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GEAP-13825-4

AEC RESEARCH AND DEVELOPMENT REPORT

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LMFBR IN-CORE INSTRUMENTATION AND IN-VESSEL SURVEILLANCE SYSTEMS

FOURTH QUARTERLY REPORT
OCTOBER-DECEMBER 1972

U.S. ATOMIC ENERGY COMMISSION

CONTRACT AT(04-3)-189 PROJECT AGREEMENT 65

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LMFBR IN-CORE INSTRUMENTATION AND IN-VESSEL
SURVEILLANCE SYSTEMS
FOURTH QUARTERLY REPORT
OCTOBER-DECEMBER 1972

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Prepared for the
United States Atomic Energy Commission
Under Contract AT(04-3)-189
Project Agreement No. 65

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ABSTRACT

This report summarizes the work performed on the research and development program for LMFBR In-Core Instrumentation and In-Vessel Surveillance Systems during the period from October 1, 1972 through December 31, 1972. The work was performed under Contract AT(04-3)-189, Project Agreement 65.

1. INTRODUCTION

This program was initiated in January 1972 with the objective of developing in-core and in-vessel instrumentation for application to LMFBR's. The program is presently divided into six major tasks:

Task A — In-vessel high-temperature neutron detectors and cable assemblies

Task B — Acoustic monitoring systems for application to the reactor core and vessel

Task C — Reactor core exit instrumentation

Task D — Failed fuel detection and location systems

Task E — On-line reactivity computer system

Task F — Plant protection system

Primary emphasis is on overall system development, making maximum use of base technology information available from the National Laboratories.

2. SUMMARY

2.1 GENERAL

Quality assurance engineering reviews of planning and technical documentation were performed as a continuing effort.

2.2 TASK A — NEUTRON MONITORING

The objective of this task is to develop in-vessel neutron and detector-cable assemblies that do not require auxiliary cooling or special shielding. Both startup (source range) and intermediate or wide range detector-cable assemblies are planned with first priority given to startup detectors.

The following significant progress was made during the quarter:

- The first phase of testing of cables for evaluation was extended to include flexure testing of the cables at 650°C.
- The analysis of the detector nuclear parameters by use of the detector physics study computer program was completed.

- The cable purchase specification was completed and sent to two vendors as part of a request for quotation (RFQ).
- The 1000-hour life test on the GE source range monitor (SRM) seals was completed successfully.
- The new design seals were received and evaluation testing has been started.
- The experiment in the zero power (ZPPR - 3) critical assembly to check neutron flux calculations has been completed.
- A 1000-hour test of uranium-on-Inconel samples was completed and evaluated.
- Functional classification of this development effort was completed.

2.3 TASK B – ACOUSTIC MONITORING

The objective of this task is to develop an acoustic system for in-service surveillance of LMFBR core and in-vessel components.

During this report period, the main actions were:

- Issuance of the Task B Development Plan
- Preparation of Development Specifications for the GE Corporate Research and Development Center (CR&DC) and Argonne National Laboratory (ANL) Task B activities
- Analysis of impact signal characteristics
- Analysis of the signal parameter relationship to test structure scale
- Preliminary preparations for acoustic characterization tests

2.4 TASK C – CORE EXIT INSTRUMENTATION

The objectives of this task are to identify system functional objectives and to define and conduct the necessary programs to produce a representative core exit instrumentation (CEI) probe design and system specification.

The following significant progress was made during the quarter:

- The task planning diagram has been drafted for review, and comments are being resolved and incorporated as required.
- A draft of the Development Plan has been completed.
- Functional requirements have been issued for distribution.
- Feasibility of conducting water flow scoping tests to define the operating environment in the channel handle assembly has been verified.
- Design of the flow mixer device for usage in the water flow scoping tests has been initiated.
- Design of CEI probe components (sensor geometrical configurations) has been initiated.

2.5 TASK D – FAILED ELEMENT DETECTION AND LOCATION (FEDAL)

The objectives of this task are to define the requirements of a system for performing detection and location of failed fuel in LMFBR demonstration plants, summarizing available instrumentation to meet these requirements, and conducting the development work required to produce an operating FEDAL system.

During the present quarter a trip was made to Hanford Engineering Development Laboratory (HEDL) to review the Fast Test Reactor (FTR) failed fuel monitoring system (FFM) as it relates to a FEDAL system for a demonstration plant.

2.6 TASK E – ON-LINE REACTIVITY COMPUTER (ORC)

The ORC reactivity model has been refined to increase anomalous reactivity detection capability.

2.7 TASK F – PLANT PROTECTION SYSTEM

Work on this task has not yet been initiated.

3. TECHNICAL ACCOMPLISHMENTS

3.1 TASK A – NEUTRON MONITORING

3.1.1 Cable Investigation

The cable flexure test fixture was modified to allow flexing of cables at 650°C. Cables from three manufacturers were flexure tested at 650°C. Cables from two of these manufacturers underwent flexing at high temperature with no apparent effect in breakdown pulse noise (BPN). The other manufacturer's cable BPN threshold was lowered but end seal replacement restored the BPN threshold to the original condition. The conclusion was that the end seals were damaged during flexure testing and that the deterioration due to flexure testing was negligible. An interim report on the results of the first phase of cable testing and evaluation has been drafted and is included in Appendix A.

A request for quotation was sent to two manufacturers for SiO₂ insulated cables. Considerable effort has been expended in working with the cable vendors to resolve the method of specifying the compaction density of the cables.

3.1.2 Detector Physics

The analysis of the source range detector fission counter nuclear parameters has been made. The study is applied specifically to the current conceptual design of a source range monitor (SRM) system for an LMFBR demonstration plant. An interim report on the study for use in the sensor development has been drafted and is included in Appendix B.

3.1.3 Seal Investigation

A 1000-hour 650°C life test on the GE standard SRM seals has been completed. Out of the four seals under test one failed. The initial surface examination indicated that the seal failed due to oxidation of the braze material.

The new design detector seals have been received. A 1000-hour test at 650°C was started.

An experimental cable seal termination has been fabricated and tested. The seal displayed poor noise characteristics at near vacuum but improved as the pressure was increased to four atmospheres. This characteristic supports the contention that the BPN for seals is a Paschen-type breakdown.

3.1.4 ZPPR – Assembly 3 Experiment

A series of experiments in the ZPPR-3 critical assembly, for the purpose of supporting the design calculations of the detector fission rate, has been completed. A detailed specification of the experiment has been reported previously.¹ The preliminary results show general agreement with previously calculated values for the relative neutron attenuation in stainless steel, B₄C bulk shielding and B₄C shielding with a window. Complete evaluation of the data is continuing.

3.1.5 Electroplating of Uranium on Inconel

A problem of coating the Development Model 2 Inconel electrodes with uranium was encountered. Further evaluation showed that the problem was one of insufficient current density in the electroplating process. Special devices are being applied to the available electroplating apparatus to adapt it to the Model 2 electrodes to obtain the correct current density.

A 1000-hour test at 650°C of four samples of electroplated and vacuum-fired uranium-on-Inconel that were backfilled with the 89.5% argon, 10% nitrogen, 0.5% oxygen gas mixture was completed. All samples passed the standard production specification (loss of uranium after heating to processing temperature) for BWR in-core detectors.

3.1.6 Source Range Detector Conceptual Design

An SRM conceptual design has been established on which continuing development activities are based. Following are some of the important aspects of the conceptual design. Some precepts may change from time to time as new information is obtained on the program.

System requirements:

- Provide 10 cps at the readout instrument during plant shutdown
- Provide initial range of 10 cps to 100,000 cps without moving the detector
- Operate for 2 years at 1050°F
- Survive transients to 1150°F
- Operate in a gamma field as high as 5×10^6 R/h
- Operate in a dry well with an argon atmosphere within the LMFBR vessel
- Provide for withdrawal of detector during reactor startup to enable on-scale reading at reactor full power
- Bend radius of dry well approximately 60 inches of less-than-90 degrees included angle
- Length of dry well approximately 30 feet

Detector specifications:

- Detector type — Fission counter
- Detector o.d. — 1.94 inches
- Detector length — 7 inches
- Integral cables (two) — one each for high voltage and pulse signal
- Cable type — coaxial, mineral insulated (SiO_2 tentative); approximately 0.160-inch o.d., 0.010-inch thick stainless steel outer sheath, 0.010-inch copper inner sheath, 0.020 copper center conductor, characteristic impedance 50 ohms
- Detector materials — body, electrodes, and parts, Inconel 600; insulators, 96% alumina; springs, Rene' 41
- Detector electrodes — three concentric cylinders; middle cylinder is the signal electrode, uranium-coated both sides; inner and outer cylinders are for the high voltage, coated with uranium on sides facing the signal electrode; uranium-coated surface of 500 cm^2 ; electrode gap spacing 0.040 inch; uranium enriched to 99.9% U-235, with a maximum U-234 content of 0.03%; uranium coating thickness 2 mg/cm^2

- Detector fill gas — 2 atmospheres of 89.5% argon, 10% nitrogen, 0.5% oxygen
- Operating voltage — 300 volts
- Electron collection time — 34 nanoseconds
- Outer shield can — thin wall stainless steel to electrically isolate detector from detector body, extends up cable pair to connectors

3.2 ACOUSTIC MONITORING

3.2.1 Overall Task Planning and Integration

Several items of direction and integration received attention. The Task B Development Plans were submitted to USAEC-RDT. Development specifications covering GE Corporate Research and Development Center (CR&DC) and Argonne National Laboratory (ANL) participation in Task B were prepared.

3.2.2 Acoustic Source Characterization of In-Vessel Components

The third quarterly report (July–September 1972)¹ reported work on the thermal protective structure, reactor vessel shielding, internal piping, and on the lower core support. The work completed since the last quarterly is summarized below.

Internal Piping

The piping system for a possible alternate shutdown control system routes an external sodium supply to three selected core positions. The piping system is shown on Figures 1 and 2. The single supply line was considered in previous work and this work analyzes the section which branches to the three core positions. The pipe is rigidly anchored to the reactor structure at one end and terminates in a slip joint at each of the three branches. Pipe vibrations result in rubbing noises generated at the slip joint. The sound path is along the pipe to its connection at the reactor structure and through the structure to the vessel wall. This noise must be considered when analyzing data from the vessel-mounted acoustic sensors.

The system's natural frequency and mode shape were calculated. The first mode natural frequency is calculated at 9.4 Hz and the mode shape is shown on Figure 3. The mode shapes do not have great significance in this problem, but it does show the program's capabilities. Mode shape information is useful for predicting impact locations and for designing vibration restraints.

Lateral Core Support/Internal Arresting Cylinder

Both the lateral core support and the internal arresting cylinder are large stainless steel cylinders surrounding the reactor core (Figure 4). During normal conditions, the cylinders are in a relatively stagnant sodium environment and are not subjected to any exciting forces. Should the flow past these cylinders increase (e.g., because of a seal failure), they could be excited in a way similar to that of the thermal shield in the Big Rock Point nuclear power station.²

The circumferential natural frequencies are calculated to be between 60 and 130 Hz for the lateral core support and between 45 and 100 Hz for the internal arresting cylinder. Both cylinders rest on the reactor vessel structure which is well coupled to the vessel wall. Vibrations of these large structures will be characterized by signal amplitudes much greater than those of the smaller components.

Reactor Closure

The reactor closure caps the reactor vessel and provides support and guidance for the control rods and instrumentation. The closure structure consists of circular plates and cylinders cantilevered from the vessel flange and ending slightly above the core channels. Many slender, loose-fitting instrument probes, wave guides, control drives, etc., penetrate the closure and extend into the outlet sodium, Figure 5. Flowing sodium could cause flow-induced vibration in both the probes and the closure.

