CHAPTER 11

Refueling Procedures

Refueling a nuclear ship is likely to be the most hazardous operation of its routine service. This is because, after many nuclear voyages, radioactive fission residues accumulate within the reactor fuel elements. When removing these fuel elements, considerable care must be taken to avoid releasing the fission residues and to keep personnel clear of radioactive areas. As a consequence, the amount of care required is significant in time, equipment, and manpower. Instead of oil refueling in a few hours using ordinary equipment such as oil hose and pumps, attended by a few members of the engine gang, nuclear refueling will impose a complexity of new procedures, new equipment, and new talents. Because of the high cost involved and the greater in-port time required, the frequency of nuclear refuelings may be compromised to coincide with other major activities, such as drydocking and annual inspections. Because of the hazards involved and the national defense features, it may be desirable that nuclear merchant ships refuel at Government (Naval) depots.

11-1 When to Refuel

With present ship reactors, the general procedure is to install a reactor core—complete with all fuel elements—and operate until the fuel becomes self-poisoned. Then the entire core is taken out and replaced with a new one. This is called "batch refueling" and is the simplest scheme for nuclear refueling.

For obvious economic reasons, we desire that the fuel elements burn as long as possible before replacing them. The extent to which this can be done, however, is determined by two conditions in the fuel elements themselves: one, physical damage; two, the accumulation of fission product residues.

Physical damage to fuel elements may occur in any number of forms, but the principal concern is leaks which release radioactive fission residues into the primary coolant stream. When the primary coolant becomes contaminated to the point where the purification system can't remove the radiocontaminants fast enough, it then becomes necessary to shut down the reactor and refuel. Refuelings due to damaged fuel elements would be infrequent in well-designed marine reactors.

The most common reason for refueling is the accumulation of fission product residues within the fuel elements. Remember: these residues are neutron absorbers and, consequently, they compete with the fuel for capturing thermal neutrons. Every atom of fuel fissioned produces two atoms of these residues . . . for as long as the fission process continues. (We are considering now only present-type marine reactors where no provision is made for fission product bleed-off.) When the total neutron absorption of the fission products equals the total neutron absorption of the fuel for fission, the fissioning process becomes *self-poisoned* . . . and dies down.

Analytical predictions of just when the die-down point occurs are not too exact. A number of nuclear factors have to be taken into account and these are not too well understood quantitatively. The atoms of fuel, for example, do not experience the same neutron fluxes in all parts of a fuel element, and each fuel element experiences a different neutron flux from that of its neighbor. Consequently, parts of each fuel element can die down before the fueled core as a whole. For fuel life computational purposes, neutron fluxes are assumed to exist in three energy categories: thermal, epithermal, and fast. But this partitioning is purely a mathematical convenience. The fluxes are continuous in energy, with the result that neutron absorption and fission data contain many discrepancies. The neutron flux profiles (radially and axially throughout the core) also are subject to discrepancies.

11-2 "Higher Chain" Nuclei

Furthermore, there is the matter of "higher chain" nuclei. These nuclei are transuranium isotopes built up from U-235 and U-238. A U-235 atom may capture a neutron to produce U-236 . . . without fission. A U-238 atom may capture a neutron to produce—after a few days—Pu-239 which is fissionable. However, a Pu-239 atom may capture a neutron to be converted to Pu-240—which is non-fissionable. In the same manner, Pu-241 is fissionable, but Pu-242 is not. And so on. All of these higher chain isotopes compete for the core neutrons both fissionably and non-fissionably. The per atom probability of this competition is listed in Table 11-1. The difficulty is that there is no universal agreement on the probability factors assigned to these new isotopes. Consequently, fuel die-out computations based on the data of Table 11-1 will vary depending on the sources of the data, and on the experimental conditions under which the data are recorded.

As should be expected, these higher chain isotopes change the fuel composition with operating time. They also change the buildup of fission residues. Each of the fissionable isotopes, namely: U-235, Pu-239 and Pu-241, when fissioned, contributes to the total yield of fission residues.

As a consequence, unavoidably the go:no-go balance between fissionable atoms and fission residues becomes a complex analytical problem. Perhaps this can be appreciated more readily by means of Fig. 11-1 which merely *typifies* the fuel-residue changes.* Note the "cross-over" areas.

Table 11-1. Competing Neutron Absorptivities of "Higher Chain" Nuclei in U-235 U-238 Fuel

Nuclei	σ_a	σ_f	σ_{nf}	η
U-235	680	575	105	2.06
U-236	9	-	9	-
U-238	3	-	3	-
Pu-239	1,900	1,200	700	1.84
Pu-240	640	-	640	-
Pu-241	1,480	1,080	400	2.14
Pu-242	20	-	20	-
FP (Fission Products)	80/fission	-	80	-

Recall that: σ = neutron cross section per atom; subscripts a = absorption;
f = fission, nf = non-fission
η = (eta) new neutrons produced per neutron absorbed in fission.
Ref: "Reactivity Changes in Fixed Fuel Thermal Reactors", Spinrod, Carter, and Eggler, Vol. 5, Physics of Reactor Design, Geneva Conference, 1955, pp. 125 ff.

11-3 Fuel Life Conservatisms

In the case of the *SAVANNAH*, for example, all of the foregoing considerations have been analytically detailed into an electronic computer program . . . resulting in Fig. 11-2.† From this figure, we note that the calculated operating lifetime of the reactor core varies from 800 to 1300 days. The spread in the calculated lifetime is due to the neutron profile that is *assumed* to exist. Since we don't know what this profile really is, we can take one of two views: the 800-day conservative view, or the 1300-day optimistic view. For either view, however, we have to back off a little, since we know that the calculational procedures have inherent discrepancies in them. We then play it safe and say that the reactor will operate somewhere between 600 days and 1200 days without refueling. We cannot pinpoint with precision the exact day that refueling will be required.

Realizing that fissionable fuel—when consumed—may cost in the neighborhood of $7500 per pound, we deplore the fact that we cannot specify with greater certainty the useful core life of the *SAVANNAH*. Nevertheless, a 600-day operating spread is the region of uncertainty that we must

* Ref: *Nuclear Chemical Engineering*, Benedict and Pigford, McGraw-Hill, 1957, p. 95.

† Ref: "Reactor Physics and Core Design of the Merchant Ship Reactor," Wood and Levine, Paper No. 96, *Nuclear Engineering and Science Conference*, Chicago, March, 1958.

acknowledge. As yet, there is no operating experience with nuclear merchant ships to prove or disprove the complexity of calculations that are necessarily involved.

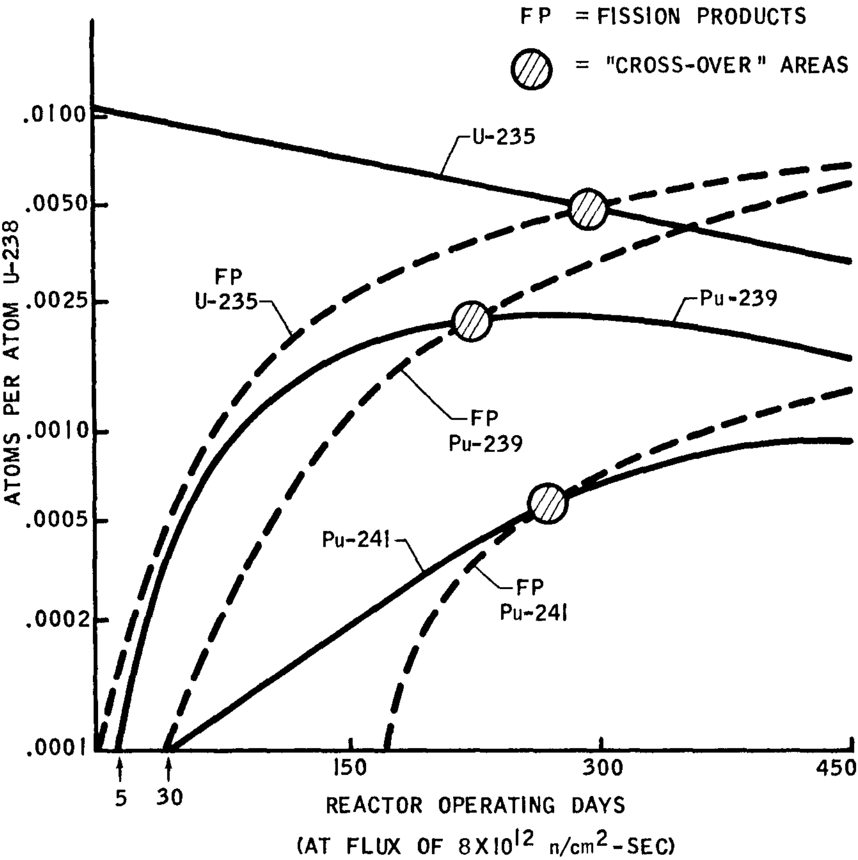


Fig. 11-1 Typical Changes in Fissionable Fuel Composition with Reactor Operating Time

Experience with Navy nuclear ships does not help very much. Naval reactors differ in design; they differ in fuel loading; they differ in operating conditions; they differ in cost philosophies. On top of this, Navy calculational procedures also have inherent discrepancies and they also are subject to operational conservatisms, which, in some cases, are more stringent than those for merchant ships. So, until the *SAVANNAH* and subsequent nuclear merchant ships get into operation, we just don't know when we should optimally refuel a marine reactor!

