NEW FLUX DETECTORS FOR CANDU-6 REACTORS

J.M. Cuttler and N. Medak
AECL CANDU
Mississauga, Ontario

INTRODUCTION

The in-core (self-powered) flux detectors in the Gentilly-2 and
Point Lepreau reactors were replaced recently* with detectors of
a different design. This paper describes the evolution of this
detector design and explains why it was chosen.

PREVIOUS DETECTOR DESIGN

As can be seen from Table 1, CANDU reactors use many in-core flux
detectors for spatial power control, flux mapping and overpower
protection.[1,2,3] In-core detectors are vital for reactor
operation.

Table 1
Number of In-Core Flux Detectors in CANDU-6 Reactors

Use	Old Design	New Design
Spatial Power Control (14 zones @ two per zone)	28	28
Flux Mapping	102	102
Shutdown System No. 1	68	34**
Shutdown System No. 2	46	24**
	244	188

The detector is a coaxial mineral-insulated cable, and when it is
in a high flux of radiation, a net current of electrons flows
from the inner conductor to the outer one.[4,5,6] Referring to
Figure 1, the detector behaves like a current source in which the
current is proportional to the radiation intensity, and the shunt
resistance is of the order of a gigaohm (1000 MΩ). The current
is fed through an amplifier, typically a current-to-voltage
converter with a low input impedance.

---

* Gentilly-2 in Sep-Oct '91, and Point Lepreau in Apr-May '92
** no installed spares

The original detectors were designed by Chalk River Nuclear Laboratories.[7] They had an outer Inconel sheath, 1.6 mm in diameter, and the inner conductor, the emitter, was made of platinum or vanadium.

The platinum detector[8] has a response that is half-sensitive to thermal neutrons and half-sensitive to gamma rays. Platinum detectors respond promptly, but since 1/3 of the gamma radiation is delayed, the detector response is approximately 85% prompt. The response of fuel power to a step increase in neutron flux is ~95% prompt, so the platinum detector underpredicts a power excursion. The detector signal needs approximately 10% of dynamic compensation for use in safety applications.

The vanadium-type detector is sensitive only to thermal neutrons, but its time response depends upon the beta decay of vanadium-52 (3.76 minute half-life). This is too slow for control or safety applications, so vanadium detectors are used to map the flux and calibrate the prompt detectors.

Both types of detectors "burn up" slowly in the CANDU thermal neutron flux of 3×10^{18} n m^{-1} s^{-1}. For the vanadium detectors, a correction can be applied as a function of the integrated detector signal (flux), based on predicted detector burnup.

The platinum detector is 3.0 m long and provides a signal of approximately one microampere at full power. To obtain a "regional" power measurement, this detector is coiled around a 9.5 mm Zircaloy carrier tube over a distance of three lattice pitches (857 mm). The vanadium detector is 1.2 m long and provides a signal of ~3 microamperes at full power. For a local flux reading, it is coiled over a distance of one lattice pitch (286 mm).

Each detector is spliced to a 1.0 mm leadcable whose geometry was optimized for negligible sensitivity to radiation. Figure 2 shows the details of the spliced joint, and Figure 3 shows a flux detector unit with several detectors mounted along the length of the carrier tube. This tube is supported, in the (unpressurized) heavy water moderator, within a guide tube. The vertical guide tubes are perforated (wet) and the horizontal ones are dry, i.e. filled with helium. The leadcables are threaded around the shield plug, through a compression-type feed-through, to a multipin electrical connector. The control/safety detectors have installed spares, bifilar wound, to increase reliability and avoid reactor power derating on random detector failure.

FLUX DETECTOR FAILURE

Detectors have been failing since they were first used in the 1960s, in the Douglas Point reactor. Detector failure is apparent when the signal ceases to track the flux in a

proportional manner, within the required power range (0.1 to 1.5 of full power) and within the required response time. The insulation resistance is often a good indicator of degradation or failure.[9,10] Penetration of the metallic sheath introduces moisture into the magnesium-oxide insulation and progressively results in erratic detector response.

Before it is installed, a detector has an insulation resistance in excess of 100 gigaohms (10^{11} ohms). In operation, the resistance immediately decreases to 1000 megohms and eventually remains in the range from 1000 MΩ to 1 MΩ. When it declines below 1 MΩ, the detector's performance becomes suspect.

There are many modes of detector failure. The epoxy seal at the end of the leadcable sometimes becomes leaky. The Inconel-600 leadcable sheath has failed due to various types of corrosion, such as pitting, intergranular corrosion due to nitric acid attack, embrittlement due to radiation damage, and/or nitride attack, etc. Brazed joints (at the splice) have also corroded, and detector endcap welds have failed. The signal has been lost due to core-wire breakage at the leadcable or at the splice.

STRAIGHT INDIVIDUALLY REPLACEABLE (SIR) DETECTORS

The vulnerability of these flux detectors was recognized, and a proposal was raised at AECL CANDU in 1975 to examine a different detector configuration that would enable individual detectors to be easily replaced.[11] At the same time, the detectors would be contained in a housing, filled with an inert gas (helium), that would protect them from hostile environments. Connectors would be provided that could withstand loss of coolant or steam break accidents.

Replacing an entire flux detector assembly is a complex operation involving significant capital cost, a long lead time for procurement, a long shutdown, a significant man-rem burden, and the cost of managing high-level radioactive waste.

The new concept, shown in Figure 4, would utilize straight detectors, each in a separate guide tube or "well". These detector guide tubes would be enclosed in a dry assembly with a shield plug to block streaming radiation. A bellows would accommodate differences in thermal expansion between the reactor and the detector assembly. The connector housing could be opened to allow a replacement detector to be inserted into a spare well and its connector jack to be plugged into the appropriate receptacle, in place of the failed detector's jack. One or more detectors could be withdrawn into a flask, if necessary, without the need to remove the entire flux detector unit. After resealing the housing, the unit could be flushed with helium to remove air and vapours.

One well tube would be reserved for a travelling flux detector (TFD).[12] This is a miniature fission chamber that could be inserted the full length of the assembly to scan the core and measure a thermal neutron flux distribution, as shown in Figure 5. It could also be employed to calibrate detector sensitivity or measure fuel channel creep/sag.

Using detectors of the original 1.5 mm diameter would have resulted in a factor of four reduction in signal which would have increased the relative signal contribution of the leadcable by the same factor. A 3.0 mm diameter seemed to be appropriate, but the effect of this change on detector response was uncertain. It was recognized that development work would be needed to determine the consequences of such changes, and this was identified in the proposal raised by AECL CANDU in 1975 April. This resulted in a development program being authorized in 1976 February that was jointly funded by AECL and Ontario Hydro.[11]

A constraint in selecting the diameter of the new detectors was the requirement of retrofittability to older CANDU reactors. If a 3.0 mm detector was selected, then 13 well tubes could fit into a SIR assembly (for new reactors). For reactors that already had coiled detectors, 12 well tubes could be installed in a dry capsule (HESIR)* that could fit into any of the existing guide tubes. If the spare safety detectors were not installed, then 12 well tubes would provide approximately six vacant wells for replacement detectors. There would be no need to remove the existing guide tubes to retrofit SIR detectors.

