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SHIELDING EXPERIMENTAL METHODS *

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ABSTRACT

Benchmark, parametric, and design-confirmation shielding measurements are made at the Tower Shielding Facility (TSF) in Oak Ridge. A powerful reactor (to 1 MW thermal) is used with spectral modifiers to provide neutron spectra close to those associated with the various parts of an LMFBR. The source strength allows measurements through shields of full reactor thickness using sensitive detectors. The detectors include spectrometers and dosimeters for both neutrons and gamma rays. A large exclusion area provides much flexibility in arranging shield assemblies to be studied.

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1. Introduction

Experiments in support of LMFBR shielding are carried out at the Tower Shielding Facility in Oak Ridge, Tennessee. The name of the facility was derived from its uses in the past and is no longer descriptive. Three important features of the facility are (1) the TSR-II reactor, (2) a large experiment and exclusion area, with location in a remote site, and (3) special instrumentation developed over a period of years.

TSR-II reactor is of special design for shielding experimentation. The active core is in spherical geometry, is comprised of ORR-MTR type fuel in spherical-shell configuration with a central control ball, and is water cooled. The reactor is certified for operation at a maximum power level of 1 MW thermal which is sufficient for the very deep penetration experiments required in the LMFBR program. The reactor can be moved and operated in various locations including the present shield and beam port which was especially constructed for LMFBR experiments in which spectrum modifiers are used to simulate LMFBR conditions.

Relevant feasures of the reactor, such as the distribution in energy and angle of the leakage neutrons, are considered in the description of each experiment. As suggested above, materials (mostly steel) are normally placed between the reactor and the shielding experiment in order to modify the neutron spectrum so that it closely simulates the portion of an LMFBR of interest.

The geometry of the reactor and its associated geometry is shown in Fig. 1. A typical arrangement of the reactor and shield is shown in the photograph (Fig. 2). The operating station is located in an underground building and all other personnel are excluded from the vicinity of the reactor ($\sim$1 km) when it is operating. Specific experimental arrangements of the facility are considered in paper No. 7, "U. S. Integral and Benchmark Experiments."

The remainder of this paper is devoted to a description of the instruments which are used to characterize the source radiations and those observed in or behind the various shields. Most of the methods have been used for many years and are rather well described in the international literature. Use of TLDs (thermoluminescent dosimeters) for accurate measurements of mixed fields of neutrons and photons is a recent development. Therefore, this instrument application is described in more detail.

A summary of the instruments used at the TSF in given in Table 1.

Table 1. Instruments Used for Shielding Measurements at the Tower Shielding Facility

For Neutrons

Proton-recoil spectrometer using NE-213 scintillators

Proton-recoil spectrometer using hydrogen counters

Proton-recoil dosimeters

Bonner-ball neutron detectors

Activation detectors

For Photons

Sodium-iodide scintillator spectrometers

High-pressure gas-filled ionization chamber

Thermoluminescent detectors

2. Proton Recoil Spectrometers Using NE-213 Scintillators

The NE-213 spectrometer measures neutron energies in the range from ∿0.8 to ∿20 MeV. The detector consists of a 2-in. x 2-in. right square cylinder filled with an organic liquid scintillator. The chemical composition of the scintillator is CH_2. The neutron spectrum is determined by first observing the distribution of pulse heights resulting from recoil protons in the liquid scintillator. This recoil proton spectrum is then "unfolded" with a code called FERDOR. The unfolded neutron spectrum has an energy resolution which varies from 30% at 1 MeV to approximately 10% at 10 MeV. We consider it most important that the unfolding procedure provides quantitative estimates of the uncertainties in the neutron spectrum.

The NE-213 system has a very high sensitivity, especially compared with other types of fast neutron spectrometers. There are approximately ten counts from the NE-213 detector for one neutron per square centimeter incident upon the detector.

A problem with the spectrometer follows since it can be used only in a very low gamma-ray field; i.e., less than ∿20 mr per hour. Gamma-ray events are discriminated against by observing the widths of the pulses (time to cross-over point) from the system. Since a recoil proton has a very short path (a fraction of a millimeter), compared to an electron (a centimeter), the duration of the pulse of light from the proton is much shorter than that from the electron. The cross-over point which reflects the pulse width is detected electronically and is used to sort neutron and gamma-ray induced events in the detector.

