CHAPTER 1

Similarities and Differences

The *NAUTILUS* will go down in history as the first naval nuclear ship; the *SAVANNAH* as the first merchant nuclear ship. The tendency with such "firsts" is to herald them as the forerunners of a great era which will overcome the handicaps of the past and which will advance mankind another notch in his technological development. To a directional extent this is true. But we should be careful to note that any "first" is only a point on the long curve of a new technology and, accordingly, we should restrain against visionary extrapolation of this point to a millennium—until other data points are presented. In a practical situation we need to examine the features of the new technology and compare them with the old. Doing so, we find numerous similarities—and differences, too—which provide us with a common ground for projecting into the technical advances ahead.

1-1 Combustion and Fission

For ship propulsion, the primary useful product of fuel oil and nuclear fuel is heat. This heat is obtained from fuel oil by combustion; from nuclear fuel by fission.

In its simplest fundamental form, combustion is a chemical reaction between the carbon in fuel oil with the oxygen in air. This reaction involves molecules of matter and is symbolized by

$$\mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2} + \text{heat}$$

In the combustion reaction, oxygen is the triggering mechanism without which there would be no heat. But once a molecule of oxygen reacts with a molecule of carbon, no new molecules of oxygen are formed. Consequently, to keep the combustion process going, we have to supply oxygen (air) continuously.

With fission, we have a different situation. Here, a nuclear particle—the neutron—plays a somewhat comparable role to oxygen. The neutron (n) combines momentarily with an atom of the nuclear fuel, uranium (U), then the fuel atom splits apart . . . or fissions. When this happens, two fission fragments (FF) appear, plus two-to-three new neutrons, plus heat. In symbolic form, the basic nuclear fuel reaction is

$$\mathrm{U} + \mathrm{n} \rightarrow 2\mathrm{FF} + 2.5\mathrm{n} + \text{heat}$$

Note that in addition to heat, which we want, new neutrons are produced. These new neutrons are available for fissioning other fuel atoms. Thus, once a nuclear reaction is started, it can continue on its own. No additional neutrons need be supplied.

Going back to combustion again, the fuel is not all pure carbon. The oil contains also hydrogen, sulphur, and traces of nitrogen and oxygen. Though the carbon content varies for different fuel oils, the average content is pretty close to 86%. This is such a high natural enrichment in carbon that nothing is done to improve it. Except where incomplete combustion occurs, all of the carbon participates in the chemical reaction.

With nuclear fuels, only certain atoms—called fissionable atoms—engage in the nuclear reaction. Natural nuclear fuel (uranium), as it comes out of the mines, contains only 0.72% (i.e., less than 1%) fissionable atoms. The remaining atoms (99.28%) generally are non-fissionable. This is to say that *natural uranium contains two types of atoms:* one, U-235, which is fissionable, and the other, U-238, which is not. Chemically and physically, these atoms appear to be the same, but only U-235 will "burn." Consequently, to improve the burnable content of natural uranium, it is necessary to enrich it. A 5% enrichment, for example, means that 5% of the fuel atoms are fissionable U-235's.

Enrichment increases the cost of nuclear fuel over that of natural uranium. But as we shall see later, enriched fuels are necessary to assure us the neutrons we need to keep the nuclear reaction going.

1-2 The Non-Useful Products

In addition to useful heat, both combustion and fission produce non-useful products. Fuel oil, as we have seen, contains hydrogen and sulphur; and air, we know, contains nitrogen. Except for the hydrogen, these constituents do not contribute to the useful production of heat. They ride along parasitically. They combine among themselves and appear in the products of combustion as heat absorbers which reduce the amount of heat available for the production of steam.

In the case of fission, the fission fragments—and their residues—are neutron absorbers. Each fragment produced by fission is an entirely new species of matter created by the violent rearrangement of nuclear particles in the splitting-up of the fuel atom. Due to the random nuclear disorientations, some fission products want additional neutrons to stabilize themselves; others give up neutrons. Some (notably xenon and samarium) are so highly neutron absorbing that they are called "poisons." In the composite, the fission products absorb more neutrons than they give off. This robs the nuclear cycle of needed neutrons to keep the reaction going. This is one way in which the products of fission are non-useful.

A second and more contrasting non-useful product of fission is the nuclear radiation involved. The neutrons themselves are one form of radiation. Two other forms of radiation are betas and gammas. All three forms of radiation originate in two time-scales: one, at the instant of fission (this is called "prompt" radiation); and two, during the decay of the fission fragments (this is called "decay" radiation). In both cases, the neutrons and gammas are capable of penetrating the fuel container to do biological harm to humans, and do damage to sensitive instruments nearby. Thus, we have a by-product liability (radioactivity) on our hands rather than something useful.

In the case of fuel oil, it is quite safe to release all of the products of combustion directly up the ship's stack. Except for the occasional nuisance of soot scattered about on deck and rigging, there is no significant biological harm in doing so. We can't do this with the residue products of fission. They are too highly radioactive. As a result, we have to "contain" them and hold them for release until a more propitious time.

To summarize the comparison between fuel oil and nuclear fuel, so far, Table 1-1 is presented. From here on, the differences between the two fuels begin to widen.

Table 1-1. Functional Comparison of Fuel Oil and Nuclear Fuel

Fuel	Reactant	Useful Product	Non-Useful Products	Waste Release
Oil	Oxygen	Heat	Parasitic Gases	Up Stack
Uranium	Neutron	Heat Neutrons	Neutron Absorbers Nuclear Radiation	Contained

1-3 The Energy of Fission

An even greater contrast between combustion and fission than the nuclear radiation hazard is the comparative heat energy produced. One pound of fuel oil burned will produce, on the average, about 18,500 Btu of heat (1.85×10^4 Btu). One pound of nuclear fuel fissioned will produce about 3.52×10^{10} Btu—**two million times that of fuel oil!** This is why we accept responsibility for the nuclear radiation and try to use nuclear fuel on shipboard.