Figure 6 shows the detector geometry selected in 1975. The splice (between the leadcable and the detector) was rejected in favour of an integral sheath design. The diameter of the (flux mapping) vanadium emitter was increased by a factor of three to provide significantly greater sensitivity (per unit length). A platinum-clad Inconel emitter was proposed in place of the solid platinum emitter in order to reduce its cost, expecting that the surface would provide most of the signal.[13] In the development program that followed, the contribution of the Inconel core was found to be quite large,[14] leading to the discovery of the Inconel detector.[15, 16]

SIR DETECTOR DEVELOPMENT PROGRAM

The development program started in 1976 and continued for several years. Most of the detector tests were carried out at Chalk River Laboratories using a test SIR detector assembly in the NRU reactor. The design of this assembly was based on the design for CANDU reactors prepared at Sheridan Park (Figure 7). A prototype of the HESIR detector assembly (Figure 8) was later designed by

* hybrid encapsulated SIR assembly

AECL CANDU and installed in Bruce NGS, Unit 4 in 1978 October for long-term tests.

The sensitivities of the SIR detectors are approximately the same as the sensitivities of the corresponding coiled detectors. With the platinum layer deleted, the resulting Inconel detector has half the sensitivity, but it gradually increases by 50% due to the transmutation of nickel-58 (in Inconel) into nickel-59, a more neutron-sensitive nuclide.[15]

The dynamic responses of the prompt SIR detectors were determined by measuring the decay of the signals after a reactor "trip" and by fitting each decay with a sum of first-order exponential functions of time.[17]

Figure 9 shows the response of each detector type to a step increase in neutron flux. The platinum-clad SIR detector has a slightly faster response than the coiled platinum detector, 90% vs 87% prompt, and needs less compensation to match the fuel power characteristic. The Inconel detector is 105% prompt because it has negative delayed components, so its signal conservatively overpredicts the thermal response of the fuel.

The principal objective of the SIR detector development was to improve maintainability and prevent failure by corrosion, without worsening detector performance. It was therefore a significant bonus to obtain superior performance by using SIR detectors.

ENCAPSULATED (COILED) DETECTORS

In the spring of 1976, while this development program was getting underway, detectors of the original design (Figures 2 and 3) were installed in Bruce Unit 2. The helium cover gas was provided over the 65°C moderator, however, it was necessary to open the volume repeatedly during the commissioning of the many reactivity mechanisms. It was very difficult to maintain the helium cover gas and prevent air from entering. Within two months, many of the vertical detector leadcables corroded to failure by pitting.

This experience caused Sheridan Park to design (in 1977) the encapsulated (coiled) detector assembly because the development of the SIR detectors had not progressed sufficiently to provide the confidence necessary to use them in power reactors. So the carrier tube with the coiled detectors was enclosed in a capsule that was degassed, filled with helium and sealed. Figure 10 shows this design, which included an environmentally-qualified connector housing. The capsule was small enough to fit into the existing guide tubes and such assemblies were installed in Bruce Units 3 and 4. Since the capital cost of encapsulated assemblies was less than the cost of SIR assemblies, the same design was later used in the Pickering NGS "B" reactors and the four CANDU-6 reactors: Gentilly-2, Point Lepreau, Cordoba and Wolsong-1.

DECISION TO REPLACE FLUX DETECTORS

By 1978 June, AECL CANDU had sufficient results from Chalk River
to recommend a change of detector design for Bruce NGS "B" from
coiled to SIR detectors. The change was accepted and Darlington
NGS subsequently requested SIR detectors as well. The good
performance of the prototype SIR assembly in Bruce Unit 4 helped
confirm this decision.

After several years of operation, (coiled) detectors began to
fail sporadically in Bruce "A", Pickering and the CANDU-6
stations. In most cases, installed spares were utilized, but
concern grew as more and more detectors failed. Eventually, the
detectors in Bruce Units 1 and 2 and in Pickering NGS "A" were
replaced. The HESIR assembly design was selected after
considering the total cost of periodic detector replacement.
Recently (1988) Pickering NGS decided to replace the detector
assemblies in the "B" station with the HESIR type. Gentilly-2
and Point Lepreau decided in 1989 to follow suit and benefitted
from economies of scale due to bulk procurement with Pickering.

In mid-1991, two SIR detectors failed in Bruce NGS "B" after
eight years of service. Two replacement flux detectors were
installed in spare well tubes successfully. This was the first
case of such a maintenance operation on failed SIR detectors.

HIGHER OVERPOWER TRIP SETPOINTS

Use of SIR detectors increases flexibility in positioning
detectors because each can be put at any location along an
assembly, whereas it is difficult to overlap coiled detectors.
Even after installation and plant operation, the detector layout
can be changed more easily to improve the performance of the
reactor regulating system and the safety shutdown systems.

The decision to replace the in-core flux detectors in Gentilly-2
and Point Lepreau provided an opportunity to redesign the
detector layout, using more advanced techniques (ROVER program)
and the increased flexibility afforded by the SIR assembly, to
achieve better "coverage" of a greater number of abnormal flux
shapes (232 vs 137). This should result in higher overpower trip
setpoints and correspondingly wider margins for power manoeuvres.

REDUCED SCHEDULES

Eliminating the need to coil the detectors around carrier tubes
greatly shortens the schedules. Procurement and manufacture of
SIR detectors and assembly hardware can proceed in parallel with
optimization of the overpower trip design (detector layout) and
design of the wiring. Cutting detectors to length and installing
them to form complete assemblies is a relatively quick process,
which is important if an assembly is damaged during installation.

CONCLUSION

The introduction of SIR detectors is making a significant improvement to plant availability and performance. Actual and potential costs associated with project schedule, shutdowns, capital equipment, radiation dose and waste management have been reduced. The detectors themselves provide better performance. The increased flexibility in positioning detectors has allowed the design of the overpower trips of the safety shutdown systems to be improved, for higher trip setpoints and a wider operating margin.

REFERENCES

1. HINCHLEY, E.M.; KUGLER, G. "On-Line Control of the CANDU-PHW Power Distribution", IAEA Specialists' Meeting on Spatial Control Problems, Studsvik (1974 Oct), AECL-5045 (1975 Mar).

2. KUGLER, G. "Distinctive Safety Aspects of the CANDU-PHW Reactor Design", AECL-6789 (1980 Jan).

3. PAPADATOS, K.; MCDONALD A.; FIEGUTH, G. "Power Measurement in CANDU Reactors", Proc. 1st Ann. Conf. Can. Nuc. Soc., Montreal, Pg 67 (1980 Jun).

4. MITEL'MAN, M.G.; EROFEEV, R.S.; ROZENBLYUM, N.D. "Transformation of the Energy of Short-Lived Radioactive Isotopes", Sov. J. At. En., Vol 10, No. 1, Pg 70 (1961 Nov).

5. HILBORN, J.W. "Self-Powered Neutron Detectors", Trans. Am. Nuc. Soc., Vol 6, Suppl., Pg 33 (1963 Oct).

6. SHIELDS, R.B. "Self-Powered Flux Detectors, A Bibliography with Summaries", AECL-8109 (1983 Feb).

7. HILBORN, J.W. "Self-Powered Neutron Detector", Can. Pat. 765,917 (1967 Aug), U.S. Pat. 3,375,370 (1968 Mar).

8. SHIELDS, R.B. "A Platinum In-Core Flux Detector", IEEE Trans. Nucl. Sci., Vol NS-20, No. 1, Pg 603 (1973 Feb), AECL-4347. See also U.S. Pat. 3,787,697 (1974 Jan).

