1.3 SITE DESCRIPTION

1.3.1 GEOGRAPHY

1.3.1.1 Location

The Plutonium Disposition Facilities are located within the F-Area of the Savannah River Site (SRS). F-Area is approximately centrally located within the SRS. SRS is an approximately circular tract of land occupying 310 square miles (198,344 acres) within Aiken, Barnwell, and Allendale Counties in southwestern South Carolina (Ref. 10). All of the area within a 5-mile (8-km) radius from the center of SRS is government-owned property. The center of SRS is approximately 25 miles (40 km) southeast of the city limits of Augusta, GA; 100 miles (160 km) from the Atlantic Coast; and about 110 miles (180 km) south-southeast of the North Carolina border. The SRS is bounded along 17 miles (27 km) of its southwest border by the Savannah River (see Figure 1.3-1). Regional safety considerations for the SRS are considered in the Site Generic Safety Analysis Report (G-GSAR-G-00001, Rev. 4).

Approximate distances to other locations of interest are given (in road miles) in Table 1.3-1. The site's location relative to towns, cities, and other political subdivisions within a 50-mile (80-km) radius is shown in Figure 1.3-2. The largest nearby population centers are Aiken, SC, and Augusta, GA (see Figure 1.3-2). The only towns within 15 miles (24 km) of the center of SRS are New Ellenton, Jackson, Barnwell, Snelling, and Williston, South Carolina, which are shown in Figure 1.3-3 (Ref. 11).

Prominent geographical features within 50 miles (80 km) of SRS are Thurmond Lake (formerly called Clarks Hill Reservoir) and the Savannah River. Thurmond Lake, operated by the U.S. Army Corps of Engineers, is the largest nearby public recreational area. This lake is an impoundment of the Savannah River about 40 miles (64 km) northwest of the center of SRS.

SRS consists of the following six major production areas:

- Reactor areas (C, K, L, P and R Areas)
- Separations areas (F and H Areas)
- Waste management areas (E, S, and Z Areas)
- Heavy water reprocessing area (D Area)
- Reactor materials area (M Area)
- Administration area (A Area)

Approximate latitude and longitude coordinates and SRS coordinates for the boundaries of SRS are given in Table 1.3-2. The SRS coordinates were developed during initial site construction. These coordinates are used in this report to define area and facility locations. The grid for SRS

coordinates is referenced to the plant north direction, which has a declination of 36° 24'15" west of geographic north.

SEPARATIONS AREAS

F Area is located in Aiken County, South Carolina, near the center of SRS, east of Road C and north of Road E (see Figure 1.3-4). F Area center point coordinates are given in Table 1.3-2. The nearest site boundary to F Area is approximately 6 miles (9.5 km) to the west.

H Area is located in Aiken and Barnwell Counties, South Carolina, near the center of SRS (see Figure 1.3-4), to the east of F Area. H Area center point coordinates are given in Table 1.3-2. The nearest site boundary to H Area is approximately 7.2 miles (11.5 km) to the west.

WASTE MANAGEMENT AREAS

The E Area Solid Waste Management Facility (SWMF) is located in Aiken County, South Carolina, near the approximate center of SRS between H Area and F Area (see Figure 1.3-4). The SWMF center point coordinates are given in Table 1.3-2. The nearest site boundary to E Area is approximately 6.5 miles (10.5 km) to the west.

S Area is located in Aiken County, South Carolina, north of H Area (see Figure 1.3-4). The S Area center point coordinates are given in Table 1.3-2. The nearest site boundary to S Area is approximately 6.8 miles (10.9 km) to the north.

Z Area is located north of S and H Areas in Aiken County, South Carolina, near the center of SRS (see Figure 1.3-4). The Z Area center point coordinates are given in Table 1.3-2. The nearest site boundary to Z Area is approximately 6.2 miles (10 km) to the north.

1.3.1.2 Exclusion Area

GENERAL SITE

SRS is owned by the U.S. Government. It was set aside in 1950, as a controlled area, for the production of nuclear materials for national defense. The DOE and its contractors are responsible for the operation of SRS.

The site is not open to the general public, but specific access is permitted for guided tours, controlled deer hunts, and environmental studies. In addition, the public can traverse portions of the site along established transportation corridors. These include a rail line for CSX Transportation Incorporated Railroad, and road traffic along South Carolina Route (SCR) 125 (SRS Road A), U.S. Route 278, and SRS Road 1 near the northern edge of the site. Figure 1.3-3 shows these roadways and railways. Figure 1.3-4 shows the relative locations of the major areas at SRS and the SRS boundary. These areas are discussed in the following paragraphs.

The production areas at SRS are broadly classified as Reactor Materials (300-M Area), Heavy Water (400-D Area), Reactors (100 Areas), Separations (200-F and 200-H Areas), Waste Management Operations (200 Areas), and Defense Waste Processing (200-S and 200-Z Areas).

Other SRS areas include the Administrative (700-A and -B Areas) and General (600-G or -N) Areas. DOE and Westinghouse Administrative Offices, Production Support, SRTC, Production Services, and Savannah River Ecology Laboratory (SREL) are located in the 700-A Area. Wackenhut Services, Inc. (WSI), the contractor for SRS Security Services, is based in the 700-B Area; WSI personnel are located throughout SRS. All facilities scattered through SRS but outside of the fenced, production areas of SRS are designated with a 600 identification "building" number. The U.S. Department of Agriculture (USDA) Soil Conservation Service (SCS), University of South Carolina Institute of Archaeology and Anthropology, USDA Savannah River Forest Station (SRFS), and river pumphouses are some of the facilities designated as 600-Area facilities.

The topographic relief of SRS and the surrounding vicinity is shown in Figure 1.3-5. Contour intervals shown are 50 feet. The elevation above sea level ranges from 80 feet at the Savannah River to approximately 400 feet about 1 mile south of the intersection of Highways 19 and 278. Two distinct physiographic subregions are represented at SRS. They are the Pleistocene Coastal Terraces, which are below 270 feet in elevation, and the Aiken Plateau, which is above 270 feet in elevation.

The lowest terrace is the present floodplain of the Savannah River. The higher terraces have level to gently rolling topography. The Aiken Plateau subregion is hilly and cut by small streams (Ref. 12).

Surface wind patterns and the occurrence of strong winds and tornadoes are discussed in Section 1.4.1.1. The wind rose developed from the 1987-1991 database is shown in Figure 1.3-6. As can be seen, there is no prevailing wind at SRS, which is typical for the lower midlands of South Carolina (Ref. 10).

Surface drainage on SRS is shown in Figure 1.3-7, and major river systems surrounding SRS are shown in Figure 1.3-8. Surface wind patterns and the occurrence of strong winds and tornadoes are discussed in Section 1.4.1.1.

The principal surface-water body associated with SRS is the Savannah River, which flows along the site's southwest border. Six principal tributaries to the Savannah River are located on SRS; these are Upper Three Runs Creek, Beaver Dam Creek, Fourmile Branch, Pen Branch, Steel Creek, and Lower Three Runs Creek. The total drainage area of the Savannah River, 10,681 square miles, encompasses all or parts of 41 counties in Georgia, South Carolina, and North Carolina. More than 77% of this drainage area lies upriver from SRS.

Natural discharge patterns on the Savannah River are cyclical: the highest river levels are recorded in the winter and spring, and the lowest levels are recorded in the summer and fall. Stream flow on the Savannah River near the site is regulated by a series of three upstream

reservoirs: Thurmond Lake, Russell, and Hartwell. These reservoirs have stabilized average annual stream flow to 10,200 cubic feet per second (cfs) near SRS.

The river overflows its channel and floods the swamps bordering the site when river elevation rises higher than 88.5 feet above msl (which corresponds to flows equal to or greater than 15,470 cfs). River-elevation measurements made at the SRS Boat Dock indicate that the swamp was flooded approximately 20% of the time (74 days per year on the average) during the period from 1958 through 1967.

The peak historic flood between the years 1954 and 1991 was estimated to be 84,500 cfs (Ref. 13). Since the construction of the upstream reservoirs, the maximum average monthly flow (during the period from 1964 to 1981) has been 43,867 cfs and occurs during the month of April (Ref. 14).

There are three significant breaches in the natural river levee at SRS; they are opposite the mouths of Beaver Dam Creek, Fourmile Branch, and Steel Creek. During periods of high river level (about 88.5 feet), river water overflows the levee and stream mouths and floods the entire swamp area. The water from these streams then mixes with river water and flows through the swamp parallel to the river and combines with the Pen Branch flow. Normally the flows of Steel Creek and Pen Branch converge 0.5 mile above the Steel Creek mouth. However, when the river level is high, the flows are diverted parallel to the river across the offsite Creek Plantation Swamp; ultimately, they join the Savannah River flow near Little Hell Landing (Ref. 15).

The topography at SRS varies from gently sloping to moderately steep. Some areas on uplands are nearly level, and those on bottom land along the major streams are level. The slopes in small, narrow areas adjacent to drainage ways are steep. Most of the soils are sandy over a loamy or clayey subsoil (Ref. 16). The well drained soils have a sandy surface layer underlain by a loamy subsoil. The somewhat excessively drained soils have a thick, sandy surface layer that extends to a depth of 80 inches or more in some areas. The soils on bottomland range from well drained to very poorly drained. In the Sand Hills area, some soils on the abrupt slope breaks have a dense, brittle subsoil. Numerous upland depressions, commonly referred to as "Carolina bays," are found on SRS. These range in size from less than an acre to many acres. Water will stand in the majority of these depressions for long periods, in most years.

The gradient of slopes at SRS ranges from 0 to 40%. The upland soils have a thick, well developed profile. The most extensive soils in the survey area are gently sloping to strongly sloping and have not been greatly affected by relief. The soils on bottomland have slopes of 0 to 2%. These soils are young and show little evidence of profile development.

Relief at SRS ranges from the long, narrow, steep areas on slopes on the east side of Upper Three Runs Creek and Tinker Creek to the nearly level areas on stream terraces west of Road 125. Elevations range from about 420 feet near the Aiken Gate House on Road 2 to about 70 feet where Lower Three Runs Creek enters the Savannah River in Allendale County. The elevation is about 80 feet where Steel Creek enters the Savannah River in Barnwell County. Most of the soils have slopes that range from about 1 to 8%. Some long, narrow breaks near streams have slopes that range to 40%.

Nearly all drainage from SRS is into the Savannah River. A small area in the northeast sector of SRS drains to the Salkehatchie River. The bottom land along the Savannah River is not flooded as extensively as it was prior to 1953 when Strom Thurmond Dam and other hydroelectric dams upstream began operation, which controlled runoff in the Savannah River. However, since streamflow is regulated somewhat by locks and the release of water through the dams, the frequency of flooding is greater, but the flooding is less severe.

Erosion is moderate on the gently sloping soils of SRS and severe on the sloping to steep soils. A permanent plant cover is needed on the more sloping soils. If land use prohibits a permanent plant cover, plant rotations, diversions or terraces, cover crops, crop residue management, and water-disposal systems should be used to control erosion (Ref. 16). Figure 1.3-9 shows the distribution of soil types as characterized by SCS. The engineering properties of SRS soils are described in Section 1.4.3.

In South Carolina, the average statewide erosion rate for soils is 6.3 tons per acre per year (T/AC/YR). The tolerable soil loss rate ranges from 2 to 5 T/AC/YR depending on the individual soil. Average soil erosion rates for the area surrounding SRS are 8.5 T/AC/YR for Aiken County, 6.8 T/AC/YR for Allendale County, and 9.0 T/AC/YR for Barnwell County (Ref. 17). The soils within SRS would be expected to have erosion rates somewhat lower than the surrounding area because SRS is covered, for the most part, with vegetation, and is not used for crop production.

The eight major plant community types at SRS are distributed along topographic and moisture gradients and are strongly controlled by local management practices. Communities range from sandhill communities in the xeric uplands to bottomland or swamp forests in low-lying areas subject to periodic flooding. The majority of the SRS land area is managed as pine plantation. However, old fields, upland hardwoods, and numerous aquatic communities including ponds, marshes, and Carolina bays cover approximately one-third of the land area on SRS (Ref. 18).

At the time of government acquisition, about 106,000 acres were forested, 68,000 acres were cleared fields, and 29,000 acres were floodplains and swamps. An intensive pine planting program and natural successional changes have dramatically altered these figures. Table 1.3-3 lists the vegetation cover of the site in 1989. Land utilization is about 56% in pine forests, 35% in hardwoods, 7% in SRS facilities and open fields, and 2% in water (Ref. 12).

The SRFS considers SRS to have an average to moderately high fire hazard potential. This fire hazard potential is caused by vast forested areas close to the production areas. Total and available fuel loading accumulations for a 5- to 10-year period are presented in Table 1.3-4. SRFS performs controlled burning to reduce the potential for forest fires. The primary impact of forest fires on the production areas is smoke, which causes visibility problems and potential damage to equipment. In fiscal year 1993, SRFS responded to 21 wildfires on and adjacent to the site. Six of these fires were in the mutual threat zone where the South Carolina Forestry Commission has primary protection responsibility. The remaining 15 fires burned 43 acres on the SRS.

The road system within SRS is shown in Figure 1.3-10. Continuation of these traffic routes offsite is shown in Figure 1.3-2. SRS highways connect with state highways leading northward to Interstate Routes 20, 26, and 85 and eastward to Interstate Routes 26 and 95. SRS has its own railroad system, which services all major facilities. Figure 1.3-11 shows the SRS rail system and the public railroad having rights-of-way onsite.

The rail network includes a main line of the CSX Railroad and the sitewide DOE-owned rail system. A classification yard is maintained near the 100-P Area, with plant-maintained connections to all of the production areas except the 400-D Area. Service to the 400-D Area is provided by the CSX tracks onto a short section of DOE-owned track. Rail traffic on the site is separated into two distinct categories according to ownership of the track: CSX operations and SRS operations. The CSX Railroad has a through line between Augusta, GA, and Yemassee, SC, and terminates in Port Royal, SC (Ref. 14). In 1989, a second line from SRS to Florence, SC was abandoned by CSX beyond Snelling, SC. CSX maintains service as required to the Dunbarton Station for SRS deliveries/pickups and a spur line into the Chem-Nuclear site near Snelling, SC.

The electrical grid on SRS operates at 115 kV and draws power from two transmission lines on separate rights-of-way from the South Carolina Electric and Gas (SCE&G) Urquhart Station and a third line from the 230-kV tie line between the Sumner and Canadys stations of SCE&G (see Figure 1.3-12). Their three feeders are tapped at SRS stations 504-1G, 504-2G, and 504-3G, respectively. The site 115-kV distribution system contains about 90 miles of power lines and is controlled by a dispatcher in Building 751-A (700-A Area) (Ref. 11). SRS also has a tie-in line to Vogtle Electric Generating Plant (VEGP). The tie-in line is shown in Figure 1.3-12. There are no natural gas or oil pipeline networks at SRS.

F AND E AREAS

F Area is centrally located within the SRS boundary (see Figure 1.3-4). Figure 1.3-13 shows F Area and the surrounding areas including the E Area. A detailed area map for F Area is shown in Figure 1.3-14.

F Area is drained by several tributaries of Upper Three Runs Creek approximately 2,200 feet to the north and west and by Fourmile Branch approximately 2,000 feet to the south. Topography in the vicinity is shown in Figure 1.3-15. Surface elevations across F Area range from approximately 200 to 320 feet msl.

F Area's main processing facility is F Canyon, which is composed of two chemical separations plants and associated waste storage facilities. In the past, the F Canyon was used to chemically separate uranium, plutonium, and fission products from irradiated fuel and target assemblies. The separated uranium and plutonium were transferred to other facilities for further processing and final use. The waste was transferred to high-level waste tanks in the area for storage. The F Area waste tank farm consists of 22 underground storage tanks that store high-level aqueous radioactive waste and evaporated saltcake.

Currently, F Canyon is conducting operations to stabilize SRS materials. Most of the stabilization actions will be the same as the historic mission (Ref. 10).

FB Line previously converted plutonium solution produced in F Canyon to plutonium-239 metal to support defense programs. FB Line's current mission is to convert plutonium-bearing solutions into a metal form suitable for storage (Ref. 10).

Analytical laboratories in F-Area (Buildings 772-F, 772-1F and 772-4F) principally support F- and H-Area reprocessing and waste activities.

The E Area Solid Waste Management Facility (SWMF) occupies 195 acres between the F and H Areas. The SWMF is used for permanent disposal of low-level radioactive solid waste and interim storage of radioactive, hazardous and mixed solid waste generated at SRS, as well as occasional special shipments from offsite. The SWMF also provides assaying, repackaging, and interim storage of transuranic (TRU) waste (Ref. 19). Other SRS facilities receive hazardous, low-level, and mixed waste for incineration and nonradioactive and hazardous waste for storage (Ref. 19). An area map is shown in Figure 1.3-16. Topography near F and E Areas is shown in Figure 1.3-15.

H, S, AND Z AREAS

H Area is located east of the SWMF near the center of SRS (see Figures 1.3-4 and 1.3-13). A detailed area map of H Area is shown in Figure 1.3-17.

Topography near H Area is shown in Figure 1.3-18. A topographic high runs through the E Area SWMF and into H Area. H Area is located near a water-table divide between Upper Three Runs Creek and Fourmile Branch. Near-surface groundwater from the southern part of H Area discharges to an unnamed tributary of Fourmile Branch, approximately 1,000 feet south of H Area. Near-surface groundwater from the northern part of H Area discharges to one of two tributaries (Crouch Branch or McQueen Branch) of Upper Three Runs Creek, which are approximately 1,500 and 4,000 feet north of H Area, respectively.

H Area covers approximately 395 acres; surface areas across H Area range from approximately 270 to 315 feet msl. In the past, H Canyon, a large, shielded chemical separations plant, processed irradiated fuel and target assemblies by utilizing solvent extraction and ion exchange to separate uranium, plutonium, and fission products from waste. The separated uranium and plutonium were transferred to other H Area facilities for processing into a solid form. The waste was transferred to high-level waste tanks in the area for storage, and some of the nuclear materials were shipped to other DOE sites for final use. DOE has issued a decision that H Canyon should be used to convert highly enriched weapons grade uranium to a low enriched form not useable for weapons production (Ref. 20).

HB Line was constructed to support the production of plutonium-238. Plutonium-238 has a unique combination of heat output and long life allowing space vehicle designers to keep weight at a minimum and still have a power supply. For example, in the mid-1990s, the HB Line

completed a production run to supply plutonium-238 for the Cassini mission, an unmanned expedition to the planet Saturn. HB Line is also used to stabilize plutonium-242 solutions (Ref. 20).

The tritium facilities in H Area consist of four main process buildings, designed for and operated to process tritium. The newest building is the 1-acre underground Replacement Tritium Facility (RTF). The main mission of the tritium facilities is to purify and maintain existing inventories of tritium for defense purposes (Ref. 20).

The Receiving Basin for Offsite Fuels (RBOF) is also located in H Area. Offsite fuels that will be processed in H Canyon are stored and packaged at RBOF. Radioactive waste generated by RBOF is stored in the high-level waste tanks in H Area (Ref. 20).

The Effluent Treatment Facility (ETF) is located on the south side of H Area. The ETF treats low-level radioactive wastewater (which was formerly sent to seepage basins). The ETF removes radioactive and nonradioactive contaminants, except tritium, from process effluents and allows the water to discharge to Upper three Runs Creek (Ref. 20).

The H Area waste tank farm consists of 29 large (up to 1.3 million gallon capacity) underground storage tanks that store high-level aqueous radioactive waste and evaporated saltcake. Seven of these tanks are now dedicated as In-Tank Precipitation Facility (ITPF) process tanks (Ref. 20).

The Consolidated Incineration Facility (CIF) is located on the east side of H Area. The CIF incinerates SRS hazardous, mixed, and low-level radioactive waste (Ref. 20).

S Area is located north of H Area near the center of SRS (see Figures 1.3-4 and 1.3-13). A detailed area map of S Area is shown in Figure 1.3-19.

Surface elevations across S Area range from approximately 300 to 320 feet msl. Surface drainage is to the east toward McQueen Branch and to the west toward Crouch Branch, both tributaries of Upper Three Runs Creek. Near-surface groundwater flows toward McQueen Branch, approximately 4,000 feet to the northeast. Topography near S Area is shown in Figure 1.3-20. The elevation above sea level is about 300 feet at the site, 150 feet at Upper Three Runs Creek 0.8 miles northwest of the S-Area fence, and 200 to 250 feet at Fourmile Branch to the south. The Savannah River, into which these streams feed some 9 miles to the southwest, is usually at an elevation of about 8 feet msl, or slightly greater. Flooding of site streams begins at a river height of 88.5 feet msl.

S Area is the site of the Defense Waste Processing Facility (DWPF) Vitrification Plant. The DWPF immobilizes high level radioactive waste sludge and precipitate by "vitrifying" it into a solid glass waste form (Ref. 20).

Z Area, which contains the DWPF Saltstone Facility, is located north of the intersection of Road F and Road 4. A detailed map of Z Area is shown in Figure 1.3-21. The Saltstone Facility treats and disposes of the filtrate created by the ITPF by stabilizing it in a solid, cement-based waste form (Ref. 20).

The original topography near Z Area is shown in Figure 1.3-22. Before grading for installation of facilities, Z-Area ground surface elevations ranged from approximately 280 to 300 feet msl. This site was selected for saltstone disposal because it is located on a well-drained topographic high, as evidenced by the lack of marshes or other bodies of standing water. Natural drainage from Z Area enters McQueen Branch, Crouch Branch, and Upper Three Runs Creek. These flow to the Savannah River. During construction of the Z-Area facilities, anthropogenic alterations to surface water drainage patterns were made. All surface water runoff, from around the saltstone disposal vaults and the Saltstone Production Facility, has been directed through a stormwater collection system and into a retention basin for silt removal. The retention basin overflows into a channel that drains to McQueen Branch.

SITE BOUNDARY

Activities conducted within SRS that are not under the control of the operating contractor, WSRC, and not related to production, are performed by the following organizations: General Services Administration (GSA), WSI, SRFS, SREL, University of South Carolina Institute of Archaeology and Anthropology, SCS, and SCE&G.

General Services Administration

The GSA is a federal agency that operates at SRS under a Memorandum of Agreement with DOE. The GSA SRS Field Office, located at SRS, is part of the South Carolina Fleet Management Center. GSA maintains the federal vehicle fleet from "cradle to grave," including acquisition, maintenance, and disposal. Eleven GSA employees are stationed in A Area.

Wackenhut Services, Inc.

WSI provides security services for SRS. These include preventing unauthorized access to site facilities, equipment, information, and personnel; restricting the impact of any unauthorized access on the site; badging; manning the various site access portals; and providing appropriate training for all security personnel.

WSI is headquartered in 700-B Area and performs security activities in all major areas. WSI facilities and personnel are distributed throughout the site. In addition, WSI uses the Small Arms Training Area and the Advanced Tactical Training Area (Ref. 11, 22).

Savannah River Forest Station

SRFS, an administrative unit of the U.S. Forest Service (USFS) provides timber management, plant and wildlife management, secondary road maintenance, and maintenance of the exterior boundaries at the SRS. SRFS manages approximately 175,000 acres or about 80% of the site area. SRFS fire crews, which have primary responsibility for fighting wild fires and conducting controlled burns, coordinate their efforts with the WSRC Fire Department (Ref. 20).

SRFS occupies or uses six buildings along SRS Road 2 about 2.5 miles south of US 278 and approximately 7 acres of adjoining land. The buildings are used for office space and equipment and material storage (Ref. 22).

Savannah River Ecology Laboratory

SREL is operated for DOE-Savannah River by the University of Georgia. The mission of SREL is to study and assess the impact of site operations on the environment. Research programs are organized into four main categories: radioecology, environmental chemistry, ecotoxicology, and ecosystem health (Ref. 20).

SREL occupies or uses approximately 30 acres of land. Land uses include offices, laboratories, shops, greenhouses, ponds, and research facilities. Most of SREL's buildings are located in A Area, southeast of SRTC.

University of South Carolina Institute of Archaeology and Anthropology

The mission of the University of South Carolina Institute of Archaeology and Anthropology is to make compliance recommendations to DOE that will facilitate the management of archaeological resources at SRS. This includes compliance activities involving reconnaissance surveys, general intensive watershed surveys, specific intensive surveys, data recovery, coordination with major land users, and reconstruction of the environmental history of the SRS (Ref. 20).

The Institute occupies offices in Building 760-11G, and uses adjacent grounds in the SRFS area (Ref. 22).

Soil Conservation Service, U.S. Department of Agriculture

The mission of SCS is to publish a soils report of SRS that meets the standards of the National Cooperative Soil Survey. Current land use includes one office in Building 760-11G and the surrounding grounds (Ref. 22).South Carolina Electric and Gas Company

SCE&G leased the D-Area powerhouse in 1995. This facility is the site's largest coal-fired powerhouse; it provides approximately 70 megawatts of electric capacity and 420,000 lb/hr of process steam capacity (Ref. 20).

BOUNDARIES FOR ESTABLISHING EFFLUENT RELEASE LIMITS

The outer perimeter fenceline of SRS is used as the basis for specification limits on the release of gaseous and liquid effluents from all SRS facilities. The outer perimeter of SRS is shown in Figure 1.3-27 (Note: Figures 1.3-23 through 1.3-26 are intentionally omitted). The Figure also shows Emergency Planning Zone/Contingency Planning Zone (EPZ/CPZ) boundaries with respect to rivers and streams. The outer perimeter is fenced, and access is controlled by the security contractor (WSI) with the assistance of the operating contractor such that public access can be restricted as the need arises. The roads that pass through or near the perimeter can be blocked by WSI personnel or with the assistance of local, law enforcement personnel.

The EPZ shown in Figure 1.3-27 is based on the Design Basis Accident under worst meteorological conditions at the reactors. Only a small portion of the EPZ extends outside the SRS boundary. The CPZ, an arbitrary zone that is within an approximately 10-mile (16-km) radius from each reactor, was established when the reactors were operating. The location of the SRS boundary with respect to rivers and population centers is shown in Figure 1.3-2.

The closest potential release points are M Area, which is approximately 1 mile (1.6 km) from the outer perimeter boundary, and SRTC, which is about 0.5 mile (0.8 km) from the outer perimeter boundary. The 200 Areas, where Separations and Waste Management facilities are located, have the largest inventory of radioactive materials that could potentially be released, and are located greater than 5 miles (8 km) from the site boundary (see Figure 1.3-4).

Onsite personnel are provided with dosimeters if they are entering potential radiation areas. Production areas enforce more stringent access controls, including special dosimeters and protective clothing, additional access authorization, and escorts for visitors. Dose equivalents to the general public and site personnel are kept As Low As Reasonably Achievable (ALARA). The limits for radiation exposure from external and internal exposure are stated in 10 Code of Federal Regulations (CFR) 835, Occupational Radiation Protection (Ref. 23). The 10 CFR 835 limit to radiation workers is 5 roentgens equivalent man (rem) total Effective Dose Equivalent (EDE). However, the DOE Administrative Control Level for a radiation worker is 2 rem/year total EDE. 10 CFR 835 further limits exposure of nonworkers, during onsite access at a DOE facility, to no more than 0.1 rem (100 mrem) per year. DOE Order 5400.5, Radiation Protection of the Public and the Environment, limits the exposure of members of the public to all radioactive sources from DOE activities to no more than 100 mrem EDE per year (Ref. 24).

ACCESS CONTROL

The outer perimeter of SRS is fenced; access is controlled by the operating contractor with the assistance of the security contractor, WSI. General access to the plant site, with the exception of public transportation corridors, is limited to badged personnel.

SCR 125 is a public access corridor and is not controlled. The CSX rail line maintains a right-of-way through the site, without barricades at either end of the site. Although these entries do not restrict pedestrian access, access would be into a nonsecured area of SRS with further entry into secured areas restricted by barricades.

Visitors to SRS must wear identification badges, and those entering areas where there is a radiation hazard are required to wear dosimeters. The roads that pass through or near the perimeter can be blocked by WSI personnel or with the assistance of local, law enforcement personnel.

Employee access within the F and H Area fences is controlled by security personnel, and restricted to employees who have the appropriate designation on their security badges. More restrictive individual facilities within F and H Areas have additional access requirements. Access to E Area is controlled by a perimeter fence and procedural controls; no security personnel are posted at the entry gate adjacent to Building 742-7E.

S and Z Areas are property protection areas. M Area is also a property protection area. Individual facilities within M Area have additional access requirements. Access to SRTC is limited to personnel with "L" clearance or higher, unless escorted. D Area is a property protection area.

EFFLUENT RELEASE POINTS

The WSRC Environmental Protection Department maintains an active permit inventory for National Pollutant Discharge Elimination System (NPDES) permitted outfalls and permitted air emission sources. The annual Environmental Data Report contains a listing of NPDES outfall locations and the sources of wastewater contained in each effluent. The Annual Environmental Report for SRS contains an annually updated listing of all air permits held by SRS, including permit number, permit title, and permitted source (Ref. 20).

RELEVANT SPECIAL FEATURES

SRS is a self-contained site that provides its own security, fire protection, medical, maintenance, and other services. To enhance the safety of the facility, a large support staff provides services such as radiological protection, industrial hygiene, and safety. In addition to the onsite resources, which include specialized equipment for tracking tritium releases, meteorological assessment systems, and monitoring equipment, a large supply of specialized equipment is available from regional DOE offices. State agencies in South Carolina and Georgia, VEGP, Fort Gordon, and other nearby sources can also provide monitoring equipment, medical facilities, and laboratory facilities in emergencies. In addition, several municipal emergency organizations are located within 25 miles of SRS. These resources are discussed in Chapter 15.0 of this report.

1.3.2 DEMOGRAPHY

1.3.2.1 Permanent Population and Distribution

GENERAL SITE

The total resident population within a 50-mile (80-km) radius of the SRS center is approximately 730,000. The largest urban center, Augusta, GA (1990 population of 44,639), lies about 25 miles (40 km) west-northwest of the site. Four other cities within the 50-mile radius had 1990 populations greater than 13,000. These are Aiken, SC, about 20 miles (32 km) north-northwest; Orangeburg, SC, 48 miles (77 km) east-northeast; North Augusta, SC, 23 miles (37 km) northwest; and Evans, GA, about 35 miles (56 km) west-northwest of the site. All other cities and towns have populations less than 7,000; the largest is Belvedere, SC, followed by Red Bank, SC; Waynesboro, GA; and Barnwell, SC (Ref. 25). Table 1.3-5 shows the sizes and geographic locations of cities and towns within the 50-mile radius.

The SRS Emergency Plan Section 3 and facility annexes establish the interrelationships with federal, state, and local organizations for offsite emergency response and for the protection of the environment and the public. Population evacuation estimates are given in the SRS Emergency Plan SCD-7 (Ref. 26). Details on emergency preparedness and the SRS Emergency Plan can be found in Chapter 15 of this report.

Projected permanent populations (residents) and their distribution within a 50-mile (80-km) radius of the plant center were updated by the Environmental Technology Section (ETS) at SRTC (Ref. 27). The "Potential Security Circle for the Savannah River Site" was used to establish the center of SRS at plant coordinates E58,000; N62,000. The 1990 census at 0.025-degree grids of latitude and longitude was used as the database. This database was used by ETS to derive population densities at 15-second cells of latitude and longitude. The results were aggregated by the geographical divisions formed by subdividing the study area into 16 radial segments centered on north and concentric circles with radii of 5, 10, 20, 30, 40, and 50 miles. The area within a radius up to 5 miles from the SRS centroid is contained within the SRS boundary. Therefore, zero permanent population exists within radii up to 5 miles. An offsite population database, based on the results of the 1990 census, was used to update populations (Ref. 27). Projections were based on the assumption that the growth rate will be similar to the growth rate of the total population in the WNW sector around 200-S Area (Ref. 27).

The growth, by decennial years, is determined using the following ratios:

Year	Population Ratio of Given Year to 1990
1990	1.000
2000	1.140
2010	1.299
2020	1.481
2030	1.688
2040	1.924

Figures 1.3-28 through 1.3-33 show the 1990 population distribution and the projected population distributions for radii 10 through 50 miles (16 through 80 km) from site center for 1990, 2000, 2010, 2020, 2030, and 2040 (Ref. 28).

Both South Carolina and Georgia have projected population compositions by county and age group for 1990 (Ref. 22, 25). The 1990 age group composition projections for the counties within 50 miles (80 km) of SRS include the following:

	Age Group (%)			
	0-4 years	5-18 years	18-64 years	65 years and over
Georgia	8.14	27.13	54.62	10.11
South Carolina	7.60	19.91	61.25	11.24

F AND E AREA

The permanent population consists of residents within a 50-mile (80-km) radius of F Area. Projected permanent populations and their distribution within a 50-mile radius of F Area were estimated for 10-year intervals through 2040, based on 1990 census data, by the SRTC (Ref. 28). The results were aggregated by geographical divisions formed by subdividing the study area into 16 radial segments. The segments are centered on north and concentric circles with radii of 1, 2, 3, 4, 5, 10, 20, 30, 40, and 50 miles (see Figures 1.3-34 through 1.3-39). These are based on the "Potential Security Circle for the Savannah River Site," which was modified to establish the F Area center point at SRS coordinates E51,345; N77,687. The areas within the 1- through 5-mile radii are DOE-owned properties within SRS; the population for these areas consists of SRS workers only.

Since the SWMF is within a few thousand feet of F Area, the population distributions for F Area shown in Figures 1.3-34 through 1.3-39 are adequate for SWMF assessments.H, S, and Z Areas

Since the H, S, and Z Areas are all within 1.5 to 2 miles of F Area, the population distributions for F Area shown in Figures 1.3-34 through 1.3-39 are adequate for assessment of H, S, and Z Areas. H, S, and Z Areas are farther away from the largest population centers in Richmond and Columbia Counties, Georgia, and Aiken County, South Carolina.

1.3.2.2 Transient Population Variations

Transient population variations for SRS are addressed for the areas within approximately 5 miles (8 km) of the various SRS activities. Any transient population fluctuations beyond this limit are not relevant to a SAR. The transient population components investigated are industrial, school, recreational, health care, and casual. There are no military reservations or correctional institutions located within 5 miles of the site boundary.

The transient population consists of all persons traveling through the vicinity of an onsite area. A 5-mile (8-km) radius is considered when discussing the transient population. The 5-mile areas for F and E Areas, and H, S, and Z Areas, shown in Figures 1.3-52 and 1.3-53, respectively, fall entirely within the SRS boundary (Note: Figures 1.3-40 through 1.3-51 are intentionally omitted). Therefore, the transient population consists only of employees, badged visitors, and vendors making deliveries at site locations within the area.

INDUSTRIAL POPULATION

The industrial population, consisting primarily of the SRS workforce, VEGP employees, and employees of 16 smaller industries located in or near Barnwell, Williston, New Ellenton, and Jackson, South Carolina, comprise a daily transient population of approximately 25,734. Most of this total population works Monday through Friday during the hours 0800 to 1600. These workers spend an average of about 45 hours per worker, per week, at their worksites.

The total onsite employment at SRS during the day shift of a weekday was 14,177 as of December 1998. According to unofficial information provided by the WSRC Public Affairs Department (Bruce Cadotte, February 1999), the distribution of onsite employees working the day shift on a weekday was estimated to be WSRC 12,622; DOE 520; WSI 742; and the rest in the USFS, SREL, and other contractors to DOE-SR.

Figure 1.3-56 boundary (Note: Figures 1.3-54 and 1.3-55 are intentionally omitted). shows total onsite population densities at SRS based on 1993 data (Ref. 29). SRS population densities were developed specifically for environmental consequence assessments, using the population of adult workers at their assigned locations during the day shift of a weekday in midsummer 1993 (Ref. 29). For multishift operating areas, it was estimated that 70% of their workforce would be present during the daytime. All construction workers were assumed to be at their paymaster locations. A total onsite population of 19,289 was obtained from November 1992 data, and population densities by 15-second cells of latitude and longitude were determined for the database.

Geographical divisions were formed by subdividing the study area into 16 radial segments centered on north and concentric circles with radii of 1, 2, 3, 4, and 5 miles. Onsite population

projections were not extrapolated from the above data due to uncertainties in predicting growth characteristics at SRS.

VEGP, located on the Savannah River in Burke County, Georgia, employs approximately 890 personnel (Ref. 30).

The industrial population within a 5-mile (8-km) radius of F and E Areas consists entirely of SRS employees at A/M, B, C, N, E, F, H, K, S, and Z Areas. The current workforce population, by area, is presented in Table 1.3-6 (Ref. 31).

The industrial population within a 5-mile (8-km) radius of H, S, and Z Areas consists entirely of SRS employees at B, C, N, E, F, H, R, S, and Z Areas. The current workforce population, by area, is presented in Table 1.3-7 (Ref. 32).

The industrial population on SRS within 5 miles (8 km) of M and A Areas (including SRTC) includes the SREL, 700-A Area, 700-B Area, M Area, and SRFS. Table 1.3-8 displays the population for the A and M Areas (including G Area, SREL, SRFS), and B Area. There are several small businesses, such as a well drilling service and a welding shop, located in Jackson and New Ellenton, South Carolina.

The industrial population on SRS within 5 miles (8 km) of D Area includes 186 employees at TNX Area, which includes the SCE&G personnel operating the powerhouse; 100 K Area (1,111 employees); and 100-C Area (831 employees). The only industry within 5 miles of D Area outside of SRS is VEGP, with a population of 890 (Ref. 30).

SCHOOL POPULATION

The existing public school population within 5 miles (8 km) of the site boundary consists of students and school personnel associated with 11 public schools located in New Ellenton, Jackson, Williston, and Barnwell, South Carolina (Ref. 25). No Georgia schools are located within 5 miles of the plant boundary (a school in Girard, GA was closed in 1987). The public school enrollment and distribution within 5 miles (8 km) of the SRS boundary are shown in Table 1.3-9 (Ref. 33). The locations of public schools in relation to the site are shown in Figure 1.3-57.

Public schools operate approximately 180 days per year, normally Monday through Friday, from late August through late May. There are no private schools or colleges in the 5-mile (8-km) vicinity.

RECREATIONAL POPULATION

The primary recreational activity within a 5-mile (8-km) radius of SRS production areas is controlled sport hunting. Hunts at SRS, supervised by DOE, are conducted annually with the

benefit of controlling deer and feral hog populations. The SRS Annual Environmental Report includes numbers of hunts and numbers of animals killed (Ref. 20).

Hunting also takes place at Crackerneck, an area of 4,780 acres, west of SRS in Aiken County. The South Carolina Department of Natural Resources (SCDNR) manages Hunts at Crackerneck for deer, hogs, small game, and waterfowl, although permits are issued by DOE (Ref. 34). Another sporting area within 5 miles of SRS is a private commercial area of 4,000 acres about 15 miles (24 km) east of Waynesboro, GA. Hunting and/or fishing, as well as available lodging, are available to the public all year for a fee. No records of usage are available.

Additional recreational usage near the vicinity is available at three state parks located outside of the 5-mile (8-km) radius of SRS production areas, but within 12 miles (19 km) of the site boundary. These areas include Redcliffe State Park a historic site located off SCR 278 at Beech Island; Aiken State Park located off U.S. Route 78, 16 miles (25 km) east of Aiken; and Barnwell State Park off SCR 3 near Blackville. Table 1.3-10 shows the yearly usage at each of the state parks (Ref. 35). During fiscal year 1994/1995, total park usage was approximately 116,000 visitor days. All of the parks are available to the public year-round.

Other recreational activities within the 5-mile (8-km) radius of SRS production areas include fishing and boating. Numerous boat landings are located on the west bank of the Savannah River, which borders the southwestern portion of the site. In addition, a 95-acre man-made lake, Lake Edgar Brown, is located within the city limits of Barnwell. No records of usage at these areas are available. Boat landings and boat registration in several surrounding counties are discussed in Section 1.3.3.2.

HEALTH CARE POPULATIONS

One hospital and three nursing homes are located within 5 miles (8 km) of the SRS boundary. Table 1.3-11 shows the facilities by type, location, and the number of licensed beds at each facility. Total licensed bed space was 163 in 1997 (Ref. 36). In addition to the above mentioned facilities, there are two facilities that provide community residential care with a population of 15 residents and four facilities that provide intermediate care for the mentally retarded with a population of 32 residents in 1997 (Ref. 36).

CASUAL TRANSIENTS

Casual transients are people who travel through the site on private business. Primarily, the casual transient population consists of vehicle passengers traveling U.S. Route 278, SCR 125, SCR 19 via SRS Road 1; freight train personnel of the CSX Railroad; and aircraft occupants using the Barnwell County Airport.

WSI no longer issues travel passes for SCR 125, located on SRS. However, unofficial data previously collected from travel passes at gate locations through June 1988 show that during a 6-day period, 953 vehicles traveled north on Route 125, and an average of 1,607 traveled south. A small unknown percentage of these estimates represents plant traffic to the 400-D Area. Major

entries onto SCR 125 from the north are U.S. Route 78 via U.S. Route 278 from North Augusta and SCRs 302 and 19 via SRS Road 1 from Aiken. Entries from the south include U.S. Route 278 from Allendale and SCR 3 from Barnwell. Traffic count maps obtained from the South Carolina Department of Transportation indicate that approximately 4,600 vehicles per day travel on U.S. Route 278 between SCR 302 in Aiken County to SCR 37 in Barnwell County. Major entries onto U.S. Route 278 are SCRs 302, 19, and 781 from U.S. Route 78 (Ref. 37).

The plant road system consists of over 120 miles (190 km) of primary roads (Ref. 38). The SRS Transportation Department is responsible for the majority of the operations traffic, which includes centralized trucking and waste hauling. Road traffic frequency is available in the Traffic Services Report (Ref. 39).

Construction traffic, both cars and trucks, results from the activities of BSRI and WSRC; construction transportation, other than construction personnel, includes equipment and materials. Construction traffic is routed either directly to a construction site or through the Central Stores area and then to a construction site. BSRI provides mobile equipment for all construction contractors onsite. Estimates of construction equipment usage and trucking operations can be found in the Traffic Services Report (Ref. 39). The heaviest road usage is on Roads 4, C, and 5.

Vendor trucking to and from SRS adds to the additional casual transient population. According to unofficial information provided by the WSRC Transportation Department (Hal Brinke, February 3, 1994), approximately 30 trucks per day off-load at Central Stores in Building 731-1N for distribution to various plant areas, and about 15 trucks per day go directly to other areas for delivery.

Traffic is counted periodically on plant roads by WSI. Selected 1996/1997 traffic count information for some of the most heavily traveled road segments is presented in Table 1.3-12. The traffic counts are based on a 24-hour period.

Personnel transport involves both private and government-owned passenger vehicles and trucks. Private vehicle traffic peaks at the commuter rush hours. During the day, most private vehicles remain parked, with government-owned and other official vehicles comprising the major portion of the traffic. Traffic counts at the various site gates are given in the Site Development and Facility Utilization Plan (Ref. 11, 22, 40).

The rail transient population on SRS consists of the crews of the CSX Railroad. A section of the Augusta, GA to Yemassee, SC line operates through SRS. This lines continues to Dunbarton Station, and on to Chem Nuclear Systems, Inc. (CNSI) near Snelling, SC, from the junction with the main line on SRS. The main line from Augusta, GA, east to Yemassee, SC, continues to operate (see Figure 1.3-11). In 1998, SRS had four shipments (approximately one shipment per quarter) into the site boundary. Each shipment consisted of approximately 10 rail cars.

In 1998, the number of inbound rail cars was 40. After all reactors were shut down, the volume of rail traffic decreased.

A Norfolk-Southern railroad track passes within 5 miles (8 km) of the SRS boundary; this track runs from Augusta, GA, to Charleston, SC, passing through Aiken (west of the site) and Williston (east of the site) (Ref. 41).

F AND E AREAS

The casual transient population consists of persons who travel through the vicinity of F Area and E Area. SCR 125 passes through the 5-mile (8-km) radius of F Area and E Area. Data from WSI officials, based on travel passes issued at the plant gate on SCR 125, indicate that 953 vehicles traveled north and 1,607 vehicles traveled south during a 6-day period in 1988. No public railroads pass within 5 miles of F Area and E Area; only the SRS rail operations falls within the 5-mile radius surrounding the H, S, and Z Areas. The remainder of the casual transient population consists primarily of personnel traveling between site areas on roads (Ref. 11).

H, S, AND Z AREAS

The casual transient population consists of persons who travel through the vicinity of H, S, and Z Areas. SCR 125 passes through the 5-mile (8-km) radius of these areas. Data from WSI officials, based on travel passes issued at the site gate on SCR 125, indicate that 953 vehicles traveled north and 1,607 vehicles traveled south during a 6-day period in 1988. No public railroads pass within 5 miles of H, S, and Z Areas; only the SRS rail operations fall within the 5-mile radius surrounding the H, S, and Z Areas. The remainder of the casual transient population consists primarily of personnel traveling between site areas on roads (Ref. 11).

1.3.3 USES OF NEARBY LAND AND WATERS

Land use within approximately 5 miles (8 km) of the SRS boundary is discussed in this section. The total area investigated is approximately 800 square miles (2,070 km^2). Of these 800 square miles, 310 square miles (800 km^2) are used for industrial purposes associated with the operation of SRS and for commercial and noncommercial timber management. DOE manages the land that forms a buffer zone around the production facilities. The countryside surrounding SRS is predominantly forested.

Land within a 5-mile (8-km) radius of F and E Areas, and H, S and Z Areas lies completely within SRS and is used for industrial purposes associated with SRS (see Table 1.3-13) and as forestland. Forested areas are managed by the SRFS, an administrative unit of the USFS. Through an interagency agreement between DOE and the USDA, the USFS maintains the SRFS to provide timber management, research support, soil and water protection, wildlife management, secondary road management, and fire management. The land in the affected area is primarily used for timbering. Small tracts of land are clear-cut on a rotating basis.

Approximately 55% of the land within a 5-mile (8-km) radius of A and M Areas is within the SRS boundary, with the remaining 45% of the land outside of the SRS boundary in Aiken County, South Carolina. Approximately 65% of the land, within a 5-mile radius of D Area, is

within the SRS boundary, with the remaining 35% of the land outside of the SRS boundary in Burke County, Georgia. Land within the 5-mile radius of SRS is used for industrial purposes associated with SRS (see Table 1.3-13) and as forestland. Forested areas are managed by SRFS, an administrative unit of USFS.

The countryside surrounding SRS is predominantly forested; some land is farmed. Farming in this area is diversified. The main crops are soybeans, corn, wheat, cotton, peaches, peanuts, and various vegetable crops (Ref. 42-44).

1.3.3.1 Land Use

Land use at SRS is listed in Table 1.3-13.

SAVANNAH RIVER SITE OPERATIONS ACTIVITIES

SRS consists of seven major operating areas: reactor areas (C, K, L, P and R Areas); separations areas (F and H Areas); waste management areas (E, G, S, and Z Areas); heavy water reprocessing area (D Area); reactor materials area (M Area); and administration area (A Area).

The five nuclear production reactor facilities (C, L, P, K, and R) occupy 934 acres of SRS. All five reactors have been placed in cold shutdown. The approximate locations of the reactors areas are shown in Figure 1.3-4. Although the reactor areas are being used for moderator and fuel storage, no effort is being expended to maintain production capability of these reactors (Ref. 20).

The two separations areas, F and H (see Figure 1.3-4), occupy 364 and 395 acres, respectively. F and H Area operations are now primarily the stabilization of radioactive waste, maintaining tritium stockpiles, and reprocessing highly enriched weapons grade material to lower enrichment levels (Ref. 20).

The E Area Solid Waste Management Facility (SWMF) occupies 195 acres between the F and H Separations Areas. The SWMF is used for disposal and/or storage of radioactive, hazardous, and mixed solid waste generated at SRS, as well as occasional special shipments from offsite. It also provides interim storage for transuranic waste (Ref. 19, 20). Other facilities receive hazardous, low-level, and mixed waste for incineration and nonradioactive and hazardous waste for storage (Ref. 19). An area map is shown in Figure 1.3-16. Topography near F and E Areas is shown in Figure 1.3-4.

The 400-D Area (see Figure 1.3-4) occupies 445 acres at SRS. The D-Area Heavy Water Rework Facility is still in operation. Degraded heavy water is sent to the facility where light water is removed and the heavy water is reconcentrated to 99.75% purity (Ref. 20).

A coal-fired power plant is also located in D Area. The power plant is leased and operated by SCE&G (Ref. 20).

The 300-M Area (see Figure 1.3-4) occupies approximately 114 acres. M Area previously provided support to the reactor facilities, heavy water facilities, and the fuel fabrication facilities. The operations of these laboratories have been discontinued. M Area is comprised of Buildings 313-M (including the Chemical Transfer Facility [CTF]), 316-M, 320-M, 321-M, 322-M, 330-M, 331-M, 340-M, and 341-M. Most of the buildings in M Area are used to store radioactive material and waste (Ref. 21).

The Liquid Effluent Treatment Facility (LETF) is operating and consists of the Dilute Effluent Treatment Facility (DETF) in 341-M and the CTF. The IT/SF 341-1M remains in operation. The waste that is stored in the IT/SF tanks is being processed as feed material for the VTP (Ref. 21).

The 700 Area (see Figure 1.3-4) consists of WSRC and DOE administrative groups, production support, SRTC, production services, and SREL. The 700 Area occupies 348 acres. A detailed area map of A Area (and the adjacent M Area) is shown in Figure 1.3-23. A Area is divided into two major fenced areas referred to as the Upper 700 Area and the Lower 700 Area (Ref. 20).

General site administrative functions are centered in A Area. The main DOE and WSRC headquarters are housed in the upper 700 Area in Building 703-A. Other organizations in A Area provide scientific and logistical support for SRS operations. SRTC supports the missions of SRS through applied research and development. SRTC is housed in buildings in the Technical Area, located in the upper 700 Area (Ref. 20).

OTHER SAVANNAH RIVER SITE ACTIVITIES

SREL, located adjacent to A Area, is operated by the University of Georgia. SREL conducts ecological studies on SRS, which was designated a National Environmental Research Park (NERP) in 1972. In addition, 891 acres are set aside in ten separate reserve areas for special studies (Ref. 11).

USFS Headquarters for the SRS land management program is located at the former U.S. Army anti-aircraft headquarters site, approximately 1.25 miles (2 km) south of the SRS barricade on SCR 19 (SRS Road 2). In addition to managing SRS timber, the USFS manages 60 acres of land set aside in two natural areas registered with the Society of American Foresters.

In June 1972, SRS was designated as the nation's first NERP. The areas of the site outside of the various production areas qualify as protected natural areas ideally suited for many kinds of ecological research. The basic concept of NERP is to provide an area, under a significant degree of protection from uncontrolled human influences, where environmental and ecological research can be conducted by qualified institutions and individuals (Ref. 20).

ACTIVITIES OUTSIDE THE SAVANNAH RIVER SITE BOUNDARY

Land in the surrounding countryside is used predominantly for forest and agriculture. The main agriculture products are soybeans, corn, wheat, cotton, peaches, peanuts, and various vegetable crops (Ref. 42-44). Tables 1.3-14, 1.3-15, and 1.3-16 list the numbers and sizes of farms in Aiken, Allendale, and Barnwell Counties, South Carolina, for 1981 through 1992 (Ref. 42-44). Agricultural and forestland uses for Richmond and Burke Counties, Georgia, are listed in Table 1.3-17.

Industrial land uses surrounding SRS are discussed in detail in Section 1.7.2.

LOCALIZED POPULATIONS

Localized populations for existing nearby industries and schools are described in Section 1.3.2.2.

1.3.3.2 Water Use

The major rivers near SRS include the Savannah, Salkehatchie, and South Fork Edisto Rivers. The Savannah River bounds the reservation for 17 miles (27 km) on the southwest side of the site and is a major source of water for SRS operations. The site is entirely outside of the Edisto drainage basin, and only a small portion of the east end of the site is within the Salkehatchie drainage basin (Ref. 11).

GENERAL USES OF THE SAVANNAH RIVER

The Savannah River forms the boundary between Georgia and South Carolina. Downstream from Augusta, GA, the Savannah River has been classified as Class B waters suitable for domestic supply after treatment, propagation of fish, and industrial and agricultural uses. The river supplies water for Augusta, GA; North Augusta, SC; and Beaufort and Jasper Counties, South Carolina; and supplements the water supply of Savannah, GA. It also receives domestic and industrial wastes from Augusta, GA; North Augusta, SC; and Horse Creek Valley (Aiken County, South Carolina).

At SRS, the coal-fired power plants are cooled with water pumped from the river. Effluents and wastewater from SRS are discharged into the Savannah River tributaries that flow across SRS.

Recreational uses of the Savannah River include boating and sport fishing, and a limited amount of contact activities such as swimming and water skiing.

NAVIGATION

During the early operation of the Thurmond and Hartwell Lakes (1953-1972), there was navigational traffic on the river from Augusta to Savannah. By the late 1970s, waterborne commerce was limited to the transportation of oil to Augusta. In 1979, this shipping was

discontinued. Since that time, except for limited movements of construction-related items, no commercial shippers have used the river. Maintenance dredging of the river was discontinued in 1979 (Ref. 45, 46).

FISHERIES

Three types of fisheries are found along the Savannah River. Freshwater trout are in the cold waters flowing from the mountains of North Carolina, South Carolina, and Georgia. Other freshwater fish species are found in the warmer waters in the Piedmont and Coastal Plain; saltwater species are found downstream in the brackish waters near the mouth and in the estuary.

Warm water fishing constitutes most of the sport fishing in the Savannah River. According to a 1988 Savannah River creel study, the annual fish harvest from the river by sport fisherman is approximately 152,000 pounds of fish. The principal species harvested by sport fishermen were redbreast sunfish, bluegill, channel catfish, and crappie (Ref. 47).