Figure 1. Sodium Supply System for Possible Alternate Shutdown System (Plan View)

Figure 2. Sodium Supply System for Possible Alternate Shutdown System (Elevation Section)

Figure 3. Sodium Supply System Mode Shape

SHIELD ROD SIZE BETWEEN SUPPORT PLATES

LOCATION	DIAMETER	LENGTH
INNER ROWS	3-1/2	166
		130
	4	166
		130
OUTER ROWS	4-1/4	300
		130
	4-1/2	200
		130

Figure 4. Lateral Core Support and Internal Arresting Cylinder

Figure 5. Reactor Closure Components

Table 1 lists the numbers and the first and second mode natural frequencies of the various items.

Table 1
MODE FREQUENCIES

Item	Number in Closure	1st Mode Frequency (Hz)	2nd Mode Frequency (Hz)
Closure Assembly	1	53	—
Heater Unit	20	4—5	28
Level Probe	4	8—9	27
Instrumentation Guide Tube	189	2—3	—
Control Rod Guide Tube			
Upper Section	19	128	417
Control Rod Guide Tube			
Mid Section	19	216	843
Control Rod Guide Tube			
Lower Section	19	44	142

Inlet Flow Chamber

Each cluster of seven fuel channels is supported by an inlet flow chamber (Figure 6). The flow chamber distributes the flow and provides the core's hydraulic hold-down feature. Although the failure mechanism is not defined, analysis shows the lower support as the weakest location. A failure at this location results in a loss of hydraulic hold down and possible flow redistribution.

With normal conditions, the calculated first mode natural frequency is 410 Hz. At the assumed failure conditions, the natural frequency is reduced to 55 Hz. The mode shapes for both conditions are shown on Figure 6. The chamber will impact against the filter screen which is well coupled through the vessel structure to the vessel wall.

3.2.3 Acoustic Source Characterization of Control Drive Component

The component characterization work is summarized below.

Control Element

The control element is the reactor shutdown and control device. The loss or immobility of this device from binding due to core bowing could greatly reduce the capability of the reactor protection and control system.

The element is positioned within the control assembly in a scrambled mode. The control drive is raised approximately 36 inches from this point to pull the B₄C section of the control element out of the core. The main acoustic signals generated by the control element are associated with rubbing and bumping of the element against the walls of the guide tube.

The prediction of frequencies for a suspended rod in parallel fluid flow is not easily made since the behavior of the element is not exactly known. The assumed behavior of the element is a function of the pressure drop which is a function of the flow passage geometry and the flow velocity along the B₄C section of the control element.

Hydraulic Cushion or Clamping Device

This device must bring the control drive shaft to a stop at the end of a scram. If this device should fail, major damage could occur to the control element and control drive. Figure 7 shows the impact energy as a function of the failure fraction of the hydraulic cushion.

Figure 6. Inlet Flow Chamber

Figure 7. Main Cylinder to Control Drive Structure Impact Energy vs Hydraulic Cushion Failure Position

Position Control Drive Screw and Motor

The position control drive screw and motor component of the drive has an important function that is essential to the continuous control of the reactor. It is somewhat different from the other components of the drive because it is actuated during normal operation of the reactor, whereas, the other components are actuated and generate signals during and after a scram. It is a d-c motor rated at 0.215 horsepower at 300 rpm. The screw threads are assumed modified acme with a pitch of 10 threads per inch.

A method for acoustically monitoring the wearing of gears associated with the motor and screw has been developed by GE's Corporate Research and Development Center. The theory is to obtain from an accelerometer a total dynamic meshing load which is the sum of the dynamic loads resulting from wear and the torque-transmitting load. By examination of the fundamental and harmonics of this part of the accelerometer signal the amount of wear can be estimated.

Coupling Lock Actuator

This device operates the mechanisms to couple the control element to the control drive shaft. Monitoring this source is a means to identify the mating of parts in the coupling sequence. Figure 8 shows the predicted signal characters due to coupling lock actuator action.

3.2.4 Acoustic Source Characterization of Core

The characterization of acoustic energy expected to emit from the core was completed. The three areas considered are as follows:

Fuel Rods

The fuel rods are composed of long, thin-walled small-diameter tubing filled with fuel pellets and supported at specific intervals to maintain coolant passages of sufficient size. The movement or loss of these supports can cause overheating. Changing support spacing can be detected by changing rod vibration character.

Figure 8. Coupling Lock Actuator Vibration Characteristics During Unlocking

Coolant flow parallel to fuel rods causes lateral vibration. The frequency is determined by the support spacing while the amplitude is determined by empirical correlation. Wire wrapped as well as both staggered and full grid spacing systems were considered. Frequencies were also obtained in the case where a support point was missing. The results are shown in Table 2.

Fuel Assembly

The 217 fuel rods are packed into a hexagonal channel which is constrained at the bottom by the core support plate and at two upper points at pads contacting adjacent assemblies. The contact between assemblies is maintained by a core clamping device. Improper clamping followed by subsequent shifting into a tighter array during operation could cause a step reactivity change. The lack of proper constraint will cause vibrational character changes from the norm that could be used to signal improper clamping.

Five fuel constraint conditions were studied. The constraint condition, vibration mode, and the frequency are shown in Figure 9. A frequency less than 35 Hz would indicate improper clamping.

Table 2
VIBRATION ANALYSIS RESULTS

Spacer Type	Wire-Wrapped Spacers		Grid Spacers			
			Full Grid		Staggered Grid	
Assumed Configuration	Minimum Contact	Design	Design	One Missing	Design	One Missing
Unsupported beam length (in.)	2	12	6	12	3	6
Fundamental frequency (Hz)	2370	66	270	67	1080	270
Isolated rod amplitude, N=1 (in.)	1.8×10^{-6}	6.0×10^{-4}	1.1×10^{-4}	6.3×10^{-4}	9.0×10^{-6}	1.1×10^{-4}
Amplitude within a bundle, N=217	2.6×10^{-5}	8.8×10^{-3}	1.6×10^{-3}	9.3×10^{-3}	1.3×10^{-4}	1.6×10^{-3}

Figure 9. Fuel Assembly Vibration

Sodium Boiling

Local or gross coolant blockage in a fuel assembly in the presence of high heat fluxes can produce damage to the fuel rods and core components. Associated with high temperatures is the phenomenon of boiling which produces noise. The early detection of boiling could preclude serious damage.

The acoustic emission of boiling sodium in fuel assemblies will produce a broadband frequency noise up to the MHz range. To effectively discriminate the acoustic emissions of boiling, it will be necessary to minimize background noises, particularly due to cavitation (because it has the same character) and to characterize the remaining background to find a suitable frequency band where boiling emission will be sufficiently powerful to be detected. Boiling detection will be based on amplitude discrimination rather than frequency.

3.2.5 Signal Characterization Tests

Emphasis has been placed on scheduling test facilities for impact monitoring and background noise tests as it has been determined that these are areas requiring the most development. Tests selected for impact characterization include:

- Test and analysis of a calibrated impact generator in a water tank to confirm analytical predictions of impact transient characteristics and the effect of impactor geometries, mass, and levels.
- Background noise measurements at Liquid Metal Engineering Center (LMEC) on the Sodium Component Test Installation (SCTI) test loop. An approval-in-principle (AIP) was prepared for the conduct of this test and a preliminary mechanical analysis performed to specify test requirements and conditions. This was accomplished by evaluating system design descriptions (SDD's) and data supplied by LMEC. This facility is attractive because of high flow conditions with high-temperature sodium, permitting analysis of noise contribution from flow pumps and internal components.

- The hydraulic core mock-up at HEDL provides a realistic environment for impact testing. Scaling studies conducted at CR&DC can be applied to this scaled mock-up and the water environment is desirable to minimize the difficulties of testing in sodium. An AIP for several tests proposed for this facility will be prepared in the future.
- Tests in the one-third-core model at HEDL will be planned for a future date to confirm all aspects of the proposed impact monitoring system.
- Data from HEDL's fuel assembly vibration test may prove useful in correlating component and impact data to analytical models and static tests previously conducted.

GE-BRD and the GE-CR&DC are continuing efforts to participate in boiling tests in the failed fuel mockup (FFM) at ORNL. These tests offer a unique opportunity to experimentally characterize the local boiling signal early enough to be of value to Task B. Current ANL acoustic monitoring plans for this test are being reviewed.

Instrumentation requirements were confirmed with ANL for GE participation in the EBR-II experiment for testing waveguides and transducers. Proposed GE usage of EBR-II test data will be discussed in a meeting at EBR-II in the next quarter. ANL's proposed test plan is compatible with GE requirements for PA-65.

3.2.6 Acoustic Signal Characterization

Analytical Prediction of the Impact Signal

A preliminary analytical investigation of the impact signal propagation was conducted. For the simple situation of a ball impinging on a simply supported beam, the transient response of the beam was analyzed by Hoppmann³ and the expression of the beam deflection at time t after impact, and at point x , is given by the following equation:

for $0 \leq t \leq T_L$,

$$w(x,t) = \sum \frac{\pi m v (1+e) \sin \frac{n\pi}{2}}{2MT_L(\omega_n^2 - \lambda^2)} \frac{\lambda}{\omega_n} \left(-\sin \omega_n t + \frac{\omega_n}{\lambda} \sin \lambda t \right) \sin \frac{\pi n x}{\ell}$$

for $t \geq T_L$,

$$w(x,t) = \sum \frac{\pi m v (1+e) \sin \frac{n\pi}{2}}{2MT_L(\omega_n^2 - \lambda^2)} \frac{\lambda}{\omega_n} \left[\sin \omega_n T_L \cdot \cos \omega_n t - (1 + \cos \omega_n T_L) \cdot \sin \omega_n t \right] \sin \frac{\pi n x}{\ell}$$

where

m = mass of a ball

v = striking velocity of the ball

M = half of the total mass of the beam

e = coefficient of restitution, ($e \approx 1$ for $\frac{m}{M} \ll 1$)

ω_n = natural frequency of the beam for the n -th mode

$$\omega_n = \frac{\lambda n}{\ell^2} \sqrt{\frac{EI}{\rho A}}$$

$$\lambda_n = (\pi n)^2$$

ℓ = length of the beam

E = Young's modulus

I = area moment of inertia of beam

ρ = density of beam

A = cross-sectional area

$$\lambda = \frac{\pi}{T_L}$$

T_L = Hertz contact time (see Figure 10)

$$T_L = 3.28 \left[\left(\frac{4}{3} \pi \rho \right)^2 \frac{(1 - \nu^2)^2}{E^2} \right]^{1/5} \frac{r}{v^{1/5}}$$

r = radius of ball

ν = Poisson's ratio

This formula was applied to estimate the acceleration level at a sensor site due to the impacting of the critical structural members in the breeder reactor. The refinement of the analysis to take more complex structural response into account is underway.

Scaling Study of the Impact Signal

Concurrent with the analytical prediction of the impact signal, an experimental program was initiated to establish the correlation between the theory and experiments. Prior to the design of the experimental apparatus, a scaling study was made in order to find the scaling factors between the small-size test and the full-scale reactor. The question to be addressed was, in addition to the obvious geometrical and material similarity between the small-size and full-size tests, what parameter should be kept the same so that the two impact signals become similar? Based again on Hoppmann's expression given above, it was concluded that the impact velocity should be maintained for the two signals to become similar in the one-dimensional sense. If the geometrical scaling factor between the small-size and full-size tests is denoted by σ , in the full-scale test, the acceleration (α) is smaller and the time scale is slower than the model test by the factor σ . Figure 11 shows this schematically.

3.2.7 Impactor Design

Two types of impact experiments were planned and the setups were designed and are being made. They are:

- Compare the impact theory with experiment in its simplest form and to experimentally establish simplifying correlations between the various impacting objects with the equivalent ball.
- Measure response of complex structure to the impact and compare with the theory.

As a means of generating impact, a drop method is adopted. Care is taken to eliminate the signal due to rebounding.

3.3 TASK C – CORE EXIT INSTRUMENTATION (CEI)

3.3.1 Overall Task Planning

The Task Planning Diagram was modified to reflect current funding and circulated internally for comments. The comments received have been resolved and the resolutions are being incorporated.