Where very high gamma-ray backgrounds prevail, a uranium slab is used to preferentially shield out the gamma rays from the neutron spectrum. The geometry is arranged so that neutrons scattered in the uranium slab will not be observed in appreciable quantities by the detector. The spectrum incident on the uranium slab can then be predicted by correcting the observed spectrum for the attenuation of the uncollided flux in the uranium slab.

For a general description of the NE-213 scintillation spectrometer, including the essential determination of its response functions for monoenergetic neutrons, see Reference 1.

3. Proton-Recoil Spectrometers Using Hydrogen Counters

The so-called Benjamin spectrometer consists of a hydrogen-gas-filled proportional counter in a spherical configuration.[2] It measures neutron energies in the range from ∿ 5 keV to ∿ 1.5 MeV. Therefore, there is overlap between the measurements of the NE-213 spectrometer and the hydrogen-counter spectrometer in the energy range from ∿0.8 MeV to 1.5 MeV.

Here again, the neutron spectrum is determined by observing the recoil proton pulse height distribution from the counter. The pulse-height distribution is unfolded using a code called SPEC-4 developed by Benjamin et al.[2] The energy resolution is essentially constant at 10% for all energies. This detector is less sensitive than the NE-213 spectrometer by a factor of approximately 10^3 because it is filled with a gas rather than a liquid and has approximately the same volume. The hydrogen counter is a 2-in. diameter sphere constructed of stainless steel. Special care was taken to minimize possible end effects for the one-mil stainless-steel wire collection electrode.

There are two techniques for discriminating against gamma-ray events in a Benjamin spectrometer. The simplest of these techniques is to use counters of

different pressures; i.e., 1 atm, 3 atm, and 10 atm, which determine the amount energy which can be deposited in the counter by a gamma-ray scattered electron. By considering only proton pulses that have energies greater than that which can be produced from an electron, a neutron spectrum can be deduced which is free of gamma-ray contamination. This system works down to neutron energies of approximately 50 keV. Below 50 keV, a system of pulse rise time discrimination similar to that in the NE-213 detector must be used. Pulse-shape discrimination allows the neutron spectra to be measured to energies somewhat below 5 keV if considerable care is taken with the measurement. The total count rate in the system must be limited to about 5,000 counts per second in order that the collecting field not be distorted. In order to utilize the hydrogen spectrometer with pulse-discrimination, a small computer is required to store the large amount of data obtained in the two-parameter mode.

4. Proton-Recoil Dosimeters

One of the first instruments developed in the shielding program was the "Hurst" dosimeter for fast neutrons. This instrument consists of a proportional counter which is lined with solid polyethylene and contains an ethylene gas. The counter thus operates as a Bragg-Gray cavity in which the ionization in the gas is proportional to the ionization in the walls. The walls are thick enough to stop a 15-MeV proton, and therefore the detector measures the energy deposition in polyethylene from recoil particles, primarily protons, induced by fast-neutron collisions. The count rate from this detector has been shown to be closely proportional to the Snyder-Neufeld calculated tissue dose for fast neutrons. In recent years this detector has been used primarily to calibrate Hornyak buttons (see below); however, in some cases it has been used for direct measurements of the fast-neutron dose.

The "Hornyak" button is used to measure fast-neutron spatial distributions with high resolution.[3] The detector essentially measures fast-neutron tissue dose. The neutron-detecting element consists of a small disc of lucite loaded with powdered zinc sulfide. Fast neutrons collide with the hydrogen in the button to produce recoil protons, which in turn lose their energy partially in the zinc sulfide particles causing them to scintillate. The scintillations are detected by a photomultiplier and the pulses from this tube are detected through conventional pulse electronics. The response of the detector is fairly closely proportional to the total energy being deposited in the scintillator by the recoil protons

from fast neutrons. The size of the zinc sulfide particles is chosen so that the gamma-ray response is very small from this detector. As a result, this detector can be used in gamma-ray fields up to several hundred r/hr. Physical size of the button can vary from 0.5 in. to 2 in. in diameter while the height is approximately 60 mils.

