Metal And Concrete Inputs For Several Nuclear Power Plants

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In nuclear energy systems, the major construction inputs are steel and concrete, which comprise over 95% of the material energy inputs. The evaluation of construction material inputs is central to life-cycle assessments for environmental impacts for nuclear and other non-fossil energy systems, and can provide a useful, if only qualitative, plausibility check for economics claims. This paper compares steel and concrete inputs for several nuclear power plants: a 1970's Generation II PWR and BWR, the Generation III EPR and ABWR, the Generation III+ ESBWR, and the Generation IV GT-MHR, PBMR (vertical), and AHTR. The steel and concrete input estimates for the Generation III, III+, and IV systems are based on available arrangement drawings, and on scaling laws, and thus are approximate. However, they show that the evolutionary Generation III plants—EPR and ABWR—use approximately 25% more steel and 70% more concrete than 1970's LWRs. This may explain, in part, the relatively large capital costs that have been observed for these plants. In contrast, the passive Generation III+ LWRs that have been selected for new construction in the United States by Nustart—ESBWR and AP-1000—achieve substantial reductions in steel and concrete inputs. For example, analysis presented here suggests that the ESBWR uses 73% of the steel, and 50% of the concrete required to construct an ABWR. This suggests that new Generation III+ nuclear power construction in the U.S. will have substantially lower capital costs than was found with Generation III LWRs. This study also shows that the advanced gas-Brayton cycle technology that will be demonstrated by the Next Generation Nuclear Plant (NGNP) has the potential to achieve comparable material inputs to LWRs at much smaller unit capacities, and when extrapolated to larger reactors, to further reductions in steel and concrete inputs.

I. INTRODUCTION

Nuclear fission energy requires small inputs of natural resources compared to most other fossil and nonfossil energy technologies [1]. The construction of existing 1970-vintage U.S. nuclear power plants required 40 metric tons (MT) of steel and 90 cubic meters (m^3) of concrete per average megawatt of electricity (MW(ave)) generating capacity, when operated at a capacity factor of 0.9 MW(ave)/MW(rated) (Fig. 1). For comparison, a typical wind energy system operating with 6.5 meters-per-second average wind speed requires construction inputs of 460 MT of steel and 870 m^3 of concrete per average MW(ave). Coal uses 98 MT of steel and 160 m^3 of concrete per average MW(ave); and natural-gas combined cycle plants use 3.3 MT steel and 27 m^3 concrete.

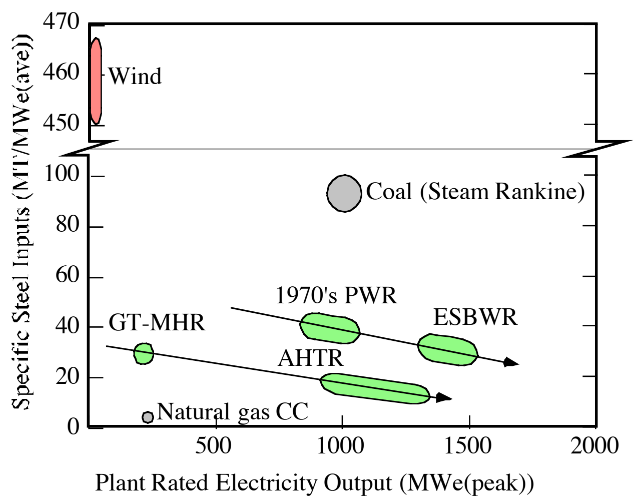


Fig. 1. Specific metal inputs for several power plants.

The quantities of materials contained in a typical 1970s 1000 MW(rated) PWR plant have been estimated in detail in previous studies. Detailed cost information, plant drawings, and, concrete and reinforcing steel input for buildings and equipments were studied, for a typical U.S. 1970s 1000 MW(rated) PWR plant studied [2] and a typical 1970s 1000 MW(rated) BWR plant was also studied during this period [3, 4] . Material input data for nuclear power plants are also given in life-cycle assessment studies [5].

For this study, design information for new light water reactors was obtained through public documents, presentations and private communications with vendors. For example, General Electric Nuclear Energy provided non-proprietary and proprietary design information for ABWR, ESBWR, and several BWR turbine island designs. EPR (European Pressurized Reactor) plant design drawings were obtained from public presentations. Non-proprietary GT-MHR (Gas Turbine – Modular High temperature Reactor) plant design information was obtained from public reports [6, 7] and proprietary plant design drawings were provided by the General Atomics. AHTR (Advanced High Temperature Reactor) plant design has been presented [8] and detailed material input for the AHTR power conversion system was studied by UC Berkeley [9]. The old 400 MWt PBMR (Pebble Bed Modular Reactor) plant design information have been reported [10, 11]. Because the detailed design information for the newest horizontal turbine design PBMR version [11] is not available, only the vertical turbine design version was assessed during this study.