The Task Development Plan was drafted. This development plan outlines the activities, their interfaces, and responsibilities required to develop a CEI probe system to meet the defined functional requirements.

Figure 10. Hertz Contact Time (T_L)

Figure 11. Scaling Effects on Acceleration and Time Response

3.3.2 Functional Objectives

The functional objectives were defined and are shown in Table 3. These objectives will be modified as required in the future if the design and testing activities indicate that a functional objective is unattainable using existing technology.

Table 3
CORE EXIT INSTRUMENTATION FUNCTIONAL OBJECTIVES

The functional objective definitions for the core exit instrumentation (CEI) were derived from the following operational objectives:

- A. Provide startup control data.
- B. Measure the fuel assembly mean coolant outlet temperature.
- C. Provide the capability of operating within the limits established by the plant protection system.

Based on the above operational objectives, the functional objectives, along with their justifications, are defined below:

I. Mechanical Configuration

1. The CEI shall be compatible with the design of the fuel and blanket assemblies.
2. The CEI shall be designed to operate with the instrument probe having a misalignment between the closure and fuel or blanket assemblies of ≤ 0.5 inches.

This is based upon the maximum misalignment between the closure and control assemblies which can be tolerated by the control system.
3. The CEI probe, in the fuel channel handle area, shall not increase the fuel assembly ΔP to a level which causes the fuel assembly to operate outside its design limits.
4. The CEI shall be removable to permit maintenance, surveillance, and replacement with minimum interference with reactor operation (high availability).

II. Measurement of Coolant Outlet Temperature and Flow Rate During Normal Operation

1. The core exit temperature and flow sensors shall have a response time capable of following the core exit temperature rise and flow rate variations during power changes from full shutdown to 30% power level.

The most likely time of operation where plugging of interstices may occur is during startup from refueling temperature. The plugging of interstices could cause sodium boiling and fuel meltdown.

2. The CEI should provide alternate (to main sodium system) measurement of the reactor (bulk average) outlet temperature for the core temperature control system.

This functional objective will provide redundancy for the temperature sensors used in the core temperature control system. In addition, the computation of this temperature from the CEI data is useful in the computation of the core ΔT .

3. The core exit temperature sensor shall have a response time fast enough to be compatible with the core temperature control system (CTCS).

Core surveillance is important during periods of transient operation where plant loads are being changed by the maximum rate of change permitted by design. One of the first indicators of an abnormality in the control system is a deviation of core exit temperature due to control rod malfunction, pump speed malfunction, or controller malfunction.

Table 3 (Continued)

- 4 The CEI shall be capable of detecting changes of 3% or more in the steady-state power in an assembly (3% change of ΔT across the fuel assembly) and/or changes in the assembly flow rate of 3% when operating at rated power and flow
- 5 The CEI shall be capable of detecting blockages which reduce the fuel assembly flow rate by 3%

A 3% change in either the power or flow will result in about a 10°F change in the mean coolant outlet temperature of the assembly at full core ΔT . This temperature change will also indicate a corresponding temperature change in the peak cladding temperature. The temperature increase will be accounted for in the fuel rod design. For good surveillance the CEI should be capable of detecting this change.
- 6 The CEI shall be capable of measuring or inferring the mean coolant outlet temperature of every fuel assembly to determine reactor core performance
- 7 The CEI shall provide temperature and flow data for reactor control and operation throughout the operating range of temperature and flow
- 8 The CEI shall be capable of operating in a sodium and radiation environment characteristic of an LMFBR
- 9 The core exit temperature sensor shall provide reproducible signals over a temperature range of 300°F to 1500°F

The core exit temperature data will be used to supplement data from the failed fuel element detection and location system (FEDAL) to determine the condition of the fuel element. The data handling equipment will provide long- and short term data presentation format for the operator to analyze to determine if the thermal hydraulic performance is within the expected performance. Therefore, the sensor output must be reproducible so as to eliminate the sensor output as a factor in the power profile variations that occur due to rod manipulation. The expected temperature range during normal operation is 300°F to 1150°F.
- 10 The CEI shall be capable of supplying core exit data to other systems such as FEDAL and the acoustic monitoring system

III Operation Within the Plant Protection System

- 1 The CEI shall provide reliable information throughout the operating cycle of the reactor
- 2 The CEI shall transmit to the reactor operator sufficient warning of any perturbation in the core (that affects flow and/or temperature) which can cause the fuel assemblies to operate outside their design limits
- 3 The warning transmitted to the operator can be an alarm or an automatic action (RDT Std C16-1T)

The functional objectives (III 2 and III 3) pertaining to the operability of the CEI in the plant protection system require that the CEI transmit to the reactor operator sufficient warning of any perturbation in the core that can cause elements to operate outside their design limits. This warning can be an automatic action if the human response time is such that the operator cannot take the necessary action to prevent against propagating damage. This functional objective requires the development and usage of fast response time temperature and flow sensors.
- 4 The CEI probe shall be capable of supplying reactor operational data during and after environmental conditions which produce peak variations of at least 125% average power

There are environmental conditions which exceed the normal operating environment. These conditions will cause the reactor core operation to exceed its normal operating condition and, therefore, to be cognizant of these abnormal environmental conditions, the CEI should be capable of supplying data during and after being subjected to peak variations of 125% average power.

A literature survey was conducted which investigated past studies and experiments relative to:

- Techniques for temperature and flow measurement
- Cross-flow effects on the instrument probe design
- Analytical techniques used to investigate flow and temperature profiles in the channel handle assembly

The information obtained from this survey will be used, along with functional requirements and reactor analysis, to define a set of preliminary quantitative design requirements where applicable.

3.3.3 Core Exit Instrumentation

The feasibility of conducting water tests using an existing flow distribution and vibration test facility (FD&VTF) was ascertained. The data obtainable from a series of tests in this facility would define the operational environment in the channel handle assembly, and these data are required before a meaningful CEI probe design can be specified. The fabrication costs, testing, and scheduling requirements are being defined, based upon the existing design of the FD&VTF with minor modifications for instrumentation sensors and fuel rod geometry. A test plan is being prepared for review. The flow mixer design has been initiated. The flow mixer is utilized in the FD&VTF to measure mixing coefficients, errors associated with the mixed mean temperature measurements, and the possibility of blockage detection with the flow mixer in place.

The design of CEI probe components was initiated based upon the functional objectives and literature survey. The design effort has centered on existing CEI probe component designs until a set of design requirements can be compiled. This activity is progressing.

3.4 TASK D – FAILED ELEMENT DETECTION AND LOCATION (FEDAL)

An information meeting was held at HEDL to review the fast test reactor FFM system. The meeting was attended to assess the latest changes in the FTR FFM system, particularly as they might relate to an LMFBR demonstration plant. Highlight changes are:

- Adopting gas tagging as the reference location system in the FTR.
- Elimination of noise analysis of core exit eddy current flowmeter signals as a reference location system, at least for the first two cores of the FTR.
- Addition of a “verification” requirement to verify that a suspect fuel duct truly contains a faulty fuel rod prior to removing the duct from the reactor vessel. A reference design does not yet exist to respond to this requirement.

Experimental information is required in several areas to support FEDAL development. Ongoing experimental programs, both at BRD and offsite, have been reviewed and revised where possible to give better support to FEDAL informational needs, including the following categories:

- Basis for FEDAL instrumentation
- Instrumentation functional requirements
- Measured signal-fuel damage correlation
- Contamination effects

Overall, it is felt that the forced circulation capsule tests (PA-10 program) present the best opportunity to obtain scoping data for all these categories, although more prototypic tests are needed in each separate area. Liaison with cognizant PA-10 engineers has influenced planning of the FCC testing program and also the "run-beyond-failure" tests (PA-10 B12 series) expected to be conducted in EBR-II as a joint PA-10, ANL program.

Other programs less directly involved with defective fuel testing, but which yield pertinent data on fission-product release characteristics, have also been made responsive to PA-65 FEDAL needs where possible. An important example in this regard is a program at Oak Ridge to measure isotopic release from mixed-oxide fuels at various linear heat ratings and for long exposures.

3.5 TASK E – ON-LINE REACTIVITY COMPUTER (ORC)

The ORC feedback and burnup reactivity model was reviewed to determine the changes required to obtain greater malfunction detection capability while minimizing the amount of renormalization required. The previous ORC reactivity model was valid only for small variations near a normalized point. The coefficients previously used were defined for linear variations of coolant temperature, power, and integrated power. Actual reactivity effects anticipated from the large changes from reactor startup to full power and over significant time intervals are nonlinear. Modifications were made in these reactivity coefficients to increase the reactor operating conditions over which the ORC can operate without renormalization. In addition, a supplementary reactivity model was defined to effectively utilize nuclear and mechanical core design calculations to compute the new reactivity coefficients for the ORC. Sensitivity studies are being made with these modifications to the ORC model to determine likely uncertainties.

4. ADMINISTRATIVE

4.1 TRIPS

1. October 13, 1972 – L. H. McCarty and G. I. Samstad of GE-BRD visited HEDL in Richland, Wash., to review the status of the FTR fuel failure monitoring system.
2. October 24, 1972 – L. R. Boyd (GE-BRD), G. I. Samstad (GE-BRD) and K. Smith (GE-CR&DC) visited LMEC in Santa Susana, Calif., to review the applicability of the test facilities to the PA-65 Acoustic Monitoring Task.
3. November 10, 1972 – L. R. Boyd (GE-BRD), G. I. Samstad (GE-BRD) and K. Smith (GE-CR&DC) visited ANL in Chicago, Ill., to review potential test facilities for PA-65, Task B, and to discuss ANL activities in support of this task.
4. December 6, 1972 – L. R. Boyd (GE-BRD), and K. Smith (GE-CR&DC) visited HEDL in Richland, Wash., to review the applicability of upcoming tests and existing test facilities for furnishing acoustic data for PA-65, Task B.
5. December 12–13, 1972 – G. Billuris, L. F. Fidrich, C. L. Larson, G. I. Samstad, and P. W. Swartz, all of GE-BRD, visited AEC-RDT in Germantown, Md., to discuss the overall work scope for PA-65.

4.2 VISITS

None.

4.3 LIST OF CONTRIBUTORS

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APPENDIX A

INTERIM REPORT ON THE EVALUATION OF MINERAL-INSULATED CABLES

A1. PURPOSE

The purpose of the evaluation was to determine the characteristics and to define the parameters necessary for a cable for use with a source range fission counter in an LMFBR and to procure and evaluate cables for detector prototype and qualification units. The approach taken was to evaluate readily available cables and gather data upon which to base a purchase specification. The second part of the evaluation includes the purchase of cables according to the specification followed by qualification testing.

A2. INTRODUCTION

It has been determined that a promising approach for source range neutron monitoring in the LMFBR is by the use of a fast collection time fission counter operated in the current mode in conjunction with suitable fast electronics.^{A-1, A-2} In order to successfully apply this technique it is necessary to use cables which are capable of functioning at temperatures of 450°C to 570°C without contributing to the noise level by creating noise or by permitting external noise pickup. The cable-generated noise is termed breakdown pulse noise (BPN) and is evidenced by a departure from the normal exponential distribution of pulse heights of statistical noise. This is observed on an integral bias curve as a departure from linearity. The threshold for the onset of breakdown pulse noise is dependent on the temperature and voltage applied to the cable and the cable's material and mechanical characteristics. Since the transmission of fast current pulses is a requirement,^{A-3} the high-frequency transmission characteristics must be adequate and this dictates that a copper conductor be used in the cable. The need for external noise screening and protection from the environment at high temperature^{A-3} militates that the sheath should have an inner layer of copper and an outer layer of stainless steel.