To see how this enormous heat equivalence comes about, let us take a typical fission event:

$$\begin{array}{lccccc} & \mathrm{U}^{235} + \mathrm{n} = & \mathrm{Ba}^{144} & + & \mathrm{Kr}^{89} & + 3\mathrm{n} + \text{energy} \\ & & \downarrow & & \downarrow & \\ \text{Radioactive Decay} & & \mathrm{Nd}^{144} & & \mathrm{Y}^{89} & \end{array} \qquad \text{[Eq. 1-1]}$$

where Ba and Kr are fission fragments barium and krypton, and Nd and Y are decay residues neodymium and yttrium. The superscripts are the number of nuclear particles (neutrons plus protons) in each atom of the fuel and its fission fragments.* Note that the whole number of particles on the left side of Equation 1-1 ($235 + 1$) balances the number on the right side ($144 + 89 + 3$). But because the particles have been rearranged and interchanged, a slight loss of the original mass of uranium takes place.

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* There are about 80 possible types of fission fragments ranging in mass number from 72 to 160.

Working to the fifth decimal place, we set up an atomic mass balance between the left- and right-hand sides of the equation as follows:

Left Side	*Right Side*	*Mass Disappearance*
	$Nd^{144} = 144.9506$	
$U^{235} = 235.12037$	$Y^{89} = 88.93712$	
$n = 1.00898$	$3n = 3.02694$	
236.12935	235.91466	0.21469

From the tabulation above, we note a mass disappearance on the left side to the extent of 0.21469 atomic mass units. The fractional disappearance of U-235, therefore, is 0.21469/235.12037 grams. This is called the change in mass or "delta-m" (Δ m). Now, by Einstein's mass-energy relationship ($\Delta E = \Delta mc^2$),* the energy equivalence of the mass disappearance is

$$\begin{aligned}\Delta E &= \frac{0.21469}{235.120} \times (2.998 \times 10^{10})^2 \\ &= 8.20 \times 10^{17} \text{ erg/gm} \\ &= 3.52 \times 10^{10} \text{ Btu/lb.}^{\dagger}\end{aligned}$$

To put this energy of fission in terms that are more meaningful for shipboard, we can say that **one pound of nuclear fuel** is approximately equivalent to **1000 tons of fuel oil.** And one pound is slightly larger than one cubic inch!

1-4 Heat from a Metal

It is one thing to compute the theoretical heat equivalence of a pound of nuclear fuel; it is a more practical endeavor to extract this heat in usable form. Of significance is the realization that we are trying to get heat out of a metal. This metal—uranium—is a dense material, half again as heavy as an equal volume of lead. Indeed, when exposed to air, it looks very much like lead, though when freshly cast it is lustrous and white. When finely powdered it ignites spontaneously, but this has nothing to do with its use as a nuclear fuel.

If we were to take one pound of this metal, or several hundred pounds, we would find that we just can't shovel it into a furnace like coal, or melt it and pipe it in like oil, and expect it to generate heat. In the first place, there is a certain minimum amount or critical mass that is required. Determining this amount involves detailed mathematical procedures. Secondly, once we have a critical mass, one atom of fuel in excess of this amount could mean runaway fission. This, of course, demands some means of nuclear control. And, thirdly, even with the proper control, how are we going to get the heat out of the metal?

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* ΔE = energy change (ergs); Δm = change in mass (grams); c = velocity of light (2.998×10^{10} cm/sec).

† 1 erg = 9.48×10^{-11} Btu; 1 pound = 453.6 gm.

Remember, we are dealing with atoms of fuel . . . not lumps of it. Atoms are submicroscopic matter, possibly spherical, with a diameter on the order of 4×10^{-9} (0.000000004) inches. As each atom is fissioned, two fragments fly off randomly in opposite directions. These fragments are stopped by the adjacent fuel material. In this stopping process, the fragments generate friction heat. This is the heat we want. But associated with this heat is the intense radioactivity of the fragments.

To extract the useful heat, while at the same time confining each radioactive fragment, we have to use a container shell which is a good heat conductor. This container shell, in turn, passes the heat to another material, a working fluid (called "coolant"), which transports the heat outside of the fuel region. Ideally, we would surround each atom of fuel with its own heat conduction shell . . . but this is impractical.

The heat extraction problem is partly met by "slicing" the fuel metal into thin plates or into small pellets. These plates and pellets are then jacketed with such metals as aluminum, zirconium, stainless steel, or other metals with the desired heat conductive, nuclear, and structural properties. The jacketed fuel usually takes the form of fuel *plates* or fuel *rods*. A number of fuel plates (or rods) are bundled into a "fuel element." As typical examples, the *NAUTILUS* originally used plate-type fuel elements; the *SAVANNAH*, rod type elements (see Fig. 1-1).

Each fuel element houses an accurately predetermined number of fissionable atoms. The greater the surface area of the fuel elements in which the fissionable atoms are contained, the greater the heat extraction efficiency. This means, usually, an increasing number of fuel elements which are thinner and thinner. The result is fabrication complexity and the increasing possibility of fuel element rupture.

1-5 Integrity of Fuel Elements

With more than one fissionable atom in a fuel element, after any period of time some will have been fissioned and some not. Of those which have fissioned, the decay residues are highly radioactive (recall Sec. 1-2). As fissioning continues, these residues accumulate within the fuel elements. Hence, the fuel elements are *always burdened* with a radiation hazard which increases with fuel burning time. Consequently, we cannot afford to risk rupturing fuel elements and thereby releasing dangerous residues.

