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OCCUPATIONAL RADIATION EXPOSURE FROM NAVAL REACTORS' DEPARTMENT OF ENERGY FACILITIES

NAVAL NUCLEAR PROPULSION PROGRAM
OFFICE OF NAVAL REACTORS
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OCCUPATIONAL RADIATION EXPOSURE
FROM NAVAL REACTORS'
DEPARTMENT OF ENERGY FACILITIES

2019

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SUMMARY

The Naval Nuclear Propulsion Program is a joint Department of Energy / Department of the Navy Program with central control by a single headquarters organization. Within the Department of Energy, the organization is designated as the Office of Naval Reactors. It operates two Department of Energy laboratories; one Department of Energy site with three prototype naval nuclear propulsion plants (one operating, one defueled and undergoing dismantlement, and one that was placed into a layup condition late in the year awaiting inactivation and defueling); one Department of Energy site that operates the Expended Core Facility (for dispositioning of naval fuel and examination of irradiated test specimens) and has three inactive and defueled prototype nuclear propulsion plants; and nuclear component engineering and procurement organizations. The two Department of Energy laboratories, the Department of Energy prototype site, and the Department of Energy site with the Expended Core Facility are collectively known as the Naval Nuclear Laboratory. Table 1 shows the facilities that have conducted radioactive work associated with the Naval Reactors Program and the date when such work began. Naval Reactors' Department of Energy facilities provide research and development, engineering, training, and supply support for the Navy's 71 nuclear-powered submarines and 11 nuclear-powered aircraft carriers in operation at the end of 2019.

Radiation exposures to personnel monitored for radiation associated with Naval Reactors' Department of Energy facilities are summarized in this report. Also included in this report is radiation exposure information from the Shippingport Atomic Power Station, near Pittsburgh, Pennsylvania, prior to its dismantlement. Shippingport was developed by the Naval Reactors Program (in conjunction with Duquesne Light Company) as the world's first full-scale nuclear power plant solely for the production of electricity. Shippingport began operation in 1957. Starting in 1974, the light water breeder reactor (LWBR) core was installed at Shippingport. This was the first reactor to prove that fuel breeding was possible in a water-cooled plant. Shippingport was shut down in 1982 and, following defueling, was turned over to another Department of Energy office for dismantlement in 1984. Dismantlement was completed in 1989, which included removing all radioactive components and returning the site to unrestricted use.

Figure 1 shows the total radiation exposure in 2019 of 88 Rem has continued the Naval Reactors trend of maintaining the Program’s total radiation exposure significantly lower than the peak year of 1975. Total radiation exposure in this figure is the sum of the annual exposure of each person monitored for radiation. The increase in radiation exposure from 2018 to 2019 was expected due to the increase in radiological work associated with the S8G Prototype refueling overhaul at the Kenneth A. Kesselring Site in New York. Naval Reactors’ average annual exposure increased from 0.007 Rem per person in 2018 to 0.014 Rem per person in 2019.

The current Federal annual occupational radiation exposure limit of 5 Rem was established in 1994, 27 years after the Naval Nuclear Propulsion Program’s annual exposure limit of 5 Rem was adopted 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 1968 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 from 1980 to 2019 (i.e., no personnel have exceeded 2 Rem in any year in the last 40 years). And no civilian or military Program personnel have ever, in over 65 years of operation, exceeded any Federal lifetime limit.

The average occupational exposure of each person monitored at Naval Reactors' Department of Energy facilities since 1958 is 0.096 Rem per year. The lifetime accumulated exposure from radiation associated with Naval Reactors' Department of Energy facilities to date for all personnel monitored has averaged less than 0.3 Rem per person.

According to the standard methods for estimating risk, the lifetime risk to the group of personnel occupationally exposed to radiation associated with the Naval Reactors Program is less than the risk these same personnel have from exposure to natural background radiation. This risk is small compared to the risks accepted in normal industrial activities and to the risks regularly accepted in daily life outside of work.

The current version of this report and other reports produced by the Naval Nuclear Propulsion Program are available online at:

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

TABLE 1

INITIAL LABORATORY AND PROTOTYPE OPERATIONS

Location	Year Initial Operations Began Involving Radioactive Work
Bettis Laboratory West Mifflin, Pennsylvania	1950
Knolls Laboratory Schenectady, New York	1950[1]
Naval Reactors Facility Idaho Falls, Idaho	1953
Kenneth A. Kesselring Site Ballston Spa, New York	1955
Windsor Site Operation Windsor, Connecticut	1959[2]
Shippingport Atomic Power Station Beaver Falls, Pennsylvania	1957[3]
Bechtel Plant Machinery, Incorporated – Pittsburgh Monroeville, Pennsylvania	N/A[4]
Bechtel Plant Machinery, Incorporated – Schenectady Schenectady, New York	N/A[4]

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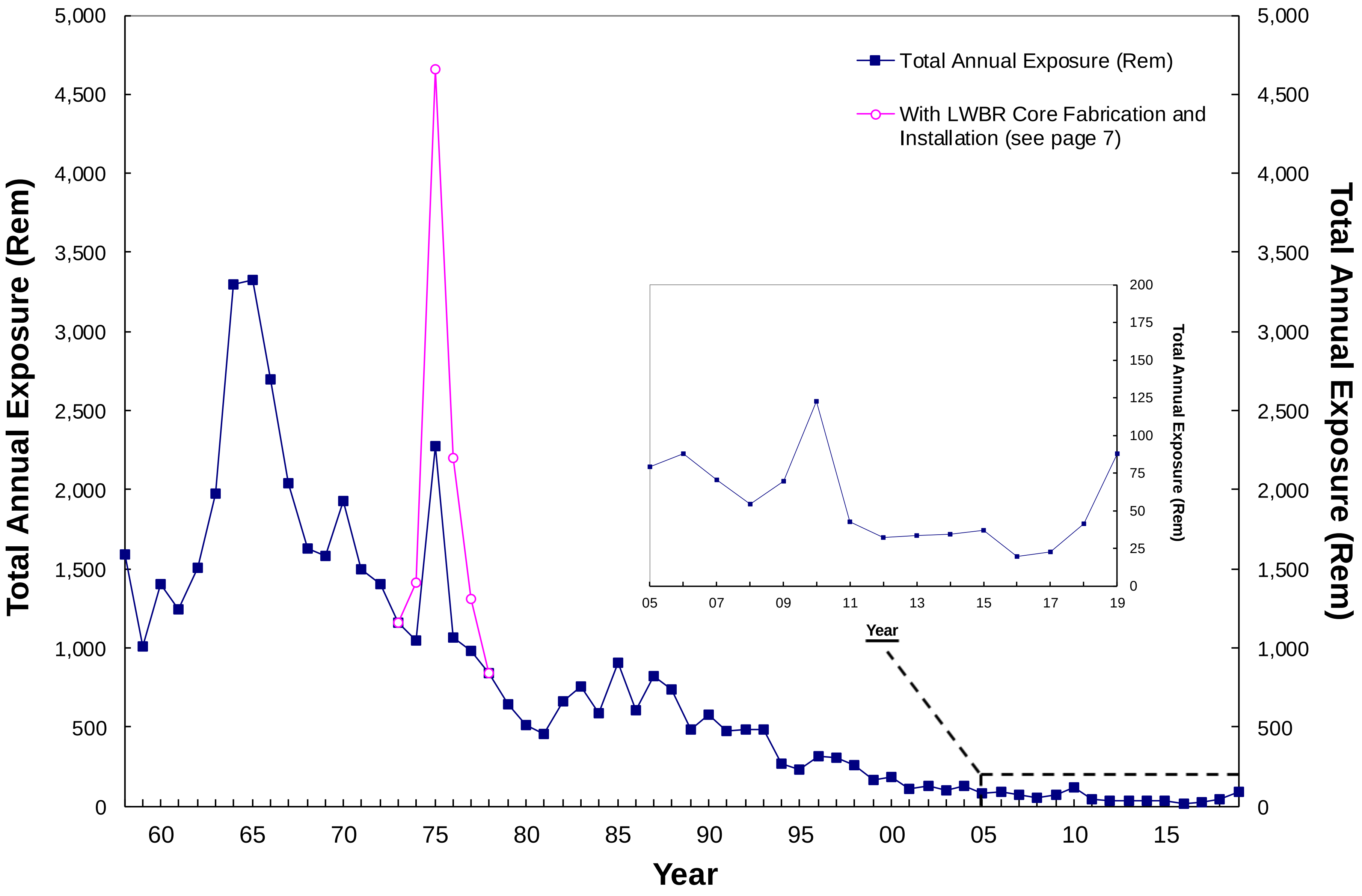
1. Naval Reactors Program work began at Knolls Laboratory in 1950. Non-Naval Reactors Program isotope separations process research work was performed at Knolls on behalf of the Atomic Energy Commission from 1947 through 1953.
2. In 1993, training operations at the Windsor Site Operation prototype stopped and the dismantlement of the prototype and support facilities began. Dismantlement was completed in 2000.
3. Shippingport Atomic Power Station was shut down in 1982 and turned over to another Department of Energy office for dismantlement in 1984. Dismantlement was completed in 1989.
4. No work involving radioactive materials is performed by Bechtel Plant Machinery, Incorporated. The small amount of radiation exposure received by personnel at these facilities is the result of visits to other Program facilities. Bechtel Plant Machinery, Incorporated – Schenectady, formerly known as Bechtel Machinery Apparatus Operation, was previously operated by Westinghouse and General Electric. Bechtel Plant Machinery, Incorporated – Pittsburgh, formerly known as Bechtel Plant Apparatus Division, was previously operated by Westinghouse.

FIGURE 1
TOTAL RADIATION EXPOSURE RECEIVED BY PERSONNEL AT NAVAL REACTORS' DEPARTMENT OF ENERGY FACILITIES
1958 - 2019



EXTERNAL RADIATION EXPOSURE

Policy and Limits

The policy of the Naval Reactors Program is to reduce exposure to personnel from ionizing radiation associated with Naval Reactors' Department of Energy facilities 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 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). 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 Reactors 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 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 radiation exposure (reference 9). The Nuclear Regulatory Commission revised the Code of Federal Regulations, Title 10, Part 20, making the 5 Rem annual limit effective on or before January 1, 1994.

The Naval Reactors Program radiation exposure limits since 1967 have been:

3 Rem per quarter
5 Rem per year

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

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[1] 1 Rem = 0.01 Sievert

[2] References are listed on pp. 58-62.

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 10), 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 of pregnancy.

Each Naval Reactors' Department of Energy facility is required to have an active program to keep radiation exposure as low as reasonably achievable.