11-4 Fuel Burnup Defined

It may be well at this point to define what we mean by fuel burnup, fuel exposure, spent fuel, and other "fuel" concepts related to refueling technology. These definitions will help us understand why nuclear ship refueling is so different from oil ship refueling.

In view of the higher chain fissionable nuclei, Pu-239 and Pu-241, we should now re-define what we mean by nuclear fuel. Back in Ch. 4 (Fuel Calculations), we considered the fuel as being the fissionable isotope U-235 only. We considered then 5% U-235 with the rest of the fuel material consisting of non-fissionable U-238. This is the normal case for a brand new reactor just starting up.

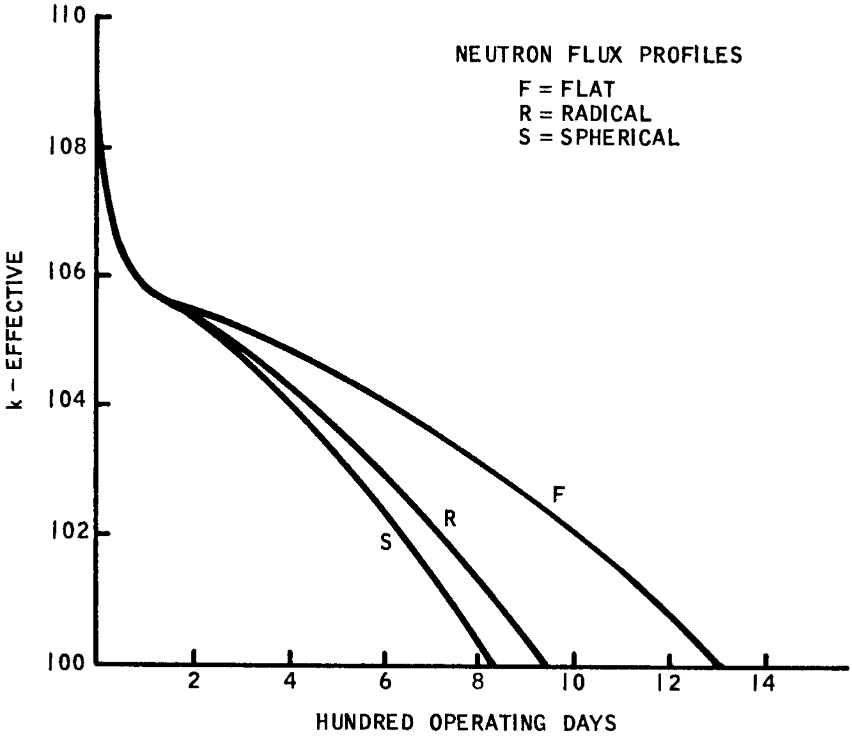


Fig. 11-2 Calculated Core Lifetime for *Savannah* Reactor

We recognize now (from Sec. 11-2) that the U-238 is actually a fertile fuel. That is, though it is thermally non-fissionable itself, it is the seeding ground for growing the new fissionable isotopes Pu-239 and Pu-241. The nuclear reactions by which this internal conversion takes place are shown in Table 11-2. Remember: neutrons can interact with the higher chain nuclei at any point in time and space.

So, now, when we speak of "nuclear fuel," we must think also of the higher chain fissionable isotopes. In other words, the total fuel in a reactor includes both U-235 and U-238. If we burn, say, 1% of the total fuel, this means we are burning about 0.84% U-235, 0.14% Pu-239, and

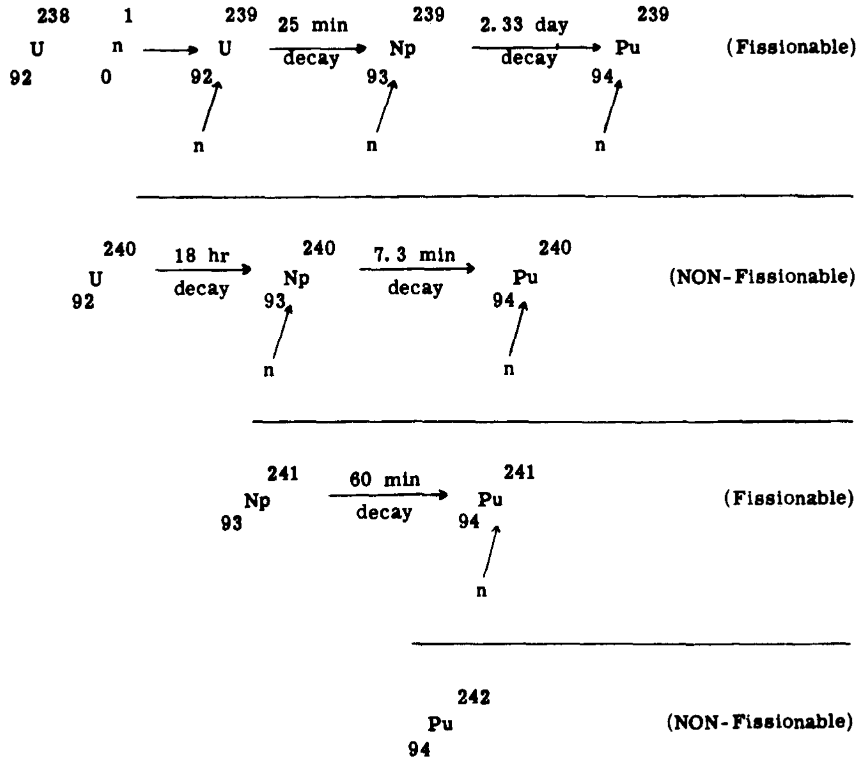
0.02% Pu-241. We should note (from Fig. 11-1), however, that the Pu-239 doesn't start contributing to the fuel until after about 5 days of operation; the Pu-241 until after about 30 days of operation.

To avoid confusion as to which fissionable atoms are consumed, we define fuel burnup as the *atom fraction* of the total fuel converted to fission products. The burnup fraction is thus expressed as

$$\dot{\beta} = \frac{(N_{FP})_{235} + (N_{FP})_{239} + (N_{FP})_{241}}{N^{0}_{U\text{-}235} + N^{0}_{U\text{-}238}} \qquad \text{[Eq. 11-1]*}$$

where N_{FP} is the number of atoms of fission products per cm^3 of the fuel elements, and the subscripts 235, 239 and 241, refer to the N_{FP}'s contributed by each of the fissionable isotopes; N^0 = the original number of fuel atoms per cm^3 of the fuel elements.

Table 11-2. Nuclear Growth of Fissionable Fuel from Fertile U-238



* Note that the burnup symbol is "beta" with a dot over it.

To burn up the fuel, we have to *expose* it to neutron flux. The power heat produced is proportional to this neutron flux (Sec. 5-2). Thus, we speak of "fuel exposure." Exposure is the total amount of heat released per unit weight of fuel. The units generally used are megawatt-days per metric ton (MWD/T).* So, when we speak of a fuel exposure of, say, 10,000 MWD/T, we are saying that a 100 MW reactor has operated for 100 days for every ton of U-235 plus U-238 in its core. In the *SAVANNAH* core, for example, the total fuel inventory is about 7.06 tons. For a total core life of 52,000 MWD, her average fuel exposure will be 7360 MWD/T (see Table 11-3).

The relationship between exposure and burnup is given by

$$\text{Exposure} = 9 \times 10^5 \beta \qquad \text{[Eq. 11-2]}\dagger$$

If we substitute the *SAVANNAH's* exposure (7360 MWD/T) into Eq. 11-2, we find that the fractional burnup of the total fuel is 0.82% . . . i.e., *less than 1%!* Let us not forget, however, that even though this is a small per cent burnup by fuel oil standards, the nuclear heat produced is equivalent to approximately *130,000 tons of fuel oil!* The actual U-235 consumed would be a mere 60 kg, or 132 lb (Table 11-3 again).

Table 11-3. Typical Inventory and Fuel Burnup Data for SAVANNAH

(52,000 MWD Core Life)

Initial enrichment	4.7%
Initial U-235 loading	332 kg
Initial U-238 loading	6734 kg
Average burnup	7360 MWD/T
Final enrichment	3.9%
Final U-235 loading	273 kg
Final Pu-239 loading	17.5 kg
Final total Pu loading	19.5 kg
Actual U-235 consumed	59 kg

Ref: "The Power Plant for the First Nuclear Merchant Ship", J. W. Landis, Bulletin AER-54 presented at the Nuclear Merchant Ship Symposium, Washington, D.C., August 1958, Table II.

It is interesting to note that 1% burnup represents "par" for today's power reactors. More advanced reactors indicate the possibility of achieving 2% burnup. A burnup of 3% is "hoped for" in the future.

We can appreciate now that we may never completely burn up all of the nuclear fuel in a fuel element. Consequently, we would never speak of

* A metric ton is equal to 2205 pounds; a long ton is 2240 pounds. So, for practical purposes, the "T" for tons is long tons for shipboard use.

