UPGRADE OF NEUTRON FLUX MONITORING SYSTEMS OF RESEARCH REACTORS WITH DIGITAL SYSTEMS

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Examples from recent modernization projects for which Mirion has supplied the neutron flux monitoring systems are presented. These examples shall provide useful information to operators of facilities which, in the near future, will need to upgrade or modernize all or parts of their aging equipment in order to assure the safety and availability of the reactor.
Included are advancements from the latest project, the upgrade of the existing linear and safety channels at the PULSTAR research reactor of the NCSU with new CICs and the digital linear multi-range signal processing units DAK 260-g. In this context, the importance of a thorough requirement engineering process, the pitfalls of incompleteness of the same and the benefits of a modular system like the proTK platform, which basically allows retrofitting a powerful digital system into any given environment, is presented.

1. Introduction

Central to Mirion's neutron flux and radiation monitoring systems is the digital signal processing platform proTK™. It encompasses the powerful and well-known TK 250 signal processing units that have been developed in the 1980s and that have since accumulated thousands of years of continuous operation, but also the newest generation of signal processing units, the so-called proTK™ / 260 series.

In the following chapters an overview of the proTK signal processing units as well as a general overview of what Mirion has to offer to the research reactor community in terms of neutron flux monitoring systems, other safety critical systems and how Mirion engineering services help to identify operator requirements, to specify the system as well as to customize it.

This offering is exemplified with one of the most recent projects, as part of which neutron flux monitors have been supplied to a research reactor in the US.

In the first part of the following section a short discussion on digital versus analog signal processing is presented.

2. Signal Processing for Neutron Flux Monitoring and Safety Critical Radiation and Process Monitoring Systems

2.1. Digital vs. Analog

Typically, when refurbishing aging equipment in a nuclear facility, the existing electronics is purely analog and one of the first questions that must be answered when selecting a vendor for the signal processing units is whether the new system shall be again purely analog or if the upgrade to a digital system isn't the better choice.

Some of the benefits of a digital system are more obvious than others. To help the operator with the decision making, some of the relevant features that distinguish digital from analog systems are discussed here.
The main advantages of a digital signal processing system consist in its operational flexibility and comfort, such as easier configuration and parameterization, but also the possibility to implement complex features and functions. This improves the performance of the system but also leads to a higher degree in reliability due to easier implementation of monitoring functions for the integrity of a system.
Analogue systems are considered as simpler and therefore by default more predictable. However, the extra information that is obtained through additional monitoring functions that are more easily implemented with a digital system are more than just compensating for the added complexity.

Apart from solving issues with analogue systems, software-based equipment also offers a series of advantages. To name just a few:

1. Digitally or numerically implemented signal processing algorithms provide stable readings with high precision over an unlimited period. This includes - but is not limited to - the calculation of logarithmic scales of output signals and the calculation of alarm and trip signals thresholds, which are not prone to gradual shifting due to drifting characteristics of analogue components.
2. The calibration of the output signals e.g. into neutron flux density or percent power consists of a simple conversion through multiplication. Again, this calibration remains stable and is not subject to any drift as long as the characteristics of the input signal does not change.
3. The useful range of the application can be significantly enlarged by the use of flexible parameters. One example given here is the integration of numerical signal lowpass filtering with a variable time constant that adapts to the level of the input signal.
4. Complex functions are more easily implemented. For example, the merging of the partially overlapping pulse and Campbell processed signals into a combined, smooth wide range signal becomes a real asset when implemented in software especially with respect to the calibration process for these signals, which is lengthy procedure for analogue implementations.

The safety of Mirion's digital signal processing units of the proTK™ product family is enforced by a series of measures:

1. A high degree of self-monitoring for hardware and software is implemented for minimizing the risk of undetected failures. This allows increasing the period between periodical tests due to increased reliability. Operational data confirms these assumptions.
2. Extensive self-testing features are integrated. This includes test signal generators that can be remotely activated and the possibility of simulating output signals of any kind (e.g. binary alarms and trips or analogue output signals). This shortens the time required for completing the periodical testing.
3. The software and the algorithms of the signal processing are implemented in EPROM (erasable programmable read-only memory) or stored in flash memory. In both cases the code is protected from malicious manipulations and is continuously monitored for potential changes.
4. User adjustable parameters are checked for validity when deliberately adjusted and continuously monitored for inadvertent changes.