Sources of Radiation at Prototypes and Naval Reactors Facility

One of the Naval Reactors Department of Energy sites (Kenneth A. Kesselring Site, Ballston Spa, New York) houses three prototype naval nuclear propulsion plants. Of the three prototypes at this site, one is currently undergoing a refueling overhaul, another completed its training mission as planned and has been placed in a shutdown layup condition since November 2019, and the remaining prototype has been defueled and is undergoing dismantlement. The Kenneth A. Kesselring Site is engaged in testing nuclear propulsion plant technology for the U.S. Navy and training U.S. Navy propulsion plant operators. The Naval Reactors Facility on the Idaho National Laboratory (INL) site near Idaho Falls, Idaho, has prototype plants that have been inactivated and defueled. The Naval Reactors Facility also houses the Expended Core Facility. Personnel at the Expended Core Facility receive, examine, and prepare spent naval fuel modules for interim storage or emplacement in a geological repository. The Expended Core Facility also examines the Naval Reactors Program's irradiated material samples from the INL's Reactor Technology Complex.

The radiation exposures at the prototype sites originate primarily 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 gamma and neutron radiation 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 gamma rays and a low-energy beta particle for every radioactive decay. Its half-life is 5.3 years.

Neutrons produced when reactor fuel fissions are also shielded from occupied areas by the primary and secondary shields. Radiation exposure to personnel from these neutrons during reactor operation is much less than from gamma radiation. After reactor shutdown, when maintenance and other support work is executed, no neutron exposure is detectable. Therefore, the radiation exposures at prototypes are primarily from gamma radiation.

Radiation exposure at the Expended Core Facility is also due primarily to gamma radiation emitted by irradiated reactor fuel and structural components that were inside the reactor vessel during operation and became radioactive by exposure to neutrons. Work on these components is performed remotely in specially designed shielded cells, in deep water pits where many feet of water shields personnel, or with shielded equipment used to place spent fuel into interim dry storage.

Exposures listed in this report for prototype personnel include Department of Energy employees and contractors as well as exposure to Navy staff and students involved in training at the sites. In most years, a large portion of the total radiation exposure for the Kenneth A. Kesselring Site is due to large numbers of Navy students who receive low doses associated with operating a naval nuclear propulsion plant. In 2019, the large portion of the total radiation exposure for the Kenneth A. Kesselring Site is due to the refueling overhaul. Since student training at the Naval Reactors Facility ended in 1995, the majority of radiation exposure there is due to work associated with shielded reactor fuel and servicing reactor fuel shipping containers.

In 2019, radiation exposure at the prototypes and Naval Reactors Facility was 78.9 Rem. This is an increase of 47.2 Rem from 2018. This increase was expected due to the planned prototype refueling overhaul involving higher radiation exposures compared to 2018.

Sources of Radiation at Laboratories

The two Naval Reactors' laboratories (Bettis Laboratory, near Pittsburgh, Pennsylvania; and Knolls Laboratory, near Schenectady, New York) conduct research and development work to improve nuclear propulsion plants for U.S. Navy warships. At the laboratories, external radiation exposure is attributable to examination and analysis of irradiated fuel and other materials, as well as decontamination and decommissioning of obsolete facilities. Gamma radiation is the significant contributor to dose. Although alpha and beta radiation are present, they are generally well shielded. Neutron radiation contributes very little to doses at the laboratories.

Irradiated materials include mixed fission products and activation products. The activation products are identical to those discussed in the preceding section. Fission products are the radioactive species produced by the fissioning of nuclear fuel. Fission products generally emit both beta and gamma radiation and have half-lives ranging from hours to many years. In cases where these materials emit significant levels of radiation, the analyses and examinations are performed remotely using special tooling in shielded cells similar to those used at the Expended Core Facility. With regard to fuel, the preparation of fuel specimens involves the handling of unirradiated uranium. The dose rates from these materials are generally low.

Radiation exposures for the Shippingport Atomic Power Station are also included under the heading for laboratory personnel. The sources of radiation exposure at Shippingport were similar to those at the prototype sites. From 1974 to 1977, the Bettis Laboratory fabricated and installed the Light Water Breeder Reactor (LWBR) core for

Shippingport. The fissile fuel for this core was uranium-233 and the fertile fuel was thorium-232. Enriched uranium-233 contains a significantly higher level of uranium-232 than enriched uranium-235. The radioactive decay chain of uranium-232, in turn, includes thallium-208, which emits a high-energy gamma ray with each decay; accordingly, the radiation exposure of personnel fabricating the LWBR core was much higher than for those fabricating traditional uranium-235 cores. In addition to fabrication, there was also significant radiation exposure due to LWBR installation inside the Shippingport power plant.

Also included is the small amount of exposure to personnel assigned to the Naval Reactors' Department of Energy nuclear component engineering and procurement organizations (Bechtel Plant Machinery, Incorporated – located in both Pittsburgh, Pennsylvania, and Schenectady, New York). In 2019, personnel at these facilities received a combined total of about 2.6 Rem of occupational radiation exposure. Since no radioactive material is handled at these facilities, this exposure is the result of visits to other Naval Reactors Program activities.

In 2019, the total radiation exposure at the Naval Reactors' Department of Energy laboratories was 9.0 Rem, a decrease of 0.6 Rem from 2018. The decrease of 0.6 Rem from 2018 was expected due to a decrease of in-service propulsion plant inspections.

Control of Radiation

Reactor plant shielding is designed to minimize radiation exposure to personnel. Shield design criteria establishing radiation levels in various parts of each prototype are personally approved by the Director, Naval Nuclear Propulsion. The Director also personally approved the shield design criteria for the Shippingport Atomic Power Station.

Prototype design is also controlled to keep locations where personnel need to spend time, such as watch stations, as far as practicable away from the reactor compartment shield. In addition, radiation outside propulsion plant spaces during reactor plant operation is not generally any greater than natural background radiation.

Laboratories, prototype sites, and the Expended Core Facility are designed so that radioactive material outside of reactor plants is handled only in specially designed and shielded facilities. Naval Reactors' Department of Energy facilities minimize the number of places where radioactive material is allowed. Stringent controls are in place during the movement of all radioactive material. 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 has to be conspicuously marked or placed in yellow plastic, the use of which is reserved solely for radioactive material. All personnel assigned to Naval Reactors' Department of Energy facilities 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 posted signs and barriers. Personnel are trained in the access requirements, including the requirement to wear dosimetric devices to enter these areas. Dosimetric devices are also posted near the boundaries of these areas to verify that personnel outside these areas do not require monitoring. Frequent radiation surveys are required, using instruments that are checked for proper response before use and calibrated regularly. Areas where radiation levels are greater than 0.1 Rem per 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 1975, 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 Naval Reactors' Department of Energy facilities, there already was widespread photodosimetry experience 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 radiation exposure records occurred when material problems with the film caused abnormal readings, such as film clouding. In such cases, a conservative estimate of radiation exposure was entered.

Thermoluminescent dosimeters (TLDs) have been the dosimetric devices worn by personnel to measure their exposure to gamma, neutron, and beta radiation since 1975. The rapid readout of TLDs was one reason for changing from film badges to TLDs. Processing film badges was a time-consuming chemical process. TLDs also permit more frequent measurement of a worker's radiation exposure than film badges did. TLDs are processed at least quarterly, and for those individuals who are expected to receive higher exposures, at least monthly.

From 1975 to July 2006, a calcium fluoride TLD was used at prototypes while a lithium fluoride TLD was used at the laboratories as explained below. Starting in July 2006, the prototypes and laboratories began using the same lithium fluoride TLD. Tests performed by the Navy showed that both 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.

Since the types of radiation to which personnel are exposed are different at the laboratories than at the prototypes and the Expended Core Facility, the design of the dosimeters were different. At the prototypes and the Expended Core Facility, because the source of radiation exposure is primarily high-energy gamma radiation, calcium fluoride TLDs were used. At the laboratories, high- and low-energy gamma radiation and beta radiation are present; therefore, lithium fluoride TLDs are used. Lithium fluoride TLDs were worn in addition to calcium fluoride TLDs at the Expended Core Facility from 1985 until 1998, when a review of monitoring data identified that the low-energy gamma and beta radiation doses were negligible compared to doses requiring monitoring by Federal standards; therefore, monitoring with lithium fluoride TLDs was determined to be no longer necessary for routine work. Shippingport used dosimeters similar to the ones used at the prototypes. At all facilities, separate TLDs are used for the few applications where neutron monitoring is required.

The calcium fluoride TLDs that were used at the prototypes and the Expended Core Facility 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 are in contact with a metallic heating strip with heater wires extending through the ends of a surrounding glass envelope. The glass bulb is protected by a plastic case designed to permit the proper response to gammas of various energies. Gammas of such low energy that they will not penetrate the plastic case constitute less than a few percent of the total gamma radiation present. To read the radiation dose, 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.

The lithium fluoride TLD contains four chips of lithium fluoride with added manganese, copper, and phosphorous. The four lithium fluoride chips are encapsulated in Teflon and mounted into pre-drilled holes in an aluminum card. Lithium fluoride TLDs are read automatically by the processing unit. The operator can load as many as 1,400 lithium fluoride cards into the reader, which automatically reads one TLD card at a time. To read the radiation dose from the lithium fluoride TLDs, the operator removes the aluminum cards from the plastic cases and places them in cartridges that are loaded into the microprocessor-controlled TLD reader. To start the read process, one TLD card is automatically removed from the cartridge and moved to the read position where the bar code is scanned. The four chips are then simultaneously heated to several hundred degrees Celsius using four precisely temperature-controlled streams of hot nitrogen gas. When heated, the lithium fluoride TLDs (like the calcium fluoride TLDs) give off light in proportion to the radiation they received. The light is converted to a graphic and digital readout, as well as digitally stored on a computer hard disk. This heating cycle also anneals the TLD chips so that the dosimeter is zeroed and ready for subsequent use. After readout, the TLD is automatically moved to a removal cartridge. The entire read cycle for one card takes, on average, 30 seconds. After processing, the computer converts the light output to dose in units of Rem.

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.

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 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 prior to processing TLDs. 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.

In addition to these calibrations and checks, the laboratories and prototypes have an independent quality assurance program to monitor the accuracy of TLDs and the TLD readers in use. TLDs are pre-exposed to exact amounts of radiation by the National Institute of Standards and Technology (NIST) or by a NIST-traceable irradiator at one of the laboratories and provided to the prototype and/or laboratory for reading. To ensure objectivity, the prototype or laboratory being tested is not told of the radiation values to which each dosimeter has been exposed. The results are then compared to the actual exposures. If these tests find any inaccuracies that exceed established permissible error, appropriate corrective action (such as recalibration of a TLD reader) is taken immediately. In addition, the laboratories participate in nationwide comparison studies as they are conducted. 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.

The lithium fluoride dosimetric system in the Naval Nuclear Propulsion Program is accredited under the National Voluntary Laboratory Accreditation Program (Laboratory Code 100565-0). This voluntary program, sponsored by NIST, provides independent review of dosimetry services for consistency with accepted standards.

Although the official record of radiation exposure is obtained from the 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. This pocket dosimeter is required in addition to a TLD when entering a reactor compartment or other high radiation area.

Discrepancies that occur between TLD and pocket dosimeter measurements or unusual TLD measurements are investigated. These investigations include making independent, best estimates of the worker's radiation 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.

