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OCCUPATIONAL RADIATION EXPOSURE FROM U.S. NAVAL NUCLEAR PLANTS AND THEIR SUPPORT FACILITIES

NAVAL NUCLEAR PROPULSION PROGRAM
DEPARTMENT OF THE NAVY
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OCCUPATIONAL RADIATION EXPOSURE

FROM U.S. NAVAL NUCLEAR PROPULSION PLANTS

AND THEIR SUPPORT FACILITIES

2023

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SUMMARY

This report summarizes the radiation exposures to Navy and civilian personnel monitored for radiation associated with U.S. naval nuclear propulsion plants. As of the end of 2023, the U.S. Navy operated 70 nuclear-powered submarines, 11 nuclear-powered aircraft carriers, and three moored training ships. Facilities that build, maintain, overhaul, or refuel these nuclear propulsion plants include six shipyards, two tenders, and six naval bases. The benefits of nuclear propulsion in our most capable combatant ships have long been recognized, and our nuclear-powered ballistic missile submarines form the strongest element of the U.S. strategic deterrent.

Figure 1 shows that the total radiation exposure in 2023 is about 2 percent of the amount in the peak year of 1966, even though today there are 17 percent more nuclear-powered ships in operation and approximately 3 times the number of ships in overhaul. Total radiation exposure in this figure is the sum of the annual exposure of each person monitored for radiation. In 2023, the number of ships in overhaul was less than 2022, and the total shipyard radiation exposure decreased from 260 Rem in 2022 to 193 Rem in 2023 (shipyard average annual radiation exposure per person decreased from 0.009 Rem in 2022 to 0.007 Rem in 2023). The total Fleet radiation exposure decreased from 103 Rem in 2022 to 87 Rem in 2023 (Fleet average annual radiation exposure per person decreased from 0.006 Rem in 2022 to 0.005 Rem in 2023).

The current Federal annual occupational radiation exposure limit of 5 Rem established in 1994 came 27 years after the Naval Nuclear Propulsion Program's (NNPP's) annual exposure limit of 5 Rem per year was established in 1967. Until 1994, the Federal radiation exposure lifetime limit allowed an accumulation of exposure of 5 Rem for each year of age beyond 18. From 1969 to 1994, no civilian or military personnel in the Program exceeded its self-imposed 5 Rem annual limit, and no one has exceeded that Federal limit since then. In fact, no Program personnel have exceeded 40 percent of the Program's annual limit between 1980 and 2023 (i.e., no personnel have exceeded 2 Rem in any year in the last 44 years). And no civilian or military Program personnel have ever, in over 65 years of operation, exceeded any Federal lifetime limit.

Personnel operating the Navy's nuclear-powered ships receive much less radiation exposure in a year than the average U.S. citizen does from natural background and medical radiation exposure. For example, the occupational exposure received by the average nuclear-trained sailor living onboard one of the Navy's nuclear-powered ships in 2023 was less than a thirtieth of the radiation received by the average U.S. citizen from natural background sources that year. This achievement is possible because of very conservative shielding designs on these ships (a tenet of the Program since it was founded in 1948).

Since 1962, no civilian or military personnel in the NNPP have ever received more than a tenth of the Federal annual occupational exposure limit from internal radiation exposure caused by radioactivity associated with naval nuclear propulsion plants.

The average occupational exposure of each person monitored since 1954 for radiation associated with naval nuclear propulsion plants is less than 0.107 Rem per year. The total lifetime average exposure during this 70-year period is less than 1 Rem per person.

According to the standard methods for estimating risk, the cancer risk to the group of personnel occupationally exposed to radiation associated with naval nuclear propulsion plants is less than the risk these same personnel have from exposure to natural background radiation. This risk is small in comparison to both the risks accepted in normal industrial activities and the risks regularly accepted in daily life outside of work.

This report and other reports produced by the Naval Nuclear Propulsion Program are available online at:

https://www.energy.gov/nnsa/articles/naval-reactors-annual-reports

NAVAL NUCLEAR PROPULSION PROGRAM MISSION AND RADIOLOGICAL CONTROLS PRINCIPLES

Mission

The Naval Nuclear Propulsion Program vision is a U.S. Navy fleet that dominates the maritime domain with unmatched power and propulsion. The Program mission, in support of this vision, is to harness the atom to safely, reliably, and affordably power a global fleet that enables unrivaled responsiveness, endurance, stealth, and warfighting capability. Successful execution of the mission is dependent on adherence to the following core values:

- People, not organizations, get things done
  - We invest in our people, progressively give them more authority and responsibility, and develop them to reach their potential. We insist on a professional and respectful culture that enables all our people to perform their best.
- Technical excellence, always
  - We endlessly pursue a more thorough understanding of our work. We are failure intolerant where necessary and accept calculated risks where practical. We provide unrivaled performance for the Navy.
- Integrity in all circumstances
  - We keep our word and do what is right, even when it’s painful. We respond forcefully and immediately to the demands of our obligations. We will never abdicate the responsibility of managing an unforgiving technology from cradle to grave.
- Challenge what’s possible
  - We relentlessly pursue opportunities to improve our Program. We identify and overcome the boundaries that restrain us. We are never satisfied with the status quo.

Radiological Controls Principles

The Naval Nuclear Propulsion Program executes the mission in a manner that protects workers, Sailors, the public, and the environment with a well-established radiological controls program that is understood and valued by all workers. The radiological controls program is based on seven radiological controls principles that implement the Program’s overriding policy: to reduce personnel exposure to ionizing radiation associated with maintenance and operation of naval nuclear propulsion plants to the lowest level that is reasonably achievable. Work involving ionizing radiation exposure is executed by trained personnel, conducted in accordance with engineered technical work documents and formal processes, under direct control of supervisors, and overseen by radiological controls personnel.

1. Control and Monitor Exposure: Since external gamma radiation is the controlling dose for whole body exposure, stringent controls ensure worker radiation exposure is known and maintained below established limits. Personnel radiation exposure is monitored using dosimeters. Procedures direct exposure controls as necessary for the

work, such as radiation surveys, dosimeter placement, and stay times. Area radiation monitoring surrounding radiological areas ensures that exposure to unmonitored personnel are within federal guidelines.

2. Prevent Ingestion or Inhalation of Radioactivity: Radioactivity is controlled such that internal radiation dose from inhalation and ingestion is insignificant, precluding the need for routine monitoring to determine internal dose. Work is engineered to prevent exposing personnel to airborne radioactivity even when the worker will be wearing respiratory protection as an added layer of defense in depth. Radiological air samples are performed during work with the potential to cause airborne radioactivity; radiological containments and additional controls are specified as the inhalation or ingestion risk of the work increases.

3. Keep Radiation Exposure As Low As Reasonably Achievable: Control of radiation exposure has always been based on the assumption that any exposure, no matter how small, may involve some risk. Therefore, work is planned and executed in a manner that minimizes total personnel exposure as much as reasonably achievable.

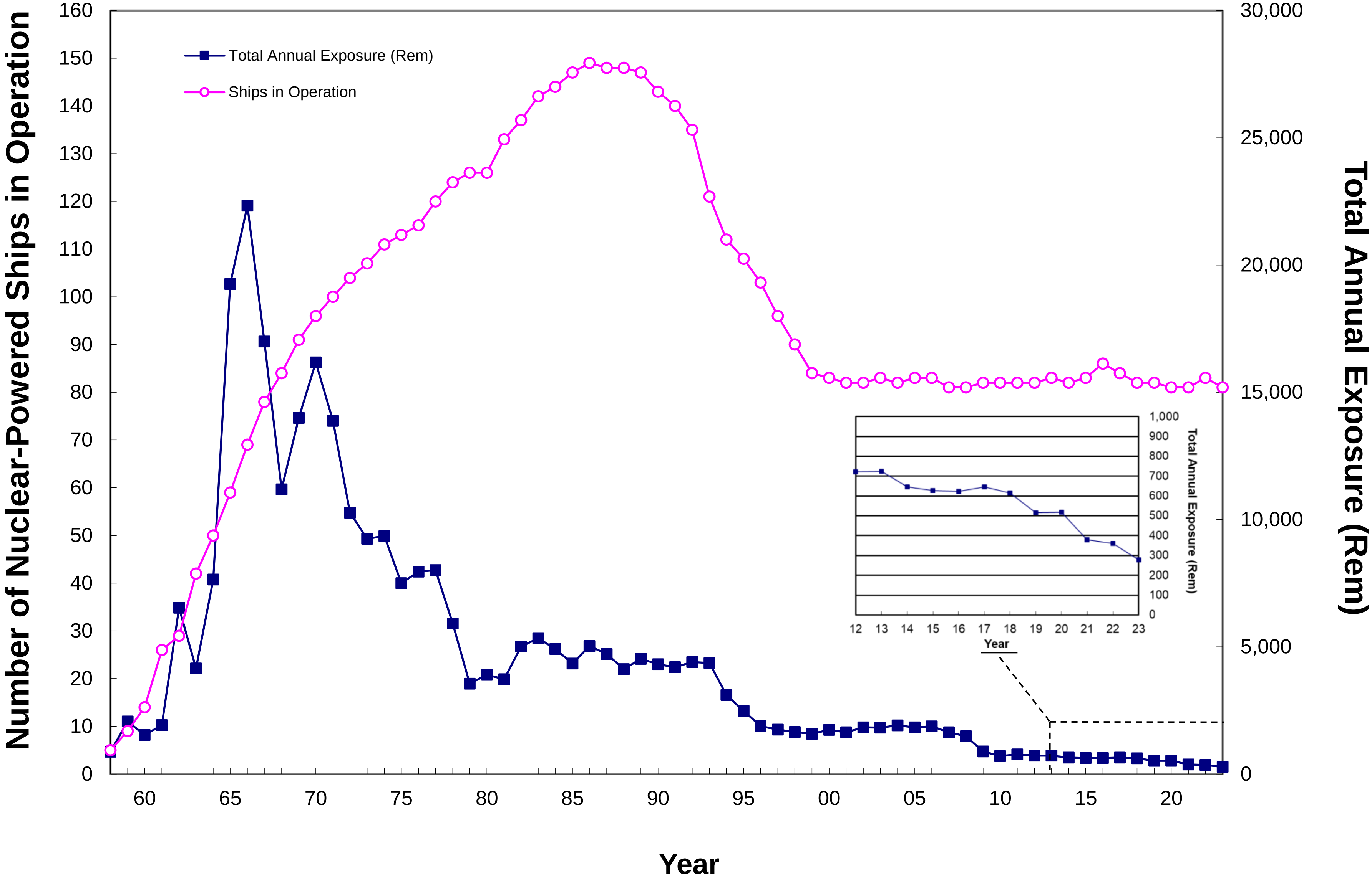
4. Maintain Control of Contamination: Radioactivity is controlled at the source to prevent the spread of radioactive contamination to the workers and outside of controlled areas. Procedures specify methods to control loose surface contamination, direct radiological surveys during operations with the potential to spread contamination, and apply additional controls as the risk of spreading contamination increases.

5. Control Radioactive Material: Radioactive material is formally accounted for and controlled to minimize personnel exposure and prevent the uncontrolled release of material to areas where the public might be affected. The generation, labeling, handling, decontamination, storage, and disposition of radioactive material is controlled by highly-trained workers in accordance with formal processes.

6. Maintain the Health of Workers and Sailors: To ensure work is performed in a manner that mitigates the risks associated with handling radioactivity, workers and Sailors are provided comprehensive radiation safety and health training, engineered procedures, appropriate supervision, and workteam backup.

7. Protect the Public and Environment: Radiological work is controlled to minimize any impact to the public and environment. Environmental monitoring is performed to validate operations associated with handling radioactive material have no adverse effect on human health or the quality of the environment. Further information about the Navy Environmental Monitoring Program can be found in Navy Report NT-24-1.

FIGURE 1
TOTAL RADIATION EXPOSURE RECEIVED BY MILITARY AND CIVILIAN PERSONNEL IN THE NAVAL NUCLEAR PROPULSION PROGRAM 1958 - 2023



EXTERNAL RADIATION EXPOSURE

Policy and Limits

The policy of the U.S. Naval Nuclear Propulsion Program is to reduce exposure to personnel from ionizing radiation associated with naval nuclear propulsion plants to a level as low as reasonably achievable.

Prior to 1960, the most restrictive Federal radiation exposure limit used in the U.S. for whole body radiation was 3 Rem[1] per 13 weeks. From 1960 to 1994, the Federal radiation exposure limits used in the U.S. for whole body radiation exposure were 3 Rem per quarter year and 5 Rem accumulated dose for each year beyond age 18. These limits were recommended in 1958 by the U.S. National Committee ("Committee" was changed to "Council" when the organization was chartered by the U.S. Congress in 1964) on Radiation Protection and Measurements (reference 1)[2] and by the International Commission on Radiological Protection (reference 2). They were adopted by the U.S. Atomic Energy Commission (AEC) and applied both within the AEC and to licensees in 1960 (reference 3). On May 13, 1960, President Eisenhower approved the U.S. Federal Radiation Council recommendation that these limits be used as guidance for Federal agencies (reference 4). The U.S. Department of Labor adopted these same limits. A key part of each of these standards has been emphasis on minimizing radiation exposure to personnel.

In 1965, the International Commission on Radiological Protection (reference 5) reiterated the quarterly and accumulated limits cited above but suggested that exceeding 5 Rem in 1 year should be infrequent. Although none of the other organizations referred to above changed their recommendations, the Naval Nuclear Propulsion Program adopted 5 Rem per year as a rigorous limit, effective in 1967.

In 1971, the National Council on Radiation Protection and Measurements (reference 6) recommended that 5 Rem be adopted as the annual limit under most conditions. In 1974, the AEC (now the Department of Energy) (reference 7) established 5 Rem as its annual limit. In 1977, the International Commission on Radiological Protection (reference 8) deleted the accumulated limit and recommended 5 Rem as the annual limit. In 1979, the Nuclear Regulatory Commission (NRC) issued a proposed change to the Code of Federal Regulations, Title 10, Part 20 to require its licensees to use 5 Rem as an annual limit. On January 20, 1987, revised guidance for Federal agencies was approved by President Reagan that eliminated the accumulated dose limit discussed above and established a 5 Rem per year limit for occupational exposure to radiation (reference 9). The Nuclear Regulatory Commission approved the change to the Code of Federal Regulations, Title 10, Part 20 that made the 5 Rem annual limit effective on or before January 1, 1994.

The Naval Nuclear Propulsion Program radiation exposure limit since 1967 has been:

5 Rem per year

Between 1960 and 2022, the Naval Nuclear Propulsion Program radiation exposure limits included a 3 Rem per quarter limit. In 1987, the National Council on Radiation

1. 1 Rem = 0.01 Sievert
2. References are listed on pp. 68-72.

Protection and Measurements (reference 10) removed their recommendation for a quarterly exposure limit. The Naval Nuclear Propulsion Program maintained the limit until 2022. In 2022, the Naval Nuclear Propulsion Program determined that requirements to implement stringent local control levels reduced the need to maintain a quarterly exposure limit. Elimination of the 3 Rem per quarter exposure limit is also consistent with the Nuclear Regulatory Commission exposure limits in Code of Federal Regulations, Title 10, Part 20. For perspective, the Naval Nuclear Propulsion Program has not had an individual exceed an annual dose of 2 Rem since 1979.

Special higher limits are in effect, such as those for hands and feet; however, there have been few cases where these limits have been more restrictive than the whole body radiation exposure limits. Therefore, the radiation exposures discussed in this report are nearly all from whole body radiation. Consistent with radiation protection guidance for Federal agencies (reference 9), the regulations of the Nuclear Regulatory Commission (reference 3), and the recommendations of the National Council on Radiation Protection and Measurements (reference 11), the Naval Nuclear Propulsion Program limits occupational radiation exposure to the unborn child of a declared pregnant worker to 0.5 Rem during the entire period of the pregnancy and controls the exposure of a declared pregnant worker to 0.05 Rem or less per month during the pregnancy.

Each organization in the Naval Nuclear Propulsion Program is required to have an active program to keep radiation exposure as low as reasonably achievable.

Source of Radiation

The radiation discussed in this report originates from pressurized water reactors. In this type of reactor, water circulates through a closed piping system to transfer heat from the reactor core to a secondary steam system isolated from the reactor cooling water. Trace amounts of corrosion and wear products are carried by reactor coolant from reactor plant metal surfaces. Some of these corrosion and wear products are deposited on the reactor core and become radioactive from exposure to neutrons. Reactor coolant carries some of these radioactive products through the piping systems where a portion of the radioactivity is removed by a purification system. Most of the remaining radionuclides transported from the reactor core deposit in the piping systems.

The reactor core is installed in a heavy-walled pressure vessel within a primary shield. The primary shield limits radiation exposure from the gammas and neutrons produced when the reactor is operating. Reactor plant piping systems are installed primarily inside a reactor compartment that is itself surrounded by a secondary shield. Access to the reactor compartment is permitted only after the reactor is shut down. Most radiation exposure to personnel comes from inspection, maintenance, and repair inside the reactor compartment. The major source of this radiation is cobalt-60 deposited inside the piping systems. Cobalt-60 emits two high-energy gammas and a low-energy beta for every radioactive decay. Its half-life is 5.3 years.

Neutrons (produced when reactor fuel fissions) are also shielded by the primary and secondary shields. Radiation exposure to personnel from these neutrons during reactor operation is much less than from gammas. After reactor shutdown, when shipyard and other support facility work is executed, no neutron exposure is detectable. Therefore, the radiation exposures discussed in this report are nearly all from gamma radiation.

Control of Radiation During Reactor Plant Operation

Reactor plant shielding is designed to minimize radiation exposure to personnel. Shield design criteria establishing radiation levels in various parts of each nuclear-powered ship are personally approved by the Director, Naval Nuclear Propulsion.

Ship design is also controlled to keep locations where personnel need to spend time, such as duty stations, as far away as practicable from the reactor compartment shield. Special attention is paid to living quarters. For example, the shield design criteria were established such that a person would have to spend more than 48 hours per day in living quarters to exceed exposure limits (which is impossible, there being only 24 hours in a day).

Radiation outside the propulsion plant spaces during reactor plant operation is generally not any greater than natural background radiation. For submarine personnel stationed outside the propulsion plant, the combination of low natural radioactivity in ship construction materials and reduced cosmic radiation under water results in less radiation exposure (from all sources including the nuclear reactor) at sea than the public receives from natural background sources ashore. Those who operate the nuclear propulsion plant receive more radiation exposure in port during maintenance and overhaul periods than they receive from operating the propulsion plant at sea.

Control of Radiation in Support Facilities

Support facilities for nuclear-powered ships consist of naval bases, shipyards, and special support ships called tenders. Tenders for nuclear-powered ships are constructed so that radioactive material is handled only in specially designed and shielded nuclear support facilities. Naval bases and shipyards minimize the number of places where radioactive material is allowed. Stringent controls are in place during the movement of all radioactive material outside these nuclear support facilities.

A radioactive material accountability system is used to ensure that no radioactive material is lost or misplaced in a location where personnel could unknowingly be exposed. Regular inventories are required for every item in the radioactive material accountability system. Radioactive material is tagged with yellow and magenta tags bearing the standard radiation symbol and the measured radiation level. Radioactive material removed from a reactor plant is required to be placed in yellow plastic, and the use of yellow plastic is reserved solely for radioactive material. All personnel assigned to a tender, naval base, or shipyard are trained to recognize that yellow plastic identifies radioactive material and to initiate immediate action if radioactive material is discovered out of place.

