CHAPTER 13

Regulatory Safety

Every minor accident to a nuclear merchant ship will be scrutinized with public apprehension and alarm. And should there ever be a major marine disaster involving a nuclear ship, very stringent safety regulation would follow indeed. Persons acquainted with maritime history know well the regulatory consequences that followed such disasters as the *MORRO CASTLE* (fire), *GRANDCAMP* (explosion), *ANDRIA DOREA* (collision, *VESTRIS* (foundering), *EASTLAND* (capsizal) . . . and others. To these customary marine hazards, there are now superimposed the hazards of uncontrolled radiation release. Assuming only the slightest radiation release in a nuclear ship accident, it is not difficult to imagine the hysteria and panic that would prevail should the radiation contaminate shores and waterfront facilities, or the coastal air overhead. The only absolutely safe way to avoid these rare possibilities is to not build any nuclear ships whatever. Then, there would be no technical progress . . . and man would not benefit from the potentials at his command. If we want to benefit from nuclear power—and we all do—then we must seek the **proper balance** between the constructive and the suppressive aspects of administrative regulation.

13-1 A "Suppose" Accident

Although every possible design precaution is taken to assure that nuclear ship accidents will not happen, there may arise practical situations in which they will happen. Let us take a hypothetical case, for example.

Suppose that a nuclear ship is underway in a typical American harbor, weather clear and sea calm. Suppose a sport-fishing boat loaded with passengers carelessly veers into a crossing situation with the nuclear ship. Suppose, on its other bow, a tug with two barges is rounding a bend, having obvious difficulty in managing against the tidal conditions at the time. Toward the stern of the nuclear ship, suppose a 70,000-ton loaded tanker is approaching in an overtaking situation. Now this is a perfectly plausible traffic situation (see Fig. 13-1); it happens almost every day in busy coastal ports. It is early morning, so the sport-fishing boat is outbound.

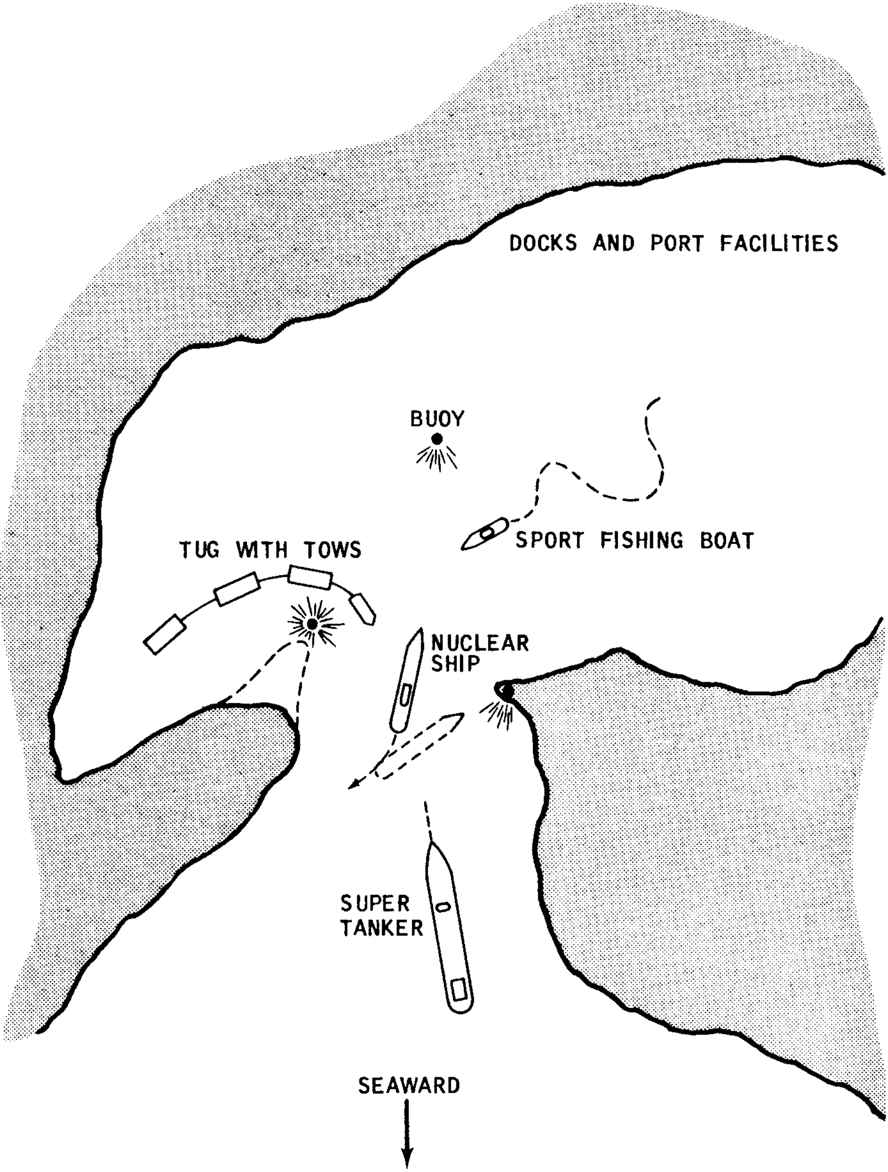

Fig. 13-1 Plausible Traffic Situation in Typical Coastal Port

To avoid the sport-fishing boat, the nuclear ship alters course and sounds the appropriate whistle signal. This is misunderstood by the tug which sounds crossing signals, forcing the nuclear ship to back down hard. This causes the nuclear ship to swing broadside to the tanker which is unable to stop or change course because of her deep momentum. Then—crash! The nuclear ship lists over, her "collision shield" torn open.

The force of the impact scrams her reactor, but opens up some leaks in the radioactive waste collection tanks and piping. Some of the radiocontaminants trickle overboard; some escape into the air. The collision itself brings instant death, say, to two members of the nuclear ship crew.

If such an accident did happen, what would be the immediate public reaction? Chances are, there would be a barrage of newspaper scare headlines, flash radio newscasts, melodramatic telecasts . . . and grapevine hysteria. The general public impression would be: "Two Killed by Radioactivity of Nuclear Ship Collision; Radioactivity Spreading Far and Wide; Reactor Scrammed but May Explode Any Time." This type of public misunderstanding is not a fictitious possibility. We have ample precedence of this from marine disasters of the past; we have recent evidence from minor nuclear mishaps ashore.*

13-2 People Must Be Informed

Because of popular misconceptions concerning radioactivity and the unreasoned fear thereof, there is dire danger that restrictive regulation would be imposed on nuclear ships in every port of call. There are advocates who sincerely believe that *all accidents* can be prohibited. Administrative regulation is the answer, they say.

The foregoing "suppose" accident was purposely contrived as an unavoidable one. Every reasonable safety precaution was taken by the nuclear ship ahead of time, and all participants in the port traffic situation were obeying the rules of the nautical road. Circumstances were such that the accident was bound to happen. There *are* such accidents, we know. Consequently, "inevitable" accidents could never be prevented by administrative regulation. Let us recognize this, otherwise we will lose perspective for the proper role of regulatory safety as it pertains to nuclear ships.

What constructive safety regulation can do is to require an accurate reporting of facts. In a nuclear accident situation, the public mind runs something like this: nuclear energy → bomb → radiation → destruction . . . or genetic malformations.

Let us face it. Sooner or later—despite all human effort to the contrary—there someday will occur a nuclear ship accident and some radiation will be released. But, by far the *greatest hazard* will be **the misinformation that ensues:** not the radiation itself. Sound administrative regulation could minimize the consequences.

For example, in the event of a nuclear ship accident, an emergency "Information Center" could be established. All on-the-scene information

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* Ref: "The Public and Nuclear Risk: Lessons Learned from a Pyrophoricity Incident," *Nucleonics*, Dec., 1956, pp. 34 ff. Also, "Kellogg Radiation Incident—Windscale Reactor Accident," *Nucleonics*, Dec., 1957, pp. 41 ff.

could be reported to this center, and all news reports could be released from it. The information releases must be *honest;* they must be prompt; and they must be in terms that everyone understands. Radiation surveys could be made by rescue craft and converted to equivalences of sun rays, dental X-rays, chest X-rays, etc. This is the only way that people are going to be able to judge for themselves the degree of the hazard involved. High-sounding official and technical descriptions will not do. These can come later when the hysteria subsides.

The gathering and reporting of radiation information from a nuclear ship accident could become another emergency routine. Information Center aircraft could report to the scene, drop buoyed radiation monitors (with radios attached) into the water around the ship, and scoop up air samples overhead. Information Center surface craft could put a radiological safety crew aboard the damaged nuclear ship, and make close-up radiation surveys. One of the "advantages" of nuclear ship accidents (as contrasted to shoreside nuclear accidents) is that natural dilution by air winds and water currents soon renders the radiation harmless.

