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DEVELOPMENT OF A 10-DECADE SINGLE-MODE REACTOR FLUX MONITORING SYSTEM*

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ABSTRACT

Conventional wide-range neutron channels employ three operational modes to monitor the required flux range from source levels to full power (typically 10 or more decades). Difficult calibrations are necessary to provide a continuous output signal when such a system switches from counting mode in the source range to mean-square voltage mode in the midrange to dc current mode in the power range. In an ORNL proof-of-principle test, a method of extended range counting was implemented with a fission counter and conventional wide-band pulse processing electronics to provide a single-mode, monotonically increasing signal that spanned ~10 decades of neutron flux. Ongoing work includes design, fabrication, and testing of a complete neutron flux monitoring system suitable for advanced liquid metal reactor designs.

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INTRODUCTION

A flux monitoring system for a liquid metal-cooled reactor (LMR) must provide prompt indications of reactor power to the plant control system (PCS) and plant protection system (PPS). It must also provide subcriticality information during fuel loading and reloading. To fulfill these requirements, a flux monitoring system (FMS) should provide flux level, reactor thermal power level, and period information to the PCS over the full reactor operating range from initial clean-core loading and subsequent refueling up to at least 130% of full reactor power and must remain monotonic at even higher power levels. PPS requirements dictate a diverse method of flux measurement in the power range as well as in situ verification of operability for the entire flux monitoring channel prior to reactor startup. Two developments are required to provide such a system for commercial LMRs.

The first development is a high temperature, high sensitivity fission counter (HTHSFC) designed for in-vessel placement and a thermal neutron sensitivity > 5 counts$\cdot s^{-1} \cdot [neutrons/(cm^2 . s)]^{-1}$ or cps/nv_{th}.[1] The second development needed for optimal LMR flux monitoring is a measurement channel with capabilities for providing continuous flux signal over a specified 10-decade range, being calibrated against reactor thermal power, and demonstrating operability prior to initial core loading. Although the 10-decade flux measuring range can be obtained with a conventional fission counter by switching between three different measurement modes (pulse counting, mean-square voltage or campbelling, and dc current), each mode requires separate circuitry with attendant complications of overlap and alignment requirements. This type of system is used in the Fast Flux Test Facility, MONJU, and in the Clinch River Breeder Reactor design. Alignment and calibration of a wide-range three-mode flux channel is usually a difficult and time-consuming operation.

Incorporation of HTHSFC into a flux monitoring channel covering both the conventional source range and the wide range has provided some of the desired characteristics. Operability of the entire channel can be verified prior to initial core loading, and addition of an extended-range counting (ERC) circuit allows a full 10-decade pulse counting range with a single-mode channel. Resulting flux monitoring system concepts have been adopted as design bases for two contemporary modular LMR designs in the United States: the Sodium Advanced Fast Reactor (SAFR) design of Rockwell International and the Power Reactor Inherently Safe Module (PRISM) design of General Electric. These designs are not final; some additional ex-vessel flux monitors (fission counters or compensated ion chambers) may be installed to provide diverse signals to the PPS in the power range, but their availability would not require additional development.

EXTENDED RANGE COUNTING APPROACH TO
WIDE RANGE FLUX MEASUREMENT

The upper end of useful range for a conventional level-sensitive counting system is often considered to be the point at which pileup-induced counting losses exceed 10%. In a well designed system, output count rate tends toward saturation beyond this point and eventually becomes insensitive to further increases in input rate. However, with properly designed linear circuitry, measurable variation in the analog signal (i.e., discriminator input) continues to occur for several more decades of input range.

A typical system for making average rate measurements of a Poisson distributed time series of discrete events (e.g., neutrons interacting in uranium oxide coatings of a fission counter, Fig. 1a) consists of a detector, a pulse-shaping amplifier (PSA), a level-sensitive discriminator (differential comparator), and a count-rate meter. The useful range of this system is limited at the low count-rate end by either signal-to-noise considerations or by constraints on sampling time; at the high end it is limited by the detection system bandwidth. For very high event rates, counting rates will saturate at

$$f_0 \approx \frac{1}{2\pi}\left(\frac{\int_0^\infty \omega^2 |T(\omega)|^2 d\omega}{\int_0^\infty |T(\omega)|^2 d\omega}\right)^{1/2} \qquad (1)$$

