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ANL-AFCI-183

Advanced Burner Reactor Preliminary NEPA Data Study

Nuclear Engineering Division

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Advanced Burner Reactor Preliminary NEPA Data Study

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Table of Contents

1. Introduction

The Global Nuclear Energy Partnership (GNEP) is a new nuclear fuel cycle paradigm with the goals of expanding the use of nuclear power both domestically and internationally, addressing nuclear waste management concerns, and promoting non-proliferation. A key aspect of this program is fast reactor transmutation, in which transuranics recovered from light water reactor spent fuel are to be recycled to create fast reactor transmutation fuels. The benefits of these fuels are to be demonstrated in an Advanced Burner Reactor (ABR), which will provide a representative environment for recycle fuel testing, safety testing, and modern fast reactor design and safeguard features.

Because the GNEP programs will require facilities which may have an impact upon the environment within the meaning of the National Environmental Policy Act of 1969 (NEPA), preparation of a Programmatic Environmental Impact Statement (PEIS) for GNEP is being undertaken by Tetra Tech, Inc. The PEIS will include a section on the ABR. In support of the PEIS, the Nuclear Engineering Division of Argonne National Laboratory has been asked to provide a description of the ABR alternative, including graphics, plus estimates of construction and operations data for an ABR plant. The compilation of this information is presented in the remainder of this report.

Currently, DOE has started the process of engaging industry on the design of an Advanced Burner Reactor. Therefore, there is no specific, current, vendor-produced ABR design that could be used for this PEIS datacall package. In addition, candidate sites for the ABR vary widely as to available water, geography, etc. Therefore, ANL has based its estimates for construction and operations data largely on generalization of available information from existing plants and from the environmental report assembled for the Clinch River Breeder Reactor Plant (CRBRP) design [CRBRP, 1977]. The CRBRP environmental report was chosen as a resource because it thoroughly documents the extensive evaluation which was performed on the anticipated environmental impacts of that plant. This source can be referenced in the open literature and is publicly available. The CRBRP design was also of a commercial demonstration plant size – 975 MWth – which falls in the middle of the range of ABR plant sizes being considered (250 MWth to 2000 MWth). At the time the project was cancelled, the CRBRP had progressed to the point of having completed the licensing application to the Nuclear Regulatory Commission (NRC) and was in the process of receiving NRC approval. Therefore, it was felt that [CRBRP, 1977] provides some of the best available data and information as input to the GNEP PEIS work. CRBRP was not the source of all the information in this document. It is also expected that the CRBRP data will be bounding from the standpoint of commodity usage because fast reactor vendors will develop designs which will focus on commodity and footprint reduction to reduce the overall cost per kilowatt electric compared with the CRBR plant. Other sources used for this datacall information package are explained throughout this document and in Appendix A. In particular, see Table A.1 for a summary of the data sources used to generate the datacall information.

Again, all of the data gathered for environmental analysis in this EIS reflects what was available from open literature sources including that available on international fast reactor designs. Data on current or future international designs was either not available or not of sufficient detail for use in this datacall and EIS. It is expected that along with U.S.-based companies, foreign countries will also propose ABR designs as part of DOE's ABR solicitation, however, those design concepts are not currently available for use as part of this datacall information package. Lastly, similar to what is anticipated for advanced U.S. designs, foreign fast reactor designs, if designed to be safe and economical, will fall within the data envelope of the information contained in this datacall package.

The remaining report sections provide a summary of the safety design approach applicable to an ABR (Sec. 2), a discussion of applicable ABR operations and requirements (Sec. 3), and a summary of the various wastes and emissions generated during plant construction and operation (Sec. 4). Details regarding the data presented in tables in the body of the report are provided in Appendices A, B, and C.

2. ABR Safety Design Approach

2.1. Sodium Coolant

When a fission reaction occurs in nuclear reactor fuel, high-energy neutrons traveling at high speed are released in the reaction. In light water reactors, the fuel is of a type that fissions mostly when it absorbs neutrons which are moving relatively slowly, and so it is necessary to slow down the neutrons through collisions with the coolant water. The water thus serves two purposes: removing heat from the reactor core and slowing down neutrons to allow for further fission reactions.

In fast reactors, the fuel is of a type such that most of the fissions are caused by fast-moving neutrons, and so a coolant must be used which does not slow neutrons to the extent that water does. The coolant used in most fast reactors is liquid sodium because it slows fission neutrons much less than does water and it has many desirable thermal and physical properties, such as excellent heat transfer and compatibility with the metals used for reactor fuel cladding, duct walls, etc.

2.2. Defense in Depth

The fundamental safety goals in nuclear power reactor design and operation are to assure the health and safety of the public, to protect the plant operating staff from harm, and to prevent plant damage. Traditionally, these goals have been fulfilled by an approach that 1) minimizes risk by maximizing safety margins in design and operation, 2) reduces the likelihood of potentially harmful events by providing safety systems to deal with foreseen events, and 3) provides additional design features to mitigate the harmful consequences of low probability events. This approach is usually identified as "defense in depth."

The basic principle of defense in depth is to provide multiple levels of protection against release of radioactive material. One part of defense in depth is physical barriers, like the multiple barriers to release of radioactivity provided by the fuel cladding, the primary coolant system boundary, and the reactor containment building. Safety systems are provided to protect the physical barriers and prevent event sequences from proceeding. Emergency planning provides an additional layer of defense in depth, should the other barriers be threatened. In all instances, the defense-in-depth strategy depends on the independence of the protective measures, so that no single event can breech more than one protective level.

2.3. Inherent and Passive Safety

In the current fleet of operating light water reactors (LWRs), the safety systems generally include the reactor shutdown systems, emergency core cooling systems and decay heat removal systems. The safety systems are generally active, depending on electrical or steam power; correct valve alignment; proper performance of pumps, valves and other equipment; and proper operator action. While these systems have proven to be effective when called upon, they are complex and have high capital and maintenance costs.

Most of the modern advanced LWR designs have reduced the dependence on active safety systems in favor of a greater reliance on passive systems that depend on natural phenomena, such as gravity or natural convection flow in cooling systems. Inherent characteristics of the design, such as negative reactivity feedback and long flow coastdown, may provide an additional level of protection.

A sodium-cooled fast reactor provides a demonstrated high level of inherent and passive safety. The coolant thermo-physical properties provide superior heat removal and transport characteristics at low operating pressure with a large temperature margin to boiling. Since the system operates at low pressure, the likelihood of a loss-of-coolant accident is greatly reduced. The reactor guard vessel is designed to hold primary coolant in the event of a leak in the primary coolant system. The reactor guard vessel assures that the reactor core remains covered with sodium and cooled by the emergency heat removal system, even if the primary reactor vessel fails. If primary coolant leaks and oxidizes in the reactor building air atmosphere, or if failures of the cladding and the primary system barriers lead to release of gaseous fission products, the reactor containment building provides a final low-leakage barrier to release of radioactivity to the environment.

The normal process of safety assessment of a design considers a spectrum of design basis accidents (DBAs) as tests of the various safety systems. These DBAs generally assume single failures. Accidents within the design basis must be accommodated by the design and shown to present risks to the public that are within regulatory standards. Beyond the design basis, there exists a class of accidents of such low probability (typically, less than 10^{-6} per reactor year, although regulators have not yet assigned a specific probability value) that they have been termed “hypothetical.” These events involve multiple failures of safety grade systems. Because of the potentially severe consequences of accidents in this class, they have received significant regulatory scrutiny in prior sodium-cooled fast reactor licensing reviews for the purpose of characterizing thermal and structural safety margins beyond the design basis.

Three beyond-design-basis accident (BDBA) sequences, each involving failure of both reactor scram systems, have received attention in past licensing safety assessments. In the unprotected loss-of-flow (ULOF) sequence, it is assumed that power is lost to all primary and secondary coolant pumps, and the reactor scram systems fail to activate. In the unprotected transient overpower (UTOP) sequence, it is assumed that one or more inserted control rods are withdrawn, plus the reactor scram systems fail to operate. In the unprotected loss-of-heat-sink (LOHS) accident, it is assumed that heat removal through the power conversion system is lost, and the reactor scram systems do not activate. Taken collectively, these three accident initiators encompass all the ways that an operating reactor can be perturbed, i.e. by a change in coolant flow, by a change in reactivity, or by a change in coolant inlet temperature.

A sodium-cooled fast reactor can be capable of accommodating these beyond-design-basis accident initiators without producing high temperatures and conditions that might lead to a severe accident, such as coolant boiling, cladding failures, or fuel melting. The inherent neutronic, hydraulic, and thermal performance characteristics of such a reactor provide self-protection in beyond-design-basis sequences to limit accident consequences without activation of engineered systems or operator actions. This characteristic has been termed 'inherent passive safety.'

The efficacy of such passive safety was demonstrated through two landmark tests conducted on the Experimental Breeder Reactor-II (EBR-II), namely loss-of-flow without scram and loss-of-heat-sink without scram tests. With the automated safety systems disabled, the two most demanding accident initiating events were deliberately induced with the reactor at full power, first one, then the other. Each time the reactor simply coasted to a safe, low power state without any damage at all to the fuel or any reactor component. These tests proved conclusively that passive safety design is achievable for metallic-fueled fast reactors with sodium cooling. Additional analyses have shown that inherent reactivity feedback and heat removal performance can be achieved in sodium-cooled, pool-type, metal fueled reactors of all sizes (see [Cahalan, 1990] and [Royl, 1990]).

Within the overall safety framework for ABR, passive safety will serve to provide additional margins for public protection in the event of very low probability events for which the frequency of occurrence is lower than the normal threshold for deterministic assessment. No abnormal radioactivity releases will occur in the event of beyond-design-basis accidents, and all of the multiple defense-in-depth barriers (fuel cladding, reactor vessel, containment building) for public protection will remain intact, just as for design-basis accidents. The passive safety performance of ABR will eliminate the potential for severe accident consequences in very low frequency, beyond-design-basis sequences. Consequently, for ABR, beyond-design-basis accidents need to be considered only in the context of probabilistic risk assessments, in which such events are analyzed with best-estimate scoping methods that demonstrate safety margins beyond the normal design basis without requiring the use of deterministic analyses.

2.4. Sodium-Cooled Reactor Operating Experience

Safe, stable and predictable operation of sodium-cooled fast reactors has been demonstrated in many countries worldwide, resulting in a comprehensive understanding of the necessary safety requirements, design features, and operating practices for these reactors. The concept of the sodium-cooled fast reactor has been proven by operational experience in the U.S., U.K., France, Germany, Russia, and Japan. In the U.S., the EBR-II and the FFTF operated safely and reliably for 40 reactor-years. While there have been incidents in sodium-cooled fast reactors, including at the Fermi-1 reactor in Michigan (a coolant flow blockage caused by a loose part leading to local fuel melting) and the MONJU reactor in Japan (a leak of non-radioactive sodium due to a piping design deficiency), in no case has there been any uncontrolled release of radioactive material, nor has there been any incident that resulted from a fundamental flaw in the concept of the sodium-cooled fast reactor.

The international community continues to develop fast reactor technology. The BN-800 power plant is under construction at Beloyarsk in Russia. China is constructing a small prototype power reactor near Beijing. India is constructing a large prototype power reactor at Kalpakkam. Construction of new, large sodium-cooled fast reactor plants has been proposed in Russia, France, Japan and the U.S.

2.5. Inherent Passive Safety in the ABR

The Advanced Burner Reactor safety design approach will implement the defense-in-depth strategy by adopting the traditional three levels of safety. Since the ABR will be a sodium-cooled fast reactor, it will provide significant safety margin enhancements by inherent characteristics that enable passive safety responses to potential accident initiators.

At the first level of safety, the ABR will be designed to operate with a high degree of reliability, so that accident initiators are prevented from occurring. The first level of safety will be assured in part by selection of fuel, cladding, coolant, and structural materials that are stable and compatible and provide large margins between normal operating conditions and limiting failure conditions. Next, the first level of safety will be assured by adopting an arrangement of components that allows monitoring, inspection, and testing for performance changes or degradation and for repair and replacement of components necessary to assure that safety margins are not degraded.

At the second level of safety, the ABR will provide protection in the event of equipment failure or operating error. This level of protection is provided by engineered safety systems for reactor shutdown, reactor heat removal, and emergency power. Each of these safety-grade back-up systems functions in the event of failure in the corresponding operating system and are subjected to continuous monitoring and periodic testing and inspection.

The ABR will incorporate an independently powered and instrumented secondary reactor shutdown system that operates automatically to reduce reactor power rapidly in the event that the primary shutdown system fails. For shutdown cooling, the ABR will include a safety-grade emergency heat removal system, independent from the normal heat removal system and capable of passively removing residual decay heat by natural circulation. In addition to the normal off-site power supply, the ABR will be equipped with a second, independent safety-grade on-site emergency power supply.

The third level of safety provides additional protection of the public health and safety in an extremely unlikely event that is not expected to occur in the life of the plant, or which was not foreseen at the time the plant was designed and constructed. As an example, level 3 protections for cooling assurance and containment of radioactivity are provided by the reactor guard vessel and the reactor containment building. The reactor guard vessel assures that the reactor core remains covered with sodium and cooled by the emergency heat removal system, even if the primary reactor vessel fails. Similarly, the reactor containment building provides a final low-leakage barrier to release of radioactivity to the environment in the event of a primary coolant leak or of failures of the cladding and the primary system barriers leading to release of gaseous fission products.

3. ABR Operations and Requirements

As described in Sec. 1, construction and operating requirements for the Advanced Burner Reactor have been derived largely from CRBRP evaluations discussed in documents available to the public. A more recent preconceptual design of a sodium-cooled fast reactor [Chang, 2006] has been identified for use in describing major plant systems. However, the description presented here is not intended to constrain future design decisions for the ABR. Where design decisions are expected to have a significant influence on environmental impact, conservative choices are made or, as in the case of fuel choice, two alternatives are presented.

The major systems of the ABR are expected to include: 1) the reactor vessel containing the reactor core and the primary sodium coolant, 2) the intermediate heat transport system, which transfers heat from the primary coolant to the secondary coolant, and 3) a power conversion system that uses heat from the secondary coolant to produce electricity. These systems are illustrated in Fig. 1. In this concept, the reactor vessel and primary and secondary heat transport systems are located below grade on a nuclear island which is seismically isolated from its foundations.

Primary system components for the ABR may be arranged in either a pool or loop configuration. Figure 2 illustrates a pool configuration, where the reactor core, primary pumps, intermediate heat exchangers (IHX), and direct reactor auxiliary cooling system heat exchangers (DRACS – not shown in Fig. 2) are contained in a pool of sodium coolant within the reactor vessel. In a pool configuration, all primary sodium coolant piping is within the sodium pool, which virtually eliminates the possibility of a loss of coolant and provides a large thermal inertia during reactor transients. In addition, the reactor vessel is a simple structure with no penetrations, surrounded by an additional guard vessel. In a loop configuration, primary pumps and intermediate heat exchangers are external to the reactor vessel and are interconnected by pipes. This type of configuration is illustrated in Fig. 3, which shows a diagram of one of the Fast Flux Test Facility (FFTF) loops.

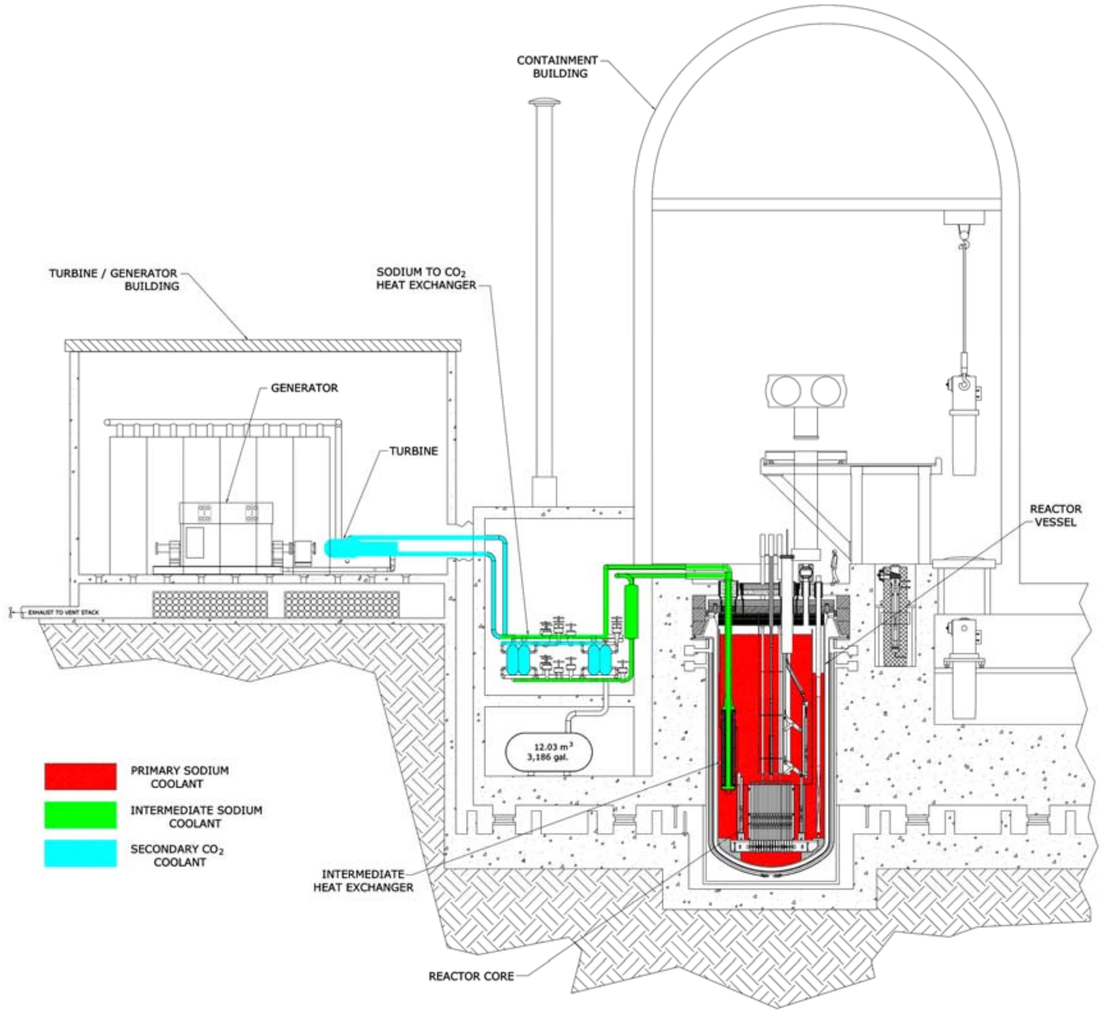

Figure 1. Elevation view shows the reactor vessel and containment secondary heat transport system and power conversion system.

The fundamental flow path for sodium is similar between pool and loop configurations. Primary pumps discharge sodium coolant into the inlet plenum of the core. The coolant is heated as it flows through the core and then exits into the outlet plenum. Heated sodium then flows through the IHXs, where it gives up its heat to the intermediate heat transport system and then returns to be drawn back into the primary pumps.

The relationship among the primary, intermediate, and secondary heat transport systems is shown in Fig. 1, where a supercritical CO_2 Brayton cycle is assumed for the power conversion system, although a steam Rankine cycle can also be used. In the intermediate

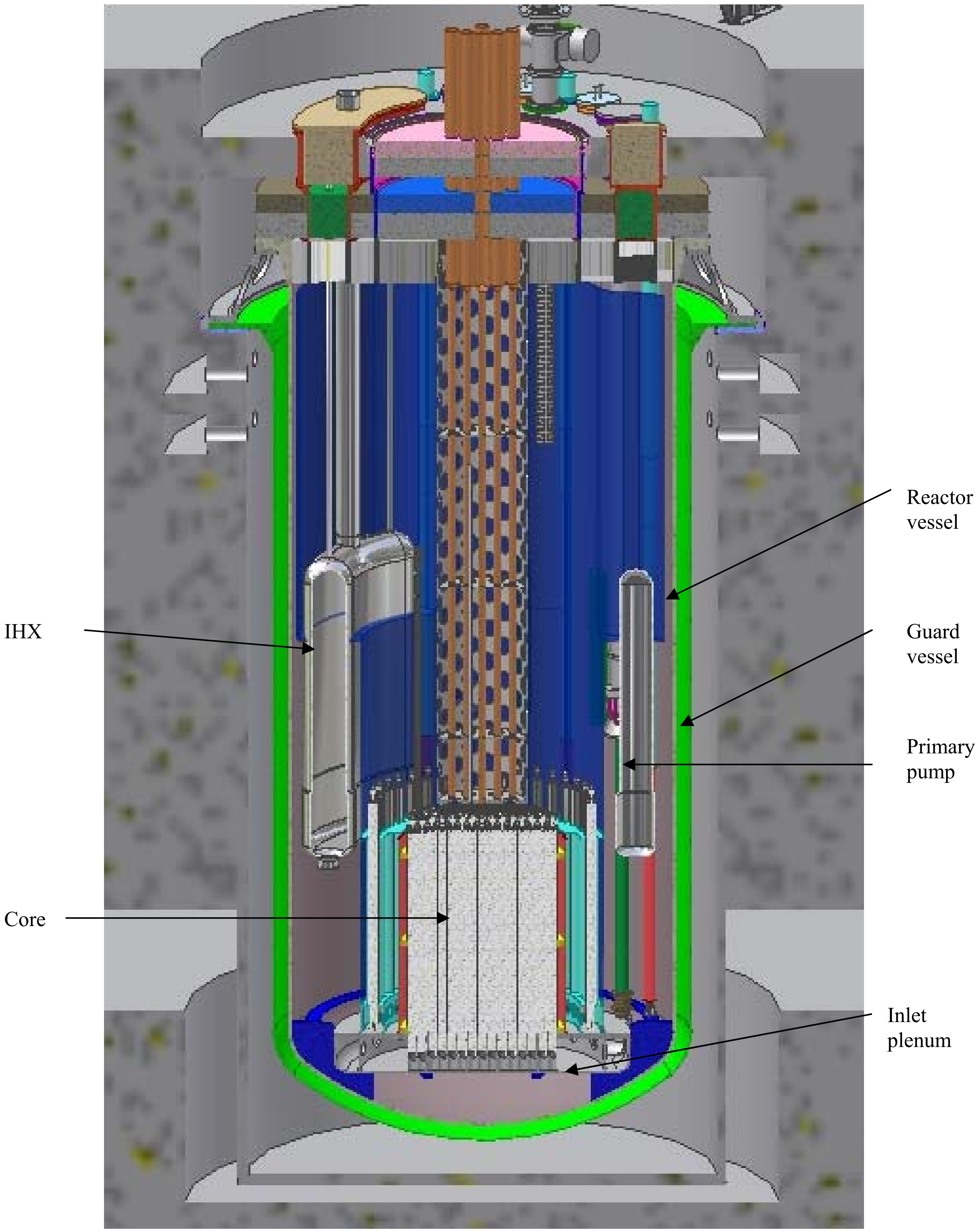

Figure 2. Cut-away view of a pool configuration shows the primary heat transport system within the reactor vessel. [Chang, 2006]

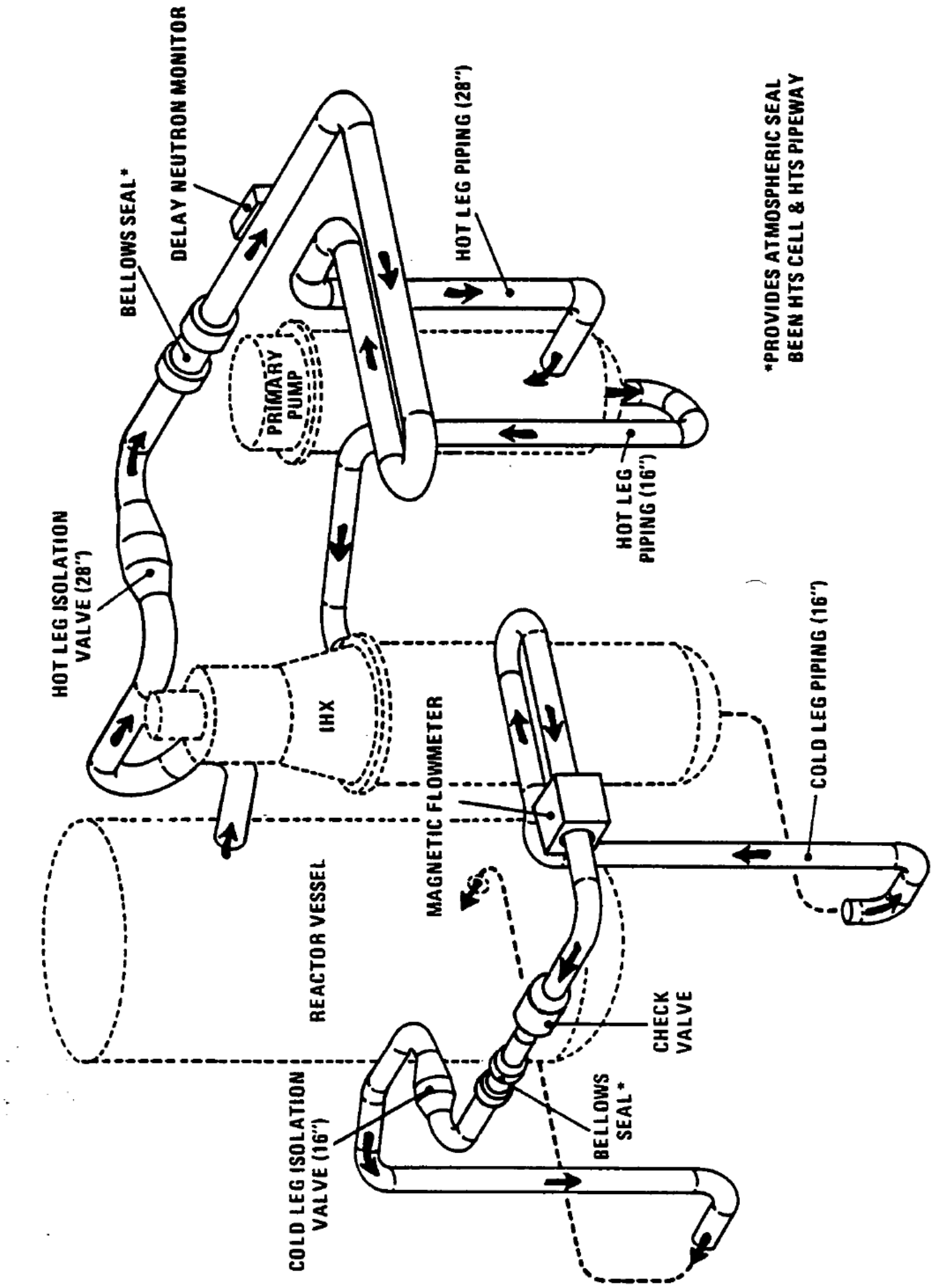

Figure 3. Diagram of the FFTF loop configuration, showing one of the loops [Cabell, 1980]

heat transport system, pumps circulate sodium coolant through the IHXs to recover heat from the primary system. The coolant then flows through steam generators (for the Rankine cycle option) or sodium-to-CO_2 heat exchangers (for the advanced supercritical CO_2 Brayton cycle option) to transfer heat to the power conversion system. The power conversion system uses the thermal energy to do mechanical work on a turbine-generator and produce electricity. A schematic of a supercritical CO_2 Brayton cycle power conversion system concept is presented in Fig. 4, and a schematic of a steam cycle system is diagrammed in Fig. 5.