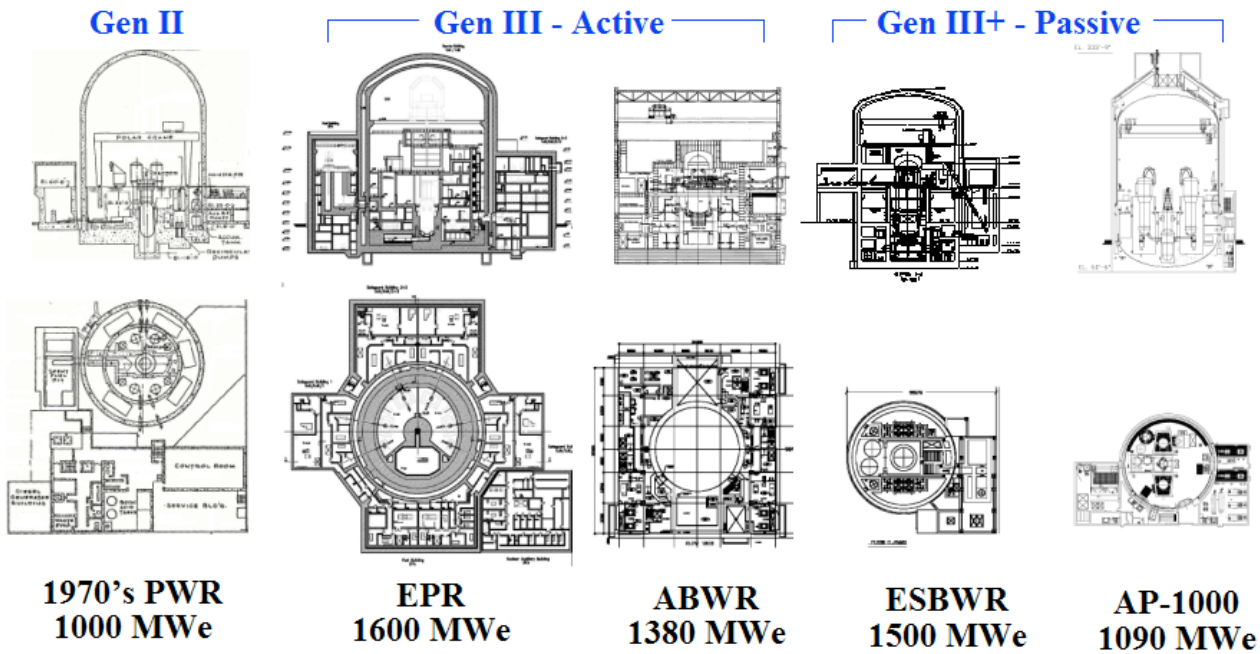
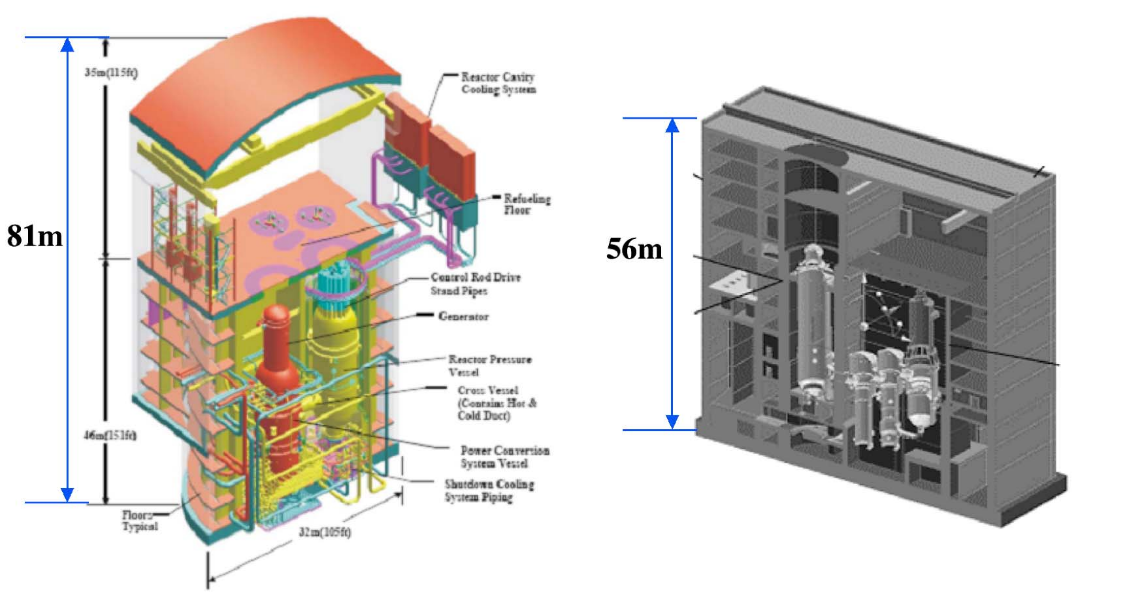
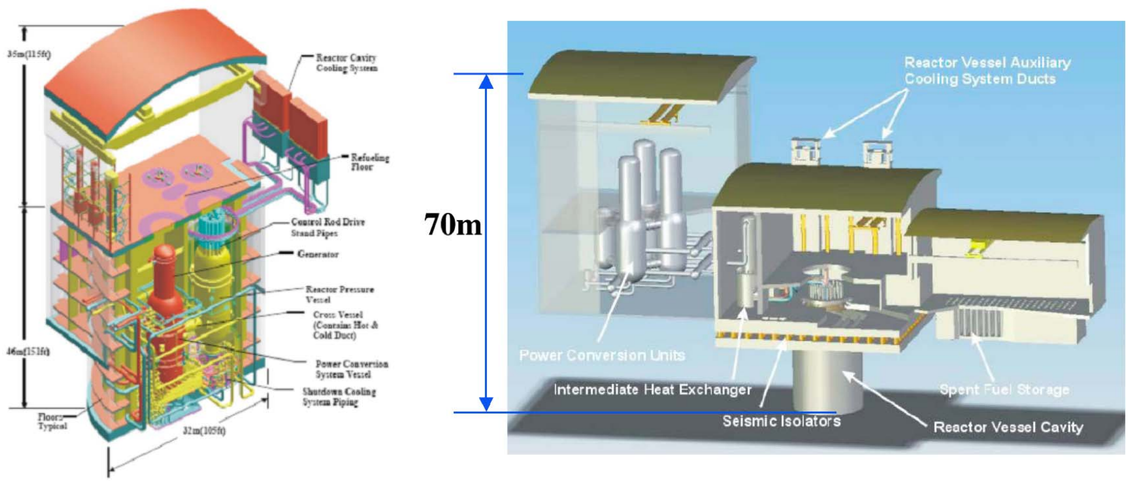


Fig. 2 Scaled comparison of plan and elevation drawings of the reference LWRs, with rated powers ranging from 1000 to 1600 MWe



GT-MHR reactor building (286MWe) **PBMR reactor building (165MWe)**

Fig. 3 GT-MHR and PBMR reactor buildings (to scale) [7, 10]



GT-MHR reactor building (286MWe)   **AHTR reactor/turbine building (1235 MWe)**

Fig. 4 GT-MHR and AHTR reactor buildings comparison (to scale) [7, 8]

Fig. 2 shows scaled comparisons of plan and elevation views of the LWRs considered in this study. The evolutionary Generation III nuclear power plants such as EPR and ABWR use large power uprating to obtain economic scale advantage, while Generation III+ plants such as ESBWR and AP-1000 greatly simplify reactor system design so that the capital cost can be further reduced. Fig.3 shows the GT-MHR and 400 MW PBMR (old design) reactor buildings. Both of these reactor designs use direct helium Brayton cycles for power conversion. Fig. 4 shows the reactor building comparison between GT-MHR and AHTR. AHTR uses molten salt as its primary coolant, allowing operation at much higher thermal power (2400 MWt), combined with a multiple-reheat helium Brayton cycle for power conversion [14]. The AHTR reactor vessel has similar size to the GT-MHR, and the very high boiling temperature of the molten salt coolant (>1200°C) allows operation with a low-pressure containment building. The AHTR is representative of the class of liquid metal and molten salt cooled Generation reactors that can operate at thermal powers above 1000 MWt and deliver heat at sufficiently high temperatures to permit the use of high-efficiency gas Brayton cycles for power conversion.

