EBR-II Primary Tank Wash-Water Alternatives Evaluation - 9431

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ABSTRACT

The EBR-II reactor at Idaho National Laboratory was a liquid sodium metal cooled reactor that operated for 30 years. Approximately 1100 kg of residual sodium remained in the primary system after draining the bulk sodium. To stabilize the remaining sodium, both the primary and secondary systems were treated with a purge of moist carbon dioxide. The passivation treatment was stopped in 2005 and the primary system is maintained under a blanket of dry carbon dioxide. Approximately 670 kg of sodium metal remains in the primary system in locations that were inaccessible to passivation treatment or in pools of sodium that were too deep for complete penetration of the passivation treatment. The EBR-II reactor was permitted by the Idaho Department of Environmental Quality (DEQ) in 2002 under a RCRA permit that requires removal of all remaining sodium. The proposed baseline closure method would remove the large components from the primary tank, fill the primary system with water, react the remaining sodium with the water and dissolve the reaction products in about 100,000 gallons of wash water.

On February 19-20, 2008, a workshop was held in Idaho Falls, Idaho, to evaluate alternatives that could meet the RCRA permit clean closure requirements and minimize the quantity of hazardous waste generated by the cleanup process. The workshop convened a panel of national and international sodium cleanup specialists, subject matter experts from the INL, and the EBR-II Wash Water Project team that organized the workshop. The workshop was conducted by a trained facilitator using Value Engineering techniques to elicit the most technically sound solutions from the workshop participants. A brainstorming session was held to identify possible alternative treatment methods that would meet the primary functions and criteria of neutralizing the hazards, maximizing byproduct removal and minimizing waste generation. An initial list of some 20 probable alternatives was evaluated and refined down to six potentially viable alternatives at the end of the workshop. The six alternatives developed in the workshop were put into a scoring matrix that weighed each alternative against five important criteria that were identified during the workshop as keys to the success of the favored sodium cleanup alternative. The results of the scoring matrix exercise identified the Optimized Baseline Approach (OBA) as the favored alternative by the wash water project team. This reaffirmed the individual recommendations of the sodium cleanup specialists in a panel discussion held at the conclusion of the workshop. The OBA consists of leaving all major components of the primary system in place, and breaching certain components with a penetrating device to allow circulation of steam and reduced wash water through the components.

INTRODUCTION

The Experimental Breeder Reactor-II (EBR-II) Wash-Water Workshop was convened to determine the best method by which the EBR-II primary tank system could be flushed clean to meet environmental closure requirements. The system currently contains a small amount of reactive sodium and does not meet the requirements for “clean closure” under the Resource Conservation and Recovery Act (RCRA). Experts from two countries (U.S. and Great Britain) were brought together in a facilitated workshop to determine if filling the EBR-II primary vessel with water, and draining it (perhaps several times) would be the most effective method of accomplishing the objective. The primary objective was to evaluate methods to remove the residual sodium from the Experimental Breeder Reactor (EBR-II) primary system. Results from the workshop include a number of recommendations and a path forward to accomplish this work. The notes from the workshop are presented in detail in Appendix A.[1] This report briefly captures the main points of the workshop and further evaluates the six alternatives developed during the workshop, and provides a path forward for the best alternative based on the assumptions and information developed for the workshop. The recommended workshop alternative (by consensus and evaluation) is the *Optimized Baseline Approach* (OBA).

The EBR-II facility at the Materials and Fuels Complex (MFC) of the Idaho National Laboratory (INL) was designed and built to test the fuel cycle operations for the second generation of fast neutron breeder reactors. The EBR-II achieved criticality in 1965 and operated continuously for 30 years. A breeder reactor produces more nuclear fuel than it consumes by converting "fertile" uranium (U-238) into fissile plutonium (Pu-239). The Pu-239 may then be used to fuel the nuclear reaction. A "fast neutron" type of breeder reactor does not use a moderator, such as water, to slow the fission causing neutrons, but instead allows a "fast" neutron that is more efficient for converting U-238 to Pu-239. Most fast breeder reactors use a liquid metal, predominantly metallic sodium or a sodium/potassium eutectic alloy (commonly referred to as NaK), to cool the reactor.