Not to be overlooked is the importance of mustering all nuclear ship personnel and explaining to them first, what happened and what the status of radiation is. Participants in a nuclear accident become involuntary authorities on radiation (by popular demand), and if not properly informed they can be unintentional bearers of misinformation . . . to their friends and neighbors. Such persons can also be unintentional spreaders of radiocontamination. So, at the same time they are being properly informed, they should be radiation monitored and be relieved of all clothing which is contaminated.

The foregoing is a case where administrative regulation can be constructive. It can establish the systems and procedures for gathering and reporting accurate radiation information. As a regulatory safety measure, this would do much to meet the community reaction of fear, misunderstanding, and protest. This kind of regulation would not suppress the normal operation of nuclear ships.

13-3 The Maximum Hazard Potential

Although the "suppose" accident alleged the leakage of radiation from waste collection tanks, these sources do not constitute the major hazard potential of a nuclear ship. In time, the wastes would be disposed overboard anyhow (recall Sec. 12-11). Instead, the primary hazard potential dwells within the reactor fuel elements. Here, the fission residues build up in quantities that could do real harm . . . if released. These fission residues, recall, are radioactive species of matter resulting from the fission process.

Every fuel atom that is fissioned produces—in addition to useful power—two fission fragments. These atomic fragments are violent disruptions of matter: highly unstable. In seeking to restabilize themselves, they emit beta rays and gamma rays. This emission process (radioactivity) may go on for hours, days, weeks, or years, depending on the energy state of the parent fragment species. There are about 80 different types of parent fission fragments and each radioactivates in one or more characteristic schemes of its own. The result is approximately 200 different daughter products which we call "fission residues." From a mixed-mean conglomerate of these fission residues, the maximum hazard potential (H-P) can be approximated by

$$(\text{H-P})_{\max} \approx 8.88\ \text{P}\ [t_s^{-0.2} - (t_o + t_s)^{-0.2}]\ \text{curies} \qquad [\text{Eq. 13-1}]^*$$

where P = reactor power in watts; t_s = time after reactor shutdown (in seconds), and t_o = reactor operating time (in seconds).

Thus, the hazard potential (H-P) increases in proportion to the useful power (P) derived from a reactor and the duration of its operating time (t_o). The hazard potential decreases the longer a reactor is shut down (t_s). This means that in a nuclear ship accident, if the ship were returning from a long voyage at sea, there would be a greater potential hazard than if she were outbound after being in port for several days.

13-4 Factors Reducing the Hazard

Note the use of the word "potential" in the foregoing paragraphs. The buildup of fission residues in a nuclear ship reactor becomes a public hazard only when the fission residues are released in an uncontrolled (accidental) manner. But, even then, the maximum hazard potential is never realized.

To endanger the health of people, the fission residues must get through **four lines of safety containment.** These are: (1) the fuel element cladding, (2) the reactor vessel, (3) the containment shell, and (4) the ship's hull. All of these are designed with radiation integrity in mind, and with the realization that release may be precipitated from the hull inward or from the fuel elements outward. Because of these design safety aspects, the worst probable release of fission residues would be their continuous seeping out. In this manner, the hazard potential is reduced to only a limited portion of the maximum content.

Upon seeping outside, the true extent of the hazard would depend on the meteorological and hydrographic conditions at the time of a nuclear ship accident. These conditions would disperse the radioactive seepage according to the relationship:

$$\text{H-D} \approx \frac{2Q}{\pi D_y D_z v x^{2-n}}\, 2.718^{\left[-x^{n-2}\left(\frac{y^2}{D_y{}^2}+\frac{z^2}{D_z{}^2}\right)\right]} \qquad [\text{Eq. 13-2}]^\dagger$$

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[*] Ref: "Reactors, Hazard vs. Power Level," T. J. Burnett, *Nuclear Science and Engineering*, May, 1957, pp. 382-393.

[†] Ref: "Evaluating Reactor Hazards from Airborne Fission Products," Mesler and Widdoes, *Nucleonics*, Sept., 1954, pp. 39-41.

where

H-D = hazard dispersal
Q = radioactivity of seepage source (i.e., H-P of Eq. 13-1 reduced to actual seepage)
x = principal direction of external movement (i.e., downwind, downstream)
v = velocity of external transport, downwind or downstream
y = horizontal direction normal to x
z = vertical direction normal to x
D_y and D_z = diffusion coefficients
n = turbulence factor

The Eq. 13-2 relationship tells us several things. One, the farther away we are (y), and the greater the air winds and ocean currents (v), the less the hazard. Two, the hazard diminishes the higher into the air it is carried and the deeper into the water (z). Three, the greater the distance downwind or downstream (x) that the hazard is carried, the more diluted it becomes. However, the downwind, downstream directions from a nuclear ship accident are the most likely hazard-probability areas.

Even so, the hazard would be one of an inhalation or ingestion type only. That is, people would have to *breathe in* or *drink in* the radioactive residues. If certain residues are taken into the body over a long period of time, there could arise some health-harming effects. The relative significance of the residues of concern is presented in Table 13-1. In the column

Table 13-1. Fission Residues of Significance as an Inhalation Hazard

Fission Residue	Radioactive Half-Life	Fission Yield (%)	Inhalation Factor	Dose mrem/μC
Bone Seekers				
Sr-89	50.5 days	4.8	0.22	312
Sr-90	27.7 yrs	5.9	0.22	34,800
Y-91	57.5 days	5.9	0.14	217
Ba-140	12.8 days	6.3	0.20	109
Ce-141	33.1 days	6.0	0.10	30
Ce-144	282.0 days	6.1	0.10	1,160
Thyroid Seekers				
I-131	8.1 days	2.9	0.15	963
I-132	2.4 hrs	4.4	0.15	36
I-133	20.5 hrs	6.5	0.15	227
I-135	6.7 hrs	5.9	0.15	63
Kidney Seekers				
Ru-106	1.0 yr	0.4	0.01	65
Te-129	33.5 days	1.0	0.02	46

Ref: "Reactors, Hazard vs Power Level", T. J. Burnett, Nuclear Science and Engineering, May, 1957, p. 384.

marked "Dose," note particularly Sr-90 (strontium-90): it's a long-lived bone seeker.

13-5 Inspection of Fuel Elements

Now we ask ourselves, from a regulatory safety point of view, what can be done to minimize the possibility of fission residue seepage . . . in the event of a nuclear ship accident? The first and most logical starting area would be the reactor fuel elements themselves. Though designed with maximum integrity in mind, it is a good safety precaution to have the fuel elements inspected by regulatory personnel. Such inspections would be in the form of a "double-check" on the fuel element fabricator, and would be sequenced in consonance with the fabricator's own test and inspection setups.

The inspection of fuel elements would be directly analogous to the inspection of boiler tubes, tube sheets, and boiler fittings on oil-fired ships.[*] These regulatory inspections take place at the manufacturer's plant. Each boiler tube is visually and nondestructively inspected, and, every so often, sample tubes are selected for destructive testing. Upon completion of a set of boiler tubes (for a specific type of boiler), a certification of the inspection is made. The findings of the destructive tests are reported in detail.

The above inspectional procedures on boiler tubes and drums are well worked out, and they are accepted by the maritime industry. There appears to be no reason to change the functional aspects of regulatory safety for nuclear ships. Instead of boiler tubes, we inspect fuel elements. The difference is that more elaborate and *more precise testing techniques* are required. This is because of the high cost of fuel elements, and the high hazard potential if found defective.

The common defects in newly fabricated reactor fuel elements are voids, cracks, inclusions, porosities, bond discontinuities, distortions of the fuel, fuel dispersion non-uniformities, fatigue cracks, welding cracks, and cladding thickness non-uniformities. These defects occur in the cladding material, the end closure welds, the heat transfer bonding, and in the fuel matrix itself. Nondestructive techniques for detecting these defects involve radiography, helium leak tests, thermal tests, dye penetrants, ultrasonics, and eddy currents.[†] A tabulation of these inspectional tests and defects which they uncover is presented in Table 13-2. Fig. 13-2 is one example of a test setup.

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[*] For example, see "Subpart 52.55—Boiler and Superheater Tubes; Subpart 52.40—Tube Sheets of Water-Tube Boilers," *Marine Engineering Regulations and Material Specifications* (for Merchant Vessels), U.S. Coast Guard, March, 1958.

[†] Ref: "Nondestructive Testing of Nuclear Fuel Elements," W. J. McGonnagle, *Nuclear Science and Engineering*, Sept., 1957, pp. 602 ff.

Destructive testing of fuel elements would involve four basic tests, namely: (1) thermal shock, (2) mechanical shock, (3) static pressure, and (4) metallography. Each of these tests would be performed on at least one fuel element (total of four) from a specified reactor core. These tests should closely simulate the maximum dynamic conditions of actual reactor operations. A detailed report on these tests would comprise a permanent official record. This record would be used for subsequent comparisons in the event of actual fuel element failures.