3.1 Fissile Material Inventory

The power level of the ABR core has not yet been finalized but is evaluated in the range between 250 MWth and 2000 MWth. A 250 MWth design would, because of its size, be economical to build, yet would be large enough to serve as a small engineering scale demonstration plant. A 2000 MWth plant, on the other hand, would provide a full-scale commercial demonstration of the ABR concept, at a higher cost. It is expected that the final ABR design will fall in between these two values. Therefore, parameters which are a function of reactor power level have been estimated in this report for a 250 MWth core, a 1000 MWth core, and a 2000 MWth core, thus providing both mid-range and bounding values for these parameters. See Appendix A, Table A.2, for a summary of the methods used to scale various parameters for reactor power.

Startup fuel type has also not been finalized but will be either metal (U-Pu-Zr or U-Zr) or mixed oxide (UO_2-PuO_2). Therefore, fuel cycle analysis results are presented for both metal and oxide candidate core designs.

Table 1 lists fissile material inventory in the reactor core at all three power levels and for both types of cores. The table also gives estimates of the maximum fissile inventory (fresh plus spent fuel) on site over sixty years of operation, assuming that the ABR is not co-located with a startup fuel reprocessing facility and that the startup fuel is stored on site indefinitely. See the discussion of Table 1 in Appendix A for details of the data calculations.

3.2 Fuel Handling

Fuel assemblies for the ABR will be delivered from one of two sources: either from a co-located fuel processing and fabrication facility [Chang, 2006] or from offsite fabrication facilities in DOE/DOT-approved shipping containers. In either case, new fuel assemblies enter the primary containment building through an intra-building transfer area. Major components in the fuel handling system are indicated in Fig. 6, which shows an artist's rendition of a candidate ABR concept. The intra-building tunnel will interface with a fuel staging/storage area that is either part of the ABR facility or part of a co-located fuel processing facility.

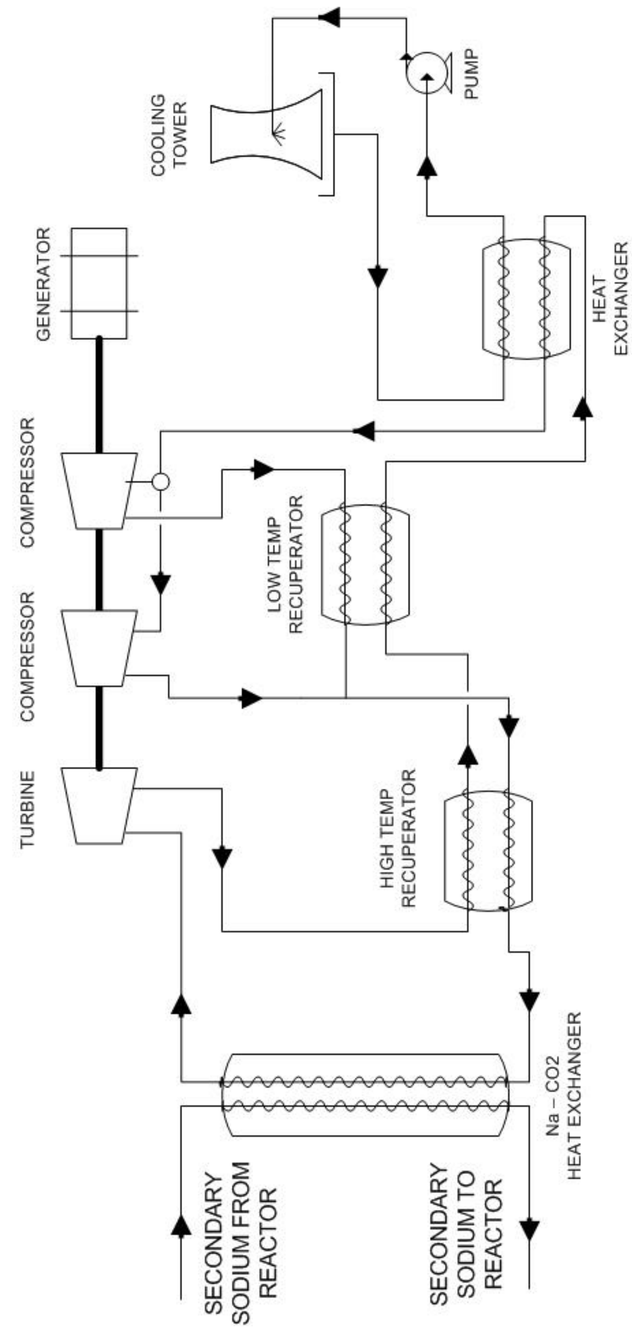

Figure 4. Candidate ABR supercritical CO_2 Brayton cycle power conversion system

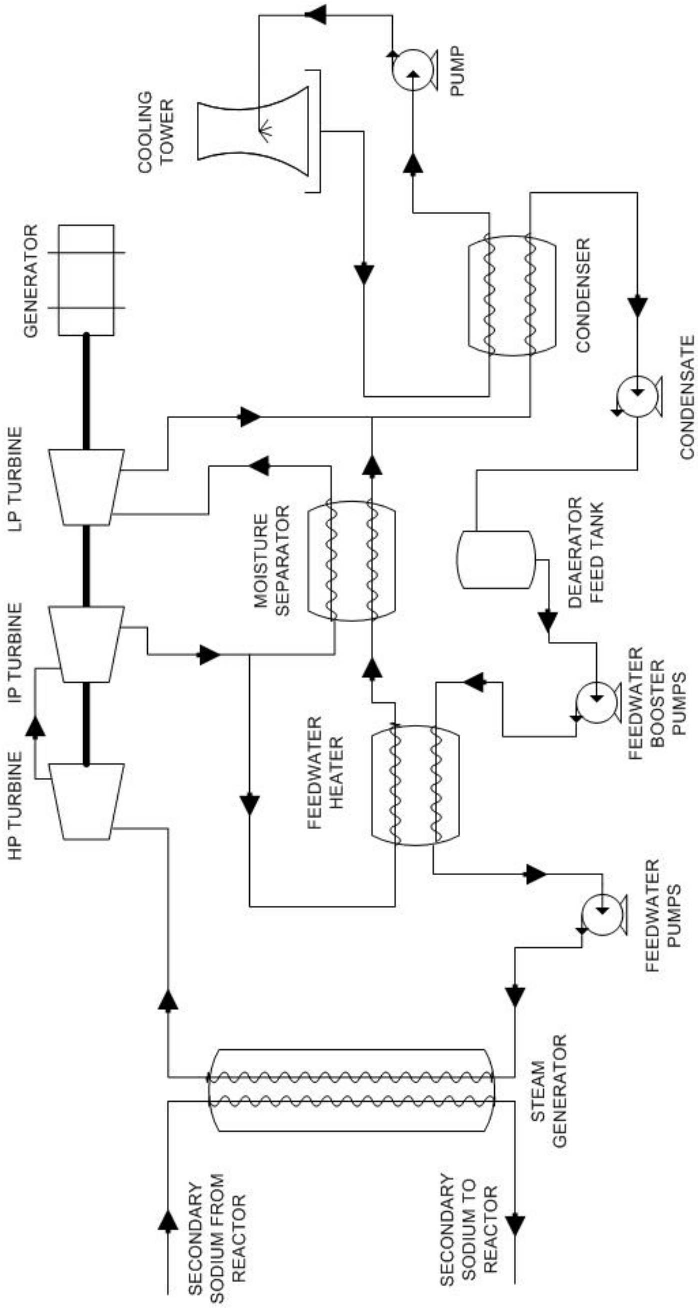

Figure 5. Candidate ABR Steam Cycle Power Conversion System

Table 1. ABR Fissile Inventory		
	Metal (kg.)	**Oxide* (kg.)**
250 MWth, core + in-vessel storage	550	580
1000 MWth, core + in-vessel storage	2260	2550
2000 MWth, core + in-vessel storage	4,600	4,770
250 MWth, maximum on site	12,500	13,200
1000 MWth, maximum on site	25,700	24,200
2000 MWth, maximum on site	60,600	63,400

* Core adjusted to the same TRU conversion ratio as the metal core

Once fuel enters the containment building, it is transferred to the fuel unloading machine for placement into the reactor vessel. An in-vessel fuel handling machine manages the movement and placement of fuel within the reactor vessel. Spent fuel that is removed from the reactor vessel by the fuel unloading machine is placed into an intra-building cask and returned to the fuel staging/storage area.

3.3 Facility Requirements

3.3.1 Industrial Security and Safeguards

The industrial security and safeguards system [Chang, 2006] is designed to protect plant equipment and personnel and to prevent the theft of special nuclear materials. The system is designed to defend against the design basis threats specified in regulations. The key requirements for the security and safeguards systems are:

- Allow plant access only to authorized personnel and material
- Prevent the theft of special nuclear materials
- Prevent the sabotage of critical plant equipment
- Deter, detect, and delay unauthorized activities and assaults on the plant

3.3.2 Buildings and Structures

In addition to buildings and structures to house the primary and secondary heat transport systems and the power conversion system, a number of other buildings necessary to support overall operations are part of the ABR facility. As discussed in [Chang, 2006], these include a control/personnel building as well as buildings for radwaste and maintenance, balance-of-plant services, emergency generators, and security. A site plan for the 2000 MWth design is shown in Fig. 7. A list of site buildings and structures for the ABR concept, including currently proposed dimensions, is given in Table 2 for a 250 MWth ABR design, a 1000 MWth design, and a 2000 MWth design. It should be noted that the ABR facility design will continue to evolve, and as it evolves, designs of particular buildings and structures may change. Therefore, dimensions and site layout of later designs may differ from those given in Table 2 and in Fig. 7.

3.3.2.1 Reactor Building

The reactor building encloses the entire primary reactor system and secondary heat transport system and is constructed on a seismically-isolated basemat structure. The building is a reinforced-concrete containment structure that contains an inner reactor containment dome and is designed for a maximum leak rate of 0.1 %/day at an internal

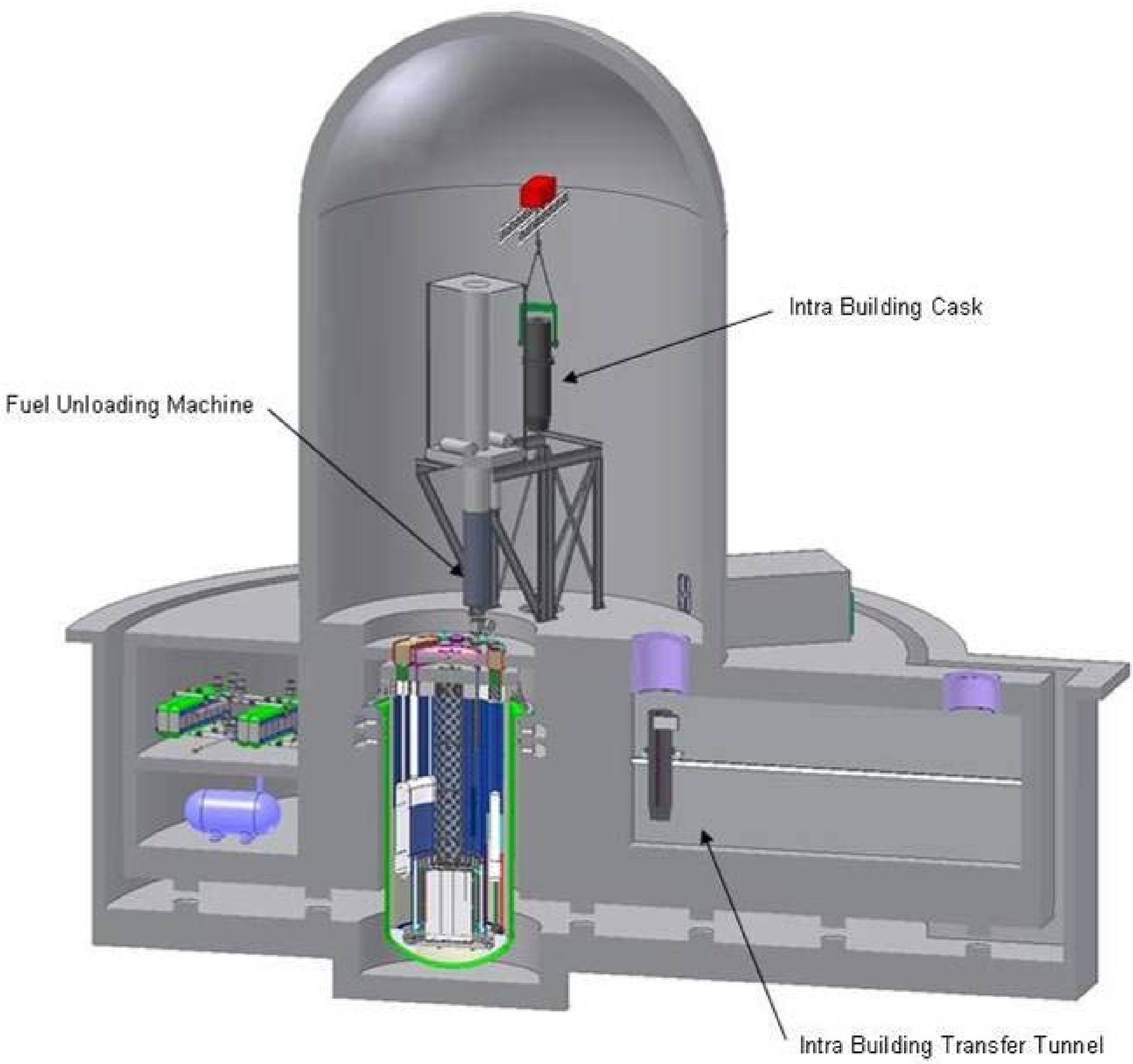

Figure 6: Major components of the fuel handling system in a candidate ABR concept. [Chang, 2006]

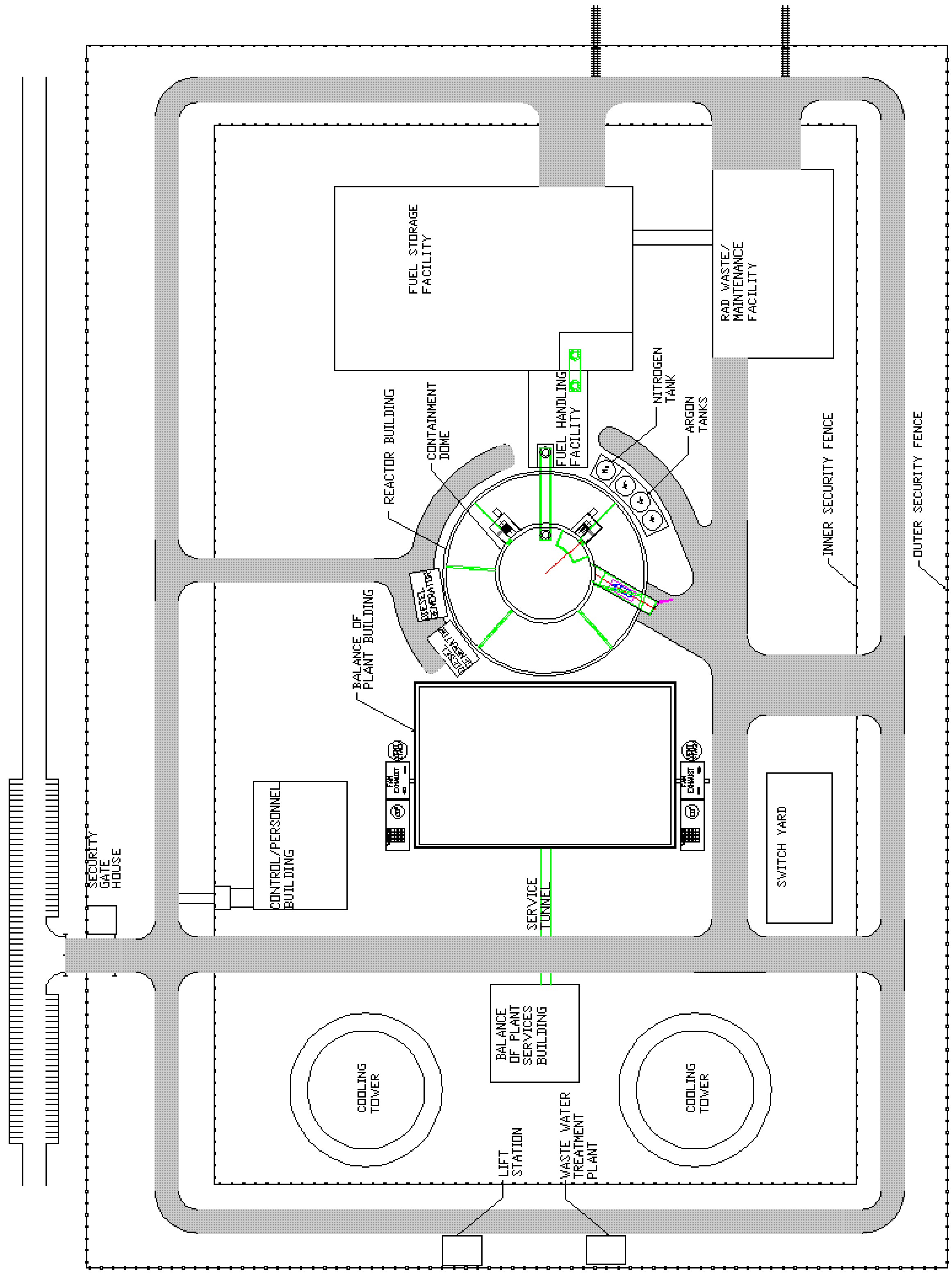

Figure 7. Site plan for the ABR.

Table 2. ABR Site Buildings and Structures with Proposed Dimensions.												
	Footprint (ft^2)			Length (ft)			Width (ft)			Height (ft)		
Building Name	**250 MWth**	**1000 MWth**	**2000 MWth**	**250 MWth**	**1000 MWth**	**2000 MWth**	**250 MWth**	**1000 MWth**	**2000 MWth**	**250 MWth**	**1000 MWth**	**2000 MWth**
Reactor Building	7,832	32,685	32,685	89 dia.	204 dia	204 dia.	-	-	-	100	140	140
BOP Building	3,336	41,860	41,860	72	260	260	46	161	161	49	75	75
Control/ Personnel Building	6,319	12,600	12,600	89	131	131	71	96	96	30	30	30
Radwaste/ Maintenance Facility	6,000	24,000	24,000	100	124	124	60	193	193	40/80*	40/80*	40/80*
Security Gate House	900	900	900	30	30	30	30	30	30	16	16	16
Emergency Gen. Bldg. (2 for 1000 and 2000 MWth ABR)	375	1,500 each	1,500 each	25	50 each	50 each	15	30 each	30 each	12	12 each	12 each
BOP Services Building	2,250	9,000	9,000	50	100	100	45	90	90	20	20	20
Lift Station	1,200	1,200	1,200	40	40	40	30	30	30	16	16	16
Wastewater Treatment Plant	1,200	4,800	9350	40	80	110	30	60	85	16	16	16
Fuel Handling Facility	6,000	6,000	6,000	100	100	100	60	60	60	16	16	16
Fuel Storage Facility	31,250	57,400	57,400	250	307	307	125	187	187	16	16	16
Cooling Towers (each)**	2,352	19,300	19,300	48	156 dia.	156 dia.	48	-	-	33	220	220
Interior Security Perimeter Fence	$1.1x10^5$	$7.1x10^5$	$7.1x10^5$	435	1,085	1,085	244	660	660	-	-	-
Exterior Security Perimeter Fence	$2.4x10^5$	$1.1x10^6$	$1.1x10^6$	616	1,253	1,253	394	885	885	-	-	-

*80 ft. high bay for maintaining tall components, 40 ft. low bay for other maintenance, waste management, etc.

** Dimensions in Table 2 are for wet cooling towers.

pressure of 10 psig. The reactor building is a conventional reactor containment structure with the reactor vessel assembly located below grade. All of the primary radioactive systems are located below grade within the reactor building.

3.3.2.2 Balance of Plant Building

The balance of plant building contains the power conversion systems, which will be based on either a steam Rankine cycle or a super-critical CO_2 Brayton cycle. Future design considerations for the ABR will determine the type of power conversion system to use. Regardless of choice, the ABR will have nearly identical operating conditions for the primary and secondary systems, and overall plant efficiency will be similar.

In the preconceptual design discussed in [Chang, 2006], the balance of plant building houses a supercritical CO_2 Brayton cycle and consists of upper and lower levels. The building heating and air conditioning system maintains an ambient temperature for the enclosed equipment and maintains a slightly negative atmospheric pressure relative to the outside so that minor CO_2 leaks would be contained within the structure. All ventilation equipment is located adjacent to the building to deliver air for cooling of the generator and ambient temperature control for the building.

The lower level is located below grade. The lower level is open to the upper floor, so that, in the event of a leak, the CO_2 will sink and collect in the lower level. The lower level also contains the inventory control tanks and the letdown tanks which are part of the Brayton cycle system on the upper level. Access to this lower level will be for inspection of the tanks or maintenance purposes only.

If a Rankine cycle is used instead for the power conversion system, the Brayton cycle equipment in the balance of plant building will be replaced by the feedwater and condensate systems equipment, such as the deaerator, condenser, feedwater pumps, etc.

3.3.2.3 Control Room and Personnel Building

The reactor control building is a multi-story building adjoining the reactor building. This concrete and steel tornado-hardened, Seismic Category 1 structure houses the control room, technical support center, and the central computers for the overall plant. It also includes space for switchgears; cable routing rooms; motor-generator sets; heating, ventilating, and air conditioning equipment; compressed air; and other auxiliary systems. Fire protection/suppression systems are also provided.

3.3.2.4 Radwaste/Maintenance Building

The radwaste/maintenance building is a slab-on-grade sheet metal high bay structure that provides two areas: a waste management area and a maintenance area. The waste management area is sized and designed to handle the collection, treatment, staging and shipment for disposal of all regulated wastes generated at the site. Waste will be generated from on-going and periodic maintenance work during the life of the plant.

Equipment will exist in this building to condition the waste streams that are expected to be generated from the plant.

The maintenance side of the building provides space and equipment for the routine and planned maintenance of the facility and equipment. The maintenance building also has a location in the structure where large components will be assembled prior to installation in the reactor building. A rail spur provides easy access and delivery of components such as the reactor vessel module, primary pumps, intermediate heat exchangers, and balance-of-plant system equipment to the maintenance area during installation and checkout of the primary and secondary systems. After the facility has been constructed, the maintenance building will then have space and equipment for performing routine and non-routine maintenance of the reactor primary and secondary systems.

3.3.2.5 Security Gate House

The security gate house is a single-story reinforced concrete non-seismic category structure with a reinforced concrete slab located at grade. The windows are made from bullet-proof glass.