Figure 1, EBR-II Reactor, Sodium Processing Facilities and Heat Exchangers

Liquid metal cooled reactors containing sodium or NaK present a difficult cleanup task. Sodium metal and NaK are very reactive and must be isolated from water and air. They may spontaneously burst into flame if in contact with any moisture. For this reason great care is taken when using sodium metal to ensure it remains within a dry, inert atmosphere (typically argon or nitrogen), especially when used as a coolant in nuclear reactors. The treatment of spent sodium is also hazardous, resulting in critical injuries.[2] As recently as 2007 an industrial plant in Florida using sodium metal as part of its process exploded killing four workers.[3]

Only a small amount of reactive sodium remains in the EBR-II reactor system. About 130,000 gallons of the sodium was drained from the primary and secondary coolant systems in the early 2000s. This material was reacted at the Sodium Processing Facility (SPF) at the INL to make sodium hydroxide that was disposed of at the Radioactive Waste Management Complex (RWMC) at the INL. Moist carbon dioxide was then introduced into the primary tank and secondary system to convert the remaining sodium into sodium bicarbonate. By analyzing the generation of hydrogen and other factors it is estimated that currently only about 100 gallons of sodium remain in the primary tank. This material is mainly located in hard to reach areas that do not have an adequate drain path or free gas exchange with the primary tank atmosphere. This actually amounts to a very small quantity of sodium (about 1/1000 of the primary system volume) that probably constitutes very little hazard, but the facility RCRA permit requires that all of the reactive sodium metal and reaction byproducts be removed before closure (within the next 12 years).[4]

The next phase of the closure process would be to remove the large reactor components and wash everything to neutralize the remaining sodium. This will likely be a difficult process because of the soldering affect of sodium metal and the buildup of sodium bicarbonate in the tank would probably prevent some of the components from being withdrawn from the vessel. Also, washing all tank surfaces and components will likely generate massive amounts (a minimum of 100,000 gallons) of contaminated water that must be treated and managed. The OBA, that will be discussed later, develops processes to breach the large components and leave them in place during treatment. As part of the optimized approach a de minimus value of sodium that may be left in the vessel will be determined, analyzed for risk (hazard), and negotiated with the Idaho Department of Environmental Quality (DEQ) prior to beginning the wash.

WORKSHOP FORMAT

A facilitated meeting was held on February 19-20, 2008 in the Bennion Student Union Building at University Place in Idaho Falls, Idaho. The primary objective was to evaluate methods to remove the residual sodium from the Experimental Breeder Reactor (EBR-II) primary system. Because the baseline approach produces a large amount of caustic waste water and other waste streams, such as metal, this meeting was organized to gather lessons learned from other sodium cleanup sites and develop alternatives to minimize the waste streams from the EBR-II cleanup. Also noted during the workshop, the resulting radiation dose from the baseline approach would be significant. Along with the INL Subject Matter Experts (SME) and the INL Wash Water Team, national and international specialists were brought in to participate in the meeting.[1]

A structured, facilitated process was followed using Value Engineering (VE) techniques to gather information, identify functions, develop alternatives, and select the top alternatives for further analysis. VE uses facilitation, function analysis, and a formal job plan to improve product or process quality, reduce cost, maintain quality, and build teamwork. The formal job plan is Preparation/Planning, Information Gathering, Creativity, Evaluation, and Development/Path Forward.

After the presentation of EBR-II background and current status, the team developed the functions and criteria that the alternatives would need to meet and what the evaluation of the criteria would use. The three primary functions were identified as neutralize hazards, maximize byproduct removal, and minimize waste. Alternatives for sodium cleanup were brainstormed based on cleaning the primary tank system only; treating the components in place if possible; and meeting RCRA clean closure requirements. Each identified alternative was discussed to determine how it might be used, and how well it addressed the three main functions. The team combined and refined the list to produce full alternatives that would meet the RCRA clean closure criteria. Finally, the team discussed the advantages and disadvantages of each alternative relative to the process and the results. See Appendix A for the initial evaluation table used to narrow-down the list to six viable alternatives.

One of the final activities of the meeting was a discussion with the sodium metal specialists about their perspectives on EBR-II primary system cleanup. While there were differences in cleanup recommendations, all agreed that developing a good and consistent relationship with the regulators would be critical to the success of the project. They also stressed that knowing the desired end state for the EBR-II reactor would be helpful in determining the best alternative for residual sodium cleanup. The team accomplished the objectives of this phase of the project through their subject matter knowledge and dedication to resolving the issues associated with sodium waste. The specialists were open and forthcoming with ideas and provided excellent advice on choosing a path forward.

