UNCLASSIFIED

OFFICIAL USE ONLY

BNWL-946

FAST FLUX
TEST FACILITY
PROJECT REPORT

4-

FFTF STATE-OF-THE-ART REPORT
FOR LOW LEVEL
NEUTRON FLUX INSTRUMENTATION

February 1969

AEC RESEARCH &
DEVELOPMENT REPORT

OFFICIAL USE ONLY

UNCLASSIFIED

INFORMATION CONCERNING USE OF THIS REPORT

~~PATENT STATUS~~

~~This document copy, as it is transmitted in advance of patent clearance, is made available in confidence solely for use in performance of work under contracts with the U. S. Atomic Energy Commission. This document is not to be published or its contents otherwise disseminated for purposes other than specified above before patent approval for such publication has been secured, upon request, from the Chief, Chicago Patent Group, U. S. Atomic Energy Commission, 9600 S. Cass Ave., Argonne, Illinois.~~

PRELIMINARY REPORT

This report contains information of a preliminary nature prepared in the course of work under Atomic Energy Commission Contract AT(45-1) 1830. This information is subject to correction or modification upon the collection and evaluation of additional data.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

PACIFIC NORTHWEST LABORATORY

RICHLAND, WASHINGTON

operated by

BATTELLE MEMORIAL INSTITUTE

for the

UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

UNCLASSIFIED

BNWL-946

3 3679 00061 2103

FFTF STATE-OF-THE-ART REPORT
FOR LOW LEVEL
NEUTRON FLUX INSTRUMENTATION

By

C. N. Jackson, Jr.

Control and Instrumentation Department
Systems and Electronics Division

Approved by

D L Condotta

February 1969

BATTELLE MEMORIAL INSTITUTE
PACIFIC NORTHWEST LABORATORY
Richland, Washington 99352

UNCLASSIFIED

1. ~~SECRET~~

2. ~~SECRET~~

TABLE OF CONTENTS

INTRODUCTION.	1
FUEL ELEMENT FAILURE DETECTION BY DELAYED NEUTRON MONITORING	1
Delayed Neutrons	2
Chalk River Systems	4
KAPL Systems	5
EBR-II System.	5
Neutron Detectors.	7
Delayed Neutron Monitor Summary	9
Advantages.	9
Disadvantages	10
LOW LEVEL NEUTRON FLUX INSTRUMENTATION	10
Low Level Neutron Instrumentation System Summary	14
Advantages.	14
Disadvantages	15
ACKNOWLEDGMENT	15
REFERENCES	16

FFTF STATE-OF-THE-ART REPORT
FOR LOW LEVEL
NEUTRON FLUX INSTRUMENTATION

C. N. Jackson, Jr.

INTRODUCTION

Operational control and safety systems for the FFTF reactor require sensitive neutron detector instrumentation channels exhibiting capability for sustained reliable service under relatively severe radiation and temperature environmental conditions. In the FTR, the 1200 °F sodium coolant, as activated during operation, causes a high gamma background environment (to 10^6 R/hr) significantly more severe than that encountered in other reactors. Thus, comprehensive developmental evaluation of detectors, electronics, and cables must be carried out to establish needed operational performance characteristics to insure the timely availability of reliable systems for the FTR. Typical required systems include those for failed fuel element monitoring and for startup control of the reactor.

This review, termed a state-of-the-art report, describes previous development and design activities and applications related to reactor startup neutron instruments and to delayed neutron monitors for determining failure of cladding of fuel elements.

FUEL ELEMENT FAILURE DETECTION BY DELAYED NEUTRON MONITORING

Delayed neutron techniques, successfully applied in water cooled reactors, should be thoroughly evaluated as a method for detection of fuel failures in liquid metal reactors. Detecting fuel failure by delayed neutron monitoring offers a distinct advantage with regard to its time response characteristics, as determined by a relatively short coolant

transport delay time of 20 to 30 sec. A basic limitation exists since measurements can be made only during the time an appreciable neutron flux exists within the reactor core, or essentially only during operation of the reactor.