5. Bonner-Ball Neutron Detectors

The most widely used neutron detector system at the TSF is the Bonner-ball system. It is extremely sensitive and can be used to measure attenuations as large as 10^{13}. The detector consists of a 2-in. diameter, spherical BF_3 proportional counter which is surrounded by a spherical shell of polyethylene which in turn is enclosed in a 30-mil shell of cadmium. The thickness of the polyethylene shells varies from 0.5 to 5 in. Thermal neutron fluxes are measured using the bare and cadmium-shielded BF_3 counter without the polyethylene shell. The detector types which are avilable for use include the bare, Cd, and the 3-, 4-, 5-, 6-, 8-, 10-, and 12-in. Bonner balls.

The response function for each of the Bonner ball detectors was calculated using the one-dimensional discrete-ordinates code ANISN. These response functions were verified using a number of neutron sources whose spectra are well known. The response function for the 3-in. Bonner ball peaks at about 1.5 eV, falls by about 40% at 10 eV, and begins to drop rapidly at about 100 keV. The Bonner balls most commonly used in the experiments are those of 3-, 6-, and 10-in. The 6-in. Bonner-ball response is flat from about 10 eV to about 1 MeV. The 10-in. Bonner-ball response peaks at about 1 MeV, and begins to drop rapidly at about 7 MeV.

6. Activation Detectors

Foils of a variety of materials such as gold, indium, sulfur, ^{238}U, etc. and fission chambers are available and are occasionally used for "in situ" shielding measurements. Problems with the comparison of the resulting activations with analysis methods cause these detectors to be little used for experiments which allow the measurement of leakage radiations.

7. Sodium-Iodide Scintillation Spectrometer

Gamma-ray spectral measurements are made with a spectrometer system with the detector consisting of a 5-in. diameter sodium-iodide crystal which is 5 in. in height. The pulse-height spectra from electrons scattered within the crystal

by gamma rays can be directly unfolded by the FERD code, developed by ORNL, to deduce the gamma-ray spectrum on the crystal.

This spectrometer is more appropriate for use in measuring spectra in shields than a germanium diode because of the ease in unfolding a gamma-ray continuum. The germanium diode system is more appropriate for looking at gamma-ray lines. The resolution of the sodium-iodide gamma-ray spectrometer varies from approximately 3% at 9 MeV to 7% at 0.6 MeV. This energy resolution is higher than that achieved in most multigroup calculations. The electronics of the system are relatively simple in that there is no requirement for pulse-shape discrimination.

The sodium-iodide cyrstal is sensitive to neutron interactions. Therefore, the normal technique is to shield the detector from neutrons using a slab of lithium hydride. The lithium-hydride shield is placed in a good geometry configuration and therefore it is practical to correct for the attenuation of the incident gamma-ray spectrum by a lithium-hydride slab.

This detector is extremely sensitive and cannot be used in gamma-ray fields exceeding $\sim$2 mr/hr. The detector is contained in a large neutron and gamma-ray shield which is penetrated by a collimator. The measured response functions reflect any perturbation in the pulse-height distribution introduced by the shield and collimator.

8. High-Pressure Gas-Filled Ionization Chamber

We have recently developed a very sensitive ionization chamber that is filled with high Z gas (a mixture of argon and krypton) to a pressure of 150 atm. This mixture of gases has a total energy absorption coefficient which is almost identical to that for iron. The chamber is designed so that the active volume of the chamber is accurately known, and the chamber has been studied to determine the magnitude of the recombination effects due to the very high pressure in the ion chamber. The high gas pressure in the chamber allows the high sensitivity needed for making energy deposition measurements in a thick shield. The chamber is approximately 1 in. in diameter and 7 in. long. The chamber shell consists of stainless steel and is thick enough to provide electron equilibrium in gamma-ray spectra with energies as high as 10 MeV.

9. Thermoluminescent Detectors

Thermoluminescent dosimeters (TLD) consisting of CaF_2 and LiF chips have been adapted to the measurement of gamma-ray energy deposition in the mixed radiation fields of shielding experiments.[4] To meet the needs of determining heating rates in

LMFBR components to the desired accuracies which approach 5%, very careful procedures have been required for the handling, calibration, annealing, storage, exposure, and readout of the TLDs. These very detailed procedures are presented in ORNL-5161 which describes the TLD-measurement of radiation heating in iron and stainless-steel reactor shields. The experience at ORNL has clearly shown that strict and absolute (if possible) adherence to the procedures is mandatory to the achievement of acceptable measurements. Poor results have almost always been traced to and directly associated with some deviation from the procedures.