ALTERNATIVES EVALUATION AND RECOMMENDATION

Building on the results of the workshop, the team was able to develop metrics to support the evaluation of the wash-water alternatives and assign numerical support for one alternative. In addition to the evaluation criteria and alternatives that were developed, a great deal of discussion was provided that leads to the development of a "path-forward." The path-forward will be discussed in greater detail in a separate section of this report, but it involves several "high-level" decisions that should be implemented in order for the recommended alternative to be developed and implemented. The baseline or any alternatives would require some additional engineering development prior to implementation. In essence, no progress on the primary tank wash down or RCRA cleanup should be pursued before addressing the items listed in the "path-forward" discussion.

The wash-water evaluation team began the task of developing the discussions and data coming from the workshop into a recommendation. A matrix of the six alternatives finalized in the workshop (through brainstorming and expert analysis) was developed that would allow scoring of the alternatives versus several common cleanup project criteria. This matrix is shown in Table 1. The team also developed a weighting for the criteria and a method of assigning a numerical score to the individual criteria. The numerical exercise represents a strong recommendation that the Optimized Baseline Approach be adopted. This affirms the consensus of the workshop that also found this to be the recommended alternative among the panel of sodium cleanup specialists.

Table 1 shows the weighting of the criteria that was used in the mathematical analysis of the options. Each of the criteria was assigned a weighted value depending on its importance to the overall project based on the discussion of those criteria during the workshop. One of the lesser developed criteria going into the workshop, that of dose (ALARA concerns), turned out to be an important factor for the evaluation. The baseline alternative fared poorly in this criteria as the baseline did not take into account the large amount of dose and the difficulties in treating large, highly radioactive components.[4] Another great concern was the relative perceived cost of each