Historically, monitoring personnel for beta radiation was not normally required at the prototypes. For most work at these sites, materials such as the metal boundaries of the reactor coolant system, clothing, eyeglasses, or plastic contamination control materials effectively shield personnel from beta radiation. However, since the transition to the lithium fluoride dosimetric system in 2006, all personnel at the prototype sites are now monitored with lithium fluoride TLDs which can measure shallow radiation dose (which includes beta radiation). Because personnel at the laboratory sites can be exposed to both gamma and beta radiation, beta monitoring for laboratory personnel has routinely been performed using either film badges or lithium fluoride TLDs throughout the Program’s history.

Monitoring for personnel external exposure due to alpha radiation is not performed. Alpha radiation does not penetrate past the dead layer of a person's skin and therefore does not contribute to an individual's external radiation dose.

Physical Examinations

Radiation medical examinations have been required since the beginning of operations by Naval Reactors' Department of Energy facilities for personnel who perform work involving radioactive contamination or who could exceed in 1 year the maximum radiation exposure allowed to a member of the general public (i.e., 0.1 Rem). These examinations are conducted in accordance with standard protocols. In these examinations the doctor pays special attention to any condition that might medically disqualify a person from receiving occupational radiation exposure, pose a health risk or safety hazard to the individual or to co-workers, or detrimentally affect 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 workers, the failure rate is a few percent. However, failure of this examination does not mean a worker will not have a job. Because workers spend most of their time performing non-radioactive work, inability to qualify for radioactive work does not mean they cannot work at the facility in any capacity. No worker at Naval Reactors' Department of Energy facilities 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, and at termination of radioactive work in the Naval Reactors 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 pre-cancerous condition. Laboratory procedures include urinalysis, blood analysis, and comparison of blood constituents to a specific set of standards. If an examination disqualifies an individual, the individual is restricted from receiving occupational radiation exposure pending medical evaluation.

Radiological Controls Training

Periodic radiological controls training is performed to ensure that all workers understand (a) the general and specific radiological conditions which they might encounter, (b) their responsibility to the Naval Reactors Program and the public for safe handling of radioactive materials, (c) the risks associated with radiation exposure, and (d) 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. A typical course for workers ranges from 16 to 32 hours. The following are the training requirements for a fully qualified worker:

1. Radiation Exposure Control

   a. State the limits for whole body penetrating radiation. Explain that the Rem is a unit of biological dose from radiation.

   b. Discuss the importance of the individual keeping track of his/her own radiation exposure. Know how to obtain year-to-date radiation exposure information.

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

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

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

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

   g. Discuss the action to be taken if an individual loses dosimetric equipment while in a posted radiation or high radiation area.

h. Discuss how to obtain and turn in dosimetric equipment.

i. Know that TLDs for monitoring whole body radiation exposure are always worn on the chest (waist for fleet personnel in prototype training) and pocket dosimeters are worn at the same location on the body as the TLD 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 in prototype training), when certain technical criteria are met. Know that only radiological controls personnel can authorize movement of dosimetric equipment from areas of the body where dosimeters are normally worn to other areas of the body.

j. Be aware of the seriousness of violating instructions on radiation warning signs and unauthorized passage through barriers.

k. Explain how "stay times" are used.

l. Know that radiological work at a facility has no significant effect on the environment and personnel living adjacent to the facility and to personnel within the facility.

m. Explain the risk associated with personnel radiation exposure. Know that any amount of radiation exposure, no matter how small, might involve some risk; however, radiation 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 practicable levels at all times, the presently permitted radiation 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. 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 effect) is considered to be even smaller than the cancer risk and that genetic effects have not been observed in human beings.

n. Know how often an individual shall read his/her pocket dosimeter while in a posted high radiation area. Know that a worker shall leave a posted high radiation area when his/her pocket dosimeter reaches three quarters scale (for ionization chambers) or when a preassigned radiation exposure is reached, whichever is lower.

o. 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 work area when either the assigned stay time or pocket dosimeter reading is reached.

2. Contamination Control

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

   b. Discuss how contamination is detected on personnel.

   c. Discuss how contamination is removed from objects and personnel.

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

   e. State the surface contamination limits. Discuss the meaning of the units for measuring contamination.

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

   g. For personnel who are trained to wear respiratory protection equipment, state the controls for use of such equipment. Know 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 or breathing becomes difficult is to remove the 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. Discuss the actions to be taken if personnel contamination monitoring equipment alarms while conducting personnel monitoring.

   j. Discuss the procedure to package and remove a contaminated item from a controlled surface contamination area.

   k. Know that if a worker’s skin receives radioactive contamination associated with laboratory or prototype operations, no health effects are expected.

   l. Discuss the procedures for donning and removing a full set of anticontamination clothing.

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

4. Waste Disposal

    a. Discuss how individual workers can reduce the amount of radioactive liquid and solid waste generated for the specific type of duties performed.

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

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

5. Radiological Casualties

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

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

    c. Discuss procedures to be followed when notified that airborne radioactivity is above the limit.

    d. Discuss procedures to be followed if a high radiation area is improperly controlled.

    e. Discuss actions to be taken when an individual discovers his/her pocket dosimeter is off-scale, alarms, or has recorded a higher reading than expected.

6. Responsibilities of Individuals: Discuss actions required in order to fulfill the worker's responsibilities. Discuss 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. Discuss 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 used by the organization.

    b. For applicable workers, demonstrate the proper procedure for donning and removing 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 and remove an item from a controlled surface contamination area.

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. This includes demonstrating how to don and remove the type of respiratory equipment in conjunction with anticontamination clothing, if anticontamination clothing must be worn with the respiratory equipment. In addition, individuals who are trained to wear respiratory equipment demonstrate the proper response to take if supply air is lost while wearing one.

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. <u>Supervisor Knowledge Requirements</u>

a. Understand the processes used to control nuclear work and how to apply these processes to work execution and risk mitigation.

b. Understand how an effective personnel exposure reduction estimating and planning process is used to achieve doses as low as reasonably achievable (ALARA). Explain how estimates are applied and managed, including the concept of avoidable radiation exposure and how it is documented.

c. Understand 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.

d. Understand how to apply technical work document (TWD) engineering decision points during the conduct of nuclear work.

e. Understand the tools engineered into TWDs to ensure radiological control levels are not exceeded.

f. Understand 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.

g. Understand the requirements for, and the significance of, radiological inspections steps in a TWD.

h. Understand the purpose and use of the radiological deficiency reporting and deficiency log systems.

i. Understand how to develop and conduct a pre-job briefing to assess work readiness.

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

k. Understand the supervisor's role for work in radiation fields greater than or equal to 1 Rem/hour. Understand that a detailed gradient survey is required to be specified in the TWD. [For supervisors who supervise this type of work]

l. Understand the requirement and basis for multiple dosimeter placement. [For supervisors who supervise this type of work]

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

n. Understand the contamination control systems in effect at the facility and the associated levels for which corresponding increases in contamination controls are required while working in controlled surface contamination areas.

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

p. Understand that in the following situations, 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 (i.e., fire, toxic gas leak, natural disaster).

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

r. Understand the requirements for temporarily securing a radiological work site.

s. Understand that proper housekeeping during work execution reduces radiological risk.

t. Understand the purpose of and how to conduct a radiological work debrief.

u. Understand the need for ensuring a worker's training and skills match the complexity of the work.

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

To continue as a worker or supervisor, personnel must requalify in a manner similar to the initial qualification at least every 2 years. Between these qualification periods, personnel are required to participate in a continuing training program, and the effectiveness of that continuing training is tested randomly and 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 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 conditions, state the immediate corrective actions required, state what additional measures are required, and perform a final analysis of the measurements to identify the specific problem. After qualification, periodic training sessions are required in which all radiological controls technicians and supervisors maintain their ability to handle situations similar to those covered in the oral examinations. At least every 2½ years, radiological controls personnel must 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 these qualification periods, radiological controls technicians and supervisors are selected at random for additional written and practical work examinations to assess their retention of knowledge and practical abilities. They also participate in unannounced drills.

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

Nuclear Power Training

Before being assigned to a prototype naval nuclear propulsion plant for training, military and civilian personnel are required to pass a 6-month basic training course at the Navy's Nuclear Power School in Charleston, South Carolina. While at Nuclear Power School and continuing while at the prototype, these personnel receive 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.

Before becoming qualified as the shift supervisor of a naval nuclear propulsion prototype plant (that is, the senior contractor supervisor on each shift who is responsible for the timeliness and quality of all training conducted by personnel assigned to his or her crew), the shift supervisor candidate must pass several 8-hour written examinations and a sequence of oral examinations. A key part of these qualification examinations is radiological controls.

Before serving as plant manager of a naval nuclear propulsion prototype plant, the prospective plant manager attends a 3-month course at the Naval Reactors Program Headquarters. The radiological controls portion of this course covers advanced topics and assumes that the individual already has detailed familiarity with naval nuclear propulsion plant radiological controls. The prospective plant manager must pass both written and oral examinations in radiological controls during this course before assuming the position of plant manager of a naval nuclear propulsion prototype plant.

Radiation Exposure Reduction

Keeping personnel radiation exposures as low as reasonably achievable involves all levels of management at Naval Reactors' Department of Energy 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 radiation exposure under certain levels and to minimize the number of workers occupationally exposed to radiation. Goals are also set for the total cumulative personnel radiation exposure for each major job and for the whole year. These goals are deliberately made difficult 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 exposure control levels, which are lower than the Program's quarterly and annual limits. Control levels at Naval Reactors' Department of Energy facilities range from 0.1 Rem to 2 Rem (maximum of 1 Rem for Fleet personnel assigned to the prototypes) for the year (depending on the amount of radioactive work scheduled), whereas 5 Rem per year is the Program annual limit.

To achieve the benefits of lower control levels in reducing 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 radiological work:

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 television)
- 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 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 most beta radiation)
- 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 Reactors Program has stressed the reduction of personnel radiation exposure. Measures that have been taken to reduce exposure include standardization and optimization of procedures, development of new tooling, improved use of shielding, improved radiation monitoring methods, and compliance with strict contamination control measures. For example, most work involving radioactive contamination is performed in total containment. This practice minimizes the potential for spreading contamination and thus reduces work disruptions, simplifies working conditions, and minimizes the cost and radiation exposure during cleanup.

Lessons learned during radioactive work and new ways to reduce radiation exposure developed at one organization are made available for use by other organizations in the Naval Reactors 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 radiation exposure at Naval Reactors' Department of Energy facilities have also had other benefits, such as reduced cost to perform radioactive work and improved reliability. Among other things, detailed work planning, rehearsing, 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

The total occupational radiation exposure received by all personnel at Naval Reactors' Department of Energy facilities in 2019 was 88 Rem. Tables 2 and 3 summarize radiation exposure received at Naval Reactors' Department of Energy facilities since 1958.