Commercial fisheries are important to the economy of the coastal region of South Carolina and Georgia. The most important cash species are blue crabs and shad. South Carolina fishermen harvested 134,000 pounds of blue crabs from the Savannah River estuary in 1989 (Ref. 47). Shrimp, clams, and oysters are harvested commercially from the Savannah River estuary. The average South Carolina annual shrimp and clam harvests from the Savannah River estuary are estimated to be 76,000 pounds and 5,500 pounds, respectively. The annual average Georgia shrimp and clam harvests are approximately 616,000 pounds and 4,200 pounds, respectively. Oysters are also harvested from the Savannah River area at a rate of approximately 30,000 pounds annually (Ref. 47). Data on the commercial fish harvest in the Savannah River were provided by the SCDNR and the Georgia Department of Natural Resources.

RECREATION

Over 95% of South Carolina's impounded waters are contained in the large reservoirs listed in Table 1.3-18. Most have multipurpose recreational uses such as swimming, water skiing, boating, and fishing. Par Pond and L Lake, both previously used for reactor cooling water, are completely within the boundary of SRS and are not accessible to the public. Thurmond Lake (Clarks Hill Reservoir), Hartwell Reservoir, and Russell Dam are located northwest of Augusta approximately 65 to 133 river miles (104 to 213 river km) from the center of the site. They are used for hydroelectric power generation, flood control, and water supply, as well as for recreation. There were more than 22 million visitors to Thurmond Lake, Hartwell Reservoir, and Russell Dam during fiscal year 1986 (Ref. 45).

Numerous multipurpose small lakes and ponds are found in Georgia and South Carolina counties adjacent to SRS. Lakes and ponds 10 acres or larger are listed in Table 1.3-19 for Aiken, Allendale, and Barnwell Counties, South Carolina, and in Table 1.3-20 for Burke, Richmond, and Screven Counties, Georgia.

Boat use on the Savannah River is estimated based on boat registrations. In 1993, there were 280,894 boats registered in South Carolina. Of these, 25,021 were registered in South Carolina counties bordering the Savannah River south of Augusta. Most of the boats for this section of the Savannah River were registered near Augusta and Thurmond Lake in Aiken County (9,841) and in Beaufort County (9,381) near the coast. Fewer boats were registered for Barnwell (1,783), Allendale (628), Hampton (2,076), and Jasper (1,312) Counties. Most of the boats registered for the counties along this part of the Savannah River were registered near Augusta and Thurmond Lake in Richmond County (6,350) and in Chatman County (12,424) near the coast. Fewer boats were registered in Burke (811), Screven (1037), and Effingham (2,757) Counties. Public boat landings on the Savannah River downstream from Augusta are listed in Table 1.3-21 for South Carolina and Georgia.

AGRICULTURAL WATER USE

Water for agricultural use in Aiken, Barnwell, and Allendale Counties is obtained primarily from lakes and ponds. Capabilities of existing sprinkler irrigation systems in these three counties are given in Table 1.3-22. Corn, peanuts, soybeans, and truck crops are the crops for which irrigation is economically feasible (Ref. 48). In Burke County, Georgia, there are approximately 225 irrigation systems with a combined capacity of 25,000 acres. Richmond County, Georgia, has seven irrigation systems with a combined capacity of 1,200 acres.

No uses of the Savannah River for crop irrigation were identified in Richmond and Burke Counties, Georgia, or for Aiken, Barnwell, and Allendale Counties, South Carolina.

MUNICIPAL USE OF LOCAL SURFACE WATER

The Savannah River and its reservoirs are the sources of water for 64 domestic and industrial users. Total withdrawals amount to approximately 1 billion gallons per day. The largest water users are SRS and VEGP. At the lower end of the river, freshwater intakes and canals are maintained by the Beaufort-Jasper Water Supply Authority, the City of Savannah Municipal and Industrial Plant, and the Savannah National Wildlife Refuge (Ref. 45).

The larger communities in Aiken, Richmond, and Burke Counties use surface water supplies as well as groundwater. None of these surface water supplies are impacted by liquid discharges from operations at SRS. These intakes are all either on the Savannah River upstream from SRS or on tributaries of the Savannah River that do not cross or drain at SRS.

In Aiken County, the City of Aiken uses water from Shaws Creek. The Graniteville Company provides water to Graniteville and Vaucluse from Horse Creek, Bridge Creek, and Good Springs. The Clearwater Water District supplies approximately 3.2 million gallons per day (mgd) from Little Horse Creek. The city of North Augusta draws about 2.78 mgd from the Savannah River. Surface water supplies for Aiken County are shown in Table 1.3-23.

In Richmond County, the Augusta city water system draws its water supply, averaging about 24 mgd, from the Savannah River at a point more than 25 miles (40 km) upstream from SRS.

Waynesboro, the largest user in Burke County, draws water from Briar Creek and from groundwater. Surface water use by these two counties in Georgia is shown in Table 1.3-24. Columbia County, Georgia, is currently constructing a surface water plant along Georgia Route 50 to withdraw water from Thurmond Lake.

MUNICIPAL AND INDUSTRIAL USE OF SAVANNAH RIVER WATER DOWNSTREAM FROM SAVANNAH RIVER SITE

There are two water treatment plants about 100 miles (160 km) downriver from SRS that supply Savannah River water to customers in Beaufort and Jasper Counties, South Carolina, and Chatham County, Georgia. The City of Savannah Industrial and Domestic Water Supply (Chatham County, Georgia) is the largest of the two water treatment plants (Table 1.3-25).

The Beaufort-Jasper Water/Sewer Authority near Hardeeville, SC has been in operation since 1965. It serves a consumer population of about 50,000 people who live in Beaufort and Jasper Counties. The plant is located about 18 miles (29 km) from the Savannah River. A canal transports water from the river to the plant. The plant processes an average of 6 mgd, varying from about 5 mgd in the winter to 10 to 12 mgd in the summer. Increased use in the summer is associated with watering lawns, filling swimming pools, and uses in the home (Ref. 48).

The City of Savannah Industrial and Domestic Water Supply at Port Wentworth has been treating water during the entire period of operation of SRS. Treated water from this plant is used primarily for industrial and manufacturing purposes in an industrial complex near Savannah, GA.

The complex serves a non-community/non-transient population of 6,000 people, primarily adults working in industrial facilities; it also serves as a backup for the City of Savannah's domestic groundwater system. The plant processes about 40 to 50 mgd. Usage of this water for the City of Savannah does not show a strong summer demand, since the water is primarily used for industrial purposes.

GROUNDWATER USE

The coastal plain sediments that underlie SRS are an important hydrologic resource, since the formations are sources for drinking water, industrial processes, and cooling water, and water used for agricultural purposes. Fifty-six municipalities and industries identified near the site use this groundwater. Total pumpage by these users in 1985 was approximately 35 mgd. In addition, several small communities, mobile home parks, schools, and small commercial interests draw from this groundwater resource (Ref. 11).

1.4 ENVIRONMENTAL DESCRIPTION

1.4.1 METEOROLOGY

Information on SRS meteorological conditions is primarily taken from Hunter with supplemental data from the National Oceanic and Atmospheric Administration Local Climatological Data (Ref. 49-52).

1.4.1.1 Regional Climatology

The SRS region has a humid subtropical climate, characterized by relatively short, mild winters and long, warm, and humid summers.

Summer weather usually lasts from May through September, when the area is subject to the influence of the western extension of the semipermanent Atlantic subtropical anticyclone (the "Bermuda high" pressure system). As a result, winds are generally light and weather associated with low pressure systems and fronts usually remains well to the north of the area. Because the Bermuda high is a persistent feature, there are few breaks in the summer heat. High temperatures during the summer months are greater than 90°F on more than half of all days (Ref. 49). The relatively high heat and humidity often result in scattered afternoon and evening thunderstorms.

The influence of the Bermuda high begins to diminish during the fall, resulting in drier weather and temperatures that are more moderate. Average rainfall for the fall months is lower than average for the other months of the year. Frequently, fall days are characterized by cool, clear mornings and warm, sunny afternoons. Average daily temperatures during the fall months range from 76°F to 50°F.

During the winter, migratory low pressure systems and associated fronts influence the weather of SRS. Conditions frequently alternate between warm, moist, subtropical air from the Gulf of Mexico region and cool, dry, polar air. Occasionally, an arctic air mass will influence the area; however, the Appalachian Mountains to the north and northwest of SRS moderate the cold temperatures associated with the polar or arctic air. Consequently, less than one-third of the winter days have minimum temperatures below freezing, and temperatures below 20°F are infrequent.

Spring is characterized by a higher frequency of occurrence of tornadoes and severe thunderstorms than the other seasons of the year. This weather is often associated with the passage of cold fronts. Although weather during the spring is variable and relatively windy, temperatures are usually mild.

ICE AND SNOW

Snow and ice storms in the region occur very infrequently. Snowfalls of 1 inch or greater occur once every 3 years on the average. Furthermore, any accumulation of snow rarely lasts for more than 3 days (Ref. 52).

The greatest single snowfall recorded in the SRS area (Augusta) during the period 1951-1995 occurred in February 1973. This storm produced a total of 14.0 inches of accumulation, including 13.7 inches in a 24-hour period. A summary of maximum total snowfalls for 24-hour and monthly periods, observed at the National Weather Service (NWS) office at Augusta, GA, is given in Table 1.4-1 (Ref. 52). The maximum ground snow load for the SRS area for a 100-year recurrence period is estimated to be about 5 lb.-force/ft^2 (Ref. 49).

For a 9-year period of record reported by Tattelman (Ref. 53), storms resulting in an accumulation of ice on exposed surfaces occurred in the SRS area an average of about once every 2 years. Average ice accumulations for various recurrence intervals for a region that includes SRS and consists of the Gulf Coast states are given in Table 1.4-2. The 100-year recurrence ice storm is estimated to produce an accumulation of approximately 0.67 inches (Ref. 53).

SURFACE WIND PATTERNS AND DISPERSION CLIMATOLOGY

A meteorological database for the 5-year period 1992-1996 is currently used for safety analysis at SRS. Wind rose plots for each of the eight SRS towers for this period of record are shown in Figures1.4-1 through 1.4-10. As indicated by these plots there is no strongly prevailing wind direction at the Site. Northeasterly winds occurred approximately 10% of the time, and west to southwest winds occurred about 8% of the time. Winds at D-Area exhibited slightly higher frequencies of southeast and west-northwesterly winds due to the effects of the terrain that defines the Savannah River valley. Annual average wind speeds at each of the towers ranged from 9.4 mph (4.2 m/s) to 8.0 mph (3.5 m/s).

The relative ability of the atmosphere to disperse air pollutants is commonly characterized in terms of Pasquill stability class. The Pasquill stability classes range from class A (very unstable conditions characterized by considerable turbulence producing rapid dispersion) to class G (extremely stable conditions with little turbulence and very weak dispersion). The percent occurrence of Pasquill stability class for each of the eight area towers is summarized in Table 1.4-3. Stable conditions were observed between 20 and 30 percent of the time during the 5-year report. Wind rose plots by stability class for each tower are shown in Figures 1.4-1 through 1.4-9 (Ref. 51).

THUNDERSTORMS

An average of about 54 thunderstorm days per year was observed in the SRS area during the period 1951-1995. Average thunderstorm days per month are listed in Table 1.4-4. Fifty percent of the annual average total occurred in June, July, and August. Thunderstorm occurrence was

least frequent during the months of October through January, with an average of about one day per month observed (Ref. 49).

The occurrence of hail with thunderstorms is infrequent. Based on observations in a 1-degree square of latitude and longitude that includes SRS, hail occurs once every 2 years on the average (Ref. 54).

The frequency of cloud-to-ground lightning strikes has been estimated using an empirical relationship described by Marshall (Ref. 55).

The estimated average number of lightning strikes per square kilometer (km^2) per year is given by:

$$NE = [0.1 + 0.35 \sin (l)]A \qquad \text{(Eq. 1.4-1)}$$

where:

NE = the number of flashes to earth/km^2/thunderstorm day

l = the latitude of the approximate geographic center of SRS (33°16')

A = given by (0.4 +/- 0.2)

Assuming the most conservative value for A (0.6), the number of flashes to earth per square kilometer was estimated to be ten per year. Measurements of cloud-to-ground lightning strikes recorded from the National Lightning Detection Network over the 5-year period 1989-1993 show an average of four strikes per square kilometer, per year in the SRS area (Ref. 56).

TORNADOES

Weber, et al, (Ref. 57) identified a total of 165 tornadoes occurring within a 2-degree square of latitude and longitude (2° by 2°) centered on SRS over a thirty-year period from 1967. Tornado occurrence by month and Fujita (F)-scale intensity category since 1951 is summarized in Table 1.4-5. About half of the total number of observed tornadoes occurred in the months of March, April, May, and November; however, tornadoes have been observed in the SRS region every month of the year.

Nine tornadoes have occurred on or in close proximity to the SRS since operations began in the 1950s. A tornado that occurred on October 1, 1989 knocked down several thousand trees over a 16-mile path across the southern and eastern portions of the site. Wind speeds produced by this F2 tornado were estimated to be as high as 150 mph. Four F2 tornadoes struck forested areas of SRS on three separate days during March 1991 (Ref. 58). Considerable damage to trees was observed in the affected area. The other four confirmed tornadoes were classified as F1 and produced relative minor damage. None of the nine tornadoes caused damage to buildings.

Estimates of the expected tornado wind speeds that are exceeded at SRS for various return frequencies are summarized in Table 1.4-7. These estimates were determined from a tornado wind hazard model developed by Lawrence Livermore National Laboratory (LLNL) (Ref. 501). The LLNL tornado wind hazard model is given by:

$$EF(v) = \lambda\Sigma_i \{\Sigma_{j\leq i} P(WS>v|Fj,Fi) \int_\theta \int_{(L,W)i} \int_{A(Sij)} dF(x,y)dH(L,W)\, dG(\theta)\}\{\Sigma_k p_{ik} P_R(Fk)]$$

Where λ is the expected frequency of a tornado occurring anywhere in the contiguous United States, P(WS>v|Fj,Fi) is the conditional probability that the wind speed is greater than v mph for a tornado with Fujita-scale intensity Fj within the damage area of an Fi intensity tornado, dF(x,y) is a tornado touchdown location density function for the site-specific area, dH(L,W) is a damage area density function for tornado damage paths of length L and width W, and dG(θ) is a density function of tornado path headings with direction θ. The expected frequency of tornado occurrence, λ, is determined from the NOAA Storm Prediction Center (SPC) tornado database for the period 1950-1995.

The conditional probability P(WS>v|Fj,Fi) is evaluated by generating a site-specific tornado F-scale intensity distribution (F0 through F6), using the historical database from SPC, for each of three areas centered on SRS: a 2° by 2° area, a 3° by 3° area and a 5° by 5° area. Each area is assigned a weight representing the uncertainty that data from the area provides a 'true' characterization of tornado intensity at the location of interest. The resulting F-scale intensity distributions are transformed to histograms expressing the frequency of occurrence of wind speed intervals that correspond to each of the seven intensity categories. Histograms are constructed for three methods of relating F-scale intensity to wind speed. For each of the three discreet wind speed distributions, maximum likelihood estimation techniques are used to determine which of three continuous distribution functions (uniform, beta, and Weibull) best fit the wind speed data. The selected distribution function is used to determine an occurrence probability for each wind speed interval which is subsequently transformed to an estimated theoretical 'recorded' F-scale intensity distribution $P_R(F_i)$. The term $\Sigma_k p_{ik} P_R(Fk)$ is then evaluated to adjust P_R for misclassification error described by the probability matrix p_{ij}. The five misclassification matrices that are employed by the model include both random error and direct classification error as identified in the literature. The result consists of 45 estimates of the F-scale intensity distributions, with associated weights for use in developing uncertainty estimates.

The LLNL model assumes that the location for hazard prediction is an area and that there is a non-uniform distribution of touchdown location within the region of interest. A tornado touchdown location density function, dF(x,y) is defined and integrated over area A(Sij) with respect to the probability distributions of the variables that define A(Sij), namely dG and dH. The area A(Sij) denotes the tornado effect subarea of intensity Fj within a tornado of intensity Fi (where index $j \leq i$). The location density function dF(x,y) is given by a normal kernel estimator which predicts the areal distribution of future tornado locations based on the historical database. The distribution of tornado heading dH also is determined from the historical database; but the model allows selection of one of three sets of empirical distributions weighted by the time period of data collection and geographic location. The damage area density function, dG, consists of a joint distributions of damage path lengths and widths by F-scale intensity as determined from the historical data. Uncertainty weights are assigned to each of the time-dependent distributions.

Final estimates of wind speed for a given return interval are determined by conducting 125 simulations of the tornado model. For each simulation, Latin Hypercube sampling techniques are used to select values for each of the stochastic variables including tornado heading, length and width, intensity and location. The estimated wind speed for each of the return intervals, summarized in Table 1.4-7, represents a mean of the resulting set of wind speed values.

PC3 and PC4 design basis tornado speeds are shown in Table 1.4-7.1.

ATMOSHERIC PRESSURE CHANGE

The tornadic atmospheric pressure change effects including the maximum rate thereof for various tornado speeds are calculated in an engineering calculation (Ref. 503). The PC3 and PC4 design basis atmospheric pressure change and the rate thereof, shown in Table 1.4-7.1, are taken as the rounded values corresponding to the tornado speeds of 180 and 240 mph, respectively.

EXTREME WINDS

Extreme winds in the SRS area, excluding tornado winds, are associated with tropical weather systems, thunderstorms, or strong winter storms. Extreme fastest 1-minute wind speeds for the 30-year period 1967-1995 are summarized in Table 1.4-8. These data were recorded at the National Weather Service Office at Augusta, GA (Ref. 52). The maximum 1-minute wind speed observed during the entire period of record at Augusta was 83 mph in May 1950.

Estimates of an expected maximum 'straight-line' (nontornadic) wind speeds (three second gust) for any point on the Site for return periods from 100 to 100,000 years are summarized in Table 1.4-7 (Ref. 57). These estimates were generated from a Fisher-Tippet Type I extreme value distribution function using historical wind speed (gust) data from the SRS meteorological database and from nearby National Weather Service stations (Columbia, SC, and Augusta, Macon, and Athens, GA). For each observing station, a maximum observed annual gust was determined for each year in the available period of record. The period of record ranged from 25 to 47 years. The resulting subsets of annual wind speed maxima were used to determine a best fit to one of three types of a generalized extreme value (GEV) distribution. The analysis indicated that a Fisher-Tippet Type I (Gumbel) distribution was appropriate for these data.

Following a method suggested by Eliasson (Ref. 502), the predicted 3-second wind speed for return period P is given by:

$$X_P = [S\{(0.8 - 0.57722)/1.28255\} + X][[1 + (0.78 / \{(1/CV_a) + 0.72\}][\log\{-\log(1(1-1/P))\} - 1.5]$$

Where X is the average of the annual observed wind speed maxima at the station of interest (Augusta, Ga), S is the standard deviation of the annual wind speed maxima for the station of interest, and CV_a is the average coefficient of variation for all stations included in the analysis.

PC3 and PC4 design basis wind speeds are given in Table 1.4-7.1.

MISSILES

The design basis straight-line wind and tornado missiles, except for the PC3 tornadic automobile missile, are based on the DOE-STD-1020 (Ref. 504) requirements for PC3 and PC4 DOE sites. The PC3 tornadic automobile missile is based on the recommendation of McDonald-Mehta (Ref. 505). McDonald (Ref. 506) provides the rationale for the PC3 and PC4 design basis missile speeds in relation to the observed data for tornado and results of simulation studies, and observes that these are different from the U. S. NRC criteria for nuclear power plants. The design basis missile criteria are given in Table 1.4-7.1.

HURRICANES

A total of 36 hurricanes have caused damage in South Carolina over the 290-year period from 1700-1992. The average frequency of occurrence of a hurricane in the state is once every 8 years; however, the observed interval between hurricane occurrences has ranged from 2 months to 27 years. The percentages of hurricane occurrences by month in South Carolina are given in Table 1.4-9. Approximately 80% of hurricanes in South Carolina have occurred in August and September.

Because SRS is approximately 100 miles (160 km) inland, winds associated with tropical weather systems usually diminish below hurricane force (sustained speeds of 75 mph (120 km/h) or greater). However, winds associated with Hurricane Gracie, which passed to the north of SRS on September 29, 1959, were measured as high as 75 mph (120 km/h) on an anemometer located in F Area. No other hurricane-force wind has been measured on the site. On September 22, 1989, the center of Hurricane Hugo passed about 100 miles (160 km) northeast of SRS. The maximum 15-minute average wind speed observed onsite during this hurricane was 38 mph (61 km/h). The highest observed instantaneous wind speed was 62 mph (100 km/h). The data were collected from the onsite tower network (measurements taken at 200 feet [60 meters] above ground). Extreme rainfall and tornadoes, which frequently accompany tropical weather systems, usually have the most significant hurricane-related impact on SRS operations (Ref. 49).

EXTREME PRECIPITATION

Maximum observed rainfall recorded at Augusta's Bush Field and the Columbia, SC airport for various accumulation periods is summarized in Table 1.4-10 (Ref. 51, 60). These data were based on a 48-year period of record (1948-95).

Estimates of expected maximum rainfall at SRS for rainfall durations of 15-minutes to 24 hours and return periods from 10 years to 100,000 years are shown in Table 1.4-11 (Ref. 57, 61). These estimates were based on a statistical analysis of hourly rainfall from eight National Weather Service first-order and cooperative stations (Augusta, Macon, Athens, Sylvania, and Louisville in Georgia and Columbia, Wagener, and Clark Hill in South Carolina), 15-minute rainfall from three of the cooperative stations (Sylvania, Louisville, and Wagener), and daily rainfall from four rain gages at SRS. Stations were selected based on proximity to and geographic similarity with the SRS. For each station (as appropriate to the data set), a annual maximum observed rainfall for each of the six duration intervals of interest over the available period of record were determined. The period of record ranged from 25 to 47 years. The resulting subsets of annual

wind speed maxima were used to determine a best fit to one of three types of a generalized extreme value (GEV) distribution.

The analysis indicated that a Fisher-Tippet Type I (Gumbel) distribution was appropriate for the 15-min and 1-hour datasets. Following a method suggested by Eliasson (Ref. 502), the predicted rainfall for return period P is given by:

$$X_P = [S\{(0.8 - 0.57722)/1.28255\} + X][[1 + (0.78 / \{(1/CV_a) + 0.72\}][\log\{-\log(1(1-1/P))\} - 1.5]$$

Where X is the average of the annual observed maxima rainfall at the station of interest (Augusta, Ga for the 1-hour duration rainfall and Sylvania, Ga for 15 minute rainfall), S is the standard deviation of the annual rainfall maxima for the station of interest, and CV_a is the average coefficient of variation for all stations included in the analysis.

A Fisher-Tippet Type II distribution was found to provide the best fit for the 3, 6, 12, and 24 hour rainfall data. The corresponding predicted rainfall for return period P is given by

$$X_P = X + S\{\beta + (a/k)(1-[-\log(1-1/P]k)\}$$

Where X and S are determined from the observed annual maxima for Augusta, and the distribution parameters a, b, and k are calculated from the annual maxima for all of the stations that were included in the analysis.

Several significant rainfall events occurred at SRS in the summer and fall of 1990 (Ref. 60). Table 1.4-11 includes the observed rainfall totals from those storms that exceeded the predicted extreme rainfall values. Short duration extreme rainfalls are generally produced by spring and summer thunderstorms. Longer duration extreme rains are usually produced by the remnants of tropical weather systems.

EXTREME AIR POLLUTION EPISODES

High air pollution potential in the southeastern U.S. is frequently associated with stagnating anticyclones (high pressure systems). According to routine radiosonde (upper air) data summarized by Holzworth, episodes of poor dispersion conditions in the SRS area lasted for 2 days on twelve occasions over a 5-year period (1960-1964) (Ref. 62). Episodes lasting at least 5 days occurred on two occasions. An episode is defined by mixing heights less than 5,000 feet (1,525 m) and average boundary layer wind speeds less than 9 mph (14.5 km/h). Results of a study reported by Korshover indicate that an average of two air stagnation episodes occurred in the SRS area each year over the 40-year period from 1936 to 1975 (Ref. 63). The total number of stagnation days averaged about 10 per year. Korshover defined stagnation days as conditions characterized by limited dispersion lasting 4 days or more (Ref. 63).

1.4.1.2 Local Meteorology

DATA SOURCES

A number of sources of data are used to describe the local climatology. These include eight meteorological towers adjacent to the major operations areas onsite, the Central Climatology Meteorological Facility located near N Area, a meteorological instrument shelter in A Area, and the NWS office at Bush Field in Augusta, GA. The NWS office at Augusta is approximately 12 miles (19 km) west-northwest of SRS. Locations of the onsite towers are shown on Figure 1.4-10.

The eight area towers are equipped with fast-response cup anemometers, bi-directional wind vanes (bivanes), slow response resistance temperature probes, and lithium chloride dew point sensors at a height of 38 feet (61 meters) above ground. The Central Climatology Facility tower is equipped with identical instrumentation at elevations of 4, 18, 36, and 61 meters. Central Climatology is also equipped with instrumentation for measuring precipitation, evaporation, solar radiation, barometric pressure, and soil temperature. Data collected at the A-Area instrument shelter consist of temperature, daily precipitation, and relative humidity. Parker and Addis (Ref. 64) provide a computer description of SRS Meteorological Monitoring Program.

Summaries of temperature, precipitation, and relative humidity are based on a composite data set consisting of data from the instrument shelter through 1994 and from Central Climatology for 1995 and 1996.

TEMPERATURE

Monthly and annual average temperatures for SRS for the 30-year period 1967-1996 are included in Table 1.4-12. At SRS, the annual average temperature is 64.7°F. July is the warmest month with an average daily high temperature of 92.1°F and an average daily low temperature of 71.5°F. January is the coldest month with an average daily high temperature of 55.9°F and an average daily low temperature of 36.0°F. Observed temperature extremes for SRS over the period 1961-1996 ranged from 107°F to -3°F.

Data for Augusta, GA indicate that prolonged periods of cold weather seldom occur. Daytime high temperatures during the winter months are rarely below 32°F. Conversely, high temperatures in the summer months are above 90°F on more than half of all days. The average dates of the first and last freeze are November 12 and March 16, respectively (Ref. 52).

PRECIPITATION

Annual average precipitation for SRS over the 30-year period 1967-1996 is 49.5 inches (see Table 1.4-13). Precipitation is fairly evenly distributed throughout the year. Average precipitation for the fall months (September, October, and November) is less than that for the other seasons, accounting for about 20% of the average annual total. For Augusta, precipitation totals greater than 0.01 inch occur on an average of about 108 days per year. The average number of days per month with measurable precipitation ranges from about 6 days in October to about 12 days in July (Ref. 52).

Monthly precipitation extremes for SRS range from a maximum of 19.62 inches, recorded in October 1990, to a trace observed in October 1963. The greatest observed rainfall for a 24-hour period was 7.5 inches in October 1990 (Ref. 60). Hourly observations at Augusta indicate that rainfall rates are usually less than 0.5 in./h, although rainfall rates of up to 2 in./h can occur during summer thunderstorms (Ref. 52).

A summary of snowfall statistics for Augusta (1951-1995) is shown in Table 1.4-1. The average annual snowfall for the SRS area (Augusta) for the period 1966-1995 was 1.1 in./year, and the average number of days per year with snow was 0.6 day. Significant snowfall is most likely to occur in February. For the reported period of record, snow has been observed during all of the months November through March.

HUMIDITY

Monthly and annual values of relative humidity for SRS (1967-1996) are given in Table 1.4-14. Average relative humidities are highest in August (ranging from an average of 97% in the morning to 50% in the afternoon) and lowest in April (ranging from an average of 88% in the morning to 36% in the afternoon).

Table 1.4-14 also summarizes monthly and annual average absolute humidities from the Central Climatology station for the 2-year period 1995-96. The annual average humidity was 11.1g/m^3. Monthly average values range from 18.4 g/m^3 in July to 6.0 g/m^3 in December and January (Ref. 50).

FOG

Heavy fog (reducing visibility to less than 1/4 mile) occurred at the Augusta NWS office on an average of about 30 days per year during the period 1951-1995 (Ref. 52). Occurrences averaged about 3 days per month during the fall and winter months and slightly more than 1 day per month during the spring and summer months. Most of the heavy fog observed at Augusta is due to the proximity of the Savannah River. Fog is observed less frequently at the SRS because the site is at a higher elevation than Augusta and is further from the river (Ref. 49).

MIXING HEIGHT

The mixing height is the level of the atmosphere below which pollutants are easily mixed; it is often equal to the base of an elevated inversion. The following estimates of seasonally averaged morning mixing heights for SRS were interpolated from data presented in Holzworth (Ref. 62). The Holzworth data are derived from radiosonde observations during the 5-year period, 1960-1964.

	Mixing Height (meters)	
Season	Morning	Afternoon
Winter	1148	3362
Spring	1230	5576
Summer	1312	5904
Fall	984	4592
Annual	1230	4756

LOW-LEVEL INVERSIONS

In 1961, Hosler analyzed 2 years of radiosonde and surface observations of the NWS to determine occurrence frequencies for low-level inversions in the U.S. Hosler's statistics show that inversions occur in the SRS area approximately 40% of all hours and 70% of all night hours (Ref. 65).

Pendergast analyzed temperature data collected from sensors located on multiple levels of the WJBF television tower for a 1-year period (1974) (Ref. 66). The WJBF tower is located approximately 9 miles (14 km) northwest of SRS. For approximately 30% of the time, an inversion extended through the entire 10- to 1,099-foot layer for which temperature measurements were made. For about 12% of the time, an inversion was observed through the upper portion of the 10- to 1,099-foot layer, and unstable conditions were observed through the lower portion. For about 9% of the time, the ground-based inversion layer height was less than the height of the tower. The latter two cases generally were found to represent the transition periods from night to day and from day to night, respectively.

TOPOGRAPHY

The topography of the SRS area is characterized by gently rolling, forested hills. In general, terrain elevations decrease gradually from the Appalachian foothills northwest of the site toward the Atlantic coastal plain to the southeast. The local SRS terrain elevations also generally decrease gradually toward the Savannah River, which runs along the southwestern boundary of the site. Site elevations range from 100 feet to about 400 feet above msl. A topographic map of SRS and the surrounding area is shown in Figure 1.3-5.

The closest pronounced topographic feature is approximately 20 miles (32 km) from the site; the local terrain has little effect on wind and stability climatology at SRS. During stable atmospheric conditions, some channeling or airflow stagnation could occur in some of the more pronounced valleys. However, any terrain-induced increase in pollutant concentrations would be much localized and short-lived.

1.4.1.3 Onsite Meteorological Measurement Program

The current meteorological monitoring program at SRS meets or exceeds criteria in Environmental Regulatory Guide DOE/EH-0173T, Safety Guide 23 of the NRC, Guide 2.5 of the American Nuclear Society, and the Environmental Protection Agency (EPA), as reported by Parker and Addis (Ref. 64). The instrumentation used to collect the meteorological data is summarized in Section 1.4.1.2.

A data logger at each monitoring tower collects a reading from each instrument every 1.5 seconds. The instantaneous data are processed and used to compute 15-minute and hourly averages of wind speed, wind direction (vector and scalar), temperature, and dew point. In addition, the 15-minute and hourly values of sigma-a and sigma-e (the standard deviation of the fluctuations of the horizontal and vertical component of wind direction, respectively) are calculated. The 15-minute data are then transmitted via a dedicated telephone line to a central computer system and archived in a relational database.

Real-time emergency response applications are the primary considerations in the operation of the monitoring network. Consequently, the data are inspected daily, so any major system malfunction can be corrected on a timely basis. An adequate supply of spare calibrated instrumentation is maintained so replacement sensors are readily available.

The instrumentation is calibrated every 6 months by SRTC instrument mechanics. A wind tunnel at SRTC is available for calibration of the wind sensors. The calibrations are conducted according to manufacturer's specifications using procedures that meet or exceed American Society of Testing and Materials (ASTM) calibration methods (Ref. 64).

Data collected from the meteorological towers are stored in a relational database and retrieved, as necessary, to develop quality assured databases for engineering, safety, and regulatory applications. A 5-year database for the period 1991-1996 is currently used for SRS SARs. The development of this database is described by Kurzeja (Ref. 67).

ONSITE AIR QUALITY

The South Carolina Department of Health and Environmental Control (SCDHEC) regulates nonradioactive air emissions, both criteria pollutants and toxic air pollutants, from SRS sources. Each source is permitted by SCDHEC, with specific limitations identified, as outlined in various South Carolina air pollution control regulations and standards. Results of the most recent regulatory compliance modeling for SRS emissions are summarized in the SRS Annual

Environmental Report (Ref. 20). A list of the SCDHEC-issued air quality permits and a description of the Airborne Emissions programs are in the SRS Annual Environmental Report.

USE OF METEOROLOGY DATA

The meteorology data are used to estimate the meteorological dispersion of released materials as discussed in Section 3.1, Methodology, in Chapter 3 of the SAR for the specific facility. A description of many of the calculational codes in use is given in the WSRC Environmental Dose Assessment Manual (Ref. 68).

1.4.2 HYDROLOGY

1.4.2.1 Surface Hydrology

HYDROLOGIC DESCRIPTION

Much of SRS is located on the Aiken Plateau (see Figure 1.4-11). The plateau slopes to the southeast approximately 5 feet per mile (1 m/km). The plateau is dissected by streams that drain into the Savannah River. The major tributaries that occur on SRS are Upper Three Runs Creek, Fourmile Branch, Pen Branch, Steel Creek, and Lower Three Runs Creek (see Figure 1.4-12). Beaver Dam Creek, the smallest of the six SRS tributaries of the Savannah River, is located north of Fourmile Branch, primarily in the floodplain of the Savannah River. Tinker Creek and Tims Branch are tributaries of Upper Three Runs Creek; Indian Grave Branch is a tributary of Pen Branch. Each creek originates on the Aiken Plateau and descends 49 to 200 feet (15 to 61 meters) before discharging to the Savannah River. The interstream upland area is flat to gently rolling and is characterized by gently dipping units of sand, sandy clay, and clayey sand.

The Savannah River is the principal surface-water system near SRS. The river adjoins the site along its southwestern boundary for a distance of about 20 miles (32 km) and is 140 river miles (225 river km) from the Atlantic Ocean.

The Savannah River cuts a broad valley approximately 250 feet deep through the Aiken Plateau (see Figure 1.4-13). Pleistocene coastal terraces lie between the Savannah River and the Aiken Plateau. The lowest terrace is the Savannah River floodplain, which is covered with a dense swamp forest. Higher terraces rise successively from the river floodplain to the Aiken Plateau and have a level to gently rolling topography.

The Savannah River Swamp lies in the floodplain along the Savannah River for a distance of about 10 miles and averages about 1.5 miles wide (see Figure 1.4-12). A small embankment or natural levee has built up along the north side of the river from sediments deposited during periods of flooding. The top of the natural levee is approximately 3 to 6 feet above the river during normal flow (river stage 85 feet) at the SRS boat dock. Three breaches in this levee (at the confluences with Beaver Dam Creek, Fourmile Branch, and Steel Creek) allow discharge of stream water to the river. During periods of high river level (above 88 feet), river water overflows the levee and stream mouths and floods the entire swamp area. The water from these streams mixes with river water and then flows through the swamp parallel to the river and combines with the Pen Branch flow. The flows of Steel Creek and Pen Branch converge 0.5 miles above the Steel Creek mouth. However, when the river level is high, the flows are diverted parallel to the river across the offsite Creek Plantation Swamp; ultimately they join the Savannah River flow near Little Hell Landing.

Surface water is held in artificial impoundments and natural wetlands on the Aiken Plateau. Par Pond, the largest impoundment on SRS, is an artificial lake located in the eastern part of the site that covers approximately 2,700 acres. A second large artificial impoundment, L Lake, lies in the southern portion of SRS and covers approximately 1,000 acres. Water from both Par Pond (200 feet) and L Lake (190 feet) drains to the south via Lower Three Runs Creek and Steel Creek, respectively, into the Savannah River. Water is also retained intermittently in natural lowland and upland marshes and natural basins, some of which are Carolina bay depressions (Ref. 69, 70).

The source of most of the surface water on SRS is either natural rainfall, which averages 48 inches annually, water pumped from the Savannah River and used for cooling site facilities, or groundwater discharging to the surface streams. Cooling water is discharged to streams that flow back to the Savannah River, L Lake, or Par Pond. Small volumes of water are also discharged from other SRS facilities to the streams.

The flow data used for computing statistics for the Savannah River and SRS streams were obtained from U.S. Geological Survey (USGS) stream measurement data. The data set consisted of daily average flows with varying periods of record (from 2 to 81 years) for SRS streams and the Savannah River.

Several flow statistics were derived from this data set over the period of record: daily minimums, maximums, and means; average flow; 7-day low flow, and the 7-day flow with a 10-year recurrence interval (7Q10) flow. The sampling locations are shown in Figure 1.4-14. Emphasis was placed on low flow statistics because disposal of wastes and maintenance of conditions for aquatic life are usually based on some type of low flow statistic. The seven-day low flow is widely used and is less likely to be influenced by minor disturbances upstream than is the minimum daily flow. The 7Q10 flow is a measure of the dependability of flow. The 7Q10 flow is derived from the frequency curve of the yearly 7-day low flow statistics over the period of record at that stream or river location. The Log Pearson Type III distribution statistics are normally used for computation of low flows in natural streams. Other distributions may be more appropriate in streams that are not naturally driven (such as those where cooling water may be the dominant component of flow).

The Log Pearson Type III distribution was applied to all SRS stream locations where a 7Q10 was computed (a program equivalent to the USGS A193 for computing Log Pearson Type III distributions was used). The climatic year, April 1 to March 31, is used for calculation of low flow statistics. In the U.S., this period contains the low flow period for each year. Flow statistics are summarized in Table 1.4-15 (average flow, standard deviation, 7Q10, and 7-day low flow).

The Savannah River drainage basin has a total area of 10,600 square miles and forms the boundary between the States of Georgia and South Carolina. The total drainage area of the river encompasses all or part of 41 counties in Georgia, South Carolina, and North Carolina. The Savannah River Basin is located in three physiographic regions or provinces: the Mountain, the Piedmont, and the Coastal Plain.

The Mountain Province contains most of the major tributaries of the Savannah River, including the Seneca, Tugaloo, and Chattooga Rivers. The region is characterized by a relatively steep gradient ranging in elevation from about 5,497 to 1,000 feet, and includes 2,042 square miles (19%) of the total drainage basin. The Mountain Province lies in the Blue Ridge Mountains and has a bedrock composed of gneisses, granites, schists, and quartzites; the subsoil is composed of brown and red sandy clays. In this region, the Savannah River and its tributaries have the character of mountain streams with shallow riffles, clear creeks, and a fairly steep gradient. The streambed is mainly sand and rubble.

The Piedmont Region has an intermediate gradient with elevations ranging from 1,000 to 200 feet. This region includes 5,234 square miles (50%) of the total drainage basin. Soils in the Piedmont are primarily red, sandy, or silty clays with weathered bedrock consisting of ancient sediments containing granitic intrusions. The Piedmont is bordered by the Fall Line, an area where the sandy soils of the Coastal Plain meet the rocky terrane of the Piedmont foothills. The city of Augusta, Georgia, is located near this line. The Savannah River picks up the majority of its silt load in the Piedmont Region, and most of this silt load is deposited in the large reservoirs located in the Piedmont Region.

The Coastal Plain has a negligible gradient ranging from an elevation of 200 feet to sea level. The soils of this region are primarily stratified sand, silts, and clays. The Coastal Plain contains 3,366 square miles (31%) of the total Savannah River drainage area (10,681 square miles), and includes the city of Savannah, GA. In the Coastal Plain, the Savannah River is slow moving. Tidal effects may be observed up to 40 miles (65 km) upriver, and a salt front extends upstream along the bottom of the riverbed for about 20 miles (32 km).

Dredging operations on the Savannah River have been conducted by the U.S. Army Corps of Engineers between the cities of Savannah and Augusta, GA. This program, initiated in October 1958, was designed to dredge and maintain a 9-foot navigation channel in the Savannah River from Savannah to Augusta, GA. Sixty-one sets of pile dikes were placed to constrict the river flow, thereby increasing flow velocities, and 38,000 linear feet of wood and stone revetment was laid to reduce erosion on banks opposite from the dikes. In addition, the channel was dredged and 31 cutoffs were made, reducing the total river distance from Augusta to Savannah by about 15 river miles. The project was completed in July 1965; periodic dredging was continued to maintain the channel until 1985.

SRS is located in the Coastal Plain Province of the Savannah River, about 25 miles downstream of Augusta, GA. Construction of upriver reservoirs (Strom Thurmond, Richard B. Russell, Hartwell, Keowee, and Jocassee), and the New Savannah River Bluff Lock and Dam have reduced the variability of the river flow. Low flows in the Savannah River typically occur during the autumn months while higher flows occur in late winter and early spring.

Upstream of SRS at Augusta, GA, the average flow for the 81-year period of record is 10,027 cfs. The average flow at Augusta, GA, since the filling of Thurmond Lake (Clarks Hill) has been 9,571 cfs (Table 1.4-15). Flows increase below Augusta, GA, to about 12,009 cfs near Clyo, GA, about 100 miles downriver (Table 1.4-15). The 7Q10 flow at Augusta, GA, is 3,746 cfs.

The peak historic flow for the 81-year period of record was 350,021 cfs in 1929. Since the construction of the upstream reservoirs, the maximum average monthly flow has been 43,867 cfs for the month of April.

Natural discharge patterns on the Savannah River are cyclic: the highest river levels are recorded in the winter and spring, and lowest levels are recorded in the summer and fall. Stream flow on the Savannah River near the site is regulated by a series of three upstream reservoirs: Thurmond, Russell, and Hartwell. These reservoirs have stabilized average, annual stream flow to 10,200 cfs near Augusta and 10,419 cfs at SRS.

The river overflows its channel and floods the swamps bordering the site when its elevation rises higher than 88.5 feet above msl (which corresponds to flows equal to or greater than 15,470 cfs). River elevation measurements made at the SRS Boat Dock indicate that the swamp was flooded approximately 20% of the time (74 days per year on the average) during the period from 1958 through 1967.

The Savannah River forms the boundary between the states of Georgia and South Carolina. Upstream of SRS, the river supplies domestic and industrial water needs for Augusta, GA, and North Augusta, SC. The river receives treated wastewater from these municipalities and from Horse Creek Valley (Aiken, SC). The Savannah River Class B waterway is used for commercial and sport fishing and pleasure boating downstream from SRS.

Water withdrawn from the river is used for various SRS activities, but is used primarily to cool the production reactors. The Savannah River downstream from Augusta, GA, is classified by the State of South Carolina as a Class B waterway, which is suitable for agricultural and industrial use, the propagation of fish, and after treatment, domestic use. The river upstream from the site supplies municipal water for Augusta, GA (river mile 187), and North Augusta, SC (river mile 201). Downstream, the Beaufort-Jasper Water Authority in South Carolina (river mile 39.2) withdraws water to supply a population of about 51,000. The Cherokee Hill Water Treatment Plant at Port Wentworth, GA (river mile 29.0) withdraws water to supply a business-industrial complex near Savannah, Georgia that has an estimated consumer population of about 20,000. It is estimated that each individual served by the two water treatment plants consumes an average of 1.3 liters of water per day. Site expansions for both systems are planned for the future.

SRS was once a major user of water from the Savannah River and withdrew a maximum of 920 cfs from the river. Currently, all SRS reactors are shut down, and river water withdrawals are minimal. Past operations typically removed about 9% of the average annual Savannah River flow, but river water usage averaged 0.133 cfs during the second quarter of 1995 (Ref. 71).

In 1995, DOE decided to discharge a minimum flow of 10 cubic feet (0.28 cubic meter) per second to Lower Three Runs Creek. Also to allow the water level in Par Pond to fluctuate naturally near its operating level (200 feet above msl) but not allowing the water level to fall below 195 feet. Additionally it was decided to reduce the flow to L Lake so long as the normal operating level of 190 feet was maintained and the flow in Steel Creek (downstream of L Lake) was greater than 10 cfs (Ref. 72).

Currently, only one of the pumps at pumphouse 3G is operated; it supplies 23,000 gallons per minute (gpm) (1.5 cubic meters per second), which is more than is needed for system uses. The excess water is discharged from reactor areas to Fourmile Branch, Pen Branch, L Lake, and the headwaters of Steel Creek. The preferred action by DOE is to eliminate the pumping of the excess water that is discharged to these streams.

The proposed shutdown of the river water system at SRS is addressed in a draft Environmental Impact Statement (EIS) (Ref. 73). The preferred action by DOE is to operate a small pump to supply 4,800 gpm of river water to L Area. The L-Area 186-basin would be maintained full for fire protection purposes. Overflow from the basin would provide blending for the L-Area sanitary wastewater discharge, keep L Lake at its normal operating level, and provide a minimum flow of 10 cfs to Steel Creek. Up to 200 gpm; this would eliminate C-Area discharges to Fourmile Branch (approximate average 265 gpm). Flows from K Area to Pen Branch would be expected to decrease from an average flow of 7,400 gpm to not more than 400 gpm. This flow would consist of overflow from the 186-basin and discharges of about 210 gpm from well-water-cooled compressors.

The river also receives sewage treatment plant effluents from Augusta, GA; North Augusta, Aiken, and Horse Creek Valley, SC; and other waste discharges along with the heated SRS cooling water via its tributaries. VEGP withdraws an average of 92 cfs from the river for cooling and returns an average of 25 cfs. The Urquhart Steam Generating Station at Beech Island withdraws approximately 261 cfs of once-through cooling water. Upstream, recreational use of impoundments on the Savannah River, including water contact recreation, is more extensive than it is near SRS and downstream. No uses of the Savannah River for irrigation have been identified in either South Carolina or Georgia.

The Beaufort-Jasper Water Authority in South Carolina (river mile 39.2) withdraws about 8 cfs to supply domestic water for a population of about 51,000. The Cherokee Hill Water Treatment Plant at Port Wentworth, GA (river mile 29.0) withdraws about 50 cfs from the river to supply a business-industrial complex near Savannah, which has an estimated consumer population of about 20,000.

Based on available information, the following sections describe surface hydrology in reference to specific local facilities.

F and E Areas

A topographic map showing surface drainage of F Area is shown in Figure 1.3-15. The F-Canyon building site is at an elevation of over 300 feet above msl. The nearest significant stream to F Canyon is Upper Three Runs Creek. It is located about 0.7 miles north and west of the F-Canyon facility. This creek flows at elevations below 150 feet. The mean annual flow at a gauging station approximately 3 miles from F-Canyon is 215 cfs. The measured maximum flow for the period 1974 to 1986 was about 950 cfs. Runoff from precipitation is diverted into storm sewers, then discharged to an unnamed tributary of Upper Three Runs Creek, which empties into the Savannah River.

Area surface water bodies near the SWMF consist of Fourmile Branch and Upper Three Runs Creek, and their tributaries. All drainage is to the Savannah River. There are no surface waters, including intermittent streams, within 2,000 feet of the SWMF, and the SWMF areas are not located in the flood-prone areas. The surface waters affected directly or indirectly by the SWMF and seepage basin outcropping from plumes caused by past operations are Fourmile Branch and the Savannah River, into which Fourmile Branch flows at an average of 18 cfs (ranging from 6.5 cfs to 96 cfs). The relatively level land and a cover growth of Pensacola Bahia grass effectively control surface erosion at the SWMF. Surface drainage ditches channels are cut to control the runoff of rainwater to provide further erosion control (Ref. 73).

H, S, and Z Areas

A topographic map showing surface drainage near H Area is shown in Figure 1.3-18. The CIF is at an elevation of approximately 300 feet above msl. The nearest significant stream is Upper Three Runs Creek, located about 1.6 miles north of the CIF. Upper Three Runs Creek flows at elevations less than 150 feet above msl. The mean annual flow at a gauging station approximately 3 miles from H Area is 215 cfs. The measured maximum flow for 1974 to 1986 was about 950 cfs. Runoff from precipitation is carried away from structures by natural contours or catch basins that divert water into the Upper Three Runs Creek watershed. Upper Three Runs Creek empties into the Savannah River. Upper Three Runs Creek is not used as a drinking water supply for any population group.

S and Z Areas are located on a local topographic high (minimum grade level 275 feet msl). S Area is within the Savannah River drainage basin at the divide between Crouch Branch and McQueen Branch watersheds. Z Area is located north of S Area. Runoff from Z Area is diverted indirectly to McQueen Branch. McQueen Branch drains into Tinker Creek near its junction with Upper Three Runs Creek, and Crouch Branch drains directly into Upper Three Runs Creek. All streams in the area are at substantially lower elevations than S and Z Areas.

USGS gauging stations for McQueen Branch and Crouch Branch are in place. Stage data are being collected to develop ratings for these newly installed stations.

HYDROSPHERE - SAVANNAH RIVER SITE AREAS

The location, size, shape, and other hydrological characteristics of streams, rivers, lakes, shore regions, and groundwater environments that influence the general site are described below.

F and E Areas

F Area is on a near-surface groundwater divide between Upper Three Runs Creek and an unnamed tributary of Fourmile Branch. The near-surface groundwater from the southern part of F Area discharges to an unnamed tributary of Fourmile Branch, approximately 2,000 feet to the south. The near-surface groundwater from the northern part of F Area discharges to one of many tributaries of Upper Three Runs Creek, approximately 1,500 feet to the north.

The nearest site boundary from the E-Area SWMF is approximately 6 miles (9.6 km) to the west. The site is located on a water-table divide. From the original Solid Waste Storage Facility (Old Burial Ground, 643-E), surface flow is southwest towards a small tributary of Fourmile Branch. Groundwater from the northeastern parts of the Solid Waste Disposal Facility (SWDF) (643-7E) and the Mixed Waste Management Facility (MWMF) (643-28E) flows toward the north-northwest. Groundwater from the southwestern portions of SWMF 643-7E and the MWMF flows toward the west-southwest. Groundwater under the northwestern parts of SWMF 643-7E and the MWMF flows toward the west, and groundwater under the eastern portions of SWMF 643-7E and the MWMF flows toward the east-southeast.

H, S, and Z Areas

H Area is located near a water-table divide between Upper Three Runs Creek and Fourmile Branch. Near-surface groundwater from the southern part of H Area discharges to an unnamed tributary of Fourmile Branch, approximately 1,000 feet south of H Area. Near-surface groundwater from the northern part of H Area discharges to one of two tributaries of Upper Three Runs Creek, which are approximately 1,500 and 4,000 feet north of H Area, respectively.

The nearest site boundary to S Area is approximately 6.5 miles (10.5 km) to the north. Near-surface groundwater flows toward McQueen Branch, approximately 0.75 mile (1.2 km) to the northeast.

HYDROSPHERE – SURFACE WATERS

Savannah River

SRS is bounded on the southwest for approximately 17 miles (27 km) by the Savannah River. The Savannah River Basin (see Figure 1.4-14) is one of the major river basins in the southeastern U.S. It has a drainage area of 10,577 square miles, of which 8,160 square miles are upstream of SRS. The headwaters of the Savannah River are in the Blue Ridge Mountains of North Carolina, South Carolina, and Georgia. The river forms at the junction of the Tugaloo and Seneca Rivers

approximately 100 miles northwest of SRS, now the site of Hartwell Reservoir, and empties into the Atlantic Ocean near Savannah, GA, approximately 95 miles southeast of SRS. From the Hartwell Reservoir Dam to the Savannah Harbor, the river runs a course of 289 river miles.

Three large reservoirs on the Savannah River upstream of SRS provide hydroelectric power, flood control, and recreation. Strom Thurmond Reservoir (2.51 million acre-feet), completed in 1952 (Table 1.3-16), is approximately 35 miles (65 river km) upstream of SRS. The Richard B. Russell Reservoir (1.026 million acre-feet), completed in 1984, is approximately 72 miles (103 river km) upstream of SRS. Hartwell Reservoir (2.549 million acre-feet), completed in 1961, is approximately 90 miles (133 river km) upstream of SRS (see Figure 1.4-15). These three dams are owned by the U.S. Army Corps of Engineers. The Stevens Creek Dam, also on the Savannah River, is owned by SCE&G.

Additional dams lie upstream of Hartwell Reservoir and are used primarily for hydroelectric power generation (see Figure 1.4-15). The Yonah, Tugaloo, Tallulah Falls, Mathis, Nacoochee, and Burton Dams are owned by Georgia Power Company, and the Keowee, Little River, and Jocassee Dams are owned by Duke Power Company. Although many of these dams impound water to depths in excess of 100 feet, only Jocassee Dam and the combined Little River-Keowee Dams impound significant quantities (approximately 1 million acre-feet each).

Dredging operations on the Savannah River have been conducted by the U.S. Army Corps of Engineers since 1958. This program was designed to dredge and maintain a 9-foot navigation channel in the Savannah River from Savannah to Augusta, Georgia. Dredging of the Savannah River was discontinued in 1979. Sixty-one sets of pile dikes were placed to constrict the river flow, increasing flow rates, and 38,000 feet of a wood and stone revetment were laid to reduce erosion on banks opposite the dikes. In addition, the channel was dredged and 31 cutoffs were made, reducing the total river distance from Augusta to Savannah by approximately 15 miles. The project was completed in July 1965; periodic dredging has been performed to maintain the channel (Ref. 45, 46).

The Savannah River is gauged above SRS near Augusta, GA (station 02197000), 0.5 mile downstream from Upper Three Runs Creek at Ellenton Landing (station 02197320), at Steel Creek (station 02197357), and below SRS at Burtons Ferry Bridge (station 02197500) and 3 miles north of Clyo, GA (station 02198500) (see Figure 1.4-14) (Ref. 74). Since upstream stabilization, the yearly average flow of the Savannah River near SRS has been approximately 10,419 cfs (Ref. 75). Flow extremes are discussed in Section 1.5.1. The elevation of the river at SRS pumphouses is 80.4 feet msl at a flow of 5,800 cfs. The Savannah River has a flow of 5,800 cfs and has an average velocity of approximately 2 mph at VEGP, which is across the river from SRS (see Figure 1.4-14) (Ref. 76). The river is about 340 feet wide and from 9 to 16 feet deep. The minimum flow that is required for navigation downstream from Strom Thurmond Dam is 5,800 cfs. From SRS, river water usually reaches the coast in approximately 5 to 6 days, but may take as few as 3 days (Ref. 74).