What could cause the fuel elements to rupture? There are many possibilities. For one, since the fuel is a metal, it will behave like other metals: it will corrode. Any corrosion of the fuel metal could induce corrosion of its jacket material and this could ultimately result in fuel element leaks. Furthermore, about 20% of the fission residues are gases. As the pressure of these gases builds up, the fuel elements could rupture at any point. The effects of both corrosion and gases are hastened if there are any imperfections in the fuel jacket and its sealing joints.

After a while, the fuel elements may twist and bow a bit due to various thermal stresses in the fuel and coolant regions. For example, thermal "spikes" may be set up by fission events too close to the jacket material. Different fissioning rates in different fuel elements may cause some to heat up more than others. The consequent temperature distortions could warp some of the elements, thus narrowing the passages to the flow of coolant. This could starve certain fuel elements and thereby promote jacket burnout. The same effect could take place if there developed constrictions to the coolant flow, upstream or downstream of the fuel elements.

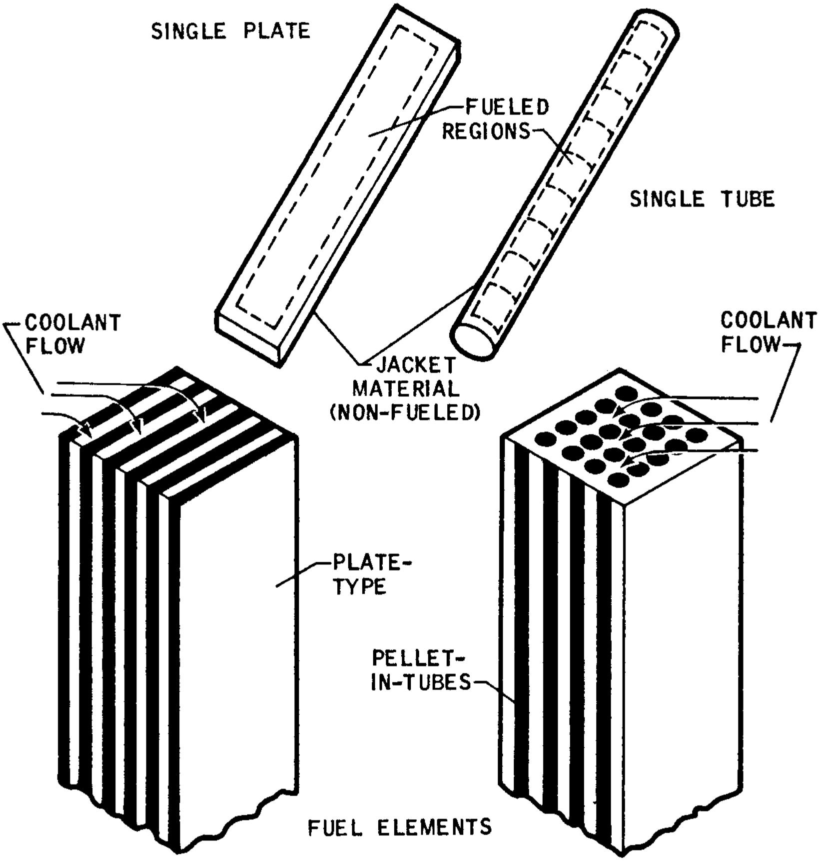

Fig. 1-1 Basic Scheme of Nuclear Fuel Elements

Or, the fuel element jacket material may experience fatigue due to vibration and tensor and flexure stresses in a ship's environment at sea. Shock due to ship collision and groundings conceivably could open up weak areas in the jacket material. These and other adverse possibilities place a great premium on the leak-tight integrity of nuclear ship fuel elements.

1-6 Reactors versus Boilers

The fuel elements must be arranged with minute care (there may be as many as 1000 fuel elements) into a geometric array that best maximizes the capture of neutrons by the fuel atoms. This geometric array is called the "core" of a nuclear reactor and is functionally analogous to the furnace of an oil-fired marine boiler. There are other analogies between boilers and reactors which may further the understanding of the latter (see Fig. 1-2).