Although delayed neutron detection methods have been used with varying degrees of success since 1946, the applications exposed the detectors to relatively low incident gamma flux. For the FTR, a preliminary estimate indicates a sodium coolant activity of 0.5 Ci/cm^3 , which would give rise to approximately $2 \times 10^4 \text{ R/hr}$ at 2 in. from the center of a 1 in. pipeline.⁽¹⁾ Based on experience at EBR-II, a larger diameter test chamber size may be required to obtain adequate neutron sensitivity, thus causing a corresponding higher gamma level as yet undetermined. This expected gamma background poses a serious tolerance condition on the detectors, cables, and preamplifiers. In addition, the coolant temperature will be 1200 °F, and although the pipes have thermal insulation, a need exists either for cooling the detector and preamplifier or for incorporating radically improved heat-tolerance components. Under all circumstances, the preamplifier must provide an adequate signal-to-noise ratio and be capable of withstanding radiation and high temperature environment required by the specific core configuration. For assurance in adequately satisfying the requirements and in providing capability for fabricating a system on schedule, considerable developmental evaluation must be done to demonstrate the usefulness and limitations of system configurations employing selected commercially available detectors, cables and preamplifiers.

DELAYED NEUTRONS

Delayed neutrons constitute a relatively small but important fraction (<1%) of the neutron yield from the fission event. Characterization of delayed neutron decay has identified six major decay groups with half-lives varying from

0.1 to 56 sec. Radiochemical study of fission products related some of these decay groups to a radioactive parent (precursor). For instance, ^{87}Br and ^{137}I are the precursors of the 55 and 22 sec half-life delayed neutron groups, respectively. Measurements of group yields and half-lives exhibit close similarity for either fast or thermal fission. Thus, the important half-life characteristics of delayed neutrons apply to both cases.

The following table depicts typical characteristics of delayed neutrons from the fission of ^{235}U both for thermal and for 15 MeV neutrons.⁽²⁾

Group Number	^{235}U , Thermal		^{235}U , 15 MeV	
	Half- Life	Relative Yield	Half- Life	Relative Yield
1	55.55	0.039	55.15	0.051
2	22.02	0.245	22.32	0.181
3	6.06	0.206	6.29	0.203
4	2.25	0.418	2.17	0.402
5	0.462	0.092	0.638	0.163

As a group, the mean emission energy of delayed neutrons centers between 0.25 and 0.450 MeV. By incorporation of suitable moderating means, conventional high sensitivity thermal neutron detectors can be employed as basic detection elements. The unique half-life characteristic combined with rapid removal of coolant from the core provides an attractive mechanism for detection of failed fuel by the delayed neutron technique. The short life of the radioactive precursors provides built-in protection against a false signal from a sudden release of fission products possibly entrained for lengthy periods of time in the cooling system.

CHALK RIVER SYSTEMS

A report⁽³⁾ covering initial work at AECL, Chalk River (1946-56) described delayed neutron monitors employed for the detection of natural uranium fuel failures in both H_2O and D_2O cooled reactors. The basic concept of these and subsequent systems rests on the detection of delayed neutrons from neutron-emitting fission fragments released from failed fuel. Thus, presence of delayed neutrons in the coolant stream constitutes direct evidence that a fuel rupture has occurred. However, precautions must be taken to prevent background neutrons, as contributed by ^{16}N or by photo-disintegration, from masking observation of "rupture-caused" delayed neutron emitters.

The delayed neutron system of the NRX reactor employed a BF_3 proportional counter inserted into a 20 in. diameter main effluent pipe. The existence of short-lived neutron emitting products, particularly from the $^{16}O(n,p)^{16}N$ reaction necessitated locating the detection instruments at a physical point corresponding to a 120 sec delay after the time the cooling water passed through the reactor. This delay restricted the instrumentation response, thus significantly reducing system sensitivity. Nevertheless, rupture indications from 22 failures spanned a signal/background ratio from 1 to 1250 (this excludes one instance of non-detection when both the delayed neutron system and the gamma ray monitor failed to detect a fuel rupture). Unfortunately, the criteria for evaluating sensitivity involved simply an expression of signal/background ratio rather than measurement of uranium concentrations in terms of a more basic quantity such as grams per liter. The overall evaluation indicated that the delayed neutron technique offered more than an order of magnitude more sensitivity than a simple gross gamma ray monitor for these H_2O or D_2O reactor applications.

