CHAPTER 12

Design Safety

The safety of human lives and the protection of property are overriding criteria in the design of nuclear ships. This, possibly, is the first time in the history of marine technology where original design—prior to specific regulatory requirements—has taken safety so seriously. There is good reason for this. Every reactor designer knows that any nuclear ship incident involving the uncontrolled release of radioactivity would set back nuclear ship progress many years. Consequently, every design precaution is taken against possible reactor internal accidents . . . and against ship external accidents. The basic effort is to utilize inherent physical phenomena and let nature be our front-line safety guardian. We then augment nature by good plant layout, good reactor design, and special safety devices. However, until more actual nuclear merchant ship experience is gained, we can only indicate the plausible areas of design safety.

12-1 The Reactor "Best Location"

The foremost nuclear ship safety consideration is where to locate the reactor. Because of the structural, hydrodynamic, and mobility characteristics of a ship, the "best location" for its reactor is not readily self-evident. Desirably, the reactor should be located to protect the passengers and crew in the event of an internal reactor incident. It also should be located to protect the reactor in the event of an external ship accident. Unfortunately, these requirements conflict with each other.

In the interest of maximum protection to passengers and crew, the reactor should be located at either end of the ship as far as possible from the center of human activity. On the other hand, in the interest of minimizing the consequences of external ship accidents (e.g., collisions, groundings, storms, etc.), a center-of-the-ship location is desired. Because end-of-the-ship locations present severe structural and hydrodynamic problems (due to the high unit loading of a reactor plant: recall Sec. 6-11), and because it is easier to shift the center of activity of people than to control external ship hazards, center-of-the-ship reactor locations are indicated.

Taking all operational factors into consideration (see Fig. 12-1), the one best location is the *geometric center of the ship* . . . nearest to the longitudinal, transverse, and vertical center of buoyancy. In this location, first of all, the reactor would be in the most stable hydrodynamic position. Moments of roll, pitch, heave, acceleration, and shock would be minimized. This is particularly important in heavy weather.

Under adverse weather conditions, weak or deteriorated fuel elements could be opened up; control rod drives could develop malfunctions; and leaks could be promoted in the coolant pumps, valves, and piping. Control instrumentation, sensitive to neutron fluxes, temperatures, flow rates, and nuclear radiation, could get out of calibration. These are possible beginnings of reactor accidents. Normally, they cause no great concern. However, we are trying to avoid even these possibilities, and we can do so by proper location of the reactor.

The stability advantages of reactor center-of-the-ship locations *also* hold true for oil tankers and ore carriers where the practice is to install boilers and machinery aft. In the case of nuclear tankers or ore carriers, a sternmost location is untenable for the reactor as well as for the ship. The weight of the reactor and shielding is approximately ten times that of oil-fired boilers (exclusive of the fuel oil).* This heavy mass hung at the end of a large ship accentuates the bending and torsional moments at sea. These stress moments would be most severe under light-load conditions. Under the circumstances, it is not inconceivable that a stern-end nuclear ship could readily break in two!

In brief, the reactor constitutes the heaviest and most sensitive device aboard ship. It is like a fine Swiss watch . . . on a multi-ton scale. For its best protection, it should be located at the approximate gravity-buoyancy center of the ship. The *SAVANNAH's* reactor is located here, and we can anticipate that all future marine reactors may be located similarly, regardless of the type of cargo or passengers carried.

12-2 Radiation Zones

In a manner analogous to the establishment of fire zones and watertight zones aboard merchant ships, radiation zones likewise can be established. Radiation, like fire or flooding, is hazardous by degrees. All radiation is not disastrous . . . nor is every fire or every leak that occurs aboard ship. Therefore, we can divide the radiation hazard into zones, and isolate the more dangerous areas from those less dangerous.

When we speak of nuclear radiation as a hazard to human beings, the appropriate unit of radiation dose is called the "roentgen equivalent man":

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* The weight of the *SAVANNAH's* reactor and shielding is approximately 2500 T (i.e., 600 T for reactor system, 1900 for containment and shielding). Ref: "Design of the Power Plant for the First Nuclear Merchant Ship," R. L. Whitelaw, Paper No. 69, N.E.&S. Conference, Chicago, March, 1958. The steaming weight of the two boilers on a *MARINER*-type ship is approximately 250 T (i.e., 100 T each plus piping and foundations). (Private communication U. S. Maritime Administration, April 20, 1955, S51:814).

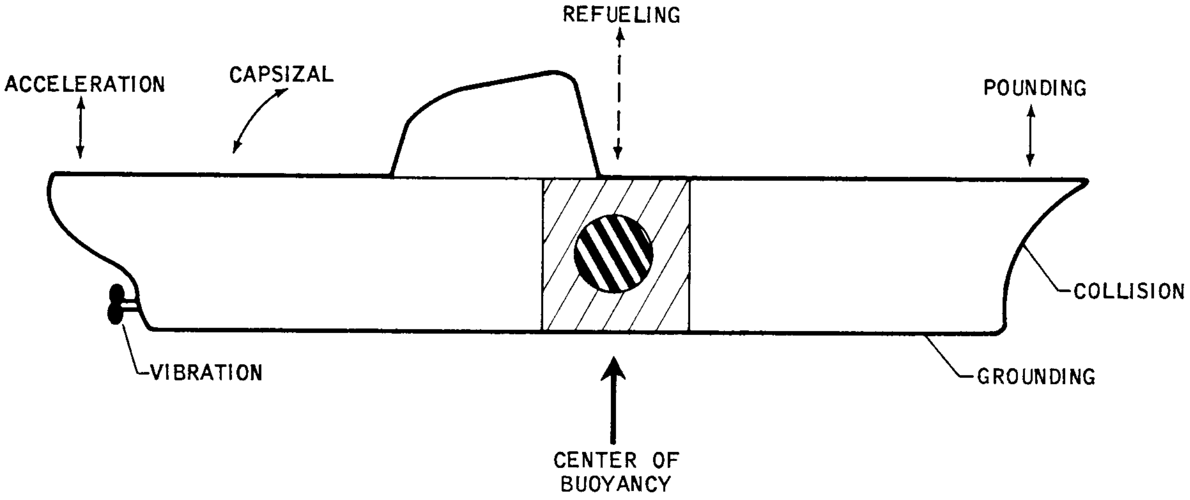

Fig. 12-1 Probable Best Location of Reactor Relative to External Hazards

written as rem.* The rem is a fairly large unit, so the millirem (mrem: 10^{-3} rem) is used.

By international agreement (i.e., the International Commission on Radiological Protection), the standard acceptable lifetime radiation exposure is 300 mrem/wk. This, when compared with ordinary sunlight, is ultra-conservative. The lifetime tolerance of sunlight is about 1 watt per week.† Our 300 mrem/wk is equivalent to about 1/20 of a microwatt, that is, 20 million times less than that of sunlight! So our acceptable standard is really quite harmless.

The 300 mrem of acceptable radiation is the accumulated dose for a 40-hr week. This dose may be taken in one day, in one hour, or in one minute, so long as in the remainder of the week there is no exposure. Actually, the 300 mrem/wk is an average for an entire year. One is allowed to go to 900 mrem/wk if in the following two weeks there is no exposure. If it were really necessary to go higher, such as in emergencies, we could take 25,000 mrem/wk . . . without detectable clinical effects.‡ This is approximately equivalent to a one-minute fluoroscopic chest X-ray examination.