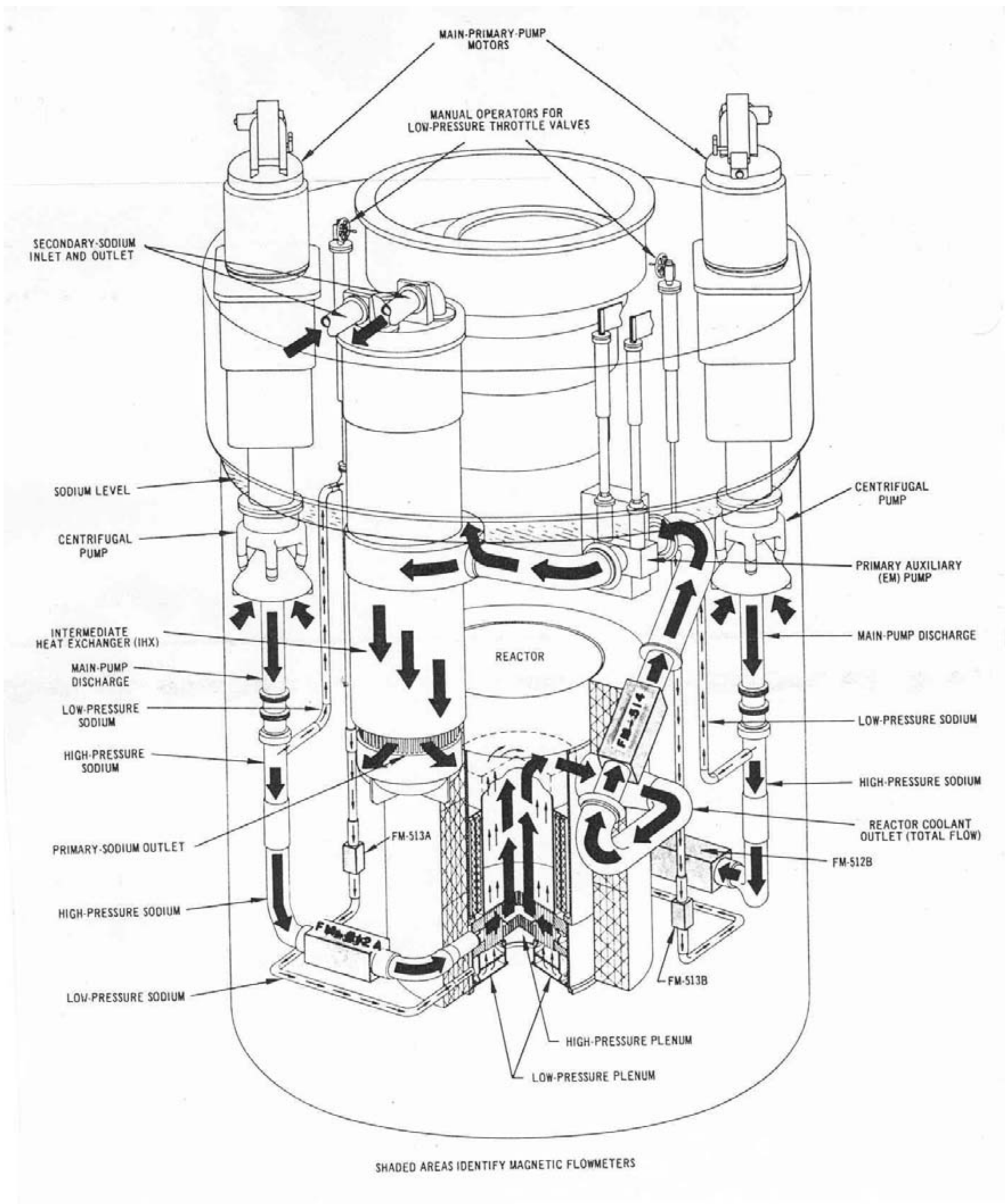

Figure 2, Primary Tank System of EBR-II.

Table 1. Alternatives Evaluation Raw Scoring and Criteria Weighting Values

Alternative	Cost	Schedule	Dose	Effectiveness	Future Impact
Weighting of Criteria	***26***	***11.5***	***31***	***19***	***12.5***
Optimized (OBA)	24	24	24	25	24
High Temp Steam	23	22	22	21	21
Grout	19	21	21	16	16
Partial Fill and Steam	17	16	16	15	15
No Action	18	18	18	10	10
Baseline	15	15	11	17	17

option. Cost was typically judged as lower (given a higher score) if fewer components were removed and if less waste would be generated as a result of the alternative. Again, all the alternatives were judged higher than the baseline with respect to cost. The effectiveness of performing the task considers how well a perceived option would neutralize the hazard and remove the byproducts. Finally, future impact and schedule were weighted approximately the same, with future impact (how versatile an alternative would be if plans changed later or additional remediation were necessary) being a little higher than accomplishing the tasks in less time.

After collecting the raw scores of the six alternatives and weighting them based on the criteria, adjusted scores were given to the individual alternatives. The weighted scores are given in Table 2 along with the possible score and percentage of that score that was given to that alternative. Again, with weightings applied as discussed above, the OBA was strongly favored (over 80% acceptance) with a more traditional steam/sodium reaction placing a strong second. These two options are seen as having high efficiency, allowing large components to be left in place during treatment (with some equipment modifications) and minimizing secondary wastes. Interestingly, a sensitivity evaluation shows that neither small changes in scoring (deviations in individual scores) nor in weighting (with or without weighting) really detract from the position of these two alternatives. Also note that these two methods are not unusual and are among the industry-accepted methods of sodium cleanup.

Table 2, Overall Weighted Alternative Scores and Acceptance Level

Alternative	Score	Possible	%
Optimized (OBA)	24.2	30.0	80.6
High Temp Steam	21.9	30.0	73.2
Grout	18.9	30.0	63.0
Partial Fill and Steam	15.9	30.0	53.2
No Action	15.5	30.0	51.6
Baseline	14.4	30.0	48.0

Most of the alternatives, especially the OBA, provide better scores than the Baseline. This is because these alternatives favor leaving the large components in place. The baseline approach includes removing certain large components, including the intermediate heat exchanger (IHX), bayonet heaters, shutdown coolers and nozzles prior to filling the system with wash-water to react with the remaining sodium, and dissolving the reaction products (sodium bicarbonate, sodium carbonate and sodium hydroxide). The OBA differs from the baseline by leaving the large components in place and puncturing them with a penetrating device, thus allowing the water or steam to flow through those components and react with the residual sodium. This substantially reduces waste volumes, greatly reduces radiation doses and decreases the overall schedule by eliminating the need to remove the large components. The high temperature steam option reduces waste beyond either of the baseline options. The steam alternative may improve the reduction of the reactive sodium hazard, because it flows into difficult geometries better than water, but may not wash out reaction product quite as well. Steam has gained acceptance for in-situ sodium treatment in the sodium cooled reactor community in Great Britain.