The response of the TLD to neutrons is an important consideration in applying TL dosimetry techniques to reactor shields which are usually subjected to characteristically high neutron-to-gamma ratios. Available neutron dose correction factors seemed inadequate for the radiation fields associated with a reactor shield. A new set of neutron dose factors was formulated using the most recent cross-section sets and other basic data.

In order to determine the accuracy that had been achieved with the TLD measurements, benchmark experiments were carried out. In one of these, the transmission of isotopically-emitted gamma rays through various thicknesses (0-6 in.) of iron was measured. This experiment was designed such that iron thicknesses and source and detector locations could be accurately determined and simply represented in two-dimensional geometry consistent with the discrete ordinates code, DOT. The expected values of the energy deposition in the TLD along with the 1/f spectral correction factors were calculated with DOT. The latest improved TLD precedures were employed along with a simultaneous ion-chamber measurement of the energy deposition. Four isotope sources (^{51}Cr, ^{137}Cs, ^{60}Co, and ^{24}Na) provided a wide range of essentially monoenergetic source gamma rays (0.32 MeV up to 2.754 MeV). A summary of the results of this experiment is presented in Table 2. Good agreement was achieved between the TLD measurements and with the calculations. The Burlin theory inspired 1/f spectral correction factors were verified over a wide range of gamma-ray energies and for transmissions through several iron thicknesses at each energy.

A second experiment was conducted at the TSF to measure heating rates within shield configurations typical of the LMFBR using CaF_2 and LiF TLDs. An auxiliary objective of the experiment was the comparison of the TLD procedures being employed by ORNL and the Argonne National Laboratory (ANL). Personnel from ANL participated directly in the experiment. Table 3 presents a comparison of the spatial distributions of TLD-measured energy depositions in a shield consisting

Table 2. Gamma-Ray Measurements and Calculations for an Iron Shield with Radioisotopic Gamma-Ray Sources

Na^{24} 0.595 Ci E_{γ_1} = 1.369 MeV (100%), E_{γ_2} = 2.754 MeV (100%)

Position†	Cal^{n}(DOT)	CaF_2:Mn	Li^7F	Ion-Chamber
0	8.860(6)*	8.697	8.800	9.140
2	3.093(6)	2.890	3.052	2.992
4	6.998(5)	6.911	6.978	6.996
6	1.510(5)	1.515	1.605	1.501

Co^{60} 0.846 Ci E_{γ_1} = 1.173 MeV (100%), E_{γ_2} = 1.333 MeV (100%)

0	8.675(6)	8.633	8.713	8.680
2	2.461(6)	2.385	2.436	2.374
4	3.826(5)	3.868	3.865	3.707
6	5.372(4)	5.542	5.657	5.274

Cs^{137} 0.809 Ci E_γ = 0.6616 MeV (84.14%)

0	2.080(6)	2.080	2.097	2.076
1	1.148(6)	1.148	1.167	1.151
2	3.788(5)	3.854	3.933	3.621
3	1.116(5)	1.147	1.160	1.069

Cr^{51} 11.06 Ci E_γ = 0.32 MeV (9.9%)

0	1.902(6)	1.881	1.942	1.882
1	7.952(5)	7.182	7.370	6.797
2	1.451(5)	1.473	1.475	1.204
3	2.252(4)	2.507	2.492	2.289

*Read as 8.860×10^6 MeV/g_{Fe}/min.

†Indicates shield thickness in inches of iron.

Table 3. Comparisons of Gamma-Ray Measurements Using TLDs With Calculations for an Iron Shield and the TSF Reactor Source

Position†	Cal^{n}(DOT)	CaF_2:Mn (ORNL)	CaF_2:Mn (ANL-Chicago)	CaF_2:Mn (ANL-Idaho)	Li^7F (ANL-Idaho)
1	3.99(4)*	3.81	3.87	3.86	3.87
2	2.26(4)	2.10	2.16	2.16	2.23
3	1.53(4)	1.57	1.59	1.57	1.59
4	1.11(4)	1.18	1.21	1.20	1.18
5	8.08(3)	8.54	8.98	8.45	8.53
6	5.77(3)	6.12	6.30	6.01	6.00
7	4.13(3)	4.24	4.37	4.42	4.24
8	2.80(3)	2.91	2.96	2.83	2.84
9	1.72(3)	1.74	1.80		
10	7.99(2)	7.68	7.67		
11	3.14(2)	3.06	2.96		

*Read as 3.99×10^4 MeV/g_{Fe}/min/kW.