It is concluded here that due to its increased functionality and versatility, a digital system outperforms a purely analog system, provided that the newly introduced risks through digital systems are addressed and eliminated through appropriate countermeasures.

2.2. Overview of proTK™ Digital Neutron Flux Channels and Cat. A Safety Critical Radiation and Process Monitoring Systems

Due to the modular design of proTK™ hardware and software, any signal processing channel can easily be configured to suit the needs of a nuclear facility. This is of particular interest when aging equipment needs to be replaced with new proTK™ channels. In such a scenario, it is vital that performance and functions of the new equipment are equal or better than what the replaced equipment had to offer. Especially, the characteristics of output signals (type, scaling, etc.) must match that of the old equipment.
In some cases, though, it is not possible to find a configuration that fulfils all requirements and it becomes necessary to adapt a piece of software or make changes to a hardware module. Nonetheless, it has been proven in the past that even in this least favourable scenario the benefits of the new proTK™ equipment surpasses by far the cost of the modernization, especially if considering the increased risk of failing for old equipment that would cause the facility to become inoperable.

Figure 2 gives an overview of typical neutron flux ranges that must be covered by the reactor protection and control instrumentation as well as examples of corresponding proTK™ equipment.

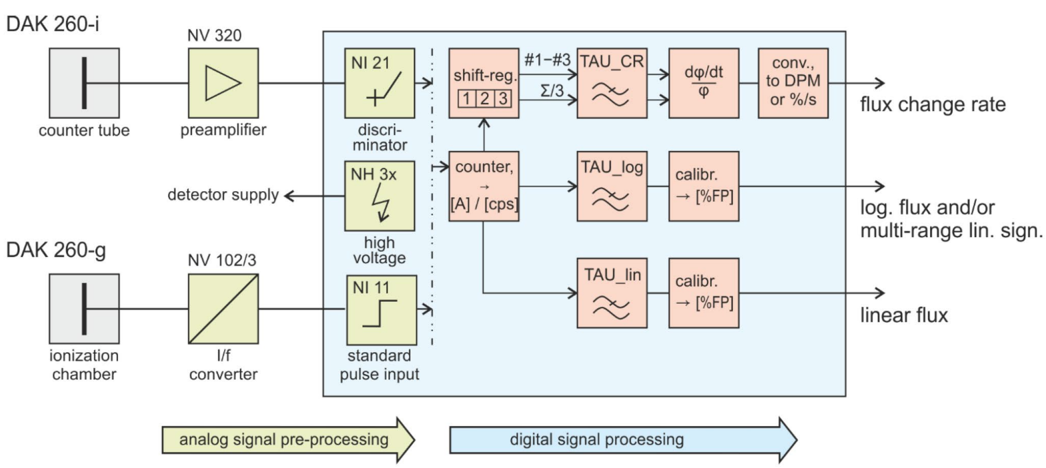

Figure 1: Typical signal path of a start-up channel in pulse or DC mode

An example of typical signal flows for two start-up configurations is shown in Figure 1. Each channel consists of a number of hardware modules with dedicated functions, e.g. for analogue pre-processing of raw detector signals and post-processing of output signals (e.g. through buffered isolation output amplifiers, binary relay cards, etc.). A significant part of the signal processing though is located in micro-controller based modules. The software of the micro-controller cards is also modular in design. Each SW module is responsible for dedicated functions. The interface between analogue and digital signal processing is either a simple pulse counter or an AD converter for scaled analogue inputs. DA converters at the output provide the interface to the subsequent post-processing analogue output modules (e.g.

to the buffered isolation output amplifiers or the binary relay cards; neither are depicted in Figure 1).

