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THE RADIATION LEAKAGE SURVEY OF THE
SHIELD OF THE NUCLEAR SHIP SAVANNAH

E. P. Blizard
T. V. Blosser
R. M. Freestone, Jr.

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

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Date Issued

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ABSTRACT

A detailed survey of the radiation from the N.S. Savannah shield was made over the period from May 20 through May 25, 1962. The study was accomplished with the reactor at its full power of 69 megawatts during a cruise of 2821 miles in the Atlantic Ocean, out of Yorktown, Virginia. The data were obtained with the ORNL Mobile Radiation Shielding Laboratory No. 1 which was designed and built especially for this survey.

The results of the detailed shield survey show that the design dose rate of 0.5 rem/yr for passenger spaces is not exceeded in any region to which passengers have access. In the areas restricted to crew access the design dose rate of 5.0 rem/yr is nowhere exceeded except in a small region on "D" deck, in a room to which entry can readily be controlled. Specifications for cargo-hold dose rates, 0.5 rem/yr at 1/5 full power, are satisfactorily met.

Additional data obtained include measurements of special points for comparison with dose rates predicted in design calculations, and an experiment examining the result of loss of water from the Savannah's subreactor shield tanks. Predicted dose rates were conservatively higher than the dose rates measured, and the result of the water-loss experiment showed that even with a total emptying of the tanks a safe condition exists only a few feet from the shield.

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INTRODUCTION

The design requirements for the shielding on the N.S. Savannah were chosen to insure that the passengers would receive no more radiation than is allowed to the general public even though they live permanently on board ship with the reactor constantly at full power. The requirements are also that the crew of the vessel receive no more radiation than workers in atomic energy installations, even though they remain on board ship all the time, also with the reactor constantly at full power. The third requirement of the shielding is that stevedores handling cargo will receive no more radiation than that permitted for the general public, even though they continuously handle cargo in the cargo spaces with the reactor at 1/5 full power. These requirements have dictated dose rates which are extremely low in passenger spaces and well below ordinary permissible levels in crew and cargo spaces, due to the presumption that these spaces are occupied continuously with the reactor at full power.

In order to determine whether these design specifications had been met, a detailed survey of the radiation from the Savannah shield was made over the period from May 20 through May 25, 1962. The study was accomplished with the reactor at its full power of 69 megawatts during a cruise of 2821 miles in the Atlantic Ocean, out of Yorktown, Virginia.

DESCRIPTION OF SHIP, REACTOR, AND SHIELD

The N.S. Savannah is a single-screw, combination passenger-cargo ship with an over-all length of 595 ft 6 in. She has a molded beam of 78 ft and draws, when fully loaded, 29 ft 6 in., displacing 22,000 tons. The vessel has three complete decks, "A," "B," and "C," with platform decks at various levels. A promenade deck extends over "A" deck for about one-

third of the ship's length. The promenade deck is devoted exclusively to public rooms and spaces, while all passenger staterooms are on "A" deck. The passengers' dining room is on "B" deck, as are some of the crew spaces. The remainder of the crew spaces are on "C" deck. The specified dose rates for the various regions are given in Table 1.

The Savannah's reactor is of the pressurized-water type, fueled with slightly enriched (4.4% U^{235}) UO_2 . The fuel is in the form of 0.426-in.-dia pellets, clad in 0.035-in.-thick stainless steel, contained in bundles of stainless steel tubes. The critical core is 90.24-in. long overall, with an active fuel length of 66 in. and an equivalent core dia of 62.06 in. Typically, an initial loading contains 312.4 kg of U^{235} and 6787.5 kg of U^{238} . The predicted lifetime of such a core is 52,200 megawatt days. A detailed description of the reactor has been given by Kulynych.¹

The primary shield for the Savannah reactor consists of an annulus of light water, 33-in. thick, contained in the primary shield tank surrounding the reactor. The water annulus is supplemented by lead in thicknesses from 1 to 4 in. at the primary shield tank outer wall. Outside of the primary shield tank are boilers, pumps, demineralizers, and other parts of the steam production system. The core, pressure vessel, primary shield, and steam-production system are enclosed in the containment vessel, a 35-ft-dia, 2.5-in.-thick steel cylinder with hemispherical ends. Its total length is 50 ft 6 in. The secondary shield is outside of the containment vessel. Above the midplane of the containment vessel the secondary shield consists of a layer of lead, varying between 5 and 6 in. in thickness,