where ω is the radial frequency and $T(\omega)$ is the total transfer function of the system from the detector to the comparator input.[2] A count-rate vs event-rate [$C(\nu)$ vs ν] characteristic for this system shows rapid saturation of count rate and attendant loss of sensitivity (i.e., $S = dC/d\nu$) for event rates $\nu > f_0/10$. In particular, S rapidly approaches zero for $\nu > 10f_0$ in which range the level-crossing rates (i.e., the rate at which a signal makes positive or negative transitions across the threshold level) are given approximately by the following equation (which assumes Gaussian statistics):

$$C(V_{th}) = f_0 \exp(-V_{th}^2/2\sigma_v^2) \quad , \qquad (2)$$

where V_{th} is the threshold level and σ_v is the rms signal voltage.[2] Through the use of Campbell's theorem, Parseval's theorem, and a small amount of manipulation, it can also be shown[2] that

$$\sigma_v^2 = \nu\overline{q^2} \int_{-\infty}^{\infty} [F(t)]^2 dt = \frac{\nu\overline{q^2}}{\pi} \int_0^\infty |T(\omega)|^2 d\omega = k\nu\overline{q^2} \quad , \qquad (3)$$

where $\overline{q^2}$ is the mean-squared value of the input charge distribution, F(t) is the time response at the PSA output to unit charge deposition in the detector, and k is a system constant derivable from either F(t) or $T(\omega)$. Thus,

$$C(V_{th},\nu) = f_0 \exp(-V_{th}^2/2k\nu\overline{q^2}) \quad , \qquad (4)$$

and consequently $\lim_{\nu\to\infty} C(V_{th},\nu) = f_0$ and $\lim_{\nu\to\infty} S = 0$. It also follows that vanishing sensitivities resulting from large values of ν can be restored by increasing $|V_{th}|$, but this measure would diminish sensitivity in the linear count-rate region.

FUNCTIONAL DEPENDENCE OF EXTENDED RANGE COUNTING [C(ν)]

Preceding considerations show that the sensitive range of a conventional counting system can be extended by operating the system at relatively low threshold values through the linear count-rate region and at increasingly higher threshold values as pileup effects begin to dominate the signal. This threshold adjustment function is accomplished automatically by adding negative feedback from the count rate output of a conventional counting system to the input of its comparator [Fig. 1a with a nonzero feedback gain (FBG) setting].

About the simplest realization of the ERC block of Fig. 1a is a single-pole inverting integrator (Fig. 1b), which has a long time constant (i.e., $\tau_1 = R_1C_1 >> 1/f_0$) so that its response to an isolated pulse from the comparator produces an insignificant change in the differential discriminator threshold, $V_d = V_{fb} - V_{th}$. However, as threshold level-crossing rates increase toward f_0, V_{fb} tends toward a level determined by the FBG adjustment. The amount of range extension provided by this simple negative feedback mechanism depends on the FBG setting. The purpose of the "ideal diode" is to provide a threshold (V_{ft}) to suppress feedback until a predetermined event rate is exceeded, thus delaying the onset of nonlinear counting.[3]

Substitution of $V_d = V_{fb} - V_{th}$ into Eq. (4) yields

$$C(V_d,\nu) = f_0 \exp[-(V_{fb}-V_{th})^2/2k\nu\overline{q^2}] \quad . \tag{5}$$

If action of the ERC feedback circuit is approximated as

$$V_{fb} \approx \begin{cases} \kappa\bar{\tau}C - V_{ft} & \text{for } \kappa\bar{\tau}C \geq V_{ft} \\ 0 & \text{otherwise} \end{cases} \quad , \tag{6}$$

where κ is a circuit gain constant and $\bar{\tau}$ is the average duration of a signal excursion above the level V_d, then Eq. (5) becomes

$$C(V_d,\nu) = f_0 \exp\left[-\kappa^2\bar{\tau}^2\left(C - \frac{V_{th} + V_{ft}}{\kappa\bar{\tau}}\right)^2/2k\nu\overline{q^2}\right] \quad . \tag{7}$$

Substitution of the final definitions, $K = \kappa^2\bar{\tau}^2/2k\overline{q^2}$ and $C_0 = (V_{th}+V_{ft})/\kappa$, results in

$$C(V_d,\nu) = C[V_d(C),\nu] = f_0 \exp[-K(C-C_0)^2/\nu] \quad , \tag{8a}$$

or, by dropping explicit functional notation, taking the logarithm of both sides, and rearranging, the following explicit expression for the event rate ν is obtained.

$$\nu = \frac{K(C-C_0)^2}{\ln(f_0/C)} \quad , \tag{8b}$$

subject to the inequality of Eq.(6).