In nuclear energy systems, the major construction inputs are steel and concrete, which comprise over 95% of the total energy input into materials. To first order, the total building volume determines total concrete volume. The quantity of concrete also plays a very important role in deciding the plant overall cost:

- Concrete related material and construction cost is important in total cost (~25% of total plant cost for 1970's PWRs [3]);
- Concrete volume affects construction time;
- Rebar (reinforcing steel in concrete) is a large percentage of total steel input (about 0.06 MT rebar per MT reinforced concrete for 1970's PWRs [3]);
- Rebar is about 35% of total steel for 1970's PWRs [3];
- Concrete volume affects decommissioning cost.

Basing on those available documents, building volume and material inventory including metal and concrete are extracted and summarized. In the following sections, the methods used and results obtained are discussed.

II. METHODS AND ERROR ANALYSIS

Accounting System

For preparation of an inventory of materials, a systematic method of accounting for material is necessary. The USAEC accounting system [12] is used for all of the plant designs considered here. The major categories of that accounting system at the two-digit level are:

20. Land and land rights
21. Structures and site facilities
22. Reactor plant equipment
23. Turbine plant equipment
24. Electric plant equipment
25. Miscellaneous plant equipment
26. Main condenser heat rejection

The two-digit accounts are further broken down into individual systems and equipment items. In this study, only three-digit levels are included.

It should be emphasized that all of these comparisons are for river cooling, so materials for cooling towers (in account 23) are not included. This undervalues the advantages of the gas-cooled reactors and AHTR, which reject much less heat and can do so at higher temperature, but is likely balanced by the other approximations (neglecting graphite, larger fraction of nuclear-grade materials, etc.)

Scaling Method and Basis

An ORNL study [2] on 1970s PWR power plant material inventories provided detailed input information for the accounted categories, and thus this information provided a major foundation for this study. Whenever direct input data for the other plants was not available, scaling methods basing plant electric power output or other data were used to derive numbers from the corresponding 1970s PWR study numbers. For example, although steam turbine technology evolved significantly from 1970s to now, the change is not revolutionary. The turbine-generator equipment material inputs such as steel for all other LWRs are scaled from the 1970s PWR value according to the ratio of electric power output (MW(e)) raised to the 0.82 power. The scaling index value 0.82 is adapted from an AHTR economic study [8]. For example, the total steel mass of the 1600 MW(e) EPR plant turbine-generator was scaled from 1970s PWR value:

$$m_{EPR} = m_{1970s\ PWR} * (1600\ MW(e) / 1000\ MW(e))^{0.82} \qquad (1)$$

Similar scaling methods were used to derive data in account categories 23 (turbine plant equipment), 24 (electric plant equipment), 25 (miscellaneous plant equipment) and some 3-digits account categories in 21 (structures and site facilities) and 22 (reactor plant equipment).

Table 1 shows a typical 1970s PWR power plant material input and building volume information. Most of data are extracted from the ORNL material inventory study [2]. Rebar data are extracted from a 1970s PWR economics study [3]. Building volume information is calculated from the plant drawings in the economic study [3]. The table shows that most of metal is carbon steel and iron, which accounts more than 97.5% of total metal input. Furthermore, in total carbon steel is more than 88% of the total metal inputs. Since we do not have sufficient information to assess the amounts of the minor metals, total steel and iron appears to be a good quantity to represent metal input. For shorthand, we can call these "steel" inputs.

A 1970s BWR economics study [4] provides another important basis for scaling for new BWRs. Complete concrete input and rebar data are presented in this study and so is component cost information. For this study, building volumes were estimated from plant arrangement drawings. Total steel input for different accounts was derived according to linear cost scaling from the corresponding 1970s PWR input data. These data were sufficiently complete to construct a similar account table as Table 1. Whenever direct input data were not available for other BWRs such ABWR and ESBWR, scaling methods were used to derive data from the 1970s BWR input.

Building Volumes

Building volumes were estimated using direct measurement and scaling methods. When detailed plant building drawings were available, dimensions are measured from plan and elevation drawings, then building volumes were calculated from these measurements; when detailed building drawings were not available, such as intake/discharge structures (account 214), their volumes were approximated by scaling the corresponding volumes from the 1970s PWR or BWR plants. While detailed schematics were not available for the ESBWR miscellaneous buildings and EPR waste and miscellaneous buildings, other pictures were available which allowed these buildings' volumes to be estimated. Because detailed plan and elevation drawings of the reactor buildings were available, the reactor building total volume and concrete volume results are among the most accurate in this study. Such drawings were also available for the remaining structures on the nuclear island (fuel, auxiliary, and safeguard structures) as well as the ABWR and ESBWR turbine building, so volume and concrete estimates for these buildings were also among the most accurate.

For the ABWR, ESBWR, EPR intake/discharge structures and ABWR, ESBWR and EPR miscellaneous buildings, no detailed drawings were available. Therefore, while the scaled data from the 1970's PWR and BWR reactors provide reasonable approximations for concrete volume, these values are not as accurate as the measured values for the other structures. For the intake/discharge structures of each reactor, the scaled values used for their total volumes are similarly reasonable, but the errors from this approximation are small because the intake/discharge structures only make a small contribution to total plant volume. For the ABWR, ESBWR and EPR miscellaneous structures, building volume could be estimated from other pictures, but also not as accurately as with the other structures.

Concrete Volumes

Concrete volumes were estimated using three methods: direct measurements from plant arrangement drawings, and scaling based on total building volume, and scaling from 1970's light water reactors data. Wherever possible, concrete volumes were estimated through direct measurements of dimensions from plan and elevation drawings available in plant design presentations, design descriptions, and design studies. Such measurements were obtained by importing the drawings into a computer aided design (CAD) program and creating an overlay of areas corresponding to where concrete is present, and also by taking direct measurements of image dimensions using Adobe Acrobat and manual methods.

