The Nuclear Test Gauge

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Abstract

Safe and efficient operation of the Savannah River Plant (SRP) production reactors required strict quality control of all fuels and targets that were loaded into the reactors. To analyze the composition of these components in a "nuclear environment," a large low-power critical facility, the 305 Test Pile, was built. This facility required about 10 minutes per test and also required a relatively large, well-trained crew operating under strict and extensive procedures.

The Nuclear Test Gauge (NTG), a small, slightly subcritical facility, was developed to analyze production reactor components about ten times faster than the 305 Test Pile with comparable accuracy and with a much smaller operating staff. After about 20 years of successful experience with the NTG, an extensive modification program was undertaken, which resulted in major improvements. The resulting "mini-NTGs" accelerated component testing with improved safety margins by operating much further below criticality. The mini-NTGs also incorporated improved instrumentation and neutron sources.

Introduction

The design and operation of the five Savannah River Plant (SRP) production reactors demonstrated an extraordinary capability to escalate power and to produce a wide variety of isotopes. Achieving this capability required developing a variety of fuel and target designs that facilitated an almost eightfold increase in reactor power. A vital factor to ensuring safe reactor operation was an efficient and accurate quality control methodology for all the fuels and targets that were charged into the reactors.

Later, the Nuclear Test Gauge (NTG) was developed at the Savannah River Laboratory (now the Savannah River Technology Center) to supplement and eventually replace the 305 Test Pile. U.S. Patent No. 2,936,274 was awarded to Gerhardt Dessauer for this concept.

When the Hanford reactors were built during World War II, nuclear testing of reactor loadings was accomplished by measuring the reactivity effect of each component using a large, low-power critical assembly—the 305 Test Pile (Cawley 1955). This facility was graphite-moderated and fueled with natural uranium slugs. It required a highly trained crew operating under extensive procedures. Each component test required about 10 minutes. When SRP was constructed some 10 years later, an identical 305 Test Pile was built and operated in the SRP fuel and target manufacturing area.

Preliminary Experiments

A small research reactor, the Standard Pile (SP) located in Building 777-M, was used to investigate the feasibility of a subcritical test facility. The SP was designed and constructed by the General Electric Company and was similar to the Thermal Test Reactor at Knolls Atomic Power Laboratory (Stewart 1953). Both reactors were graphite-moderated and used aluminum alloy fuel containing uranium highly enriched in the U-235 isotope. The critical mass was only 2.3 kg of U-235, making the SP highly sensitive to small variations in test pieces inserted into the center of the reactor core.

The objective of the preliminary experiments was to establish a subcritical operating regime wherein the response time to small changes in the composition of test samples was rapid while the resultant changes in the neutron population were accurately measurable. As a subcritical reactor containing a neutron source is brought closer to criticality, the response time increases from the effect of the delayed neutrons within the fission process. Simultaneously, the neutron multiplication, M, increases so that the neutron flux produced in the reactor core can be measured with increasing precision. The criticality status of a nuclear reactor is characterized by the effective multiplication factor, k_{eff}.(1)

From experiments conducted in the SP, it was concluded that k_{eff} values between about 0.98 and 0.99 (corresponding to neutron multiplications of 50 to 100, respectively) would be appropriate to achieve the required compromise between response time and sensitivity.

The next stage in the evolution of a production testing facility was to construct a working prototype. Readily available fuel, components, and instrumentation were used to expedite this development. Nuclear safety was paramount throughout the entire development program. The prototype NTG was installed in a shielded room in Building 777-M, so that any operation involving close approaches to criticality could be carried out remotely. The most-suitable fuel elements available were aluminum alloy cylindrical rods containing highly enriched U-235 and measuring about 1 inch in diameter and 12 inches long (Mark II fuel rods).

A great advantage of these fuel rods was that experimental data were available from the Oak Ridge National Laboratory on the optimum spacing for a triangular lattice array in light water (H_2O) moderator. Thus, if any distortion of the core occurred (e.g., from the impact of a falling object), k_{eff} would decrease.