9. SHIELDS, R.B. "Some Practical Considerations in the Use of Self-Powered Flux Detectors", Proc. IAEA Specialists' Meeting on In-Core Instr. and Failed Fuel Detection and Location, Mississauga, (1974 May), AECL-5124 (1975 Jun).

10. DREWELL, N.H.; DELCOL, K. "Dynamic Response Degradation of Platinum Self-Powered Detectors with Low Insulation Resistance", OECD-NEA Specialists' Meeting on In-Core Instrumentation and Reactor Assessment, Fredrikstad (Norway) (1983 Oct), AECL-8265.

11. CUTTLER, J.M.; ERVEN, J.H. "An Improved In-Core Flux Detector for CANDU Reactors", Trans. Am. Nuc. Soc., Vol 34, Pg 585 (1980 Jun).

12. ALLAN, C.J.; MCDONALD, A.M.; CUTTLER, J.M.; ERVEN, J.M. "The Development and Use of a Travelling Flux Detector System for CANDU Reactors", IEEE Trans. Nuc. Sci., Vol NS-28, No. 1, Pg 720 (1981 Feb), AECL-7206.

13. ALLAN, C.J.; SHIELDS, R.B.; LYNCH, G.F.; CUTTLER, J.M. "Self-Powered Neutron and Gamma-Ray Flux Detector", Can. Pat. 1,085,066 (1980 Sep), U.S. Pat. 4,284,893 (1981 Aug).

14. ALLAN, C.J. "Experimental Measurements of Neutron and Gamma-Ray Sensitivities of Flux Detectors Having Mixed Response", IEEE Trans. Nuc. Sci., Vol NS-29, Pg 660 (1982 Feb), AECL-7479.

15. ALLAN, C.J. "A New Self-Powered Flux Detector", AECL-6681 (1979 Nov).

16. ALLAN, C.J.; MCINTYRE, I.L. "Self-Powered Neuton Flux Detector", Can. Pat. 1,084,176 (1980 Aug).

17. ALLAN, C.J. "A Review of the Dynamic Response of Self-Powered Flux Detectors in CANDU Reactors", Proc. 2nd Ann. Conf. Can. Nuc. Soc., Ottawa, Pg 290 (1981 Jun).
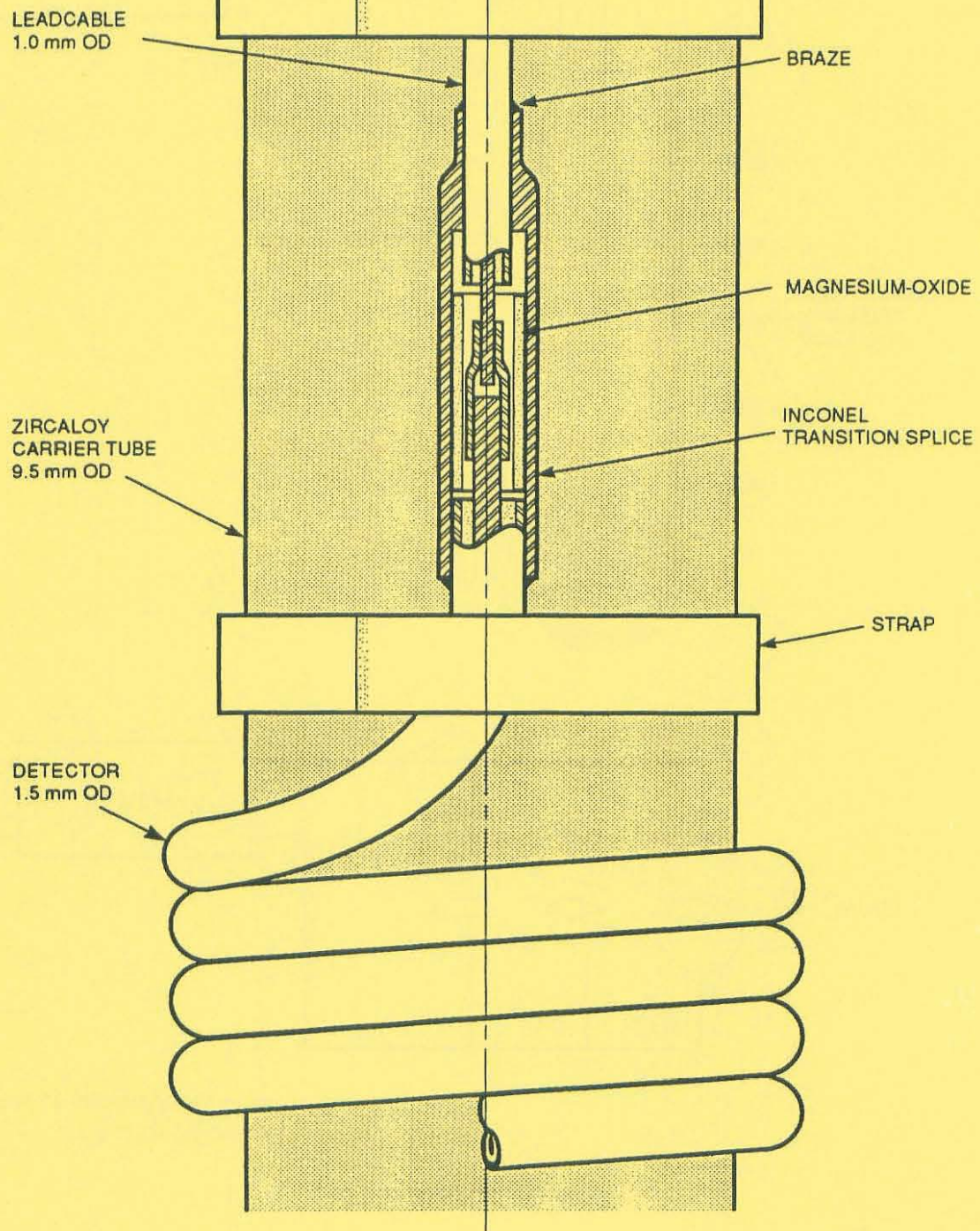
AMPLIFIER

FLUX DETECTOR
(SELF-POWERED)