For buildings and structures that lack reliable diagrams from which measurements could be taken, concrete volume estimates were obtained by scaling data from a 1970's PWR or BWR plants. This approach was used for the intake/discharge structures and cooling structures of all reactor designs, as well as the EPR, ABWR, and ESBWR miscellaneous buildings and the EPR turbine building. Also, site improvements for all plants designs, such as roads, landscaping, fencing, and drainage, were accounted for by scaling by the total plant volumes instead of the plant powers. While this method can provide reasonable estimates, it is mostly useful for systems that have not changed radically over time, and is not preferable to direct measurement in terms of accuracy.

For the EPR waste building, the above scaling method is unsuitable because the reference 1970's PWR reactor does not include a separate waste building. While drawings of the EPR waste building's internal structure were unavailable, preventing direct measurement of concrete volumes, it was possible to estimate its overall building volume from a site layout picture. From this, an estimate of waste building concrete input was made by assuming the waste building's concrete to total volume ratio is similar to that of the 1970's PWR fuel building, for which concrete and total volume can both be measured directly.

Table 1. 1970s PWR material input and building volume information [2,3]

Account	System	Concrete, m^3	Total Steel and Iron Input, MT	Total metal input, MT	Total volume, m^3	Rebar, MT
	Entire plant	**74867**	**36069**	**36989**	**336115**	**9595**
	Nuclear Island	**43702**	**15078**	**15300**	**153565**	
	Non-nuclear	**31165**	**20991**	**21688**	**182550**	
21	**Structures and site**	**61030**	**17362**	**17433**	**336115**	**8610**
211	Site improvements	2036	1711	1713	N/A	100
212	Reactor building	22637	7571	7581	95010	5761
213	Turbine building	6638	3838	3841	161182	381
214	Intake and discharge	5506	337	338	6653	254
215	Reactor auxiliaries	14115	1469	1469	33850	1179
216	Radioactive waste building	N/A	N/A	N/A	N/A	N/A
217	Fuel storage	2985	429	430	9990	200
218	Miscellaneous buildings	7113	2008	2061	29430	735
22	**Reactor plant equipment**	**409**	**4605**	**4790**		**0**
221	Reactor equipment	56	705	712		
222	Main heat transfer system	305	1891	2025		
223	Safeguards cooling system	0	474	477		
224	Radwaste system	0	68	68		
225	Fuel handling systems	5	149	149		
226	Other reactor equipment	42	1056	1062		
227	Instrumentation and control	0	262	297		
23	**Turbine plant equipment**	**12711**	**11846**	**11927**		**985**
231	Turbine-generators	4730	4269	4324		454
232	Heat rejection systems	6310	2512	2516		531
233	Condensing systems	534	1753	1756		
234	Feed-heating system	46	1590	1595		
235	Other equipment	1091	1632	1634		
236	Instrumentation and control	0	91	102		
24	**Electric plant equipment**	**526**	**1397**	**1968**		
241	Switchgear	0	32	36		
242	Station service equipment	53	663	690		
243	Switchboards	0	87	105		
244	Protective Equipment	0	6	45		
245	Structures and Enclosure	473	534	534		
246	Power and control wiring	0	76	559		
25	**Miscellaneous equipment**	**191**	**859**	**871**		
251	Trasportation and lifting equipment	0	529	530		
252	Air and water service systems	191	239	240		
253	Communications equipment	0	5	7		
254	Furnishings and Fixtures	0	86	94		

Steel Masses

Because steel is used in both structural and equipment applications, it is difficult to accurately account for a reactor and turbine system's total steel input without detailed information about the equipment used in the reactor and the balance of plant. It is still possible, however, to obtain a useful figure for total steel input by taking structural and equipment steel separately, using previously calculated concrete information to estimate reinforcing bar steel quantities, and scaling known data to estimate equipment steel quantities. Structural steel includes both rebar and non-rebar contributions. Since rebar is incorporated into the concrete, its mass can be calculated with the following formula:

$$M_s = f_s * V_c / (1/\rho_c + f_s/\rho_s) \qquad (2)$$

where V_c is the volume of reinforced concrete, ρ_c and ρ_s are the densities of concrete and steel respectively, and f_s is the ratio of rebar mass to concrete mass. This last parameter, f_s, varies for different types of structures. For this study, values for f_s are taken from known rebar to concrete mass ratios for the corresponding types of structures in 1970's reference reactors [3, 4]. Table 2 gives the rebar to concrete mass ratios for the typical 1970's PWR and BWR power plant buildings. For non-rebar structural steel, the quantity of non-rebar structural steel in the corresponding reference reactor building is scaled to the ratio of building volumes.

Table 2. Rebar to concrete mass ratios for 1970s PWR and BWR power plants

Account	System	1970s PWR	1970s BWR
	Entire plant	**0.062**	**0.048**
21	**Structures and site**		
211	Site improvements	0.038	0.038
212	Reactor building	0.106	0.058
213	Turbine building	0.027	0.040
214	Intake and discharge	0.030	0.030
215	Reactor auxiliaries	0.036	N/A
216	Radioactive waste building	N/A	0.040
217	Fuel storage	0.031	N/A
218	Miscellaneous buildings	0.068	0.071
23	**Turbine plant equipment**		
231	Turbine-generators	0.048	0.048
232	Heat rejection systems	0.032	0.032

The 1970's PWR non-structural steel mass was scaled to estimate the EPR equipment steel mass, using the same scaling factor defined earlier. A similar procedure is used to estimate the ABWR and ESBWR non-rebar steel, but with modifications made to incorporate BWR differences, including removing the steam generator account, directly calculating the mass of the larger BWR reactor pressure vessel, and accommodating the ESBWR's passive safeguard system. For the GT-MHR and AHTR, reactor equipment inputs are calculated according to the design documents [6, 8]. For the PBMR, nuclear equipment inputs are scaled from GT-MHR according to power output.

For steel masses, estimates of structural steel quantities are not as accurate as the concrete volume estimates for the corresponding structure, due to the uncertainty in the rebar mass fraction in reinforced concrete. Also, while the scaled data used to compute steel quantities used in plant equipment provide a useful figure, they are not as accurate as a detailed evaluation of the steel input for separate systems would be.