Figure 1 shows the core assembly of the prototype NTG. The core components were mounted in a 55-gallon drum, and shielding was provided by a thin cadmium sheet that absorbs thermal neutrons and by concrete blocks to absorb gamma radiation. A through tube was located in the center so that test specimens of known composition could be inserted. A Po-Be neutron source emitting about 10 million neutrons per second was mounted near the core center. Two boron-lined ion chambers were suspended in the fuel drum; one chamber actuated the safety system and one chamber supplied a signal used to detect small changes in the neutron flux corresponding to changes in the composition of test specimens. Three other external neutron-counting systems monitored the neutron flux leaking from the core tank.

The safety system consisted of a cadmium safety blade suspended above the core by an electromagnet, which released the blade automatically in the event of an unexpected increase in the neutron flux. The safety blade could also be released by a push-button on the instrument rack.

After construction of the prototype NTG was completed and tested, fuel was added incrementally until a neutron multiplication of about 55 was attained. About 4 kg of U-235 were required. The assembly was moderated by deionized H_2O and had H_2O reflectors about 10 cm thick on the sides but no reflectors on the top or bottom of the core.

Experiments with the prototype NTG demonstrated that a sensitivity could be obtained that was adequate for production tests of reactor components. The experience derived from constructing and operating the prototype NTG provided vital information for designing a permanent model.

Much of the sensitivity of the NTG is from its small size relative to the 305 Test Pile. Thus, the fuel content of a test sample is a much larger fraction of the NTG fuel loading compared to the 305 Test Pile. Additionally, the NTG ion