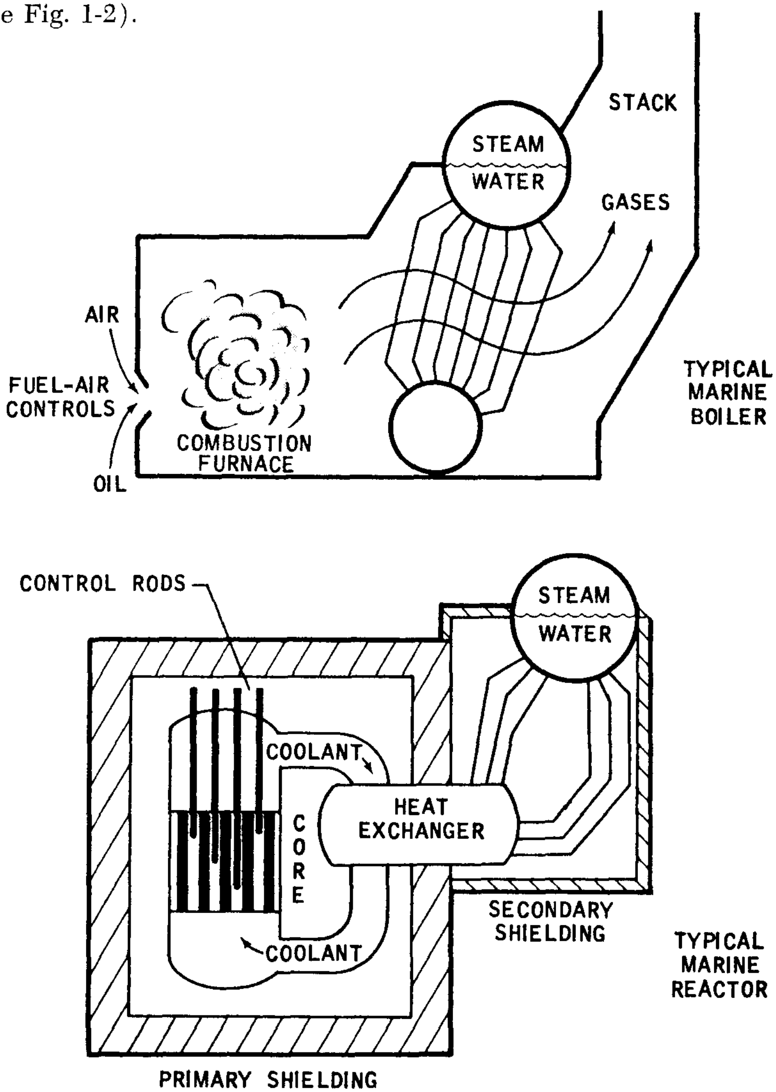

Fig. 1-2 Schematic Comparison Between Marine Boilers and Reactors

In boilers, the rate of combustion is controlled by the pressure and atomization of the fuel oil (i.e., by fuel oil pumps and burner nozzle tips) and by the pressure and flow of air (i.e., by blowers and furnace registers). Reactors have none of these control features. Instead, mechanical "control rods" are used. These rods move in and out of the reactor core to control the fission multiplication therein. The rods are constructed of a neutron absorbing material (e.g., boron, cadmium, hafnium) which sops up neutrons at strategic locations throughout the core. In this manner, the desired neutron balance is maintained.

In the case of boilers again, fuel oil is stored throughout the ship in various tanks (i.e., double-bottom tanks, deep tanks, transfer tanks, settling tanks). This widespread location of the liquid fuel helps to utilize otherwise non-useful irregular spaces of a ship's hull. Furthermore, the distribution of fuel weight helps to trim and stabilize a ship during heavy weather and light cargo voyages at sea. None of these by-product advantages accrues with reactors. All of the nuclear fuel must be built into the reactor core at one time.

A boiler has only one working medium—water—which is converted directly to steam by the hot combustion gases (see Fig. 1-2 again). On the other hand, a reactor has two working (coolant) mediums: a primary and a secondary. The primary coolant is the heat transmission agent. This may be water, an organic liquid, a liquid metal, or a gas. The secondary coolant is water. The two coolants are thermodynamically coupled by means of a heat exchanger which transfers the heat from the primary to the secondary . . . to subsequently produce steam. Each coolant, therefore, comprises a separate continuous loop.

The primary coolant, it should be noted, passes directly adjacent to the fuel elements in the reactor core. Any seepage of radioactive residues from the fuel elements will be picked up by this coolant stream. Unavoidably, also, some of the neutrons scurrying about in the core will interact with the coolant atoms and thereby induce what is called "secondary radioactivity." By maintaining a separate closed-cycle primary loop, the possibility of any radiocontamination getting out of the core is remote.

The nuclear radiation shielding around a ship reactor has no counterpart in a marine boiler. Oh, in a sense, perhaps, boiler insulation (top and sides) may be regarded as a thermal shield not only for the purpose of retaining heat within the boiler, but for protecting operating personnel against radiant temperatures. In contrast, the purpose of reactor shielding is to protect personnel and materials against nuclear radiations rather than against any temperature consequences. This nuclear shielding, however, is divided into two parts. One part is inside the reactor and is called "thermal shielding" . . . to protect the reactor structure against gamma radiations. The major part of the shielding is outside of the reactor and is called "biological shielding" . . . to protect people against neutrons and gammas.

In both types of nuclear shielding, a point to note is that when nuclear radiation is stopped, friction heat is generated. This, in principle, is comparable to the generation of friction heat in the fuel elements, though much less in magnitude. This means that the reactor shielding heats up . . . and, therefore, it too has to be cooled.

Table 1-2 summarizes the comparative features of boilers and reactors.

Table 1-2. Functional Comparison of Marine Boilers and Nuclear Reactors

	Fuel Location	Heat Generator	Heat Control	Heat Transport	Heat Exchange	Type Shielding	End Product
BOILERS	Tankage throughout ship	Combustion Furnace	Air Blowers Air Registers Oil Pumps Burner Tips	Combustion Gases	Water-Filled Tubes	Thermal	Steam
REACTORS	Built into core	Fission Core	Neutron Absorber Rods	Primary Coolant	Water-Filled Tubes	Thermal Nuclear	Steam

1-7 Competition in the Core

Though not specifically stated, it has been implied that the neutron plays the predominant role in a fission reactor. This is true. Because of its importance to fission production, it is desired that all neutrons born in fission recycle directly back into new fissionable atoms without any losses whatsoever. Unfortunately, in the neutron search for new fuel atoms, there are many intervening non-fuel materials which prevent the neutrons from doing their intended job. Excluding the fuel atoms themselves, every atom of every other material in the reactor is competing to grab off the neutrons non-fissionably. Hence, much reactor design effort is devoted to using only materials that have a low affinity for neutrons.