Table 13-2. Typical Nondestructive Tests of Reactor Fuel Elements

Test Type	Defects Disclosed
Helium Leak	Minute holes, cracks, fissures in cladding and end welds.
Penetrants	Surface discontinuities, pinhole defects, machining cracks, forging laps, weld leaks, seam leaks.
Thermal	Heat transfer through cladding (i.e., thermal bond discontinuities or abnormalities).
Radiography	Small internal inhomogeneities; small variations in thickness; dissimilar materials; location of fuel; lack of penetration and fusion in end welds.
Electrical Resistance	Bond defects; surface scale; general flaws.
Eddy-current	Below-the-surface cracks; curved surface defects; differences in physical structure; voids or gas pockets in bonding layer.
Ultrasonic	Nonbonded areas; deep defects; air-solid interfaces; minute variations in density; length and depth of flaw.

13-6 General Leak Testing

There is another area of constructive regulatory safety against radiation seepage possibilities: leak testing the *entire* reactor plant. This includes the reactor vessel, the primary loops, heat exchangers, auxiliaries, containment shell, waste collection tanks, and ship's hull (comprising the reactor compartment). The purpose of leak testing would be to assure that radioactive materials—in any form—would not be released under operating circumstances. For a nuclear ship, leak testing is a major undertaking. But, fortunately, there is ample precedent for this type of effort on non-nuclear ships.

The leak testing and inspection of boilers, pressure vessels, and piping on oil-fired merchant ships has been an established regulatory procedure for many years. The purpose of these tests is to detect leaks, defects, and other weaknesses that could lead to marine casualties at sea . . . or in port. Included in these tests are boiler drums, heat exchangers, feedwater piping, main steam piping, fuel tanks, fuel oil piping, etc.* So, functionally, the testing of nuclear ship plants would merely involve an extension of procedures already in effect. There is one significant difference, however: leak-tight standards for nuclear ships are *far more stringent* than those standards ever considered for oil ships.

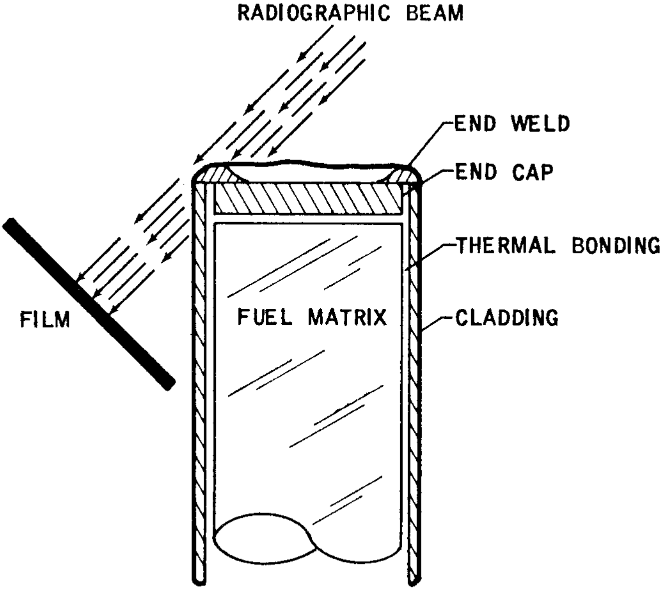

Fig. 13-2 Typical Radiographic Testing of Fuel Element End Weld

On oil ships, leak testing is largely a matter of hydrostatic and pneumatic testing at 1¼ to 1½ times the working pressure. Test sensitivity is by visual examination of surface wetting, soap bubbles, and pressure gauge fall-offs.

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* See "Subpart 61.20—Tests and Inspection of Boilers," "Subpart 61.25—Tests and Inspection of Pressure Vessels," "Subpart 61.30—Tests and Inspection of Piping, Valves, and Fittings," *Marine Engineering Regulations* (for Merchant Vessels), U.S. Coast Guard, March, 1956, CG-115.

On nuclear ships, in contrast, leak tightness within 10 cm^3 per day (about ½ cubic inch per day!) is indicated.[*] The human eye could never detect this infinitesimal leakage. Yet, even this minute amount of radioactive seepage (over a long period of time) could lead to possible health hazards. To detect this leakage, instruments are required which have at least a sensitivity of 1 part in 10,000 parts. In the nuclear field, commercial detectors are available (namely: helium mass spectrometers) capable of detecting 1 part of test helium in 300,000 parts of reactor plant air. To obtain this ultimate in sensitivity, however, the tested surfaces must be scrupulously clean and extreme care must be exercised in the test procedure.

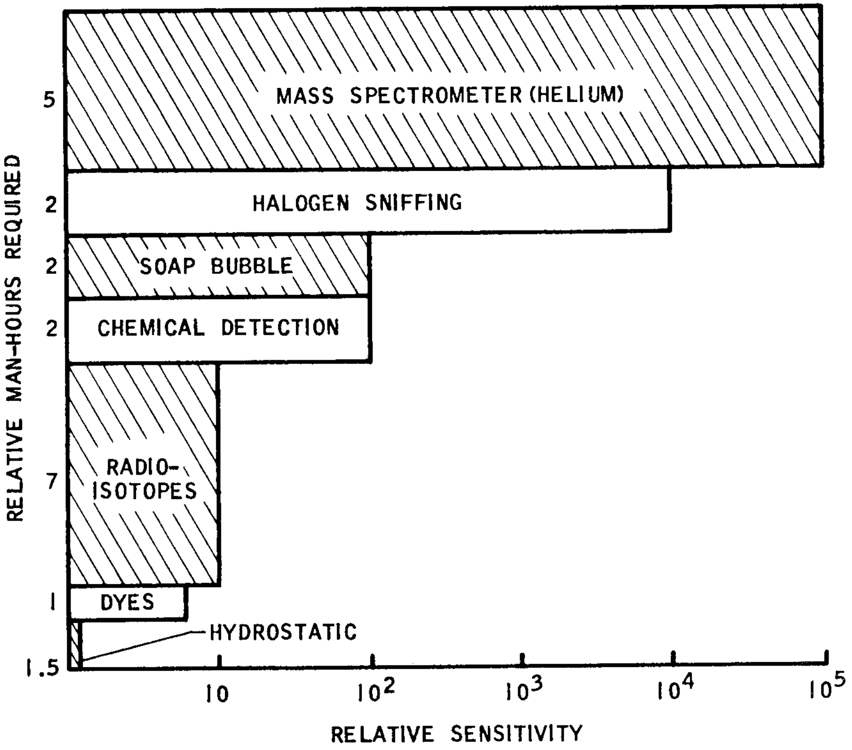

Fig. 13-3 Comparative Sensitivities of Nuclear Leak-Testing Methods

Generally, a progressive program of leak testing is desired. That is, small components and subassemblies are shop tested before being incorporated into larger subsystems. Then the larger subsystems are tested before being installed aboard ship. A final installation leak test is then given. If properly programmed and correlated, sequential leak testing

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[*] Ref: "Testing Nuclear Plant Leaktightness," Verkamp and Williams, *Nucleonics*, June, 1956, pp. 54-57.

can save much rework time, and can use less sensitive but quicker methods for determining the larger leaks. Once the larger leaks are found and repaired, more sensitive—and more time consuming—methods can be used. See Fig. 13-3 for a comparison of the time consumed and sensitivities of nuclear leak detecting methods.

To facilitate testing of the final installation, the basic reactor plant design should be "clean." There should be a minimum of flanges, fittings, openings, and irregularities; there should be primarily seamless construction; welding should be used as the final leak-tight seals. Even with this preparatory effort, the practicalities of shipboard—space limitations, structural irregularities, and poor lighting—make tracking down leaks extraordinarily difficult. This means that specialized leak detection adaptors and probes are required. Table 13-3 describes three types of high-sensitivity leak tests which are adaptable to marine use.

Table 13-3. Helium Mass Spectrometer Tests for Nuclear Plant Leaktightness

Type of Test	Test Procedure	Comments
Hood Test Test item (or section of it) surrounded by plastic "hood"; adaptable where test item can be evacutated.	1. Evacuate test item to 50 microns. * 2. Introduce helium into hood over test item (hood is taped in place). 3. Draw sample of evacuation into spectrometer. 4. Localize leak with fine helium jet.	Tests entire surface; sums total leakage; slow response on large test items; stringent cleanliness required.
Sniffer Test Uses a probe "sniffer" across outer surface of test item; adaptable where test item can be pressurized.	1. Pressurize test item with 20% helium and air. 2. Assure sufficient pressure differential to drive helium through leaks. 3. Pass sniffer probe over outer surface. 4. Pin-point leaks with fine sniffer probe.	Useful for high degree of leaktightness; careful probing is tedious; short hose-length to tester required; efficiency depends on operator's experience.
Boot Test Uses contoured cup or "boot" to outside surface of test item; adaptable to specialized areas of large test items.	1. Apply cup or boot to portion of outside surface of test item; seal tightly. 2. Introduce helium into test item near boot. 3. Evacuate space between boot and surface of test item. 4. Draw sample of evacuation into spectrometer. 5. Localize or pin-point leak with smaller boots.	Permits rapid repetitive testing; requires several boot sizes (single boot not applicable to every test); sealing boot to test item is major problem.