Figure 1 (on page 4) shows the total occupational radiation exposure received at Naval Reactors' Department of Energy facilities. The data show major increases in total radiation exposure in 1964 through 1966 and in 1975. In 1964 through 1966, and in 1975, the increase in the exposures was primarily due to an increase in reactor plant overhaul and refueling efforts. Increased occupational radiation exposure occurred in 1974 through 1977 associated with a civil project: the fabrication and installation of the light water breeder reactor (LWBR) at the Shippingport Atomic Power Station. LWBR work was unique because the fuel was uranium-233 rather than uranium-235. In addition to fabrication, there was also increased radiation exposure due to LWBR installation inside the Shippingport power plant.

Decreases in total annual radiation exposures, numbers of personnel monitored, and numbers of personnel with annual exposures over 2 Rem have been achieved as a result of continuing efforts to reduce radiation exposures to the minimum practicable. From 1980 to 2019, the total annual radiation exposure for the laboratories has averaged about 27.5 Rem and for all of the prototype sites has averaged about 272 Rem.

Since a worker is usually exposed to radiation in more than 1 year, the total number of personnel monitored cannot be obtained by adding the annual numbers. The total number of personnel monitored for radiation exposure associated with Naval Reactors' Department of Energy facilities is about 190,742 (including approximately 110,319 Navy personnel trained as naval nuclear propulsion plant operators at the prototype sites). Table 4 provides further information about the distribution of their radiation exposures. In 2019, 99.7 percent of those monitored for radiation received less than 0.5 Rem for that year. Since 1958, the average annual radiation exposure per person monitored is 0.096 Rem—less than the 0.3 Rem average annual radiation exposure a person receives from natural background radiation (including the inhalation of radon and its progeny) and less than the radiation exposure allowed for an unmonitored member of the general public (reference 11).

Table 4 also lists the numbers of personnel who have exceeded the 3 Rem quarterly exposure limit. The total number of persons who have exceeded the quarterly limit since the limit was imposed in 1960 is 14. Of these, 13 personnel had quarterly exposures in the range of 3 to 4 Rem, and the person with the highest exposure received 8.1 Rem in a quarter; no one has exceeded the quarterly limit since 1973. In none of these cases did personnel exceed the pre-1994 Federal accumulated limit of 5 Rem for each year of age over 18, which was also established in 1960. Since it was adopted in 1967, no Program personnel have exceeded Naval Reactors' limit of 5 Rem per year for radiation associated with the Naval Reactors Program at Department of Energy facilities. The 5 Rem per year Federal limit was formally adopted by the Department of Energy in 1989 and by the Nuclear Regulatory Commission in 1994.

The average lifetime accumulated radiation exposure for the 190,742 personnel who have been monitored at Naval Reactors' Department of Energy facilities is about 0.273 Rem. Although they account for a significant percentage of the radiation exposure received at the prototype sites each year, the approximately 110,319 Navy personnel trained to date receive a small percentage of their lifetime radiation exposure at the prototype sites. The bulk of their radiation exposure is received later in their naval careers when they are assigned to ships or maintenance activities; therefore, their accumulated dose is not representative of the lifetime radiation exposure received by personnel permanently assigned to these facilities. If the Navy trainees are subtracted from the total number of personnel monitored, the average lifetime accumulated exposure from radiation associated with Naval Reactors' Department of Energy facilities is about 1 Rem. This radiation exposure is much less than the exposure the average American receives from natural background radiation during his or her working lifetime (reference 11).

TABLE 2
OCCUPATIONAL RADIATION EXPOSURE RECEIVED BY PERSONNEL MONITORED AT NAVAL REACTORS' DEPARTMENT OF ENERGY LABORATORIES

	Number of Persons Monitored Per Year Who Received Exposure in the Following Ranges (Rem)						Total Personnel Monitored	Total Exposure (Rem)[1]
Year	0-1	1-2	2-3	3-4	4-5	>5[2]		
1958	1,923	74	15	20	8	31	2,071	762
1959	2,050	94	21	16	4	0	2,185	586
1960	2,056	105	43	14	4	3	2,225	581
1961	3,717	120	57	27	9	4	3,934	671
1962	3,956	67	38	13	3	1	4,078	414
1963	5,124	135	47	27	6	1	5,340	647
1964	5,195	265	135	127	52	23	5,797	1,854
1965	5,586	188	36	33	2	0	5,845	977
1966	4,493	105	36	12	3	1	4,650	600
1967	5,006	120	52	34	13	0	5,225	668
1968	4,958	96	44	29	16	0	5,143	606
1969	5,589	72	49	42	26	0	5,778	754
1970	6,346	99	61	39	47	0	6,592	819
1971	7,378	109	48	32	5	0	7,572	646
1972	7,000	138	41	17	2	0	7,198	626
1973	6,867	68	7	0	0	0	6,942	368
1974	7,568	96	28	1	1	0	7,694	221[3]
1975	4,719	290	151	57	68	0	5,285	280[3]
1976	5,304	371	88	0	0	0	5,763	219[3]
1977	4,639	81	5	0	0	0	4,725	201[3]
1978	3,609	10	0	0	0	0	3,619	143
1979	3,367	4	0	0	0	0	3,371	100
1980	3,330	0	0	0	0	0	3,330	78
1981	2,510	0	0	0	0	0	2,510	72
1982	2,672	0	0	0	0	0	2,672	82
1983	2,717	6	0	0	0	0	2,723	93
1984	2,933	1	0	0	0	0	2,934	67
1985	2,338	4	0	0	0	0	2,342	59
1986	2,261	0	0	0	0	0	2,261	35
1987	2,189	0	0	0	0	0	2,189	27
1988	2,029	0	0	0	0	0	2,029	31
1989	2,108	0	0	0	0	0	2,108	31
1990	2,228	0	0	0	0	0	2,228	28
1991	2,216	0	0	0	0	0	2,216	28
1992	2,162	0	0	0	0	0	2,162	25
1993	2,066	0	0	0	0	0	2,066	22
1994	1,894	0	0	0	0	0	1,894	25
1995	1,853	0	0	0	0	0	1,853	30
1996	1,814	0	0	0	0	0	1,814	19
1997	1,795	0	0	0	0	0	1,795	18
1998	1,778	0	0	0	0	0	1,778	15
1999	2,017	0	0	0	0	0	2,017	17
2000	1,970	0	0	0	0	0	1,970	16
2001	1,856	0	0	0	0	0	1,856	14
2002	1,877	0	0	0	0	0	1,877	16
2003	1,862	0	0	0	0	0	1,862	13
2004	1,890	0	0	0	0	0	1,890	19
2005	1,972	0	0	0	0	0	1,972	15

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1. Data for 1958-1962 do not include exposure information for personnel monitored at the Shippingport Atomic Power Station. Data are not available in summary format.
2. Limit for Naval Reactors' Department of Energy facilities was changed to 5 Rem per year in 1967.
3. Total radiation exposure for 1974 -1977 does not include exposure received as part of fabrication and installation of the Light Water Breeder Reactor core at the Shippingport Atomic Power Station. If included, the totals become: 588, 2,660, 1,354, and 524.

TABLE 2 **(CONTINUED)**
OCCUPATIONAL RADIATION EXPOSURE RECEIVED BY PERSONNEL MONITORED AT NAVAL REACTORS' DEPARTMENT OF ENERGY LABORATORIES

	Number of Persons Monitored Per Year Who Received Exposure in the Following Ranges (Rem)						Total Personnel Monitored	Total Exposure (Rem)
Year	0-1	1-2	2-3	3-4	4-5	>5		
2006	1,879	0	0	0	0	0	1,879	14
2007	1,977	0	0	0	0	0	1,977	17
2008	1,861	0	0	0	0	0	1,861	11
2009	1,858	0	0	0	0	0	1,858	7
2010	1,938	0	0	0	0	0	1,938	11
2011	1,946	0	0	0	0	0	1,946	7
2012	1,965	0	0	0	0	0	1,965	5
2013	1,922	0	0	0	0	0	1,922	12
2014	1,847	0	0	0	0	0	1,847	10
2015	1,918	0	0	0	0	0	1,918	8
2016	2,122	0	0	0	0	0	2,122	6
2017	2,165	0	0	0	0	0	2,165	9
2018	2,189	0	0	0	0	0	2,189	10
2019	2,398	0	0	0	0	0	2,398	9

TABLE 3
OCCUPATIONAL RADIATION EXPOSURE RECEIVED BY PERSONNEL MONITORED AT NAVAL REACTORS' DEPARTMENT OF ENERGY PROTOTYPE SITES AND NAVAL REACTORS FACILITY

	Number of Persons Monitored Per Year Who Received Exposure in the Following Ranges (Rem)						Total Personnel Monitored	Total Exposure (Rem)[1]
Year	0-1	1-2	2-3	3-4	4-5	>5[2]		
1958	2,415	83	77	50	27	3	2,655	833
1959	2,390	63	18	3	1	0	2,475	420
1960	2,558	126	40	28	2	2	2,756	822
1961	2,600	79	42	13	2	0	2,736	576
1962	3,653	185	45	20	8	4	3,915	1,090
1963	4,354	270	74	29	12	0	4,739	1,332
1964	4,940	203	102	65	16	2	5,328	1,446
1965	5,595	267	110	80	73	58	6,183	2,351
1966	5,765	311	145	81	39	7	6,348	2,099
1967	6,409	241	72	35	12	0	6,769	1,372
1968	6,564	172	69	5	0	0	6,810	1,026
1969	5,713	188	57	9	0	0	5,967	827
1970	5,748	215	82	12	0	0	6,057	1,113
1971	5,499	148	26	1	0	0	5,674	856
1972	7,634	116	3	0	0	0	7,753	773
1973	7,518	181	28	0	0	0	7,727	791
1974	8,427	109	20	9	3	0	8,568	824
1975	7,515	270	131	98	83	0	8,097	1,998
1976	8,282	145	19	0	0	0	8,446	845
1977	8,813	101	17	2	0	0	8,933	782
1978	8,890	157	1	0	0	0	9,048	698
1979	9,908	64	0	0	0	0	9,972	546
1980	9,818	11	0	0	0	0	9,829	433
1981	9,679	2	0	0	0	0	9,681	381
1982	10,464	25	0	0	0	0	10,489	576
1983	10,816	77	0	0	0	0	10,893	660
1984	8,694	13	0	0	0	0	8,707	525
1985	9,136	127	0	0	0	0	9,263	851
1986	8,122	35	0	0	0	0	8,157	576
1987	9,021	47	0	0	0	0	9,068	798
1988	8,328	43	0	0	0	0	8,371	707
1989	7,261	12	0	0	0	0	7,273	451
1990	6,548	73	0	0	0	0	6,621	549
1991	6,369	57	0	0	0	0	6,426	444
1992	5,301	125	0	0	0	0	5,426	458
1993	4,934	133	0	0	0	0	5,067	466
1994	4,368	16	0	0	0	0	4,384	241
1995	3,645	0	0	0	0	0	3,645	203
1996[3]	3,221	37	0	0	0	0	3,258	304
1997	3,450	29	0	0	0	0	3,479	295
1998	3,379	27	0	0	0	0	3,406	241
1999	3,448	7	0	0	0	0	3,455	150
2000	3,216	14	0	0	0	0	3,230	165
2001	3,090	13	0	0	0	0	3,103	99
2002	2,947	22	0	0	0	0	2,969	113
2003	2,748	4	0	0	0	0	2,752	90
2004	3,110	18	0	0	0	0	3,128	111
2005	3,279	0	0	0	0	0	3,279	65

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1. Data for 1958-1971 do not include Combustion Engineering personnel monitored at Windsor Site Operation who did not become employees of KAPL when operation of the Windsor Site was transferred from Combustion Engineering to General Electric.
2. Limit for Naval Reactors' Department of Energy facilities was changed to 5 Rem per year in 1967.
3. Student training and prototype operation at NRF ended in 1995.