The security gate house provides a controlled means of access to the plant site to prevent inadvertent access, industrial sabotage or the theft of nuclear materials. All personnel must pass through this building and be checked by the associated security systems for ingress and egress to sensitive plant structures/areas, or areas where radioactive materials are stored. The plant security system is monitored and operated from this building. A truck trap is located adjacent to this building that allows for security force control and containment of trucks requiring access to the site for deliveries or pickups.

3.3.2.6 Emergency Generator Buildings

Gas or diesel generator buildings are located adjacent to the reactor control building. The 250 MWth plant has one building housing two modular 1 MWe generators that provide emergency power to the primary and secondary systems upon demand. The 1000 MWth plant has two buildings housing one 3 MWe generator each, while the 2000 MWth plant has two buildings housing two 3 MWe generators each. The emergency generator buildings are shipped as single integrated units that can be quickly installed at the site and made operable to support the construction activities during the facility construction, emergency power during reactor operations, and as an alternative source of power during reactor decommissioning.

3.3.2.7 Balance of Plant Services Building

The balance of plant services building provides space for equipment that supports the balance of plant building, cooling towers, and other services. This includes recirculation pumps, water conditioning equipment, air compressors, electrical switchgears, motor control centers, plant heating systems, and other support equipment.

3.3.2.8 Lift Station Building and Wastewater Treatment Plant Building

The lift station building provides pumps and filtration system to pump water from the river (or other suitable cooling water source) to the plant for use in cooling and domestic water services. The lift station footprint should be about the same for all three candidate plants, since pump footprint does not increase much as pump flow increases within the range of the plants, plus, if additional pumps are needed, the pumps can be stacked vertically. All wastewaters go through the wastewater treatment plant, where the water is treated prior to being discharged. Assuming the wastewater treatment function is approximately proportional to the surface area of ponds, tanks, etc. and that the surface area of these components should scale approximately linearly with reactor power, the wastewater treatment plant building footprint should scale approximately linearly with reactor power, as shown in Table 2. The slight deviation from linear scaling between the 1000 MWth and 2000 MWth footprints comes from having restricted the building length and width to whole numbers which would give approximate linear increases with power in the building area.

3.3.2.9 Fuel Handling Facility Building

The fuel handling facility houses the fuel receiving, storage, and shipping system. It also contains the instrumentation and control system that is used to operate 1) the fuel receiving, storage, and shipping system and 2) the fuel handling system. New core assemblies enter the fuel handling facility and are unloaded from the shipping containers and inspected. They are then temporarily stored in the air cell, from which they are transferred by the inter-building coffin to the reactor building prior to core loading. A spent fuel assembly is removed by the pantograph fuel handling machine from storage around the core barrel and transferred to the fuel unloading machine, which places the assembly in the inter-building coffin and transfers it back to the air cell in the fuel handling facility.

3.3.2.10 Fuel Storage Facility Building

The fuel storage facility provides long-term storage for spent ABR fuel. The building can be used simply for spent fuel storage, or it can house a fuel cycle facility for processing spent fuel. Fuel is transferred from the fuel handling facility to the fuel storage facility via an inter-building coffin.

3.3.2.11 Cooling Towers

Four open-evaporative, forced-air counter flow wet cooling towers are used in the 250 MWth design to reject heat to the atmosphere. Each tower has an induced draft, axial fan at the tower outlet. The 1000 and 2000 MWth plant designs operate with natural draft wet cooling towers (one for the 1000 MWth plant, two for the 2000 MWth plant). Forced convection towers are more cost effective for lower heat loads and so are suitable for the 250 MWth design. The large natural draft towers are more efficient for larger heat loads and are therefore used for the 1000 and 2000 MWth plants. Figure 8 shows an example of forced convection cooling towers similar to those proposed for the 250 MWth ABR plant design. Dry cooling towers could be used with any of the three plants if indicated by local conditions.

3.3.3 Radioactive and Hazardous Wastes from Operations

Estimates of annual low-level, mixed low-level, and hazardous wastes in both liquid and solid form are shown in Table 3. Liquid low-level waste is generated from decontaminating radioactive systems and is assumed to scale approximately linearly with reactor power. Solid low-level waste is a mixture of items, some of which do not scale with power. Transuranics will appear only in miniscule amounts in the liquid waste effluent, and so there will be no transuranic waste requiring separate disposal. Hazardous liquid waste comes from the chemical waste treatment system and may include, if a steam Rankine cycle is used in the power conversion system, clarifier blowdown, backwashes, and regenerant wastes and will also include rinse water from the process water treatment systems and non-radioactive building floor drainage. Hazardous solid

Figure 8. Example of forced convection cooling towers.

waste is the result of processing solid wastes from the balance of plant system.

The bases for the values given in Table 3 are detailed in the discussion of Table 3 in Appendix A.

3.3.4 Non-hazardous Operations Wastes

Table 4 provides data on non-hazardous wastes from plant operations. Sanitary waste is assumed to be processed on site by a sanitary waste system. Water effluent from the waste system will be returned to a local body of water, similar to practices in most municipalities. Sludge from the processing of sanitary waste will be transported off site. See the discussion of Table 4 in Appendix A for details of the data calculations.

All other non-hazardous waste is expected to be ordinary trash, which would be transported off site.

Table 3. Estimated Annual Radioactive and Hazardous Wastes from Operations

ABR Power Capacity	**250 MWth**		**1000 MWth**		**2000 MWth**	
	Liquid	Solid	Liquid	Solid	Liquid	Solid
Low-Level	7.9 x10^4 gal.	55 yd^3	3.2 x10^5 gal.	82 yd^3	6.3 x10^5 gal.	119 yd^3
Mixed Low-Level	negligible	4.3 $yd.^3$	negligible	11.4 $yd.^3$	negligible	19.6 $yd.^3$
Hazardous	4.6x10^6 gal.	9.1x10^4 lb. max.	1.84x10^7 gal.	3.65x10^5 lb max.	3.7x10^7 gal.	7.3x10^5 lb. max.

Table 4. Estimated Annual Non-hazardous Operations Wastes

	250 MWth		**1000 MWth**		**2000 MWth**	
	Liquid (gal.)	Solid (yd^3)	Liquid (gal.)	Solid(yd^3)	Liquid (gal.)	Solid(yd^3)
Sanitary	1.9x10^6	3.5 yd^3	2.2x10^6	4.0	2.4x10^6	4.5
Other	negligible	1150	negligible	1300	negligible	1450

3.3.5 Annual Operations Data

Estimates of plant electrical requirements are summarized in Table 5. Appendix A provides details on how these estimates were calculated. The majority of the electrical energy demand is from the motors on the primary and intermediate sodium pumps, the water recirculation pumps, and, if a Brayton cycle is used for power conversion, the CO_2 compressors, if the compressors are powered by electric motors (option 2), rather than being driven directly by the turbine (option 1). If a Rankine cycle is used instead, the electrical demand of the power conversion system will come from the feedwater and the condensate pumps [Lomperski, 2007].

Table 5. ABR Estimated Annual Electrical Requirements				
	Plant Specifications			Consumption/Use
Electrical Energy	250 MWth	Brayton option 1	Centrifugal pumps	$5.09\text{x}10^4$ MWh
			Electromagnetic pumps	$6.04\text{x}10^4$ MWh
		Rankine	Centrifugal pumps	$7.20\text{x}10^5$ MWh
			Electromagnetic pumps	$8.15\text{x}10^5$ MWh
		Brayton option 2	Centrifugal pumps	$5.33\text{x}10^5$ MWh
			Electromagnetic pumps	$5.42\text{x}10^5$ MWh
	1000 MWth	Brayton option 1	Centrifugal pumps	$1.22\text{x}10^5$ MWh
			Electromagnetic pumps	$1.59\text{x}10^5$ MWh
		Rankine	Centrifugal pumps	$2.07\text{x}10^5$ MWh
			Electromagnetic pumps	$2.44\text{x}10^5$ MWh
		Brayton option 2	Centrifugal pumps	$2.05\text{x}10^6$ MWh
			Electromagnetic pumps	$2.45\text{x}10^6$ MWh
	2000 MWth	Brayton option 1	Centrifugal pumps	$2.17\text{x}10^5$ MWh
			Electromagnetic pumps	$2.93\text{x}10^5$ MWh
		Rankine	Centrifugal pumps	$3.86\text{x}10^5$ MWh
			Electromagnetic pumps	$4.62\text{x}10^5$ MWh
		Brayton option 2	Centrifugal pumps	$4.07\text{x}10^6$ MWh
			Electromagnetic pumps	$4.15\text{x}10^6$ MWh
Peak Electrical Demand	250 MWth	Brayton option 1	Centrifugal pumps	5.8 MWe
			Electromagnetic pumps	6.9 MWe
		Rankine	Centrifugal pumps	8.2 MWe
			Electromagnetic pumps	9.3 MWe
		Brayton option 2	Centrifugal pumps	60.8 MWe
			Electromagnetic pumps	61.9 MWe
	1000 MWth	Brayton option 1	Centrifugal pumps	13.9 MWe
			Electromagnetic pumps	18.2 MWe
		Rankine	Centrifugal pumps	23.6 MWe
			Electromagnetic pumps	27.9 MWe
		Brayton option 2	Centrifugal pumps	234 MWe
			Electromagnetic pumps	238 MWe
	2000 MWth	Brayton option 1	Centrifugal pumps	24.8 MWe
			Electromagnetic pumps	33.4 MWe
		Rankine	Centrifugal pumps	44.1 MWe
			Electromagnetic pumps	52.7 MWe
		Brayton option 2	Centrifugal pumps	465 MWe
			Electromagnetic pumps	473 MWe

Brayton cycle option 2 [Sienicki, 2007] is the bounding case of several possible options for driving the compressors. This case has a 156.4 MW turbine (for the 250 MWth plant) driving a larger size generator than would be the case if the compressors are driven directly by the turbine. Assuming a 1.5 % efficiency loss, the generator output is 154 MWe versus 95.9 MWe for the best estimate single-shaft case (Option 1). The excess plant electrical output essentially goes to energizing the motors that drive the compressors. Thus, while the compressors draw AC power from the grid, the larger generator outputs that power to the grid. The net electrical power leaving the plant is still close to but slightly less than the 95.9 MWe value for the single-shaft case. For the 1000 MWth plant, these power values increase by a factor of four, and for the 2000 MWth plant, they increase by a factor of eight.

Other ABR plant annual operational data estimates are presented in Table 6, with a detailed discussion available in Appendix A. Fossil fuel usage is from grounds maintenance, from monthly testing and potential emergency operation of the emergency

Table 6. ABR Estimated Annual Operations Data			
Data	**ABR Power Capacity**		
	250 MWth	**1000 MWth**	**2000 MWth**
Diesel fuel (No. 2 oil) for backup generator testing (gal/yr)	200	600	1200
Diesel fuel for grounds maintenance (gal/yr)	3350	4200	5000
Water	See Table 7	See Table 7	See Table 7
Process gases.			
Argon	Used in closed system, expected consumption less than 10 scf/hr.		
Nitrogen (scf)	7300	29,000	58,000
Hydrogen (liquid, ft^{3})	-	325, total per yr. 70 stored, if shipped in. 5 stored, if generated on-site.	650, total per yr. 150 stored, if shipped in. 10 stored, if generated on-site.
Carbon dioxide - CO_2 (kg.) – Brayton cycle only	54,000	216,000	432,000
Chemical use			
Sodium hypochlorite - NaOCl (lb/day, max)	160	630	1260
Sulfuric acid - H_2SO_4 (lb/day, max)	850	3400	6800
Sodium hydroxide - NaOH (lb/day max)	550	2200	4400
If a Rankine steam cycle is used:			
Steam - H_2O	Used in closed loop steam generators, minimal consumption		
Hydrazine – N_2H_4 (gal.)	550 annually 200 max. stored	2,200 annually 750 max. stored	4,400 annually 1,500 max. stored
Monoethanolamine (gal.)	1300 annually 200 max. stored	5,100 annually 650 max. stored	10,200 annually 1300 max. stored
Operational Employment			
Workers on site during normal operations	110	125	140
Workers on site during service shutdown	185	210	235
Total workers on payroll (all shifts)	300	344	385
Total RAD trained workers	220	250	280
Average annual dose to workers	To be provided by Tetra Tech		
Maximum worker dose	To be provided by Tetra Tech		

diesel generators, and possibly from a diesel fire pump, if it is determined that one is needed.

In general, the main process gases used are argon and hydrogen, plus CO_2 if a Brayton cycle is used, or nitrogen if a Rankine cycle is used [Chang, 2006]. Argon is used as a cover gas in the reactor, the intermediate heat transport system (IHTS), the IHTS cold traps, and for steam plant applications. Argon is also used for inerting the annular space between the reactor vessel and the guard vessel. Data from [Cutforth, 1971] indicate very low loss of argon from the system is expected. Nitrogen gas is used for steam generator water-side purging. For the 1000 and 2000 MWth plant designs, hydrogen gas is used to cool the main generator stator core and rotating field during operation, whereas the 250 MWth generator is small enough to be air-cooled. Two options are considered for providing hydrogen: having hydrogen delivered by an outside supplier and stored for use, or installing a hydrogen generator on-site and generating hydrogen continuously, with a 6-day reserve in storage. Argon, nitrogen, and CO_2 are all stored in tanks in liquid form and vaporized for use. Hydrogen is stored as a liquid in the hydrogen system.

If wet cooling towers are used, the makeup water required dwarfs the makeup required for process water treatment, as indicated in Table 7. If dry cooling towers are used, makeup water requirements are very low, but dry cooling towers would be much larger than wet cooling towers. Details of the data calculations are given in the discussion of Table 7 in Appendix A.

Table 7. Estimated Annual Makeup Water Usage

					Total		**Waste Water (blowdown plus process water)**	
ABR Power (MWth)	Cooling Tower Evaporation (gal.)	Cooling Tower Drift (gal.)	Cooling Tower Blowdown (gal.)	Max. Process Water (gal.)	Wet Cooling (gal.)	Dry Cooling (gal.)	Wet Cooling (gal.)	Dry Cooling (gal.)
250	5.57×10^8	1.47×10^7	3.55×10^8	1.64×10^7	9.43×10^8	1.64×10^7	3.71×10^8	1.64×10^7
1000	2.23×10^9	5.78×10^7	1.42×10^9	6.57×10^7	3.77×10^9	6.57×10^7	1.49×10^9	6.57×10^7
2000	4.46×10^9	1.16×10^8	2.84×10^9	1.31×10^8	7.55×10^9	1.31×10^8	2.97×10^9	1.31×10^8

Sodium hypochlorite is injected intermittently for bio-fouling control in the cooling tower and groundwater intake, plus minor amounts to the sanitary system discharge. Sulfuric acid is added occasionally to the cooling tower water and the chemical waste treatment system to control high pH. Sodium hydroxide pellets are added intermittently to the chemical waste treatment system. If a Rankine cycle is used, hydrazine is added to the feedwater as an oxygen scavenger, and monoethanolamine is added to control pH.

4. Summary of Nuclear Materials, Wastes, Effluents, Emissions, and Utilities during Operations and Construction

4.1 High-level Waste/Spent Nuclear Fuel

On average, one-third of the core is replaced each year. Table 8 lists the annual discharge for both fuel types and for the high and low candidate powers. See Appendix A for further details. The cycle length, or time elapsed between stoppages for refueling, is one year for the 1000 and 2000 MWth ABR designs, two months for the 250 MWth ABR. The 250 MWth ABR has a much shorter cycle length because a core this small has only limited room for control rods and so cannot accommodate a large reactivity swing. In the 1000 and 2000 MWth ABR candidate core designs, the cycle length was targeted at one year in order to increase the capacity factor. The longer cycle length results in a large reactivity swing, which can be handled by including a large number of control rods, since the core designs have sufficient space for many control rods.

Spent nuclear startup fuel will be stored on-site for eventual reprocessing

Table 8. Annual Spent Fuel Discharge from the ABR

ABR Power (MWth)	Metal Fuel		Oxide Fuel	
	Heavy Metal (kg.)	Assemblies	Heavy Metal (kg.)	Assemblies
250	850	24	890	24
1000	3100	45	2500	36
2000	5560	110	5760	110

4.2 Effluents from Operations

Table 9 provides estimated activities of significant radionuclides in the liquid radioactive waste effluent. Liquid radioactive waste comes from rinses to clean radioactivity and residual sodium from components removed from the primary and intermediate systems, plus liquid from floor drains, shower drains, and laboratory drains. The concentrations given in Table 9 assume that, after distillation and demineralization, a decontamination factor of 10^5 is achieved. Effluent radioactivity is assumed to scale approximately linearly with reactor power. This estimate is based upon the CRBRP evaluation of concentration of radionuclides in the effluent from the liquid radwaste systems ([CRBRP, 1977], Table 3.5-3), which assumed the effluent would be diluted by mixing with the blowdown from the wet cooling tower. If a dry cooling tower is used instead for the ABR plant, radioactive effluent will either need to be diluted by some other means or will need to be transported off-site for dilution and release.

Table 9. Estimated Activity of Liquid Waste Effluent from the ABR			
Isotope	**250 MWth ABR (μCi/cc)**	**1000 MWth ABR (μCi/cc)**	**2000 MWth ABR (μCi/cc)**
H-3	$2.06x10^{-9}$	$8.24x10^{-9}$	$1.65 x10^{-8}$
Na-22	$1.77 x10^{-14}$	$7.09 x10^{-14}$	$1.42 x10^{-13}$
Na-24	$5.05 x10^{-15}$	$2.02 x10^{-14}$	$4.04 x10^{-14}$
Cr-51	$1.42 x10^{-13}$	$5.68 x10^{-13}$	$1.14 x10^{-12}$
Mn-54	$1.00 x10^{-12}$	$4. 00 x10^{-12}$	$8.00 x10^{-12}$
Co-58	$6.15 x10^{-13}$	$2.46 x10^{-12}$	$4.92 x10^{-12}$
Fe-59	$4.93 x10^{-15}$	$1.97 x10^{-14}$	$3.94 x10^{-14}$
Co-60	$9.83 x10^{-13}$	$3.93 x10^{-12}$	$7.86 x10^{-12}$
Sr-89	$1.13 x10^{-13}$	$4.51 x10^{-13}$	$9.02 x10^{-13}$
Y-89m	$1.13 x10^{-13}$	$4.51 x10^{-13}$	$9.02 x10^{-13}$
Sr-90	$8.10 x10^{-14}$	$3.24 x10^{-13}$	$6.48 x10^{-13}$
Y-90	$8.10 x10^{-14}$	$3.24 x10^{-13}$	$6.48 x10^{-13}$
Y-91	$1.66 x10^{-13}$	$6.63 x10^{-13}$	$1.33 x10^{-12}$
Zr-95	$3.13 x10^{-13}$	$1.25 x10^{-12}$	$2.50 x10^{-12}$
Nb-95	$3.13 x10^{-13}$	$1.25 x10^{-12}$	$2.50 x10^{-12}$
Mo-99	$3.53 x10^{-14}$	$1.41 x10^{-13}$	$2.82 x10^{-13}$
Ru-103	$4.33 x10^{-13}$	$1.73 x10^{-12}$	$3.46 x10^{-12}$
Ru-106	$3.35 x10^{-13}$	$1.34 x10^{-12}$	$2.68 x10^{-12}$
Rh-106	$3.35 x10^{-13}$	$1.34 x10^{-12}$	$2.68 x10^{-12}$
Ag-111	$1.15 x10^{-14}$	$4.58 x10^{-14}$	$9.16 x10^{-14}$
Sb-125	$4.68 x10^{-16}$	$1.87 x10^{-15}$	$3.74 x10^{-15}$
Te-129m	$5.73 x10^{-16}$	$2.29 x10^{-15}$	$4.58 x10^{-15}$
Te-129	$5.73 x10^{-16}$	$2.29 x10^{-15}$	$4.58 x10^{-15}$
I-131	$2.17 x10^{-14}$	$8.68 x10^{-14}$	$1.74 x10^{-13}$
Te-132	$3.88 x10^{-15}$	$1.55 x10^{-14}$	$3.10 x10^{-14}$
I-132	$3.88 x10^{-15}$	$1.55 x10^{-14}$	$3.10 x10^{-14}$
Cs-134	$2.20 x10^{-15}$	$8.78 x10^{-15}$	$1.76 x10^{-14}$
Cs-136	$9.88 x10^{-15}$	$3.95 x10^{-14}$	$7.90 x10^{-14}$
Cs-137	$3.93 x10^{-14}$	$1.57 x10^{-13}$	$3.14 x10^{-13}$
Ba-140	$2.27 x10^{-13}$	$9.07 x10^{-13}$	$1.81 x10^{-12}$
La-140	$2.27 x10^{-13}$	$9.07 x10^{-13}$	$1.81 x10^{-12}$
Ce-141	$3.73 x10^{-13}$	$1.49 x10^{-12}$	$2.98 x10^{-12}$
Pr-143	$1.96 x10^{-13}$	$7.83 x10^{-13}$	$1.57 x10^{-12}$
Ce-144	$2.65 x10^{-13}$	$1.06 x10^{-12}$	$2.12 x10^{-12}$
Pr-144	$2.65 x10^{-13}$	$1.06 x10^{-12}$	$2.12 x10^{-12}$
Nd-147	$8.20 x10^{-14}$	$3.28 x10^{-13}$	$6.56 x10^{-13}$
Pm-147	$1.52 x10^{-13}$	$6.06 x10^{-13}$	$1.21 x10^{-12}$
Eu-155	$1.50 x10^{-14}$	$5.99 x10^{-14}$	$1.20 x10^{-13}$
Ta-182	$1.18 x10^{-13}$	$4.7 x10^{-13}$	$9.4 x10^{-13}$
Pu-239	$2.09 x10^{-16}$	$8.35 x10^{-16}$	$1.67 x10^{-15}$
Pu-240	$2.73 x10^{-16}$	$1.09 x10^{-15}$	$2.18 x10^{-15}$
Pu-241	$2.29 x10^{-14}$	$9.14 x10^{-14}$	$1.83 x10^{-13}$
Pu-242	$5.80 x10^{-19}$	$2.32 x10^{-18}$	$4.64 x10^{-18}$

4.3 Air Emissions from Operations

4.3.1 Radionuclide Emissions

Table 10 gives estimated annual gaseous emissions for significant radionuclides, based on expected annual releases calculated for CRBR ([CRBRP, 1977], Table 3.5-8). Releases are assumed to scale approximately linearly with reactor power.

4.3.2 Hazardous Air Pollutants

The only air pollutants emitted from the plant result from testing or emergency operation of the emergency generators and use of diesel-powered equipment for grounds maintenance. Releases from monthly testing are presented in Table 11, assuming the generators are diesel. Appendix A provides details of how the pollutant quantities were estimated. All pollutants are covered by the National Ambient Air Quality Standards of the U.S. Environmental Protection Agency.

Table 10. Estimated Annual Gaseous Radionuclide Emissions from the ABR

Radionuclide	Total Release from 250 MWth ABR, Ci	Total Release from 1000 MWth ABR, Ci	Total Release from 2000 MWth ABR, Ci
Xe-131 m	1.28×10^{-3}	5.1×10^{-3}	1.02×10^{-2}
Xe-133m	8.0×10^{-3}	3.2×10^{-2}	6.4×10^{-2}
Xe-133	0.145	0.58	1.16
Xe-135m	0.01	0.04	0.08
Xe-135	0.6	2.4	4.8
Xe-138	0.017	0.066	0.132
Kr-83m	0.017	0.066	0.132
Kr-85m	0.045	0.18	0.36
Kr-85	5.75×10^{-4}	2.3×10^{-3}	4.6×10^{-3}
Kr-87	0.0375	0.15	0.3
Kr-88	0.08	0.32	0.64
Ar-39*	0.3	1.2	2.4
Ar-41*	0.011	0.044	0.088
Ne-23*	4.75×10^{-3}	1.9×10^{-2}	3.8×10^{-2}
H-3*	0.17	0.66	1.32
Total	1.5	5.8	11.6

* Release rate independent of failed fuel fraction

Table 11. ABR Estimated Annual Release of Hazardous Air Pollutants

Pollutant	Annual Release (tons)		
	250 MWth	1000 MWth	2000 MWth
SO_2	4.1	5.5	7.1
Hydrocarbons	4.1	5.5	7.1
NO_x	41	45	71
CO	8.2	11.0	14.1

4.4 Transportation

4.4.1 Transportation Data for Shipment of Wastes

Estimated numbers of 55-gallon drums of solid radioactive waste which would be generated annually are provided in Table 12, based upon estimates for CRBR [CRBRP, 1977]. These quantities are consistent with the waste volumes discussed in Table 3. See Appendix A for calculation details.

Control rod assemblies, control rod assembly lines (cut to fit in the shipping cask), and radial shield assemblies can probably be shipped in any of several currently licensed shipping casks for radioactive materials.

Sanitary waste sludge and non-hazardous solid waste would be transported off site to commercial processing and/or disposal facilities.