† Ref: *Nuclear Chemical Engineering*, Benedict and Pigford, McGraw-Hill, 1957, p. 87.

used fuel elements as being "burned up." Instead, we would refer to them as "spent" fuel elements. We "expend" 1% of the fuel . . . so we have 99% left. At $7500 per fissionable pound, we can't afford to throw 99% of the fuel away.

11-5 General Preparation of Ship

For two very important reasons, considerable care must be taken when removing a spent core from a nuclear ship's reactor. These reasons are: (1) the high dollar value of the unfissioned fuel, and (2) the high radiation hazard from the fission residues. Both the unfissioned fuel and fission residues are contained within the same fuel elements (see Fig. 11-3). Consequently, if we damage the fuel elements when removing the spent core, we risk not only the losing of valuable fuel but also the releasing of dangerous radiation.

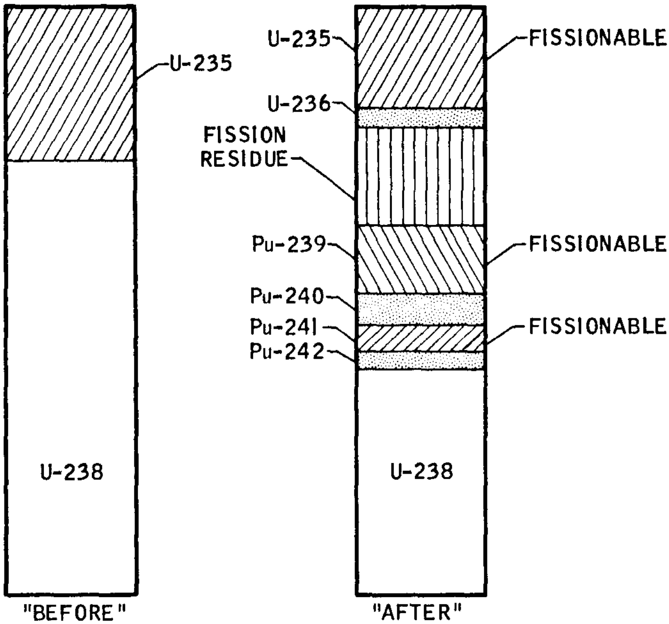


Fig. 11-3 Typical Content of Fuel Element Before and After Exposure

Accordingly, in preparing a nuclear ship for refueling, two principles must be borne in mind. One, the ship must be a stable platform from which to work, and two, there must be direct access to the reactor core. These two principles also are used when preparing a merchant ship for loading or unloading dangerous commercial cargoes, such as explosives, chemicals, and the like. Indeed, there are many analogies between dangerous commercial cargoes and spent nuclear fuels.

Ordinarily, a ship at dockside is subjected to unstable motion caused by tidal changes and by local winds and water-surface conditions. Though normally these factors are of no concern to ordinary cargo handling operations, they are of much concern to nuclear refueling. This is particularly true once the reactor vessel is opened up and the fuel elements are ready for withdrawal.

Direct access to the reactor core means "direct access." The fuel elements constituting the spent core must be transferred from the reactor location aboard ship to dockside containers . . . in the most direct line of travel practicable. This travel should be straight up, straight over, and straight down. This is paramount for safety reasons.*

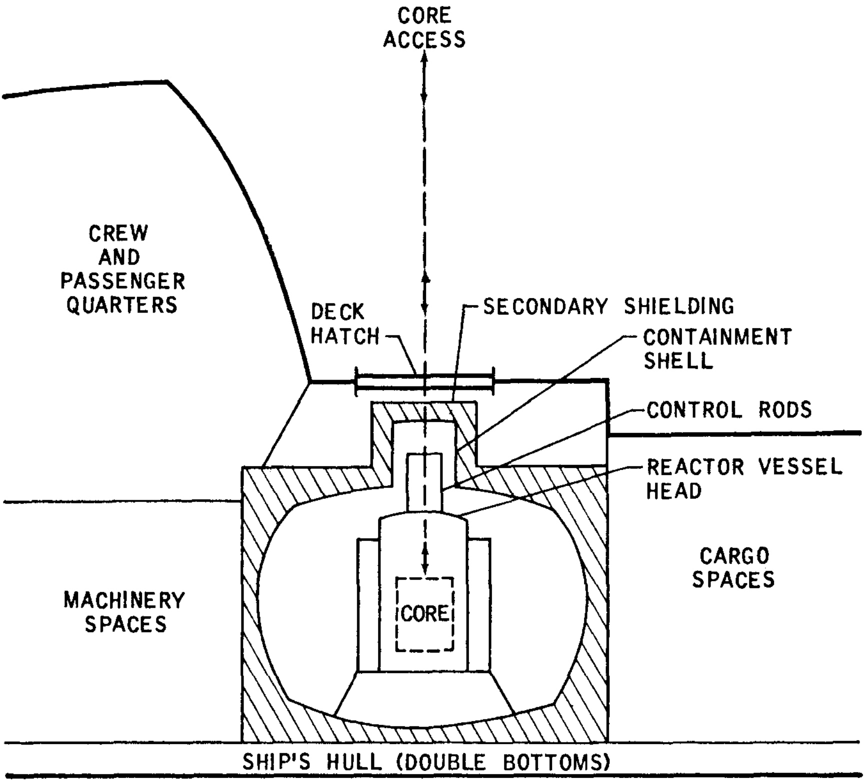


Fig. 11-4 Typifying Direct Access to Core of *Savannah* Reactor

* Because of the infrequency of refuelings, and because of the highly specialized equipment required, it is unlikely that nuclear ships will be fitted with their own gear for refueling. So, we can assume that the refueling would be done in a shipyard, preferably in drydock.

Direct access to a spent core is typified in Fig. 11-4. Deck hatching has to be removed; access through top secondary shielding has to be made; access hatches through the containment shell have to be opened, control rods have to be cleared away; and the reactor vessel's top head has to be removed. All of these access steps involve heavyweight items, which may or may not be radioactivated.

A radiation survey must be made prior to, and after, each access step. We proceed to the next step only after the radiation levels have been determined safe, or after adequate precautions are prescribed. To attest to this, it is necessary to post "radiation safety certificates." These certificates serve both as a warning and as instructions to workmen who will be entering the access areas.

This radiation survey and the posting of radiological safety instructions are analogous to gas-free inspection and certification on merchant ships today, before allowing workmen to enter oil cargo holds or other compartments which have been closed for long periods of time. There are consequences of death or injury to workmen if we ignore gas-free inspections. The same consequences occur if we ignore radiation surveys.

11-6 Radiation from Spent Fuel

To appreciate the precautions necessary when removing a spent nuclear core, a discussion of the radiation hazards is in order.

The radiation dose that one could receive from a *bare*, point source of spent fuel is approximated by

$$\text{Dose} \approx \frac{6CE}{d^2} \quad \text{r/hr} \qquad \text{[Eq. 11-3]*}$$

where

C = radiation source strength in curies
(one curie equals 3.7×10^{10} radioactive disintegrations per sec)
D = distance from radiation source in feet
E = energy of radiation source in Mev
r/hr = roentgen per hour: a measure of gamma radiation dosage†

Since we are discussing a spent fuel core, we should keep in mind that we are dealing primarily with gamma radiation. That is, the reactor is shut down (no neutrons), and the radiation emanates from the radioactive decay of fission residues in the spent core. Although there is also beta decay radiation, betas generally are of little concern as a refueling hazard. They are easily self-absorbed by the fuel element cladding.

* Ref: *Principles of Nuclear Reactor Engineering*, S. Glasstone, Van Nostrand, 1955, p. 545.

† The term "roentgen" is derived from the discoverer of X rays. X rays and gamma rays have much in common. One roentgen is that amount of X or gamma radiation absorbed in 1 cm^3 of dry air at standard conditions.

Now, to appreciate the hazards of gamma decay, let us assume that we have access to a bare core . . . with no shielding of any kind. Let us assume further that all gammas less than 1 Mev are self-absorbed by the fuel cladding, so that E in Eq. 11-3 is taken conservatively as 1. Based on these premises, the minimum radiation dose becomes

$$D_{min} \approx \frac{6C}{d^2} \text{ r/hr} \qquad \text{[Eq. 11-4]}$$

Using published data (see Fig. 11-5),* we approximate that the *SAVANNAH's* spent core—for example, after 500 days' operation (at 70 MW), would have a C-value of about 5×10^7 curies. This severe radioactivity would persist for several days after shutdown. Using this C-value in Eq. 11-4, we can compute the radiation doses at various distances from the core.

