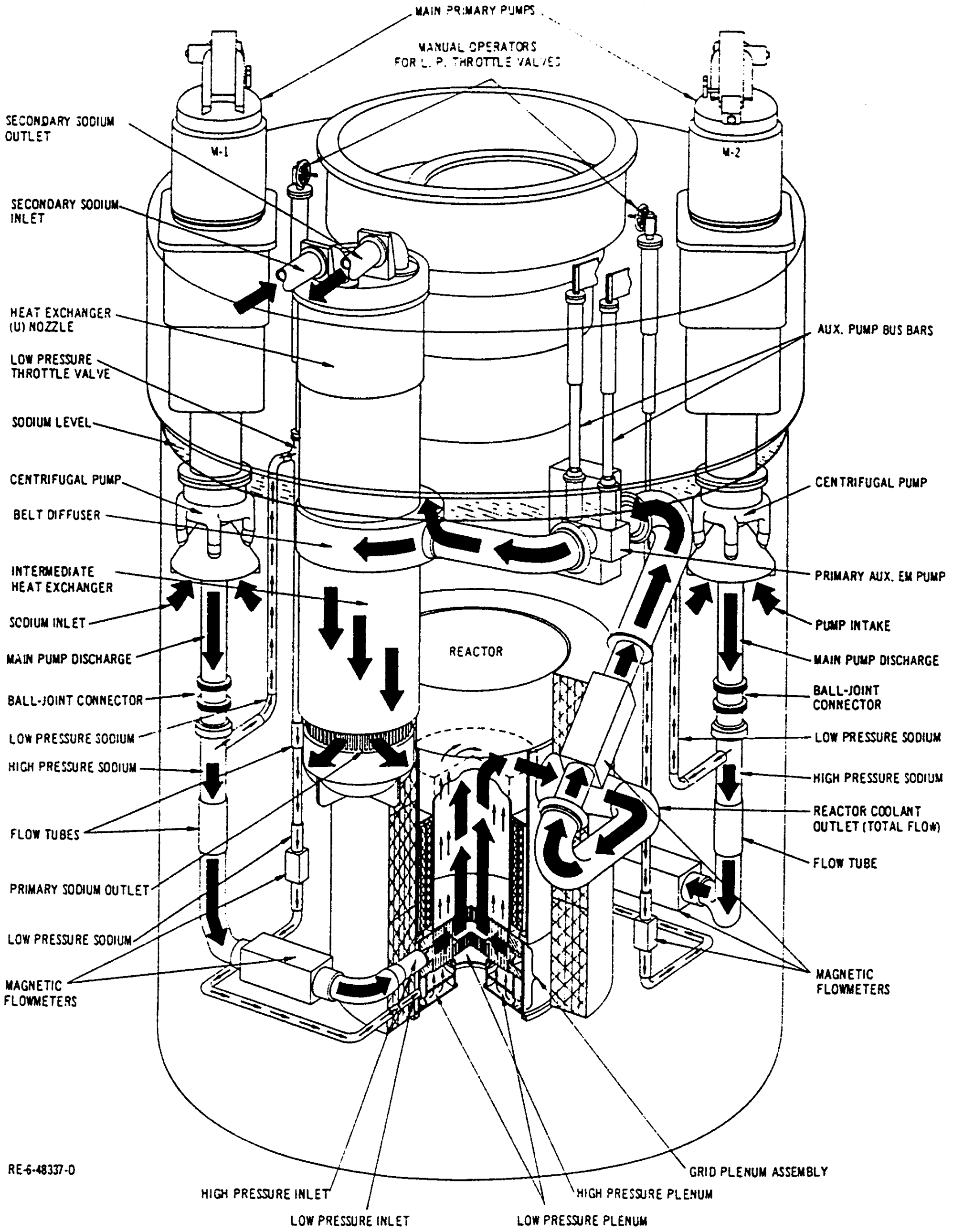

Figure 2. EBR-II Primary Tank