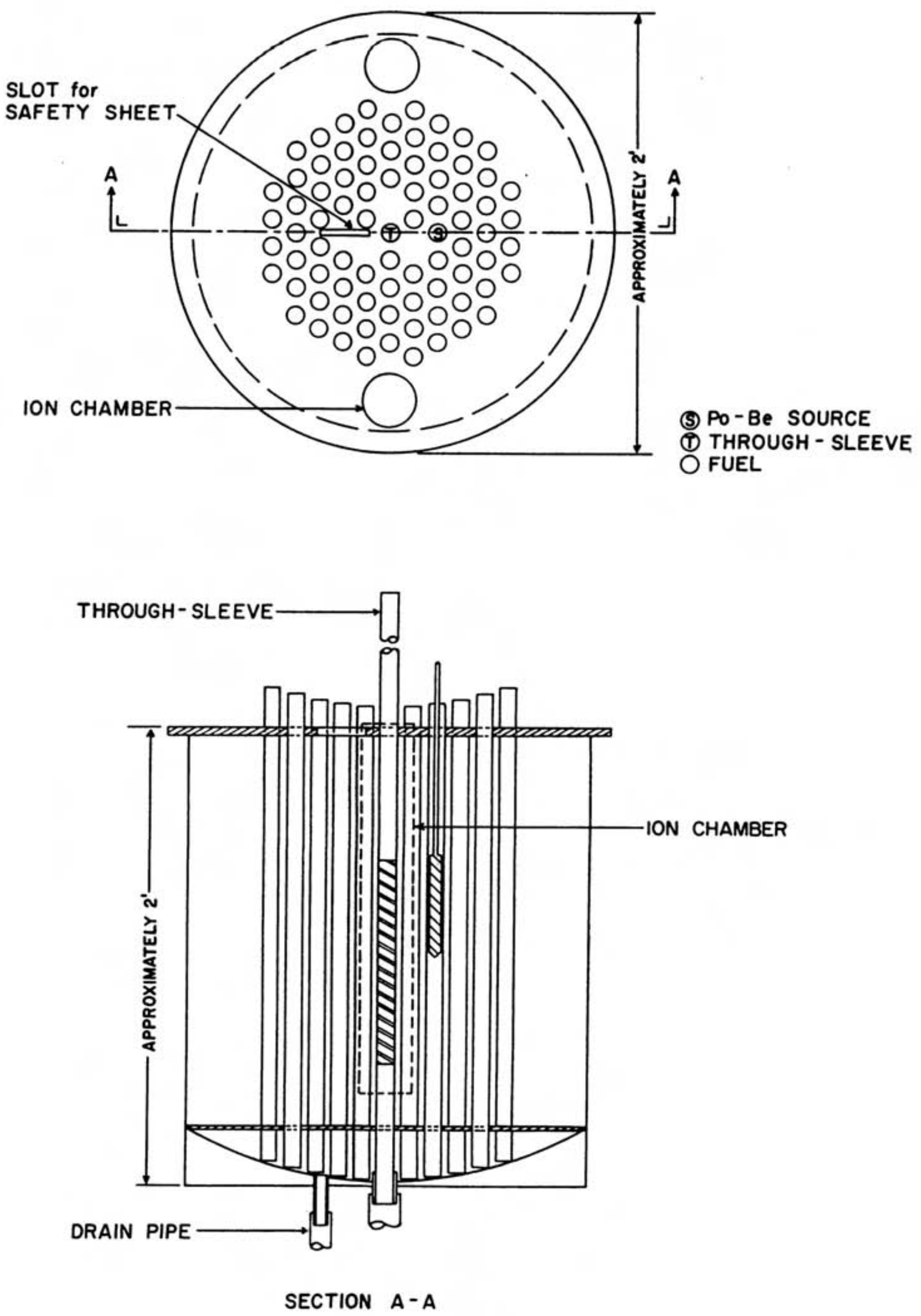

Figure 1. Prototype NTG

chamber absorbs a much larger fraction of the total neutrons produced than the 305 Test Pile ion chambers. The precision achieved in sample analyses could be enhanced by using a stronger neutron source and by efficiently collecting thermal neutrons leaking from the core.

A complete description of the prototype NTG is given in the reports by Axtmann, Dessauer, and Parkinson (1955a and 1955b).

Production Model NTG

Design Features

The basic core design of the prototype NTG was preserved in the production model except that the core axis in the latter was horizontal rather than vertical. This change was made to simplify the sample feed system for the production model.

To facilitate testing a wide variety of fuel and target designs, the production NTG core had a hexagonal polyethylene plug that could be removed from the core and replaced with plugs, which could accept more advanced fuel and targets designs.

The single cadmium safety blade was replaced with two large boral safety sheets in the production model NTG. These sheets were automatically dropped into the core in the event of an unexpected increase in neutron flux. In addition, a dump valve was provided in the production model that could automatically drain the H_2O moderator to the midplane of the lattice in five seconds.

Based on radiation surveys of the prototype NTG, the shielding of the production model was designed to provide a safe radiation environment for operations personnel. (See Figure 2.) A concrete wall 2 feet thick and 9 feet high surrounded the entire system except for open-