NEUTRON
AND GAMMA
RADIATION

AMPLIFIER

$I(n, \gamma)$ *

R**

C
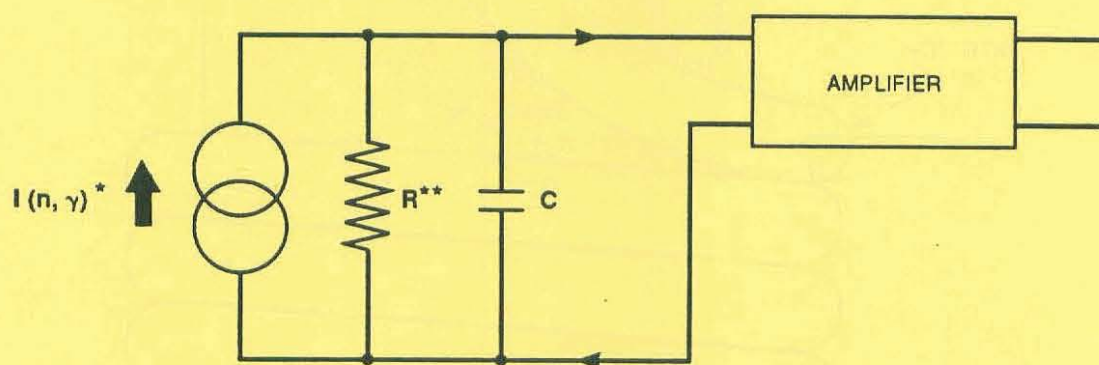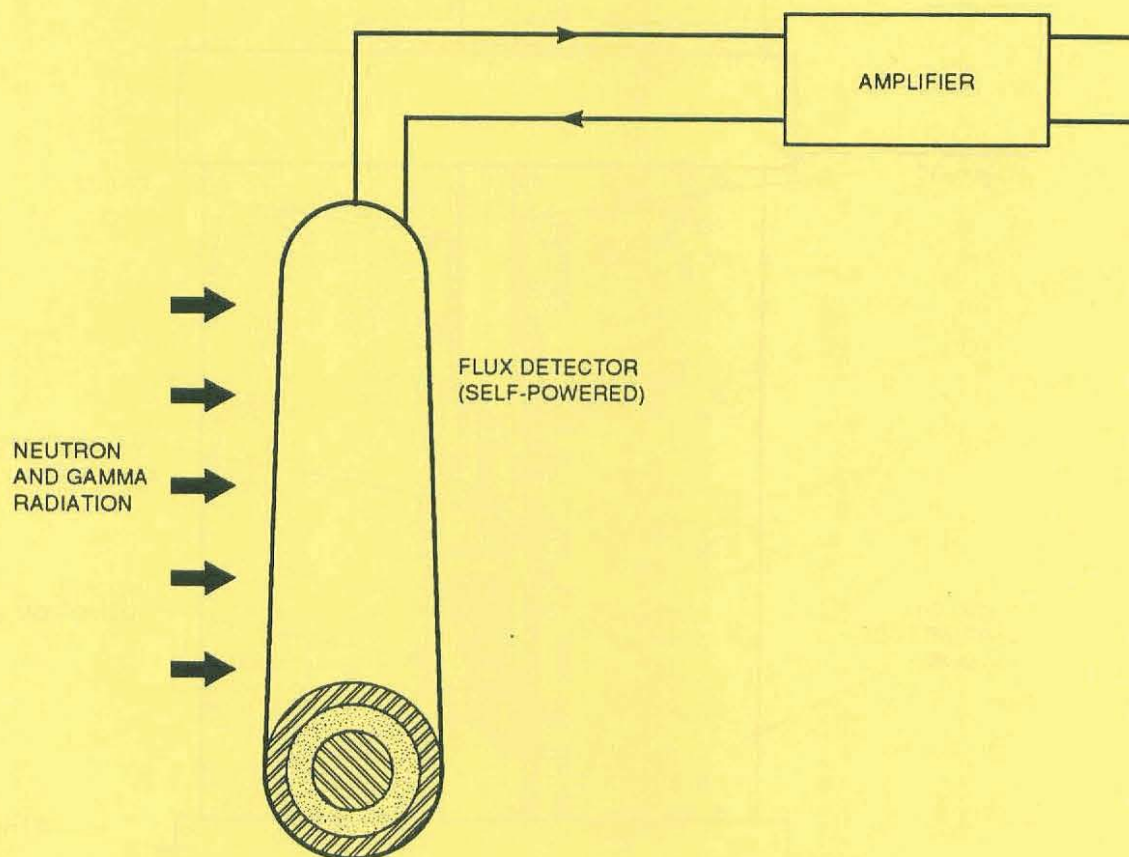
• ~ 1 MICROAMPERE AT FULL POWER
** 1000 MΩ TO 10 MΩ

CURRENT SOURCE MODEL

920470

FIGURE 1 ELECTRICAL MODEL OF SELF-POWERED FLUX DETECTOR

LEADCABLE
1.0 mm OD

BRAZE

MAGNESIUM-OXIDE

ZIRCALOY
CARRIER TUBE
9.5 mm OD

INCONEL
TRANSITION SPLICE

STRAP

DETECTOR
1.5 mm OD

920470

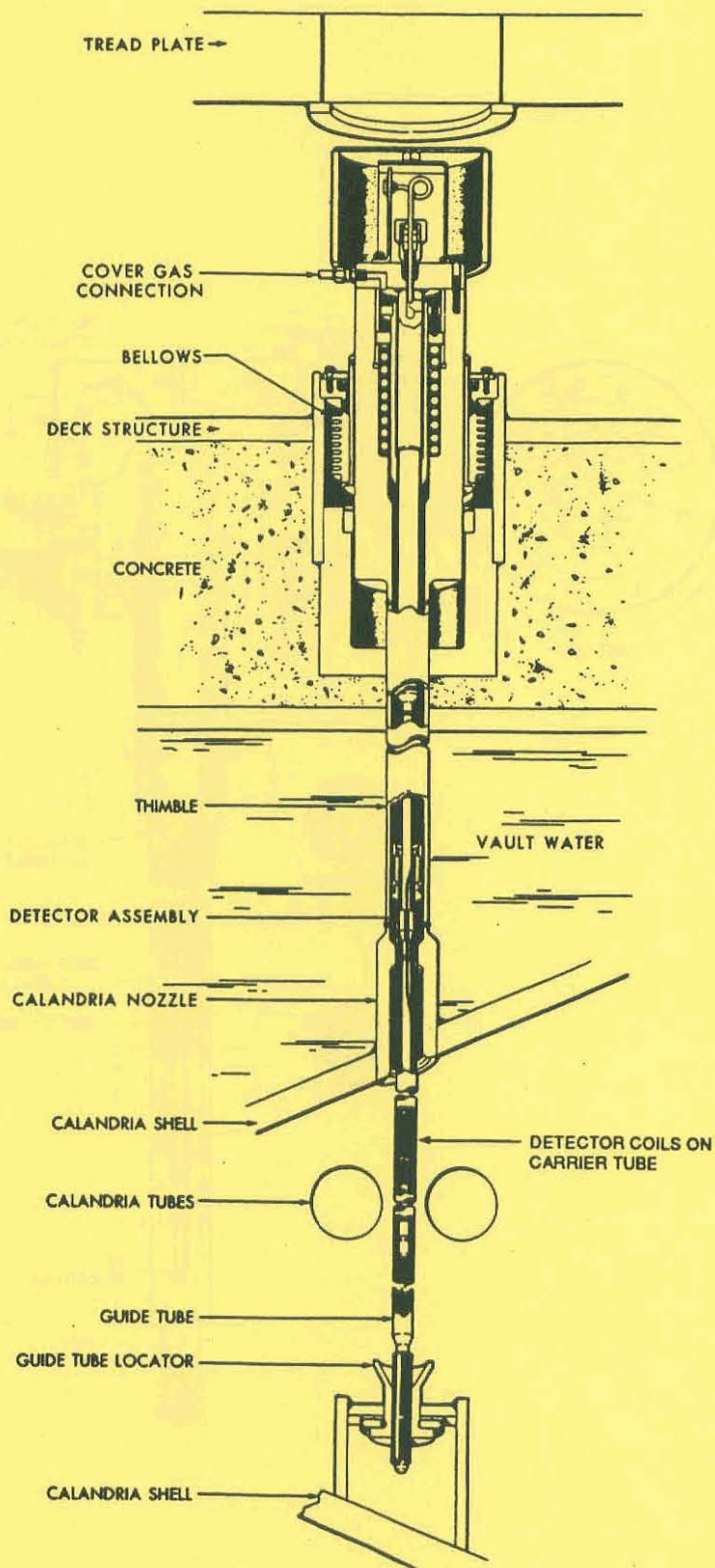**FIGURE 2 SPLICE BETWEEN LEAD CABLE AND COILED DETECTOR**

