CHARACTERIZATION OF SPENT FUEL DISASSEMBLY HARDWARE AND NONFUEL BEARING COMPONENTS AND THEIR RELATIONSHIP TO 10 CFR 61

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ABSTRACT

There are a variety of wastes that will be disposed of by the federal waste management system under the Nuclear Waste Policy Act of 1982. The primary waste form is spent nuclear fuel. Currently, this is in the form of fuel assemblies. If the fuel pins are removed from the fuel assembly, as in consolidation, then the fuel pins and the structural portion of the fuel assembly must be considered as separate waste streams. The structural hardware consists of end fittings, grid spacers, water rods (BWR 8 x 8 only), control rod guide tubes (PWR only) and various nuts, washers, springs, etc. These are referred to as spent fuel disassembly (SFD) hardware. There will also be a number of other components which are defined in Appendix E of 10 CFR 961, the standard utility contract. These are referred to as nonfuel-bearing (NFB) components, and include fuel channels (BWR), control rods, fission chambers, neutron sources, thimble plugs, and other components. This paper characterizes spent fuel disassembly (SFD) hardware, and nonfuel-bearing (NFB) components for the most abundant fuel types. The descriptions and figures given are representative for the items described. Many subvariants exist due to design evaluation, which are not covered. This paper also discusses the relationship of these wastes to 10 CFR 61 waste classification.

Tables I and II list the variety of fuel types by rod configuration and vendor used in BWR and PWR reactors. Though there are quite a few different fuels to be considered, the problem of uniquely identifying all the hardware is more complex than Tables I and II indicate. Within fuel types, there are differences of design details and materials over time. One major recent change has been the replacement of Inconel grid spacers by ones manufactured of Zircaloy. There have been other changes, many of them minor. This makes it impossible to uniquely identify a fuel design based solely on its rod configuration designation.

TABLE I

BWR Fuel Manufacturers and Fuel Assembly Array Descriptions

General Electric Corporation (GE)	Advanced Nuclear Fuels Corporation (Exxon)
6 x 6	7 x 7 (GE design)
7 x 7	8 x 8 (GE design)
8 x 8	10 x 10 (AC design)
9 x 9	9 x 9 (GE design)
11 x 11	11 x 11 (GE design)
Westinghouse	**Allis-Chalmers (AC)**
8 x 8 (QUAD+)	10 x 10

TABLE II

PWR Fuel Manufacturers and Fuel Assembly Array Descriptions

Westinghouse (WE)	Babcock and Wilcox (BW)
13 x 13	14 x 14 (all reprocessed)
14 x 14	15 x 15
15 x 15	17 x 17
16 x 16	
17 x 17	
Combustion Engineering (CE)	**Advanced Nuclear Fuels Corporation (Exxon)**
14 x 14	14 x 14 (WE design)
15 x 15	15 x 15 (WE design)
16 x 16	17 x 17 (WE design)
	14 x 14 (CE design)
	15 x 15 (CE design)

Many design details are considered proprietary by the various fuel vendors. Some consider only the mechanical design proprietary while others consider the material used for specific components as proprietary. This has made it impossible to present the same level of detail for all the fuel types.

Inevitably there will be other fuel types over the course of time. Westinghouse is currently marketing replacement fuel for General Electric reactors. It is not unreasonable to expect that other fuel vendors will offer replacement products for their competitors. This will complicate the logistics of fuel consolidation and handling of spent fuel hardware.

BOILING WATER REACTOR

GENERAL ELECTRIC (GE)

General Electric Fuel

General Electric has made five different fuel designs. Their current fuel is designated as the BWR/6. It is an 8 x 8 fuel array. GE designates a fuel assembly and the fuel channel surrounding it as a fuel bundle. Figure 1 is an isometric drawing of a fuel bundle. Previous designs have included 6 x 6, 7 x 7, 9 x 9, and 11 x 11 arrays. The 8 x 8 fuel design is described here as representative of BWR fuel design.

A BWR/6 fuel bundle contains 62 or 63 fuel rods and two or one water rods in a square 8 x 8 array. It contains approximately 0.183 metric ton of initial

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[a] This work was performed for the U.S. Department of Energy's Office of Civilian Radioactive Waste Management through the Waste Systems Data Development Program at Oak Ridge National Laboratory.

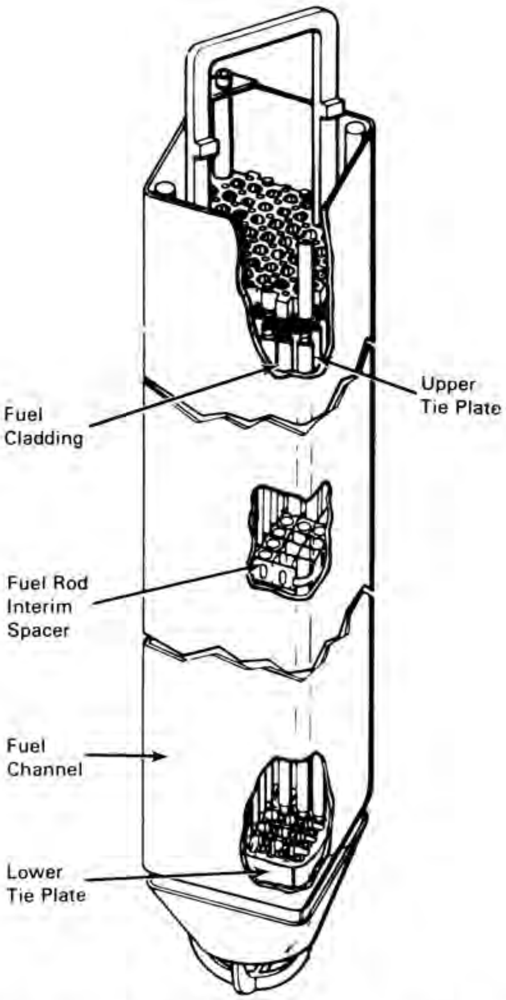


Fig. 1. General Electric 8 x 8 PWR Fuel Assembly.