Based on information gathered in the detector state-of-the-art review^{A-3} and an analysis of the requirements for the cable it was determined that the candidate cables should have magnesia or silica insulation in addition to having a copper center conductor and a composite stainless steel-copper sheath. Because of the need for mechanical flexibility, the cable should be reasonably small in diameter but not so small that the assembly to the detector would be troublesome. This leads to a selection in the range of 0.125 to 0.180-inch outside diameter. Because of the normal difficulties in attaching the cable center conductor to other components it is necessary that it not be fragile; 0.020-inch diameter which is fairly common, was considered a minimum acceptable diameter. The cable mechanical requirements lead to silica as the preferred dielectric since, as shown in Equation A-1. The low dielectric constant, 1.58 for 50% compaction to 3.78 for 100% compaction permits the smallest possible ratio of sheath inside diameter to conduction diameter.

$$Z_o = \frac{138.1}{d} \log_{10} \frac{b}{a} \quad (A-1)$$

where

- Z_o = characteristic impedance
- d = dielectric constant
- b = i.d. of sheath
- a = o.d. of center conductor

A plot of b/a vs d shows this relation for 50-ohm cable and 75-ohm cable (see Figure A-1).

Figure A-1. Cable Diameter vs Dielectric Constant

One manufacturer (A) has a line of high-temperature silica-insulated cables which fit the general requirements; manufacturer B has a similar cable and has capabilities for varying the sheath and center conductor diameter. Cables from these manufacturers, as well as magnesia-insulated cables from three other suppliers (manufacturers C, D, and E) were obtained for evaluation, and are summarized in Table A-1.

Table A-1
CABLE DESCRIPTIONS

Cable No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Manufacturer	A	A	A	B	B	C	C	D	D	E	E	E	E
Insulation	SiO ₂	SiO ₂	SiO ₂	SiO ₂	SiO ₂	MgO	MgO	MgO	MgO	MgO	MgO	MgO	MgO
Outer Diameter	0.160	0.292	0.142	0.150	0.150	0.161	0.161	0.209	0.209	6mm	6mm	4mm	4mm
Stainless Steel	0.010	0.010	0.010	0.010 ^a	0.010 ^a	0.010	0.010	—	—	—	—	—	—
Sheath thickness				0.010	0.010								
Copper	—	0.003	0.010	0.012	0.012	0.010	0.010	—	—	—	—	—	—
Sheath thickness													
Conductor	0.040	0.100	0.030	0.020 ^b	0.020 ^b	0.020	0.020	0.020	0.020	0.012 ^b	0.012 ^b	0.012 ^b	0.012 ^b
Remarks	—	—	—	Short Sample	Long Sample	—	—	—	—	—	—	—	—

Notes: a. Laminated stainless steel-copper-stainless steel
b. Stainless steel clad copper conductor
All dimensions in inches unless otherwise marked

A3. TEST PROCEDURE

The procedures prescribed in RDT F3-39T^{A-4} were followed, in general, for the tests. The BPN procedure was modified in that the cables were evaluated only at room temperature and 650°C and the time for each data point was 10 seconds except for the lower count rate points where 100 seconds were used. Voltage increments of 200 were normally used and except in rare cases did not exceed 800. The breakdown pulse noise test configuration was as shown in Figure A-2.

The insulation resistance and leakage current vs temperature tests were conducted with a Fluke Model 412B power supply and an EG&G Model 726A picoammeter, and the ovens and controller used with the BPN test.

The capacitance measurements were made with a Tektronix Type 130L-C meter.

The characteristic impedance measurements were made only at room temperature using a Hewlett-Packard time domain reflectometer, Model 1415A.

Most of the effort was directed at BPN tests and the related problems of cable outgassing and sealing. The tests were conducted in accordance with RDT Standard F3-39T for those data points of interest to this program.

A4. RESULTS

1. Breakdown Pulse Noise

Manufacturer A Cable

The first cable samples to be tested for BPN were the 0.160 o.d. and 0.292 o.d. samples, cables 1 and 2 in Table A-1. Ceramic-to-metal seals were attached to the cables, they were outgassed at 650°C, backfilled with argon at one atmosphere and sealed. The performance as shown in Figures A-3a and A-4a was poor as evidenced by departure from linearity at too low values of voltage and temperature. However, both cables improved as shown in Figures A-3b, A-4b and A-4c, after the seals were opened and the cables were outgassed at 700°F to remove the argon. Figure A-4b shows the performance after approximately 1 hour of baking; Figure A-4c is after approximately 5 hours of baking. These curves demonstrate that the presence of argon lowers the BPN threshold, that the 0.160 o.d. cable is quiet to 700°C with 600 volts applied, and that the seal zone is the more critical part of the cable insofar as noise generation is concerned, Cable 1, which is not a prime candidate because of its size, appears to perform adequately for BPN. Cable 2 performed satisfactorily as shown by Figure A-4c. Comparison of Figures A-3a and A-3b shows the improvement in cable 1 after additional outgassing at 700°C and the improvement in performance effected by changing the seal. Even though the seal condition illustrated by Figure A-4d is better than in Figure A-4b, it is still far from acceptable.

Figure A-2. Breakdown Pulse Noise Test Configuration

Figure A-3a. Cable 1 BPN

Figure A-3b. Cable 1 BPN

Figure A-4a. Cable 2 BPN

Figure A-4b. Cable 2 BPN

Figure A-4c. Cable 2 BPN

Figure A-4d. Cable 2 BPN

Cable 3, the 0.142-inch o.d. cable, is a close approximation of the cable required for the LMFBR source range detector because of its size and electrical characteristics. As shown in Figure A-5, it performed acceptably insofar as BPN is concerned.

Manufacturer B Cable

A short length of cable from manufacturer B was tested initially without seals and then with temporary glass seals. There was a definite shift of the curve toward higher discriminator voltages as shown in Figure A-6a until the cable was at 427°C; then as the temperature was increased further the curve shifted back to lower values indicating that the cable was improving by outgassing of the dielectric. The same cable was tested with glass seals; the results are shown in Figure A-6b. A departure from the room temperature — 0V curve occurred at 650°C — 600V and 650°C — 1000V. However, these could not be repeated on this cable and, since there was a high external noise level at this location, it was concluded that these deviations were caused by external noise. The same cable was retested 2 weeks later in a different location and the results, as shown in Figure A-6c, were much worse than the original test, indicating that the seals were leaking; a visual examination showed that they had indeed developed hairline cracks. A further retest as shown in Figure A-6d after another 2 weeks which included additional bake out showed some improvement but not a return to the original performance. A longer section of cable, Sample 5, was provided with ceramic-metal end seals, baked in air for 12 hours at 650°C and then sealed off without back filling. The performance as shown in Figures A-7a and A-7b was far from satisfactory. However, the seals were removed, the cable baked at 700°C and resealed with glass after which the performance of the bulk cable was improved as shown in Figure A-7c.

Manufacturer C Cable

Two pieces of cables, cables 6 and 7, were evaluated with less than satisfactory results. Cable 6 had ceramic metal seals attached and after baking was found to have developed an intermittent short. Investigation by x-ray photographs showed that this was caused by a loop in the conductor which shorted to the sheath. Cable 7, which was tested with glass seals, initially appeared likely to perform satisfactorily even though the discriminator voltage for 1 cps was much higher than for other cables in the same test location with the same preamplifier. This is shown in Figure A-8. It was then found that the insulation resistance of the cable had dropped to 50 ohms, the cause of which was traced to zones of dark insulation. X-ray photographs of the low-resistance sections did not reveal additional defects in the center conductor. A discussion with the manufacturer revealed that he was not satisfied with the ceramic beads received for this cable and was attempting to expedite an order from a second supplier for additional cables.

A second shipment of cables was received and evaluated. The performance was significantly better than the first group. However, there was a room temperature insulation resistance problem which appeared to be caused by moisture in the cable and which improved during testing. The new cables had a BPN threshold of 600 volts at 650°C. The BPN performance is as shown in Figures A-9 and A-10.

Manufacturer D Cable

Cable 8, a 0.209-inch o.d. cable exhibited increasing noise levels as applied voltage was raised during the initial test as shown in Figure A-11a. After bake out at 700°C, the cable improved somewhat as shown in Figure A-11b. Placing the open end in the hot zone resulted in worse performance (Figure A-11c). However, providing additional shielding from external noise resulted in much improved performance as shown in Figure A-11d. Adding a glass seal to this cable resulted in poor performance as shown in Figure A-11e and removing the seal brought the performance back to an acceptable level as shown in Figure A-11f. Since other experiments with the glass seal had been successful in that it was shown that the material could be added without deleterious effects, it was concluded that the technique for adding the seal was at fault in this instance. A possible explanation for the problem is that a pocket was created between the glass and the cable dielectric and the gas which collected in this pocket provided a discharge path. A retest of this same cable as shown in Figure A-11g demonstrates that the bulk cable is acceptable to 600 volts at 650°C. The second cable with a glass seal attached performed acceptably to 1000 volts at 650°C as shown in Figure A-12.

Manufacturer E Cable

The cable from manufacturer E, which had been rated highly from the standpoint of high BPN threshold, turned out to be less than satisfactory. However, this may have been related to bake-out procedures. The performance of cables 10 and 11 as shown in Figures A-13 and A-14 was less than satisfactory. It is possible that with additional effort the seal zones could have been better outgassed and the performance upgraded. However, the extremely fragile center conductors broke off repeatedly in test and it was decided that for this reason alone the cables could not be used. The performance of cables 12 and 13 as shown in Figures A-15 and A-16 was even worse. It was concluded that further evaluation of the cables would be of academic interest only.

Figure A-5. Cable 3 BPN

Figure A-6a. Cable 4 BPN

Figure A-6b. Cable 4 BPN

Figure A-6c. Cable 4 BPN

Figure A-6d. Cable 4 BPN

Figure A-7a. Cable 5 BPN

Figure A-7b. Cable 5 BPN

Figure A-7c. Cable 5 BPN

Figure A-8. Cable 7 BPN

Figure A-9. Cable 6B BPN

Figure A-10. Cable 7B BPN

Figure A-11a. Cable 8 BPN

Figure A-11b. Cable 8 BPN

Figure A-11c. Cable 8 BPN

Figure A-11d. Cable 8 BPN

Figure A-11e. Cable 8 BPN

Figure A-11f. Cable 8 BPN

Figure A-11g. Cable 8 BPN

Figure A-12. Cable 9 BPN

Figure A-13. Cable 10 BPN

Figure A-14. Cable 11 BPN

Figure A-15. Cable 12 BPN

Figure A-16. Cable 13 BPN

2. Insulation Resistance

The insulation resistance vs temperature evaluation was performed on six cables, two each from manufacturers B and C, and one each from manufacturers A and D. The temperature vs resistance curves for the six cables are shown on Figures A-17a and A-17b. A comparison of the curves shows that cable 4 performed best, with an insulation resistance of 5×10^8 ohm-ft at 650°C. Three cables, 5, 6B, and 8, show approximately the same resistance in the mid- 10^7 ohm-ft range at 650°C. Cables 3 and 6 show an order of magnitude of poorer insulation resistance, being in the low 10^7 or high 10^6 ohm-ft range at 650°C. The room temperature insulation resistance ranged from 10^{12} to 10^{14} ohm-ft for all cables, with cable 4 performing best as it did at the high temperature. The portion of the curves showing initial resistance during heat up are of no particular significance to the evaluation, since all operational cables will be baked out, backfilled, and permanently sealed prior to attachment to a detector.

3. Characteristic Impedance

The characteristic impedance of the cables was measured by use of a time domain reflectometer with the following results:

Cable	Z_0 (ohms)
3	50
5	71
7	50
8	50
10	54

The selected value for characteristic impedance is 50 ohms in order to match the 50 ohms input of the preamplifier and to minimize the time constant (τ) of the detector cable assembly which is determined by:

$$\tau = RC$$

where C is the detector capacitance and R is the input impedance of the preamplifier, which for optimum matching must be equivalent to the characteristic impedance of the cable.