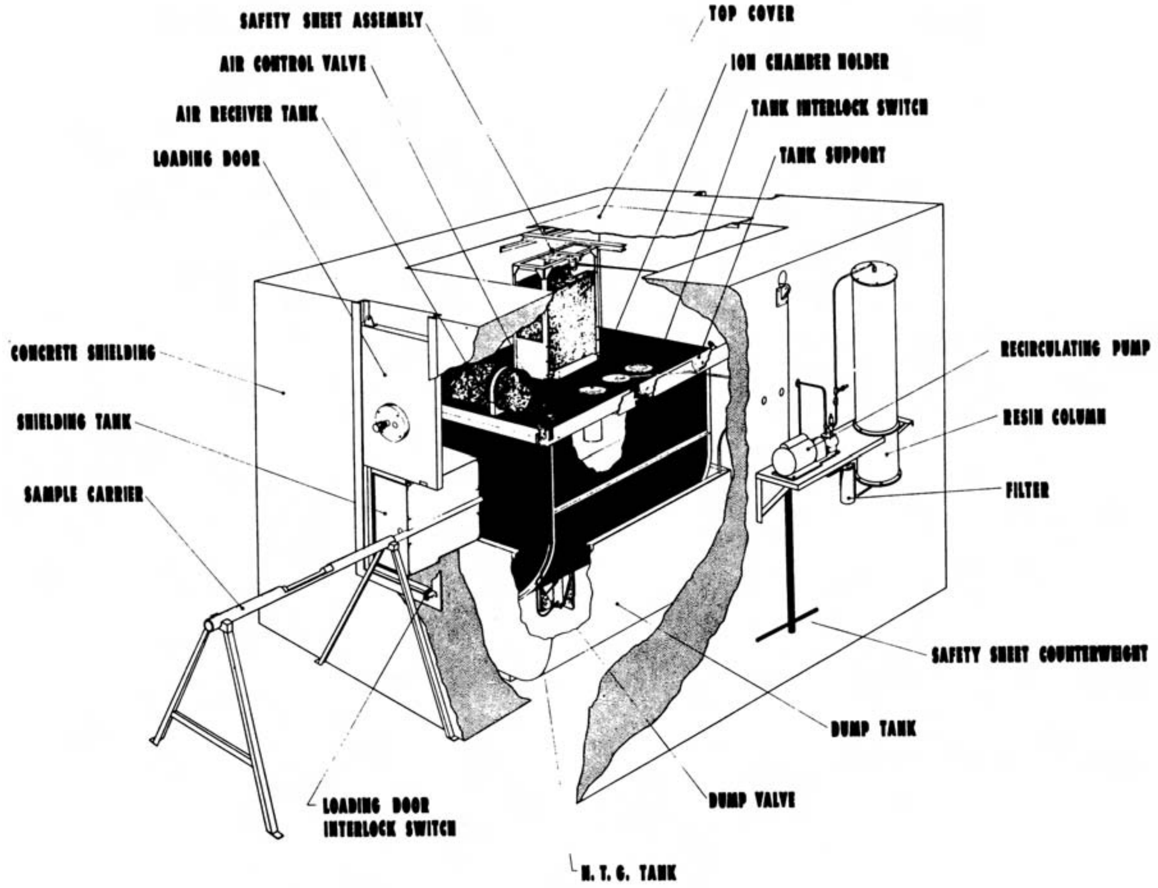

Figure 2. Production NTG

ings on the top and two sides. The inner concrete surface was lined with cadmium sheet, and access to the front and rear of the core tank was via removable H_2O-filled shield tanks and by lead-filled loading doors.

Neutron detection was achieved by six ion chambers lined with boron-10 and suspended in the H_2O-filled tank, which contained the core. Two of the ion chambers provided input to the emergency shutdown system. The other four ion chambers were connected in parallel and fed a differential electrometer capable of detecting the small changes in current corresponding to changes in the composition of test samples.

The emergency shutdown system was actuated by two independent circuits that caused the two safety sheets to fall within one-third of a second and that in turn opened the dump valve and drained the core tank. Rapid shutdown also resulted if the loading doors were raised during operation of the system.

A Po-Be neutron source was installed in one of the fuel tubes near the core center. This source initially emitted about 30 million neutrons per second. The emission rate decreased with a 138-day half-life during the course of the initial calibration experiments and subsequent production testing. Consequently, carefully pre-