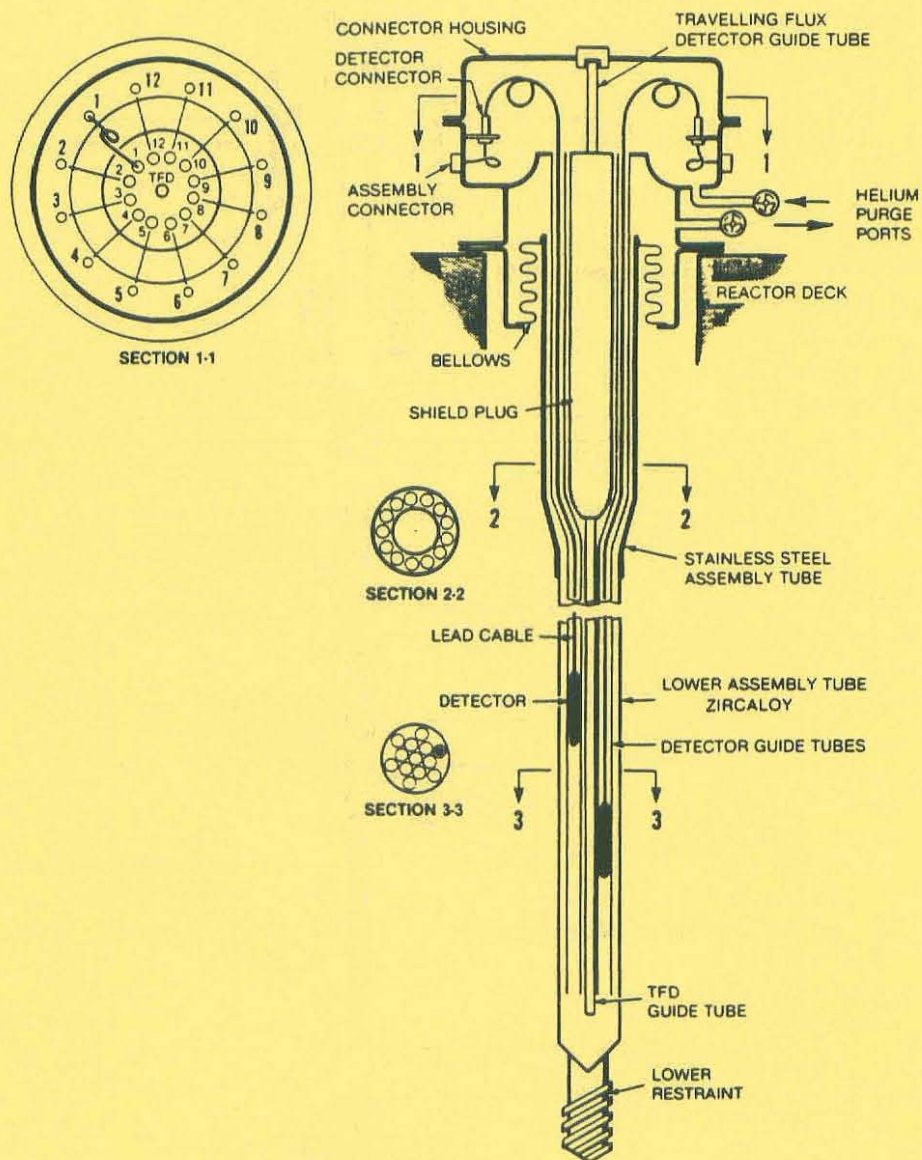**FIGURE 3   COILED DETECTOR ASSEMBLY (ORIGINAL DESIGN)**
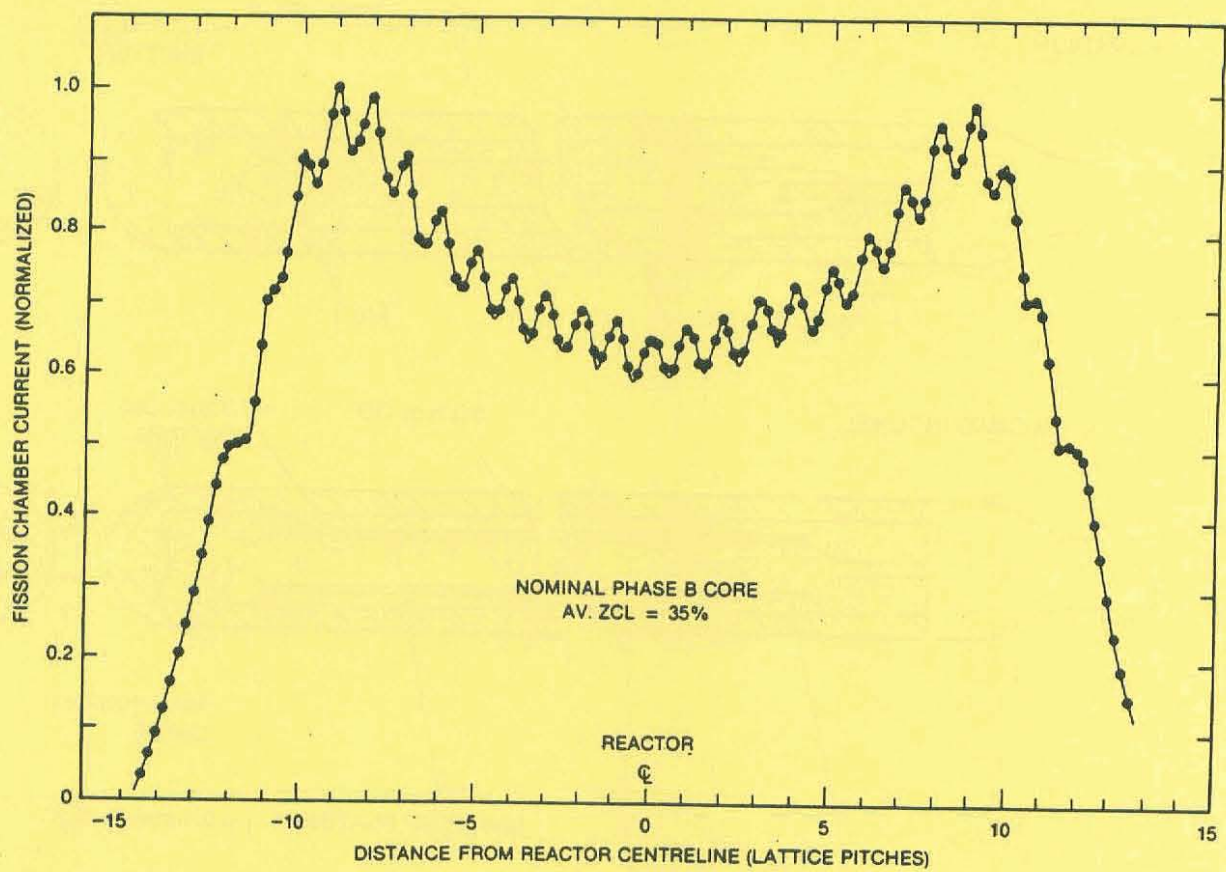
FIGURE 4 DESIGN CONCEPT OF SIR DETECTOR ASSEMBLY