Grouting the primary tank in place was a novel alternative that had not been discussed before it was suggested at the workshop. This option also involves leaving all the primary system components in place and simply filling the tank up with grout. Though grouting typically means using a Portland cement based material, other materials, including a paraffin-based grout, were discussed. Grouting is a very attractive option because no secondary waste is generated for further treatment or disposal. However, it does not satisfy all the required criteria, because it may not fully react with nor will it remove any sodium products from the primary system. This may not be an overwhelming disadvantage though, because the hazardous sodium would be encapsulated and isolated. In addition none of the other alternatives would likely remove 100% of the sodium either.

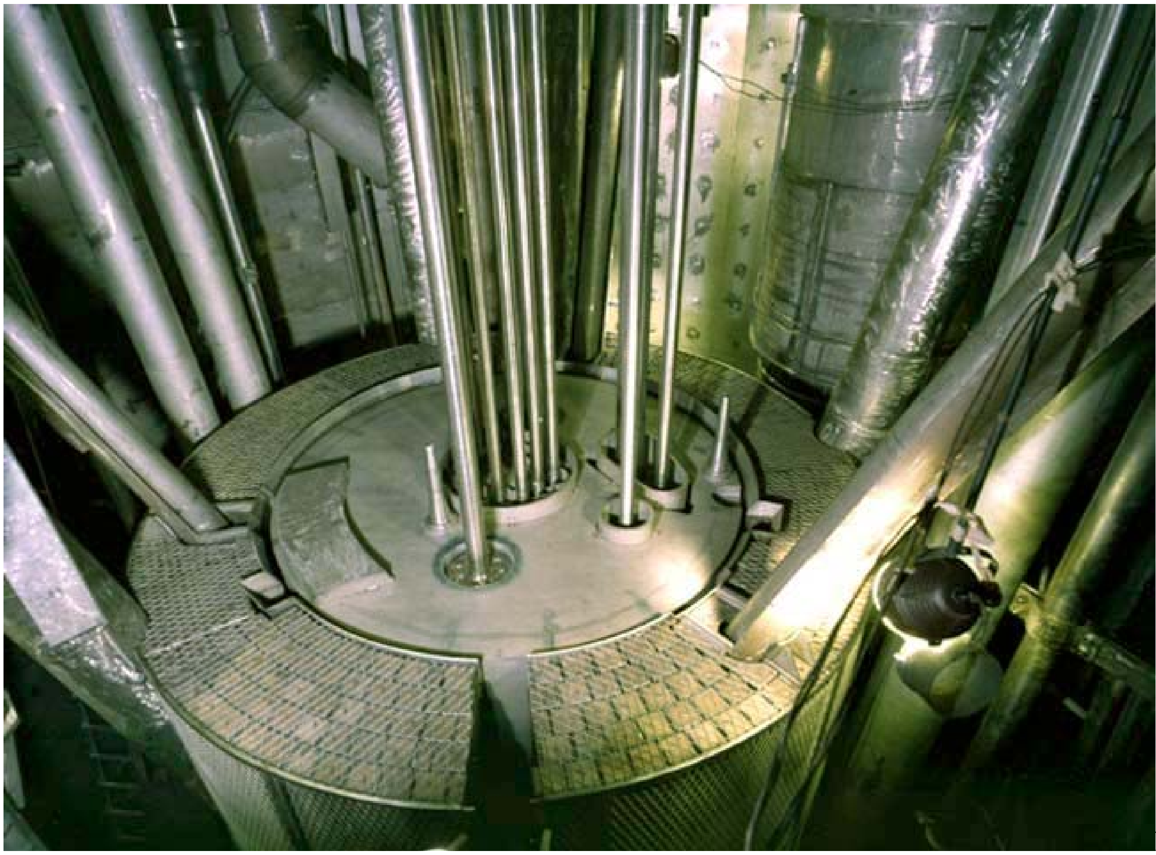

Figure 3, Reactor System Inside Primary Tank with IHX Behind on Right.

The partial steaming approach combines part of the optimized approach with heating up the primary tank to react the remaining sodium in the upper portions of the tank with steam. This option likely has little advantage over either the optimized or the full steam option. The No Action alternative is particularly attractive because of its savings in time, waste and money. It does nothing to reduce the hazard though and was not favored in anyone's opinion, though there is something to be said for leaving the residual sodium and allowing ambient atmosphere to enter the primary tank.