Access to radiation areas is controlled by signs and barriers. Personnel are trained in access requirements, including the requirement to wear dosimetric devices to enter these areas. Dosimetric devices are also posted near the boundaries of radiation areas to verify that personnel outside these areas do not require monitoring. Frequent radiation surveys are required using instruments that are checked before use and calibrated regularly. Areas where radiation levels are greater than 0.1 Rem/hour are called “high radiation areas” and are locked or guarded. Compliance with radiological controls requirements is checked frequently by radiological controls personnel, as well as by other personnel not affiliated with the radiological controls organization.

Dosimetry

Since the beginning of the Naval Nuclear Propulsion Program, personnel radiation exposure has been monitored using dosimetric devices worn on an individual's body. Dosimetric devices are worn on the trunk of the body, normally at the waist or chest. In some special situations, additional dosimeters are worn at other locations, for example on the hands, fingers, or head.

Before 1974, film badges like those used for dental x-rays were worn by personnel to monitor occupational radiation exposure. The film packet was placed in holders designed to allow differentiating between types of radiation. The darkness of the processed film was measured with a densitometer and converted to units of radiation exposure. When the first personnel radiation exposures were measured in the Naval Nuclear Propulsion Program, there already was widespread photodosimetry experience in the Navy and precise procedures existed to provide reproducible results. Each film badge was clearly marked with a name or number corresponding to the individual to whom it was assigned. This number was checked by a radiological controls technician before a worker entered a high radiation area. In high radiation areas every worker also wore a device that provided an immediate exposure reading called a pocket dosimeter, which was read by radiological controls personnel when the worker left the area. At the end of each month when the film badges were processed, the film badge measurements were compared with the sum of the pocket dosimeter readings. The film badge results were, with few exceptions, entered in the permanent personnel radiation exposure records. The few exceptions where film badge results were not entered into exposure records occurred when material problems with the film caused abnormal readings, such as film clouding. In such cases, a conservative estimate of exposure was entered.

Results of numerous tests conducted by shipyards under the same conditions that most radiation exposure was received showed that film measurements averaged 15 percent higher than actual radiation exposures. This was a conscious conservatism to ensure that even in the worst case, the film measurement was not less than the actual radiation exposure. Film response varies with the energy of the gamma radiation. The calibration of the film was performed at high energy where the film has the least response to radiation exposure. Radiation of lower energies corresponding to scattered radiation from shielded cobalt-60 caused the film to indicate more radiation exposure than actually present.

Thermoluminescent dosimeters (TLDs) have been the dosimetric devices worn by personnel to measure their exposure to gamma radiation since 1974. The use of TLDs permits more frequent measurement of a worker's radiation exposure than film badges did. TLDs are currently required to be processed at least monthly in naval shipyards and typically once per quarter for Navy personnel on ships. More frequent processing is required for anyone entering a reactor compartment or high radiation area when necessary to ensure individuals do not exceed radiation exposure local control levels.

From 1974 to 2010, a calcium fluoride TLD was used by shipyard and prototype personnel and by Navy personnel assigned to ships. The calcium fluoride TLD contained two chips of calcium fluoride with added manganese. It is characteristic of thermoluminescent material that radiation causes internal changes that make the material, when subsequently heated, give off an amount of light directly proportional to the radiation dose. In order to make it convenient to handle, these chips of calcium fluoride were in contact with a metallic heating strip with heater wires extending through the ends of a surrounding glass envelope. The glass bulb was protected by a plastic case designed to permit the proper response to gammas of various energies. Gammas of such low energy that they cannot penetrate the plastic case constitute less than a few percent of the total gamma radiation present. To read the radiation exposure, a trained operator removed the glass bulb and put it in a TLD reader, bringing the metal heater wires into contact with an electrical circuit. An electronically controlled device heated the calcium fluoride chips to several hundred degrees Celsius in a timed cycle, and the intensity of light emitted was measured and converted to a digital readout in units of Rem. The heating cycle also annealed the calcium fluoride chips so that the dosimeter was zeroed and ready for subsequent use. The entire cycle of reading a TLD described here took about 30 seconds. This rapid readout capability was one reason for changing from film badges to TLDs.

To ensure accuracy of the calcium fluoride TLD system, periodic calibration and accuracy checks were performed. For example, calcium fluoride TLDs were checked when new, and once every 9 months thereafter, for accurate response to a known radiation exposure. Those that failed were discarded. Calcium fluoride TLD readers were calibrated once each year by one of several calibration facilities, using precision radiation sources and precision TLD standards. In addition, weekly, daily, and hourly checks of proper calcium fluoride TLD reader operation and accuracy were performed when readers were in use, using internal electronic standards built into each reader. The calcium fluoride dosimetric system in the Naval Nuclear Propulsion Program was accredited under the National Voluntary Laboratory Accreditation Program. This voluntary program, sponsored by the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards), provides independent review of dosimetry services for consistency with accepted standards.

Starting in July 2006, shipyard and prototype personnel began using a new, state-of-the-art lithium fluoride TLD. In May 2008, Navy personnel on selected ships began to use the same lithium fluoride TLDs worn by shipyard and prototype personnel. The transition of all ships to the lithium fluoride TLD was completed in 2010. Tests performed by the Navy showed that the lithium fluoride and calcium fluoride dosimetric systems provide an equivalent means of accurately monitoring personnel radiation exposure. The lithium fluoride dosimetric system also provides additional features such as an automated readout capability, as discussed below.

The lithium fluoride TLD contains four chips of lithium fluoride with added magnesium, copper, and phosphorous that are mounted on a card. The TLD card is enclosed in a plastic case with filters, corresponding to each chip, that were specifically designed to permit the proper response to gamma, beta, and neutron radiation of various energies. All lithium fluoride TLDs used by Navy personnel are processed by trained operators at shore-based facilities. To determine the radiation exposure, a trained operator removes the TLD card from the plastic case and puts it in a TLD reader. The computer controlled reader heats the lithium fluoride chips to several hundred degrees Celsius in a timed cycle, and the intensity of light emitted is measured and recorded. The heating cycle also anneals the lithium fluoride chips so that the TLD card is zeroed and ready for subsequent use. The operator can load as many as 1,400 lithium fluoride TLD cards into the reader, which automatically reads one TLD card at a time. Upon completion of reading the TLD cards and recording of the light output information, these data are processed in an algorithm to produce deep and shallow gamma, beta, and neutron dose values.

TLDs measure dose from any radiation source they are exposed to, including natural background sources that exist everywhere. For lithium fluoride dosimeters, occupational dose is determined by subtracting the dose due to natural background sources from the total dose measured by the TLD. To determine what portion of the total dose measured on the TLD is from natural background radiation versus Naval Nuclear Propulsion Program sources of radioactivity, control TLDs are stored in the ship in a space far removed from the propulsion plant during the TLD issue period, or posted in shipyards for extended periods of time in areas where background radiation is the only source. The dose measured by the control TLDs is then subtracted from the total dose measured by an individual's TLD so that occupational radiation dose is the only dose recorded for the worker.

To ensure accuracy of the lithium fluoride TLD system, periodic calibration and accuracy checks are performed. TLDs are initially calibrated by the Naval Dosimetry Center. After calibration, TLDs are checked when first received by the local processing site and at least every three years thereafter by the Naval Dosimetry Center, for accurate response to a known radiation exposure. Those that fail are not put into service. Lithium fluoride TLD readers have their calibration response verified daily. In addition, checks of proper TLD reader operation and accuracy are performed with the use of quality control TLD cards interspersed among personnel TLD cards. Each quality control card is exposed to a specific amount of radiation by an irradiator internal to the TLD reader and is then processed by the reader. The TLD reader is programmed to halt processing operations if the result of any quality control card is outside of a specified limit. The electronics and light measurement functions are checked before, during, and after TLD card processing. The TLD reader automatically stops dosimeter processing operations if any of these checks are outside a specified range. Personnel operating the TLD reader are required by procedure to investigate and resolve any unsatisfactory quality control check prior to continued use of the machine. Qualified supervisors review all results. Additionally, the lithium fluoride TLD system in the Naval Nuclear Propulsion Program is accredited under the National Voluntary Laboratory Accreditation Program (Laboratory Code 100565-0) and all sites are tested to ensure consistency with accepted standards.

In addition to these calibrations and checks, the Navy has an independent dosimetry quality assurance program to monitor the accuracy of lithium fluoride TLDs and TLD readers in use at Naval Nuclear Propulsion Program activities. Precision TLDs are pre-exposed to known amounts of radiation by NIST, or by a NIST-traceable irradiator at one of the DOE laboratories. The TLDs are then provided to Program activities for reading. The activity's results are then compared to the actual exposures. A random sample of dosimeters in use at the activity being tested is also selected and sent to a DOE facility for accuracy testing. To ensure objectivity, the activity being tested is not told the radiation values to which the dosimeters have been exposed and is not permitted to participate in the selection of the dosimeter sample. If these tests find any inaccuracies that exceed established permissible error, appropriate corrective action (such as recalibration of a failed TLD reader) is immediately taken. The results of this program demonstrate that the radiation to which personnel are exposed is being measured by the TLD system with an average error of less than 10 percent.

Data gathered in over 20 years of neutron monitoring aboard ships using neutron film badges demonstrated that the monitored individuals did not receive neutron exposure above the minimum detection level for neutron film. Naval nuclear-powered ships and their support facilities now use lithium fluoride TLDs to monitor neutron exposure of the few personnel exposed to neutron sources, such as for reactor plant instrumentation source handling. These measured neutron exposures have been added to gamma exposures in the total whole body radiation exposure in this report, but because neutron exposures are so low, the radiation exposures in this report are almost entirely from gamma radiation.

Monitoring for beta radiation is not normally required. Shielding such as the metal boundaries of the reactor coolant system, clothing, eyeglasses, or plastic contamination control materials effectively shields the individual from beta radiation of the energies normally present. However, all shipyard and Navy personnel are now monitored with lithium fluoride TLDs which can measure shallow radiation dose (which includes beta radiation).

Monitoring for alpha radiation is not a normal part of operation or maintenance of naval nuclear propulsion plants because alpha contamination is not encountered by shipyard or Fleet personnel. However, alpha surveys are sometimes necessary to identify radon progeny naturally present in the atmosphere.

Personnel entering a high radiation area or a reactor compartment which is posted as a high radiation area are required to wear a pocket dosimeter in addition to a TLD. Pocket dosimeters (either an ionization chamber with an eyepiece or an electronic personal dosimeter with a digital display) permit wearers to read and keep track of their own radiation exposure during a work period. The official record of radiation exposure is still obtained from the TLD.

Discrepancies between TLD and pocket dosimeter measurements or unusual TLD measurements are investigated. These investigations include making independent, best estimates of the worker's exposure using such methods as time spent in the specific radiation area and comparing the estimates with the TLD and pocket dosimeter measurements to determine which measurement is the more accurate.

Physical Examinations

Radiation medical examinations have been required since the beginning of the Naval Nuclear Propulsion Program for personnel who handle radioactive material or who could exceed in one year the maximum exposure allowed to a member of the general public (i.e., 0.1 Rem). These examinations are conducted in accordance with the Navy's Radiation Health Protection Manual (reference 12). In these examinations the doctor pays special attention to any condition that might medically disqualify a person from receiving occupational radiation exposure or pose a health or safety hazard to the individual, to co-workers, or to the safety of the workplace.

Passing this examination is a prerequisite for obtaining dosimetry, which permits entry to radiation and radiologically controlled areas and allows handling of radioactive material. Few of the military personnel who have already been screened by physical examinations fail this radiation medical examination. For civilian shipyard workers, the failure rate is a few percent. However, failure of this examination does not mean a shipyard worker will not have a job. Since shipyard workers spend most of their time on non-radioactive work, inability to qualify for radioactive work does not restrict their job opportunities. No shipyard worker in the Naval Nuclear Propulsion Program has been released solely for inability to pass a radiation medical examination.

When required, radiation medical examinations are given prior to initial work, periodically thereafter depending on the worker's age, and at termination of qualification to perform radioactive work in the Naval Nuclear Propulsion Program (or at termination of employment). The periodic examinations are conducted in accordance with the following frequencies:

Age	Interval
18-49	Every 5 years
50-59	Every 2 years
≥60	Annually

A radiation medical examination includes a review of medical history to determine, among other things, past radiation exposure, history of cancer, and history of radiation therapy. In the medical examination, particular attention is paid to evidence of cancer or a precancerous condition. Laboratory procedures include urinalysis, blood analysis, and comparison of blood constituents to a specific set of standards. If an examination of naval civilian or military personnel disqualifies the individual, the individual is restricted from receiving occupational radiation exposure and the results of the examination are reviewed by the Bureau of Medicine and Surgery's Radiation Effects Advisory Board. Only after approval from the Board would the individual be permitted to receive occupational radiation exposure.

Shipyard, Tender, and Naval Base Training

Periodic radiological controls training is performed to ensure that all workers understand the general and specific radiological aspects they might encounter, their responsibility to the Navy and the public for safe handling of radioactive materials, the risks associated with radiation exposure, and their responsibility to minimize their own radiation exposure. Training is also provided on the biological risk of radiation exposure to the unborn child.

Before being authorized to perform radioactive work, an employee is required to pass a radiological controls training course, including a written examination. Typical course lengths for workers range from 16 to 32 hours. The following are the training requirements for a fully qualified worker:

1. Radiation Exposure Control:

    a. Know the definition of radiation. Know that the Rem is a unit of biological dose from radiation.

    b. Know the limits for occupational exposure to the whole body to penetrating radiation.

    c. Discuss the importance of the individual keeping track of their own exposure. Know how to obtain year-to-date exposure information.

    d. Know that local administrative control levels are established to keep personnel radiation exposure as low as reasonably achievable. Know their own radiation exposure control level and who can approve changes to this level.

e. Discuss the procedures and methods for minimizing exposure, such as working at a distance from a source, reducing time in radiation areas, and using shielding.

f. Know that a worker is not authorized to move, modify, or add temporary shielding without specific written authorization.

g. Discuss potential sources of radiation associated with work performed by the individual's trade.

h. Know the actions to be taken in the event of radiological problems, such as: lost, separated, or damaged dosimetry equipment while in a radiation area, radioactive material is found in uncontrolled areas, radioactive spill, high airborne radioactivity.

i. Know how to obtain and turn in dosimetry equipment, to include all required checks.

j. Know that a TLD for monitoring whole body exposure is always worn on the chest (waist for Fleet personnel), and is double captured. Know that pocket dosimeters are worn at the same location on the body as TLDs when in a high radiation area. Know that additional TLDs and pocket dosimeters may be required to be worn on the areas of the body that receive the highest exposure, if other than the chest (waist for Fleet personnel), when the technical criteria are met. Know that only radiological controls personnel can authorize additional TLD(s) and pocket dosimeters to be worn on other areas of the body.

k. Know the seriousness of violating instructions on radiation warning signs and unauthorized passage through barriers.

l. Know that stay times and predetermined pocket dosimeter readings are assigned when working in radiation fields of 1 Rem/hour or greater. Know that the worker shall leave the worker area when either the assigned stay time or pocket dosimeter reading is reached.

m. Know that naval nuclear work at a facility has no significant effect on the environment or on personnel living adjacent to or to personnel within the facility.

n. Discuss the risk associated with personnel radiation exposure. Know that any amount of radiation exposure, no matter how small, might involve some risk; however, exposure within accepted limits represents a risk that is small compared with normal hazards of life. The National Council on Radiation Protection and Measurements has stated that while exposures of workers and the general population should be kept to the lowest practical levels at all times, the presently permitted exposures limit the risk to a reasonable level in comparison to non-radiation risks. Know that cancer is the main potential health effect of receiving radiation exposure.

o. Know that any amount of radiation exposure to the unborn child, no matter how small the exposure, might involve some risk; however, exposure of the unborn child within accepted limits represents a risk that is small when compared with other risks to the unborn child. Know that the risk to future generations (genetic effects) is considered to be even smaller than the cancer risk and that genetic effects have not been observed in humans.

p. Know how often an individual shall read their pocket dosimeter while in a posted high radiation area. Know that a worker shall leave a posted high radiation area when their preassigned exposure is reached.

2. <u>Contamination Control</u>:

a. Know how contamination is controlled during radioactive work (e.g., containment in plastic bags and use of contamination control areas). Know that these controls limit exposure to internal radioactivity to insignificant levels.

b. Know how contamination is detected on personnel.

c. Know how contamination is removed from an item.

d. Know potential sources of contamination associated with work performed by the individual's trade.

e. Know the beta-gamma surface contamination limit. Know the meaning of the units for measuring contamination.

f. Know what radioactive contamination is. Know the difference between radiation and radioactive contamination.

g. For personnel who are trained to wear respiratory protection equipment, know what form(s) of radiological respirators the individual is authorized to wear. Know that air-supplied respirators are the preferred form of respiratory protection. Discuss that the use of a respirator is based on minimizing inhalation of radioactivity. Know that the respirators used for radiological work are not used for protection in any atmospheres that threaten life or health. Therefore, know that the proper response to a condition in which supply air is lost to a respirator not having escape capability or breathing becomes difficult is to remove the respirator. Know that the individual is responsible for notifying management personnel of physical or medical conditions that may affect the individual's ability to wear a respirator.

h. Discuss the required checks to determine whether personnel contamination monitoring equipment is operational before conducting personnel monitoring. Discuss the action to be taken if the checks indicate the equipment is not operating properly.

i. Know the actions to be taken if personnel contamination monitoring equipment alarms while conducting personnel monitoring.

j. Know the individual’s responsibilities in the radioactive material accountability process.

k. Know that no health effects are expected from receiving radioactive contamination on the skin and how radioactive contamination is removed from personnel.

l. Know the definition of Airborne Radioactivity Area. Know how these areas are posted.

3. Accountability of Radioactive Materials: Know that radioactive materials are accounted for when transferred between radiologically controlled areas by tagging, tracking location, and through use of radioactive material escorts.

4. Waste Disposal:

   a. Know how to minimize the amount of radioactive liquid and solid waste generated for the specific type of duties performed.

   b. Know the importance of properly segregating non-contaminated, potentially contaminated, and contaminated material.

   c. Know what reactor plant reuse water is. Discuss the appropriate uses of reactor plant reuse water.

5. Radiological Casualties:

   a. Know the need for consulting radiological controls personnel when questions or problems occur. Know the importance of complying with the instructions of radiological controls personnel in the event of a problem involving radioactivity.

   b. Know procedures to be followed in the event of a spill of material (liquid or solid), which is, or might be, radioactive.

   c. Know procedures to be followed when notified that airborne radioactivity is above the control level.

   d. Discuss the actions to be taken in the event that a high radiation area is improperly controlled.

   e. Discuss the actions to be taken when an individual discovers their pocket dosimeter: malfunctions, alarms, displays a low battery indication, indicates a higher or lower reading than expected, or reads greater than 150 mrem. Discuss actions to be taken when an individual discovers their pocket dosimeter or TLD is separated from the body or lost.

6. Responsibilities of Individuals: Know actions required in order to fulfill the worker's responsibilities. Know the responsibility of the individual to notify the Radiation Health Department or the Medical Department of radiation medical therapy, medical diagnosis involving radioisotopes, open wounds or lesions,

physical conditions that the worker feels affect his or her qualification to receive occupational radiation exposure, or occupational radiation exposure from past or current outside employment. Know the responsibility of the individual to report to area supervision or radiological controls personnel any condition that might lead to or cause avoidable exposure to radiation.

