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Why routine radioactive releases occur:

The ideal, theoretical operation of a pressurized water reactor (PWR) relies upon keeping the fission products in the uranium fuel rods isolated from the primary cooling system, and the primary cooling system isolated from the secondary cooling system. It relies further upon the isolation of the secondary cooling system from the environment.

However, these so-called "closed cycle" cooling systems are not isolated. They are not really completely closed. Some of the radioactive materials generated in the reactor vessel leak within the plant and are released to the environment as a part of the routine operation of every nuclear power plant. Others are caught by filters and demineralizer resins, or are evaporated down to sludges -- all of which have to be stored permanently somewhere, somehow as "low-level" waste.

A. The primary cooling water in the reactor vessel becomes radioactive in the following ways:

1. The fuel rods leak: The metal tube or "cladding" of a fuel rod is about 12 feet long and is made of a zirconium alloy about 0.02 inch thick. Each rod contains at least 250 ceramic uranium pellets stacked end to end, each the size of a cigarette filter. The core of a typical 1000-megawatt PWR contains about 50,000 fuel rods. As the fuel is bombarded by neutrons during the chain reaction, it fissions or splits -- creating energy and heat and hundreds of different types of fission products. Other radioactive materials (activation products) result from the capture of neutrons.

   a. Some of the solid fission products get into the cooling water through fissures or pin-holes in the cladding.

   b. Each fuel rod is welded shut at the top and bottom. Some fission products leak out of the rods through faulty welds.

   c. Some of the fission products escape as gases from the uranium pellets and move through holes in the cladding into the cooling water. Some of those gases remain entrained or dissolved in the coolant, and are released with the liquid effluent. Others escape into the atmosphere of the buildings, and while most gases normally are stored temporarily before being released, in order for shorter-lived gases to decay, some are released suddenly during ventings or purges (please see C.2. below). For some gases, such as noble gases, it would be economically prohibitive to attempt to filter them.

(Whereas noble gases do not chemically interact with the body -- that is, form chemical compounds in the body -- they can physically interact: They give off physical energy in the form of radioactive particles which can change the structure of a DNA molecule, etc. In addition, some of the noble gases which reach the environment break down into radioactive solid daughter-products which can be incorporated into the body. For example:

krypton-89	3.2 min. half-life	→	strontium-89	52 days
xenon-135	9.17 hours	→	cesium-135	3 million years
xenon-137	3.9 minutes	→	cesium-137	30 years

Please see Dr. John Gofman's Radiation and Human Health, Sierra Club Books, 1981, pp. 536-539; or in the Pantheon paperback, pp. 320-322.)

d. "Tramp uranium," inadvertantly left on the outside of the rods at the factory where the rods are fabricated, may be bombarded by neutrons. The resulting radioactive products also accumulate in the coolant.

e. Some additional information about fuel rod leakage:

(1) "During irradiation the structural changes that occur cause the fuel to swell, thus producing cracks and breaks in the fuel material. With metal fuels, operating temperatures are generally limited by phase changes [e.g., from a solid to a gaseous state]. All of these changes tend to place stresses on the fuel cladding so that eventually the clad may break or lose its integrity. The fuel is designed to operate for a given period with only minimal failures, but even so the escaping fission products may make a major contribution to the radioactivity released in the effluents during normal operations." (from the Atomic Energy Commission publication: Meteorology and Atomic Energy -- 1968, David Slade, editor, p. 315.)

(2) Whereas in the past, a fuel rod would have been kept in a reactor vessel for an average of three years, the NRC has begun to allow licensees to keep the rods in longer -- lengthening the permissible "burn-up" time, in some cases, to as long as six years. Concomitantly, licensees are being given permission to use fuel enriched to a maximum of 4.2 weight percent uranium-235, as opposed to the previous approved maximum of 3.5 weight percent. The implications of this change in fuel design are unpredictable and potentially serious with regard to amounts of radioactivity ultimately released to the environment. The higher the level of radiation to which the cladding is subjected, and the longer it is subjected to this radiation, as well as to heat, chemical reactions, pressure, and mechanical vibration, the greater will be the amount of cladding deterioration and subsequent leakage of radioactive materials into the primary coolant. This, in turn, will add to the amount of evaporator sludges, resins, and saturated filters ("low-level" waste) a plant will accumulate.