It can be inferred from Eq. (8b) that the count rate C is approximately proportional to $\nu^{1/2}$ for $C \gg C_0$ (e.g., $C_0 = 0$) and for $f_c/C \gg 1$. Thus an ERC measurement bears some similarity to a root-mean-square voltage measurement of a shot noise signal as well as to the mean-square voltage (MSV) or campbelling measurement technique. However, ERC has potentially a distinct advantage over campbelling, as shown in Fig. 2, which depicts the stochastic signal $\tilde{V}(t)$ at the output of a linear amplifier having output saturation levels of $\pm V_S$. Since campbelling involves a time average of $\tilde{V}^2(t)$, it is very sensitive to clipping caused by output saturation, and deviations from the expected linear relationship between V^2 and ν can be large and device dependent. The ERC method, however, will exhibit a predictable C vs ν relationship even in the presence of extensive clipping if the following two conditions are met:

1) $-V_S < V_d < +V_S$,

2) Signal saturation for $t_1 \leq t \leq t_2$ has no effect on the value of $\tilde{V}(t)$ for $t < t_1$ and $t > t_2$.

Another way of stating the second condition is that the amplifier output stages must enter and depart a saturated state quickly and gracefully. Fulfillment of both conditions should result in a system with inherent monotonicity.

ERC PROOF-OF-PRINCIPLE MEASUREMENT

A neutron flux monitoring system was assembled using prototypic ERC circuitry to investigate the feasibility of obtaining > 10 decades of flux measurement range with a single ERC counting mode. ORNL's system consisted of a 25-cps/nv_{th} transmission line fission counter,[4,5] two low-noise 60-MHz bandwidth preamplifiers,[6] and a prototype ERC data processing module. Incorporated in the module were a linear pulse shaping amplifier of ~20 MHz bandwidth and a fast comparator with an embodiment of the ERC feedback loop as shown in Fig. 1b. The system was installed at the ORNL Bulk Shielding Reactor Facility with the fission counter suspended in the pool near the core's face. Count-rate outputs from the prototype module were interfaced to an automatic data acquisition system, allowing us to follow exponential flux excursions resulting from 30-s reactor periods. Concurrent high voltage supply current (I_{dc}) measurements were obtained with a digital microammeter, as were rms values of the signal voltage ($\overline{V^2}^{1/2}$) using a true rms voltmeter.

Data obtained during one of these 30-s excursions are plotted in Fig. 3. The need for complex mode switching in a conventional flux measuring system (i.e., a system consisting of a non-ERC counting channel, an MSV channel, and an I_{dc} channel) is evident. For example, at a flux of ~10^5 nv_{th}, the counting channel becomes nonlinear, but the flux is sufficiently high to override nonlinear fission product contributions to the response of the MSV channel. The measurement mode would therefore be switched to MSV which is linear up to about 10^8 nv_{th}. This latter flux is high enough to override any nonlinear response of I_{dc} to fission product activity. Note that even if nonlinear response were acceptable, the conventional counting channel is fully saturated at 10^7 nv_{th} and the I_{dc} channel is saturated below 10^5 nv_{th} so neither mode can span the full range.

Data on the bold curve, $C = C[\nu(\phi_{th})]$, are the responses of the prototype ERC system. Apparent saturation below 100 nv_{th} is due to nonfission neutron sources including delayed contributions and photoneutrons; in a "clean-core" situation, its response would follow the linear portion of the conventional count rate curve, C'. The effective sensitivity of the fission counter was reduced from 25 to ~8 cps/nv_{th} because electromagnetic interference and ground loops required a relatively high value for the counting threshold (V_{th}) to eliminate spurious counts. Despite these difficulties, the ERC system provided a monotonically increasing response from 100 to > 10^9 nv_{th}. Further, it is clear that if the flux could have been reduced below the shutdown value, the linear counting region would extend to ~10^{-1} nv_{th} for a total dynamic range of 10 decades.