7. Practical Ability Demonstrations: These demonstrations are performed on a mockup.

   a. Demonstrate the ability to read all types of pocket dosimeters that the personnel will be required to use prior to the job.

   b. For applicable workers, demonstrate the ability to don and remove a full set of anticontamination clothing.

   c. Demonstrate the proper procedures for entering and leaving a high radiation area, a radiologically controlled area, and a control point area, including proper procedures for self-monitoring. Demonstrate the ability to read and interpret posted radiation and contamination survey maps.

   d. For applicable workers, demonstrate the ability to properly package, mark, and store radioactive materials, including the responsibilities associated with accountability.

   e. Demonstrate action to be taken by one or two workers in the event of a spill of radioactive liquid.

   f. For personnel who will enter or remain in areas where respiratory protection equipment is required, demonstrate the proper procedure for inspection and use of the type(s) of respiratory equipment the individual will be required to wear as part of mockup training for the job or in a training environment for casualty response personnel. This includes demonstrating how to don and remove the type of respiratory equipment in conjunction with anticontamination clothing, if anticontamination clothing is required to be worn with respiratory equipment. In addition, individuals who are trained to wear respirators demonstrate the proper response to a condition in which supply air is lost or breathing becomes difficult.

   g. For personnel who are trained to work in contamination control areas, demonstrate the proper procedures for working in these areas. This demonstration includes a pre-work inspection, transfer of an item into the area, a work evolution in the area, and transfer of an item out of the area.

Production supervisors who oversee radiological work are required to have at least the same technical knowledge and abilities as the workers; however, passing scores for supervisors' examinations are either higher or more difficult to attain than they are for workers. In addition to the technical knowledge requirements for workers, supervisors are required to understand the following:

8. Supervisor Knowledge Requirements:

a. Know how effective radiation exposure estimating and planning processes are used to minimize personnel radiation exposure. Know how these estimates are applied and managed, including the concept of avoidable radiation exposure and how it is documented.

b. Know how to interpret radiological survey maps of radiological job sites in order to understand the radiological environment and effectively plan/accomplish radiological work to minimize radiation exposure.

c. Know how to apply technical work document engineering decision points during the conduct of nuclear work.

d. Know the requirements for identification and control of radioactive material, particularly the need to determine the control and disposition of material and waste during planning for work.

e. Know the requirements for, and the significance of, radiological inspections steps in a technical work document.

f. Know the purpose of the radiological deficiency reporting and deficiency log systems.

g. Know the processes used to control nuclear work and how to apply these processes to work execution and risk mitigation.

h. Know how to develop and conduct a pre-job briefing to assess work readiness. Know the purpose of and how to conduct a radiological work debrief.

i. Know how to identify dynamic work operations that have a potential for increasing radiation and contamination levels.

j. Know the tools engineered in technical work documents to ensure radiological control schemes are not exceeded.

k. Know the requirement and basis for multiple dosimeter placement.

l. Know that the supervisor's role for work in radiation fields greater than or equal to 1 Rem/hour is to directly observe the worker(s) and ensure that specified body position is maintained. Know that a detailed gradient radiation survey is required to be specified in the technical work document.

m. Know the methods for identifying, posting, controlling access to, and securing high radiation areas.

n. Know the contamination levels for which corresponding increases in contamination controls are required while working in controlled surface contamination areas. Know the risks and limitations associated with such work.

o. Know the marking, tagging, transport, and storage requirements for radioactive material.

p. Discuss, in the following situations, that emergency response actions take precedence over radiological controls:

   (1) Medical treatment of seriously injured personnel.
   (2) Extinguishing fires.
   (3) Responding to security alarms.
   (4) Evacuating personnel due to an announced casualty (e.g., flooding, fire, ship collision, toxic gas leak).

q. Discuss supervisory techniques for oversight of work, with emphasis on identifying, correcting, and documenting problems.

r. Know that proper housekeeping during work execution reduces radiological risk.

s. Know the requirements for leaving a radiological work site in a satisfactory condition.

In addition to passing a written examination, completion of this training course requires satisfactory performance during basic types of simulated work operations.

To continue as a radiation worker or production supervisor, personnel must requalify in a manner similar to the initial qualification at least every two years. Between these qualification periods, personnel are required to participate in a continuing training program, and the effectiveness of that continuing training is tested often. Training is also conducted by individual shop instructors in the specific job skills for radiation work within each trade. For complex jobs this is followed by special training for the specific job, frequently using mockups outside radiation areas.

Radiological controls technicians are required to complete a 6-12 month course in radiological controls, to demonstrate their practical abilities in work operations and drills, and to pass comprehensive written and oral examinations. Radiological controls technician supervisors are required to have at least the same technical knowledge and abilities as the technicians; however, passing scores for supervisors' examinations are either higher or more difficult to attain than they are for technicians. Oral examinations, which are conducted by radiological controls managers and senior supervisors, require personnel to evaluate symptoms of unusual radiological controls situations. The radiological controls technician or supervisor is required to evaluate initial symptoms, state immediate corrective actions required, state what additional measurements are required, and do a final analysis of the measurements to identify the specific problem. After qualification, periodic training sessions are required in which each radiological controls technician and supervisor demonstrates the ability to handle situations similar to those covered in the oral examinations. At least every 2½ years, radiological controls technicians have to requalify through written and practical abilities examinations similar to those used for initial qualification. Additionally, their first requalification includes an oral examination similar to the one required for initial qualification. Between qualification periods, radiological controls technicians and supervisors are required to be selected at random for additional written and practical abilities examinations. They also must participate in unannounced drills.

In addition to the above training for those who are involved in radioactive work, each shipyard employee and each person assigned to a nuclear-powered ship or a support facility that is not involved in radioactive work is required to receive basic radiological training which is repeated at least annually. This training is to ensure personnel understand the posting of radiological areas, the identification of radioactive materials, and not to cross radiological barriers. This instruction also explains that the radiation environment of personnel outside radiation areas and outside the ship or shipyard is not significantly affected by nuclear propulsion plant work.

Nuclear Power Training

Military personnel who operate naval nuclear propulsion plants are required to pass a six-month basic training course at Nuclear Power School and a six-month qualification course either at a land-based prototype of a shipboard reactor plant or at a moored training ship. Each nuclear-trained officer and enlisted person receives extensive radiological controls training, including lectures, demonstrations, practical work, radiological controls drills, and written and oral examinations. This training emphasizes the ability to apply basic information on radiation and radioactivity.

Those enlisted personnel who will have additional responsibilities for radiological controls associated with operation of nuclear propulsion plants are designated Engineering Laboratory Technicians and receive an additional three months of training after completion of the one-year program. Engineering Laboratory Technicians and other selected nuclear-trained personnel who are assigned radiological controls duties at naval bases and tenders normally receive an additional intensive four-month training program in the practical aspects of radiological controls associated with maintenance and repair work.

Before becoming qualified to head the engineering department of a nuclear-powered ship, a nuclear-trained officer must pass a written examination and a series of oral examinations conducted at Naval Nuclear Propulsion Program Headquarters. A key part of these qualification examinations is radiological controls.

Any officer who is to serve as commanding officer of a nuclear-powered ship must attend a three-month course at Naval Nuclear Propulsion Program Headquarters. The radiological controls portion of this course covers advanced topics and assumes the officer starts with detailed familiarity with shipboard radiological controls. The officer must pass both written and oral examinations in radiological controls during this course before assuming command of a nuclear-powered ship.

Radiation Exposure Reduction

Keeping personnel radiation exposures as low as reasonably achievable involves all levels of management in nuclear-powered ships and their support facilities. Operations, maintenance, and repair personnel are required to be involved in this subject; radiation exposure reduction is not left solely to radiological controls personnel. To evaluate the effectiveness of radiation exposure reduction programs, managers use a set of goals. Goals are established in advance to keep each worker's exposure under certain levels and to minimize the number of workers involved. Goals are also set for the total cumulative personnel radiation exposure for each major job, for the entire overhaul or maintenance period, and for the whole year. These goals are deliberately made hard to meet in order to encourage personnel to improve performance.

Of the various goals used, the most effective in reducing personnel radiation exposure has been the use of individual exposure control levels, which are lower than the Navy's annual limits. Control levels in shipyards range from 0.5 Rem to 2 Rem for the year (depending on the amount of radioactive work scheduled), whereas 5 Rem per year is the Navy limit. Because of the conservative shielding design, control levels for personnel on nuclear-powered ships are maintained even lower than those in shipyards, with no personnel exceeding 1 Rem for the year.

To achieve the benefits of lower control levels in reducing total radiation exposure, it is essential to minimize the number of workers permitted to receive radiation exposure. Otherwise, the control levels could be met merely by adding more workers. Organizations are required to conduct periodic reviews to ensure that the number of workers is the minimum for the work that has to be performed.

The following is a synopsis of the principles that have been in use for years to keep personnel radiation exposure as low as reasonably achievable during maintenance, overhaul, and repair.

Preliminary Planning

- Plan well in advance
- Delete unnecessary work
- Determine expected radiation levels

Preparation of Work Procedures

- Plan access to and exit from work area
- Provide for service lines (air, welding, ventilation, etc.)
- Provide communication (sometimes includes closed-circuit video)
- Remove sources of radiation
- Plan for installation of temporary shielding
- Decontaminate
- Work in lowest radiation levels
- Perform as much work as practicable outside radiation areas
- State requirements for standard tools
- Consider special tools
- Include inspection requirements (these identify steps where radiological controls personnel must sign before the work can proceed)
- Minimize discomfort of workers
- Estimate total radiation exposure

Temporary Shielding

- Control installation and removal by written procedure
- Inspect after installation
- Conduct periodic radiation surveys
- Minimize damage caused by heavy lead temporary shielding
- Balance radiation exposure received in installation against exposure to be saved by installation

- Shield travel routes
- Shield components with abnormally high radiation levels early in the maintenance period
- Shield the work area based on worker body position
- Perform directional surveys to improve design of shielding by locating sources of radiation
- Use mockup to plan temporary shielding design and installation

Rehearsing and Briefing

- Rehearse
- Use mockup duplicating working conditions
- Use photographs
- Brief workers

Performing Work

- Post radiation levels
- Keep excess personnel out of radiation areas
- Minimize beta radiation exposure (anticontamination clothing effectively shields cobalt-60 betas)
- Supervisors and workers keep track of radiation exposure
- Workers assist in radiation and radioactivity measurements
- Evaluate use of fewer workers
- Reevaluate reducing radiation exposures

Since its inception, the Naval Nuclear Propulsion Program has stressed the reduction of personnel radiation exposure. Beginning in the 1960s, a key part of the Program's effort in this area has involved minimizing radioactive corrosion products throughout the reactor plant, which in turn has significantly contributed to reducing personnel radiation exposure. Additional measures that have been taken to reduce exposure include standardization and optimization of procedures, development of new tooling, improved use of temporary shielding, improved radiation monitoring methods, and compliance with strict contamination control measures. For example, most work involving radioactive contamination is performed in a containment. This practice minimizes the potential for spreading contamination and thus reduces work disruptions, simplifies working conditions, and minimizes the cost of—and the exposure during—cleanup.

Lessons learned during radioactive work and new ways to reduce exposure developed at one organization are made available for use by other organizations in the Naval Nuclear Propulsion Program. This effort allows all of the organizations to take advantage of the experience and developments at one organization and minimizes unnecessary duplication of effort.

The extensive efforts that have been taken to reduce exposure in the Naval Nuclear Propulsion Program have also had other benefits, such as reduced cost to perform radioactive work and improved reliability. Among other things, detailed work planning, rehearsing, total containment, special tools, and standardization have increased efficiency and improved access to perform maintenance. The overall result is improved reliability and reduced costs.

Radiation Exposure Data

Radioactive materials had been handled in shipyards for years before naval nuclear propulsion plant work started. Examples of such work include non-destructive testing using radiography sources and radiation instrument calibration using radioactive sources. Since this work is licensed by the Nuclear Regulatory Commission or by a state under agreement with the Nuclear Regulatory Commission, the radiation exposure from this licensed work has been excluded whenever practicable from this report of occupational exposure received from naval nuclear propulsion plants and their support facilities.

Table 1 shows the dates when radioactive work associated with naval nuclear propulsion plants started in each of the 11 shipyards. Seven of these shipyards have constructed naval nuclear-powered ships; however, little radiation exposure is received in new construction. The dates of starting reactor plant overhaul, therefore, are the significant dates for start of radioactive work.

The total occupational radiation exposure received by all Navy and shipyard personnel in the Naval Nuclear Propulsion Program in 2023 was 280 Rem. Table 2 summarizes radiation exposure received in nuclear-powered ships and their supporting tenders and naval bases since the first nuclear-powered ship went to sea in January 1955. Most of the radiation exposure in this table results from inspection, maintenance, and repair work in the reactor compartments of ships. In general, radiation exposures for reactor compartment work increase as reactor plant radiation levels increase with the age of the plant.

Table 3 summarizes radiation exposures of shipyard personnel since the start of naval nuclear propulsion plant radioactive work in 1954. Figure 2 shows the total shipyard personnel radiation exposure alongside the amount of work at the shipyards. Since ship overhauls frequently overlap calendar years, the number of ships in overhaul shown in Figure 2 were determined by dividing by 12 the total number of months each ship was in overhaul during a calendar year. Overhauls include defueling and inactivation of decommissioned ships.

Figure 2 shows that, from the peak in 1966 until the 1990s, total personnel radiation exposure was reduced in the shipyards while the amount of work increased. The total shipyard radiation exposure decreased from 260 Rem in 2022 to 193 Rem in 2023. The total Fleet radiation exposure decreased from 103 Rem in 2022 to 87 Rem in 2023.

The increase in the numbers of personnel monitored and total radiation exposure in the early years shows the increase in reactor plant work as the number of ships increased. By 1962, four submarine reactor plants had been overhauled and major efforts were underway to reduce radiation levels. By 1966, the number of ships in overhaul had quadrupled, as indicated by the buildup to the peak in total radiation exposure. Subsequently, the number of ships in overhaul more than quadrupled again. Decreases in total annual exposures, numbers of personnel monitored, and numbers of personnel with annual exposures over 2 Rem have been as a result of efforts to reduce radiation exposures to the minimum practicable.

The total number of shipyard personnel monitored for radiation exposure associated with the Naval Nuclear Propulsion Program is about 277,000. Since a worker usually is exposed to radiation in more than one year, the total number of personnel monitored cannot be obtained by adding the annual numbers.

Table 4 provides further information about the distribution of shipyard and Fleet personnel radiation exposures. In 2023, 100 percent of those monitored for radiation in shipyards and 100 percent of those in ships received less than 0.5 Rem in a year. Since 1954, the average annual exposure per person monitored is 0.154 Rem in shipyards and 0.06 Rem in ships, which is less than the 0.3 Rem average annual exposure a person in the U.S. receives from natural background radiation (including the inhalation of radon and its progeny) (reference 13).

Table 4 also lists the numbers of personnel who have exceeded the former 3 Rem quarterly exposure limit in effect from 1960 to 2022. In no case did personnel exceed the pre-1994 Federal accumulated limit of 5 Rem for each year of age over 18. Only 37 personnel exceeded the quarterly limit after imposing the limit in 1960 of whom 4 were military personnel aboard ships. Of the 37 personnel, 30 had quarterly exposures in the range of 3 to 4 Rem, and the highest exposure was 9.7 Rem in a quarter. Navy procedures require any person who receives greater than 25 Rem in a short time period to be placed under medical observation. No Program personnel have ever reached this level. Since 1967 no person has exceeded 3 Rem per quarter year (the Federal government eliminated the quarterly limit in the Presidential Guidance of 1987). Additionally, since 1968 no person has exceeded the Navy's self-imposed limit of 5 Rem per year for radiation exposure associated with naval nuclear propulsion plants. The 5 Rem per year Federal limit was formally adopted by the Nuclear Regulatory Commission in 1994.

The average lifetime accumulated exposure from radiation associated with naval nuclear plants for all shipyard personnel is 0.78 Rem. Since the average annual exposure per person since 1954 is 0.154 Rem, this means that the average shipyard radiation worker is monitored because of naval nuclear propulsion plant work for approximately 5 years. The average lifetime accumulated exposure for the approximately 152,000 naval officers and enlisted personnel trained to date to operate a nuclear propulsion plant is approximately 0.55 Rem. These radiation exposures are much less than the exposure the average American receives from natural background radiation or from medical diagnostic x-rays during a working lifetime (reference 13).

TABLE 1

SHIPYARD FIRST REACTOR PLANT OPERATION
AND FIRST RADIOACTIVE OVERHAUL WORK

Shipyard	Year First New Construction Reactor Started Operation	Year First Reactor Plant Overhaul Started
General Dynamics Electric Boat[1] Groton, Connecticut	1954	1957
Portsmouth Naval Shipyard Kittery, Maine	1958	1959
Mare Island Naval Shipyard[2,3] Vallejo, California	1958	1962
Pearl Harbor Naval Shipyard Pearl Harbor, Hawaii	None	1962
Charleston Naval Shipyard[2,3] Charleston, South Carolina	None	1963
Huntington Ingalls Industries – Newport News Shipbuilding[4] Newport News, Virginia	1960	1964
Bethlehem Steel Shipbuilding[3] (Subsequently Electric Boat Division) Quincy, Massachusetts	1961	None
New York Shipbuilding Corporation[3] Camden, New Jersey	1963	None
Norfolk Naval Shipyard Portsmouth, Virginia	None	1965
Puget Sound Naval Shipyard[2] Bremerton, Washington	None	1967
Ingalls Shipbuilding Division[3] Pascagoula, Mississippi	1961	1970

1. General Dynamics Electric Boat performed overhauls from 1957 until 1977. Between 1978 and 2001, Electric Boat performed new construction work primarily. In 2001, Electric Boat began performing routine radioactive work on nuclear-powered ships.
2. Radioactive work of less extent than an overhaul began in Mare Island in 1958, in Charleston in 1961, and in Puget Sound in 1965.
3. Work on naval nuclear-powered ships was discontinued at Camden, New Jersey, in 1967; at Quincy, Massachusetts, in 1969; at Pascagoula, Mississippi, in 1980; at Vallejo, California, in 1996; and at Charleston, South Carolina, in 1996.
4. Formerly known as Newport News Shipbuilding until 2001. Known as Northrop Grumman Newport News from 2001 until 2011.