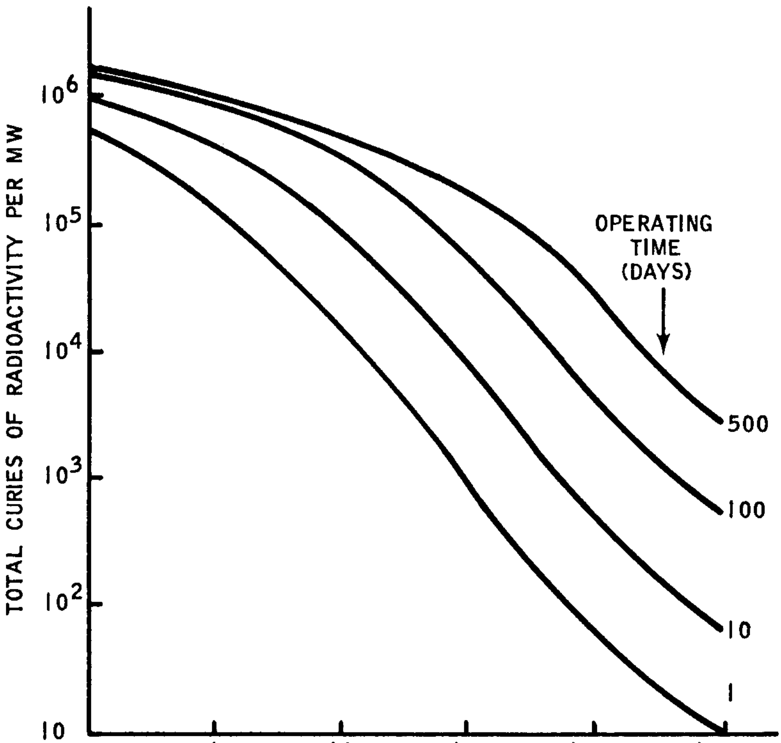


Fig. 11-5 Total Radioactivity from Spent Fuel per MW of Reactor Power

* 1955 Proceedings of Geneva Conference, Vol. 13, p. 106. (The Fig. 11-5 includes both betas and gammas.)

A person exposed to 600 r (roentgen) of radiation over his whole body for one hour is almost certain to die within two weeks.* This is called the "lethal dose."

Accordingly (from Eq. 11-4), workmen as far as 700 feet away from the *SAVANNAH's* **bare core** could be subjected to lethal radiation doses. At 400 feet they could get the same lethal dose in 10 minutes. At 100 feet, one minute's exposure would be equivalent to death. Remember, we are considering only a bare, unshielded, spent core.

We would never attempt refueling without adequate gamma shielding. The shielding would be divided into two categories, namely: that enclosing the spent core proper, and that arranged as portable shielding behind which workmen would operate. With portable shielding, we can take advantage of attenuation by distance ("d" in Eq. 11-4). Portable shielding could be handled by heavy-lift gear or could be design-mounted on fork-lift trucks, overhead cranes, etc. Also, there could be shielding bells—analogous to underwater diving bells (with workmen inside)—for emergencies or difficult spent core access problems. Shielding partitions (temporarily erected) would be used quite extensively. Indeed, a whole new field of shielding-for-refueling equipment awaits development for nuclear ships.

11-7 Importance of Aftercooling

The fission product residues contained in the spent fuel elements generate considerable internal heat. This is called "decay heat." This heat is generated by radioactive decay of nuclear particles (principally betas and gammas) as the fission residues settle down to a stable energy state. The heat is generated within the fuel elements, just the same as if fission were taking place, though to a much lesser degree. The decay heat gradually cools off, but this may take days, weeks—and months.

The amount of decay heat is approximated by

$$H_{decay} \approx 0.07\, P_o t^{-0.2} \qquad \text{[Eq. 11-5]}\dagger$$

where P_0 = operating power of the reactor in watts, and t = time after shutdown in seconds. In the case of the *SAVANNAH*, for example, a few seconds after shutdown the decay heat would amount to well over two MW. At the end of the first day, the decay heat would amount to about one MW. This is about 3.5 million Btu/hr.‡ One month later, the decay heat generation would approximate 350,000 Btu/hr—still an appreciable amount of heat. This slow fall-off in decay heat is typified in Fig. 11-6.** When using Fig. 11-6, recall that full power for the *SAVANNAH* is 70 MW and that its operating time is in excess of one year.

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* Ref: *Principles of Nuclear Engineering*, S. Glasstone, Van Nostrand, 1955, p. 555.

† Ref: "Delayed Energy Production," *Safety Aspects of Nuclear Reactors,* C. R. McCullough, Van Nostrand, 1957, pp. 145 ff.

‡ 1 MW = 3.413 million Btu/hr.

** Ref: Argonne National Laboratory Report, AECD-3454, February 25, 1952.

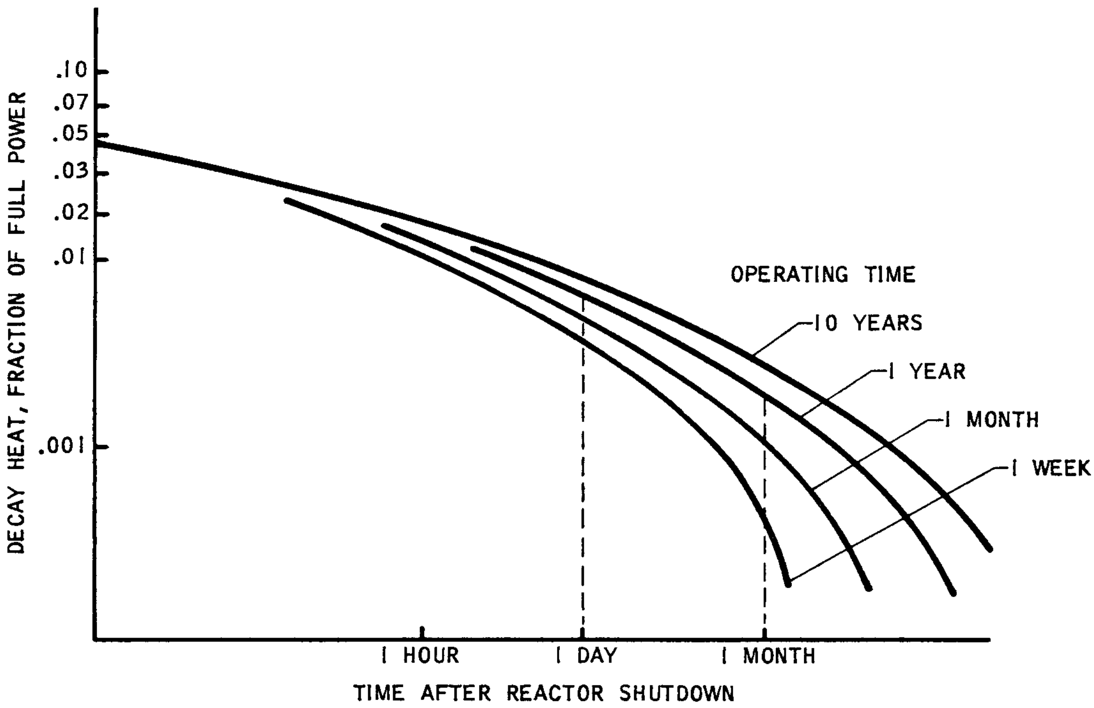

Fig. 11-6 Decay Heat from Spent Fuel Following Reactor Shutdown

Now, the importance of decay heat is this: if the heat is not removed continuously, the fuel elements will heat up . . . then melt down. This would release radioactive fission residues to the surroundings. In the shipboard refueling situation, these surroundings would be the reactor vessel, primary pumps and piping, primary shielding, ship's framing, bulkheads, and rigging. The gaseous fission residues would disperse upward; the particulates would disperse outward. The result would be a widespread area of radiocontamination.

To prevent the meltdown of fuel elements in a spent core, "aftercooling" is required. That is, means must be provided to continuously cool the core whenever the reactor is shut down. Usually, a separate, auxiliary, aftercooling system—independent of the main reactor cooling system—is provided. The aftercooling system has its own pump, piping, and heat dissipation arrangement. The system automatically starts up when the reactor shuts down. In addition, the aftercooling system is tied in to the reactor's emergency plant, in the event of ship collision, grounding, sinking, or other external casualty.

The aftercooling system must reliably function from the time of reactor shutdown until the fuel elements have been sufficiently cooled to make meltdown impossible. For refueling, the problem is to provide this aftercooling while the spent core is being removed from the reactor. This problem is met by the use of portable aftercooling facilities which travel with the spent fuel elements from the reactor vessel to semi-permanent dockside cooling equipment.

11-8 Organization for Defueling

Defueling is the process of getting inside a reactor vessel and removing the spent core fuel elements. Up to this point, we have merely said that we need access to the core in the most direct manner practicable. We have also pointed out that in gaining this access, we require portable shielding and portable cooling equipment. But this is not all. There is the matter of organizing personnel, providing them with the necessary protective clothing and tools, and myriads of other details before we commence defueling the core.

The preparation for defueling requires a lot of planning and organization. Defueling personnel must be shift-organized so that in the event of a mishap a new crew can substitute quickly so as to time-limit the radiation exposure of all. Monitoring personnel must be on hand with detection instruments, and the instruments must be in ample supply so that, in the event of instrument contamination from leaks and spills, replacements can be promptly made. Reactor dismantling equipment must be in good order with stand-by spares and emergency power, in the event of equipment contamination and utility failures. Spent fuel handling equipment must be rugged, fail-safe, and precision aligned so that once the defueling operation begins, it can be carried to completion in minimum time . . . with minimum risk to personnel.