†Each increase in position number adds about 2 in. of iron. See ORNL-5161 for detailed explanation of geometrical arrangement.

mostly of iron with the results of two-dimensional discrete-ordinates (DOT) calculations. All measured results presented here have been corrected for gamma-ray spectral and neutron-dose effects. The agreement among the measurements was very good - to within ±3% on an absolute basis.

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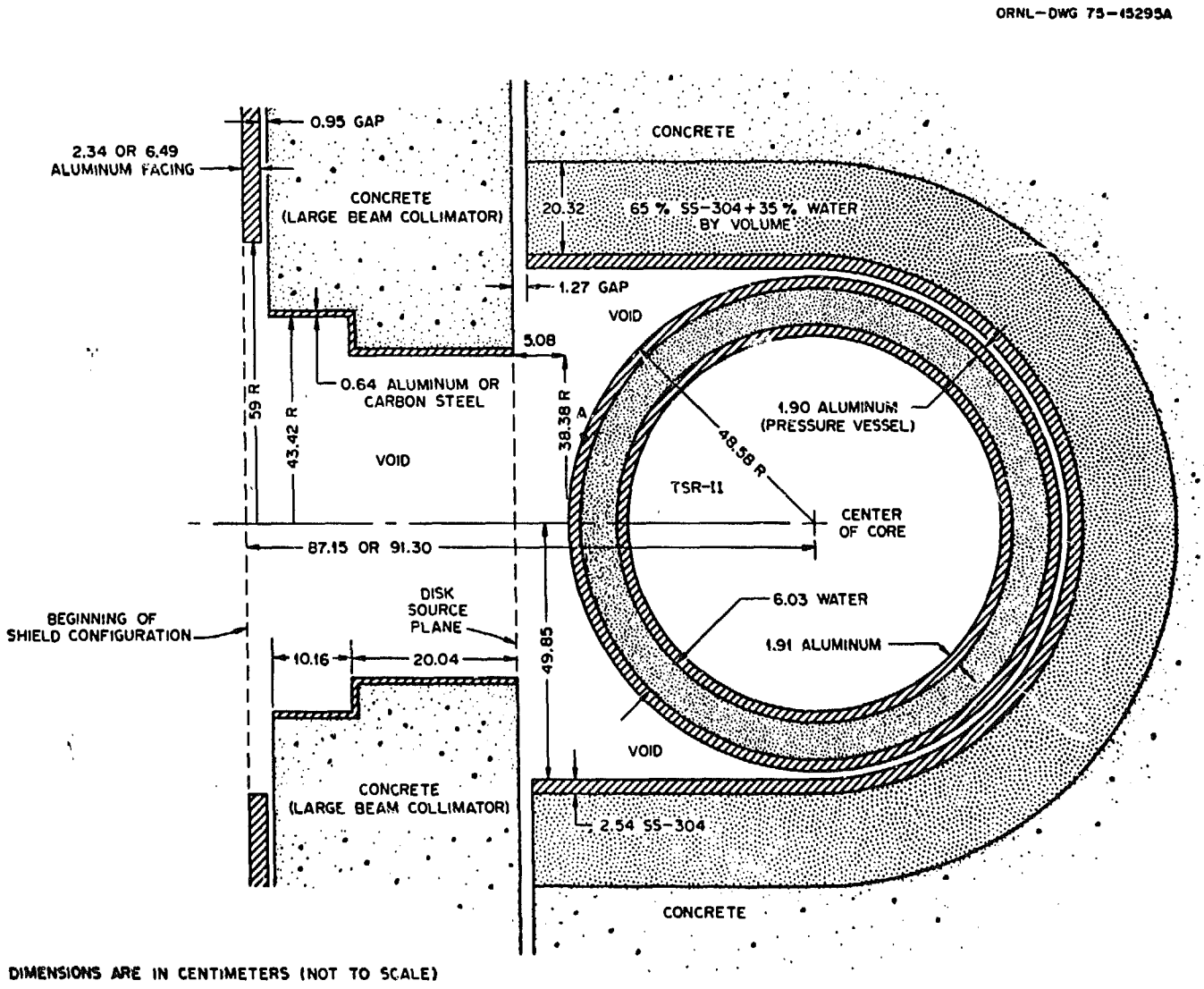

Fig. 1. Top View of Tower Shielding Facility Reactor and Large Beam Collimator Geometry.