2. Radioactive corrosion products slough off into the cooling water: Just as regular plumbing pipes exposed to water become encrusted over time with rust and other metal oxides, so do the many pipes and parts of a nuclear power plant. The crucial difference, however, is that at nuclear facilities the corrosion products, bombarded by stray neutrons, become radioactive.

a. The metal oxides which accumulate on the surfaces of the primary cooling system -- on the reactor vessel itself, on the piping, heaters and pumps, fuel rod cladding, control rods, etc. -- are officially called "crud."

b. Although some of the corrosion products precipitate out or slough off into the primary coolant, others continue accumulating -- causing the equipment to become clogged and inefficient. Furthermore, because some of the corrosion products include radioactive materials with notoriously powerful gamma rays, such as cobalt-60, the radiation fields within the plant buildings become extremely hazardous for inspectors and maintenance workers. Some of the corrosion products are extremely long-lived, such as nickel-63, which has a half-life of 92 years. Other common radioactive corrosion products include iron;, manganese, niobium, zinc and chromium.

c. When corroded pipes, valves, pumps and other highly-radioactive primary system components are replaced they, too, become a part of the low-level waste that must be stored. The curie content of these wastes is incredibly high: from 1,000 to 5,000 curies per cubic meter -- as compared with medical wastes which average 1.6 millicuries per cubic meter. If concern exists over the disposal of medical wastes containing 1.6 millicuries per cubic meter, what does that say about wastes from nuclear power plants which are a million times more hazardous? (The enclosed graphic gives this comparison for a 55-gallon drum, measuring .2 cubic meters.)

3. Radioactive hydrogen, or tritium, also accumulates in the coolant. And since no economically feasible process exists to separate and remove tritium from regular hydrogen in the cooling water effluent at commercial-sized nuclear power plants, the nuclear industry is not required to remove it. Therefore, whatever tritium accumulates in the cooling water is ultimately released to the environment, either with the gaseous emissions to the atmosphere, or with liquid releases to the plant's cooling water source (river, lake or ocean). Tritium has a half-life of twelve years, and if ingested can damage or destroy spermatocytes and oocytes (sperm and ovum precursor cells), and DNA molecules, etc. (If interested in recent research on the radiotoxicity of tritium, please write to me for abstracts.)

a. Some of the tritium at nuclear plants is created as a fission product or tertiary fission product within the fuel rods. It then diffuses through the cladding into the coolant. Some forms as a fission product from tramp uranium on the surface of the cladding

b. Tritium is also formed in the reactor vessel as the result of the absorption by boron of neutrons produced by the fission process. Boron is commonly used in water-cooled reactors because of its ability to absorb neutrons, thereby controlling the rate of the nuclear reaction. It is customarily added directly into the cooling water in the form of boric acid.

c. Two other chains of events also cause the formation of tritium: (1) A regular hydrogen atom in a molecule of the cooling water may capture a neutron, becoming deuterium (or heavy hydrogen). The deuterium in turn captures a neutron and becomes tritium. (2) Tritium is also produced by neutron capture-reactions in lithium, which may exist in the cladding, or naturally or as an additive in the coolant.

4. Other radioactive materials in the coolant include carbon-14, a substance which is known to be extremely radiotoxic and which has a half-life of 5730 years. It is primarily produced by neutron-induced reactions with oxygen-17 and nitrogen-14 in the fuel and in the coolant.

B. The secondary cooling water in the steam generator-turbine loop becomes radioactive also:

In pressurized water reactors (PWRs) the primary cooling water is kept highly pressurized so that it remains below the boiling point. It is pumped through piping out of the reactor vessel into tubes within a steam generator, and then back into the reactor vessel again. The steam generator tubes are surrounded by the secondary cooling water, which is enclosed in the steam generator vessel. When the steam generator tubes leak, which they do, radioactive primary coolant gets into the secondary, steam generator-turbine coolant loop. (Some plants have as many as four secondary loops, each with its own steam generator and pump.)

Steam generator tube leakage remains one of the nuclear industry's most threatening "unresolved safety issues." It also remains a leading source of low-level waste in the form of evaporator sludge, saturated filters, and even whole discarded steam generators themselves. Steam generator repairs are the leading radiation source of nuclear power plant workers.

A typical Westinghouse 1000-megawatt PWR has four steam generators, each with approximately 5500 thin-walled (0.04 inch thick) metal tubes bent in an upside-down U shape. A series of metal tube support plates within each generator has a separate hole for each tube, to keep the tubes from vibrating against one another. (Please see enclosed diagrams.) As corrosion products build up around the inside of one of the holes in one of the plates, the tube that is lodged within that hole may become dented and may ultimately leak, thereby releasing the highly radioactive primary cooling water from within the tube into the secondary coolant flowing around the tubes. Among other causes of tube-wall thinning and leakage is inter-granular stress corrosion (brittle cracking along the grain boundaries in the tube's metal wall caused by a combination of high stresses and a corrosive environment).