KAPL SYSTEMS

Experiments conducted by KAPL in loops (30 and 37) at the MTR provided the technical basis for similar fuel rupture detection concepts developed for the S3G reactor, and a report⁽⁴⁾ analyzed the performance of a candidate delayed neutron detection system. It predicted neutron signal/background ratios in the order of 1.72 to 2.45 for indicating failures from small cladding ruptures that expose as little as 1 cm² of fuel to the coolant.

These systems employed BF₃ counters to detect the delayed neutrons. Though not documented, relatively low background gamma radiation levels were necessarily involved because of the limited gamma tolerance capability of BF₃ detectors. Unfortunately, the papers provide a paucity of operational performance data relating to gamma tolerance problems. In this regard, other papers^(5,6,7) report that a gamma field of 10 R/hr can cause a 10% reduction in sensitivity, while 10³ R/hr can render a BF₃ detector temporarily inoperative. Apparently, the gas disassociates, releasing free fluorine, but after several hours, the sensor recovers sensitivity as the free fluorine dissipates by absorption on the inner walls of the counter. Thus, BF₃ detectors have a severe gamma limitation essentially negating their use with sodium-cooled reactors where the radioactive sodium might approach a level of 0.1 to 0.5 Ci/cm³.

EBR-II SYSTEM

The FERD (Fuel Element Rupture Detection) system of EBR-II^(8,9) employs both ¹⁰B lined and BF₃ high sensitivity neutron detectors in a total of three separate channels. Two identical channels each use one large neutron-sensitive BF₃ counter (2 in. diameter by 11 in. long). The third channel uses a group of detectors consisting of three ¹⁰B (1 in. diameter) plus three BF₃ counters (1 in. diameter) for a total of six detectors.

In this system, the sample of sodium coolant reaches the rupture monitor location about 20 sec after leaving the reactor core. Inside the delayed neutron test chamber, the sodium flows through a cylindrical test volume (2 in. diameter by 3 ft long) at a rate of 100 gal/min. A vacuum jacket surrounds the circumferential surface of the sample volume and thermally insulates the neutron detectors from the liquid sodium (750 °F). Mounting the eight thermal neutron detectors in a graphite medium around the sample-containing cylinder provides suitable moderation of the delayed neutrons. Gamma background from the ^{24}Na of the test sample caused less than 2 counts/min background from an estimated incident gamma flux of 10^3 R/hr at reduced reactor power of 9.1 MW.

Dynamic testing⁽⁹⁾ of the FERD system encompassed insertion and withdrawal of an unclad fuel element fastened to a reactor control rod. This simulated fuel failure specimen comprises a bare fuel pin measuring 0.188 in. diameter by 14.22 in. long fabricated from 68 g of uranium enriched to 52.4% of ^{235}U . Testing with this specimen at a reduced reactor power of 9.1 MW established a relatively strong failed fuel indication capability. Each of the three monitors indicated a signal/background delayed neutron response of about 6.5 to 1. Greater statistical accuracy was apparent in the recorded trace of the third channel which has a significantly larger group of neutron detectors. This testing confirmed favorable sensitivity responses both of the FERD system and of a complementary wire-type electrostatic precipitator that monitored the blanket gas.

Characteristically, delayed neutron detection systems for fuel failure detection encounter a residual neutron background. For example, initial information for the French "Phenix" reactor⁽¹⁰⁾ indicates the rupture detection system will experience a background of about 10 nv from "normal" sodium coolant.