Three locations below the mouth of Upper Three Runs Creek pump raw water from the Savannah River for drinking water supplies. The Cherokee Hill Water Plant at Port Wentworth, GA (see Figure 1.4-14) can withdraw about 70 cfs for an effective consumer population of about 20,000. The Beaufort-Jasper Water Treatment Plant at Hardeeville, SC (see Figure 1.4-14) can withdraw

about 12 cfs for a consumer population of approximately 51,000. The SRS D Area, downstream of the mouth of Upper Three Runs Creek, removes approximately 0.1 cfs from the river.

Savannah River water is also used for industrial water cooling purposes by several facilities. SRS is a major user, with intake points downstream of the confluence of Upper Three Runs Creek with the Savannah River. SRS could remove 1,450 cfs with all pumps in three pumphouses concurrently in use, but usually withdraws a maximum of 1,320 cfs from the river. C, K, and L Reactors could each receive about 400 cfs of cooling water when active. The coal-fired power plant in D Area receives about 100 cfs, and Par Pond receives about 20 cfs to compensate for seepage and evaporation. VEGP uses 100 cfs and SCE&G's Urquhart Steam Station, located between Augusta and SRS (see Figure 1.4-14), uses 260 cfs.

Upper Three Runs Creek

Upper Three Runs Creek is the longest of the plant streams. It drains an area of over 195 square miles and differs from the other five onsite streams in two respects. It is the only stream with headwaters arising outside the site. It is the only stream that has never received heated discharges of cooling water from the production reactors. Tims Branch receives primarily treated industrial wastewaters from M Area, SRTC, a small coal-fired plant, and treated sanitary wastewater and remediated groundwater from A and M Areas.

The minimum and maximum flow history for Upper Three Runs Creek is discussed in Section 1.5.1.2. The Upper Three Runs Creek stream channel has a low gradient and is meandering, especially in the lower reaches. Its floodplain ranges in width from 0.25 to 1 mile and contains extensive stands (about 98% coverage) of bottomland hardwood forest (Ref. 77). Within SRS, the Upper Three Runs Creek valley is asymmetrical, having a steep southeastern side and a gently sloping northwestern side.

Upper Three Runs Creek is gauged near Highway 278 (station 02197300 relocated downstream), at SRS Road C (station 02197310), and at SRS Road A about 3 miles above the confluence of Upper Three Runs Creek with the Savannah River (station 02197315) (see Figure 1.4-12). The Highway 278 station is a National Hydrologic Benchmark Station. Benchmark streams are measured monthly for water flow, temperature, and quality to provide hydrologic data on river basins governed by natural conditions.

The average Upper Three Runs Creek flow at Highway 278 from 1966 to 1986 was 106 cfs, which represents a water yield of about 1.0 cubic feet per square mile or 16.55 inches/year from the drainage basin (Ref. 77). The average annual precipitation at SRS is 48.3 inches (Ref. 78). Thus, in the upper reaches of Upper Three Runs Creek, about 35% of the rainfall appears as stream discharge. Flow rates are also measured downstream of the Route 278 site at SRS Road C and at SRS Road A. Average daily flows were calculated to be 102, 203, and 251 cfs, respectively. The minimum daily flow rates recorded at these sites during this period were 45, 117, and 124 cfs, respectively.

Fourmile Branch

Fourmile Branch drains about 23 square miles within SRS, including much of the F, H, and C Areas (see Figure 1.4-12). The creek flows to the southwest into the Savannah River Swamp and then into the Savannah River. The valley is V-shaped, with the sides varying from steep to gently sloping. The floodplain is up to 1,000 feet wide. There is no human population resident in the Fourmile Branch drainage.

Fourmile Branch receives effluents from F, H, and C Areas; and a groundwater plume from the burial ground, F Seepage Basin, and H Seepage Basin (use discontinued in November 1988). Until June 1985, it received large volumes of cooling water from the production reactor in C Area. The creek valley has been modified by the cooling water discharge, which has created a delta into the Savannah River Swamp. Fourmile Branch also receives tritium and strontium-90 migrating from the F- and H-Area seepage basins and the SWMF.

Water flow measurements have been made on Fourmile Branch near Road A-12.2 at SRS (station 02197344) since November 1976. Mean monthly flows for water years 1986 and 1987, after C Reactor shutdown, ranged from 88 cfs in January 1986 to 17 cfs in August 1987 (Ref. 74, 79). Extreme flows for this period were 436 cfs (gage height 3.14 feet) on March 1, 1987, to 13 cfs on August 24-25 and 28-29, 1987. The maximum and minimum discharges for the period of record are 903 cfs (gage height 3.93 feet) on March 13, 1980, and 13 cfs on August 24-25 and 28-29, 1987, respectively (Ref. 74).

ENVIRONMENTAL ACCEPTANCE OF EFFLUENTS

All NPDES permitted outfalls within the SRS are identified in the annual Savannah River Site Environmental Report (Ref. 20).

CHEMICAL AND BIOLOGICAL COMPOSITION OF ADJACENT WATERCOURSES

Upper Three Runs Creek

The Upper Three Runs Creek valley is swampy with a meandering and braided channel, especially in the lower reaches. In the SRS, the stream has a gradient of approximately 5.3 ft/mile (l m/km). A study of Upper Three Runs Creek stream channel sediments (Ref. 94) found sand to be the dominant fraction, with silt plus clay fractions increasing to about 40% at Road A.

Upper Three Runs Creek is a slightly dystrophic, large, cool, blackwater stream. The stream is neutral to somewhat acidic and carries a relatively low load of suspended and dissolved organics compared to other streams of the southeastern Atlantic Coastal Plain (Ref. 94). Suspended solid loads are heaviest during periods of highest stream flow, normally late winter to early spring when vegetative cover is reduced. From the upper to lower reaches, the suspended load increases substantially. Although inorganic sediments are preferentially deposited in the floodplains, there is a concurrent input of organics from the floodplains, which causes an increase in total

suspended solids (mostly organic matter). This increase is more pronounced in periods when the stream overflows its banks and floods the surrounding swamps. Water quality samples for Upper Three Runs Creek are collected monthly and the data are presented in the annual SRS Environmental Report (Ref. 20).

The water of Upper Three Runs Creek is soft, usually clear, and low in nutrients. The temperature ranges from approximately 5 to 26°C, with lows occurring from December through February. The highest temperature and lowest flow are normally observed in July. Temperature, pH, and dissolved oxygen levels in the stream meet South Carolina Water Classification Standards for Class B streams (Ref. 94). Conductivity, suspended solids, and alkalinity concentrations increase in the downstream direction, but the concentrations are low at all stations. Nutrient levels are also low, although phosphorus and nitrate levels are highest during the spring and summer, possibly due to offsite agricultural activities.

The effluents include process wastes, cooling water, surface runoff, and ash basin effluent. The F/H ETF discharges into Upper Three Runs Creek near Road C. Tims Branch (see Figure 1.4-12), a tributary to Upper Three Runs Creek, has received trace amounts of radioactivity and heavy metals contamination and is currently receiving elevated levels of nitrates from M Area (Ref. 93). Total discharges to Upper Three Runs Creek range from approximately 10 gpm to over 1,000 gpm. By comparison, the minimum recorded flow at the Highway 278 gage about 10 miles upstream on Upper Three Runs Creek is 66 cfs, which is approximately 30,000 gpm (Ref. 92).

The cation exchange capacity (CEC) ranged from 0.1 to 12.4 milliequivalent per 100 grams (meq/100 g) in all Upper Three Runs Creek and tributary sediments, indicating low CEC values throughout the Upper Three Runs Creek watershed. Elevated levels of nickel were found in Tims Branch sediments, probably originating from the nickel plating operations in M Area (Ref. 94). Sediments from the Upper Three Runs Creek watershed exhibited background levels of Cs-137 ($\leq$ 2 pCi/g) and naturally occurring radionuclides (K-40, radium, Tl-208, and natural uranium) (Ref. 95).

The swamp forest of the Upper Three Runs Creek floodplain consists primarily of bald cypress (Taxodium distichum) and tupelo gum (Nyssa aquatica), while the bottomland hardwoods associated with the stream are mostly sweet gum (Liquidambar styraciflua), red oak (Quercus rubra), and beech (Fagus grandifolia). The stream is well shaded in most reaches.

Leaf litter input is high, and the leaves are rapidly broken down by macroinvertebrate shredders. The relatively complete canopy results in low periphyton and macrophyte biomass, especially in summer when the creek is most shaded. The periphytons that do occur are largely green algae and diatoms (Ref. 90).

Sampling conducted in 1984 and 1985 found ichthyoplankton densities to be low, with spotted suckers the dominant taxon. Crappie and darters also composed a large portion of the overall ichthyoplankton population. The dominant fish species found were redbreast sunfish, spotted suckers, channel catfish, and flat bullhead. Species numbers tend to peak in the spring and drop in the summer (Ref. 93).

Fourmile Branch

Fourmile Branch originates on SRS and flows southwest across the plant toward the Savannah River. In the Savannah River Swamp, when C Reactor operated, part of Fourmile Branch flowed to Beaver Dam Creek, which flows directly into the Savannah River through a breach in the natural levees. With C Reactor in cold standby, Fourmile Branch flows parallel to the river behind the natural levees and enters the river through a breach downriver from the Beaver Dam Creek.

Fourmile Branch receives nonradioactive effluents from C, F, and H Areas, which increase the hardness, nutrient content, and trace metal concentrations in the water. From March 1955 to June 1985, Fourmile Branch also received 180,000 gpm of cooling water from the production reactor in C Area. During this period, water quality in the thermal reaches of the creek generally reflected the waters of the Savannah River, which served as source water for C Reactor (Ref. 96).

During reactor operations, stream temperatures near the mouth of Fourmile Branch (station 02197328) ranged from less than 10°C during the winter to more than 40°C during the summer (Ref. 92), with the highest temperature recorded at 46.8°C on August 22, 1983 (Ref. 88). Mean temperatures for June, July, and August often were greater than 38°C. Temperatures in excess of 60°C were recorded upstream near the C-Area discharge site (Ref. 96). Temperature extremes since reactor shutdown have been 1.5° and 34°C, with mean temperatures for summer months ranging from about 22 to 29°C (see Figure 1.4-16) (Ref. 74, 79).

Fourmile Branch has been greatly influenced by the temperature and volume of cooling water it received from the C-Area production reactor. The native swamp forest has been eliminated and the stream is mostly unshaded. Nutrient removal and reduction of the organic load in the swamp do not occur as effectively as in the past due to the effects of standing hot water from C Area (Ref. 90).

Above its thermal reach, the water quality of Fourmile Branch resembles that of other nonthermal streams on the site (Ref. 94). Samples taken from 1983 to 1985 showed this portion of Fourmile Branch to have higher conductivity, nitrate (as N), calcium, and sodium levels than Upper Three Runs Creek. Levels of copper, cadmium, mercury, nickel, lead, chromium, and zinc were at or near detection limits (Ref. 97). Water temperatures in the nonthermal reaches of Fourmile Branch averaged approximately 17°C, with highs usually less than 30°C.

Water quality samples for Fourmile Branch are collected monthly and the data are presented in the annual SRS Environmental Report (Ref. 20). The mean temperature, the pH range, and the mean dissolved oxygen concentration were similar to those for Upper Three Runs Creek at Road C during the same period. The mean concentrations of most other parameters measured were higher or approximately equal to those for Upper Three Runs Creek. Turbidity, volatile solids, chemical oxygen demand, nitrites, nitrates, and manganese were lower in Fourmile Branch than in the lower reaches of Upper Three Runs Creek (measured at Road C).

When C Reactor was in operation, only the thermophilic blue-green algae (i.e., Phormidium and Oscillatoria spp.) survived regularly in waters exceeding 50°C (Ref. 97, 98). Leaf decomposition was low due to the absence of macroinvertebrate shredders. The macroinvertebrate populations

exhibited low biomass and low densities except for some oligochaetes, nematodes, and chironomids that were more heat tolerant. Upstream from this zone, diatoms were the predominant and most diverse primary producers. Blue-green algae of the genera Microcoleus, Schizothrix, and Oscillatoria were found in decaying organic surfaces such as submerged logs and leaf litter. Besides the thermophilic blue-green algae, the mosquito fish was the only other survivor during periods of thermal stress.

Following reactor shutdown in 1985, the macroinvertebrate density and biomass increased. Many fish species have readily reinvaded during this period, and fish catch rates have increased markedly. It is expected that the current biology of Fourmile Branch will more closely resemble that of other site streams.

1.4.2.2 Regional Hydrogeology (Within 75 Mile Radius)

The following subsections are based on and draw directly from information and illustrations contained in Aadland et. al, Hydrogeologic Framework of West-Central South Carolina (1995) (Ref. 100).

REGIONAL HYDROGEOLOGICAL SETTING

Two hydrogeologic provinces are recognized in the subsurface beneath the SRS region (Figure 1.4-18) (Note: Figure 1.4-17 is intentionally omitted.). The uppermost province, which consists of the wedge of unconsolidated Coastal Plain sediments of Late Cretaceous and Tertiary ages, is referred to as the Southeastern Coastal Plain hydrogeologic province. It is further subdivided into aquifer or confining systems, units, and zones. The underlying province, referred to as the Piedmont hydrogeologic province, includes Paleozoic metamorphic and igneous basement rocks and Upper Triassic lithified mudstone, sandstone, and conglomerate in the Dunbarton basin (see Section 1.4.3.1). For reference, a geological time scale is shown in Figure 1.4-19.

The following hydrogeological characteristics are of particular interest from a safety perspective. (The following subsections provide additional details.)

- The layered structure of the coastal plain sediments effectively controls migration of contaminants in the subsurface, limiting vertical migration to deeper aquifers.
- Between the ground surface and the primary drinking water aquifer(s) are several low permeability zones which restrict vertical migration from a given point source.
- The abundance of clay size material and clay minerals in the aquifer and aquitard zones affects groundwater composition and vertical migration. The concentration of some potential contaminants, especially metals and radionuclides, may be attenuated by exchange and fixation of dissolved constituents on clay surfaces.
- The recharge area(s) for the deeper drinking water aquifers used are updip of SRS, near the fall line. Some recharge areas are located at the northern-most fringe of the site.

- Recharge for the water-table aquifers, namely the Upper Three Runs and Gordon Aquifers, is primarily from local precipitation.
- Discharge of groundwater from the Upper Three Runs and Gordon aquifers is typically to the local streams on the SRS.
- Groundwater at the SRS is typically of low ionic, low dissolved solids and moderate pH (typically ranging from 4.4 to 6.0). Other constituents such as dissolved oxygen and alkalinity are more closely associated with recharge and aquifer material. Dissolved oxygen is typically higher in the updip and near-surface recharge areas, and alkalinity, pH and dissolved solids are typically higher in those portions of the aquifers regions containing significant carbonate materials.
- The presence of an upward vertical gradient or "head reversal" between the Upper Three Runs and Gordon aquifers and the Crouch Branch aquifer is significant in that it prevents downward vertical migration of contaminants into deeper aquifers over much of central SRS (Figure 1.4-20).

HYDROSTRATIGRAPHIC CLASSIFICATION AND NOMENCLATURE OF COASTAL PLAIN SEDIMENTS

The method for establishing a nomenclature for the hydrogeologic units in the following discussion is based on Aadland et al. (Ref. 100) and generally follows the guidelines set forth by the South Carolina Hydrostratigraphic Subcommittee.

A hydrogeologic unit is defined by its hydraulic properties (hydraulic conductivity, hydraulic head relationships, porosity, leakance coefficients, vertical flow velocity and transmissivity) relative to those properties measured in the overlying and underlying units (Ref. 101-103). The properties are measured at a type well or type well cluster location (see Figure 1.4-21). Aquifer and confining units are mapped on the basis of the hydrogeologic continuity, potentiometric conditions, and leakance-coefficient estimates for the units. These properties are largely dependent on the thickness, areal distribution, and continuity of the lithology of the particular unit. However, a hydrogeologic unit may traverse lithologic unit boundaries if there is not a significant change in hydrogeologic properties corresponding to the change in lithology.

Delineation and Classification of Units

The hydrostratigraphic classification is based on aquifer and confining units ranked at four levels (I through IV):

Level I - Hydrogeologic Province

A hydrogeologic province is a major regional rock and/or sediment package that behaves as a single unified hydrologic unit. The names, areal extent and underlying geological context of the regional hydrogeologic provinces used in this report are the same as those defined by Miller and Renken (Ref. 104) as regional hydrologic systems. For example, the "Southeastern Coastal Plain

hydrologic system" of Miller and Renken reads "Southeastern Coastal Plain *hydrogeologic* province" in this report (Figure 1.4-22).

Level II - Aquifer and Confining Systems

These define the primary or regional units of the hydrogeologic province. The aquifer system may be composed of a single aquifer or two or more coalescing aquifers that transmit ground water on a regional basis. Aquifer systems may be locally divided by confining units that impede ground water movement but do not greatly affect the regional hydraulic continuity of the system (Ref. 105). A confining system may be composed of a single confining unit or two or more confining units that serve as an impediment to regional ground water flow. The regional aquifer/confining systems at SRS are presented in Figures 1.4-18 and 1.4-23).

The SRS is located near the updip limit of the aquifer and confining systems comprising the Coastal Plain sediments in the region. Here, the lateral continuity and thickness of the clay and clayey sand beds that constitute the confining systems decrease, and the beds become increasingly discontinuous. Where the clay beds no longer separate the overlying and underlying aquifers, the updip limit of a confining system is defined. Updip from this line, the overlying and underlying aquifer systems coalesce into a single unified aquifer system. Where aquifer systems have combined, some of the individual aquifer and confining units may persist in the updip-combined system.

Level III - Aquifer and Confining Units

These are the fundamental units of the classification. An aquifer is a mappable (> 1036 km^2 [~400 mi^2]) body of rock or sediments that is sufficiently permeable to conduct ground water and yield significant quantities of water to wells and springs (Ref. 106). A confining unit, on the other hand, is a mappable (> 1036 km^2 ~ 400 mi^2]) body of rock or sediments of significantly lower hydraulic conductivity than an adjacent aquifer, and that serves as an impediment to groundwater flow into or out of an aquifer (Ref. 107). A confining unit's hydraulic conductivity may range from nearly zero to some value distinctly lower than that of the nearby aquifer. The assignment of a unit level and name to a hydrostratigraphic unit does not imply a quantitative ranking of hydraulic continuity, but is intended to distinguish relative differences in hydraulic properties between adjacent units. Where the confining unit that separates one aquifer from another thins and becomes laterally discontinuous and/or is breached by faults and fractures, the overlying and underlying aquifers coalesce and a single unified aquifer may be defined. The aquifer/confining units in the SRS region are presented in Figure 1.4-22).

Level IV - Aquifer and Confining Zones

Aquifer and confining units may be informally subdivided into zones that are characterized by properties significantly different from the rest of the unit, such as hydraulic conductivity, water chemistry, lithology, and/or color. For example, an aquifer may contain a "confining zone" such as the "tan clay" confining zone of the Upper Three Runs aquifer. Conversely, a confining unit may contain an "aquifer zone" such as the "middle sand" aquifer zone of the Crouch Branch

confining unit. Miller (Ref. 108) describes the "Fernandina permeable zone" in the Lower Floridan aquifer in coastal areas of Georgia, where the permeability greatly exceeds that of the rest of the aquifer.

In the study area, zonal differentiation is undertaken on a local site-specific scale where useful and necessary distinctions are made in the hydraulic characteristics of specific aquifer or confining units. Thus, the intermittent but persistent clay beds in the Dry Branch Formation, informally referred to as the "tan clay" in previous SRS reports, is designated the tan clay confining zone of the Upper Three Runs aquifer. The "tan clay" confining zone is defined specifically for the Dry Branch clay in the General Separations Area of SRS. Correlative clay beds in other parts of the study area may usefully be designated a confining zone but would be given a separate and distinct name.

SOUTHEASTERN COASTAL PLAIN HYDROGEOLOGIC PROVINCE

The Southeastern Coastal Plain hydrogeologic province underlies 310,798,560 km^2 (120,000 square miles) of the Coastal Plain of South Carolina, Georgia, Alabama, Mississippi, and Florida and a small contiguous area of southeastern North Carolina. This hydrogeologic province grades laterally to the northeast into the Northern Atlantic Coastal Plain Aquifer System (Ref. 109) and to the west into the Mississippi embayment and Coastal Lowlands Aquifer Systems (Ref. 110). In South Carolina, the northern and northwestern limits of the province are its contact with crystalline rocks at the Fall Line, which marks the updip limit of Coastal Plain sediments.

The Southeastern Coastal Plain hydrogeologic province comprises a multilayered hydraulic complex in which retarding beds composed of clay and marl are interspersed with beds of sand and limestone that transmit water more readily. Ground water flow paths and flow velocity for each of these units are governed by the unit's hydraulic properties, the geometry of the particular unit, and the distribution of recharge and discharge areas. Miller and Renken (Ref. 104) divided the Southeastern Coastal Plain hydrogeologic province into seven regional hydrologic units. These are four regional aquifer units separated by three regional confining units. Six of the seven hydrologic units are recognized in the SRS area and are referred to as hydrogeologic systems. These systems have been grouped into three aquifer systems divided by two confining systems, all of which are underlain by the Appleton confining system. The Appleton separates the Southeastern Coastal Plain hydrogeologic province from the underlying Piedmont hydrogeologic province. The regional lithostratigraphy and hydrostratigraphic subdivision of the Southeastern Coastal Plain hydrogeologic province is shown in Figure 1.4-18.

In descending order, the aquifer systems beneath SRS are the Floridan Aquifer System, the Dublin Aquifer System, and the Midville Aquifer System (see Figure 1.4-18). In descending order, the confining systems are the Meyers Branch confining system, the Allendale confining system, and the Appleton confining system.

Beneath the SRS, the Midville and Dublin Aquifer Systems each consists of a single aquifer, the McQueen Branch aquifer and Crouch Branch aquifer, respectively. Downdip, beyond the SRS, these aquifer systems are subdivided into several aquifers and confining units.

The Floridan Aquifer System consists of two aquifers in the study area, the Upper Three Runs aquifer unit, and the underlying Gordon aquifer unit, which are separated by the Gordon confining unit. Northward, the Gordon and Upper Three Runs aquifer units coalesce to form the Steed Pond aquifer.

The Allendale and Meyers Branch confining systems each consists of a single confining unit in the study area, the McQueen Branch and Crouch Branch confining units, respectively. The basal Appleton confining system is thought to consist of a single confining unit in the study area. The confining unit, "Appleton" however, has not been formally defined owing to insufficient data. Downdip, each confining system may be subdivided into several confining units and aquifer units.

Where the confining beds of the Allendale confining system no longer regionally separate the Dublin and Midville Aquifer Systems hydrologically, the Dublin-Midville Aquifer System is defined (see Figures 1.4-18 and 1.4-23). Similarly, where the Meyers Branch confining system no longer regionally separates the Floridan Aquifer System from the underlying Dublin-Midville Aquifer System, the entire sedimentary sequence from the top of the Appleton confining system to the water-table is hydraulically connected and the Floridan-Midville Aquifer System is defined.

In general, the number of aquifer systems present beneath the SRS decreases updip (see Figure 1.4-22). This is due to pinch out of confining units in the updip direction. Thus, in the southern site area, three aquifer systems are designated. As the confining systems become ineffective flow barriers updip, the number of aquifer systems decreases to one (Floridan-Midville) in the northern site region. As indicated in Figure 1.4-22, the nomenclature and stratigraphic position of the two aquifer system areas is dependent on which confining system (Allendale or Meyers Branch) pinches out.

The following discussion treats each of the hydrogeologic units in greater detail. It presents the units in descending order, from water-table to the Piedmont hydrogeologic province. Within each unit, the discussion traces the unit updip. In general, confining layers pinch out and aquifers coalesce in an updip direction.

Floridan Aquifer System

Miller (Ref. 106) defined the Floridan Aquifer System as a "vertically continuous sequence of carbonate rocks of generally high permeability that are mostly of middle and late Tertiary age and hydraulically connected in varying degrees and whose permeability is, in general, an order to several orders of magnitude greater than that of those rocks that bound the system above and below". Thus, the definition of the Floridan Aquifer System is partly lithologic and partly hydraulic. The system is sometimes referred to as the principal artesian aquifer in South Carolina, Georgia, and Alabama (Ref. 106, 110). The rocks that characterize the main body of the Floridan are mostly platform carbonates.

The Floridan Aquifer System includes the platform carbonates as noted by Miller (Ref. 106) as well as the updip equivalent clastics that are in hydrogeologic communication with the carbonates. The updip clastic facies equivalents of the Floridan carbonate rocks are not

considered by Miller (Ref. 106) to be part of the Floridan Aquifer System. However they are hydraulically connected with it and are part of its regional flow system. Thus, the updip clastic facies equivalent of the Floridan Aquifer System and the carbonate phase of the Floridan Aquifer System are treated as a single hydrologic unit (the Florida Aquifer System) (Ref. 100). The updip clastic facies equivalents represent the recharge areas for the downdip Floridan. The downdip carbonate phase of the Floridan Aquifer System is used extensively in the southeastern part of the South Carolina Coastal Plain as an aquifer.

The transition zone between the carbonate rocks of the Floridan and the updip clastic facies equivalents of the system is the approximate northern extent of the thick carbonate platform that extended from the Florida peninsula through the coastal area of Georgia to southwestern South Carolina during early Tertiary time. The transition zone extended toward the north to a line approximated by the updip limit of the Santee Limestone platform carbonate beds (Ref. 111). At SRS, which lies mostly north of the line established for the updip limit of the carbonate phase of the Floridan Aquifer System, there are thin beds and lenses of limestone that may be either connected to the main limestone body or isolated from it, owing in part to depositional isolation or to postdepositional erosion or diagenetic alteration. They are considered part of the updip clastic phase of the Floridan.

Carbonate Phase of the Floridan Aquifer System

The carbonate phase of the Floridan Aquifer System that develops in the southernmost fringe of the SRS, just south of well C-10 (see Figure 1.4-22), is divided into the Upper and the Lower Floridan aquifer units (Ref. 111), separated by the "middle confining unit". The hydraulic characteristics of the carbonate phase of the Floridan Aquifer System vary considerably in the South Carolina-Georgia region. This results from several different processes, the most important being the dissolution of calcium carbonate by groundwater. The variability in the amount of dissolution is strongly influenced by the chemical composition of the water and the local differences in geology and lithology that affect the rate of groundwater movement.

Hydraulic parameters data for the Floridan Aquifer System are given in Table 1.4-18.

Clastic Phase of the Floridan Aquifer System

The updip clastic phase of the Floridan Aquifer System dominates in the SRS region and consists of a thick sequence of Paleocene to late Eocene sand with minor amounts of gravel and clay and a few limestone beds. At the southern fringe of the SRS, the clastic sediments of the aquifer system grade directly into the platform limestone that forms the carbonate phase of the Floridan. The lithologic transition between the clastic phase and the carbonate phase of the aquifer system does not represent a hydrologic boundary, and the two lithofacies are in direct hydrogeologic communication. The Floridan Aquifer System overlies the Meyers Branch confining system throughout the lower two-thirds of the study area. Toward the north, the confining beds of the Meyers Branch confining system thin, become intermittent, and the entire Floridan Aquifer System coalesces with the Dublin-Midville Aquifer System to form the Floridan-Midville Aquifer System (see Figures 1.4-18 and 1.4-23).

In the central portion of SRS, clay to sandy clay beds in the Warley Hill Formation (Figure 1.4-18) support a substantial head difference between overlying and underlying units. These fine-grained sediments constitute the Gordon confining unit, which divides the system into two aquifers: the Gordon aquifer unit and the overlying Upper Three Runs aquifer unit. The former of the two is between the lower surface of the Gordon confining unit and the upper surface of the Crouch Branch confining unit. Updip, the Warley Hill sediments do not support a substantial head difference; thus, there is only one aquifer unit (the Steed Pond aquifer).

The sedimentary sequence that corresponds to the updip clastic phase of the Floridan Aquifer System is penetrated in the P-27 reference well (see Figure 1.4-22) near the center of SRS. The system at P-27 is 65.8 meters (216 feet) thick; the base is at 14.6 meters (48 feet) msl, and the top occurs at the water-table, which is at 80.5 meters (264 feet) msl, or 3.1 meters (10 feet) below land surface. The system includes 6.7 meters (22 feet) of clay in five beds, and the remainder consists of sand and clayey sand beds. The stratigraphic units that constitute the clastic phase of the Floridan Aquifer System include the Fourmile Formation and the locally sandy parts of the Snapp Formation of the Black Mingo Group, all of the Orangeburg and Barnwell Groups, and the overlying Miocene/Oligocene "Upland unit" (see Figure 1.4-18).

Recharge of the Floridan occurs generally in the northwestern part of the study area, where rainfall percolates into the outcrop of the Gordon and Upper Three Runs aquifers. The Savannah River has the greatest area-wide influence on water levels, followed by the South Fork Edisto River and, to a much lesser degree, the Salkahatchie River. In the updip portion of the study area, Upper Three Runs Creek controls the direction of groundwater movement. Here, the Gordon confining unit has been breached by the stream, creating a groundwater sink that induces flow out of the Gordon toward the stream. Using an average transmissivity value of 28 m^2/day (300 ft^2/day) and an average hydraulic gradient of 4.7 m/km (25 ft/mi) near Upper Three Runs Creek, an estimated 423,920 L/day (112,000 gal/day) is being discharged through each 1-mile strip of the aquifer along the creek, for a total of 5.3 million L/day (1.4 million gal/day).

The transmissivity of the clastic and carbonate phases of the Floridan is lowest near their updip limits because of the reduced aquifer thickness there. Krause (Ref. 112) observed that the transmissivity increases rapidly from the northwest to the southeast along the Savannah River through the clastic facies and across the limestone facies change of the Floridan Aquifer System.

Upper Three Runs Aquifer Unit

The Upper Three Runs Aquifer Unit occurs between the water-table and the Gordon Confining Unit and includes all strata above the Warley Hill Formation (in updip areas) and the Blue Bluff Member of the Santee Limestone (in downdip areas, Figure 1.4-18). It includes the sandy and sometimes calcareous sediments of the Tinker/Santee Formation and all the heterogeneous sediments in the overlying Barnwell Group. The Upper Three Runs aquifer is the updip clastic facies equivalent of the Upper Floridan aquifer in the carbonate phase of the Floridan Aquifer System (see Figure 1.4-22).

The Upper Three Runs aquifer is defined by the hydrogeologic properties of the sediments penetrated in well P-27 (see Figure 1.4-21) located near Upper Three Runs Creek in the center of

SRS. Here, the aquifer is 40 meters (132 feet) thick and consists mainly of quartz sand and clayey sand of the Tinker/Santee Formation; sand with interbedded tan to gray clay of the Dry Branch Formation; and sand, pebbly sand, and minor clay beds of the Tobacco Road Formation. Calcareous sand, clay, and limestone, although not observed in the P-27 well, are present in the Tinker/Santee Formation throughout the General Separations Area near well P-27.

Downdip, at the C-10 reference well, the Upper Three Runs aquifer is 116 meters (380 feet) thick and consists of clayey sand and sand of the upper Cooper Group; sandy, shelly limestone, and calcareous sand of the lower Cooper Group/Barnwell Group; and sandy, shelly, limestone and micritic limestone of the Santee Limestone (see Figure 1.4-21).

Water-level data are sparse for the Upper Three Runs aquifer unit except within SRS. The hydraulic-head distribution of the aquifer is controlled by the location and depth of incisement of creeks that dissect the area. The incisement of these streams and their tributaries has divided the interstream areas of the water-table aquifer into "groundwater islands." Each "groundwater island" behaves as an independent hydrogeologic subset of the water-table aquifer with unique recharge and discharge areas. The stream acts as the groundwater discharge boundary for the interstream area. The head distribution pattern in these groundwater islands tends to follow topography and is characterized by higher heads in the interstream area with gradually declining heads toward the bounding streams (see Figure 1.4-24). Groundwater divides are present near the center of the interstream areas. Water-table elevations reach a maximum of 76 meters (250 feet) msl in the northwest corner of the study area and decline to approximately 30 meters (100 feet) msl near the Savannah River.

Porosity and permeability of the Upper Three Runs aquifer are variable across the study area. In the northern and central regions, the aquifer yields only small quantities of water, owing to the presence of interstitial silt and clay and poorly sorted sediments that combine to significantly reduce permeability. Local lenses of relatively clean, permeable sand however, may, yield sufficient quantities for domestic use. Such high-permeability zones have been observed in the General Separations Area near the center of the study area and may locally influence the movement of groundwater (Ref. 113).

Porosity and permeability were determined for Upper Three Runs aquifer sand samples containing less than 25 percent mud, using the Beard and Weyl method (Ref. 114). Porosity averages 35.3 percent; the distribution is approximately normal, but skewed slightly toward higher values. Geometric mean permeability is 31.5 Darcies (23 m/day [76.7 ft/day]) with about 60 percent of the values between 16 and 64 Darcies (12 and 48 m/day [39 and 156 ft/day]).

Pumping-test and slug-test results in the General Separations Area indicate that hydraulic conductivity is variable, ranging from less than 0.3 (1.0 ft/day) to 10 m/day (32.8 ft/day). Hydraulic conductivity values derived from long-duration, multiple-well aquifer tests are in the range of 3 m/day (10 ft/day), which may be a more reliable estimation of average hydraulic conductivity. At the south end of the study area, near well C-10, sediments in the aquifer become increasingly calcareous, the amount of silt and clay tends to decline, and permeability and yields generally increase. Here, hydraulic-conductivity values are in the 18 m/day (59 ft/day) range.

The majority of hydrogeologic data available on the Upper Three Runs aquifer is from wells in the General Separations Area at SRS. Thus, the discussion that follows is largely focused on that area. The Upper Three Runs aquifer is divided into two aquifer zones divided by the tan clay confining zone. In the General Separations Area, the "upper" aquifer zone consists of all saturated strata in the upper parts of the Dry Branch Formation and the Tobacco Road Formation that lie between the water-table and the "tan clay" confining zone. The aquifer zone has a general downward hydraulic potential into the underlying aquifer unit. The confining beds of the "tan clay" located near the base of the Dry Branch Formation impede the vertical movement of water and often support a local hydraulic head difference. The "lower aquifer" zone of the Upper Three Runs aquifer occurs between the "tan clay" confining zone and the Gordon confining unit and consists of sand, clayey sand and calcareous sand of the Tinker/Santee Formation and sand and clayey sand of the lower part of the Dry Branch Formation.

Slug tests, minipermeameter tests, pumping tests, and sieve analyses have been used to calculate hydraulic-conductivity values for the "upper" aquifer zone near the General Separations Area. Hydraulic-conductivity values derived from 103 slug tests range from a high of 14 m/day (45.4 ft/day) to a low of 0.02 m/day (0.07 ft/day) and average (arithmetic mean) 1.5 m/day (5.1 ft/day) (Ref. 115).

As stated previously, the "tan clay" confining zone at the General Separations Area separates the "upper" aquifer zone from the "lower" aquifer zone in the Upper Three Runs aquifer. This zone is a leaky confining zone. Total thickness of the "tan clay" confining zone, based on measurements at 46 wells distributed throughout the General Separations Area, ranges from 0 to 10 meters (32.8 feet) and averages 3.4 meters (11 feet). The sandy clay to clay beds range from 0 to 5.5 meters (18 feet) in thickness and average 2.1 meters (7 feet). The clayey sand beds range from 0 to 3.7 meters (12 feet) and average 1 meter (3 feet).

Laboratory analyses, including horizontal and vertical hydraulic conductivity, were run on 28 selected clayey sand samples and 55 sandy, often silty clay, and clay samples from the various confining units and "low-permeability" beds in the aquifers (Ref. 103). The results are presented in Table 1.4-19. The generally accepted value of effective porosity used in the study to determine vertical-flow velocities is 5% for the clay to sandy clay beds (Ref. 116) and 12% for the clayey sand beds (Ref. 117).

Recharge to the Upper Three Runs aquifer occurs at the water-table by infiltration downward from the land surface. In the "upper" aquifer zone, part of this groundwater moves laterally toward the bounding streams while part moves vertically downward. The generally low vertical hydraulic conductivities of the "upper" aquifer zone and the intermittent occurrence of the "tan clay" confining zone retard the downward flow of water, producing vertical hydraulic-head gradients in the "upper" aquifer zone and across the "tan clay" confining zone.

Downward hydraulic-head differences in the "upper" aquifer zone vary from 1.4 to 1.64 meters (4.5 to 5.4 feet), and differences across the "tan clay" are as much as 6.5 meters (15.8 feet) in H Area. At other locations in the General Separations Area, the head difference across the "tan clay" confining zone is only 0.3 to 1 meter (0.1 to 3.2 feet), essentially what might be expected due simply to low vertical flow in a clayey sand aquifer. Therefore, the ability of the "tan clay" confining zone to impede water flow varies greatly over the General Separations Area.

Groundwater leaking downward across the "tan clay" confining zone recharges the "lower" aquifer zone of the Upper Three Runs aquifer. Most of this water moves laterally toward the bounding streams; the remainder flows vertically downward across the Gordon confining unit into the Gordon aquifer. All groundwater moving toward Upper Three Runs Creek leaks through the Gordon confining unit or enters small streams. Vertical hydraulic-head differences in the "lower" aquifer zone range from 0.5 to 1 meter (1.5 to 3.2 feet) in H Area and indicate some vertical resistance to flow.

Gordon Confining Unit

Clayey sand and clay of the Warley Hill Formation and clayey, micritic limestone of the Blue Bluff Member of the Santee Limestone constitute the Gordon confining unit. The Gordon confining unit separates the Gordon aquifer from the overlying Upper Three Runs aquifer. The unit has been informally termed the "green clay" in previous SRS reports.

In the study area, the thickness of the Gordon confining unit ranges from about 1.5 to 26 meters (5 to 85 feet). The unit thickens to the southeast. From Upper Three Runs Creek to the vicinity of L Lake and Par Pond, the confining unit generally consists of one or more thin clay beds, sandy mud beds, and sandy clay beds intercalated with subordinate layers and lenses of quartz sand, gravelly sand, gravelly muddy sand, and calcareous mud. Southward from L Lake and Par Pond, however, the unit undergoes a stratigraphic facies change to clayey micritic limestone and limey clay typical of the Blue Bluff Member. The fine-grained carbonates and carbonate-rich muds constitute the farthest updip extent of the "middle confining unit" of the Floridan Aquifer System (the hydrostratigraphic equivalent of the Gordon confining unit), which dominates in coastal areas of South Carolina and Georgia.

North of the updip limit of the Gordon confining unit, the fine-grained clastics of the Warley Hill Formation are thin, intermittent, and no longer effective in regionally separating groundwater flow. Here, the Steed Pond aquifer is defined. Although thin and intermittent, the clay, sandy clay, and clayey sand beds of the Warley Hill Formation can be significant at the site-specific level and often divide the Steed Pond aquifer into aquifer zones.

The values for hydraulic conductivity obtained from the Gordon confining unit are comparable to the average vertical hydraulic-conductivity values of clayey sand 2.71×10^{-3} m/day (8.9×10^{-3} ft/day) and sandy clay to clay 5.09×10^{-5} m/day (1.7×10^{-4} ft/day) calculated for 83 samples analyzed in the Tertiary/Cretaceous section. Selected parameters determined for the unit are listed in Table 1.4-20.

Gordon Aquifer Unit

The Gordon aquifer consists of all the saturated strata that occur between the Gordon confining unit and the Crouch Branch confining unit in both the Floridan - Midville Aquifer System and the Meyers Branch confining system. The aquifer is semiconfined, with a downward potential from the overlying Upper Three Runs aquifer observed in interfluvial areas, and an upward potential observed along the tributaries of the Savannah River where the Upper Three Runs

aquifer is incised. The thickness of the Gordon aquifer ranges from 12 meters (38 feet) at well P-4A to 56 meters (185 feet) at well C-6 (see Figure 1.4-21) and generally thickens to the east and southeast. Thickness variations in the confining lithologies near the Pen Branch Fault suggest depositional effects owing to movements on the fault in early Eocene time. The Gordon aquifer is partially eroded near the Savannah River and Upper Three Runs Creek. The regional potentiometric map of the Gordon aquifer (see Figure 1.4-25) indicates that major deviations in the flow direction are present where the aquifer is deeply incised by streams that drain water from the aquifers.

The Gordon aquifer is characterized by the hydraulic properties of the sediments penetrated in reference well P-27 located near the center of SRS. The unit is 23 meters (75.5 feet) thick in well P-27 and occurs from 38 to 15 meters (125 to 48 feet) msl. The aquifer consists of the sandy parts of the Snapp Formation and the overlying Fourmile and Congaree Formations (see Figure 1.4-18). Clay beds and stringers are present in the aquifer, but they are too thin and discontinuous to be more than local confining beds. The aquifer in wells P-21 and P-22 (see Figure 1.4-25) includes a clay bed that separates the Congaree and Fourmile Formations. The clay bed appears sufficiently thick and continuous to justify splitting the Gordon aquifer into zones in the southeastern quadrant of SRS.

Downdip, the quartz sand of the Gordon aquifer grades into quartz-rich, fossiliferous lime grainstone, packstone, and wackestone, which contain considerably more glauconite than the updip equivalents. Porosity of the limestone as measured in thin-section ranges from 5 to 30 percent and is mostly moldic and vuggy.

South of SRS, near well ALL-324 (see Figure 1.4-21), the Gordon aquifer consists of interbedded glauconitic sand and shale, grading to sandy limestone. Farther south, beyond well C-10, the aquifer grades into platform limestone of the Lower Floridan aquifer of the carbonate phase of the Floridan Aquifer System.

The Gordon aquifer is recharged directly by precipitation in the outcrop area and in interstream drainage divides in and near the outcrop area. South of the outcrop area, the Gordon is recharged by leakage from overlying and underlying aquifers. Because streams such as the Savannah River and Upper Three Runs Creek cut through the aquifers of the Floridan Aquifer System, they represent no-flow boundaries. As such, water availability or flow patterns on one side of the boundary (stream) will not change appreciably due to water on the other side. In the central part of SRS, where the Gordon confining unit is breached by faulting, recharge to the Gordon aquifer is locally increased (Ref. 100).

Most of the Gordon aquifer is under confined conditions, except along the fringes of Upper Three Runs Creek (i.e., near the updip limit of the Gordon Confining Unit) and the Savannah River. The potentiometric-surface map of the aquifer (see Figure 1.4-25) shows that the natural discharge areas of the Gordon aquifer at SRS are the swamps and marshes along Upper Three Runs Creek and the Savannah River. These streams dissect the Floridan Aquifer System, resulting in unconfined conditions in the stream valleys and probably in semiconfined (leaky) conditions near the valley walls. Reduced head near Upper Three Runs Creek induces upward flow from the Crouch Branch aquifer and develops the "head reversal" that is an important aspect of the SRS hydrogeological system (see Figure 1.4-20). The northeast-southwest oriented

hydraulic gradient across SRS is consistent and averages 0.9 m/km (4.8 ft/mi). The northeastward deflection of the contours along the Upper Three Runs Creek indicates incisement of the sediments that constitute the aquifer by the creek.

Hydraulic characteristics of the Gordon are less variable than those noted in the Upper Three Runs aquifer. Selected parameters are given in Table 1.4-21. Hydraulic conductivity decreases downdip near well C-10 owing to poor sorting, finer grain size, and an increase in clay content.

Floridan - Dublin Aquifer System

Over most of the study area, the Meyers Branch confining system extends north of the Allendale confining system, hydraulically isolating the Floridan from the underlying Dublin and Dublin-Midville systems (see Figures 1.4-18 and 1.4-23). However, in a small region in the eastern part of the study area near well C-5, clay beds of the Meyers Branch confining system thin dramatically, leakance values increase, and the Floridan and Dublin Aquifer Systems are in overall hydraulic communication. In this region, the Floridan and Dublin Aquifer Systems coalesce to form the Floridan-Dublin Aquifer System (see Figure 1.4-23). Thick, continuous clay beds in the underlying Allendale confining system continue to hydrogeologically isolate the Midville and Floridan-Dublin Aquifer Systems.

The Floridan-Dublin Aquifer System is divided into three aquifers in the study area. In descending order, these include the Upper Three Runs, Gordon, and Crouch Branch aquifers separated by the Gordon and Crouch Branch confining units (see Figures 1.4-18 and 1.4-22). The Upper Three Runs and Gordon aquifers coalesce updip forming the Steed Pond aquifer. The Crouch Branch aquifer is continuous across the entire study area.

The Floridan-Dublin Aquifer System is defined by the hydrogeologic properties of sediments penetrated in well C-5 located north of the town of Barnwell. Here, the system is 171 meters (560 feet) thick and includes all sediments from the water-table to the top of the McQueen Branch confining unit. The Upper Three Runs aquifer is 44 meters (144 feet) thick and consists entirely of sand. The Gordon aquifer is 33 meters (108 feet) thick and consists of two sand beds that total 32 meters (105 feet). The Crouch Branch aquifer is 74 meters (244 feet) thick and consists of two sand beds that total 70 meters (230 feet).

Floridan - Midville Aquifer System

Northwest of Upper Three Runs Creek, the permeable beds that correspond to the Floridan and Dublin-Midville Aquifer Systems are often in hydrologic communication owing to the thin and laterally discontinuous character of the intervening clay and silty clay beds, to faulting that breaches the confining beds, and to erosion by the local stream systems that dissect the interval. Here, the Floridan and Dublin-Midville Aquifer Systems coalesce to form the Floridan - Midville Aquifer System (see Figures 1.4-18, -22, -23).

The Floridan-Midville Aquifer System is divided into three aquifers: in descending order, the Steed Pond aquifer, the Crouch Branch aquifer, and the McQueen Branch aquifer, separated by the Crouch Branch and McQueen Branch confining units. Both the Crouch Branch and the

McQueen Branch aquifers extend northwestward from the southern part of SRS. The Steed Pond aquifer is the updip hydrostratigraphic equivalent of the Gordon and Upper Three Runs aquifer units (see Figure 1.4-22). At the northern fringe of the study area, the Steed Pond and underlying Crouch Branch aquifers coalesce and a single, yet unnamed, aquifer unit is present.

The Floridan-Midville Aquifer System is defined by the hydrogeologic properties of the sediments penetrated in the GCB-1 type well located in the A/M Area in the northwest corner of SRS (see Figure 1.4-21). Near GCB-1, the system is 170 meters (557 feet) thick and includes all sediments from the water-table to the top of the Appleton confining system. The Steed Pond aquifer is 30 meters (97 feet) thick at the GCB-1 well and consists of 26 meters (86 feet) of sand in four beds. The Crouch Branch aquifer is 51 meters (167 feet) thick and consists of 42 meters (139 feet) of sand in four beds. It is overlain by the Crouch Branch confining unit, which is 25 meters (81 feet) thick and consists of 9 meters (31 feet) of clay in four beds. The McQueen Branch aquifer is 52 meters (169 feet) thick and consists of 45 meters (147 feet) of sand in three beds. The McQueen Branch confining unit is 13 meters (43 feet) thick and consists of 9 meters (28 feet) of clay in two beds.

Steed Pond Aquifer Unit

North of Upper Three Runs Creek where the Floridan - Midville Aquifer System is defined, the permeable beds that correspond to the Gordon and Upper Three Runs aquifers of the Floridan Aquifer System are only locally separated, owing to the thin and intermittent character of the intervening clay beds of the Gordon confining unit (Warley Hill Formation) and to erosion by the local stream systems that dissect the interval. Here, the aquifers coalesce to form the Steed Pond aquifer of the Floridan-Midville Aquifer System.

The Steed Pond aquifer is defined by hydrogeologic characteristics of sediments penetrated in well MSB-42 located in A/M Area in the northwest corner of SRS. The aquifer is 29.6 meters (97 feet) thick. Permeable beds consist mainly of subangular, coarse- and medium-grained, slightly gravelly, submature quartz sand and clayey sand (Ref. 118). Locally, the Steed Pond aquifer can be divided into zones. In A/M Area three zones are delineated, the "Lost Lake" zone, and the overlying "M Area" aquifer zones, separated by clay and clayey sand beds of the "green clay" confining zone (Ref. 119).

In A/M Area, water enters the subsurface through precipitation, and recharge into the "M-Area" aquifer zone occurs at the water-table by infiltration downward from the land surface. A groundwater divide exists in the A/M Area in which lateral groundwater flow is to the southeast towards Tims Branch and southwest towards Upper Three Runs Creek and the Savannah River floodplain. Groundwater also migrates downward and leaks through the "green clay" confining zone into the "Lost Lake" aquifer (Ref. 119). The "green clay" confining zone that underlies the "M-Area" aquifer zone is correlative with the Gordon confining unit south of Upper Three Runs Creek (Ref. 119).

Meyers Branch Confining System

The Meyers Branch confining system separates the Floridan Aquifer System from the underlying Dublin and Dublin-Midville Aquifer Systems (see Figures 1.4-18 and 1.4-22). North of the updip limit of the confining system, the Floridan and Dublin-Midville Aquifer Systems are in hydraulic communication and the aquifer systems coalesce to form the Floridan-Midville Aquifer System (Figure 1.4-23).

Sediments of the Meyers Branch confining system correspond to clay and interbedded sand of the uppermost Steel Creek Formation, and to clay and laminated shale of the Sawdust Landing/Lang Syne and Snapp Formations (see Figure 1.4-18). In the northwestern part of the study area, the sediments that form the Meyers Branch confining system are better sorted and less silty, with thinner clay interbeds. This is the updip limit of the Meyers Branch confining system (see Figure 1.4-22).

Crouch Branch Confining Unit

In the SRS area, the Meyers Branch confining system consists of a single hydrostratigraphic unit, the Crouch Branch confining unit, which includes several thick and relatively continuous (over several kilometers) clay beds. The Crouch Branch confining unit extends north of the updip limit of the Meyers Branch confining system where the clay thins and is locally absent and faulting observed in the region locally breaches the unit. Here, the Crouch Branch confining unit separates the Steed Pond aquifer unit from the underlying Crouch Branch aquifer unit. Downdip, generally south of the study area, the Meyers Branch confining system could be further subdivided into aquifer and confining units if this should prove useful for hydrogeologic characterization.

As indicated earlier (see Figure 1.4-20), a hydraulic-head difference persists across the Crouch Branch confining unit near SRS. Owing to deep incisement by the Savannah River and Upper Three Runs Creek into the sediments of the overlying Gordon aquifer, an upward hydraulic gradient (vertical-head reversal) persists across the Crouch Branch confining unit over a large area adjacent to the Savannah River floodplain and the Upper Three Runs Creek drainage system. This "head reversal" is an important aspect of the groundwater flow system near SRS and provides a natural means of protection from contamination of the lower aquifers.

The total thickness of the Crouch Branch confining unit where it constitutes the Meyers Branch confining system ranges from 17.4 to 56.1 meters (57 to 184 feet). Updip, the thickness of the Crouch Branch confining unit ranges from < 1 to 31.7 meters (3.3 to 104 feet). The confining unit dips approximately 5 m/km (16 ft/mi) to the southeast. The confining unit is comprised of the "upper" and "lower" confining zones, which are separated by a "middle sand" zone.

In general, the Crouch Branch confining unit contains two to seven clay to sandy clay beds separated by clayey sand and sand beds that are relatively continuous over distances of several kilometers. The clay beds in the confining unit are anomalously thin and fewer in number along a line that parallels the southwest-northeast trend of the Pen Branch and Steel Creek Faults and the northeast southwest trending Crackerneck Fault (Ref. 100). The reduced clay content near

the faults suggests shoaling due to uplift along the faults during deposition of the Paleocene Black Mingo Group sediments.

In A/M Area, the Crouch Branch confining unit can often be divided into three zones: an "upper clay" confining zone is separated from the underlying "lower clay" confining zone by the "middle sand" aquifer zone. The "middle sand" aquifer zone consists of very poorly sorted sand and clayey silt of the Lang Syne/Sawdust Landing Formations. The "middle sand" aquifer zone has a flow direction that is predominantly south/southwest toward Upper Three Runs Creek (Ref. 120).

In places, especially in the northern part of A/M Area, "upper clay" confining zone is very thin or absent. Here, only the "lower clay" confining zone is capable of acting as a confining unit and the "middle sand" zone is considered part of the Steed Pond aquifer. Similarly, when the clay beds of the "lower clay" confining zone are very thin or absent, the "middle sand" aquifer zone is considered part of the Crouch Branch aquifer unit. This is the case in the far northeastern part of the study area.

The "lower clay" confining zone has been referred to as the lower Ellenton clay, the Ellenton clay, the Peedee clay, and the Ellenton/Peedee clay in previous SRS reports. It consists of the massive clay bed that caps the Steel Creek Formation. The zone is variable in total thickness and, based on 31 wells that penetrate the unit, ranges from 1.5 to 19 meters (5 to 62 feet) and averages 7.3 meters (24 feet) thick.

Dublin Aquifer System

The Dublin Aquifer System is present in the southeastern half of SRS and consists of one aquifer, the Crouch Branch aquifer. It is underlain by the Allendale confining system and overlain by the Meyers Branch confining system (see Figures 1.4-18 and 1.4-22). The updip limit of the Dublin Aquifer System in the study area corresponds to the updip limit of the Allendale confining system. North of this line, the Dublin-Midville Aquifer System is defined.

The thickness of the Dublin Aquifer System generally increases toward the south and ranges from approximately 53 to 88 meters (175 to 290 feet). The top of the unit dips 3.79 m/km (20 ft/mi) to the southeast. The unit thins to the east toward the Salkehatchie River and to the west toward Georgia. Near the updip limit of the system, thicknesses are variable and probably reflect the effects of movement along the Pen Branch Fault during deposition of the middle Black Creek clay.