We see, now, that we can go to various levels of radiation, as long as we average it over the years. This provides us the safety basis for establishing various radiation zones. For practical convenience, we can establish three zones as follows:

A-Zone — Limited Access
B-Zone — Intermittent Access
C-Zone — Continuous Access

The A-Zone would be that enclosed by the reactor plant containment shell, that is, the reactor itself and its control rods, flux sensing instruments, primary loops, primary pumps, etc. The B-Zone would enclose the reactor auxiliaries, such as purifiers, ion exchangers, waste collection system, aftercooling system, secondary side of the heat exchangers, etc. The C-Zone would be all other areas of the ship, such as propulsion machinery, central control room, navigation areas, and passenger and crew quarters. The relative arrangement of these zones would be tailor-designed for each class of nuclear ship.

It should be possible to gain access to the A- and B-Zones while at sea. For this purpose, special quick-opening-closing radiation doors would be provided. These zonal doors would be appropriately marked, and their opening and closing would be reported to the central control room. Maximum safe time limits could be established within these zones, with auto-

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[*] The rem applies to both neutrons and gammas, the effect of each being additive.

[†] Ref: *Reactor Shielding Design Manual*, T. Rockwell, US AEC TID-7004, 1956, p. 17.

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

matic alarm signals to warn personnel when their exposure limits had been reached.

12-3 Negative Temperature Coefficient

The most important single index of the inherent safety of the reactor is called its "temperature coefficient." This coefficient tells us the direction and magnitude of changes in the fission multiplication of the core, for changes in temperature. In other words, the temperature coefficient indexes the behavior of k-effective (k_e: recall Sec. 4-5). If this index is positive, k_e will increase with increasing temperature . . . and the reactor will "run away." If the coefficient is negative, k_e will decrease, and the reactor will shut itself down.

For nuclear ships, it is mandatory that the reactor temperature coefficient be negative. When so, unexpected temperature excursions would be self-stabilizing.

The degree of self-safety is indexed by the magnitude of the temperature coefficient. A good number to remember (as a reference value) is $20 \times 10^{-5}/\text{F}^\circ$—the approximate coefficient of the *SAVANNAH*.* This means that for every degree of reactor core temperature, the fission multiplication (k_e) reduces itself by the factor 0.0002. We shall see later that this amount of reduction in k_e is wholesomely safe. This is one of the reasons for selecting a pressurized water reactor for the first nuclear merchant ship.

When comparing temperature coefficients of reactors, we must take care to note (or to inquire of) the temperature level involved. At one temperature, a reactor may have a negative coefficient, whereas at another temperature it may be positive (same reactor). This is true in the case of the organic moderated reactor, for example. At 250°F, the coefficient for OMR is $10 \times 10^{-5}/^\circ\text{F}$; at 450°F the coefficient is zero; at 750°F it is $-10 \times 10^{-5}/^\circ\text{F}$.† So, at operating temperatures competitive with the *SAVANNAH*, the OMR has an adequately safe negative temperature coefficient.

The temperature coefficient is a lumped algebraic sum of many factors (both positive and negative) of reactor core design. These factors appear in the buildup of the equation for k_e (from Ch. 4), that is:

$$k_e = \frac{[\eta \epsilon p f]\,[e^{-B^2\tau}]}{[1 + L^2B^2]} \qquad \text{[Eq. 12-1]}$$

We should recall that η, ε, p, and f are properties of the fuel; that τ and L^2 are properties of the moderator; and that B^2 is a property of core geometry. Poisons in the core affect the properties of both fuel and moderator.

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* Note with care the 10^{-5} factor. The temperature coefficient is sometimes expressed as 10^{-4} or 10^{-6}, thus leading to confusion in the true magnitude of the coefficient.

† Ref: "OMRE Core Characteristics," *Power Reactor Technology*, AEC, Sept., 1958 (Vol. 1, No. 4), p. 42.

We now express the temperature coefficient as $1/k_e \, \frac{dk_e}{dT}$. This is a mathematical way of saying "fractional rate of change of k_e with incremental changes in temperature." Carrying the mathematical definition further, we can set up a temperature coefficient equation as follows:

$$\begin{aligned}\frac{1}{k_e}\frac{dk_e}{dT} = &+\left[\frac{1}{\eta}\frac{d\eta}{dT}+\frac{1}{p}\frac{dp}{dT}+\frac{1}{f}\frac{df}{dT}\right]\\ &-\left[\tau B^2\left(\frac{1}{\tau}\frac{d\tau}{dT}+\frac{1}{B^2}\frac{dB^2}{dT}\right)\right]\\ &-\left[\frac{L^2B^2}{1+L^2B^2}\left(\frac{1}{L^2}\frac{dL^2}{dT}+\frac{1}{B^2}\frac{dB^2}{dT}\right)\right] \quad \text{[Eq. 12-2]*}\end{aligned}$$

In Eq. 12-2, we note three pairs of brackets: one "plus" and two "minus." The plus brackets represent the characteristics of the fuel; the minus brackets characterize the moderator and geometry. In general, because the moderator is a much larger fraction of the core than fuel, the magnitude of its temperature effects normally produces a negative coefficient.

Depending on the choice of fuel, however, the η-value (eta: recall Sec. 4-1) in the plus brackets may be sufficiently large to override the minus brackets. This positive override results, to a large extent, from the so-called "Doppler broadening" of resonance regions (for neutron capture) in the fuel atoms. These Doppler effects vary with temperature, and with higher chain fuel nuclei. As we recall from Sec. 11-2 (Fig. 11-1), the fuel nuclei change with operating time. So do their η-values . . . and so does the temperature coefficient.

12-4 Control by Delayed Neutrons

Another intrinsic feature which we take safety advantage of is the effect of delayed fission neutrons. In the fission process, the greatest percentage, by far, of new neutrons is emitted instantaneously, that is, within about 10^{-4} seconds. A few, however, are emitted sometime after the act of fission . . . averaging about 10^{-1} seconds. Compared with the instantaneous or prompt neutrons, the time delay ratio is about 1000 to 1.

The delayed neutrons are decay emissions from the fragments of fission. As such, delayed neutrons possess decay phenomena in that they do not all come off at one time. In the case of U-235, they come off in five distinct groups (see Table 12-1). The symbol β (beta: not beta rays nor burnup, this time) is used to denote the total fraction of delayed neutrons, and λ (lambda) to denote the decay constant (in sec^{-1}).† For first approximations, it is convenient to treat all of the delayed neutrons as a single group.

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[*] Ref: *The Physical Theory of Neutron Chain Reactors,* Weinberg and Wigner, University of Chicago Press, 1958, pp. 482 ff.

[†] Technical and scientific literature very frequently use the same symbol to signify different entities. No difficulties arise if one is cognizant of the particular subject at hand.

Table 12-1. Properties of Delayed Neutrons from U-235 and Pu-239

Emitter	Half-Life (sec)	Decay Constant $(\lambda, \text{sec}^{-1})$	Neutron Energy (kev)	Fraction of Total Neutrons per Fission	
				U-235 β	Pu-239
1	0.43	1.62	250	0.00085	0.00119
2	1.52	0.455	570	0.00241	--
3	4.51	0.153	412	0.00213	0.00126
4	22.0	0.031	670	0.00105	0.00058
5	55.6	0.012	400	0.00014	0.00018
				0.00730	0.00364

Ref: Nuclear Reactor Physics, R. L. Murray, Prentice-Hall, 1957, p. 148.

Except for the time-of-birth, delayed neutrons behave like all other neutrons in a fission multiplying region. They join the neutron multiplication cycle and thereby influence the neutron flux in the reactor core. But the importance of delayed neutrons is this: by proper control design, they can prevent a reactor from running away.