The bold curve segment extending from 2 × 10^4 to 2 × 10^9 nv_{th} was generated from Eq. (6b) with $K = 7.58 \times 10^{-4}$ s, $C_0 = 1.16 \times 10^5$ s^{-1}, and $f_0 = 2.9$ MHz. Although these values were chosen to provide a good fit to the data, K and C_0 were within 20% of values based on estimates of system parameters (e.g., $\overline{q^2}^{1/2}$ ~0.18 pC, $\kappa = 10$, $k = 8 \times 10^{16}$ Ω^2/s, etc.), while f_0 appeared to be low by a factor of 3. We found that, although the prototype ERC module was capable of counting at rates > 8 MHz in a conventional mode, the output stages of our linear amplifiers were not responding well to hard saturation in an ERC mode, and f_0 was effectively being reduced to < 3 MHz.

Departure of the analytic curve from the data for fluxes < 2 × 10^5 nv_{th} is due to failure of Gaussian statistics at lower count rates. However, we are encouraged by good agreement in the high flux range because count-rate to flux conversion functions will be an important consideration for practical control and safety systems.

SINGLE-MODE ERC FLUX MONITORING SYSTEM

We are presently designing a demonstration flux measurement system (Fig. 4) intended to provide a continuous single-mode signal over a flux range of at least 10 decades. This system will be functionally similar to the previously described proof-of-principle prototype but with several modifications that were indicated by our experimental results. The three most important modifications are as follows:

(1) No feedback threshold will be incorporated in our demonstration unit (i.e., $V_{ft} = 0$). The incentive for setting $V_{ft} > 0$ was to extend the linear counting range; however, our microprocessor based demonstration system incorporates count rate to flux (or full power) conversion algorithms, so linearity of raw signals is not a critical issue. In fact, the absence of a feedback threshold appears to have several advantages. Namely, the circuitry is simpler and will provide a smooth transition from linear counting into the ERC region (i.e., the knee of the C vs ν curve of Fig. 3 will be much less distinct and will not contain the inflections due to our imperfect realization of an "ideal diode"). A related effect will be increased measurement sensitivity in the ERC region.

(2) The output stage of the linear pulse shaping amplifier that drives the comparator input has been modified to minimize saturation recovery time.

This measure should eliminate any reduction of the effective f_0-value and hence increase the dynamic range.

(3) Overall gain of the linear pulse shaping amplifier has been reduced to the minimum value required for reliable operation in the linear counting range. As seen from Eq. (3), a gain reduction of $\sqrt{10}$ will defer saturation effects by a full decade of flux.

With the above noted modifications, we expect that the useful range of this system will be at least 10 and perhaps as many as 11 decades. Note that ERC does not have to be used with high sensitivity detectors if conventional detectors can provide adequate data rates in the source range.

Our demonstration system will not be nuclear 1E qualified but will allow us to study important aspects of ERC mode operation such as accuracy, reproducibility, temperature stability, etc. It will have many features found in conventional flux monitoring systems plus a few nonconventional features. Since this system is microprocessor based, its operating characteristics will not be fully determined until operating firmware is completed. However, currently planned features supported by our hardware design include the following:

(1) a 10-decade single mode flux range;
(2) conventional outputs of cps, log cps, d/dt cps, d/dt log cps, linear % power, d/dt % power, and tone bursts;
(3) dc current mode indication in the power range (backup to ERC measurements);
(4) continuous flux calibrations against reactor thermal power based on signals derived from flow rate and ΔT of the primary coolant;
(5) continuous flux summation for estimating fluence-dependent properties such as detector sensitivity and remaining expected lifetime;
(6) suitable output interfaces for plant control, safety, and display systems (both serial and parallel);
(7) automatic self-test features such as electrical continuity through the detector (with two-cable, transmission line fission counters), continuous monitoring of local supply voltages, and a fail-safe configuration of setpoint optical isolators.

DISCUSSION

There is still much work to be done before single-mode ERC flux monitoring systems will be found in the PCS and PPS of an LMR, but results obtained thus far are very encouraging. We have demonstrated a proof of principle with a measurement that also provides some additional insights into improved design methods for the ERC portion of the circuitry. Experimental data in the extended counting range were found to be in good agreement with a probabilistic model based on Gaussian statistics, which indicates that relatively simple functions may be used to perform conversions from count rate to flux. In the linear counting range the count rate will be proportional to the flux (i.e., the conventional relationship), and the proportionality constant will be the detection sensitivity of the fission counter. The transition region between linear and extended range counting will require a

Poisson statistical treatment which might be replaced by an arbitrary polynomial function with appropriate side conditions (e.g., Lagrange) to match value, slope, and curvature at the two transition points. Analysis of data to be obtained with the demonstration system will hopefully shed some light on these matters.