PATH FORWARD

Tackling several high-level activities is necessary for completing the closure of the EBR-II Primary Reactor Tank System. While the recommended alternative is to develop a well engineered Optimized Baseline Alternative, real progress will require initiation of most of these high level tasks. A number of these tasks were discussed during the workshop and are listed below. Other activities outside of the workshop scope, that pertain mainly to general closure and demonstrating annual progress to the regulators, are developed in the 2006 RCRA closure report listed in the references at the end of this report.[2] The most important tasks that were brought out in the workshop are:

- Transfer the project out of DOE-NE to DOE-EM.
- Prioritize the closure project (within DOE-EM) so that it can be funded.
- Develop a "project" mentality with a dedicated project team.
- Negotiate a de minimus value with the Idaho Department of Environmental Quality (DEQ) for how much sodium can be left behind based on level of risk.

Not all of these tasks need to be completed immediately in order to move forward with the OBA. However, little progress is going to be shown without spending substantially more resources. Without transferring the project, DOE-NE could fund engineering studies and hazard analyses that feed into discussions with DEQ to determine a quantity of sodium that could remain (the current permit states that the large components must be removed and all sodium reacted and removed). The sodium treatment experts all suggested that an acceptable quantity of residual sodium should be negotiated and agreed upon with DEQ, because it is nearly impossible to remove all of the residual sodium from the tank. Little real risk is associated with small amounts of sodium left in the primary tank system. A consensus was also held that resources should be retained and not lost to attrition by developing this work into a large project and integrating it with D&D or future activities.

SODIUM AND WATER TREATMENT ANALYSIS

To address the impact of the sodium and contaminated water discussed in this wash-water project it was necessary to develop some additional information concerning the quantity and location of the remaining sodium and the characteristics of the produced wash-water. The data shown in Table 3 below, is taken from two INL reports[4, 5] written in 2006. As noted, about 650 kg (668 liters, about 176 gallons) of unreacted sodium metal and NaK remain in the primary tank system.

After the bulk of the sodium was drained from the EBR-II primary sodium system, residual amounts of sodium remained at various places in the primary system. Precise locations and estimates of residual quantities at each location were determined by studying the engineering drawings. Twenty-four unique locations with hydraulic low points capable of retaining liquid sodium were identified within the EBR-II primary sodium system[5]. The potential quantity of residual sodium for each location listed in the table (Residual Sodium Deposits in EBR-II Primary Tank) was calculated using the internal geometry from the drawings and the elevation of the drain path for each identified location. The primary assumption used in deriving the volume

Table 3, Estimated Location and Quantity of Residual Sodium in the Primary Tank.

Location	Amount Before Carbonation (L)	Amount After Carbonation (L)
High Pressure Plenum (HPP)	125	66
HPP Inlet Pipes	117	49
Reactor Baffles and Equipment	104	99
Fuel Handling Equipment	12	4
Press. Transmitter Piping	8 (NaK)	8 (NaK)
Primary Tank Bottom	473	0
Intermediate Heat Exchanger	151	140
Primary Tank Heater Thimbles	112	112
Shutdown Cooler Bayonets	190 (NaK)	190 (NaK)

calculations was that, except for locations with no outlets, the liquid sodium drained towards the bottom of the primary vessel as the bulk sodium metal was withdrawn. Based upon visual observations via video camera, vertical surfaces were assumed to have negligible sodium residue on them. In addition to the 24 locations mentioned above, some sodium is also left in the IHX, Primary Tank Heater Thimbles, and NaK in the Shutdown Cooler Bayonets[4].

The column "Amount After Carbonation" lists the quantity of sodium metal remaining after the carbonation treatment process was stopped. In some locations geometric restrictions prevented carbonation of any of the residual sodium, in other locations a portion of the residual sodium metal was reacted, and in other locations it was expected that 100% of residual sodium reacted with the CO_2 and water to form carbonates. In summation the EBR-II primary sodium system was estimated to contain about 1550 liters of residual sodium metal before the carbonation treatment. The carbonation process stabilized the majority of sodium by reaction to form sodium carbonates. Based on the study of the engineering drawings and process data from the carbonation process, over 650 liters of unreacted sodium metal remain in the primary system.