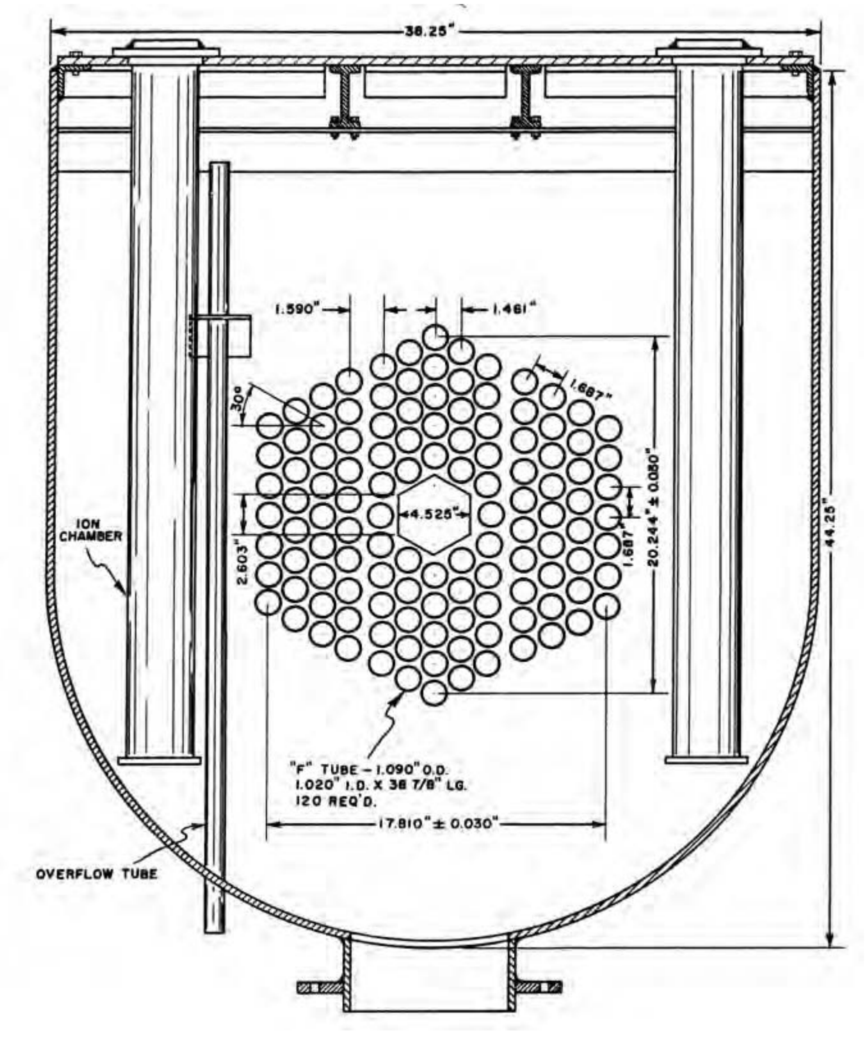

Figure 3. NTG core tank

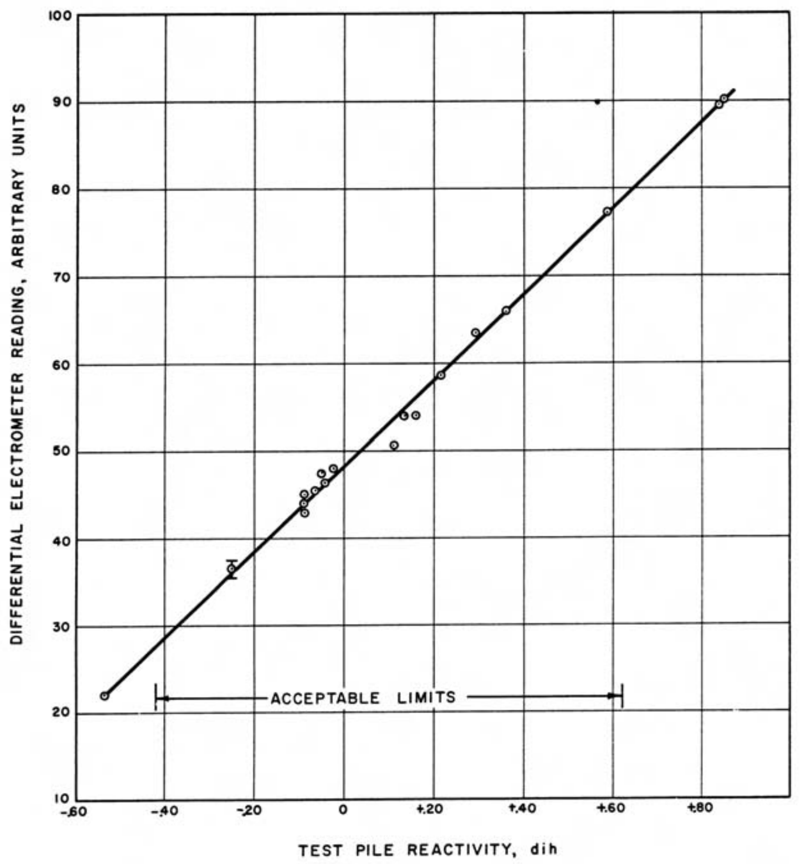

Figure 4. Correlation of NTG and 305 Test Pile data

pared standards were essential to periodically calibrate the NTG. Subsequently, a longer-lived Ra-Be neutron source was substituted for the Po-Be source.