The Dublin Aquifer System was defined and named by Clarke et al. (Ref. 121) for sediments penetrated by well 21-U4 drilled near the town of Dublin in Laurens County, Georgia. The upper part of the Dublin Aquifer System consists of fine to coarse sand and limestone of the lower Huber-Ellenton unit. Comparable stratigraphic units serve as confining beds in the SRS area and are considered part of the overlying Meyers Branch confining system. Clarke et al. (Ref. 21) noted that to the east near the Savannah River, clay in the upper part of the lower Huber-Ellenton unit forms a confining unit that separates an upper aquifer of Paleocene age from a lower aquifer of Late Cretaceous age. The upper aquifer of Clarke et al. (Ref. 121) is the Gordon aquifer as defined in the study, and their confining unit constitutes the Meyers Branch confining system of

the SRS region. The lower part of the Dublin Aquifer System consists of alternating layers of clayey sand and clay of the Peedee-Providence unit.

Sediments typical of the Dublin Aquifer System are penetrated in the reference well P-22 (see Figure 1.4-21). The system consists of the well-sorted sand and clayey sand of the Black Creek Formation and the moderately sorted sand and interbedded sand and clay of the Steel Creek Formation. The aquifer is overlain by the clay beds that cap the Steel Creek Formation. These clay beds constitute the base of the Meyers Branch confining system.

The Dublin Aquifer System is 65 meters (213 ft) thick in well P-22; the top is at an elevation of -68 meters (-223 feet) msl and the bottom at -133 meters (-436 feet) msl. The Dublin includes five clay beds in this well.

In the southern part of the study area and farther south and east, the Dublin shows much lower values for hydraulic conductivity and transmissivity, probably due to the increase of fine-grained sediments toward the coast (Ref. 122).

Dublin - Midville Aquifer System

The Dublin-Midville Aquifer System underlies the central part of SRS. The system includes all the sediments in the Cretaceous Lumbee Group from the Middendorf Formation up to the sand beds in the lower part of the Steel Creek Formation (see Figure 1.4-18). The system is overlain by the Meyers Branch confining system and underlain by the indurated clayey silty sand and silty clay of the Appleton confining system. The updip limit of the system is established at the updip pinchout of the overlying Meyers Branch confining system (see Figure 1.4-22). The downdip limit of the Dublin-Midville is where the Allendale becomes an effective confining system (see Figure 1.4-22). The Dublin-Midville and the updip Floridan-Midville Aquifer Systems were referred to as the Tuscaloosa aquifer by Siple (Ref. 123).

The thickness of the Dublin-Midville Aquifer System ranges from approximately 76 to 168 meters (250 to 550 feet). The dip of the upper surface of the system is about 3.8 m/km (20 ft/mi) to the southeast. Near the downdip limit of the system, thicknesses are variable and probably reflect the effects of movement along the Pen Branch Fault. Shoaling along the fault trace resulted in a relative increase in the thickness of the aquifers at the expense of the intervening confining unit.

The Dublin-Midville Aquifer System includes two aquifer units, the McQueen Branch aquifer, and the Crouch Branch aquifer, separated by the McQueen Branch confining unit. The two aquifers can be traced northward, where they continue to be an integral part of the Floridan-Midville Aquifer System and southward where they constitute the aquifer units of the Midville and Dublin Aquifer Systems, respectively.

The Dublin-Midville Aquifer System is defined at the type well P-27. Here, the system is 153 meters (505 feet) thick and occurs from -25 meters (-82 feet) msl to -179 meters (-587 feet) msl. It consists of medium- to very coarse-grained, silty sand of the Middendorf Formation and clayey, fine to medium sand and silty clay beds of the Black Creek Formation (Ref. 118).

The system includes a thick clay bed, occurring from -100 meters (-329 feet) msl to -117 meters (-384 feet) msl, which constitutes the McQueen Branch confining unit.

A regional potentiometric surface map prepared by Siple (Ref. 123) for his "Tuscaloosa aquifer," indicates that the Savannah River has breached the Cretaceous sediments and is a regional discharge area for the Floridan-Midville Aquifer System, the Dublin-Midville Aquifer System, and the updip part of both the Dublin and Midville Aquifer Systems (Ref. 124). The Savannah River, therefore, represents a no-flow boundary preventing the groundwater in these aquifer systems from flowing southward into Georgia.

Crouch Branch Aquifer Unit

The Crouch Branch aquifer constitutes the Dublin Aquifer System in the southern part of the study area. Farther south, the Dublin can be subdivided into several aquifers and confining units. In the central part of the study area, the Crouch Branch aquifer is the uppermost of the two aquifers that constitute the Dublin-Midville Aquifer System. Farther north in the northwestern part of SRS and north of the site, the Crouch Branch aquifer is the middle aquifer of the three aquifers that constitute the Floridan-Midville Aquifer System.

The Crouch Branch aquifer is overlain by the Crouch Branch confining unit and is underlain by the McQueen Branch confining unit. It persists throughout the northern part of the study area, but near the updip limit of the Coastal Plain sedimentary clastic wedge, the Crouch Branch confining unit ceases to be effective and the Crouch Branch aquifer coalesces with the Steed Pond aquifer.

The Crouch Branch aquifer ranges in thickness from about 30 to 107 meters (100 to 350 feet). Thickness of the unit is variable near the updip limit of the Dublin Aquifer System where sedimentation was affected by movement along the Pen Branch Fault. The reduced clay content in this vicinity suggests shoaling due to uplift along the fault during Late Cretaceous and Paleocene time, resulting in the deposition of increased quantities of shallow-water, coarse-grained clastics along the crest of the fault trace. The sandy beds act hydrogeologically as part of the Crouch Branch aquifer, resulting in fewer and thinner, less persistent clay beds in the overlying and underlying confining units.

The Crouch Branch aquifer thins dramatically in the eastern part of the study area at the same general location where the underlying McQueen Branch confining unit and the overlying Crouch Branch confining unit thicken at the expense of Crouch Branch sand. Clay beds in the Crouch Branch aquifer generally thicken in the same area and constitute as much as 33 percent of the unit at the well C-6 (see Figure 1.4-21).

Sediments of the Crouch Branch aquifer are chiefly sand, muddy sand, and slightly gravelly sand intercalated with thin, discontinuous layers of sandy clay and sandy mud. Hydraulic conductivity of the Crouch Branch aquifer, determined from eleven pumping tests by Siple (Ref. 123) and from analyses made by GeoTrans (Ref. 125), ranges from 8.5 to 69 m/day (28 to 227 ft/day). Comparatively high hydraulic conductivity occurs in a northeast-southwest trending region connecting D Area, Central Shops, and R Area and defines a "high permeability" zone in the aquifer. Here, hydraulic conductivities range from 36 to 69 m/day (117 to 227 ft/day). The "high

permeability" zone parallels the trace of the Pen Branch Fault, and reflects changing depositional environments in response to movement along the fault as described above. South of the trace of the Pen Branch Fault, hydraulic conductivity for the aquifer reflects the return to a deeper water shelf/deltaic depositional regime. A potentiometric map for the Crouch Branch Aquifer is presented in Figure 1.4-26.

Allendale Confining System

The Allendale confining system is present in the southeastern half of the study area and separates the Midville Aquifer System from the overlying Dublin Aquifer System (see Figure 1.4-18). In the study area, the Allendale confining system consists of a single unit, the McQueen Branch confining unit. The confining system is correlative with the unnamed confining unit that separates the Middendorf and Black Creek aquifers of Aucott et al. (Ref. 122) and with the Black Creek-Cusseta confining unit of Clark et al. (Ref. 121). The system dips approximately 6.7 m/km (27 ft/mi) to the southeast and thickens uniformly from about 15.2 meters (50 feet) at the updip limit to about 61 meters near the eastern boundary of the study area. The rate of thickening is greater in the east than in the west. The updip limit of this confining system is established where pronounced thinning occurs parallel to the Pen Branch Fault.

Sediments of the Allendale confining system are fine grained and consist of clayey, silty sand, clay, and silty clay and micritic clay beds that constitute the middle third of the Black Creek Formation. North of the updip limit of the confining system, where the McQueen Branch confining unit is part of the Dublin-Midville Aquifer System, the section consists of coarser-grained, clayey, silty sand and clay beds.

McQueen Branch Confining Unit

The McQueen Branch confining unit is defined by the hydrogeologic properties of the sediments penetrated in well P-27 (see Figure 1.4-21). At its type-well location, the McQueen Branch confining unit is 17 meters (55 feet) thick, and is present from -100 to -117 meters (-329 to –384 feet) msl. Total clay thickness is 14 meters (45 feet) in three beds, which is 82% of the total thickness of the unit, with a leakance coefficient of 3.14×10^{-6} m/day (1.03×10^{-5} ft/day). The confining unit in well P-27 consists of the interbedded, silty, often sandy clay and sand beds that constitute the middle third of the Black Creek Formation.

The clay beds tend to be anomalously thin along a line that parallels the southwest-northeast trend of the Pen Branch Fault and the north-south trend of the Atta Fault (Ref. 126). The reduced clay content in these areas suggests shoaling due to uplift along the faults during Upper Black Creek-Steel Creek time.

Midville Aquifer System

The Midville Aquifer System is present in the southern half of the study area; it overlies the Appleton confining system and is succeeded by the Allendale confining system. In the study area, the Midville Aquifer System consists of one aquifer, the McQueen Branch aquifer unit.

South of well C-10 (see Figure 1.4-21), the system may warrant further subdivision into several aquifers and confining units. Thickness of the unit ranges from 71 meters (232 feet) at well P-21 to 103 meters (339 feet) at well C-10. Variation in the thickness of the unit, as well as the updip limit of the system, results from variation in the thickness and persistence of clay beds in the overlying Allendale confining system. Near the Pen Branch Fault, contemporaneous movement on the fault may have resulted in shoaling in the depositional environment, which is manifested in a thickening of the sands associated with the Midville Aquifer System. The upper surface of the aquifer system dips approximately 4.73 m/km (25 ft/mi) to the southeast across the study area.

The Midville Aquifer System was defined and named by Clarke et al. (Ref. 121) for the hydrogeologic properties of the sediments penetrated in well 28-X1, near the town of Midville in Burke County, Georgia. Here, the upper part of the aquifer system consists of fine to medium sand of the lower part of the Black Creek-Cusseta unit. The Midville is comparable to the lower portion of the Chattahoochee River aquifer of Miller and Renken (Ref. 104) and correlative with the Middendorf aquifer of Aucott and Sperian (Ref. 127).

McQueen Branch Aquifer Unit

The McQueen Branch aquifer unit occurs beneath the entire study area. It thickens from the northwest to the southeast and ranges from 36 meters (118 feet) at well AIK-858 to 103 meters (339 feet) at well C-10 to the south. Locally, thicknesses are greater along the trace of the Pen Branch Fault because of the absence and/or thinning of clay beds that compose the overlying McQueen Branch confining unit. The upper surface of the McQueen Branch dips approximately 4.7 m/km (25 ft/mi) to the southeast.

The McQueen Branch aquifer unit is defined for the hydrogeologic properties of sediments penetrated by well P-27 near the center of the study area. Here, it is 62 meters (203 feet) thick and occurs from -117 to -180 meters (-384 to –587 feet) msl. It contains 56 meters (183 feet) of sand in four beds, (which is 90% of the total thickness of the unit). The aquifer consists of silty sand of the Middendorf Formation and clayey sand and silty clay of the lower one-third of the Black Creek Formation (Ref. 118). Typically, a clay bed or several clay beds that cap the Middendorf Formation are present in the aquifer. These clay beds locally divide the aquifer into two aquifer zones.

Eight pumping tests of the McQueen Branch aquifer were made in F and H Areas, in the central part of the study area (Ref. 123). Hydraulic-conductivity values ranged from 16 to 64 m/day (53 to 210 ft/day) and averaged 36 m/day (18 ft/day). Three pumping tests of the aquifer were reported by GeoTrans: two in F Area and one in L Area (Ref. 128). Hydraulic conductivity ranged from 13 to 88 m/day (41 to 290 ft/day) in F Area and was 28 m/day (93 ft/day) in L Area.

Appleton Confining System

The Appleton confining system is the lowermost confining system of the Southeastern Coastal Plain hydrogeologic province and separates the province from the underlying Piedmont hydrogeologic province. It is equivalent to the Black Warrior River aquifer of Miller and Renken

(1988) and to the basal unnamed confining unit of Aucott et al. (Ref. 122). The confining system is essentially saprolite of the Paleozoic and Mesozoic basement rocks and indurated, silty and sandy clay beds, silty clayey sand and sand beds of the Cretaceous Cape Fear Formation. Thickness of saprolite ranges from 2 to 14 meters (6 to 47 feet), reflecting the degree of weathering on the basement unconformity prior to deposition of the Cape Fear terrigenous clastics. Thickness of saprolite determined from the Deep Rock Borings study (DRB wells) ranges from 9 to 30 meters (30 to 97 feet) and averages 12 meters (40 feet) in wells DRB-1 to DRB-7 (Ref. 128). In the northern part of the study area, the Cape Fear Formation pinches out and the Appleton consists solely of saprolite.

Some variability in thickness is noted along the trace of the Pen Branch Fault. It dips at about 5.9 m/km (31 ft/mi) to the southeast and thickens from 4.6 meters (15 feet) in well C-2 near the north end of the study area to 22 meters (72.2 feet) in well C-10 in the south. Sediments of the confining system do not crop out in the study area. Thinning of the Appleton confining system in well PBF-2 (see Figure 1.4-21) is probably a result of truncation of the section by the Pen Branch Fault.

The confining system consists of a single confining unit throughout the study area. Toward the coast, however, the Appleton confining system thickens considerably and includes several aquifers (Ref. 121). The aquifers included in the confining system in the downdip region are poorly defined because few wells penetrate them. They are potentially water producing but the depth and generally poor quality of water in the aquifers probably precludes their utilization in the foreseeable future (Ref. 122). The Appleton confining system includes no aquifer units or zones in the northern and central parts of the study area.

Fine- to coarse-grained sand beds, often very silty and clayey, occur in the upper part of the Cape Fear Formation in the southern part of the study area. The sand appears to be in communication with sand of the overlying McQueen Branch Aquifer System and is included with that unit.

HYDROGEOLOGY OF THE PIEDMONT PROVINCE

The basement complex, designated the Piedmont hydrogeologic province in this report, consists of Paleozoic crystalline rocks, and consolidated to semiconsolidated Upper Triassic sedimentary rocks of the Dunbarton basin. All have low permeability (Ref. 129). The hydrogeology of the province was studied intensively at SRS to assess the safety and feasibility of storing radioactive waste in these rocks (Ref. 130-134). The upper surface of the province dips approximately 11 m/km (36 ft/mi) to the southeast. Origins of the crystalline and sedimentary basement rocks are different, but their hydraulic properties are similar. The rocks are massive, dense, and practically impermeable except where fracture openings are encountered. Water quality in these units is also similar. Both contain water with high alkalinity and high levels of calcium, sodium, sulfate, and chloride. The low aquifer permeability and poor water quality in the Paleozoic and Triassic rocks render them undesirable for water supply in the study area.

1.4.2.3 Area Hydrogeology (Selected Savannah River Site Operations Areas)

The following section focuses on the general hydrogeology of selected operations areas at SRS. The operations areas selected are those that include facilities that require a SAR. The most detailed information for any facility is discussed in its facility-specific SAR.

In general, updated hydrogeological data and descriptions of facility-specific hydrostratigraphy are included in reports of field investigations at or near the facility of interest. These reports may include Resource Conservation and Recovery Act (RCRA) Part B Applications, RCRA Facility Investigations/Remedial Investigations or Baseline Risk Assessments, environmental assessments of various kinds, or other field investigation reports. Field activities at the various site facilities are reported in the annual SRS Environmental Report (Ref. 20).

AREA HYDROGEOLOGICAL CHARACTERISTICS - GENERAL SEPARATIONS AREAS

The General Separations Area as defined herein includes F Area, E Area, H Area, S Area, and Z Area. In the past, the focus of facilities in this area has been on chemical separations; changes in the site mission have impacted operations in the General Separations Area, including the construction and startup of Tritium Facilities and various waste management facilities (DWPF, E-Area Vaults and the CIF).Water Usage

Water usage at the F Area/E Area facilities varies from year to year and is a function of increased or decreased site activities. Current data for pumping in F Area/E Area is reported in the SRS Annual Environmental Report (Ref. 20). To date, operation of production water wells has not caused subsidence of the F-Canyon foundation nor influenced potential contaminant flow paths in the post-Cretaceous aquifers.

Hydrogeologic Setting

The General Separations Area sits above a water-table ridge, defined on the south by Fourmile Branch and on the north and west by Upper Three Runs Creek (see Figure 1.4-27). The ridge is dissected on the northern flank by Crouch Branch (between E Area and H Area) and McQueen Branch (east of Z Area). Thus, the facilities lie above minor groundwater divides; flow at the water-table is generally away from the facilities and toward the nearest surface water (Ref. 100). The majority of water that reaches the water-table beneath the General Separations Area is discharged into either Upper Three Runs Creek (or its tributaries) or Fourmile Branch.

In general, there is very limited downward migration of groundwater across the Meyers Branch confining system beneath the General Separations Area. Therefore, the hydrostratigraphic units linked to General Separations Area operations are the Upper Three Runs Aquifer (the water-table aquifer), the Gordon confining unit, and the Gordon aquifer unit. A discussion of the hydraulic properties and hydraulic gradients for these units is included above under the "Southeastern Coastal Plain Hydrogeologic Province" section. This discussion is pertinent because only limited data are available from outside the General Separations Area; thus, the data can be used to characterize conditions beneath the General Separations Area.

Hydraulic conductivity values for the Upper Three Runs, Gordon, and Steed pond aquifers are presented in Table 1.4-22. Typically, data from short-duration single well tests and slug tests are the best representative of the true hydraulic parameters for a hydrogeologic unit (Ref. 100). If available, these data should be used for calculating groundwater flow velocity, contaminant migration, and other pertinent hydraulic properties.

1.4.2.4 Groundwater Chemistry

REGIONAL GROUNDWATER CHEMISTRY

SRS groundwater quality samples are collected quarterly, and the data, as well as interpreted results, are presented in the Annual SRS Environmental Report (Ref. 20). For illustrative purposes, Table 1.4-23 presents a set of water analyses from sources within SRS and vicinity. The location of industrial and municipal groundwater users near SRS are shown in Figure 1.4-29. The pumpages are tabulated in Table 1.4-24.

An investigation of the geochemistry of the water residing in the principal aquifer units at SRS was undertaken as part of the Baseline Hydrologic Investigation (Ref. 103). This study investigated the effects of the mineralogy of the aquifer materials, source of the water, and the effect of biological activity on the evolution and chemistry of the groundwater. Groundwater chemistry and geologic data utilized for this study were obtained from monitoring wells and core samples collected during drilling activities. The majority of the ensuing discussions were adapted directly from this report.

The primary source of groundwater at the SRS is precipitation. As the water migrates away from the source or recharge area, it experiences a decrease of pH and an increase in total dissolved solids. In addition, the overall chemistry changes as it encounters different aquifer material. The primary recharge areas for the deeper aquifers in the SRS vicinity are located near the fall line or Coastal Plain onlap. From there, the groundwater migrates in a general southwest direction. The extent to which the local discharge and recharge areas impact the groundwater chemistry is dependent upon the depth of a particular aquifer system below ground surface and the overall aquifer material. Recharge for the water-table aquifers is derived from local, recent precipitation at the site as evidenced by elevated amounts of short-lived isotopes such as tritium, and the ionic composition of the groundwater.

According to Strom and Kaback (Ref. 137), tritium levels in local precipitation are in excess of the normal background levels for the Northern Hemisphere. Washout from the atmosphere during periods of precipitation has elevated the concentration of rainfall tritium to where pre- and post-1954 rainfall-derived water can clearly be distinguished in groundwater. The year 1954 is significant in that it represents the beginning of Savannah River Plant facility operations.

The impact of rainfall-derived tritium on the groundwater is observed in groundwater resident at depths of less than 61 meters (200 feet).

The ionic composition of the groundwater also clearly reflects a meteoric origin of the water. Chemical data from rainwater collected near SRS exhibit approximately the same ratio of sodium

to chlorine as that in seawater, which is a principal source of atmospheric salts, but higher levels of sulfate and calcium. These latter constituents are commonly contributed to the atmosphere over landmasses by natural biological processes and industrial emissions.

Aquifer Materials

Groundwater principally resides in the pore spaces of the sandy aquifers. In these aquifers, quartz is the dominant mineral. Despite its abundance, its affect on overall water chemistry is negligible due to the low reactivity of this quartz (except in cases of extremely basic pH). The minerals that potentially impact the chemistry of the groundwater are less abundant. Minerals identified by x-ray diffraction and x-ray fluorescence data include feldspars and a host of phyllosilicates (i.e., clays and micas). Other non-silicate minerals such as pyrite, gypsum, barite, calcite, and hematite were also identified, but these are relatively sparse and have little impact on the overall groundwater chemistry. Clay minerals present include kaolinite, smectites and in minor amounts, illite.

Groundwater Chemistry (Hydrochemical Facies)

The evolution of groundwater in the Coastal Plain sediments can be defined from the source or recharge areas down the hydraulic gradient within the aquifer. Although groundwaters at SRS are very dilute, they show significant changes in the levels of dissolved oxygen, redox potential, dissolved trace constituents, and in the major cations and anions present. The variations in these major constituents are useful in delineating the chemical reactions, which occur during the chemical development of the groundwater.

On the northern edge of the site where there is a single aquifer system (see Figure 1.4-23), the waters are of very low total dissolved solids (less than 20 mg/L). They contain high concentrations of dissolved oxygen, have pH lower than 6.0, and are classified as mixed water types (i.e., there are no predominant cations or anions in the water). The confining units that separate the aquifers are only of local extent and the hydraulic gradient is downward from the Tertiary formations into the underlying Cretaceous formations over much of this portion of the site. The Cretaceous aquifer receives recharge from Tertiary units where the confining units are thin or absent.

South of this region, where two or more aquifer systems are present (see Figure 1.4-23), the waters become geochemically distinctive because of bio-geochemical and geochemical interaction with the water and the sediments and buried organic materials. Water samples in both

of the aquifers are shown to have a predominance of calcium-bicarbonate. The presence of calcium-bicarbonate is most frequently attributed to the dissolution of $CaCO_3$. Several reaction mechanisms are known to exist for the dissolution reactions. The dissolution by weak carbonic acid;

$$CaCO_3 + H_2CO_3 \text{ ---> } Ca^{2+} + 2HCO_3^- \qquad \text{(Eq. 1.4-2)}$$

produces two bicarbonate ions per calcium ion whereas the hydrolysis reaction produces a single bicarbonate plus a hydroxyl ion.

$$CaCO_3 + H_2O \text{ ---> } Ca^{2+} + HCO_3^- + OH^- \qquad \text{(Eq. 1.4-3)}$$

In either case, equal amounts of alkalinity are produced by the reaction so that the bicarbonate concentration calculated from alkalinity data in this study are not useful indicators to distinguish the reaction mechanisms. It is probable that both reactions contribute in the Tertiary aquifers. There have not been sufficient ^{13}C isotopic data obtained on these aquifer units or direct measurement of dissolved inorganic carbon to generalize at the present time.

The samples from monitoring wells screened in the Tertiary section at the P-19 well (see Figure 1.4-21) site cluster are anomalous in their water chemistry because they are low in total dissolved solids and show no evidence of having had opportunity to react with carbonates (low alkalinity and moderate pH). This is true of the P-19 wells screened in the Upper Three Runs aquifer and Gordon aquifer. In addition limestones, marls, and clay units are conspicuously absent from the Tertiary section at this locality (Ref. 137) and, therefore, high vertical permeabilities are expected.

The Cretaceous or deeper aquifers (Midville, Dublin, and or Dublin-Midville) south of Upper Three Runs Creek have a somewhat more complex chemistry. Examination of Piper diagrams for these units shows a marked evolution from sulfate-rich waters at low total dissolved solids (TDS) toward bicarbonate-rich waters at higher TDS. The evolution toward calcium-rich waters is not as pronounced as in the Tertiary units. Alkalis (Na+K) are major contributors to the cation compositions, and the waters would be classified as mixed water types or Na+K-HCO_3 waters by Back's classification system. The reaction pathways toward these compositions are complex and not well understood at present.

The calcium in these waters may be derived from several sources, including dissolution of gypsum from confining beds such as the Rhems (Ellenton) Formation, which is the downdip equivalent of the Lang Syne/Sawdust Landing Formation (Ref. 115), the dissolution of calcite or calcium plagioclase, or displacement of calcium by potassium in cation exchange reactions. The alkalis in the Cretaceous aquifer waters are primarily derived from the breakdown of silicate minerals including feldspars, mica, and various clay minerals including illite.

There is no consistent trend in the proportion of potassium to sodium in the waters as total dissolved solids increases. Because potassium is usually the most tightly bound ion in cation exchange reactions, its relative abundance in the samples from McQueen Branch and Crouch Branch aquifer units suggests that cation exchange has not played a dominant role in the evolution of these waters. The exceptions are the samples from well C-10 (see Figure 1.4-21), where sodium is clearly the dominant cation. In this down-gradient locality south of SRS, cation exchange processes have led to water conditions comparable to those formed by exchange processes observed in other regions of the South Carolina Coastal Plain (Ref. 122).

Increases in the HCO_3^- concentration are apparently largely through the microbial oxidation of lignite within the aquifers. The ^{13}C signatures of the water are typically light; in the range of

-0% to -25% . Usually, these light values indicate an organic source of carbon rather than the dissolution of limestone or other inorganic ion source.

Dissolved oxygen is less than 0.1 mg/L for most of the samples from the Dublin-Midville Aquifer System. From Upper Three Runs Creek southward, the aquifers in this system are anaerobic and contain abundant dissolved iron. The iron content in these aquifers is undesirably high, usually between 1 and 5 mg/L. The anaerobic conditions allow the dissolved iron to remain in the ferrous form but have not become reducing to the extent that sulfate has been reduced to the sulfide form.

Chapelle and Loveley (Ref. 138) have described a high-iron groundwater zone in the Middendorf Aquifer (comparable to McQueen Branch), approximately 40 km (124 miles) wide, that extends across South Carolina from SRS to North Carolina approximately paralleling the Fall Line. This high-iron zone is inferred to result from the reduction of iron oxyhydroxide grain coatings by bacteria during the oxidation of organic matter within the confined zones of the aquifer. According to Strom and Kaback (Ref. 137), the activity of the iron-reducing bacteria may inhibit the activity of sulfate-reducing bacteria. Sulfate reduction begins further downgradient after the more easily oxidized organics have been consumed.

AREA GROUNDWATER CHEMISTRY

The following sections focus on the general groundwater chemistry and groundwater use of selected operations areas at SRS. The operations areas selected are those that include facilities that require a SAR. The most detailed information for any facility is discussed in its facility-specific SAR.

Water Chemistry - F and E Areas

A monitoring well network consisting of over 100 wells has been installed to monitor groundwater quality in F Area. Well construction information, including maps showing well location, is provided in the Environmental Protection Department's quarterly well inventory. The most recent sampling information is presented in the quarterly SRS Groundwater Monitoring Report and the SRS Annual Environmental Report (Ref. 20).

The potential local groundwater recharge zone closest to F Canyon is the upland area with downward vertical gradients just to the southeast of F Area. Recharge areas for the Cretaceous aquifers are located outside of the SRS boundary. Table 1.4-25 provides radiological and chemical analyses data from a part of a 16-well monitoring network located near accessible expansion joints beside Building 221-F.

Construction of the F-Area facilities has had no effect on groundwater recharge areas; groundwater had no effect on construction activities.

Water Chemistry - H, S, and Z Areas

The results of the groundwater monitoring program, including background levels and flagging criteria, are discussed in the SRS Annual Environmental Report (Ref. 20).

The potential local groundwater recharge zone closest to H Area is the upland area with downward vertical gradients just to the southeast of H Area. Recharge areas for the Cretaceous aquifers are located outside of the SRS boundary.

Construction of facilities in the H, S, and Z Areas has had no effect on groundwater recharge areas. Groundwater has not affected construction activities. No groundwater injections or withdrawals that would affect the underlying aquifers are planned for this site.

1.4.3 GEOLOGY

1.4.3.1 Regional Geology (320 km [200 mile] Radius)

The following discussion on the regional geology is based on DOE-STD-1022-94 (Ref. 139). The area of interest is a radius of about 320 km (200 miles) from the site. The information also provides the basis for understanding the regional tectonics as applied to SRS.

SRS has conducted many investigations and used extensive literature review to reach the conclusion that there are no geologic threats affecting the SRS, except the Charleston Seismic Zone and the minor random Piedmont earthquakes. These topics are discussed in greater technical detail in Section 1.4.4. Possible threats to groundwater contamination are discussed in Section 1.4.2.

The southeastern continental margin, within a 320-km (200-mile) radius of SRS, contains portions of all the major divisions of the Appalachian orogen (mountain belt) in addition to the elements that represent the evolution to a passive margin.

Within the Appalachian orogen, several lithotectonic terranes that have been extensively documented include the foreland fold belt (Valley and Ridge) and western Blue Ridge Precambrian-Paleozoic continental margin; the eastern Blue Ridge-Chauga Belt-Inner Piedmont terrane; the volcanic-plutonic Carolina Terrane; and the geophysically defined basement terrane beneath the Atlantic Coastal Plain (see Figure 1.4-30) (Ref. 140, 141). These geological divisions record a series of compressional and extensional events that span the Paleozoic. The modern continental margin includes the Triassic-Jurassic rift basins that record the beginning of extension and continental rifting during the early to middle Mesozoic. The offshore Jurassic-Cretaceous clastic-carbonate bank sequence covered by younger Cretaceous and Tertiary marine sediments, and onshore Cenozoic sediments represent a prograding shelf-slope (Ref. 140) and the final evolution to a passive margin. Other offshore continental margin elements include the Florida-Hatteras shelf and slope and the unusual Blake Plateau basin and escarpment (Ref. 142-144).

From the Cumberland Plateau and the Valley and Ridge provinces to the offshore Blake Plateau basin, the regional geology records the complete cycles of opening and closing of Paleozoic oceans and the opening of a new ocean (Atlantic) (Ref. 140). Late Proterozoic rifting is recorded in rift-related sediments at the edge of the frontal Blue Ridge province and the Ocoee and Tallulah Falls basins in the western and eastern Blue Ridge, respectively. Passive margin conditions began in the middle Cambrian and persisted through early Ordovician. The Cambro-Ordovician sedimentary section in the Valley and Ridge reflects this condition. The

collision-accretionary phase of the Appalachians began in the middle Ordovician and persisted with pulses through the early Permian. Mesozoic rifting of the continents led to the creation of Triassic rift basins on the modern eastern continental margin and ultimately to the creation of the Atlantic Ocean basin. The evolution to a passive margin is recorded in the Cretaceous through Holocene Coastal Plain sediments and offshore carbonate bank and shelf sequences.

The two predominant processes sculpting the landscape during this tectonically quiet period included erosion of the newly formed highlands and subsequent deposition of the sediments on the coastal plain to the east. The passive margin region consists of a wedge of Cretaceous and Cenozoic sediments that thicken from near zero at the Fall Line to about 335 meters (1,100 feet) in the center of SRS, and to approximately 1,220 meters (4,000 feet) at the South Carolina coast. The fluvial to marine sedimentary wedge consists of alternating sand and clay with tidal and shelf carbonates common in the downdip Tertiary section.

VALLEY AND RIDGE PROVINCE

The Valley and Ridge Province (see Figure 1.4-30) includes Paleozoic sedimentary rocks consisting of conglomerate, sandstone, shale, and limestone. The shelf sequence was extensively folded and thrust faulted during the Alleghanian collisional event. The physiography is expressed as a series of parallel ridges and valleys that are a result of the erosion of breached anticlines with the oldest layers exposed in the valleys and the younger layers forming the ridges. The topographic expression of the folds is best expressed in the central and southern Appalachians. In the central and northern Appalachians the folded structure is dominant and thrust faults are not as numerous or expressed at the surface. The eastern boundary with the Blue Ridge province is formed by the Blue Ridge-Piedmont thrust. This boundary is distinct in most places along the strike of the Appalachians and marks the change from folded rocks that are not penetratively deformed to rocks that are penetratively deformed.

BLUE RIDGE PROVINCE

The Blue Ridge geologic province is bounded on the southeast by the Brevard fault zone and on the northwest by the Blue Ridge-Piedmont fault system (see Figure 1.4-30) (Ref. 145-147). The province is a metamorphosed basement/cover sequence that has been complexly folded, faulted, penetratively deformed, and intruded. These rocks record multiple late Proterozoic to late Paleozoic deformation (extension and compression) associated with the formation of the Iapetos Ocean and the Appalachian orogen (Ref. 145, 148-151). The province consists of a series of westward-vergent thrust sheets, each with different tectonic histories and different lithologies (including gneisses, plutons, metavolcanic, and metasedimentary rift sequences), as well as continental and platform deposits (Ref. 140, 145). The Blue Ridge-Piedmont fault system thrust the entire Blue Ridge province northwest over Paleozoic sedimentary rock of the Valley and Ridge province during the Alleghanian orogeny (Ref. 149-154). The Blue Ridge geologic province reaches its greatest width in the southern Appalachians.

The Blue Ridge is divided into a western and an eastern belt separated by the Hayesville-Gossan Lead fault. Thrust sheets in the western Blue Ridge consist of a rift-facies sequence of clastic sedimentary rocks deposited on continental basement, whereas thrust sheets in the eastern Blue

Ridge consist of slope and rise sequences deposited in part on continental basement and in part on oceanic crust (Ref. 145, 149). Western Blue Ridge stratigraphy consists of basement gneisses, metasedimentary, metaplutonic, and metavolcanic rocks, whereas Eastern Blue Ridge stratigraphy consists of fewer lithologies, more abundant mafic rocks, and minor amounts of continental basement. These divisions of the Blue Ridge are discussed in more detail below.

Western Blue Ridge

The western Blue Ridge consists of an assemblage of Middle Proterozoic continental (Grenville) basement nonconformably overlain by Late Proterozoic to Early Paleozoic rift and drift facies sedimentary rock (Ref. 140, 155, 156). The basement consists of various types of gneisses, amphibolite, and gabbroic and volcanic rock and metasedimentary rock. All basement is metamorphosed to granulite or uppermost amphibolite facies (Ref. 140). The calculated ages of these rocks generally range from 1000-1200 Ma (mega annum or millions of years) (Ref. 157-159).

The rifting event during the Late Proterozoic through Early Paleozoic that formed the Iapetos Ocean is recorded in the rift-drift sequence of the Ocoee Supergroup and Chillhowie Group (Ref. 160, 161). These rocks, basement and sedimentary cover, were all later affected by Taconic and possibly Acadian deformation and metamorphism. The entire composite thrust sheet was transported west as an intact package during the Alleghanian collision event on the Blue Ridge-Piedmont thrust.

Eastern Blue Ridge

The eastern Blue Ridge is located southeast of the western Blue Ridge and is separated from that province by the Hayesville-Gossan Lead fault. The Brevard fault zone forms the southeastern boundary with the Inner Piedmont (see Figure 1.4-31). Lithologically, the eastern Blue Ridge is composed of continental slope, rise, and ocean floor metasedimentary rocks in association with oceanic or transitional to oceanic crust (Ref. 140, 162). This contrasts with the western Blue Ridge, which contains metasedimentary rocks suggesting continental rift-drift facies of a paleomargin setting. The eastern Blue Ridge is structurally complex with several major thrust faults, multiple fold generations, and two high-grade metamorphic episodes (Ref. 140). Metamorphism took place during the Taconic and possibly Acadian orogenies.

The stratigraphy within the eastern Blue Ridge includes rare Grenville (Precambrian) gneisses, metasedimentary rocks of the Tallulah Falls Formation and the Coweeta Group, metamorphosed Paleozoic granitoids, and mafic and ultramafic complexes and rocks of the Dahlonega Gold Belt. The Paleozoic granitoids are a part of a suite of similar granites that are found in the western Inner Piedmont suggesting a common intrusive history. Metasedimentary rock sequences in the eastern Blue Ridge are correlated along strike as well as across some thrust fault boundaries also suggesting a commonality in the original depositional history. Based on geochemical data, the mafic and ultramafic complexes that are found in particular thrust sheets in the eastern Blue Ridge have oceanic as well as continental affinities. However, exact tectonic origin is not clear because the contacts with the host metasedimentary rock are obscure.

PIEDMONT PROVINCE

The Piedmont province in northwestern South Carolina consists of variably deformed and metamorphosed igneous and sedimentary rocks ranging in age from Middle Proterozoic to Permian (1100-265 Ma). The province consists of the Western Piedmont and the Carolina terrane (see Figure 1.4-32). This designation is made because of different tectonic origins for the western and eastern parts of the province. The province can also be subdivided into seven distinctive tectonostratigraphic belts, separated by major faults (e.g., Towaliga fault), contrasts in metamorphic grade, or both. From northwest to southeast, these are the Chauga, Inner Piedmont, Kings Mountain, Charlotte, Carolina Slate, Kiokee, and Belair belts. The metamorphic grade of these belts alternates between low grade (Chauga, Kings Mountain, Carolina Slate, and Belair) and medium to high grade (Inner Piedmont, Charlotte, and Kiokee). The Charlotte and Carolina Slate belts are combined and discussed as the Carolina Terrane. The rocks of the Piedmont have been deformed into isoclinal recumbent and upright folds, which have been refolded and are contained in several thrust sheets or nappes. These metamorphic rocks extend beneath the Coastal Plain sediments in central and eastern South Carolina. The southeastern extent of the Piedmont province underneath the Coastal Plain is unknown.

Western Piedmont

The Western Piedmont encompasses the Inner Piedmont block, the Smith River Allochthon, and the Sauratown Mountains Anticlinorium (see Figure 1.4-31) (Ref. 163). It is separated from the Blue Ridge province on the northwest by the Brevard Fault zone. It is separated from the Carolina Terrane on the southeast by a complex series of fault zones approximately coincident with the Central Piedmont suture (Ref. 149). These faults include Lowndesville, Kings Mountain, Eufola, Shacktown, and Chatham fault zones (Ref. 163). The province is a composite stack of thrust sheets containing a variety of gneisses, schists, amphibolite, sparse ultramafic bodies and intrusive granitoids (Ref. 146, 164, 165). The protoliths are immature quartzo-feldspathic sandstone, pelitic sediments, and mafic lavas.

The Sauratown Mountains Anticlinorium is a complex structural window of four stacked thrust sheets that have been exposed by doming and subsequent erosion. Each sheet contains Precambrian basement with an overlying sequence of younger Precambrian to Cambrian metasedimentary and metaigneous rocks (Ref. 163). The Smith River Allochthon contains two predominantly metasedimentary units and a suite of plutonic rocks. It is a completely fault-bounded terrane, as is the Sauratown Mountains anticlinorium. The Inner Piedmont block is a fault-bounded, composite thrust sheet with metamorphic complexes of different tectonic affinities (Ref. 163). There is some continental basement within the block (Ref. 165) and scattered mafic and ultramafic bodies and complexes (Ref. 166) suggesting the presence of oceanic crustal (Ref. 163). The rest of the block contains a coherent though poorly understood stratigraphy of metasedimentary rock, metavolcanic gneisses, and schists (Ref. 163). The eastern Blue Ridge and Inner Piedmont contain some stratigraphically equivalent rocks (Ref. 167).

The western Piedmont reflects the effects of a complex tectonic history from the Precambrian Grenville through Late Paleozoic Alleghanian orogenies. Metamorphism affected the basement rocks of the Sauratown Mountains anticlinorium at least twice: during the Precambrian Grenville

and later during the Paleozoic. The metasedimentary cover sequence as well as the Smith River allochthon and the Inner Piedmont block were affected by one metamorphic event (prograde and retrograde) in the Paleozoic (Ref. 163). The Alleghanian continental collision is reflected in the thrust and dextral strike slip fault systems such as the Brevard and Bowens Creek fault zones. A few late Paleozoic granites were emplaced in the Inner Piedmont block; however, most lie further east in the Carolina Terrane. Early Mesozoic extension resulted in the formation of rift basins (Dan River and Davie County basins).

Carolina Terrane

The Carolina Terrane is part of a late Precambrian-Cambrian composite arc terrane, exotic to North America (Ref. 168, 169), and accreted sometime during the Ordovician to Devonian (Ref. 170, 171). It consists of felsic to mafic volcanic rock and associated volcanoclastic rock. Middle Cambrian fossil fauna indicate a European or African affinity (Ref. 168).

The northeastern boundary of the Carolina terrane is formed by a complex of faults that comprise the Central Piedmont suture (see Figure 1.4-31) and separate the terrane from rocks of North American affinity (Ref. 172-177). This structure was reactivated during the later Alleghanian collisional events as a dextral shear fault system (Ref. 178). Subsequent investigators have further established understanding of the complicated structure (Ref. 173, 179-185) suggested that the Central Piedmont suture is a low-angle normal fault. The Carolina terrane is bounded on the southeast by the Modoc fault zone and the Kiokee belt (see Figure 1.4-32).

The Carolina terrane is the combination of the earlier Charlotte and Carolina slate belts. The belts were initially distinguished by metamorphic grade (Ref. 147) and were later recognized as the same protolith and thus were combined (Ref. 140). Metamorphic grade increases to the northwest from lower greenschist facies to upper amphibolite facies. Pre-Alleghanian structure is dominated by large northeast trending folds with steeply dipping axial surfaces. All country rock of the Carolina terrane has been penetratively deformed, thereby producing axial plane cleavage and foliation (Ref. 140).

The Charlotte belt contains numerous intrusions and moderate- to high-grade metamorphic rock. Much of the belt was metamorphosed to amphibolite grade during the Taconic orogeny (Ref. 182), but retrograde metamorphism is also widespread. The oldest rocks are amphibolite, biotite gneiss, hornblende gneiss, and schist and probably were derived from volcanic, volcanoclastic, or sedimentary protoliths.

The Carolina Slate belt is characterized by thick sequences of metasedimentary rocks derived from volcanic source areas and felsic to mafic metavolcanic rocks. The oldest rocks within the Carolina Slate belt consist of intermediate to felsic ashflow tuff and associated volcanoclastic rocks. These rocks are overlain by a sequence of mudstone, siltstone, sandstone, greywacke, and greenstone with some interbedded volcanic tuff and flows. The belt was subjected to low- to medium-grade regional metamorphism and folding from 500-300 Ma and was intruded subsequently by granitic and gabbroic plutons about 300 Ma.

Kiokee Belt

The Kiokee belt is located between the Carolina terrane and the Belair belt in Georgia and South Carolina (see Figure 1.4-32). It is referred to as the Savannah River terrane in some of the recent literature (Ref. 186, 187). The Kiokee belt is bounded on the northwest by the Modoc fault zone and on the southeast by the Augusta Fault. It is a medium- to high-grade metamorphic belt with associated plutonism . Snoke (Ref. 188) recognized the Kiokee belt as the Alleghanian metamorphic core. The faults are mylonite zones that overprint the amphibolite facies infrastructure of the core of the belt (Ref. 140). The core was deformed and metamorphosed prior to the development of the plastic shear zones bounding it (Ref. 182, 183).

The Kiokee belt is an antiformal structure that strikes northeast. The interior is a migmatitic complex of biotite amphibole paragneiss, leucocratic paragneiss, sillimanite schist, amphibolite, ultramafic schist, serpentinite, feldspathic metaquartzite, and granitic intrusions of Late Paleozoic age (Ref. 189). Some of the lithologic units found in the Carolina slate belt may occur at higher metamorphic grade in the Kiokee belt (Ref. 140).

From extensive field studies and geochronological dating a complex Alleghanian history can be derived from the studies of the Kiokee belt (Ref. 188, 190-193). The pre-Alleghanian structure and stratigraphy are only partially known. The nature of the crustal rock that played a part in the metamorphism, deformation, and intrusion is still unknown. The possible role of a Precambrian basement in the Kiokee belt is an essential question proposed by Hatcher et al. (Ref. 140). No rock in the Kiokee belt has been identified at this time as Precambrian basement. However, Long (Ref. 194) suggested, based on gravity data, that a large rifted block of continental crust underlies the Kiokee belt.

Belair Belt

The Belair belt (also Augusta terrane) (Ref. 191, 195) is locally exposed in the Savannah River valley, near Augusta, GA (see Figure 1.4-32). It is largely concealed beneath the Atlantic Coastal Plain with several small erosional windows through the Coastal Plain sediments in eastern Georgia (Ref. 196). The Belair belt consists of intermediate to felsic volcanic tuffs and related volcanoclastic sediments penetratively deformed and metamorphosed to greenschist facies (Ref. 186, 188, 195-201). The Belair belt contains similar characteristics to the Carolina terrane (Ref. 202). Geophysical and well data indicate that the Belair belt extends beneath the Atlantic Coastal Plain (Ref. 202).

MESOZOIC RIFT BASINS

Mesozoic age rift basins are found along the entire eastern continental margin of North America from the Gulf Coast through Nova Scotia (see Figure 1.4-33). The basins formed in response to the continental rifting episode that broke up the super continent, Pangea, and led to the formation of the Atlantic ocean basin. Rift basins are exposed in the Piedmont province as well as buried beneath Cretaceous and younger Coastal Plain sediments. Many underlie offshore regions. Structurally, the basins are grabens or half grabens, elongated in a northeast direction and are

bounded by normal faults on one or both sides (Ref. 203). Several basins were localized along reactivated Paleozoic ductile or brittle fault zones (Ref. 204-207).

There are two belts of basins that trend northeastward along the continental margin from the Carolinas to Pennsylvania (Ref. 208). In North and South Carolina the Deep River, Elberbe and Crowburg basins are included in the eastern belt, and the Dan River and Davie County basins are in the western belt (Ref. 208). The Dunbarton, Florence, Riddleville, and South Georgia basins are buried beneath Coastal Plain sediments in the eastern belt (see Figure 1.4-34). The basins are generally filled with lacustrine sedimentary and igneous rock.

Strata within the basins consist mainly of non-marine sandstone, conglomerate, siltstone, and shale. Carbonate rocks and coal are found locally in several basins. Igneous rocks of basaltic composition occur as flows, sills, and stocks within the basins and as extensive dike swarms within and outside the basins (Ref. 209). These basin fill strata have been described and named the Newark Supergroup (Ref. 208, 210, 211). In general, the stratigraphy can be broken out into three sections. The lower section is characteristically fluvial (Ref. 211, 212) and contains reddish-brown, arkosic coarse-grained sandstone, and conglomerate. The middle section mainly includes sediments of lacustrine origin (Ref. 211). These sediments include grey-black fossiliferous siltstone, carbonaceous shale, and thin coal beds (Ref. 208). The upper section is a complex of deltaic, fluvial, and lacustrine environments (Ref. 213. 214). These sediments include red-brown siltstone, arkosic sandstone, pebbly sandstone, and red and grey mudstone and conglomerate (Ref. 208).

In North Carolina, there are two exposed major basins, the Dan River and Deep River basins. There are many similarities between the two basins as well as significant differences (Ref. 208). Both basins exhibit half-graben geometry, bounded on one side by a major normal fault zone. Basin strata typically dip towards the border fault. However, the border faults on the two basins are on opposite flanks of the basin: Dan River's Chatham Fault dips to the southeast. Deep River's Jonesboro fault zone is located on the basin's southeast flank and dips northwest (Ref. 208). There are also significant differences in the internal stratigraphy and component of basalt intrusion.

The Dunbarton basin beneath SRS has a master border fault dipping to the southeast (Ref. 215), and so does the Riddleville basin in Georgia (Ref. 208). The Dunbarton basin is not known to contain any basalt sills. The South Georgia Rift, in Georgia and South Carolina, is a much larger, deeper and more complex basin than either the Riddleville or Dunbarton basins. The basin is as wide as 100 km and as deep as 7 km (Ref. 216). It is not a single basin but is a complex of isolated synrift grabens with limited to major crustal extension. The major border fault dips northward (Ref. 216) as opposed to southeastward for the master faults bounding Riddleville and Dunbarton basins.

ATLANTIC COASTAL PLAIN STRATIGRAPHY, LITHOLOGY, AND STRUCTURE

The information in this section is based largely on Aadland et al., Hydrogeologic Framework of West Central South Carolina (Ref. 100). (Text excerpts and figures from that document are included here with permission of the authors.)

The sediments of the Atlantic Coastal Plain in South Carolina are stratified sand, clay, limestone, and gravel that dip gently seaward and range in age from Late Cretaceous to Recent. The sedimentary sequence thickens from essentially zero at the Fall Line to more than 1,219 meters (4,000 feet) at the coast. Regional dip is to the southeast, although beds dip and thicken locally in other directions because of locally variable depositional regimes and differential subsidence of basement features such as the Cape Fear Arch and the South Georgia Embayment. A map depicting these regional features and the study area discussed in the following sections is presented in Figure 1.4-35.

The Coastal Plain sedimentary sequence near the center of the region (i.e., SRS) consists of about 213 meters (700 feet) of Late Cretaceous quartz sand, pebbly sand, and kaolinitic clay, overlain by about 18 meters (60 feet) of Paleocene clayey and silty quartz sand, glauconitic sand, and silt. The Paleocene beds are in turn overlain by about 107 meters (350 feet) of Eocene quartz sand, glauconitic quartz sand, clay, and limestone grading into calcareous sand, silt, and clay. The calcareous strata are common in the upper part of the Eocene section in downdip parts of the study area. In places, especially at higher elevations, the sequence is capped by deposits of pebbly, clayey sand, conglomerate, and clay of Miocene or Oligocene age. Lateral and vertical facies changes are characteristic of most of the Coastal Plain sequence, and the lithologic descriptions below are therefore generalized. A surface geologic map for SRS is presented in Figure 1.4-36. The stratigraphic section, which delineates the coastal plain lithology (see Figure 1.4-18), is divided into several formations and groups based principally on age and lithology.

Geology of the Coastal Plain Sediments - General

The following sections describe regional stratigraphy and lithologies, with emphasis on variations near the SRS. The data presented are based upon direct observations of surface outcrops; geologic core obtained during drilling of bore holes; microfossil age dating; and borehole geophysical logs. Several key boring locations within the SRS boundaries and in the adjacent regions (presented in Figure 1.4-21) are referenced throughout the following discussions.

Rocks of Paleozoic and Triassic ages have been leveled by erosion and are unconformably overlain by unconsolidated to poorly consolidated Coastal Plain (Ref. 217-219). This erosional surface dips approximately 7 m/km (37 ft/mile) toward the southeast. The Atlantic Coastal Plain sediments in South Carolina are stratified sand, clay, limestone, and gravel that dip gently seaward and range in age from Late Cretaceous to Recent. Near the coast, the wedge is approximately 1,219 meters (4,000 feet) thick (Ref. 220).

Upper Cretaceous Sediments

Upper Cretaceous sediments overlie Paleozoic crystalline rocks or lower Mesozoic sedimentary rocks throughout most of the study area. The Upper Cretaceous sequence includes the basal Cape Fear Formation and the overlying Lumbee Group, which is divided into three formations (see Figure 1.4-18). The sediments in this region consist predominantly of poorly consolidated, clay-rich, fine- to medium-grained, micaceous sand, sandy clay, and gravel (Ref. 100), and is

about 213 meters (700 feet) thick near the center of the study area. Thin clay layers are common. In parts of the section, clay beds and lenses up to 21 meters (70 feet) thick are present. Depositional environments were fluvial to prodeltaic.

Cape Fear Formation

The Cape Fear Formation rests directly on a thin veneer of saprolitic bedrock and is the basal unit of the Coastal Plain stratigraphic section at SRS. The saprolite ranges from less than 3 meters (10 feet) to more than 12 meters (40 feet) in thickness and defines the surface of the crystalline basement rocks and sedimentary rocks of the Newark Supergroup (Middle to Upper Triassic age). The thickness of the saprolite reflects the degree of weathering of the basement prior to deposition of the Cape Fear Formation. The Cape Fear is encountered at about 61 meters (200 feet) msl just south of well C-3 in the north and at about 366 meters (1,200 feet) msl at well C-10 (see Figure 1.4-21) in the south. The Cape Fear does not crop out in the study area, and its northern limit is north of the C-1 and P-16 wells and south of wells C-2 and C-3. The unit thickens to more than 70 meters (230 feet) at well C-10 and has a maximum known thickness of about 213 meters (700 feet) in Georgia (Ref. 221). The top of the Cape Fear Formation dips approximately 5 m/km (30 ft/mile) to the southeast across the study area.

The Cape Fear Formation consists of firm to indurated, variably colored, poorly sorted, silty, clayey sand and sandy silt and clay. Bedding thickness of the sand, silt and clay ranges from about 1.5 meters (5 feet) to 6 meters (20 feet), with the sand beds generally thicker than the clay beds. The sand grains are typically coarse-grained with common granule and pebble. The sand is arkosic with rock fragments common in the pebbly zones.

The Cape Fear Formation is more indurated than other Cretaceous units because of the abundance of cristobalite cement in the matrix. The degree of induration decreases from north to south across the area. In the northern part of the area, the formation is represented on geophysical logs as a zone of low resistivity. In the southern part of the study area, the unit is more sandy, and is noted on geophysical logs by increased electrical resistivity (wells ALL-324 and C-10 on Figure 1.4-21). The transition from the more indurated clayey sand in the north to the poorly consolidated cleaner sand in the south may be due to deeper fluvial incisement and erosion of the Cape Fear section to the north. This may bring the deeper, more cristobalite-rich part of the section into proximity with the overlying unconformity that caps the formation. Clark et al. (Ref. 121) attribute the differences between updip and downdip lithologies to changes in source material during deposition or to the southern limit of the cristobalite cementation process.

The lithologic characteristics and the paucity of marine fossils are indicative of a high-energy environment close to a sediment source area. Thus, these sediments may represent deposition in fluvial-deltaic environments on the upper parts of a delta plain (Ref. 221), grading downdip to marginal marine (Ref. 222). The Cape Fear Formation was erosionally truncated prior to deposition of the overlying Middendorf Formation, resulting in a disconformity between the two formations.