Another area of ERC performance requiring some attention is effects of signal statistics on operation of the PCS and PPS. In the linear counting region, performance will be identical to a conventional counting channel, but in the extended range, each datum is still a Poisson distributed variable with predictable statistical properties. For instance, we do not expect f_0 values to greatly exceed 10 MHz, so if a time response of 1 ms is required from the system at full reactor power then $C\Delta t < 10^4$ counts and the associated deviation is $\sigma_C > 1\%$. It can be shown that if C is assumed to be locally proportional to $\phi_{th}^{1/n}$, then the associated percent statistical uncertainty in the measurement is $\sigma_\phi = n\sigma_C$. In the extended counting range, n-values are always greater than 2 and increase as C approaches f_0. Thus, ERC circuit parameters must be chosen to minimize n (and hence maximize the measurement sensitivity) over the required flux range. Statistical deviations are superposed on any systematic errors which we would minimize by careful design and calibration. These effects will be most noticeable in rate calculations (e.g., reactor period) and may necessitate significance tests to smooth the statistical fluctuations.

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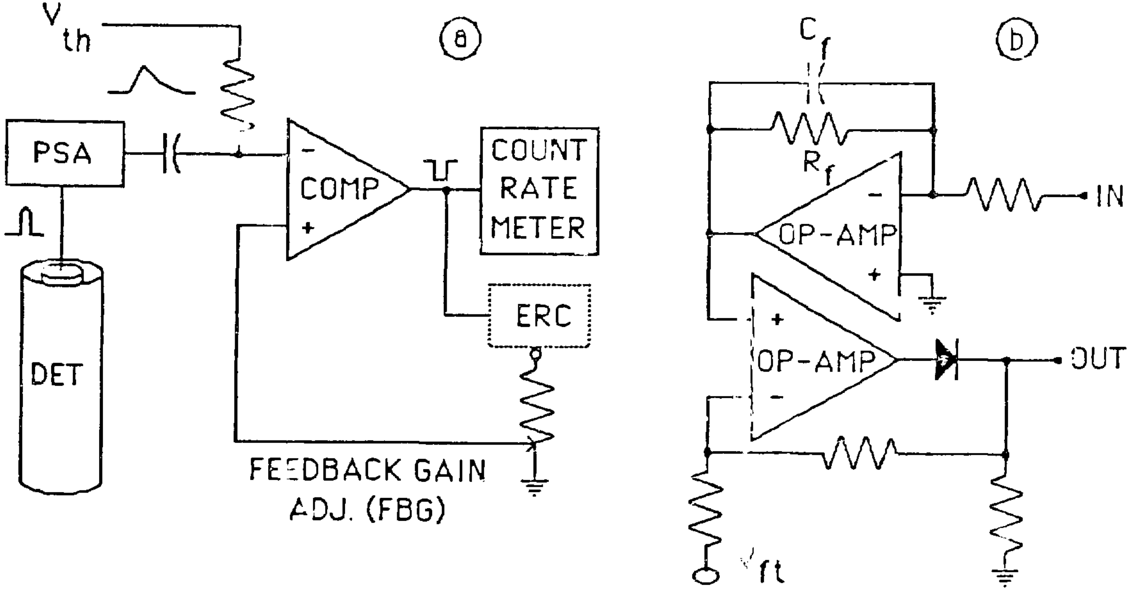
Figure Captions

Fig. 1. (a) In a conventional pulse counting system (i.e., one without ERC circuitry), V_{th} must be negative enough to limit the spurious count rate to an acceptable level. The ERC circuit increases the differential counting threshold with increasing output count rate from the comparator. (b) A simple realization of the ERC negative feedback loop consists of a single-pole integrator with an optional "ideal diode" to suppress feedback until a preset value of ν is exceeded (determined by V_{ft}).

Fig. 2. A time trace of the stochastic signal $\tilde{V}(t)$ shows clipping due to amplifier saturation at $\pm V_s$. An MSV measurement is sensitive to this clipping, but an ERC measurement depends only on signal values at the discrimination threshold V_d and is therefore unaffected.