4.4.2 Physics Data for Transportation of Spent Startup Driver Fuel

Several options for spent startup driver fuel from the ABR are currently being considered. These include 1) storing the spent fuel in the ABR Fuel Storage Facility indefinitely, 2) reprocessing the fuel in an on-site reprocessing facility, or 3) shipping the spent fuel off site for processing. If the fuel is shipped off site for processing periodically, the decay heat and isotopic composition of the spent fuel as a function of time after discharge must be evaluated against the heat and radiation limits of the spent fuel shipping casks. Table 13. lists decay heat per assembly as a function of time for both metal and oxide fuels at peak discharge burnup from the 250 MWth, 1000 MWth, and 2000 MWth cores. [Kim, 2007a] Tables 14 through 25 display, for each of the six candidate cores, isotopic mass per assembly of heavy metal nuclides and of fission products which are the dominant contributors to decay heat over the first ten years of post-irradiation cooling. [Kim, 2007a]

Table 12. Annual Estimated Low-Level Waste from the ABR

Waste Type	Number of 55-Gallon Drums		
	250 MWth	**1000 MWth**	**2000 MWth**
Compactible solids	28	28	28
Non-compactible solids	155	155	155
Solidified liquid radwaste	35	140	280

Table 13. Decay Heat per ABR Spent Startup Driver Fuel Assembly at Peak Discharge Burnup

Time	Decay Heat (kW)					
	250 MWth ABR		1000 MWth ABR		2000 MWth ABR	
	Metal	Oxide	Metal	Oxide	Metal	Oxide
discharge	227.4	227.1	300.6	281.4	334.1	329.3
30 days	10.5	10.6	9.3	8.6	10.0	10.1
1 year	2.9	3.0	5.9	5.5	2.6	2.6
2 years	1.4	1.5	2.6	2.4	1.3	1.4
3 years	1.0	1.0	1.4	1.3	0.8	0.8
5 years	0.7	0.7	0.8	0.8	0.4	0.4
10 years	0.6	0.6	0.4	0.5	0.2	0.2
15 years	0.5	0.6	0.3	0.3	0.2	0.2
20 years	0.5	0.6	0.2	0.3	0.2	0.2

Table 14. Actinide Isotopic Masses at Peak Discharge Burnup of 250 MWth ABR Spent Metal Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
U-234	6.51	6.77	9.76	13.10	16.44	23.05	39.14	54.63	69.53
U-235	21.57	21.58	21.73	21.89	22.06	22.38	23.19	24.01	24.82
U-236	4.25	4.28	4.63	5.01	5.39	6.16	8.06	9.97	11.88
U-237	0.08	3.8E-03	2.5E-05	2.4E-05	2.3E-05	2.1E-05	1.6E-05	1.3E-05	1.0E-05
U-238	17077.25	17077.25	17077.25	17077.25	17077.25	17077.25	17077.25	17077.25	17077.25
Np-237	486.14	486.49	487.18	488.56	489.60	492.02	498.94	506.89	515.53
Np-239	3.77	6.9E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04
Pu-238	402.81	407.31	427.71	430.48	428.40	422.18	406.62	391.40	376.88
Pu-239	5743.13	5746.59	5746.59	5746.59	5746.59	5746.59	5743.13	5743.13	5743.13
Pu-240	3647.80	3647.80	3647.80	3651.26	3651.26	3654.72	3661.63	3665.09	3668.55
Pu-241	842.97	839.51	803.21	765.52	729.56	662.48	520.72	409.38	321.87
Pu-242	755.84	755.84	755.84	755.84	755.84	755.84	756.18	756.18	756.18
Am-241	642.08	645.54	680.81	717.46	752.04	816.69	951.19	1054.58	1133.41
Am-242m	32.73	32.72	32.58	32.43	32.28	31.99	31.27	30.57	29.88
Am-243	162.27	162.27	162.27	162.23	162.23	162.20	162.13	162.06	161.96
Cm-242	35.86	31.71	7.69	1.69	0.42	0.09	0.08	0.07	0.07
Cm-243	1.37	1.36	1.33	1.30	1.27	1.21	1.07	0.95	0.84
Cm-244	52.56	52.42	50.62	48.72	46.89	43.43	35.86	29.61	24.46
Cm-245	6.17	6.17	6.17	6.17	6.16	6.16	6.16	6.16	6.16

Table 15. Fission Product Isotopic Masses at Peak Discharge Burnup of 250 MWth ABR Spent Metal Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
Kr-85	1.97	1.96	1.84	1.73	1.62	1.42	1.03	0.75	0.54
Y-90	9.5E-03	8.8E-03	8.6E-03	8.4E-03	8.2E-03	7.8E-03	7.0E-03	6.2E-03	5.5E-03
Sr-90	35.20	35.13	34.39	33.58	32.79	31.26	27.75	24.64	21.88
Rh-106	3.7E-05	3.5E-05	1.9E-05	9.4E-06	4.7E-06	1.2E-06	3.8E-08	1.2E-09	3.9E-11
Ag-108m	5.7E-07	5.7E-07	5.6E-07	5.6E-07	5.6E-07	5.5E-07	5.4E-07	5.2E-07	5.1E-07
Sb-125	3.26	3.21	2.56	1.99	1.55	0.94	0.27	0.08	0.02
Te-125m	0.04	0.04	0.04	0.03	0.02	1.3E-02	3.8E-03	1.1E-03	3.1E-04
Cs-134	7.02	6.83	5.02	3.59	2.56	1.31	0.24	0.05	0.01
Cs-137	159.92	159.60	156.25	152.69	149.20	142.45	126.93	113.06	100.76
Ba-137m	2.5E-05	2.4E-05	2.4E-05	2.3E-05	2.3E-05	2.2E-05	1.9E-05	1.7E-05	1.5E-05
Pr-144	1.5E-03	1.4E-03	6.2E-04	2.5E-04	1.0E-04	1.8E-05	2.0E-07	2.4E-09	2.8E-11
Sm-147	14.57	15.27	22.18	28.03	32.52	38.62	45.02	46.75	47.20
Pm-147	31.88	31.96	25.19	19.34	14.85	8.75	2.34	0.62	0.17
Sm-151	19.86	19.88	19.75	19.59	19.45	19.15	18.42	17.73	17.06
Eu-154	2.16	2.15	2.00	1.84	1.70	1.45	0.97	0.65	0.43
Eu-155	4.60	4.54	4.00	3.47	3.02	2.28	1.14	0.56	0.28

Table 16. Actinide Isotopic Masses at Peak Discharge Burnup of 250 MWth ABR Spent Oxide Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
U-234	7.28	7.57	10.90	14.61	18.32	25.66	43.52	60.73	77.30
U-235	23.47	23.49	23.64	23.82	23.99	24.34	25.20	26.07	26.93
U-236	5.00	5.04	5.41	5.82	6.22	7.04	9.07	11.12	13.16
U-237	8.6E-02	4.0E-03	2.7E-05	2.5E-05	2.4E-05	2.2E-05	1.7E-05	1.4E-05	1.1E-05
U-238	18932.27	18932.27	18932.27	18932.27	18932.27	18932.27	18932.27	18932.27	18932.27
Np-237	490.85	490.85	491.97	493.09	494.21	496.82	504.29	512.50	521.46
Np-239	4.35	7.9E-04	1.5E-04	1.5E-04	1.5E-04	1.5E-04	1.5E-04	1.5E-04	1.5E-04
Pu-238	447.92	452.78	475.55	478.16	475.92	469.20	451.66	434.86	418.44
Pu-239	6099.24	6102.97	6102.97	6102.97	6102.97	6102.97	6099.24	6099.24	6099.24
Pu-240	3896.94	3896.94	3900.68	3900.68	3900.68	3904.41	3911.87	3915.61	3919.34
Pu-241	902.19	898.84	860.01	819.33	780.88	709.21	557.67	438.22	344.53
Pu-242	799.55	799.55	799.55	799.55	799.55	799.92	799.92	799.92	800.29
Am-241	658.45	661.81	699.88	739.08	776.40	845.46	989.54	1100.40	1185.13
Am-242m	35.63	35.61	35.47	35.30	35.14	34.83	34.04	33.27	32.52
Am-243	173.57	173.61	173.57	173.57	173.53	173.50	173.42	173.35	173.27
Cm-242	39.23	34.69	8.42	1.85	0.46	0.10	0.08	0.08	0.08
Cm-243	1.84	1.84	1.79	1.75	1.71	1.63	1.44	1.28	1.13
Cm-244	59.69	59.54	57.48	55.32	53.23	49.31	40.72	33.64	27.78
Cm-245	7.33	7.33	7.32	7.32	7.32	7.32	7.32	7.32	7.31

Table 17. Fission Product Isotopic Masses at Peak Discharge Burnup of 250 MWth ABR Spent Oxide Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
Kr-85	2.00	1.99	1.87	1.76	1.65	1.45	1.05	0.76	0.55
Y-90	9.6E-03	9.0E-03	8.8E-03	8.6E-03	8.4E-03	8.0E-03	7.1E-03	6.3E-03	5.6E-03
Sr-90	35.89	35.82	35.05	34.23	33.42	31.87	28.29	25.12	22.30
Rh-106	3.7E-05	3.5E-05	1.9E-05	9.4E-06	4.7E-06	1.2E-06	3.9E-08	1.2E-09	4.0E-11
Ag-108m	5.7E-07	5.7E-07	5.7E-07	5.7E-07	5.6E-07	5.6E-07	5.4E-07	5.3E-07	5.1E-07
Sb-125	3.32	3.27	2.60	2.02	1.58	0.96	0.27	0.08	0.02
Te-125m	0.04	0.04	0.04	0.03	0.02	1.3E-02	3.8E-03	1.1E-03	3.1E-04
Cs-134	6.72	6.54	4.80	3.43	2.45	1.25	0.23	0.04	0.01
Cs-137	163.04	162.75	159.35	155.69	152.15	145.28	129.41	115.30	102.72
Ba-137m	2.5E-05	2.5E-05	2.4E-05	2.4E-05	2.3E-05	2.2E-05	2.0E-05	1.8E-05	1.6E-05
Pr-144	1.5E-03	1.4E-03	6.2E-04	2.5E-04	1.0E-04	1.8E-05	2.1E-07	2.4E-09	2.8E-11
Sm-147	15.32	16.04	23.15	29.17	33.79	40.05	46.66	48.45	48.90
Pm-147	32.84	32.90	25.92	19.91	15.28	9.01	2.40	0.64	0.17
Sm-151	20.48	20.51	20.37	20.21	20.06	19.75	19.00	18.28	17.59
Eu-154	2.11	2.09	1.95	1.79	1.66	1.41	0.94	0.63	0.42
Eu-155	4.69	4.64	4.08	3.55	3.08	2.33	1.16	0.58	0.29

Table 18. Actinide Isotopic Masses at Peak Discharge Burnup of 1000 MWth ABR Spent Metal Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
U-234	0.23	0.24	0.34	0.46	0.57	0.80	1.35	1.88	2.39
U-235	40.61	40.62	40.84	41.06	41.29	41.74	42.87	44.00	45.14
U-236	16.13	16.14	16.32	16.51	16.71	17.09	18.05	19.01	19.96
U-237	0.27	1.3E-02	5.2E-06	4.9E-06	4.7E-06	4.3E-06	3.4E-06	2.6E-06	2.1E-06
U-238	54912.55	54912.55	54912.55	54912.55	54912.55	54912.55	54912.55	54912.55	54912.55
Np-237	33.48	33.74	33.78	33.83	33.89	34.05	34.61	35.36	36.28
Np-239	13.21	1.9E-03	1.4E-06	1.4E-06	1.4E-06	1.4E-06	1.4E-06	1.4E-06	1.4E-06
Pu-238	13.99	14.14	14.68	14.74	14.65	14.44	13.89	13.37	12.86
Pu-239	7992.70	8003.58	8003.58	8003.58	8003.25	8003.25	8002.59	8002.26	8001.94
Pu-240	1839.94	1839.94	1839.61	1839.61	1839.18	1839.18	1838.09	1836.90	1836.14
Pu-241	175.64	174.96	167.41	159.57	152.06	138.08	108.55	85.32	67.08
Pu-242	21.44	21.44	21.44	21.45	21.45	21.45	21.45	21.45	21.45
Am-241	18.37	19.06	26.58	34.40	41.84	55.64	84.62	107.05	124.37
Am-242m	0.70	0.70	0.70	0.69	0.69	0.69	0.67	0.65	0.64
Am-243	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62
Cm-242	0.98	0.87	0.21	0.05	1.1E-02	2.1E-03	1.6E-03	1.6E-03	1.5E-03
Cm-243	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	2.0E-02
Cm-244	0.28	0.28	0.27	0.26	0.25	0.23	0.19	0.16	0.13
Cm-245	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	2.4E-02

Table 19. Fission Product Isotopic Masses at Peak Discharge Burnup of 1000 MWth ABR Spent Metal Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
Kr-85	4.80	4.77	4.50	4.22	3.95	3.47	2.51	1.82	1.32
Y-90	2.4E-02	2.2E-02	2.1E-02	2.1E-02	2.0E-02	1.9E-02	1.7E-02	1.5E-02	1.4E-02
Sr-90	87.02	86.83	84.99	82.99	80.99	77.28	68.59	60.90	54.07
Rh-106	5.1E-05	4.8E-05	2.5E-05	1.3E-05	6.4E-06	1.6E-06	5.2E-08	1.7E-09	5.4E-11
Ag-108m	1.4E-06	1.4E-06	1.4E-06	1.4E-06	1.4E-06	1.4E-06	1.3E-06	1.3E-06	1.2E-06
Sb-125	0.03	3.4E-03	1.2E-13	4.6E-25	1.8E-36	0.00	0.00	0.00	0.00
Te-125m	0.09	0.09	0.08	0.06	0.05	0.03	7.9E-03	2.3E-03	6.5E-04
Cs-134	27.35	26.61	19.54	13.96	9.98	5.09	0.95	0.18	0.03
Cs-137	362.72	362.00	354.42	346.33	338.40	323.14	287.89	256.49	228.48
Ba-137m	5.6E-05	5.5E-05	5.4E-05	5.3E-05	5.2E-05	4.9E-05	4.4E-05	3.9E-05	3.5E-05
Pr-144	2.1E-03	2.0E-03	8.7E-04	3.6E-04	1.5E-04	2.5E-05	2.9E-07	3.3E-09	3.9E-11
Sm-147	41.90	42.98	53.65	62.67	69.60	79.01	88.91	91.54	92.25
Pm-147	49.41	49.35	38.87	29.85	22.92	13.51	3.61	0.96	0.26
Sm-151	38.83	38.85	38.58	38.29	37.99	37.41	36.00	34.64	33.33
Eu-154	7.66	7.61	7.07	6.52	6.02	5.12	3.42	2.29	1.53
Eu-155	9.33	9.23	8.12	7.06	6.14	4.64	2.31	1.15	0.57

Table 20. Actinide Isotopic Masses at Peak Discharge Burnup of 1000 MWth ABR Spent Oxide Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
U-234	0.35	0.37	0.51	0.67	0.83	1.15	1.92	2.66	3.38
U-235	35.49	35.51	35.75	36.01	36.26	36.78	38.07	39.36	40.65
U-236	18.62	18.64	18.91	19.19	19.48	20.06	21.49	22.93	24.36
U-237	0.22	1.0E-02	9.2E-06	8.7E-06	8.3E-06	7.6E-06	6.0E-06	4.7E-06	3.7E-06
U-238	53121.47	53121.47	53121.47	53121.47	53121.47	53121.47	53121.47	53121.47	53121.47
Np-237	29.88	30.10	30.17	30.27	30.38	30.67	31.69	33.06	34.72
Np-239	12.90	1.9E-03	3.3E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06
Pu-238	19.05	19.31	20.48	20.65	20.56	20.27	19.52	18.79	18.09
Pu-239	9100.22	9115.84	9115.84	9115.84	9115.84	9115.84	9112.46	9108.03	9108.03
Pu-240	2757.29	2757.29	2756.85	2756.85	2756.85	2756.07	2754.51	2753.28	2751.72
Pu-241	311.15	309.92	296.55	282.58	269.28	244.59	192.27	151.12	118.80
Pu-242	43.93	43.93	43.93	43.93	43.93	43.94	43.94	43.95	43.95
Am-241	36.65	37.87	51.21	65.05	78.21	102.63	153.93	193.66	224.28
Am-242m	1.51	1.51	1.50	1.49	1.49	1.47	1.44	1.41	1.37
Am-243	3.79	3.80	3.80	3.79	3.79	3.79	3.79	3.79	3.79
Cm-242	1.99	1.76	0.43	0.09	0.02	4.4E-03	3.5E-03	3.4E-03	3.3E-03
Cm-243	0.10	0.10	0.09	0.09	0.09	0.08	0.07	0.07	0.06
Cm-244	0.81	0.81	0.78	0.75	0.72	0.67	0.55	0.46	0.38
Cm-245	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Table 21. Fission Product Isotopic Masses at Peak Discharge Burnup of 1000 MWth ABR Spent Oxide Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
Kr-85	5.27	5.24	4.94	4.63	4.34	3.81	2.76	2.00	1.45
Y-90	2.6E-02	2.5E-02	2.4E-02	2.3E-02	2.3E-02	2.2E-02	1.9E-02	1.7E-02	1.5E-02
Sr-90	98.06	97.90	95.78	93.54	91.30	87.10	77.32	68.63	60.93
Rh-106	4.9E-05	4.6E-05	2.4E-05	1.2E-05	6.2E-06	1.6E-06	5.0E-08	1.6E-09	5.2E-11
Ag-108m	1.6E-06	1.6E-06	1.6E-06	1.6E-06	1.6E-06	1.6E-06	1.6E-06	1.5E-06	1.5E-06
Sb-125	6.87	6.75	5.37	4.18	3.26	1.97	0.56	0.16	0.05
Te-125m	0.09	0.09	0.08	0.06	0.05	0.03	7.9E-03	2.3E-03	6.5E-04
Cs-134	27.02	26.29	19.31	13.79	9.86	5.03	0.94	0.17	0.03
Cs-137	415.08	414.26	405.60	396.28	387.28	369.74	329.43	293.48	261.48
Ba-137m	6.4E-05	6.3E-05	6.2E-05	6.1E-05	5.9E-05	5.7E-05	5.0E-05	4.5E-05	4.0E-05
Pr-144	2.0E-03	1.8E-03	8.1E-04	3.3E-04	1.4E-04	2.3E-05	2.7E-07	3.1E-09	3.6E-11
Sm-147	57.94	59.09	70.52	80.20	87.60	97.68	108.32	111.11	111.86
Pm-147	53.07	52.88	41.63	31.96	24.54	14.47	3.86	1.03	0.27
Sm-151	45.64	45.66	45.34	44.99	44.65	43.97	42.31	40.71	39.17
Eu-154	8.37	8.31	7.72	7.12	6.57	5.59	3.74	2.50	1.67
Eu-155	10.14	10.02	8.82	7.67	6.67	5.04	2.51	1.25	0.62

Table 22. Actinide Isotopic Masses at Peak Discharge Burnup of 2000 MWth ABR Spent Metal Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
U-234	0.10	0.10	0.11	0.16	0.23	0.30	0.44	0.77	1.08
U-235	31.78	31.80	31.83	31.99	32.21	32.43	32.85	33.93	35.01
U-236	11.31	11.33	11.37	11.52	11.73	11.94	12.36	13.42	14.46
U-237	0.19	8.9E-03	2.5E-05	6.2E-06	5.9E-06	5.6E-06	5.1E-06	4.0E-06	3.2E-06
U-238	38106.10	38106.10	38106.10	38106.10	38106.10	38106.10	38106.10	38106.10	38106.10
Np-237	15.53	15.72	15.73	15.75	15.80	15.86	16.02	16.64	17.49
Np-239	12.95	1.9E-03	1.6E-06	1.6E-06	1.6E-06	1.6E-06	1.6E-06	1.6E-06	1.6E-06
Pu-238	7.89	8.04	8.24	8.70	8.82	8.79	8.66	8.34	8.03
Pu-239	7589.82	7603.81	7603.81	7603.81	7603.81	7603.81	7603.81	7601.96	7601.96
Pu-240	2017.40	2017.40	2017.21	2017.21	2016.83	2016.65	2016.27	2015.52	2014.39
Pu-241	209.86	209.03	207.39	200.02	190.60	181.63	164.97	129.69	101.95
Pu-242	24.96	24.96	24.96	24.96	24.96	24.96	24.96	24.97	24.97
Am-241	15.17	16.00	17.64	25.01	34.36	43.25	59.75	94.42	121.31
Am-242m	0.58	0.58	0.58	0.58	0.58	0.58	0.57	0.56	0.55
Am-243	1.88	1.88	1.88	1.88	1.88	1.88	1.88	1.88	1.87
Cm-242	1.09	0.97	0.75	0.23	0.05	1.2E-02	1.9E-03	1.4E-03	1.3E-03
Cm-243	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03
Cm-244	0.34	0.34	0.34	0.33	0.32	0.31	0.28	0.23	0.19
Cm-245	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03

Table 23. Fission Product Isotopic Masses at Peak Discharge Burnup of 2000 MWth ABR Spent Metal Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
Kr-85	3.82	3.80	3.76	3.59	3.36	3.15	2.77	2.00	1.45
Y-90	1.9E-02	1.7E-02	1.7E-02	1.7E-02	1.6E-02	1.6E-02	1.5E-02	1.3E-02	1.2E-02
Sr-90	67.58	67.46	67.19	65.99	64.43	62.93	60.00	53.27	47.29
Rh-106	5.5E-05	5.2E-05	4.7E-05	2.8E-05	1.4E-05	7.0E-06	1.8E-06	5.7E-08	1.8E-09
Ag-108m	1.1E-06	1.1E-06	1.1E-06	1.1E-06	1.1E-06	1.1E-06	1.1E-06	1.1E-06	1.0E-06
Sb-125	5.87	5.78	5.55	4.60	3.58	2.79	1.69	0.48	0.14
Te-125m	0.07	0.08	0.07	0.06	0.05	0.04	0.02	0.01	1.9E-03
Cs-134	20.71	20.14	19.06	14.79	10.57	7.55	3.86	0.72	0.13
Cs-137	291.08	290.55	289.44	284.44	277.95	271.59	259.31	231.03	205.83
Ba-137m	4.5E-05	4.4E-05	4.4E-05	4.4E-05	4.3E-05	4.2E-05	4.0E-05	3.5E-05	3.1E-05
Pr-144	2.3E-03	2.2E-03	1.9E-03	9.5E-04	3.9E-04	1.6E-04	2.7E-05	3.1E-07	3.7E-09
Sm-147	27.15	28.17	30.17	38.31	46.90	53.50	62.44	71.87	74.36
Pm-147	46.81	46.92	45.12	36.98	28.39	21.80	12.85	3.43	0.92
Sm-151	32.13	32.18	32.14	31.95	31.70	31.46	30.98	29.81	28.68
Eu-154	5.54	5.50	5.43	5.11	4.71	4.35	3.70	2.47	1.65
Eu-155	7.90	7.81	7.64	6.87	5.98	5.20	3.93	1.95	0.97

Table 24. Actinide Isotopic Masses at Peak Discharge Burnup of 2000 MWth ABR Spent Oxide Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
U-234	0.11	0.12	0.13	0.19	0.27	0.35	0.53	0.95	1.34
U-235	23.17	23.19	23.23	23.39	23.62	23.83	24.28	25.39	26.50
U-236	10.65	10.67	10.72	10.93	11.22	11.50	12.06	13.46	14.87
U-237	0.19	8.75E-03	2.84E-05	9.69E-06	9.22E-06	8.75E-06	8.04E-06	6.26E-06	4.96E-06
U-238	31310.54	31310.54	31310.54	31310.54	31310.54	31310.54	31310.54	31310.54	31310.54
Np-237	13.12	13.31	13.32	13.36	13.43	13.52	13.77	14.70	16.03
Np-239	13.26	2.01E-03	3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06
Pu-238	9.31	9.57	9.94	10.78	11.02	10.99	10.85	10.45	10.06
Pu-239	7835.27	7848.22	7848.22	7848.22	7848.22	7848.22	7848.22	7848.22	7845.74
Pu-240	2698.41	2698.41	2698.23	2698.23	2697.88	2697.71	2697.18	2695.79	2694.57
Pu-241	328.56	327.27	324.70	313.12	298.42	284.38	258.28	203.03	159.61
Pu-242	45.14	45.14	45.14	45.14	45.14	45.14	45.14	45.14	45.14
Am-241	21.19	22.49	25.06	36.59	51.24	65.16	91.03	145.30	187.39
Am-242m	0.92	0.92	0.92	0.91	0.91	0.91	0.90	0.87	0.85
Am-243	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
Cm-242	1.93	1.71	1.32	0.41	0.09	0.02	2.96E-03	2.13E-03	2.13E-03
Cm-243	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.07	0.07
Cm-244	0.85	0.85	0.84	0.82	0.79	0.76	0.70	0.58	0.48
Cm-245	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Table 25. Fission Product Isotopic Masses at Peak Discharge Burnup of 2000 MWth ABR Spent Oxide Fuel

Isotope	Mass per Assembly (g.)								
	discharge	30 days	1 yr.	2 yr.	3 yr.	5 yr.	10 yr.	15 yr.	20 yr.
Kr-85	4.48	4.46	4.41	4.20	3.94	3.69	3.24	2.34	1.70
Y-90	2.2E-02	2.0E-02	2.0E-02	1.9E-02	1.9E-02	1.9E-02	1.8E-02	1.5E-02	1.4E-02
Sr-90	78.79	78.64	78.33	76.96	75.14	73.38	69.96	62.10	55.14
Rh-106	6.7E-05	6.3E-05	5.7E-05	3.3E-05	1.7E-05	8.5E-06	2.1E-06	6.9E-08	2.2E-09
Ag-108m	1.4E-06	1.3E-06	1.3E-06	1.3E-06	1.3E-06	1.3E-06	1.3E-06	1.3E-06	1.3E-06
Sb-125	6.73	6.62	6.36	5.26	4.10	3.19	1.94	0.56	0.15
Te-125m	0.08	0.08	0.08	0.07	0.06	0.05	0.02	0.01	2.2E-03
Cs-134	25.47	24.79	23.45	18.20	13.00	9.29	4.74	0.89	0.17
Cs-137	344.86	344.21	342.91	337.01	329.29	321.79	307.24	273.72	243.86
Ba-137m	5.3E-05	5.3E-05	5.2E-05	5.2E-05	5.1E-05	5.0E-05	4.7E-05	4.1E-05	3.8E-05
Pr-144	2.7E-03	2.6E-03	2.2E-03	1.1E-03	4.6E-04	1.9E-04	3.2E-05	3.8E-07	4.4E-09
Sm-147	31.51	32.71	35.03	44.54	54.55	62.23	72.67	83.66	86.61
Pm-147	54.57	54.70	52.61	43.12	33.11	25.42	14.99	4.00	1.06
Sm-151	37.66	37.71	37.66	37.43	37.15	36.87	36.30	34.93	33.62
Eu-154	6.73	6.68	6.58	6.21	5.72	5.28	4.49	3.00	2.01
Eu-155	9.43	9.33	9.11	8.20	7.13	6.19	4.69	2.33	1.16

4.5 Construction

4.5.1 General Construction Requirements

Preliminary estimates of construction requirements for the ABR plant are summarized in Table 26. Steel usage includes structural steel, component steel, furnishings, support systems such as fire protection and railroads, fences, and steel used in the HVAC and electrical systems. Water requirements include compaction of fill, dust control, fire protection, sanitary facilities, production of concrete, and other construction-related activities. See the discussion of Table 26 in Appendix A for further details regarding the basis for the estimates presented in the table.