Lumbee Group

Three formations of the Late Cretaceous Lumbee Group (Ref. 223) are present in the study area (Ref. 124). These are, from oldest to youngest, the Middendorf, Black Creek, and Steel Creek Formations (see Figures 1.4-18).

The Lumbee Group consists of fluvial and deltaic quartz sand, pebbly sand, and clay in the study area. The sedimentary sequence is more clayey and fine-grained downdip from the study area, reflecting shallow to deep marine shelf sedimentary environments. Thickness ranges from about 122 meters (400 feet) at well C-3 (see Figure 1.4-21) in the north, to about 238 meters (780 feet) near well C-10 in the south. At least part of the group crops out in the northern part of the study area but it is difficult to distinguish the individual formations. Consequently, the Lumbee Group was mapped as undifferentiated Upper Cretaceous by Nystrom and Willoughby (Ref. 224). The dip of the upper surface of the Lumbee Group is to the southeast at approximately 4 m/km (20 ft/mile) across the study area.

The Middendorf Formation unconformably overlies the Cape Fear Formation with a distinct contact. The contact is marked by an abrupt change from the moderately indurated clay and clayey sand of the underlying Cape Fear to the slightly indurated sand and lesser clayey sand of the Middendorf. The basal zone is often pebbly. The contact is unconformable and is marked by a sudden increase in electrical resistivity on geophysical logs. Thickness of the formation ranges from approximately 37 meters (120 feet) in well C-2 (see Figure 1.4-21) in the north, to 73 meters (240 feet) in well C-10 in the south. It has a maximum known thickness of about 158 meters (520 feet) in Georgia (Ref. 121). The top of the formation dips to the southeast at about 4.9 m/km (26 ft/mile) across the study area. Fossil data for the Middendorf are sparse and the formation is not well dated in the study area.

The sand of the Middendorf Formation is medium to very coarse grained, typically angular, slightly silty, tan, light gray, and yellow in color. It is much cleaner and less indurated than the underlying Cape Fear sediments. Sorting is generally moderate to poor. Pebble and granule zones are common in updip parts of the study area, whereas clay layers up to 3 meters (10 feet) thick are more common downdip. Clay clasts are abundant in places. Some parts of the unit are feldspathic and micaceous, but not as micaceous as in the overlying Black Creek Formation. Lignitic zones are also common.

Over much of the study area, a zone of interbedded sand and variegated clay up to 18 meters (60 feet) thick is present at or near the top of the Middendorf Formation. The interbedded sand is upward fining in places. This lithology and the marine microfauna found in core samples indicate that the unit was deposited in lower delta plain and delta front environments under some marine influence (Ref. 225). In the northern part of the study area, the formation is variably colored, composed of tan, red, and purple sand. Here, the sediments have the characteristics of fluvial and upper delta plain deposits.

Near Bamberg, SC, the Middendorf Formation consists of poorly sorted, gray, medium- to very coarse-grained, angular to subangular quartz sand with quartz pebbles and sparse feldspar grains (Ref. 222). Silt and fine-grained sand are present. The angularity and large overall grain size of the quartz and the presence of feldspar indicate that deposition occurred relatively close to the

source area, most likely in an upper delta plain environment. In southeastern Georgia, the Middendorf includes some shallow shelf sediments. Farther downdip, sediments of the Middendorf become finer grained. In Allendale County, SC, near Millet, the unit consists of light gray to colorless, fine- to coarse-grained quartzose sand, clayey sand, and silty clay. The sand is unconsolidated and poorly to moderately sorted. Trace amounts of heavy minerals and lignite are present. Deposition most probably occurred on a lower delta plain (Ref. 222).

Paleontological control for the Black Creek is poor updip in South Carolina and Georgia. Prowell et al. (Ref. 225), citing Christopher (Ref. 226) and Sohl and Christopher (Ref. 227), suggested a Late Cretaceous age for the Black Creek Formation as indicated by various paleontological data from the unit. Sediments assigned to the Black Creek Formation in the vicinity of the SRS yield Late Cretaceous paleontological ages and unconformably overlie the Middendorf Formation (see Figure 1.4-18) (Ref. 222).

The Black Creek Formation is penetrated at virtually all well-cluster sites in the study area. The unit ranges in thickness from approximately 46 meters (150 feet) at well C-2 in the north to 91 meters (300 feet) near the center of the study area in well PBF-3 and to 113 meters (370 feet) at well C-10 in the south. The unit dips approximately 4 m/km (22 ft/mile) to the southeast.

The Black Creek is distinguished from the overlying and underlying Cretaceous units by its better sorted sand, fine-grained texture, and relatively high clay content. It is generally darker, more lignitic, and more micaceous, especially in the updip part of the section, than the other Cretaceous units. In much of the study area, the lower one-third of the formation is mostly sand that is separated from the upper two-thirds of the unit by clay beds. These beds are 6 meters (20 feet) to 12 meters (40 feet) thick in the northern part of the region and more than 46 meters (150 feet) at well C-10 in the south. In general, the top of the Black Creek Formation is picked at the top of a clay bed that ranges from 3 meters (10 feet) to 8 meters (25 feet) in thickness. The clay bed is exceptionally thick but not laterally extensive. For example, it is essentially absent in wells P-21, CPC-1, P-26, and P-29. This suggests lagoonal back barrier bay deposition associated with nearby shorelines. Often the thick clay beds flank the areas where shoaling is suggested owing to uplift along the Pen Branch and Steel Creek Faults, which was contemporaneous with deposition. Overall, the Black Creek consists of two thick, fining-upward sequences, each capped by thick clay beds. The lower sequence is predominantly silty, micaceous sand in the area of SRS, while the upper sequence is mostly clay and silt.

Where the Black Creek Formation is present north of SRS, it consists of clayey, micaceous, poorly to moderately well sorted, fine to medium-grained, subangular to subrounded quartz sand beds and silty clay beds. Pebbly beds are present throughout the unit. This sandy lithology is indicative of fluvial to upper delta-plain environments; the clay beds that cap the upward-fining sandy sequences are typical of lower delta plain depositional environments. Near Millet, SC, the basal beds of the Black Creek consist of sand and silty clay and are similar to underlying Middendorf sediments. Here, deposition occurred on a lower delta plain. Fossils recovered from the unit suggest marine influences during deposition of the sediments, especially the clay (Ref. 225).

In the central and downdip part of the study area (wells P-22, ALL-324, C-6, C-10), the unit grades into gray-green clayey silt, micritic clay, and fine- to medium-grained, upward fining sand

that is moderately well sorted, micaceous, carbonaceous, and locally glauconitic. The sequence suggests deposition in a delta front or shallow shelf environment, as indicated by the lithology and an abundance of marine macrofauna and microfauna (Ref. 225). The transition from fine-grained, prodelta or delta front deposits in the southern part of the study area to coarser-grained, more landward deltaic deposits in the northern part of the area is reflected in the general increase in electrical resistivity noted on geophysical logs in the wells in the north, especially in the upper part of the Black Creek section.

The Peedee Formation was previously considered by some investigators to be absent in the study area (Ref. 220); however, recent paleontological evidence provides dates of Peedee age from sediment samples in the southern part of SRS (Ref. 222). Because there is a considerable difference in lithology between the type Peedee (Ref. 228) and the sediments in the SRS region, Peedee-equivalent sediments in the vicinity of SRS were referred to as the "Steel Creek Member" of the Peedee Formation (Ref. 115). Raising the Steel Creek Member to formational status was recommended by Aadland et al. (Ref. 100) and it is so used in this document. The type well for the Steel Creek Formation is P-21, located near Steel Creek. The top of the Steel Creek is picked at the top of a massive clay bed that ranges from 1 meter (3 feet) to more than 9 meters (30 feet) in thickness. The formation dips approximately 4 m/km (20 ft/mile) to the southeast.

The unit ranges in thickness from approximately 18 meters (60 feet) at well P-30 (see Figure 1.4-21) to 53 meters (175 feet) at well C-10 in the south. It has a maximum known thickness of 116 meters (380 feet) in Georgia (Ref. 120). The Steel Creek section thins dramatically between the ALL-324 and the P-22 wells due to truncation by erosion at the Cretaceous-Tertiary unconformity. The Steel Creek Formation overlies the Black Creek Formation and is distinguished from it by a higher percentage of sand, which is represented on geophysical logs by a generally higher electrical resistivity and lower natural gamma radiation count.

The formation consists of yellow, tan, and gray, medium to coarse, moderately sorted sand interbedded with variegated clay. The lower part of the unit consists of medium- to coarse-grained, poorly to well-sorted, quartz sand, silty sand, and off-white to buff clay that contains thin beds of micaceous and carbonaceous clay. Pebbly zones are common, as are layers with clay clasts. Fining-upward sand is interbedded with the clay and silty clay beds in some areas. It is difficult to differentiate the Steel Creek from the underlying Black Creek in the northwestern part of the study area. The unit appears to have been deposited in fluvial environments in updip areas and upper to lower delta plain environments in the south. The massive clay that caps the unit suggests lower delta plain to shallow shelf depositional

environments. The presence of certain microfossils indicates some marine influence in parts of the Steel Creek (Ref. 225). A pebble-rich zone at the base of the unit suggests a basal unconformity.

Tertiary Sediments

Tertiary sediments range in age from Early Paleocene to Miocene and were deposited in fluvial to marine shelf environments. The Tertiary sequence of sand, silt, and clay generally grades into highly permeable platform carbonates in the southern part of the study area and these continue southward to the coast. The Tertiary sequence is divided into three groups, the Black Mingo

Group, Orangeburg Group, and Barnwell Group, which are further subdivided into formations and members (see Figure 1.4-18). These groups are overlain by the ubiquitous Upland unit.

The Tertiary sedimentary sequence deposited in west-central South Carolina has been punctuated by numerous sea level low stands and/or affected by subsidence in the source areas (which reduced or eliminated sediment availability) resulting in a series of regional unconformities. Four such regionally significant unconformities are defined in the Tertiary stratigraphic section in A/M Area (Ref. 229). From base upwards they include the "Cretaceous-Tertiary" unconformity, the "Lang Syne/Sawdust Landing" unconformity, the "Santee" unconformity and the "Upland" unconformity. Based on these unconformities, four sequence stratigraphic units (unconformity bounded sedimentary units) have been delineated (Figure 1.4-18). Work is currently underway to place the units in the global sequence stratigraphic framework.

Sequence stratigraphic unit I includes the sediments deposited between the "Cretaceous-Tertiary" unconformity and the "Lang Syne/Sawdust Landing" unconformity, and includes the Lang Syne/Sawdust Landing formations undifferentiated of the Black Mingo Group. Sequence unit II lies between the Lang Syne/Sawdust Landing unconformity and the Santee unconformity, and includes from oldest to youngest the Fourmile/Congaree formations undifferentiated, the Warley Hill Formation, the Tinker/Santee Formation of the Orangeburg Group and the carbonates (Utley Member) of the Clinchfield Formation. The Santee unconformity that caps the sequence is a major erosional event in the SRS region. Sequence unit III lies between the Santee unconformity and the "Upland unit" unconformity, and includes the Dry Branch and Tobacco Road formations of the Barnwell Group. Sequence unit IV includes all the fluvial sediments overlying the "Upland unconformity".

Black Mingo Group

The Black Mingo Group consists of quartz sand, silty clay, and clay that suggest upper and lower delta plain environments of deposition (Figure 1.4-37) generally under marine influences (Ref. 225). In the southern part of the study area, massive clay beds, often more than 50 feet (15 meters) thick, predominate. Downdip from the study area, thin red to brown sandy clay beds, gray to black clay beds and laminated shale dominate the Black Mingo Group and suggest deposition in clastic shelf environments. At the South Carolina coast, carbonate platform facies-equivalents of the updip Black Mingo clastic sediments first appear. The carbonate units are all referred to as "unnamed limestones" by Colquhoun et al. (Ref. 220). These are equivalent to the thick beds of anhydrite and dolomite of the Paleocene Cedar Keys Formation (Ref. 108, 111) and the lower Eocene glauconitic limestone and dolomite of the Oldsmar Formation. Both carbonate units are delineated and mapped in coastal Georgia and northeastern Florida.

Basal Black Mingo sediments were deposited on the regional "Cretaceous-Tertiary" unconformity of Aadland (Ref. 229) that defines the base of Sequence Stratigraphic unit I. There is no apparent structural control of this unconformity. Above the unconformity, the clay and clayey sand beds of the Black Mingo Group thin and often pinch out along the traces of the Pen Branch and Crackerneck Faults. This suggests that coarser-grained materials were deposited preferentially along the fault traces, perhaps due to shoaling of the depositional surface. This, in

turn, suggests movement (reactivation) along the faults. This reactivation would have occurred during Black Mingo deposition, that is, in Paleocene and lower Eocene time.

The upper surface of the Black Mingo Group dips to the southeast at 3 m/km (16 ft/mi.), and the group thickens from 18 meters (60 feet) at well C-2 in the north, to about 52 meters (170 feet) near well C-10 in the south. The group is about 213 meters (700 feet) thick at the South Carolina coast (Ref. 220). Throughout the downdip part of the South Carolina Coastal Plain, the Black Mingo Group consists of the Rhems Formation and the overlying Williamsburg Formation.

The Rhems Formation contains four members, each representing a depositional facies. They are the Sawdust Landing Member, an upper delta plain fluvial deposit which unconformably overlies the Cretaceous Peedee Formation; the Lang Syne Member, a lower delta-plain deposit of estuarine and littoral origin; the Perkins Bluff Member, a shallow shelf deposit; and the Browns Ferry Member, a deep-water shelf deposit. Additionally, an unnamed unit represents the carbonate-shelf facies (Ref. 220).

In the updip part of the South Carolina Coastal Plain, the Black Mingo Group consists of the Sawdust Landing and Lang Syne Formations (Ref. 118), which are equivalent to the Ellenton Formation of Siple (Ref. 123); the Snapp Formation (Ref. 118), which is the updip equivalent of the Williamsburg Formation of Colquhoun et al. (Ref. 220); and the Fourmile Formation (Ref. 118), which is the updip equivalent of the Fishburne Formation of Gohn et al. (Ref. 230).

Lang Syne/Sawdust Landing Formations. Siple proposed the name Ellenton Formation for a subsurface lithologic unit in the SRS area consisting of beds of dark, lignitic clay and coarse sand, which are equivalent to the Sawdust Landing and Lang Syne Members of the Rhems Formation of Colquhoun et al. (Ref. 220). Fallaw and Price (Ref. 118) suggested that the Sawdust Landing Member and the overlying Lang Syne Member of the Rhems Formation be raised to formational status and replace the term Ellenton in the study area

In the absence of detailed paleontological control, the Sawdust Landing Formation and the overlying Lang Syne Formation could not be systematically separated for mapping in this region. Thus, they are treated as a single unit; the Lang Syne/Sawdust Landing undifferentiated, on all sections and maps. This is consistent with the approach taken by Fallaw and Price (Ref. 231). The sediments of the unit generally consist of two fining-upward sand-to-clay sequences, which range from about 12 meters (40 feet) in thickness at the northwestern boundary of SRS to about 30 meters (100 feet), near the southeastern boundary. The unit is mostly dark gray to black, moderately to poorly sorted, fine to coarse-grained, micaceous, lignitic, silty and clayey quartz sand interbedded with dark gray clay and clayey silt. Pebbly zones, muscovite, feldspar, and iron sulfide are common. Individual clay beds up to 6 meters (20 feet) thick are present in the unit. Clay and silt beds make up approximately one-third of the unit in the study area. The dark, fine-grained sediments represent lower delta plain, bay-dominated environments (Figure 1.4-37). Tan, light gray, yellow, brown, purple, and orange sand, pebbly sand, and clay represent upper delta plain, channel-dominated environments.

In the southern part of the study area, dark, poorly sorted, micaceous, lignitic sand and silty sand containing a diverse assemblage of pollen and microfauna of early and middle Paleocene

(Midwayan) age are present (Ref. 225). This is the Perkins Bluff Member of the Rhems Formation, which was deposited in lower delta plain or shallow marine shelf environments.

Toward the coast, the Rhems Formation includes shallow to increasingly deeper water clastic shelf facies sediments (Browns Ferry Member) that ultimately pass into a shallow carbonate platform facies at the South Carolina coastline. Colquhoun et al. (Ref. 220) referred to the carbonate platform facies equivalent as "unnamed limestone." The carbonate platform sequence is correlative with the anhydrite- and gypsum-bearing dolomitized limestone and finely crystalline dolomite of the lower part of the Cedar Keys Formation (Ref. 111) that is mapped in coastal Georgia and northeastern Florida. The carbonate sequence is about 76 meters (250 feet) thick at the South Carolina coastline (Ref. 220). The Cedar Keys Formation has a maximum thickness of 130 meters (425 feet) in coastal areas of Georgia (Ref. 232). The carbonate platform sediments of the Cedar Keys Formation are generally impermeable, and the unit acts as the underlying confining unit of the Floridan Aquifer System in the coastal areas of South Carolina and Georgia.

Snapp Formation (Williamsburg Formation). Sediments in the study area that are time equivalent to the Williamsburg Formation differ from the type Williamsburg and have been designated the "Snapp Member of the Williamsburg Formation" (Ref. 233). Fallaw and Price (Ref. 231) have suggested that the "Snapp Member" of the Williamsburg be raised to formational status. The Snapp Formation is used in this report. The unit is encountered in well P-22 (see Figure 1.4-21) in the southeastern part of SRS near Snapp Station. The basal contact with the underlying Lang Syne/Sawdust Landing undifferentiated is probably unconformable. The Snapp Formation appears to pinch out in the northwestern part of SRS and thickens to about 15 meters (50 feet) near the southeastern boundary of the site.

The Snapp Formation (Williamsburg Formation) crops out in Calhoun County. The sediments in the upper part of the unit consist of low-density, fissile, dark-gray to black siltstone and thin layers of black clay interbedded with sand in the lower part. These and similar sediments in Aiken and Orangeburg Counties were probably deposited in lagoonal or estuarine environments (Figure 1.4-37). Within and near SRS, the Snapp sediments typically are silty, medium- to coarse-grained quartz sand interbedded with clay. Dark, micaceous, lignitic sand also occurs, and all are suggestive of lower delta plain environments. In Georgia, the unit consists of thinly laminated, silty clay locally containing layers of medium- to dark-gray carbonaceous clay. This lithology is indicative of marginal marine (lagoonal to shallow shelf) depositional environments. Clayey parts of the unit are characterized on geophysical logs as zones of low electrical resistivity and a relatively high-gamma ray response. In the southernmost part of the study area, the Snapp (Ref. 120) consists of gray-green, fine to medium, well-rounded, calcareous quartz sand and interbedded micritic limestone and limey clay that is highly fossiliferous and glauconitic. This lithology suggests deposition in shallow shelf environments somewhat removed from clastic sediment sources.

Farther south toward the coast, the Williamsburg Formation (Snapp equivalent) exhibits deeper-water, clastic facies, which give way to the carbonate-platform facies that were first established in early Paleocene time. Colquhoun et al. (Ref. 220) referred to the carbonate platform sediments, which are about 350 feet (106 meters) thick at the coast, as "unnamed limestone." The unit is equivalent to the anhydrite- and gypsum-bearing dolomitized limestone

and finely crystalline dolomite of the upper part of the Cedar Keys Formation mapped in southeastern Georgia and northeastern Florida (Ref. 111, 234). The carbonate platform expanded dramatically during upper Paleocene time, reaching as far north as Bamberg County, South Carolina (Ref. 220).

The upper surface of the Williamsburg Formation is defined by the "Lang Syne/Sawdust Landing" unconformity (Ref. 229) and defines the upper boundary of Sequence Stratigraphic Unit I (Figure 1.4-18). The surface has been offset by normal faulting as noted in A/M Area (Ref. 229)

Fourmile Formation. Early Eocene ages, derived from paleontological assemblages, indicate that the sand immediately overlying the Snapp Formation in the study area is equivalent to the Fishburne (Ref. 231). These sediments were deposited on the "Lang Syne/Sawdust Landing" unconformity (Ref. 229) and constitute the basel unit of Sequence Stratigraphic Unit II (Figure 1.4-18). The Fishburne is a calcareous unit that occurs downdip near the coast. The sand was initially designated the Fourmile Member of the Fishburne Formation (Ref. 233). Owing to the distinctive difference in lithology between the type, Fishburne Formation and the time-equivalent sediments observed in the study area, Fallaw and Price (Ref. 231) have recommended that the Fourmile Member of the Fishburne be raised to formational rank. The term Fourmile Formation is used in this report.

The Fourmile Formation averages 9 meters (30 feet) in thickness, is mostly tan, yellow-orange, brown, and white, moderately to well-sorted sand, with clay beds a few feet thick near the middle and at the top of the unit. The sand is very coarse to fine grained, with pebbly zones common, especially near the base. Glauconite, up to about 5%, is present in places, as is weathered feldspar. In the center and southeastern parts of SRS, the unit can be distinguished from the underlying Paleocene strata by its lighter color and lower content of silt and clay. Glauconite and microfossil assemblages indicate that the Fourmile is a shallow marine deposit (Figure 1.4-37).

Overlying the Fourmile Formation in the study area is 9 meters (30 feet) or less of sand similar to the Fourmile. This sand is better sorted, contains fewer pebbly zones, less muscovite and glauconite, and in many wells is lighter in color. Microfossil assemblages indicate that the sand is correlative with the early middle Eocene Congaree Formation. In some wells a thin clay occurs at the top of the Fourmile, separating the two units; however, the difficulty in distinguishing the Fourmile Formation from the overlying Congaree Formation has led many workers at SRS to include the entire 293 meters (960 feet) section in the Congaree Formation.

Downdip from the study area, the clean, shallow shelf sand of the Fourmile Formation passes into silt, massive clay, siltstone, and mudstone suggestive of a deep clastic shelf facies (Ref. 111) (see Figure 1.4-37). Toward the coast, the stratigraphic interval is composed of calcareous, glauconitic sand and clay and sandy glauconitic, fossiliferous limestone indicative of deep shelf to carbonate platform environments (Figure 1.4-37). The carbonate facies equivalent of the Fourmile is correlative with the glauconitic, micritic limestone and interbedded fine to medium, commonly vuggy, crystalline dolomite platform facies of the Oldsmar Formation in coastal Georgia and northeastern Florida (Ref. 111, 234). The Oldsmar Formation equivalents in South Carolina unconformably overlie clastic sediments of the Rhems Formation downdip in South Carolina and the correlative Clayton Formation in Georgia. The unit signals the rapid northward

advance of the leading edge of the carbonate platform first established in lower Paleocene time near the South Carolina coast. The early Eocene carbonate sediments reach 241 meters (800 feet) in thickness in coastal Georgia (Ref. 234).

Orangeburg Group

The Orangeburg Group consists of the lower middle Eocene Congaree Formation (Tallahatta equivalent) and the upper middle Eocene Warley Hill Formation and Santee Limestone (Lisbon equivalent) (see Figure 1.4-18). Over most of the study area, these post-Paleocene units are more marine in character than the underlying Cretaceous and Paleocene units; they consist of alternating layers of sand, limestone, marl, and clay.

The group crops out at lower elevations in many places within and near SRS. The sediments thicken from about 26 meters (85 feet) at well P-30 near the northwestern SRS boundary to 61 meters (200 feet) at well C-10 (see Figure 1.4-21) in the south. Dip of the upper surface is 2 m/km (12 ft/mile) to the southeast. Downdip at the coast, the Orangeburg Group is about 99 meters (325 feet) thick (Ref. 220) and is composed of shallow carbonate platform deposits of the Santee Limestone.

In the extreme northern part of the study area, the entire middle Eocene Orangeburg Group is mapped as the Huber Formation (Ref. 224). The micaceous, poorly sorted sand, abundant channel fill deposits and cross bedding, and carbonaceous kaolin clay in the Huber is indicative of fluvial, upper delta plain environments (Figure 1.4-37).

In the central part of the study area the group includes, in ascending order, the Congaree, Warley Hill, and Tinker/Santee Formations (Ref. 233) (see Figure 1.4-18). The units consist of alternating layers of sand, limestone, marl, and clay that are indicative of deposition in shoreline to shallow shelf environments (Figure 1.4-37). From the base upward, the Orangeburg Group passes from clean shoreline sand characteristic of the Congaree Formation to shelf marl, clay, sand, and limestone typical of the Warley Hill and Santee Limestone. Near the center of the study area, the Santee sediments consist of up to 30 vol% carbonate. The sequence is transgressive, with the middle Eocene Sea reaching its most northerly position during Tinker/Santee deposition.

Toward the south, near wells P-21, ALL-324, and C-10 (see Figure 1.4-21), the carbonate content of all three formations increases dramatically. The shoreline sand of the Congaree undergoes a facies change to interbedded glauconitic sand and shale, grading to glauconitic argillaceous, fossiliferous, sandy limestone. Downdip, the fine-grained, glauconitic sand, and clay of the Warley Hill become increasingly calcareous and grades imperceptibly into carbonate-rich facies comparable to both the overlying and underlying units. Carbonate content in the glauconitic marl, calcareous sand, and sandy limestone of the Santee increases towards the south. Carbonate sediments constitute the vast majority of the Santee from well P-21 southward.

Toward the coast, the sediments of the entire Orangeburg Group grade into the pure white to creamy-yellow fossiliferous and partly glauconitic Santee Limestone (Ref. 220) that was deposited on the shallow carbonate platform first established in early Paleocene time. The Santee is correlative with the chalky or indurated pelloidal to micritic limestone interbedded with

fine to medium, crystalline, slightly vuggy dolomite of the Avon Park Formation in coastal sections of Georgia and northeastern Florida (Ref. 111, 234). The Avon Park Formation unconformably overlies the Oldsmar Formation, and reaches a thickness of about 305 meters (1,000 feet) in coastal Georgia.

The carbonate platform reached its maximum northern extent during middle Eocene time when the leading edge extended into Allendale County north of well ALL-19. The three largely clastic formations that constitute the Orangeburg Group in the study area are the updip clastic equivalents of the platform carbonate rocks of the Santee to the south.

Congaree Formation. The early middle Eocene Congaree Formation has been traced from the Congaree valley in east central South Carolina into the study area. It has been paleontologically correlated with the early and middle Eocene Tallahatta Formation in neighboring southeastern Georgia by Fallaw et al. (Ref. 233).

The Congaree is about 9 meters (30 feet) thick near the center of the study area and consists of yellow, orange, tan, gray, green, and greenish gray, well-sorted, fine to coarse quartz sand, with granule and small pebble zones common. Thin clay laminae occur throughout the section. The quartz grains tend to be better rounded than those in the rest of the stratigraphic column are. The sand is glauconitic in places suggesting deposition in shoreline or shallow shelf environments (Figure 1.4-37). To the south, near well ALL-324, the Congaree Formation consists of interbedded glauconitic sand and shale, grading to glauconitic, argillaceous, fossiliferous sandy limestone suggestive of shallow to deeper shelf environments of deposition. Farther south, beyond well C-10 (Ref. 220), the Congaree grades into platform carbonate facies of the lower Santee Limestone (see Figure 1.4-37).

The equivalent of the Congaree northwest of SRS has been mapped as the Huber Formation (Ref. 224). At these locations it becomes more micaceous and poorly sorted, indicating deposition in fluvial and upper delta plain environments. On geophysical logs, the Congaree has a distinctive low gamma ray count and high electrical resistivity.

Warley Hill Formation. Unconformably overlying the Congaree Formation are 3 meters (10 feet) to 6 meters (20 feet) of fine-grained, often glauconitic sand and green clay beds that have been referred to respectively as the Warley Hill and Caw Caw Members of the Santee Limestone. The green sand and clay beds are referred to informally as the "green clay" in previous SRS reports. Both the glauconitic sand and the clay at the top of the Congaree are assigned to the Warley Hill Formation (Ref. 233). In the updip parts of the study area, the Warley Hill apparently is missing or very thin, and the overlying Tinker/Santee Formation rests unconformably on the Congaree Formation.

The Warley Hill sediments indicate shallow to deeper clastic shelf environments of deposition in the study area, representing deeper water than the underlying Congaree Formation (Figure 1.4-37). This suggests a continuation of a transgressive pulse during upper middle Eocene time. To the south, beyond well P-21, the green silty sand, and clay of the Warley Hill undergo a facies change to the clayey micritic limestone and limey clay typical of the overlying Santee Limestone. The Warley Hill blends imperceptibly into a thick clayey micritic limestone that divides the Floridan Aquifer System south of the study area. The Warley Hill is correlative with the lower

part of the Avon Park Limestone in southern Georgia and the lower part of the Lisbon Formation in western Georgia.

In the study area, the thickness of the Warley Hill Formation is generally less than 6 meters (20 feet). In a part of Bamberg County, South Carolina, the Congaree Formation is not present, and the Warley Hill rests directly on the Williamsburg Formation (Ref. 222).

Tinker/Santee Formation. The late middle Eocene deposits overlying the Warley Hill Formation consist of moderately sorted yellow and tan sand, calcareous sand and clay, limestone, and marl. Calcareous sediments dominate downdip, are sporadic in the middle of the study area, and are missing in the northwest (Figure 1.4-38). The limestone represents the farthest advance to the northwest of the transgressing carbonate platform first developed in early Paleocene time near the South Carolina and Georgia coasts (Figure 1.4-37).

Fallaw et al. (Ref. 233) divided the Santee into three members in the study area: the McBean, Blue Bluff, and Tims Branch Members. The McBean Member consists of tan to white, calcilutite, calcarenite, shelly limestone, and calcareous sand and clay. It dominates the Santee in the central part of the study area and represents the transitional lithologies between clastics in the north and northwest (Tims Branch Member), and fine-grained carbonates in the south (Blue Bluff Member).

The carbonates and carbonate-rich clastics are restricted essentially to three horizons in the central part of, the Griffins Landing Member of the Dry Branch Formation, the McBean Member of the Tinker/Santee Formation and the Utley Limestone member of the Clinchfield Formation (Figures 1.4-18, 1.4-39, 1.4-40). The uppermost horizon includes the carbonates of the Griffins Landing Member of the Dry Branch Formation found below the "tan clay" interval that occurs near the middle of the Dry Branch. The isolated carbonate patches of the Griffins Landing are the oyster banks that formed in the back barrier marsh zone behind the barrier island system (Figures 1.4-37 and 1.4-40). Underlying the Dry Branch, directly below the regionally significant Santee Unconformity (Figure 1.4-39), is the Utley Limestone Member of the Clinch Field Formation. Without the benefit of detailed petrographic and paleontological analysis, the Utley carbonates cannot be systematically distinguished from the carbonates of the underlying Tinker/Santee Formation. Thus the carbonate-rich sediments between the Santee Unconformity (Figure 1.4-39), and the Warley Hill Formation are referred to as the Tinker/Santee (Utley) sequence in this report.

Approximately 40-50% of the wells that drilled through the Tinker/Santee (Utley) interval in the GSA penetrated quantities of carbonate ranging from 5-78% of the sediment sampled (Figure 1.4-38). The calcareous sediment in the GSA consists of calcareous sand, calcareous mud, sandy limestone, muddy limestone, and sandy muddy limestone. Viewing the Tinker/Santee (Utley) sedimentary package parallel to the shoreline (Figure 1.4-37), the carbonate-rich sediments would be concentrated in the areas furthest removed from the tidal inlets at the shore face where clastic sediments supplied by riverine input is concentrated. The clastic-rich on the other hand would concentrate opposite the tidal inlet areas where clastic sediment is more readily available. The lateral facies transition of the sediments in the subtidal shelf environment from carbonate-rich to clastic-rich lithologies is therefore gradual and measures in the thousands of feet. Shifting

locations of the tidal inlets at the shoreline has resulted in a complex sedimentary package where facies gradually transition from one lithology to another both laterally and vertically.

The GSA is in that part of the mixed clastics/carbonate zone where the clastic sediments generally constitute a greater percentage of the section than the carbonates (Figure 1.4-38). Figure 1.4-40 illustrates the environments of deposition of the Tinker/Santee (Utley) sediments in the SRS region. In northern SRS the Tinker/Santee (Utley) sediments are mostly sands and muddy sands (Tims Branch Member) deposited in shoreline to lesser lagoonal and tidal marsh environments (Figure 1.4-37). In the central SRS the sequence was deposited in middle marine shelf environments resulting in a varied mix of lithologies from carbonate-rich sands and muds to sandy and muddy limestones. In southern SRS the Tinker/Santee (Utley) sediments were deposited further offshore, further removed from riverine clastic input into the shelf environment resulting in deposition of carbonate muds (Blue Bluff Member).

The Blue Bluff Member consists of gray to green, laminated micritic limestone. The unit includes gray, fissile, calcareous clay and clayey micritic limestone and very thinly layered to laminated, clayey, calcareous, silty, fine sand, with shells and hard, calcareous nodules, lenses, and layers. Cores of Blue Bluff sediments are glauconitic, up to 30% in places. The Blue Bluff lithology suggests deposition in offshore shelf environments. Blue Bluff sediments tend to dominate the formation in the southern part of the study area and constitute the major part of the "middle confining unit" that separates the Upper and Lower Floridan aquifers south of the study area.

Fallaw et al. (Ref. 233) described the Tims Branch Member of the Santee as the siliciclastic part of the unit, consisting of fine- and medium-grained, tan, orange, and yellow, poorly to well sorted, and slightly to moderately indurated sand. The clastic lithologies of the Tims Branch Member dominate the Santee in the northern part of the study area. Because the clastic lithologies differ so markedly from the type Santee, Fallaw and Price (Ref. 118) raised the Tims Branch Member of the Santee to formational rank, namely the Tinker Formation. Because the clastic and carbonate lithologies that constitute the Tinker/Santee sequence in the upper and middle parts of the study area are hydrologically undifferentiated, the units are not systematically separated, and they are designated Tinker/Santee Formation on maps and sections. The thickness of the Tinker/Santee Formation is variable due in part to displacement of the sediments, but more commonly to dissolution of the carbonate resulting in consolidation of the interval and slumping of the overlying sediments of the Tobacco Road and Dry Branch Formations into the resulting lows (Figure 1.4-41).

The Tinker/Santee (Utley) interval is about 21 meters (70 feet) thick near the center of SRS, and the sediments indicate deposition in shallow marine environments (Figure 1.4-40). The top of the unit is picked on geophysical logs where Tinker/Santee (Utley) sediments with lower electrical resistivity are overlain by the more resistive sediments of the Dry Branch Formation (Figure 1.4-39). In general, the gamma-ray count is higher than in surrounding stratigraphic units.

Often found within the Tinker/Santee (Utley) sediments, particularly in the upper third of the interval, are weak zones interspersed in stronger carbonate-rich matrix materials. The weak zones, which vary in apparent thickness and lateral extent, were noted where rod drops and/or

lost circulation occurred during drilling, low blow counts occurred during SPT pushes, etc. The weak zones have variously been termed as "soft zones", the "critical layer", "underconsolidated zones", "bad ground", and "void". For this report, the preferred term used to describe these zones will be "soft zones."

The initial Corps of Engineers (COE) characterization in 1952 identified soft zones as being the major concern for foundation design. This initial study made many important observations concerning the formation, geometry, distribution, and physical attributes of soft zones (and potential associated voids) within the Santee Formation. Some of the soft zone observations and hypotheses set forth by the COE report have remained unchanged to this day. However, several important aspects of early soft zone analyses run counter to current thinking on this subject (Ref. 235)

Barnwell Group

Upper Eocene sediments of the Barnwell Group (see Figure 1.4-18) represent the Upper Coastal Plain of western South Carolina and eastern Georgia (Ref. 222). Sediments of the Barnwell Group are chronostratigraphically equivalent to the lower Cooper Group (late Eocene) of Colquhoun et al. (Ref. 220). The Cooper Group includes sediments of both late Eocene and early Oligocene age and appears downdip in the Lower Coastal Plain of eastern South Carolina.

Sediments of the Barnwell Group overlie the Tinker/Santee Formation and consist mostly of shallow marine quartz sand containing sporadic clay layers. Huddleston and Hetrick (Ref. 236) recently revised the upper Eocene stratigraphy of the Georgia Coastal Plain, and their approach has been extended into South Carolina by Nystrom and Nystrom and Willoughby (Ref. 224, 237). These authors elevated the Eocene "Barnwell Formation" to the "Barnwell Group." In Burke County, Georgia, the group includes (from oldest to youngest) the Clinchfield Formation, and Dry Branch Formation, and the Tobacco Road Formation. The group is about 21 meters (70 feet) thick near the northwestern boundary of SRS and 52 meters (170 feet) near its southeastern boundary. The regionally significant Santee Unconformity that defines of boundary between Sequence Stratigtraphic units II and III (Figure 1.4-18) separates the Clinchfield Formation from the overlying Dry Branch Formation. The Santee Unconformity is a pronounced erosional surface observable throughout the SRS region (Figures 1.4-18 and 1.4-39).

In the northern part of the study area, the Barnwell Group consists of red or brown, fine to coarse-grained, well-sorted, massive sandy clay and clayey sand, calcareous sand and clay, as well as scattered thin layers of silicified fossiliferous limestone. All are suggestive of lower delta plain and/or shallow shelf environments (Figure 1.4-37). Downdip, the Barnwell undergoes a facies change to the phosphatic clayey limestone that constitutes the lower Cooper Group. The lower Cooper Group limestone beds indicate deeper shelf environments.

Clinchfield Formation. The basal late Eocene Clinchfield Formation consists of light colored quartz sand and glauconitic, biomoldic limestone, calcareous sand, and clay. Sand beds of the formation constitute the Riggins Mill Member (Ref. 236) of the Clinchfield Formation and are composed of medium to coarse, poorly to well sorted, loose and slightly indurated, tan, clay, and green quartz. The sand is difficult to identify unless it occurs between the overlying carbonate layers of the Griffins Landing Member and the underlying carbonate layers of the Santee

Limestone. The Clinchfield is about 8 meters (25 feet) thick in the southeastern part of SRS and pinches out or becomes unrecognizable at the center of the site.

The carbonate sequence of the Clinchfield Formation is designated the Utley Limestone Member (Ref. 231). It is composed of sandy, glauconitic limestone and calcareous sand, with an indurated, biomoldic facies developed in places. In cores, the sediments are tan and white and slightly to well indurated. Without the benefit of detailed petrographic and paleontological analysis, the Utley carbonates cannot be systematically distinguished from the carbonates of the underlying Tinker/Santee Formation. Thus the carbonate-rich sediments between the Santee Unconformity (Figures 1.4-18 and 1.4-39), and the Warley Hill Formation are referred to as the Tinker/Santee (Utley) sequence in this report.

Dry Branch Formation. The late Eocene Dry Branch Formation is divided into the Irwinton Sand Member, the Twiggs Clay Member, and the Griffins Landing Member (Ref. 231). The unit is about 18 meters (60 feet) thick near the center of the study area. The top of the Dry Branch is picked on geophysical logs where a low gamma-ray count in the relatively clean Dry Branch sand increases sharply in the more argillaceous sediments of the overlying Tobacco Road Sand.

The Dry Branch sediments overlying the Tinker/Santee (Utley) interval in the central portion of SRS were deposited in shoreline/lagoonal/tidal marsh environments (Figure 1.4-40). The shoreline retreated from its position in northern SRS during Tinker/Santee (Utley) time to the central part of SRS in Dry Branch time. Progradation of the shoreline environments to the south resulted in the sands and muddy sands of the Dry Branch being deposited over the shelf carbonates and clastics of the Tinker/Santee (Utley) sequence.

The Twiggs Clay Member does not seem to be mappable in the study area. Lithologically similar clay is present at various stratigraphic levels in the Dry Branch Formation. The tan, light-gray, and brown clay is as thick as 4 meters (12 feet) in SRS wells but is not continuous over long distances. This has been referred to in the past as the "tan clay" in SRS reports (Figure 1.4-39). The Twiggs Clay Member, that predominates west of the Ocmulgee River in Georgia, is not observed as a separate unit in the study area.

The Griffins Landing Member is composed mostly of tan or green, slightly to well indurated, quartzose calcareous micrite and sparite, calcareous quartz sand and slightly calcareous clay (Ref. 233). Oyster beds are common in the sparry carbonate facies (Figure 1.4-40). The unit seems to be widespread in the southeastern part of SRS, where it is about 15 meters (50 feet) thick, but becomes sporadic in the center and pinches out. Carbonate content is highly variable. In places, the unit lies unconformably on the Utley Limestone Member, which contains much more indurated, moldic limestone. In other areas, it lies on the noncalcareous quartz sand of the Clinchfield. Updip, the underlying Clinchfield is difficult to identify or is missing, and the unit may lie unconformably on the sand and clay facies of the Tinker/Santee Formation. The Griffins Landing Member appears to have formed in lagoonal/marsh environments (Figure 1.4-40).

The Irwinton Sand Member is composed of tan, yellow and orange, moderately sorted quartz sand, with interlaminated and interbedded clay abundant in places (Ref. 233). Pebbly layers are present, as are clay clast-rich zones (Twiggs Clay lithology). Clay beds, which are not continuous over long distances, are tan, light gray, and brown in color, and can be several feet

thick in places. These are the "tan clay" beds of various SRS reports. Irwinton Sand beds have the characteristics of shoreline to shallow marine sediments (Figures 1.4-37 and 1.4-40). The Irwinton Sand crops out in SRS. Thickness is variable, but is about 12 meters (40 feet) near the northwestern site boundary and 21 meters (70 feet) near the southeastern boundary.

Tobacco Road Formation. The Late Eocene Tobacco Road Formation consists of moderately to poorly sorted, red, brown, tan, purple, and orange, fine to coarse, clayey quartz sand (Ref. 233). Pebble layers are common, as are clay laminae and beds. Ophiomorpha burrows are abundant in parts of the formation. Sediments have the characteristics of lower Delta plain to shallow marine deposits (Figure 1.4-37). The top of the Tobacco Road is characterized by the change from a comparatively well-sorted sand to the more poorly sorted sand, pebbly sand, and clay of the "Upland unit." Contact between the units constitutes the "Upland" unconformity (Ref. 229). The unconformity is very irregular due to fluvial incision that accompanied deposition of the overlying "Upland unit" and later erosion. As stated previously, the lower part of the Cooper Group (upper Eocene) is the probable downdip equivalent of the Tobacco Road Formation.

"Upland Unit"/Hawthorn/Chandler Bridge Formations. Deposits of poorly sorted silty, clayey sand, pebbly sand, and conglomerate of the "Upland unit" cap many of the hills at higher elevations over much of the study area. Weathered feldspar is abundant in places. The color is variable, and facies changes are abrupt. Siple (Ref. 123) assigned these sediments to the Hawthorn Formation. Nystrom et al. (Ref. 237), who mapped it as the "Upland unit", discuss evidence for a Miocene age. The unit is up to 18 meters (60 feet) thick. The environment of deposition appears to be fluvial, and the thickness changes abruptly owing to channeling of the underlying Tobacco Road Formation during "Upland" deposition and subsequent erosion of the "Upland" unit itself. This erosion formed the "Upland" unconformity (Ref. 229). The unit is up to 18 meters (60 feet) thick (Ref. 237).

Lithologic types comparable to the "Upland" unit but assigned to the Hawthorn Formation overlie the Barnwell Group and the Cooper Group in the southern part of the study area. In this area, the Hawthorn Formation consists of very poorly sorted, sandy clay, and clayey sand, with lenses of gravel and thin beds of sand very similar to the "Upland unit". Farther downdip, the Hawthorn overlies the equivalent of the Suwanee Limestone and acts as the confining layer overlying the Floridan Aquifer System. It consists of phosphatic, sandy clay and phosphatic, clayey sand and sandy, dolomitic limestone interbedded with layers of hard, brittle clay resembling stratified fuller's earth.

Colquhoun et al. (Ref. 238) suggest that the "Upland unit", Tobacco Road Formation, and Dry Branch Formation are similar in granularity and composition, indicating that they might be similar genetically, that is that they are part of the same transgressive/regressive depositional cycle. The "Upland unit" represents the most continental end member (lithofacies) and the Dry Branch Formation represents the most marine end member. Thus, the "Upland unit" is the result of a major regressive pulse that closed out deposition of the Barnwell Group/Cooper Group depositional cycle. Colquhoun et al.(Ref. 238) suggested that the "Upland unit" is correlative with the Chandler Bridge Formation downdip toward the coast. This hypothesis is significant because it implies that there was no major hiatus between the "Upland unit" and the underlying

Tobacco Road and Dry Branch Formations. The existence of a hiatus between the units has been reported by numerous studies of the South Carolina Coastal Plain (Ref. 118, 123, 222, 237).

Quaternary Surfaces and Deposits

Determining fault capability requires assessing the potential for Quaternary (1.6 - 0.01 Ma) deformation (Ref. 239). The Quaternary and neotectonic studies conducted at SRS during 1991-1992 by Geomatrix were designed to span the geologic record between deposition of the "Upland unit" and the present, and to determine if deformation has affected Quaternary-age deposits or surfaces (Ref. 239, 240). The Quaternary record in the SRS area is preserved primarily in fluvial terraces along the Savannah River and its major tributaries and in deposits of colluvium, alluvium, and eolian sediments on upland interfluve areas (see Figure 1.4-36).

SRS lies within the interfluve area between the Savannah and the Salkahatchie Rivers. The drainage systems within the site consist entirely of streams that are tributary to the Savannah River. A series of nested fluvial terraces are preserved along the river and major tributaries. Fluvial terraces are the primary geomorphic surface that can be used to evaluate Quaternary deformation within SRS. However, there is limited data available for the estimation of ages of river terraces in both the Atlantic and Gulf Coastal Plains (Ref. 241-245).

Major stream terraces form by sequential erosional and depositional events in response to tectonism, isostasy, and climate variation. Streams respond to uplift by cutting down into the underlying substrate in order to achieve a smooth longitudinal profile that grades to the regional base level. Aggradation or deposition occurs when down-cutting is reversed by a rise in base level. The stream channel is elevated and isolated from the underlying marine strata by layers of newly deposited fluvial sediments. Down-cutting may resume and the aggraded surface is abandoned. The result is a landform referred to as a fill terrace.

At the SRS there are two prominent terraces above the modern floodplain (Qal (see Figure 1.4-36). These designations are based on morphology and relative height above local base level. Local base level is the present elevation of the Savannah River channel. In addition, there are other minor terraces: one lower and several higher, older terrace remnants.

The terraces of Upper Three Runs and Steel Creeks were mapped on false color, infrared aerial photography, and field checked. Although exposures of fluvial deposits are extremely limited, these terraces are laterally continuous. Upper Three Runs terraces are of interest to SRS because of their position over the Atta and Upper Three Runs Faults. The terraces along Steel Creek represent a family of seven sets of well-defined fluvial terraces, one of the best sequences of terraces at SRS. These terraces range from less than 1 meter to 30 meters (3 to 100 ft) above local base level. The lower terraces appear to be fill terraces whereas the higher terraces appear to be strath terraces that cut into Tertiary strata. The Steel Creek drainage parallels the trace of the subsurface Steel Creek Fault.

Estimated ages of the terraces are based on several techniques including radiometric carbon-14 dates, soil chronosequences, relative position above base level and correlation to other dated river or marine terraces. The modern floodplain is as old as the latest Pleistocene to Holocene (Ref. 240). Others have indicated a much younger age of 4,000 years (Ref. 244). Based on soil

chronosequences, it is at least 400 ka to perhaps 1 Ma. Brooks and Sassaman (Ref. 246) conclude early to middle Holocene (less than 10 ka) based on geoarchaeological studies. The terraces on Upper Three Runs range from 11 ka for the lower (0.5 to 4.5 meters) terrace to 38 to 47 ka for the higher (greater than 6 meters [30 ft]) terrace. Overall, the terraces at SRS represent ages from middle Holocene (less than 10 ka) to late Pleistocene (1 Ma).

Carolina Bays

Carolina bays are shallow, elliptical depressions with associated sand rims that are found on the surface of the Coastal Plain sediments. They are found from southern New Jersey to northern Florida with the greatest occurrence in the Carolinas (Ref. 247). One hundred ninety-seven confirmed or suspected Carolina bays have been identified at SRS (see Figure 1.4-42). The long axes of the bays are oriented S50°E (Ref. 248) and the sand rims are observed on the east and southeast flanks. Numerous authors have provided several hypotheses for the timing and mode of origin for these bays (Ref. 70, 249-253). Theories regarding the origin of bays include meteorite impact, sinks, wind, and water currents. The origin of these features continues to be studied.

Soller and Mills (Ref. 247) suggest that the work done by Savage (Ref. 254) and Kaczorowski (Ref. 253) provides the most likely explanation of formation. They suggest that the bays were formed by action of strong unidirectional wind on water ponded in surface depressions. The resulting waves caused the formation of the sand rims as shoreline features, and the sand rims formed perpendicular to the wind direction. Therefore, the wind that formed the bays we observe today was a southwesterly wind (Ref. 247).

The Carolina bays are surficial features that have no effect on the subsurface sediments. Based on subsurface core data, Gamble et al. (Ref. 249) demonstrated that a clay layer mapped beneath the bays and beyond had no greater relief beneath the bays than beyond them. Additional evidence of the surficial character of Carolina bays is povided by Thom (Ref. 252). In these studies certain identified strata could be mapped and found continuous and undeformed beneath bay and interbay areas. In Horry and Marion Counties, South Carolina, there was no evidence of solution-related subsidence of the Carolina bays, in spite of the presence of carbonate-rich strata in the subsurface and some localized sink holes of irregular shape with depths on the order of 6 meters (20 feet).

Gamble et al. (Ref. 249) indicated that there are two types of bay rims, a primary, and a secondary. They may have a cross cutting relationship with each other or exist as rims within a rim. Bays may have secondary rims, but it is not a necessary condition. Formation of secondary bay rims as a consequence of wind and water action along the shores of a shallow body of water can account for the development of multiple bay rims and bays within bays. Receding water levels could alter the shape of the shoreline and cause one or more subsequent secondary rims to develop inside the confines of the first one. The altered shape of the water body could cause the new secondary rim to truncate and obliterate part of the old secondary rim.

The age of the bays is based on Soller (Ref. 245) and Thom (Ref. 252). A minimum age was set at middle to late Wisconsinian based on radiocarbon dating (Ref. 252). The maximum age can be relatively determined by examination of the formations on which the bays rest. If one

assumes a single generation of formation for all bays, then the bays formed after deposition of the Socastee Formation and before the Wando Formation (Ref. 243). This places bay formation between 100 and 200 ka. If there is more than one generation, then the bays could be as old as the formations on which they rest.

Carbonate and Soft Zones

Often found within the Tinker/Santee (Utley) sediments, particularly in the upper third of this section, are weak zones interspersed in stronger carbonate-rich matrix materials. These weak zones, which vary in apparent thickness and lateral extent, were recorded where rod drops and/or lost circulation occurred during drilling, low blow counts occurred during SPT pushes, etc. They have variously been termed as "soft zones", "the critical layer", "underconsolidated zones", "bad ground", and "void". The preferred term used to describe these zones is "soft zones".

The initial Corps of Engineers (COE) characterization in 1952 (Ref. 255) identified soft zones as being the major concern for foundation design. This initial study made many important observations concerning the formation, geometry, distribution, and physical attributes of soft zones (and potential associated voids) within the Santee Formation. Some of the soft zone observations and hypotheses set forth by the COE report have remained unchanged to this day. However, several important aspects of early soft zone analyses run counter to current thinking on this subject.

Historically, the soft zones were grouted as an expedient way of resolving any potential foundation stability issues. This method continued through the restart of the K-reactor where the project chose to grout the Santee formation beneath the cooling water lines to resolve a potential foundation stability issue. The results of that effort were carefully studied and it was found that the grout was not having the desired effect on the subsurface soft zones. The results showed that the grout traveled in thin sheets along preferential pathways. Soft zones that existed prior to grouting still existed after grouting was completed. The grouting provided limited benefit in reducing the potential settlement from the soft zones.

More recently, technology improvements have allowed sampling and testing which have resulted in additional insight to the properties of the soft zone soils. With these properties, advanced analytical techniques have been used to resolve the foundation stability issues without requiring soil remediation. The information provided herein allows for a clearer understanding of the geologic underpinnings that established the carbonates and the attendant soft zones.

In general, where carbonates are found (Figures 1.4-38 and 1.4-39) soft zones are likely to be found as well. This conclusion is based on a significant study of soil samples from borings, boring logs, geophysical logs, and cone penetration test soundings throughout the GSA (Ref. 235). This review was instrumental in delineating the extent of both carbonates and soft zones. The data were studied in many different ways but resulted in the simple conclusion that although carbonates and soft zones are not found in every drill hole or CPT, they are generally found in every area that was investigated in the GSA.

Isopach maps (Ref. 235) reveal that carbonate thickness and concentration is directly related to the isopach thickness of the Tinker/Santee (Utley) interval. Where the Santee-Utley interval is

thick, carbonate is more concentrated, where the interval is thin, carbonate thickness and concentration is reduced. It is further observed that where carbonate is concentrated in the Santee-Utley section the overlying "upland unit", Tobacco Road/Dry Branch section (Figure 1.4-41) is generally structurally high, and where the carbonate content is reduced or absent the overlying "upland unit," Tobacco Road/Dry Branch section is generally structurally low. This indicates that the removal (dissolution) of carbonate and the thinning of the Santee-Utley interval occurred in post Tobacco Road time

Since the thickness and distribution of soft zones is closely linked to the thickness and distribution of carbonate, those areas where clastic sediments were initially concentrated and in structurally low areas where a great deal of carbonate has been removed would be areas where soft zones may not be present. This however would not reduce the need to investigate these areas for potential siting of new facilities but would aid in siting and land use issues.