As of 1985, as each new steam generator model or water chemistry has been tried in an operating plant, new problems have been created.

Based upon operating experience at 14 PWRs (as reported by the licensees), the NRC expects a leakage rate of about 12 gallons (100 pounds) per day of the primary into the secondary coolant (according to the NRC's "Calculation of Releases of Radioactive Materials in Gaseous & Liquid Effluents from Pressurized Water Reactors," NUREG-0017, 1976, pp. 2-18, 2-21).

Thus the so-called "closed-cycle" operation of PWRs results not only in the accumulation of significant amounts of radioactivity within the primary cooling system (please see "A" above), but also in the leakage of the primary into the secondary cooling system, from which the radioactivity is more likely to reach the environment and affect the public. Some of these emissions are not monitored and thus may not be included in the overall total of radioactivity released during routine operation, as reported by the licensee to the NRC.

C. Some primary cooling water is intentionally removed from the reactor vessel daily; some leaks out.

Some of the resulting radioactive water and related gases and particulates are intentionally released to the environment in daily batches; some are released in continuous streams; and some escape during "events" (accidents). For example:

1. The chemistry and volume control system (in a 1000-megawatt Westinghouse PWR) shim-bleeds an average of 1,840 gallons per day of the reactor coolant in order to reduce the concentration of corrosion and fission products. Ninety percent of the water is demineralized and returned to the vessel; some fresh demineralized water is added. (from the most recent revision of the SNUPPS Callaway/Wolf Creek "Final Safety Analysis Report," Appendix 11.1A)

2. The reactor containment building atmosphere is vented (a valve is opened) frequently each year to control the building's pressure buildup, temperature, humidity, and air-borne radioactivity levels. In addition, the building atmosphere is purged (a fan is used to push the atmosphere out) an average of four times a year to enable workers to enter the building for fuel loading and maintenance. (NUREG-0017, starting at p. 2-25) In addition, newer PWR designs include small-diameter purge lines to allow for more continuous purging. Union Electric, the Callaway plant licensee, had asked the NRC for permission to leave its 18-inch mini-purge exhaust valve open for up to 5000 hours per calendar year, instead of the 500-hour limit originally established. The NRC granted an extension, but of "only" up to 2000 hours (as of October 1984 when the full-power operating license was issued.)

3. For PWRs the NRC estimates a leakage rate of 40 gallons per day of primary coolant into the containment building, 21 gallons per day of primary coolant to the auxiliary building, and 6720 gallons per day of secondary coolant steam into the turbine building. (AEC: "Numerical Guides for ... the Criterion 'As Low As Practicable' ... in ... Reactor Effluents," WASH-1258, Volume 2, Appendix B; July 1973)

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In this summary it has not been possible to go into detail on any one of the aspects of nuclear power plant design or operation which results in so-called routine releases. I'd be happy to provide additional information.

A postscript added in 1998: David Lochbaum of the Union of Concerned Scientists, after reading this packet on routine releases, suggested adding the following information to the above section on corrosion products [p. 2]:

> During outages, it is not uncommon for utilities to flush out piping, heat exchangers, etc., to remove crud buildup. Sometimes they do this to reduce radiation levels. Sometimes they do it to improve the heat transfer capability of tubes. Whatever the reason, the flushing process sends crud to radwaste. Some of this crud is retained on demineralizer resins and is shipped off as low-level waste. Some of the crud ends up being released to the river, lake, or ocean.