heavy metal per assembly. The hardware of a GE 8 x 8 fuel assembly includes an upper and lower end fitting. The lower end fitting is a nozzle which directs coolant to the fuel pins. The upper end fitting, in part, serves as the handling fixture. Both end fittings are made of castings of type-304 stainless steel. The ends of the fuel pins are secured by these fittings. Seven grid spacers maintain uniform rod to rod spacing along the length of the assembly. The grid spacers are made primarily of Zircaloy-4. However, the tabs on the grid spacers that bear against the fuel pins are made of Inconel X-750. There is an Inconel spring at the upper end of each individual fuel pin that allows for rod expansion. The water rods have the same diameter as a fuel pin but contain water instead of fuel. The water rods have "keys" which vertically locate the spacer grids. There is a total of 8.5-13.5 kg of disassembly hardware per fuel assembly.

General Electric Nonfuel Bearing Components

The major Nonfuel bearing component of the GE fuel assembly is the fuel channel. The fuel channel is a Zircaloy-4 box surrounding the fuel assembly and is attached to it. Fuel channels vary in thickness from 80-120 mil and weigh 30-45 kg each with the newer design having the thicker walls. In general, one fuel channel has a lifetime of one fuel assembly. However, some have been reused. The newer, thicker (120 mil), channels are designed to last up to twice as long. This results in an average of 22-45 kg of component waste associated with each fuel assembly due to the fuel channel alone. This depends on whether a channel lasts for one fuel assembly lifetime (45 kg) or two life times (22 kg).

There are also several components which are not explicitly noted in Appendix E of 10 CFR 961, but which DOE may have to accept for geologic disposal. For example, control blades (Fig. 2) weigh slightly more than 100 kg. They are constructed of type-304 stainless steel with a boron carbide absorber contained in stainless steel tubes. Depending on how the control blade is positioned in the core, it may exceed the limits for shallow land burial. Additionally the upper end of the control blade has four sets of pins and rollers. Four sets of pins and rollers weigh about 0.043 kg and they are made of Haynes-25 and Stellite-3 respectively. Both of these are high cobalt alloys (approximately 50% cobalt). The estimated lifetime of control blades ranges from 3-25 years. Their lifetime is fluence limited and dependent on how they are positioned in the core.

There are other components such as poison curtains and local power range monitors which are located, in part, within the core. These items are

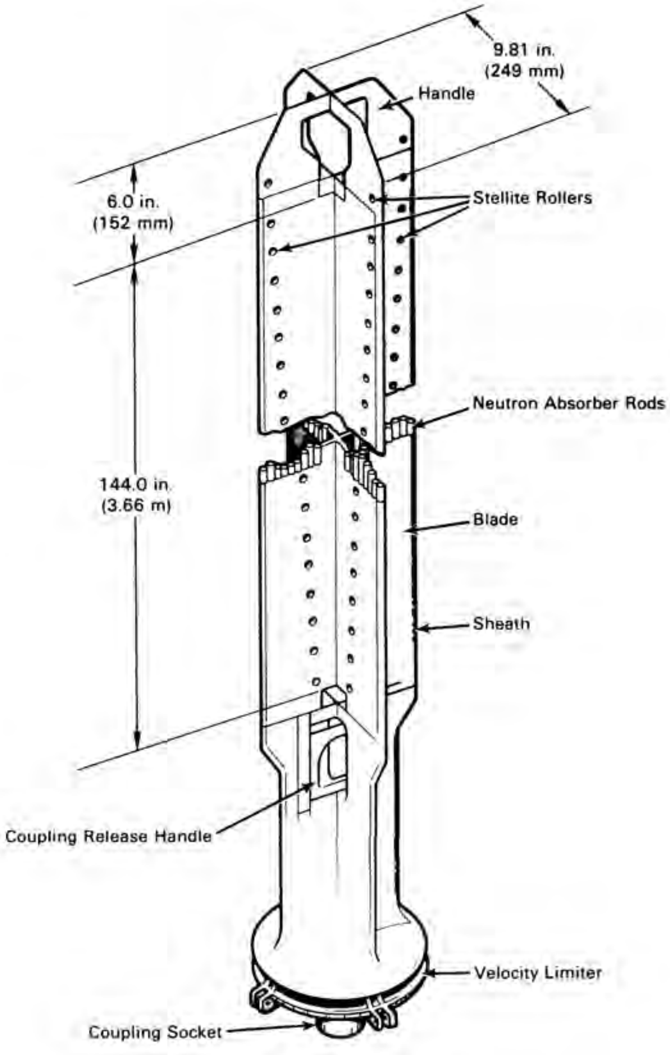


Fig. 2. Cruciform.

discarded infrequently and would not significantly increase the amount of NFB components which may require geologic disposal.

It is estimated that on the average there will be 25-50 kg of NFB components, other than control blades (aka cruciforms), per assembly. The total estimate of spent fuel assembly hardware and nonfuel-bearing components is 34-64 kg per fuel assembly.

OTHER BWR FUEL TYPES

This paper covers the major fuel types, and as such, it is not all inclusive. Exxon fuel is similar to the fuel that it replaces and is not discussed separately. Westinghouse and Allis-Chalmers BWR fuels are not covered in this paper.

PRESSURIZED WATER REACTOR (PWR)

There are four vendors who have manufactured fuel for pressurized water reactors. They are Westinghouse, Babcock & Wilcox, Combustion Engineering, and Exxon.