Table 4, Estimated Radioactivity Concentration of Wash-Water

Radionuclide	1994 Analyses (current value)	Units	Estimated Total (2008)	Units	Concentration in Wash-Water	Units
H-3	1.10E-07	Ci/g	2.49E-02	Ci	7.33E-08	Ci/l
Na-22	2.82E-09	Ci/g	6.39E-04	Ci	1.88E-09	Ci/l
Mn-54	8.28E-15	Ci/g	1.88E-09	Ci	5.52E-15	Ci/l
Sr-89	2.10E-39	Ci/g	4.76E-34	Ci	1.40E-39	Ci/l
Sr-90	9.42E-11	Ci/g	2.14E-05	Ci	6.29E-11	Ci/l
Ag-110m	3.55E-15	Ci/g	8.06E-10	Ci	2.37E-15	Ci/l
Sn-113	2.17E-20	Ci/g	4.93E-15	Ci	1.45E-20	Ci/l
Sb-125	2.66E-10	Ci/g	6.04E-05	Ci	1.78E-10	Ci/l
Cs-134	2.65E-11	Ci/g	6.01E-06	Ci	1.77E-11	Ci/l
Cs-137	1.71E-08	Ci/g	3.88E-03	Ci	1.14E-08	Ci/l
Po-210	2.35E-21	Ci/g	5.33E-16	Ci	1.57E-21	Ci/l
Pu-239	3.15E-13	Ci/g	7.15E-08	Ci	2.10E-13	Ci/l

An analysis of the radioactivity of the residual sodium confirms that, while the radiation levels have decayed to fairly low levels since the shutdown of the EBR-II reactor, the residual radioactivity must be managed. Table 4 shows the sodium analysis performed in 1994[6] which examined some 25 different radionuclides that were expected to be present in the sodium coolant. Some of these, such as Co-58 and Co-60 proved to be below detection levels in the original analyses. Others, such as Sn-117m and I-131 decayed to such low levels (less than 1E-100) over the last 13 years that they had no practical contribution to the radiation levels. In fact, the only real problem radionuclides (those exceeding picocurie levels in the wash-water) are H-3, Na-22, Sr-90, Sb-125, Cs-134 and Cs-137.

Even those levels of cesium and other radionuclides are not high enough to cause significant problems for disposal. All evaporation pond liquid disposal facilities at the INL will accept radioactive water at those levels. The Reactor Technology Complex (RTC) evaporation pond allows water at levels up to 20 mCi/L[7] - approximately 5 orders of magnitude higher than the level anticipated for this wash water. In addition to the RTC evaporation pond, this water could be sent to the Idaho CERCLA Disposal Facility (ICDF) or the new Idaho Waste Treatment Unit (IWTU) at the Idaho Nuclear Technology Engineering Center (INTEC). Another option is off-site disposal at Energy Solutions in Utah.

The team briefly evaluated these different disposal options and found that some were quite attractive. Off-site disposal is estimated to cost $17/gallon while on-site disposal ranged from an estimated $5/gallon for the evaporation ponds to perhaps as much as $100/gallon for the IWTU (no real costs have been quoted for the IWTU for non-INTEC Tank Farm Waste at this time). For the estimated 90,000 gallons of wash-water waste from the primary tank the total on-site disposal costs would probably be in the $400,000 range. Since this waste can be managed more effectively with the OBA, some savings (perhaps $100,000) could be realized. However, since the overall cost for RCRA clean closure of the EBR-II facility is expected to run over $20,000,000, the cost of the primary tank wash-water disposal is not a significant budget concern to the project as a whole, and will probably not drive the project to extreme efforts in cost avoidance.

SUMMARY

The Optimized Baseline Approach was the alternative method recommended by the panel of sodium cleanup specialists at the workshop, and confirmed as the best alternative by the weighted scoring matrix analysis performed by the wash water project team. This alternative was chosen because it scored the highest among the common project criteria in the matrix, and most importantly it reduced the quantity of waste that would be generated for disposal. As discussed in Path Forward section of the report, actual progress towards clean closure of EBR-II will require elevating this activity to a priority project within DOE-EM. This will require transferring ownership of the EBR-II facilities from DOE-NE to DOE-EM. In addition, an acceptable de minimus level of sodium left in the primary system must be negotiated with DEQ, as it is practically impossible to remove every last gram of sodium from the system.

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