III RESULTS AND DISCUSSION

All input results are summarized in the form of the USAEC accounting system. Tables 3 to 7 show concrete volume input, total metal input and building volume for different accounts for ABWR, ESBWR, EPR, GT-MHR, and AHTR-IT (Advanced High Temperature Reactor – Intermediate Temperature design). Note that the numbers in the italic font are direct results through measurement, design data, or design calculations, while normal font numbers are obtained through different scaling methods. Nuclear input includes reactor building (212), reactor auxiliaries (215), radioactive waste building (216), fuel storage (217), half of miscellaneous buildings (218), and all the reactor plant equipment (22). Non-nuclear input includes all others except for the nuclear island input. From these results, it can be seen that for LWRs most concrete consumption occurs in the power plant buildings, especially the reactor and turbine buildings. In order to compare BWR turbine building volume and concrete consumption, several BWR turbine building designs were studied, with results shown in Table 8. This comprehensive comparison of the new ESBWR turbine island design with the ABWR and with several Gen II GE BWRs shows that the ESBWR turbine building design uses substantially less concrete than the ABWR. To perform this comparison, the turbine island building was assumed to not increase in size to accommodate the uprating from 1380 to 1500 MW(e). The values for the 1970s BWR study turbine building seem appear to be relatively low in comparison to the values for actual turbine buildings built during this period.

Table 3 Concrete, total metal, and building volume for ABWR (1380 MW(e)). Values in italics are directly measured; other values are derived by scaling 1970's BWR values.

Account	System	Concrete, m^3	Total Metal, MT	Volume, m^3
	Entire plant	**191293**	**63439**	**627554**
	Nuclear island	**101722**	**28840**	**259095**
	Non-nuclear	**89571**	**34599**	**368459**
21	**Structures and site**	**173402**	**39299**	**627554**
211	Site improvements	3055	2766	
212	Reactor building	*67540*	18541	*209100*
213	Turbine building	*61149*	12598	*348000*
214	Intake and discharge	4630	439	8664
215	Reactor auxiliaries	*22070*	2093	*44060*
216	Radioactive waste building			
217	Fuel storage	*8800*	835	*38200*
218	Miscellaneous buildings	*6158*	2028	*23590*
22	**Reactor plant equipment**	**233**	**6357**	
221	Reactor equipment	124	*3976*	
222	Main heat transfer system	49	306	
223	Safeguards cooling system	0	0	
224	Radwaste system	0	221	
225	Fuel handling systems	13	367	
226	Other reactor equipment	47	1178	
227	Instrumentation and control	0	309	
23	**Turbine plant equipment**	**16724**	**15427**	
231	Turbine-generators	6251	5559	
232	Heat rejection systems	8297	3272	
233	Condensing systems	696	2283	
234	Feed-heating system	60	2070	
235	Other equipment	1421	2125	
236	Instrumentation and control	0	119	
24	**Electric plant equipment**	**686**	**1257**	
241	Switchgear	0	40	
242	Station service equipment	70	852	
243	Switchboards	0	113	
244	Protective Equipment	0	8	
245	Structures and Enclosure	616	146	
246	Power and control wiring	0	98	
25	**Miscellaneous equipment**	**248**	**1098**	
251	Transportation and lifting equipment	0	689	
252	Air and water service systems	248	303	
253	Communications equipment	0	6	
254	Furnishings and Fixtures	0	100	

Table 4 Concrete, total metal, and building volume for ESBWR (1500 MW(e))

Account	System	Concrete, m^3	Total Metal, MT	Volume, m^3
	Entire plant	**104231**	**50099**	**485477**
	Nuclear island	**41167**	**18260**	**184100**
	Non-nuclear	**63064**	**31840**	**301377**
21	**Structures and site**	**85074**	**24533**	**485477**
211	Site improvements	2475	2140	
212	Reactor building	*29200*	8923	*110800*
213	Turbine building	*33807*	8214	*257000*
214	Intake and discharge	4957	470	9277
215	Reactor auxiliaries			
216	Radioactive waste building			
217	Fuel storage	*8800*	835	*38200*
218	Miscellaneous buildings	5835	3952	*70200*
22	**Reactor plant equipment**	**250**	**6526**	
221	Reactor equipment	133	*3976*	
222	Main heat transfer system	53	328	
223	Safeguards cooling system	0	0	
224	Radwaste system	0	237	
225	Fuel handling systems	14	393	
226	Other reactor equipment	50	1262	
227	Instrumentation and control	0	331	
23	**Turbine plant equipment**	**17907**	**16519**	
231	Turbine-generators	6693	5953	
232	Heat rejection systems	8884	3503	
233	Condensing systems	745	2444	
234	Feed-heating system	64	2216	
235	Other equipment	1521	2275	
236	Instrumentation and control	0	127	
24	**Electric plant equipment**	**734**	**1346**	
241	Switchgear	0	42	
242	Station service equipment	74	912	
243	Switchboards	0	121	
244	Protective Equipment	0	8	
245	Structures and Enclosure	660	157	
246	Power and control wiring	0	105	
25	**Miscellaneous equipment**	**266**	**1176**	
251	Transportation and lifting equipment	0	738	
252	Air and water service systems	266	324	
253	Communications equipment	0	7	
254	Furnishings and Fixtures	0	107	

Table 5 Concrete, total metal, and building volume for EPR (1600 MW(e))