4.5.2 Construction Land Requirements

Table 27 outlines the estimated land use needed to build an ABR. Details of how these estimates were obtained are given in Appendix A. Once an accident analysis of the ABR is completed and radioactivity release values are available, the total site area will be adjusted consistent with regulatory requirements governing releases at the site boundary.

4.5.3 Construction Wastes

It is assumed that no low-level or mixed low-level radioactive wastes will be generated during the construction of the ABR plant. The estimated quantities of all hazardous and non-hazardous construction wastes are listed in Table 28. These wastes are assumed to scale with plant size. The information used to generate these waste estimates is provided in the discussion of Table 28 in Appendix A and in the spreadsheet tables listed in Appendix B.

Table 26. Preliminary Construction Requirements for the ABR

	ABR Power Capacity		
	250 MWth	**1000 MWth**	**2000 MWth**
Construction Period (including cold start-up)	5 years	5.5 years	6 years
Construction Employment			
Total worker years	2700	7000	11400
Peak workers (4th or 5th year)	780	2050	3330
Materials/Resources Consumed During Construction Period			
Electrical Power required (Peak)	9 MWe	23 MWe	38 MWe
Power available from back-up generators	2 MWe	6 MWe	12 MWe
Back-up generators, fuel type.	Internal combustion, diesel or natural gas		
Concrete (yd^3)	76,000	200,000	325,000
Steel (tons)	9,900	24,700	39,200
Liquid fuel (gal.)	60,000	144,00	243,000
Lube oil (gal.)	700	1,700	2,900
Water (gal/day, max.)	20,000	51,000	83,000

Table 27. Estimated ABR Construction Land Requirements

	ABR Power Capacity		
	250 MWth	**1000 MWth**	**2000 MWth**
Land Use	**Land Area (acres)**	**Land Area (acres)**	**Land Area (acres)**
Total Permanent Site	1100	1400	1640
Facilities	80	100	120
Plant	3	4	5
Temporary Laydown Area	60	160	250
Temporary Parking Lots	5	12	20
Permanent Parking Lots	2	2	3

Table 28. Estimated Total Construction Wastes for an ABR Plant						
Waste	**Liquid (gal.)**			**Solid**		
	250 MWth	**1000 MWth**	**2000 MWth**	**250 MWth**	**1000 MWth**	**2000 MWth**
Hazardous	7,200	21,000	37,200	1.4 yd^3	4.1 yd^3	7.2 yd^3
Non-hazardous (sanitary):	-	-	-	440 tons	1,150 tons	1,870 tons
- Liquid waste processed on site	23,000,000	61,000,000	99,000,000	-	-	-
- Portable toilets	196,000	518,000	841,000	-	-	-
Non-hazardous (other)	82,000	217,000	352,000	32,400 yd^3	85,600 yd^3	139,000 yd^3

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Appendix A: Bases for Data Presented

As mentioned in Sec. 1, the datacall information presented in this report was derived from a number of information sources. Table A.1 identifies these sources with the particular data parameters to which each source contributed.

Table A.1. Data Sources for Various Parameters

Data Source	**Parameters**
Clinch River Breeder Reactor Plant Environmental Report [CRBRP, 1977]	Employment estimates (construction and operations), liquid radioactive waste effluent activities, radionuclide gaseous emissions, radioactive and hazardous wastes volumes, sanitary liquid waste, plant power consumption, fossil fuel usage (construction and operations), chemical usage (sodium hypochlorite, sulfuric acid, sodium hydroxide), water usage (construction and operations), quantities of hazardous air pollutants, concrete volume for construction, land requirements, sanitary liquid wastes, plant electrical requirements
Clinch River Breeder Reactor Preliminary Safety Analysis Report [CRBRP, 1982]	Employment estimates
National Enrichment Facility Safety Analysis Report [NEF, 2005] and Environmental Impact Statement [USNRC, 2005]	Construction hazardous wastes
Missouri Department of Natural Resources [MDNR, 2006]	Construction solid sanitary wastes
Energy Economic Data Base [USDOE , 1988]	Construction sanitary and non-hazardous wastes, steel usage
Caterpillar Performance Handbook [Caterpillar 1990]	Construction liquid fuel and lube oil.
ABTR Preconceptual Design Report [Chang, 2006]	Plant power consumption, plant layout and building dimensions, inert gases used, plant electrical requirements, operations fossil fuel usage, process gases
Fuel cycle analyses performed for the ABR [Kim, 2006a], [Kim, 2006b], [Kim, 2007a], [Kim, 2007b]	Fissile inventory, spent fuel discharge, decay heat and isotopic masses of spent fuel.
Spallation Neutron Source [Lawson, 2007]	Construction electrical requirements
San Onofre Nuclear Generating Station [Flores, 2007]	Process gases, chemical usage (hydrazine, monoethanalomine
Zeeland Generating Plant [Mirant, 2007] and [Speranza, 2005]	Hydrogen usage
Portable Sanitation Association International [PSAI, 2006]	Construction liquid sanitary wastes
Power Engineering article on cooling of generators [Smith, 2002]	Hydrogen usage

As indicated in Sec. 3.1, values for some operational parameters and some construction parameters are dependent upon reactor power, but not necessarily by a simple linear dependence. Table A.2 summarizes the various techniques used to adjust parameters for reactor power. Details of these adjustments are discussed in the explanations below of the calculations used for the data presented in each table.

Table A.2. Approaches to Scaling for Reactor Power for Various Parameters

Parameters	Scaling Approach
Fissile inventory, spent fuel discharge, spent fuel physics data	Fuel cycle analysis of candidate core designs
Building and structure dimensions	Sized to fit equipment
Low-level liquid waste	Linear with power
Low-level solid waste	Linear with power for solidified liquid radwaste
Mixed low-level solid waste	Linear with power for most components
Hazardous liquid and solid wastes	Linear with power
Sanitary liquid and solid wastes	Linear with power
Solid non-hazardous waste	Linear with power
Electrical demand for operations	Linear scaling with power for sodium and water pumps, CO_2 compressors (Brayton cycle option), feedwater and condensate pumps (Rankine cycle option)
Emergeny generator fossil fuel use	Linear with generator capacity
Grounds maintenance fossil fuel use	Scaled to facilities areas
Process gases	Linear with power
Process chemicals	Linear with power
Operations employment	88% of CRBRP for 250 MWth, 112% for 2000 MWth
Water usage	Linear with power
Activity of liquid waste effluent and gaseous radionuclide emissions	Linear with power
Hazardous air pollutants	Linear with power
Construction time	Data on construction of existing plants
Construction employment	$(P_{ABR}/P_{CRBR})^{0.7}$ (take P_{CRBR} to be 1000 MWth)
Construction electrical power	Linear scaling
Concrete	$(P_{ABR}/P_{CRBR})^{0.7}$ (take P_{CRBR} to be 1000 MWth)
Steel	Primarily scaling by $(P_{ABR}/P_{PWR})^{0.7}$
Construction liquid fuel and lube oil	Proportional to land requirements and concrete volume
Construction water consumption	$(P_{ABR}/P_{CRBR})^{0.7}$ (take P_{CRBR} to be 1000 MWth)
Land requirements	80% of CRBRP for 250 MWth, 120% for 2000 MWth
Construction wastes	Primarily scaling by $(P_{ABR}/P_{PWR})^{0.7}$

Table 1 (fissile inventory):

The maximum inventory of core fissile material is in the startup cores. Isotopes included are U-235, Pu-239, Pu-241, and Am-242m. Inventories for the 2000 MWth core designs include an entire batch of discharged fuel assemblies in the in-vessel storage. BOEC inventories discussed in [Kim, 2006b] for a 250 MWth ABR and in [Kim, 2007b] for a 1000 MWth ABR do not include in-vessel storage; therefore, the fissile discharge from a single batch (the annual discharge for the 1000 MWth ABR; one-sixth of the annual discharge for the 250 MWth ABR, since fuel is discharged from the 250 MWth design every two months) was added to the BOEC inventory in order to make a consistent comparison with the inventories for the 2000 MWth plant.

In-vessel 2000 MWth metal fuel fissile inventory = 28.3 + 4536.5 + 42.6 + 0.1
≈ 4600 kg.
(from Table 4.3, [Kim, 2006a])

In-vessel 1000 MWth metal fuel fissile inventory = (17.4 + 1824.1 + 12.8) +
(2.6 + 396.3 + 5.8)
≈ 2260 kg
(from [Kim, 2007b])

In-vessel 250 MWth metal fuel fissile inventory = (1.9 + 446.5 + 66.7 + 0.9) +
(0.7 + 173.6 + 25.5 + 0.7)/6
≈ 550 kg
(from Table 6.7, [Kim, 2006b])

The 2000 MWth oxide core discussed in [Kim, 2006a] has a higher TRU conversion ratio than the 2000 MWth metal core, and so, in order to estimate fissile inventory for the oxide core on the same basis as for the metal core, the oxide core must be adjusted as follows to achieve the same TRU conversion ratio as the metal core.

For a 2000 MWth oxide core,

oxide fissile discharge rate = oxide fissile charge rate –
oxide fissile material consumption

If the oxide core achieves the same conversion ratio as the metal core, then

oxide core fissile material consumption = metal core fissile material consumption
= metal startup core fissile charge –
metal startup core fissile discharge
= (9.5+1314.3+8.7) – (4.7+943+18.8+0.1)
≈ 370 kg./yr.
(from Table 3.4, [Kim, 2006a])

The oxide fissile charge rate is adjusted for the TRU conversion ratio as follows:

oxide adj. fissile charge rate = (oxide TRU charge rate at the orig. conv. ratio)x
(metal fissile charge rate)/(metal TRU charge rate)
= (1468.9)(9.5+1314.3+8.7)/1422.1)
≈ 1380 kg./yr.
(from Table 3.4, [Kim, 2006a])

The adjusted oxide fissile discharge rate is then

oxide adjusted fissile discharge rate ≈ 1380 – 370 ≈ 1010 kg./yr.

The adjusted BOEC oxide core fissile inventory, assuming that replacing the entire core requires three batches, can be found from

adj. oxide core fissile inv. = (adj. oxide core heavy metal (HM) inv.)x
(metal core fissile inventory)/(metal core HM inv.)

adj. oxide core HM inv. = (no. of batches)x((total metal HM charge)/
(total metal TRU charge))x(orig. oxide TRU charge) -
(oxide HM consumption)
= (3)x((6233.0)/(1422.1))*(1468.9) – (4884.9-4209.4)
≈ 18,640 kg.
(from Table 3.4, [Kim, 2006a])

The metal core fissile inventory is the total BOEC fissile inventory minus the in-vessel storage, or

metal core fissile inventory = BOEC total fissile inventory
– BOEC in-vessel storage fissile inventory
= (28.3-4.7)+(4536.5-948.8)+(42.6-17.3)+0.1
≈ 3700 kg
(from Table 4.3, [Kim, 2006a])

Therefore,

adj. oxide core fissile inv. = (18,640)*(3700)/(2657.9+5848.2+9522.7)
≈ 3760 kg.
(from Table 4.3, [Kim, 2006a])

The in-vessel fissile inventory for the 2000 MWth oxide core is therefore

In-vessel 2000 MWth oxide fuel fissile inventory = core fissile inv. +
1 cycle discharge
≈ 3760 + (1010)/1
= 4770 kg.

Making similar adjustments to the 250 MWth oxide core,

oxide core fissile material consumption = metal core fissile material consumption
= metal startup core fissile charge –
metal startup core fissile discharge
= (1.0+222.6+33.8) –
(0.7+173.6+25.5+0.7)
≈ 57 kg./yr.
(from Table 6.7, [Kim, 2006b])

The oxide fissile charge rate is then adjusted for the TRU conversion ratio as

oxide adj. fissile charge rate = (oxide TRU charge rate at the orig. conv. ratio)x
(metal fissile charge rate)/(metal TRU charge rate)
= (449.2)(1.0+222.6+33.8)/431.0)
≈ 268 kg./yr.
(from Tables 6.7 and 6.8, [Kim, 2006b])

The adjusted oxide fissile discharge rate is then

oxide adjusted fissile discharge rate ≈ 268-57 ≈ 211 kg./yr.

The adjusted BOEC oxide core fissile inventory, assuming that the average fuel residence time is 2.25 batches, can be found from

adj. oxide core fissile inv. = (adj. oxide core heavy metal (HM) inv.)x
(metal core fissile inventory)/(metal core HM inv.)

adj. oxide core HM inv. = (no. of batches)x((total metal HM charge)/
(total metal TRU charge))x(orig. oxide TRU charge) -
(oxide HM consumption)
= (2.25)x((932.7)/(431.0))*(449.2) – (1007.8-923.5)
≈ 2,103 kg.
(from Tables 6.7 and 6.8, [Kim, 2006b])

The metal core fissile inventory is the BOEC fissile inventory, or

BOEC core fissile inventory = 1.9+446.5+66.7+0.9 ≈ 516 kg.
(from Table 6.7, [Kim, 2006b])

Therefore,

adj. oxide core fissile inv. = (2,103)*(516)/(1984.6)
≈ 545 kg.
(from Table 6.7, [Kim, 2006b])

The in-vessel fissile inventory for the 250 MWth oxide core is therefore

In-vessel 250 MWth oxide fuel fissile inventory = core fis. inv. + 1 cycle discharge
≈ 545 + (211)*(2/12 yr.)
= 580 kg.

The 1000 MWth oxide and metal cores addressed in [Kim, 2007b] have very similar conversion ratios. Therefore, the in-vessel fissile inventory for the 1000 MWth oxide core is calculated directly from the inventory and mass flow values given in [Kim, 2007b], or

In-vessel 1000 MWth oxide fuel fissile inventory = core fis. inv. + 1 cycle discharge
= (16.2+2137.6+21.4) + (1.8+362.8+8.6)
≈ 2550 kg.

Assuming the startup fuel is stored on-site indefinitely, the maximum fissile inventory at the plant can be estimated from the annual fissile discharge inventory over the sixty years of reactor operation, plus the beginning of equilibrium cycle (BOEC) core fissile inventory (total metal fuel fissile inventory, minus the spent fuel fissile inventory in the in-vessel storage). For a 2000 MWth metal core operating sixty years and discharging fuel annually,

Total discharge fissile inventory = (60-(cycle length (mo.))/12)(discharge inv. rate)
= (60-(12/12) yrs.)(4.7+943.0+18.8+0.1 kg/yr)
≈ 57,000 kg.
(from Table 3.4, [Kim, 2006a])

BOEC core fissile inventory = BOEC total fissile inventory
– BOEC in-vessel storage fissile inventory
= (28.3-4.7)+(4536.5-948.8)+(42.6-17.3)+0.1
≈ 3600 kg
(from Table 4.3, [Kim, 2006a])

Maximum 2000 MWth metal fissile inventory = Total discharge fissile inv. + BOEC core fissile inv.
= 57,000 + 3600
= 60,600 kg.

For a 1000 MWth metal core operating sixty years and discharging fuel annually,

Total discharge fissile inventory = (60-(cycle length (mo.))/12)(discharge inv. rate)
= (60-(12/12) yrs.)(2.6+396.3+5.8 kg/yr)
≈ 23,900 kg.
(from [Kim, 2007b])

BOEC core fissile inventory = 17.4+1824.1+12.8 ≈ 1850 kg.
(from [Kim, 2007b])

Maximum 1000 MWth metal fissile inventory ≈ 23,900 + 1850 ≈ 25,700 kg.

Finally, the maximum fissile inventory for a 250 MWth metal core ABR which discharges fuel every two months can be estimated as

Total discharge fissile inventory = (60-(2/12)yr.)(0.7+173.6+25.5+0.7 kg/yr.)
≈ 12,000 kg.
(from Table 6.7, [Kim, 2006b])

BOEC core fissile inventory = 1.9+446.5+66.7+0.9 ≈ 500 kg.
(from Table 6.7, [Kim, 2006b])

Maximum 250 MWth metal fissile inventory ≈ 12,000 + 500 = 12,500 kg.

Using the adjusted oxide fissile discharge rate and the adjusted oxide core fissile inventory calculated above for a 2000 MWth oxide core, the maximum fissile inventory for a 2000 MWth ABR oxide core plant operating 60 years is

Maximum 2000 MWth oxide fissile inventory ≈ (60-(12/12) yr.)*(1010 kg/yr.)
+ 3760 kg.
≈ 63,400 kg.

The maximum fissile inventory for a 1000 MWth ABR oxide core plant operating 60 years is calculated as

Total discharge fissile inventory = (60-(cycle length (mo.))/12)(discharge inv. rate)
= (60-(12/12) yrs.)(1.8+362.8+8.6 kg/yr)
≈ 22,000 kg.
(from [Kim, 2007b])

BOEC core fissile inventory = 16.2+2137.6+21.4 ≈ 2200 kg.
(from [Kim, 2007b])

Maximum 1000 MWth oxide fissile inventory ≈ 22,000+2200 ≈ 24,200 kg.

Finally, using the adjusted oxide fissile discharge rate and the adjusted oxide core fissile inventory calculated above for a 250 MWth oxide core, the maximum fissile inventory for a 250 MWth ABR oxide core plant operating 60 years is

Maximum 250 MWth oxide fissile inventory ≈ (60-(2/12)yr.)*(211 kg/yr.)
+ 545 kg.
≈ 13,200 kg.

Table 3 (radioactive and hazardous wastes from operations):

Low-level liquid waste ([CRBRP, 1977], Secs. 3.5.1.2, 3.5.1.3). In the CRBRP design, there are two systems which produce low-level liquid waste: an intermediate activity level liquid process system, which processes aqueous effluent from cleaning residual sodium and radioactivity from components removed from the primary and intermediate sodium loops, and a low activity level liquid radwaste system, which processes liquid effluents from floor drains, shower drains, and laboratory drains. Both systems decontaminate liquids by filtration, evaporation, and demineralization. Both systems discharge liquid only after sampling and analysis confirm that the liquid meets release limits. The intermediate activity level liquid process system discharges 4,000 gal. of water per year, diluted by the cooling tower blowdown. The low activity level liquid radwaste system drains 850 gal./day into a discharge stream. Combined discharge is therefore

$$[4000 \text{ gal./yr.} + (850 \text{ gal./day})\text{x}(365 \text{ days/yr.})] = 3.14\text{x}10^5 \text{ gal./yr.}$$

Since the CRBRP power was nearly 1000 MWth, this is the value taken for the 1000 MWth ABR. To adjust for the power difference between CRBR and a 2000 MWth ABR, this quantity is doubled, so the total discharge is 6.3 x10^5 gal./yr. To adjust for the power difference between CRBR and a 250 MWth ABR, this quantity is cut by a factor of four, so the total discharge is 7.9 x10^4 gal./yr.

Low-level solid waste ([CRBRP, 1977], Sec. 3.5.3, Table 3.5-10). Includes compactible solids (rags, paper, seals – 200 cu. ft. after compaction, assuming compaction decreases volume by a factor of ten), non-compactible solids (low activity scrapped components and components metal from cutting operations, 572 cu. ft., and resins, 450 cu. ft.), and solidified liquid radwaste (concentrated material from the bottom of the low-level and intermediate level system evaporators which is drawn off and solidified, 1,000 cu. ft.). The solidified liquid radwaste quantity was assumed to scale linearly with ABR power. Therefore, for a 2000 MWth ABR, the total volume of low-level solid waste is estimated as

$$(200 + 572 + 450 + 2\text{x}1000 \text{ ft}^3.)/(27 \text{ yd}^3./ \text{ ft}^3.) = 119 \text{ yd}^3/\text{yr.}$$

For a 1000 MWth ABR, the total volume of low-level solid waste is estimated as

$$(200 + 572 + 450 + 1000 \text{ ft}^3.)/(27 \text{ yd}^3./ \text{ ft}^3.) = 82 \text{ yd}^3/\text{yr.},$$

and for a 250 MWth ABR, the total volume of low-level solid waste is estimated as

$$(200 + 572 + 450 + 1000 \text{ ft}^3./4)/(27 \text{ yd}^3./ \text{ ft}^3.) = 55 \text{ yd}^3/\text{yr.}$$

Mixed low-level solid waste ([CRBRP, 1977], Sec. 3.8.3 and Sec. 3.5.3, Table 3.5-10). Includes control rod assemblies and drive lines and radial shield assemblies, which are both radioactive and contaminated with sodium. Also, from Table 3.5-10, Sec. 3.5.3, includes 1) filters contaminated with radioactivity and sodium (165 cu. ft.),

2) ex-vessel storage tank sodium (42 cu. ft.), and 3) sodium-bearing solids (235 cu. ft.).

According to Sec. 3.8.3 of [CRBRP, 1977], all nineteen CRBR control rods were to be replaced every year, nineteen drive lines were to be replaced every ten years, and shield assemblies were to be replaced as follows: 72 assemblies every three years for the first row, 78 assemblies every six years for the second row, 84 assemblies every twelve years for the third row, and 90 assemblies every twenty-four years for the fourth row. ANL has not yet optimized either the number of control rods or the control rod worths for the candidate ABR cores, nor has an evaluation been done to determine the frequency with which control rods, reflectors, and shields would be replaced. Therefore, the CRBR values given in [CRBRP, 1977] for waste from replacing in-vessel components are considered the best estimate available at present. Because these numbers are only a rough estimate, no scaling for the various candidate ABR power ratings has been used. As control rod requirements and in-vessel component replacement are evaluated, the mixed low-level solid waste estimate should be revised.

Assuming control rod assemblies and shield assemblies are the same length as a fuel rod, both have dimensions 115 in. long (Fig. 3.8-2, [CRBRP, 1977]) and a hexagonal cross-section 4.7 in. across the flats (Sec. 3.8.1.1, [CRBRP, 1977]). The assembly volume is approximately

$$V=A(L)$$
$$L = 115 \text{ in.}$$
$$A = 6(4.7/2)(4.7/(2(SQRT(3)))\ \text{in.}^2 = 19.1\ \text{in.}^2$$

Therefore,

$$V = (19.1)(115) = 2200\ \text{in.}^3 = 4.7\text{x}10^{-2}\ \text{yd.}^3$$

As described above, the number of assemblies shipped each year = 19 + 72/3 + 78/6 + 84/12 + 90/24, or just under 67 per year on average (e.g., 66 or 67 each year).

Control rod assembly lines are 30 feet long and have a 2 in. outside diameter, so the volume is

$$V=30(3.14)(1)(1)\ \text{in.}^3 = 94.3\ \text{in.}^3 = 0.002\ \text{yd.}^3$$

The volume of waste from control rod assemblies, drive lines, and radial shield assemblies is then

$$V = 67(4.7\text{x}10^{-2}) + 19(.002)/10\ \text{yd.}^3\text{, or } 3.2\ \text{yd.}^3\text{/year.}$$

The volume of waste from filters, metallic sodium from fuel handling operations, and sodium-bearing solids (primary, intermediate, and ex-vessel storage tank cold traps ([CRBRP, 1974], Sec. 3.4, "Solid Radwaste System,") is

165+42+235 ft.^{3}/yr.)/(27 ft.^{3}/ yd.^{3} = 8.2 yd.^{3}/yr.