The fate of a neutron in a reactor depends largely on its kinetic energy expressed in electron volts (ev). At fission birth, the average energy of a neutron is around 2.5 Mev (million ev). Yet, for maximum efficiency in causing fission, it must slow down to an energy of around 0.025 ev. This is an energy spread of 100 million-fold! It is throughout this energy spread that an array of interaction and escape processes competes for every neutron.

Why do we want to slow a neutron down 100 million-fold in energy? Because the probability of fission improves at the lower neutron energies. This is evident in Fig. 1-3.

The lower neutron energies are called "thermal energies" because a neutron moves with the energy-equivalence of its temperature environment. For any reactor temperature in degrees Fahrenheit (°F), the thermal neutron energy can be determined from

[Eq. 1-2]

$$E_n = 4.8 \times 10^{-5} \, (460 + {}^{\circ}\mathrm{F}) \ \mathrm{ev}$$

Using this equation, several selected reactor temperatures are superimposed on Fig. 1-3. Note that the higher the reactor temperature, the less the fission probability.

1-8 Moderation of Neutrons

To thermalize the high-speed fission neutrons, a moderating material is used. This material may be a liquid or a solid. Its primary feature must be: good energy-retarding capability . . . with minimum capture of the neutrons. Materials which best satisfy this requirement are hydrogen- and carbon-containing materials, such as water and graphite.*

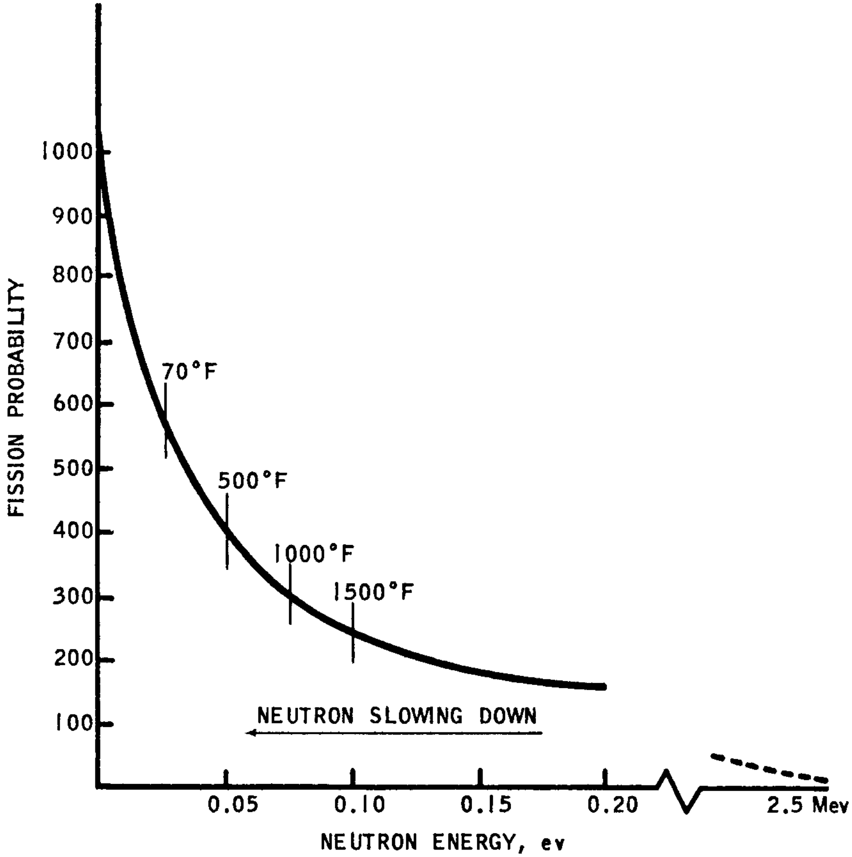

Fig. 1-3 Increasing Probability of U-235 Fission with Slower Neutrons

The atomic nuclei of the moderating material surround the fuel elements in the form of ever-present point scatterers. In this manner, when a new neutron speeds out from a fissioned fuel atom, it is almost certain to strike a moderator atom. When it does so, the neutron will scatter off

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* In the case of the *NAUTILUS* and the *SAVANNAH*, water is the moderating material. This water is also used as the primary coolant.

in a new direction at less energy than it had initially. As the neutron scatters and re-scatters from the moderating nuclei, it—if it is lucky—is eventually thermalized.

In the process of scattering around, every neutron approaches and re-approaches the atomic nuclei in fission product poisons, in the primary coolant, in the fuel element jackets, in the core reflector, in the reactor structure, in the control rods, and . . . in the non-fissionable portion of the fuel (i.e., the U-238). Each of these non-moderating nuclei possesses "absorption wells" which try to snare off the neutron for itself. If not absorbed, a neutron may escape from the core entirely. It may escape at fast speeds, or at slow speeds.

Each neutron crosses back and forth between the various fuel elements—and moderating material—before actually causing fission. It's like a pin-ball machine game: the object is to make a skilful shot to the target, starting out at high speed and ending up at slow speed (see Fig. 1-4).