NEUTRON DETECTORS

Special ^{235}U coated fission chambers (sensors) have performed satisfactorily in high gamma levels to 10^6 R/hr and at elevated temperatures to 500°C .^(11,12,18,21) However, the low neutron sensitivity of about 0.01 counts/sec/nv for the special environmental tolerance units and of 0.7 counts/sec/nv for off-the-shelf commercial units, along with relatively long pulse rise times, present difficult limitations for achieving needed sensitivity in a delayed neutron monitoring system. Also, the combination of small electrical output pulses and the necessity for long signal cables can lead to serious electrical background noise problems. The maximum charge per pulse from a fission chamber is about 4×10^{-13} coulombs with a rise time of 0.2 μsec , while a comparable proportional counter with gas gain of about 300 exhibits a maximum signal of about 2.0×10^{-12} coulombs with rise times as short as 30 nsec.

Inherently, the fission chamber exhibits good discrimination against gamma-caused pulse pileup because the fission event results in the release of approximately 100 MeV of energy. Comparatively, in a boron-lined proportional counter, the reaction releases a maximum of about 1.5 MeV of energy. However, with high gamma backgrounds as will be apparent in the FTR, the pulse pileup due to the rise time situation still presents a considerable problem and adjustment of the discrimination level to bias out gamma-caused pulses reduces the neutron sensitivity. For optimum signal response preamplifier and amplifiers must exhibit appropriately fast rise times (<50 nsec) and corresponding pulse shaping capability for minimizing signal pulse length. This implies suitably fast integrating, differentiating or delay line pulse shaping circuits.

Recently developed boron-lined proportional counters of 0.25 to 0.5 in. diameters may very well improve the detection of neutrons under high gamma conditions. Sensitivities to 10 counts/sec/nv were achieved with a "cluster package" of nine 0.25 in. diameter units, and despite problems with reliable performance, as many as 68 single units have been clustered to achieve higher neutron counter efficiency.⁽¹³⁾ Part of the problem with the multiple units stems from the fact that individual elements must be selected and matched on the basis of gas gain characteristics, relatively difficult to control during fabrication. Isolated cases of detector operation under high gamma levels have been reported for the small 0.25 in. ^{10}B units for limited exposures at 10^5 R/hr⁽⁵⁾ and 4×10^3 R/hr.⁽³⁾ Unfortunately, the accompanying loss in neutron sensitivity to compensate for gamma effects was either not stated or else not determined. Efforts to improve reliability led to fabrication of a 0.5 in. diameter, boron-lined counter, where the compromise with regard to size should provide a more reliable design at the expense of some reduction in gamma tolerance. To our knowledge, no operational performance data have been published for this new detector.

Clustering of detectors also increases the overall capacitance and the system electrical background noise, thus posing an increased burden on the system electronics. Fast circuits (20 nsec rise time) compatible with clustered units have been reported both for a charge-sensitive amplifier and a low input impedance current pulse amplifier.^(13,14) State-of-the-art circuits include charge and current sensitive preamplifiers that can accommodate relatively large electrical input capacitances (up to 2200 pF) and thus can amplify signals from relatively high capacitance detectors. The optimization of preamplifier and system must accommodate this and other

somewhat conflicting requirements posed by the need for high neutron sensitivity, minimization of gamma pulse pileup and the problems of high electrical noise and long signal cables associated with reactor installations.

DELAYED NEUTRON MONITOR SUMMARY

Rapid detection of fuel element failures demands a reliable monitor system for the prevention of radiological problems and possible serious physical damage to a reactor. Operational performance studies of delayed neutron monitors will provide needed valuable information concerning the relative merits of such fuel failure monitor systems. The following considerations for delayed neutron monitoring systems for liquid sodium cooled reactors have importance:

Advantages

1. Relatively rapid response time of about 20 sec can be attained.
2. Delayed neutron detection provides a technique highly specific to fuel failure, as it does not suffer from a buildup of long-lived background radiation, particularly in a recirculatory type system.
3. Commercial availability of high sensitivity neutron detectors provides a source for needed sensors; similarly, necessary electronic components are available.
4. Delayed neutron monitoring for failed fuel detection has enjoyed a long history of acceptance in H_2O , D_2O , and organic cooled as well as sodium cooled reactors.
5. The method provides an independent detection mechanism with characteristics that complement other types of failed fuel monitoring for systems that require redundancy.
6. Delayed neutron monitoring includes capability for locating failed fuel by monitoring localized coolant samples from specific fuel subassemblies (in appropriate system configurations).