WESTINGHOUSE

Westinghouse Fuel

Westinghouse has made four different fuel designs, the most recent being the 17 x 17. Figure 3 shows an isometric drawing of a 17 x 17 fuel assembly. Other designs include 14 x 14, 15 x 15, and 16 x 16 arrays, both standard and optimized (low neutron absorption) fuel assemblies. The 17 x 17 fuel design is described here as representative of Westinghouse fuel but the other fuel designs are accounted for in the estimated quantities of waste.

The 17 x 17 design incorporates an array of 289 positions, of which 264 are occupied by fuel pins. It contains approximately 0.461 metric ton of initial heavy metal per assembly. The remaining 25 positions are occupied by 24 guide tubes and one instrument tube, in which a variety of other components are inserted. The 17 x 17 includes upper and lower end fittings, both of which are made of cast type-304 stainless steel. Together they weigh 12.5 kg. On the top fitting, there are several leaf springs made of Inconel. Ten fuel rod spacers (grid spacers) maintain rod-to-rod configuration along the length of the assembly. In the past, these have been made of Inconel-718. Recent designs have replaced the middle Inconel grid spacers with Zircaloy grid spacers. These are referred to as optimized fuel assemblies (ofa). The 24 guide tubes and one instrument tube are externally larger than fuel pins but only replace one fuel pin each. They guide the travel of control rod cluster assemblies and other components. In total, there is 26-38 kg of spent fuel disassembly hardware per fuel assembly, depending on the specific fuel design.

Westinghouse Nonfuel Bearing Components

A Westinghouse core has a number of NFB components that require disposal. These components include control rod cluster assemblies, absorber assemblies, thimble plugs, and neutron sources. These components are primarily constructed of stainless steel with other constituents as required (absorber material, neutron sources, etc.). Each fuel assembly will have one of these components located within the guide tubes. Figure 4 shows a control rod cluster inserted into a Westinghouse fuel Assembly.

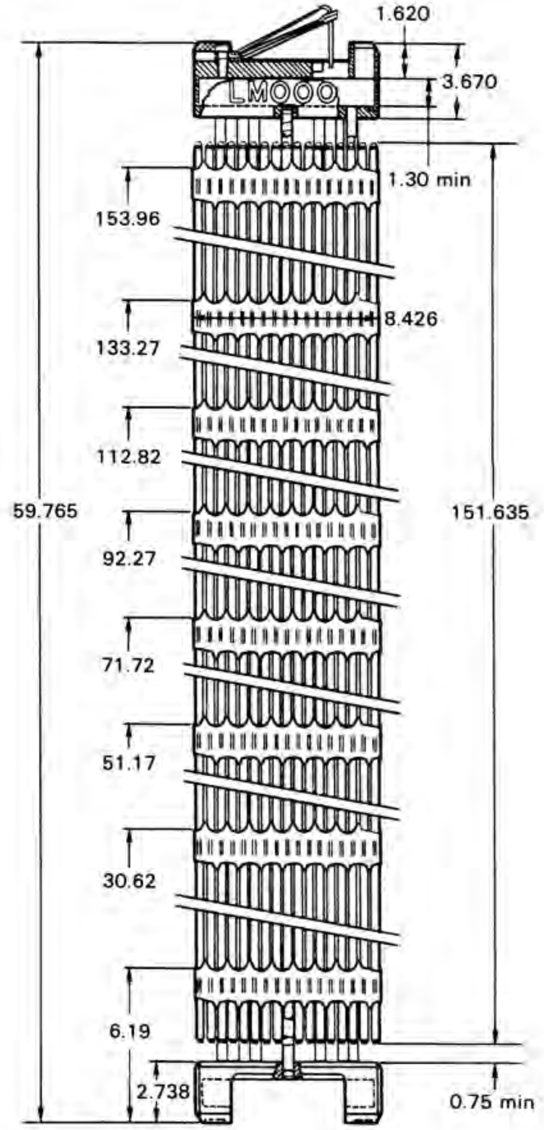


Fig. 3. Westinghouse Fuel Assembly.

Control rod clusters weigh 6-8 kg and have a nominal useful life of 15 years. A core can have 50-60 of these assemblies, which are expected to be replaced once during the life of the plant. Burnable poison rod assemblies weigh about 4-6 kg each and it is estimated that approximately 10 per year are changed out. There are a few neutron source assemblies and fission chambers that come out intermittently. The remainder of the fuel assemblies have thimble plugs in them (Fig. 5). They only weigh three kg and are replaced only when damaged. It is estimated that there is 65-90 kg of NFB components per year per reactor. With slightly over 50 fuel assemblies discharged per year, this is about 1-2 kg of NFB components per assembly. The total estimate of spent fuel disassembly hardware and NFB components range from 27 to 40 kg per assembly.

BABCOCK & WILCOX (B&W)

Babcock & Wilcox Fuel

B&W fuel assemblies are similar to the Westinghouse design in that they have 24 control rod guide tubes and one instrument tube into which a