TABLE 2
OCCUPATIONAL RADIATION EXPOSURE RECEIVED BY PERSONNEL
ASSIGNED TO TENDERS, BASES, AND NUCLEAR-POWERED SHIPS FROM
OPERATION AND MAINTENANCE OF NAVAL NUCLEAR PROPULSION PLANTS

	Number of Persons Monitored Who Received Exposures in the Following Ranges of Rem for the Year						Total Personnel Monitored[1]	Total Exposure (Rem)[2]
Year	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**>5**[3]		
1954	36	0	0	0	0	0	36	8
1955	90	11	0	0	0	0	101	25
1956	108	10	4	0	0	0	122	50
1957	293	7	1	0	0	0	301	60
1958	562	11	3	0	0	0	576	100
1959	1,057	41	8	3	0	0	1,109	200
1960	2,607	88	8	4	3	1	2,711	375
1961	4,812	106	31	4	4	0	4,957	680
1962	6,788	182	75	31	17	2	7,095	1,312
1963	9,188	197	39	14	3	1	9,442	1,420
1964	10,317	331	93	35	15	14	10,805	1,964
1965	11,883	592	224	96	30	27	12,852	3,421
1966	18,118	541	156	95	44	28	18,982	3,529
1967	21,028	339	139	48	11	0	21,565	3,084
1968	24,200	373	102	20	2	1	24,698	2,466
1969	26,969	577	127	39	6	0	27,718	2,918
1970	26,206	610	134	30	0	0	26,980	3,089
1971	26,090	568	122	31	2	0	26,813	3,261
1972	33,312	602	180	13	1	0	34,108	3,271
1973	30,852	600	102	15	1	0	31,570	3,160
1974	18,375	307	65	2	0	0	18,749	2,142
1975	17,638	330	28	1	0	0	17,997	2,217
1976	17,795	369	56	9	0	0	18,229	2,642
1977	20,236	346	95	36	3	0	20,716	2,812
1978	22,089	290	23	1	0	0	22,403	2,234
1979	21,121	75	1	0	0	0	21,197	1,528
1980	21,767	78	0	0	0	0	21,845	1,494
1981	23,781	27	0	0	0	0	23,808	1,415
1982	27,563	59	0	0	0	0	27,622	1,660
1983	27,593	52	0	0	0	0	27,645	1,832
1984	30,096	10	0	0	0	0	30,106	1,729
1985	31,447	18	0	0	0	0	31,465	1,549
1986	33,944	16	0	0	0	0	33,960	1,593
1987	34,987	2	0	0	0	0	34,899	1,536
1988	34,782	4	0	0	0	0	34,786	1,422
1989	35,116	52	0	0	0	0	35,168	1,599
1990	36,036	15	0	0	0	0	36,051	1,501
1991	35,669	0	0	0	0	0	35,669	1,332
1992	34,940	2	0	0	0	0	34,942	1,460
1993	32,521	3	0	0	0	0	32,524	1,452
1994	30,646	0	0	0	0	0	30,646	1,214
1995	28,825	0	0	0	0	0	28,825	1,125
1996	24,797	0	0	0	0	0	24,797	918
1997	23,793	0	0	0	0	0	23,793	818
1998	22,401	0	0	0	0	0	22,401	770
1999	21,918	0	0	0	0	0	21,918	711

TABLE 2 **(CONTINUED)**
OCCUPATIONAL RADIATION EXPOSURE RECEIVED BY PERSONNEL ASSIGNED TO TENDERS, BASES, AND NUCLEAR-POWERED SHIPS FROM OPERATION AND MAINTENANCE OF NAVAL NUCLEAR PROPULSION PLANTS

	Number of Persons Monitored Who Received Exposures in the Following Ranges of Rem for the Year						Total Personnel Monitored[1]	Total Exposure (Rem)[2]
Year	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**>5**[3]		
2000	20,890	0	0	0	0	0	20,890	727
2001	19,527	0	0	0	0	0	19,527	723
2002	20,613	0	0	0	0	0	20,613	745
2003	20,821	0	0	0	0	0	20,821	808
2004	20,985	0	0	0	0	0	20,985	789
2005	20,564	0	0	0	0	0	20,564	750
2006	20,858	0	0	0	0	0	20,858	723
2007	19,745	0	0	0	0	0	19,745	710
2008	20,306	0	0	0	0	0	20,306	669
2009	19,701	0	0	0	0	0	19,701	440
2010	16,765	0	0	0	0	0	16,765	213
2011	16,397	0	0	0	0	0	16,397	193
2012	16,420	0	0	0	0	0	16,420	203
2013	16,183	0	0	0	0	0	16,183	192
2014	16,715	0	0	0	0	0	16,715	200
2015	17,677	0	0	0	0	0	17,677	186
2016	17,813	0	0	0	0	0	17,813	181
2017	18,161	0	0	0	0	0	18,161	157
2018	17,153	0	0	0	0	0	17,153	157
2019	16,946	0	0	0	0	0	16,946	142
2020	15,585	0	0	0	0	0	15,585	134
2021	17,557	0	0	0	0	0	17,557	114
2022	17,982	0	0	0	0	0	17,982	103
2023	17,766	0	0	0	0	0	17,766	87

Note: Final exposure numbers were not yet available for ships that were deployed at the end of the reporting year. Final numbers for 2023 will be updated in the next annual report. After accounting for final exposure reports received after last year's publication, total fleet exposure for 2022 in this table changed from 101 Rem to 103 Rem.

1. Of the 17,766 personnel monitored for radiation in this category in 2023, 13,972 were Fleet radiation workers and 3,794 were visitors from organizations that do not report radiation exposure to the Naval Nuclear Propulsion Program. These visitors are not expected to receive significant exposure from Naval Nuclear Propulsion Program sources but are reported in this table for accountability purposes.
2. Implementation of lithium fluoride dosimeters in the Fleet began in May 2008 and was completed in early 2010. As discussed earlier in this report, natural background radiation exposure is subtracted when processing lithium fluoride dosimeters.
3. Limit in the Naval Nuclear Propulsion Program was changed to 5 Rem per year in 1967.

TABLE 3
OCCUPATIONAL RADIATION EXPOSURE RECEIVED BY SHIPYARD PERSONNEL
FROM WORK ASSOCIATED WITH NAVAL NUCLEAR PROPULSION PLANTS

	Number of Persons Monitored Who Received Exposures in the Following Ranges of Rem for the Year						Total Personnel Monitored	Total Exposure (Rem)
Year	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**>5**[1]		
1954	508	9	3	5	3	0	528	64
1955	2,563	80	25	6	3	2	2,679	344
1956	2,834	20	5	2	0	1	2,862	162
1957	3,473	97	31	1	2	4	3,608	495
1958	5,766	165	46	10	4	7	5,998	779
1959	10,388	221	133	78	49	23	10,892	1,864
1960	12,047	198	97	22	4	0	12,368	1,158
1961	13,383	198	91	44	14	3	13,733	1,241
1962	14,411	642	366	247	146	108	15,920	5,222
1963	19,164	446	159	71	34	28	19,902	2,725
1964	24,044	804	445	215	144	41	25,693	5,678
1965	22,630	2,306	1,314	814	618	525	28,207	15,829
1966	29,490	2,352	1,623	1,057	1,139	513	36,174	18,804
1967	29,853	2,388	1,563	1,096	733	1	35,634	13,908
1968	30,159	1,344	773	496	279	0	33,051	8,719
1969	25,672	1,790	1,080	753	375	0	29,670	11,077
1970	21,182	2,127	1,382	740	492	0	25,923	13,084
1971	20,041	1,928	1,066	650	240	0	23,925	10,616
1972	17,514	1,692	849	139	5	0	20,199	7,002
1973	13,036	1,403	604	203	6	0	15,252	6,083
1974	12,587	1,464	745	311	50	0	15,157	7,206
1975	12,825	1,116	598	82	42	0	14,663	5,285
1976	13,042	1,268	633	30	0	0	14,973	5,310
1977	13,835	1,277	586	25	0	0	15,723	5,199
1978	13,700	1,016	268	0	0	0	14,984	3,680
1979	15,032	227	7	0	0	0	15,266	2,024
1980	15,287	377	0	0	0	0	15,664	2,402
1981	17,414	304	0	0	0	0	17,718	2,310
1982	19,210	648	0	0	0	0	19,858	3,353
1983	20,407	714	0	0	0	0	21,121	3,506
1984	20,684	502	0	0	0	0	21,186	3,181
1985	20,940	412	0	0	0	0	21,352	2,796
1986	21,186	875	0	0	0	0	22,061	3,495
1987	21,404	788	0	0	0	0	22,192	3,187
1988	20,969	543	0	0	0	0	21,512	2,702
1989	23,789	633	0	0	0	0	24,422	2,941
1990	25,077	501	0	0	0	0	25,578	2,812
1991	24,873	492	0	0	0	0	25,365	2,866
1992	24,703	440	0	0	0	0	25,143	2,936
1993	23,542	572	0	0	0	0	24,114	2,913
1994	18,912	362	0	0	0	0	19,274	1,890
1995	16,422	212	0	0	0	0	16,634	1,355
1996	14,997	80	0	0	0	0	15,077	962
1997	14,501	87	0	0	0	0	14,588	935
1998	14,735	53	0	0	0	0	14,788	882
1999	16,238	60	0	0	0	0	16,298	863

TABLE 3 **(CONTINUED)**
OCCUPATIONAL RADIATION EXPOSURE RECEIVED BY SHIPYARD PERSONNEL
FROM WORK ASSOCIATED WITH NAVAL NUCLEAR PROPULSION PLANTS

	Number of Persons Monitored Who Received Exposures in the Following Ranges of Rem for the Year						Total Personnel Monitored	Total Exposure (Rem)
Year	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**>5**[1]		
2000	15,617	84	0	0	0	0	15,701	1,009
2001	16,358	84	0	0	0	0	16,442	915
2002	17,883	128	0	0	0	0	18,011	1,087
2003	18,109	112	0	0	0	0	18,221	1,017
2004	19,273	129	0	0	0	0	19,402	1,127
2005	19,327	74	0	0	0	0	19,401	1,084
2006	20,144	107	0	0	0	0	20,251	1,152
2007	19,642	45	0	0	0	0	19,687	930
2008	19,871	42	0	0	0	0	19,913	818
2009	20,396	0	0	0	0	0	20,396	445
2010	23,511	17	0	0	0	0	23,528	489
2011	24,072	19	0	0	0	0	24,091	583
2012	23,994	0	0	0	0	0	23,994	518
2013	23,945	0	0	0	0	0	23,945	531
2014	24,624	4	0	0	0	0	24,628	446
2015	25,530	0	0	0	0	0	25,530	441
2016	26,601	0	0	0	0	0	26,601	441
2017	28,199	0	0	0	0	0	28,199	489
2018	28,436	0	0	0	0	0	28,436	461
2019	29,265	5	0	0	0	0	29,270	372
2020	26,278	5	0	0	0	0	26,283	383
2021[2]	28,106	0	0	0	0	0	28,106	269[3]
2022[2]	27,521	0	0	0	0	0	27,521	260
2023	26,354	0	0	0	0	0	26,354	193

1. Limit in the Naval Nuclear Propulsion Program was changed to 5 Rem per year in 1967.
2. The 2021 and 2022 annual reports underreported shipyard personnel who received radiation exposure for work associated with naval nuclear propulsion plants. This report corrects the values.
3. Radiation exposure for 2021 was updated to account for a revised final radiation exposure report that was not accounted for in the 2022 annual report.

FIGURE 2
TOTAL RADIATION EXPOSURE RECEIVED BY SHIPYARD PERSONNEL FROM WORK ON NAVAL NUCLEAR PROPULSION PLANTS 1958 - 2023

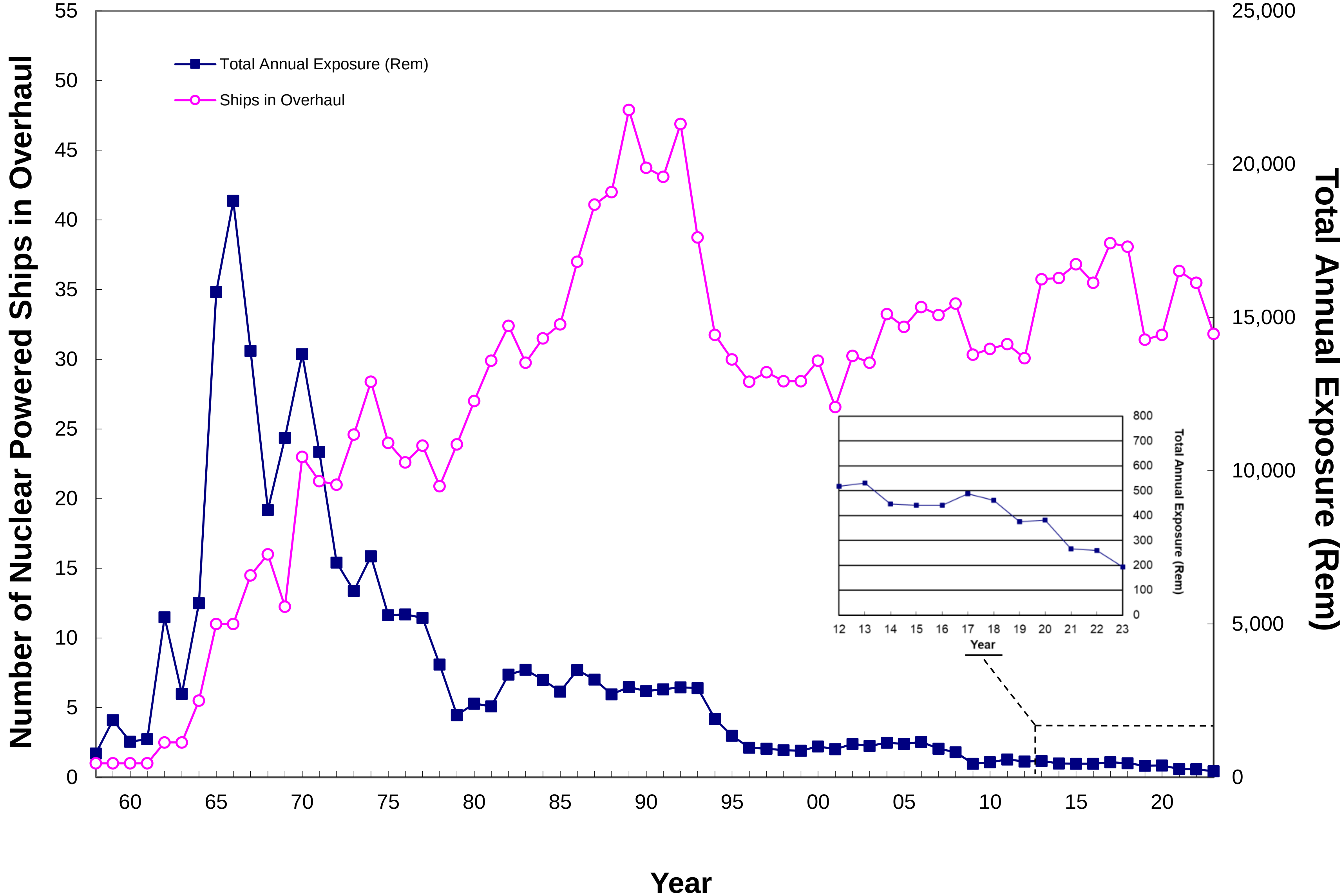


TABLE 4
SHIPYARD AND FLEET DISTRIBUTION OF PERSONNEL RADIATION EXPOSURE

Year	Average Rem Per Person Monitored		Percent of Personnel Monitored Who Received Greater Than 1 Rem[1]		Number of Personnel Who Exceeded 3 Rem/Quarter
	Fleet	Shipyard	Fleet	Shipyard	
1954	.222	.121	0	3.8	0
1955	.248	.128	10.9	4.3	0
1956	.410	.057	11.5	1.0	0
1957	.199	.137	2.7	3.7	0
1958	.174	.130	2.4	3.9	0
1959	.180	.171	4.7	4.6	8
1960	.138	.094	7.5	2.6	0
1961	.137	.090	2.9	2.5	0
1962	.185	.328	4.3	9.5	9
1963	.150	.137	2.7	3.7	2
1964	.182	.221	4.5	6.4	4
1965	.266	.561	7.5	19.8	5
1966	.186	.520	4.6	18.5	6
1967	.143	.390	2.5	16.2	3
1968	.100	.264	2.0	8.8	0
1969	.105	.373	2.7	13.5	0
1970	.114	.505	2.9	18.3	0
1971	.122	.444	2.7	16.2	0
1972	.096	.347	2.3	13.3	0
1973	.100	.399	2.3	14.5	0
1974	.114	.475	2.0	17.0	0
1975	.123	.360	2.0	12.5	0
1976	.145	.355	2.4	12.9	0
1977	.136	.331	2.3	12.0	0
1978	.100	.246	1.4	8.5	0
1979	.072	.133	0.4	1.5	0
1980	.068	.153	0.4	2.4	0
1981	.059	.130	0.1	1.7	0
1982	.060	.169	0.2	3.3	0
1983	.066	.166	0.2	3.4	0
1984	.057	.150	0.0	2.4	0
1985	.049	.131	0.1	1.9	0
1986	.047	.158	0.0	4.0	0
1987	.044	.144	0.0	3.6	0
1988	.041	.126	0.0	2.5	0
1989	.045	.120	0.1	2.6	0
1990	.042	.110	0.0	2.0	0
1991	.037	.113	0.0	1.9	0
1992	.042	.117	0.0	1.8	0
1993	.045	.121	0.0	2.4	0
1994	.040	.098	0.0	1.9	0
1995	.039	.081	0.0	1.3	0
1996	.037	.064	0.0	0.5	0
1997	.034	.064	0.0	0.6	0
1998	.034	.060	0.0	0.4	0
1999	.032	.053	0.0	0.4	0

TABLE 4 **(CONTINUED)**
SHIPYARD AND FLEET DISTRIBUTION OF PERSONNEL RADIATION EXPOSURE

Year	Average Rem Per Person Monitored		Percent of Personnel Monitored Who Received Greater Than 1 Rem[1]		Number of Personnel Who Exceeded 3 Rem/Quarter[2]
	Fleet	Shipyard	Fleet	Shipyard	
2000	.035	.064	0.0	0.5	0
2001	.037	.056	0.0	0.5	0
2002	.036	.060	0.0	0.7	0
2003	.039	.056	0.0	0.6	0
2004	.038	.058	0.0	0.7	0
2005	.036	.056	0.0	0.4	0
2006	.035	.057	0.0	0.5	0
2007	.036	.047	0.0	0.2	0
2008	.032	.041	0.0	0.2	0
2009	.022	.022	0.0	0.0	0
2010	.013	.021	0.0	0.1	0
2011	.012	.024	0.0	0.1	0
2012	.012	.022	0.0	0.0	0
2013	.012	.022	0.0	0.0	0
2014	.012	.018	0.0	0.0	0
2015	.011	.017	0.0	0.0	0
2016	.010	.017	0.0	0.0	0
2017	.009	.017	0.0	0.0	0
2018	.009	.016	0.0	0.0	0
2019	.008	.013	0.0	0.0	0
2020	.009	.015	0.0	0.0	0
2021[3]	.007	.010	0.0	0.0	0
2022[3]	.006	.009	0.0	0.0	0
2023	.005	.007	0.0	0.0	0
Average	0.059	0.154	0.73	4.5	
NNPP AVERAGE	0.107		2.6		

Note: Final exposure numbers were not yet available for ships that were deployed at the end of the reporting year. Final numbers for 2023 will be updated in the next annual report.

1. As part of a continued effort to keep personnel exposure as low as reasonably achievable, in 2010 the maximum individual control level for personnel on nuclear-powered ships was reduced from 2 Rem per year to 1 Rem per year. Control levels for shipyard personnel may exceed 1 Rem (as determined by planned radiological maintenance).
2. As discussed on page 7, the Naval Nuclear Propulsion Program removed the 3 Rem quarterly limit in 2022.
3. The 2021 and 2022 annual reports underreported shipyard personnel who received radiation exposure for work associated with naval nuclear propulsion plants. As a result, the average shipyard personnel radiation exposure has been corrected to 0.010 Rem (from 0.011 Rem) for 2021 and 0.009 Rem (from 0.011 Rem) for 2022.