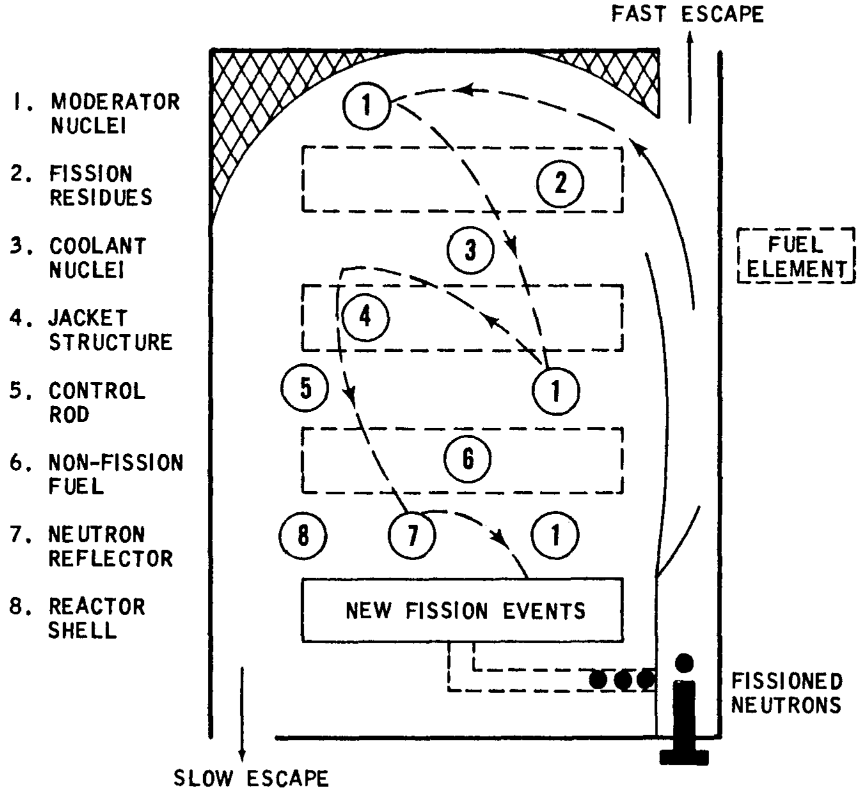

Fig. 1-4 "Pin-Ball Machine" Concept of the Neutron-Fission Cycle

After the neutron has slowed down to the thermal environment of the core (which depends on the reactor operating temperature), it roams around for a while until it lobs into a U-235 well. This, then, triggers a new fission event . . . and new neutrons.

Because of the great number of possible fates between fission and re-fission, it is desirable to use fuel material which produces the largest number of new neutrons per neutron absorbed in the fuel. This would increase our chances of maintaining the fission cycle. For this reason, enriched fuels are used.

1-9 Fission Startup

We have treated fission, thus far, as "once . . . started, it can continue on its own" (Sec. 1-1). We have not yet discussed "how" fission gets started in a reactor. We do so now, making certain comparisons with a boiler.

Combustion in a boiler is usually started with a torch and pocket match. The lighted torch is inserted through the air register opening, and it is withdrawn when combustion begins (assuming that the fuel and air have been properly adjusted).

To start fission in a reactor, we apply a neutron source (a neutron torch?). This source is a capsule-size mixture of polonium and beryllium (Po-Be) which is inserted in the core during the final stages of its assembly. The polonium—which is radioactive—emits alpha particles which interact with beryllium nuclei to produce neutrons. The Po-Be source remains in the core until it burns itself out. So, like the nuclear fuel, the fission startup source also is built into the reactor.

Prior to the startup of a "clean-cold" reactor, a programmed sequence of warm-ups and check-offs is required. This is much the same as the startup of any cold boiler plant. The reactor check-off program includes warm-up and testing of the primary and secondary coolant loops, radiation leakage and power level sensing instruments, control rod mechanisms, safety devices, and the host of auxiliaries such as pumps, heaters, strainers, actuators, power supplies, etc. A brand-new reactor may take several days—perhaps weeks—to prepare for the delicate fission starting events that follow.

Analogous to increasing the fuel oil pressure and opening the air registers in a boiler is the ever-so-gradual withdrawing of control rods from the reactor. These rods are withdrawn a small amount at a time—held, then withdrawn again—in small repeated steps until criticality is reached. Despite all the precision of design calculations, we cannot predict with certainty the exact instant nor the exact control rod positions at which the reactor will go critical. Achieving criticality in a reactor for the very first time always is a suspenseful moment.

Criticality means that the reactor core is able to maintain a fission multiplication factor of precisely 1, that is, 1.00000. A slight amount above this, say, 1.00001 means supercriticality and, depending on other factors at the time, could lead to disaster . . . if unchecked. A slight amount below criticality, say, 0.99999 means that the fission cycle will not sustain itself and the reactor will die out.

The significance of these decimal places becomes apparent when we consider that a ship reactor operates at a neutron flux* level of about 10^{13} neutrons per cm^2-sec. This means that to maintain the fission cycle we have to have 50,000,000 neutrons chasing each other around . . . exactly reproducing themselves. If we have an increase of 1.00001 times this number, we are adding 5,000,000 neutrons to the fission cycle *each second.*† If we wait too long to correct this, it may be too late.

Criticality can exist at any neutron flux level whatever. So long as the neutron-fission events exactly reproduce themselves, no matter how many neutrons are involved, the reactor is critical. Theoretically, if there were just one neutron in the cycle, criticality could exist. But such a value couldn't possibly be detected. The fission startup source itself gives off about 10^6 neutrons per cm^2-sec, and this we can just barely pick up with neutron detection instruments. We have to get up to about 10^9 neutrons per cm^2-sec before instruments can reliably tell us what the state of criticality is.

Once instrument criticality is achieved, the fission cycle is leveled off and the reactor plant is re-checked out again. Then the neutron flux is increased to the "simmer flux" range. This range is approximately 1% of the reactor's rated power, say, 10^{11} if 10^{13} is full power. Once a reactor attains its simmer neutron flux, it need never go below this value the rest of its core life. Any increase in flux thereafter becomes an operating power feature which is dependent on the time notice of output demand.

Fig. 1-5 summarizes (functionally) the neutron flux-criticality aspects of a fission reactor startup.

