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Light Water Designs of Small Modular Reactors: Facts and Analysis

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Underground SMR containment structure concept.

Light Water Designs of Small Modular Reactors: Facts and Analysis

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Some proponents of nuclear power are advocating for the development of small modular reactors (SMRs) as the solution to the huge financial risk ("bet my company" risk as Jeffrey Immelt, the CEO of General Electric put it in 2007 (Financial Times 2007)) and safety problems confronting present-day commercial nuclear power reactors. This paper discusses why SMRs are a poor bet to solve these problems and the ways in which they might actually exacerbate them.

This fact sheet focuses on light water reactor (LWR) SMR designs, whose development and certification the Department of Energy is subsidizing (DOE 2013 and Taxpayers for Common Sense 2013). Other SMR designs were also discussed in a fact sheet published in 2010 (IEER-PSR 2010). All four light water SMR designs (see box) in the running for this federal largesse have essentially the same underlying concept as present day U.S. commercial nuclear reactors. They would use "light water" (which is ordinary water) as a coolant to carry away the heat produced by fission and also to "moderate" (slow down) the neutrons that are needed to sustain the chain reaction that keeps the reactor operating. The DOE allocated the first chunk of money to a consortium consisting of Babcock & Wilcox (B&W, a reactor vendor) and the Tennessee Valley Authority (DOE 2013, Stout 2013).

The four SMR designs are all pressurized water reactors (PWRs) (see box on page 3).

All of these designs are proposed to be built underground and would use standard fuel assemblies, at either full or half length. A major difference from present PWRs is that the steam generators are inside the reactor pressure vessel in three of the four SMR designs, while they are separate units outside it in present commercial designs. None of the reactor vendors have as yet applied for certification of their respective designs; the NRC expects an mPower application and a Westinghouse application in 2014 (NRC 2013a and NRC 2013b).

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[1] Based in part on a 2010 SMR fact sheet produced by the Institute for Energy and Environmental Research and Physicians for Social Responsibility (http://ieer.org/resource/factsheets/small-modular-reactors-solution). A list of IEER funders can be found at www.ieer.org.

PRESSURIZED WATER REACTORS

- **mPower Reactor** by Babcock & Wilcox Company (B&W): This 180 MWe reactor would be a pressurized water reactor using fuel enriched to less than five percent. The reactor modules would be built underground and refueled every four years (B&W 2013a). The fuel would be in 17x17 assemblies, as in present-day PWRs, but only about half the length. The steam generator would be in the pressure vessel. The reactor vessel would be about 72 feet high and almost 12 feet in diameter. The overnight cost (excluding interest during construction) is estimated at $5,000 per kilowatt or $900 million per unit (WNA 2013a). B&W, in partnership with the Tennessee Valley Authority, could get up to $226 million in funding from the Department of Energy (DOE), of which $79 million has been secured, to support reactor design and certification by the Nuclear Regulatory Commission (NRC) (B&W 2013b).

- **Westinghouse SMR:** This would be 225 MWe (800 megawatts thermal). The reactor vessel would be more than 80 feet tall and about 11.5 feet in diameter. It would be refueled every two years. Like the mPower unit, it would be installed underground. Ameren, a Missouri utility, is partnering with Westinghouse (now a part of Toshiba) in an attempt to secure DOE funding for reactor design and certification. (WNA 2013a)

- **Holtec SMR 160:** This 160 MWe reactor pressure vessel would be just over 100 feet high. It would be installed underground. The anticipated refueling interval is three-and-half years. The 17x17 assemblies would be full length, as in present-day PWRs. The cost is anticipated at $5,000 per kW, or $800 million per unit. Holtec proposes to offer an option of a corrosion-resistant air-cooled condenser design (made of stainless steel tubes and aluminum fins). The DOE has signed an agreement to build a demonstration unit at its Savannah River Site, which is a nuclear-weapon materials facility. (WNA 2013a; see also Holtec 2012)

- **NuScale Power Reactor** by NuScale Power: This 160 MWt, 45 MWe (or more) reactor would use a 9-foot diameter, 65-foot high pressure vessel with 17x17 PWR bundles that are one-half the length of conventional rods which would be enriched to "less than 4.95 percent." Each module would be installed underground in a pool of water. NuScale proposes a nuclear plant with 12 such modules that would be installed in a larger underground water-filled pool. The expected cost is less than $5,000 per kilowatt for such a plant (NuScale 2013), amounting to a station cost of under $2.6 billion. The modules would be refueled every two years. The DOE has also signed an agreement with NuScale to build a demonstration unit at the Savannah River Site (WNA 2013a).