TABLE 3 **(CONTINUED)**
OCCUPATIONAL RADIATION EXPOSURE RECEIVED BY PERSONNEL MONITORED AT NAVAL REACTORS' DEPARTMENT OF ENERGY PROTOTYPE SITES AND NAVAL REACTORS FACILITY

	Number of Persons Monitored Per Year Who Received Exposure in the Following Ranges (Rem)						Total Personnel Monitored	Total Exposure (Rem)
Year	0-1	1-2	2-3	3-4	4-5	>5		
2006	3,014	1	0	0	0	0	3,014	74
2007	3,287	0	0	0	0	0	3,287	54
2008	3,608	0	0	0	0	0	3,608	45
2009	3,414	0	0	0	0	0	3,414	64
2010	3,969	14[1]	0	0	0	0	3,983	113
2011	4,023	0	0	0	0	0	4,023	37
2012	4,084	0	0	0	0	0	4,084	27
2013	3,728	0	0	0	0	0	3,728	21
2014	3,856	0	0	0	0	0	3,856	24
2015	3,924	0	0	0	0	0	3,924	29
2016	3,822	0	0	0	0	0	3,822	13
2017	3,869	0	0	0	0	0	3,869	14
2018	4,067	0	0	0	0	0	4,067	32
2019	4,094	5[2]	0	0	0	0	4,099	79

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1. These exposures were due to planned prototype maintenance in higher radiation fields as discussed in the 2010 version of this report; 11 were Naval shipyard personnel.
2. These exposures were due to planned prototype refueling overhaul in higher radiation fields as discussed elsewhere in this report; all 5 were Naval shipyard personnel.

TABLE 4
NAVAL REACTORS' DEPARTMENT OF ENERGY FACILITIES
DISTRIBUTION OF PERSONNEL RADIATION EXPOSURE

Year	Average Rem Per Person Monitored[1]		% of Personnel Who Received Greater Than 1 Rem[1]		Number Exceeded 3 Rem/Quarter
	Prototype & NRF	Laboratory	Prototype & NRF	Laboratory	
1958	0.314	0.368	9.0	7.1	0
1959	0.170	0.268	3.4	6.2	0
1960	0.298	0.261	7.2	7.6	1
1961	0.211	0.171	5.0	5.5	0
1962	0.278	0.102	6.7	3.0	1
1963	0.281	0.121	8.1	4.0	0
1964	0.271	0.320	7.3	10.4	2
1965	0.380	0.167	9.5	4.4	1
1966	0.331	0.129	9.2	3.4	1
1967	0.203	0.128	5.3	4.2	1
1968	0.151	0.118	3.6	3.6	0
1969	0.139	0.130	4.3	3.3	0
1970	0.184	0.124	5.1	3.7	5
1971	0.151	0.085	3.1	2.6	1
1972	0.100	0.087	1.5	2.8	0
1973	0.102	0.053	2.7	1.1	1
1974	0.096	0.076	1.6	1.6	0
1975	0.247	0.503	7.2	10.7	0
1976	0.100	0.235	1.9	8.0	0
1977	0.088	0.111	1.3	1.8	0
1978	0.077	0.040	1.7	0.3	0
1979	0.055	0.030	0.6	0.1	0
1980	0.044	0.023	0.1	0.0	0
1981	0.039	0.029	0.0	0.0	0
1982	0.055	0.031	0.2	0.0	0
1983	0.061	0.034	0.7	0.2	0
1984	0.060	0.023	0.1	0.0	0
1985	0.092	0.025	1.4	0.2	0
1986	0.071	0.015	0.4	0.0	0
1987	0.088	0.012	0.5	0.0	0
1988	0.084	0.015	0.5	0.0	0
1989	0.062	0.015	0.2	0.0	0
1990	0.083	0.013	1.1	0.0	0
1991	0.069	0.013	0.9	0.0	0
1992	0.084	0.012	2.3	0.0	0
1993	0.092	0.011	2.6	0.0	0
1994	0.055	0.013	0.3	0.0	0
1995	0.056	0.016	0.0	0.0	0
1996[2]	0.093	0.011	1.1	0.0	0
1997	0.085	0.010	0.8	0.0	0
1998	0.071	0.008	0.8	0.0	0
1999	0.043	0.008	0.2	0.0	0
2000	0.051	0.008	0.4	0.0	0
2001	0.032	0.008	0.4	0.0	0
2002	0.038	0.009	0.7	0.0	0
2003	0.033	0.007	0.2	0.0	0
2004	0.036	0.010	0.4	0.0	0
2005	0.020	0.007	0.0	0.0	0
2006	0.025	0.007	0.2	0.0	0

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1. Laboratory data for 1958-1962 do not include exposure information for personnel monitored at the Shippingport Atomic Power Station. Data are not available in summary format. Prototype data for 1958-1971 do not include Combustion Engineering personnel monitored at the Windsor Site Operation, who did not become employees of KAPL when operation of the Windsor Site was transferred from Combustion Engineering to General Electric.
2. Student training and prototype operation at NRF ended in 1995.

TABLE 4 **(CONTINUED)**
NAVAL REACTORS' DEPARTMENT OF ENERGY FACILITIES
DISTRIBUTION OF PERSONNEL RADIATION EXPOSURE

Year	Average Rem Per Person Monitored		% of Personnel Who Received Greater Than 1 Rem		Number Exceeded 3 Rem/Quarter
	Prototype & NRF	Laboratory	Prototype & NRF	Laboratory	
2007	0.016	0.008	0.0	0.0	0
2008	0.012	0.005	0.0	0.0	0
2009	0.018	0.004	0.0	0.0	0
2010	0.028	0.005	0.4	0.0	0
2011	0.009	0.003	0.0	0.0	0
2012	0.007	0.002	0.0	0.0	0
2013	0.006	0.006	0.0	0.0	0
2014	0.006	0.005	0.0	0.0	0
2015	0.007	0.004	0.0	0.0	0
2016	0.003	0.003	0.0	0.0	0
2017	0.004	0.004	0.0	0.0	0
2018	0.008	0.004	0.0	0.0	0
2019	0.019	0.004	0.1	0.0	0
Average	0.098	0.092	2.0	2.4	0
Overall Average	0.096		2.1		

Table 5 provides information on the distribution of lifetime accumulated radiation exposures for all personnel, excluding visitors, who were monitored in 2019 for radiation exposure associated with Naval Reactors' Department of Energy facilities.

TABLE 5
LIFETIME RADIATION EXPOSURE ASSOCIATED WITH
NAVAL REACTORS' DEPARTMENT OF ENERGY FACILITIES

Range of Lifetime Accumulated Radiation Exposures (Rem)	Personnel Monitored in 2019 with Lifetime Accumulated Radiation Exposure Within that Range
0-5	5,338 (99.11%)
5-10	38 (0.70%)
10-15	10 (0.19%)
>15	0 (0.00%)

Until the 1994 changes to the Code of Federal Regulations, Title 10, Part 20, the Federal radiation exposure limits used in the U.S. limited an individual's lifetime exposure to 5 Rem for each year beyond age 18. With the 1994 changes, lifetime radiation 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 that organizations control lifetime accumulated radiation exposure to less than 1 Rem times the person's age (reference 10). Among all personnel monitored in 2019, 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 the Naval Reactors Program.

INTERNAL RADIOACTIVITY

Policy and Limits

Naval Reactors' policy on internal radioactivity for personnel associated with Naval Reactors' Department of Energy facilities 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 specified 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). Since 1972, no one has received more than one-tenth (10 percent) of the Federal annual internal occupational exposure limit from internal radiation exposure caused by radioactivity associated with work at Naval Reactors' Department of Energy facilities. Since 1980, 27 personnel have had internally deposited radioactivity greater than one-thousandth (0.1 percent) of the Federal annual limit on intake (ALI) from radioactivity associated with work at Naval Reactors' Department of Energy facilities or greater than 0.01 millionths of a curie of cobalt-60 (about 0.05 percent of the ALI). The equivalent whole body dose associated with each of these events was less than 0.050 Rem (about one-sixth of the average annual radiation exposure a member of the general public receives from natural background sources in the U.S.). Table 6 includes a summary of internal contamination events at Naval Reactors' Department of Energy Facilities. Although these occurrences had no adverse impact on the health of the personnel involved, each of these events was thoroughly evaluated to prevent recurrence.

Before 1972, two individuals had internal depositions between 50 and 80 percent of the Maximum Permissible Lung Burden (MPLB), and three individuals had internal depositions ranging from 10 to 50 percent of the MPLB[1]; no one had a deposition that exceeded the MPLB (the MPLB is the level of radioactivity retained in the individual's lung that would result in an exposure to the lung equal to the dose limit for the lung of 15 Rem per year if the radioactivity level remained constant throughout the year). Additionally, one individual received a very high localized exposure to his eardrum in 1955 as a result of a fine particle of radioactive material that became lodged in his ear canal for approximately 9 days. Although there is no explicit limit for radioactivity deposited in a person's ear, this case resulted in partial hearing loss. This case is discussed further on page 54.

As discussed above for the lungs, the basic Federal limit for radiation exposure to organs of the body from internal radioactivity was 15 Rem per year prior to 1994. 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 at Naval Reactors' Department of Energy facilities.

For most organs of the body, the limit recommended by the U.S. National Committee on Radiation Protection and Measurements in 1954 (reference 1), by the U.S. Atomic

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1. One Knolls Laboratory individual was reported to the Department of Energy in 1982 as exceeding 50 percent of the maximum permissible lung burden (MPLB) for the year 1969. In 1988, the Laboratory reassessed this case. The reassessment found that the original internal monitoring analysis, performed by a subcontractor, had a systemic high bias. Taking this high bias into account, the 1988 assessment was that no intake greater than 10 percent of the MPLB had occurred.

Energy Commission in the initial edition of reference 3 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 12). The Federal guidance approved by President Reagan in 1987 adopted these revised recommendations and methods (reference 9) and were incorporated as Federal limits in 1994.

Sources of Radioactivity at Prototypes and Naval Reactors Facility

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 at the prototypes 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 13 contains more details on why cobalt-60 is the radionuclide of most concern for internal radioactivity.