Origin of Carbonates and Soft Zones. The origin of the carbonates in the Tinker/Santee (Utley) interval is fairly clear. The carbonate content ranges from zero to approximately 90 percent. The presence of glauconite along with a normal marine fauna including foraminifers, molluscs, bryozoans, and echinoderms, indicates that the limestones and limy sandstones were deposited in clear, open-marine water of normal salinity on the inner to middle shelf (Figures 1.4-37 and 1.4-40). The abundance of carbonate mud (micrite) in the limestones suggests deposition in quiet water below normal marine wave base. The presence of abraded and well-worn skeletal grains indicates that bottom transport by currents or storm-generated waves alternated with quiet-water conditions in which the sediments accumulated.

Viewing the Santee sedimentary package parallel to the shoreline, the carbonate-rich sediments would be concentrated in the areas furthest removed from the tidal inlets at the shore face where clastic sediments supplied by riverine input is concentrated (Figure 1.4-37). The clastic-rich sediments on the other hand would concentrate opposite the tidal inlet areas where clastic sediment is more readily available. The lateral facies transition of the sediments in the subtidal shelf environment from carbonate-rich to clastic-rich lithologies is therefore gradual and measures in the thousands of feet. Shifting locations of the tidal inlets at the shoreline has resulted in a complex sedimentary package where facies gradually transition from one lithology to another both laterally and vertically. Therefore, both vertical and lateral lithologic variability in the Tinker/Santee (Utley) sequence is the rule rather than the exception. Locally the contact between carbonate sediments and laterally comparable clastic sediments is often sharply drawn, occurring over distances of only a few feet.

The original thoughts were that the soft zones were the result of the dissolution of the shell debris concentrated in bioherms (oyster banks). This premise has since been proven to be false. Significant study of the deposition of the Tinker/Santee (Utley) sediments precludes the formation of bioherms. Several hypotheses exist concerning the origin of the soft zones: one being that these zones consisted of varying amounts of carbonate material that has undergone dissolution over geologic time leaving sediments that are now subjected to low vertical effective stresses due to arching of more competent soils above the soft zone intervals.

A second hypothesis is based on recent studies that indicate that soft zones occur where silica replacement/cementation of the carbonate occurred. The silicification (by amorphous opaline

silica) of the enclosing carbonate sediment would follow and spread along bedding planes, along microfractures of varied orientations and along corridors of locally enhanced permeability (Figure 1.4-43). The resulting "soft zone" could be in the form of irregular isolated pods, extended thin ribbons or stacked thin ribbons separated by intervening unsilicified parent sediment. Careful observations of the grouting programs conducted by the COE in the early 1950s, and more recently for the restart of K Reactor, corroborate these recent findings. They observed that the grout was not having the desired effect on the subsurface soft zones as was previously thought. The results showed that the grout traveled in thin sheets along preferential pathways. Soft zones that existed prior to grouting still existed after grouting was completed. Soft zones encountered in one cone penetrometer test (CPT) sounding could be absent in the neighboring CPT only a few feet away. Only where silicification has spread far enough away from the bedding planes and/or fractures along which the silica replacement has taken place, where all the intervening sediment is replaced, would the soft zones be large enough and coherent enough to pose a question for the siting of new facilities. In all likelihood this would be a most uncommon event.

Geotechnical investigation programs are performed routinely for new facilities at SRS. Detection of soft zones will not prevent the siting of new facilities in these areas. Exploration to locate soft zones should include soil borings and cone penetration test (CPT) soundings. Our experience indicates that the CPT is the best tool to determine the presence of soft zones. However, exploration programs for critical facilities include combinations of soil borings, CPT soundings, surface and down-hole geophysical measurements, compression and shear wave velocity determinations, and sampling for laboratory testing. It is recommended that initial soft zone identification be determined using the CPT tip resistance and the SPT N-value. For depths between 100 and 150 feet below the ground surface, the CPT criteria would be tip stress less than 1.44 Mpa (15 tons per square foot) and the SPT criteria would be an N-value less than 5. The exploration program depth must be designed to penetrate through the layer where soft zones occur. In the GSA, that translates to depths of approximately 55 meters (180 feet) below ground surface.

For critical facilities it is recommended that a phased investigation program be performed. This could be done in combination with a site selection program, if warranted. The phased program allows for determination of stratigraphy (particularly soft zones) early in the program, then targeting those critical layers that require sampling and laboratory testing. Generally, the initial phase relies heavily on the CPT, and the second phase relies heavily on drilling, sampling and laboratory testing. Because of the depth of the soft zones (30 meters [100 ft] to 46 meters [150 ft] in the GSA) there is no static stability issue. Dynamic settlement, on the other hand, requires evaluation. Analyses include dynamic settlement determinations from partial liquefaction and consolidation from load transfer due to a seismic event.

More recently, technology improvements have allowed sampling and testing which have resulted in additional insight to the properties of the soft zone soils. With these properties, advanced analytical techniques have been used to resolve the foundation stability issues without requiring soil remediation. The information provided herein allows for a clearer understanding of the geologic underpinnings that established the carbonates and the attendant soft zones.

REGIONAL PHYSIOGRAPHY

The site region, defined as the area within a 320-km (200-mile) radius of the center of SRS, includes parts of the Atlantic Coastal Plain, Piedmont and Blue Ridge physiographic provinces. SRS is located on the upper Atlantic Coastal Plain, about 50 km (30 miles) southeast of the Fall Line.

The Atlantic Coastal Plain extends southward from Cape Cod, Massachusetts, to south central Georgia where it merges with the Gulf Coastal Plain. The surface of the Coastal Plain slopes gently seaward. Colquhoun and Johnson (Ref. 218) divided the South Carolina Coastal Plain into three physiographic belts: Upper, Middle, and Lower Coastal Plain. The Upper Coastal Plain slopes from a maximum elevation of 200 meters (650 feet) msl at the Fall Line to about 75 meters (250 feet) msl on its southeastern boundary (see Figure 1.4-44). Primary depositional topography of the Upper Coastal Plain has been obliterated by fluvial erosion. The Upper Coastal Plain is separated from the Middle Coastal Plain by the Orangeburg scarp, which has a relief of approximately 30 meters (100 feet) over a distance of a few miles. The Orangeburg scarp is the locus of Eocene, Upper Miocene, and Pliocene shorelines (Ref. 218). The Middle Coastal Plain, separated from the Lower Coastal Plain by the Surry scarp, is characterized by lower elevations and subtle depositional topography that has been significantly modified by fluvial erosion (Ref. 256). The Lower Coastal Plain is dominated by primary depositional topography that has been modified slightly by fluvial erosion.

Siple (Ref. 118) and Cooke (Ref. 219) previously divided the Upper Coastal Plain of South Carolina into the Aiken Plateau and Congaree Sand Hills. The Aiken Plateau, where SRS is located, is bounded by the Savannah and Congaree Rivers and extends from the Fall Line to the Orangeburg scarp. The plateau's highly dissected surface is characterized by broad interfluvial areas with narrow, steep-sided valleys. Local relief is as much as 90 meters (295 feet) (Ref. 123). The plateau is generally well drained, although many poorly drained sinks and depressions exist, especially on the topographically high (above 76 meters [250 feet] msl) "Upland unit". The Congaree Sand Hills trend along the Fall Line northeast and north of the Aiken Plateau. The sand hills are characterized by gentle slopes and rounded summits that are interrupted by valleys of southeast-flowing streams and their tributaries (Ref. 123).

The site region contains Carolina bays. (Carolina bays are discussed in detail in the previous section.)

The Piedmont province extends southwest from New York to Alabama and lies adjacent to the Atlantic Coastal Plain. It is the eastern-most physiographic and structural province of the Appalachian Mountains. The Piedmont is a seaward-sloping plateau whose width varies from about 10 miles (16 km) in southeastern New York to almost 125 miles (200 km) in North Carolina; it is the least rugged of the Appalachian provinces. Elevation of the inland boundary ranges from about 60 meters (200 feet) msl in New Jersey to over 550 meters (1,800 feet) msl in Georgia.

The Blue Ridge province extends from Pennsylvania to northern Georgia. It varies from about 48 km (30 miles) to 120 km (75 miles) wide north to south. Elevations are highest in North Carolina and Georgia, with several peaks in North Carolina exceeding 1,800 meters (5,900 feet)

msl. Mount Mitchell, North Carolina, is the highest point (2,000 meters , 6,560 feet) msl in the Appalachian Mountains. The Blue Ridge front, with a maximum elevation of 1,200 meters (4,000 feet) msl in North Carolina, is an east-facing escarpment between the Blue Ridge and Piedmont provinces in the southern Appalachians.

GENERAL GEOLOGIC SETTING AT SAVANNAH RIVER SITE (40 km RADIUS)

The 40-km (25-mile) radius study area is taken from DOE-STD-1022-94 (Ref. 139) as the area in which to conduct geoscience investigations to locate possible seismogenic sources and surface deformation or to demonstrate that such features do not exist.

The SRS is located on the Atlantic Coastal Plain, which is an essentially flat-lying, undeformed wedge of unconsolidated marine and fluvial sediments. The sediments are stratified sand, clay, limestone, and gravel that dip gently seaward and range in age from Late Cretaceous to Holocene. The sedimentary sequence thickens from zero at the Fall Line to more than 4,000 feet (1,200 meters) at the coast. Several investigations have provided a great deal of data and insight into the evolution of the southeastern United States Coastal Plain, including Cook (Ref. 219), Siple (Ref. 118), Huddlestun and Hetrick (Ref. 257), Colquhoun and Steele (Ref. 258); Prowell et al. (Ref. 259), Dennehy et al. (Ref. 260), Fallaw and Price (Ref. 231), Fallaw et al. (Ref. 233), Nystrom et al. (Ref. 261), and Bledsoe et al. (Ref. 103). The Coastal Plain section is divided into several rock-stratigraphic groups, based principally on age and lithology (see Figure 1.4-45). The details of Coastal Plain stratigraphy have been discussed in the preceding section.

Beneath the Coastal Plain sedimentary sequence and below a pre-Cretaceous unconformity are two geologic terranes: (1) the Dunbarton basin, a Triassic-Jurassic Rift basin, filled with lithified terrigenous and lacustrine sediments with possible minor amounts of mafic volcanic and intrusive rock (Ref. 262-266); and (2) a crystalline terrane of metamorphosed sedimentary and igneous rock that may range in age from Precambrian to late Paleozoic (see Figure 1.4-46). The Paleozoic rocks and the Triassic sediments were leveled by erosion, forming the base for Coastal Plain sediment deposition. The erosional surface dips southeast approximately 8 m/km (42 ft/mile).

Information about the Dunbarton basement and crystalline terrane comes primarily from deep borings. The U.S. Army Corps of Engineers drilled a single hole into basement rock in 1950 for the startup of the plant (Ref. 267). In 1961, The Bedrock Waste Storage Project rock exploration program was conducted to determine the feasibility of long-term storage of radioactive waste in mined rock chambers . Twelve deep rock borings, the DRB well series, were completed into basement to various depths greater than 300 meters (980 feet) to accomplish this goal. This information is also augmented by deep borings used to constrain seismic reflection informationboth in the early 1970s (P-R series) and more recently acquired information (MMP and GCB series). The topography of the crystalline basement is shown on Figure 1.4-47.

In addition to the direct information furnished by the deep borings, information about the composition, extent and structure of crystalline terrane and the Dunbarton basin are also provided by potential field geophysical methods. Detailed gravity information concerning SRS and vicinity exists (Ref. 268, 269) and has been used to provide a detailed gravity map of the site (Figure 1.4-48). In addition high resolution aeromagnetic data are available from the U.S. Geological

Survey (Ref. 202) and have been used to produce a high resolution aeromagnetic map of SRS and vicinity (Ref. 270) (Figure 1.4-49). Several recent studies have been the focus on integrating this geophysical information with the boring information listed above to evolve a fairly detailed model of the crystalline terrane and Dunbarton Basin (Ref. 266, 272-277).

Crystalline Terrane

The studies mentioned above have determined that the lithologies and structures in the crystalline terrane are basically similar to that seen in the eastern Piedmont province as exposed in other parts of the southeastern United States. The crystalline rocks form a volcanic – intrusive sequence of calc-alkaline composition, portions of which record both ductile and brittle deformational events. These relationships indicate that these rocks are the metamorphosed and deformed remnants of an ancient volcanic arc that are interpreted to be Carolina Terrane equivalents.

The crystalline rocks were mapped as three formations (Ref. 275) (Figure 1.4-46). The Crackerneck formation consists of weakly to unmetamorphosed and mildly to undeformed volcanic rocks of intermediate to felsic composition with minor amounts of mafic material. The rocks in this formation are represented mainly by tuffs and lapilli tuffs (extrusive volcanic rocks).

The DRB Formation (named after the Deep Rock Borings in which it is found) consists of moderately metamorphosed and highly to moderately deformed volcanic and plutonic rocks of mafic to intermediate compositions. The DRB Formation is cut by deformed amphibolite dikes and by undeformed dikes of basaltic and rhyolitic compositions, indicating that these rocks were intruded both before deformation and after the major episode of deformation had ceased. The DRB Formation may also contain a minor amount of quartz-rich sedimentary rock. However, the identification of this material is uncertain.

The PBF Formation (named after the Pen Branch Fault borings in which it is found) occurs as a thin slice between the Dunbarton Basin to the south and the DRB Formation to the north. This formation contains strongly metamorphosed gneisses and amphibolites that have experienced relatively high thermal effects and appear to be deeper equivalents of the DRB Formation. The plutonic rocks of both the DRB Formation and PBF Formation have radiometerically dated crystallization ages of 620 Ma. Based on the association of these rocks with the Carolina Terrane, the metavolcanic rocks of the Crackerneck Formation are interpreted to have been deposited unconformably on the DRB formation at about 620 Ma.

Subsequent to the formation of this volcanic stratigraphy these rocks underwent multiple deformational episodes and chemical changes. The rocks of the DRB formation record highly developed deformational fabrics that indicate that these rocks have undergone significant amounts of ductile shearing at moderately high temperatures. These fabrics, in association with the superposition and juxtaposition of the higher temperature PBF formation indicate that this deformation resulted from thrust and strike-slip faulting, which placed the PBF formation over the DRB formation. Based on radiometric age dating of biotite in the fault zone, this deformation is Paleozoic in age (approximately 300 Ma). In addition to ductile deformation features, the sub-Cretaceous basement rocks also record the effects of brittle deformation episodes characterized by fractures, brittle faults, and frictional melting. The presence of

mineralized veins associated with these fractures and brittle faults indicate that the brittle faulting was often accompanied by the movement of hot waters. Radiometric dating of these effects suggest that at least one phase of brittle deformation occurred around 220 Ma. This age would make this phase of brittle deformation most likely associated with formation of the Dunbarton basin. Other younger brittle deformation features are also present, and are most likely associated with Tertiary deformation in the basement such as the Pen Branch Fault. Radiometric dating of fracture filling yielded an age of 23 Ma. However, the radiometric systematics of the mineral dated are not well known so the geologic meaning of this age is uncertain.

Dunbarton Triassic Rift Basin

The Dunbarton basin underlies the southeastern portion of SRS and was first identified based on aeromagnetic and well data (Ref. 264). Subsequent seismic reflection surveys, potential field surveys, and additional well data have led to the current understanding of the basin (Ref. 262-266, 268, 269, 271, 272, 277-279). The structure is currently interpreted as an asymmetric graben approximately 50 km (30 miles) long and 10 to 15 km (6 to 9 miles) wide. The axis of the basin strikes north 63° east, which is parallel to the regional strike of crystalline basement (Ref. 264). The basin extends 8 km (5 miles) southwest of the Savannah River and 40 km (24 miles) to the northeast of SRS, where it terminates against a granite body interpreted from magnetic data (Ref. 220, 264, 268, 272). The master border fault, named the Pen Branch Fault, is on the northwest boundary of the basin and dips to the southeast.

The southeast boundary of the basin is poorly constrained but is interpreted as a fault (Ref. 124, 265). Southeast of the Dunbarton basin aeromagnetic and gravity data indicate a terrane heavily influenced by basalt flows and sills. The magnetic data contain numerous high-frequency, closed-contour features indicative of shallow structures, and lower frequency features indicative of deeper-seated features. The host rock is perhaps crystalline metamorphosed rock similar to what is found further to the northwest beneath SRS. In addition, Madabhushi and Talwani (Ref. 440) suggest that this terrane separates the Piedmont orogeny from crust of a different affinity further to the southeast. In effect, the mafic intrusions define the southeastern boundary of the Dunbarton basin and the northern boundary of the South Georgia Rift basin (Ref. 215).

Ten wells drilled in the southeastern half of SRS penetrated sedimentary rocks of the Dunbarton basin (see Figure 1.4-46). Recovered core is clastic rock (Ref. 264, 280). Conglomerate, fanglomerate, sandstone, siltstone, and mudstone are the dominant lithologies. These rocks are similar to the clastic facies in other Newark Supergroup basins. In addition, four of the Pen Branch fault series wells penetrated Triassic rock. Conglomerate and red clayey siltstone are the dominant lithologies in these cores. Parsons et al. (Ref. 280) conclude that the lithology and stratigraphy identified in these core indicate that the proximal side of the basin is to the northwest. There is a larger component of coarse-grained rock types on the proximal side than on the southeast side of the basin. Marine and Siple (Ref. 264) found an upward increase of total fines in each core. Further, the sediments fine upward in each core. A detailed study of the Dunbarton Basin core that integrated the above observations with some new information (Ref. 266) grouped the sediments in the basin into four lithofaces:

1. A proximal fan facies occurs near the hanging wall of the Pen Branch Fault (see Figure 1.4-50) and consists mainly of poorly sorted, matrix-supported conglomerates dominated by debris flows.
2. A distal fan facies includes silty and sandy mudstones interbedded with massive immature sandstones and wackes.
3. A fringe fan facies which is dominated by mudstones but also contains intervals with bioturbation, roots, and caliches, which indicate periods of flooding overprinted during periods of nondeposition by burrowing and soil formation.
4. A braided plain facies includes cross-stratified channel sandstones erbedded with bioturbated mudstones and fine sandstones containing caliches.

The facies relationships described above suggest an asymmetric basin that subsided faster to the northwest than to the southeast. The asymmetry led to greater local relief along the northern boundary, where high-energy fluvial processes dominated, and the resulting sediments were more coarse grained than farther out in the basin. The predominance of alluvial fan facies with abundant mud and debris flows, and caliches in paleosols suggests that the basin and surrounding areas were poorly vegetated, and an arid to semi-arid climate.

Gravity and magnetic modeling suggests that the Triassic section in the Dunbarton basin averages about 2 km (1.2 miles) thick. Boreholes have encountered up to 899 meters (3,000 feet) of Triassic fill, but the base of the Dunbarton was not encountered (Ref. 264). Seismic reflection data do not unequivocally constrain the base of the basin, as the transition between the Triassic rock and the crystalline terrane is unclear. However, interpreted Triassic reflectors are at least as deep as 1,188 meters (3,900 feet) to 3,688 meters (12,100 feet) (Ref. 269).

SITE GEOLOGIC MAP

A geologic map of the SRS was completed by the USGS and provided to SRS in 1994 (Ref. 281) (see Figure 1.4-36). This map shows the Coastal Plain formations that crop out at the surface. Other, deeper Coastal Plain formations may not be observed at the surface within the boundaries of the site, however, these formations are known to exist in the subsurface based on drill core data and outcrops in nearby regions.

Erosion by the Savannah and Edisto Rivers and tributaries have truncated the uppermost stratigraphic units such as the Upland unit and the Tobacco Road Sand. This gives the geologic map its characteristic dendritic pattern and indicates that the strata are sub-horizontal. Deeper and older formations are exposed in stream valley walls Paleocene and Cretaceous formations crop out in nearby regions and are mapped on the USGS Barnwell sheet (Ref. 281).

Superposed on the Coastal Plain sediments are a variety of alluvial and colluvial deposits that have resulted from streams cutting the valleys they occupy. The alluvial deposits are located in the stream valleys and on terraces and are indicated on the map (see Figure 1.4-36) as Qal 1, Qal 2, and Qt. The reworked sediments are derived from the uppermost Coastal Plain sediments and effectively cover up the deepest formations exposed in the stream valley bottoms.

Contacts separating the geological formations were mapped by examination of natural and manmade surface exposures and from subsurface drill core. Original compilation of field data was done at 1:100,000 scale. The subsequent SRS map is presented at 1:48,000 scale.

1.4.3.2 Tectonic Features

DEFINITION OF PLATE TECTONICS

Plate tectonics is the concept that the earth's crust is broken into large blocks with portions of each block being continually renewed or destroyed. The theory integrates the concepts of rift zone/sea-floor spreading, continental collision/subduction zone, and seismic/volcanic zones into a unified theory. Plate tectonics within the 320-km (200-mile) radius of the SRS would provide the description of the major structural or deformational features of the region, as well as the origins, evolution, and interrelationship of these features.

The implementation of Natural Phenomena Hazards Mitigation requires that the tectonic elements of the site region should be understood and described in sufficient detail to allow an evaluation of the safety of a proposed or existing facility. The major issue with respect to the tectonic framework and site suitability is concern for tectonic features influencing the seismicity of the region.

Based on previous studies at SRS and elsewhere, there are no known capable or active faults within the 320-km radius of the site that influence the seismicity of the region with the exception of the blind, poorly constrained faults associated with the Charleston seismic zone (see Section 1.4.4).

DEFINITION OF SEISMOGENIC FAULTS

Various definitions have been established to evaluate the issues of describing the deformational features and relating specific features to seismicity. These definitions are derived from classical geology and regulatory geology. In some cases, the same concept is defined with different terminology. The definitions that follow are taken from the NRC and DOE.

The NRC provided their definition in 10 CFR Part 100, Appendix A, as follows (Ref. 282):

Capable fault: a fault, which has one or more of the following characteristics:

1) Movement at or near the ground surface at least once in the past 35,000 years or repeatedly within the past 500,000 years.

2) Macro-seismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault.

3) A structural relationship to a capable fault according to characteristics 1 or 2 such that movement on one could be reasonably expected to be accompanied by movement on the other.

The NRC has proposed the following definition in amendments to 10 CFR Part 100 (Section 100.23).

Capable tectonic source: a tectonic structure that can generate both vibratory ground motion and tectonic surface deformation such as faulting or folding at or near the earth's surface in the present seismotectonic regime. Characterized by the attributes defining a capable fault in the 1973 regulations.

The NRC is also defining a seismogenic source as a portion of the earth that has uniform earthquake potential (same expected maximum earthquake and frequency of recurrence) distinct from other regions. A seismogenic source will generate vibratory ground motion but is not assumed to cause surface displacement. Seismogenic sources cover a wide range of possibilities from a well-defined tectonic structure to simply a large region of diffuse seismicity (seismotectonic province) thought to be characterized by the same earthquake recurrence model. A seismogenic source is also characterized by its involvement in the current tectonic regime (the Quaternary, or approximately the last 2 million years).

The DOE, in DOE-STD-1022-94 (Ref. 139) provides fault terminology as follows:

Fault: a geologic feature which demonstrates deformation or/and rupture of geologic deposits.

Active fault: a capable tectonic structure which demonstrates surface or near surface deformation of geologic deposits of a recurring nature within approximately the last 500,000 years or once in the last 50,000 years or/and associated with one or more large earthquakes or sustained instrumentally recorded earthquake activity.

Seismic source: seismic events, which contribute significantly (more than 5% to the total seismic hazards) to a probabilistic ground motion assessment.

SRS currently works to DOE-STD-1022-94 Natural Phenomena Hazards Site Characterization Criteria (Ref. 139). At this time, there are no faults classified as active or capable at SRS (Ref. 283).

Crustal geometry of the region and SRS area

Thickness of the Crust

Along continental margins the nature of the crust changes from continental-type crust to oceanic-type crust. Continental crust is generally thicker, less dense, and chemically distinct from ocean crust. The boundary at the base of either continental or oceanic crust also marks a fundamental change in physical parameters and is referred to as the Mohorovicic discontinuity. Density and P-wave velocity is significantly greater below this layer than above.

With the onset of continental rifting, the North American continent began to break away from Africa. Continental crust was stretched and thinned and was intruded with mafic magmas. At the point that one spreading center became dominant, the continental crust ceased to stretch and ocean crust was generated at the spreading center. This marked the initiation of a passive margin along the Atlantic continental margin.

In general, the thickness of continental crust thins from west to east across the eastern U.S. continental margin. The zone of transition from continental crust to oceanic crust is thought to underlie the offshore Carolina Trough and the Blake Plateau basin (see Figure 1.4-35) (Ref. 142, 284). Sheridan and Grow (Ref. 285) provide a cross-section through the continental margin and Baltimore trough (offshore New Jersey) (see Figure 1.4-51). This is a typical Atlantic-type margin showing the geometry of oceanic crust to the east and continental crust to the west. The Moho deepens from east to west from about 15 km (9 miles) to about 40 km (25 miles), respectively. The continental crust along the margin has been extended and intruded during Mesozoic rifting and is described as rift stage crust. Further east in the middle of the cross section is a complicated zone of transition from continental crust to oceanic crust. The data that support this interpretive model come largely from seismic reflection and refraction surveys and potential field surveys. Offshore South and North Carolina show a similar geometry of thinning crust (see Figure 1.4-52) (Ref. 143).

Further inland, the base of crust is discerned by following the configuration of the Moho on seismic refraction or reflection lines. From seismic reflection data collected at SRS (Ref. 278), the Moho is interpreted at about 30.0 to 31.5 km (18.6 to 19.6 miles) depth (Ref. 269). On the deep seismic profiles, a wide ban of reflections (200 to 300 milliseconds wide) at 10.5 to 11.05 seconds are interpreted to be the Moho (Ref. 269). Luetgert et al. (Ref. 279) report crustal thickness changes along a survey from SRS southeast to Walterboro, SC. They find a crust that thins from 37 km (23 miles) beneath the Dunbarton basin to 32 km (19.9 miles) near Walterboro, SC. This interpretation is based on long seismic refraction and wide-angle seismic reflection data and constrained by gravity and aeromagnetic data (see Figures 1.4-48 and 1.4-49). The effect of continental extension and thinning during the Mesozoic rifting event is thus observed in the configuration of the Moho as well as the geologic evidence from the existence of the Dunbarton basin.

TECTONIC STRUCTURES: FAULTING, FOLDING, AND RIFT BASINS

Tectonic structures of interest in the SRS region include faults, folds, arches, basins (rift and post-rift) and paleoliquefaction features from earthquakes. The various structural features in this section are discussed in terms of the age of the feature, starting with the oldest structures. The age of the structure is to be distinguished from the age of the rock in which the structure formed. The primary interest is on how the age of the feature can be discerned with greater or lesser confidence with respect to the definitions of active and capable features in the previous section.

Paleozoic and Precambrian Structures

Modoc Fault Zone

The Modoc fault zone (see Figure 1.4-32), located in South Carolina and Georgia, separates greenschist facies metamorphic rocks of the Carolina Terrane (Carolina Slate and Charlotte belts) from the amphibolite facies migmatitic and gneissic rocks of the Kiokee belt (Ref. 182, 189). The Modoc fault zone is an east-northeast trending ductile shear zone that can be traced from central Georgia to central South Carolina based on geological and geophysical data. The Modoc fault zone dips steeply to the northwest and contains quartzites, phyllite, paragneiss, and button schists correlative with units in the Asbill Pond Formation of the Carolina terrain. The lower grade Carolina terrane rocks underwent significant granitic sheet intrusion, prograde metamorphism, and penetrative strain during the Alleghanian orogeny (Ref. 182, 188, 189). Fabric in the fault zone is characterized by brittle and ductile deformation produced by ductile shear during an early phase of the Alleghanian orogeny (315 Ma) (Ref. 177, 286). The Modoc zone is overprinted by the Irmo antiform near Columbia, SC. Extension of the Modoc fault zone further to the northeast is uncertain but there are shear zones in North Carolina and Virginia that may be of the same deformational phase (Ref. 178, 287). Sacks and Dennis (Ref. 288) report an important normal-sense component in the Modoc zone on the northwest flank of the Kiokee belt. The significance of the age of myonitic fabric on this fault at 315 Ma is that the fault is very old and therefore not in the realm of active or capable in terms of regulatory guidance.

Augusta Fault

The Augusta fault zone (see Figure 1.4-32) is located near Augusta, GA, and juxtaposes amphibolite grade rocks of the Kiokee belt against the greenschist facies rocks of the Belair belt (Ref. 191). The fault trends east-northeast and dips approximately 45° southeast. The fault contains two distinct deformation fabrics: a mylonite about 250 meters (820 feet) thick is overprinted by a brittle fabric. Kinematic analysis within the mylonite zone reveals a hanging wall down component during the movement history (Ref. 191). Furthermore, the hanging wall consists of lower greenschist facies while the footwall contains upper amphibolite facies. Lower grade rocks structurally positioned above higher grade rocks in combination with shear sense indicators suggests a low-angle normal fault movement for the Augusta fault zone. This is a new view of the Augusta fault zone, which previously had been considered a ductile-to-brittle thrust fault or a strike-slip fault (Ref. 181, 188, 289). It now appears that ductile faults with a normal

sense component were an important aspect of late Alleghanian deformational history (Ref. 140). Recently Maher et al. (Ref. 186) reported $^{40}Ar/^{39}Ar$ ages from samples along a traverse across the Modoc fault and Augusta fault zones. They concluded that a 274 Ma cooling age closely dates initiation of extensional movement on the Augusta fault zone. This cooling age indicates the time when the ductile fabric was generated and therefore when the fault moved. This fault does not fall into the capable or active fault definitions of the regulatory guides.

Near Augusta, GA, the Augusta Fault and the southeast edge of the Kiokee belt are offset by the north-northeast trending Belair Fault (see Figure 1.4-32). Bramlett et al. (Ref. 196) suggest that the Belair Fault was a tear fault linking two segments of the Augusta fault zone. Within the Atlantic Coastal Plain province sediments, the final stage of movement on the Belair fault occurred during the Cenozoic as high angle reverse faulting that offset the Late Cretaceous uniformity by 30 meters (100 feet) and the Early Eocene uniformity by 12 meters (40 feet).

Hatcher et al. (Ref. 198) suggested that the Modoc shear zone, the Irmo shear zone, and the Augusta Fault are part of the proposed Eastern Piedmont Fault System, an extensive series of faults and splays extending from Alabama to Virginia. Aeromagnetic, gravity, and seismic data indicate that the Augusta fault zone continues in the crystalline basement beneath the Coastal Plain province sediments.

Paleozoic Basement Beneath SRS

Information concerning structural features in the basement beneath Savannah River Site is mainly derived from analysis of structural fabrics recorded in core samples from deep borings and at larger scales from geophysical techniques such as gravity and magnetic surveys and seismic reflection profiles. Seismic reflection surveys were conducted onsite in 1972 and 1987 to 1988 to image the basement reflector. In 1972, Seismograph Services Incorporated did a seismic reflection survey as part of the Bedrock Waste Storage Project. Approximately 60 line miles of survey were completed. This was the first survey that indicated the presence of basement faults, some of which disturbed Coastal Plain sediments. Offset reflectors were interpreted as basement faults. No official report was written for the survey.

During the period 1987 to 1988, Conoco, Inc. (Ref. 278) completed a more thorough seismic reflection survey of SRS (see Figure 1.4-53). The program consisted of two phases, which covered approximately 134 line miles distributed over much of the SRS. These data were used to further define basement faults and to image any shallower or deeper structures. Subsequent seismic reflection and field potential geophysical data have led to various basement fault interpretations (Ref. 265, 269, 270).

These data were reprocessed and re-interpreted at Virginia Polytechnic and State University Regional Geophysical Laboratory (Ref. 269, 290). The overall goal was to produce improved images of the Coastal Plain section and faults known to deform Coastal Plain sediments. Recovery of the shallow time section (40-200 milliseconds) in conjunction with recovery of the deep section (7-14 seconds) led to the discovery of additional faults clearly rooted in the midcrust and deforming Coastal Plain sediments.

An integrated analysis of the structural fabric in the basement core in addition to the geophysical data (Ref. 276, 273) concluded that at least two regional scale ductile faults are present in the basement beneath Savannah River Site and vicinity, the Upper Three Runs fault and the Tinker Creek Fault. These faults are expressed in the aeromagnetic data as lineaments and are interpreted to be associated with a thrust duplex that emplaces the rocks of the PBF Formation (Tinker Creek Nappe) over the DRB formation (Figure 1.4-46). The age of the faulting is constrained by a radiometric age on biotite that dates the movement at about 300 Ma, which would indicate that these faults are part of the Paleozoic Eastern Piedmont Fault System.

In order to resolve faulting that deform Coastal Plain sediments, the topography of the basement surface was mapped utilizing the data listed above along with more recently acquired seismic reflection profiles (Ref. 270). The map of basement topography indicates that offsets of the basement surface that range from approximately 30 meters (100 ft) in magnitude down to the resolution limits of the data are present on the basement surface. However most of these offsets are of relatively small magnitude and have limited lateral extents. Faults that involve Coastal Plain sediments that are considered regionally significant based on their extent and amounts of offset (i.e., Atta, Crackerneck, Martin, Pen Branch, and Tinker Creek) are shown on Figure 1.4-54. The Crackerneck and Pen Branch Faults are relatively well constrained with borings. The other faults are projected from geophysical data only and their parameters are less well known. Of these faults the Pen Branch fault has been extensively studied and found to be not capable or not active (see Section 1.4.3.2).

Mesozoic: Extensional Tectonics and Rift Basins

A broad zone of extended (rifted) continental crust formed along the eastern continental margin of the U.S., especially the southeastern portion during the early Mesozoic when North America broke away from Africa and South America. This region extends from Florida to Newfoundland and includes the area where the SRS exists. The Eastern Seaboard domain as it is identified in Kanter (Ref. 291) encompasses this extended crust and is a sub-domain of the North American stable continental crust. Its significance is that within stable continental crust, areas of extended crust potentially contain the largest earthquakes. The Eastern Seaboard domain is bounded on the west by the western-most edge of Triassic-Jurassic onshore rift basins or the boundaries of the structural blocks in which they occur (see Figure 1.4-34) (Ref. 143, 291, 292). The eastern boundary is the continental/ oceanic boundary which is coincident with the East Coast magnetic anomaly (see Figures 1.4-35) (Ref. 291). Rifted crust is crust that has been stretched, faulted, and thinned slightly by rifting but is still recognizable as continental crust. The faulting is extensional or normal and down-dropped blocks form rift basins.

Geometric and kinematic arguments suggest that early Mesozoic normal faults may have been reactivated Alleghanian faults (Ref. 293, 294). Studies of exposed and buried rift basins in the eastern U.S. show that the faults controlling basin formation are complex, with border faults of variable dip, antithetic faults of variable displacement, and cross or transfer faults that fragment the basin into sub-basins (Ref. 293, 294). Within the SRS region, there is the Dunbarton rift basin (see Section 1.4.3.1), which is part of this tectonic setting. The fault that controls the basin

formation, the Pen Branch fault, initially moved as a normal fault during the Triassic. However, it may have been a reactivated Paleozoic fault, and it has moved since the rifting episode (Ref. 215, 276, 295).

One locus of major extension during early stages was in the South Georgia rift, which extends from Georgia into South Carolina (see Figure 1.4-33). The Dunbarton basin, underlying the SRS, is most likely structurally related to that rift basin (see Figure 1.4-34) (Ref. 215). During the later stage of rifting (early Jurassic), the focus of extension was shifted eastward to the major marginal basins that would become the site of the Atlantic Ocean basin. The extension in the onshore, western-most basins, such as the Dunbarton, Florence, and Riddleville, waned. Eventually, rifting of continental crust ceased as sea floor spreading began in the Atlantic spreading center sometime around 175 Ma (Ref. 143). The oldest ocean crust in contact with the eastern continental margin is late middle Jurassic (Ref. 296). The significance of the age of transition from rifting to seafloor spreading is that the tectonic regime of rifting is no longer acting on the crust in the Eastern seaboard domain. The basins are not continuing to form and for the most part, the crust is quiescent. The modern tectonic environment is partly based on ridge push from the Atlantic spreading center, and recent crustal stress measurements indicate a compressive northeast directed stress for the region (Ref. 297).

Post-Rift and Cenozoic Structures

The following discussion includes tectonic features that have formed on the continental margin since the end of the Mesozoic rift stage (post-rift stage). Therefore, the discussion will include the late Mesozoic, as well as Cenozoic, tectonic elements. Post-rift tectonism is expressed along the eastern continental margin in a variety of structures originating in the crystalline basement and affecting the deposition of sediments and deformation of Coastal Plain sediments from the Cretaceous through the Cenozoic. These structures include offshore sedimentary basins, such as the Carolina trough and the Blake Plateau basin; transverse arches and embayments, such as the Cape Fear arch and the Southeast Georgia Embayment; Coastal Plain faulting; and paleoliquefaction features that provide information on the recurrence of the Charleston earthquake.

Outer Margin Basins

Sedimentary basins along the continental margin (offshore) have formed in response to subsidence in the outer continental margin crust. Outer margin subsidence resulted from 1) the extension and thinning of the crust during early Mesozoic rifting followed by thermal contraction as the lithosphere cooled, and (2) from sediment loading on the lithosphere (Ref. 298-300). The outer margin sediment basins formed on this transitional crust (see Figure 1.4-52). Toward the continent, continental crust was less altered and thicker. This portion of the margin subsided at a slower rate than the outer margin. Because of the differing rates and total amount of subsidence, a hinge zone developed all along the continental margin (Ref. 298). Seaward of the hinge zone the crust is rift-stage continental crust. The crust here has subsided to greater depths. This is also the location of the outer margin basins (see Figures 1.4-35 and 1.4-52). Landward of the hinge zone, the crust is the thicker, unaltered crust. The depth to crust in this region is significantly shallower with a corresponding thinner veneer of post-rift sediments (see

Figures 1.4-35 and 1.4-52). The Atlantic Coastal Plain is located landward of the hinge zone and has been affected by the outer margin subsidence. For detailed discussion on the evolution and structure of the East Coast outer margin basins and the effects within the Atlantic Coastal Plain, see Sheridan and Grow (Ref. 285).

Folding and Arching

Not all tectonism along the continental margin is due to outer margin subsidence. Lithospheric cooling and sediment loading were dominant processes during Middle Jurassic through early Cretaceous. The sediments now present in the outer margin basins are mostly Jurassic and early Cretaceous. Compressional faults, folds and thickness variations in the late Cretaceous and Cenozoic are due to intraplate stress fields rather than margin subsidence (Ref. 200, 301, 302). These latest features are seen as highs and lows in the crust that control Coastal Plain sedimentation and are oriented perpendicular to the hinge zone. They are thought to be indicative of continued, episodic, differential crustal movements (tectonic) from Cretaceous through Pleistocene (Ref. 303). The sedimentary sections are thinner, incomplete on the highs, or arches, and thicker with complete sections in the lows or embayments. The most prominent arch is the Cape Fear arch near the North Carolina-South Carolina border (see Figure 1.4-55). Other arches in the region include the Norfolk arch near the North Carolina-Virginia border, and the Yamacraw arch near the South Carolina-Georgia border (see Figure 1.4-56).

The Cape Fear arch has a variable history, receiving sediments during the Late Cretaceous and then acting as a sedimentary divide or arch from Latest Cretaceous through Late Tertiary (Ref. 298, 304). Upper Cretaceous Santonian sediments are the oldest strata to completely cover the Cape Fear arch (see Figure 1.4-56) (Ref. 298). Paleocene, Eocene, and Oligocene strata comprise 640 meters (2,100 feet) of marine carbonate in the southeast Georgia embayment and thin to the northeast, toward the Cape Fear arch. The sediments become largely terrigenous on the flank of the arch and are completely missing over the crest of the arch; thus suggesting the arch was acting as a sedimentary divide beyond the Oligocene (Ref. 142, 143). Uplift on the arch may have continued through the Pleistocene (Ref. 304).

Faulting

The most definitive evidence of crustal deformation in the Late Cretaceous through Cenozoic is the reverse sense faulting found in the Coastal Plain section of the eastern U.S. Under the auspices of the Reactor Hazards Program of the late 1970s and early 1980s, USGS conducted a field mapping effort to identify and compile data on all young tectonic faults in the Atlantic Coastal Plain (Ref. 305). Consequently, many large, previously unrecognized Cretaceous and Cenozoic fault zones were found (Prowell, 1983). Of 131 fault localities cited, 26 were within North and South Carolina (see Figure 1.4-57). The identification of Cretaceous and younger faults in the eastern United States is greatly affected by distribution of geologic units of that age. Many of the faults reported by Prowell (Ref. 306) are located in proximity to the Coastal Plain onlap over the crystalline basement. This may be due to the ease of identifying basement lithologies in fault contact with Coastal sediments (Ref. 305).

Prowell and Obermeier (Ref. 305) characterized the faults as mostly northeast trending reverse slip fault zones with up to 100 km (62 miles) lateral extent and up to 76 meters (250 feet) vertical displacement in the Cretaceous. The faults dip 40° to 85°. Offsets were observed to be progressively smaller in younger sediments. This may be due to an extended movement history from Cretaceous through Cenozoic (Ref. 305). Based on their similar characteristics Prowell (1988) was able to associate Cretaceous and younger faulting in the Coastal Plain into several Fault Provinces. The Savannah River Site falls in to Prowell's (1988) Atlantic Coast Fault Province. A comparison of Cretaceous and younger faulting in the Savannah River Site (Cumbest and others, 2000) found that faulting on Savannah River Site shared similar characteristics with the faults in the Atlantic Coastal Fault Province including orientation and offset history. This comparison concluded that Cretaceous and younger faulting on Savannah River Site was not unique in comparison to The Atlantic Coast Fault Province in general and as a result shared the same seismic hazard.

Offset of Coastal Plain sediments at SRS includes all four Tertiary unconformities (Ref. 229). Following deposition of the Snapp Formation some evidence indicates oblique-slip movement on the existing faults (Ref. 136). The offsets involve the entire Cretaceous to Paleocene sedimentary section. In A/M Area, this faulting formed a serious of horsts and grabens bounded by subparallel faults that truncate at the fault intersections. The strike orientations of the individual fault segments vary from N 11°E to N 42°E, averaging about N 30°E. Apparent vertical offset varies from 4.5 to 18 meters (15 to 60 feet), but throws of 9 to 12 meters (30 to 40 feet) are most common.

This faulting was followed by erosion and truncation of the Paleocene section at the Lang Syne/Sawdust Landing unconformity. Subsequent sediments were normal faulted following deposition of the Santee Formation. Typically, the offset is truncated at the Santee unconformity, and the overlying Tobacco Road/Dry Branch formations are not offset (Ref. 229). Locally, however, offset of the overlying section indicates renewed movement on new or existing faults after deposition of Tobacco Road/Dry Branch sediments.

In conjunction with these observations of Coastal Plain faults, modern stress measurements provide an indication of the likelihood of Holocene movement. Moos and Zoback (Ref. 307, 308) report a consistent northeast-southwest direction of maximum horizontal compressive stress (N 55-70°E) in the southeast U.S. Their determination is based on direct in situ stress measurements, focal mechanisms of recent earthquakes, and young geologic indicators. Shallow seismicity in the area, within crystalline terranes, is predominantly reverse character (Ref. 309). Moos and Zoback (Ref. 307) conclude that the northeast directed stress would not induce damaging reverse and strike-slip faulting earthquakes on the Pen Branch fault, a northeast striking Tertiary fault in the area. These same conclusions may be implied for the other northeast trending faults mapped by Prowell (Ref. 306).

In A/M Area at SRS, faulting appears to have been episodic and to have varied in style during the Tertiary (Ref. 229). Oblique-slip faulting dominated the Cretaceous/Paleocene events, with a local north-south stress orientation. Subsequently, left-lateral shear on the pre-existing faulting and normal faulting occurred, with a corresponding shift in the direction of maximum compressional stress oriented N 20°E to N 30°E.

Pen Branch Fault

The Pen Branch fault has been regarded as the primary structural feature at SRS that has the characteristics necessary to pose a potential seismic risk. As stated below, studies have indicated that, despite this potential, the fault is not capable.

The Pen Branch fault (see Figures 1.4-46 and 1.4-57) is an upward propagation of the northern boundary fault of the Triassic Dunbarton basin that was reactivated in Cretaceous/Tertiary time. The fault dips steeply to the southeast. In the crystalline basement, slip was originally down to the southeast, resulting in the formation of the Dunbarton rift basin. However, movement during Cretaceous into Tertiary time was reverse movement, that is, up to the southeast (Ref. 310). There could also be a component of strike-slip movement (Ref. 311).

The bulk of evidence collected for the Pen Branch Fault Program supports the conclusion that the most recent faulting on the Pen Branch fault is older than 500,000 years. Therefore, the Pen Branch fault is not a capable fault per 10 CFR 100, Appendix A. In a study designed to examine only the sediments with an age of 1 Ma or less, deformation was not found to exist (Ref. 239).

The Pen Branch Fault was identified in the subsurface at SRS in 1989. It was interpreted from seismic reflection surveys and other geologic investigations (Ref. 126, 278, 295, 312). A program was initiated at that time to determine the capability of the fault to release potentially damaging seismic energy as defined in NRC regulatory guidelines, 10 CFR 100, Appendix A (Ref. 278). Separate actions completed under this program title include the following:

- Shallow drilling of Coastal Plain sediments with eight paired drill holes to bracket the location and the amount of displacement on the Pen Branch fault (Ref. 126, 313)
- Formation of the Earth Science Advisory Committee for independent assessment and verification of the data gathered
- A deep drilling program into the fault zone in basement underlying Coastal Plain sediments
- A high-resolution, shallow seismic reflection survey over the fault trace (Ref. 126, 313, 314)
- Reprocessing Conoco seismic reflection data by geophysicists at Virginia Polytechnic Institute to enhance the shallow portions of the data and then the deeper portions of the data under separate processing protocols (Ref. 269, 271, 283, 290)
- Quaternary geology investigation by Geomatrix to examine the youngest surfaces and deposits onsite for indications of neotectonism (Ref. 239, 240).
- Confirmatory Drilling Project: The final investigation carried out under the 1989 Pen Branch Fault Program. The investigation focused on a small zone over the fault where seismic reflection data had been collected previously and indicated that the fault deforms the subsurface reflector at 200 milliseconds two-way travel time. Eighteen drill holes, two to basement and the others to a depth of 300 feet, were arranged to adequately define the configuration of the layers deformed by the

fault. Boreholes were spaced over a zone of 245 meters (800 feet), north to south. Results suggest that deformation by the fault is limited to the Lang Syne/Sawdust Landing unconformity (~50 Ma) (Ref. 283). Other interpretations may be offered (Ref. 135, 136) where offset on the Pen Branch Fault involved the Tobacco Road and Dry Branch Formations. However, based on presently available data, the Pen Branch fault is not capable.

WSRC thus concludes that the Pen Branch fault is not a capable fault per 10 CFR 100, Appendix A (Ref. 126, 283, 315).

Belair Fault Zone

The Belair fault is a Cenozoic fault located on the inner margin of the Coastal Plain near Augusta, GA (see Figure 1.4-32). The fault was first documented by O'Connor et al. (Ref. 316) and has been further investigated by USGS and others (Ref. 196, 199, 201, 317). The fault is really a set of en echelon faults extending at least 24 km (15 miles) and trending northeast (Ref 199). Individual fault segments are 2 to 5 km (1.25 to 3 miles) long. The fault zone places Late Precambrian phyllites of the Belair belt over Middle Tertiary Coastal Plain sediments. All the faults show oblique-reverse slip movement and as much as 30 meters (100 feet) of vertical offset has taken place since the deposition of the Barnwell Group sediments. Bramlett et al. (Ref. 196) reported that the Belair fault zone has a protracted history of movement in that it initiated as a tear fault on the Augusta fault during the late Alleghanian (Hercynian). The fault was later reactivated as an oblique-reverse slip fault during the Cretaceous. The age of latest movement on the Belair fault zone can only be determined based on available stratigraphic marker horizons. The age of last movement can be bracketed between the age of the sediment that is offset and the age of the stream terrace that caps this strata and is not deformed. The age of the deformed strata can be as young as 40 Ma and the age of the stream fill terrace is between 26,000 and 1,550 years based on carbon-14 dates of peat (Ref. 199). This makes the age determination on the fault uncertain because the age of undeformed deposits capping the deformation is poorly defined and because the fault age can only be bracketed based on deposits that precede a large time period unconformity. However, it has been concluded that the Belair fault zone records movement from late Early Cretaceous through at least Eocene (Ref. 318), which makes the fault approximately 40 Ma.

Buried or Blind Faulting in the Charleston Seismic Zone

Seismic activity in the southeastern U.S. has been dominated by the 1886 Charleston, SC, earthquake, aftershocks, and the continuing low-level seismic activity that persists in the area today. The search for structures to explain seismicity near Charleston has been complicated by the absence of surface faulting, fault scarps, or other fault-generated topographic features. Because the seismic zone is buried in the subsurface, the presence of possible causal geologic structures at depth must be inferred through geophysical methods. Many geologic, geophysical, and seismic studies have been completed by a number of researchers since the mid-1970s resulting in the emergence of some widely diverse models and hypotheses (Ref. 319). A review of the more recent models reveals that uncertainty still exists on details of the causal relationship

between local geologic structures and seismic activity in the region (Ref. 320, 321). However, significant progress has been made.

Most hypotheses relating southeast U.S. seismicity to geologic structure assume activity to occur along preexisting zones of weakness favorably oriented with respect to the ambient stress field. Understanding the regional stress is an essential element in the formation of causative models.

Models developed in the early 1980s involved possible slip along a master decollement located under the coastal plain at a depth of 10-12 km (6.2 – 7.5 miles). This was primarily based on interpretations of deep seismic reflection profiling coupled with an inferred orientation of the regional maximum horizontal stress axes in a northwest-southeast direction (Ref. 289, 321). The implications of this model were that the observed seismicity near Charleston was not particularly unique to that region and that similar large events could potentially occur anywhere east of the Appalachians. However, there were problems associated with this model. They stem primarily from (a) lack of consensus on the existence of a master decollement and (b) subsequent data gathered over the years that establishes the preferred regional maximum horizontal stress axis in a northeast direction, making movement along a decollement unlikely.

Spatial association of buried plutons and seismicity has also been noticed in the Charleston region (Ref. 322, 323). Stress amplification due to rigidity contrasts between plutons and the country rock near these plutons has also been suggested as a mechanism where the mafic or ultramafic plutons lying deep below the ground surface are inferred from localized gravity highs. However, it is unknown if the large contrasts required exist for this model. An alternative explanation suggests that the plutons are symptomatic of a zone of weakness (Ref. 320). Thus, any seismic response to the stress field would occur at the zones of weakness. A problem with this scenario is that mafic bodies defined by gravity highs occur throughout the southeastern U.S., but Charleston remains the only location to show evidence of historical earthquake activity.

Recent Models. Tarr et al. (Ref. 324) noted that eastern U.S. coastal plain seismic activity occurred in distinct zones superposed on a regional background of very low level seismicity. The most active of these zones and the one assumed likely to be associated with the 1886 Charleston event is the Middleton Place-Summerville Seismic Zone (MPSSZ). The MPSSZ lies some 20 km (12 miles) northwest of Charleston well within the mesoseismal area of the 1886 Charleston earthquake. It was in this area that Talwani identified the delineation of two possible intersecting faults when relocating instrumentally recorded earthquakes from 1974 to 1980 (see Figure 1.4-58) (Ref. 325). The first was a shallow, northwest-trending fault defined by hypocenters 4 to 8 km (2.5 to 5 miles) deep striking parallel to the Ashley River. This he named the Ashley River fault. The second fault was labeled the Woodstock fault. The Woodstock fault trends north-northeasterly and is defined by planar distribution of hypocenters with depths between 9 and 13 km 5.6 – 8.1 miles). It intersects and appears deeper than the Ashley River fault. Recent studies by Madabhushi and Talwani (Ref. 279) refine and complement the 1982 effort by utilizing 58 additional well-recorded events located in the MPSSZ from 1980 to 1991 (Ref. 279). Fault-plane solutions from the new data reinforce the northeast-southwest maximum horizontal stress direction of previous studies. However, the epicentral distribution of this new data displayed no obvious pattern of association with the Ashley River fault or the Woodstock fault. Therefore, the seismicity was divided into sets according to focal mechanism in an attempt to infer a structural cause of the earthquakes. Results of this breakout revealed:

- The first set of data favored a northwest-southeast strike and southwest dip direction, suggesting compatibility with the Ashley River fault zone. Solutions were found to have components of mostly strike-slip and/or reverse faulting mechanisms.
- The second set of data was further divided into two subsets with the first displaying mainly vertical fault planes striking north-south and the second subset striking north northeast-south southwest with shallower dips to the southwest. These two subsets were classified as belonging to the Woodstock fault zone. Solutions of these events revealed mostly strike-slip motion on the vertical fault with a strong thrust component on the shallower dipping events.

Results indicated that the Ashley River and the Woodstock faults are not simple planar features, but resemble zones composed of short segments of varying strike and dip. When location was factored into the analyses, it was found that events associated with all sets of data occurred in the same area. From these observations, Madabhushi and Talwani (Ref. 279) conclude that the seismicity in the MPSSZ defines the intersection of two fault zones, which they infer to be the Ashley River fault zone and the Woodstock fault zone.

Paleoseismic Data. Estimating seismic recurrence intervals of moderate to large earthquakes within the southeastern U.S. is difficult. These difficulties stem from the relatively short (300 years) historical record coupled with an absence of surface faulting, offset features, or prehistoric ruptures.

Geologic field study methods developed to extend the seismic record assess both the temporal and spatial distribution of past moderate and large earthquakes. This assessment is carried out through identification and dating of secondary deformation features resulting from strong ground shaking. In the southeast, this extension of the seismic record has been accomplished through field search for earthquake-induced liquefaction flowage features called "sand blows" associated with prehistoric earthquake-induced paleoliquefaction features.

These features are attributed to prehistoric earthquake induced liquefaction as defined by the transformation of sediments from solid to liquid state caused by increased pore water pressure (Ref. 326). The increased pore pressure is caused during or immediately after an earthquake. "Sand blows" are features formed where earthquake shaking causes liquefaction at depth followed by the venting of the liquefied sand and water to the surface.