Inherently more expensive?

Nuclear reactors are strongly sensitive to economies of scale: the cost per unit of capacity (kilowatt, in the case of a reactor) goes up as the size goes down. This is because the surface area per kilowatt of capacity, which dominates materials cost and much of the labor cost, goes up as reactor size is decreased. Similarly, the cost per kilowatt of secondary containment, as well as independent systems for control, instrumentation, and emergency management, increases as size decreases. Cost per kilowatt also increases if each reactor has dedicated and independent systems for control, instrumentation, and emergency management. For these reasons, the nuclear industry has historically built larger and larger reactors in an effort to benefit from economies of scale. The four designs would reduce the size of each reactor considerably: by a factor of five (Westinghouse) to a factor of twenty five (NuScale) relative to the AP1000, now being built in Georgia and South Carolina. Such large size reductions imply significant increases in unit cost due to loss of economies of scale.

Additional resources containing information and diagrams of the reactors:

- **Holtec SMR**, at http://www.smrllc.com/news/hh_28_09.pdf
- **mPower**, at http://www.babcock.com/products/modular_nuclear/
- **NuScale SMR**, at http://www.nuscalepower.com/overviewofnuscalestechnology.aspx
- **Westinghouse SMR**, at http://www.westinghousenuclear.com/SMR/2012_SMR_Product_Sheet.pdf

A part of the reduction in financial risk is supposed to come from the reduction in overall cost per reactor so that each one is not a huge, “bet my company” risk. But if just two or three small reactors are built at a site, the site preparation, licensing, security, and other operating costs per unit of electricity would increase sharply. If a site is prepared for many, the costs for the first units would be high and achievement of the economies would depend on how accurately electricity demand is projected. The record for that has been mixed at best, so many projects risk being stuck with high siting and operating costs because the total installed capacity at the site will be small compared to that achieved at present with just two or three large reactors at one location. The industry already acknowledges that non-fuel operating and maintenance costs are expected to be higher than present reactors (Stout 2013, at 45 min 44 secs).[2] Uranium resource and enrichment requirements are likely to be higher (Glaser, Hopkins, and Ramana 2013); hence, fuel costs will likely be higher too.

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[2] Also see slide 11 of B&W 2012, where the operating and maintenance cost excluding fuel is estimated at $18.3 per megawatt-hour for an mPower two-reactor, 360 MW plant; B&W estimates O&M costs for a four-SMR unit, 720 MW plant are at $14.8, which is comparable to 2011 costs for existing reactors at $15.1 per MWh (NEI 2013).

Mass manufacturing cure?

SMR proponents claim that small size will enable mass manufacturing in a factory and shipment to the site as an assembled unit, which will enable considerable savings in two ways. First, it would reduce onsite construction cost and time; second, mass manufacturing will make up in economies of volume production what is lost in economies of scale. In other words, modular reactors will be economical because they will be more like assembly-line cars than hand-made Lamborghinis. Here is how Dan Stout, who is the Tennessee Valley Authority's senior manager for its Small Modular Reactor project, put it at a colloquium at the University of Tennessee in Knoxville on February 6, 2013:

> So the concept is that you got to have an assembly line cranking out repeatable parts, achieving a standardized vision of lots of mPower reactors. That creates the nth of a kind plant that has the efficiency in cost. I'm building Unit One. I don't want to pay for B&W's factory with automation to crank out repeatable parts. So that creates a contracting challenge… So as you scratch your head and puzzle how does this work, *remember the math won't work on one unit.* In fact our unit is most likely going to be, I'm going to use the word "cobbled together", it's going to be manufactured within existing facilities. But if B&W can get *an order backlog of a hundred SMRs and they are going to start delivering them in China and India and, etc., then* they'll be able to go get financing and build the building and have new stuff put in place to crank out these parts in a more automated manner. So as long as the design's the same, this should all work. The devil is going to be in the detail and in the oversight and in the inspection. [Stout 2013, at 29 min 51 secs, italics added. Transcribed by author]