We recall (Eq. 5-1) that neutron flux is directly proportional to reactor power. The flux, in turn, varies according to the Eq. 1-3 relationship in Sec. 1-10:

$$\phi_t = \phi_0 e^{t/T^*} \qquad \text{[Eq. 12-3]}$$

where ϕ_t is the neutron flux at any time t following a change from flux at time zero, ϕ_0. The T^* in Eq. 12-3 is called the reactor "period." This period is the time in seconds required to change the flux level by the factor e (2.716). For this reason, the reactor period is often called the "e-folding time." A reactor period exists only when the reactor is changing its flux level (recall Fig. 1-5).

The magnitude of the reactor period is influenced by prompt neutrons and by delayed neutrons according to the expressions

$$T^* = \frac{\bar{l}}{\Delta k_e} \text{ (prompt)} \qquad \text{[Eq. 12-4(a)]}$$

$$T^* = \frac{\beta - \Delta k_e}{\lambda \Delta k_e} \text{ (delayed)} \qquad \text{[Eq. 12-4(b)]}$$

where $\bar{l}$ (called "l-bar") is neutron lifetime (i.e., average time between successive prompt neutron generations); Δk_e (delta k_e) is the fission multiplication in excess of criticality (i.e., $\Delta k_e = k_e - 1$); and β and λ are as above. In the conservative case, l is about 10^{-3} sec, β about 0.0075, and λ about 0.1 sec^{-1}. This leaves Δk_e which can be varied by insertion or withdrawal of control rods (recall Sec. 4-8).

Let us now withdraw control rods to the equivalent Δk_e of, say, + 0.003. If all the neutrons were prompt, T^* (by Eq. 12-4 [a]) would be 0.33 sec. At, say, the end of 3 sec (by Eq. 12-3), the neutron flux level will have risen by a factor of 8000! This obviously invites reactor runaway. Fortunately, this does *not* happen . . . because of the delayed neutrons.

The effective value of T^*, therefore, (by Eq. 12-4 [b]) is 15 sec. Thus, at the end of 3 sec the actual flux level will have risen only by a factor of two: a much safer situation.

12-5 Rod Action "Always Safe"

If, however, we permitted the control rods to be withdrawn the Δk_e equivalent of the total fraction of delayed neutrons (β), we would negate entirely the effect of the delayed neutrons. This is evident in Eq. 12-4(b) where, as Δk_e approaches β in magnitude, T^* approaches zero. Under Δk_e conditions greater than β, the flux changes on prompt neutrons alone. This is called the "prompt critical" condition. This we must avoid.

We avoid prompt criticality by design limiting the control rod system. We do this in three ways:

(1) the Δk_e of each control rod never exceeds β;
(2) the withdrawal of each control rod is time-rate limited;
(3) no combination of control rod motion ever exceeds β.

By these rod actions, the control of the reactor is "always safe."

Using the *SAVANNAH* again as an example, the total Δk_e subject to rod control is 0.15.* Now, the value of β during the initial operation with U-235 U-238 fuel is 0.0073 (Table 12-1). So we simply limit the Δk_e of each control rod to a value just below 0.0073 (say 0.00715). On this basis, the number of control rods required is 0.15/0.00715 . . . or 21 rods. This is the number of *SAVANNAH* rods mentioned in Sec. 6-7. With this number of rods, the malfunction of any one rod could not possibly subject the reactor to prompt criticality.

By design, we can select a control rod drive speed and gear arrangement which will limit the rod withdrawal rate to any value we want. Say the withdrawal rate is 0.0001 Δk_e/sec—a typical always safe value. At this rate, the withdrawal of one control rod over its entire Δk_e length would entail 70 seconds of time.† Even if we withdrew all 21 rods simultaneously, we could not introduce more than 0.0021 Δk_e/sec. This is less than one-third the Δk_e required for prompt criticality.

The 0.0021 Δk_e/sec is the maximum instantaneous reactivity that we can induce into the fission multiplication system. Recall that Δk_e is the amount by which the fission multiplication differs from unity (unity is critical; greater than unity is supercritical). As we introduce fission supercriticality, we bring into play the effect of temperature coefficient (Sec. 12-3). The relationships involved are

$$\Delta k_e = (\Delta k_e)_i + \alpha \Delta T \qquad \text{[Eq. 12-5]‡}$$

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* 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.

† On the *SAVANNAH*, whose active core height is 66 inches, a rod withdrawal of 0.0001 Δk_e/sec would correspond to a withdrawal speed of approximately 1 inch/sec.

‡ Ref: *Introduction to Nuclear Engineering*, R. L. Murray, Prentice-Hall, 1954, pp. 138 and 32.

where α (alpha) is the temperature coefficient and ΔT is the reactor temperature change during the transient $(\Delta k_e)_i$ ("i" for instantaneous).

If we use the *SAVANNAH's* temperature coefficient (i.e., $-20 \times 10^{-5}/°\text{F}$) and say that the reactor change in temperature is 10°/sec, the effective Δk_e from Eq. 12-5 would be 0.0001.* Thus, we see that the temperature coefficient can almost negate the impressed Δk_e.

Because of the large core mass, temperature non-uniformities, and large coolant flow, the core temperature will not respond instantaneously to changes in Δk_e (as presumed in Eq. 12-5). This is called the "thermal lag" of the reactor. To take thermal lag into account, we limit the time duration of control rod withdrawal. At the end of 3 sec, say, ($\Delta k_e = 0.0063$—still less than β), all control rod motion stops. This allows the reactor temperature to catch up and level itself off, before proceeding to the next step higher in neutron flux level.

In other words, all control rod motion from full-in (reactor shutdown) to full-out is divided into time-limited steps. This is done by electrical time delays and interlocks. The reactor will not go from one step to the next without deliberate actuation by an operator . . . and then only for one step length (e.g., 3 sec) at a time. Should the electrical interlock system fail, automatic control takes over and the reactor is scrammed.

12-6 Automatic Scram Control

A reactor is "scrammed" when it is shut down suddenly. Special safety rods (called scram rods) are tripped for this purpose. The result is a severe shock to the reactor complex. We never routinely scram a reactor: we may be forced to do so under duress. The consequences, if we fail to scram, must be greater than the severity of the scram action itself.

Although we attempt to design a marine reactor with an "always negative" temperature coefficient and an "always safe" reactor period, we cannot "always" guarantee these things. Because of the complexity and uncertainties in reactor systems, any one or more of the following major hazards may arise:

(1) Excessively high neutron flux level
(2) Excessively short reactor period
(3) Excessive radioactivity in primary coolant
(4) Excessive temperature of reactor and coolant
(5) Excessive reduction of coolant flow
(6) Loss of electrical power

The first three of these hazards are nuclear; the second three are non-nuclear.

The scram system of a reactor is a specifically designed safety action in the event of any of the foregoing major hazards. In order to soften the severity of scram on a reactor, scram actions are generally divided into five

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* $(\Delta k_e)_i = 0.0021$; $\alpha \Delta T = -20 \times 10^{-5} \times 10 = -0.0020$. So, $0.0021 - 0.0020 = 0.0001$.

categories. These are: fast scram, slow scram, stop-reverse, fast setback, and slow setback. Thus, scram action can be taken in proportion to the degree of the hazard involved.* Typical such actions are given in Table 12-2.

Table 12-2. Typical Automatic Scram-Safety Actions for a Reactor

Condition	Fast Scram	Slow Scram	Stop-Reverse	Fast Setback	Slow Setback
Neutron Level (% Full power)					
200%	X				
150%			X		
120%					X
Reactor Period					
1 sec	X				
5 sec			X		
Coolant Contamination (% Max.)					
150%			X		
125%				X	
100%					X
Reactor Temperature (% Max.)					
130%		X			
120%				X	
110%					X
Coolant Flow (% Normal)					
80%		X			
90%					X
Loss of Electrical Power		X			

Note particularly in Table 12-2 the reactor period. All control rods are stopped and reversed when the reactor period falls to 5 sec. Should it decrease to 1 sec, fast scram is actuated. Fig. 12-2 illustrates what would happen to the reactor power level if we permitted shorter reactor periods than 1 sec.