*Micron = micrometer = 0.001 millimeter (recall that 1 atmosphere pressure = 760 mm of mercury).

Once a new nuclear ship is "certified leak tight," there arise operational practicalities which may jeopardize this condition. Geographic temperature changes, hydrodynamic forces at sea, and corrosion may create leaks which did not formerly exist. This suggests that modified leak-tightness inspections be repeated at periodic intervals after a nuclear merchant ship commences service. Such repeat testing, however, must take into account the presence of radioactivity.

13-7 Standards for Radiation Monitors

Once a nuclear reactor is started up, it and its associated plant become radioactivated. Though the radioactivity is originally confined, primary leaks and neutron radioactivation of materials external to the reactor core create buildups and dispersions throughout the over-all plant. Thus, the reactor plant remains radioactivated—to a greater or lesser extent—throughout its entire operational life. It is important, therefore, that we always know what the state of radioactivity is.

To determine this radioactivity, radiation monitors are used. Monitors are instruments which sample, measure, record, and report the state of radioactivity . . . on a continuous or semi-continuous basis. The reporting takes place in the form of meter readings, audible alarms, flashing lights, and closure interlocks which close off access to high radiation areas. Radiation monitors may be fixed, semi-fixed, or portable. Whatever the type, there are a multitude of commercial systems available.

But not all of the commercially available monitoring systems are adaptable to shipboard. The environmental rigors of merchant ship service (i.e., salt atmosphere, humidity, wide temperature changes, vibrations, torsion and flexure, and pounding) necessitate specialized marine equipment: rugged and reliable. It becomes a function of regulatory safety, therefore, to devise marine standards and acceptance tests for nuclear ship radiation monitors.

There is no single, all-purpose radiation monitor. Consequently, one of the first regulatory considerations is the classification of monitor systems into service requirements and application categories. For example, we might require a fixed installation to monitor fission products leaking from the fuel elements into the primary coolant; a semi-fixed system to monitor the primary shielding for leaks; and portable equipment to localize leaks and for general radiation survey purposes. A generalized classification of radiation monitors for shipboard is given in Table 13-4.

The principal feature of a fixed monitoring system is that sample collection lines are permanently installed, and the readout is displayed at the main control console (recall Sec. 6-8). Much sample-collection equipment is required (see Fig. 13-4), and there are different arrangements for sampling gases and liquids.

Fixed systems are employed for continuous monitoring. Semi-fixed monitors, on the other hand, are used for continuous or semi-continuous monitoring, usually for solid materials. The principal feature of the semi-fixed monitor is that it does away with the sample collection subsystem. Instead, the radiation detector is mounted directly on or near the item to be monitored (e.g., primary coolant pump), or the contaminated item is brought to the monitor.

With either the fixed or semi-fixed monitors, it is desirable that two detector heads be used (see Fig. 13-5) in order to obtain maximum reliability and good radiation discrimination.

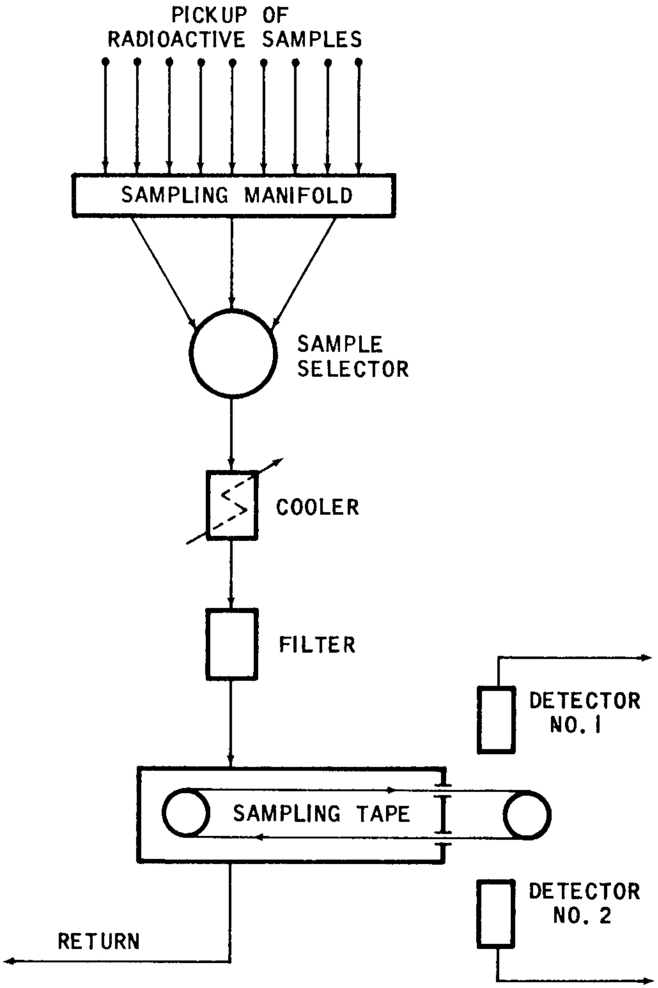

Fig. 13-4 Typical Radioactive Sample Collection for Fixed Monitor System

13-8 Selectivity of Monitors

Each monitor is limited in the type of radiation it will detect. This follows from the sensory element (in the detector head) and the range of its sensitivity (recall Sec. 12-7). We simply cannot devise a detector that will pick up alphas, betas, gammas, fast neutrons, and thermal neutrons—of all energies—all at one time. We must select one type of radiation, and shield out or compensate for the others. If we select gammas, say, we have to determine whether we are going to monitor the low-energy gammas (i.e., less than 3 Mev), or those higher in energy. We can't do both at the same time, unless we use two gamma detectors. Sometimes, too, we have to directionalize the detectors and block out extraneous background and scattered radiations.

The consequence of all of this is that the sensitivity characteristics of the radiation detectors used in monitoring systems must be known. These characteristics must be standardized . . . and they must be posted. In other words, we must know exactly what the detector detects!

Table 13-4. Possible Classification of Radiation Monitors for Nuclear Ships

Type of Monitor	Equipment Involved	Applications
FIXED	(1) Sample Collection ·sampling heads, collection tubes, manifold selector, filters and coolers, sample display, return tubes. (2) Radiation Detection ·detector heads, directional orientation, background shields, signal amplification, electronic circuitry. (3) Console Readout ·meter displays, alarm circuits, warning lights, chart recorder, scale-change switches.	Where continuous monitoring of gases or liquids is required: (1) fission products in primary loops (2) containment shell air (3) overboard waste discharges (4) general area monitoring
SEMI-FIXED	(1) Radiation Detection ·detector heads, detector-head mounts, background shields, signal amplification, electronic circuitry, electrical cabling and plug-ins (note: detector heads may be moved and re-mounted). (2) Panel Readout ·meter displays, alarm bells, chart recorders (when at "warning" level of radiation), control switches, repeaters on main console.	Where continuous or semi-continuous monitoring of solids or large items is required: (1) primary shielding tanks (2) heat exchangers and secondary piping (3) purifiers and demineralizers (4) large tools, auxiliary equipment (5) hand-and-foot counters (6) personnel access closures
PORTABLE	(1) Hand-Carrying Detectors ·detector head, housing, electronic circuitry, and meter readouts all self-contained, timers. (2) Shoulder-or Dolly-Carrying Detectors ·long-arm detector probes, meter readouts convenient for operator, electronic circuitry and power supply separately housed, timers and buzzers.	Where special monitoring is required, and where radiation readings are separately recorded: (1) plant maintenance and refueling surveys (2) localizing leaks and survey of spills (3) survey of solid wastes (4) small tools, clothing, isolated "hot spots"

If we are worried about strontium-90 (a soft beta emitter), we can't detect it if we are using a monitor sensitive to, say, nitrogen-16, which is a combined hard beta and hard gamma emitter. Nitrogen-16, incidentally, is a prevalent radioisotope in the air around the reactor (see Table 13-5) and it is of more practical concern than strontium-90. Hence, regulatory safety could establish appropriate specifications for identifying the type of radiation being monitored.

The usual readout units of radiation monitors are: (1) counts per minute (cpm), (2) microcuries (μC), (3) milliroentgen per hour (mr/hr), and

(4) neutrons per centimeter squared per second (n/cm^2-sec). Each of these units is scaled to the particular type and energy of the radiation being monitored. No one radiation measuring unit is universal, though all units can be converted to biological tolerances in mrem/hr.[*] Accordingly, regulatory safety could establish standard conversion factors (mounted on each monitor) and relate them to biological tolerances which are placard-displayed throughout the nuclear ship. This would enable operating personnel to evaluate immediately the state of radioactivity present.