1. G. E. Kulynych, Nuclear Merchant Ship Reactor Final Safeguards Report, Vol. I, March, 1960, BAW-1164, p. 21.

Table 1. Design Dose Rates for N.S. Savannah

Location	Operating Conditions	Type Access	Design Dose Rate
Access spaces outside of secondary shield wall (passenger spaces)	Full power operation	Unrestricted	0.5 rem/yr
Access spaces outside of secondary shield wall (crew spaces)	Full power operation	Unrestricted (crew)	5.0 rem/yr
Cargo holds	Operation at 1/5 full power	Unrestricted	500 mrem/yr
Inside containment	Reactor operating	None permitted	
Inside containment	Reactor shut down 1/2 hr or longer. No fission products in primary loop.	Limited	200 mr/hr
Locations occupied during fuel transfer operations	Reactor shut down 3 days or longer. Refueling operations	Limited	200 mr/hr transient conditions 10 mr/hr continuing conditions

plus a minimum of 8 in. of polyethylene. Below the midplane of the containment vessel the shield is primarily concrete, in thicknesses ranging from 33 to 48 in. Fore and aft, on the hemispherical ends, ilmenite concrete is used, while ordinary concrete is used at the sides. Collision mats consisting of alternate layers of redwood and steel replace some of the concrete on the sides. A schematic diagram of the shield is shown in Fig. 1.

Water-storage tanks, approximately 5-ft deep, extend the secondary shield below the containment vessel from the tank tops to the hull. These tanks were the subject of a special experiment, described below, in which the effect of water loss from the tanks was evaluated.

EXPERIMENTAL APPARATUS

The principal challenge existing in the present investigation lay in the measurement of the extremely low dose rates specified in the Savannah's design. For this purpose a complete set of special equipment was developed, the ORNL Mobile Radiation Detection Laboratory No. 1.² The mobile laboratory, shown in Fig. 2, is contained in a light Ford vanette. Inside the vanette are six racks of laboratory-type scalars, linear amplifiers, electronic timers, and power supplies. This equipment is interchangeably coupled to specially developed dosimeters by 250-ft lengths of coaxial cable. Three types of dosimeter were used in the Savannah survey. All gamma-ray dose rate measurements were obtained with an anthracene scintillation detector in which the sensitive element is a 1-in.-dia, 1/2-in.-thick anthracene crystal. The construction and calibration of this instru-

2. A description of the ORNL Mobile Radiation Detection Laboratory No. 1 has been submitted to Nucleonics for publication.

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Fig. 1. Schematic Cross Section at Midplane of
N.S. Savannah Reactor Shield

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Fig. 2. The ORNL Mobile Shielding Laboratory No. 1

ment has previously been described.³ The choice of anthracene was made because the energy lost within anthracene by a secondary electron resulting from a given-energy gamma-ray photon is very nearly proportional to the (computed) single-collision dose, over the energy range from 100 kev to 10 Mev. The instrument has a sensitivity of about $13,300 \text{ counts} \cdot \text{min}^{-1} \cdot \text{mr}^{-1} \cdot \text{hr}$. Thermal-neutron dose rates (proportional to flux) were measured with a 1-in.-dia BF_3 proportional counter having an active length of 12 in. In the construction of this counter high sensitivity was achieved by filling the tube with 96% B^{10} -enriched BF_3 at the relatively high pressure of 76 cm of Hg. This pressure, essentially 1 atm., results in a sensitivity of $\sim 7400 \text{ counts} \cdot \text{min}^{-1} \cdot \text{mrad}^{-1}(\text{tissue}) \cdot \text{hr}$ and also makes the counter more resistant to accidental damage during use. The construction and calibration of this instrument have also been previously described.⁴

Fast-neutron dose rates were measured with a modified long counter which uses the BF_3 tube of the thermal-flux detector as the sensitive element within an 8-in.-dia, 12-in.-long, cadmium-covered polyethylene cylinder. The polyethylene thicknesses at the end and side of the cylinder have been adjusted, by experiments with monoenergetic neutrons from a Van de Graaff accelerator, to give a counter response proportional to the multi-collision tissue dose curve to within $\pm 10\%$ over the energy range from 0.025 Mev to ~ 10 Mev. The sensitivity of this instrument is $\sim 7800 \text{ counts} \cdot \text{min}^{-1} \cdot \text{mrad}^{-1}(\text{tissue}) \cdot \text{hr}$. A report giving details of construction and calibration of the modified long counter is in preparation.