For example, if the reactor period would be permitted to go to, say, 0.2 sec, the power rise would be 150-fold . . . within one second of time! At a one sec reactor period, on the other hand, the corresponding power rise would be only 3-fold.

Strictly speaking, the stop-reverse and setback actions of Table 12-2 are not scram actions. They are safety actions of the regular control rods actuated in preference to the scram rods, though the regular control rods are tied in to the scram system. All scram-safety actions are automatic . . . with provision for manual cut-in.

Nuclear sensing devices detect neutron levels, reactor period, and coolant radioactivity. The electronic signals from these devices are amplified, then fed into a "scram bus" (see Fig. 12-3). Provided the signals are below the trip-point, the scram bus holds the scram rods in check by

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* Ref: *Control of Nuclear Reactors and Power Plants,* M. A. Schultz, McGraw-Hill, 1955, pp. 256 ff.

means (usually) of electromagnets. Non-nuclear sensing devices also tie in to the scram bus.

An "auctioneer" circuit scans the signal levels of the various amplifiers, and compares these signals with the values listed in Table 12-2. Depending on the signal comparison, the auctioneer circuit (electronic computer) either trips the scram bus or actuates servomotors on the regular control rods. The scram bus may be tripped by any one of the hazards mentioned.

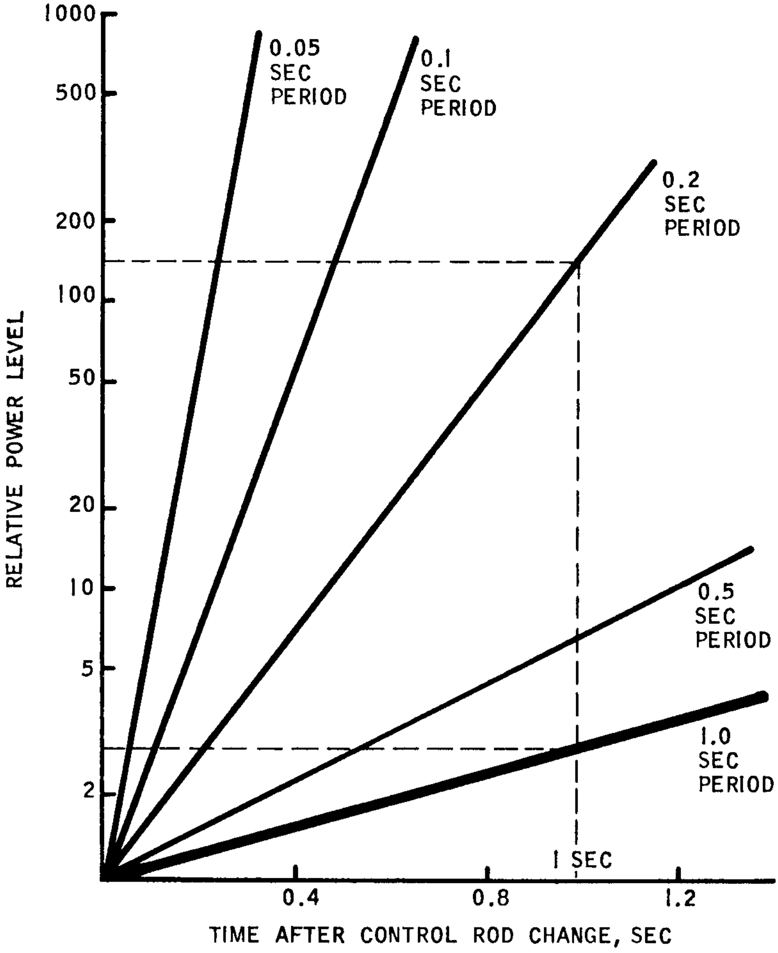

Fig. 12-2 Relative Change in Power Level for Short Reactor Periods

Tripping releases the scram rod holding magnets, whereupon the scram rods are driven home by gravity, loaded springs, or pneumatic pistons. Scram time is on the order of 50 milliseconds.*

12-7 Reactor Control Sensors

Control sensors are electronic devices which detect and report the neutron and gamma history of the reactor core. We must know this history—and we must keep continuous record of it—for purposes of safety control. We are interested in the neutrons as a means of power level control and control of the reactor period (rate of change of power level). We are interested in the gammas for monitoring the primary coolant (for burst fuel elements) and for the detection of excessive shielding leakages.

Since neither neutrons nor gammas can be detected by direct means, indirect techniques are used. That is, we deliberately permit nuclear radiations to interact with sensory materials whose nuclear interaction characteristics are known. Then we take the secondary products of these interactions and cause them to produce an electrical signal, which we amplify and use. This electrical signal is the end sensory result of positive and negative ions produced by the friction-stopping of secondary nuclear products (see Fig. 12-4).

The sensory nuclear mechanisms are identical with those of shielding attenuation (Ch. 10). For control purposes, however, we are interested only in a minute portion of the total radiation. And, instead of the attenuation friction being dissipated as heat (in the case of shielding), we use the friction-stopping (ionization) phenomena to generate electrical signals.

There are three basic sensory instruments of interest to reactor safety control. They are:

(1) the simple ionization chamber
(2) the coated ionization chamber
(3) the compensated ionization chamber

(see Fig. 12-5). The first type detects gammas only; the second, neutrons; and the third detects both neutrons and gammas. All three produce positive and negative ions which are collected as electrical current. All three require high voltages, pressurized gases (as the ion source), and extraordinary electrical insulation. All sensors require electronic circuitry to amplify, discriminate, and scale the electrical signals generated.

In the simple ionization chamber, gammas interact with the electrons of the chamber gas (e.g., argon, krypton, xenon, etc.) and the electrons race off to produce ions. Because gas atoms are too sparse for large yields of neutron interactions (in the small chamber space), solid coatings of neutron absorption materials are used. Typical neutron absorber coatings are: boron-10 and U-235 (for thermal neutrons), indium and gold (for

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* Ref: Paper No. 57-15 "The Development of Universal Control Drive Mechanisms for Nuclear Reactors," Roland and Hinricks, 2nd Nuclear Engineering and Science Conference, March, 1957, Philadelphia.