**FIGURE 5 RADIAL DISTRIBUTION OF THERMAL NEUTRON FLUX
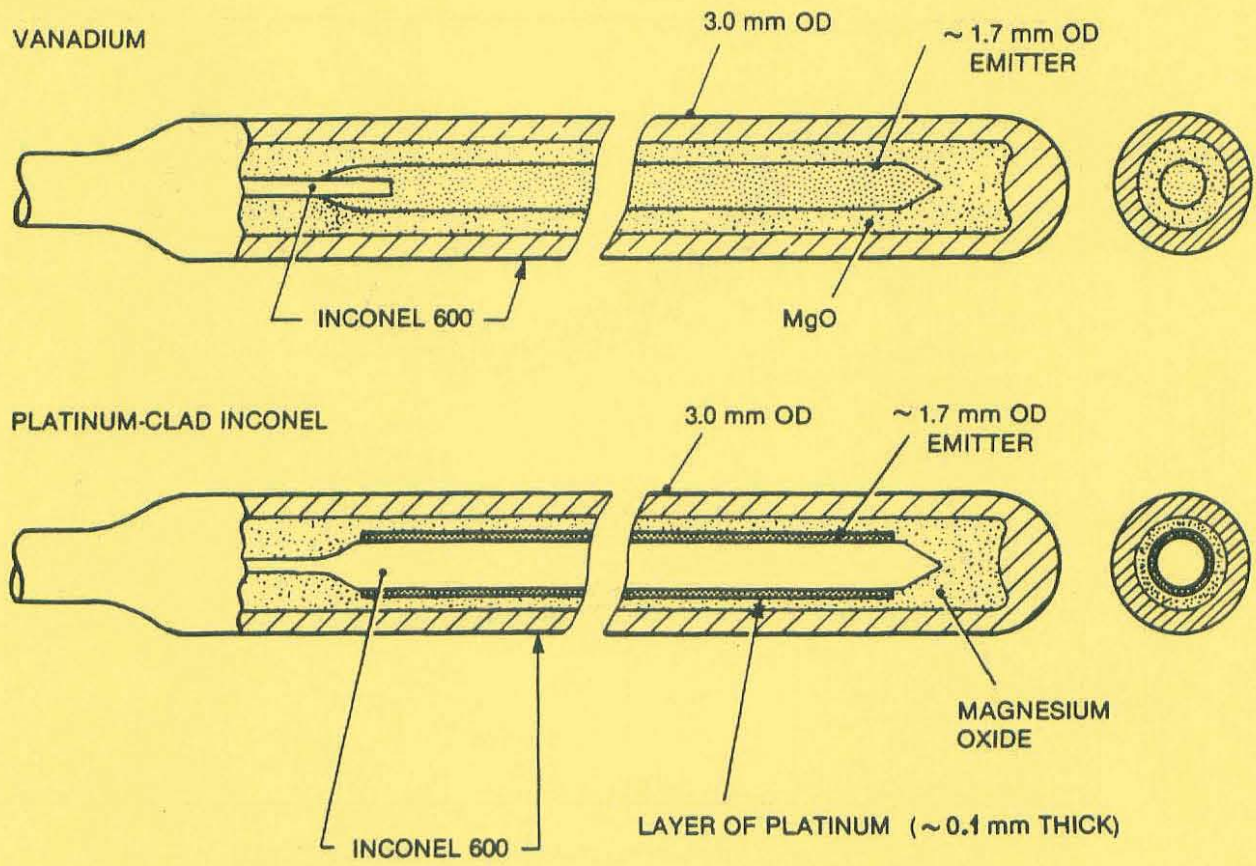(MEASURED IN BRUCE NGS 'A' WITH TRAVELLING FLUX DETECTOR)**