Table 13-5. Radioactivity of Air Passing Near or Through Reactor

Radioisotope	Neutron Cross Section	Half-Life	Betas (Mev)	Gammas (Mev)
Nitrogen-16	0.08 mb	7.3 sec	3.8 4.3 10.5	6.2 6.7
Oxygen-19	0.22 mb	29 sec	2.9 4.5	1.6
Neon-23	0.04 b	40 sec	1.2 4.2	3.0
Argon-41	0.6 b	1.9 hr	1.2 2.5	1.4

Air contains 78.03% Nitrogen; 20.99% Oxygen; 0.94% Argon; and 0.0012% Neon.

One liter of air remaining for one second in a neutron flux of 10^{12} n/cm^2-sec produces the following radioactivity:

Argon-41	14,000 dps (disintegrations per sec)
Nitrogen-16	1,000 dps (note the "hard gammas" above)
Neon-23	400 dps
Oxygen-19	100 dps

Ref: "Detection of Breaks in the Cladding in Gas Phase Cooled Reactors", Labeyrie and Roguin, Vol. 3, Geneva Conference, 1955, p. 86.

We should not overlook the fact that radiation monitors themselves become radiocontaminated, particularly the sample collection lines and the detector heads. Over a period of time, the buildup of self-contamination may lead to erroneous readings or to complete failure of the monitoring equipment. This imposes the necessity for periodic monitoring (with portable instruments) of the monitor systems, and the necessity for periodic recalibrations. Here again, regulatory safety could devise standards and procedures.

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[*] For example:

$$1 \mu C = 2.22 \times 10^6 \text{ dpm} \quad (\text{dpm} = \text{cpm} \times \text{instrument scaling factor})$$

$$1 \text{ mrem/hr} = \frac{6 \times 10^6 \, E \mu C}{d^2} \quad (E = \text{energy in Mev; } d = \text{distance in ft})$$

$$1 \text{ mrem/hr} = \frac{4.83 \times 10^{-23}}{\sigma_s E} \text{n/cm}^2\text{-sec} \quad (\sigma_s = \text{neutron scattering probability, barns})$$

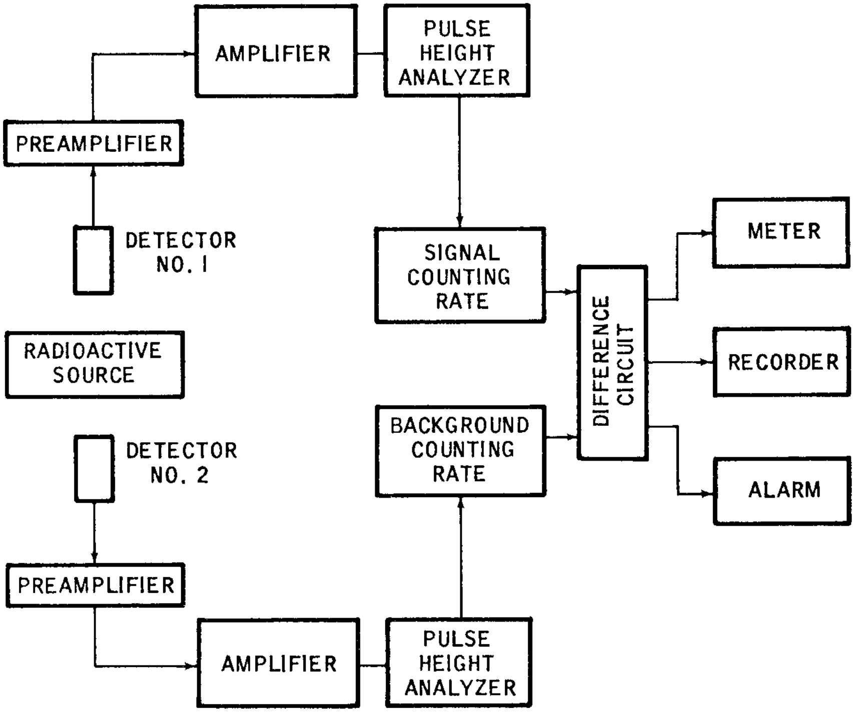

Fig. 13-5 Typical Detection and Readout Circuit for Radiation Monitor System

13-9 Control of Waste Disposal

Under proper conditions, it is perfectly safe to dispose of radioactive wastes at sea. These "proper conditions" involve: (1) low level wastes, (2) high dilution factors, and (3) considerable distances off shore. To assure that these conditions prevail, regulatory safety procedures could be promulgated.

The primary concern about dumping nuclear ship wastes into the ocean is the pickup of the radioactivity by aquatic life and the possible subsequent consumption by humans. The amount of pickup (in trace quantities) is dependent upon the chemistry of the radiowastes and upon the physiological nature of the aquatic species. Plankton, which are the small animal and plant organisms in the upper strata of seawater, absorb radioactivity most readily.* These plankton, in turn, are eaten by caddis larvae, which in turn are eaten by minnows . . . then by squid . . . small fish . . . medium fish . . . large fish, up to the size of salmon, tuna, and swordfish. These larger fish, in turn, are eaten by humans. This is the biological cycle of the seafood chain.

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* Ref: "The Accumulation of Radioactive Substances in Aquatic Forms," Foster and Davis, Vol. 13, Geneva Conference, 1955, pp. 364 ff.

Each organism in the food-step acts as a filter and reservoir which decreases the transfer of radioactivity to the next higher form. Simultaneously, the radioactivity undergoes natural decay as the fish go from one water-depth stratum to the next. When the large fish are caught, the radioactivity is considerably weakened.

It is conceivable, nevertheless, that some fish could become radioactive to the point of being unfit for human consumption. This was thought to be the case in the tuna market of Japan in 1955.* During the period of concern, many fish were found radiocontaminated and ordered disposed.

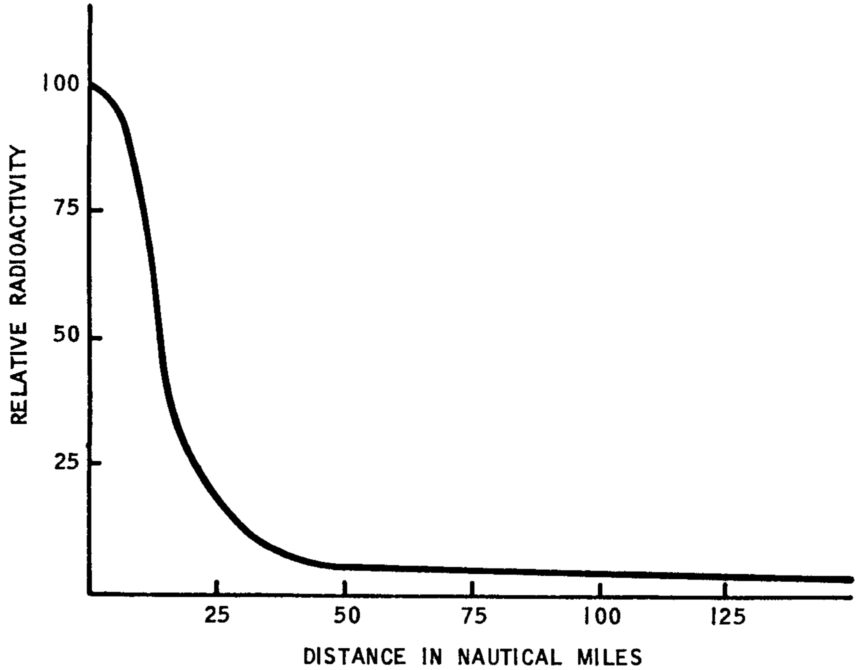

Fig. 13-6 Radioactivity in Plankton with Distance from Point of Disposal

The percentage of contaminated fish, however, was only about ½% of all fish examined. Further investigation revealed that these fish were contaminated by nuclear bomb-test fallout, mostly on the decks of fishing boats. We want to emphasize that this extent of seafood radioactivity is considerably above that ever expected from normal nuclear ship operations.

Nevertheless, to protect the fishing waters of the world, regulatory safety standards could be prescribed for the disposal of radioactive wastes at sea. In addition to safe release levels (e.g., say, 10^{-6} $\mu C/cm^3$), regu-

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* Ref: "Biological Cycle of Fission Products Considered from Viewpoint of Contamination of Marine Organisms," Y. Hiyama, Vol. 13, Geneva Conference, 1955, pp. 368 ff.

latory standards could stipulate the dilution factors (e.g., say, 10,000 to 1) at time of release. Waste disposal in port or along coastal shores, of course, would be prohibited. Minimum distances for release offshore might be at least 50 miles . . . preferably 100 (see Fig. 13-6). Remember, we are considering only large, fast ocean ships traveling many thousands of miles (recall Ch. 2). So, distant offshore disposal grounds would not inconvenience nuclear merchant ships.

The waste disposal compliance with regulatory standards would take two forms. One, a *permanent radiation monitoring record* would be made on all gaseous and liquid waste discharges.* This would be done by automatic instrumentation requiring only the periodic changing and dating of paper charts. Secondly, in the case of solids (i.e., 55-gal concrete-in-steel drums), the sea position, date, and time of disposal would be recorded in the Ship's Log. The nuclear ship's Master would be responsible for recording this information, along with his other regulatory record-keeping duties. In port, both forms of records would be available for examination by regulatory personnel.