3. T. Mustafa and T. V. Blosser, Neutron Phys. Div. Ann. Prog. Rep. Sept. 1, 1961, ORNL-3191, p. 110.

4. T. Mustafa and T. V. Blosser, op. cit., p. 102.

The instrumentation described above was carefully calibrated against known sources and fluxes and compared to standard instrumentation in a series of experiments⁵ at the ORNL Bulk Shielding Facility (BSF). The BSF experiments employed an idealized mockup of the Savannah's shield, thus insuring that the comparisons would be valid for the energy spectrum which would be encountered aboard the Savannah.

ORGANIZATION OF THE SURVEY

Preliminary estimates of the magnitude of the intended survey indicated that a round-the-clock operation was desirable in order to minimize the time that the ship would be at sea. For such operation the minimum personnel requirement totaled 41. Of these, 11 were furnished by the Neutron Physics Division of the Oak Ridge National Laboratory, 7 by the Maritime Reactor group of ORNL, 2 by the ORNL Health Physics Division, and 1 each by Oak Ridge Gaseous Diffusion Plant Health Physics, Oak Ridge Y-12 Health Physics, and Y-12 Engineering. A nucleus of 23 people, therefore, came from various Oak Ridge installations. The remainder of the group came from a variety of locales. The Martin-Marietta Corp. of Baltimore, Md. volunteered 2 people; the Todd Shipyards Corp., operators of the "Atomic Servant," which is the floating service headquarters for the Savannah, 5 people; Babcock and Wilcox of Lynchburg, Va., 5 people; and the U. S. Maritime Administration, 6 people.

The survey was under the general supervision of the senior author. Personnel were divided into 3 watches of 12 persons each, comprising 5 two-man detector-counter teams plus a watch captain and his assistant.

5. T. V. Blosser, Maritime Reactor Project Ann. Prog. Rep. Nov. 30, 1961, ORNL-3238, p. 7.

Supporting forces included two instrument maintenance engineers, one of whom was constantly on call, and a data coordinator.

Normally two gamma-ray detectors and two thermal-neutron detectors were in continuous operation, with the fifth team employed in various special measurements.

The survey vanette was driven from Oak Ridge to Yorktown during May 10 and 11, and was lifted aboard the Savannah on the evening of May 11 and lashed down in Hold 4 of Deck B. After calibrations and instrument checks were completed, a set of background measurements were taken with the reactor completely "down." Survey personnel boarded the ship at 0930 hrs on Sunday, May 20, and the survey began with the 2000 watch of the 20th. The survey was completed at 2000 hrs on the 24th, and the ship returned to port at 0930 hrs on Saturday, May 26.

EXPERIMENTAL PROCEDURES

The experimental procedures employed in the Savannah survey were developed and tested in a series of studies of land-based reactors made during the months preceding this study. By the time the Mobile Laboratory was lifted aboard the Savannah, methods and procedures were firm and a group of trained and experienced personnel was available to act as a nucleus for the large group required for the present work.

Prior to the start of the survey, the secondary shield was completely marked with a rectangular 3-ft grid. This work was done by the Todd people under the direction of Mr. Ernest Resner, States Marine Lines health physicist. The grid was marked to correspond with the grid shown on the lucite model of the shield earlier prepared by the New York Shipbuilding Corp. A photograph of the model is shown as Fig. 3.