Fig. 3. Data obtained with a prototype ERC flux channel during a 30-s period reactor excursion (labeled C) show the linear counting range followed by a transition to the extended counting range. The C′ curve is the calculated response of this channel without ERC circuitry. Also shown are the dc current (I_{dc}) and the MSV ($\overline{V^2}$), which were measured concurrently.

Fig. 4. A simplified block diagram of the demonstration ERC flux measurement system shows the major hardware functions that are implemented. The heart of the system is an embedded microprocessor that controls data acquisition, communications, autocalibration, and self-testing. Capabilities for exploiting the directionality and in situ verification of operability[1] will be supplied by external diagnostic equipment.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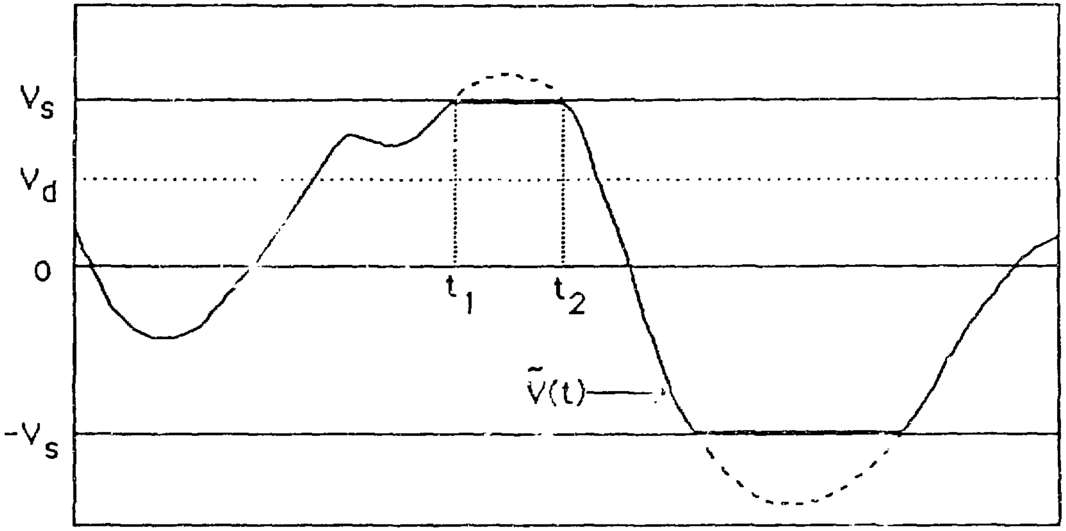