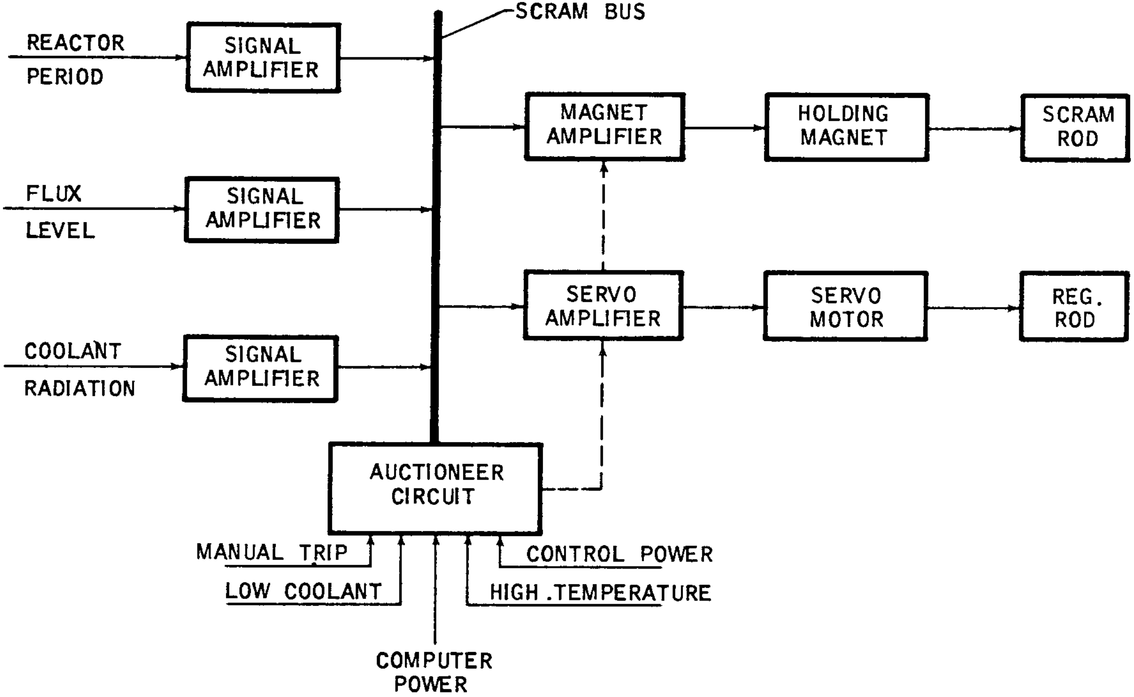

Fig. 12-3 Principle of Scramming Bus and Auctioneer Circuit for Control Safety

epithermal neutrons), and U-238 and hydrogen (for fast neutrons). The "compensated" chamber is a means of balancing out the component of signal caused by gamma rays when in a neutron field. This compensation increases the neutron detectability under high-power reactor conditions.

Neutrons are the primary radiation by which reactors are controlled. But neutrons co-exist in a profusion of gammas. Consequently, compensated ion chambers are more frequently used. The signal outputs are calibrated to read the reactor power in proportion to the neutron flux. A logarithmic meter takes this neutron flux and computes its time rate of change. The readout is the reactor period.

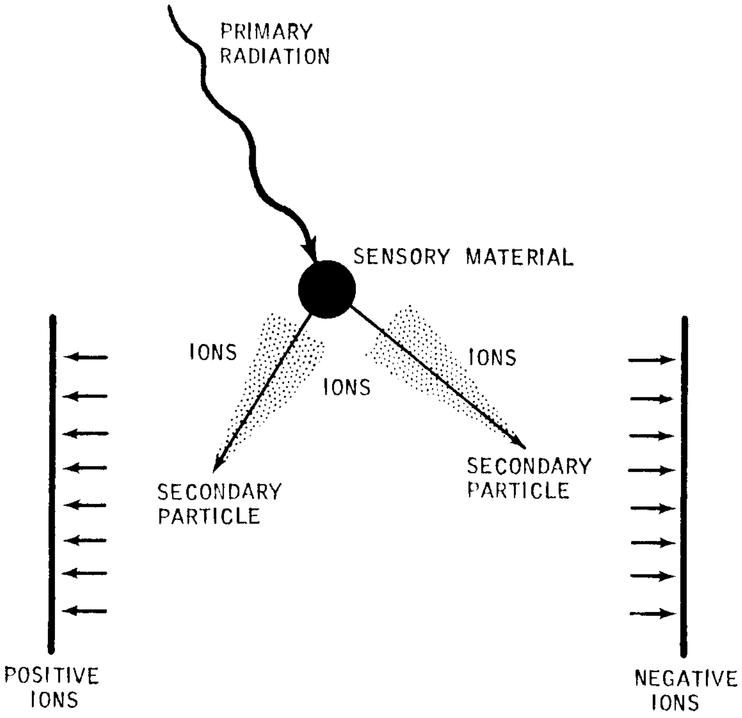

Fig. 12-4 Principle of Indirection for Sensing Nuclear Radiation

Control sensors are made in a wide variety of sizes, shapes, and materials . . . and manufacturers' patents. Nevertheless, they all are of small size: seldom more than a few inches in diameter and a foot or so in length. They are mounted in instrument tubes or "thimbles" adjacent to the reactor vessel and its core (see "Instrument Thimble" in Fig. 6-13). These instrument tubes are positioned at a sufficient number of peripheral locations to obtain the average reactor power distribution.

The control sensors are not placed directly in the fission core because the damage caused by fission is too great, and because of other complexities entailed in the core design. The sensors do, however, penetrate the primary shielding.

No one type of sensor serves all control purposes, nor at all power levels. Each sensor has its own range limit of sensitivity. And this sensitivity changes with reactor operating time, reactor temperature, position of control rods, etc. For these reasons, control sensors are "overlapped" (see Fig. 12-6). This assures instrument coverage from the very lowest . . . to the very highest power levels.

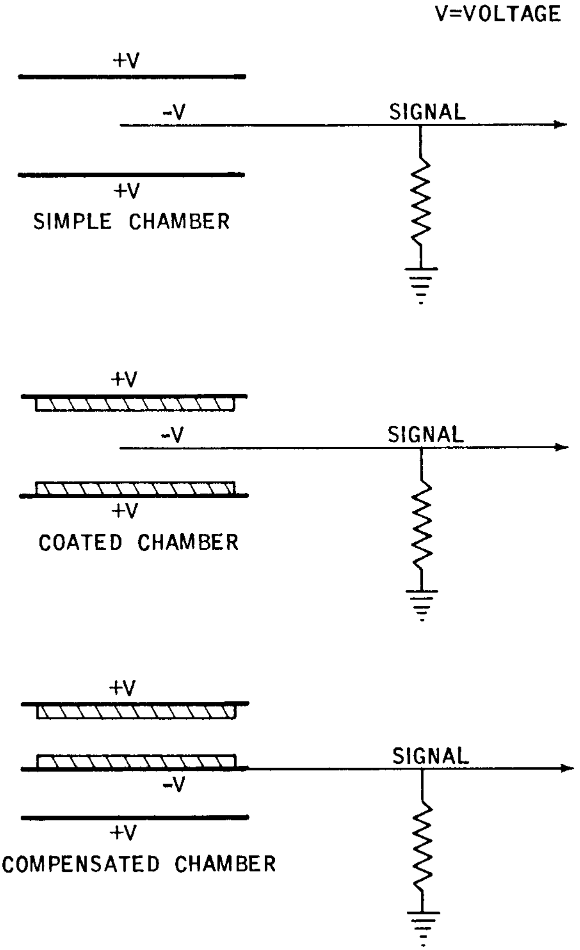

Fig. 12-5 Basic Types of Ionization Chambers for Reactor Control

Because instrument sensitivity changes with time, recalibrations are necessary. This is provided for in the design (and number) of instrument thimbles which permits withdrawal and replacement of the control sensors.

12-8 "Last-Ditch" Shutdown

The nature of man-made equipment is such that we cannot place complete, total, and irrevocable confidence in automatic scram-safety control. And besides, there may occur shipboard catastrophes such as explosions, collisions, fire, and grounding, which could render inoperative the automatic scram devices. For these catastrophic possibilities we must provide some "last-ditch" emergency action. This action may be initiated manually, or by some inherent device that is positive and simple.

There are several methods for last-ditch shutdown. All such methods assume that the control rod mechanisms and shafting may be distorted or destroyed, and that the control element passages in the reactor core may be blocked. Emergency—final—shutdown, therefore, involves drastic means.

Table 12-3. Neutron Absorbers for Flood-Scramming a Reactor

Material	Thermal Neutron Absorptivity (barns)	Abundance of Important Isotope (%)	Film Thickness for Neutron Blackness* (inches)
Boron:			
B (nat)	650	—	0.0090
B-10	3,470	18.8	
Cadmium:			
Cd (nat)	2,210	—	0.0077
Cd-113	18,000	12.3	
Samarium:			
Sm (nat)	4,760	—	0.0055
Sm-149	57,200	13.8	
Europium:			
Eu (nat)	3,980	—	0.0070
Eu-151	7,800	47.8	
Gadolinium:			
Gd (nat)	39,800	—	0.0007
Gd-155	60,600	14.7	
Gd-157	139,000	15.7	
Dysprosium:			
Dy (nat)	950	—	0.0270
Dy-164	2,340	28.2	

*"Blackness" is the complete choke-off of thermal neutrons.