The following section summarizes paleoliquefaction studies in the southeastern United States. Aspects that are of particular importance to SRS include the following:

- No conclusive evidence of large prehistoric earthquakes originating outside of coastal South Carolina has been found.
- Young fluvial terraces at or slightly above the level of the modern floodplain and Carolina bays are the most likely depositional environments for potentially liquefiable deposits in the SRS region.

Paleoliquefaction Studies in the Eastern United States. Dutton originally reported the widespread occurrence of earthquake-induced sand blows throughout the meizoseismal area of

the 1886 Charleston, SC, earthquake (Ref. 327). Excavation and detailed analyses of these liquefaction flow features provided the first insight into the pre-history of the Charleston earthquake (Ref. 328, 329). Other pre-1886 liquefaction flow features (mostly sand blows) were discovered and investigated near the town of Hollywood, about 25 km (15 miles) west of Charleston (Ref. 330, 331). Searches for sand blows were continued throughout the Charleston area and expanded to the remaining coastal South Carolina areas. Eventually, areas of study were broadened to include Delaware, Virginia, North Carolina, and Georgia (Ref. 332). The objective was to identify other epicentral regions, if they existed, and to estimate the sizes of pre-1886 earthquakes assuming the areal extent of sand blows caused by an earthquake are a function of earthquake intensity in areas of similar geologic and groundwater settings. Figure 1.4-58 shows the study region of current paleoliquefaction areas of interest (Ref. 333). To date, no conclusive evidence of large prehistoric earthquakes originating outside of coastal South Carolina have been found (Ref. 332).

In coastal South Carolina investigations, identification of paleoliquefaction features generally adheres to specific local geologic criteria. Some specific relations between liquefaction susceptibility and subsequent formation of liquefaction features (sand blows) are summarized below (Ref. 332, 333):

- A water-table very near the ground surface greatly increases susceptibility to liquefaction (depth <1 m (<3 feet).
- Virtually all seismically induced liquefaction sites are located in either beach-ridge, backbarrier, or fluvial depositional environments. Of these, beach-ridge deposits were found to be the most favorable for the generation and preservation of seismically induced liquefaction features.
- Due primarily to the effects of chemical weathering, materials older than about 250 ka were less susceptible to liquefaction than were younger deposits. This indicates that the probabilities of sand blows forming in deposits of late Pleistocene and early Holocene age are extremely low.
- The liquefied materials are generally fine-grained, well-sorted (i.e., uniformly graded), clean beach sand. The principal properties of sand that control liquefaction susceptibility during shaking are degree of compaction (measured as relative density by geotechnical engineers), sand-grain size and sorting, and cementation of the sand at grain-to-grain contacts. Fine grained well-sorted sand of ancient and modern beaches are much more susceptible to liquefaction than standard sand used for engineering analyses (Ref. 333).
- Features large enough to be interpreted as possibly having an earthquake origin in the low country were found only in sand deposits having total thickness greater than 2 to 3 meters (7 to 10 feet).
- The depth of the probable source beds at liquefaction sites is generally less than 6 to 7 meters (20 to 23 feet), and the groundwater table is characteristically less than 3 meters (10 feet) beneath present ground surface.

Liquefaction features that typify the coastal South Carolina area have been described as sand blow explosion craters and sand-vents/fissures (Ref. 332).

Sand Blow Explosion Craters or Filled Sand-blow Craters. Following the onset of seismic loading from a moderate to large earthquake, development of sand blow craters can be described by four sequential phases: (a) an explosive phase, (b) a flowage phase, (c) a collapse phase, and (d) a filling phase. These were first described by Gohn et al. based on historical accounts and the internal morphology of exhumed features (Ref. 330). Figure 1.4-59 is a vertical section of a filled sand-blow that is representative of the type observed at most study sites. This feature illustrates characteristics consistent with earthquake-induced liquefaction origin. The soil horizon is cut by an irregular crater and filled with stratified to nonstratified and graded sediments. The fill materials are fine-to medium-grained sand and clasts from the original soil profile, as well as sand from source beds at depths below the exposed C horizon (Ref. 333). Sand-blow explosion craters were found primarily on beach deposits, and are notably absent in fluvial settings (Ref. 332).

Sand-Vents/Fissures or Sand Volcanoes. Sand volcanoes vent to the surface and leave relict sand mounds. These features generally form in circumstances where the liquefying source zone, at depth, is overlain by a cohesive, finer grained, non-liquefiable layer, or "cap". The thickest part of the mound ranges from a few centimeters to as much as 25 centimeters (10 inches). The mounds are generally thickest directly above source feeder vents that extend downward through clay-bearing stratum (Ref. 333). This type of liquefaction feature was rare in beach settings, but commonly found within backbarrier marine sediments and in interbedded fluvial deposits (Ref. 332).

Dating paleoliquefaction episodes can be accomplished either qualitatively or quantitatively. Qualitative methods include degree of staining and weathering of sands within the feature, thickness of overlying profiles, and cross cutting relations of one feature compared to another. A more quantitative approach involves radiometric dating of organic material within or cut by the liquefaction feature. An example of a minimum age constraint is dating of roots that have grown into the feature. A maximum constraint can be determined from roots cut by the feature or by dating organic materials recovered from the collapsed area of the crater during the liquefaction episode. The most accurate estimates for the age of a liquefaction episode are obtained from radiometric dating of leaves, pine needles, bark or small branches that were washed or blown into the liquefaction crater following formation (Ref. 332).

Utilizing the above methods, Amick, and Amick and Gelinas described at least four pre-1886 liquefaction episodes at approximately 580 +104 (CH-2), 1311+ 114 (CH-3), 3250+ 180 (CH-4), and 5124+ 700 (CH-5) years before the present (Ref. 332, 334). CH refers to Charleston source with CH-1 designated as the 1886 earthquake. An even older episode (CH-6) was found to be cut by a CH-5 feature.

Changes in hydrologic conditions (groundwater levels) play an important role in determining an area's susceptibility to liquefaction. On the basis of published sea-level curves, groundwater levels in the southeastern U.S. have been assumed at or near present levels for only the past 2,000 years. Consequently, the paleoliquefaction record is probably most complete for this period (Ref. 334). However, beyond the 2,000-5,000 year range, knowledge of groundwater conditions is considerably less reliable, making gaps in the paleoseismic record much more probable.

Paleoliquefaction at the Savannah River Site. Amick and Gelinas carried out reconnaissance surveys in search of paleoliquefaction sites as far as 65 km (40 miles) inland along the Savannah River (Ref. 354). However, no South Carolina paleoliquefaction surveys or studies have yet been performed as far inland as SRS. Several factors suggest that it would be difficult to locate and evaluate the origin of potential liquefaction features within the geomorphic and geologic environment of the SRS. Investigations elsewhere in South Carolina have shown that aerial photographs are useless for locating 1886 and pre-1886 sand blows (Ref. 332, 333). The SRS region has no Pleistocene beach ridges for sand-blow crater formation. Young fluvial terraces at or slightly above the level of the modern floodplain and Carolina bays are the most likely depositional environments for potentially liquefiable deposits in the SRS region. However, the search for liquefaction features in these areas is severely limited by the lack of access, high water-table conditions, dense vegetative cover, and few exposures.

Existing exposures in the Savannah River fluvial terraces above the modern floodplain were examined by Geomatrix for evidence of liquefaction (Ref. 240). Extensive reconnaissance of the Bush Field and Ellenton terraces on the SRS revealed few exposures of adequate depth and extent to evaluate the presence or absence of liquefaction. Terrace alluvium associated with these terraces contains a high percentage of sand, but based on the degree and depth of pedogenic modification and probable depth to the water-table, these terraces were judged to have had a relatively low susceptibility to liquefaction during the late Pleistocene and Holocene. In this fluvial environment, the most likely liquefaction features are sand vents or fissures. No evidence of sand vents, fissures, or other liquefaction features were observed in any of the available exposures examined by Geomatrix (Ref. 240). Recognition of paleoliquefaction features in the pre-Quaternary deposits at SRS would be extremely difficult, if not impossible.

A paleoliquefaction assessment of SRS was prepared by WSRC in 1996 (Subcontract C001015P). This investigation indicated that several hydrologic, sedimentological, and logistical conditions must be met for seismically induced liquefaction (SIL) to occur and be identified. These included: (1) the presence of Quaternary-age deposits; (2) the presence of a shallow groundwater table; (3) proximity to potential seismogenic features; (4) geologic sections of several different types of unconsolidated deposits; and (5) quality and extent of exposure.

Based on these considerations, the floodplains of the Savannah River and its tributaries were identified as the areas on the SRS with the highest potential for generating and recording Holocene SIL features. The terraces of the Savannah River and tributaries were also considered potential areas for recording Quaternary SIL features, though these features would likely be older than ones in the floodplains. The upland areas on the SRS have a low potential for recording Quaternary SIL because they are pre-Quaternary in age, partially indurated, and generally high above the water table. Paleoliquefaction investigations in the SRS uplands, therefore, only targeted those sites postulated by previous workers as containing evidence of SIL.

Conclusions from this paleoliquefaction assessment fell into two categories: (1) field studies of floodplain deposits along the Savannah River, and (2) evaluation of previously reported paleoliquefaction and neotectonic features located in pre-Quaternary sediments. A brief summary of findings in these two areas follows.

Investigation of banks along 110 km (68 miles) of the Savannah River adjacent to the SRS revealed a large number of excellent exposures of floodplain deposits. Most of the exposed deposits were clay and silt, and had a low liquefaction potential. Locally however, clean sand deposits with a high liquefaction potential were present. Given the extensive amount of exposure and the local presence of liquefiable materials, SIL features would likely be present in these deposits if strong earthquakes had occurred after they were deposited. However, the presence of buried historical objects and radiocarbon dates from these materials illustrated that most or all of the exposed floodplain deposits were historical in age. As no strong ground motions have occurred in historical times in the SRS area, SIL features could not exist in these deposits. Furthermore, the fact that they date to historical times precludes them from providing any information of earlier earthquake history.

The absence of SIL features in the bank exposures does not preclude the possibility that SIL features exist deeper in the section or on the older, higher terraces. In fact, the local presence of liquefiable materials in the Modern floodplain deposits suggests that, if strong prehistoric earthquakes had occurred, SIL features are probably present at depth in the floodplain deposits or on the older/higher terraces. These key areas were not investigated, and exposure is limited.

The upland areas of the SRS were considered to have a low potential for recording Quaternary SIL because the deposits are old (pre-Quaternary), generally high above the water table (>10 meters [>30 feet]), and are indurated. However, previous investigators described several features in the Tertiary section as clastic dikes, and attributed them to SIL and/or neotectonic activity. The sites were evaluated to determine if they have the diagnostic characteristics that have recently been documented for true SIL.

Four types of post-depositional features were identified: (1) irregularly shaped cutans; (2) structurally controlled cutans; (3) joints; and (4) faults. Cutans are a modification of the texture, structure, or fabric of the host material by pedogenic (soil) processes, either by a concentration of particular soil constituents or in-situ modification of the matrix. These features were interpreted through the process of elimination procedure of multiple working hypotheses. None were thought to be the result of SIL. Summary observations of these four elements are given below.

Irregularly Shaped Cutans. The absence of offset on irregularly shaped cutans eliminated the possibility that they were faults, and the undisrupted bedding within and across the feature eliminated the possibility that they were clastic dikes, SIL features, or ice wedges. The higher density of these features near the ground surface and their similarity in appearance to the zone of more intense geochemical alteration at the top of each exposure suggested these features were pedogenic in origin. They were interpreted as an in-situ, pedogenic modification of the texture, structure, and fabric of the host material, and therefore were referred to as "irregularly shaped cutans".

Structurally Controlled Cutans. There was no evidence of rapid injection of liquefied material into structurally controlled cutans. The similarity of the material within the features and that of the host material, as well as undisrupted pebbly horizons within and across the features, demonstrated the features were not clastic dikes, ice wedges, or SIL features. The absence of offset across virtually all of the features demonstrated that they did not develop as faults. They were interpreted to have developed through pedogenic processes based on: (1) the similarity and

relationships that illustrate the features formed concomitantly with the sub-horizontal zone of more intense geochemical alteration at the top of each exposure, and (2) an overall downward thinning and local pinch-out of the features. Strong preferred orientations at most exposures, parallelism with adjacent joints, and their occurrence along fault planes at one locality, suggested that the orientation of most of the features was controlled by pre-existing structures, and were therefore referred to as "structurally controlled cutans".

Joints. Joints are common on the SRS and vicinity. Though their mechanism of formation is not well understood, their age was determined to be constrained by interpretation that cutans often developed along pre-existing joints. The joints, therefore, pre-dated the pedogenic processes that formed the cutans. Highly variable orientations of cutans suggested that the orientation of joints on the SRS was also highly variable. A gradual and consistent change in orientation of cutans over 30 to 60 meters (100 to 200 feet) at some outcrops suggested the orientation of joints also locally changed gradually and consistently. A lack of consistent preferred orientations of joints across the SRS did not favor a tectonic origin for these features. Furthermore, no clear relationship existed between the joint-controlled cutans and the local topography. The joints, therefore, were probably not related to slope mass wasting. A local, gradual change in orientation over several hundred feet, and the common occurrence of closed depressions on the SRS, are consistent with differential settling from subsurface dissolution. This hypothesis was not addressed directly during this study.

Faults. Small scale faults were clearly present at several locations on and adjacent to the SRS. Most faults had normal separations, though one small, sub-vertical feature had a component of reverse motion. All separations observed were less than 1 meter (3 feet). The amount of horizontal slip was not determined for any of the faults. Low, medium, and high angle faults were also present. The presence of cutans on several faults suggested that these faults were older than the pedogenic processes that formed the cutans. A 0.6 meter (2 feet) thick Pliocene loess deposit overlies one fault zone, indicating these faults are probably older than Pliocene. One fault zone was of particular interest because it was located at the approximate upward projection of the Pen Branch fault. Furthermore, the faults in outcrop trended northeast, sub-parallel to the Pen Branch fault. The relationship between the faults in outcrop and the Pen Branch fault, if any, was not investigated.

1.4.4 SEISMOLOGY

1.4.4.1 Earthquake History of the General Site Region

This section includes a broad description of the historic seismic record (non-instrumental and instrumental) of the southeastern U.S. and SRS. Aspects that are of particular importance to SRS include the following:

- The Charleston, SC, area is the most significant seismogenic zone affecting the SRS.
- Seismicity associated with the SRS and surrounding region is more closely related to South Carolina Piedmont-type activity. This activity is characterized by

occasional small shallow events associated with strain release near small scale faults, intrusive bodies, and the edges of metamorphic belts.

HISTORIC RECORD

The earthquake history of the southeastern U.S. (of which the SRS is a part) spans a period of nearly three centuries, and is dominated by the catastrophic Charleston earthquake of August 31, 1886. The historical database for the region is essentially composed of two data sets extending back to as early as 1698. The first set is comprised of pre-network, mostly qualitative data (1698-1974), and the second set covers the relatively recent period of instrumentally recorded or post-network seismicity (1974-present). Sibol and Bollinger created a comprehensive catalog that successfully merged macroseismic, historical pre-network data with instrumental, mostly microseismic, post-network data (Ref. 335). Table 1.4-26 lists significant earthquake locations within 200 miles (327 km) of SRS excerpted from this catalog. Today seismic monitoring results from all southeastern seismic networks are cataloged annually in the Southeast U.S. Seismic Network bulletins. Figure 1.4-60 shows both pre-network and post-network locations of activity for the southeastern U.S., from 1568 to the present within a 200-mile (327-km) radius of SRS.

The information chronicled on earthquakes within the Southeast and the SRS region during the pre-network period consists of intensity data. Intensity refers to the measure of an earthquake's strength by reference to "intensity scales" that describe, in a qualitative sense, the effects of earthquakes on people, structures, and land forms. A number of different intensity scales have been devised over the past century, but the scale generally used in North America and many other countries is the modified Mercalli (MMI) Scale (Table 1.4-27). Using this intensity scale, it is possible to summarize the macroseismic data for an earthquake by constructing maps of the affected region that are divided into areas of equal intensity. These maps are known as isoseismal maps. It was through construction of isoseismal maps that epicenters of pre-network earthquakes were located at or near centers of areas experiencing highest ground shaking intensity. There is considerable uncertainty (up to several tens of miles) in locating the epicenters with this method because it depends heavily upon population density of the region in which the earthquake occurred.

The Charleston, SC, area is the most significant source of seismicity affecting SRS, in terms of both the maximum historical site intensity and the number of earthquakes felt at SRS. The greatest intensity felt at the SRS has been estimated at MMI VI-VII and was produced by the intensity X earthquake that struck Charleston, SC, on August 31, 1886, at 9:50 p.m. local time (see Figure 1.4-61). An earthquake that struck Union County, South Carolina (about 100 miles [160 km] north-northeast of SRS), on January 1, 1913, is the largest event located closest to SRS outside of the Charleston area. It had an intensity greater than or equal to MMI VII. This earthquake was felt in the Aiken-SRS area with an intensity of MMI II-III. Several other earthquakes, including some aftershocks of the 1886 Charleston event, were felt in the Aiken-SRS area with intensities estimated to be equal to or less than MMI IV.

Several large earthquakes outside the region were probably felt at SRS, including the earthquake sequence of 1811 and 1812 that struck New Madrid, Missouri (about 535 miles west-northwest of SRS) and the earthquake that struck Giles County, Virginia (about 280 miles north of SRS),

on May 31, 1897. Bollinger et al. (Ref. 336) judged the temporal completeness of the existing earthquake catalog to be complete for recent network data to mb = 2.5, historical period between 1939 and 1977 complete to mb = 4.5 and the historical period between 1870 and 1930 to mb = 5.7 level.

SRS Activity (within 50 mile radius)

The SRS is located within the Coastal Plain physiographic province of South Carolina. However, seismic activity associated with SRS and the surrounding region displays characteristics more closely associated with the Piedmont province, that is, a marked lack of clustering in zones. The activity is more characteristic of the occasional energy strain release occurring through a broad area of central Piedmont of the state. Epicentral locations for events near (within 50 miles from center of site) SRS are presented in Table 1.4-28. Figure 1.4-62 shows the distribution of earthquake epicenters within 50 miles (80 km) of SRS.

A description of each historical event is presented below. The numbers in parentheses refer to numbers on Figure 1.4-62 and Table 1.4-28.

1897, May 06, 24, and 27 (1,3,4): These three small earthquakes were reported to have occurred around the farming community of Blackville, SC. They were lightly felt by residents of the town and surrounding farms. No intensity values have been assigned to these events as they have only been mentioned as being felt (Ref. 337). When researching local newspapers of the area, the only reference found to any of these small events appeared as a small sentence in the May 13 issue of the *Barnwell People* from Blackville, which said, "Quite an earthquake shock was felt here on last Friday evening at 8:10." No mention of the 24th or 27th events was found in newspapers published shortly following those dates.

1897, May 09 (2): This has been documented as a small "lightly" felt event in the area of Batesburg, SC (Ref. 337). No intensity values have been assigned to this event.

1945, July 26: This event was felt most in the Columbia and Camden, SC areas. Historically it has been more closely associated with Lake Murray, near Columbia, SC. However, Dewy (Ref. 338) relocated it using some instrumental recordings at regional and teleseismic distances. Dewy's relocation moved the epicenter some 50 km to an area southwest of Columbia and to within the 80-km radius of interest for this study. This location, though instrumental, seems extremely questionable. An isoseismal map for this event prepared by Vivanathan ((Ref. 337) defined the area of greatest intensity (VI) to be near Camden, SC. Newspaper reports from Aiken, Columbia and Camden, SC the day following the event tend to confirm this original location. In this case, the location indicated from the intensity felt reports is favored over the Dewy instrumental location.

1972, August 14 (5): Felt reports for this earthquake were reported at Barnwell, Bowman, Cordova, Horatio, North, Springfield, and Summerton, SC with an intensity of between I and III (Ref. 337). Location of this earthquake also seems tenuous. Although the event was instrumentally located, the location can only be assumed approximate because the nearest station was over 100 km northeast of the computed epicenter. It may possibly have occurred closer to the Bowman area and outside the area of interest for this study.

1974, October 28 (6), **and November 5** (7): These two events were estimated to have occurred in McCormick and southern Edgefield counties, South Carolina. Magnitudes of 3.0 and 3.7 respectively were assigned on the basis of felt reports collected at the time. An isoseismal map constructed by Talwani (Ref. 339) for the October event shows an elongated isoseismal roughly following the Fall Line with a maximum felt intensity of III-IV. No instrumental locations are available for either of these events.

INSTRUMENTAL RECORD (POST-NETWORK SEISMICITY)

By the middle of the 20th century, instrumental recordings from a few regional seismographic stations (less than ten for the entire southeastern U.S.) reduced uncertainty in locating epicenters to fewer than 10 miles (16 km). However, it was not until the early 1970s that the detection and location of earthquakes in the region greatly improved with the installation of seismic networks in South Carolina as well as other regions of the eastern U.S.

The first seismic network in the region was deployed by the USGS and the University of South Carolina in 1974. Operation continues today under the management of the University of South Carolina and is known as the South Carolina Seismic Network (SCSN). It currently consists of some 28 stations strategically located throughout the state. By 1976, a three-station short-period vertical component network was also established at SRS to monitor potential earthquake activity near the SRS. A fourth station, consisting of a vertical and two horizontal instruments, was added to the network in 1986. Figure 1.4-63 shows the current station configuration of the SRS short-period seismic recording stations.

With the advent of modern seismic network installation, it was possible to estimate local magnitudes from collected data. Magnitudes are more quantitative estimates of an earthquake's size using instrumentally recorded data. They are based on the amplitude of motion on a standard instrument (seismograph) normalized to account for the separation of the instrument and the earthquake. Within South Carolina and the SRS region, the University of South Carolina developed a duration magnitude scale normalized to the world-wide seismic station in Atlanta, GA, that has been commonly employed since the mid-1970s within South Carolina and the SRS region. Magnitudes reported using the duration scale are approximately equivalent to body wave magnitude. The uncertainty in the instrumentally determined duration magnitudes is about +0.3 magnitude units.

In addition to more accurate determinations of epicenters and magnitudes, a major benefit of instrumentation has been the ability to determine focal depths and focal mechanisms of locally recorded earthquakes. Bollinger et al. (Ref. 336) and Bollinger (Ref. 340) noted that there is a systematic difference between the depths of earthquakes occurring in the Appalachian highlands and those occurring in the Piedmont and Coastal Plain. In the Appalachian highlands, the 90% depth (i.e., the depth above which 90% of all foci lie) is 12 miles (19 km), with a peak in the focal depth distributions at 6 to 7 miles (9.6 to 11.3 km). The corresponding depths for Piedmont and Coastal Plain earthquakes are 8 miles (13 km) and 4 to 5 miles (6.4 to 8 km), respectively. Bollinger et al. (Ref. 336) argue that these depth variations indicate a significant difference in the thickness of the seismogenic crust between the adjacent provinces. Details of this focal depth study can be found in Bollinger et al. (Ref. 336).

Focal mechanism data for the region have been presented by many researchers through the years. A summary of current results can be found in Bollinger et al. (Ref. 336). Madabhushi and Talwani (Ref. 440) present some of the most recent Charleston area data with event relocations and 58 focal mechanism solutions for coastal South Carolina. Most focal mechanisms for the South Carolina-SRS region can be summarized to indicate thrust or strike-slip faulting, with the direction of the P-axis (inferred to be the direction of maximum horizontal compressive stress, oriented in a northeast southwest to east-northeast, west-southwest direction. An updated summary of existing fault mechanism result presented in Figure 1.4-64 is modified from Bollinger et al. (Ref. 336).

INSTRUMENTAL LOCATIONS (POST-NETWORK)

A detailed review of all existing data pertaining to instrumentally located earthquake activity within 50 miles of SRS has recently been completed. The purpose of the review was to refine as much as possible the locations of reported event locations -- both historical and instrumental. Historical activity was addressed above in the previous section and with the exception of the 1945 event the number of reported occurrences and locations did not change. Examination of data associated with instrumentally obtained epicenters revealed that many of the reported events would benefit from using a more detailed velocity model developed since the locations were originally noted. Additionally, waveform data not employed in some of the original locations was added from old records of the SRS network and incorporated into the location algorithm. All new locations were derived using HYPOELLIPSE (Ref. 341). Repeated trial runs revealed that the most stable locations were obtained when P and discernible S arrivals were used from stations within a 100-km radius of the computed hypocenter. HYPOELLIPSE provides a multiple crustal structure option for refinement of locations by allowing the use of varying velocity structure models for groups of stations according to their proximity to geologically differing areas of South Carolina. Varying velocity models have been developed using 20 years of seismic refraction surveys completed throughout South Carolina (Ref. 279, 309). A total of five velocity models covering the entire state of South Carolina were developed from this data. These five velocity models change from one physiographic province to another and have been applied to each recording station accordingly. Further refinement to reflect the structure of a buried Triassic basin (Dunbarton Basin) lying beneath two SRS stations has also been provided.

Relocation results are presented in Table 1.4-28 and plotted on Figure 1.4-62. The solid triangles represent old locations and solid circles represent the new locations. Four events – 26 July 1945, 15 November 1978, 16 January 1979, and 07 January 1992 -- have no circles associated with them because their revised locations either plotted out of our 50-mile (80-km) radius (26 July 1945, and 07 January 1992) or upon closer inspection were discovered not to be real events at all (15 November 1978 and 16 January 1979). Consequently these four events have been removed from consideration as reflected in Table 1.4-28. All relocations showed improvement in quality estimates. The revised locations show few if any changes between triangles and solid circles. The depth estimate parameter returned by the HYPOELLIPSE on all relocated events remained less than 12 km. However, no relocated event had a depth of less than 2.3 km, where original estimates had some events with depths at less than 1 km.

The largest felt event to have occurred within a 50-mile radius of SRS is the August 8, 1993 (09:24 UCT, 5:24 a.m. EDST), Couchton earthquake near Aiken, SC (approximately 40 miles [65 km] north of SRS). It was widely felt throughout the region in Williston, New Ellenton, and the SRS. The MMI intensity for this event was estimated at IV-V with a duration magnitude of 3.2. No alarms were triggered. The location of this event plotted on the flanks of a localized gravity low indicating relation to Piedmont-type activity associated with the boundary of a buried intrusive rather than a large-scale regional feature.

Recorded Activity (Regional)

The distribution of eastern U.S. instrumentally located epicenters essentially coincides with pre-network, historical seismicity. That is, the pattern of historical activity, which is based on larger-magnitude, felt events, is reproduced in the pattern of smaller, instrumentally located events. Bollinger noted a non-random spatial distribution of epicenters with patterns that lie parallel as well as transverse to the northeasterly tectonic fabric of the Appalachians (Ref. 336, 342). Appreciable seismic activity is displayed trending along the Appalachian highlands (i.e., the Blue Ridge) with other broad trends of activity seen primarily in the Piedmont and Coastal Plain provinces of Virginia, South Carolina and Georgia. These apparent trends led Bollinger to a zonal interpretation of southeast regional seismicity that includes the Appalachian zone, Virginia zone, and the South Carolina-Georgia zone (Ref. 342). However, Bollinger modified his earlier interpretation by presenting a broader and simpler zonation concept that includes the dominant regional trend (along Appalachian highlands) and specific zones defined by areas of concentrated activity (see Figure 1.4-60) (Ref. 340).

Results obtained from network data within the South Carolina-SRS region also allowed Tarr et al. (Ref. 324) to identify the Piedmont and Coastal Plain physiographic provinces as two diffuse areas of seismic activity. Through these studies, the Coastal Plain was further divided into three distinct clusters of seismicity that include the Bowman Seismogenic Zone, the MPSSZ, and the Jedburg-Adams Run Seismogenic Zone. The most active zone is the MPSSZ, which is the only one to coincide with the meizoseismal area of the 1886 Charleston earthquake. (Refer to Section 1.4.4.2 for more details on this zone.) Earthquake activity within the Piedmont not associated with reservoir-induced activity can best be characterized by occasional small shallow events associated with strain release near small-scale faults, intrusives, and edges of metamorphic belts.

SRS, On-Site Earthquake Activity

Three earthquakes of MMI III or less have occurred with epicentral locations within the boundaries of SRS. On June 9, 1985, an intensity III earthquake with a local duration magnitude of 2.6 occurred at SRS (Ref. 343). Felt reports were more common at the western edge of the central portion of the plant site. Figure 1.4-65 shows the resulting isoseismal intensity map, and Figure 1.4-66 shows a fault plane solution for this event (Ref. 311, 343). Another event occurred at SRS August 5,1988, with an MMI I-II and a local duration magnitude of 2.0. A survey of SRS personnel who were at the plant during the 1988 earthquake indicated that it was not felt at SRS (Ref. 344). Neither of these earthquakes triggered the seismic alarms (set point 0.002g) at SRS

facilities (Ref. 311, 344). These earthquakes were of similar magnitude and intensity as several recent events with epicenters southeast of SRS (Table 1.4-28).

On the evening of May 17, 1997, at 23:38:38.6 UTC (7:38 pm EDST) an MD ~ 2.3 (Duration Magnitude) earthquake occurred within the boundary of the Savannah River Site. It was reported felt by workers in K-Area and by Wackenhut guards at a nearby barricade. An SMA (strong motion accelerograph) located 3 miles southeast of the epicenter at GunSite 51 was **not** triggered by the event. The SMA located approximately 10 miles (16 km) north of the event in the seismic lab building 735-11A was **not** triggered. The closest instrument to the epicenter (GunSite 51) is set at a trigger threshold of 0.3% of full scale where full scale is 2.0g (0.006g). The more distant lab SMA is set to trigger at a threshold of 0.1% of full scale where full scale is 1.0g (0.001g).

SEISMIC NETWORKS

Local

As discussed above, a short-period seismic network was established at SRS in 1976 with the installation of three single-component vertical stations. In 1987, digital recording capability and a fourth three-component (one vertical and two horizontal) site were added to the network. Other short-period instrumentation has been added through the years to more completely cover the site with the total number of short-period stations currently at eight. In addition to the short-period network a ten station strong motion accelerometer (SMA) network was more recently (1998, 1999) installed throughout the SRS complex.

SMA Network

Ten new SMAs have been installed in selected mission-critical structures at foundation level, other selected elevations and in the free-field. In the event of an earthquake of sufficient size to trigger the installed instrumentation, free-field instrumentation data will be used to compare measured response to the design input motion for the structures and to determine whether the OBE has been exceeded. The instruments located at the foundation level and at elevation in the structures will be used to compare measured response to the design input motion for equipment and piping, and will be used in long-term evaluations. In addition, foundation-level instrumentation will provide data on the actual seismic input to the mission critical structures and will be used to quantify differences between the vibratory ground motion at the free-field and at the foundation level. All instruments are Kinemetrics Etna Strong Motion Accelerographs with dial-up modem data download capability. All SMA instrumentation is set to trigger at 2.0% full scale with full scale being 1g (i.e. trigger set at 0.02g). Figure 1.4-67 shows the current station configuration with specific instrument locations. Numbered locations on the figure correspond to the numbers in parentheses appearing just before location description described below.

A-Area (1) One free-field SMA is located on floor of seismic laboratory.

F-Area	(2) One SMA is located in close proximity to top of tanks in F-tank farm. (3) One SMA is located at foundation level in F-Canyon.
H-Area:	(4,5) Two SMAs are located near H-Tank farm. One at the top of the tanks and one at the bottom. (6,7) Two SMAs are located at H-Canyon. One at elevation on the roof and one at the foundation level. (8) One SMA is located in Replacement Tritium Facility (RTF) at foundation level
K-Area	(9) One SMA is located in K-Reactor building at foundation level
L-Areal	(10) One SMA is located in L-Reactor building at foundation level.
S-Area	(11) One SMA is located at Defense Waste Processing Facility (DWPF)
Other	Two additional SMAs are located in remote field locations at: (12) PAR Pond and (13) Gun Site 51

Short-Period Seismic Monitoring Network (1991-Present)

From 1991 to the present, the following short-period instrumentation has been operated and maintained onsite (see Figure 1.4-63):

- Vertical short-period digital seismic array. This consists of geophones (sensors) placed at different levels within a deep borehole located near the center of SRS to monitor effects of soil column for engineering analysis and design.
- Seven-station continuous-recording short-period telemetered seismic monitoring network for location and depth determination of locally occurring seismic activity.

Regional

To address the regional seismic issues within 150 to 200 miles (240 to 320 km) of the SRS, supplemental support has been provided to the University of South Carolina. This assistance is for operation and maintenance of the SCSN, which includes regional state-wide stations located east of the SRS as well as a small network of stations surrounding the most significant seismic source zone affecting SRS: the Charleston, SC, region. Figure 1.4-68 depicts the station locations for the SRS and surrounding region. This program serves to complement current ongoing local SRS seismic data and studies by providing access to important regional data and reliable independent sources of data and expertise.

1.4.4.2 Relationship of Geologic Structure to Seismic Sources in the General Site Region

Within the southeastern United States, seismicity generally occurs in distinct zones superimposed on a regional background of very low level seismicity. These distinct zones of epicentral distribution are both parallel and oblique to the general northeastern trend of the tectonic

structures in the region. As a general result, the relationship between the observed tectonic structures and seismic activity in the region remains unknown. Therefore, in most instances, the seismic sources are inferred rather than demonstrated by strong correlation with geologic structure. This diffuse characteristic of foci suggests the presence of multiple rather than specific seismogenic structural elements such as small-scale faults, intrusive bodies and edges of metamorphic belts.

In this region, only about 65 percent of the instrumentally recorded earthquakes have focal depth determined, and only then with modest accuracy of about +/- 5 km (3 miles) (Ref. 345). Bollinger et. al. (Ref. 336) estimate that about 90 percent of these earthquakes occur above a depth of 19 km (11 miles) and that this depth defines the thickness of the brittle seismogenic crust (Ref. 345). In the SRS region, the foci peak at about 5 km (3 miles) depth, although there is a smaller peak at about 8 km (5 miles).

For this discussion, we have defined a seismic zone to extend from the Brevard zone in northwest South Carolina to just northwest of Charleston, SC, where another seismic zone has been defined. The length of the zone is about 400 km (250 miles), and the width is 150 km (93 miles) on each side of the Savannah River. This places the SRS in about the center of the zone and includes the COCORP seismic reflections lines in Georgia .

The SRS seismic reflection data reprocessed by Virginia Polytechnical Institute present a remarkably high-resolution image of the crust from within 20 meters of the surface to the Moho. The upper crust is highly reflective and is dominated by southeast dipping bands of laminar reflective packages that are correlatable across the SRS (Ref. 346). Two of the most prominent of these packages appear to correspond to reflections identified in COCORP lines 5 and 8 in Georgia as the Augusta fault and a mid-crustal detachment (Ref. 289, 347). The midcrustal detachment at SRS is a discrete mappable southeastern dipping reflection that occurs at 14-22 km (8.7-13.7 miles) (Ref. 346). The Augusta fault is denoted by a distinct laminar southeast dipping reflector at 3.6-12 km (2.2-7.4 miles) depth (see Figure 1.4-32) (Ref. 346). In the southeastern portion of SRS, reflections from deformed Triassic-Jurassic strata are evident. These reflections are truncated by a complex southeast dipping package of reflections that may mark the detachment along which the Dunbarton basin formed (Ref. 346).

The quality of the reflection seismic data outside of the SRS is not as good except for the ADCOH data at the north northwestern end of the Savannah River Corridor and the COCORP lines 1, 5, and 8 obtained on the Georgia side on the Savannah River. The ADCOH data clearly imaged highly reflective strata of lower Paleozoic age beneath the Blue Ridge allochthon. This interpretation now appears to be generally accepted by most workers in the area. A similar seismic signature has also been imaged on COCORP line 5, suggesting that the lower Paleozoic platform rock extend southeastward at least as far as COCORP line 5 (Ref. 346). If these interpretations are correct, then the master decollement must lie above the highly reflective shelf strata.

Studies of the seismotectonics in central Virginia by Coruh et al. (Ref. 348) have shown a correlation between the distribution of hypocenters and seismic reflectors. They suggest that the earthquake activity might be associated with reactivation along existing faults above a major decollement. The seismic reflection data in the Savannah River Corridor also suggest that not

only is the seismicity similar to that in central Virginia, but it may be related to the seismic reflection data in a similar manner. That is, the seismicity is related to reactivation of existing faults above major detachments (Blue Ridge master decollement and August fault), but in general, does not penetrate below the midcrustal reflections until one approaches the East Tennessee seismic zone at the northwestern end of the corridor.

Although there are uncertainties in the determination of hypocentral depths, the earthquakes in the zone do appear to be localized above what is interpreted to be lower Paleozoic platform rock, which is separated by the master decollement from the overlying allochthon. It is reasonable to suggest that the earthquakes have been localized in the more brittle crystalline allochthon rather than in the more ductile underlying Paleozoic platform shelf strata. Indeed, this is generally the case for all of the seismic zones in the eastern U.S. as pointed out by Bollinger et al. (Ref. 349). Thus, there does appear to be an association of the seismicity with pre-existing structure in the upper 12 km of the brittle crust, which forms the seismogenic zone. This is important in that for earthquakes with a moment magnitude M>5.5, the main shock usually occurs near the base of the seismogenic zone (Ref. 350-352). This may then represent the largest earthquakes that possibly could occur in the SRS region due to the limits on size created by the depth of the seismogenic zone.

1.4.4.3 Development of Design Basis Earthquake

This section describes the basic approach to the development of the Design Basis Earthquake (DBE) spectra for the SRS. Probabilistic hazard, deterministic ground motion prediction methodologies, and the DBE history for the SRS are described. The summary of the evolution of the SRS design basis provides the necessary background for facility construction that spans four decades. This section also describes the DOE seismic criteria. A description of ground motion prediction methodologies is presented in Section 1.4.4.4. Discussions of current design guidance are contained in Section 1.4.4.5.

For engineering design of earthquake-resistant structures, empirically derived seismic response spectra are most commonly used to characterize ground motion as a function of frequency. These motions provide the input parameters used in the analysis of structural response and/or geotechnical evaluation. Response spectra are described in terms of oscillator damping, amplitude, and frequency and are defined as the maximum earthquake response of a suite of damped single degree-of-freedom oscillators. The response spectra are related to earthquake source parameters, the travel path of the seismic waves, and local site conditions. Over the last two decades, SRS response spectra have evolved from the use of a single scaled record of a western US earthquake to a composite spectra that may represent the response of more than one earthquake. In the latter approach, controlling DBEs represent a suite of earthquake magnitude and distance pairs that provide the maximum oscillator response in discrete frequency bands. The basis for controlling earthquakes is derived from detailed geologic and seismologic investigations conducted in accordance with 10 CFR 100 Appendix A and taking into consideration proposed changes as described in Draft 10 CFR 100, Appendix B (Ref. 282). This approach is typically labeled the "deterministic" approach. The primary disadvantage of this approach is that the selection of controlling earthquakes does not explicitly incorporate the rate of seismicity or the uncertainty in earthquake source parameters and ground motion.

An important alternative to the deterministic approach is the Probabilistic Hazards Assessment (PHA). The PHA incorporates the source zone definition and ground motion prediction assessments required for the deterministic approach, but also considers the estimated rates of occurrence of earthquakes, and explicitly incorporates the uncertainties in all parameters. This approach predicts the probability of exceeding a particular ground motion value at a location during a specified period of time. This approach is essential for hazard mitigation of spatially distributed facilities having different risk factors. The current DOE criteria are probabilistic based.

For SRS, design spectral shapes are employed for earthquakes of different magnitudes and travel paths. The following principal spectra have been developed for the SRS using deterministic methodologies or combinations of deterministic methodologies:

- Housner (Ref. 353)
- Blume (Ref. 354)
- Geomatrix (Ref. 355)
- WSRC (Ref. 356)
- WSRC (Ref. 357)
- WSRC (Ref. 358)

Each of these portrays a step in the evolution of the understanding of the seismic process. Because no one facility SAR portrays the evolution of the scientific and technical basis for the DBE, background for development of the DBE is described herein.

The Housner spectra was the response of a single record, the Taft record, from the 1952 Tehachippi earthquake. In contrast, the Blume study developed a composite free-field spectrum that enveloped three postulated events: (1) a random local (<25 km [<15 mile)]), (2) a large earthquake originating near Bowman, SC, and (3) a repeat of the 1886 Charleston, SC, earthquake (Ref. 354). Although different methodologies were used to develop response spectra, the Geomatrix study used the same three earthquake sources except that the 1886 Charleston earthquake was increased slightly in magnitude and moved a few tens of km closer to the site (Ref. 355). In both Geomatrix and Blume investigations, the postulated Bowman earthquake did not control motions at any spectral frequency; consequently, only two controlling events were modeled: the random local earthquake and the larger, more distant, Charleston event.

The Housner and Blume spectra were based on western U.S. strong motion data, because strong motion data were unavailable at that time in the eastern U.S. for earthquake magnitudes and distances necessary for design. Since the Blume study was conducted, ground motion studies have shown that seismic path and site properties are very different between the eastern U.S. and western U.S. Current analytical approaches directly estimate spectra by using SEUS Coastal Plain conditions to model path effects on wave propagation (Ref. 357).

Current design basis spectra are based on a hybrid of deterministic and probabilistic approaches. Some analyses (e.g., RTF and H-Area facilities) have required site-specific design basis motion for determination of liquefaction susceptibility and structural integrity.

CRITERIA

Seismic design criteria for nonreactor DOE facilities are contained in DOE Order 420.1 and DOE-STD-1020-94 and DOE-STD-1024-92 (Ref. 59, 359, 361). Additionally, criteria can be found in DOE STD-1022-94 (Ref. 139).

Earlier estimates of ground motion for SRS critical facilities have generally adopted U.S. NRC regulatory guidance provided in 10 CFR 100, Appendix A (Ref. 282). This deterministic guidance was applied, for example, at K-Reactor. However, the more recent seismic evaluations have employed the probabilistic guidance contained in DOE-STD-1024-94 and DOE-STD-1023-95 (Ref. 361, 362).

DOE Order 420.1 provides requirements for mitigating natural phenomena hazards that include seismic, wind, flood, and lightning (Ref. 359).

DOE-STD-1020-94 defines the performance goals for seismic, wind, tornado, and flood hazards (Ref. 59).

DOE-STD-1021-93 provides guidelines for selecting performance categories of Systems, Structures, and Components (SSCs), for the purpose of Natural Phenomena Hazard (NPH) design and evaluation (Ref. 363). This standard recommends general procedures for consistent application of DOE's performance categorization guidelines.

DOE-STD-1020-94 and DOE-STD-1024-92 require the use of median input response spectra that are determined from site-specific geotechnical studies and anchored to Peak Ground Accelerations (PGAs) determined for the appropriate facility-use annual rate of exceedance (Ref. 59, 361). Guidance regarding the specific characterization of seismic hazard is found in the Systematic Evaluation Program guidance and DOE-STD-1022-94 (Ref. 139).

DOE-STD-1024-92 was an interim standard which requires deterministic and probabilistic methodologies be used for hazard evaluation, and superseded by DOE-STD-1023-95 (Ref. 361, 362). The guidelines for probabilistic hazard analyses are: (1) sites can use a combined Electric Power Research Institute (EPRI) and Lawrence Livermore National Laboratory (LLNL) result if applicable, or (2) complete a new estimate using site-specific data including definition of source zones, earthquake recurrence rates, ground motion attenuation, and computational methodologies that are spelled out in the Systematic Evaluation Program.

DOE-STD-1023-95 provides guidelines for developing site-specific probabilistic seismic hazard assessments, and criteria for determining ground motion parameters for the design earthquakes (Ref. 362). It also provides criteria for determination of design response spectra. Five performance categories are specified, from Performance Category 0 (PC0) for SSCs that require no hazard evaluation, to design of PC4, a desired performance level comparable to commercial nuclear power plants. These criteria address weaknesses in prior guidance by specifying Uniform Hazard Spectrum (UHS) controlling frequencies, requiring a site-specific spectral shape and a historic earthquake check, to assure that the DBE contains sufficient breadth to accommodate anticipated motions from historic earthquakes above moment magnitude (Mw) 6.

The fundamental elements of the criteria for higher hazard nuclear facilities (PC3 and PC4) are as follows:

1. A probabilistic seismic hazard assessment (PSHA) must be conducted for the site (or use an existing PSHA that is less than 10 years old).
2. A target DBE response spectrum is defined by the mean UHS.
3. Mean UHS shapes are checked by median site-specific spectral shapes, which are derived from de-aggregated PSHA earthquake source parameters. The median site-specific spectral shapes are scaled to the UHS at two specific frequencies (average 1-2.5, and 5-10 Hz).
4. Estimated site-specific ground motions from historical earthquakes (significant felt or instrumental with Mw > 6) are developed using best estimate magnitude and distance.
5. Spectral shapes are adjusted until DBE response spectra have a smooth site-specific shape.
6. Probabilistic assessment of ground failure should be applied if necessary (i.e., wherever there may be instances of liquefaction or slope failure).

Recently, NEHRP-97 (Ref. 364) criteria have been adopted by WSRC and DOE for evaluation of spectra for PC1 and PC2 facilities and structures (Ref. 358). DOE-STD-1023-95 (Ref. 362) allows the use of building codes and/or alternate design criteria for PC1 and PC2 design. The NEHRP design criteria is defined as 2/3 of the maximum considered earthquake ground motion (i.e., 2/3 of the 2500 year UHS).

HISTORICAL PERSPECTIVE ON DESIGN BASIS EARTHQUAKES AT THE SAVANNAH RIVER SITE

Because maximum potential causative fault structures within the Coastal Plain, Piedmont, and Blue Ridge provinces are not clearly delineated by lower-level seismicity or geomorphic features, past regulatory guidance prescribes the use of an assumed local earthquake. The magnitude/intensity is conservatively assumed to be a repeat of the largest historic event in a given tectonic province located at that province's closest approach to the site. Application of this guidance has resulted in the definition of two controlling earthquakes for the seismic hazard at SRS. One earthquake is a local event comparable in magnitude and intensity to the Union County earthquake of 1913 but occurring within a distance of about 25 km (15 miles) from the site. The other controlling earthquake represents a potential repeat of the 1886 Charleston earthquake. Selection of these controlling earthquakes for design basis spectra has not changed significantly in over 20 years. However, the assumed maximum earthquake moment and magnitude estimates have increased in the more recent assessments of the 1886 Charleston earthquake. In addition, the assumed distance to a repeat of the 1886 Charleston-type earthquake has slightly decreased.

Until the late 1980s, investigations performed for the NRC focused on the uniqueness of the location of the Charleston earthquake, due to a lack of knowledge of a positive causative

structure at Charleston. At issue was the possibility of a rupture on any one of the numerous northeast-trending basement faults located throughout the eastern seaboard. Further, there were no obvious geomorphic expressions that might suggest large repeated faulting.

Evidence that defines the Charleston Seismic Zone (CSZ) is as follows:

- The detailed analyses of isoseismals following the 1886 Charleston earthquake (Ref. 327, 365).
- Instrumental locations and focal mechanisms of seismicity defining the 50-km long Woodstock fault lineament, which closely parallels the north-northeast trending Dutton isoseismals
- The remote-sensed 2.5-meter high, 25-km long lineament that also parallels the Woodstock fault (Ref. 366, 367).

Paleoliquefaction investigations along the Georgia, North and South Carolina coasts (Ref. 332, 333) have identified and dated multiple episodes of paleoliquefaction that have constrained the latitude of the episodes (Section 1.4.3.2). Crater frequency and width are greatest in the Charleston area, and decrease in frequency and width with increased distance along the coast, away from Charleston. This evidence led the NRC in 1992 to its position that a repeat of the Charleston earthquake was assumed to be restricted to the Charleston, Middleton Place region. NRC guidance for the nearby VEGP commercial nuclear power plant has, therefore, been based on an assumed recurrence of the 1886 Charleston earthquake in the Summerville-Charleston area (Ref. 355). Sporadic and apparently random low level seismicity is characteristic of the Coastal Plain and Piedmont geologic provinces (excepting clusters of seismicity in Bowman and Middleton Place). Regulatory guidance has prescribed a design basis local event to occur at a random location within a specified radius of the site.

The following sections contain, for historical reasons, brief summaries of the important deterministic and probabilistic seismic hazard investigations that have been conducted at or applied to various facilities at the SRS.

Housner

The earliest spectra used at SRS were developed by Housner who used a 5% damped response from the 1952 Taft earthquake (Ref. 353, 368). For a repeat of the Charleston earthquake, Housner predicted 0.1g at SRS and conservatively recommended 0.2g for the DBE. These spectra were used in an early evaluation of the seismic adequacy of production reactors at the site, but are no longer considered acceptable for design basis analysis.

Blume

Recommended site acceleration and spectra in the Blume analysis were based on conservative assumptions for the occurrence of specific earthquakes (Ref. 354). The anticipated ground motions from those events were developed from recorded earthquakes and synthetic seismograms for those postulated events. A probabilistic hazard evaluation was also done. Two

hypothetical earthquakes consistent in size with earthquakes that have occurred in similar geologic environments were found to control SRS spectra and peak ground motion: (1) a hypothesized site MM intensity VII local earthquake of epicentral intensity VII causing an estimated site PGA of 0.10g; and (2) a hypothetical intensity X (1886 Charleston-type), occurring at a distance of 145 km causing an estimated site PGA of <0.1g. For added conservatism, the site PGA was increased to 0.2g, this corresponded to a site intensity of VIII (see Figure 1.4-61).

The PHA indicated that the mean annual rate of exceedance of $2x10^{-4}$, corresponding to 0.2g, was comparable to those probabilistic hazard studies developed for nearby nuclear power plants. The spectra also compared well to LLNL report UCRL 53582.

In the Blume study, the following three seismogenic source regions were considered for ground motion assessment:

- Appalachian Mountains including the Piedmont and Blue Ridge geologic provinces assessed at a maximum intensity VIII.
- Atlantic Coastal Plain, including SRS, assessed at a maximum intensity VII.
- The CSZ with an epicentral intensity of X. A hypothetical Charleston event was also assumed to occur at Bowman for the purposes of estimating the distance for the attenuation of ground motion.

The length of the 1886 Charleston seismogenic zone was estimated as 50 km based on the elongation of the highest intensity isoseismal and on the length and location of the inferred Woodstock fault as determined by instrumental location and mechanisms of earthquakes (Ref. 327, 366). A displacement of 200 cm was estimated for the Charleston event based on the source dimension and the seismic moment. The source mechanism was assumed to be similar to the mechanisms recorded along the Woodstock fault: steeply dipping right lateral strike-slip fault oriented N10°E.

The estimated PGAs for postulated maximum events were based on the following:

- A local earthquake of MMI VII as a maximum credible earthquake (MCE) for the Atlantic Coastal Plain.
- A Fall Line event, MMI VIII with distance > 45 km, is an MCE for the Piedmont.
- A Middleton Place event of MMI X, a repeat of the Charleston 1886 earthquake
- A Bowman, MMI X, a postulated and considered extremely unlikely occurrence of a 1886 type-event at closest credible distance of 95 km.

Blume applied a confidence margin of one intensity unit to the estimates in Table 1.4-29, resulting in a site intensity of VIII with a corresponding doubling of the estimated PGA (to 0.2g). Using the PHA, Blume noted that a doubling of the PGA results in an approximate order of magnitude smaller probability of exceedance.

Local and distant earthquake response spectral shapes were derived from statistical analysis of primarily western U.S. (western) data. The recommended response spectra were computed from the envelope of the mean spectral shapes (see Figure 1.4-69).

Geomatrix (K-Reactor)

In a manner similar to Blume, Geomatrix performed a deterministic analysis following NRC SRP 2.5.2 for K-Reactor (Ref. 355). The resulting spectra were developed for a distant Charleston source and a local source. The Charleston source was modeled for a moment magnitude (Mw) 7.5 using the Random Vibration Theory (RVT) model. Site-specific soil data were used to address the impact of local conditions of the spectral content. The local source assumed a Mw 5 and used empirical western U.S. deep soil strong motion data corrected for eastern U.S. soil and rock conditions. The 5% damped spectra for the two hypothetical controlling earthquakes are illustrated in Figure 1.4-69.

The primary uncertainty related to the 1886 Charleston earthquake moment magnitude estimate was the interpretation of intensity, which was derived from Dutton's damage patterns (Ref. 369). The fault rupture width was estimated to be 20 km based on a range of deepest Coastal Plain hypocenters (Ref. 355). The rupture length was determined from regressions of world-wide M_O vs. rupture area. From the rupture dimensions and moment, Geomatrix estimated a stress-drop of 65 bars and an average displacement of 400 cm.

The Bowman seismicity zone, located in the Coastal Plain province, consists of M3.5-4.0 events occurring along a northwest trend from Charleston. Because of the timing and mechanisms of events, they are not believed to be associated with the CSZ. The largest historical earthquake in the Piedmont Province was the 1913 Union County earthquake having an epicentral intensity of VI-VII. Based on Johnston isoseismal areas, that earthquake was estimated to be Mw 4.5. The largest Appalachian province earthquake was the 1875 Central Virginia event of MMI VII and Mw = 4.8. These earthquakes suggest Mw_{max} of 5.0 for Bowman, but because it was part of a diffuse north-west trend, Geomatrix used 6.0 for conservatism. The Bowman earthquake did not control site motions (similarly to the Blume study) and consequently was not used in specification of design basis motions.

For the local earthquake, the occurrence of a random earthquake within 25 km of K-Reactor was assumed. With the largest site vicinity events limited to magnitude range 2–3, regulatory guidance suggests using largest historical events in the Piedmont Province: $M_{Wmax} = 5.0$.

Geomatrix developed 5% damped response of the horizontal component from an Mw 7.5, 150 bar stress drop Charleston-type earthquake using the parameters described above (see Figure 1.4-69). The vertical component of motion was estimated to be half the horizontal. Table 1.4-30 summarizes the source parameters and predicted motions from these earthquakes.