Performance

A remarkable feature of the five SRS production reactors was their capability for power escalation. This capability required an extensive development program to manufacture advanced fuels and targets. Accordingly, the production model NTG had to have the versatility required to test components of vastly different geometries from the initial Mark I natural uranium fuel for plutonium production through the Mark 22 extruded aluminum alloy fuels and targets for tritium production. As shown in Figure 3, the removable octagonal plug provided the requisite versatility.

The NTG tests do not provide an absolute analytical method, so testing of core components depends on calibration with standards of known composition. Initial calibrations utilized existing standards prepared for the 305 Test Pile. Numerous correlations were obtained between NTG and Test Pile data to ensure that no loss in precision occurred with the former. Typical results of these correlations are shown in Figure 4. In addition, it was demonstrated that testing in the NTG was about 10 times faster than testing in the 305 Test Pile, and that the staff required for the NTG was only about 20% of that required for the Test Pile. Substantial cost savings resulted.

For the extruded fuel and target tubes, standards were fabricated from ingots whose compositions were known from material balance and whose concentrations covered the

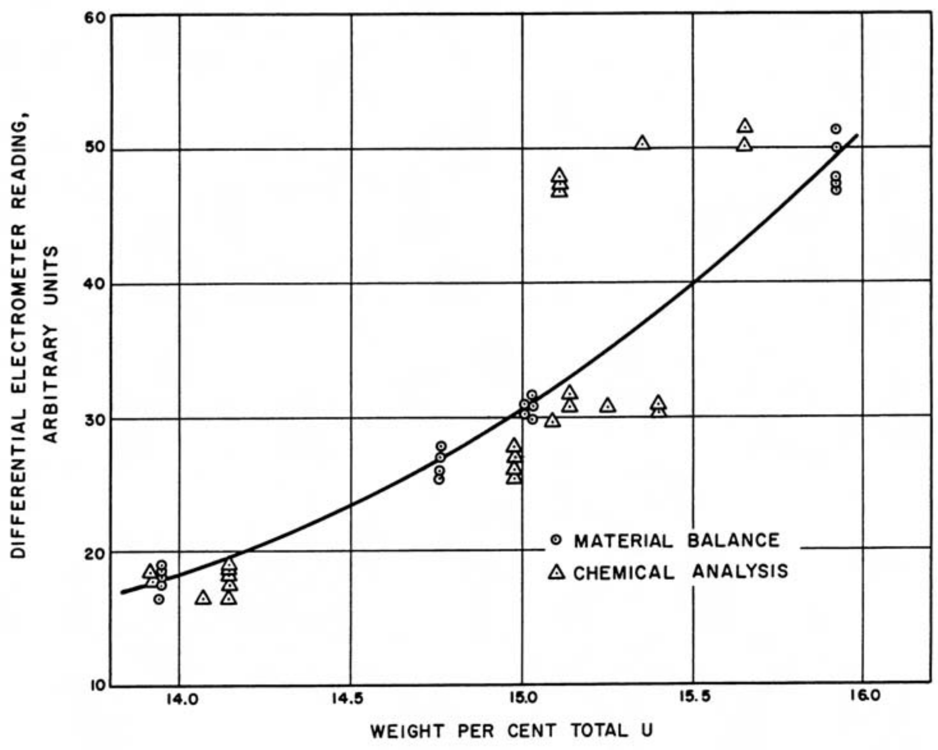

Figure 5. Calibration for tubes of enriched U-Al alloy

range to be expected from production runs. Small samples were then taken from the extruded tubes for chemical analysis. However, the variations in the chemical analyses compromised their usefulness. Thus, the material balance values represented the most reliable data for the calibration standards. A typical calibration curve is shown in Figure 5. A complete description of the NTG is given in Parkinson et al. (1956).