The design specifications for reactor fuel are much more stringent for warships than for commercial power reactors. Naval nuclear propulsion prototype plants are built to the same high standards as nuclear-powered warships. As a result of being designed to withstand the rigor 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 prototype plants. Similarly, alpha-emitting radioisotopes (such as uranium and plutonium) are retained within the fuel elements and are not accessible to personnel operating or maintaining a naval nuclear propulsion prototype 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 prototype 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 prototype plants.

At the Expended Core Facility, the radioactivity of primary concern is from radionuclides associated with irradiated nuclear fuel. Highly trained, specialized personnel examine and evaluate the reactor cores removed from U.S. naval nuclear-powered submarines, aircraft carriers, and prototype plants. These evaluations are performed to obtain important technical data to verify and improve the design of nuclear cores. Although the quantity of radioactive material handled is large, advanced personnel radiological training, radiological engineering designs (e.g., shielded cells and special handling equipment), and radiological monitoring programs (e.g., air monitoring systems) prevent any significant internal or external exposure.

Sources of Radioactivity at Laboratories

The radionuclides of primary concern at the laboratories are those associated with the nuclear fuel process; these include the fuel itself (uranium-234, uranium-235, and uranium-238) and the principal fission products (strontium-90 and cesium-137). Radioactivity with more restrictive limits than the above radionuclides (e.g., thorium and plutonium) is also present at the laboratories, but only in isolated and specially controlled operations. Highly trained, specialized personnel design and test new fuel systems and verify the integrity of existing materials. Laboratory personnel handle only small quantities of fuel. The small quantities handled—coupled with advanced radiological training, radiological engineering designs (e.g., containment boxes), and radiological monitoring programs (e.g., air monitoring systems)—prevent any significant internal exposure.

Residues of the radionuclides described above are present at low levels in some laboratory equipment and facilities that were used for radioactive work in the past. Radiological cleanup is being undertaken to remove these radioactive materials. This effort is carefully controlled. The radiological controls techniques followed during this work (e.g., special radiological training, formal procedures, and radiological engineering designs) are designed to prevent internal exposure.

Control of Airborne Radioactivity

Airborne radioactivity is controlled during routine operations such that respiratory equipment is not normally required. To prevent exposure of personnel to airborne radioactivity, contamination containment tents, bags, or boxes are used. These containments are ventilated to the atmosphere through high-efficiency filters that have been designed and tested to remove at least 99.95 percent of particles of a size comparable to cigarette smoke. Radiologically controlled areas are also required to be ventilated through high-efficiency filters whenever work that could cause airborne radioactivity is in progress. Airborne radioactivity surveys are required to be performed regularly in radioactive work areas. If airborne radioactivity above the limit is detected in occupied areas, work that might be causing airborne radioactivity is immediately stopped. This conservative action is taken to minimize internal radioactivity even though the Naval Reactors airborne radioactivity limit 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 limit 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 conditions such as temperature inversions 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 underlying ground. In fact, most cases of airborne radioactivity above Naval Reactors' conservative airborne radioactivity limit in occupied areas have been caused by atmospheric radon, which has a higher airborne concentration limit, not from prototype plant or laboratory operations. Procedures have been developed to reduce the radon levels when necessary and to allow work to continue after it has been confirmed that the elevated airborne radioactivity is from naturally occurring radon.

Control of Radioactive Surface Contamination

Perhaps the most restrictive regulations in Naval Reactors' 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 have 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 these 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 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 be found. Workers are trained to survey themselves (e.g., frisk), and their performance is checked by radiological controls personnel. Upon leaving an area that has radioactive surface contamination, 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 radioactive 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 spread of contamination, not wash it away.

Table 6 presents data concerning the number of personnel with detectable radioactive skin contamination since 1980. A radioactive skin contamination is an event where radioactive contamination above the Program's low limit for surface contamination is detected on the skin. 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 199 instances of skin contamination occurred, with zero instances in the last 11 years. None of these occurrences caused personnel to exceed one-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 senior personnel to validate 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 annually.

Control of Food and Water

Smoking, eating, drinking, and chewing are prohibited in radiologically controlled areas. By prohibiting these hand-to-mouth contacts, the possibility of internal contamination is reduced even further.

Wounds

Skin conditions or open wounds, which might not readily be decontaminated, are cause for temporary or permanent disqualification from doing 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 the wound adequately protected, he or she may remove the temporary disqualification.

There have been only a few cases of contaminated wounds at Naval Reactors' Department of Energy facilities. In most years, none occur. 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 site rather than being absorbed into the blood stream. Most contaminated wounds have been promptly and easily decontaminated.

Monitoring for Internal Radioactivity at Prototypes and Naval Reactors Facility

The radionuclide of most concern for internal radiation exposure from naval nuclear propulsion prototype 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, a microcurie (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 at Naval Reactors' Department of Energy facilities. Therefore, if a person had as little as a one-millionth of a curie of cobalt-60 internally, it would readily be detected.

Swallowing a microcurie 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 1989, Department of Energy regulations limit organ exposure from internal radioactivity to 50 Rem per year.

A microcurie of cobalt-60 still remaining in the lungs 1 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 12). These calculations provide a convenient way to estimate the 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, which has a half-life of 5.3 years. 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. Equipment designed specifically for monitoring internal radioactivity uses a type of gamma scintillation or semiconductor detector that will reliably detect an amount of cobalt-60 inside the body more than 100 times lower than a microcurie as used in the examples above. Naval Reactors' prototype sites and the Naval Reactors Facility monitor each employee for internal radioactivity before initially performing radiation work, after terminating radiation work, and periodically in between. At the Naval Reactors Facility, individuals are also monitored for internally deposited cesium-137. Detection of cesium-137, a gamma-emitting fission product, is used to identify the presence of mixed fission products and other radionuclides associated with irradiated fuel. The sensitive internal monitoring equipment used at the Naval Reactors Facility can detect cesium-137 in the body at similarly low levels as cobalt-60.

Anyone at the prototype or Naval Reactors Facility who has radioactive contamination above the limit anywhere on the skin during regular monitoring at the exit from a radiologically controlled area is monitored for internal radioactivity with the sensitive internal monitoring equipment. Also, anyone who might have breathed airborne radioactivity above limits is monitored with the sensitive equipment.

Internal monitoring equipment is periodically calibrated and the calibration is verified each day the equipment is used. This calibration involves checking the equipment's response to a known source of radiation. In addition, Naval Reactors has an independent quality assurance program in which prototype organizations that perform 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 NIST. 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.

Monitoring for Internal Radioactivity at Laboratories

The radionuclides of most concern for internal radiation exposure from laboratory operations include uranium isotopes (uranium-234, uranium-235, and uranium-238) and fission products (primarily strontium-90 and cesium-137). Uranium isotopes are principally alpha emitters. Alpha particles deposit their energy over a much shorter distance than beta or gamma rays because alpha particles are considerably larger in size and have a much greater charge. Fission products emit beta and gamma radiation similar to cobalt-60.

Although uranium-235 is principally an alpha emitter, it also emits several low-energy gamma rays. Thorium-234 (a daughter of uranium-238) also emits low-energy gamma radiation. This low-energy radiation can be detected with sensitive gamma scintillation or semiconductor detectors. For internal monitoring, each laboratory employs a state-of-the-art low-energy gamma radiation detection system in a shielded enclosure.

These systems are designed to detect levels of uranium in the lungs at levels on the order of one billionth of a curie. In addition, other systems allow for the detection of higher energy, gamma radiation emitting fission products such as cesium-137 at roughly the same sensitivity as uranium-235. In addition to this type of internal exposure monitoring, personnel who work with certain forms of radioactivity are also required periodically to submit urine samples for extremely sensitive radionuclide analysis. Fecal analysis is also sometimes performed as discussed below. As a measure of the sensitivity of laboratory internal monitoring techniques, the systems used to measure radioactivity in urine and fecal samples can measure one ten-trillionth of a curie per liter for urine and one trillionth of a curie per gram for feces. The dose that corresponds to these levels is less than 0.015 Rem to the lungs over the following year and 0.075 Rem over a lifetime, when monitoring is conducted within 24 hours of a potential internal exposure event.

The laboratories require personnel to be internally monitored before initially assuming duties involving radiation exposure, upon terminating from such duties, and periodically in between. The frequency at which personnel are monitored is determined by their assigned duties: the more often they work with radioactive materials, the more often they are monitored. In addition, like the prototype sites, any person who has radioactive contamination above the limit anywhere on the skin or who might have been exposed to airborne radioactivity above the limit is immediately monitored with the sensitive detector system; these individuals are also required to submit urine and fecal samples (as appropriate) for the radionuclides involved.

Internal monitoring equipment is calibrated and the calibration is checked each day the equipment is in use. This process involves checking the equipment's response to a known source of radiation. In addition, background checks are performed daily during equipment use to further verify system performance.

Although internal monitoring is routinely performed at Naval Reactors' Department of Energy facilities, internal monitoring results are not used to control personnel radiation exposure below limits. Rather, work is engineered to prevent radioactivity from becoming internally deposited, and the monitoring is performed to verify that.

Results of Internal Monitoring in 2019

During 2019, a total of 2,453 personnel were monitored for internally deposited radioactivity. There were no internal contamination events at Naval Reactors' Department of Energy facilities during 2019 that resulted in personnel with internally deposited radioactivity detected greater than one-tenth of one percent (0.1 percent) of the Federal Annual Limit on Intake (ALI) from radioactivity associated with work at Naval Reactors' Department of Energy facilities.

Table 6 includes a summary of radioactive skin contamination occurrences and internal deposits of radioactivity at Naval Reactors' Department of Energy facilities. Radioactive skin contaminations that have occurred over the years involved low levels of radioactive contamination associated with maintenance operations at prototype sites and from laboratory operations. Skin doses associated with these occurrences are well below Federal limits. Occurrences of internally deposited radioactivity at Naval Reactors' Department of Energy facilities over the years have involved the uptake of very low levels of radioactivity. In each case, the resulting exposure to the individual has been less than 1 percent of the corresponding Federal limit.

Table 6
Occurrences of Personnel Radioactive Skin Contaminations and Internal Radioactivity Depositions[1]

	Radioactive Skin Contaminations		**Internal Radioactivity Depositions**	
Year	Prototypes and NRF	Laboratories	Prototypes and NRF	Laboratories
1980	15	4	0	0
1981	22	6	1	1
1982	18	4	0	0
1983	8	4	0	0
1984	5	2	0	0
1985	19	2	8	0
1986	7	6	0	0
1987	13	4	0	0
1988	9	1	1	0
1989	3	0	0	0
1990	2	1	0	0
1991	3	2	0	0
1992	2	1	0	0
1993	1	2	0	3
1994	3	1	0	0
1995	2	2	0	0
1996	2	3	0	0
1997	2	2	0	0
1998	2	0	0	0
1999	1	0	0	0
2000	0	0	0	0
2001	2	2	0	2
2002	1	1	0	1
2003	0	1	0	0
2004	0	1	0	0
2005	0	2	0	9
2006	1	0	0	0
2007	0	1	0	0
2008	0	1	0	1
2009	0	0	0	0
2010	0	0	0	0
2011	0	0	0	0
2012	0	0	0	0
2013	0	0	0	0
2014	0	0	0	0
2015	0	0	0	0
2016	0	0	0	0
2017	0	0	0	0
2018	0	0	0	0
2019	0	0	0	0

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[1] This table includes occurrences of internally deposited radioactivity that resulted in greater than a tenth of a percent (0.1 percent) of the Federal ALI from radioactivity associated with work at Naval Reactors' Department of Energy facilities or greater than 0.01 millionths of a curie of cobalt-60 (about 0.05 percent of the Federal ALI).