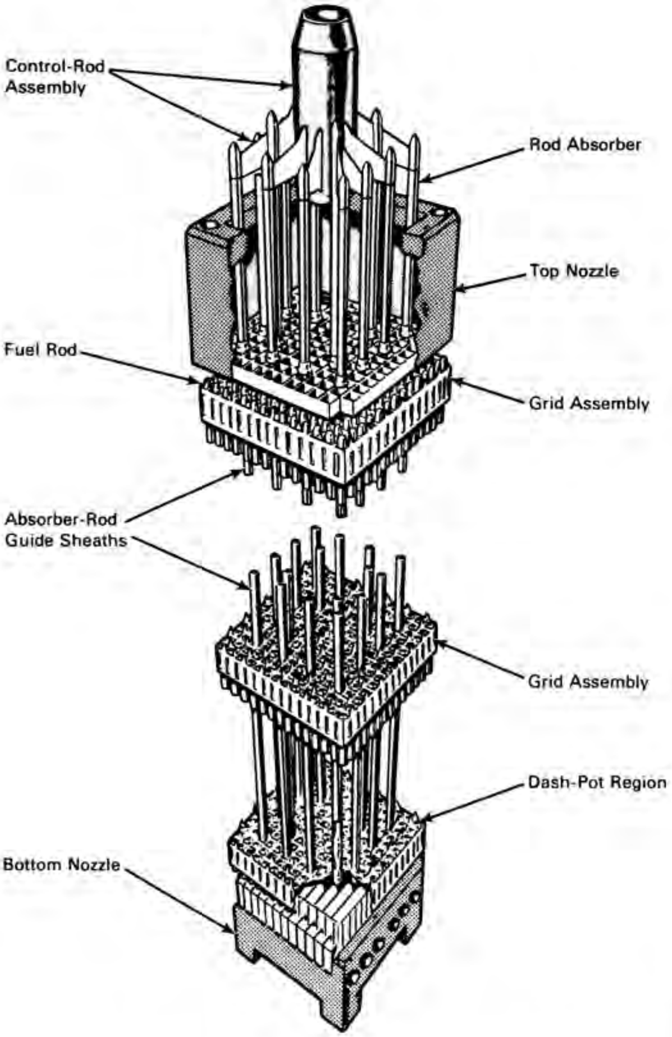


Fig. 4. Control of Reactivity Sesanske.

variety of core components are located. However, their detailed design is markedly different from the Westinghouse design.

B&W has manufactured three different fuel designs: 14 x 14, 15 x 15, and 17 x 17. Currently only 15 x 15's are being used in the U.S. (All of the 14 x 14 manufactured have been reprocessed at West Valley and will be disposed of as commercial high-level waste.) They have two end fittings with eight spacer grids between them. The end fittings are made of cast stainless steel while the spacer grids have been made from Inconel. However, current production fuel assemblies have the middle six grids manufactured from Zircaloy. The total SFD hardware ranges from 31.5 to 45.5 kg per assembly.

A B&W assembly (Fig. 6) has top and bottom end fittings that are both made of either CF8 or CF3M (a cast stainless steel). The top end fitting weighs approximately 14 kg and the bottom one weighs 7 kg. Each of the end fittings has an Inconel-718 grid spacer attached to it. These grid spacers weigh two to four pounds each. There are six intermediate grid spacers. These have traditionally been manufactured of Inconel-718, with a weight of 0.75 kg each. Recently the spacer grid material has been replaced with Zircaloy-4, with a weight of 1.0 kg. The change was initiated because the Zircaloy does not absorb as many neutrons as does the Inconel, and hence provides long term neutron economy that translates into monetary savings through reduced fuel costs. The top end fitting has one helical spring. The spring is made of Inconel X-750 and weighs approximately 2 kg. There are 16 guide tubes and one instrumentation tube in the fuel skeleton that connect the top and bottom end fittings. The guide tubes themselves are made of Zircaloy-4, weighing approximately 7.5 kg total. The instrument tube is also made of Zircaloy-4 and weighs 0.3 kg. They attach to the end fittings with stainless steel and Inconel fasteners.

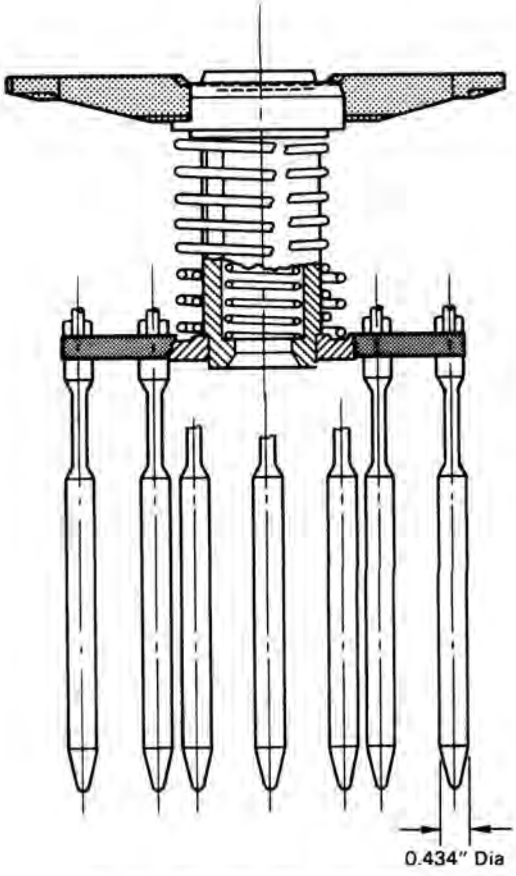


Fig. 5. Thimble Plug Assembly.

The spent fuel disassembly hardware from a B&W 17 x 17 fuel assembly is similar to a B&W 15 x 15 with some minor differences (Fig. 7). One of the differences is in the number of guide tubes. The B&W 17 x 17 has 24 guide tubes instead of 16. These are made of Zircaloy-4 and weigh approximately 11 kg in total. These are in addition to the 0.3 kg Zircaloy-4 instrumentation tube. The other major difference is in the number of helical springs in the top end fitting. The B&W 17 x 17 has four Inconel X-750 springs, each weighing 1.4 kg, whereas the B&W 15 x 15 has only one spring. Aside from these differences, the remaining hardware is similar.

Babcock & Wilcox Nonfuel Bearing Components

B&W reactors have a number of nonfuel components. Each fuel assembly has 2 control rod guide tubes into which either a burnable poison rod assembly, control rod assembly (Fig. 8), orifice rod assembly (Fig. (), or an axial power shaping rod assembly are located.