This waste volume should scale approximately linearly with reactor power, so for a 2000 MWth ABR, the volume of waste would be about 16.4 yd.^{3}/yr., and for a 250 MWth ABR, the volume of waste would be about 1.1 yd.^{3}/yr.

An upper bound on the total amount of solid mixed low-level waste can be estimated by assuming that sodium in all sodium-bearing components will be treated off site. In this case, the total solid mixed low-level waste would be

16.4 + 3.2 = 19.6 yd.^{3}/yr. for a 2000 MWth ABR,
8.2 + 3.2 = 11.4 yd.^{3}/yr. for a 1000 MWth ABR,
1.1 + 3.2 = 4.3 yd.^{3}/yr. for a 250 MWth ABR.

The more likely option is that metallic sodium and some or all of the sodium-bearing solids and filters would be treated on-site. In this case, the volume of mixed low-level solid waste to be disposed of off-site would be reduced accordingly.

Hazardous liquid waste ([CRBRP, 1977], Sec. 3.3.4).

The CRBRP design chemical waste treatment system discharges effluent at about 35 gal./minute, or

(35 gal./min.)x(60 min./hr.)x(24 hr./day)x(365 days/yr.) = 1.84x10^7 gal./yr.,

so a 1000 MWth ABR plant would generate about 1.84x10^7 gallons of hazardous liquid waste per year. Assuming the effluent volume varies approximately linearly with plant power, a 250 MWth plant would generate about (1.84x10^7)/4 = 4.6x10^6 gallons of hazardous liquid waste per year, while a 2000 MWth plant would produce about (1.84x10^7)x2 = 3.7x10^7 gallons per year.

Hazardous solid waste ([CRBRP, 1977], Sec. 10.4.1.1.1 and Table 10.4-2).

Hazardous solid waste estimates for CRBRP were based on processing solid wastes from the cooling tower basin, neutralizing and settling facility, and sludge dewatering beds. The estimated average solid waste stream from the CRBRP chemical waste treatment system is 1,000 lb/day, or 3.65x10^5 lb/yr. Wastes would be somewhat less if a Brayton cycle were used. Therefore, assuming that the waste produced is approximately linearly dependent on plant power, an upper bound for the hazardous solid waste from a 250 MWth plant would be (3.65x10^5)/4 = 9.1x10^4 lb./yr.; for a 1000 MWth ABR plant it would be 3.65x10^5 lb/yr., and for a 2000 MWth plant, it would be (3.65x10^5)x2 = 7.3x10^5 lb./yr.

Table 4 (non-hazardous operations wastes):

Sanitary liquid waste ([CRBRP, 1977], Sec. 5.5).

Assume a liquid sanitary waste figure of 25 gal./day per operations staff member and that each staff member works about 250 days per year. Total number of workers employed by a 250 MWth plant is estimated at 300, based on employment numbers given for CRBRP (see discussion of Table 6 in Appendix A for the basis for the number of workers). The annual liquid sanitary waste produced for a 250 MWth plant would then be

$$25x250x300 \approx 1.9x10^6 \text{ gallons/year}$$

The total employment for CRBRP was expected to be 344 workers (see the discussion in Appendix A of Table 6). Since CRBRP and the 1000 MWth ABR are comparable sized plants, this is also taken to be the total employment for the 1000 MWth ABR. The annual liquid sanitary waste produced for a 1000 MWth plant would then be

$$25x250x344 \approx 2.2x10^6 \text{ gallons/year}$$

For a 2000 MWth plant, total employment is estimated at 385 workers (see the discussion of Table 6 in Appendix A). The annual liquid sanitary waste produced for a 2000 MWth plant would then be

$$25x250x385 \approx 2.4x10^6 \text{ gallons/year}$$

Sanitary solid waste ([USEPA, 1999].

The reference describes a water treatment plant which treats 11 million gallons of sanitary wastewater per day (MGD) and produces 7500 cubic yards of biosolids (sludge) per year. If a 250 MWth ABR plant processed $1.9x10^6$ gallons of wastewater per year (see above), the annual production of biosolids to be hauled away would be $7500x(1.9x10^6)/(11x365)/(10^6)$, or approximately 3.5 cubic yards. For a 1000 MWth plant, the annual amount of biosolids would be $7500x(2.2x10^6)/(11x365)/(10^6)$, or approximately 4.0 cubic yards. For a 2000 MWth plant, the annual amount of biosolids would be $7500x(2.4x10^6)/(11x365)/(10^6)$, or approximately 4.5 cubic yards.

Other non-hazardous solid waste

During normal plant operation, non-hazardous solid waste (i.e., ordinary trash) is produced at a rate of about 1.5 yd^3 per 100 employees per day. Assuming the average employee works 250 days per year, the amount of trash generated annually for a 250 MWth plant (300 employees, see Table 6) would be about 300x1.5x250/100 = 1150 yd^3 per year. The amount for a 1000 MWth plant (344 employees from Table 6) would be about 344x1.5x250/100 = 1300 yd^3 per year. The amount for a 2000 MWth plant (385 employees from Table 6) would be about 385x1.5x250/100 = 1450 yd^3 per year.

Table 5 (electrical requirements):

Electrical energy and peak electrical demand.

In-plant power consumption for the CRBR plant was projected to be 30 MWe ([CRBRP, 1977], Sec. 3.2.3). Some of this power consumption is independent of reactor power, but the power required for the three primary sodium pumps, the three intermediate sodium pumps, and the three water recirculation pumps would scale linearly with pump volumetric flow rate, and the flow rates of all three types of pumps are assumed to scale approximately linearly with reactor power. Each CRBR primary pump and each intermediate pump was designed with a 5000 HP main motor, while each recirculation pump was designed with a 2000 HP motor ([CRBRP, 1974], Sec. 3.1 ("Primary Pump") and Sec. 3.5, Table 3-9), so at full power, these pumps would require

$$P_{pumps} = (6x5000 + 3x2000\ HP)x(746x10^{-6}\ MW/HP) = 26.9\ MWe.$$

Therefore, the portion of the CRBR plant power consumption that would be independent of reactor power is estimated as

$$P_{fixed} = 30 – 26.9 = 3.1\ MWe$$

This estimate is used for the fixed portion of an ABR plant power consumption.

The 250 MWth, the 1000 MWth, and the 2000 MWth ABR plant designs all include four primary sodium pumps and two intermediate sodium pumps. Both centrifugal mechanical pumps and EM pumps have been considered for the primary pumps; only EM pumps have been considered for the intermediate pumps. For the 250 MWth plant design [Chang, 2006], the centrifugal primary pump option specifies 0.34 MW required per pump, while the EM pump option requires 0.61 MW per pump. Therefore, the two primary pump options for a 250 MWth ABR would require

$$P_{primary\ cent.\ pumps,\ 250\ MWth} = 4x0.34 = 1.36\ MWe$$

$$P_{primary\ EM\ pumps,\ 250\ MWth} = 4x0.61 = 2.44\ MWe.$$

Assuming primary pump power scales approximately linearly with reactor power, the two primary pump options for a 1000 MWth ABR would require

$$P_{primary\ cent.\ pumps,\ 1000\ MWth} = 4x1.36 = 5.44\ MWe$$

$$P_{primary\ EM\ pumps,\ 1000\ MWth} = 4x2.44 = 9.76\ MWe,$$

and the two primary pump options for a 2000 MWth ABR would require

$$P_{primary\ cent.\ pumps,\ 2000\ MWth} = 8x1.36 = 10.9\ MWe$$

$$P_{primary\ EM\ pumps,\ 2000\ MWth} = 8x2.44 = 19.5\ MWe.$$

The intermediate pump design discussed in [Chang, 2006] specifies a power requirement of 0.41 MWe per pump. Therefore, the intermediate pumps for a 250 MWth ABR would need

$$P_{\text{int. pumps, 250 MWth}} = 2\text{x}0.41 = 0.82 \text{ MWe},$$

the intermediate pumps for a 1000 MWth ABR would need

$$P_{\text{int. pumps, 1000 MWth}} = 4\text{x}0.82 = 3.28 \text{ MWe},$$

and the intermediate pumps for a 2000 MWth ABR would need

$$P_{\text{int. pumps, 2000 MWth}} = 8\text{x}0.82 = 6.56 \text{ MWe},$$

The circulating water pumps in the balance-of-plant system require 0.53 MWe for a 250 MWth plant, 2.1 MWe for a 1000 MWth plant, and 4.3 MWe for a 2000 MWth plant [Lomperski, 2007].

If the supercritical CO_2 Brayton cycle is used in the power conversion system, the CO_2 compressors may add considerably to the plant electrical requirements, depending upon the design option used [Sienicki, 2007]. In option 1, the two compressors are on the same shaft as the turbine such that they are driven directly by the turbine and not by electric motors. Thus, there is no motor electric power requirement. However, an alternate design possibility (option 2) is to have the compressors and turbine on three separate shafts and drive each compressor with an electric motor rather than its own dedicated turbine (in which case, a larger generator is used to make up the difference in the net power provided by the plant). If option 2 is used, the main compressor requires 27.9 MWe and the recompressing compressor requires 27.1 MWe for a 250 MWth plant. These power demands are assumed to scale approximately linearly with reactor power, so for a 1000 MWth ABR, the main compressor requires 112 MWe and the recompressing compressor requires 108 MWe, while for a 2000 MWth ABR, the main compressor requires 223 MWe and the recompressing compressor requires 217 MWe.

Using the value of 3.1 MWe evaluated above for the fixed portion of the ABR plant electrical demand, the peak electrical demand for a 250 MWth ABR using option 1 of the supercritical CO_2 Brayton cycle is then estimated as

$$P_{\text{peak, 250 MWth, Brayton option 1, cent. prim. pumps}} = 3.1 + 1.36 + 0.82 + 0.53 = 5.8 \text{ MWe}$$

$$P_{\text{peak, 250 MWth, Brayton option 1, EM prim. pumps}} = 3.1 + 2.44 + 0.82 + 0.53 = 6.9 \text{ MWe}$$

If option 2 of the Brayton cycle is selected, the power requirements become

$$P_{\text{peak, 250 MWth, Brayton option 2, cent. prim. pumps}} = 3.1 + 1.36 + 0.82 + 0.53 + 27.9 + 27.1$$

$$= 60.8 \text{ MWe}$$

$$P_{\text{peak, 250 MWth, Brayton option 2, EM prim. pumps}} = 3.1 + 2.44 + 0.82 + 0.53 + 27.9 + 27.1 = 61.9 \text{ MWe}$$

For a Rankine cycle power conversion system, the feedwater pumps for a 250 MWth ABR would require approximately 2.1 MWe and the condensate pumps approximately 0.31 MWe [Lomperski, 2007]. The power requirements would then be

$$P_{\text{peak, 250 MWth, Rankine, cent. prim. pumps}} = 3.1 + 1.36 + 0.82 + 0.53 + 2.1 + 0.31 = 8.2 \text{ MWe}$$

$$P_{\text{peak, 250 MWth, Rankine, EM prim. pumps}} = 3.1 + 2.44 + 0.82 + 0.53 + 2.1 + 0.31 = 9.3 \text{ MWe}$$

For a 1000 MWth ABR, peak electrical demand for the two primary pump options and option 1 of the Brayton cycle is estimated as

$$P_{\text{peak, 1000 MWth, Brayton option 1, cent. prim. pumps}} = 3.1 + 5.44 + 3.28 + 2.1 = 13.9 \text{ MWe}$$

$$P_{\text{peak, 1000 MWth, Brayton option 1, EM prim. pumps}} = 3.1 + 9.76 + 3.28 + 2.1 = 18.2 \text{ MWe.}$$

Peak electrical demand for a 1000 MWth ABR using option 2 of the Brayton cycle and either primary pump option would be

$$P_{\text{peak, 1000 MWth, Brayton option 2, cent. prim. pumps}} = 3.1 + 5.44 + 3.28 + 2.1 + 112 + 108 = 234 \text{ MWe}$$

$$P_{\text{peak, 1000 MWth, Brayton option 2, EM prim. pumps}} = 3.1 + 9.76 + 3.28 + 2.1 + 112 + 108 = 238 \text{ MWe.}$$

For a Rankine cycle, it is assumed that the feedwater and condensate pump powers scale linearly with reactor power, so the feedwater pumps for a 1000 MWth ABR would require approximately 2.1x4 = 8.4 MWe, and the condensate pumps would require approximately 0.31x4 = 1.24 MWe [Lomperski, 2007]. Therefore, peak electrical demand for a 1000 MWth ABR using a Rankine cycle and either primary pump option would be

$$P_{\text{peak, 1000 MWth, Rankine, cent. prim. pumps}} = 3.1 + 5.44 + 3.28 + 2.1 + 8.4 + 1.24 = 23.6 \text{ MWe}$$

$$P_{\text{peak, 1000 MWth, Rankine, EM prim. pumps}} = 3.1 + 9.76 + 3.28 + 2.1 + 8.4 + 1.24 = 27.9 \text{ MWe.}$$

For a 2000 MWth ABR, peak electrical demand for the two primary pump options and option 1 of the Brayton cycle is estimated as

$$P_{\text{peak, 2000 MWth, Brayton option 1, cent. prim. pumps}} = 3.1 + 10.9 + 6.56 + 4.3 = 24.8 \text{ MWe}$$

$$P_{\text{peak, 2000 MWth, Brayton option 1, EM prim. pumps}} = 3.1 + 19.5 + 6.56 + 4.3 = 33.4 \text{ MWe.}$$

Peak electrical demand for a 2000 MWth ABR using option 2 of the Brayton cycle and either primary pump option would be

$$P_{\text{peak, 2000 MWth, Brayton option 2, cent. prim. pumps}} = 3.1 + 10.9 + 6.56 + 4.3 + 223 + 217 = 465 \text{ MWe}$$

$$P_{\text{peak, 2000 MWth, Brayton option 2, EM prim. pumps}} = 3.1 + 19.5 + 6.56 + 4.3 + 223 + 217 = 473 \text{ MWe.}$$

For a Rankine cycle, the feedwater pumps for a 2000 MWth ABR would require approximately 2.1x4 = 8.4 MWe, and the condensate pumps would require approximately 0.31x4 = 1.24 MWe [Lomperski, 2007]. Therefore, peak electrical demand for a 2000 MWth ABR using a Rankine cycle and either primary pump option would be

$$P_{\text{peak, 2000 MWth, Rankine, cent. prim. pumps}} = 3.1 + 10.9 + 6.56 + 4.3 + 16.8 + 2.48 = 44.1 \text{ MWe}$$

$$P_{\text{peak, 2000 MWth, Rankine, EM prim. pumps}} = 3.1 + 19.5 + 6.56 + 4.3 + 16.8 + 2.48 = 52.7 \text{ MWe.}$$

Estimates for maximum annual power consumption for the various 250 MWth ABR options are then

$$P_{\text{annual, 250 MWth, Brayton option 1, cent. prim. pumps}} = (5.8 \text{ MWe})*(8760 \text{ hr./yr}) = 5.09\text{x}10^4 \text{ MWh}$$

$$P_{\text{annual, 250 MWth, Brayton option 1, EM prim. pumps}} = (6.9 \text{ MWe})*(8760 \text{ hr./yr}) = 6.04\text{x}10^4 \text{ MWh}$$

$$P_{\text{annual, 250 MWth, Brayton option 2, cent. prim. pumps}} = (60.8 \text{ MWe})*(8760 \text{ hr./yr}) = 5.33\text{x}10^5 \text{ MWh}$$

$$P_{\text{annual, 250 MWth, Brayton option 2, EM prim. pumps}} = (61.9 \text{ MWe})*(8760 \text{ hr./yr}) = 5.42\text{x}10^5 \text{ MWh.}$$

$$P_{\text{annual, 250 MWth, Rankine, cent. prim. pumps}} = (8.2 \text{ MWe})*(8760 \text{ hr./yr}) = 7.20\text{x}10^5 \text{ MWh}$$

$$P_{\text{annual, 250 MWth, Rankine, EM prim. pumps}} = (9.3\text{ MWe})*(8760\text{ hr./yr}) = 8.15\text{x}10^5\text{ MWh.}$$

Maximum annual power consumption for the various 1000 MWth ABR options is estimated as

$$P_{\text{annual, 1000 MWth, Brayton option 1, cent. prim. pumps}} = (13.9\text{ MWe})*(8760\text{ hr./yr}) = 1.22\text{x}10^5\text{ MWh}$$

$$P_{\text{annual, 1000 MWth, Brayton option 1, EM prim. pumps}} = (18.2\text{ MWe})*(8760\text{ hr./yr}) = 1.59\text{x}10^5\text{ MWh}$$

$$P_{\text{annual, 1000 MWth, Brayton option 2, cent. prim. pumps}} = (234\text{ MWe})*(8760\text{ hr./yr}) = 2.05\text{x}10^6\text{ MWh}$$

$$P_{\text{annual, 1000 MWth, Brayton option 2, EM prim. pumps}} = (238\text{ MWe})*(8760\text{ hr./yr}) = 2.45\text{x}10^6\text{ MWh.}$$

$$P_{\text{annual, 1000 MWth, Rankine, cent. prim. pumps}} = (23.6\text{ MWe})*(8760\text{ hr./yr}) = 2.07\text{x}10^5\text{ MWh}$$

$$P_{\text{annual, 1000 MWth, Rankine, EM prim. pumps}} = (27.9\text{ MWe})*(8760\text{ hr./yr}) = 2.44\text{x}10^5\text{ MWh.}$$

Maximum annual power consumption for the various 2000 MWth ABR options is estimated as

$$P_{\text{annual, 2000 MWth, Brayton option 1, cent. prim. pumps}} = (24.8\text{ MWe})*(8760\text{ hr./yr}) = 2.17\text{x}10^5\text{ MWh}$$

$$P_{\text{annual, 2000 MWth, Brayton option 1, EM prim. pumps}} = (33.4\text{ MWe})*(8760\text{ hr./yr}) = 2.93\text{x}10^5\text{ MWh}$$

$$P_{\text{annual, 2000 MWth, Brayton option 2, cent. prim. pumps}} = (465\text{ MWe})*(8760\text{ hr./yr}) = 4.07\text{x}10^6\text{ MWh}$$

$$P_{\text{annual, 2000 MWth, Brayton option 2, EM prim. pumps}} = (473\text{ MWe})*(8760\text{ hr./yr}) = 4.15\text{x}10^6\text{ MWh.}$$

$$P_{\text{annual, 2000 MWth, Rankine, cent. prim. pumps}} = (44.1\text{ MWe})*(8760\text{ hr./yr}) = 3.86\text{x}10^5\text{ MWh}$$

$$P_{\text{annual, 2000 MWth, Rankine, EM prim. pumps}} = (52.7\text{ MWe})*(8760\text{ hr./yr}) = 4.62\text{x}10^5\text{ MWh.}$$

Table 6 (operations data):

Emergency generator fossil fuel usage ([CRBRP, 1977], Tables 3.7-2 and 5.5-1; [CRBRP, 1974], Sec. 4.4, “Emergency Power System”, and Sec. 3.1, “Primary Pump”; [Chang, 2006], Sec. 2.9.6)

The only fossil fuel usage identified for CRBR is for the two emergency diesel generators and the diesel fire pump. From [CRBRP, 1977], Table 5.5-1, fuel consumption for each is 95 lbs./hr of No. 2 oil. Per [CRBRP, 1977], Table 3.7.2, each engine is run for 24 hours/year for testing. According to [CRBRP, 1974], Sec. 4.4, each diesel generator is rated at 3.3 MWe. The 250 MWth ABR plant design ([Chang, 2006], Sec. 2.9.6) includes two 1 MWe emergency generators and considers the option of making the generators either diesel or gas. If diesel generators were used, and if the fuel usage scales approximately linearly with generator size, the mass of fuel used per year for a 250 MWth ABR plant would be

$$M = 2(24\text{ h./yr.})(95\text{ lbs/hr. for }3.3\text{ MWe})/3.3 = 1382\text{ lbs No. 2 oil/yr.}$$

The density of No. 2 oil is 7.05 lb./gal. [Perry, 1997]. Therefore, the volume of fuel used per year for emergency generator testing for a 250 MWth ABR plant would be:

$$V = 1382\text{ lbs/yr}/(7.05\text{ lb./gal.}) \approx 200\text{ gal./yr.}$$

The ABR 1000 MWth design assumes that the emergency generator capacity consists of two 3 MWe generators, or 6 MWe, so the volume of fuel used per year for a 2000 MWth ABR plant would be

$$V \approx (200\text{ gal./yr.})\text{x}3 = 600\text{ gal./yr.}$$

The ABR 2000 MWth design assumes that the emergency generator capacity consists of four 3 MWe generators, or 12 MWe, so the volume of fuel used per year for a 2000 MWth ABR plant would be

$$V \approx (200\text{ gal./yr.})\text{x}6 = 1200\text{ gal./yr.}$$

Grounds maintenance fossil fuel usage

Assume that diesel powered equipment is used 25 times per year for grounds maintenance and that 5 gallons of fuel are consumed per hour by all the equipment used. Also, assume that maintenance can be completed on three acres each hour. From Table 27, a 250 MWth plant will have about 80 acres committed to landscaped facilities, so the amount of fossil fuel consumed in grounds maintenance per year would be about 80x25x5/3 ≈ 3350 gal./yr. For a 1000 MWth plant, Table 27 indicates 100 acres of landscaped facilities, so the fossil fuel consumption for grounds maintenance would be about 100x25x5/3 ≈ 4200 gal./yr. Finally, for a 2000 MWth plant, Table 27 shows 120 acres of landscaped facilities, so the fossil fuel consumption for grounds maintenance would be about 120x25x5/3 = 5000 gal./yr.

Process gases ([Chang, 2006], Secs. II.10.1 and II.10.17).

Nitrogen. If the Rankine cycle option is selected for the power conversion system, nitrogen would be used for sparging in the steam generators. Sparging occurs when a steam generator is taken out of service either due to malfunction of a piece of equipment or for maintenance. Hydrazine would be injected into the water in the steam generator, then nitrogen gas would be blown in through the bottom of the steam generator to mix the hydrazine with the water and to blanket the water. A 6900 MWth commercial nuclear plant (two 3450 MWth reactors) uses about 200,000 scf (one tanker truck) of nitrogen per year for steam generator sparging [Flores, 2007]. The quantity of nitrogen used will scale approximately linearly with plant power. A 250 MWth ABR would therefore require about (200,000)x(250/6900) ≈ 7300 scf of nitrogen annually, a 1000 MWth ABR plant would require about (200,000)x(1000/6900) = 29,000 scf of nitrogen annually, and a 2000 MWth ABR plant would require about (200,000)x(2000/6900) = 58,000 scf of nitrogen per year.

Hydrogen. Both 1000 and 2000 MWth ABR plants would probably use a generator cooled by hydrogen. Hydrogen flow and initial charge to such a generator are discussed in [Smith, 2002], which describes a GE Frame 7 gas turbine generator as taking an initial charge of 7,500 ft.^{3} of hydrogen gas for purge and filling and requiring 21 ft.^{3} of hydrogen gas per hour for makeup. Hydrogen-cooled generators for the 903 MWe generating plant at Zeeland, Michigan are discussed in [Mirant, 2007] and [Speranza, 2005]. These three generators require a total of about 70 scf/hr. of hydrogen makeup for cooling. Assuming each of these generators also takes an initial charge of about 7,500 scf of hydrogen gas, the Zeeland plant would require about 3x7500 + 70x24x365 = 635,700 scf of hydrogen per year. Assuming that hydrogen required would scale approximately linearly with total generator power, a rough estimate of the hydrogen requirements of a 1000 MWth ABR plant generator (380 MWe, assuming 38% efficiency) would be about (380/903)x635,700 = 268,000 scf/yr., while the hydrogen requirements of a 2000 MWth ABR plant generator (760 MWe, assuming 38% efficiency) would be about (760/903)x635,700 = 535,000 scf/yr. The volume ratio between hydrogen gas at 1 atm. and liquid hydrogen is about 825. Therefore, a 1000 MWth ABR generator would require about 268,000/825 = 325 ft.^{3} of liquid hydrogen per year., while a 2000 MWth ABR generator would require about 535,000/825 = 650 ft.^{3} of liquid hydrogen per year. If hydrogen is delivered to the site and stored on-site in tanks in liquid form, and assuming liquid hydrogen deliveries about five times per year, a reasonable quantity to store onsite for a 1000 MWth plant would be about 70 ft.^{3}, and for a 2000 MWth plant about 150 ft.^{3}. If a hydrogen generator is used to generate hydrogen continuously, only a reserve of a few days needs to be stored on site. Assuming a reserve for six days, about (70x24x6)x(380/903)/825 = 5 ft.^{3} of liquid hydrogen would be stored on-site as reserve for a 1000 MWth ABR, and about (70x24x6)x(760/903)/825 = 10 ft.^{3} for a 2000 MWth ABR. For a 1000 MWth ABR, approximately (3x7500)x380/903) = 9,500 scf of hydrogen gas would be required to purge and charge the generator, and for a 2000 MWth ABR, approximately (3x7500)x(760/903) = 19,000 scf would be required.