Account	System	Concrete, m^3	Total Metal, MT	Volume, m^3
	Entire plant	**204498**	**70903**	**675081**
	Nuclear island	**157830**	**39470**	**339250**
	Non-nuclear	**46667**	**31432**	**335831**
21	**Structures and site**	**183961**	**43400**	**675081**
211	Site improvements	3649	3436	
212	Reactor building	*61900*	18488	*169800*
213	Turbine building	9759	4311	*171800*
214	Intake and discharge	8095	700	9781
215	Reactor auxiliaries	*14500*	1616	*44100*
216	Radioactive waste building	*12600*	929	*32200*
217	Fuel storage	*23700*	3131	*60400*
218	Miscellaneous buildings	10458	4505	*65500*
	Guard buildings	*5835*	6283	*121500*
22	**Reactor plant equipment**	**601**	**6770**	
221	Reactor equipment	83	*1037*	
222	Main heat transfer system	449	2780	
223	Safeguards cooling system	0	697	
224	Radwaste system	0	100	
225	Fuel handling systems	8	219	
226	Other reactor equipment	62	1552	
227	Instrumentation and control	0	386	
23	**Turbine plant equipment**	**18881**	**17416**	
231	Turbine-generators	7057	6276	
232	Heat rejection systems	9367	3694	
233	Condensing systems	785	2577	
234	Feed-heating system	67	2337	
235	Other equipment	1604	2399	
236	Instrumentation and control	0	134	
24	**Electric plant equipment**	**774**	**2053**	
241	Switchgear	0	47	
242	Station service equipment	79	974	
243	Switchboards	0	128	
244	Protective Equipment	0	9	
245	Structures and Enclosure	695	785	
246	Power and control wiring	0	111	
25	**Miscellaneous equipment**	**280**	**1263**	
251	Transportation and lifting equipment	0	778	
252	Air and water service systems	280	351	
253	Communications equipment	0	8	
254	Furnishings and Fixtures	0	126	

Table 6 Concrete, total metal, and building volume for GT-MHR (286 MW(e))

Account	System	Concrete, m^3	Total Metal, MT	Volume, m^3
	Entire plant	**21816**	**7707**	**118364**
	Nuclear island	**18280**	**5802**	**113490**
	Non-nuclear	**3537**	**1905**	**4874**
21	**Structures and site**	**21559**	**2540**	**118364**
211	Site improvements	1027	602	
212	Reactor building	*18000*	1707	*111000*
213	Turbine building			
214	Intake and discharge	1973	141	2384
215	Reactor auxiliaries			
216	Radioactive waste building			
217	Fuel storage			
218	Miscellaneous buildings	559	89	4981
22	**Reactor plant equipment**		**4050**	
221	Reactor equipment		*3260*	
222	Main heat transfer system			
223	Safeguards cooling system			
224	Radwaste system			
225	Fuel handling systems			
226	Other reactor equipment			
227	Instrumentation and control			
	Helium storage and service system		*790*	
23	**Turbine plant equipment**		**N/A**	
24	**Electric plant equipment**	**189**	**500**	
241	Switchgear	0	11	
242	Station service equipment	19	237	
243	Switchboards	0	31	
244	Protective Equipment	0	2	
245	Structures and Enclosure	169	191	
246	Power and control wiring	0	27	
25	**Miscellaneous equipment**	**68**	**308**	
251	Transportation and lifting equipment	0	190	
252	Air and water service systems	68	85	
253	Communications equipment	0	2	
254	Furnishings and Fixtures	0	31	
26	**Heat rejection system**		309	
	Power conversion cooling system		*46*	
	Circulating water system		*263*	

Table 7 Concrete, total metal, and building volume for AHTR-IT (1235 MW(e))

Account	System	Concrete, m^3	Total Metal, MT	Volume, m^3
	Entire plant	**51508**	**19348**	**184354**
	Nuclear island	**26059**	**6163**	**71620**
	Non-nuclear	**25449**	**13185**	**112734**
21	**Structures and site**	**50655**	**6211**	**184354**
211	Site improvements	1380	938	
212	Reactor building	*8909*	1219	*24880*
213	Turbine building	*15880*	1506	*96000*
214	Intake and discharge	6547	467	7910
215	Reactor auxiliaries	16360	1398	41500
216	Radioactive waste building			
217	Fuel storage			
218	Miscellaneous buildings	1579	683	14064
22	**Reactor plant equipment**		**3205**	
221	Reactor equipment		*1029*	
222	Main heat transfer system		*387*	
223	Safeguards cooling system		*1029*	
224	Radwaste system			
225	Fuel handling systems			
226	Other reactor equipment			
227	Instrumentation and control			
	Salt processing line		*760*	
23	**Turbine plant equipment**		**7022**	
231	Turbine-generators		*5039*	
232	Heat rejection systems			
233	Condensing systems			
234	Feed-heating system			
235	Other equipment		*1983*	
236	Instrumentation and control			
24	**Electric plant equipment**	**626**	**1660**	
241	Switchgear	0	38	
242	Station service equipment	64	788	
243	Switchboards	0	103	
244	Protective Equipment	0	7	
245	Structures and Enclosure	562	634	
246	Power and control wiring	0	90	
25	**Miscellaneous equipment**	**227**	**1021**	
251	Transportation and lifting equipment	0	629	
252	Air and water service systems	227	284	
253	Communications equipment	0	6	
254	Furnishings and Fixtures	0	102	
26	**Heat rejection system**		228.8	
	Power conversion cooling system		*176*	

	Circulating water system			52.8	

Table 8 Specific building volume and specific concrete volume for several BWR turbine building designs

BWR Plant	Location	Power, MW(e)	Year	Specific Building Volume, m^3/MW(e)	Specific Concrete Volume, m^3/MW(e)
1970s BWR	Generic	1000	1972	200	21
Enrico Fermi –2*	Michigan	1110	1969	310	Not calculated
Columbia-2*	Washington	1112	1972	200	Not calculated
Grant Gulf –1*	Mississippi	1210	1974	190	30
ABWR	Japan	1380	1996	250	49
ESBWR	Generic	1500	2010?	170	27

* GE provided design drawings

Fig. 5 shows the comparison of building volume, concrete volume, and total steel input for the power plants studied here. All of the values are scaled to the values for the 1970s PWR, to assist in showing trends. This comparison is particularly useful for the Gen II, III, and III+ LWRs, because the capacity factors for all the LWRs are close. Direct comparison is not as meaningful between the LWRs and gas-cooled reactors, especially for PBMR, which may have a higher capacity factor due to continuous refueling. However, this should not affect the overall trend this figure reveals. For example, the vertical PBMR design uses 3 times concrete and 2 times steel per MW electric output as GT-MHR uses. Although there exists large difference in reactor and power conversion system designs, PBMR and GT-MHR have similar operating pressure and highest temperature. The material requirement such as for high temperature alloy should be similar. Therefore, it appears unlikely that the capital cost per unit electricity of the vertical PBMB design can compete with GT-MHR. It should be mentioned that PBMR has experienced dramatic design change in 2004. The power conversion system changes to horizontal turbines from vertical turbines. Because no detailed plant drawings are available, no assessment for the new PBMR design is tried.