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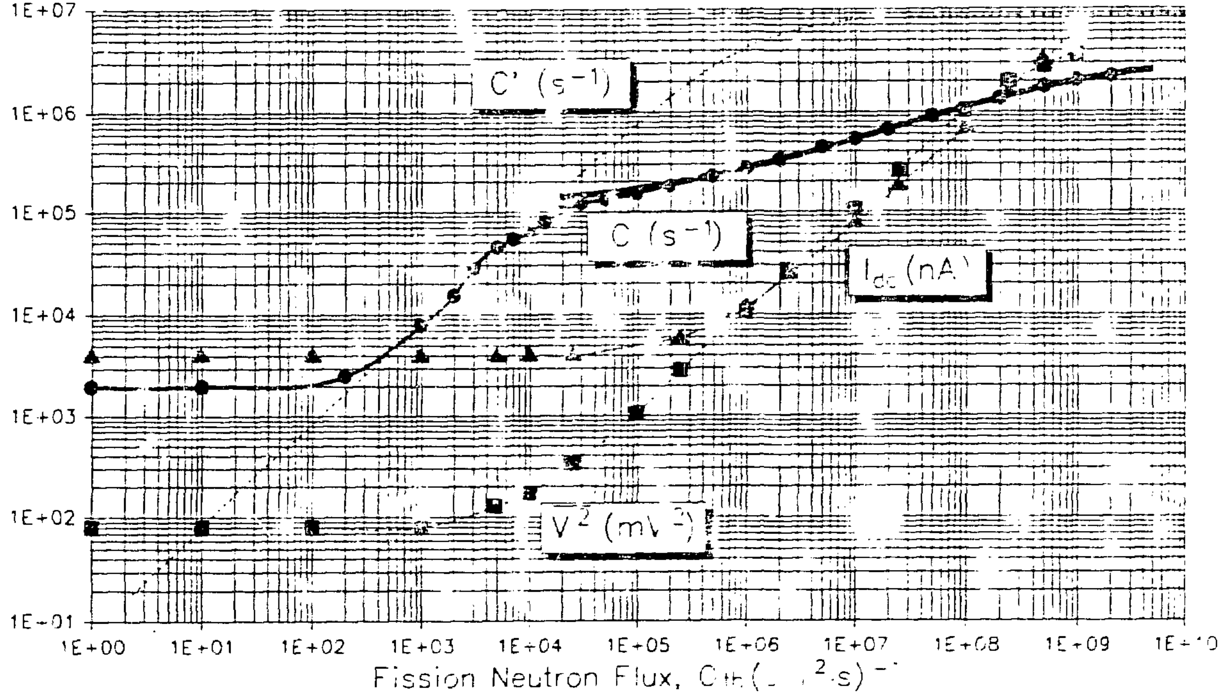
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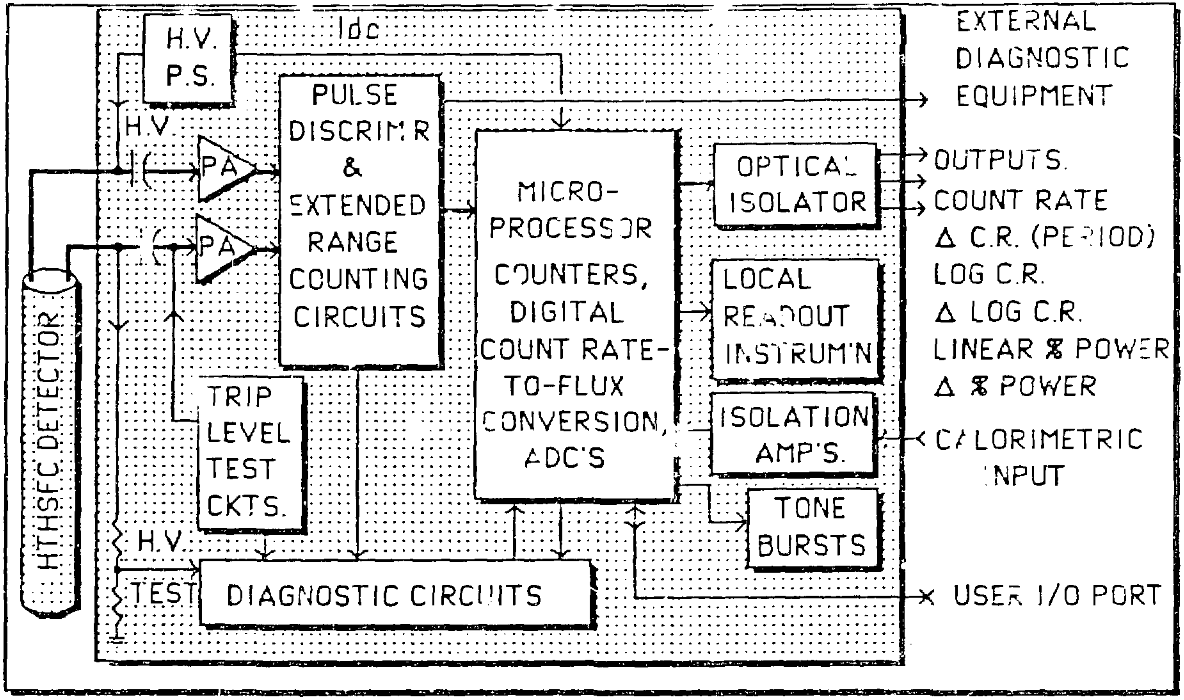
H.V. P.S.
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H.V.
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PULSE DISCRIM'R & EXTENDED RANGE COUNTING CIRCUITS
MICRO-PROCESSOR
COUNTERS, DIGITAL COUNT RATE-TO-FLUX CONVERSION, ADC'S
OPTICAL ISOLATOR
LOCAL READOUT INSTRUM'N
ISOLATION AMP'S.
TONE BURSTS
TRIP LEVEL TEST CKTS.
HTHSFC DETECTOR
H.V.
TEST
DIAGNOSTIC CIRCUITS
EXTERNAL DIAGNOSTIC EQUIPMENT
OUTPUTS.
COUNT RATE
Δ C.R. (PERIOD)
LOG C.R.
Δ LOG C.R.
LINEAR % POWER
Δ % POWER
CALORIMETRIC INPUT
USER I/O PORT