4. Cable Capacitance

The capacitance was measured for four cables, with 1 kHz excitation. Within the accuracy provided by the equipment there was no capacitance change over the temperature range of interest, 25°C to 650°C. At the high temperatures, there were several inconclusive readings which probably are related to the fact that measurements were made with 1 kHz rather than 1 MHz excitation.

Cable	Capacitance pf/ft
3	27
5	21.2
8	50.9
6B	56.3

5. Flexure Test

A flexure test was conducted to determine if repeated flexing during insertion and retraction would degrade the BPN performance of the cables. The test consisted of a BPN test, then 100 cycles of flexure through 60 degrees of bend at a radius of 60 inches at room temperature and a repeat of the BPN test. Cables 3, 5, and 8 were subjected to this test and all passed successfully. They were then subjected to an additional 500 cycles and again all passed successfully.

The test setup was modified to provide for heating the cables to 650°C during flexing. Cables 3, 5, and 6B were subjected to this for 100 cycles and again all of them passed. At first it appeared that cable 6B had failed. However, the seals were removed, the ends outgassed and new seals added and the cable behaved normally again.

Figure A-17a. Cable Internal Resistance

Figure A-17b. Cable Internal Resistance

6. Breakdown Voltage

Cables 3, 5, 6B, 7B, and 8 were tested to determine breakdown voltage as a function of temperature. As shown by Figures A-18, A-19, A-20, A-21, and A-22, all of these cables are acceptable in the voltage range of interest.

A5. DISCUSSION

1. Bakeout

The samples tested for performance at 650°C were baked at 750°C for a minimum of 4 hours prior to test. It was found that baking the ends only, approximately 1 foot, provided performance as good as if the entire cable was baked. However, it is apparent that different cables outgas at different rates. That is, the gas transmission through the dielectric varies, so the same schedule is not necessarily suitable for all cables. The best performance was obtained when open-ended cables were air baked and then glass seals added while the cable was still hot.

It is probable that a more thorough outgassing procedure followed by controlled backfill and seal off will result in improved performance insofar as BPN and room temperature insulation resistance are concerned. This should become possible with the development of a "quiet" seal.

2. Seals

Two types of standard product ceramic-to-metal seals were used to terminate cables and, as reported by others, it was found that the seal zone was a source of BPN at high temperature. Whether the noise source was the seal itself, interfaces within the termination, or gas pockets was not determined in this phase of the investigation. Seals which did not cause BPN were made using Corning 7574 glass frit. The frit was placed in the end of a thoroughly baked cable and fused to the cable dielectric, sheath, and center wire so that no voids existed. These were intended as temporary seals for test purposes. Because of the poor thermal expansion match with the metal components the glass invariably cracked after removal from the furnace and the cable performance would degrade in time. Because of this it was decided to use Corning 7570 glass frit to make seals. This provided a reliable seal; however, it would not withstand the 650°C test temperature and it was concluded that a thorough evaluation of sealed ends would have to await the development of a suitable seal. This development is proceeding as a parallel effort.

Figure A-18. Cable 3 Current Leakage

Figure A-19. Cable 5 Current Leakage

Figure A-20. Cable 8 Leakage Current

Figure A-21. Cable 6B Current Leakage

Figure A-22. Cable 7B Current Leakage

3. Failures

Since this program is aimed at the eventual procurement and qualification of reliable cables which will perform in the LMFBR source range detector, there are more factors involved than just satisfactory BPN performance. First, if the cable is not mechanically reliable and cannot be fabricated into an assembly without causing serious problems during or after assembly, the electrical performance is of no consequence. For this reason, the cables from manufacturers D and E were considered to be not acceptable. The small center wire of the cable from manufacturer E, which is badly battered in the swaging operation, is very fragile. It was difficult to expose the center wire without breaking it, and was even more troublesome to attach leads to perform tests. Experience has shown that even 0.020-inch diameter center wires can be easily broken and therefore it was decided that the cable with a 0.012-inch center wire would not provide for a reliable assembly and was not acceptable. The outer sheath of the cable from manufacturer D was not well bonded to the copper inner sheath and easily slid off when the cable was cut into short pieces. It was feared that in detector assemblies differential expansion might cause relative movement between the inner and outer sheaths resulting in either cracked seals, electrical shorts, or creation of voids which might contribute to BPN. Also, this cable at 0.209-inch o.d. is too rigid for the application.

As mentioned earlier, the cable from manufacturer C was found to have a loop in the center wire and zones of dark, low-resistance insulation. The loop is obviously a mechanical fabrication problem which can be corrected in the manufacturing operation. The insulator problem is somewhat more difficult to resolve. The manufacturer stated that he had received unsatisfactory ceramics from one supplier and was trying to expedite an order from another supplier. A second batch of cable recently received from this vendor looks much better. The BPN performance is comparable to other cables, and other parameters look acceptable. Room temperature insulation resistance is 2×10^{12} ohm-ft and the 650°C insulation resistance, 7×10^7 ohm-ft, was comparable to the other cables.

4. Noise

It was extremely difficult to eliminate the sources of noise which influenced the BPN tests. Initially it was found that an office copying machine as well as other items of office equipment had a pronounced effect on the test. The test setup was moved to another building and it was found that the proximity to vacuum pumps and welders was intolerable. A third move to a better shielded section of the same building provided relative freedom from external noise. However, periodically noise enters the system through 220-volt power cables, ground, or by radiation, and has not been completely eliminated.

A6. CONCLUSIONS

It is obvious that development of a cable suitable for use with an LMFBR source range detector is no simple task; however, this evaluation leads to the conclusion that either silica- or magnesia-insulated cables can perform adequately provided certain other attributes are present. These include but are not necessarily limited to the following:

- a. The cable must be constructed so as to minimize breakdown pulse noise. While no proof is offered it is generally accepted that high compaction of the dielectric is necessary along with the elimination of defects such as crevices or voids.
- b. The cable must be well outgassed.
- c. The cable must provide adequate shielding from external noise.
- d. There must be a reliable seal provided at each end which will maintain the cable integrity during use and which will not contribute to the noise.
- e. The cable must have good pulse transmission characteristics. This was a prerequisite for all the candidate cables and is determined by material geometry.
- f. The cable must be constructed so that with normal use, including whatever flexure may be required, the mechanical integrity of the dielectric and conductors will be maintained.

The lower dielectric constant of silica permits a smaller diameter cable with a larger center wire than is possible with magnesia and, since this is desirable for mechanical consideration, it appears that silica cable is a better choice than magnesia assuming equality in BPN characteristics and realistic tradeoffs in cost.

Existing cable end seals are not acceptable because of their contribution to breakdown pulse noise. However, it is felt that this contribution is primarily from the interface between the cable dielectric and seal rather than the seal itself. An acceptable solution to the seal problem would probably involve a cable termination in which no voids exist or at least where there is no optical path between the conductors.

While it was possible at times to apply as much as 1000 volts at 650°C without reaching the BPN threshold, the same cable might reach the BPN threshold at lower voltages at other times depending on the seal condition and whether or not the cable dielectric was still dry. It appears that with reasonable outgassing it is possible to use the cables at 400 volts minimum while at 650°C without reaching the BPN threshold. This is in accord with the goal of developing a fission counter to operate at voltages less than 400 volts.

REFERENCES

- A-1 Hoitink, N. C., Jackson, C. N., and Thompson, D. C., Performance Characteristics of Commercially Available Neutron Detection System, Hanford Engineering Development Laboratory, January 12, 1972, (HEDL-TME-72-47).
- A-2 Roux, D. P., Ricker, C. W., and DeLorenzo, J. T., *A Neutron Detection System for Operation in Very High Gamma Fields*, (ORNL-TM-2693).
- A-3 Wimpee, L. C., *State of the Art Review for LMFBR Source Range Fission Counter*, General Electric Co., July 1972, (GEAP-10611).
- A-4 *Testing of High Temperature Cable for Nuclear Detectors*, August 1971, (RDT Standard F3-39T).

APPENDIX B

AN ANALYTICAL STUDY OF THE PERFORMANCE OF A CONCEPTUAL DESIGN SOURCE RANGE MONITORING SYSTEM FOR AN LMFBR DEMONSTRATION PLANT (INTERIM REPORT)

B1. INTRODUCTION

This report presents the results of an analytic study as applied specifically to the current conceptual design of a source range monitor (SRM) system for a typical LMFBR demonstration plant.

The analytic techniques developed are general enough to predict the performance of an arbitrarily designed SRM system located in an arbitrary neutron and gamma field, and will be used to optimize the system design.

Analysis of system performance is performed by several computer programs developed for this study, which use as their input the various system design parameters. The design parameters studied here are those that affect the neutron gamma and alpha sensitivity of the SRM system; and fall broadly into five categories: (1) detector geometry, (2) uranium coating, (3) fill gas, (4) cable pulse transmission, and (5) electronics. The report describes explicitly how these input parameters are handled and how results for other system designs can be obtained.

B2. SUMMARY

A summary of the analytic results for the LMFBR SRM conceptual design is given in Table B-1. The results are described in terms of the expected neutron count rates for three different locations in the LMFBR corresponding to three different neutron and gamma field conditions. The values of the fission rates and gamma fields at these locations were obtained from shielding calculations.

Table B-1
ANALYTICAL RESULTS SUMMARY

Reactor Parameters			Parameters Affecting Detector Neutron Sensitivity			
Location	Gamma Field (R/h)	U-235 Fission Rate per gm U-235 at Shutdown (fissions/s)	Detector Fission Rate (fissions/s)	Discriminator (volts)	Probability Factor	Neutron Count Rate (cps)
1.Vessel Shield	0.535×10^6	8.25	$7.66 \pm 200\%$	$0.24 \pm 13\%$	$0.61 \pm 25\%$	$4.66 \pm 200\%$
2.Radial Shield	8.59×10^6	140	$131.0 \pm 200\%$	$0.94 \pm 13\%$	$0.11 \pm 40\%$	$14.4 \pm 200\%$
3.Vessel Shield with Na window	0.535×10^6	24.75	$23.0 \pm 200\%$	$0.24 \pm 13\%$	$0.61 \pm 25\%$	$14.0 \pm 200\%$

The detector fission rates are accurate to about a factor of 2. Assuming no electronic noise the discriminator volts are accurate to within $\pm 13\%$ which corresponds to the indicated uncertainties in the probability factor. The net uncertainty in neutron count rate is about a factor of 2 due to the large uncertainty in the fission rate.

The discriminator settings shown in Column 5 are not important on the absolute scale, but reflect the levels of discrimination necessary to reduce the alpha and gamma noise counts to an insignificant fraction of the neutron counts. For each of these settings the neutron sensitivity probability factor, defined to give the neutron count when multiplied by the fission rate, and calculated in the body of this report, is shown in Column 6.

In all three positions the neutron sensitivity is gamma-limited for the current design. The alpha count is quite high for discriminator voltages up to approximately 0.23 volt corresponding to the maximum single alpha pulse height, but drops abruptly to a negligible value for higher settings due to virtually no pileup. Thus the discriminator settings of 0.24 and 0.94 volt necessary to discriminate against the gamma fields shown above, automatically discriminate adequately against the alpha counts.

In Position 2 the neutron flux is higher, but the gamma flux is higher, too, and discrimination against these gamma counts requires the discriminator to be set at 0.94 volt where the probability factor is only 0.11. Thus even though the fission rate is six times higher than Position 3, the neutron count rate is about the same, showing the penalty that must be paid for discriminating against the higher gamma field. These high discriminator settings correspond to the steeply declining portion of the integral neutron pulse height spectrum, where small changes in the gamma field can result in large changes in neutron sensitivity. Thus, it appears that this detector should not be operated in Position 2 even though the neutron count rate is about the same as in Positions 1 or 3.

All the above calculations assume no significant counts from either noise pickup in the detector and cable, breakdown pulse noise in the cable, or electronic noise. It should be cautioned that if the count rate due to these noise sources is significant, the neutron count rates will be significantly below the values shown.