Table 5 provides information on the distribution of lifetime accumulated exposures for all personnel, excluding visitors, who were monitored in 2023 for radiation exposure associated with naval nuclear propulsion plants. The 5 Rem annual Federal radiation exposure limit would allow accumulating up to 100 Rem in 20 years of work, or 200 Rem in 40 years. The fact that no one shown in Table 5 comes close to having accumulated this much radiation exposure is the result of deliberate efforts to keep lifetime radiation exposures low.

TABLE 5

DISTRIBUTION OF TOTAL LIFETIME RADIATION EXPOSURE ASSOCIATED WITH NAVAL NUCLEAR PROPULSION PLANTS

Range of Accumulated Lifetime Radiation Exposures (Rem)	Personnel Monitored in 2023 With Lifetime Accumulated Radiation Exposure Within that Range	
	FLEET	SHIPYARDS
0 – 5	13,964 (100%)	24,310 (99.196%)
5 – 10	0 (0%)	163 (0.665%)
10 – 15	0 (0%)	25 (0.102%)
15 – 20	0 (0%)	8 (0.033%)
20 – 25	0 (0%)	1 (0.004%)
> 25	0 (0%)	0 (0%)

The Federal radiation exposure limits used in the U.S. until the 1994 change to the Code of Federal Regulations, Title 10, Part 20, limited an individual's lifetime exposure to 5 Rem for each year beyond age 18. Since the 1994 change, lifetime exposure is not specifically limited, but is controlled as the result of the annual limit of 5 Rem. In their most recent radiation protection recommendations, the National Council on Radiation Protection and Measurements (NCRP) recommends organizations control lifetime accumulated exposure to less than 1 Rem times the person's age (reference 11). Among all personnel monitored in 2023, there is currently no worker with a lifetime accumulated exposure greater than the NCRP recommended level of 1 Rem times his or her age from radiation associated with naval nuclear propulsion plants.

Table 6 provides a basis for comparison between the radiation exposure for light water reactors operated by the Navy and commercial nuclear power reactors licensed by the Nuclear Regulatory Commission. The 2021 data in this table cover 95 licensed commercial nuclear power reactors with a total of 5,303 Rem (reference 14). The 2021 average annual exposure of each worker at commercial nuclear power reactors was about 0.063 Rem. Licensees of commercial nuclear power reactors reported 279 overexposures to external radiation during the years 1971 through 1992. Since 1992, licensees have reported zero overexposures to external radiation. Numbers in excess of 5 Rem are not necessarily overexposures; prior to January 1, 1994, Nuclear Regulatory Commission regulations permitted exposures of 3 Rem each quarter (up to 12 Rem per year) within the accumulated total limit of 5 Rem for each year of a person's age beyond 18.

TABLE 6

PERSONNEL RADIATION EXPOSURE FOR COMMERCIAL NUCLEAR-POWERED REACTORS LICENSED BY THE U.S. NUCLEAR REGULATORY COMMISSION

SUMMARY OF ANNUAL EXPOSURE BY INCREMENT

			Number of Individuals by Exposure Increment (Rem)												
Year	Total Monitored	Not Measurable	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	>10	Total Exposure (Rem)	Number of Over-Exposures
1971	9,581	8,996			315	137	105	17	11	0	0	0	0		2
1972	15,713	14,783			532	199	111	46	21	9	6	6	0		16
1973	33,823	19,043	9,798	2,468	1,584	422	251	125	71	38	16	7	0	13,963	19
1974	38,938	20,472	13,766	2,503	1,378	471	226	86	30	6	0	0	0	13,722	43
1975	44,343	18,854	18,289	3,948	1,872	691	423	169	60	24	12	0	1	20,879	14
1976	61,151	25,704	26,636	4,880	2,354	789	487	188	70	26	11	5	1	26,433	20
1977	61,673	22,688	28,165	5,660	2,858	1,290	661	186	89	47	23	6	0	32,521	27
1978	69,137	26,360	31,873	5,984	3,050	1,194	517	110	37	9	0	1	2	31,785	9
1979	100,834	40,535	47,196	7,574	3,401	1,403	545	117	42	17	3	1	0	39,908	23
1980	119,345	44,716	56,312	10,672	4,607	1,816	831	235	119	29	7	1	0	53,739	73
1981	116,030	39,258	58,047	11,174	4,809	1,999	533	103	93	9	3	1	1	54,163	7
1982	121,013	41,704	61,576	10,220	4,716	2,066	596	97	31	5	0	1	1	52,201	2
1983	126,736	47,027	59,878	11,342	5,334	2,270	716	121	38	8	2	0	0	56,484	8
1984	145,157	54,637	71,345	11,284	5,208	2,122	487	52	22	0	0	0	0	55,251	3
1985	146,551	59,625	72,150	10,042	3,574	1,002	157	1	0	0	0	0	0	43,048	3
1986	161,656	67,677	79,662	10,241	3,062	868	146	0	0	0	0	0	0	42,386	1
1987	181,401	85,170	82,882	10,611	2,192	477	69	0	0	0	0	0	0	40,406	1
1988	183,294	87,281	82,723	10,310	2,442	511	26	0	1	0	0	0	0	40,772	6
1989	184,038	83,954	89,432	8,633	1,615	370	34	0	0	0	0	0	0	35,931	1
1990	182,442	83,875	87,824	8,594	1,791	337	21	0	0	0	0	0	0	36,602	0
1991	178,333	87,247	83,935	5,977	938	219	17	0	0	0	0	0	0	28,519	0
1992	181,889	87,717	87,199	6,076	808	85	4	0	0	0	0	0	0	29,297	1
1993	169,259	83,066	80,152	5,322	638	76	5	0	0	0	0	0	0	26,364	0
1994	138,584	67,700	66,114	4,222	508	40	0	0	0	0	0	0	0	21,534	0
1995	132,267	61,505	66,126	3,906	595	133	2	0	0	0	0	0	0	21,674	0
1996	126,402	58,292	64,441	3,194	408	67	0	0	0	0	0	0	0	18,874	0
1997	126,781	58,647	65,209	2,598	286	41	0	0	0	0	0	0	0	17,136	0
1998	114,373	57,041	55,305	1,829	182	15	1	0	0	0	0	0	0	13,169	0
1999	114,562	55,121	57,280	1,898	245	18	0	0	0	0	0	0	0	13,666	0

TABLE 6 **(CONTINUED)**

PERSONNEL RADIATION EXPOSURE FOR COMMERCIAL NUCLEAR-POWERED REACTORS LICENSED BY THE U.S. NUCLEAR REGULATORY COMMISSION

SUMMARY OF ANNUAL EXPOSURE BY INCREMENT

			Number of Individuals by Exposure Increment (Rem)												
Year	Total Monitored	Not Measurable	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	>10	Total Exposure (Rem)	Number of Over-Exposures
2000	110,557	53,324	55,295	1,734	186	18	0	0	0	0	0	0	0	12,652	0
2001	104,928	52,636	50,626	1,392	221	53	0	0	0	0	0	0	0	11,109	0
2002	107,900	53,440	52,284	1,820	320	35	1	0	0	0	0	0	0	12,126	0
2003	109,983	54,028	54,102	1,651	184	18	0	0	0	0	0	0	0	11,956	0
2004	110,293	57,420	51,482	1,190	188	13	0	0	0	0	0	0	0	10,368	0
2005	114,262	56,709	55,913	1,490	147	3	0	0	0	0	0	0	0	11,456	0
2006	116,351	57,546	57,314	1,407	82	2	0	0	0	0	0	0	0	11,021	0
2007	114,581	57,314	56,061	1,100	97	9	0	0	0	0	0	0	0	10,120	0
2008	118,692	61,336	56,396	922	38	0	0	0	0	0	0	0	0	9,196	0
2009	126,774	66,310	59,248	1,144	68	4	0	0	0	0	0	0	0	10,025	0
2010	130,171	74,218	55,076	832	42	3	0	0	0	0	0	0	0	8,631	0
2011	137,355	78,090	58,405	837	23	0	0	0	0	0	0	0	0	8,771	0
2012	137,504	79,222	57,573	672	37	0	0	0	0	0	0	0	0	8,035	0
2013	126,786	76,261	50,077	430	18	0	0	0	0	0	0	0	0	6,760	0
2014	124,831	73,390	50,794	589	58	0	0	0	0	0	0	0	0	7,125	0
2015	122,099	71,980	49,442	647	27	3	0	0	0	0	0	0	0	7,019	0
2016	111,694	67,685	43,660	332	16	1	0	0	0	0	0	0	0	5,366	0
2017	109,115	62,882	45,690	532	11	0	0	0	0	0	0	0	0	5,366	0
2018	102,354	59,356	42,514	462	20	2	0	0	0	0	0	0	0	5,829	0
2019	94,237	55,718	38,113	402	4	0	0	0	0	0	0	0	0	5,081	0
2020	87,655	50,006	37,189	457	13	0	0	0	0	0	0	0	0	4,899	0
2021	83,796	48,780	34,346	646	24	0	0	0	0	0	0	0	0	5,303	0

Note: Numbers of personnel for the years 1977-2020 have been adjusted by the NRC for the multiple reporting of transient individuals.

INTERNAL RADIOACTIVITY

Policy and Limits

The Navy's policy on internal radioactivity for personnel associated with the Naval Nuclear Propulsion Program continues to be the same as it was more than five decades ago—to prevent significant radiation exposure to personnel from internal radioactivity. The limits invoked to achieve this objective are one-tenth of the levels allowed by Environmental Protection Agency guidance to comply with Federal radiation protection limits for occupational exposure (reference 9). Radiological work in the Program is engineered to contain radioactivity at the source and keep exposure to airborne radioactivity below levels of concern (i.e., to preclude routine monitoring of personnel to determine internal dose, such that external radiation exposure is the limiting dose to Naval Nuclear Propulsion Program personnel). The results of this program have been that since 1962, no one has received more than one-tenth the Federal annual internal occupational exposure limits from internal radiation exposure caused by radioactivity associated with naval nuclear propulsion plants.

Table 7 shows that from 1980 through 2023, only 20 personnel have had internally deposited radioactivity above 0.01 millionths of a curie of equivalent cobalt-60, and the equivalent whole body dose associated with each of these events was less than 0.020 Rem (about one-fifteenth of the average annual radiation exposure a member of the general public receives from natural background sources in the U.S.). Although these events had no adverse impact on the health of the personnel involved, each of these events was thoroughly evaluated to prevent recurrence.

Prior to 1994, the basic Federal limit for radiation exposure to organs of the body from internal radioactivity was 15 Rem per year. There have been higher levels applied at various times for the thyroid and for bones; however, use of these specific higher limits was not necessary in the Naval Nuclear Propulsion Program.

The limit recommended for most organs of the body by the U.S. National Committee on Radiation Protection and Measurements in 1954 (reference 1), by the U.S. Atomic Energy Commission in the initial edition of reference 3 which was applicable in 1957, and by the International Commission on Radiological Protection in 1959 (reference 2) was 15 Rem per year. This limit was adopted for Federal agencies when President Eisenhower approved recommendations of the Federal Radiation Council on May 13, 1960 (reference 4).

In 1977, the International Commission on Radiological Protection revised its recommendations (reference 8), particularly regarding internal exposure. The new recommendations provided a method of combining, and controlling, exposure from internal radioactivity with exposure from external radiation. The effect of the 1977 recommendations was to raise the allowable dose to many organs, with no organ allowed to receive more than 50 Rem in a year. In conjunction with these recommendations, more recent knowledge on the behavior and effect of internal radioactivity was used to derive new limits for its control (reference 15). The Federal guidance approved by the President in 1987 adopted these revised recommendations and methods, and were incorporated as Federal limits in 1994. As discussed below, cobalt-60 is the radionuclide of most concern for internal radioactivity in the Naval Nuclear Propulsion Program. The derived airborne radioactivity concentration control levels for cobalt-60 established at the inception of the Program, which control exposure to below one-tenth the Federal annual internal occupational exposure limit, remain unchanged under the new recommendations and methodology.

Source of Radioactivity

Radioactivity can get inside the body through air, through water or food, and through surface contamination via the mouth, skin, or a wound. The radioactivity of primary concern is the activated metallic corrosion products on the inside surfaces of reactor plant piping systems. These are in the form of insoluble metallic oxides, primarily iron oxides. Reference 16 contains more details on why cobalt-60 is the radionuclide of most concern for internal radioactivity.

The design conditions for reactor fuel are much more severe for warships than for commercial power reactors. As a result of being designed to withstand the rigors of combat, naval reactor fuel elements retain fission products—including fission gases—within the fuel. Sensitive measurements are frequently made to verify the integrity of reactor fuel. Consequently, fission products such as strontium-90 and cesium-137 make no measurable contribution to internal exposure of personnel from radioactivity associated with naval nuclear propulsion plants. Similarly, alpha emitters such as uranium and plutonium are retained within the fuel elements and are not accessible to personnel operating or maintaining a naval nuclear propulsion plant.

Because of the high integrity of reactor fuel and because soluble boron is not used in reactor coolant for normal reactivity control in naval nuclear propulsion plants, the amount of tritium in reactor coolant is far less than in typical commercial power reactors. The small amount that is present is formed primarily as a result of neutron interaction with the deuterium naturally present in water. The radiation from tritium is of such low energy that the Federal limits for breathing or swallowing tritium are more than 300 times higher than for cobalt-60. As a result, radiation exposure to personnel from tritium is far too low to measure. Similarly, the low-energy beta radiation from carbon-14, which is formed in small quantities in reactor coolant systems as a result of neutron interactions with nitrogen and oxygen, does not add measurable radiation exposure to personnel operating or maintaining naval nuclear propulsion plants.

Control of Airborne Radioactivity

Airborne radioactivity is controlled in maintenance operations such that respiratory equipment is not normally required. To prevent exposure of personnel to airborne radioactivity when work might release radioactivity to the atmosphere, contamination containment tents or bags are used. These containments are ventilated to the atmosphere through high-efficiency filters that have been tested to remove at least 99.95 percent of particles of a size comparable to cigarette smoke. Radiologically controlled areas such as reactor compartments are also required to be ventilated through high-efficiency filters anytime work that could cause airborne radioactivity is in progress. Airborne radioactivity surveys are required to be performed regularly in radiological work areas. Anytime airborne radioactivity above the control level is detected in occupied areas, work that might be causing airborne radioactivity is stopped. This conservative action is taken to minimize internal radioactivity even though the Naval Nuclear Propulsion Program's airborne radioactivity control level would allow continuous breathing for 40 hours per week throughout the year to reach an annual exposure of one-tenth the Federal committed effective dose equivalent limit. Personnel are also trained to use respiratory equipment when airborne radioactivity above the control level is detected. However, respiratory equipment is seldom needed and is not relied upon as the first line of defense against airborne radioactivity.

It is not uncommon for airborne radioactivity to be caused by radon naturally present in the air. Atmospheric temperature inversion conditions can allow the buildup of radioactive particles from radon. Radon can also build up in sealed or poorly ventilated rooms in homes or buildings made of stone or concrete, or it can migrate from the surrounding ground. In fact, most cases of airborne radioactivity above the Naval Nuclear Propulsion Program's conservative airborne radioactivity control level in occupied areas have been caused by radioactive particles from atmospheric radon, which has a higher airborne concentration limit, and are not from the reactor plant. Procedures have been developed to reduce the radon levels when necessary and to allow work to continue after it has been determined that the elevated airborne radioactivity is from naturally occurring radon.

Radon is also emitted from radium used for making luminous dials. Historically, there were cases where a single radium dial (such as on a wristwatch) caused the entire atmosphere of a submarine to exceed the airborne radioactivity control level used for the nuclear propulsion plant. As a result, radium in any form was banned from submarines to prevent interference with keeping airborne radioactivity from the nuclear propulsion plant as low as practicable.

Control of Radioactive Surface Contamination

Perhaps the most restrictive regulations in the Naval Nuclear Propulsion Program's radiological controls program are those for controlling radioactive contamination. Work operations involving potential for spreading radioactive contamination use containments to prevent personnel contamination or the generation of airborne radioactivity. The controls for radioactive contamination are so strict that precautions sometimes had to be taken in the past to prevent tracking contamination from the world's atmospheric fallout and natural sources outside radiological areas *into* radiological spaces because the contamination control limits used in the nuclear areas were below the levels of fallout and natural radioactivity occurring outside in the general public areas.

Anticontamination clothing, including coveralls, hoods (to cover the head, ears, and neck), shoe covers and gloves, is provided when needed. However, the basic approach is to avoid the need for full anticontamination clothing by containing the radioactivity at the source. As a result, most work on radioactive materials is performed with hands reaching into gloves installed in containments, making it unnecessary for the worker to wear anticontamination clothing. In addition to providing better control over the spread of radioactivity, this method has reduced radiation exposure because the worker can usually do a job better and faster in normal work clothing. A basic requirement of contamination control is to monitor all personnel leaving any area where radioactive contamination could possibly occur. Workers are trained to survey themselves (e.g., frisk), and their performance is checked by radiological controls personnel. Frisking of the entire body is required, normally using sensitive hand-held survey instruments. Major work facilities are equipped with portal monitors, which are used in lieu of hand-held friskers. Washing or showering at the exit of radiological work areas, which is a practice in some parts of the commercial nuclear industry, is not allowed in the Naval Nuclear Propulsion Program. Personnel monitor before, not after, they wash. The basic philosophy is to prevent the spread of contamination, not wash it away.

Table 7 presents data concerning the number of personnel with detectable radioactive skin contamination from 1980 to 2023. A radioactive skin contamination is an event where radioactive contamination above the Program's low limit for surface contamination is detected on the skin. For perspective, the Program's limit for surface contamination is less than the amount of naturally occurring radioactivity found in a banana spread over a 20 square centimeter area, which is the size of the typical survey probe. In each of these cases the radioactivity was quickly removed with simple methods (e.g., by washing with mild soap and warm water). Since 1980, a total of 533 instances of skin contamination occurred, with approximately 9 percent of the total occurring since 2000. None of these occurrences caused personnel to exceed a tenth of the Federal limit for radiation exposure to the skin.

Trained radiological controls personnel frequently survey for radioactive contamination. These surveys are reviewed by supervisory personnel to verify that no abnormal conditions exist. The instruments used for these surveys are checked against a radioactive calibration source daily and before use, and they are calibrated at least every 12 months.

Control of Food and Water

Smoking, eating, drinking, and chewing are prohibited in radioactive areas. Aboard ship, drinking water is made from seawater, in some cases by distilling seawater using steam from the secondary plant steam system. However, the steam is not radioactive, because it is in a secondary piping system separate from the reactor plant radioactive water. In the event radioactivity were to leak into the steam system, sensitive radioactivity and leak detection methods would give early warning.

Wounds

Skin conditions or open wounds that might not readily be decontaminated are cause for temporary or permanent disqualification from performing radioactive work. Workers are trained to report such conditions to radiological controls or medical personnel, and radiological controls technicians watch for open wounds when workers enter radioactive work areas. In the initial medical examination prior to radiation work and in subsequent examinations, skin conditions are also checked. If the cognizant local medical officer determines that a wound is sufficiently healed or considers that the wound is adequately protected, the cognizant medical officer may remove the temporary disqualification.