The New Mini-NTGs

The original design of the NTG served its function well, but over time two related major shortcomings became apparent. First, the NTG could not perform all of the functions of the 305 Test Pile, so it was necessary to continue to operate both facilities. Second, the NTG operated so close to criticality that it had to be designed and operated much as a critical facility. This included a SCRAM system, a water dump capability, and several mechanical safety devices. In addition, as critical facilities, both the NTG and the Test Pile required a large investment in highly trained manpower and time consuming procedures. After the initial installation, little was done to upgrade nuclear instrumentation or neutron detectors. Over the years, nuclear instrumentation had improved dramatically, so exploitation of these improvements was clearly indicated. In addition, mini- and micro-computers became available.

The Low-k_{eff} Concept

The original NTG had a reference multiplication constant k_{eff} of about 0.96 to 0.98. With highly enriched fuel inserted, criticality could be closely approached. Computations showed that if the reference k_{eff} could be reduced to about 0.84, no conceivable misloading and flooding could result in a k_{eff} above 0.95. Thus, the facility could be totally designed and operated without consideration for criticality safety, and no special operator training would be required. Computations supported by reactivity tests in the NTG showed that the low k_{eff} could be attained by removing either the inner or the outer ring of U-235 fuel slugs and replacing them with polyethylene rods of the same diameter. The major problem of low-k_{eff} operation was the reduction in sensitivity. This was a combined result of a lowering of the reference neutron flux and of the smaller percent neutron flux change caused by insertion of a test component. The sensitivity was not only recovered, but was enhanced by a sequence of modifications:

- The two ion chambers previously devoted to the SCRAM circuit were devoted to data acquisition.
- Replacing the Ra-Be source with its intense gamma rays with Cf-252 sources eliminated the need for compensated ion chambers. Uncompensated chambers with boron coatings on all surfaces doubled the current (and were more stable as a bonus).
- The biggest contribution was obtained by revamping the method of data taking. The original NTG assayed fuel and target tubes by moving them in incremental steps. A full-length tube was inserted, a waiting time established, and a reading taken. The tube was then advanced and the process repeated. Only a fraction of the time was spent recording usable data. Most of the time was spent waiting for the delayed neutrons to come to equilibrium. Low-k_{eff} operation greatly reduced the time and relative magnitude of the operation. It was possible to eliminate the incrementing, replace it with a continuous uniform speed drive, and thus use all of the ion chamber current.
- For small samples, with a small effect on reactivity, the desired sensitivity was obtained by using the "pile-oscillator" technique. In this procedure, the test sample is repetitively inserted and withdrawn over an extended time period to obtain both statistical accuracy and compensation for slow drifts in the response of the system. This system was used for "bottle samples" containing solutions of gadolinium and boron as well as heavy water samples. These assays were eventually relegated to a neutron blackness tester.

Analysis

The original analysis method consisted of reading off values from a calibration curve drawn manually through calibration points plotted for grams per foot values assigned to the standards. This procedure was replaced with the "NTG Index" that was simply the fractional change in neutron flux level caused by introducing the sample relative to the reference flux with the test port empty. This value is independent of the source strength and small drifts in reactivity and instrument sensitivity. Moreover, it can be verified at a later time if necessary.

This Index has a simple relation to the effective multiplication constant, k_{eff}, for the system. The value of k_{eff} can be calculated from various reactor codes (e.g., ANISN). In general, the ANISN calculations do not exactly agree with the indices measured for the standard, but if the k_{eff} values are normalized to give the best fit to the standards over the range of interest, a good fit to the standards is obtained with a shape much more accurate than simply fitting to the measured points. Finally, the ANISN values are fitted to a low order polynomial for g/ft as a function of the Index.