Rather than attempting to describe defueling preparations in detail, a partial checklist of defueling functions and equipment is given in Table 11-4. Necessarily, these functions would be expanded considerably and

Table 11-4. Partial Checklist of Items for Nuclear Ship Defueling

Defueling Personnel	
· adequately trained	· specified assignments
· standbys available	· badges and dosimeters
· protective clothing	· changeroom procedures
· exposure history	· emergency procedures
Monitoring Personnel	
· monitoring plan	· control access areas
· instruments calibrated	· roped-off areas
· time limits posted	· waste disposal
· warning signs	· emergency procedures
Dismantling Equipment	
· remote disconnect tools	· lights and microphones
· scavenging equipment	· periscopes and mirrors
· drip pans and buckets	· top-plug storage
· portable shields	· control rod storage
· aftercooling facilities	· tongs and manipulators
Defueling Equipment	
· shielded defueling crane	· closed circuit TV
· defueling coffins	· underwater manipulators
· extraction tools	· emergency power
· underwater lights	· area monitors
Transfer and Cleanup	
· cooling pits	· absorbing paper
· transport facilities	· decontamination of tools
· danger signs	· reactor repairs
· cleanup equipment	· reloading approval

tailored to each particular nuclear ship and its particular reactor design. As the fleet of nuclear merchant ships grows and defueling experiences unfold, standardized procedures undoubtedly will evolve.

Because of the mandate for safety and the specialized personnel training required, defueling functions would rarely be performed by a ship's engineroom crew. The preparational planning—as well as the actual work of defueling—would be done by shoreside personnel. Even if shipboard personnel had the experience, one ship's reactor crew might not be enough. Generally, it requires from three to five times the number of workers and amount of equipment to perform a nuclear defueling operation as it does to perform a similar operation if no radiation were present.* The paragraphs which follow indicate some of the reasons why

11-9 Reactor Dismantling Procedures

To typify the procedural aspects in gaining access to the fuel elements in a spent core, let us consider the *SAVANNAH's* reactor. This reactor, we recall, is a pressure vessel designed for 2000 psi. It has 21 controls rods

* Ref: "Maintenance Work in the Field of Nuclear Energy," K. K. Campbell, 1953 Conference on Nuclear Engineering, University of California, Berkeley.

and drives, 32 fuel elements, three-pass coolant flow . . . and 48 five-inch studs closing the reactor's head. Let us assume that access through the ship's main deck, and through the containment shell hatch, has been made (as per Sec. 11-5). We are down to the control rod extensions and drives. Our problem, now, is to "dismantle" the reactor and go in and remove the spent fuel.

Assuming that the necessary personnel and equipment are available, the first procedure would be to have the dismantling personnel don two suits of overalls; then leggings, overshoes, full face masks, and two pairs of gloves. Personnel who are not going to take part in the operation must be cleared out. Radiation exposure time limits must be established, with prearranged (audible) timing signals for reliefs. A few dry runs (on deck) should be made to be sure that the dismantling personnel know their jobs, and that they have the right tools.

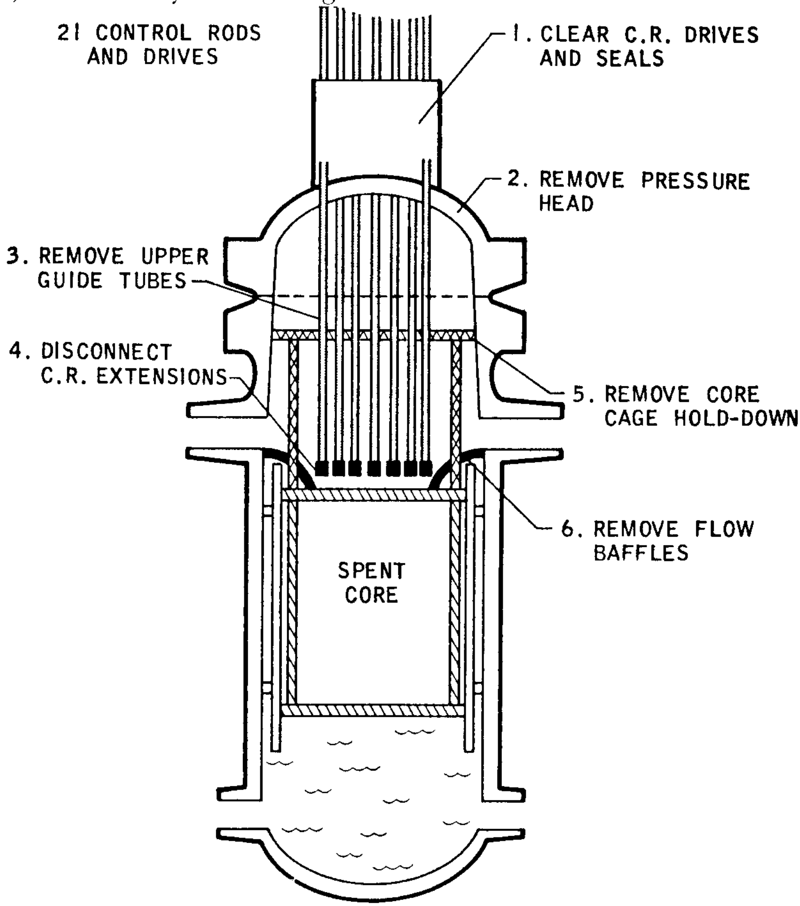

Fig. 11-7 Sequential Steps in Access to *Savannah's* Spent Core

Procedure two (assuming aftercooling in operation) would be to disconnect the control rods and their drive mechanisms (see Fig. 11-7). Clearing away the 21 drive mechanisms—with their power connections, seals, covers, scram trips, instrument wiring, etc.—is a significant chore in itself. This actuation equipment must be completely removed so that the rods are free inside their guide tubes, inside the reactor. Then, the control rod extensions and lead screws (external to the reactor) are disconnected. All of the disconnected mechanisms are radiation monitored, then set aside for repair or replacement.

Procedure three is to remove the six-inch-thick pressure head from the reactor vessel. This necessitates freeing up the 48 five-inch-diameter studs. The stored-up pressure stresses (2000 psi) in these studs would have to be relieved by electrical or pneumatic impact wrenches. These wrenches would be controlled and operated from behind portable shields by workers looking through periscopes, corner mirrors, and listening to speakers from microphones attached to the wrench heads. Locating and freeing bolt studs in this manner is no ordinary task, to say nothing of remote hooking-on to pressure head hoisting lugs when the studs are clear. Removing the pressure head exposes the control rod guide tubes, and leaves the spent core staring up through several feet of water with an eerie-blue radiation (Cerenkov) glow.*

At this point, procedure four, an extension sleeve is fitted to the opened flange of the reactor vessel. This "sleeve" is filled with water to serve as additional shielding and coolant for working above the spent core. To facilitate visual operations, all of the spent core water must be filtered and purified. Maximum clearness of the water is required (see Fig. 11-8).

Next, procedure five, underwater lights are lowered into position to focus on the core grid plates, on the fuel element locking assemblies, and on the control rod guide shafts. A closed circuit TV camera or other remote viewing equipment is rigged in place. An overhead crane—with the operator in a shielded cab, looking through shielding windows and at a TV screen—lowers remote manipulator tools and tongs into the core water.† The manipulators disconnect the control rod upper guide tubes, then the control rod extension shafts, leaving the poison portion of the control rods to safeguard the spent core. The control rod shafts are removed and stored in a special shielded container. The coolant flow top baffles and hold-down assembly are disconnected, removed, and also stored in a special shielded container. Other reactor internal fittings are removed to give direct access to each of the 32 fuel elements.

* When radiation traverses a transparent medium (e.g., water or air), it emits a "Cerenkov glow." This is a velocity effect from the radiation which is faster than the speed of light.

† Shielding windows are of lead-glass or zinc bromide solution; they have combined optical and gamma shielding properties. Manipulator tools are mechanical arms and grippers with all degrees of human motion; they are remotely operated.

11-10 Extraction of Fuel Elements

The extraction of spent fuel elements must be done carefully—purposely—with the skill, precision, and determination of a dental surgeon. For this reason, a specially designed extraction tool is used. Extraction (withdrawal) force is applied . . . gently at first, then the steady pull. The fuel elements are withdrawn *one at a time.*