EFFECTS OF RADIATION ON PERSONNEL

Control of radiation exposure at Naval Reactors' Department of Energy facilities 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 U.S. 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 14) 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 15) and 2006 (reference 16). 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 Reactors Program since its inception in 1948.

Radiation Exposure Comparisons

The success of Naval Reactors' Department of Energy facilities 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 1979, no individual has received more than 2 Rem in a year as a result of working at Naval Reactors' Department of Energy facilities. Also, from Table 4 it can be determined that the average annual exposure per person monitored since 1979 is about 0.051 Rem for prototype and Naval Reactors Facility personnel and 0.013 Rem for laboratory personnel; the overall average annual exposure since 1979 is about 0.04 Rem. The following comparisons give perspective on these individual annual doses in relation to Federal limits and other exposures:

- The Naval Nuclear Propulsion Program limits an individual's dose to 3 Rem in one ***quarter***. No one in the Naval Reactors' Program has exceeded 2 Rem in one ***year*** since 1979—less than half the Federal annual limit of 5 Rem.

- A total of 65,064 workers at NRC-licensed commercial nuclear power reactors have exceeded 2 Rem in a year over this same period (reference 17).

- The average annual exposure since 1979 of 0.04 Rem is:

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

  - Less than one-fourth the average annual exposure of commercial nuclear power plant personnel over the same time period (reference 17).

  - Less than one-sixth the average annual exposure received by U.S. commercial airline flight crew personnel due to cosmic radiation (reference 11).

For additional perspective, the annual exposures for personnel at Naval Reactors' Department of Energy facilities may also be compared to natural background and medical exposures:

- The maximum annual exposure of 2 Rem is less than half the annual exposure from natural radioactivity in the soils in some places in the world, such as Tamil Nadu, India (reference 18).

- The average annual exposure since 1979 of 0.04 Rem is:

  - Less than one-sixth the average annual exposure to a member of the population in the U.S. from natural background radiation (reference 11).

  - Less than one-sixth the average annual exposure to a member of the population in the U.S. from common diagnostic medical x-ray procedures (reference 11).

  - Less than the difference in the annual exposure due to natural background radiation between Denver, Colorado, and Washington, D.C. (reference 19).

- The average **annual** exposure since 1979 of 0.013 Rem for laboratory personnel is less than the **monthly** exposure to a member of the population in the U.S. from natural background radiation (reference 11).

Collective Dose

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 at Naval Reactors' Department of Energy facilities 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 6,497 personnel monitored at Naval Reactors' Department of Energy facilities in 2019 was 88 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-third of the average annual collective dose received by a comparable number of commercial nuclear power plant personnel (reference 17).
- Less than one-fourth of the average annual collective dose received by a comparable number of persons in the medical field (reference 11).
- Less than 6 percent of the average annual collective dose received by a comparable number of commercial airline flight crew personnel (reference 11).

For even further perspective, this collective dose to personnel at Naval Reactors' Department of Energy facilities may also be compared to collective doses from radiation exposures not related to an individual's occupation. This collective dose is:

- Less than 6 percent of the average annual collective dose of 2,020 Rem received by a comparable number of individuals in the U.S. population due to natural background radiation (reference 11).
- Less than 6 percent of the average annual collective dose of 1,940 Rem received by a comparable number of individuals in the U.S. population due to medical diagnostic procedures (reference 11).
- Less than one-half of the average annual collective dose of 230 Rem received by a comparable number of average smokers due to the natural radioactivity in tobacco smoke (reference 11) (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 at Naval Reactors' Department of Energy facilities 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 20 the National Council on Radiation Protection and Measurements reviewed the occupational exposures to the U.S. working population. 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).

The same success achieved by the Naval Nuclear Propulsion Program for occupational radiation exposure to Navy personnel has also been achieved for the personnel at Naval Reactors' Department of Energy facilities.

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 16).

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 21). Although there still exists some uncertainty about the exact level of risk, the National Academy of Sciences stated in reference 22:

> 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 obtained from studies of human populations that have been exposed to radiation in various ways (reference 22). 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 16).

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 the Department of Energy or predecessor agencies. The Naval Reactors 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 keep 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 90,000 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 16 and 23).

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 23).

While it is often stated that radiation causes all forms of cancer, many forms of cancer actually show no increase among atomic bomb survivors. These include chronic lymphocytic leukemia, multiple myeloma, Hodgkin lymphoma, and cancers of the rectum, pancreas, uterus, prostate, cervix, and kidney (references 16, 23, 24, and 25).

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 26). As of December 2003, studies of over 86,000 survivors from the same population find that there have been 10,929 solid cancer deaths. Of these, an estimated 527 solid cancer deaths are in excess of expectation (reference 24). 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 27). In the same population, as of December 2000, there were 310 leukemia deaths of which an estimated 103 deaths are in excess of expectation (reference 28). These studies did not reveal a statistically significant excess of cancer below doses of 6 Rem (reference 29). 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 16 and 23).

About 40 years ago, the major concern of the effects from radiation exposure centered on possible genetic changes (the possible effects from radiation exposure to reproductive cells prior to conception of a child). Ionizing radiation was known to cause such effects 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 16).

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 15). 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 15 suggests that the threshold dose for formation of vision-impairing cataracts may be lower than previously considered (references 10 and 30). 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 30). 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 that the preponderance of the evidence indicates the threshold is in the range of 100-200 Rem (reference 31). 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 15). 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, recent analysis suggests that during a certain stage of development (the 8th to 15th week of pregnancy), the developing brain appears to be especially sensitive to radiation. A slight lowering of IQ might follow doses of 10 Rem or more (reference 15).

From this discussion of the health effects observed in studies of human populations exposed to high doses of radiation, it is concluded that the most important of the effects from the standpoint of occupationally exposed workers is the potential for induction of cancer (reference 16).

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 16). Attempts to observe increased cancer in a human population 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 (approximately three times the average lifetime accumulated dose for an individual working at a Naval Reactors' Department of Energy facility), 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 32]). This is approximately three times the number of people who have performed radioactive work at all the Naval Reactors' Department of Energy facilities over the last 56 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 being relatively rare and having 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 15 and 22. 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 15).

This conclusion has been supported by studies that have been completed since reference 15 was published and reviewed by the National Academy of Sciences (reference 16). 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 conclusion of the National Cancer Institute study was that there was no evidence to suggest that the occurrence of 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 33).

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 (TMI) 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 34).

Of particular interest to workers at Naval Reactors' Department of Energy facilities 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 35). For several decades, Naval Reactors Program personnel have been 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). Congress also chartered an independent oversight committee of nine national experts to oversee the performance of the study in order to ensure technical adequacy and independence of the results. NIOSH concluded, "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" (reference 36). NIOSH did two follow-up studies focusing on leukemia and lung cancer and also concluded that radiation exposure at PNSY could not be shown to have contributed to the number of deaths from these causes (references 37 and 38).

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 39). The cohort was expanded by including all PNSY workers employed through December 31, 1992, and included worker vital statistics obtained 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 U.S. naval nuclear-powered ships. These findings are generally consistent with previous studies.

The study did not show any statistically significant cancer risks linked to radiation exposure, when compared to the general U.S. population. Further, the overall death rate due to cancer among PNSY occupational radiation workers was less than the death rate for the general U.S. population.

Several additional analyses using the PNSY data have been performed by NIOSH, for which reports of the results have been published.

- In the December 2005 issue of *Radiation Research* (reference 40), 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 which was 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 epidemiological 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 41) 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 42). 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 43) NIOSH published the results of a case-control study of CLL mortality and ionizing radiation. Workers at four 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 44), 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 45) 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 46) 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 47).

In 1991, researchers from Johns Hopkins University in Baltimore, Maryland, completed a more comprehensive epidemiological study of the health of workers at six naval shipyards (including PNSY, discussed above) and two private shipyards that serviced U.S. naval nuclear-powered ships (references 48 and 49). This independent study evaluated a population of 70,730 civilian workers over a period from 1957 (beginning with the first overhaul of the first nuclear-powered submarine, USS NAUTILUS) through 1981, to determine whether there was an excess risk of leukemia or other cancers associated with exposure to low levels of gamma radiation. This study is of particular interest to workers at Naval Reactors' Department of Energy facilities because the type of radioactivity, level of exposure, and method of radiological controls at these shipyards are similar to Naval Reactors' Department of Energy facilities.

This study did not show any cancer risks linked to radiation exposure. Furthermore, the overall death rate due to cancer among radiation-exposed shipyard workers was actually less than the death rate due to cancer 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 Johns Hopkins study 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. The average annual radiation exposure from 1957 to 1981 for these shipyard workers is over 2½ times higher than the average annual exposure of 0.096 Rem received by personnel assigned to Naval Reactors' Department of Energy facilities since 1958. Considering the substantial amount of information that can be learned from the greater than twenty years of health and exposure data since the 1981 cutoff date in the original Johns Hopkins study, an update to this study was initiated in 2010. The study is expected to be completed in 2020 and will at a minimum update the vital status of the original cohort members and will account to the extent possible for confounders such as exposure to asbestos and other hazardous materials.

In 2005, NIOSH published the results of an epidemiological study of the health of workers at the Idaho National Laboratory (INL) occupationally exposed to ionizing radiation. This study included civilian workers at the Naval Reactors Facility, which is located within INL. The study's conclusions are consistent with past studies of health effects of low level occupational radiation exposure. The study did not show an excess risk of cancer mortality following radiation exposure for most cancers. The study found some evidence of slightly increased mortality from certain types of cancers (e.g., non-CLL leukemia, brain tumors, and non-Hodgkin's lymphoma) at lifetime doses above 5 Rem, but the excess risk was not statistically significant when compared to non-radiation workers (reference 50).