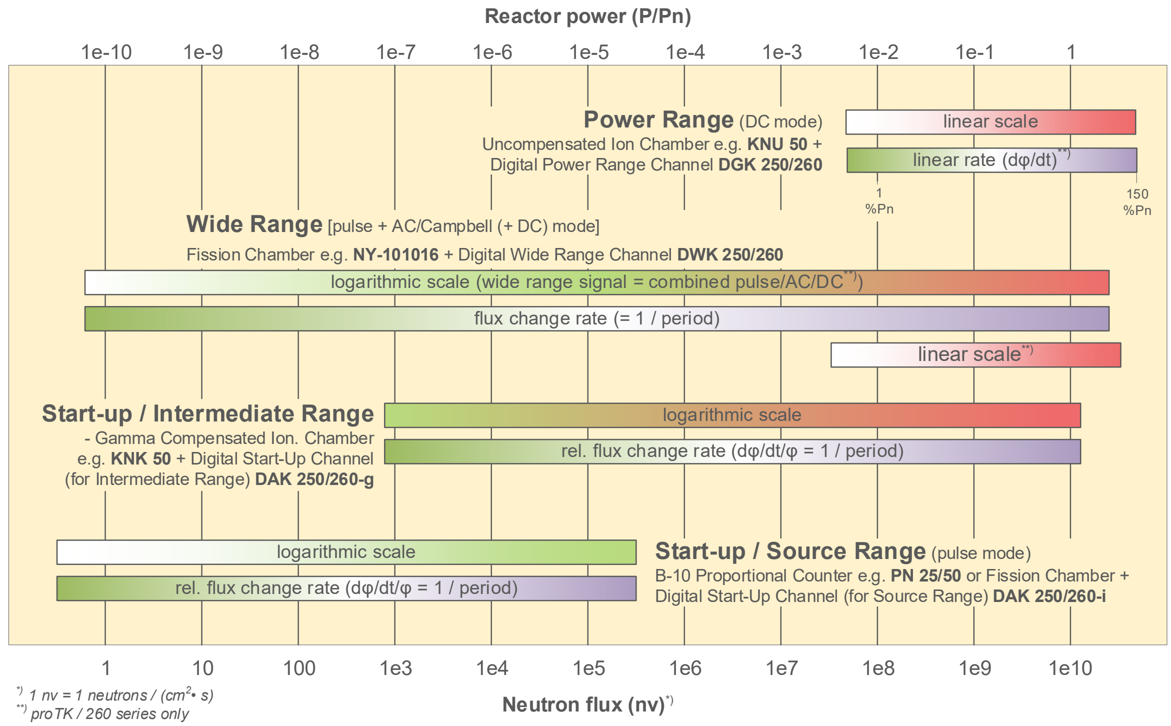

Figure 2: Coverage of neutron flux ranges (or reactor power) through proTK™ channels

In Figure 3, proTK™ neutron flux monitoring systems are listed by operating modes in power generating or research reactors.

Neutron Flux Range		Mirion Monitors	Detector Position / Type		Signal Processing Electronics / Channel	Typical Quantities
Start-Up	Source	SRM 5xx	Ex-Core	B-10, BF3 (PN 25 / PN 50)	Start-up Ch. in Source Range **DAK 250-i / DAK 260-i**	2 … 3 channels
Start-Up	Intermediate	IRM 5xx	Ex-Core	CIC (KNK 50 ACH)	Start-up Ch. in Intermediate Range **DAK 250-g / DAK 260-g**	2 … 4 channels
Start-Up	Wide	WRM 5xx	Ex-Core	Wide-Range FC (NY-10116)	Wide Range Channel **DWK 250 / DWK 260**	3 … 4 channels
Power	Power	PRM 5xx	Ex-Core	UIC (KNU 50 ACH)	Power Range Channel **DGK 250 / DGK 260**	8 … 16 det. 4 DGK
Power	Flux / Power Distribution	PDM 5xx	In-	SPND (WL-xxxxx)	Power Distrib. Channel **DLK 250**	18 … 36 det. 3 … 6 DLK

Figure 3: Typical neutron flux channels in a pressurized water power generating reactor or research reactor; by operation mode of reactor and neutron flux range and the corresponding proTK™ signal processing units and detectors. On the right: designation of corresponding proTK™ monitors from Mirion Technologies (examples).

All signal-processing units mentioned in this paper consist of a configuration of hardware and software modules, similar to those shown in Figure 1.

Furthermore, proTK™ signal processing units can equally be used for other safety critical applications that require similar functions. Examples of such applications include the N-16 or steam generation line monitors SGLM 503/504 (see Figure 4) and the Boron Concentration Monitor BM 501, which is used for continuous monitoring of the concentration of the isotope B-10, which is typically used in PWRs for regulating the level of excess reactivity in the reactor core (see Figure 5).
One SGLM 503/504 channel consists of one digital start up-channel DAK 250-i and one NaI(Tl) gamma scintillation detector SG 65 M or SG 66 R. There are up to two channels per cabinet.