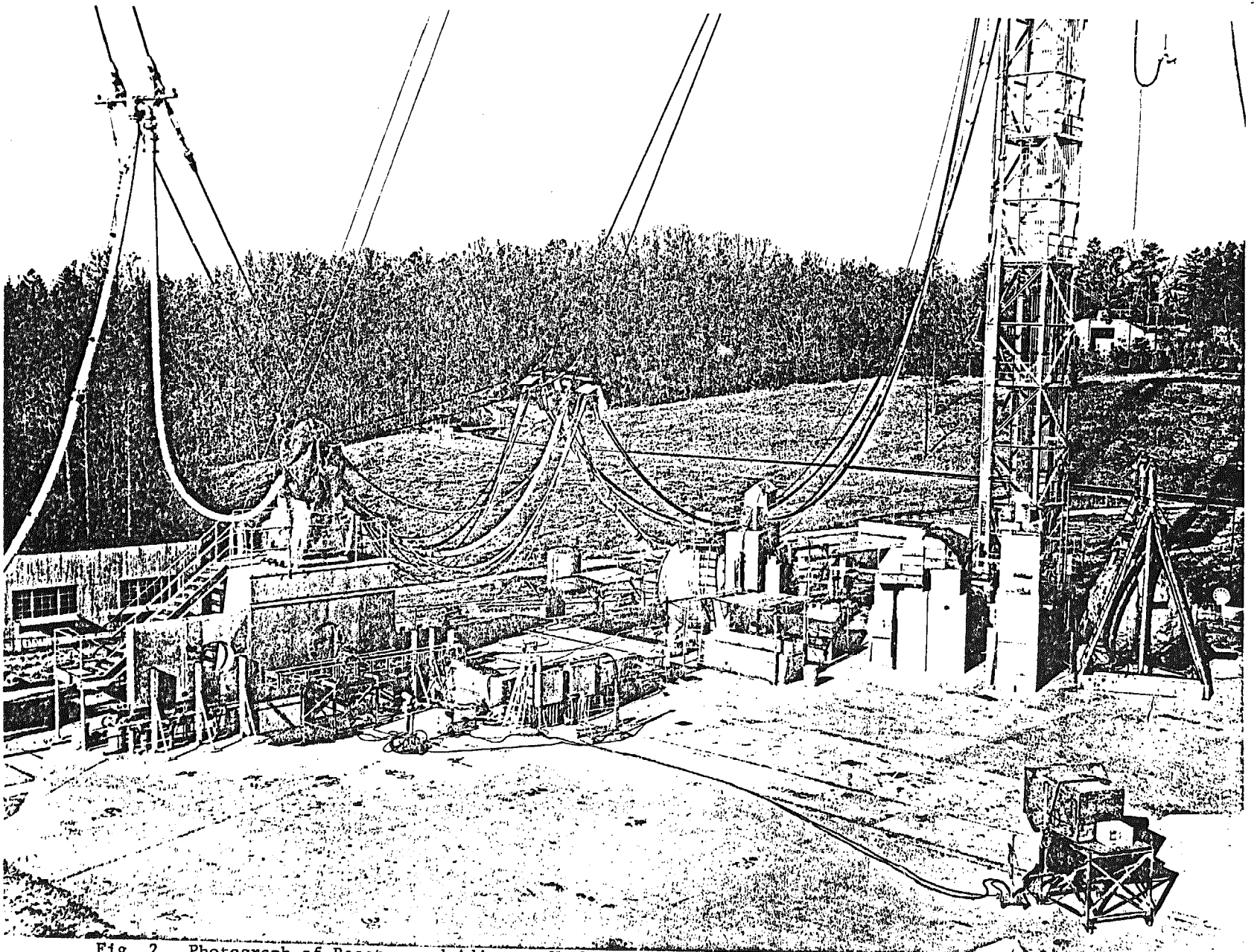

Fig. 2. Photograph of Reactor and Adjacent Work Space at the Tower Shielding Facility.