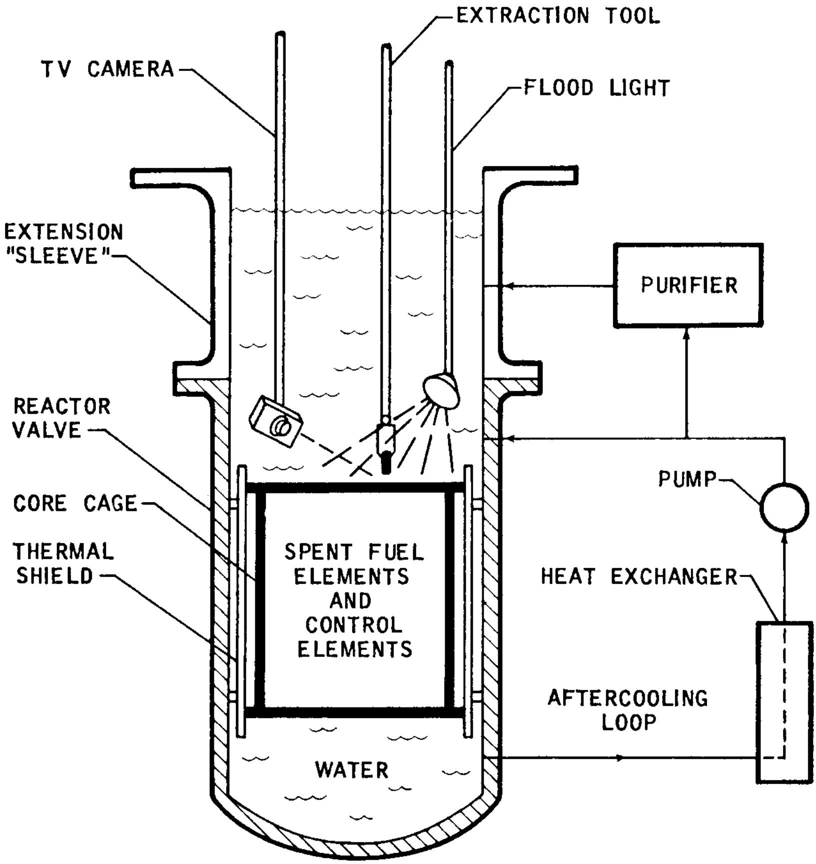

Fig. 11-8 Typical Arrangement for Extraction of Spent Fuel

Once the force of extraction starts, the direction of motion must be up. No sidewise motion; no twisting—just straight up. There is good reason for this "one-direction only." Some of the spent fuel elements may be warped or slightly damaged; some may have small leaks; the cladding walls may be corroded thin. They could be easily punctured by careless handling, with the result that fission product gases and particulates could readily escape. Hence, we must withdraw with precision.

Generally, some form of electro-hydraulic extraction rig is used. The extraction tool is on an extendable shaft which reaches (with three degrees of freedom) into the reactor. An electronic centering device positions the tool head with respect to the grid structure. Then the tool head is positioned over a designated fuel element by means of azimuth and extension drives, commanded by a synchro intelligence system.* Exact and positive

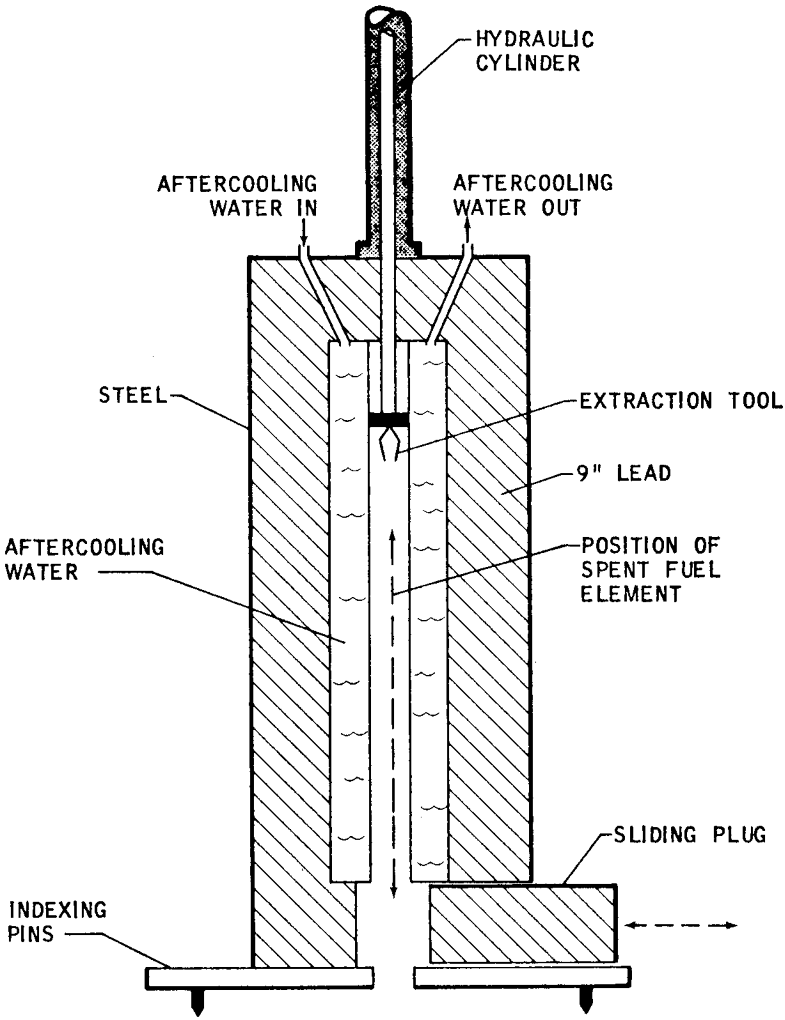

Fig. 11-9 Schematic Arrangement of Defueling Coffin

* Ref: "Reactor Refueling," pamphlet by United Shoe Machinery Corp., Atomic Power Dept., Beverly, Mass.

latching on to a fuel element is accomplished by lowering the tool head into the mating fuel element coupling, at which time the tool is rotated and locked to the fuel element. Simultaneously, this unlocks the fuel element from the core grid structure. A load sensing device, which also determines the direction and magnitude of the load, permits final adjustments before actual withdrawal begins.

Each of the fuel elements is withdrawn into a lead-lined steel handling "coffin." This coffin is indexed over the opened reactor on top of the extension sleeve. The coffin is fitted with a sliding lead bottom plug and an aftercooling system of its own. Often, the coffin, extraction tool, and aftercooling apparatus form an integral piece of equipment (see Fig. 11-9). One, or more than one, fuel element may be housed in the coffin, depending on its particular design. When the fuel elements are inside the coffin, the lead bottom plug closes to provide total shielding.

The coffin, with its load of spent fuel elements, is transferred from the reactor vessel to special facilities at dockside. In this process, also, precision movements are required. The overhead crane which transfers the coffin to dockside must lift vertically only, until the coffin is free and clear. Then it may be moved horizontally and laterally . . . with great care. The coffin, it should be pointed out, weighs on the order of 25 tons. We can't afford to bang this weight—and this hazard—around.

The fuel elements are extracted, a coffin-load at a time, until all have been removed. Then the control elements, which are still in the core, are removed similarly. All defueling procedures are necessarily slow. There is always the danger of a fuel element breaking or sticking either in the core, in the extraction tool, or in the coffin. Consequently, precision and patience are the keynotes to defueling.

When all fuel elements and control elements are removed, the core cage basket, coolant flow baffles, thermal shields, and other reactor internal fittings are visually inspected. This is usually done by means of a closed circuit TV (under water), using floodlights, manipulators, and microphones. Damaged and deteriorated reactor parts are removed and replaced.

11-11 Transfer to Reprocess Plants

At dockside, the fuel elements are unloaded from the handling coffins and reloaded into transfer casks. These transfer casks are larger than the defueling coffins, less complicated, and less precisely designed. They are generally of steel and concrete construction with appropriate brackets and mountings for securing the fuel elements in the upright position. These casks are flooded with water which is circulated through an external cooling source. The size of these transfer casks can be made to accommodate a single bank of fuel elements . . . or an entire reactor core. Design care must be exercised, however, not to permit the storage of spent fuel elements in those arrangements which approach criticality nuclear proportions. Otherwise, a live reactor would be on one's hands instead of a safely arranged stacking of spent fuel elements.

The transfer casks may be mounted on railroad cars or on barges at the nuclear ship's side. These transport facilities may be routed to a remote off-site location to await further decay-cooling of the spent fuel elements. Then follows the long trek to the reprocess plants inland via railroad car.

The trek to reprocess plants is a major undertaking in itself. Remember, we are dealing with a heavy transfer package—on the order of 50 to 100 tons—and one that is potentially hazardous. The familiar "Do Not Hump" signs on railroad cars now take on a new significance. The spent fuel elements are in the same fragile condition as they were when they came out of the reactor. A wreck or careless handling of railroad cars could open up hairline cracks in the fuel element walls, thus releasing radioactive fission residues.

This possibility means that radiation monitoring equipment and personnel must accompany the fuel element transfer to the reprocess plants. These personnel must be alert to detect, report, and remedy any radiation leakage. Also, an armed guard should accompany the operation, in the event of a railroad accident. The role of the guard would be to keep inexperienced workers and curious people away.

At the present time, there exists only one nuclear ship spent fuel reprocess facility. This is the Navy's "Expended Core Facility" at the National Reactor Testing Station, Idaho Falls, Idaho.* This is the facility to which the first 62,000-mile spent core from the *NAUTILUS* was shipped.† One of the principal functions of this facility is to cut open the spent fuel elements and examine them with the purpose in mind of finding better ways to advance the technology of nuclear ship fuels. Subsequently, the spent fuel is sent to nearby process plants for reclaiming the unspent fissionable portions.

11-12 Reloading New Fuel

Prior to reloading new fuel into a ship's reactor, considerable decontamination of equipment and area cleanup are required. This is because the defueling operation unavoidably contaminates that equipment used in contact with the spent fuel elements and with the reactor vessel. The "contamination" is in the form of radioactive rust and radioactive water droplets which can be spread around with amazing ease. These radiocontaminants are not a lethal hazard, yet they do necessitate extensive radiation monitoring precautions. As a result, practically all of the dismantling and defueling equipment must be decontaminated before it can be used again. The same is true of the defueling personnel's clothing. They must take off their defueling clothing and put on clean clothing before starting the reloading operation.