Ref: "Nuclear Requirements for Control Materials", H. E. Stevens, Nuclear Science and Engineering, Sept. 1958, p. 375.

On shipboard, the most practical last-ditch methods are the dumping in of *great quantities* of neutron absorbing materials (poisons) through special tubes, ports, or other flood-release piping. The neutron absorbing materials (see Table 12-3) may be in the form of liquid, gas, powder, shot or foam.* The effort is to douse the reactor core and choke down the neutron flux. This action is taken, presumably, after all other shutdown methods have failed.

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* Ref: "Special Safety Devices," Huston and Miller, *Nucleonics,* May, 1958, pp. 86-87.

The injection force behind the neutron poison is a high-pressure gas . . . somewhat analogous to fixed CO_2 and foam systems for fire smothering aboard oil-fired ships.

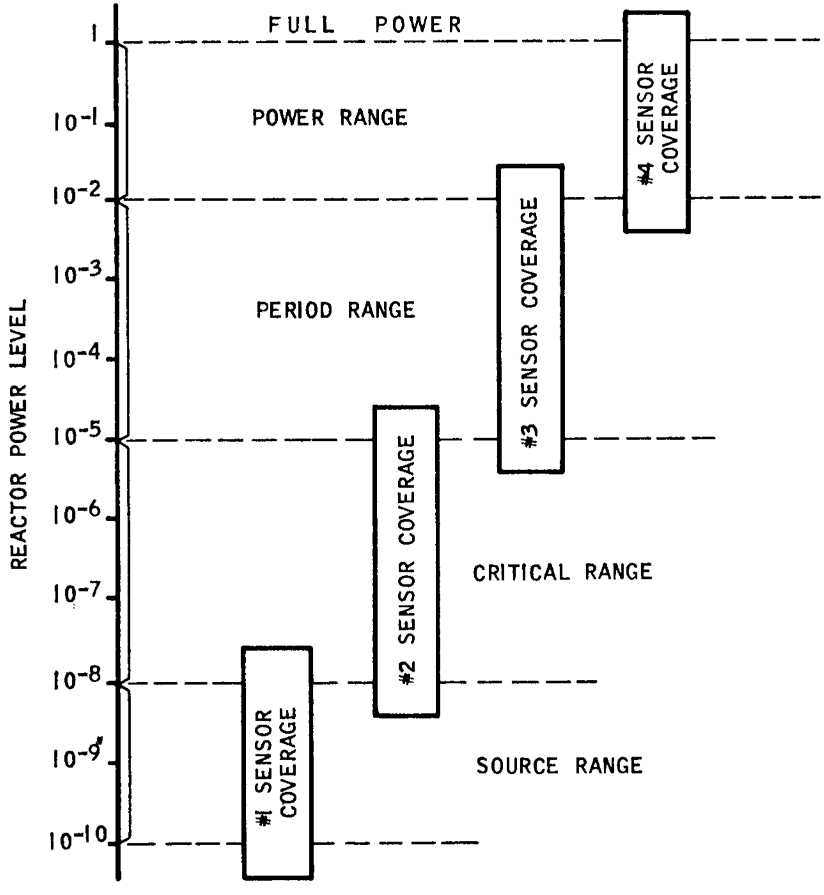

Fig. 12-6 Typical Overlap in Sensitivity Ranges of Control Sensors

Poison release mechanisms are in the form of remotely punctured diaphragms actuated by manual trips and safety fuses. The manual trips are mounted in strategic locations of the ship, and the safety fuses are mounted in the reactor vessel walls. The neutron poison is stored outside of the reactor . . . charged and ready to go (see Fig. 12-7).

A reactor safety fuse is an adaptation of the solder-base fuse so common in fire detection systems aboard ship. In addition to the solder, however, a reactor fuse consists of a thermal pad and a fissionable layer. The thermal pad is placed toward the reactor core, in contact with the primary coolant. The fission layer consists (usually) of enriched UO_2 in suitable physical form.* Neutrons enter this fission layer through the thermal pad and cause fission.

Under normal operations, the fission heat is drained off through the thermal pad by the reactor coolant. This keeps the temperature of the solder about ⅓ below its melting point. However, when the neutron flux reaches, say, 250% of normal, the fission heat melts the solder which, in turn, triggers the poison release.

Manual trips—like the ship's general alarm—can be located on the navigating bridge, in the main control room, and at some emergency accessible location on the main deck. The "emergency accessible location" would be used in the event of Abandon Ship!

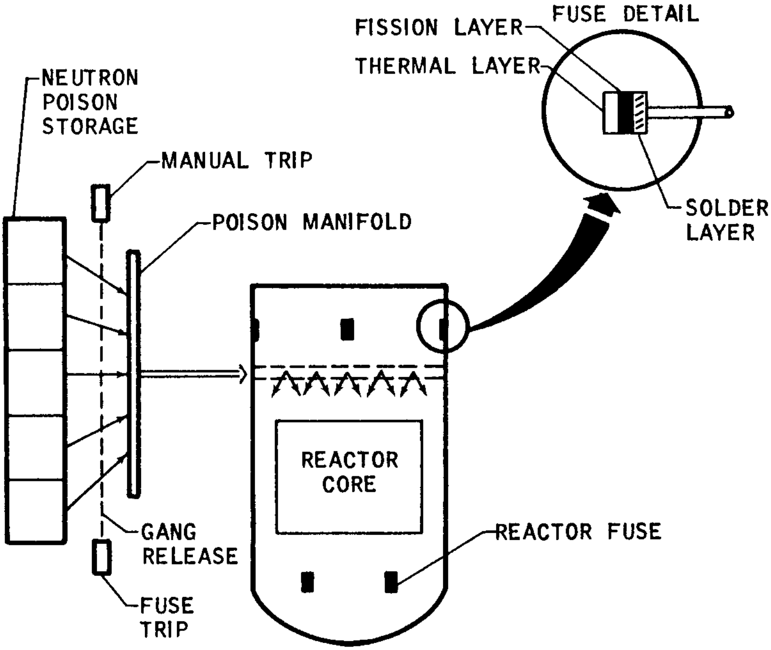

Fig. 12-7 Possible Arrangement for "Last-Ditch" Reactor Scram

12-9 Effective Containment Design

Should it ever become necessary to flood-poison a ship's reactor, the reactor core—in all probability—would have to be replaced. Chances are, it would be destroyed. Every effort, of course, would be made to insert the control rods manually, and have them perform the fission choke-down function. But this effort may not prove rewarding.

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* Ref: "Reactor Fuse: New Safety Element," *Nucleonics*, June, 1957, p. 116.

In order for the flood poison to do its job effectively, it must be kept in place for a considerable period of time after fission choke-down. If the poison were diluted or removed, say, by the primary coolant, the fission cycle could start up again . . . and, thereafter, would be beyond control. Consequently, the primary coolant loops, if not already damaged and shut off, would have to be shut down. This would completely isolate the flood-scrammed reactor.

Because the flood poisons are such strong neutron absorbers, they become highly radioactive. We discussed neutron-induced radioactivity back in Secs. 5-12 and 10-3. Poisons are no different from other materials insofar as their radioactivity characteristics are concerned. They capture neutrons and re-emit gamma rays.