13-10 Calibration of Control Rods

Back in Secs. 4-8 and 12-5, we told how the use of control rods changes the Δk_e (excess fission multiplication) of the reactor core, thereby producing changes in the neutron flux and reactor period. We didn't say so, but the inference was that the Δk_e changes were a linear response to the control rod positions. Unfortunately, such linearity is not the case. When we change the position of a control rod, we do not know (exactly) what the corresponding change in Δk_e will be. This leads us to the necessity for calibrating the control rods.

There are at least four methods for calibrating control rods (see Table 13-6) and other methods may evolve as marine reactor technology unfolds. Each method requires a certain amount of time and equipment, and each method gives results applicable only to conditions under which the calibration was performed. A calibration performed when a reactor is new will not be valid after the reactor has operated for a period of time. For safety reasons, calibration is usually done at low power levels and for safe reactor periods. This is a handicap, as only a small portion of the uppermost control rod range can be calibrated. Yet, a precise knowledge of Δk_e—under all conditions of control rod motion—is vital to nuclear ship safety.

It is appropriate, therefore, that standardized calibration and re-calibration procedures be adopted. Establishing these procedures, and confirming their results, would be a constructive function of regulatory safety. The situation can be likened to the regulatory aspects of calibrating safety valves and steam gauges on oil-fired merchant ship boilers.

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* Ref: "Ocean Disposal of Radioactive Waste," *Nucleonics*, Dec., 1954, p. 54.

The calibration method nearest simulating actual operating conditions is probably the "bump-period" method of Table 13-6. But calibrating one control rod takes about four hours' time.* In the case of a multi-rod reactor (e.g., the *SAVANNAH* with its 21 rods), it would be impractical to calibrate each rod independently of all others. Hence, practical judgment suggests that only the regulating rods be calibrated (of which typically there are four: see Fig. 13-7), with the calibration carried out for specified gang settings of the shim rods. For purposes of definition, shim rods make appreciable step changes in Δk_e. The regulating rods then permit vernier adjustments in Δk_e . . . within a designated shim rod setting. These two types of control rods are sometimes called fine and coarse rods, respectively.

Table 13-6. Typical Methods for Calibrating Control Rods

Method	Principle	Comments
BUMP PERIOD	Reactor power level made steady; rod withdrawn a measured distance; corresponding reactor period noted; repeat about 12 times for each rod under calibration; Δk_e computed for each value of reactor period.	All transients must die out before each new data point taken; requires recently calibrated period meter; extreme caution required when calibrating at maximum flux levels.
ROD DROP	Reactor power level made steady with rod withdrawn; record neutron detector response C_1; rod suddenly "dropped"; record instantaneous neutron response C_2; Δk_e computed from $\beta \left(\frac{C_2 - C_1}{C_2}\right)$.	Finite length of time to drop rod makes determination of C_2 difficult; repeated dropping of rods can be severe on control system.
ROD OSCILLATED	Pneumatic oscillating device attached to rod; limit stops allow selection of oscillating amplitude; frequency of rod oscillations varied; average rod positions given by selsyns; period measured for each oscillating frequency; Δk_e computed for each value of period.	Requires disconnecting regular control rod drives; once oscillator attached, time consumed per data point is small; rod amplitudes from 0.5 to 1.5 inches; requires oscillator frequency measuring devices.
SOURCE JERK	Rod fixed at definite height, reactor made critical and leveled off; neutron source introduced into core region; record neutron detector response C_1; jerk source out and record C_2; Δk_e computed from $\beta \left(\frac{C_1 - C_2}{C_2}\right)$.	Measures subcriticality state of reactor; requires special "thimble" for introducing neutron source into reactor; jerk-out or blow-out time of source must be less than shortest delayed neutron emitter.

The bump-period calibrating procedure involves bringing the reactor to shim criticality at a specified power level . . . and letting it level off there.† Then the regulating rod under calibration is withdrawn or

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* Ref: "Calibration of Control Rods," Jankowski, Klein and Miller, *Nuclear Science and Engineering,* May, 1957, pp. 289 ff.

† Ref: "Experiment 7-3: Startup, Calibration of Control Rods, and Shutdown of a Reactor," J. B. Hoag, *Nuclear Reactor Experiments,* Van Nostrand, 1958, pp. 206 ff.

"bumped" a small measured distance (determined by rod position indicators) and the associated reactor period $T^{\bullet}$ is noted (on period-measuring meters). The regulating rod is returned to its zero position and the reactor re-leveled off at its previous power level. The regulating rod is withdrawn a slightly larger measured distance and again the reactor period noted. The procedure is repeated (each time returning to the original power setting) until the reactor period becomes undesirably short. The result is a compilation of period data $T^{\bullet}$ versus position of the regulating rod. Approximately twelve data-points are required for each rod under calibration.

The period data $T^{\bullet}$ is converted to its Δk_e equivalent by means of the expression

$$\Delta k_e \approx \frac{\bar{l}}{T^{\bullet}} + \sum_{i=1}^{i=m} \frac{\beta_i}{1+\lambda_i T^{\bullet}} \qquad \text{[Eq. 13-3]*}$$

where $\bar{l}$ = neutron lifetime, β_i = fraction of delayed neutrons of i-th group, and λ_i = decay constant of i-th delayed neutrons. These values are determined from the physics of the reactor core at the time of calibration (Table 12-1). Since $T^{\bullet}$ is in terms of rod position, we therefore get Δk_e also in terms of rod position. We then plot this information as a calibration curve typified in Fig. 13-8. Presumably, regulatory safety would require the preparation of a calibration curve for each regulating control rod.

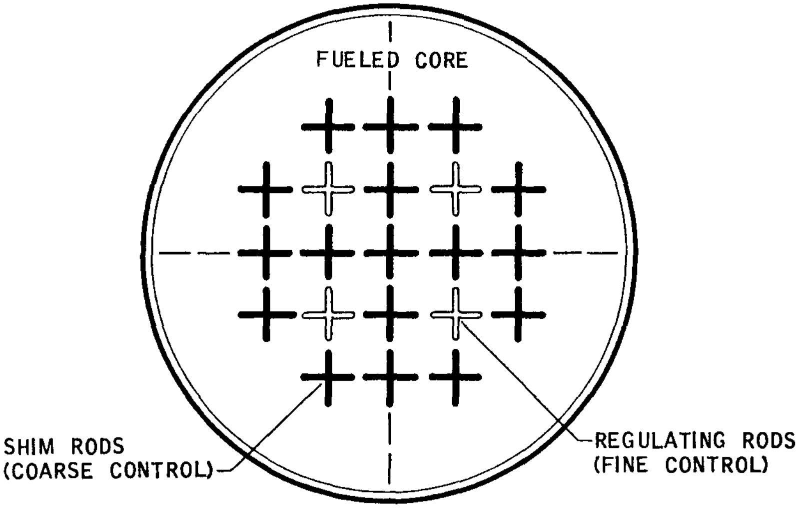

Fig. 13-7 Typical Distinction Between Reactor Control Rods

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[*] The Σ is a summation symbol meaning the addition of all i-terms.

13-11 Calibration of Neutron Sensors

The neutron sensors used for reactor control (Sec. 12-7) are continuously getting out of calibration. The principal reasons for this are (1) changes in relative position and "worth" of control rods, (2) variations in temperature, (3) deterioration from gamma fluxes, and (4) natural drifts in sensitivity. Consequently, when calibrating control rods, we should calibrate simultaneously the neutron sensors.

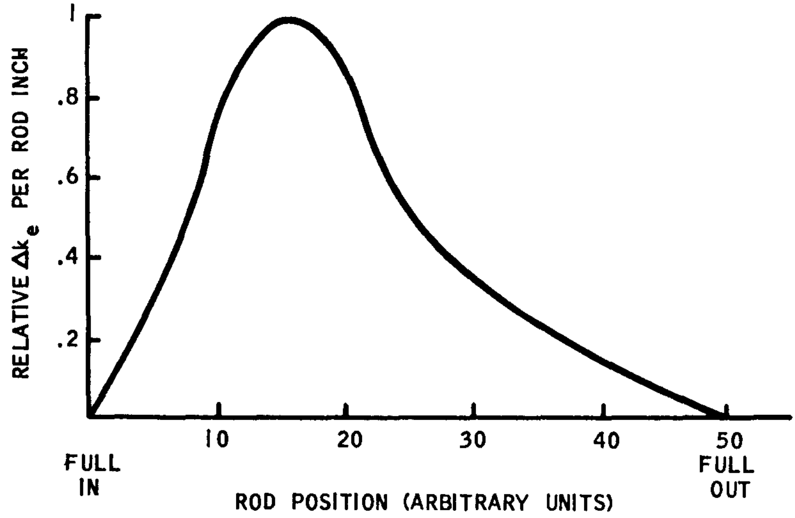

Fig. 13-8 Typical Calibration Curve for Control Rod

The common procedure for calibrating neutron sensors is the "foil" technique. Accurately measured thin foils of indium, cadmium, or gold are exposed—for a measured length of time—to the neutron flux seen by the control sensors. The foils are removed (special handling equipment is required for this) and their neutron-induced radioactivity (A_r) is determined. This A_r determination is made by radiochemical analysis and radioactivity counting-rate methods (again with special equipment). The true neutron flux ϕ is then determined from the relationship

$$\phi = \frac{A_r}{N\sigma t}, \quad n/cm^2\text{-sec} \qquad [Eq.\ 13\text{-}4]^*$$

where A_r = number of foil atoms irradiated, N = total number of foil atoms originally present, σ = neutron capture cross section of each foil atom, t = time of exposure in seconds.