Disadvantages

1. At present a paucity of operational performance information seriously limits the design of a system intended for a high gamma, high temperature condition.
2. A degree of uncertainty attaches to actual arrival of neutrons at the monitor because of possible plate-out effects of the delayed neutron precursors.
3. The relatively rapid decay of delayed neutrons after reactor shutdown necessarily restricts system use to reactor operation.
4. The buildup of "neutron background" accumulates during reactor operation, leading to a radiation masking problem, where corrosion products, coolant impurities and residual effects of previous failures all contribute to this problem.

The above comments focus on the liquid sodium reactors in particular, but they also apply in general to other reactors.

LOW LEVEL NEUTRON FLUX INSTRUMENTATION

The FTR (a high temperature, liquid sodium cooled, fast neutron reactor), will require a sensitive, versatile, and reliable startup instrument system capable of measuring neutron flux density over several decades of power. Anticipated operating conditions for the detectors include a maximum gamma level of 10^6 R/hr and an ambient temperature of 600 °F. Thus, comments in the preceding discussion about high sensitivity neutron chambers also apply directly to the low level reactor startup system and will not be repeated.

Historically, direct measurement of fast neutron flux by fast flux detectors has been bypassed because of the low neutron sensitivities obtainable. However, developmental programs now in progress may change this situation in time. Candidate

detector materials offer low response due to the very small fast neutron cross sections typically in the millibarn range. Ordinarily, neutron instruments used in the source range of fast reactors have simply been an extension of thermal detection techniques. For instance, a usual thermal neutron detector plus a suitable moderating medium for thermalizing the fast flux constitutes a "source range detector." Typically, guide tubes position the detectors in the reactor shield at desired spatial locations, usually outside extremely hostile environments of the core.

The reactor total operating range spans typically twelve or more decades, extending from initial source level to 150% of full power. Conventional control system design usually specifies the use of fission counters, compensated ion chambers, and ion chambers in a progressive system for full range instrumentation. The details of detectors and counting rate meter used in reactor startup systems are quite well known, and an excellent discussion of representative systems occurs in Price.⁽¹⁵⁾

In prior work, plant design options resulted in the selection of detector cooling at EBR-II and Dounreay, whereas the Fermi reactor employs high temperature detectors without cooling. Detector technology has advanced steadily and contemporary source range sensors claim temperature ratings to 700 °F for commercial units.

Another important facet of the neutron instrumentation system focuses on the selection of appropriate cables, connectors, and preamplifiers for adequately transmitting the low level detector signals. Relatively rigid, metal-sheathed, hermetically sealed, mineral-insulated cables can be obtained for high temperature applications. They feature

a stated radiation tolerance to 10^8 R/hr, temperature to 650 °F, dielectric ratings to 1000 V and relatively low capacitance of 25 pF/ft. Spare cable and detectors installed in critical locations for nuclear safety and control channels help reduce maintenance problems. Preamplifiers pose considerable problems for use in difficult environments.

The detector, electronics and environmental requirements of the low level, startup range monitoring system for the FTR can be partially characterized as follows:

- Counter Sensitivity, 10 counts/sec/nv or more
- Cable, 50 ft length or greater
- Preamplifier, 50 nsec rise time or shorter
- Amplifier, <50 nsec pulse shaping time constants
- Gamma, 10^5 R/hr or greater at detector
- Temperature, possibly 500 °F or greater at the detector location.