There have been only a few cases of contaminated wounds in the Naval Nuclear Propulsion Program. In most years, none occurred. Examples of such injuries that have occurred in the past include a scratched hand, a metallic sliver in a hand, a cut finger, and a puncture wound to a hand. These wounds occurred at the same time the person became contaminated. Insoluble metallic oxides that make up the radioactive contamination remain primarily at the wound rather than being absorbed into the bloodstream. These radioactively contaminated wounds have been easily decontaminated. No case of a contaminated wound is known where the radioactivity present in the wound was as much as 0.1 percent of that permitted for a radiation worker to have in his or her body.

Monitoring for Internal Radioactivity

The radioactivity of most concern for internal radiation exposure from naval nuclear propulsion plants is cobalt-60. Although most radiation exposure from cobalt-60 inside the body will be from beta radiation, the gamma radiation given off makes cobalt-60 easy to detect. Complex whole body counters are not required to detect cobalt-60 at low levels inside the body. For example, one-millionth of a curie of cobalt-60 inside the lungs or intestines will cause a measurement of two times above the background reading with the standard hand-held survey instrument used for personnel frisking. This amount of internal radioactivity will cause the instrument to reach the alarm level. Every person is required to monitor the entire body upon leaving an area with radioactive surface contamination. Monitoring the entire body (not just the hands and feet) is a requirement in the Naval Nuclear Propulsion Program. Therefore, if a person had as little as one-millionth of a curie of cobalt-60 internally, it would readily be detected.

Swallowing one-millionth of a curie of cobalt-60 will cause internal radiation exposure to the gastrointestinal tract of about 0.02 Rem. The radioactivity will pass through the body and be excreted within a period of a little more than a day. Since 1994, Federal regulations limit organ exposure from internal radioactivity to 50 Rem per year.

One-millionth of a curie of cobalt-60 still remaining in the lungs one day after an inhalation incident is estimated to cause a radiation exposure of about 2 Rem to the lungs over the following year and 6 Rem total over a lifetime, based on standard calculations recommended by the International Commission on Radiological Protection (reference 15). Since 1994, Federal regulations limit organ exposure from internal radioactivity to 50 Rem per year. These techniques provide a convenient way to estimate the amount of radiation exposure a typical individual might be expected to receive from small amounts of internally deposited radioactivity. These techniques account for the gradual removal of cobalt-60 from the lungs through biological processes and the radioactive decay of cobalt-60 with a 5.3 year half-life. However, if an actual case were to occur, the measured biological elimination rate would be used in determining the amount of radiation exposure received.

In addition to the control measures to prevent internal radioactivity and the frisking frequently performed by those who work with radioactive materials, more sensitive internal monitoring is also performed. Procedures designed specifically for monitoring internal radioactivity use a type of gamma radiation scintillation or semiconductor detector, which will reliably detect an amount of cobalt-60 inside the body more than 100 times lower than the one-millionth of a curie used in the examples above. Shipyards typically monitor each employee for internal radioactivity as part of each radiation medical examination, which is given before initially performing radiation work, after terminating radiation work, and periodically in between. Tenders, bases, and nuclear-powered ships require personnel to be internally monitored before initially assuming duties involving radiation exposure and upon terminating from such duties.

During the year, shipyards, tenders, and bases also periodically monitor groups of personnel who did the work most likely to have caused spread of radioactive contamination. Any person—whether at a shipyard, tender, base, or aboard a nuclear-powered ship—who has radioactive contamination above the limit anywhere on the skin during regular monitoring at the exit from a radioactive area is monitored for internal radioactivity with the sensitive detector. Also, any person who might have breathed airborne radioactivity above control levels is monitored with the sensitive detector.

Table 7 presents data concerning the number of personnel with internally deposited radioactivity since 1980. There have been 20 instances of internally deposited radioactivity above 0.01 millionths of a curie of equivalent cobalt-60 since 1980, with none since 1992. In each instance, the resulting exposure to the individual was less than 1 percent of the Federal equivalent whole body and organ exposure limits. Internal monitoring equipment is calibrated each day the equipment is in use. This calibration involves checking the equipment's response to a known source of radiation. In addition, the Navy has an independent quality assurance program in which organizations performing internal monitoring are tested periodically. This testing involves monitoring a human-equivalent torso phantom, which contains an amount of radioactivity traceable to standards maintained by the National Institute of Standards and Technology. The exact amount of radioactivity in the test phantom is not divulged to the organization being tested until after the test is complete. Any inaccuracies found by these tests that exceed established permissible error limits are investigated and corrected.

Results of Internal Monitoring in 2023

During 2023, a total of 7,705 personnel were monitored for internally deposited radioactivity associated with naval nuclear propulsion plants. Equipment and procedures provide detection of at least 0.01 millionths of a curie of cobalt-60 (i.e., about 0.05 percent of the Federal annual limit on intake). No personnel monitored during 2023 had internal radioactivity above this level.

Table 7

Occurrences of Radioactive Skin Contaminations and Internal Radioactivity Depositions in Shipyard Personnel and Fleet Personnel Assigned to Tenders, Bases, and Nuclear-Powered Ships [1]

	Radioactive Skin Contaminations		Internal Radioactivity Depositions[1]	
Year	Shipyard	Fleet	Shipyard	Fleet
1980	21	36	1	1
1981	15	36	1	0
1982	16	46	1	2
1983	14	18	0	0
1984	16	20	3	2
1985	8	29	1	0
1986	8	20	0	0
1987	9	14	0	0
1988	4	10	0	1
1989	7	11	1	0
1990	6	14	0	0
1991	10	11	0	0
1992	19	13	6	0
1993	14	3	0	0
1994	11	1	0	0
1995	8	3	0	0
1996	2	1	0	0
1997	2	4	0	0
1998	1	0	0	0
1999	2	0	0	0
2000	1	1	0	0
2001	2	1	0	0
2002	3	0	0	0
2003	2	0	0	0
2004	0	1	0	0
2005	0	0	0	0
2006	1	0	0	0
2007	5	0	0	0
2008	0	0	0	0
2009	0	1	0	0
2010	0	0	0	0
2011	1	0	0	0
2012	1	5	0	0
2013	5	1	0	0
2014	1	0	0	0
2015	0	3	0	0
2016	0	3	0	0
2017	0	0	0	0
2018	0	0	0	0
2019	4	1	0	0
2020	4	1	0	0
2021	0	1	0	0
2022	0	0	0	0
2023	1	0	0	0

1. Includes all occurrences of detectable internal radioactivity above 0.01 millionths of a curie of equivalent cobalt-60. The equivalent whole body dose associated with each of these events was less than 0.020 Rem.

EFFECTS OF RADIATION ON PERSONNEL

Control of radiation exposure in the Naval Nuclear Propulsion Program has always been based on the assumption that any exposure, no matter how small, may involve some risk; however, exposure within the accepted limits represents a risk small in comparison with the normal hazards of life. The basis for this statement is presented below.

Risks Associated with Radiation Exposure

Since the inception of nuclear power, scientists have cautioned that exposure to ionizing radiation in addition to that from natural background may involve some risk. The National Committee on Radiation Protection and Measurements in 1954 (reference 1) and the International Commission on Radiological Protection in 1958 (reference 2) both recommended that exposures should be kept as low as practicable and that unnecessary exposure should be avoided to minimize this risk. The International Commission on Radiological Protection in 1962 (reference 17) explained the assumed risk as follows:

> The basis of the Commission's recommendations is that any exposure to radiation may carry some risk. The assumption has been made that, down to the lowest levels of dose, the risk of inducing disease or disability in an individual increases with the dose accumulated by the individual, but is small even at the maximum permissible levels recommended for occupational exposure.

The National Academy of Sciences-National Research Council Advisory Committee on the Biological Effects of Ionizing Radiation included similar statements in its reports in the 1956-1961 period and most recently in 1990 (reference 18) and 2006 (reference 19). In 1960, the Federal Radiation Council stated (reference 4) that its radiation protection guidance did not differ substantially from recommendations of the National Committee on Radiation Protection and Measurements, the International Commission on Radiological Protection, and the National Academy of Sciences. This statement was again reaffirmed in 1987 (reference 9).

One conclusion from these reports is that radiation exposures to personnel should be minimized, but this is not a new conclusion. It has been a major driving force of the Naval Nuclear Propulsion Program since its inception in 1948.

Radiation Exposure Comparisons

The success of the Naval Nuclear Propulsion Program in minimizing exposures to personnel can be evaluated by making some radiation exposure comparisons.

Annual Exposure

One important measure of personnel exposure is the amount of exposure an individual receives in a year. Tables 2 and 3 show that since 1980, no individual has exceeded 2 Rem in a year while working in the Naval Nuclear Propulsion Program. Also, from Table 4 it can be seen that the average exposure per person monitored has been on a downward trend the last 44 years and averaged about 0.035 Rem for Fleet personnel and 0.065 Rem for shipyard personnel since 1980. Fleet personnel monitored in 2023 received an average of 0.005 Rem; shipyard personnel, an average of 0.007 Rem. The following comparisons give perspective on these average annual exposures in comparison to Federal limits and other exposures:

- No one in the Naval Nuclear Propulsion Program has exceeded 2 Rem in one ***year*** since 1980—less than half of the Federal annual limit of 5 Rem.

- A total of 65,105 workers at NRC-licensed commercial nuclear power reactors have exceeded 2 Rem in various years over this same period (reference 14).

- The average annual exposure since 1980 of 0.035 Rem for Fleet personnel is:

  - less than 1 percent of the Federal annual limit of 5 Rem.

  - less than one-fourth of the average annual exposure of commercial nuclear power plant personnel over the same time period (reference 14).

  - less than one-eighth of the average annual exposure received by U.S. commercial airline flight crew personnel due to cosmic radiation (reference 13).

- The average annual exposure of 0.065 Rem since 1980 for shipyard personnel is:

  - less than 2 percent of the Federal annual limit of 5 Rem.

  - less than one-half of the average annual exposure of commercial nuclear power plant personnel over the same time period (reference 14).

  - less than one-fourth of the average annual exposure received by U.S. commercial airline flight crew personnel due to cosmic radiation (reference 13).

For additional perspective, the annual exposures for personnel in the Naval Nuclear Propulsion Program may also be compared to natural background and medical exposures:

- The maximum annual exposure for Program personnel of 2 Rem is less than half of the annual exposure from natural radioactivity in the soils in some places in the world, such as Tamil Nadu, India (reference 20).

- The average annual exposure since 1980 of 0.035 Rem for Fleet personnel is:

  - less than 15 percent of the average annual exposure to a member of the population in the U.S. from natural background radiation (reference 13).

  - less than the difference in the annual exposure due to natural background radiation between Denver, Colorado, and Washington, D.C. (reference 21).

- Fleet personnel operating nuclear-powered submarines receive less total annual exposure than they would if they were stationed ashore performing work not involving occupational radiation exposure. This exposure is less because of the low natural background radiation in a steel hull submerged in the ocean compared to the natural background radiation from cosmic, terrestrial, and radon sources on shore (and the effectiveness of the shielding aboard ships).

- The average annual exposure of 0.065 Rem since 1980 for shipyard personnel is:

    - less than one-fourth of the average annual exposure to a member of the population in the U.S. from natural background radiation (reference 13).

    - less than one-half of the exposure from common diagnostic medical procedures such as an x-ray of the back (reference 13).

<u>Collective Dose</u>

The sum of all individual exposures gives the collective dose. Collective dose is used as a measure of the theoretical effect on the personnel occupationally exposed from the Naval Nuclear Propulsion Program taken as a group, and is an indicator of the effectiveness of the Program's efforts to minimize radiation exposure. From Tables 2 and 3, it can be seen that the collective dose received by all personnel in the Naval Nuclear Propulsion Program in 2023 was 280 Rem. The following statements give perspective on this collective dose in comparison to collective doses from other occupations. This annual collective dose is:

- less than one-fourth of the average annual collective dose received by a comparable number of commercial nuclear power plant personnel (reference 14).

- less than one-fifth of the average annual collective dose received by a comparable number of occupationally exposed persons in the medical field (reference 13).

- less than 3 percent of the average annual collective dose received by a comparable number of commercial airline flight crew personnel (reference 13).

For even further perspective, the annual collective dose received by personnel in the Naval Nuclear Propulsion Program may also be compared to collective doses from radiation exposures not related to an individual's occupation. This annual collective dose is:

- less than 3 percent of the average annual collective dose of 13,721 Rem received by a comparable number of individuals in the U.S. population due to natural background radiation (reference 13).

- less than 3 percent of the average annual collective dose of 13,236 Rem received by a comparable number of individuals in the U.S. population from common diagnostic medical x-rays (reference 13).

- less than one-fourth of the average annual collective dose of 1,588 Rem received by a comparable number of individuals in the U.S. population due to the natural radioactivity in tobacco smoke (reference 13) (rough comparison due to the difficulty in estimating the average annual collective dose received from smoking).

Conclusions on Radiation Exposure to Personnel

The preceding statements show that occupational exposures to individuals working in the Naval Nuclear Propulsion Program are small when compared to other occupational exposures and limits and are within the range of exposures from natural background radiation in the U.S. and worldwide. Additionally, the total dose to all persons (collective dose) each year is small compared to the collective doses to workers in other occupations, and insignificant compared to the collective doses to the U.S. population from natural background radiation, medical procedures, and tobacco smoke. In reference 22 the National Council on Radiation Protection and Measurements reviewed the exposures to the U.S. working population from occupational exposures. This included a review of the occupational exposures to personnel from the Naval Nuclear Propulsion Program. Based on this review, the National Council on Radiation Protection and Measurements concluded:

> These small values [of occupational exposure] reflect the success of the Navy's efforts to keep doses as low as reasonably achievable (ALARA).

Studies of the Effects of Radiation on Human Beings

Observations on the biological effects of ionizing radiation began soon after the discovery of x-rays in 1895 (reference 19).

Numerous references are made in the early literature to the potential biological effects of exposure to ionizing radiation. These effects have been intensively investigated for many years (reference 23). Although there still exists some uncertainty about the exact level of risk, the National Academy of Sciences has stated in reference 24:

> It is fair to say that we have more scientific evidence on the hazards of ionizing radiation than on most, if not all, other environmental agents that affect the general public.

A large amount of experimental evidence of radiation effects on living systems has come from laboratory studies on cell systems and on animals. However, what sets our extensive knowledge of radiation effects on human beings apart from other hazards is the evidence that has been obtained from studies of human populations that have been exposed to radiation in various ways (reference 24). The health effects demonstrated from studies of people exposed to high doses of radiation (that is, significantly higher than current occupational limits) include cancer, cataracts, sterility, and developmental abnormalities (from prenatal exposure). Results from animal studies indicate the potential for genetic effects although none have been observed in human beings (reference 19).

Near the end of 1993, the Secretary of Energy requested the disclosure of all records and information on radiation experiments involving human subjects performed or supported by Department of Energy or predecessor agencies. The Naval Nuclear Propulsion Program has never conducted or supported any radiation experiments on human beings. As discussed in this report, the Program has adopted exposure limits recommended by national and international radiation protection standards committees (such as the National Council on Radiation Protection and Measurements, and the International Commission on Radiological Protection) and has relied upon conservative designs and disciplined operating and maintenance practices to minimize radiation exposure to levels well below these limits.

High-Dose Studies

The human study populations that have contributed a large amount of information about the biological effects of radiation exposure include the survivors of the atomic bombings of Hiroshima and Nagasaki, x-rayed tuberculosis patients, victims of various radiation accidents, patients who have received radiation treatment for a variety of diseases, radium dial painters, and inhabitants of South Pacific islands that received unexpected doses from fallout due to early nuclear weapons tests. All of these populations received high or very high exposures.

The studies of atomic bomb survivors have provided the single most important source of information on the immediate and delayed effects of whole body exposure to ionizing radiation. The studies have been supported for over 50 years by the U.S. and Japanese governments and include analysis of the health of approximately 105,000 survivors of the bombings. Continued follow-up of the Japanese survivors has changed the emphasis of concern from genetic effects to the induction of cancer (references 19 and 25).

The induction of cancer has been the major latent effect of radiation exposure in the atomic bomb survivors. The tissues most sensitive to the induction of cancer appear to be the blood-forming organs, the thyroid, and the female breast. Other cancers linked to radiation, but with a lower induction rate, include cancers of the lung, stomach, colon, bladder, liver, and ovary. A wave-like pattern of leukemia induction was seen over time beginning about 2 years after exposure, peaking within 10 years of exposure, and generally diminishing to near baseline levels over the next 40 years. For other cancers, a statistically significant excess was observed 5 years or more after exposure, and the excess risk continues to rise slowly with time (reference 25).

While it is often stated that radiation causes all forms of cancer, many forms of cancer actually show no statistically significant increase among atomic bomb survivors. These cancers include chronic lymphocytic leukemia, multiple myeloma, Hodgkin lymphoma, and cancers of the rectum, pancreas, uterus, prostate, cervix, and kidney (references 19, 25, 26, and 27).

To understand the impact of cancer induction from the atomic bombings in 1945, it is necessary to compare the number of radiation-related cancers to the total number of cancers expected in the exposed group. As of 1998, studies of approximately 105,000 survivors identified 17,448 cases (i.e., incidences) of solid cancer, of which an estimated 853 were in excess of expectation (reference 28). As of December 2003, studies of over 86,000 survivors from the same population find that there have been 10,929 solid cancer deaths and of these, an estimated 527 solid cancer deaths are in excess of expectation (reference 26). An updated analysis of the same population of approximately 105,000 survivors through 2009 found 22,538 cases of solid cancers, of which an estimated 992 were in excess of expectation (reference 29). In that same population, as of December 2000 there were 310 leukemia deaths of which an estimated 103 deaths are in excess of expectation (reference 30). These studies did not reveal a statistically significant excess of cancer below doses of 6 Rem (reference 31). The cancer mortality experience of the other human study populations exposed to high doses (referenced above) is generally consistent with the experience of the Japanese atomic bomb survivors (references 19 and 25).

About 40 years ago, the major concern of the effects from radiation exposure centered on possible genetic changes (i.e., possible effects from radiation exposure to reproductive cells prior to conception of a child). Ionizing radiation was known to cause such changes in many species of plants and animals. However, intense study of nearly 70,000 offspring of atomic bomb survivors has failed to identify any increase in genetic effects. Based on a recent analysis, human beings now appear less sensitive to the genetic effects from radiation exposure than previously thought, and at low doses the genetic risks are small compared to the baseline risks of genetic disease (reference 19).

Radiation-induced cataracts have been observed in atomic bomb survivors and persons receiving high radiation doses to the eye. In 1990, the National Academy of Sciences stated the threshold for a vision-impairing cataract under conditions of protracted exposure was thought to be no less than 800 rem, which greatly exceeds the amount of radiation that can be accumulated by the lens through occupational exposure to radiation under normal working conditions (reference 18). Additional epidemiological evidence evaluated by the International Commission on Radiological Protection and the National Council on Radiation Protection and Measurements since the publication of reference 18 suggests that the threshold dose for formation of vision-impairing cataracts may be lower than previously considered (references 11 and 32). The International Commission on Radiological Protection has stated that unless the exposure to the eye exceeds 50 Rem, vision-impairing cataracts should not form (reference 32). The National Council on Radiation Protection and Measurements has stated that the limitations and uncertainties of available data make it difficult to estimate the threshold dose for radiation-induced effects on the lens of the eye, but the preponderance of the evidence indicates the threshold is in the range of 100-200 Rem (reference 33). These estimates of the threshold dose for cataract formation exceed the amount of radiation that should be accumulated by the lens of the eye through Naval Nuclear Propulsion Program occupational exposure to radiation under normal working conditions, especially considering implementation of the ALARA principle.