In the process of emitting capture-gammas, the poisons heat up. This radioactive decay heat on the outside of the fuel elements combines with the fission residue decay heat on the inside of the fuel elements to hasten meltdown of the core. The combined heat of all radioactive decay may be sufficient to melt through the reactor vessel proper. For example, in the case of the *SAVANNAH*, its melted-down core could burn through the bottom of its 6-inch reactor vessel in approximately 3 hours.* Should this happen, great quantities of hazardous radiocontaminants would gush from the reactor vessel. However, this rare possibility is taken into account in the design of the containment shell around the reactor (recall Sec. 6-9).

An obvious further consideration of effective containment is that the containment shell be protected from damage against external causes, such as ship collision, heavy weather, explosion, etc. One way of providing this protection is in the form of a "collision shield." This shield could be a double-hull cofferdam-type construction . . . all around the ship's reactor compartment. We could carry this double-configuration concept one more step and design the containment shell with its own inner and outer shells (see Fig. 12-8). Then, surely, this two double-configuration structure would give maximum guarantee of containment against all credible accidents. The only exception would be those fantastic situations created by idiots and saboteurs.

In the event of a ship's sinking and the flooding of its reactor hold, the double-containment shell would do two things. One, it would withstand the hydrostatic pressure forces from without; two, it would withstand the chemical reaction pressures and nuclear decay heat from within. Between the double shell—in addition to framing and stiffeners—there could be special heat conduction bars and fins (say of copper) to collect and conduct the decay heat from the inner shell to the outer. Then natural sea-water convection would dissipate the heat from the outer shell. In this manner, a sunken nuclear ship would present no radiological hazard to navigation nor to marine life.

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* Ref: "Ship Propulsion: Hazards," *Nucleonics*, Sept., 1958, p. 92.

12-10 Access for Salvage and Repair

Once the radiocontaminants created by an emergency reactor situation are safely contained, salvage and repair need not be an urgent matter. Of course, a melted-down or otherwise damaged reactor cannot be left in a ship's hull indefinitely, regardless of whether it be above or below the surface of the sea. The radiocontaminants must be collected and prepared for permanent disposal. Accordingly, appropriate salvage, decontamination, clean-up, and repair equipment must be brought to the scene.

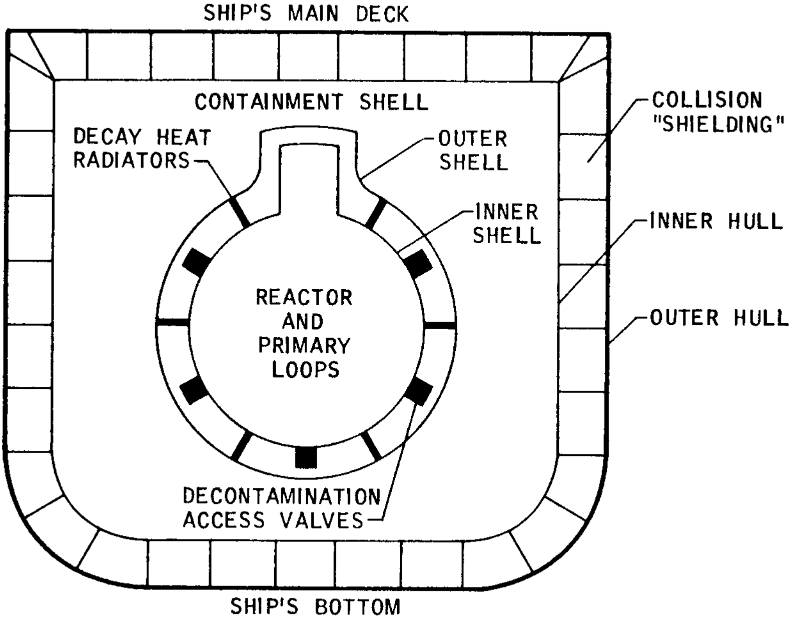

Fig. 12-8 Possible Construction for Maximum Credible Reactor Containment

To permit salvage operations, the containment shell could be designed with means for releasing the radiocontaminants in a controlled manner. Between the inner and outer containment shells, there could be special "decontamination valves" normally canned and sealed (see Fig. 12-8 again). These valves would be strategically located around—and attached directly to—the inner containment shell. They could be accessible from any conceivable position of a damaged ship. The outer containment shell would entirely enclose these valves to provide structural protection. Opposite each valve, however, there would be some permanent marking on the outer shell to identify each valve's location.

The first salvage step, then, would be to burn through the outer containment shell and make clear access to the decontamination valves. Then the valves would be fitted with flanges and adaptors, to which would be attached portable (shielded) radiocontamination collection tanks. Pumps, too, would be fitted. The uppermost valves would be used for the pump-out of contained gases; the lower valves for the pump-out of contained liquids. Separate portable tanks would collect each type of contaminant. When most of the radioactive gases and liquids have been collected, wash-down facilities would be connected. Wash-down would continue until the radioactivity in the containment shell was sufficiently reduced to permit direct human access.

12-11 Waste Collection and Disposal

Aside from reactor emergencies, radioactive wastes accumulate under normal operating conditions at sea. There are those inevitable leaks from the primary coolant piping, pumps, heat exchangers . . . and from the primary shielding tanks. Air, rust, and dust become activated in the vicinity of the reactor vessel proper. Filters in ventilating, cooling, lube oil, and other auxiliaries collect radiocontaminants. Resins used in demineralizers, purifiers, and ion exchangers are collection centers of contamination. Maintenance tools, gloves, cleaning rags, and protective clothing also become contaminated. Minor mishaps, too, add to the radioactive accumulations.

For obvious reasons, these radioactive wastes cannot be dumped or pumped overboard at random at sea. Instead, a systematic arrangement of collection tanks, decontamination auxiliaries, monitoring instruments, and dilution equipment is required. This disposal system is designed into the ship as part of the reactor plant auxiliaries.

Radioactive wastes are classified as high-level and low-level. Low-level wastes can be discharged into the air or into the sea, without any biological harm whatsoever. They are "low-level" because their radioactive content is not more than:

$$10^{-10}\ \mu\text{C/cm}^3 \text{ in air}$$
$$10^{-7}\ \mu\text{C/cm}^3 \text{ in water.}$$

(The "μC" is microcuries.) These safe values are based on strontium-90 which, as a bone seeker, is the most objectionable radioactive species to human and animal life.*

All wastes are collected into appropriate tanks which may be stainless steel clad or glass lined for protection against internal corrosion. Because the total radioactivity of wastes does not exceed more than about 20 curies per day (compared with the megacuries of Sec. 11-6), no particular gamma shielding is required other than the structural steel of the tanks themselves. The wastes are held up in these tanks for a while to allow natural radioactive decay before decontamination and disposal.

From these hold-up (decay) tanks, the wastes are processed through scrubbers, demineralizers, evaporators, filters, strippers, etc., whereupon

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* Ref: *Principles of Nuclear Reactor Engineering*, S. Glasstone, Van Nostrand, 1955, p. 554.

they are radiation monitored and separated.* The decontaminated gases and liquids are sent to additional tanks for further decay. The high-level liquid concentrates, the insoluble solids, and the resins (from the primary loop ion exchangers) are prepared for "fixation" (see Fig. 12-9).

Fixation is the process of sealing the solid wastes into impervious clays, ceramic glazes, and other chemically inert materials. Fixation may be done aboard ship or ashore, depending on the facilities available. The "fixed wastes" are placed into 50-gal steel drums whereupon they are further sealed in with concrete. They are then ready for burial at sea.

The held-up gases and liquids are diluted and then discharged at sea. Dilution equipment consists of air-blowers (for the waste gases) and saltwater pumps (for the waste liquids). Appropriate piping, valving, and radiation monitoring equipment are provided. When diluted below safe levels, the waste gases are discharged through the ship's mast, and the waste liquids are discharged through the ship's hull (under water). Both types of discharges are automatically monitored by fail-safe shutdown valves, should the radiation levels exceed safe values. This provides the necessary protection to passengers and crew—and to the general public—against the non-vigilant release of radiocontaminants.