Because of the similarity between the environmental requirements for the previously described delayed neutron monitoring system and the startup monitor, components (detector, cables, and preamplifiers) developed for one should be applicable to both systems. This could enable a marked cost reduction in design and subsequent operations.

Control systems based on the "Campbell Method"^(16,17) provide improvement in discrimination against gamma and leakage current "background" interference. Essentially, the technique discards the dc component and utilizes only the ac portion of the signals for measurement of neutron flux density. Though the mean square signal approach of a Campbell system reduces errors due to gamma background, the system sensitivity does not extend to the lower 4 to 5 decade startup range of operation. Thus, the choice of a low level neutron flux monitor narrows to selection of an optimum type of pulse detector with

associated electronics. Count rate startup systems enjoy almost universal acceptance and have been used on many reactors, including the Hanford N Reactor. This reactor employed conventional, large-sized ^{235}U coated fission chambers with sensitivities in the range of 0.1 to 0.5 counts/sec/nv.

Pulse ionization chambers exhibit less sensitivity to temperature change than other types of detectors, such as scintillation counters, solid state devices, and mean current chambers. Limited information obtained on developmental prototype fission counters⁽¹⁸⁾ (0.400 in. diameter) indicates that temperatures to 500 °C caused negligible reduction in chamber neutron sensitivity for a sensor with a neutron sensitivity of 0.01 counts/sec/nv. A smaller chamber (0.125 in. diameter) filled to a pressure of 100 psi argon exhibited a reduction in sensitivity of only 5% at 800 °C. Pulse-mode operation of high temperature counters evidence promise in that discriminator circuits help factor out effects due to temperature-induced leakage current. For such operation, the control response derives from the ac component of the chamber collection pulse. Thus, changes in dielectric insulation resistance and the corresponding dc current shift have little effect on the pulse signal characteristics.

Acquisition of basic operational performance characteristics of neutron detectors and preamplifiers for FTR environmental conditions will provide needed information for the design and/or development of a reliable low-level neutron monitoring system, where the accepted system should be directly applicable to future reactors. Previous theoretical work identified pulse shaping and analyzing⁽¹⁹⁾ methods applicable to the matching of detectors and circuits with an aim of optimizing system performance with regard to gamma-caused pileup. Minimization of the rise time, decay time, and pulse duration

reduces the probability of pulse pileup. Multiplication provides amplification of the pulse signals in the ^{10}B coated detector, but practical limitations posed by gamma and temperature effects require experimental evaluation.

Discussions with vendors indicate limited availability of operational performance data for candidate sensors with specifications approaching FTR requirements. However, optimum system design strongly depends on performance evaluation data obtained on available detectors and amplifying systems, including combined gamma and temperature effects to approximately 1×10^6 R/hr and 500 °F, respectively. Increasingly severe environmental conditions will decrease detector sensitivity and ultimately cause permanent damage to the units. Availability of technical evaluation information about these effects, even though relatively limited, will greatly facilitate timely designs compatible with the FTR core and shielding configurations.

LOW LEVEL NEUTRON INSTRUMENTATION SYSTEM SUMMARY

The source range instrumentation must be capable of monitoring a representative number of decades of the reactor neutron flux level during reactor startup and shutdown. The range of operation must provide several decades of dynamic range, including sufficient overlap with the intermediate-range system, and the low level system must demonstrate a high degree of reliability under the severe environmental conditions of the FTR. The accuracy and response time must be sufficient for maintaining reliable, efficient, and safe control of the reactor. The following list shows significant characteristics of candidate sensors for the source range measurements:

Advantages

1. Fission chambers or proportional counters provide prompt measurement of core neutron flux conditions necessary for insuring safe nuclear operation of a reactor.

2. Highly specific to neutron flux including excellent, though not sufficiently evaluated, tolerance of gamma and temperature background.
3. Established commercial availability of ^{10}B proportional counters and ^{235}U fission chambers, although not yet "proven" for the expected environmental conditions.
4. Promising, yet unproven, capability for increased gamma tolerance by use of upgraded broad-band electronic components.
5. A legacy of operational performance from extensive use with thermal nuclear reactors.