VANADIUM

3.0 mm OD
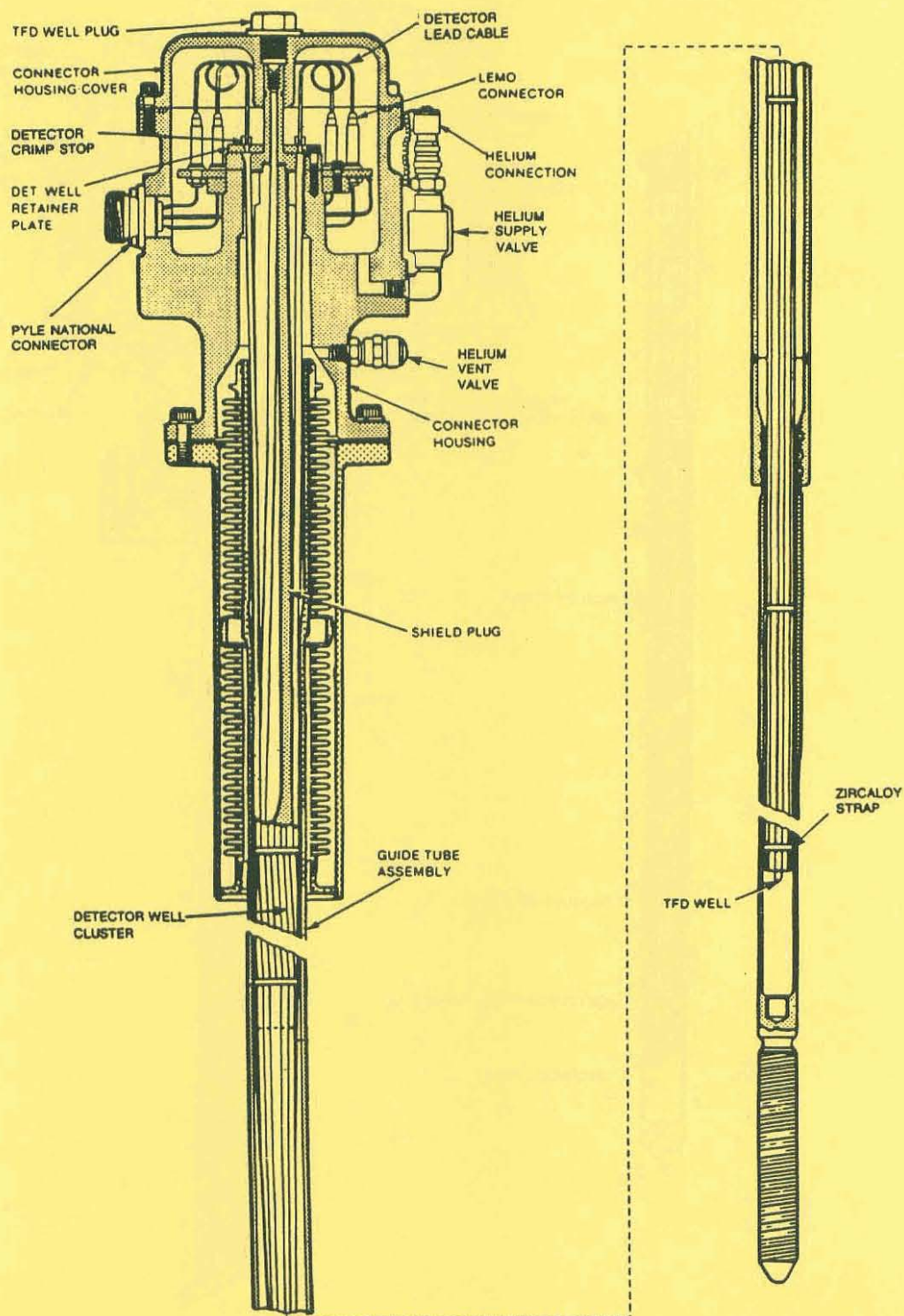
~1.7 mm OD
EMITTER

INCONEL 600

MgO

PLATINUM-CLAD INCONEL

3.0 mm OD

~1.7 mm OD
EMITTER

INCONEL 600

LAYER OF PLATINUM (~0.1 mm THICK)

MAGNESIUM
OXIDE

FIGURE 6 SIR DETECTORS

TFD WELL PLUG

DETECTOR LEAD CABLE

CONNECTOR HOUSING COVER

LEMO CONNECTOR

DETECTOR CRIMP STOP

HELIUM CONNECTION

DET WELL RETAINER PLATE

HELIUM SUPPLY VALVE

PYLE NATIONAL CONNECTOR

HELIUM VENT VALVE

CONNECTOR HOUSING

SHIELD PLUG

ZIRCALOY STRAP

GUIDE TUBE ASSEMBLY

DETECTOR WELL CLUSTER

TFD WELL

FIGURE 7 SIR DETECTOR ASSEMBLY

TFD WELL PLUG

DETECTOR
LEAD CABLE

CONNECTOR
HOUSING
COVER

CONNECTOR
MOUNTING RING

LEMO CONNECTOR

PYLE NATIONAL
CONNECTOR

HELIUM SUPPLY
VALVE

HELIUM PURGE VALVE
(SHOWN OUT OF TRUE POSITION)

LEMO RECEPTACLE

CONNECTOR HOUSING

ZIRCALOY STRAP

SHIELD PLUG

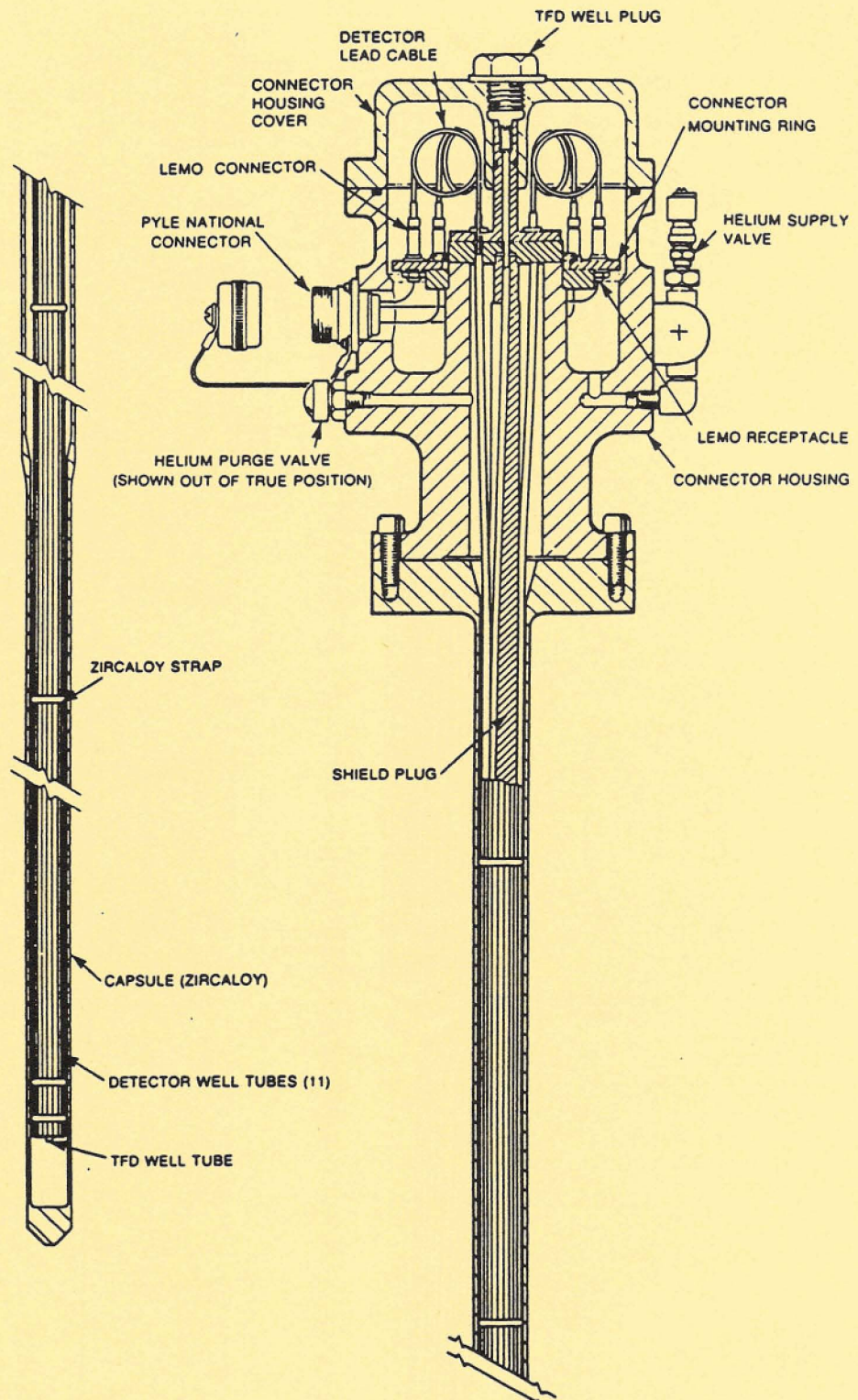CAPSULE (ZIRCALOY)

DETECTOR WELL TUBES (11)