A hundred reactors, each costing about $900 million, including construction costs (B&W 2012, Slide 10), would amount to an order book of $90 billion, leaving aside the industry's record of huge cost escalations. This would make the SMR assembly-line launch something like creating a new commercial airliner, say like Dreamliner or the Airbus 350. There were a total of 350 orders for the A350 in 2007, when it was seriously launched as a rival to Boeing's Dreamliner (Wikipedia 2013). The list price of the A350 is between about $250 million and $332 million (rounded, Airbus 2013), which would make the initial order total about the same order of magnitude in cost as 100 completed mPower SMRs. So the SMR investment risk is still huge – actually bigger than existing reactor projects since there must now be investment to create an entire mass manufacturing supply chain designed to sell scores of reactors each year to try and replace the economies of scale by the economies of replication by mass manufacturing. SMRs will still present enormous financial risks, but that risk would be shifted from the reactor site to the supply chain and the assembly-lines. Shifting from the present behemoths to smaller unit sizes is a financial risk shell game, not a reduction in risk.

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Concept for the layout of a SMR power plant.

Mr. Stout imagines that the chicken-and-egg problem (you need a lot of orders before you can set up your assembly line and produce cheap reactors, but you have to have demonstrated your reactors are cheap before private industry will order them in large numbers) would be solved by China or India ordering lots of reactors. But it stretches credulity that China and India, which along with Russia, are the main centers of nuclear power ambitions today, would order a hundred reactors from the United States. Indeed, if they were that attracted to SMRs, why would they not just license the design and set up the assembly lines and supply chain themselves? Most notably, China, where 28 reactors are under construction (WNA 2013b), already has a much better supply chain than the United States. So the U.S. government subsidies to B&W, TVA, and Westinghouse and others may pave the way for an assembly line in China! In fact, Westinghouse has already signed a memorandum of understanding with China's State Nuclear Power Technology Corporation (SNPTC) "to develop an SMR based on Westinghouse SMR technology." Westinghouse assures us that "SMR plants deployed in the USA would be domestically sourced and manufactured." But it is early days for SMRs. Westinghouse has huge nuclear interests in China, which is building or planning at least a dozen AP1000s of Westinghouse design. It should not go unnoticed that "The announcement of the latest Westinghouse-SNPTC collaboration comes days after the companies launched a joint venture to develop the *global* supply chain for the AP1000." (World Nuclear News 2013 and WNA 2013b, italics added)

The alternative to Chinese manufacture would be federal government subsidies to set up manufacturing in the United States. Dr. Vic Reis, a senior advisor to the Department of Energy, recognizing that private capital would be unlikely to invest huge sums of money into the SMR venture, set forth a number of ways in which the government could assist the birth of an SMR industry (Reis 2012 Video and Reis 2012 Slides, slides 21 and 23):

- Contribute $200 million per year for five years "beyond licensing";
- Offer loan guarantees;
- Provide tax credits;
- Provide government guarantees of an electricity price for the early reactors in the form of power purchase agreements;
- Install 2,000 megawatts of capacity at DOE facilities to supply them with electricity;
- Consider additional purchases of capacity by the Department of Defense for its use, for instance at its bases around the country

Even apart from the loan guarantees, the rest of the list could amount to tens of billions of dollars of support. Just the 2,000 megawatts of DOE capacity would be a huge sum, since the early reactors would cost much more than when the entire supply chain has been set up. Assuming that the initial reactors would cost twice as much per unit of capacity as the $5,000 per kilowatt now estimated,[3] the capital cost of the 2,000 megawatts of suggested DOE capacity alone would be $20 billion. On the order of half of this purchase amount might be offset by the electricity generated. Comparable subsidies might be provided in the form of tax credits and again on Department of Defense purchases. These are vast sums, especially in a period when federal budgets are under severe pressure, and Pentagon as well as civilian spending is being cut.