For LWRs, this comparison reflects some interesting changes from Gen II to Gen III to Gen III+ power reactors. Gen III power reactors such as EPR and ABWR use more material to construct. A large power uprating is used to reduce unit electricity capital cost, but material inputs still exceed substantially those of 1970’s LWRs. The Gen III+ reactors such as ESBWR use passive safety systems. By eliminating expensive active safety systems and other design refinement, the ESBWR obtains significant material saving than ABWR. It is likely that the ESBWR may end up having substantially lower capital cost than ABWR and EPR, and even than the reference 1970’s LWRs.

Gen IV reactors such as GT-MHR, PBMR, and AHTR have much higher thermal efficiency than Gen III LWRs. Brayton cycles are used to eliminate expensive and large turbomachinery and condensers in steam Rankine cycles. Gen IV reactors also depend on passive safety features to provide safety. Gas cooled reactors usually have lower power density than liquid cooled reactors, which may need more material for reactor buildings per unit thermal power. For GT-MHR [13] and PBMR [10], modular designs are usually used. For example, 4 GT-MHR reactors compose one plant. Modular design can save equipment and building cost, which is not accounted in this study. GT-MHR is a promising candidate for near term commercial deployment in the United States. This 600MWt GT-MHR power conversion unit (PCU) has a net plant efficiency of 48% with a turbine inlet temperature of 848ºC. This study estimates that the GT-MHR PCU uses 7 MT/MW(e) steel. The reactor vessel adds 4.5

MT/MW(e). The remaining material is primarily in the structures and supports, particularly in the reinforcing steel. For a concrete input of 76 m^3/MW based on building arrangement drawings, the total GT-MHR steel inputs are about 27 MT/MW, 75% of the 1970s PWR value. This value is comparable to the Gen III+ ALWR estimated to have the lowest inputs, the 1500 MW(peak) General Electric ESBWR, with 69 m^3/MW(e) concrete and 33 MT/MW(e) steel. This supports the idea that nth-of-a-kind capital costs for high-temperature gas cooled reactors can be attractive compared to Gen. II LWR costs.

The AHTR is a new reactor concept that combines four technologies in a new way: coated particle nuclear fuels traditionally used for helium cooled reactors, Brayton power cycles, passive safety systems and plant designs from liquid cooled fast reactors, and low pressure molten salt coolants [14]. The new combination of technologies may enable the development of a large high efficiency, lower cost high temperature (700 to 1000ºC) reactor for electricity. As the peak reactor coolant temperatures approach 700ºC, several technologies (Brayton cycles, passive reactor safety systems, available materials, etc.) work together to improve total system performance while significantly reducing costs relative to those for other reactors. Detailed point designs have been developed for the molten coolant multiple reheat gas cycle (MCGC) [15], derived from the direct-cycle GT-MHR PCU (Power Conversion Unit), but using indirect liquid-to-gas heating and multiple PCU modules to permit reheating. Figure 6 compares the size of a Intermediate-high-temperature helium MCGC (MCGC-IT) point design (3 expansion stages, 750°C turbine inlet temperature, 1245 MW(e) output) to the turbine building of a 1380 MW(e) steam Rankine cycle of a modern light water reactor (LWR). With similar power output, the MCGC system is clearly more compact, and thus provides the potential for major reductions in the turbine building volume, and power conversion system capital cost, for future high-temperature nuclear energy systems, both fission and fusion. It is found that MCGC-IT PCU design has almost a factor of two reduction in specific steel inputs (3.3 MT/MW(e)), compared to the GT-MHR PCU design. This is in part because it can be optimized to run at higher operating pressures, and because the additional reheat stages give a 5 to 10 % increase in the cycle thermodynamic efficiency for the same turbine inlet temperature. Coupled to a heat source such as AHTR, significant reductions in total concrete and metal inputs appear possible as shown in Fig.1 and Fig. 5.

In interpreting the cost implication of Fig. 5, one must take caution, because material cost is only part of total capital cost and different steel (such as carbon steel and high temperature alloy) may have large differences in cost. Another fact needs to be noted is that same material in nuclear application usually costs as much as twice the cost for non-nuclear applications. Fig. 7 shows the total equivalent specific concrete and steel input (nuclear input times 2 plus non-nuclear input). In this comparison, the relative sequence in specific steel input changes for some reactors. In Fig. 5, both specific concrete and steel inputs for ABWR are slightly larger than the inputs for EPR. But in Fig. 6, the sequence is just reversed. A similar change happens for the specific steel input comparison between ESBWR and GT-MHR. GT-MHR uses direct cycle; therefore, nuclear input dominates in the total material input. The total equivalent specific concrete and steel inputs for 1970s PWR and 1970s BWR are very close; and so are for EPR and ABWR. These are consistent with the fact that the unit power output capital costs for 1970s PWR and 1970s BWR are very close and the costs for EPR and ABWR are also close. The advance of AHTR in material saving is also very obvious in Fig. 7, which suggests the potential for substantial capital cost reduction relative to the current LWRs and gas-cooled reactors.

History is the key to the future. Reviewing the change of material inputs for nuclear plants in different ages also reveals the developing trend and possible way to a bright future for advanced nuclear energy. The early 1970s was a golden age for nuclear energy, when nuclear energy was cheap and competitive. With the TMI accident, reactor safety issues brought designer’s attention to increase reliability and safety of reactors, as well as substantial construction delays and interest charges for plants then under construction. More safety equipment and systems were added into existing designs, which increased safety but also cost. The new passive reactor designs (e.g., ESBWR/AP1000) reverse the trend of increasing steel and concrete inputs. Technology progress often mean lower cost and the consumption of less material, e.g. computers, cell phones, and engines. Nuclear energy for the 21st century is also likely to follow this trend when facing the competition from traditional fossil plants and renewable power plants such solar and wind energy (Fig. 1). The innovative new Gen III+ reactors and further down the road, Gen IV reactors such as AHTR, bring hope to the renaissance of nuclear energy.