B3. DESIGN PARAMETERS

The basic system configuration is a detector with concentric cylinder electrode configuration, coated on one or both of the electrodes, connected by a cable to a preamplifier operated in the current mode (when input impedance equals the characteristic impedance of the cable), and then an amplifier and discriminator. The circuit is shown in Figure B-1.

The design parameters for the conceptual design SRM system are outlined below.

Detector

No. of gaps = 2
 i.d., o.d., length of first gap = 1.32, 1.40, and 4.03 in.
 i.d., o.d., length of second gap = 1.50, 1.58, and 4.26 in.
 Capacitance = 212.6 pF
 Gas = argon + 10% N₂
 Pressure = 2 atm at 75°F, Density = 3.45×10^{-3} gm/cc
 ionization energy = 28.5 eV
 Uranium coating = 2 mg/cm², on both i.d. and o.d. of both gaps
 U-235 enrichment = 93.0%
 U-234 content = 0.03% of U-235 content
 Coated surface area = 500 cm²
 Coating density = 6 gm/cc

Cable

Sheath o.d. = 0.160 in.
 Sheath i.d. = 0.120 in.
 Center conductor = 0.020-in. diameter copper
 Resistance of center conductor = 0.0725 ohms/ft at 500°C
 Cable capacitance = 40 pF/ft
 Leakage resistance = 3.3×10^9 ohms/ft
 Terminating resistor = 50 ohms

EQUIVALENT CIRCUIT OF DETECTOR, CABLE, PREAMPLIFIER INPUT

Figure B-1. Schematic of SRM Circuit

Electronics

Preamplifier rise time < 5 nsec

Amplifier time constant < 1 nsec

Voltage gain = 10,660 (important only for absolute pulse heights, and not for relative neutron, gamma, or alpha pulse heights).

Operating Parameters

Detector voltage = 200 volts

Electron collection time = 34.4 nsec

B4. RESULTS

Pulse Shape

An ionizing particle (fission fragment, Compton electron or alpha) passing through the gas gap and causing ionization along its entire track, produces a current pulse in the detector output circuit. Neglecting detector capacitance, it can be shown that this pulse is triangular, starting at some maximum value at time zero when all the electrons* in the track start drifting towards the positive electrode and becoming zero at time T equal to the electron collection time when all the electrons are collected. The detector capacitance, however, distorts this pulse so that the pulse actually entering the cable has a finite rise time, has a smaller peak and is broader than the original triangular one. The shape of the pulse and the distortion effect of the detector capacitance can be studied by a program DETPULSE, which calculates the pulse voltage as a function of time using the detector geometry as input. A typical fission fragment track length equal to 3.5 times the gap is used to calculate the typical neutron pulse voltage. From the pulse magnitude point of view DETPULSE describes a typical neutron pulse, but since the pulse shape is independent of ionizing particles, it can be used to study gamma and alpha pulses. DETPULSE is primarily a diagnostic program which can be used to evaluate design alternatives by comparing their typical neutron pulses.

Results from DETPULSE for the detector design analyzed here are shown in Table B-2 and Figure B-2. The results show that the peak is reduced by about a factor of two, and the width increased by almost a factor of two, due to the detector capacitance. However, the typical neutron pulse height of $440 \mu\text{V}$ is still well above the expected noise level of the few μV (at amplifier input), and the pulse width of ~ 70 nsec is still short enough to where gamma pileup at gamma fields 10^6 R/h is not too severe.

The DETPULSE calculations assume perfect cable pulse transmission properties for the frequencies of interest, i.e., no pulse distortion by the cable. This assumption is substantiated by previous GE calculations of how the cable attenuates the various frequencies in the pulse, and a new computer program, PULSPWR, which calculates what fraction of the total pulse energy is carried in these frequencies. In the PULSPWR calculation, the frequency content of the detector pulse was calculated by doing a Fourier analysis of the detector pulse and obtaining its power spectral density as a function of frequency. This was then numerically integrated between the frequencies 0 and f and normalized with respect to the total pulse energy to get the fraction of pulse energy between 0 and f .

The results from PULSPWR are given in terms of the differential and integral power spectrum of the detector pulse. The integral spectrum gives the fraction of the total pulse power that is contained between the frequencies 0 and f , for various values of f ; and the differential spectrum is its derivative which gives the power per f for various values of f . Results from PULSPWR are given in Table B-3 and Figure B-3 for the current detector design, and show that 95% of the power is contained in the frequency band 0 to 23 MHz. Since cable attenuation is less than 20% for these frequencies it can be concluded that the detector pulse is not seriously distorted by the cable.

*The positive ion current is neglected in comparison with the electron current since the drift velocity of positive ions is much smaller than that for electrons.

Table B-2
Results from DETPULSE

*OLD DETPULSE
READY
*RUN

PULSE FROM CYLINDRICAL DETECTOR

ELECTRON COLLECTION TIME (NSECS) = 34.4
TERMINATING RESISTOR (OHMS) = 50
NUMBER OF ACTIVE VOLUMES = 2

VOLUME NO. -----	ID(IN) -----	OD(IN) -----	LENGTH(IN) -----	CAP.(PFDS) -----
1	1.32	1.4	4.03	96.74931
2	1.5	1.58	4.26	115.8142

TOT. CAPACITANCE (PFDS) = 212.5635

AVERAGE GAP (MILS) = 40

GAS PRESSURE (ATM) = 2
GAS TYPE FACTOR Z = 1
IONIZATION ENERGY W (EV) = 28.5
TYPICAL NEUT PULSE HT WITH 0 CAPAC (UVOLTS) = 214.1983

TIME/EC TIME -----	TIME(NSECS) -----	OUTPUT(UVOLTS) -----	NORM TO MAX -----	NORM TO PEAK -----
.05	1.72	31.1833	.1455814	.2628147
.1	3.44	56.10701	.2619396	.4728733
.15	5.16	75.70643	.3534408	.6380584
.2	6.88	90.7771	.4237994	.765075
.25	8.6	101.9957	.4761742	.8596261
.3	10.32	109.9378	.5132524	.9265625
.35	12.04	115.093	.5373197	.9700105
.4	13.76	117.8776	.5503199	.9934796
.45	15.48	118.6459	.5539069	.999955
.5	17.2	117.6992	.5494869	.9919759
.55	18.92	115.2936	.5382566	.9717019
.6	20.64	111.6473	.5212333	.9409703
.65	22.36	106.9455	.4992828	.9013435
.7	24.08	101.346	.4731412	.8541506
.75	25.8	94.98295	.4434347	.8005222
.8	27.52	87.97038	.410696	.7414198
.85	29.24	80.40536	.3753782	.6776614
.9	30.96	72.37044	.3378666	.6099425
.95	32.68	63.93583	.298489	.5388551
1	34.4	55.16124	.2575242	.4649023
1.25	43	24.5593	.1146569	.2069873
1.5	51.6	10.93448	.0510484	.0921565
1.75	60.2	4.868331	.0227281	.0410306
2	68.8	2.167515	.0101192	.0182679
2.25	77.4	.9650373	.0045053	.0081334
2.5	86	.4296612	.0020059	.0036212
2.75	94.6	.191297	.0008931	.0016123
3	103.2	.0851707	.0003976	.0007178
3.25	111.8	.0379203	.000177	.0003196
3.5	120.4	.0168832	7.88203E-05	
.0001423				

TIME TO PEAK (NSECS) = 15.34475
PEAK VOLTAGE (MICROVOLTS) = 118.6512

Table B-3
Results from PULSPWR

*RUN
= 34.4, 50, 212.56

PROGRAM STOP AT 0
*LIST OUT 6

POWER IN DETECTOR PULSE

ELECTRON COLLECTION TIME (NSEC) = 34.400
TERMINATING RESISTOR (OHMS) = 50.000
DETECTOR CAPACITANCE (PFDS) = 212.560

X (WT)	FREQUENCY (MEGAHERTZ)	DIFF PWR SPEC (FRAC ENGY/X)	INTEG PWR SPEC (FRAC EN 0-X)
-----	-----	-----	-----
2.3750E-01	1.0986E+00	3.8788E-01	9.2906E-02
4.8750E-01	2.2551E+00	3.7749E-01	1.8859E-01
7.3750E-01	3.4116E+00	3.6079E-01	2.8078E-01
9.8750E-01	4.5680E+00	3.3895E-01	3.6807E-01
1.2375E+00	5.7245E+00	3.1335E-01	4.4935E-01
1.4875E+00	6.8810E+00	2.8540E-01	5.2388E-01
1.7375E+00	8.0375E+00	2.5643E-01	5.9125E-01
1.9875E+00	9.1939E+00	2.2756E-01	6.5138E-01
2.2375E+00	1.0350E+01	1.9967E-01	7.0441E-01
2.4875E+00	1.1507E+01	1.7338E-01	7.5067E-01
2.7375E+00	1.2663E+01	1.4912E-01	7.9064E-01
2.9875E+00	1.3820E+01	1.2712E-01	8.2485E-01
3.2375E+00	1.4976E+01	1.0746E-01	8.5387E-01
3.4875E+00	1.6133E+01	9.0114E-02	8.7831E-01
3.7375E+00	1.7289E+01	7.4990E-02	8.9871E-01
3.9875E+00	1.8446E+01	6.1943E-02	9.1562E-01
4.2375E+00	1.9602E+01	5.0800E-02	9.2954E-01
4.4875E+00	2.0759E+01	4.1375E-02	9.4091E-01
4.7375E+00	2.1915E+01	3.3480E-02	9.5014E-01
4.9875E+00	2.3072E+01	2.6929E-02	9.5758E-01
5.2375E+00	2.4228E+01	2.1548E-02	9.6355E-01
5.4875E+00	2.5384E+01	1.7173E-02	9.6832E-01
5.7375E+00	2.6541E+01	1.3654E-02	9.7211E-01
5.9875E+00	2.7697E+01	1.0856E-02	9.7513E-01
6.2375E+00	2.8854E+01	8.6583E-03	9.7753E-01
6.4875E+00	3.0010E+01	6.9544E-03	9.7945E-01
6.7375E+00	3.1167E+01	5.6510E-03	9.8100E-01
6.9875E+00	3.2323E+01	4.6680E-03	9.8227E-01
7.2375E+00	3.3480E+01	3.9367E-03	9.8333E-01
7.4875E+00	3.4636E+01	3.3994E-03	9.8424E-01
7.7375E+00	3.5793E+01	3.0082E-03	9.8503E-01
7.9875E+00	3.6949E+01	2.7238E-03	9.8575E-01
8.2375E+00	3.8106E+01	2.5147E-03	9.8640E-01
8.4875E+00	3.9262E+01	2.3561E-03	9.8700E-01
8.7375E+00	4.0419E+01	2.2290E-03	9.8757E-01
8.9875E+00	4.1575E+01	2.1194E-03	9.8812E-01
9.2375E+00	4.2731E+01	2.0175E-03	9.8863E-01
9.4875E+00	4.3888E+01	1.9168E-03	9.8912E-01
9.7375E+00	4.5044E+01	1.8133E-03	9.8959E-01
9.9875E+00	4.6201E+01	1.7054E-03	9.9003E-01

TOT PULSE ENERGY/TOT PULSE ENERGY FOR 0 DET. CAPAC = 0.61031

Figure B-2. Detector Pulse Shape

Figure B-3. Integral Power Spectrum of Detector Pulse

Neutron Pulse Height Analysis

The neutron integral pulse height spectrum was calculated by TSS FORTRAN programs NSPEC and NNSPEC for the uranium coating on the outer and inner cylinders, respectively. These programs obtain the distribution of pulse heights for fission fragments emitted in various directions, taking into account the energy loss in the uranium coating and treating the light and heavy fragments separately rather than as an average. Results from NSPEC and NNSPEC are shown in Figure B-4. The X axis represents the pulse height V_O (volts) and the discriminator, and the Y axis is the probability $P(V_O)$ that neutron pulses will be larger than V_O . Actually, the programs NSPEC and NNSPEC give the pulse height in terms of the number of electrons produced per fission fragment track which is a function only of the detector design variables. The conversion of pulse height to volts at the discriminator was achieved by a TSS BASIC program NOVOLT. The NOVOLT calculation takes a pulse produced by a certain number of electrons per track in the detector and calculates the pulse peak in volts at the discriminator input, taking into account the amplifier gain and the pulse distortion by two time constants – the detector time constant and an effective amplifier time constant. A new program, XPULSE, has recently been completed which can handle up to four time constants, but that has not been described here.