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Fig. 3. The New York Shipbuilding Corp. Model of the Shield of the N.S. Savannah

The general procedure for the survey consisted of obtaining a one-minute or half-minute count, depending on counting statistics, in the center of each grid with both the thermal-neutron and gamma-ray dosimeters. After the count, the detector was slowly swept over the area within the grid, in order to detect any small area of unusual leakage. The sound-powered phones which provide communication between the detector operator and the scaler operator in the vanette also audibly monitor the count rate being observed, and even a surprisingly small change in the count rate is immediately evident to both operators. The entire shield was covered with both thermal-neutron and gamma-ray dosimeters. Fast-neutron dose rates were measured at carefully chosen locations over the shield, permitting a good evaluation of the ratio of fast to thermal neutrons over the shield.

A number of special points, for comparison with the predicted dose rates of the Babcock and Wilcox shield design,⁶ were measured. At these points a complete set of gamma-ray and fast- and thermal-neutron dose rates was obtained.

Finally, an experiment was performed to determine the effect of the loss or removal of water from the shield tanks under the containment shell. In this experiment, fast-neutron, gamma-ray, and thermal-neutron detectors were positioned both fore and aft of the reactor shield at tank-top level on the vessel's center line, as well as approximately amidship at one side of the shield. Counts were made at closely spaced, regularly timed intervals as the water was being pumped from the tanks. After the tanks were emptied, counters were interchanged and the experiment repeated while the tanks were being refilled.

6. W. R. Smith and M. R. Turner, Nuclear Merchant Ship Reactor Shield Design Summary Report, Aug. 1, 1959, BAW-1144-1, p. 46.

As data were accumulated, the results were immediately plotted on large-scale photographs of the NYS shield model. In this way areas of higher-than-normal dose rate were quickly discovered and rechecked, and areas skipped were recovered.

RESULTS

Backgrounds

The background measurements were taken on May 15, 16, and 17. The reactor had been shut down since 2038 hrs on May 3. All background measurements were extremely low, very nearly at the lower limit of detection of the counters. On "A" deck, for instance, the highest gamma-ray dose rate observed was 5.42×10^{-3} mr/hr, which represents essentially the natural background level of the geographic region in which the Savannah was berthed. The value quoted may be taken as representative of background gamma-ray dose rates over the entire surface of the shield.

Thermal-neutron backgrounds over the Savannah's shield were not far from nonexistent. Values ranged from zero, noted at several locations randomly dispersed over the shield, to maxima of only 1 or 2×10^{-4} mrem/hr. Again all of this dose can be attributed to natural background.

Fast-neutron backgrounds ranged from a low of 9×10^{-4} mrad/hr, on the port bulkhead of "B" deck, to a high of 8.6×10^{-3} , on the port bulkhead of "D" deck.

Full-Power Shield Data

The reactor was held at approximately its full power of 69 megawatts for the entire duration of the detailed shield survey. The dose rates recorded thus represent the maximum to be expected.

The results of the detailed thermal-neutron measurements are plotted in Figs. 4 and 5. Each figure presents, in isometric projection, approximately half of the shield. Gamma-ray dose rates are presented in similar fashion in Figs. 6 and 7. The hatched areas on the drawings represent regions that are physically and permanently inaccessible because of ship's structure, machinery, etc.

Fast-Neutron to Thermal-Neutron Ratios

The ratio of fast-neutron dose rate to thermal-neutron dose rate was measured in selected locations on all surfaces of the shield. These ratios have been plotted, again in isometric projection, in Fig. 8. It is important to note that the units in which the two quantities are measured are different. Fast-neutron dose is measured in units of physical dose, or rads, while thermal-neutron dose is given directly as biological dose, or rem. Thus the ratios shown must be corrected by a suitable factor, the relative biological efficiency (RBE), to obtain the ratio in terms of relative biological damage. The RBE for the fast-neutron dosimeter used in the present survey varies slightly according to the neutron energy spectrum being observed. The RBE has been calculated to be 8.32 for a fission spectrum modified by 160 cm of water, 8.58 for a 1/E spectrum, and 8.93 for the fission spectrum of Watt.⁷

Special Points

In the report describing the design of the shield of the Savannah,⁶ a tabulation is included which gives the calculated dose rates at a number of selected points on all decks. It was of interest to compare the measured

7. B. E. Watt, Phys. Rev. 87, 1037 (1952).

All values are mrem/hr. Digit in parentheses indicates power-of-ten multiplier, i.e., $3.54(-4) \equiv 3.54 \times 10^{-4}$. Data include background.