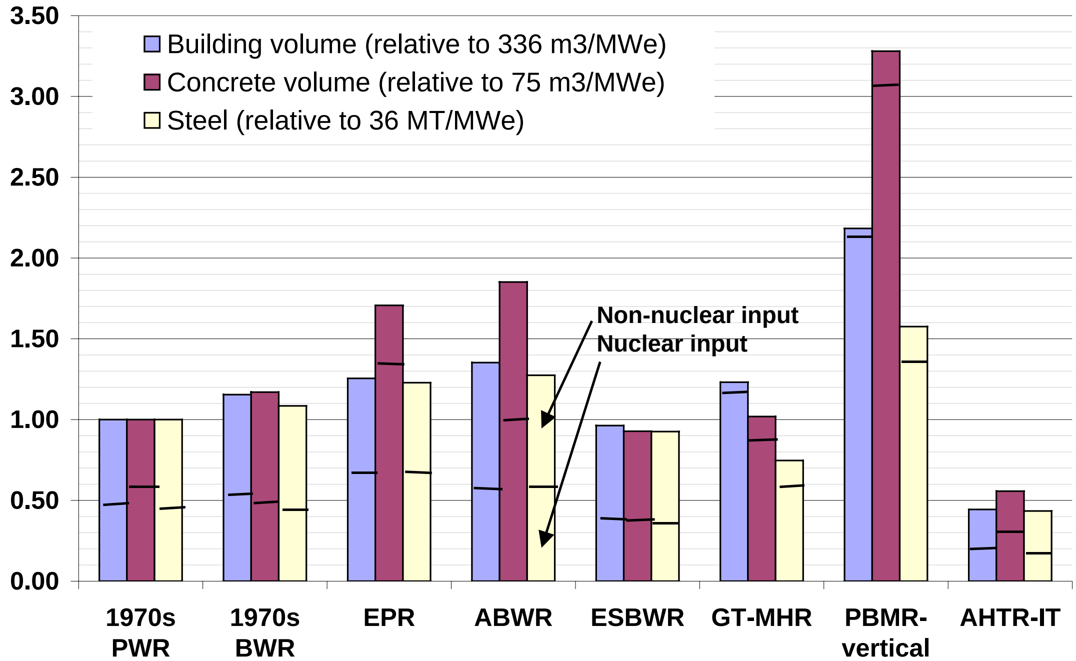


Fig. 5 Comparison of building volume, concrete input, and total steel input for several nuclear power plants

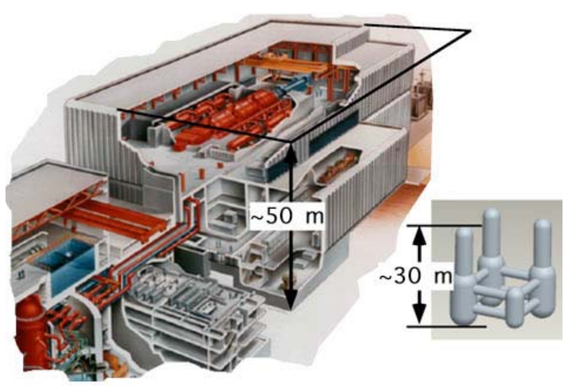


Fig. 6. Size comparison between the power conversion units of an intermediate-high-temperature, 1245 MW(e) MCGC-IT, and the 1380 MW(e) turbine building of the Advanced Boiling Water Reactor.

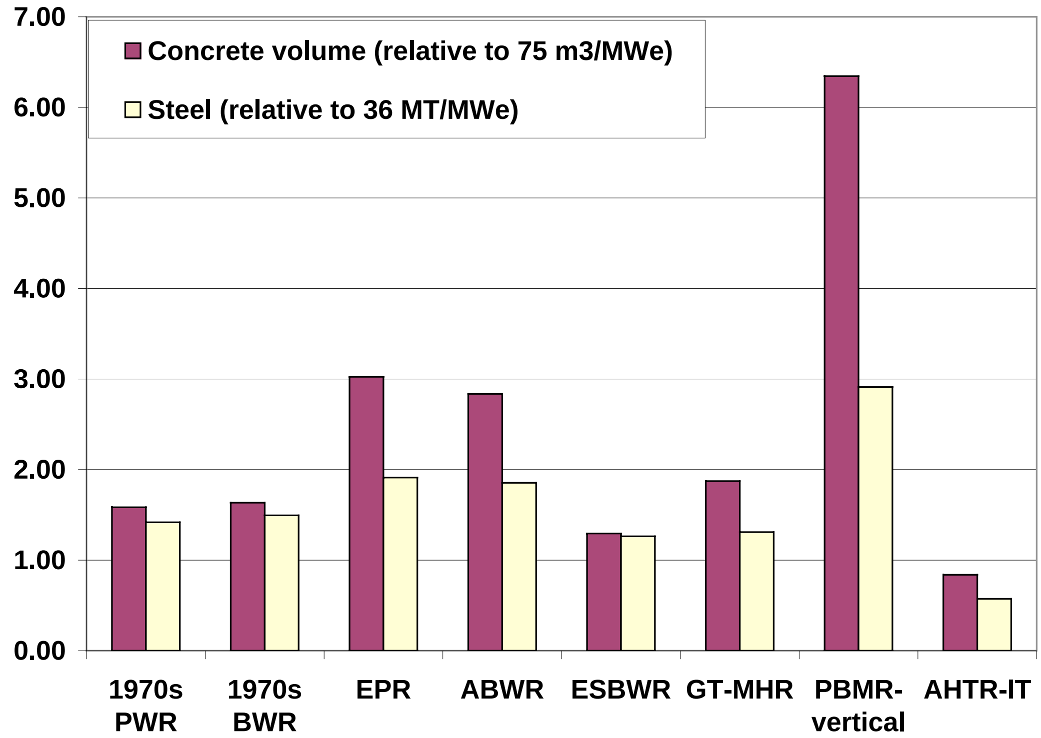


Fig. 7 Total equivalent specific concrete and steel input (nuclear input times 2 + non-nuclear input) for several nuclear plants.

IV CONCLUSIONS

The material input comparison among various nuclear power conversion systems provides a useful, if qualitative, measure to compare energy technologies. It clearly must be used with care, and supported by detailed evaluation of all system materials, including non-steel and non-concrete inputs. However, it has been observed that when the argument is framed in terms of material inputs, rather than claims about capital costs, that it can be easier to convince skeptics that nuclear energy can compete. Moreover, estimation of materials inputs for future high-temperature reactor systems does strengthen the arguments that the Next Generation Nuclear Plant (NGNP), with its compact and highly efficient gas Brayton cycle power conversion technology, is the correct place to make a major investment toward advancing nuclear energy technology.

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