SUMMARY

We have discussed only briefly the effort that goes into the design of a nuclear ship reactor to make it as safe and as foolproof as is humanly possible. This is done because nuclear ship safety—at sea or in port—is a dominant criterion of design and because, if unheeded, marine nuclear technology could be set back many years.

Foremost is the recognition that a nuclear reactor is like a fine Swiss watch . . . on a multi-ton scale. It is the heaviest (i.e., from five to ten times heavier than oil-fired boilers) and the most sensitive piece of equipment aboard. As such, it deserves a preferred location, namely, one nearest the center of buoyancy of the ship. This is for hydrodynamic and external damage reasons. The center-of-ship preference holds even for oil tankers and ore carriers which have grown accustomed to aft-end locations of boilers and propulsion plants.

An important index of the self-regulation of a reactor is its "temperature coefficient." This coefficient represents the decrement in fission multiplication experienced by a reactor for each degree rise of its average temperature. A good reference-of-safety value is the *SAVANNAH's* coefficient, which is $-20 \times 10^{-5}/°F$.

Another intrinsic safety feature is the effect of delayed neutrons. These delayed neutrons are capable of maintaining a safe reactor period at all times when changing from one neutron flux level to another. To guarantee this safety, we design limit the control rods so that the variance of the fission multiplication from unity (Δk_e) never equals nor exceeds the fractional yield of delayed neutrons (i.e., 0.0073 for clean reactors). This is done by limiting the Δk_e of each control rod individually, and by limiting all control rods collectively.

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* Ref: "How Radioactive Wastes will be Handled at PWR," J. R. LaPointe, *Nucleonics,* May, 1957, pp. 114 ff.

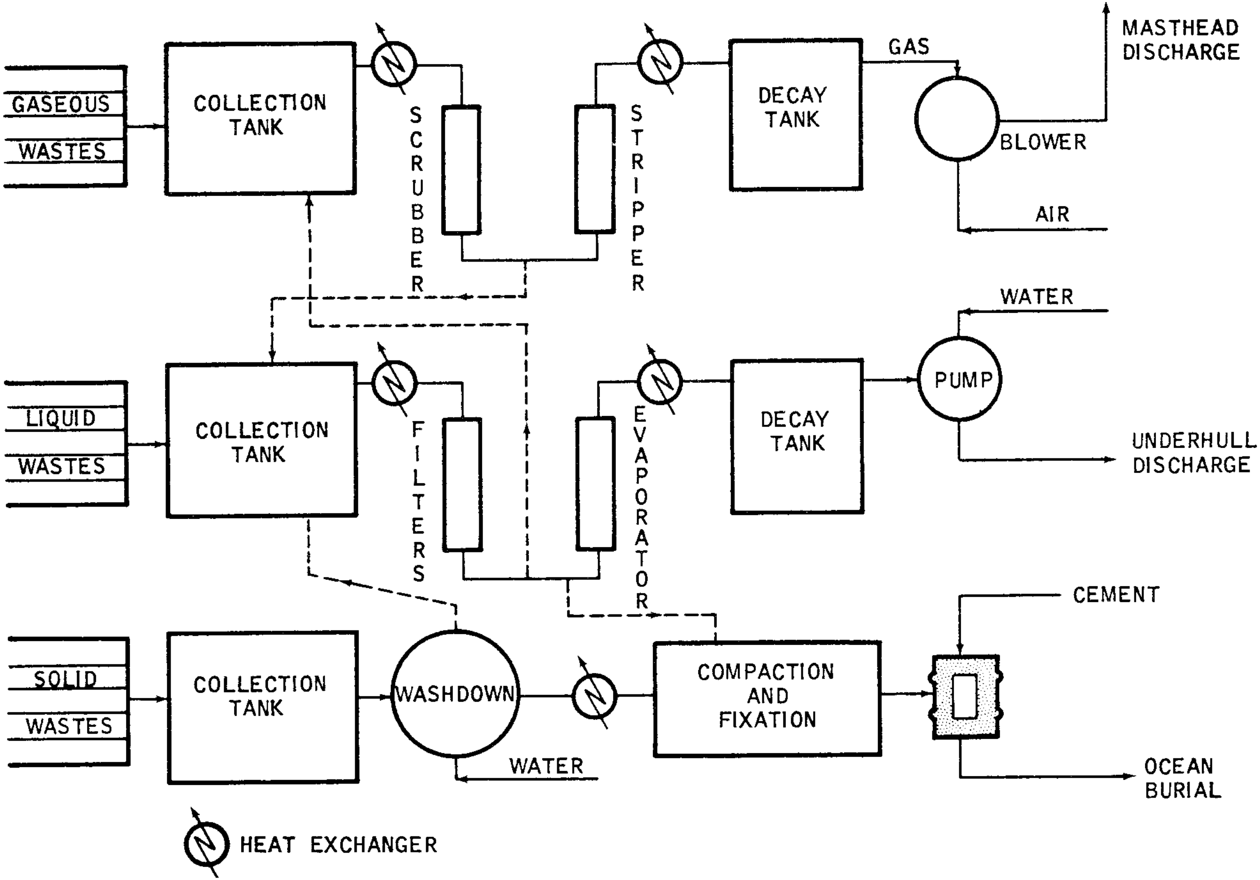

Fig. 12-9 Schematic Arrangement of Radioactive Waste Collection and Disposal System

Additional design safety is by choice of drive motor withdrawal speed (say, 0.0001 Δk_e per sec), and by time-limiting the actuation of these motors. At the end of a specific time (e.g., 3 sec), all rod withdrawal motion stops (electrical interlocks and relays do this). This allows the reactor flux, power, and temperature to level off at a steady state. Then—and only then—manual actuation places the rods into the next sequential step. In other words, the whole gamut of neutron flux levels from criticality to full power is broken up into a series of time-limited steps. The reactor cannot go from one step to the next until it has been self-equalized at the end of each step.

Should any of the control rod safety interlocks fail, the reactor is automatically scrammed. But because of the severity of a scram, there are several degrees of scram action. All are programmed into the control rod system by means of nuclear and non-nuclear sensing devices, a "scram bus," and an "auctioneer circuit."

Should scram effort fail, "last-ditch" shutdown measures are provided. These measures involve the dumping in of great quantities of strong neutron-absorbing materials through special tubes, ports, or other flood-release piping. These flood poisons—contained external to the reactor under pressure—may be released by strategically located manual trips or by automatic safety fuses mounted in the reactor vessel walls.

Should flood-scramming become necessary, the reactor core—in all probability—would have to be replaced. The neutron-induced decay heat from the poisons on the outside of the fuel elements, together with the fission residue decay heat inside the fuel elements, would almost surely melt down the reactor core. However, this indeed rare possibility is taken into account by the design of a containment shell around the reactor vessel and its primary loops.

The reactor containment shell is protected against external damage by means of a "collision shield." This shield can be in the form of a double-hull all around the reactor compartment, for protection against external damage from above, below, forward, or aft of the containment shell, as well as from the sides. In the event of a nuclear ship's sinking, the containment shell is provided with canned and sealed "decontamination valves." Through these valves, the radioactive contaminants can be drained off and collected for safe permanent disposal.

Aside from reactor emergencies, radioactive wastes accumulate during normal reactor operation. These wastes are collected, processed, and—if of sufficiently low level—are released up the ship's mast or through the underwater hull. The higher level wastes are concentrated and "fixed" in impervious clays and ceramic glazes. They are then concrete-sealed into steel drums for subsequent burial at sea.