Implementation

The physics design of the new NTG closely matched the original with respect to dimensions, lattice pitch, and H/U-235 ratio. The water tank was replaced with a cubical block of water extended polyester (WEP). The test port and cylindrical channels for the fuel were drilled into the WEP block. Water retention was obtained by coating all surfaces with a lacquer impervious to water vapor. Separate NTGs were built for Building 321-M (enriched fuel) and Building 320-M (targets). Locating a separate NTG in Building 321-M has obvious safeguards advantages, but separate units also enabled different optimum core designs to be used for each. For Building 321-M, the outer ring of fuel was replaced by 1-inch-diameter polyethylene rods; for Building 320-M, the inner fuel ring was removed and replaced instead. The latter configuration had the advantage of greatly increasing the sensitivity to U-235 and greatly reducing the sensitivity to neutron-absorbing atoms such as U-238, U-236, and U-234. A result was that small calculated corrections could be made for variations in isotopic content rather than requiring standards with varied isotopic content.

Standards

With the improvement of the sensitivity (i.e., precision), it became apparent that uncertainties were due primarily to the accuracy to which the content of the standards was known. Various methods, both destructive and non-destructive, were explored to develop new methods for assay of the standards. Of these, a non-destructive assay based on thermal neutron transmission was the most successful. An assay could be made using the measured transmission along with known thermal neutron cross sections and a geometrical description of the tube.

Conclusions

For over two decades, the Nuclear Test Gauge served a vital function in the quality control of many thousands of components that were irradiated in the five SRS production reactors. The success of the NTG resulted in cost savings of millions of dollars. The NTG served SRS well from its initial installation until the reactors were shut down. The NTG was essential for the implementation of co-extruded tubes (i.e., Mark-16) in reactor charges. The NTG provided the data for estimating initial critical configurations as well as providing the data for proper internal heat splits in the fuel and target matching computer programs.

Starting in 1978, an extensive effort was made to improve the safety and performance of the NTG. To avoid any credible accidents that might cause a super-critical excursion, some fuel rods were removed from the NTG cone. Improved instrumentation and improved neutron sources enabled faster and more accurate analyses to be achieved.

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End Note

1. The status of a nuclear reactor is characterized by k_{eff}, the effective multiplication constant. If k_{eff} is less than one, the reactor is subcritical, and the neutron population falls to zero unless a supplementary neutron source is

provided. If k_{eff} is exactly one, then the reactor is critical, and the neutron population is constant since the neutrons produced by fission are just equal to the neutrons lost by absorption and leakage from the reactor. If k_{eff} is greater than one, the reactor is supercritical, and the neutron population increases.

In a subcritical reactor like the NTG, a supplementary neutron source is provided, and this neutron source is multiplied by a factor, M, given by

$$M = \frac{1}{1 - k_{eff}}$$

Biographies

Thomas F. Parkinson

After completing his undergraduate degree at Auburn University, Mr. Parkinson worked for nearly two years at Oak Ridge before enrolling at the University of Virginia. He completed his Ph.D. in Physics in late 1952 and started work for DuPont at the Savannah River Laboratory (SRL) in experimental reactor physics and instrument development. In 1960, he joined the faculty of The University of Florida, College of Engineering. Mr. Parkinson was a Fulbright Fellow in Madrid during 1966-67, after which he was appointed Nuclear Engineering Chairman at the University of Missouri-Columbia. In 1975, he joined the faculty at Virginia Tech, and after his retirement in 1990, he was designated Professor Emeritus. Mr. Parkinson is a Fellow of the American Nuclear Society and served as the first president of the Alpha Nu Sigma honor society. He made numerous visits to Argentina as a technical expert for the International Atomic Energy Agency.

Norman P. Baumann

Mr. Baumann received a Ph.D. in Nuclear Physics from Kansas University in 1954. He worked in experimental reactor physics and nuclear instrumentation from 1954 to 1993 at the Savannah River Laboratory. His expertise is in lattice physics, criticality control, reactor dynamics, activation analysis, and non-destructive analysis, including technical support of NTG operations. Mr. Baumann retired in 1993 as senior advisory scientist at SRS.