Carbon Dioxide. For the preconceptual design 250 MWth ABR plant, the CO_2 inventory in the S-CO_2 Brayton cycle is 10,800 kg. There will also be a cryogenic storage tank or tanks located near to the turbine generator building holding additional CO_2 needed for makeup to compensate for any losses and to recharge the system if it needs to be depressurized for maintenance or repair. The inventory in the storage tank(s) is estimated as four times the cycle inventory, or 43,200 kg. Thus, the total CO_2 onsite during normal operation is (10,800 + 43,200) = 54,000 kg., or about 963,000 scf, since CO_2 has a density of 1.98 kg/m^3 at standard temperature and pressure, or 0.056 kg/scf. There is a need for a flow of CO_2 for the shaft seals on the turbomachinery. It is anticipated that this CO_2 will be captured for reuse and not vented. It is also anticipated that leakages from the cycle will be negligible. These numbers should scale roughly linearly with the power level such that, for a 1000 MWth plant, there would be four times as much, or 216,000 kg (3.9 million scf) of CO_2 onsite, while for a 2000 MWth plant, there would be eight times as much, or 432,000 kg (7.7 million scf) of CO_2 onsite. [Sienicki, 2007]

<u>Chemical Use</u> ([CRBRP, 1977], Sec 3.6, Fig. 3.6-1)

Sodium hypochlorite. The CRBRP design called for intermittent injection of sodium hypochlorite for bio-fouling control in the cooling tower water (maximum of 450 lb./day) and in the ground water intake (maximum of 180 lb./day), plus minor amounts to the sanitary system discharge. Thus, a 1000 MWth plant should require 450+180=630 lb. per day. Assuming the requirements for this chemical scale linearly with water volume, which should scale approximately linearly with plant power, a 250 MWth ABR would require a maximum daily addition of (450+180)/4 ≈ 160 lb., while a 2000 MWth ABR would take at most (450+180)x2 = 1260 lb. per day.

Sulfuric acid. This chemical was to be added occasionally to the CRBRP cooling tower water and the chemical waste treatment system to control high pH. A maximum of 3400 lb./day was specified, so a 1000 MWth plant would need a maximum of 3400 lb./day. Scaling this quantity linearly with power would result in a 250 MWth ABR plant requiring occasional addition of 3400/4 = 850 lb. of sulfuric acid per day, while a 2000 MWth plant would receive 3400x2 = 6800 lb.

Sodium hydroxide. The CRBRP chemical waste treatment system was expected to require a maximum of 2200 lb. of sodium hydroxide a day on an intermittent basis, so a 1000 MWth ABR would be expected to require occasional addition of at most 2200 lb per day. Adjusting linearly for power, a 250 MWth ABR plant chemical waste treatment system would use 2200/4 = 550 lb. of sodium hydroxide per day on occasion, while a 2000 MWth plant would periodically require 2200x2 = 4400 lb./day.

<u>Steam</u> ([CRBRP, 1977], Sec. 3.2, Table 3.2-1)

Steam is used only if a steam generator is used in the power conversion system. In this case, steam would be the working fluid within the closed loop of the steam generator. For CRBR, steam flow to the turbine would be 3.34 x10^6 lb/hr., or

$$(3.34\text{x}10^6 \text{ lb/hr. x 24 hr./day x 365 d/yr})/(2000 \text{ lb/ton}) = 1.46\text{x}10^7 \text{ ton/yr.}$$

Assuming steam produced varies approximately linearly with reactor power, then steam flow for a 1000 MWth ABR would be $1.46\text{x}10^7$ ton/yr., for a 2000 MWth ABR, steam flow = 2.92 $\text{x}10^7$ ton/yr., and for a 250 MWth ABR, steam flow = 3.66 $\text{x}10^6$ ton/yr.

Hydrazine. If a Rankine cycle is used, hydrazine would be added to the feedwater as an oxygen scavenger. Hydrazine is used to control oxygen in the steam cycle at nearly all U. S. nuclear power plants. The quantity of hydrazine added scales approximately with reactor power. A 6900 MWth nuclear plant (two 3450 MWth reactors) requires 15,000 gal. of hydrazine per year and receives deliveries of the chemical three times per year [Flores, 2007]. A 250 MWth ABR would therefore require about (15,000)x(250/6900) = 550 gal. of hydrazine per year and would store at most 200 gal. at one time, a 1000 MWth ABR would require about (15,000)x(1000/6900) = 2,200 gal. annually and would store at most 750 gal. at one time. and a 2000 MWth ABR would require about (15,000)x(2000/6900) = 4,400 gal. annually and would store at most 1500 gal. at one time.

Monoethanolamine. If a Rankine cycle is used, the steam and water must be kept alkaline in order to control corrosion. An organic amine is added to the water to control pH; nearly all U. S. power plants use one of the following three: monoethanolamine, morpholine, or ammonia. Of these, monoethanolamine distributes best throughout the system and controls pH in the condensate the best. A 6900 MWth nuclear plant requires 35,000 gal. of monoethanolamine per year and receives the chemical in eight shipments per year [Flores, 2007]. The plant therefore stores at most 4500 gal. at one time. The quantity of the chemical required scales approximately linearly with reactor power. A 250 MWth ABR would therefore require about 1300 gal. of monoethanolamine annually and, if it followed the same delivery schedule, would store less than 200 gal. at a time. A 1000 MWth ABR would use about 5,100 gal. annually and would store about 650 gal. at a time, and a 2000 MWth ABR would use about 10,200 gal. annually and would store about 1300 gal. at a time.

Employment. Values expected for the CRBRP are found in [CRBRP, 1977], Sec. 3.7.1, and_[CRBRP, 1982], Ch. 13, Figure 13.1-2: CRBRP Organizational Chart. It was expected that there would be 125 workers present on site at any one time during normal operations, with 210 workers on site at any one time during the annual service shutdown. Total employment of the plant was expected to be 344 workers. A certain number of these were rad workers, as describe in [CRBRP, 1982], Ch. 13, Figure 13.1-2: CRBRP Organizational Chart. Rad workers were taken to be all workers in health physics, engineering, operations, and plant maintenance, other than the following: Training, Shift Clerks, Janitor and Labor Services Supervisor. The total number of employees classified as rad workers would then be:

$$69 + (59-10) + 15 + 59 + 35 + 4 + 21 \approx 250$$

These numbers should be representative of employment at a 1000 MWth ABR.

To reflect some economy of scale regarding plants of different sizes, the employment numbers for the 250 MWth plant were taken as about 88% of those for the CRBRP, while the employment numbers for the 2000 MWth plant were assumed to be about 112% of those for the CRBRP.

Table 7 (makeup water usage):

Water usage ([CRBRP, 1977], Sec. 3.3, Table 3.3-1 and Figure 3.3-1; [Tawney, 2003])

The CRBR plant was designed with a mechanical draft wet cooling tower, which represents most of the plant makeup water. The remainder of the water makeup goes to process waste treatment, which includes chemical waste treatment, radwaste systems, the potable water and sanitary waste systems, demineralizer regenerations, and the condensate polishing system, which treats condensate to maintain the feedwater chemistry needed by the steam generator. Systems other than the cooling tower require on average 67 gpm of water, with a peak design capacity of 125 gpm (6.57×10^7 gal./yr.). At 975 MWth, the cooling tower requires 7,050 gpm (3.71×10^9 gal./yr.) of makeup water, with 2,700 gpm (1.42×10^9 gal./yr.) returned to the water source, 4,240 gpm (2.23×10^9 gal./yr.) lost to evaporation, and 110 gpm (5.78×10^7 gal./yr.) lost to drift (droplets of water discharged from the system during operation). Waste water to be processed is therefore the sum of the water used in process waste treatment plus cooling tower blowdown, or (125+2,700) = 2,825 gpm (1.49×10^9 gal./yr.) The water requirements are assumed to vary linearly with reactor operating power and to be approximately independent of the type of wet cooling tower used, as shown in Table 7.

If dry cooling technology is used instead of a wet cooling system, no makeup water is required by the plant heat sink, and the makeup water requirements are limited to those for process water treatment, plus a minor amount to compensate for any leaks in the power conversion system if a Rankine cycle is used.

Table 8 (spent fuel discharge):

From Table 3.4 in [Kim, 2006a],

metal 2000 MWth startup core spent fuel discharge ≈ 5560 kg. HM/yr.

From [Kim, 2007b],

metal 1000 MWth startup core spent fuel discharge ≈ 3100 kg. HM/yr.

From Table 6.7 in [Kim, 2006b],

metal 250 MWth startup core spent fuel discharge ≈ 850 kg. HM/yr.

As covered above in the discussion of Table 1, the 2000 MWth oxide core discussed in [Kim, 2006a] has a higher TRU conversion ratio than the 2000 MWth metal core, and so, in order to estimate annual discharge for the oxide core on the same basis as for the metal core, the oxide core must be adjusted as follows to achieve the same TRU conversion ratio as the metal core.

For a 2000 MWth oxide core,

oxide HM discharge rate = oxide HM charge rate – oxide HM consumption

If the oxide core achieves the same conversion ratio as the metal core, then

oxide core HM consumption = metal core HM consumption
= metal startup core HM charge –
metal startup core HM discharge
= 6233.0 – 5558.5 kg./yr.
≈ 675 kg./yr.
(from Table 3.4, [Kim, 2006a])

The oxide HM charge rate is adjusted for the TRU conversion ratio as follows:

oxide adj. HM charge rate = (oxide TRU charge rate at the orig. conv. ratio)x
(metal HM charge rate)/(metal TRU charge rate)
= (1468.9)*(6233.0/1422.1)
≈ 6440 kg/yr.
(from Table 3.4, [Kim, 2006a])

The adjusted oxide HM discharge rate is then

2000 MWth startup oxide core HM discharge rate ≈ 6440 – 675 ≈ 5760 kg./yr.

Similarly, for a 250 MWth oxide core,

oxide HM discharge rate = oxide HM charge rate – oxide HM consumption

If the oxide core achieves the same conversion ratio as the metal core, then

oxide core HM consumption = metal core HM consumption
= metal startup core HM charge –
metal startup core HM discharge
= 932.7 – 848.2 kg./yr.
≈ 85 kg./yr.
(from Table 6.7, [Kim, 2006b])

The oxide HM charge rate is adjusted for the TRU conversion ratio as follows:

oxide adj. HM charge rate = (oxide TRU charge rate at the orig. conv. ratio)x

(metal HM charge rate)/(metal TRU charge rate)
= (449.2)*(932.7/431.0)
≈ 973 kg/yr.
(from Tables 6.7 and 6.8, [Kim, 2006b])

The adjusted oxide HM discharge rate is then

250 MWth startup oxide core HM discharge rate ≈ 973 – 85 ≈ 890 kg./yr

The spent fuel discharge for the 1000 MWth oxide startup core is taken directly from [Kim, 2007b] as

1000 MWth startup oxide core HM discharge rate ≈ 2500 kg. HM/yr.

Both metal and oxide 1000 MWth ABR cores contain 180 fuel assemblies and have a cycle length of one year. However, the fuel is dicharged in four batches for the metal core, and so the 1000 MWth metal ABR discharges 180/4 = 45 assemblies per year, whereas the oxide core fuel is discharged in five batches, or 180/5 = 36 assemblies per year.

Table 11 (hazardous air pollutants):

References: [CRBRP, 1977], Table 3.7-2; [Chang, 2006], Sec. 2.9.6.

Hazardous air pollutants would be released to the atmosphere during testing or emergency operation of the emergency generators and during use of diesel-powered equipment for grounds maintenance. Assuming the emergency generators are diesel powered, emissions can be estimated from data for CRBR plant diesel operation in [CRBRP, 1977], Table 3.7-2. CRBR diesels included the two 3.3 MWe emergency diesel generators and a diesel fire pump. Since no data on the diesel fire pump could be found, it was conservatively assumed that the total maximum air pollutants given in Table 3.7-2 could be attributed to testing of the two emergency generators. The total maximum pollutant releases given in Table 3.7-2 are

Pollutant	Release, ton/yr.
SO_2	0.75
Hydrocarbons	0.75
NO_x	7.5
CO	1.5

Assume that these releases are from testing of two 3.3 MWe generators and that 1) emissions scale approximately linearly with generator fuel usage and 2) fuel usage scales approximately linearly with generator power. The 250 MWth ABR plant design includes two 1.0 MWe emergency generators, the 1000 MWth design assumes two 3.0 MWe emergency generators, and the 2000 MWth plant design includes four 3.0 MWe emergency generators. Therefore, the maximum annual emissions for testing emergency diesel generators for both sizes of plant should be approximately as given in Table A.3 below.

Table A.3. Approximate Annual Release of Hazardous Air Pollutants During Emergency Diesel Generator Testing and Grounds Maintenance

Pollutant	Release, ton/yr.			
	Plant Size	**Generator Testing**	**Grounds Maintenance**	**Total**
SO_2	250 MWth	0.75/3.3 = 0.23	0.23x(3350/200) = 3.9	4.1
	1000 MWth	(0.75/3.3)*3 = 0.68	0.23x(4200/200) = 4.8	5.5
	2000 MWth	(0.75/3.3)*6 = 1.36	0.23x(5000/200) = 5.7	7.1
Hydrocarbons	250 MWth	0.75/3.3 = 0.23	0.23x(3350/200) = 3.9	4.1
	1000 MWth	(0.75/3.3)*3 = 0.68	0.23x(4200/200) = 4.8	5.5
	2000 MWth	(0.75/3.3)*6 = 1.36	0.23x(5000/200) = 5.7	7.1
NO_x	250 MWth	7.5/3.3 = 2.3	2.3x(3350/200) = 39	41
	1000 MWth	(7.5/3.3)*3 = 6.8	2.3x(4200/200) = 48	45
	2000 MWth	(7.5/3.3)*6 = 13.6	2.3x(5000/200) = 57	71
CO	250 MWth	1.5/3.3 = 0.46	0.46x(3350/200) = 7.7	8.2
	1000 MWth	(1.5/3.3)*3 = 1.36	0.46x(4200/200) = 9.7	11.0
	2000 MWth	(1.5/3.3)*6 = 2.73	0.46x(5000/200) = 11.4	14.1

Testing of the emergency generators for the 250 MWth ABR would consume about 200 gallons of diesel fuel per year (see discussion above of Table 6). Grounds maintenance would require about 3350 gallons of diesel fuel per year for the 250 MWth ABR, about 4200 gallons per year for the 1000 MWth ABR, and about 5000 gallons per year for the 2000 MWth ABR (again, see the discussion above of Table 6). Assuming the grounds maintenance equipment produces about the same amount of air pollutants per gallon of diesel fuel as the emergency generators, the air pollutants released annually from grounds maintenance would scale linearly with the amount of diesel fuel consumed. Therefore, grounds maintenance for each size of ABR plant would produce the quantities of pollutants shown in Table A.3.

Table 12 (low-level waste):

Information taken from [CRBRP, 1977], Table 3.5-11. One 55-gallon drum is eqiuivalent to 7.4 $ft.^3$. The estimates of numbers of containers required per year given in [CRBRP, 1977] appear to also account for empty space within the drum for each waste type. The table combines filters, which are mixed low-level waste (due to sodium residue), with resins, which are low-level waste, so the quantity for resins was estimated by scaling the total value (100 55-gallon drums) using the annual volume numbers for resins (450 $ft.^3$) and filters (165 $ft.^3$) from [CRBRP, 1977], Table 3.5-10. This gives

No. of drums containing resins = 100(450/(450+165) = 73 drums

The total number of drums of non-compactible solids is the sum of the number of drums of scrapped components (82 from Table 3.5-11) and the number of drums of resins, or 73+82 = 155.

The only waste which scales with reactor power is the solidified liquid radwaste (140 drums for CRBR), so this value was scaled directly with candidate ABR power.

Table 26 (construction requirements):

Construction period: Figure A.1 plots construction time vs. plant power for 41 U.S. power reactors [IAEA,]. The plot indicates that plants around 2000 MWth took about six years to complete, so the construction time estimate for the 2000 MWth ABR has been taken as six years. This is an estimate for time during which construction activities are in progress; delays due to regulatory issues, etc., during which construction work may be suspended, are not included, since construction wastes, fossil fuel emissions, etc. will not be generated and thus the idle time will have little, if any, environmental impact.

Since construction employment is adjusted for plant size, construction time is not expected to vary much with plant size, since the larger the plant size, the more staff and equipment are available for tasks such as pouring concrete, installing electrical systems, etc. Therefore, it is estimated that a 250 MWth ABR would take perhaps a year less to build than a 2000 MWth plant, or five years and that a 1000 MWth ABR would take about 5.5 years to build.

Construction employment: CRBRP total employment and peak employment are taken from Sec. 8.2, Table 8.2-1, [CRBRP, 1977]. These values are then scaled by $(P_{ABR})/(P_{CRBR})^{0.7}$

Construction peak electrical requirements: This parameter has been estimated by looking at a comparable size of construction project, the Spallation Neutron Source. According to [Lawson, 2007], a 9 MWe line supplied the electrical needs of about 800 construction workers during the 6.5 year construction period, or about 11.25 kW per worker. Assuming this estimate is applicable to ABR construction, a 250 MWth plant would require about 780x11.25 ≈ 9 MWe maximum during construction, while a 1000 MWth plant would need about 2050x11.25 ≈ 23 MWe maximum and a 2000 MWth plant would need about 3330x11.25 ≈ 38 MWe maximum during construction.

Diesel or gas generators would be used during construction ([Chang, 2006], Sec. 11.9.6). The current design calls for two 1 MWe back-up generators for the 250 MWth plant, two 3 MWe back-up generators for the 1000 MWth plant, and four 3 MWe back-up generators for the 2000 MWth plant. Thus, either temporary generators would be needed during construction to supplement the permanent back-up generators, or a temporary power line would need to be installed for construction.

Concrete used in construction: Concrete estimate from Sec. 4.3.3, [CRBRP, 1977] is 200,000 yd^3, so the amount of concrete needed to construct a 1000 MWth ABR would be about 200,000 yd^3. If a volume-to-power factor of

$$(V_{ABR})/(V_{CRBR}) = (P_{ABR})/(P_{CRBR})^{0.7}$$

is used, similar to that described in Appendices B and C, and using P_{CRBR} = 1000 MWth, then the amount of concrete for a 250 MWth ABR can be estimated as

$$\text{250 MWth ABR concrete} = 200{,}000x(250/1000)^{0.7} = 76{,}000\ yd^3,$$

while the amount for a 2000 MWth ABR would be estimated as

$$\text{2000 MWth ABR concrete} = 200{,}000x(2000/1000)^{0.7} = 325{,}000\ yd^3,$$

Steel used in construction: Details used in making the steel estimates are given in the spreadsheet table provided in Appendix C.

Use of liquid fuel and lube oil during construction: The major tasks requiring liquid fuel and lube oil are site preparation, excavation, hauling, backfill, and site finishing. Table A.4 presents details of the assumptions and data taken from [Caterpillar, 1990] and applied to the estimated land requirements and concrete usage for the two bounding ABR designs to generate estimates for liquid fuel and lube oil requirements during construction.

Construction water usage: A construction water usage estimate is available for CRBRP from Sec. 4.1.2.1, [CRBRP, 1977]. This value is consistent with assuming 25 gallons of water used per day per worker. Peak daily construction water use can therefore be estimated by multiplying the anticipated number of workers in the peak year by 25.

Table 27 (construction land requirements):

Land requirements are calculated from the CRBRP land requirements found in [CRBRP, 1977], Sec. 4.1 and Table 4.1-1. The CRBRP site was expected to cover 1,364 acres total, most of it natural wooded area. Table 4.1-1 of [CRBRP, 1977] provides a detailed breakdown of the types of land usage included in the laydown area during construction. Land usage for a 250 MWth plant is assumed to be 80% of that for CRBRP, while land for a 2000 MWth plant is assumed to be 120% of CRBRP, to a first approximation. Land usage for a 1000 MWth plant is taken as the CRBRP estimate, with the total site area rounded to 1400 acres.

Laydown area for the CRBRP is given as 156 acres in [CRBRP, 1977], Table 4.1-1. This value is rounded to 160 acres for the 1000 MWth ABR plant. The laydown area is scaled for reactor power by $(P_{ABR}/P_{CRBR})^{0.7}$, so for the 250 MWth ABR, the laydown area is calculated as $(156)x(250/1000)^{0.7}$, or 60 acres, and for the 2000 MWth ABR, the laydown area is $(156)x(2000/1000)^{0.7}$, or 250 acres.

Table A.4. Estimation of Liquid Fuel and Lube Oil Consumed During ABR Construction			
Supporting data from [Caterpillar, 1990]			
Land clearing	250 MWth	1000 MWth	2000 MWth
Assume light vegetation, level terrain, good footing, clay subsoil.			
Assume area cleared is equal to Facilities, Laydown, and Temp parking areas (see Table 27).			
Assume D7H, Weldco brush rake, medium duty load factor			
Area to be cleared (acres) (from Table 27)	145	272	390
Hours per acre	1.8	1.8	1.8
Gallons per hour	9	9	9
Gallons per acre cleared	16.2	16.2	16.2
Fuel for land clearing (gal)	**2349**	**4406**	**6318**
Site preparation			
Assume site prep includes construction of roads and preliminary utility work, drainage.			
Assume site is nominally flat (<10% grade), clay subsoil, with good footing.			
Assume site prep work is equal to twice plant area (see Table 27).			
Area to be prepped (acres)	6	8	10
Gallons per acre prepped	255	255	255
Fuel for site prep (gal)	**1530**	**2040**	**2550**
Excavation			
Assume excavation volume is equal to four times the volume of concrete placed.			
Assume excavation is by hydraulic excavator, hauling by articulated dump.			
Concrete volume (yd.^{3}) (from Table26)	76000	200000	325000
Excavation volume (yd.^{3}) (4x concrete volume)	304000	800000	1300000
Excavation productivity (yd.^{3}/hr)	375	375	375
Excavation fuel consumption (gal/hr)	14.5	14.5	14.5
Excavation fuel (gal)	**11755**	**30933**	**50267**
Hauling			
Assume excavation spoil is hauled 0.3 miles for storage/reuse.			
Haul/dump volume (yd.^{3}) (excavation volume, see above)	304000	800000	1300000
Haul productivity (yd.^{3}/hr)	360	360	360
Haul fuel consumption (gal/hr)	10.2	10.2	10.2
Haul/dump fuel (gal)	**8613**	**22667**	**36833**
Backfill			
Assume backfill/disposition requires same amount of fuel to load/haul/dump as Exc + Haul.			
Backfill / disposition fuel (gal)	**20368**	**53600**	**87100**
Site finishing			
Assume site finishing requires same amount of fuel as land clearing.			
Site finishing fuel (gal)	**2349**	**4406**	**6318**
Fuel for misc equipment (gal)	**15000**	**30000**	**60000**
Total fuel (gal)	**59615**	**143646**	**243068**
Assume that lube oil and grease consumption is 1.2% of fuel volume, per Caterpillar data.			
Lube oil and grease (gal)	**715**	**1724**	**2917**

Permanent parking areas are calculated assuming 120 parking spaces per acre and 1.4 employees on average per car. Allowing for shift change overlap and temporary contract staff during shutdown periods, permanent parking for a 250 MWth plant can be estimated from the total number of plant employees as 300/(120x1.4), rounded up to 2 acres. For a 1000 MWth plant, permanent parking can be estimated as 344/(120x1.4), or about 2 acres. For a 2000 MWth plant, permanent parking can be estimated as 385/(120x1.4), rounded up to 3 acres.

Temporary parking lot size is estimated using the peak employment figures and the same assumptions as for permanent parking lots. Thus, temporary parking for a 250 MWth plant can be estimated as 780/(120x1.4), rounded up to 5 acres. For a 1000 MWth plant, temporary parking can be estimated as 2050/(120x1.4), or about 12 acres. For a 2000 MWth plant, permanent parking can be estimated as 385/(120x1.4), rounded up to 20 acres.

Table 28 (construction wastes):

Hazardous liquid and solid wastes: see Appendix B, Table B.2.

Sanitary liquid and solid wastes ([CRBRP, 1977], Sec. 4.1.1.5 and Table 8.2-1; Appendix B, Table B.3)

These two references differ considerably in estimates of sanitary liquid waste. The CRBR report lists a capacity to process a peak of 61,250 gallons per day, comprised of normal domestic sanitary wastewater, including laundry wastes and sink and toilet wastes. Liquid sanitary wastes were planned to be treated in an on-site treatment system during both construction and operations, with sludge to be collected and disposed of off-site by a contractor. Very limited use was to be made of chemical toilets. Assuming liquid sanitary waste of 25 gal./person/day and the annual construction employment figures from Table 8.2-1, total liquid sanitary waste during construction would be

$$365(150+450+1000+1500+1980+1483+450/4) = 61{,}000{,}000 \text{ gal.},$$

which is a reasonable estimate of the liquid sanitary wastes during construction for a 1000 MWth ABR plant. If the CRBR liquid sanitary wastes are scaled by a power factor, as described in Appendix B, then for construction of a 2000 MWth plant,

$$\text{Liquid sanitary waste} = (61{,}000{,}000)*(2000/1000)^{0.7} \approx 99{,}000{,}000 \text{ gal.}$$

and for construction of a 250 MWth plant,

$$\text{Liquid sanitary waste} = (61{,}000{,}000)*(250/1000)^{0.7} \approx 23{,}000{,}000 \text{ gal.}$$

By contrast, the analysis presented in Table B.3 assumes sanitary liquid waste to be exclusively from waterless portable toilets, with this waste then transported off site to be processed. Because the ABR plant design has not yet developed to the point of addressing sanitary waste expected during construction, both approaches are included in this document.