* Ref: "Thumbnail Sketch—National Reactor Testing Station," Idaho Falls AEC Office, p. 9.

† Ref: "Radiation Safety and Major Activities in the Atomic Energy Program," July-December, 1956, USAEC, pp. xiv and 60.

The new fuel elements may be one of two types. They may contain all-clean (brand new) fuel material, or they may consist of reprocessed fuel material. Both types have equally good power generation capabilities. The difference is that the all-clean fuel elements could actually be handled by hand without shielding, coffins, or remote devices. The reprocessed fuel elements contain some—not much—fission product residue from the predecessor spent fuel. Thus, some shielding and handling precautions would be required. With either type of new fuel, however, the reloading operation is considerably less hazardous than the unloading, though the time consumed may be nearly as great.

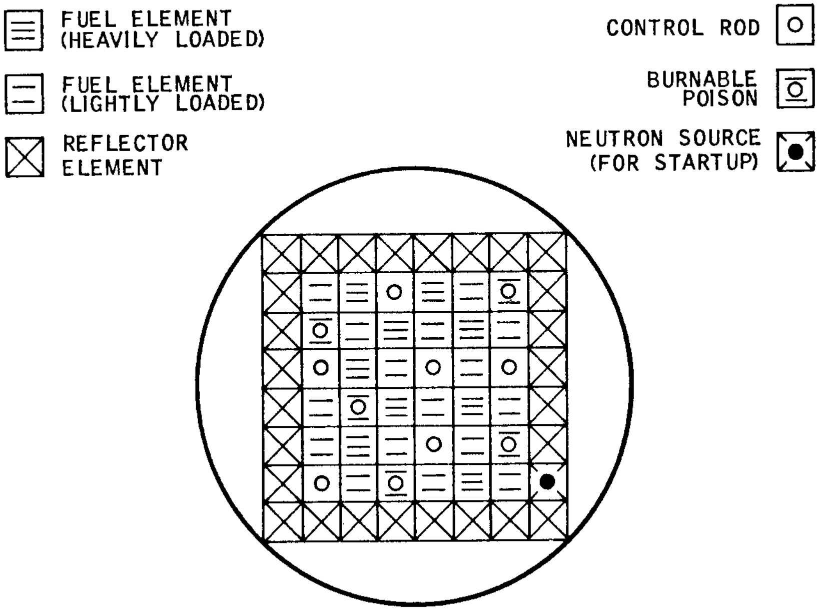

Fig. 11-10 Typical Core Plan for Nuclear Reactor Fueling

Generally speaking, all fuel elements for a given reactor are the same size and shape, and therefore look the same physically. But their nuclear properties can be vastly different. In order to achieve as nearly uniform power generation in the reactor as possible (this increases total power, reduces thermal stress, minimizes hot spots, etc.), the fissionable fuel nuclei are dispersed in varying amounts. The fissile material in the center fuel elements of the reactor, for example, is "thinned out" so that the peak neutron and thermal fluxes do not burn up this section of fuel elements before all others. In other fuel elements, such as those towards the outer regions of the core, the fissile content is increased. Some of the fuel elements may contain burnable poison in their cladding material, and there may even be some "dummy" fuel elements . . . for spacing reasons.

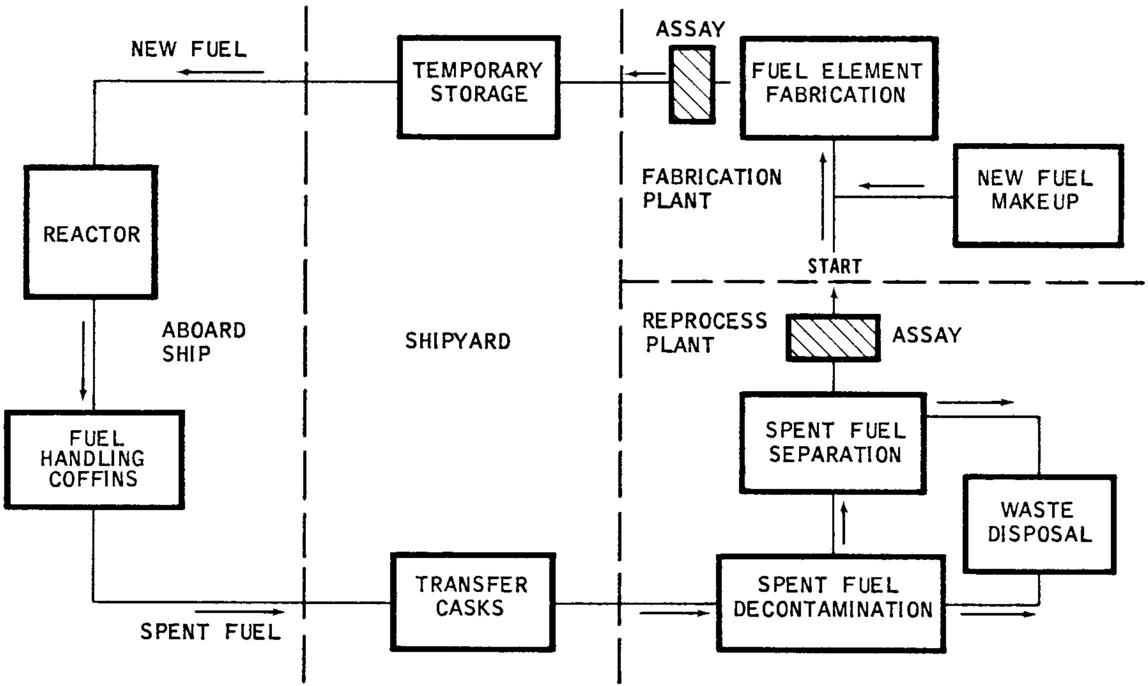

Fig. 11-11 Generalized Flow Diagram of Nuclear Ship Fueling Cycle

Also, there are the control elements, neutron reflector elements and, lastly, the neutron source which must be installed (recall Sec. 1-9). Consequently, the loading of a reactor core must be a planned undertaking.

For guidance in loading new fuel—and for defueling also—a "core plan" is used. This is simply a top plan of the core grid structure, which designates the specific location of each fuel element and each control element. Such a typical plan is shown in Fig. 11-10. The core plan is specified by reactor physicists who have calculated the desired power profile and the fissile fuel content throughout all regions of the core. Failure to conform to the core plan when loading the fuel elements would jeopardize reactor performance.

11-13 Accountability for the Fuel

To close the circle and summarize the cycle of nuclear ship refueling, Fig. 11-11 is presented. The flow scheme is highly generalized, of course, but it illustrates the major functions involved. Of particular note in Fig. 11-11 are the two blocks labeled "Assay."

As part of the final inspection of newly fabricated fuel elements, an accurate assay of the fissionable and fertile fuel content is made. Then, at the other end of the cycle, that is, when the spent fuel is "cleaned up," the fuel content is again assayed. The difference between the new and the spent fuel is the *fuel consumed.* This is what the nuclear ship operator pays for, i.e., the fuel burned plus the fuel loss during reprocessing.

The fuel assaying or accountability is a Government supervised function inasmuch as the Government is the sole owner of the fuel.

Exclusive ownership of all nuclear fuel (fissile and fertile), regardless of how produced, has been dedicated to the Government by the Atomic Energy Act of 1954.* With this sole ownership, however, provision has been made for leasing the fuel to reactor operators and for the establishment of lease-charges compatible with private economic incentives.

The cost aspects of nuclear fuels encompass the following categories of lease-charges:

(1) Fuel element fabrication
(2) Initial fuel inventory
(3) Total fuel burnup
(4) Spent fuel reprocessing

The first and second charges are capital cost items; the third and fourth charges are operating costs. To minimize the total effect of these Government charges, it is incumbent upon the reactor designer to seek long fuel element life . . . and the attainment of high heat transfer efficiency.

* Section 52 of the Act says, "All rights, title and interest in or to any special nuclear material within or under the jurisdiction of the United States, now or hereafter produced, shall be the property of the United States and shall be administered by the (Atomic Energy) Commission." The Commission, however, is authorized " . . . to issue licenses . . . to make available for the period of the license, and to distribute special nuclear material within the United States to qualified applicants. . . . The Commission may make a reasonable charge . . . (based upon) (1) the extent to which the use will advance . . . the development of peaceful uses of atomic energy; and (2) the energy value . . . (used)."