1-10 Instrumentation for Control

Analogous to reading the temperature gauge on a boiler is the reading of the neutron flux meter on a reactor. Indeed, many of the physical laws and phenomena which pertain to temperature also pertain to neutrons. Engineering-wise, the design and installation of sensors, amplifiers, and readout devices for neutron measurement are much the same as for temperature measurement. There are differences, of course. For one, temperature is read directly in degrees Fahrenheit, whereas neutron flux is displayed as per cent of full power, with overage allowance . . . red-lined. Another difference: neutron detectors inside of sensing wells in the reactor are subject to more rapid deterioration than are thermocouple wells in a boiler. But, on the whole, one can think of neutron flux and temperature synonymously.

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* Neutron flux is defined as the number of neutrons per unit volume times their velocity, that is, $n/cm^3 \times cm/sec$ or n/cm^2-sec. The thermal velocity of a neutron is 2.2×10^6 cm/sec. The *SAVANNAH's* operating neutron flux level is about 8×10^{12} n/cm^2-sec.

† The average lifetime of a fission cycle is 10^{-4} sec.

Similarly, as pressure is related to temperature in a boiler, so is the reactor period related to neutron flux. The period of a reactor is a dynamic quantity and is related to the rate of change of neutron flux by the expression

[Eq. 1-3]

$$\phi = \phi_0 e^{t/T^{\bullet}}$$

where

ϕ = (phi) neutron flux after period effect
ϕ_0 = neutron flux before period effect
e = 2.716
t = time of the flux change in seconds
$T^{\bullet}$ = reactor period in seconds.

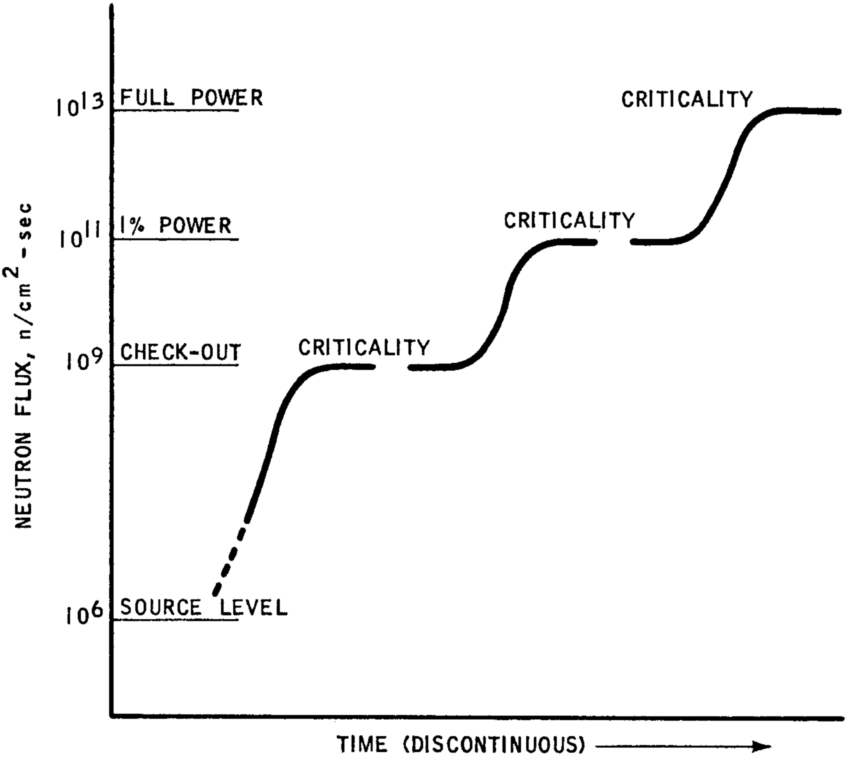

Fig. 1-5 Functional Relationship Between Neutron Flux and Nuclear Criticality

The "period" comes into play only when changing from one neutron flux level to another. If there is no flux change, there is no reactor period. The period may be either positive or negative: positive for increasing flux, negative for decreasing. The increase or decrease in $T^{\bullet}$ is established by the number of control rods withdrawn or inserted.

All modern marine boilers use automatic combustion control systems which sense the boiler temperature and pressure and compare them with command reference values. Corrections are then signaled to the fuel oil pumps, air blowers, and feed water regulators. Likewise, automatic fission control systems are used on reactors. These automatic controls sense the neutron flux and reactor period and feed back correction signals to the control rod drive mechanism and to the primary coolant pumps. Hence, the control rods automatically move in and out, to shape the desired neutron flux pattern. A simplified reactor automatic control concept is shown in Fig. 1-6.

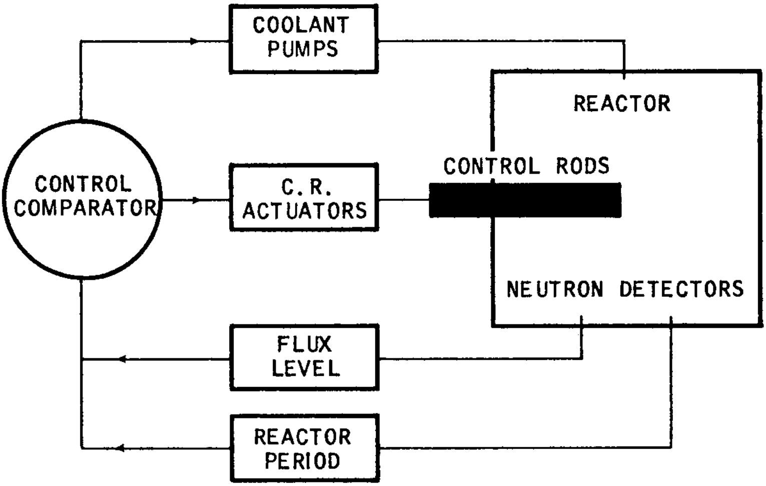

Fig. 1-6 Simplified Automatic Control Loop of a Nuclear Reactor

1-11 Phenomena at Shutdown

From this point on, the similarities between reactors and boilers fade fast. When a boiler is shut down (fuel and air off), it takes a few hours to cool off. Then personnel can commence routine boiler maintenance, such as packing valves, replacing furnace brick, cleaning tubes, etc. With a reactor—no!