In sum, SMR costs are unlikely to fall below current reactor designs, and may well be higher. The investments risks will be at least as high, and probably higher, though most of these risks will be shifted to the setup of the supply chain and the assembly line. Setting up a U.S. mass manufacturing supply chain would likely require vast government subsidies, probably in the tens of billions of dollars.

How about recalls?

Proponents of SMRs point to the higher quality control that would accompany mass manufacture of parts and assembly of reactors in factories. This is indeed quite possible. But, so far as we are aware, none have so far pointed out the underbelly of

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[3] A factor of two is an approximate estimate of the increase due to loss of economies of scale without any gain from economies of mass manufacturing, which would apply to early units. The actual factor could be higher or lower depending on the actual unit size selected and whether the government chooses a single design or more than one design for these initial orders.

mass manufacturing: recalls. Millions of cars, presumably made to high quality control standards, are routinely recalled. The most comparable example in terms of the size of the supply chain and overall order books for SMRs would be passenger aircraft. Boeing Dreamliners were presumably rigorously designed, tested, and certified before they entered into service. But battery failures, including a fire in flight (NTSB 2013 and Parker 2013) resulted in a worldwide grounding of all the planes.

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A single SMR module.

How would a similar situation with SMRs be handled? Would they all be shut down pending resolution of an issue of comparable significance? What about grid stability, if SMRs supply almost 25 percent of the electricity by 2035, as suggested by Dr. Reis (Reis 2012 Slides, slide 18). Would the reactors be sent back to the factory on trucks or trains? Would the manufacturer train and equip technicians and engineers and send them to sites all over the world to be fixed? The public SMR literature is silent on such issues.

Consider steam generators as an example. They have often worn out prematurely in PWRs. Replacements well before the expiry of the initial 40-year licensing period have been common. SMRs advertise service life of 60 years, even 80 years. In three of the four SMR designs, the steam generators are inside the reactor vessel. Only the Holtec design has external steam generators (WNA 2013a). How would a steam generator design problem discovered after dozens or hundreds of reactors had been put into service be handled? Could the steam generators inside the reactor vessel actually be replaced in an environment that would be much more radioactive than in present-day PWRs? If they are somehow replaced, would it require methods that might compromise the integrity of the reactor vessel?

This is not mere theory. The OK-900 reactor, used by Russia in its nuclear ice-breakers, has had an operational life of only 34 years, with the reactors operating at 20 to 30 percent capacity factor. It has a design similar in concept to the three SMRs that have the steam generator within the reactor vessel. While the operating conditions of ice-breakers are much harsher than baseload power reactors, it is important to note that OK-900 steam generators indicated specific vulnerabilities that led to failures "after the expected service life":

> Failures occurred after the expected service life was exhausted. Specifically, depressurization of the pipe systems of steam generators and the pipelines of the pressurizing system occurred. Analysis of the reasons for the failures showed previously overlooked phenomena affecting equipment damageability. The main such phenomena are hydrogen pickup in the titanium tube systems of steam generators, thermal cycling of pipelines and equipment assemblies, and nodal corrosion of core elements made of zirconium alloys. [Zverev et al. 2013]

It is a symptom of the boosterism that, despite widespread premature replacements of steam generators in commercial PWRs, the problems that may arise from the need for premature SMR steam generator replacements have not been seriously discussed in the public literature by SMR proponents.

Reliability

Mass manufactured SMRs may exacerbate a phenomenon in nuclear power that emerged slowly after Chernobyl but accelerated since the March 11, 2011, Fukushima disaster. Japan's nuclear plants were built in a country vulnerable to severe earthquakes and tsunamis. After the Fukushima Daiichi meltdowns and hydrogen explosions, nuclear power plants in Japan were progressively closed. Only 2 of 54 pre-accident commercial reactors have been restarted (JAIF 2012-09); four are lost to the accident;[4] two others are at the same site that is heavily contaminated; 46 are theoretically operational but are closed until authorities declare them safe to open – which may or may not happen. Essentially, Japan went from about 30 percent nuclear generation to about one percent in just over a year, where it remains, despite the fact that many of Japan's nuclear plants are not the same as the stricken Fukushima early boiling water designs. Further, Germany shut down eight reactors in May 2011 and decided to accelerate its nuclear phase out as a result of Fukushima (WNA 2013 Germany).