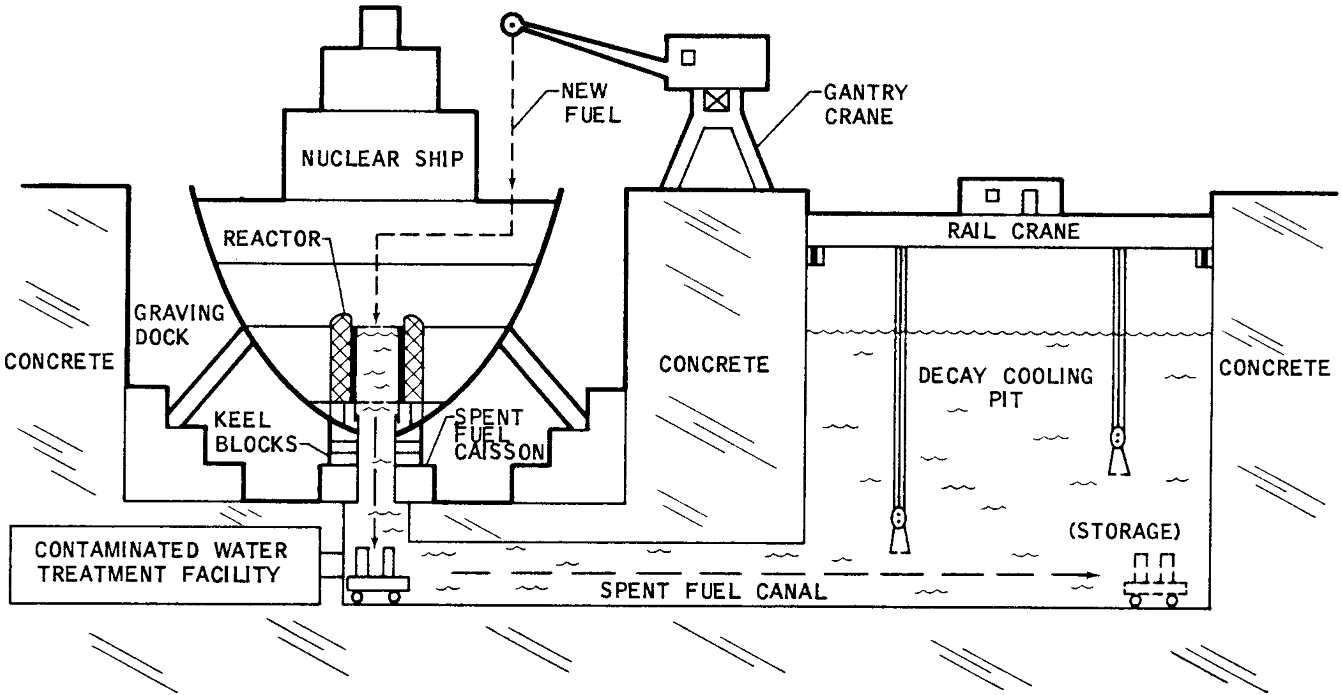

Fig. 11-12 Possible Future Refueling Depot: Bottom Defueling

As an incentive toward attaining higher fuel element efficiency, the actual design and fabrication of fuel elements are undertaken by private commercial enterprises. These organizations obtain the fuel (i.e., the initial inventory) directly from Government sources. Thus, the nuclear ship reactor designer need only specify the type of fuel elements that he wants, and the fuel fabricator does the rest. For the spent fuel reprocessing, however, the reprocess plants are Government owned . . . though privately operated. The tremendous amount of equipment, real estate, and public hazard involved are beyond the financial risk capabilities of private organizations at the present time.

Because of its cost and energy value, spent nuclear fuel (i.e., the U-235 U-238 mixture) is used over and over again. After each reprocessing, it is re-enriched with new U-235 content. By re-enrichment, reprocessed fuel can always be restored to its original heating value.

11-14 Special Refueling Depots

At the present time, the special procedures for nuclear ship refueling are not of great concern. For the next few years, only a few nuclear merchant ships will be involved. The emphasis will be on developing nuclear propulsion technology, with refueling considerations as secondary matters. Any refueling to be done would be taken care of in regular shipyards . . . with due precautions as previously described.

With a well-trained refueling crew and a well-equipped shipyard organization, the complete refueling job could be done (perhaps) in a week's time. Such refueling would be on a single-ship basis. On a fleet basis, we wonder if the refueling couldn't be speeded up, and cost reduced . . . without sacrifice in safety. Yes, there are ways. But further technical evolutions are required.

We typified nuclear ship refueling (Sec. 11-9) by the *SAVANNAH*, which necessitates defueling from the reactor top. This, as we have seen, indeed is a satisfactory and safe method for defueling. An even safer way—and much less time consuming—is the method of **bottom defueling.** In other words, the spent fuel elements are pushed out through the bottom of the reactor via a water chute, where they drop into a water canal. This practice is used successfully at the Materials Testing Reactor, Idaho Falls.* Possibly, this method could be adapted to shipboard reactors. If so, the defueling procedure might go something like the following.

The nuclear ship would moor in a graving dock, and the water would be pumped out, in normal drydocking procedures. Adequately below the dock, there would be a spent-fuel transfer canal (see Fig. 11-12). From this canal, an hydraulically operated caisson (with appropriate water locks and guide surfaces to keep the fuel elements upright) would rise up through the graving dock floor. Simultaneously, an hydraulically operated

* Ref: "Remote Handling—Reactor Refueling Systems," Goertz and Bevilacqua, *The Reactor Handbook*, Vol. 2, USAEC-3646, pp. 855-859.

defueling port in the ship's bottom would open up. The graving dock caisson would then attach to a defueling adaptor permanently designed as part of the mounting structure of the reactor shell. Then the bottom of the reactor shell would open up, making a complete U-tube water head between the water level in the reactor and that in cooling pits alongside of the graving dock (see Fig. 11-12 again). It would then be a matter of remotely unlocking the spent fuel elements (by integral mechanisms in the reactor shell design) and letting them sink slowly to a conveyance on the canal floor. From here, they would be transferred under water to designated cooling storage spaces where they would remain until all chance of meltdown was gone.

Concurrent with the defueling operation above, regular ship's bottom cleaning and painting, overhaul of fittings and discharges, and tail shaft and propeller inspections could be carried on. Concurrently, also, new fuel elements could be reloaded through the reactor's top. Thus, the complete cycle of nuclear refueling—including normal drydocking work—could be performed in a day or two at most.

There is future possibility that such a refueling depot as just described could come into being. Because of the capital cost involved and the necessity for national security, it conceivably would be Government owned and, most likely, Navy operated. Possibly, one such depot would be centrally located on both the East and the West Coasts of continental U.S. It would seem that for reasons of mutual technical interest, sharing of costs, and nuclear safety, each refueling depot would serve both Navy and merchant nuclear ships.

SUMMARY

We would like to predict, with certainty, how long we could operate a merchant ship with a given batch of nuclear fuel. Unfortunately, we cannot yet do this. We know that sooner or later the fission process becomes self-poisoned . . . and dies down. But we cannot accurately pinpoint when this will occur.

Calculational assumptions, nuclear discrepancies, and operational uncertainties lead us to conservatisms in fuel-life expectancy. For example, the calculated lifetime of the *SAVANNAH* reactor varies from 800 to 1300 full power operating days. To play it safe, we say that the reactor will operate somewhere between 600 and 1200 days before refueling. This is the best we can do until we accumulate actual operating experience with nuclear merchant ships to prove or disprove the technicalities involved.

At the end of the *SAVANNAH's* useful core life, she will have been exposed to about 7360 MWD/T fuel burnup. This is less than 1% consumption of the total fuel. By total fuel, we mean the U-235 fissionable content plus the U-238 fertile content. This fertile fuel is helpful in that it is the seeding ground for new fissionable isotopes: Pu-239 and Pu-241. To avoid confusing which fissile isotope is consumed, we define "burnup" as the atom fraction of total fuel converted to fission product residues.

Fission residues accumulate for every fuel atom fissioned. They are dangerously radioactive. In the *SAVANNAH* reactor, for example, the sum total hazard of these radioactive residues—from a bare spent core—could kill a man at a distance of 100 feet . . . in one minute! Fortunately, we are able to protect refueling personnel against these radiations, and refueling can be performed without danger to personnel.

In preparation for defueling the spent core, the ship must be a stable platform from which to work, and there must be an unobstructed route directly to and from the reactor core. These conditions are necessary because of the high dollar value of the unburned fuel, and the high radiation hazard involved. Consequently, we must not damage the fuel elements when removing them from the spent core. As a further precaution in this regard, we must "aftercool" the shut-down core to avoid radioactive decay heat melting down the fuel elements. We must especially train the defueling personnel and provide them with protective clothing, radiation-warning instrumentation, and special remote-handling tools, including viewing and listening devices. Although we cannot yet prescribe standard refueling procedures, we can typify them by considering the *SAVANNAH* as an example.

It is mandatory that extraction of the fuel elements—one at a time—be undertaken with purpose and precision. Reasons: some of the fuel elements may be warped or damaged; some may have small leaks; some may have cladding walls corroded thin. They could be easily punctured by careless handling. So precision extraction tools must be used.

The spent fuel elements are withdrawn into a special lead-lined steel handling "coffin," with a separate aftercooling system of its own. Then the fuel elements are transferred, coffin-load at a time, to large concrete transfer casks on railroad flat cars or barges, at the ship's side. After proper arrangement and securing of the fuel elements to avoid nuclear criticality conditions, the spent core is sent to reprocess plants for reclaiming the unspent fuel.

Following routine cleanup of the defueled reactor, new fuel elements are loaded back in. The difference between the new fuel and the reprocessed spent fuel is the actual "fuel consumed." This is what the shipowner pays for . . . plus all of the associated handling and reprocess charges. The spent fuel is used over and over again by re-enriching it to its original heating value.