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[*] Ref: "Calibrating Power Level of a Water-Boiler," Flora and Shortall, *Nucleonics*, Jan., 1956, pp. 67-68.

The true flux (Eq. 13-4) is compared with the flux recorded by the control sensor. This gives one calibration point. A series of foil exposures (calibration points) is taken and a calibration curve prepared. Here, too, presumably, the establishment of procedures and standards for calibrating control sensors would be a function of regulatory safety.

13-12 Qualification of Reactor Operators

The manual control of a reactor is a delicate operation. The rapidity and finality with which disasters take place are functionally analogous to the take-off and landing of a large aircraft. Instrument consoles with myriads of knobs, buttons, switches, dials, meters, and lights confront the operator. In a moment of hesitancy or human error, he could bring misfortune to the aircraft . . . or meltdown to the reactor.

A clear example of this operational delicacy was the EBR-1 meltdown incident at the Argonne National Laboratory in late 1955.* An experiment was in process with the reactor on a 0.27 sec period. Special fast-acting scram rods were to be manually tripped upon visual signal from short time-constant instruments. Upon receiving the proper signal, the reactor operator pressed first the wrong button, then the right one. The time delay was not more than two seconds. But this was sufficient to cause reactor runaway . . . and meltdown.

Those who design nuclear ship reactors are aware of the necessity for precaution in the manual startup and operation of reactor controls. To assist in this regard, a "procedure panel" generally is part of the control console design. This panel is a series of lights which come on successively as the various conditions are satisfied for safe warmup, startup, steamup . . . and shutdown. But these lights are no substitute for operating personnel who must sequentially push buttons, energize relays, open valves, turn knobs, watch meters, check recorders, listen to annunciators, etc. These and other procedures require **human competence and discretion** to assure that the reactor is in a safe status at all times.

In the case of reactors, the degree of human operator competence required is considerably above that required for the operation of high pressure boilers on oil-fired ships. In the latter case, operating personnel must meet certain regulatory requirements with regard to technical training and experience. To attest to this, written qualifying examinations are given.† It can be anticipated, therefore, that regulatory qualifications would be extended also to nuclear ship personnel.

There are two major differences in the operator qualifications for reactor plants as compared with boiler plants: one, the supreme necessity for reliance on control instrumentation; two, the possible presence of radioactivity (fuel element leaks, shielding leaks, waste tank leaks) and the

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* Ref: "A Letter on EBR-1 Fuel Meltdown," W. H. Zinn, *Nucleonics*, June, 1956, p. 103.

† Ref: "Licensing and Certificating of Merchant Marine Personnel," U.S. Coast Guard (CG 191), Sept., 1955, Subpart 10.10 (Professional requirements for engineer officers' licenses) and Subpart 12.15 (Qualified members of the engine department).

psychological consequences thereof. The fear of radioactivity can be overcome by sound indoctrination in nuclear processes. This, however, places even more reliance on instrumentation. Thus, the reactor operator aboard a nuclear ship must become an *instrumentation specialist.*

All in all, over 100 different types of instruments may be required aboard nuclear ships. Not only must operating personnel read these instruments—the correct scales and correct units—they should know something of the technical principles on which the various instruments work, and the limitations, inaccuracies, and reliabilities thereof. Instrument failures do occur . . . sometimes too frequently. So human operators must be capable —and alert—to detect these failures, and to take corrective action. To do this properly, adequate training is needed. This could be done in conformance with regulatory safety requirements.

One way to provide the necessary operator training is through the use of reactor "simulators." A simulator console consists of meters, recorders, knobs, and switches which are replicas of those on the actual reactor control console itself. These simulator instruments, however, are actuated by servo-components and computers which can be designed to simulate virtually any operational phenomenon of a live reactor. A very high degree of realism can be achieved.* A separately mounted panel enables an instructor to inject various trouble conditions and emergencies. Trainee performance can be checked and valuable experience can be gained without jeopardizing the safety of the reactor plant or the safety of the operators themselves.

But there can be no all-purpose simulator: each is designed to match the characteristics of one particular type of reactor plant. An operator checked out on one type of simulator—say, one simulating a pressurized boiling water reactor—would not necessarily be qualified to operate another type of reactor, say, a gas cooled system. The situation is analogous to the checkout of pilots in aircraft. Each power plant has some similarities to others, but differences in fundamental design spell major differences in performance capability, response to control, and the magnitude of the mishaps involved. Hence, regulatory standards would differentiate between operator qualifications so that an operator qualified for one class of reactors is not given carte blanche license to operate all reactors.

13-13 General Operational Checkout

When reactor personnel have been qualified, control rods calibrated, radiation monitors installed, and leak tightness and other inspections made, the next regulatory concern is an operational checkout of the overall reactor plant.† The checkout is performed in logically sequential

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* Ref: "PWR Training Simulator," Franz and Alliston, *Nucleonics,* May, 1957, pp. 80-83.

† Ref: "How to Test a Nuclear Plant," *Nucleonics,* Oct., 1954, pp. 22-25.

phases and no phase is performed until its predecessor phase is complete. This precaution is mandatory for safety reasons. However, it also affords operating personnel the opportunity to familiarize (or re-familiarize) themselves with the plant and to establish confidence in its performance capabilities. Functionally, the over-all checkout is somewhat as illustrated in Fig. 13-9.

The role of regulatory personnel during the checkout phase would be one of verification of results only, not of operational responsibility. This responsibility rests with the nuclear ship operator (in conjunction with the reactor designer, if a new reactor). The operating organization thereby is permitted to work out safe procedures and detailed sequences within each phase of the checkout program. The presence of regulatory personnel would give a note of officialdom to the checkout. This officialdom, then, becomes a form of notice to the public that the ship operator is capable of operating the nuclear ship with all necessary regard for human safety.

Of particular regulatory concern is that the ship's organization clearly delineate the one person responsible for reactor safety in situations of "imminent emergencies."* In other words, the question must be answered: who has authority to break routine and order the reactor scrammed? On nuclear merchant ships, this authority would be vested in two persons, each under nonconflicting sets of circumstances. Regulatory procedures would spell out these circumstances.

Normally, on merchant ships the Chief Engineer has sole responsibility for the engine department and the safety of that which it contains. The Master communicates operational requirements to the engine department via telephone and telegraph. The Master has no authority to shut down the boiler plant without going through the Chief Engineer. This aspect of responsibility and authority would be different on nuclear ships.

Suppose a collision were imminent. If so, there would not be time to communicate to the engine department in the normal way. Under such circumstances, public safety becomes the dominant concern. Therefore, the Master must have authority to shut down the reactor directly from the bridge. If, on the other hand, a reactor emergency were imminent, the Chief Engineer must have authority to shut down, regardless of the operational requirements of the ship. Here, then, are two situations—and there are others—requiring the careful delineation of reactor safety responsibility.

Following each emergency shutdown of a reactor, a written report would be made. This report would be a regulatory requirement, and would follow existing procedures for other forms of engine or ship casualty reports.

13-14 Coordination of Safeguards

There is one remaining aspect of regulatory safety which we should discuss with rational, unemotional candor. This pertains to the great

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* Ref: "AEC Inspects Reactors for Safety," *Nucleonics*, March, 1955, pp. 25-27.