Recall that for every fuel atom fissioned, two radioactive fission fragments are formed. Each in turn forms its own chain of decay residues. These residues emit a profusion of beta and gamma rays until nuclear stability is achieved. This may take seconds in some cases; in others, hours, weeks . . . and years.

A typical fission fragment decay scheme is the xenon-135 chain. The radioactive changes occurring with time are as follows:

$$\text{Fission} \longrightarrow \text{Te}^{135} \xrightarrow{(2\text{ min})} \text{I}^{135} \xrightarrow{(6.7\text{ hr})} \text{Xe}^{135} \xrightarrow{(9.2\text{ hr})} \text{Cs}^{135} \xrightarrow{(20{,}000\text{ yr})} \text{Ba}^{135} \longrightarrow (\text{stable})$$

where Te = tellurium; I = iodine; Xe = xenon; Cs = cesium; Ba = barium. Note the decay life of cesium: 20,000 years! Now remember, also, that all of these radioactive residues are contained *within the fuel elements.* And, for each pound of fuel fissioned, there's a nearly equal weight of residue.

Take a 70 MW (megawatt) reactor, for example, (the size of the *SAVANNAH*) which has been shut down after operating, say, between 100 and 500 days. In this case, the shutdown core would "generate" approximately 4 megacuries of radioactivity.* This peak radioactivity would prevail within a few hours after shutdown. Three months after shutdown, the total radioactivity would be reduced only to less than one megacurie. One megacurie, for mental scaling purposes, is 3.7×10^{16} radioactive disintegrations per second. One megacurie is a whale of a lot of radiation, capable of killing many men unless they are protected by shielding and distance. So shutdown radiation is a phenomenon of concern.

Another shutdown phenomenon is the xenon-135 poison buildup. During reactor operation, the xenon poisoning factor approaches an equilibrium maximum of 0.05. This is because a balance is reached between xenon buildup and burnout by neutrons. But when the reactor is shut down the neutrons are not present, so the poison builds up to a maximum of 0.5 . . . a 10-fold increase.† The maximum is reached approximately ten hours after shutdown, then gradually decays to some insignificant value. If we wanted to start the reactor up again, say, within a 24-hour period, we would have some difficulty.

The Xe-135 is called a "poison" because it has a neutron capture affinity of close to 3,000,000 barns, as against approximately 600 barns for U-235.‡ So, with a fair amount of poison in the core, neutrons are snatched off by it rather than by the fuel.

The adversities of xenon poisoning, however, are overcome in several ways:

(1) by operating at near-constant maximum flux level which permits only a small poison buildup;

(2) by "simmering" the flux level for a day or so after ship operations cease: this burns out the poison; and

(3) by building excess fuel in the reactor to override the poison when operations demand.

The *NAUTILUS* and *SAVANNAH* do all three.

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* For shutdown (gamma) radiation, the customary unit of radioactivity is called the "megacurie" (millions of curies: "Curie" is the name of the French nuclear physicist who first discovered radioactivity).

† For high neutron fluxes of around 10^{14}.

‡ The units of neutron capture affinity are "barns"; one barn is 10^{-24} cm^2.

SUMMARY

We have seen that the useful propulsion product of both combustion and fission is heat, but that the heat-producing potential of nuclear fission is about two million times that from the combustion of an equal weight of oil. For this great potential, however, we accept major liabilities in the form of fission residues and fission radiation. The residues are contained within the fuel elements and continue to accumulate throughout the active life of the reactor core. The radiation is stopped by shielding which protects operating personnel—and sensitive instruments—against nuclear damage.

The star actor in the fission cycle is the neutron. It must survive many competitive events in the reactor core in order to re-fission new fuel atoms. The maintenance of criticality, a cycle which exactly reproduces itself regardless of the number of neutrons involved, is fraught with traps, snares, and escapes which seek to capture or let leak out the neutrons non-fissionably. To increase the success of criticality, enriched fuels are used, and an effort is made to design the reactor of non-fuel materials with a low affinity for the capture of neutrons.

Reactors and boilers have a number of features and functions in common, though, of course, there are major differences, too. The reactor core is the furnace of a boiler; the reactor primary coolant compares with the combustion gases of a boiler; and the reactor heat exchanger constitutes the water tubes and steam drum of a boiler. Lighting off a boiler is a routine matter, whereas starting up a reactor is a more delicate operation.

Boiler combustion control is maintained by automatic temperature, pressure, and feed-water regulation devices. Similarly, reactor fission control is maintained by automatic (neutron) level, period, and coolant pump devices. When a reactor is shut down after operating for a period of time, fission residue hazards persist and neutron poisons build up. These latter features have no counterpart in marine boiler operations.

With all of this—and with the existence of the *NAUTILUS* and *SAVANNAH* at hand—we can conclude that we have a few initial points on the long curve of a new technology. We can also conclude, or anticipate, that these noted "firsts" represent obsolete marine reactor models, and that many technical changes and improvements lie ahead. It would be rare indeed for mankind to initiate a new technology that was his ultimate . . . at the start.