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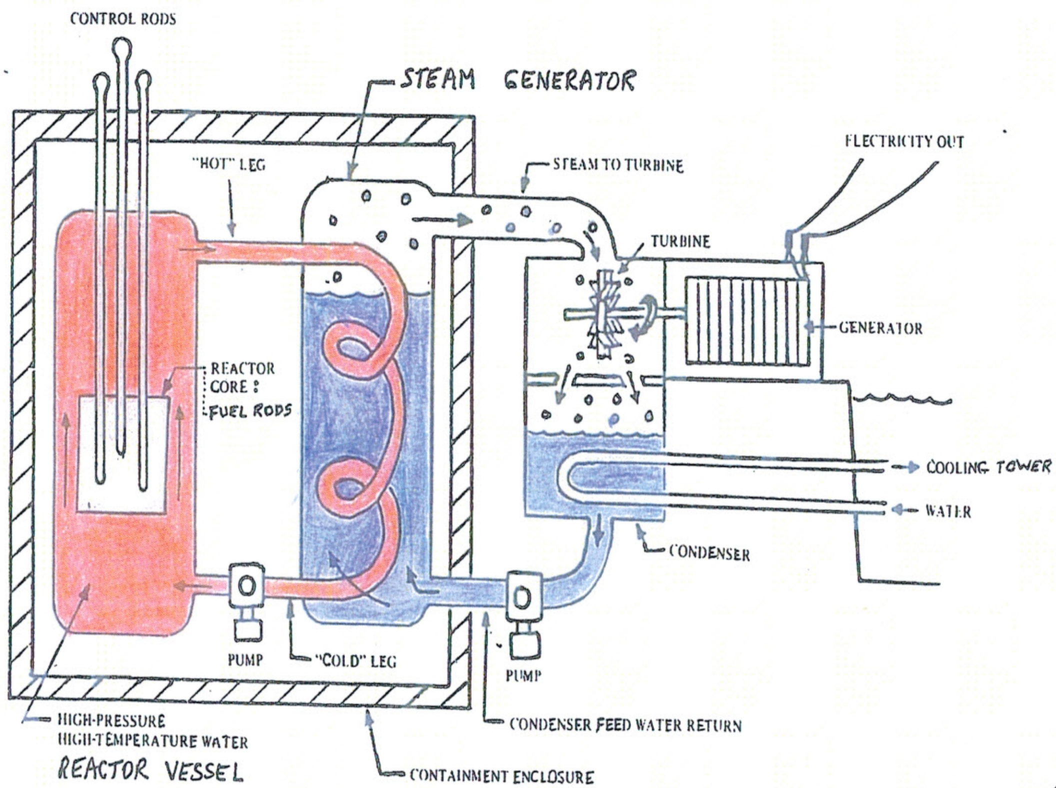
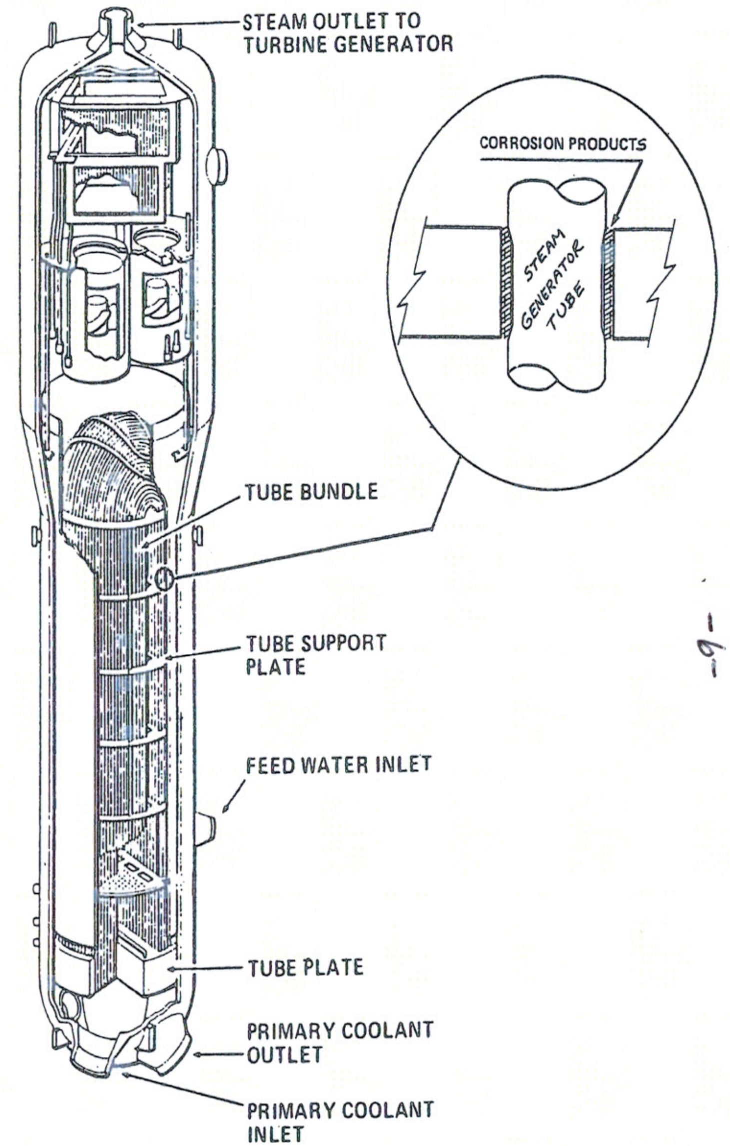
Schematic of
PRESSURIZED-WATER REACTOR
power system:

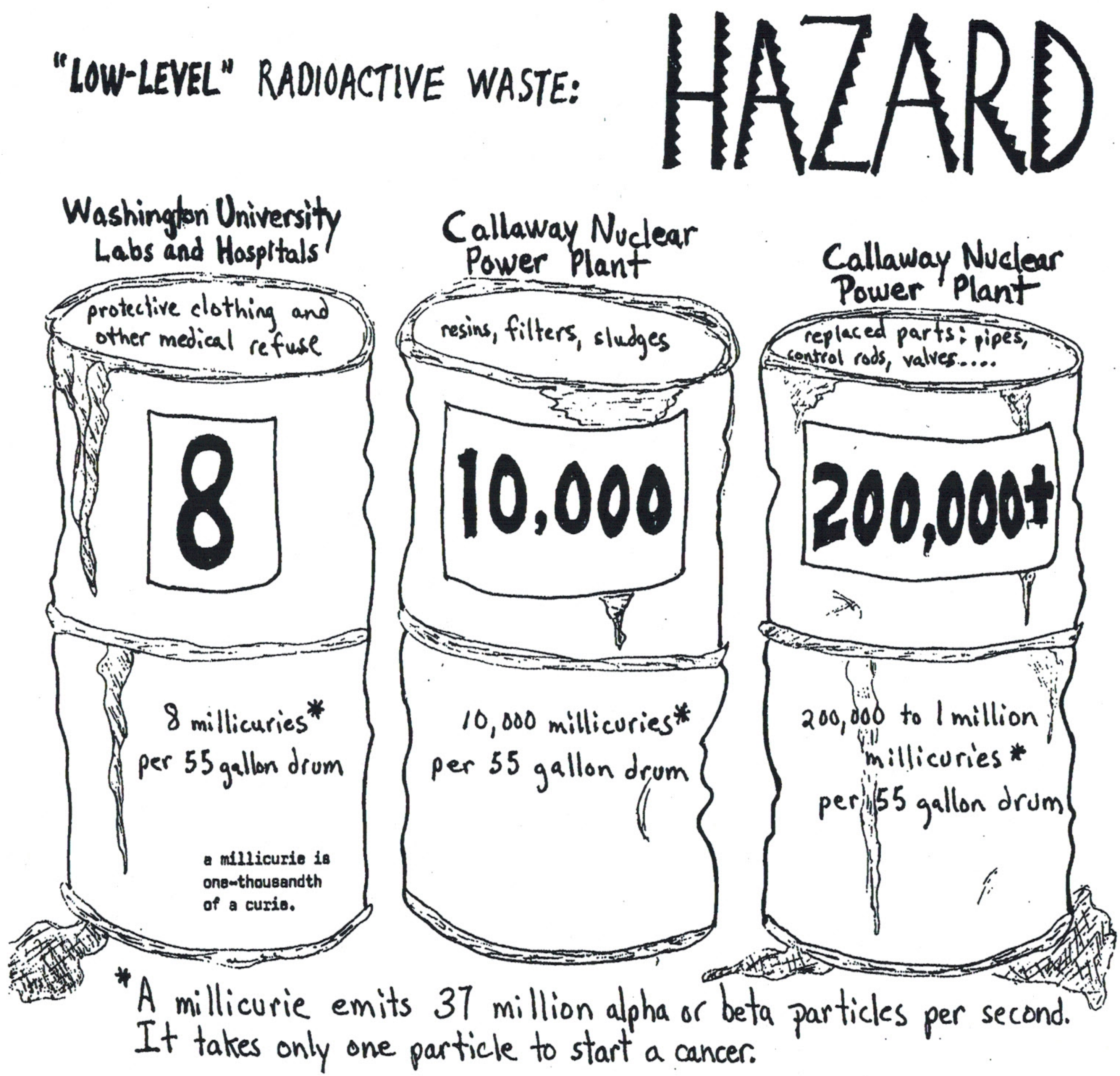


- PRIMARY COOLING SYSTEM
- SECONDARY COOLING SYSTEM



STEAM GENERATOR

- inside the tubes = PRIMARY COOLANT
- outside the tubes = SECONDARY COOLANT



I submitted this graphic piece as part of my testimony during the 1983 session of the Missouri legislature.