Radiation damage to the reproductive cells at very high doses can result in sterility. Impairment of fertility requires a dose large enough to damage or deplete most of the reproductive cells and is close to a lethal dose if exposure is to the whole body. The National Academy of Sciences estimates the threshold dose necessary to induce permanent sterility is approximately 350 Rem in a single dose (reference 18). This dose far exceeds that which can be received from occupational exposure under normal working conditions.

Among the atomic bomb survivors' children who received high prenatal exposure (that is, their mothers were pregnant at the time of the exposure), developmental abnormalities were observed. These abnormalities included stunted growth, small head size, and mental retardation. Additionally, analysis suggests that during a certain stage of development (the 8^{th} to 15^{th} week of pregnancy), the developing brain appears to be especially sensitive to radiation. A slight lowering of IQ might follow even relatively low doses of 10 Rem or more (reference 18).

From this discussion of the health effects observed in studies of human populations exposed to high doses of radiation, it can be seen that the most important of the effects from the standpoint of occupationally exposed workers is the potential for induction of cancer (reference 19).

Low-Dose Studies

The cancer-causing effects of radiation on the bone marrow, female breast, thyroid, lung, stomach, and other organs reported for the atomic bomb survivors are similar to findings reported for other irradiated human populations. With few exceptions, however, the effects have been observed only at high doses and high dose rates. Studies of populations chronically exposed to low-level radiation have not shown consistent or conclusive evidence upon which to determine the risk of cancer (reference 19). Attempts to observe increased cancer in human populations exposed to low doses of radiation have been difficult.

One problem in such studies is the number of people needed to provide sufficient statistics. As the dose to the exposed group decreases, the number of people needed to detect an increase in cancer goes up at an accelerated rate. For example, for a group exposed to 1 Rem (equivalent to the average lifetime accumulated dose in the Naval Nuclear Propulsion Program), it would take more than 500,000 people in order to detect an excess in lung cancers (based on current estimates of the risk (reference 34). This is almost two times the number of people who have performed nuclear work in all the naval shipyards over the last 70 years. Another limiting factor is the relatively short time since low-dose occupational exposure started being received by large groups of people. As discussed previously, data from the atomic bomb survivors indicate a long latency period between the time of exposure and expression of the disease.

There is also the compounding factor that cancer is a generalization for a group of approximately 300 separate diseases, many of which are relatively rare and have different apparent causes. With low-dose study data, it is difficult to eliminate the possibility that some factor other than radiation may be causing an apparent increase in cancer induction. This difficulty is particularly apparent in studies of lung cancer, for example, where smoking is (a) such a common exposure, (b) poorly documented as to individual habits, and (c) by far the primary cause of lung cancer. Because cancer induction is statistical in nature, low-dose studies are limited by the fact that an apparent observed small increase in a cancer may be due to chance alone.

Despite the above-mentioned problems and the lack of consistent or conclusive evidence from such studies to date, low-dose studies fulfill an important function. They are the only means available for eventually testing the validity of current risk estimates derived from data accumulated at higher doses and higher dose rates.

Low-dose groups that have been, and are currently being, studied include groups exposed as a result of medical procedures; exposed to fallout from nuclear weapons testing; living near U.S. commercial nuclear installations; living in areas of high natural background radiation; and occupational exposure to low doses of radiation. The National Academy of Sciences has reviewed a number of the low-dose studies in references 18 and 24. Their overall conclusion from reviewing these studies was:

> Studies of populations chronically exposed to low-level radiation, such as those residing in regions of elevated natural background radiation, have not shown consistent or conclusive evidence of an associated increase in the risk of cancer (reference 18).

This conclusion has been supported by studies that have been completed since reference 18 was published and reviewed by the National Academy of Sciences (reference 19). For example, in 1990 the National Cancer Institute completed a study of cancer in U.S. populations living near 62 nuclear facilities that had been in operation prior to 1982. This study included commercial nuclear power plants and Department of Energy facilities that handle radioactive materials. The National Cancer Institute study concluded that there was no evidence that leukemia or any other form of cancer was generally higher in the counties near the nuclear facilities than in the counties remote from nuclear facilities (reference 35).

At the request of the Three Mile Island Public Health Fund, independent researchers investigated whether the pattern of cancer in the 10-mile area surrounding the Three Mile Island nuclear plant had changed after the TMI-2 accident in March 1979 and, if so, whether the change was related to radiation releases from the plant. A conclusion of this study was:

> For accident emissions, the authors failed to find definite effects of exposure on the cancer types and population subgroups thought to be most susceptible to radiation. No associations were seen for leukemia in adults or for childhood cancers as a group (reference 36).

Of particular interest to workers in the Naval Nuclear Propulsion Program are studies of groups occupationally exposed to radiation. As of 2018, there were about 800,000 radiation workers under study in the U.S. (reference 37). For several decades, Naval Nuclear Propulsion Program personnel, including those at shipyards and in the Fleet, have been included among populations being studied. These studies are discussed below.

In 1978, Congress directed the National Institute for Occupational Safety and Health (NIOSH) to perform a study of workers at the Portsmouth Naval Shipyard (PNSY) in response to an article in the *Boston Globe* newspaper describing research by Dr. T. Najarian and Dr. T. Colton, assisted by the *Boston Globe* staff. Their research suggested that PNSY workers who were occupationally exposed to low-level radiation suffered twice the expected rate of overall cancer deaths and five times the expected rate of leukemia deaths. Congress also chartered an independent oversight committee of nine national experts to oversee the performance of the NIOSH study in order to ensure technical adequacy and independence of the results. The following is a NIOSH summary of the study and their results. This summary was prepared by NIOSH at the conclusion of their study phase in February 1986.

> In December 1980, NIOSH researchers completed the first report on a detailed study of the mortality among employees of the shipyard. Included in the study were all those who had been employed at Portsmouth Naval Shipyard since January 1, 1952 (the earliest date that records existed that could identify former employees). In this report it was concluded that "Excesses of deaths due to malignant neoplasms and specifically due to neoplasms of the blood and blood-forming tissue, were not evident in civilian workers at Portsmouth Naval Shipyard. . . ." in contrast to the results of the original study conducted by the physician. Later, in an investigation to determine why the physician's study results differed so greatly from the NIOSH study, a number of shortcomings in his original study were found that resulted in incorrect conclusions.
>
> To make more certain that workers who had died from leukemia did not die because of radiation exposures received at the shipyard, a second study was conducted. That study compared the work and radiation histories of persons who died of leukemia, with persons who did not. In this analysis, again, no relationship was found between leukemia and radiation, although the NIOSH researchers were unable to rule out the possibility of other occupational exposures having a role.

> In this current and third NIOSH paper, we investigated the role that radiation and other occupational exposures at the shipyard may have had in the development of lung cancer. This study is an outgrowth of an observation made in the 1980 NIOSH study referred to above. The observation was that persons with greater than 1 Rem cumulative exposure to radiation had an increase in lung cancer.
>
> In this report entitled, "Case Control Study of Lung Cancer in Civilian Employees at the Portsmouth Naval Shipyard," we compared the work and radiation histories of persons who died of lung cancer with persons who did not. We found that persons with radiation exposures in excess of 1 Rem had an excess risk of dying of lung cancer, but the radiation was in all likelihood not the cause. This was due to the fact that persons with radiation exposure tended also to have exposure to asbestos (a known lung carcinogen) and to welding by-products (suspected to contain lung carcinogens).

Thus, the earlier reports of excessive cancer rates among PNSY workers exposed to low-level radiation were not substantiated by NIOSH. The NIOSH studies were published in the scientific literature in references 38 through 41.

NIOSH published the results of an update to the 1980 study in the July 2004 edition of the *Journal of Occupational and Environmental Medicine* (reference 42). The cohort was expanded by including all PNSY workers employed through 1992 and included worker vital statistics up to December 31, 1996. The NIOSH study found nothing to conclude that the health of shipyard workers has been adversely affected by low levels of occupational radiation exposure incidental to work on nuclear-powered ships. These findings are generally consistent with previous studies.

The study showed no statistically significant cancer risks linked to radiation exposure, when compared to the general U.S. population. Further, the overall death rate among PNSY occupational radiation workers was less than the death rate for the general U.S. population. Other key conclusions reached in the study include the following:

- The study found a slightly higher death rate for all types of cancer in personnel who were never radiation workers, when compared to the general U.S. population. Although not statistically significant, the study also found an equivalent slightly higher death rate for all types of cancer for those who received occupational radiation exposure when compared to the general U.S. population. Fewer deaths than expected were observed for tuberculosis, diseases of the heart, circulatory system, and digestive system, as well as for accidents and violence.

- Consistent with the 1981 NIOSH study, the current study did not find a statistically significant difference in the death rates from leukemia for shipyard personnel and the general U.S. population. Although NIOSH concludes that the result is not statistically significant, the data suggest the potential for a small increase in the low risk of leukemia for workers receiving occupational radiation exposure. The small number of leukemia cases (34 out of 11,791 workers receiving occupational radiation exposure) reflects the low risk of this disease. The researchers considered this potential relationship of radiation exposure and leukemia to be considerably uncertain and to require additional study before any conclusions can be made.

- The study found a slightly higher death rate for lung cancer for workers that were never radiation workers, when compared to the general U.S. population. The study found a slightly higher death rate for lung cancer for workers receiving occupational radiation exposure, when compared to the general U.S. population. The researchers concluded that the slightly higher rates were accounted for by factors other than radiation exposure; the other factors were smoking, exposure to welding fumes, and asbestos work during the early years covered by the study when the hazards associated with asbestos were not so well understood as they are today.

Several additional analyses using the PNSY data have been performed and published by NIOSH.

- In the December 2005 issue of *Radiation Research* (reference 43), NIOSH published the results of a case-control study of leukemia mortality and ionizing radiation. The study found that although the overall risk of leukemia mortality for radiation workers was the same as the general population, a small increase in risk was noted with increasing radiation dose. NIOSH estimated that the lifetime risk for leukemia mortality would increase from 0.33% to 0.36% for workers receiving the average lifetime radiation dose for shipyard workers (1 Rem). The study also found a small increase in leukemia mortality associated with potential solvent exposure (benzene or carbon tetrachloride). NIOSH cautioned that the relatively small number of leukemia cases among radiation workers (34 cases in a population of 11,791 workers) makes it difficult to be certain of the findings. However, the risk estimate is consistent with other radiation epidemiologic study results.

- The results of a much larger case-control study of leukemia mortality (excluding chronic lymphocytic leukemia (CLL)) and ionizing radiation were published in the February 2007 issue of *Radiation Research* (reference 44) by NIOSH. The study included workers at four Department of Energy (DOE) facilities and PNSY. NIOSH did not find a statistically significant risk associated with occupational radiation exposure, although the results suggest the potential for a small increase in the low risk of leukemia (approximately five times less risk than the smaller 2005 case-control study of only PNSY workers discussed above). NIOSH stated that the risk estimates are consistent with the results of other studies of nuclear workers and high dose populations.

- NIOSH reported the results of a lung cancer case-control study of PNSY workers in the September 2007 issue of *Radiation Research* (reference 45). In addition to occupational radiation exposure, the data analysis considered the effects of asbestos and welding fumes (confounders) on the lung cancer risk. The study found a slight non-statistically significant increase in lung cancer risk with increasing radiation exposure but the risk diminished when all confounders were considered.

- In the December 2007 issue of the *British Journal of Haematology (*reference 46) NIOSH published the results of a case-control study of CLL mortality and ionizing radiation. Workers at four Department of Energy (DOE) facilities and PNSY were included in the study. The results of the study, which is one the largest studies to specifically evaluate the risk of CLL among nuclear workers, did not find a consistent association between radiation and CLL.

- In the June 2015 issue of *Radiation Research* (reference 47), NIOSH reported the results of a pooled cohort study of PNSY and four DOE facilities. The study found a slight non-statistically significant increase in solid cancer risk and leukemia risk. The study also found a small statistically significant increase in multiple myeloma risk; the lifetime risk for multiple myeloma mortality (reference 48) would increase from 0.42% to 0.44% for workers receiving the average lifetime radiation dose for shipyard workers (1 Rem). However, the finding was based on a relatively small number of cases, included a high degree of statistical uncertainty, and is not consistent with studies of other populations exposed to ionizing radiation (e.g., Japanese atomic bomb survivors). Overall, the risk of death from multiple myeloma in the study population was less than that of the United States population in general. Data from PNSY was also included in a similar study of radiation workers from three nations (the United States, United Kingdom, and France) – the International Nuclear Workers, or INWORKS, study. The INWORKS study group found no evidence of a statistically significant increase in solid cancer risk among occupationally exposed workers (reference 49) and a small, statistically significant increase in the risk of leukemia (excluding CLL) consistent with leukemia risk estimates from studies of Japanese atomic bomb survivors (reference 50).

In January of 2022, researchers from Johns Hopkins University, Baltimore, Maryland updated their 1991 study and completed a more comprehensive epidemiological study of the health of workers at the six naval shipyards (including PNSY, discussed above) and two private shipyards that serviced U.S. naval nuclear-powered ships (reference 51). This independent study evaluated a population of 372,047 shipyard workers over a period from 1957 (beginning with the first overhaul of the first nuclear-powered submarine, USS NAUTILUS) through 2011, to determine whether there was an excess risk of leukemia or other cancers associated with exposure to low levels of gamma radiation.

The study did not show any cancer risks linked to radiation exposure. Furthermore, the overall death rate among radiation-exposed shipyard workers was actually less than the death rate for the general U.S. population. It is well recognized that many worker populations have lower mortality rates than the general population: the workers have to be healthy to do their jobs. This study shows that the radiation-exposed shipyard population falls into this category.

The death rate for cancer and leukemia among the radiation-exposed workers was slightly lower than that for non-radiation-exposed workers and that for the general U.S. population. However, an increased rate of mesothelioma, a type of respiratory system cancer linked to asbestos exposure, was found in both radiation-exposed and non-radiation-exposed shipyard workers, although the number of cases was small (reflecting the rarity of this disease in the general population). The researchers suspect that shipyard worker exposure to asbestos in the early years of the Program, when the hazards associated with asbestos were not so well understood as they are today, might account for this increase.

The findings of the 2022 Johns Hopkins study are consistent with those of a smaller study of the shipyard workers completed by Johns Hopkins in 1991 (references 52 and 53). Both the 1991 and 2022 studies found no evidence to conclude that the health of people involved in work on U.S. naval nuclear-powered ships has been adversely affected by exposure to low levels of radiation incidental to this work.

In 1987, the Yale University School of Medicine completed a study (reference 54) sponsored by the U.S. Navy Bureau of Medicine and Surgery of the health of Navy personnel assigned to nuclear submarine duty between 1969 and 1981. The objective of the study, begun in 1979, was to determine whether the enclosed environment of submarines has had any impact on the health of these personnel. Although not strictly designed as a cancer study of a low-dose population, the study did examine cancer mortality as a function of radiation exposure. The study concluded that submarine duty has not adversely impacted the health of crewmembers. Furthermore, there was no correlation between cancer mortality and radiation exposure. These observations were based on comparison of death rates among the approximately 76,000 enlisted submariners and 8,000 submarine officers (all who served between 1969 and 1981) with an age-matched peer group. The results of this study were published in the Journal of Occupational Medicine (reference 55).

Table 8 below summarizes the Yale study results for enlisted submariners. The officer data show similar trends. (Note the ballistic missile submarine [SSBN] population was larger than the fast-attack submarine [SSN] population, hence the larger number of expected cancer deaths. Also, SSBN & SSN is defined as "service aboard both types of submarines.") As seen in Table 8, cancer deaths among both SSBN and SSN Sailors are less than cancer deaths among their age-matched peers in the civilian population.

TABLE 8

YALE STUDY RESULTS

Enlisted Submariners (76,160)	Cancer Deaths Observed in Submarine Group	Cancer Deaths Expected in Age-Matched Group
SSBN	55	61
SSN	18	36
SSBN & SSN	4	12
Total	77	109

In 1996, New York University (NYU) was contracted to update and expand the Yale study, updating the vital statistics of the cohort through 1995. Updating the Yale study was appropriate because of the increased follow-up time and more statistical power provided by the aging cohort. NYU completed their study update and provided a report to the Navy in 2001. Among the 85,498 enlisted submariners in the expanded cohort, 3,263 deaths (3.8%) from all causes had occurred by the end of 1995, which is 30% less than would be expected when compared to age-matched peers in the civilian population. Consistent with the Yale study, the NYU study team concluded that there is no evidence of increased cancer from chronic low doses of ionizing radiation associated with this cohort. NYU published the results of the 1996 study in the *Journal of Occupational and Environmental Medicine* (reference 56). Table 9 below summarizes the NYU study results.

TABLE 9

NYU STUDY RESULTS

Enlisted Submariners (85,498)	Cancer Deaths Observed in Submarine Group	Cancer Deaths Expected in Age-Matched Group
SSBN	161	178
SSN	129	155
SSBN & SSN	294	352
Total	584	685

Numerical Estimates of Risk from Radiation

One of the major aims of the studies of exposed populations as discussed above is to develop numerical estimates of the risk of radiation exposure. These risk estimates are useful in addressing the question of how hazardous is radiation exposure, evaluating and setting radiation protection standards, and helping resolve claims for compensation by exposed individuals.

The development of numerical risk estimates has many uncertainties. As discussed above, excess cancers attributed to radiation exposure can only be observed in populations exposed to high doses and high-dose rates. However, the risk estimates are needed for use in evaluating exposures from low doses and low-dose rates. Therefore, the risk estimates derived from the high-dose studies must be extrapolated to low doses. This extrapolation introduces a major uncertainty. The shape of the curve used to perform this extrapolation becomes a matter of hypothesis (that is, an assumption) rather than observation. The inability to observe the shape of this extrapolated curve is a major source of controversy over the appropriate risk estimate.

Scientific committees, such as the National Academy of Sciences (reference 19), the United Nations Scientific Committee on the Effects of Atomic Radiation (reference 25), and the National Council on Radiation Protection and Measurements (reference 11) all conclude that accumulation of dose over weeks, or months, as opposed to in a single dose, is expected to reduce the risk. A dose and dose rate effectiveness factor (DDREF) is applied as a divisor to the risk estimates at high doses to permit extrapolation to low doses. The National Academy of Sciences (reference 19) suggested that a range of DDREF between 1.1 and 2.3 may be applicable and reported a best estimate of 1.5, based on studies of laboratory animals and atomic bomb survivor data. The United Nations Scientific Committee on the Effects of Atomic Radiation (reference 25) suggested that a DDREF of 2 would be reasonable based on available data. However, despite these conclusions by the scientific committees, some critics argue that the risk actually increases at low doses, while others argue that cancer induction is a threshold effect and the risk is zero below the threshold dose. As stated at the beginning of this section, the Naval Nuclear Propulsion Program has always conservatively assumed that radiation exposure, no matter how small, may involve some risk.