So about one-sixth of the world's light water reactors (IAEA 2012, Table 2 (p. 12)), regardless of age or specific design, were shut for the long-term or perhaps forever in the aftermath of Fukushima. Mass manufacturing may well accentuate this problem, due to possible common defects stemming from the supply chain.

Safety

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[4] Since four reactors were destroyed by the accident, the count of Japanese reactors is now officially listed as 50 (IAEA 2012).

The four SMR designs all have passive safety features; in all cases the reactor cores would be underground. These features would reduce some risks. But they could create new problems as well. For instance, they could aggravate the problem of flooding, as was pointed out by Dr. Lyman of the Union of Concerned Scientists in 2011 Congressional testimony:

> Some SMR vendors argue that their reactors will be safer because they can be built underground. While underground siting could enhance protection against certain events, such as aircraft attacks and earthquakes, it could also have disadvantages as well. For instance, emergency diesel generators and electrical switchgear at Fukushima Daiichi were installed below grade to reduce their vulnerability to seismic events, but this increased their susceptibility to flooding. And in the event of a serious accident, emergency crews could have greater difficulty accessing underground reactors. [Lyman 2011 p. 2]

Dr. Lyman also pointed out that even with passive cooling, critical pieces of equipment such as valves must operate reliably.

Safety improvements may be reduced because SMR proponents are already arguing for changes in regulations to reduce costs. For instance, the current mPower design would have just three personnel for operating for two reactors – an operator for each reactor and one supervisor overseeing them both (Stout 2013, at 41 min 25 secs). This raises serious safety questions – will three operating staff be able to adequately respond to and manage a serious accident?

Reducing security requirements, the plant exclusion zone, and the 10-mile emergency planning zone are other industry regulatory goals for SMRs (Stout 2013 and Lyman 2011, p. 4).[5] The emergency planning zone would need to be reduced, according to Dan Stout of the TVA:

> Generally speaking, the B&W SMR may be able to have a footprint that's as small as 1000 to 2000 feet. That's pretty small….The devil will be in the detail of proving out what your design basis accident is, analyzing it, you're doing a Level III Probabilistic Risk Assessment and calculating the results and packaging it and communicating it in a license that is site specific. That's where the rubber meets the road. [At Clinch River] the easy way is to go in and do a 10-mile EPZ. We've got a huge site; it doesn't matter. We can go get our plant built but we haven't pushed the NRC to license what's required. So this is going to be an interesting year to two as the industry and the vendors challenge the NRC and as we learn whether or not the NRC is serious about licensing these innovations or not. [Stout 2013, at 44 min 6 secs. Transcribed by author.]

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[5] For a comparative international perspective on SMR licensing see Ramana, Hopkins, and Glaser 2013.

B&W appears to believe that the Emergency Planning Zone could be reduced from 10 miles to just 1000 feet, less than a fifth of a mile, at least in some circumstances (B&W 2012, slide 2). It describes this reduction by more than a factor of fifty in the EPZ radius as one of the ten "game-changers" that its mPower design would bring to nuclear power.

If such reductions in safety requirements (and hence cost) are not achieved, SMRs may not be viable even according to their proponents. Consider this rather frank statement by Dan Stout of the TVA, where he refers to changes in safety and security regulations as "innovations":

> From our perspective it's critical that the NRC allows these innovations in safety and security to be licensable and realizable. If we have to go meet old regulations with large amounts of staff, SMRs will never get built. [Stout 2013, at 43 min 1 sec. Transcribed by author.]

Proliferation

It is acknowledged at the outset that the once-through fuel use scheme without reprocessing proposed for SMRs is relatively robust from a proliferation point of view compared to any scheme that involves any method of reprocessing. But within that framework SMRs would increase proliferation risks, other things being equal. A team at Princeton University has analyzed the proliferation risks of SMRs of various kinds, including light water reactor designs considered here (to which they give the generic name iPWRs) and concluded that the proliferation risks would increase significantly unless specific design and safeguards steps were taken to mitigate them:

> As shown, iPWRs are likely to have higher requirements for uranium ore and enrichment services compared to gigawatt-scale reactors. This is because of the lower burnup of fuel in iPWRs, which is difficult to avoid because of smaller core size and all-in/all-out core management. These characteristics also translate into an increased proliferation risk unless they are offset by technical innovations in reactor and safeguards design and institutional innovations in the nuclear fuel cycle. In a Markov-method analysis, this risk increases by about 45 percent compared to LWRs for an equivalent power capacity. [Glaser, Hopkins, and Ramana 2013, p. 14]

This initial analysis of proliferation risk did not take into account the potentially much larger geographical dispersal of SMRs due to the very fact that they would be smaller. SMRs, notably the smaller ones, such as the NuScale 45 MWe reactor, could be accommodated on smaller grids and in many more situations. The safeguarding of the reactors and spent fuel would be a more difficult and complex task than with the large reactors of today.

Conclusions

SMRs are being promoted vigorously in the wake of the failure of the much-vaunted nuclear renaissance. But SMRs don't actually reduce financial risk; they increase it, but transfer it from the reactor purchaser to the manufacturing supply chain. Given that even the smaller risk of projects consisting of one or two large reactors is considered a "bet my company" risk it is difficult to see that Wall Street would be interested in betting much larger sums on financing that supply chain without firm orders. But those orders would not be forthcoming without a firm price, which cannot be established without a mass manufacturing supply chain. This indicates that only massive federal intervention with subsidies and orders could make mass-manufacturing of SMRs a reality in the United States.

Further, the costs are unlikely to be lower even if mass manufacturing is established; they may well be higher. In the meantime, the cost of early units, which some proponents advocate the government should acquire, will be higher. Without huge federal subsidies, the supply chain is likely to be in other countries, notably China, even if the designs are proven and tested in the United States. Why would China order large numbers of U.S. reactors when it can set up its own supply chain and can manufacture industrial goods more cheaply. It is fanciful and impractical to believe that SMRs can bring large numbers of industrial jobs to the United States in a globalized world economy governed by World Trade Organization rules. The May 2013 Memorandum of Understanding between Westinghouse and China's State Nuclear Power and Technology Corporation is a portent of future SMR reality, though Westinghouse says it intends to source U.S. orders in the United States.

Essential problems, such as how recalls might be managed have not been addressed seriously, even though recalls are a routine feature of even carefully considered, expensive mass manufacturing. The industry is calling for relaxed safety rules (one proponent calls them "innovations") without which SMRs would be unlikely to be built. Is it really wise to relax energy planning and exclusion zones in the post-Fukushima era?

Finally, the conclusion that the United States could have a fully renewable energy system by 2050 was not commonly held when, in 2007, IEER first published its analysis of such a system in *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy* (Makhijani 2007). There are now literally dozens of plans for energy systems that are fully renewable or nearly so (80 percent or more). Cities and states have committed themselves to such goals.

Efficiency improvements and wind-generated electricity, are already cheaper than new large reactors. The cost of distributed solar PV systems of even residential small systems of 10 kilowatts or less was about $2,300 per peak kilowatt in Germany at the end of 2012 (BSW Solar 2013).[6] Commercializing SMRs will take at least two decades. The first one, the B&W scheme with TVA, is not due to be operational until 2022. This reactor will be "cobbled together" as TVA's Dan Stout has noted. Commercialization will require mass manufacturing facilities for the entire supply chain, which will take a decade or more, if there are sufficient orders. By that time, a distributed grid is likely to be a reality, and this new round of nuclear reactors will likely turn into an economic liability that prudent corporate CEOs would not want without government subsidies any more than the CEO of General Electric wanted to bet on the current generation of large reactors without them.

In closing we might note that the World Nuclear Association's article on SMRs (WNA 2013a) thought fit to recall a well known quote from Admiral Rickover, who led the creation of the U.S. Nuclear Navy:

> An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development will be required. It will use off-the-shelf components. (8) The reactor is in the study phase. It is not being built now.
>
> On the other hand a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It requires an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated. [Quoted in WNA 2013a, Originally in Adm. Rickover's testimony before Congress, published in *AEC Authorizing Legislation: Hearings Before the Joint Committee on Atomic Energy* (1970), p. 1702.]

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[6] Exchange rate used: 1 euro = $1.30.

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