Solid sanitary wastes are assumed to be generated primarily by lunch waste and hand cleaning. The analysis described in Appendix B, Table B.3 estimates the mass of these untreated wastes from ten years of data on per capita solid wastes generated in Missouri. No average density value is estimated, so the solid waste estimate is given in tons.

Other non-hazardous wastes: see Appendix B, Table B.4.

Appendix B: ABR Construction Wastes Spreadsheet Tables

Construction wastes for an ABR plant have been estimated primarily based upon information from construction of an existing reactor power generating station. Information was organized in a spreadsheet which was then used to perform the necessary calculations. Tables B.1 through B.6 list each sheet in the spreadsheet. Table B.1 summarizes the assumptions and results of the evaluation. Tables B.2 through B.4 provide details of the calculations for hazardous wastes, sanitary wastes, and other non-hazardous wastes. Tables B.5 and B.6 provide information supporting the calculations.

Table B.1. Summary of Waste Generated During Construction of a Commercial Scale Advanced Burner Reactor.

	250 MWth		1000 MWth		2000 MWth			
	Solid	**Liquid**	**Solid**	**Liquid**	**Solid**	**Liquid**	**Units**	**Source/Factor**
Hazardous/Special Waste	1.3	25.4	3.7	73.8	6.6	130.8	tons	comparable project est.
Sanitary Waste	436	750	1,150	1,980	1,868	3,217	tons	per capita-day
Other Waste	5,692	342	15,022	904	24,403	1,468	tons	per trade hours

Assumptions:

Greenfield site - no prior structures to remove, no D&D.
Estimates include only waste generated on site.
Soil spoil will be reused on site.
Landscape and land clearing debris (green wood materials) will be reused onsite.
Construction period - from site planning through initial commissioning.
Reasonable efforts will be made to reduce, reuse, reclaim, recycle.
No on-site residential workers.
Assume craft hours scale by PWR/ABR Cost Factor.
Reasonable efforts will be made to avoid specification and use of hazardous/special materials.
Wastewater will be separated from surface runoff.
Liquid sanitary wastes - assumed based on primary use of no-flush portable toilets.
(Same qty of sanitary waste would be generated w/wo ABR project.) ???
Sanitary wastes are similar to those generated if manpower were on another project or stayed home.
Waste generated will scale proportionate to ABR Cost Factor. Waste comes from purchased material (packaging, waste, scrap) and purchased labor hours, so a reasonable first-order assumption is that the amount of waste is proportional to dollar cost.

Cost/Power Factor

Assume: (cost / COST) = (power / POWER)^0.7
(empirical correlation that compensates for economies of scale)

	250 MWth	1000 MWth	2000 MWth
Power factor exponent	0.7	0.7	0.7
PWR Power, MWe	1144	1144	1144
ABR Power (Pth), MWth	250	1000	2000
ABR Power effiency(Pe/Pth)	39%	39%	39%
ABR Power (Pe), MWe	97.5	390	780
ABR/PWR cost factor	**0.18**	**0.47**	**0.76**

Note: Cost/Power factor was estimated from PWR information because this information was not available for CRBR, since CRBR was never actually built.

Table B.2. ABR Construction Hazardous / Special Waste

Includes:Oils, paints and thinners, cleaners, sealants, glues and adhesives, batteries, pesticides

Hazardous Waste - Solid

Assume Hazardous Waste - Solid will be generated at a rate similar to that estimated in [USNRC, 2005]. These numbers are annual construction wastes, taken from the National Enrichment Facility Safety Analysis Report [NEF, 2005]. This analysis is a recent evaluation of a facility of comparable size to the ABR and so was preferred to CRBR estimates.

	250 MWth		1000 MWth		2000 MWth	
Adhesives, resins, sealers, caulking.	466.5 lb/yr	0.277 yd.^{3}/yr.	1231.1 lb/yr	0.730 yd.^{3}/yr.	2000 lb/yr	1.186 yd.^{3}/yr.
Lead (batteries)	46.7 lb/yr	0.002 yd.^{3}/yr	123.11 lb/yr	0.006 yd.^{3}/yr	200 lb/yr	0.010 yd.^{3}/yr
Estimated density of adhesives, etc. (varies from 1 to 2 g/cc; 1g/cc = 1/5.93E-04 lb/cu. yd. 1 g/cc chosen as a conservative value for density)	1,686 lb/yd.^{3}					
Density of lead (11.35 g/cc - CRC Handbook of Tables for Engineering Science)	19,140 lb/yd.^{3}					
Annual ABR Construction Hazardous Waste - Solid	**0.26 ton/yr**	**0.279 yd.^{3}/yr**	**0.68 ton/yr**	**0.74 yd.^{3}/yr**	**1.10 ton/yr**	**1.196 yd.^{3}/yr**
Years for construction	5.0		5.5		6.0	
Total ABR Construction Hazardous Waste - Solid	**1.283 ton**	**1.395 yd.^{3}**	**3.724 ton**	**4.051 yd.^{3}**	**6.6 ton**	**7.179 yd.^{3}**

Hazardous Waste - Liquid

Assume Hazardous Waste - Liquid will be generated at a rate similar to that estimated in [USNRC, 2005]. These numbers are annual construction wastes, taken from the National Enrichment Facility Safety Analysis Report [NEF, 2005].

	250 MWth		1000 MWth		2000 MWth	
Paints, solvents, thinners, organics	4,898 lb/yr	700 gal/yr	12,927 lb/yr	1,847 gal/yr	21,000 lb/yr	3,000 gal/yr
Petroleum products, oils, lubricants	4,898 lb/yr	700 gal/yr	12,927 lb/yr	1,847 gal/yr	21,000 lb/yr	3,000 gal/yr
Sulfuric acid (batteries)	187 lb/yr	23 gal/yr	492 lb/yr	62 gal/yr	800 lb/yr	100 gal/yr
Pesticides	187 lb/yr	23 gal/yr	492 lb/yr	62 gal/yr	800 lb/yr	100 gal/yr
Annual ABR Construction Hazardous Waste - Liquid	**5.09 ton/yr**	**1,446 gal/yr**	**13.42 ton/yr**	**3,817 gal/yr**	**21.80 ton/yr**	**6,200 gal/yr**
Years for construction	5.0		5.5		6.0	
Total ABR Construction Hazardous Waste - Liquid	**25.43 ton**	**7,231 gal.**	**73.8 ton**	**20,991 gal.**	**130.8 ton**	**37.200 gal.**

Table B.3. ABR Construction Sanitary Waste Generation

Estimation Strategy: Assume that sanitary waste generation is proportional to the number of workers on the project. Ratio number of workers by PWR/ABR Cost Factor. Assume that a percentage of the Missouri average solid waste rate is generated on worksite. Assume that sanitary waste - liquid is generated at a rate equal to Portable Sanitation Association International data.

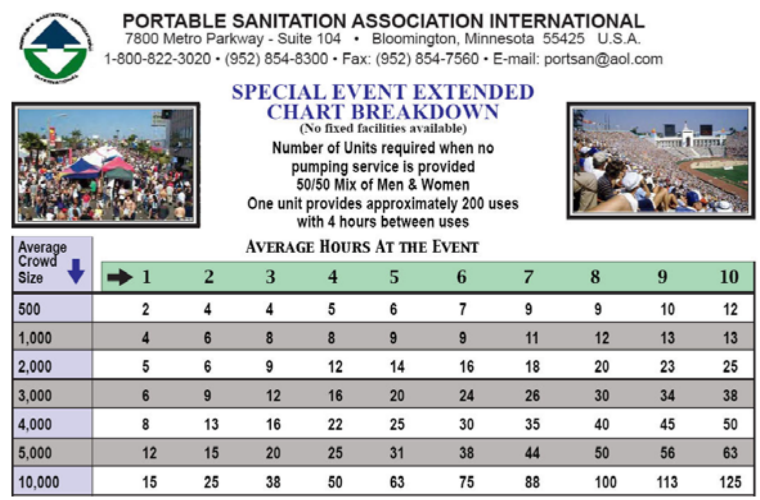
Missouri Solid Waste Generation - Ten Year History [MDNR, 2006]

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Population	5,117,073	5,157,507	5,193,872	5,237,867	5,281,280	5,226,784	5,358,692	5,402,058	5,438,559	5,468,338	5,595,211
Missouri Solid Waste Generation (tons)	7,540,000	7,623,009	7,844,367	8,107,229	8,411,596	8,563,780	8,771,303	9,048,000	9,227,853	9,559,890	10,288,232
per capita ton/yr	1.5	1.5	1.5	1.5	1.6	1.6	1.6	1.7	1.7	1.7	1.8
per capita lb/day	8.1	8.1	8.3	8.5	8.7	9.0	9.0	9.2	9.3	9.6	10.1
										AVG	**8.9**

ABR Construction Sanitary Waste - Solid

Assume daytime sanitary waste - solid will be a percentage of Missouri daily per capita average.
Primarily lunch waste and hand washing waste

	250 MWth	1000 MWth	2000 MWth
Missouri daily avg per capita (lb)	8.9	8.9	8.9
Ratio - daytime factor	0.2	0.2	0.2
Craft man-hours, median, PWR	2.20E+07	2.20E+07	2.20E+07
ABR/PWR cost factor	0.178	0.471	0.765
Craft man-hours, median, ABR	3.92E+06	1.04E+07	1.68E+07
Craft man-days, median, ABR	4.90E+05	1.29E+06	2.10E+06
Sanitary Waste - Solid (lb.)	8.71E+05	2.30E+06	3.74E+06
Sanitary Waste - Solid (ton)	**436**	**1,150**	**1,868**



Average Crowd Size	1	2	3	4	5	6	7	8	9	10
500	2	4	4	5	6	7	9	9	10	12
1,000	4	6	8	8	9	9	11	12	13	13
2,000	5	6	9	12	14	16	18	20	23	25
3,000	6	9	12	16	20	24	26	30	34	38
4,000	8	13	16	22	25	30	35	40	45	50
5,000	12	15	20	25	31	38	44	50	56	63
10,000	15	25	38	50	63	75	88	100	113	125

[PSAI, 2006]

ABR Construction Sanitary Waste - Liquid

Primarily toilet waste - Assume predominantly waterless portable toilet.
Assume liquid waste is proportionate to labor hours.

	250 MWth	1000 MWth	2000 MWth
Craft man-days, median, ABR	4.90E+05	1.29E+06	2.10E+06
Avg daily per capita SW-L (lb)	3.1	3.1	3.1
Sanitary Waste - Liquid (lb.)	1.50E+06	3.96E+06	6.43E+06
Sanitary Waste - Liquid (ton)	750	1,980	3,217
Sanitary Waste - liquid (gal.)	**1.96E+05**	**5.18E+05**	**8.41E+05**

portable toilets	20	number of users/day	2000
gallons each unit	40	pound per person-day	3.06
pound per gallon	7.65		

Table B.4. Other ABR Non-Hazardous Construction Waste

Construction waste generated on site will be similar in nature and volume to waste generated during construction of a similar sized industrial facility.

Other Waste - Solid
material trimmings
packaging materials
spoiled materials
rebar scraps
crates, skids
carpet scraps
drywall scraps

Assume generation rates by craft man-hours, see Table B.5.
Assume waste generation scales by cost factor.

	250 MWth				1000 MWth				2000 MWth			
PWR Other Waste - Solid	31906	ton	1.82E+05	yd.^{3}	31906	ton	1.82E+05	yd.^{3}	31906	ton	1.82E+05	yd.^{3}
ABR/PWR cost factor	0.178		0.178		0.471		0.471		0.765		0.765	
ABR Other Waste - Solid	**5,692**	**ton**	**3.24E+04**	**yd.^{3}**	**15,022**	**ton**	**8.56E+04**	**yd.^{3}**	**24,403**	**ton**	**1.39E+05**	**yd.^{3}**

Other Waste - Liquid
Water from washing and cleaning (density = 1 kg/m.^{3})
Assume generation rates by craft man-hours, see Table B.5.
Assume waste generation scales by cost factor.

	250 MWth				1000 MWth				2000 MWth			
PWR Other Waste - Liquid	1919	ton	4.60E+05	gal.	1919	ton	4.60E+05	gal.	1919	ton	4.60E+05	gal.
ABR/PWR cost factor	0.178		0.178		0.471		0.471		0.765		0.765	
ABR Other Waste - Liquid	**342**	**ton**	**8.21E+04**	**gal.**	**904**	**ton**	**2.17E+05**	**gal.**	**1,468**	**ton**	**3.52E+05**	**gal.**

Table B.5. Man-hours to Construct a Power Station

Per [USDOE, 1988] -
Direct Craft Man-hours for 1144MWe PWR Power Generating Station.

Craft	Median Man-hours	Better Man-hours	Median Construction other solid waste: per man-week, in pounds	Median Construction other solid waste: per project, in tons	Median Construction other liquid waste: per man-week, in pounds	Median Construction other liquid waste: per project, in tons
Boiler Makers	951,041	667,062	100	1189	5	59
Bricklayers	340,127	215,368	350	1488	10	43
Carpenters	1,718,442	1,322,745	200	4296	5	107
Electricians	3,817,045	2,201,879	90	4294	2	95
Ironworkers	2,276,271	1,314,267	100	2845	5	142
Laborers	2,469,131	1,587,579	125	3858	10	309
Millwrights	241,073	192,938	100	301	5	15
Operating Engineers	1,635,640	903,182	50	1022	2	41
Painters	744,695	292,610	100	931	20	186
Pipe Fitters	6,904,749	3,025,010	125	10789	10	863
Sheet Metal Workers	359,071	160,302	100	449	10	45
Teamsters	355,036	154,652	50	222	2	9
All Others	177,453	150,412	100	222	2	4
			Sum	**31906**	**Sum**	**1919**
Sum	21,989,774	12,188,006				

Table B.6. Weight to Volume Conversions

Material	Conversion Rate	Units
	300.0	lbs./yd.^{3}
Wood	6.7	yd.^{3}/ton
	30-100	lbs./yd.^{3}
Cardboard (loose)	20-50	yd.^{3}/ton
	400.0	lbs./yd.^{3}
Drywall	5.0	yd.^{3}/ton
	350.0	lbs./yd.^{3}
Mixed Waste	5.7	yd.^{3}/ton

Appendix C: ABR Plant Steel Requirements Spreadsheet Table

Table C.1 below shows the spreadsheet table assembled to estimate steel usage in constructing an ABR plant. Estimates are given for a 250 MWth, a 1000 MWth, and a 2000 MWth plant. Estimates are based on an actual PWR because it was felt that steel usage would be better estimated from actual detailed construction information on a commercial PWR than from much less detailed information on CRBR, which was never constructed.

Table C.1. Advanced Burner Reactor Steel Requirements

			2000 MWth		1000 MWth		250 MWth	
Structures per ABR Plans	**L (ft)**	**W (ft)**	**Area (SF)**	**Roofed**	**Area (SF)**	**Roofed**	**Area (SF)**	**Roofed**
Security Gate House	30	30	900	900	900	900	900	900
Control Bldg, 1000 and 2000	131	96	12576	12576	12576	12576		
Control Bldg, 250	89	71					6319	6319
BOP Bldg, 1000 and 2000	260	161	41860	41860	41860	41860		
BOP Bldg, 250	72	46					3312	3312
Reactor Bldg, 1000 and 2000	204	204	41616	41616	41616	41616		
Reactor Bldg, 250	89	89					7921	7921
Fuel Handling Facility, all	100	60	6000	6000	6000	6000	6000	6000
Fuel Storage Facility, 1000 and 2000	307	187	57409	57409	57409	57409		
Fuel Storage Facility, 250	250	125					31250	31250
RW/Maint Facility, 1000 and 2000	120	200	24000	24000	24000	24000		
RW/Maint Facility, 250	100	60					6000	6000
Switch Yard	100	89	8900		8900		8900	
BOP Services Bldg, 1000 and 2000	100	90	9000	9000	9000	9000		
BOP Services Bldg, 250	50	45					2250	2250
Cooling Tower, 2000 (two)	156	dia	38227					
Cooling Tower, 1000	156	dia			19113			
Cooling Tower, 250 (four)	48.5	48.5					2352	

Back-up generator bldg, 1000 and 2000	100	30	3000	3000	3000	3000			
Back-up generator bldg, 250	25	15					375	375	
Lift Station Bldg	40	30	1200	1200	1200	1200	1200	1200	
Waste Water Tx Bldg, 2000	110	85	9350	9350					
Waste Water Tx Bldg, 1000	80	60			4800	5800			
Waste Water Tx Bldg, 250	40	30					1200	1200	
		Sum	**254038**	**206911**	**230374**	**202361**	**85036**	**66727**	

Volume/Power factor to scale various size facilities.

Data derived from 1144 MWe PWR

Convert to 250, 1000, and 2000 MWth

Volume/Power Factor			
Assume: (volume / VOLUME) = (power / POWER)^0.7			
	250 MW	**1000 MW**	**2000 MW**
Volume factor exponent	0.7	0.7	0.7
PWR Power, MWe	1144	1144	1144
ABR Power, MWth	250	1000	2000
ABR Power efficiency (Pe/Pth)	39%	39%	39%
ABR Power, MWte	97.5	390	780
ABR/PWR cost factor	**0.178**	**0.471**	**0.765**
250/2000 cost factor	**0.233**		
1000/2000 cost factor	**0.616**		

Steel Usage, per 1144 MWe Pressurized Water Reactor, 1987

Historical Data

Commodity	**Experience Median Qty**	**Better Qty**	**2000 MWth (ton)**	**1000 MWth (ton)**	**250 MWth (ton)**

Reinforcing steel	ton	25,328	20082		19372	11925	4519
Embedded steel	ton	1921	1324		1469	904	343
Structural steel	ton	10906	7198		8341	5135	1946
Carbon steel piping (NS)	ton	1038	813		794	489	185
Stainless steel piping (NS)	ton	342	283		261	161	61
Carbon steel piping (NNS)	ton	3995	3228		3055	1881	713
Stainless steel piping (NNS)	ton	315	258		241	149	56
	Sum(ton)	**43,845**	33,186	**Sum(ton)**	**33534**	**20643**	**7822**
NS - Nuclear Safety Grade							
NNS - Non-Nuclear Safety Grade							

Steel Used in Reactor		**Equivalent Volumes and Masses**						
		by rectangular approximations, at 2000 MWth, adjusted to 250 and 1000 MWth.						
	Qty	**L**	**W**	**T**	**V**	**Density**	**Steel Weight**	
		in	**in**	**in**	**in^3**	**lb/in^3**	**Tons**	
Primary Vessel	1	1319	688	2	1814944	0.29	263.2	
Secondary Vessel	1	1400	700	1	980000	0.29	142.1	
Core & support	1	100	100	50	500000	0.29	72.5	
Redan	1	1450	435	1	630750	0.29	91.5	
Cover	1	1000	1000	3	3000000	0.29	435.0	
IHX	4	1150	150	0.5	345000	0.29	50.0	
Primary Pump/Motor	4	1500	16	16	1536000	0.29	222.7	
Sample service equipment	1	1200	60	1	72000	0.29	10.4	
Secondary Piping	1	1200	31.4	0.6	22608	0.29	3.3	
Miscellaneous	1	100	25	25	62500	0.29	9.1	
						Sum	**1300**	**tons**
				1000	**2000**	**250**		
				MWth	**MWth**	**MWth**		

				Steel (ton)	**800**	**1300**	**303**		
					1000 MWth	**2000 MWth**	**250 MWth**		
Generating equipment	**P (MWe)**			**Ton/MWe**	**Ext (ton)**	**Ext (ton)**	**Ext (ton)**	**Spec**	**Resource**
Steam turbines	780			2.31	1109	1802	420	HP+LP steam turbine	www.genesispower.co.nz/genesis
Generators	780			1.03	495	803	187	Distributed winding, hydrogen cooled	^
				Sum(ton)	**1604**	**2605**	**608**		www.nzcid.org.nz
Backup generators					**Wt (ton)**	**Wt (ton)**	**Wt (ton)**	**Spec**	**Resource**
2000 MWth	12,000	kWe				168		Cat 1000 kW standby diesel genset	www.cat.com/cda
1000 MWth	6,000	kWe			84			Cat 1000 kW standby diesel genset	www.cat.com/cda
250 MWth	2000	kWe					28	Cat 1000 kW standby diesel genset	www.cat.com/cda
				Sum(ton)	**84**	**168**	**28**		
Security Fences	**L (ft)**	**W (ft)**	**Perimeter(ft)**		**Ext (ton)**	**Ext (ton)**	**Ext (ton)**	**Spec**	**Resource**
Inner Security Fence, 1000 and 2000	1085	660	3490		25	25		fence, chain link, industrial, sch 40, 8 ft , 6 ga. wire, 2.5"post, galv. steel.	NFPA, RSMeans*
Inner Security Fence, 250	435	244	1358				10	^	^
Outer Security Fence, 1000 and 2000	1253	885	4276		30	30		^	^

Outer Security Fence, 250	616	394	2020					14	^	^
Switchyard fence	50	89	278			2	2	2	^	^
					Sum(ton)	**57**	**57**	**26**		
Railroad spurs	**3.5**	**miles**	**ton/mile**			**Ext (ton)**	**Ext (ton)**	**Ext (ton)**	**Spec**	**Resource**
Rail	3.5	miles	ton/mile		202	707	707	707	RE115 rail, plates, spikes,splices	www.akrailroad.com/
Plates	3.5	miles	ton/mile		33	116	116	116	^	^
Joints	3.5	miles	ton/mile		12.8	45	45	45	^	^
Bolts	3.5	miles	ton/mile		1.6	6	6	6	^	^
Spikes	3.5	miles	ton/mile		4.06	14	14	14	^	^
					Sum(ton)	**887**	**887**	**887**		
Fire Protection						**Ext (ton)**	**Ext (ton)**	**Ext (ton)**	**Spec**	**Resource**
Fire protect system, internal, 2000	206911	ft^2	0.92	lb/ft^2			95		Dry valve system, extra hazard,	NFPA, RSMeans
Fire protect system, internal, 1000	202361	ft^2	0.92	lb/ft^2		93			^	^
Fire protect system, internal, 250	66727	ft^2	0.92	lb/ft^2				31	^	^
Fire hydrant system, external, 1000 and 2000	6000	ft	24.5	lb/ft		74	74		12" main, hydrants, PIV	^
Fire hydrant system, external, 250	3000	ft	24.5	lb/ft				37	12" main, hydrants, PIV	^
					Sum(ton)	**167**	**169**	**67**		
HVAC and Electrical						**Ext (ton)**	**Ext (ton)**	**Ext (ton)**	**Spec**	**Resource**
Heating, 2000	206911	ft^2	1.12	lb/ft^2			116		hydronic, tube-fin, electric boiler	RSMeans
Heating, 1000	202361	ft^2	1.12	lb/ft^2		113			hydronic, tube-fin, electric boiler	RSMeans
Heating, 250	66727	ft^2	1.12	lb/ft^2				37	hydronic, tube-fin, electric boiler	RSMeans

Air conditioning, 2000	206911	ft^2	0.52	lb/ft^2		54		packaged chiller, fan cooled coil unit	RSMeans
Air conditioning, 1000	202361	ft^2	0.52	lb/ft^2	53			packaged chiller, fan cooled coil unit	RSMeans
Air conditioning, 250	66727	ft^2	0.52	lb/ft^2			17	packaged chiller, fan cooled coil unit	RSMeans
Domestic electrical, 2000	206911	ft^2	0.76	lb/ft^2		79		service, branch, lighting, receptacles	RSMeans
Domestic electrical, 1000	206911	ft^2	0.76	lb/ft^2	77			service, branch, lighting, receptacles	RSMeans
Domestic electrical, 250	66727	ft^2	0.76	lb/ft^2			25	service, branch, lighting, receptacles	RSMeans
			Sum(ton)		**243**	**248**	**80**		
Furnishings						**Ext (ton)**	**Ext (ton)**	**Spec**	**Resource**
Steel content/furn 2000	206911	ft^2	1.8	lb/ft^2		186		office, maintenance, MRO	RSMeans
Steel content/furn 2000	202361	ft^2	1.8	lb/ft^2	182			^	RSMeans
Steel content/furn, 250	66727	ft^2	1.8	lb/ft^2			60	^	RSMeans
			Sum(ton)		**182**	**186**	**60**		
Transmission Towers	Existing								

		2000 MWth	**2000 MWth**	**250 MWth**
	Total ABR Steel Requirements (ton)	24666	**39155**	**9882**

Assumptions

Some site facilities do not scale with power levels.

*RSMeans - *RSMeans Square Foot Costs*, 26th Edition (2005) and *RSMeans Building Construction Cost Data*, 63rd edition (2005)

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