Fig. 5. Thermal-Neutron Dose Rates, Forward and Port Surfaces of the N.S. Savannah Shield

Fig. 6. Gamma-Ray Dose Rates, Aft and Starboard Surfaces of the N.S. Savannah Shield

All values are mr/hr. Digit in parentheses indicates power-of-ten multiplier, i.e., 3.54(-2) = 3.54 x 10⁻². Data include background.

Fig. 7. Gamma-Ray Dose Rates, Forward and Port Surfaces of the N.S. Savannah Shield

Fig. 8. Measured Ratio of Fast-Neutron Dose Rate, in mrad/hr, to Thermal-Neutron Dose Rate, in mrem/hr, at the Surfaces of the N.S. Savannah Shield

dose rates with these predictions, and a special team was detailed to obtain these data. The measurements are compared to calculation in Table 2, in which predicted primary and secondary gamma-ray dose rates have been lumped. Locations of the special points are shown in Figs. 9 and 10.

In general, the actual dose rates appear to be considerably lower than the predicted dose rates, reflecting the intended conservatism in the design. A few randomly chosen spot checks of the comparisons show overestimates of the gamma-ray dose rate, underestimates of the neutron dose rate.

Shield Tank Pumping Experiment

An integral part of the Savannah's shielding are the water-filled tanks which fill the space between the containment shell and the hull of the ship. The effect of the removal or loss of water from these tanks is shown in Fig. 11. The greatest effect was observed by the fast-neutron detector placed against the shield amidship of the port side. During the first third of the emptying of the tanks the fast-neutron dose rate at this point increased by a factor of over 100. In contrast, over the same period the fast-neutron dose rate at the forward face of the shield increased only about 25 times. Gamma-ray dose rates increased moderately, as shown by the curves. It is clear that the major portion of the effect sensed by all counters occurred during the first third of the pumpdown with a leveling-off taking place after this point.

An attempt was made to repeat this experiment during the refilling of the tanks, but pumping was stopped and filling by gravity flow began before any significant change in dose rate was noted, and the experiment was terminated.

Table 2. Comparison of Measured Dose Rates with Calculated
Dose Rates at Special Points

Point Number	Observed Dose Rate				BAW-1144-1 Calculated Dose Rate		
	Fast-Neutron (mrad/hr)	Thermal (mrem/hr)	Gamma (mr/hr)	Total (mrem/hr)	Neutron (mrem/hr)	Gamma (mrem/hr)	Total (mrem/hr)
PROMENADE DECK							
	(x 10 ⁻³)	(x 10 ⁻⁴)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻¹)
44	1.50	1.31	0.925	2.23	1.0	41.9	4.29
45	0.988	1.16	1.42	2.28	0	9.5	0.95
46	0.976	0.771	0.569	1.42	0.7	17.9	1.86
47	1.65	1.52	1.14	2.58			
48	1.51	0.412	1.09	2.39	1.0	11.0	1.20
49	1.92	0.581	1.16	2.82			
50	1.43	0.422	1.36	2.59			
52	0.923	0.242	0.669	1.46			
53	1.29	3.21	1.80	2.94			
54	1.40	0.570	1.53	2.75	2.4	8.4	1.08
56	0.897	2.09	0.624	1.42	1.6	11.0	1.26
57	0.845	0.369	0.360	1.10			
71	1.09	0.232	0.823	1.76	4.3	8.4	1.27
72	1.43	0.318	0.68	1.91	4.6	8.4	1.30
80	1.72	1.87	1.16	2.57			
81	1.73	1.26	1.60	3.10			
82	2.17	2.54	3.46	5.36			
85	1.39	0.635	0.579	1.79			
86	1.37	1.09	1.27	2.46			

Table 2 (cont.)