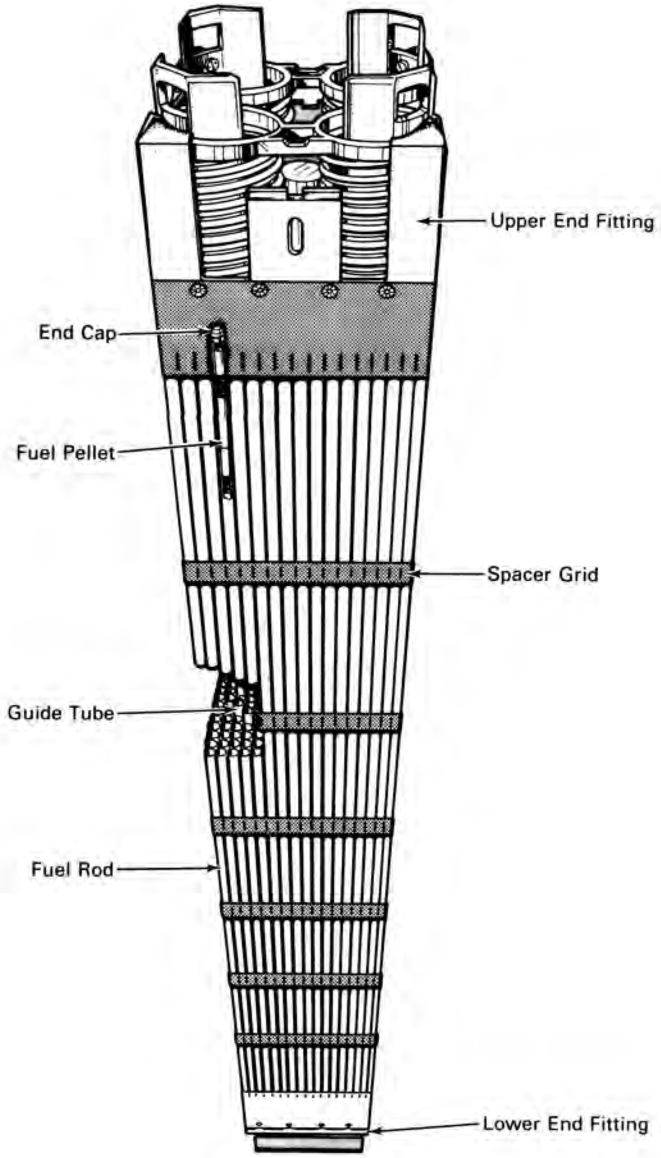
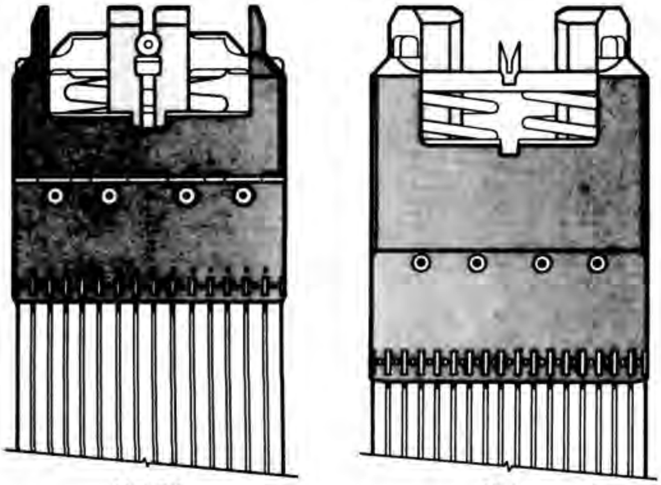
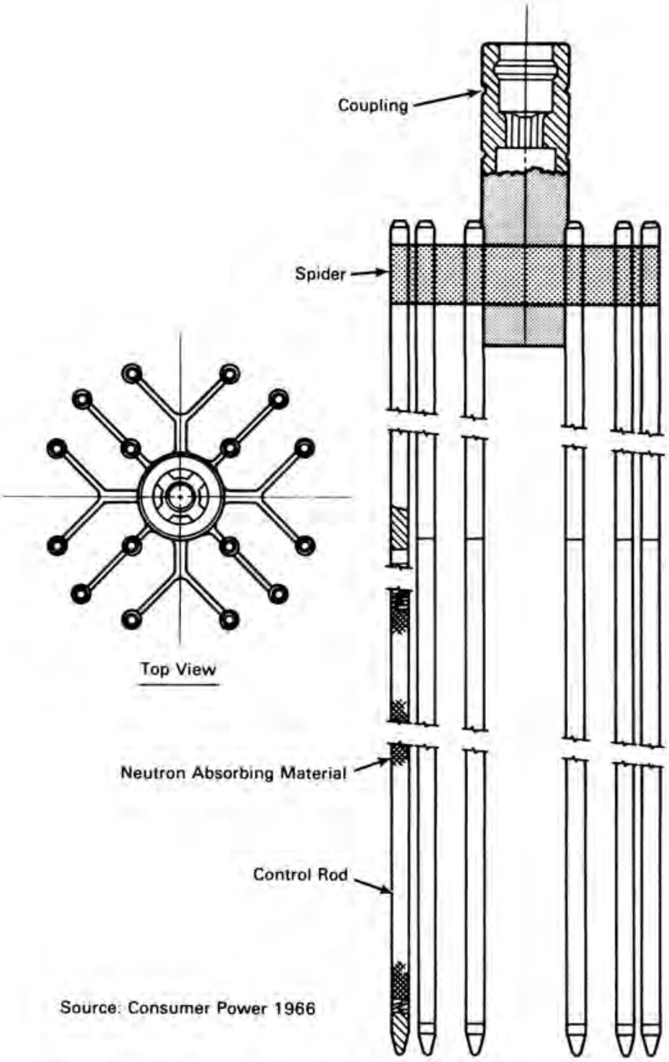


Fig. 6. Fuel Assembly.


Mark B-4
15 x 15

Mark C
17 x 17

Fig. 7. Babcock and Wilcox Fuel Assemblies
Source: Babcock and Wilcox.