Disadvantages

1. Necessity for thermalization of fast flux since all high sensitivity neutron detectors respond basically to thermal neutrons.
2. Use of relatively sophisticated electronic instrumentation because sensor signals require high gain amplification and pulse shaping.
3. Requirement for finite space allocations in reactor locations for housing redundant numbers of neutron detectors.
4. Requirements for periodic detector replacement due to "burnup" effects. However, regenerative techniques⁽²⁰⁾ may extend the life, particularly for the ^{235}U fission chambers. This remains to be considered and determined.

ACKNOWLEDGMENT

I wish to thank many colleagues for their advice and cooperation in the course of this investigation. I am particularly grateful to W. G. Spear, D. P. Brown, D. C. Thompson, and M. R. Wood for their advice and consultation.

REFERENCES

1. W. L. Bunch and R. E. Shaver. Shielding Calculation for Conceptual Design of FFTF Sodium Systems, BNWL-388. Pacific Northwest Laboratory, Richland, Washington. April 1967.
2. G. Robert Keepin. Physics of Nuclear Kinetics, Addison-Wesley Publishing Co., Inc., Palo Alto, California. 1965.
3. C. H. Millar, B. W. Sargent and J. C. Horseman. "Delayed-Neutron Monitors for the Detection of Sheath Failures in Reactor Fuel Rods," Nucl. Sci. Eng., vol. 2, p. 83. 1957.
4. R. A. Dewes. Fuel Element Failure Detection and Location - Estimate of Sensitivity, KAPL-M-RAD-2. D/N System S3G, Knolls Atomic Power Laboratory. November 1957.
5. J. E. Strain. The Design and Evaluation of a Delayed-Neutron Leached-Hull Monitor, ORNL-4135. Oak Ridge National Laboratory. February 1968.
6. A. J. Stokes, T. J. Meal and J. E. Meyer, Jr. "Improved Performance of BF₃ Neutron Counters in High Gamma Fluxes," Conference Paper at IEEE Nuclear Science Symposium, San Francisco, California. 1965.
7. W. M. Trenholme. "Effects of Reactor Exposure on Boron-Lined BF₃ Proportional Counters," Nucl. Eng. and Sci. Conf. Reprint, V-58. 1959.
8. K. Moriarty. Unpublished Data. ANL Idaho Division. (Personal Communication)
9. R. R. Smith and C. B. Doe. Cladding Failure Simulation Tests in EBR-II, ANL-7067. Argonne National Laboratory, Idaho Division. December 1966.
10. J. Graftiaux. Reacteur "Phenix" La Detection De Rupture De Gaine, CEA-R-3339. Centre D'Etudes Nucleaires De Saclay. 1967. (In French)
11. A. Goodings. A Note on the Irradiation Testing of Pulse Fission Chamber Design, AEEW-M-493. United Kingdom Atomic Energy Authority, Winfrith, Dorchester, England. 1964.
12. S. H. Hanauer. "Improvements in Instrumentation for High-Performance Power Reactors," Third International Conference on Peaceful Uses of Atomic Energy, vol. 8, p. 395. 1964.

13. H. A. Thomas. *Unpublished Data. Gulf-General Atomic Incorporated. (Personal Communication)*
14. R. Crumley. *Unpublished Data. Edgerton Germeshausen and Grier (EG&G). (Personal Communication)*
15. W. J. Price. Nuclear Radiation Detection, McGraw-Hill Book Co., San Francisco, California. 1964.
16. Mean Square Voltage Monitor, Type NC12, General Electric Company, San Jose, California. 1966.
17. Wide Range Log Channel, Model NLW-2, General Atomic, San Diego, California. 1967.
18. W. Alson, W. R. Loosemore and P. G. Salmon. New Developments in Fission Chamber Detectors for Neutron Flux Measurement, Atomic Energy Research Establishment, Harwell, United Kingdom. 1960.
19. E. Fairstein and J. Hahn. "Nuclear Pulse Amplifiers - Fundamentals and Design Practice," Nucleonics, vol. 23, no. 9. September 1965.
20. C. N. Jackson, Jr. Reactor In-Core Regenerative Neutron Detectors - Interim Development Report, BNWL-430. Pacific Northwest Laboratory, Richland, Washington. October 1967.
21. A. Goodings. "Wide-Range Neutron Flux Measurements at High Temperature," Proceedings of International Conference on Radiation Measurements in Nuclear Power, Berkeley Nuclear Labs, England. 1966.