Statistics for the Geomatrix local earthquake were selected following the approach outlined by Kimball using strong motion records from earthquakes of Mw 5.0 ± 0.5 within 25 km of epicenter (Ref. 370). The Geomatrix local earthquake spectral shape was scaled per DOE-STD-1024-92 guidance (Ref. 361).

Evaluation Basis Earthquake Spectra

For the 1993 liquefaction studies at RTF, the design basis envelope spectra contained in the Blume report were not recommended because the spectra were not representative of a specific earthquake (Ref. 371). Seismic hazard results show that the site can be characterized by local events with R <25 km, controlling the PGA. Larger events, at some distance from the site, controlled peak ground velocity at SRS. These results compared favorably with the deterministic analyses performed for the site by Blume and Geomatrix.

The controlling earthquakes used in the liquefaction study at RTF were selected to be consistent with the DOE probabilistic acceptance criteria (Ref. 59, 371). A spectral shape was taken from the local event spectra developed for K-Reactor (Ref. 355). The distant event spectra were recommended unscaled (see Figure 1.4-69). The results were then compared to the past deterministic study of Blume and the disaggregated LLNL and EPRI hazard analyses. Induced stresses were calculated for the liquefaction analysis based on the two controlling earthquakes. Separate analysis is warranted based on the difference in shape of the two spectra.

The RTF spectra were later named the Evaluation Basis Earthquake (EBE), and used to support initial geotechnical evaluations for the ITPF and H-Area Tank Farms. The EBE spectra were used until site-specific spectra could be developed to judge adequacy. The EBE spectra, which account for local and distant earthquakes, were consistent with DOE criteria, and were used for the initial geotechnical evaluation.

WSRC (H-Area Spectrum)

Following initial site-specific evaluations done for the ITPF and H-Area, a revised spectrum (84th percentile deterministic spectrum) was developed and recommended for structural engineering and geotechnical analysis of facilities in H-Area (Ref. 356). The geotechnical analysis utilized the basement results in a convolution analysis and the structural engineering groups developed an envelope for use in analysis of SSCs. The resulting structural design spectrum envelope is shown in 1.4-70.

The fundamental change was to the distant earthquake component. The parameters used to develop a 50th and 84th percentile spectra were site-specific soil and revised stress drop for a Charleston earthquake.

EPRI and LLNL hazard spectra were used to estimate the probability of exceedance of the spectra. The local event spectrum was unchanged from the EBE. The resulting local and distant spectra were then enveloped into a surface design spectrum 1.4-70.

WSRC (PC-3 And PC-4 Site-Wide Design Spectra)

The site-wide design spectra fully implement DOE-STD-1023-95 (Ref. 357, 362). DOE-STD-1023-95 specifies a broadened mean-based UHS representing a specified annual probability of exceedance (for an SSC performance category) and a historical earthquake deterministic spectrum that ensures breadth of the UHS. For the SRS, the deterministic spectrum

is represented by a repeat of the 1886 Charleston earthquake. The development of the SRS design basis spectra uses a statistical methodology to verify that a mean-based response is achieved at the soil free surface.

The design spectra were intended for simple response analysis of SSCs and are not appropriate for soil-structure interaction analysis or geotechnical assessments. The design basis spectra for PC3 and PC4 are given in Figures 1.4-71 and 1.4-72, respectively.

The EPRI and LLNL bedrock level uniform hazard spectra were averaged and broadened per DOE-STD-1023-95 (Ref. 362). Available SRS soil data were used to parameterize the soil shear-wave velocity profile. The parameterization was used to establish statistics on site response for ranges of soil column thickness present at the SRS. The mean soil UHS was obtained by scaling the bedrock UHS by the ground motion dependent mean site amplification functions.

The soil data used to develop the sitewide spectra incorporate the available SRS velocity and dynamic property database available to about mid-1996. The spectra are based on soil properties and stratigraphy from specific locations at the SRS, and are parameterized to represent the variability in measured properties. Because of the potential for variation of soil properties in excess of what have been measured at the SRS, the design basis spectra are issued as "committed" in accordance with the WSRC Quality Assurance Manual 1Q (Ref. 372). The open item is the soil column variability used in the calculations. To eliminate the open item and upgrade the design basis spectrum to "confirmed," the soil parameters available at the specific site or facility where it is being used must be reviewed and determined to be consistent with the data parameterized in the study.

Comparison of PC3 and PC4 design spectra to the SRS interim spectrum and the Blume envelope spectrum are shown in Figure 1.4-73 (Ref. 354, 357). There is broad general agreement between the PC3 and interim spectral shape. The SRS Interim Spectrum shape is significantly more conservative in the 0.5 to 2.0 Hz frequency range compared to the PC3 spectrum because the interim shape enveloped the 84th percentile Charleston deterministic spectrum rather than the 50th percentile as required by DOE-STD-1023-95 (Ref. 362). Comparisons of the Blume 0.20g anchored spectrum to the PC3 design spectrum indicate significant shape differences. The Blume spectrum was derived from deep soil recordings of western U.S. earthquakes and is not representative of eastern U.S. spectral shapes. The spectra show a generally more broadened shape as compared to the Blume spectra (see Figure 1.4-73). Low frequencies are enhanced with respect to Blume because the Blume spectra do not contain the fundamental site resonance (about 0.6 Hz). High frequencies are also enhanced with respect to Blume because of the difference in eastern and western U.S. attenuative properties. Both the PC3 spectrum and the Blume spectrum have a dynamic amplification of about 2.7 at 3 Hz. The significantly larger Blume PGA scaling factor causes the excess (as compared to the design basis spectrum) spectral values at the mid-range.

WSRC (PC1 And PC2 Site-Wide Design Spectra)

Design spectra guidelines for PC1 and PC2 facilities are reported by Lee (Ref. 358). The PC1 and PC2 design spectra were derived using DOE-STD-1023-95 guidelines and NEHRP-97

(Ref. 364) design criteria and account for the wide range in SRS material properties and geometries including soil shear-wave velocities, uncertainty or range in soil column thickness, and type of basement material. Additional design guidance is contained in the current revision of WSRC Engineering Standard 01060 (Ref. 373).

SRS-SPECIFIC PROBABILISTIC SEISMIC HAZARD ASSESSMENTS

An SRS-specific probabilistic seismic hazard assessment (PSHA) is critically dependent upon the local geological and geotechnical properties at the site or facility location. Past PSHAs, specifically those conducted by EPRI (NEI, 1994) and LLNL (Bernreuter, 1997; Savy, 1996) for the SRS, did not incorporate these detailed site properties and consequently, those soil hazard results were not appropriate for use at the SRS. An SRS-specific PSHA should account for soil properties derived from site geological, geophysical, geotechnical and seismic investigations (WSRC, 1997). An SRS-specific PSHA was developed using bedrock outcrop EPRI and LLNL hazard and SRS site properties including soil column thickness, soil and bedrock shear-wave velocity, and dynamic properties (WSRC, 1998).

The bedrock seismic hazard evaluations used for the SRS-specific soil surface hazard were the EPRI and LLNL results for bedrock for the SRS and vicinity (a later evaluation was completed using the U.S. National Map bedrock seismic hazard (WSRC, 1999, Frankel et al., 1996)). These evaluations did not revise or confirm in any way the experts' evaluations of activity rates, seismic source zonation, or the decay of ground motion with distance used in the LLNL or EPRI seismic hazard assessments. The analysis results in a SRS-specific hazard evaluation for a soil site by continuing the hazard from bedrock to the soil surface using detailed soil response functions. Earthquake magnitude and ground motion level dependence of the site response is accommodated by applying site response functions consistent with the distribution of earthquake magnitude and ground motion levels obtained from dissaggregating the bedrock uniform hazard spectrum.

Frequency and ground motion level dependent soil amplification functions (SAFs) developed in WSRC (1997) were used to account for the observed variations in properties throughout the SRS including: soil column thickness, stratigraphy, shear-wave velocity, and material dynamic properties, as well as basement properties. SAFs (frequency dependent ratio of soil response to bedrock input) were derived in WSRC (1997) by performing a statistical analysis of the response of bedrock spectra through realizable soil columns bounded by the observed variations in soil-column properties over the SRS. Ground motion level dependent distributions of SAFs were derived for each of 6 soil categories: three on crystalline basement and three on Triassic basement. Those SAF distributions were used to compute soil surface hazard.

The methodology to compute soil surface hazard was formalized by Cornell and Bazzurro (1997). The technique is to difference the bedrock hazard disaggregation for a suite of bedrock motions and sum the probability of exceedance (POE) of surface motions using the appropriate

magnitude and ground motion level-dependent soil/rock transfer functions. The approach yields soil surface hazard that would be obtained from correctly applying local site soil transfer functions to the ground motion attenuation model used in a PSHA. The analysis is repeated at the oscillator frequencies available in the bedrock hazard disaggregation and for each soil column thickness and bedrock type. The envelope of the hazard curves is taken from the soil and bedrock categories.

The curves represent hazard at the top of the soil column for oscillator frequencies of 1, 2.5, 5 and 10 Hz (Figure 1.4-7new). Open symbols on the dashed lines indicate extrapolation beyond either the LLNL or EPRI bedrock hazard values. Solid lines are computed soil surface hazard derived from the bedrock hazard disaggregations and distributions on soil transfer functions. Application of the hazard curves to PC3 and PC4 facilities require additional site-specific data to validate that the facilities properties are well represented by the SRS-specific properties.

High and low probability extrapolations of bedrock hazard curves were made to meet the ranges of probability required for engineering risk assessments (annual probabilities as low as 10^{-7} were considered). Soil surface hazard results computed in the range of bedrock hazard extrapolations are considered more uncertain. Consequently, computed ground surface hazard curves for annual probabilities greater than about 10^{-2} or less than about 10^{-6} should be used with caution. These results were computed using a 3-□ truncation on the ground motion probability of exceedance and a lower bound of 0.5 on the SAF.

PSHAs developed for the SRS prior to the LLNL and EPRI studies (i.e., Coats and Murray, 1984, URS/Blume, 1982) as well as the hazard derived from the combination of the original EPRI and LLNL soil surface hazard (Wingo, 1994), were derived for PGA only and did not use SRS-specific soils data. Historically, engineering applications and earthquake design used PSHAs that were PGA-based, a practice that has diminished for the last 20 years because of improved interpretations from broader-band seismic recording and the better understanding of the broad-band nature of seismic hazard. The engineering use of PGA PSHAs is neither recommended nor consistent with DOE-STD-1023.

1.4.4.4 Ground Motion Prediction Methodologies

This section briefly describes current ground motion prediction methodology and earthquake source, path, and site assumptions used for H Area, the most recent DBE work conducted for the SRS.

RANDOM VIBRATION THEORY (RVT) MODELING

To model ground motion, an RVT model (also called Band Limited White Noise) is used to estimate ground motion for the distant Charleston-type event (Ref. 374, 375). The RVT model is widely accepted and, with proper parameterization, is found to predict ground motion as successfully as empirically derived relationships (Ref. 376). Because of the model's simplicity, computational speed, ability to parameterize source, geometrical spreading, crustal attenuation, and site response, it is ideally suited to quantifying ground motion. The RVT methodology appears to be well suited in geologic environments where empirical strong motion data may not exist in the earthquake magnitude and distance ranges of interest. Nonlinear wave propagation within the soil column is accounted for by using a computer modeling program, such as SHAKE, or equivalent approach.

EARTHQUAKE SOURCE PARAMETERS

This section discusses the earthquake source parameter uncertainty affecting ground motion prediction for the SRS. Source parameters for the "distant event" or Charleston-type earthquake have been the most contentious in past design studies. Figure 1.4-61 shows a distance from the SRS site center to the 1886 Charleston MMI X isoseismal contour of approximately 120 km. The SRS center to the southern end of the Woodstock fault is approximately 130 km. The center of SRS to the center of the 1886 MMI X isoseismal, close to Middleton Place and central to Dutton's isoseismals, measures approximately 145 km. URS/Blume used 145 km as the distance from the SRS center to the 1886 Charleston earthquake epicenter (Ref. 354). Current ground motion studies analyze a recurrence of the 1886 event with a distance of 120 km. For estimates of median ground motions for a recurrence of the 1886 earthquake, a source distance of 120 km is conservative since the center of the isoseismal zone is at a distance of approximately 145 km.

For simplicity, the RVT models of ground motion assume a point source. The effects of focal depth and crustal structure on predicted ground motion are described in Lee (Ref. 356).

The distance and stress drop effects on rock motion predictions for a repeat of the Charleston Mw 7.5 event were described in Lee (Ref. 356). The 100-150 bar range in stress-drop is a probable range for the median value of an eastern U.S. earthquake. Somerville et al. (Ref. 377) found a value of 100 bars as the median stress-drop for eastern U.S. earthquakes; the EPRI guidelines (Ref. 376) report estimated a value of 120 bars as a median for stress drop, from data with reported stress-drops in the range of 20-600 bars.

Prior ground motion studies for SRS have used expected or median stress drops of 100-150 bars for a Charleston-type event. Peak ground motion is sensitive to the selection of stress drop (Ref. 356).

The 1886 isoseismal data are consistent with ground motion models with a slightly reduced earthquake moment magnitude of Mw 7.3, but with a corresponding higher stress-drop. The favored median model uses a Mw 7.3 at 120 km and stress drop of 150 bars (Ref. 357).

BEDROCK AND CRUSTAL PATH PROPERTIES

Ground motion estimates used a modified Herrmann crustal model developed from surface wave dispersion from Bowman, SC, to Atlanta, GA (Table 1.4-31) (Ref. 357, 378).

For geometrical attenuation, a plane-layered crustal model approximation by Ou and Herrmann is used that accounts for the post critical reflection (Ref. 379). The effect of this approximation is to decrease the attenuating loss between about 80-120 km. Using a point source and the local crustal structure for the Charleston event, the attenuation model predictions were found sensitive to source depth and source distance.

For development of the RVT rock spectra, anelastic attenuation is accounted for in two ways: (1) the crustal path operator Q that is frequency dependent; and (2) the site-dependent factor Kappa, related to Q by H/(Vs*Qs). Where Qs is the average quality factor over a several kilometer range of the near surface rock. The preferred Q model for these investigations is EPRI (Ref. 376).

The best mean EPRI model is given by (Ref. 376):

$$Qc = Qo*(f/f_o)^n = 670*f^{0.33} \qquad \text{(Eq. 1.4-4)}$$

The ranges of the rock site attenuation operator Kappa are estimated to be 0.010-0.004 seconds with a median of 0.006 seconds (Ref. 376). RVT calculations for the SRS ground motion predictions use this median value of 0.006 seconds for Kappa.

For SRS ground motion predictions, bedrock properties underlying most of the SRS facilities are assumed uniform with a Vs of approximately 3.4 km/s(11,500 fps). For facilities situated above the Triassic rift basin (Dunbarton basin), filled with 3 km (1.8 miles) of sedimentary rock, a Vs estimated to be 2.4 km/s (8,000 fps) is used. This basin is surrounded by crystalline rock. For a first approximation to the ground motion effects of the basin, a one-dimensional plane-layer model is used to approximate the effect of contrasting velocities.

SOIL PROPERTIES

The SRS is located on soils (sedimentary strata) ranging in thickness from 180 to 460 meters (600 to 1,500 feet) overlying crystalline or Triassic basement. A sitewide design basis spectrum must account for the range and variability in SRS soil properties. Deep stiff soils, such as those present at the SRS, severely condition bedrock spectra by frequency-dependent amplification or deamplification. Depending upon the frequency and amplitude of bedrock motion, the key soil properties controlling the soil spectrum are the soil column thickness, the dynamic properties (strain dependent shear-modulus ratio and damping), low-strain soil shear-wave velocity structure and impedance contrast with the basement.

To accommodate the range of shear wave-velocity in the soil column, a database of velocity profiles was compiled for the SRS (Ref. 357). This database contains the range of soil and rock shear-wave velocities available from various borings and seismic surveys that have been conducted at the SRS using seismic cross-hole, down-hole, velocity logger, and refraction techniques. The shallow profiles database for the SRS is based primarily on site-specific seismic

piezocone penetration test soundings (SCPTU). An example of SCPTU shear-wave velocity profile is shown in Figure 1.4-74. Other velocity profiles consist of cross-hole and down-hole seismic surveys. The deeper soil profiles are based on measurements made in five deep boreholes drilled to basement at the SRS.

Other, more numerous, deep holes are used for stratigraphic purposes and to estimate the elevation of the top of bedrock. Nearly all of the velocity data are from the SRS F-, H-, A-, K-, and L-Areas, and the New Production Reactor site.

Basement shear-wave velocities are estimated from compressional-wave velocities measured at the SRS. These velocities were collected using seismic refraction techniques (Ref. 278). These data show that there is a significant shear-wave velocity contrast in the SRS basement between the Dunbarton Triassic basin rock and crystalline rock. The Pen Branch fault is the demarcation for basement contrasts in velocity.

Predicted peak soil strains for the SRS are sufficient to exceed the linear range of the constitutive relations (stress-strain). Consequently, laboratory testing of site-specific soil samples was required for reliable ground motion prediction of all critical facilities.

The normalized shear modulus and damping ratio versus shear strain relationships were developed for specific stratigraphic layers. Stratigraphic formation identification and their corresponding dynamic properties were developed specifically for the SRS by K.H. Stokoe of the University of Texas (Ref. 380, 381).

Stokoe et al. compiled a dynamic soil property database from available SRS reports on dynamic soil properties and new dynamic measurements made by the University of Texas. The SRS areas from which data were obtained are:

1. Area of the Pen Branch Fault Confirmatory Drilling Program;
2. H-Area ITPF;
3. H-Area RTF;
4. H-Area Building 221-H;
5. Proposed New Production Reactor site,
6. Par Pond Dam;
7. K-Reactor Area;
8. Burial Ground Expansion;
9. L-Reactor Area;
10. L-Area Cooling Pond Dam; and
11. F-Area, Sand Filter Structure.

These eleven areas represent eight general locations at the SRS.

Figure 1.4-756 illustrates the University of Texas recommended normalized mean shear modulus versus cyclic shear strain by formation. Figure 1.4-76 summarizes the hysteric damping versus cyclic shear strain by formation. These curves form the basis for the dynamic properties used in the site response analysis. Figures 1.4-75 and 1.4-76 summarize cyclic shear strain and damping for SRS.

Velocity Model Parameterization

An SRS generic shear-wave velocity profile was developed from the location-specific data and includes randomness in both stratigraphic layer thickness and velocity. Because the area-specific simulations were generally consistent with the generic simulations, the SRS generic (sitewide) simulation is applied to all areas of the SRS. There is no significant reduction in the site amplification variability by applying area-specific velocity model simulations for ground motion evaluations.

1.4.4.5 Current Design Response Spectra

This section describes the current recommended SRS design basis spectra.

The current PC-3 and PC-4 sitewide spectra are based on the WSRC analysis (Ref. 357) developed in 1997, and incorporates variability in soil properties and soil column thickness. Following the development of PC3 and PC4 design basis spectra (Ref. 357) and the PC1 and PC2 design basis spectra (Ref. 358), the Defense Nuclear Facilities Safety Board (DNFSB) had several interactions with the DOE and WSRC on seismic design spectra. As a result, additional conservatisms were applied to the PC3 spectral shape at high and intermediate frequencies (Ref. 382). The shape change was incorporated in the Site Engineering Standard (Ref. 373). The shape change, illustrated in Figure 1.4-77, increased the low-frequency (0.1-0.5 Hz) portion of the PC-3 spectrum and also increased intermediate frequencies (1.6-13 Hz) of the design basis spectrum. As a result of interactions with the DNFSB, SRS is committed to apply a load factor of 1.2 on seismic loads in the applicable load combinations for new PC3 and PC4 structures (Ref. 373). The factor provides additional conservatism in seismic designs.

The WSRC Civil/Structural Committee reviewed the PC1 and PC2 design spectra (Ref. 383) and recommended to the Engineering Standards Board (ESB) that the current Uniform Building Code (UBC) be used for the Site Engineering Standard (Ref. 373). The basis for the decision was that the UBC was more conservative than the WSRC (Ref. 358) spectra.

1.4.5 STABILITY OF SUBSURFACE MATERIALS

Soil properties vary across the SRS due to changes in depositional processes from area to area over time. Consequently, soil properties at SRS are highly site-specific and are detailed in the facility-specific SARs. However, geotechnical stability concerns at the SRS are categorized generically and listed below with the intent of defining the approaches and methods used to address stability of subsurface materials in site-specific studies. Geotechnical stability concerns at SRS fall into the following categories:

- Excavation and Backfill (Section 1.4.5.1),
- Foundation Settlement (Section 1.4.5.2),
- Liquefaction (Section 1.4.5.3), and
- Soft Zones (Section 1.4.5.4).

The following sections describe these categories on a SRS site-wide basis. For MFFF, a site-specific geotechnical program will be completed which will address these categories from a site and facility specific point of view.

1.4.5.1 Excavation and Backfill

Quality of backfill affects the stability of structures built on fill areas. The requirements and specifications for excavation and backfill have changed with time. Currently there are SRS guidelines for excavation and backfill (Ref. 384), however, project specifications take precedence over the general site guidelines. Geotechnical investigations should identify areas where fill has been placed and give some indication of the quality of the fill prior to building new structures. Following is a summary of excavation and backfill requirements that have been used at the SRS.

From 1950 to 1992, engineering requirements for the excavation and backfill were based on Du Pont Standard Engineering Specifications (Ref. 385), Civil Sections SC3E, SC3.1E, SC4E, and SC5E.

From 1992 to 1995, Requirement Document 02224-01-R (Ref. 386) provided engineering requirements of the excavation and backfill. This document allowed for the use of Controlled Low Strength Material (CLSM), a lean cement mixture having a 28-day compressive strength of 30 to 150 pounds per square inch.

Since 1995, excavation and backfill have been controlled by project specifications. Specifications are prepared to satisfy project-specific needs and may be more restrictive than the Requirement Document. The project specifications take precedence over the Requirement Documents.

In 1997, Engineering Guide 02224-G (Ref. 387) was issued to provide guidance for the excavation, backfill, and grading. Provisions provided in the Engineering Guide can be mandatory, if the Engineering Guide is invoked by the project or operation documents. Provisions in the Engineering Guide include:

- General requirements for excavation, drainage, fill materials, fill placement, CLSM, moisture control, compaction, test fill, grading, testing, erosion control, and inspection
- Requirements for structural fill including:
    a. Soil classified as well-graded sand or silty sand
    b. Range of gradation distribution
    c. Maximum plastic index of 15
    d. Compaction to a minimum density of 95% of the maximum dry density as determined by ASTM D1557 (Ref. 388).
- Requirements for common fill including:
    a. Soil classified as well-graded sand, poorly graded sand, silty sand, or clayey sand
    b. Range of gradation distribution
    c. Compaction to a minimum density of 90% of the maximum dry density as determined by ASTM D1557 (Ref. 388).
- Requirements for CLSM are also provided in the Engineering Guide 02224-G (Ref. 387).

1.4.5.2 Foundation Settlement

Settlement estimates are generally made prior to design of major facilities. Estimates require facility-specific structure information and site-specific geotechnical information for evaluation. Settlement issues are discussed in the facility-specific SARs. Major facilities are surveyed, analyzed, and evaluated routinely for settlement during construction and throughout service life. Allowable settlement is a function of the soil conditions, structure geometry, and loading and the magnitude of settlement that a facility may withstand without adversely affecting performance. Settlement may occur through (1) static settlement due to loading during operation and secondary consolidation, and (2) dynamic settlement due to dissipation of seismically induced pore water pressures. Estimation of static settlement has been performed for many years using various techniques proposed by many authors. There are currently many accepted analytical and empirical methods for estimating settlement published in the geotechnical literature. Two such references (by the ASTM and Department of the Navy) contain accepted methods for estimating settlement (Ref. 389, 390). Static settlements for larger SRS facilities generally fall in the range of 0.5 to 3 inches (1 to 8 cm) (Ref. 391, 392).

Seismically induced dynamic settlement is due to liquefaction or soft zone collapse discussed in the following sections.

1.4.5.3 Liquefaction Susceptibility

The liquefaction susceptibility of the subsurface materials at SRS has been evaluated using qualitative and quantitative approaches. Site-specific investigations have been conducted for F-Area (to include F-Separations, F-Tank Farm, and general F-Area), the CIF, the RTF, ITPF, H-Tank Farm, APSF, and CLWR-TEF (Ref. 383, 393-397). In each case, the potential for liquefaction has been determined to be either small or negligible. Approaches implemented include criteria for clayey soils, shear wave velocity evaluation, the stress method and the strain method. Field and laboratory testing programs have been conducted to characterize site conditions and to measure the cyclic shear strength and strain behavior of the native SRS soils. In this section, a summary of liquefaction evaluation methodologies used currently at SRS is presented. Each facility has its own particular soil profile and characteristics and requires site-specific characterization using one or more of the methodologies described below.

CRITERIA FOR CLAYEY SOILS

Laboratory tests and field performance data have shown that the majority of clayey soils will not liquefy during earthquakes. Criteria expressing these observations have been formulated by Wang (Ref. 398) and have been extended to laboratory testing conditions in the United States by Koester and Franklin (Ref. 399). The extended criteria state that clayey soils must satisfy all three of the following conditions to be considered potentially liquefiable:

- Laboratory-determined water content (increased by 2%) is greater than 90% of the laboratory-determined liquid limit (increased by 1%).
- Liquid limit (increased by 1%) is less than 35%.
- Clay content (decreased by 5%) is less than 15%.

In general, the SRS soils do not meet these criteria and are therefore considered non-liquefiable.

SHEAR WAVE VELOCITY EVALUATION

Several investigators have correlated liquefaction susceptibility to shear wave velocity using field performance data. For example, Seed et al. (Ref. 400) concluded, "Liquefaction will never occur in any earthquake if the shear wave velocity in the upper 50 feet (15 meters) of soil exceeds about 1200 fps (365 m/s)." This conclusion was based on the actual levels of cyclic shear stresses and corresponding shear moduli required to induce liquefaction and on the world-wide field observations of earthquakes.

In 1997, the National Center for Earthquake Engineering Research published proceedings of its workshop on evaluation of liquefaction resistance of soils (Ref. 401). The proceedings contain a chapter on Liquefaction Resistance Based on Shear Wave Velocity. In that chapter Andrus and

Stokoe have compiled field data from earthquakes that showed relationships between cyclic stress ratio and normalized shear wave velocity (Ref. 401). These relationships separate sands into liquefaction-susceptible or liquefaction-nonsusceptible groups (see Figure 1.4-78). In general, based on measured shear wave velocities and site-specific Cyclic Stress Ratios, SRS soils are not subject to liquefaction according to the work of Andrus and Stokoe (Ref. 401).

THE STRESS METHOD

The stress method compares the cyclic shear stress imposed by the earthquake with the cyclic shear strength of the soil. In cases where the earthquake-induced stress exceeds the cyclic shear strength of the soil, the soil is considered potentially liquefiable. To estimate the shear stress imposed by the earthquake, dynamic response analysis is used with SRS soil profiles. The cyclic shear strength is estimated from earthquake field performance data or from laboratory test data correlated with field results, such as Standard Penetration Test (SPT) N-value or Cone Penetrometer Test (CPT) tip resistance (see Figure 1.4-79).

The empirical chart proposed by Seed et al. (Ref. 400) is considered inappropriate for use at SRS because of the geologically older soils present at the site (Ref. 402). In its present form, this chart was developed from liquefaction case histories of recent (Holocene) sands and silty sands. In all cases, the liquefied sands were recent alluvial, beach, or deltaic deposits and are granular, clean sands with silty fines in some cases. However, older sand deposits exhibit greater liquefaction resistance than younger deposits (Ref. 403-410). From these studies, it appears that liquefaction is greatly restricted in deposits older than about 10,000 years.

Increased liquefaction resistance in older sand deposits may be a result of cementation, weathering (which chemically breaks down micas and feldspars into clays that inhibit liquefaction), increased exposure to low-level seismic shaking, cold bonding, and consolidation. All of these factors tend to increase the liquefaction resistance of sands. In addition to increasing liquefaction resistance, most of these factors probably increase, to some degree, the CPT tip resistance and the SPT blow count. Therefore, laboratory cyclic shear testing and the development of site-specific liquefaction curves are recommended when employing the stress method at the SRS (Ref. 394, 402).

Settlement due to liquefaction can be estimated from laboratory volumetric strain test results, which have been correlated to CPTU field data (Ref. 394). For example, the curves shown in Figure 1.4-79 have been used to determine Cyclic Stress Ratio (CSR) required to induce liquefaction. The CSR due to the design earthquake is divided by the CSR required to induce liquefaction to determine a factor of safety. Figure 1.4-80 relates CPTU field data to post-earthquake settlement once the factors of safety against liquefaction are known. Final estimates of post-earthquake settlement will depend on site-specific geotechnical information.

STRAIN METHOD

Cyclic shear straining and porewater pressure development of undrained sand is fundamental in the evaluation of seismic liquefaction potential (Ref. 411, 412). The strain method compares earthquake motion-induced cyclic shear strains to threshold cyclic strain. For this method,

site-specific laboratory testing and analysis is required. The cyclic shear strains are obtained from dynamic response analysis, and laboratory testing is used to model pore pressure buildup. For example, Figure 1.4-81 shows the relationship between induced porewater pressure ratio and repeated cyclic strains of various amplitudes for the Santee Formation at the ITPF (Ref. 394). For this case, the maximum induced shear strain for the EBE was about 0.03%, which results in an excess pore water pressure ratio of less than 15% (see Figure 1.4-81). Liquefaction is not expected to occur for this modest level of induced porewater pressure.

1.4.5.4 Evaluation of Soft Zones

Across SRS the soil zone between approximately 30 to 70 meters (100 to 250 feet) below the ground surface is a marine deposit labeled the Santee Formation. Within this interval are areas having locally high concentrations of calcium carbonate. Often found within these sediments, particularly in the upper third of this section, are weak zones interspersed in stronger matrix materials. These weak zones, which vary in thickness and lateral extent, are termed "soft zones". The existence of soft zones and the potential for settlement is a site-specific characteristic and requires subsurface characterization and engineering evaluation on a site-specific basis.

The soft zones are stable under static conditions. The Santee section, in which the carbonate and soft zones are found, is generally in the saturated zone well below the water table. Here the sediments are in a stable chemical environment, and carbonate dissolution is minimal. The further dissolution and removal of the Santee carbonate (in the engineering sense; i.e., the next 100 years) is a non-issue.

For the types of facilities constructed at the SRS, the increase in load on the soft zone soils is negligible. However, potential load increase due to a seismic event needs consideration even though the geologic record shows that soft zones encountered today have withstood the earthquakes that have occurred since their formation.

A complete summary of the origin, extent and stability of soft zones is presented by Aadland et al. in WSRC-TR-99-4083 (Ref. 235), "Significance of Soft Zone Sediments at the Savannah River Site." Details on the impact of soft zones for specific facilities can be found in the facility-specific SARs.

PREVIOUS STUDIES

Beginning with site exploration, a great many geological and geotechnical studies have been performed at SRS. As part of the original efforts to evaluate foundation conditions for various facilities, the United States Army Corps of Engineers (COE) conducted a geologic and engineering investigation, which comprised the first comprehensive evaluation of sitewide subsurface conditions (Ref. 255). Subsequent regional and area-wide studies include Colquhoun and Johnson and Siple (Ref. 218, 413).

As described in previous sections, the Santee Limestone consists of varying thicknesses of calcareous sediments that are intercalated with non-calcareous, fine-grain, quartz sand.

Calcareous horizons are rare in the northwestern part of SRS, more abundant but sporadic in the central part, and widespread and relatively thick in the southeastern part.

Siple hypothesized that calcareous materials have undergone post-depositional dissolution, which has caused subsidence of the overlying beds and resulted in ground surface depressions (Ref. 413). Siple mentions encounters with "voids" or loosely compacted sediments during drilling and notes that large amounts of cement grout were used to stabilize these subsurface "soft zones" before construction of heavy structures for the original plant facility. The COE performed foundation grouting in the early 1950s for each of the five reactors (C, K, L, P, and R) and both canyon facilities (221-H and 221-F). Since that time, foundation grouting has been performed at other SRS facilities, including K-Area cooling tower and cooling water line, Steel Creek Dam, portions of H- and F-Tank Farms, and DWPF.

Since 1980, several extensive subsurface investigations at scattered site locations within SRS have been completed, yielding more detailed information on the local extent and character of soft zones. In each case, the investigation demonstrated significant variations in subsurface stratigraphy such that the application of general design criteria for soft zone evaluation is not recommended. The investigations have revealed that soft zones within the calcareous materials are found at depths approximately 40 to 52 meters (130 to 170 feet) below natural ground surface and are probably the result of millions of years of carbonate and shell dissolution within the strata. This slow dissolution has resulted in zones of lower density and strength and, consequently, higher compressibility when compared with the surrounding, more intact and sometimes silicified, sandy material. The soft zones behave as local, underconsolidated pockets with overburden stresses arching around the underconsolidated zones. Because the soft zones have formed over a considerable period of time (late Eocene, or about 40 Ma), have survived for millions of years, and have apparently persisted through several historic earthquakes, it is reasonable to assume that the soft zones are of no engineering concern to the dynamic stability of surface or near-surface facilities. However, site-specific evaluations are required.

METHODOLOGIES

Analyses at several SRS facilities, such as K-Area (Ref. 414), assumed that the underconsolidated zones are "arched" by more competent material and that the arch is broken during an earthquake. In those analyses, very conservative subsurface conditions were assumed for the potential width, depth, and extent of the soft zones within the surrounding matrix material. Two basic methods were used to calculate the magnitude of potential surface settlement following a postulated collapse during an earthquake: (1) empirical, using analogies to both soft ground tunneling and coal mining, and (2) numerical modeling. Analyses of the K-Area soft zone suggest that the sandy soil matrix is incapable of arching soft zones larger than about 15 meters (50 feet) in diameter. Thus, zones of larger diameter could not occur (Ref. 414). For soft zone widths of about 15 meters (50 feet) and less, the numerical analyses predicted surface settlements of up to approximately 25% of the surface settlement predicted by the empirical approaches. Which analytical methods are used should depend on the facility under evaluation, the design criteria, and the site-specific subsurface conditions.

Numerical analyses of soft zone soils were conducted for the APSF site (Ref. 415). Computed ground settlements after all soft zones are compressed, varied up to approximately 7.6 cm (3 inches), depending on the configuration of soft zones used in the analysis. The results of the settlement analysis are considered in the design of the facility.

1.4.5.5 Current Design for Settlement

Static settlement due to loading during operation and secondary consolidation are considered in the structural design as self limiting loads in accordance with the Site Engineering Standard (Ref. 373).

Seismically induced dynamic settlement is also considered in the structural design as a self limiting load (Ref. 373). As a result of interactions with the DNFSB, SRS is committed to apply a load factor of 1.2 on the magnitude of seismically induced dynamic settlement for new PC3 and PC4 structures (Ref. 373). The 1.2 factor provides additional conservatism in seismic designs. Seismically induced differential settlement occurs after the inertial seismic loading, discussed in Section 1.4.4.5, and the effects of seismically induced differential settlement are not combined with the inertial load.

1.5 NATURAL PHENOMENA THREATS

This section identifies and describes natural phenomena events considered potential accident initiators at specific SRS facilities.

1.5.1 FLOODS

1.5.1.1 Flood History

All the floods represented by the data in this section were the result of excess precipitation runoff and the associated creek or stream flooding. There have been no floods caused by surge, seiche, dam failure, or ice jams.

FLOOD HISTORY OF THE SAVANNAH RIVER

Annual maximum daily flows for the Savannah River are presented in Table 1.5-1. Historical records span from 1796 to 1995. The earliest historical data were determined primarily from high-water marks; flow gauging by the USGS began in 1882. The record historical flood at Augusta, GA, occurred in 1796, with an estimated discharge of 360,000 cfs; the peak flow recorded by the USGS (350,000 cfs) occurred on October 3, 1929 (Ref. 79). Since Strom Thurmond Dam was constructed, no major flood has occurred at Augusta, GA. The United States Army Corps of Engineers (Ref. 507) simulated the October 3, 1929 storm event using current control requirements. The unregulated peak flow of 350,000 cfs resulted in a regulated peak flood flow of 252,000 cfs at Augusta, Georgia.

A statistical analysis of Savannah River annual maximum flows downstream at Augusta, GA, was conducted using the Log Pearson Type III distribution as described by Linsley et al. (Ref. 416). For the 30-year period from 1921 to 1950, before construction of Strom Thurmond Dam, the mean annual maximum flow was 92,600 cfs, the 10-year maximum flow was 211,000 cfs, and the estimated 50-year maximum flow was 362,000 cfs. After construction of the Strom Thurmond Dam, the Savannah River flows were controlled to meet various demands: hydroelectric power, water supply allocations, flood control, water qualities, habitat, recreation, and aquatic plant control. For the 44-year period from 1956 to 1999, after construction of Strom Thurmond Dam, the mean annual maximum flow, based on mean daily flow rates, was 36,300 cfs, the 10-year maximum flow was 55,400 cfs, and the estimated 50-year maximum flow was 74,600 cfs.

FLOOD HISTORY OF UPPER THREE RUNS CREEK

The annual instantaneous maximum flows for Upper Three Runs Creek gauging stations at Highway 278 near SRS Road C and at SRS Road A are listed in Table 1.5-2. The station at Highway 278 has the longest historical record.

For Upper Three Runs Creek at Highway 278, the maximum flood recorded was 820 cfs on October 23, 1990, and the corresponding flood stage elevation was 183.5 feet msl (Ref. 508). Similarly, the maximum flow at Road C was 2,040 cfs (129.4 feet msl) on October 12, 1990 and at Road A was more than 2,580 cfs (97.9 feet msl) on October 12, 1990. No dams are located in the Upper Three Runs Creek watershed.

FLOOD HISTORY OF TIMS BRANCH

The annual maximum daily flows for station 02197309 on Tims Branch at Road C are listed in Table 1.5-3. Data for water years 1974, 1975, and 1977 to 1984 were not available at the time this report was prepared.

The maximum flood discharge recorded for Tims Branch was 129 cfs on October 12, 1990, with a corresponding gage height of approximately 145.67 feet msl (Ref. 508). Highest flood stage level recorded was approximately 146.71 feet msl on May 29, 1976 (Ref. 508).

FLOOD HISTORY OF FOURMILE BRANCH

The annual instantaneous maximum flows for Fourmile Branch gauge stations at SRS Road C, SRS Road A-7, and SRS Road A-12.2 are listed in Table 1.5-3.1. The maximum floods occurred on August 2, 1991. The flood elevation at SRS Road C was 194.2 ft msl, at SRS Road A-7 was 161.9 ft msl, and at SRS Road A-12.2 was 116.7 ft msl (Ref. 508).

1.5.1.2 Flood Design Considerations

All safety-related structures are located on topographic high points and are well inland from the coast. The only significant impoundments, Par Pond and L Lake, are relatively small and sufficiently lower than any of the safety-related structures that there is no safety threat to safety-related structures from high water.

The calculated Probable Maximum Flood (PMF) water level for the Savannah River at the VEGP site is 118 feet above msl without wave run-up (Ref. 417). With wave run-up, the water may reach as high as 165 feet above msl. Because the minimum plant grade near a structure (L Reactor) is approximately 250 feet above msl, they are all well above the flood stage. If the valley storage effect between Strom Thurmond Dam and VEGP is taken into account, this results in a lower flood peak and lower flood stage.

Chen (Ref. 509) calculated the flood levels as a function of return period (annual probability of exceedance) for the Upper Three Runs, Tims Branch, Fourmile Branch, and Pen Branch basins due to precipitation. Reference 509 concluded that the probabilities of flooding at A-, C-, E-, F-, H-, K-, L-, S-, Y-, and Z-Areas are significantly less than 10E-5 per year. Chen used the basin hydrologic routing method to calculate the flood level as a function of the annual probability of exceedance, as described in Section 1.5.1.4.

D Area is located at an elevation slightly above the maximum flood. A flood could submerge pumphouse 5-G and make it inoperative, stopping cooling water flow to the powerhouse.

1.5.1.3 Effects of Local Intense Precipitation

Flood design considerations are described below in reference to specific local facilities. The descriptions are based on available information.

Unusually intense local rainfalls occurred on the SRS on July 25, 1990; August 22, 1990; October 10-12, 1990; and October 22-23, 1990. A report on these unusual rainfalls was prepared by the Environmental Transport Group of SRTC (Ref. 418). The report concluded that although over 6 inches of rain fell in a 10 square mile area during the August 22 storm, this amount is just 20% of the 6-hour probable maximum precipitation (PMP) of 31.0 inches (Ref. 418).

Rainfall amounts in SRS areas are identified below.

F AND E AREAS

The 6-hour, 10-square-mile PMP is 31 inches, as indicated in Schreiner and Reidel (Ref. 419), with a maximum intensity of 15.1 inches in 1 hour. This rainfall was adjusted to a point PMP of 19 inches in 1 hour, as shown by Hansen et al. (Ref. 420) and used to generate the PMF for the small watershed of the unnamed tributary near the SRS. Incremental rainfall for 1-hour periods adjacent to the PMP was also determined as shown in Table 1.5-4 (Ref. 421). A synthetic hydrograph was used to determine peak flow (Ref. 422). The peak stage corresponding to the PMF is 224.5 feet above msl or 75 feet below the F-Canyon site grade. Because F Area lies near a watershed divide, incident rainfall naturally drains away from the facilities.

Unusual short-duration heavy rainfall occurred in F Area and E Area in August 1990 and October 1990. Total rainfall measured in F Area was as follows:

- August 22, 1990, 6.10 inches rainwater collected in a trench used to dispose of radioactive waste. The water was sampled and later discharged to Fourmile Branch (Ref. 418).
- October 11 and 12, 1990, about 10 inches.

H, S, AND Z AREAS

The 6-hour cumulative PMP for a 10-square-mile area surrounding H, S, and Z Areas is 31 inches (Table 1.5-5) (Ref. 419). This rainfall was adjusted to a point PMP, as shown by Hansen and others and used to generate the PMF for the small watershed of Crouch Branch near the site (Ref. 420). A synthetic hydrograph was used to determine peak flow (Ref. 422). The peak stage corresponding to the PMF is 224.5 feet above msl or 83 feet below the area grades.

Unusual short duration heavy rainfall also occurred at H, S, and Z Areas in August 1990 and October 1990. Total rainfall measured at 200-H was:

- August 22, 1990, 6 inches
- October 11 and 12, 1990, about 10 inches

1.5.1.4 Flood Hazard Recurrence Frequencies

Reference 509 has calculated the flood levels due to precipitation as a function of annual probability of exceedance for the Upper Three Runs Creek, Tims Branch, Fourmile Branch, Pen Branch,and Steel Creek upstream from L-Lake basins. A basin hydrologic routing method was employed to calculate the flood level as a function of the annual probability of exceedance. The procedures used for the method are presented next.

Step 1. Hyetographs (rainfall depth or intensity as a function of time) for various return periods were synthesized based on rainfall intensity-duration-frequency data.

Step 2. The Hydrologic Modeling System computer code (Ref. 510) was used to calculate basin peak flow based on the hyetograph for a given return period and basin properties.

Step 3. The peak flow calculated by HEC-HMS (Step 2) was then used in the Computer Model for Water Surface Profile Computations (WSPRO), (Ref. 511) to calculate the flood water elevations. WSPRO was developed by the USGS for the Federal Highway Administration. WSPRO uses a step-backwater analysis method to calculate water surface elevations for one-dimensional, gradually-varied, steady flow through bridges and overtopping embankments.

Step 4. Steps 2 and 3 were repeated for each return period.

Steps 1 through 4 were applied to both the Upper Three Runs and Fourmile Branch basins.

DESIGN BASIS FLOOD

Flood flows and elevations for the Upper Three Runs Creek, Tim Branch, Fourmile Branch, and Pen Branch basins were calculated by the steps described above. Table 1.5-6 presents the synthesized 24-hour storm hyetographs for various annual probabilities of exceedance. Tables 1.5-7 to 1.5-8 show the calculated flood elevations at A-, C-, E-, F-, H-, K-, S-, and Y- and Z-Areas, and the proposed MFFF site as a function of performance category, respectively (Ref. 509).

L-Area sits at the north end of the L-Lake. Flooding of L-Area is determined by the L-lake water elevation. L-Lake was constructed in 1985 to function as a cooling water reservoir for L-Reactor at SRS to minimize the thermal damage to the Steel Creek flood plain. L-Lake occupies the middle reach of Steel Creek between SRS Road B at the north end of the lake and just upstream of Highway 125 at the south end of the lake. The L-Lake dam is at the south end of the lake. The top of the dam is at 200 feet above mean sea level and a natural spillway is at 195 feet above mean sea level. Factors that determine the L-Lake elevation during a severe storm include initial lake level, basin runoff to the lake, direct rainfall to the lake, discharge through the L-Lake dam gates, and the lake storage-elevation relationship. Operator action can affect discharge through the L-Lake gates. Ultimately, the lake level is limited by the spillway elevation at 195 feet above

mean sea level. Table 1.5-7 shows the calculated L-Area flood flows and flood elevations as a function of performance category. A conservative assumption, L-lake dam gates were closed, was used to calculate Table 1.5-7 (Ref. 509).

1.5.1.5 Potential Dam Failures (Seismically Induced)

RESERVOIR DESCRIPTION

The only significant dams or impoundment structures that could affect the safety of SRS are large dams on the Savannah River and its tributaries upstream of Augusta, GA (see Figure 1.4-12). Section 1.4.2.1 contains information on these structures. The Stephens Creek Dam is owned by SCE&G. All other dams on the Savannah River are owned by the U.S. Army Corps of Engineers. The dams on the Tugaloo and Tallulah rivers are owned by Georgia Power Company. The dams on the Keowee and Little Rivers are owned by Duke Power Company.

DAM FAILURE PERMUTATIONS

A domino failure of the dams on the Savannah River and its tributaries upstream of VEGP was analyzed in the VEGP Final SAR (Ref. 417). The worst possible case resulted from Jocassee Dam failing during a combined standard project flood and earthquake, with the resulting chain reaction.

Using conservative assumptions, this worst dam failure would yield a peak flow of 2,400,000 cfs at Strom Thurmond Dam. This rate, undiminished in magnitude, was transferred to below Augusta, GA. However, because of the great width of the flood plain, routing of the dam failure surge to the VEGP site (Savannah River Mile 151) resulted in a peak discharge of 980,000 cfs, with a corresponding stage of 141 feet above msl.

UNSTEADY FLOW ANALYSIS OF POTENTIAL DAM FAILURES

No dams are located near SRS Areas. Therefore, this section does not apply.

WATER LEVEL AT FACILITY SITE

The peak water surface elevation of the Savannah River that corresponds to wave run-up of a wind-induced wave, superimposed upon the passage of a flood wave resulting from a sequence of dam failures, is discussed in Section 1.5.1.2.

1.5.1.6 Probable Maximum Surge and Seiche Flooding

No large water bodies exist near the site; therefore, this section does not apply. Run-up of flood waters from the worst combination of wind and waves on the Savannah River is not a hazard at

the site because the peak flood elevation is well below minimum plant grade, and the maximum wave under the worst circumstances is less than 3 feet.

1.5.1.7 Ice Flooding

Because of regional climatic conditions, the formation of significant amounts of ice on streams and rivers rarely occurs. The Hartwell, Richard B. Russell, and Strom Thurmond dams moderate water temperature extremes, making ice formation on the Savannah River at SRS unlikely.

No historical ice flooding has been noted, although ice has, on several occasions, been observed in the Savannah River. Because the sites are so much higher than the nearest streams and rivers, it is not considered credible that they could be affected by ice flooding, even if the climatic conditions were conducive to ice formation.

1.5.1.8 Water Canals and Reservoirs

Each reactor has a 25-million-gallon intake basin, which is a concrete structure that is 225 feet wide, 800 feet long, and 20 feet deep with an open top. The basin is divided into three chambers that can be isolated from each other. These basins were used to store cooling water for the reactors and as reservoirs for cooling water to allow the operators to shut down the reactors if needed. These basins were designed as safety-related structures, including withstanding a DBE, and are located well above any PMF (Ref. 423).

1.5.1.9 Channel Diversions

There is no historical record of diversions of streams or rivers in the site area. Outside of precipitation, the only source of water to the site is groundwater. No waterway diversion could flood the sites because the sites are much higher than the surrounding streams and rivers.

1.5.1.10 Flooding Protection Requirements

Because the site is located on a local topographic high, there is no threat to the SRS from flooding, as described in previous sections. Special flooding protection requirements are not necessary to assure the safety of F, H, S, Z, and M Areas, and SRTC because they are located at elevations well above the maximum flood. D Area elevations are higher than the maximum flood; only the pump houses on the river could be flooded and inoperative.

1.5.1.11 Low Water Considerations

LOW FLOW IN RIVERS AND STREAMS

Low flow in the Savannah River adjacent to SRS is regulated by Strom Thurmond Dam and the New Savannah Bluff Lock and Dam. A minimum flow of 5,800 cfs is required for navigation in the river downstream from Strom Thurmond Dam. However, it should be noted that a discharge of 6,300 cfs is normal 80% of the time. A minimum required flow of 4,130 cfs is released from New Savannah Bluff Lock and Dam. The Strom Thurmond Dam project is designed for a maximum drawdown of 18 feet from the top of the power pool elevation of 330 feet msl to a minimum pool at 312 feet msl. However, it is not anticipated that the minimum pool will be reached more often than once in every 150 years.

During extreme drought conditions from July 1987 through April 1989, average discharge at Strom Thurmond Dam was cut to 3,600 cfs (Ref. 424). The reduced discharge lasted from April 1988 to April 1989 and was the minimum flow necessary to maintain water quality criteria for the Savannah River downstream of SRS. River flow at Augusta, GA, however, averaged 4,300 cfs weekly from April 1988 to December 1988 due to higher than normal influx downstream of Thurmond Lake. Discharges from Hartwell and Russell Reservoirs, upstream of Thurmond Lake, were also severely restricted. During this drought period, Thurmond Lake conservation pool elevations decreased substantially, reaching a low point of 1 foot above minimum pool level in February 1989.

A low flow stage at SRS corresponding to minimum river flow of 5,800 cfs is 80.4 feet msl at the SRS pumphouse.

Flow records for Augusta, GA, for the periods 1884 through 1906 and 1926 through 1970 were examined. A hypothetical extreme drought flow of 957 cfs was determined by statistical analysis of 1926 through 1950 flow records. During this period, no major dams were built on the river or its tributaries upstream of Augusta. It is concluded that the hypothetical extreme drought would have a stage elevation of 74 feet msl, which is 6 feet below the minimum required to operate any of the river pumping facilities.

From the flow records for the 62 years of examined data from the USGS, it is concluded that a sustained minimum release of 5,800 cfs (the planned operation of Hartwell and Thurmond reservoirs) could have been maintained for this period. A flow of 3,600 cfs at Ellenton Landing is required under present conditions to provide water to the pump intakes.

LOW WATER RESULTING FROM SURGES OR SEICHES

This situation does not apply because SRS does not withdraw water from a large body of water, nor is it located in a region of active seismicity or volcanism, which produce such surges.

HISTORICAL LOW WATER

The available flow records (62 years) for Augusta, GA, for the periods 1884 through 1906 and 1926 through 1970 were examined. The low flow of record for gauging station 02197000, on the Savannah River at New Savannah Bluff Lock and Dam (river mile 189.8) near Augusta, GA, before construction of Strom Thurmond Dam, occurred on September 24, 1939. This was caused by the operation of the gates at New Savannah River Lock and Dam. If the rating curve is extended below 1,400 cfs, an extreme minimum discharge of 648 cfs is reached. This is an extrapolated instantaneous minimum. Water stage recorder graphs and discharge measurements were furnished by the Corps of Engineers. On the day this low flow was recorded, the average daily flow was 2,940 cfs. Examination of the hydrograph for this day indicates that the lowest flow occurred for about 10 hours, the daily flow being over 2,000 cfs. The lowest mean daily flow shown in the Augusta record was 1,040 cfs, which occurred on October 2, 1927.

The minimum mean daily discharge for the period 1963 through 1970 (after the filling of both reservoirs) was 5,130 cfs in 1963. The storage for power and navigation releases (between normal and minimum pool levels) from Hartwell and Thurmond Reservoirs was 2,445,000 acre-feet, which would provide an average release of 3,350 cfs for 1 year assuming no inflow. The total storage (between top of gates and minimum pool level) from both reservoirs was 3,128,000 acre-feet, which would provide an average release of 4,300 cfs for 1 year assuming no inflow.

The Savannah River has been gauged at Augusta, GA, for more than a century. More recently (in 1971), a gauging station was established at Jackson, SC. Upper Three Runs Creek has been gauged since 1966 at Highway 278 near New Ellenton, SC, and near SRS Road A, below F Area. An additional gauging station on Upper Three Runs Creek was established near SRS Road C in 1974.

The minimum recorded flow for the Savannah River at Augusta, GA, was 1,040 cfs on October 2, 1927 (Ref. 100). This occurred during a period when the Savannah River was essentially unregulated. Since Strom Thurmond Dam was finished in the early 1950s, the river has been regulated by the Corps of Engineers. A minimum daily flow of 4,000 cfs was recorded October 22, 1991.

The minimum daily flow for Upper Three Runs Creek is 49 cfs at Highway 278; 111 cfs near SRS Road A; and 105 cfs near SRS Road C (Ref. 89). Although the period of data recording is short, Upper Three Runs Creek has a smaller range of flow variation than other streams in the area (Ref. 89).

Tims Branch has been gauged since March 1974 near its confluence with Upper Three Runs Creek. The minimum daily flow for Tims Branch was 1 cfs. Although the period of data recordings is short, Tims Branch has a smaller range in flow variation than other streams in the area (Ref. 81).

1.5.1.12 Future Control

Minimum flow conditions are controlled mainly by upstream dam releases, and no additional users of large amounts of water are anticipated.

1.5.2 EARTHQUAKES

Earthquakes are discussed in Section 1.4.4.

1.5.3 TORNADOES

Tornadoes are discussed in Section 1.4.1.1.

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