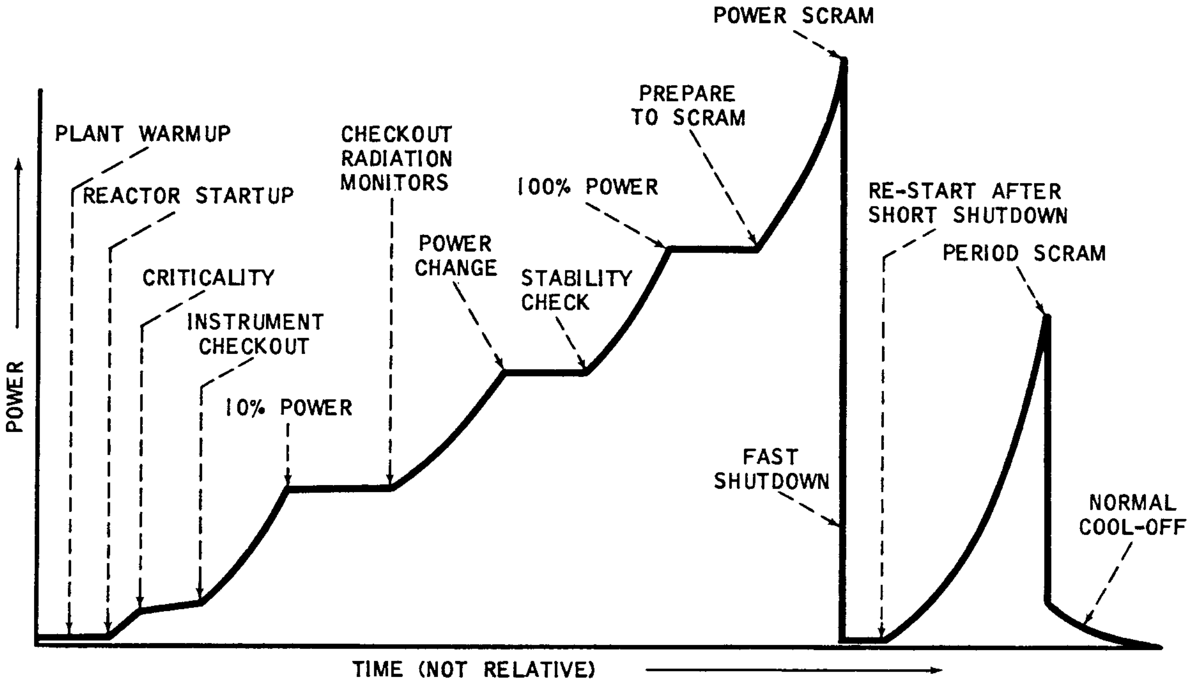

Fig. 13-9 Functional Representation of Over-all Reactor Plant Checkout

number of regulatory agencies, and the many divisions and offices thereof, that have legitimate interests in nuclear ship safety. The existence of so many regulatory bodies is a hazard potential in itself. Too many agencies: too much regulation . . . overlaps, conflicts, oversights. This, as a trigger mechanism, could lead to a really major nuclear ship disaster.

Because of the fear of such a disaster, there could be a deluge of nuclear ship regulation from shipping company operating departments, municipal bodies, state bureaus, federal agencies, and international commissions. Why? Because none of these bodies wants the public finger of scorn pointed at it, should there ever be a major nuclear ship accident. Each regulatory body is motivated by the innate desire to protect itself, and one way of doing so would be to prescribe an abundance of regulation . . . to be on record. Each would attempt to define the objectives of safety in its own terms; each would strive for absolute safety.

Here are some examples of the type of regulatory stringency that could be imposed. It might be required that a nuclear ship in port have its shim rods locked and sealed by port inspectors, who would permit only the use of regulating rods for in-port power changes. All radiation waste disposal outlets (i.e., mast exhaust and underwater discharges) might be plugged and monitored around the clock. Docking might be limited to remote assigned areas and movement in the harbor might be limited to daylight only. Some port authorities might even prohibit nuclear ships from entering port at all! This type of suppressive regulation indeed would be a serious blight on the progress of nuclear merchant ship technology.

Interestingly enough, one of three primary missions of the *SAVANNAH* is to probe regulatory pitfalls as she moves from port to port, country to country.* The experiences and information that she gathers will be invaluable to other nuclear merchant ships that follow. Those who conceived of this "regulatory probe" of the *SAVANNAH* are to be commended for their practical foresight.

We can anticipate, even now, one of the basic outcomes of the regulatory probe. Chances are, there will be some form of recommendation that a coordinative body be established (possibly on a committee or council basis) to coordinate all nuclear ship regulatory safeguards. The need for coordination of this type is inevitable.

When a merchant ship (nuclear or otherwise) has complied with applicable regulatory safeguards, a certificate or document is issued in attestation thereof. This attestation is a piece of paper. Difficulties arise because there are many pieces of paper, issued by many regulatory agencies, by many departments within an agency, by many local branches

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* The three primary missions are (1) exhaustive AEC checkout of reactor safety and performance; (2) Maritime Administration regulatory exploration in entering-clearing U.S. and foreign ports; and (3) commercial operation in competitive passenger-cargo markets. Ref: "Nuclear Merchant Ships—First U.S. Ship Nears the Ways," *Nucleonics,* Nov., 1957, p. 79.

of a department, by many people in a local office, under many different degrees of regulatory compliance (see Table 13-7). There is a revealing amount of duplication in these pieces of paper. The dissatisfying result is that no one piece of paper brings together all supporting pieces of paper into an over-all Nuclear Safety Certificate . . . contributed to and honored by all.

Table 13-7. Typical Certificates Issued by Federal Agencies Attesting Merchant Ship Safety

Non-Nuclear Ships

1. Certificate of Classification - Hull
2. Certificate of Classification - Machinery
3. Equipment Certificate for Anchors
4. Equipment Certificate for Boilers
5. Equipment Certificate for Tailshaft
6. Equipment Certificate for Wire Rope
7. Seaworthy Certificate
8. International Load Line Certificate
9. Certificate to Carry Oil in Bulk
10. Certificate of Ratproof Construction
11. Drinking Water Certificate
12. Vessel Sanitation, Record of Inspection
13. Certificate of Safety Inspection
14. International Safety Certificate
15. Certificate of Radio Station Inspection
16. Certificate of Radar Station Inspection
17. Certificate of Cargo Handling Equipment
18. Record of Dangerous Cargo Inspection

Nuclear Ships (?)

19. Certificate of Fuel Element Inspection
20. Certificate of Leak-Tightness Inspection
21. Certificate of Radiation Monitor Inspection
22. Inspection of Waste Collection System
23. Calibration of Control Rods and Sensors
24. Certificate of Reactor Plant Inspection
25. Certificate of Health Physics Inspection

Hence, as a final regulatory safety measure, we postulate the necessity for **one** Nuclear Ship Safety Certificate . . . *and no others.* We add, however, that this one certificate should provide a checklist of compliance with every regulatory or quasi-regulatory body concerned. In other words, this one piece of paper carried by a nuclear merchant ship would express the coordination of all regulatory safeguards toward a common goal. Such an achievement would be the supreme valor of regulatory safety.

SUMMARY

We have only touched upon some of the constructive areas where nuclear ship regulatory safety could prevail. There are other areas, but they create a grave danger: that of suppressing the technical progress of nuclear merchant ships.

Despite all safety regulation, marine accidents do happen and, sooner or later, a nuclear ship will be involved. A plausible case is that of a collision resulting in the release of some radioactivity, say, from its damaged waste collection tanks. Any spread of the radioactivity would induce panic and hysteria among the port citizenry. But, actually, the greatest harm would be the spread of misinformation—not the radiation itself. Instead of restraining nuclear ship activities, good regulation would require an accurate reporting of radiation facts, and would establish procedures for determining same.

Sound regulation could help reduce the possibilities of accidental radiation release. This could be done through a well-defined program of fuel element inspection, and through leak-tightness inspections of the over-all reactor plant. Fabrication defects can be determined in advance of reactor operation, and the in-service leakage possibilities can be minimized by "clean" reactor designs.

But operating leaks inevitably will arise due to temperature changes, hydrodynamic forces, corrosion, and other practicalities of a nuclear ship at sea. In this case, regulatory standards could prescribe the use of radiation monitors and could stipulate standards for their construction, sensitivity, identification, readout, and calibration. Of the numerous types of radiation monitoring equipment commercially available, many are not sufficiently rugged and reliable for merchant ship service at sea.

Helpful regulatory measures could prescribe procedures and conditions for calibrating reactor control rods and neutron sensors. Unfortunately, control rods do not induce linear changes in Δk_e (excess fission multiplication) corresponding to linear changes in control rod positions. The true Δk_e response must be determined by calibration procedures which are time consuming. Neutron sensors require calibration because of: (1) changes in relative position and "worth" of control rods, (2) variations in reactor temperature, (3) deterioration from gamma fluxes, and (4) natural drifts in sensitivity.

We expect that regulatory personnel would verify the various operational checkout phases of the reactor plant, its auxiliaries and subsystems. This verification would constitute notice to the public that personnel aboard a nuclear ship were capable of operating the ship with all necessary regard for human safety. Special delineation of reactor shutdown authority between the Master and Chief Engineer would be prescribed for "imminent emergencies."

There are a great number of—too many—regulatory bodies and authorities (including private shipping company operating departments) that would prescribe various facets of nuclear ship safety. This situation alone could constitute the triggering mechanism to a really major nuclear ship disaster. Such a disaster could arise through administrative conflicts and oversights in processing the many pieces of paper (called certificates) which attest to compliance with "applicable regulations." The hazard is much regulatory duplication and unnecessary harassment of nuclear ship operating personnel. To minimize this hazard, why not just one piece of paper—a Nuclear Ship Safety Certificate—contributed to and honored by all regulatory bodies? An achievement of this kind would constitute the greatest single regulatory inducement to an accident-free nuclear merchant marine.