DISTRIBUTION

No. of
Copies

OFFSITE

1	<u>AEC Chicago Patent Group</u>
G. H. Lee, Chief
20	<u>AEC Division of Reactor Development and Technology</u>
M. Shaw, Director, RDT
Asst Dir for Nuclear Safety
Research and Development Br, RDT:NS
Asst Dir for Plant Engrg, RDT
Applications and Facilities Br, RDT:PE
Components Br, RDT:PE
Instrumentation and Control Br, RDT:PE
Asst Dir for Program Analysis, RDT
Asst Dir for Project Mgmt, RDT
FFTF Project Manager, RDT:PM (3)
Asst Dir for Reactor Engrg
Control Mechanisms Br, RDT:RE
Core Design Br, RDT:RE (2)
Asst Dir for Reactor Tech
Reactor Physics Br, RDT:RT
Special Technology Br, RDT:RT
Asst Dir for Engrg Standards, RDT
4	<u>AEC Site Representatives</u>
Argonne National Laboratory
Atomics International
Atomic Power Development Assoc.
General Electric Co.
3	<u>Argonne National Laboratory</u>
R. A. Jaross
N. J. Swanson
LMFBR Program Office
3	<u>Atomics International</u>
<u>Liquid Metal Information Center</u>
R. N. Dickinson
J. Meyer (2)
5	<u>Bechtel Corporation</u>
J. J. Teachnor, Project Administrator, FFTF

No. of
Copies

- 1 BNW Representative
 N. A. Hill (ZPR III)
- 3 General Electric Co.
 Advanced Products Operation
 K. Cohen (2)
 P. Pluta (1)
- 2 Gulf General Atomic Inc.
 General Atomic Div
 D. Coburn
- 10 Westinghouse Electric Corp.
 Atomic Power Division
 Advanced Reactor Systems
 J. C. R. Kelly (7)
 C. Roderick (3)

ONSITE-HANFORD

- 1 AEC Chicago Patent Group
 R. K. Sharp (Richland)
- 4 AEC RDT Site Representative
 P. G. Holsted
- 3 AEC Richland Operations Office
 J. M. Shivley
- 3 Battelle Memorial Institute
- 1 Bechtel Corporation
 D. H. Weiss (Richland)
- 1 Westinghouse Electric Corp.
 R. Strzelecki (Richland)
- 73 Battelle-Northwest
 E. R. Astley J. C. Cochran
 R. A. Bennett P. D. Cohn
 C. L. Brown D. L. Condotta
 D. P. Brown R. R. Cone
 W. L. Bunch J. M. Davidson

Battelle-Northwest (contd)

G. E. Driver	D. W. Shannon
E. A. Evans	D. E. Simpson
V. W. Gustafson	W. G. Spear (10)
K. M. Harmon	R. J. Squires
R. E. Heineman	J. T. Stringer
J. W. Helm	C. D. Swanson
P. L. Hofmann	D. C. Thompson
N. C. Hoitink (3)	N. G. Wittenbrock
C. N. Jackson (3)	M. R. Wood (3)
B. M. Johnson	D. C. Worlton
W. W. Little	FFTF Files (10)
D. Marinos	Technical Publications (2)
L. McClellan	Technical Information (5)
W. B. McDonald	Legal (2)
J. W. Mitchell	
R. E. Peterson	
C. A. Ratcliff	
W. E. Roake	
F. H. Shadel	