Point Number	Observed Dose Rate				BAW-1144-1 Calculated Dose Rate		
	Fast-Neutron (mrad/hr)	Thermal (mrem/hr)	Gamma (mr/hr)	Total (mrem/hr)	Neutron (mrem/hr)	Gamma (mrem/hr)	Total (mrem/hr)
A DECK							
	(x 10 ⁻³)	(x 10 ⁻⁴)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻¹)
1	3.43	3.58	3.47	6.46	1.4	19.2	2.06
2	3.32	4.33	4.17	7.07	1.4	19.1	2.05
3	1.98	1.34	2.26	3.97	1.6	12.7	1.43
4	2.83	3.45	2.79	5.27	1.4	21.4	2.28
5	4.17	4.19	4.30	7.93	1.4	23.8	2.52
6	2.68	2.41	3.84	6.17	1.9	18.1	2.00
7	2.76	1.26	2.93	5.32	2.9	14.6	1.75
8	1.98	1.02	2.59	4.30	2.9	9.7	1.26
9	2.30	2.11	2.45	4.45	1.8	23.7	2.55
10	2.38	2.19	1.56	3.63	1.4	22.2	2.36
11	2.29	1.56	1.91	3.90	1.4	13.3	1.47
12	2.03	1.46	2.93	4.70	1.9	14.5	1.64
13	2.89	3.04	3.43	5.95			
14	2.26	1.25	2.05	4.01	5.0	15.2	2.02
17	8.84	0.803	1.70	9.32	4.7	27.2	3.19
22	1.911	0.792	1.72	3.37	1.9	8.9	1.08
23	1.55	0.697	1.12	2.46	5.0	9.0	1.40
26	9.75	0.422	0.694	9.09	5.0	17.0	2.20
201	1.81	0.729	0.806	2.37	8.4	11.4	1.98
204	1.05	0.887	0.428	1.34	8.2	10.6	1.88
801	3.59	2.76	4.34	7.46	1.8	46.0	4.78
802	7.53	5.44	4.61	11.14			
803	2.35	1.17	2.45	4.52	9.0	18.3	2.73
804	1.86	0.232	1.26	2.86	9.0	12.4	2.14

Table 2 (cont.)

Point Number	Observed Dose Rate				BAW-1144-1 Calculated Dose Rate		
	Fast-Neutron (mrad/hr)	Thermal (mrem/hr)	Gamma (mr/hr)	Total (mrem/hr)	Neutron (mrem/hr)	Gamma (mrem/hr)	Total (mrem/hr)
B DECK							
	(x 10 ⁻³)	(x 10 ⁻⁴)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻¹)
214	7.67	5.33	4.59	11.24	13.7	23.9	3.76
215	3.85	2.00	5.96	9.29	15.8	19.8	3.56
216	2.67	2.40	2.52	4.84	16.2	29.7	4.59
217	3.32	1.40	1.54	4.41	10.5	54.0	6.45
218	4.76	1.59	2.67	6.78	21.3	55.0	7.63
219	11.58	10.4	21.0	31.06	4.9	31.8	3.67
220	13.10	10.88	14.1	25.49			
221	12.75	10.43	22.4	25.49	5.7	36.8	4.25
232	3.25	3.44	4.20	7.03	19.3	27.0	4.63
233	2.71	1.53	2.78	5.13	17.1	26.0	4.31
314	6.01	4.85	9.41	14.63	15.4	26.7	4.21
805	12.42	21.9	7.27	18.19	1.5	20.2	2.17
806	15.54	97.9 26.9	16.76	31.12 30.41	2.5	19.1	2.16
807	12.08	8.04	12.0	22.48	3.0	23.4	2.64
C DECK							
	(x 10 ⁻³)	(x 10 ⁻⁴)	(x 10 ⁻²)	(x 10 ⁻¹)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻¹)
252	7.76	12.77	13.78	2.059	33.2	23.5	5.67
253	2.25	2.76	2.19	0.416	0	9.5	0.95
261	4.56	1.66	0.820	0.576	0.4	10.8	1.12
324	5.37	10.90	15.79	2.052	33.6	24.9	5.85
325	1.87	2.49	4.53	0.617	0	1.8	0.18
611	2.94	2.64	2.13	0.469	0	33.7	3.37
612	3.15	2.47	3.46	0.620			
613	2.33	2.25	13.2	1.525	0	20.2	2.02

Table 2 (cont.)