The expected neutron count rate $C_n(V_D)$ for any discriminator setting (V_D) can then be obtained by multiplying the probability $P(V_D)$ by the fission rate FR. Thus $C_n(V_D) = FR \cdot P(V_D)$.

Since the detector being analyzed is coated equally on both the inner and outer surfaces, the average pulse height spectrum (dashed line in Figure B-4) and the total fission rate in the detector can be used to give the count rate. Thus if the discriminator is set at 0.24 volt, the corresponding probability factor will be 0.61 and if the fission rate is 23 fissions per second the expected count rate will be only 70% of the fission rate, which implies that 30% of the fragments directed towards the gap are absorbed in the coating and never get out.

Figure B-4. Neutron Pulse Height Spectrum

The computer outputs of NSPEC, NNSPEC and NOVOLT from which Figure B-4 was obtained, are shown in Tables B-4, B-5, and B-6.

Gamma Pileup Analysis

The gamma pulses result from the passage of Compton electrons through the gas gap. Individually these pulses are quite small, but piled up they can interfere with neutron pulses to a degree that depends on the gamma field. The gamma pulse pileup calculation was done by a TSS FORTRAN program GSPEC. The calculation treats the piled up gamma signal as noise and uses the statistical formulae of Rice* and Neisselt† to find the rate at which this noise signal exceeds an arbitrary discriminator setting. This statistical treatment requires the values of pulse rate and average energy per pulse. GSPEC calculates the former by calculating the mean charge per pulse and the latter by calculating the mean square charge per pulse for Compton electrons emitted in arbitrary directions in the gas gap. Results of this analysis for the present system are shown in Table B-7. The program calculates the piled up gamma count rate for zero discriminator setting, and the discriminator setting needed to get gamma count rates of 1 cps and 0.1 cps. These values were chosen because they represent a gamma count rate significantly less than the 10 cps required nominally for the neutron count rate at reactor shutdown.

The results show that for a gamma field of 10^6 R/hr, the discriminator would have to be set at 0.32 volt to get 1 cps for the same electronic gain of 10,660 used to get the neutron pulse height distribution shown in Figure B-4. At this discriminator setting the neutron count rate would be 57% of the fission rate.

GSPEC results for gamma fields of 5.35×10^5 R/h and 8.59×10^6 R/h are shown in Tables B-8 and B-9.

Alpha Pulse Height Analysis

The alpha pulses result from the passage of alpha particles (emitted during U-234 decay) through the gas gap. The U-234 is usually present as an impurity in the U-235-enriched coating. The alpha pulses are several thousand times larger than the gamma pulses but individually are still a factor of ~ 20 less than the neutron pulses. However, the alpha pulse rate is much larger than the neutron pulse rate for low fluxes, so that these alpha pulses must be discriminated against to a point where even overlapped pulses do not interfere with the neutron counts. The alpha pulse height distribution and pulse rate were calculated by TSS FORTRAN programs ASPEC and AASPEC for uranium coatings on the outer and inner cylinder, respectively. This calculational procedure was the same as for the neutron pulse height analysis, except that the energy loss in the coating and gas is different for alphas than for fission fragments, and there is only one alpha per decay event instead of the two fission fragments per fission event.

The alpha pulse height distribution from ASPEC and AASPEC is in terms of number of electrons per alpha track, which can be converted to volts at the discriminator by NOVOLT just as in the case of the neutron pulse height distribution from NSPEC and NNSPEC. In fact, for the same detector, cable, and electronics the conversion factor is the same for the alpha and neutron cases.

Results from ASPEC, AASPEC, and NOVOLT for the present system are shown in Figure B-5 and Tables B-10 and B-11. Once again for a detector coated equally on both the inner and outer electrodes, the alpha count rate can be calculated from the average (dashed line) of the ASPEC and AASPEC distributions. These results show that if the discriminator is set at 0.025 volt the probability of getting single alpha counts larger than that is 0.075. Thus, for an alpha generation rate of 6.84×10^4 alpha per second corresponding to a U-234 content of 0.0003 gm for the present case, the alpha count rate for a discriminator setting of 0.025 volt is

$$C_{\alpha}(0.025V) = 6.84 \times 10^4 \times 0.075 = 5120 \text{ cps}$$

assuming no pulse overlap. At a discriminator setting of 0.2289 volt which is the maximum pulse height (corresponding to a loss of the entire 4.75 MeV alpha energy in the gas), the count rate is ~ 18.5 cps, assuming no pulse overlap.

*Rice, S. O. "Mathematical Analysis of Random Noise," from selected papers on *Noise & Stochastic Processes*, 133–294; Dover Publications, 1954.

†DuBridge, R. A., Neissel, J. P., et al., *Reactor Control Systems Based on Counting and Cambelling Techniques*, July 1965, (GEAP-4900).

Table B-4
Results from NSPEC

SYSTEM ?FORT
OLD OR NEW-OLD NSPEC
READY
*RUN
M 4.25,1450,40,.5,28.5,3.45E-3,2.6,0

PROGRAM STOP AT 0
*LIST OUT

NEUTRON PULSE HEIGHT DISTRIBUTION IN A CYLINDRICAL CHAMBER
COATED ON INSIDE OF OUTER TUBE ONLY. END EFFECTS NEGLECTED

LENGTH (IN) = 4.25 ANODE DIAM (MILS) =1450.0 GAP (MILS) = 40.0

FRAC DIST ABOVE BOTTOM = .500

IONIZATION ENERGY W (EV) = 28.50 GAS DENSITY (GM/CC) = 3.450E-03
COATING THICKNESS(MG/CM2) =2.00 COATING DENSITY (GM/CC) = 6.00

TOTAL PROBABILITY = 0.44421

DESCR. (VD) VOLTS FROM NOVOLT	DISCR.(VD) (NO. ELEC)	INTEG PROB (TOTAL)
-----	-----	-----
0.	0.	6.550E-01
0.236	1.719E+05	5.827E-01
0.472	3.439E+05	4.632E-01
0.708	5.158E+05	2.311E-01
0.944	6.877E+05	1.210E-01
1.180	8.596E+05	7.487E-02
1.416	1.032E+06	4.961E-02
1.652	1.204E+06	3.605E-02
1.888	1.375E+06	2.625E-02
2.125	1.547E+06	2.090E-02
2.361	1.719E+06	1.634E-02
2.597	1.891E+06	1.257E-02
2.833	2.063E+06	9.525E-03
3.069	2.235E+06	7.082E-03
3.305	2.407E+06	4.654E-03
3.541	2.579E+06	3.457E-03
3.777	2.751E+06	2.763E-03
4.013	2.923E+06	2.339E-03
4.249	3.095E+06	1.994E-03
4.485	3.267E+06	1.643E-03

READY

*

Table B-5
Results from NNSPEC

DATA SAVED--NNSPEC

*RUN

= 4.25, 1450, 40, .5, 28.5, 3.45E-3, 2, 6, 0

PROGRAM STOP AT 0

*LIST OUT

NEUTRON PULSE HEIGHT DISTRIBUTION IN A CYLINDRICAL CHAMBER
COATED ON OUTSIDE OF INNER TUBE ONLY. ENDEFFECTS NEGLECTED

LENGTH (IN) = 4.25 ANODE DIAM (MILS) = 1450.0 GAP (MILS) = 40.0

FRAC DIST ABOVE BOTTOM = .500

IONIZATION ENERGY W (EV) = 28.50 GAS DENSITY (GM/CC) = 3.450E-03
COATING THICKNESS(MG/CM2) = 2.00 COATING DENSITY (GM/CC) = 6.00

TOTAL PROBABILITY = 0.49675

DISCR. (VD) VOLTS FROM NOVOLT	DISCR. (VD) (NO. ELEC)	INTEG PROB (TOTAL)
0.	0.	7.408E-01
0.236	1.719E+05	6.659E-01
0.472	3.439E+05	4.405E-01
0.708	5.158E+05	2.005E-01
0.944	6.877E+05	9.441E-02
1.180	8.596E+05	5.135E-02
1.416	1.032E+06	2.727E-02
1.652	1.204E+06	1.789E-02
1.888	1.375E+06	1.235E-02
2.125	1.547E+06	9.205E-03
2.361	1.719E+06	6.556E-03
2.597	1.891E+06	4.601E-03
2.833	2.063E+06	2.875E-03
3.069	2.235E+06	2.094E-03
3.305	2.407E+06	1.314E-03
3.541	2.579E+06	1.103E-03
3.777	2.751E+06	8.913E-04
4.013	2.923E+06	7.469E-04
4.249	3.095E+06	6.024E-04
4.485	3.267E+06	3.973E-04

READY

*

Table B-6
Results from NOVOLT

*RUN

CONVERSION OF PULSE HEIGHT FROM
NO. OF ELECTRONS/TRACK TO VOLTAGE AT DISCRIMINATOR

VOLTAGE GAIN = 10660 , ELEC COLLEC TIME (NSEC) = 34.4
N. IMP./TERM. RES(OHMS) = 50 , DET. CAPAC (PFD) = 212.56
DET. TIME CONST (NSEC) = 10.628 , AMP. TIME CONST (NSEC) = -1

#ELECTR/TRACK	DISCR.(VOLTS)
-----	-----
1000000	1.373244

READY
*

Table B-7
Results from GSPEC $\phi_\gamma = 10^6$ R/hr

*RUN

= 4.25, 1450, 40, .5, 28.5, 3.45E-3, 50, 1.066E4, 34.4, -1.2E-11, 1E6
= 1.5, 3, 212.56

HTD-1

PROGRAM STOP AT 0
*LIST OUT3

GAMMA/ALPHA PULSE PILEUP CALCULATION

LENGTH(IN)= 4.25 ANODE DIAM (MILS) =1450.0 GAP (MILS) = 40.0
FRAC DIST ABOVE BOTTOM =.500

	CATH. EMIT ANOD. HITS	CATH. EMIT CATH. HITS	ANOD. EMIT CATH. HITS	AVERAGE
PROBALITY	7.874E-01	1.689E-01	9.908E-01	9.736E-01
AVGE R (IN)	7.685E-02	2.970E-01	8.075E-02	2.273E-01
AV R ² (IN ²)	1.533E-02	5.357E-01	1.281E-02	2.819E-01

TERM RES (OHMS) = 50.00 AMP GAIN = 10660.00
ELEC COLLEC TIME (NSEC) = 34.40 DET CAPAC (PFDS) =212.56
DET TIME CONST (NSEC) = 10.63 CKT TIME CONST (NSEC) = -1.00
IONIZATION ENERGY W (EV) =28.50 GAS DENSITY (GM/CC) = 3.450E-03
DE/DX FOR COMPT ELEC (MEV.CM²/GM) = 1.500E+00
GAMMA SENSITIVITY (AMPS/R/HR) = 2.000E-11 GAMMA FLUX (R/HR) = 1.000E+06
RISE TIME OF ELECTRONICS (NSEC) = 3.000E+00

AVERAGE CHARGE (COUL) = 1.6798E-17
PULSE RATE (1/SEC) = 1.1906E+12
SIGMA² (VOLTS²) = 3.0798E-03
FACTOR Z = 2.0344E-01
COUNT RATE AT ZERO DISCR (CPS) = 1.9037E+07
DISC VOLTAGE TO GET 1 CPS (VOLTS) = 3.2132E-01
DISC VOLTAGE TO GET 0.1 CPS (VOLTS) = 3.4268E-01

READY

Table B-8
Results from GSPEC $\phi_\gamma = 5.35 \times 10^6$ R/hr

SYSTEM ?FORT
OLD OR NEW-OLD GSPEC
READY
*RESEQUENCE HTD-1
*RESAVE GSPEC
DATA SAVED--GSPEC
*RUN
= 4.25, 1450, 40, .5, 28.5, 3.45E-3, 50, 1.066E4, 34.4, -1, 2E-11, .535E6
= 1.5, 3, 212.56

PROGRAM STCP AT 0
*PERM OUT HAHA
SUCCESSFUL!