In 1972, both the United Nations Scientific Committee on the Effects of Atomic Radiation and the National Academy of Sciences-National Research Council Advisory Committee on the Biological Effects of Ionizing Radiation issued reports (references 57 and 58) that estimated numerical risks for specific types of cancer from radiation exposure to human beings. Since then, international and national scientific committees have been periodically re-evaluating and revising these numerical estimates based on the latest data. The most recent risk estimates are from the same two committees and are contained in their 2000 and 2006 reports, respectively (references 19 and 31). Both committees re-evaluated risk estimates based on the use of new models for projecting the risk, revised dose estimates for survivors of the Hiroshima and Nagasaki atomic bombs, and additional data on the cancer experience both by atomic bomb survivors and by persons exposed to radiation for medical purposes. A risk estimate for radiation-induced cancer derived from recent analyses, references 19 and 25, can be briefly summarized as follows:

> In a group of 10,000 workers in the U.S., a total of about 2,000 (20 percent) will normally die of cancer. If each of the 10,000 received over his or her career an additional 1 Rem, then an estimated 4 additional cancer deaths (0.04 percent) might occur. Therefore, the average worker's lifetime risk of cancer has been increased nominally from 20 percent to 20.04 percent.

The above risk estimate was extrapolated from estimates applicable to high doses and dose rates using a DDREF of about 2. The National Academy of Sciences (reference 18), in assessing the various sources of uncertainty, concluded that the true lifetime risk may be contained within an interval from 0 to about 6. The Academy points out that the lower limit of uncertainty extends to zero risk because “the possibility that there may be no risks from exposure comparable to external natural background radiation cannot be ruled out."

These statistics can be used to develop a risk estimate for personnel exposed to radiation associated with naval nuclear propulsion plants. As stated previously, the average lifetime accumulated exposure is approximately 0.78 Rem for all shipyard personnel and approximately 0.55 Rem for all Fleet personnel. Therefore, based on a Program-wide average of about 1 Rem and the risk estimate presented above, the average worker's lifetime risk of cancer mortality in the Naval Nuclear Propulsion Program may be increased a very small amount, from 20 percent to 20.04 percent.

<u>Risk Comparisons</u>

Table 10 compares calculated risks from occupational exposure in the Naval Nuclear Propulsion Program to other occupational risks. This allows us to evaluate the relative hazard of this risk versus risks normally accepted in the workplace. It should be kept in mind that the radiation risk is calculated based on risk estimates, whereas the other occupational risks are based on actual death statistics for the occupation.

TABLE 10

LIFETIME OCCUPATIONAL RISKS

Occupation (reference 59)	Lifetime Risk[1] Percent
Agriculture, Forestry, and Fishing	0.9
Transportation and Warehousing	0.7
Construction	0.5
Wholesale Trade	0.3
All Industries Average	0.3
Professional and Business Services	0.1
Leisure and Hospitality	0.1
Retail Trading	0.1
Manufacturing	0.1
Government	0.1
Radiation exposure associated with naval nuclear propulsion plants (risk estimate)	0.04[2]

Further perspective on the lifetime risk from radiation exposure in the Naval Nuclear Propulsion Program may be gained by comparison to other everyday risks as shown in Table 11.

TABLE 11

SOME COMMONPLACE LIFETIME RISKS

Risk (references 60, 61, and 62)	Lifetime Risk[3] Percent
Tobacco	9.7
Accidents (all)	5.9
Accidental Poisoning	1.5
Infectious Agents	1.2
Motor Vehicle Accidents	1.0
Falls	1.0
Firearms	1.0
Pedestrian Accident	0.2
Drowning	0.1
Fire	0.07
Radiation exposure associated with naval nuclear propulsion plants (risk estimate)	0.04[2]

1. Assumes a working lifetime of 47 years (age 18 to 65)
2. According to BEIR VII (reference 19), the risk for 1 Rem of lifetime exposure for males is 0.036 and for females 0.051. The table above assumes a 75 percent male to 25 percent female ratio, which conservatively estimates the number of females in the Program.
3. The risk associated with tobacco is an estimated risk to the adult population, based on an adult smoking rate of 19.3% and a 50% mortality rate for adult smokers due to smoking related causes. Other risks assume the population is at risk for a lifetime (76.5 years).

Low-Level Radiation Controversy

A very effective way to cause undue concern about low-level radiation exposure is to claim that no one knows what the effects are on human beings. Critics have repeated this so often that it has almost become an article of faith. They can make this statement because, as discussed above, human studies of low-level radiation exposure cannot be conclusive as to whether or not an effect exists in the exposed groups, because of the extremely low incidence of an effect. Therefore, assumptions are needed regarding extrapolation from high-dose groups. The reason low-dose studies cannot be conclusive is that the risk, if it exists at these low levels, is too small to be seen in the presence of all the other risks of life.

In summary, the effect of radiation exposures at occupational levels is extremely small. There are physical limits to how far scientists can go to ascertain precisely how small. Instead of proclaiming how little is known about low-level radiation, it is more appropriate to emphasize how much is known about the small actual effects.

As stated earlier, the most important health effect observed in studies of humans exposed to high doses of radiation (such as survivors of the atomic bombings of Hiroshima and Nagasaki, patients with high doses from x-rays or radiation treatments, and radium dial painters) is the potential for the induction of cancer. While there are studies of the potential for cause and effect from low doses of radiation, the incidence of cancer in an individual who received occupational radiation exposure does not necessarily mean that occupational exposure was the cause. Reference 48 documents that the lifetime risk of being diagnosed with cancer for a person living in the United States is 41 percent for males and 39 percent for females. The median age for being diagnosed with cancer is 66 years old, meaning that half of those diagnosed with cancer are younger than 66 at the time of diagnosis. In addition, the lifetime risk of dying from cancer for a person living in the United States is 20 percent for males and 18 percent for females.

As discussed earlier, the Navy has participated in several epidemiology studies by authoritative scientists of mortality of personnel who served on U.S. naval nuclear-powered submarines or worked in shipyards. All but one of these studies concluded that there was no discernible correlation between cancer mortality and the low-level radiation exposure associated with naval nuclear propulsion plants. As discussed earlier, one study of a limited population found a slight increase in the risk of incurring leukemia with increasing radiation dose. The Navy continues to support updates to these studies.

Conclusions on the Effects of Radiation on Personnel

This perspective provides a better position to answer the question, "Is radiation safe?" If safe means “zero effect,” then the conclusion would have to be that radiation may be unsafe. But to be consistent, background radiation and medical radiation would also have to be considered unsafe. Or more simply, being alive is unsafe.

"Safe" is a relative term. Comparisons are necessary for actual meaning. For a worker, *safe* means the risk is small compared to other risks accepted in normal work activities. Aside from work, *safe* means the risk is small compared to the risks routinely accepted in life.

Each recommendation on limits for radiation exposure from the scientific and advisory organizations referenced herein emphasized the need to minimize radiation exposure. Thus, the Naval Nuclear Propulsion Program is committed to keeping radiation exposure to personnel as low as reasonably achievable. Scientific and advisory organizations have not agreed on a radiation exposure level below which there is no effect. Similarly, it is difficult to find a single human activity for which the risk can be confidently stated as zero. However, the above summaries show that the risk from radiation exposure associated with naval nuclear propulsion plants is low compared to the risks normally accepted in industrial work and in daily life outside of work.

CLAIMS FOR RADIATION INJURY TO PERSONNEL

Personnel who consider they have or might have had occupational injury may file claims. Naval shipyard personnel are employees of the U.S. Government and therefore file claims with the U.S. Department of Labor's Office of Workers' Compensation. Shipyards hold no hearings on injury claims. They are not handled in an adversary procedure. The claim does not even have to be filed through the shipyard. The shipyard is not permitted to appeal a decision, but the employee may appeal. The primary consideration in the Federal laws and procedures set up for injury compensation is to take care of the Federal employee. The program to compensate Federal employees is well publicized.

In private shipyards injury compensation claims are handled under the Longshore and Harbor Workers' Compensation Act. The claim may be handled through the shipyard's insurance carrier or by a U.S. Department of Labor claims examiner. Either the employee or the employer may appeal.

Claims for military personnel concerning prior duty are handled through the U.S. Department of Veterans Affairs (VA).
In any case, the Naval Nuclear Propulsion Program would support any claim for radiation injury where it could be technically and scientifically shown that the injury was more likely than not caused by the individual’s occupational radiation exposure from the Program.

There have been a total of 1899 claims filed for injury from radiation associated with naval nuclear propulsion plants. Of these, 159 originated from employees of the naval shipyards, 98 from private shipyards, and 1642 from Navy personnel. There were no new claims filed at Naval and private shipyards in 2023. As summarized in Table 12, about one-fifth of the total claims were filed for injuries other than cancer or leukemia. Approximately 90 percent of the claims filed for cancer or leukemia involved workers with lifetime radiation exposures less than 5 Rem, which is the exposure a nuclear worker is permitted to receive in 1 year by Federal regulations.

TABLE 12[1],[2]

CLAIMS FOR RADIATION INJURY TO PERSONNEL

Injury Claimed	Claims Filed	Claims Awarded	Claims Denied	Claims Deferred	Claims Active
Leukemia	144	10	120	13	1
Cancer Other than Leukemia	1282	37	1216	27	2
Other	473	26	413	33	1
Total	1899	73	1749	73	4

Naval shipyard personnel workers' compensation claims are generally decided upon by the Office of Workers' Compensation within 1-2 years of filing. The Longshore and Harbor Workers' Compensation Act, however, will not require a decision on a case subsequent to filing unless it is actively pursued by the claimant. For cases that are not actively pursued, the claim may lie dormant for many years (theoretically to be pursued at a later date, whereupon a decision will be made). For the purpose of Table 12, claims which have had no activity in the last 5 years are listed as deferred.

Seventy-three claims have been awarded for which radiation associated with the Naval Nuclear Propulsion Program was an alleged causal agent: ten for leukemia; thirty-seven for other types of cancer; and twenty-six for non-cancerous conditions. The Office of Workers' Compensation awarded three claims, and the VA awarded seventy claims. For VA claims, other considerations (such as whether the injury is reasonably considered to have occurred while the claimant was in the Armed Forces and other causal factors) are used when awarding claims. The Navy considers all seventy-three of these awards were unjustified on the basis of radiation exposure, as follows:

1. Table 12 was substantially updated in the 2020 version of this report. In 2020, the NNPP identified that the data provided by the Veteran's Administration for claims initiated by former active duty Navy personnel were incomplete. Following an investigation into this error, Table 12 was updated to reflect an addition of 73 claims filed, with an award granted by the Veteran's Administration in 43 of those cases.

2. The Promise to Address Comprehensive Toxics (PACT) Act was introduced in 2022 to improve healthcare access and disability funding for veterans who were exposed to toxic substances during military service. While occupational radiation exposure associated with the Naval Nuclear Propulsion Program is not identified as a presumptive exposure category under the PACT Act, the VA experienced a large increase in radiation-related claims associated with the NNPP following the law's implementation. The Navy expressed concerns to the VA that many of these claims were awarded with no medical or scientific basis that occupational radiation exposure was more likely than not the cause of the claimants' injuries. The VA committed to evaluate the radiation claims review process. However, no updates were provided to the Navy to date, and the Navy continues to seek to address the concern.

For perspective, in 2023, 442 radiation injury claims associated with the Naval Nuclear Propulsion Program were filed with the VA and 45 were awarded, which represents a 38 percent increase in the amount of claims awarded over the entire history of the Program attributed to a single year. 84 percent of the lifetime doses for these claims were under 1 rem, and the maximum lifetime dose was 7 rem (received over 5 years). None of these exposures exceeded Federal limits. The Navy considers all 45 of these awards unjustified on the basis of radiation exposure. The Naval Nuclear Propulsion Program is excluding new VA radiation injury claims in Table 12 due to the lack of medical and scientific justification for awards granted by the VA.

- Only six of these claimants (eight percent) received more than five Rem of occupational radiation exposure from the Navy during their careers. Or, in other words, the vast majority of these claimants received less occupational radiation exposure in their multi-year Naval careers than they were allowed to receive in a single year based on Federal exposure limits.

- Forty of these claimants (fifty-five percent) received less than one Rem of occupational radiation exposure from the Navy during their careers, or less than twenty percent of the occupational radiation exposure allowed in a single year based on Federal exposure limits.

- Twenty-eight of these claimants (thirty-eight percent) received less occupational radiation exposure from the Navy than the average member of the U.S. population receives in a single year from natural sources of background radiation. Radiation exposure at these very low levels has never been scientifically proven to cause an increase in the risk of cancer or any other health effect (reference 19).

- Of the claims awarded for leukemia, the highest lifetime occupational exposure received was 5.38 Rem. This claimant also received hundreds of Rem in medical radiation exposure for adenoids. If radiation were to be selected as the cause of this leukemia, then the occupational exposure could not have been more than an insignificant part of the total radiation exposure.

- Of the claims awarded for cancers other than leukemia, the highest lifetime occupational exposure received was 12.9 Rem over a 23-year career. In other words, the claimant's average annual occupational radiation exposure was less than the exposure the average member of the U.S. population receives every year from natural background and medical sources of radiation. Further, this claim was filed for prostate cancer, a disease that has never been scientifically linked to low-level occupational radiation exposure (reference 19).

- Of the claims awarded for non-cancerous conditions, the highest lifetime occupational radiation exposure received was 15.5 Rem over an 8-year period. This amount of exposure is less than 40 percent of the amount current Federal regulations would have allowed the claimant to receive over the same time period. This case, which alleged the claimant's leukocytosis (elevated white blood cell count) was caused by radiation exposure, was evaluated by the medical research center of a national laboratory, which concluded that the cause of the leukocytosis was unknown. Overall, there is no direct evidence of increased risks of non-cancerous conditions associated with low-dose occupational radiation exposures (reference 19).

- Four claims have been awarded for cataracts. Two of the cataract cases had lifetime radiation exposures of about 3 Rem, one case had less than 1 Rem, and one case had 0.02 Rem. Of these cases, even the highest exposure, 3 Rem, is fifteen times smaller than exposure needed to produce cataracts in the eyes (reference 32).

In addition to the above claims, six suits have been filed in court alleging injury from radiation. One suit involved leukemia; three involved other cancers; and the two others did not involve a cancer. Five of these suits were dismissed and one was settled.

AUDITS AND REVIEWS

Checks and cross-checks, audits, and inspections of numerous kinds have been shown to be essential in maintaining high standards of radiological controls. First, all workers are specially trained in radiological controls as it relates to their own job. Second, written procedures exist that require verbatim compliance. Third, radiological controls technicians and their supervisors oversee radioactive work. Fourth, personnel independent of radiological controls technicians are responsible for personnel radiation exposure records.

Fifth, a strong independent audit program is required, covering all radiological controls requirements. In all shipyards, this radiological audit group is independent of the radiological controls organization; the audit group's findings are reported regularly to senior shipyard management, including the shipyard commander or shipyard president. This group performs continuing surveillance of radioactive work. It conducts in-depth audits of specific areas of radiological controls, and checks all radiological controls requirements at least annually.

Sixth, the U.S. Department of Energy assigns to each shipyard a representative who reports to the Director, Naval Nuclear Propulsion, at Headquarters. At least one assistant to this representative is assigned full-time to audit and review radiological controls, both in nuclear-powered ships and in the shipyard. Seventh, Naval Nuclear Propulsion Program Headquarters personnel conduct periodic inspections of radiological controls in each shipyard. Similarly, there are multiple levels of audits and inspections for the other naval shore facilities, tenders, and nuclear-powered ships.
In addition to the above, various aspects of the Naval Nuclear Propulsion Program have been reviewed by other Government agencies. For example, the National Institute for Occupational Safety and Health conducted an evaluation of the radiological controls program at Portsmouth Naval Shipyard in conjunction with its mortality study at the shipyard (discussed earlier in this report). NIOSH published the results of its evaluation in a report (reference 63) in April 1983, which stated the following conclusions:

- The employee dose data provided NIOSH by Portsmouth Naval Shipyard is complete and provides a reasonable estimate of the individual worker's dose.
- The Portsmouth Naval Shipyard personnel dosimetry program provides accurate internal and external dose data.
- The external and internal doses received by Portsmouth Naval Shipyard personnel are low compared to present occupational exposure guidelines.
- The probability of unreported accidents/incidents or undocumented exposures is extremely small.
- The radiological controls employed are adequate to protect the worker from internal and external hazards.
- The impact of the nuclear work at Portsmouth Naval Shipyard to the surrounding environment is minimal or negligible.
- Nuclear operations at Portsmouth Naval Shipyard are not contributing a significant radiation dose to the general public.

Another example of an independent governmental review of the Naval Nuclear Propulsion Program was the General Accounting Office (GAO) 14-month in-depth review of various aspects of the Program's Department of Energy facilities. These Department of Energy facilities operate to the same radiological control requirements as other Naval Nuclear Propulsion Program (Naval Reactors) facilities. In August 1991 (reference 64), the GAO published the following conclusions:

- We believe Naval Reactors Laboratories are accurately measuring, recording, and reporting radiation exposures.
- Naval Reactors reported exposures show that exposures have been minimal and overall are lower than commercial nuclear facilities and other DOE facilities.

ABNORMAL OCCURRENCES

It is a fact of human nature that people make mistakes. The key to a good radiological controls program is to find the mistakes while they are small and prevent the combinations of mistakes that lead to more serious consequences. The preceding section on inspections supports the conclusion that the Naval Nuclear Propulsion Program gives more attention to errors and their prevention than to any other single subject. Requiring constant focus on improving performance of radiological work has proven effective in reducing errors.

In addition, radiological controls technicians are authorized and required to stop anyone performing work in a manner that could lead to radiological deficiencies. One definition of "deficiency" is a failure to follow a written procedure verbatim. However, the broadest interpretation of the term "deficiency" is used in the Navy's radiological controls program. *Anything involved with radiation or radioactivity that could have been done better* is also considered a radiological deficiency. All radiological deficiencies receive management attention.

Higher levels of deficiency are termed “radiological incidents.” Incidents receive further management review, including evaluation by senior personnel at Headquarters and review by the Director, Naval Nuclear Propulsion. Improvement programs over the years have constantly aimed at reducing the numbers of radiological incidents. As improvements occurred, the definition of what constituted an incident was changed to define smaller and smaller deficiencies as incidents. These changes were necessary so that the incident reporting system would continue to play a key role in upgrading radiological controls. As a result, it is not practicable to measure performance over time merely by counting numbers of radiological incidents or deficiencies.

The Department of Energy and its predecessors have used a separate reporting system that has been nearly constant over time and therefore can be used as a basis for comparison. This system requires appointing an Accident Investigation Board for a radiation exposure occurrence that causes an individual's external radiation exposure to equal or exceed 10 Rem (reference 65). The Nuclear Regulatory Commission uses similar criteria to define an abnormal occurrence; abnormal occurrences are included in the NRC's quarterly report to Congress. The Navy regularly evaluates radiological events using these criteria for comparison.

Since the beginning of operations in the Naval Nuclear Propulsion Program, there has never been a single radiation incident that met the criteria requiring appointment of an Accident Investigation Board (formerly a Type A or abnormal occurrence).

The policy of the Navy is to provide for close cooperation and effective communication with State radiological officials involving occurrences that might cause concern because of radiological effects associated with the ships or shore facilities. The Navy has reviewed radiological matters with State radiological officials in the States where naval nuclear-powered ships are based or overhauled. Although there has never been an abnormal occurrence resulting in radiological effects to the public outside these facilities or that resulted in radiological injury to residents of the States working inside these facilities, States were notified when inquiries showed public interest in the possibility such events had occurred.

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