Point Number	Observed Dose Rate				BAW-1144-1 Calculated Dose Rate		
	Fast-Neutron (mrad/hr)	Thermal (mrem/hr)	Gamma (mr/hr)	Total (mrem/hr)	Neutron (mrem/hr)	Gamma (mrem/hr)	Total (mrem/hr)
D DECK							
	(x 10 ⁻³)	(x 10 ⁻⁴)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻¹)
276	10.51	0.781	0.644	9.69	1.6	6.7	0.83
278	1.41	0.400	0.706	1.92	0.6	5.9	0.65
332	1.38	0.517	0.777	2.02	1.6	8.5	1.01
813	2.02	1.01	2.24	3.99	2.3	15.6	1.79
815	1.13	0.370	1.63	2.61	2.6	69.4	7.20
823	-	Inaccessible	-		1.9	65.4	6.73
14-ft LEVEL							
	(x 10 ⁻³)	(x 10 ⁻⁴)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻¹)	(x 10 ⁻¹)
286	0.910	0.349	0.985	1.77	0.8	5.1	0.59
TANK TOP							
	(x 10 ⁻³)	(x 10 ⁻⁴)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻²)	(x 10 ⁻¹)
297	0.390	0.465	0.343	0.684	0.9	9.5	1.04
307	0.338	0.317	0.338	0.532	1.9	2.9	0.48
334	0.910	0.190	0.273	1.06	1.5	2.6	0.41
640	1.24	0.486	0.685	1.76	28.5	121.4	14.99
641	0.754	0.317	0.288	0.939	2.1	6.2	0.83
856	-	Inaccessible	-		0.2	35.8	3.60
OBSERVATION GALLERY - C DECK							
	(x 10 ⁻³)	(x 10 ⁻⁴)	(x 10 ⁻²)	(x 10 ⁻²)			
G1	2.22	0.391	0.945	2.86	E of Ship - Forward Side of Gallery		
G2	1.81	0.475	0.875	2.44	E of Ship - Aft Side of Gallery		
G3	1.82	0.401	0.995	2.57	8 ft Starboard of G1		
G4	2.15	0.486	0.885	2.74	8 ft Port of G1

PROMENADE DECK

"A" DECK

"B" DECK

"C" DECK

Fig. 9. "Special Point" Locations on Promenade, "A,"
"B," and "C" Decks, N.S. Savannah

"D" DECK

14-FOOT LEVEL

HOLD

Fig. 10. "Special Point" Locations on "D" Deck, 14-ft Level, and in Hold of N.S. Savannah

Fig. 11. Gamma-Ray, Thermal-Neutron, and Fast-Neutron Dose Rates at 3 Locations During Emptying of N.S. Savannah Sub-Reactor Shield Tanks. All detectors were at tank-top level, against the reactor shield.

ERRORS

The thermal-neutron and fast-neutron instruments used in this survey are believed to have an inherent error of $< \pm 6\%$ at 1 mrem/hr, based on previous calibrations. The calibrations of the gamma-ray instrument indicate that an error of $\pm 10\%$ is conservative. Since counting was for a fixed time, counting statistics vary with the dose rate measured at any given point. For the significant fast- and thermal-neutron values, however, an over-all error of $\pm 8\%$ is believed conservative. A similar value for gamma-ray dose measurements is $\pm 12\%$.

CONCLUSIONS

The results of the detailed gamma-ray and thermal-neutron dose rate surveys show that in no areas where passenger access is permitted do the dose rates exceed the tolerance limits of 0.5 rem/yr, or 0.057 mrem/hr. In the areas to which only the crew is permitted access the design dose rate is exceeded only in a small region on "D" deck, in the so-called "water-sampling" room against the forward bulkhead. Entry to this area can readily be controlled so as to insure that no hazard ensues.

Although the dose rates at tank-top level in the hold did indeed increase with the emptying of the tanks, the dose rate from all sources at the forward face of the shield only totaled about 0.7 mrem/hr. At only a few feet from the shield face a safe condition should exist even with total loss of water from the tanks.

The results of the complete survey show that the shield of the Savannah is sound and tight and that the dose rate limitations established in its specifications have been satisfied.

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