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 radiation exposure is, 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-National Research Council Advisory Committee on the Biological Effects of Ionizing Radiation (reference 16), the United Nations Scientific Committee on the Effects of Atomic Radiation (reference 23), and the National Council on Radiation Protection and Measurements (reference 10)—all conclude that accumulation of dose over weeks, or months, as opposed to in a single dose, is expected to reduce the risk appreciably. 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 16) suggested that a range of DDREFs between 1.1 and 2.3 may be applicable and reported a best estimate of 1.5 for the DDREF, based on studies of laboratory animals and atomic bomb survivor data. The United Nations Scientific Committee on the Effects of Atomic Radiation (reference 23) 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 Reactors 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 Radiations issued reports (references 51 and 52) that estimated numerical risks for specific types of cancer from radiation exposures 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 16 and 29). 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 the most recent analyses, references 16 and 23, 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 15), 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 exposures 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 Reactors' Department of Energy facilities. As stated previously, the average lifetime accumulated exposure for these personnel is about 1 Rem. Therefore, based on the risk estimate presented above, the average worker's lifetime risk of cancer mortality at Naval Reactors' Department of Energy facilities may be statistically increased by about four one-hundredths of one percent, or from 20 percent for the general population to 20.04 percent for a worker at Naval Reactors' Department of Energy facilities.

Risk Comparisons

Table 7 compares calculated risks from occupational exposure at Naval Reactors' Department of Energy facilities to other occupational risks. This permits evaluation of the relative hazard of this risk versus risks normally accepted in the workplace. It should be kept in mind that the calculated radiation risk is based on risk estimates, whereas the other occupational risks are based on actual death statistics for the occupation.

TABLE 7
LIFETIME OCCUPATIONAL RISKS

Occupation (reference 53)	Lifetime Risk[1] Percent
Agriculture, Forestry, and Fishing	1.4
Mining	0.9
Transportation and Warehousing	0.7
Construction	0.5
Wholesale Trade	0.2
Utilities	0.2
All Industries Average	0.2
Professional and Business Services	0.1
Manufacturing	0.1
Government	0.1
Radiation exposure associated with Naval Reactors' Department of Energy facilities (risk estimate for 1 Rem of lifetime exposure)	0.04[2]

Further perspective on the lifetime risk from radiation exposure at Naval Reactors' Department of Energy facilities may be gained by comparison to other everyday risks, as shown in Table 8.

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[1] Assumes a working lifetime of 47 years (age 18 to 65).

[2] According to BEIR VII (reference 16), the risk 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 population of females in the Program.

TABLE 8
SOME COMMONPLACE LIFETIME RISKS

Risk (reference 54, 55, and 56)	Lifetime Risk[1] Percent
Tobacco	9.7
Accidents (all)	2.9
Infectious Agents	1.7
Motor Vehicle Accidents	1.1
Firearms	0.8
Accidental Poisoning	0.8
Falls	0.6
Pedestrian Accident	0.15
Drowning	0.09
Fire	0.09
Radiation exposure associated with Naval Reactors' Department of Energy facilities (risk estimate for 1 Rem of lifetime exposure)	0.04[2]

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 are able to 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. But 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 45 documents that the lifetime risk of being diagnosed with cancer for a person living in the United States is 40 percent for males and 39 percent for females. The median age for being

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1. 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).
2. According to BEIR VII (reference 16), the risk 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 population of females in the Program.

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 21 percent for males and 18 percent for females.

As discussed earlier, the Navy has participated in several epidemiological studies by authoritative scientists of mortality of personnel who worked in shipyards. All but one of these studies concluded that there was no discernable correlation between cancer mortality and the low-level radiation exposure associated with naval nuclear propulsion plants. 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 has emphasized the need to minimize radiation exposure. Thus, the Naval Reactors Program is committed to keeping radiation exposure to personnel as low as reasonably achievable. Scientific and advisory organizations have not agreed on a radiation 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 Reactors' Department of Energy facilities is low compared to the risks normally accepted in industrial work and in daily life outside of work.

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. To that end, the Naval Reactors Program has from its inception established a rigorous system of audits and reviews. 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 processing personnel dosimeters and maintaining radiation exposure records.

Fifth, a strong independent audit program covers all radiological controls requirements. In all facilities this radiological audit group is independent of the radiological controls organization; the audit group’s findings are reported regularly to senior management. This group performs continuing surveillance of radioactive work. It conducts in depth audits of specific areas of radiological controls, and checks radiological controls requirements at least biennially.

Sixth, the Department of Energy assigns to each facility a representative who reports to the Director, Naval Nuclear Propulsion. At least one assistant to this representative is assigned full-time to audit and review radiological controls. Seventh, Naval Reactors Headquarters personnel conduct periodic inspections of radiological controls in each facility.

In addition, various aspects of the Naval Reactors Program have been reviewed by other Government agencies. For example, the General Accounting Office (GAO) performed a 14-month in depth review of various aspects of Naval Reactors' Department of Energy facilities. In August 1991 (reference 57), 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 Department of Energy facilities.

CLAIMS FOR RADIATION INJURY TO PERSONNEL

Personnel who believe they have received an occupational injury may file claims. The personnel who operate Naval Reactors' Department of Energy facilities are employees of corporations operating facilities under contract to the Department of Energy. These personnel file claims under State workmen's compensation laws. The claim may be handled through the contractor's insurance carrier or adjudicated by an administrative law judge. Either the employee or the contractor may appeal the judge's decision. In any case, the Naval Reactors 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.

A case does not require a decision after filing unless it is actively pursued. A 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 this report, claims that have had no activity in the last 5 years are counted as deferred.

There have been a total of seven claims filed for injury from radiation associated with Naval Reactors' Department of Energy facilities. Of these claims, one was awarded and five have either been denied or deferred. The one case that was awarded occurred in 1955 and involved loss of hearing. A fine particle of radioactive material had entered the individual's ear canal and become lodged. The particle remained in the ear canal for approximately 9 days; as a result, the individual received a very high localized exposure to the eardrum. Following this incident, the individual suffered a 65 percent hearing loss in the affected ear. The claim was awarded in 1959. In 2019, one new claim was filed that is still pending and no claims were awarded.

Energy Employees Occupational Illness Compensation Program Act

In 2000, Congress passed the Energy Employees Occupational Illness Compensation Program Act (EEOICPA) to provide an alternative Federal compensation program for workers whose health was impacted as a result of nuclear weapons related work for Department of Energy contractors. The EEOICPA generally covers contractors and Department of Energy employees, as designated by the Secretary of Energy, who worked in facilities that processed or produced radioactive material for use in the production of atomic weapons.

Because of the effectiveness of Naval Reactors' worker protection, worker training, and workplace monitoring programs, employees who performed Naval Reactors' related work at Naval Reactors' Department of Energy facilities were not included in the EEOICPA. As discussed earlier, the GAO reported to Congress in 1991 that "Naval Reactors Laboratories are accurately measuring, recording, and reporting radiation exposures," and "exposures have been minimal and overall are lower than commercial nuclear facilities and other Department of Energy facilities." This longstanding record of effectiveness supports the decision by Congress that workers at Naval Reactors' Department of Energy facilities did not need the compensation alternatives created for workers in the nuclear weapons complex by the EEOICPA.

Some personnel who were employed at Naval Reactors' Department of Energy facilities during certain periods are covered by the EEOICPA because those facilities performed nuclear weapons work unrelated to the Naval Reactors Program. These facilities include the Separations Process Research Unit at the Knolls Laboratory, the Peek Street Facility in Schenectady, New York; the Sacandaga Facility in Glenville, New

York; and the decommissioning work of the Shippingport Atomic Power Station. Each of these facilities is discussed in more detail below.

The Separations Process Research Unit at the Knolls Laboratory involved laboratory testing of radionuclide separation processes used in production processes at the Atomic Energy Commission's Hanford Site in Washington and at the Savannah River Plant in South Carolina. This work began in the 1940s and was initially conducted under the direction of the Atomic Energy Commission. Following completion of this research in 1953, remediation of related work areas and waste products began; most of the cleanup work was completed by 1965. Areas requiring additional remediation have been maintained in protective layup pending final remediation. In March 1965, the radiological controls previously used for this work under the Atomic Energy Commission were supplanted by controls specifically approved by Naval Reactors. Therefore, work after March 1965 to maintain Separation Process Research Unit facilities in protective layup were under the authority of Naval Reactors and outside the scope of the EEOICPA. Property containing the legacy Separations Process Research Unit facilities was turned over to the Department of Energy Division of Environmental Management for remediation in 2007 and is no longer under the authority of Naval Reactors.

In the late 1940s and early 1950s, the General Electric Company operated two Federal Government facilities in support of developmental programs for the Atomic Energy Commission. These two facilities were the Peek Street Facility and the Sacandaga Facility. Though these sites were decontaminated, decommissioned, and sold to private parties in the mid-1950s, Naval Reactors resurveyed these sites between 1988 and 1991 to ensure compliance with current Department of Energy guidelines. Based on those surveys, additional minor remediation was completed by Naval Reactors in 1994. Therefore, work at the Peek Street Facility and the Sacandaga Facility in the 1980s and 1990s was under the regulatory oversight of Naval Reactors and is outside the scope of the EEOICPA.

As discussed earlier in this report, Naval Reactors was responsible for regulatory oversight throughout the construction and operation of the Shippingport Atomic Power Station. When operation of the station ended and defueling was completed in September 1984, Naval Reactors transferred oversight responsibility for the station to the Department of Energy Office of Terminal Waste Disposal and Remedial Action. Therefore, work at the Shippingport Atomic Power Station before September 1984 is outside the scope of the EEOICPA.

Naval Reactors and its contractors maintain custody of employment and radiation exposure records for personnel who worked at the Peek Street Facility, the Sacandaga Facility, and the Separation Process Research Unit. When requested by the Department of Labor or the National Institute for Occupational Safety and Health (NIOSH) division of the Department of Health and Human Services, Naval Reactors provides employment verification and radiation exposure information in accordance with the procedures required by the EEOICPA.

As defined in the EEOICPA, the Department of Labor determines the eligibility of personnel filing a compensation claim; and if needed, NIOSH performs a radiation dose reconstruction to support a determination of causation and ultimate award or denial of benefits. Through December 2019, Naval Reactors has provided dose information to NIOSH for 62 claims for personnel whose employment included non-Naval Nuclear Propulsion Program work at facilities now under Naval Reactors cognizance.

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 Reactors 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 Naval Reactors' Department of Energy facilities' 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 defined as “radiological incidents.” Incidents receive further management review, including evaluation by senior personnel at Naval Reactors Headquarters and review by the Director, Naval Nuclear Propulsion. Improvement programs over the years have consistently aimed at reducing the number of radiological incidents. As improvements occurred, the definition of what constitutes a Naval Reactors incident was changed to define smaller and smaller deficiencies as incidents. These changes were made 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 58). The Nuclear Regulatory Commission uses similar criteria to define a radiation-related abnormal occurrence; abnormal occurrences are included in the NRC's quarterly report to Congress. Naval Reactors regularly evaluates radiological events using these criteria for comparison.

Since the beginning of operations at Naval Reactors' Department of Energy facilities, 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 Naval Reactors Program 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 Program facilities. The Naval Reactors Program has reviewed radiological matters with State radiological officials in the States where Naval Reactors' Department of Energy facilities operate. Although there has never been an abnormal occurrence that has resulted 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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