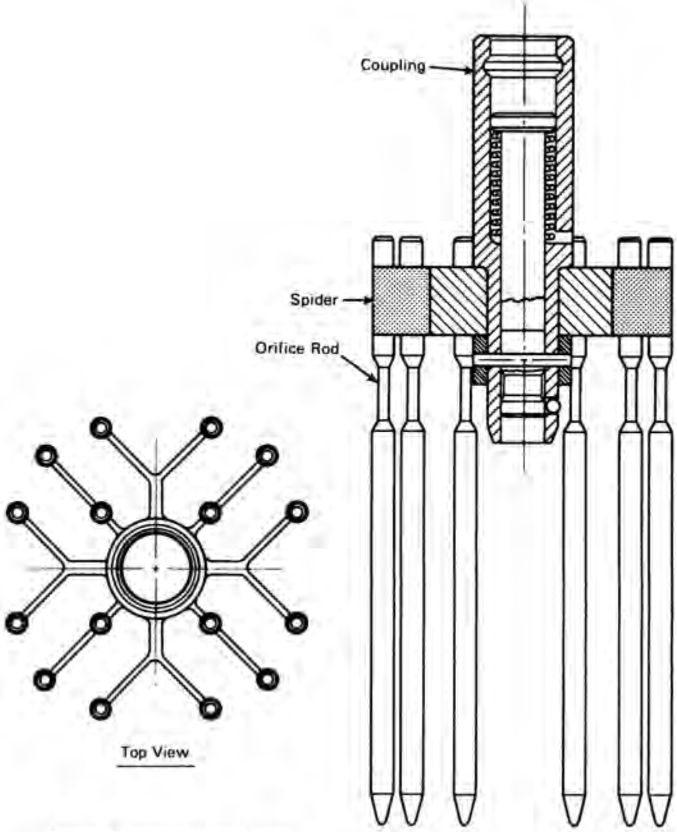
Source: Consumer Power 1966

Fig. 8. Babcock and Wilcox Control Rod Assembly.

There are approximately 60 control rods in a B&W reactor. They utilize a Ag-In-Cd poison encased in stainless steel cladding. As in other PWR reactors, they generally reside in the reactor in a withdrawn position. They have nominal lifetimes of 7-10 cycles but can last much longer.

B&W reactors also have a number of other nonfuel bearing components intended for power control. The primary component is the burnable poison rod assembly (BPRA). There are approximately 60 BPRA's within a core. They have a burnable poison of $B_4C-Al_2O_3$ encased in a Zircaloy cladding. Their purpose is to provide negative reactivity during the early part of a fuel cycle. They are changed out each cycle. The other components used for power control are axial power shaping rods (APSR) and gray axial power shaping rods (GAPSR). These are physically similar to the BPRA's, but use a different (weaker) poison. The APSR's use Ag-In-Cd while the GAPSR's use Inconel-718, both of which are clad in stainless steel. There are 4-8 of each of these components and their expected lifetimes are 5-8 cycles.

There are also primary neutron sources (PNS) and regenerative neutron sources (RNS) in the reactor. There are only 1-2 of each of these in the reactor.



Source: Consumers Power 1966

Fig. 9. Babcock and Wilcox Orifice Rod Assembly.

The PNS is only used in the first few cycles of reactor life. The RNS's last 10-20 cycles. The components are either a neutron source or an antimony-beryllium encased in type-304 stainless steel.

All fuel assemblies that do not have any of the components mentioned above have an orifice rod assembly. These are stainless steel components designed to plug the fuel assembly guide tubes. They are expected to last the life of the plant and are changed out only if damaged.

These nonfuel bearing components (NFB) vary in weight from 4-10 kg. It is estimated that there will be approximately 6-8 kg of NFB components per fuel assembly that must be disposed of.

COMBUSTION ENGINEERING (CE)

Combustion Engineering Fuel

CE fuel assemblies are similar to other PWR fuel assemblies in several aspects. They have two cast stainless steel end fittings and ten spacer grids made of Zircaloy and one of Inconel. They also have guide tubes, however, there are only five of them. Each tube is larger in diameter and takes up four fuel pin positions unlike the smaller diameter Westinghouse and Babcock & Wilcox guide tubes. Figure 10 shows a 16 x 16 fuel assembly. Figure 11 shows an exploded view of an end fitting.

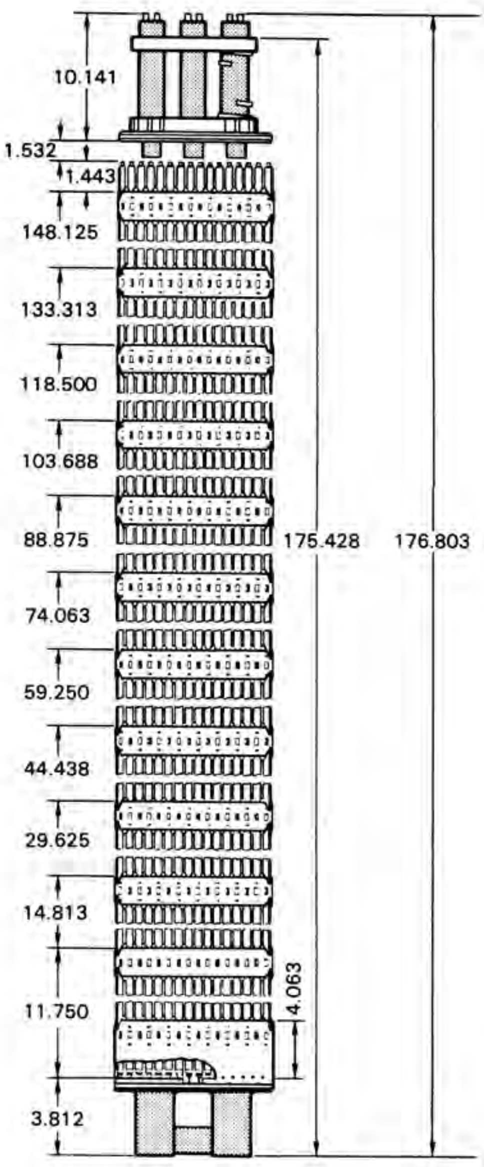


Fig. 10. Combustion Engineering Fuel Assembly, ANO-11 16 x 16.