TFD WELL TUBE
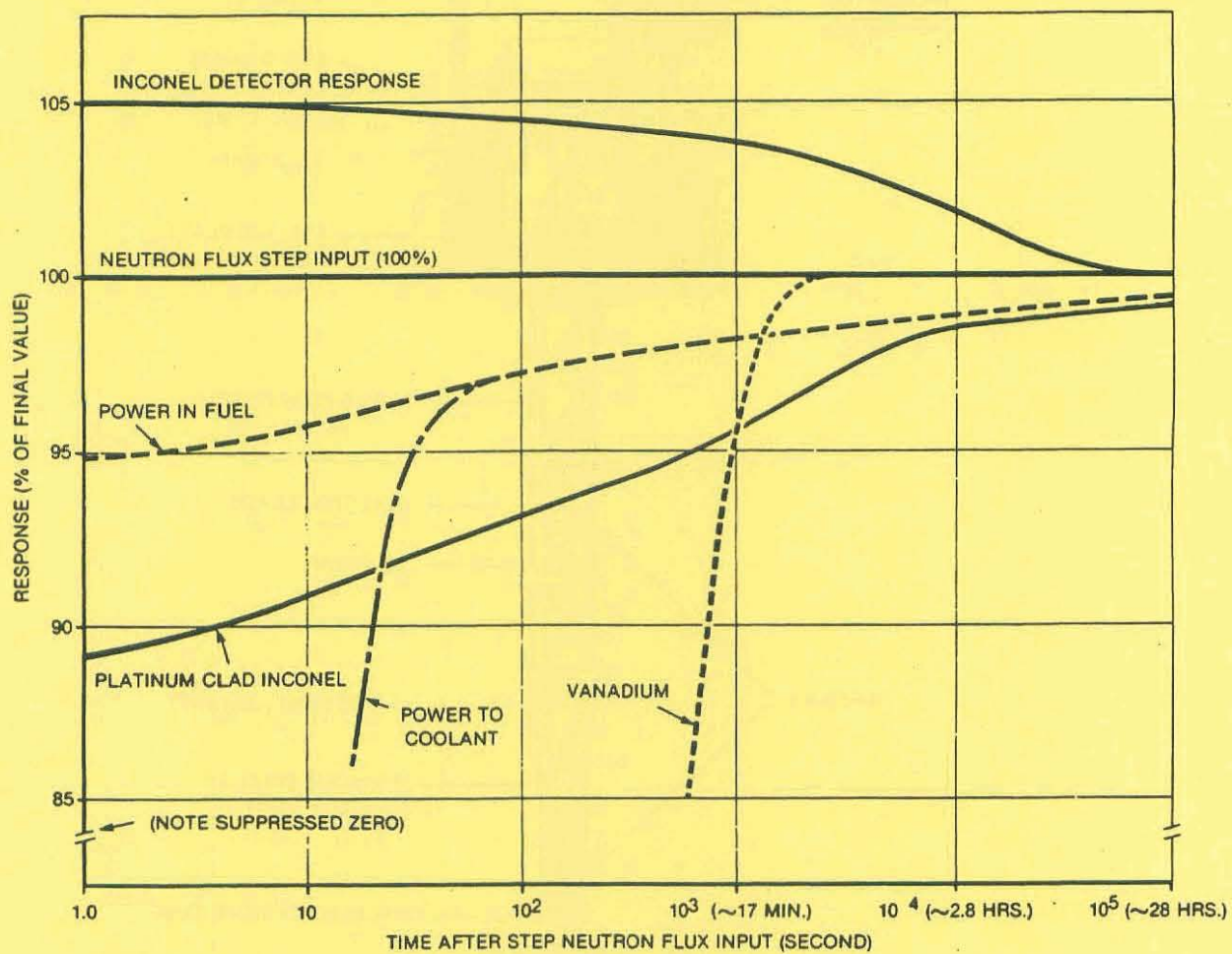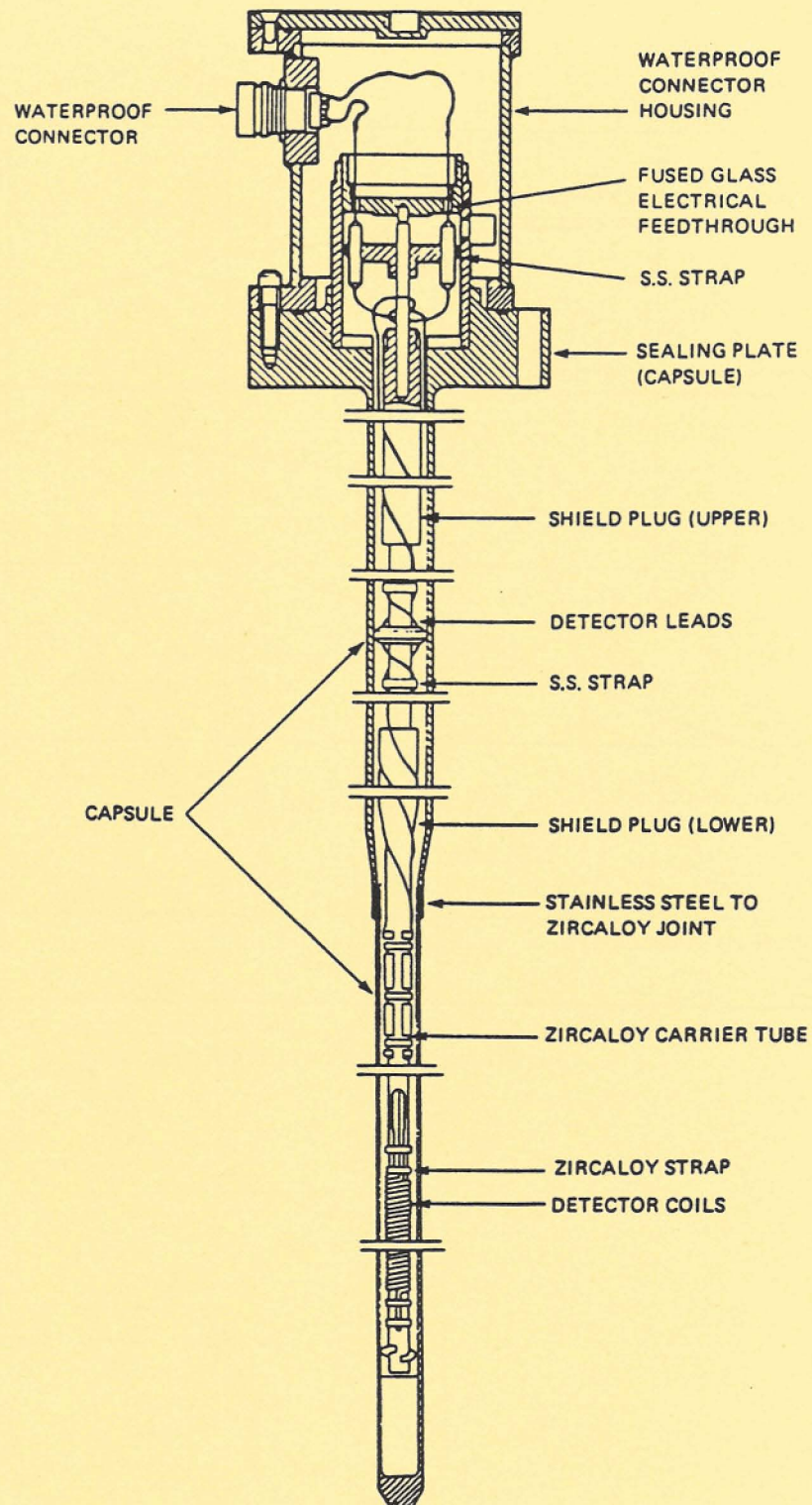
FIGURE 8 HESIR DETECTOR ASSEMBLY

FIGURE 9 DYNAMIC RESPONSE OF SIR DETECTORS

**FIGURE 10 ENCAPSULATED COILED DETECTOR ASSEMBLY
(ORIGINAL CANDU 6 DESIGN)**