*LIST HAHA

GAMMA PULSE PILEUP CALCULATION

LENGTH(IN)= 4.25 ANODE DIAM (MILS) =1450.0 GAP (MILS) = 40.0

FRAC DIST ABOVE BOTTOM =.500

	CATH. EMIT ANOD. HITS	CATH. EMIT CATH. HITS	ANOD. EMIT CATH. HITS	AVERAGE
PROBABILITY	7.874E-01	1.689E-01	9.908E-01	9.736E-01
AVGE R (IN)	7.685E-02	2.970E-01	8.075E-02	2.273E-01
AV R ² (IN ²)	1.533E-02	5.357E-01	1.281E-02	2.819E-01

TERM RES (OHMS) = 50.00 AMP GAIN = 10660.00
ELEC COLLEC TIME (NSEC) = 34.40 DET CAPAC (PFDS) =212.56
DET TIME CONST (NSEC) = 10.63 CKT TIME CONST (NSEC) = -1.00
IONIZATION ENERGY W (EV) =28.50 GAS DENSITY (GM/CC) = 3.450E-03
DE/DX FOR COMPT ELEC (MEV.CM²/GM) = 1.500E+00
GAMMA SENSITIVITY (AMPS/R/HR) = 2.000E-11 GAMMA FLUX (R/HR) = 5.350E+05
RISE TIME OF ELECTRONICS (NSEC) = 3.000E+00

AVERAGE CHARGE (COUL) = 1.6798E-17
PULSE RATE (1/SEC) = 6.3698E+11
SIGMA² (VOLTS²) = 1.6477E-03
FACTOR Z = 2.0344E-01
COUNT RATE AT ZERO DISCR (CPS) = 1.9037E+07
DISC VOLTAGE TO GET 1 CPS (VOLTS) = 2.3503E-01
DISC VOLTAGE TO GET 0.1 CPS (VOLTS) = 2.5065E-01

READY

Table B9

Results from GSRHC $\phi_{\gamma} = 8.59 \times 10^6$ R/hr

*RDN
 = 4.25, 1450, 40, .5, 22, .5, 3.45E-3, 50, 1.06684, 34.4, -1.2E-11, 8.59E6
 = 1.5, 3, 212.56

PROGRAM STOP AT 0

HTD-1

*LIST OUT

GAMMA PULSE PILEUP CALCULATION

LENGTH(D)= 4.25 ANODE DIAM (CMLS) =1450.0 GAP (CMLS) = 40.0

FRAC DIST ABOVE BOTTOM =.500

	CATH. HMIT ANOD. HITS	CATH. HMIT CATH. HITS	ANOD. HMIT CATH. HITS	AVERAGE
PROBABILITY	7.874E-01	1.689E-01	9.908E-01	9.736E-01
AVER R (C/D)	7.685E-02	2.970E-01	8.075E-02	2.273E-01
AV R*2(XIN2)	1.533E-02	5.357E-01	1.350E-02	2.819E-01

THIN RES (CMFS) = 50.00 AMP GAIN = 10660.00
 HLRC COLLCT TIME (NSEC) = 34.40 DET CAPAC (PFDS) =212.56
 DET TIME CONST (NSEC) = 10.63 CRT TIME CONST (NSEC) = -1.00
 IONIZATION ENERGY W (eV) =22.50 GAS DENSITY (GM/CC) = 3.450E-03
 INDIX FOR COMPT HLRC (SEU-CMB/CM) = 1.500E+00
 GAMMA SENSITIVITY (CMPS/R/HR) = 2.000E-11 GAMMA FLUX (R/HR) = 8.590E+06
 RISE TIME OF ELECTRONICS (NSEC) = 3.000E+00

AVERAGE CHARGE (COUL) = 1.6798E-17
 PULSE RATE (1/SEC) = 1.0827E+13
 SIGMA*2 (VOLTS*2) = 2.6455E-02
 FACTOR Z = 2.0344E-01
 COUNT RATE AT ZERO DISCR (CPS) = 1.9037E+07
 DISC VOLTAGE TO GET 1 CPS (VOLTS) = 9.4175E-01
 DISC VOLTAGE TO GET 0.1 CPS (VOLTS) = 1.0044E+00

READY

*ERE

11 TEMPORARY FILES CREATED.

OUT ?

**RESOURCES USED \$ 5.66, USED TO DATE \$ 2129.39= 43%

**TIME STOPPING OFF AT 10-183 ON 06/30/72

Table B-10
Results from ASPEC

DATA SAVED--ASPEC

*OL00RUN

= 4.25, 1450, 40, .5, 28.5, 3.45E-3, 2, 6, 0, 1, 1000.03, 1

PROGRAM STOP AT 0

*LIST OUT

ALPHA PULSE HEIGHT DISTRIBUTION IN A CYLINDRICAL CHAMBER
COATED ON INSIDE OF OUTER TUBE ONLY. END EFFECTS NEGLECTED

LENGTH (IN) = 4.25 ANODE DIAM (MILS) = 1450.0 GAP (MILS) = 40.0

FRAC DIST ABOVE BOTTOM = .500

IONIZATION ENERGY W (EV) = 28.50 GAS DENSITY (GM/CC) = 3.450E-03

COATING THICKNESS(MG/CM2) = 2.00 COATING DENSITY (GM/CC) = 6.00

% U234 IN U = 0.03000 MASS OF U (GMS) = 1.00

ALPHA PULSE GENERATION RATE (1/SEC) = 6.840E+04

TOTAL PROBABILITY = 0.44421

DISCR (VD) VOLTS FROM NOVOLT	DISCR.(VD) (NO. ELEC)	INTEG PROB (TOTAL)
0.	0.	3.443E-01
0.0114	8.333E+03	2.907E-01
0.0229	1.667E+04	8.993E-02
0.0343	2.500E+04	4.442E-02
0.0458	3.333E+04	2.234E-02
0.0572	4.167E+04	1.403E-02
0.0687	5.000E+04	9.067E-03
0.0801	5.833E+04	6.753E-03
0.0915	6.667E+04	4.443E-03
0.103	7.500E+04	3.387E-03
0.114	8.333E+04	2.371E-03
0.126	9.167E+04	1.578E-03
0.137	1.000E+05	1.058E-03
0.149	1.083E+05	9.322E-04
0.160	1.167E+05	8.071E-04
0.172	1.250E+05	7.442E-04
0.183	1.333E+05	6.816E-04
0.195	1.417E+05	6.225E-04
0.206	1.500E+05	5.634E-04
0.217	1.583E+05	5.102E-04

READY

*

Table B-11
Results from AASPEC

DATA SAVED--AASPEC

*RUN

= 4.25, 1450, 40, .5, 28.5, 3.45E-3, 2, 6, 0, .03, 1

PROGRAM STOP AT 0

*LIST OUT\$

ALPHA PULSE HEIGHT DISTRIBUTION IN A CYLINDRICAL CHAMBER
COATED ON OUTSIDE OF INNER TUBE ONLY. ENDEFFECTS NEGLECTED

LENGTH (IN) = 4.25 ANODE DIAM (MILS) = 1450.0 GAP (MILS) = 40.0

FRAC DIST ABOVE BOTTOM = .500

IONIZATION ENERGY W (EV) = 28.50 GAS DENSITY (GM/CC) = 3.450E-03

COATING THICKNESS (MG/CM2) = 2.00 COATING DENSITY (GM/CC) = 6.00

% U234 IN U = 0.03000 MASS OF U (GMS) = 1.00

ALPHA PULSE GENERATION RATE (1/SEC) = 6.840E+04

TOTAL PROBABILITY = 0.49675

DISCR. (VD) VOLTS FROM NOVOLT	DISCR. (VD) (NO. ELEC)	INTEG PROB (TOTAL)
-----	-----	-----
0.	0.	4.036E-01
0.0114	8.333E+03	2.681E-01
0.0229	1.667E+04	9.491E-02
0.0343	2.500E+04	3.855E-02
0.0458	3.333E+04	1.741E-02
0.0572	4.167E+04	9.007E-03
0.0687	5.000E+04	4.806E-03
0.0801	5.833E+04	2.995E-03
0.0915	6.667E+04	1.681E-03
0.103	7.500E+04	1.200E-03
0.114	8.333E+04	7.758E-04
0.126	9.167E+04	5.185E-04
0.137	1.000E+05	3.667E-04
0.149	1.083E+05	3.251E-04
0.160	1.167E+05	2.836E-04
0.172	1.250E+05	2.610E-04
0.183	1.333E+05	2.384E-04
0.195	1.417E+05	2.211E-04
0.206	1.500E+05	2.038E-04
0.217	1.583E+05	1.748E-04

READY

Figure B-5. Alpha Pulse Height Spectrum

The calculation of count rate due to piled up alpha pulses is complicated. The alpha pulse rate is not high enough to use the method outlined for gamma pileup, and the use of Poisson's statistics is unwieldy due to the wide distribution in alpha pulse heights. An approximate analysis was carried out by dividing the alpha pulse height spectrum into 20 groups, and considering overlap of only two pulses using Poisson's statistics. The calculation was performed by a TSS FORTRAN program POISON, which takes the integral pulse height distribution from ASPEC and AASPEC, differentiates it and arranges the pulses in a 20-group structure. Then by using Poisson's statistics, POISON calculates the rate at which these pulses pile up (two at a time) to give a sum peak greater than a preselected discriminator setting taking into account the actual pulse shape. Results from POISON for the current design are given in Table B-12 and show that for the narrow pulses and small pulse rates of concern here, no significant pileup occurs. At a discriminator setting of 0.2294 volt, slightly above the maximum single pulse height of 0.2289 volt, the pulse rate is only 0.012 cps, well below the single pulse count rate of 18.5 cps at 0.2289 volt. This is because the single pulse count rate is dependent only on the alpha pulse generation rate, whereas for piled up pulses Poisson's statistics must be used and hence pulse width becomes an important factor. In fact if the pulse width was zero (delta pulse), the probability of pulse overlap would be zero, and the count rate above 0.2289 volt would be zero.

Table B-12
Results from POISON

DATA SAVED--POISON
*RUN

PROGRAM STOP AT 0
*LIST OUT7

ALPHA COUNT RATE
(DISC BETWEEN MAX AND TWICE MAX ALPHA PULSE HEIGHT)

COATING THICKNESS (MG/CM2) = 2.00

MASS OF U235 (GMS) = 1.000 % U234 IN U235 = 0.0300

TERM RES (OHMS) = 50.000 DET. CAPAC (PFDS) = 212.560

ELEC COLLEC TIME (NSEC) = 34.400 DET. RC TIME CONST (NSEC) = 10.628

MAX ALPHA PULSE HEIGHT (VOLTS) = 2.2887E-01

DISCRIMINATOR (VOLTS)	COUNT RATE (CPS)
-----	-----
2.294E-01	1.218E-02
2.507E-01	1.195E-03
2.782E-01	1.669E-04
3.058E-01	5.820E-05
3.333E-01	1.384E-05
3.609E-01	5.569E-06
3.884E-01	3.593E-06
4.160E-01	1.543E-06
4.435E-01	1.044E-06

READY

*

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