CE 14 x 14 have end fittings made of type-304 stainless steel. The combined weight of the end fittings is 12-14 kg, depending on the plant. In addition to the end fitting proper, there are four holdown springs. These springs are constructed of Inconel X-750 and weigh between 0.6-0.7 kg in total. There are also five guide tubes in the fuel assembly. These are made of Zircaloy-4 and weigh between 9.5-11.5 kg total. There are eight to nine grid cages in the fuel assembly. Except for the lowest one, which is connected to the lower end fitting, they are constructed of Zircaloy-4 and weigh approximately 5.5 kg. The bottom grid cage is constructed of Inconel-625 and weighs 0.75 kg.

The CE 16 x 16 is similar to design to the CE 14 x 14 with only minor differences in weights of the individual components. The upper and lower end fittings, made of type-304 stainless steel, weigh 15-17 kg. The Inconel X-750 holdown springs weigh 1.6-4.4 kg. The Zircaloy-4 guide tubes range in weight from 10.3-11.3 kg. There are 10 Zircaloy-4 grid spacers, weighing a total of 7.3-11.4 kg, and one Inconel-625 spacer at the bottom weighing 1.2 kg.

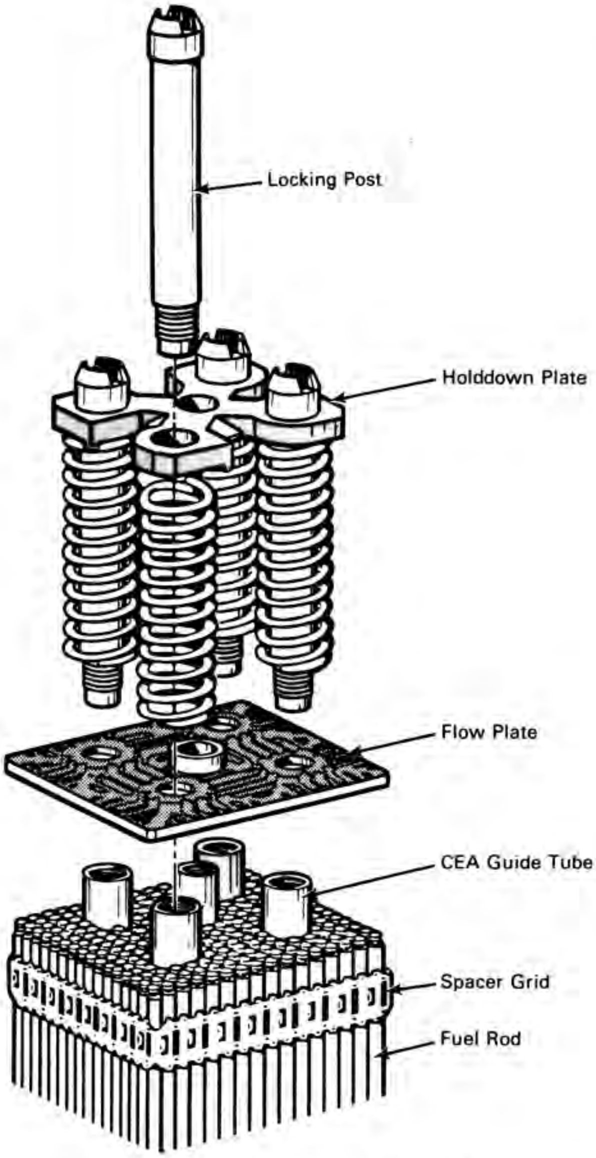


Fig. 11. End Fitting Exploded View

Exxon has supplied reloads for this type of fuel assembly which is very nearly identical to the original CE design. From a materials point of view, the only difference that can be identified is that Exxon uses a bi-metallic grid spacer. Whereas the majority of the grid spacer is made of Zircaloy-4, the tabs that form the spring are made of an Inconel alloy.

Combustion Engineering Nonfuel Bearing Components

The only major NFB components of CE cores are control element assemblies (CEA). The CEA's are control rods that enter into the fuel assembly guide tubes from the top. In System 80 plants, the current design, a design evolution occurred. The older plants have CEA's that have five control rods (fingers) each, whereas the newer System 80 CEA's have 4, 8, or 12 control rods. The control material is either B4C or Ag-In-Cd, and is clad in either stainless steel or Inconel-625.

Control element assemblies come in a variety of configurations, with either 4, 8 or 12 elements each. Figures 12 and 13 illustrate the different type of CEA's. All three types are used in a reactor core simultaneously. They are approximately 5.5 meters long, extending from above the upper guide structure base plate to the bottom of the fuel assembly when fully inserted. The distance from the upper guide structure base plate to the fuel assembly alignment plate is 1.5 meters. Some of the CEA's will have control rods that are shorter than the typical full length ones. There are only about eight of this type. The four element CEA's are used for power shaping and make up the first control group to be inserted during high power. Eight and twelve finger CEA's make up the balance of the control groups and provide shutdown capability. The partial length CEA's provide control of axial power distribution. The partial length CEA's are nonscramming and remain in place during a reactor scram. The four element CEA's are inserted into one fuel assembly, whereas the eight CEA's are inserted into portions of three separate fuel assemblies, and the twelve element CEA's are inserted into portions of five fuel assemblies.

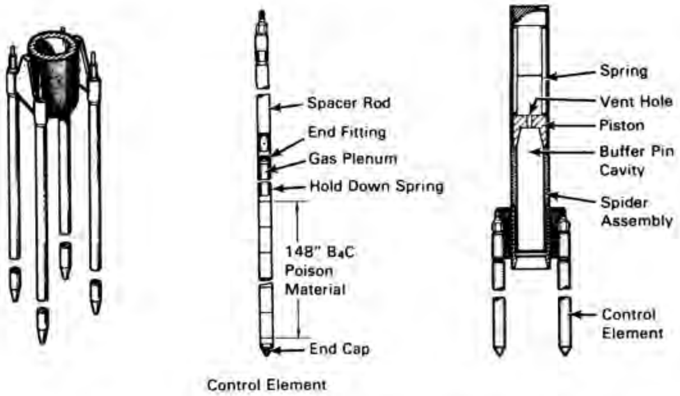


Fig. 12. Four-Element Control Element Assembly

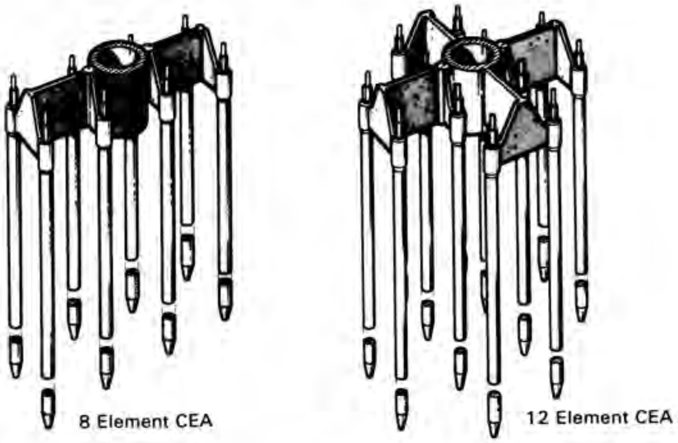


Fig. 13. Eight-Element and Twelve-Element Control Element Assemblies

The CEA's range in weight from 30.5 to 45.5 kg. A CE plant will have 77-89 CEA's, and they can be expected to be changed out approximately once during the life of the plant.

10 CFR 61

NRC regulation 10 CFR 61 provides for three classifications of waste that are acceptable for near-surface burial. They are classes A, B, and C, with Class C being the most highly radioactive. The classification scheme is based on the concentration of long-lived and short-lived radionuclides. Tables III and IV list the isotopes and their limits.

Most of the spent fuel disassembly hardware and nonfuel bearing components will have concentrations of isotopes that will classify them as greater than Class C. This conclusion is based on activation products in the metal. The isotopes of particular interest are Ni-59, Ni-63, C-14, and Nb-94. In general, the problem is more severe for those items that reside in the active fuel zone of the reactor core, such as most of the spent fuel disassembly hardware. Those items further from the active core, such as the Nonfuel bearing components, are exposed to a lower neutron flux, but are in for a longer period of time. Items made of Inconel alloys will most likely be Class C due to higher amounts of nickel and niobium in the base metal.

The radionuclides of interest are the result of activation during irradiation. Both Ni-59 and Ni-63 are the result of activation of naturally occurring isotopes of nickel by (n,gamma) reactions. The C-14 is a result of activating nitrogen by (n,p) reactions. The Nb-94 is the result of (n,gamma) activation of niobium.

The three most commonly used construction materials for reactor internals (including fuel skeletons and other components) are alloys of stainless steel, Inconel and Zircaloy. All of these materials have nickel, nitrogen, and niobium as either major constituents or trace elements. Calculating the amount of activation is a matter of determining the amount of the target isotope present, the fluence it is exposed to, and the length of time it is exposed. Unfortunately, there are large uncertainties involved in all these activities.

TABLE III

Radionuclide	Concentration curies per cubic meter
C-14	8
C-14 in activated metal	80
Ni-59 in activated metal	220
Nb-94 in activated metal	0.2
Tc-99	3
I-129	0.08
Alpha emitting transuranic nuclides in half-life greater than five years	100(a)
Pu-241	3,500(a)
Cm-242	20,000(a)

(a) Units are nanocuries per gram.

TABLE IV

Radionuclide	Col. 1	Col. 2	Col. 3
Total of all nuclides with less than 5 year half-life	700	(a)	(a)
H-3	40	(a)	(a)
Co-60	700	(a)	(a)
Ni-63	3.5	70	700
Ni-63 in activated metal	35	700	7000
Sr-90	0.04	150	7000
Cs-137	1	44	4600

(a) *There* are no limits established for these radionuclides in Class B or C wastes. Practical consideration such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentration for these wastes. These wastes *shall* be Class B unless the concentrations of other nuclides in Table II determine the waste to be Class C independent of these nuclides.

The greatest uncertainty associated with material composition is the niobium impurity in stainless steel and Zircaloy. In many alloys of Inconel, niobium is a major constituent ranging from 1% - 5% by weight. However, in Zircaloy and stainless steel, it is a trace element found in quantities of less than 100 ppm. The actual range can vary quite a bit. In twelve samples of type 304 stainless steel, measured values ranged from less than 5 ppm to 300 ppm, with an average of 90 ppm. For Zircaloy, values range somewhat lower. Current supplies of Zircaloy have values in the 20-30 ppm while past supplies have been as high as the 60-70 ppm range. Often the actual value of the niobium impurity is not available in the material certifications. That is because the ASTM specifications for Zircaloy and stainless steel, do not list niobium as an impurity that must be controlled. [An exception is that some steels add niobium as a minor constituent.] Therefore, many of the chemical analyses done on the raw materials do not necessarily include niobium. Predictions of calculated concentrations of the isotopes of interest can be found elsewhere.

The fact that these wastes are primarily greater than Class C implies that they are not generally suitable for near-surface disposal. This is the only disposal option currently available. Therefore, some alternate disposal option/method will have to be developed. A spent fuel repository is one option that may be considered in the future.

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