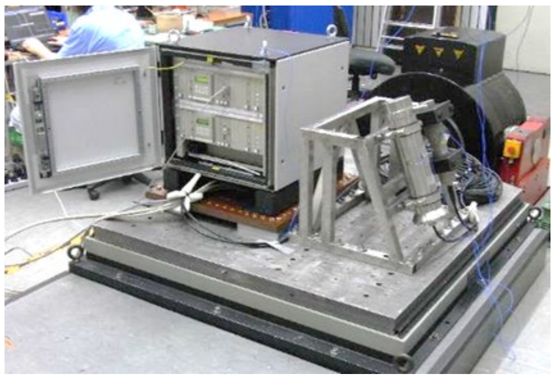

Figure 4: Seismic test set-up for cabinet with two signal processing units DAK 250 i and two NaI scintillation detectors SG 65 M (inside thermal shield) plus SG 66 R on support

The BM 501 is designed to continuously measure the B-10 concentration in water circulating in process pipes in a light water reactor (LWR). Two proTK™ digital signal processing channels DBK 250 and two pre-amplifiers NV 320 are combined with one detection assembly consisting of two B-10 lined proportional counters, a neutron source and moderating/shielding materials.

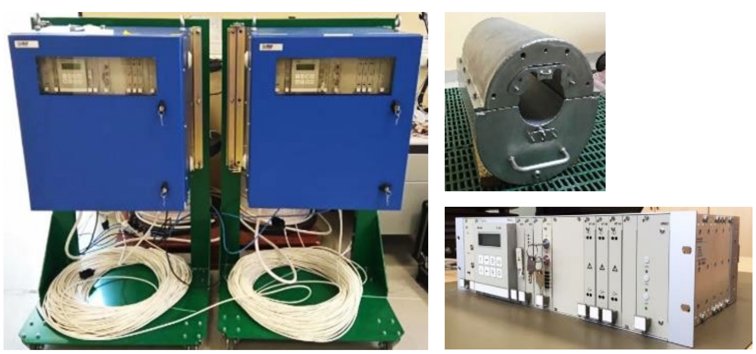

Figure 5: Boron Concentration Monitor (from left, clockwise): Signal processing units in cabinet; detection unit; DBK 250 signal processing modules in 19” rack

3. Recent Installations of Neutron Flux Monitoring Systems

3.1. General considerations

Current and past modernization or upgrade projects for neutron flux instrumentation in which Mirion has been involved have shown that there is a significant amount of insecurity among the stakeholders of such a project. These insecurities can have various causes, but here only the technical aspects are covered.
The two main reasons for the uncertainty about how a modernization project must be approached are derived from 1) the lack of information about all or some of the characteristics of the equipment due to the fact that the equipment is in operation for a very long time and that the documentation is no longer available or not in a state that it can easily "digested" and 2) the fact that the original vendor may be out of business or that technology has evolved and a one-to-one replacement is no longer an option. This may lead to the situation that a new type of equipment will need to be specified and licensed.
The existence of such insecurities among the operators of research reactors has been confirmed in a survey that has been conducted during the last TRTR in 2022.

The same survey also showed that many current installations do not operate equipment from one single vendor but rather have a "mix-n-match" situation. Therefore, it is inevitable that at such a facility part of the neutron flux monitoring system is still functioning and can still be used for some time while other sections of the equipment have aged beyond repair.
This specific situation adds another level of complexity to the modernization process. Not only does it involve specifying the underlying range of the physical parameters (i.e. the neutron flux range) that must be monitored or the number and type of output signals as interfaces to the facility, but since parts of the existing equipment may remain in place, additional, intermediary mechanical and electrical interfaces must be identified and specified.

Therefore, Mirion is supporting any modernization projects not only with state-of-the-art equipment but also with additional services and supporting tasks, including but not limited to:

- Active support with requirements engineering before and after an order is placed, e.g. by informing the buyer/operator on what must be considered for the acquisition, installation, commissioning and operation of neutron flux monitoring equipment and by requesting all the necessary information needed by the vendor for a suitable offering.

- On a case-to-case basis, this support can consist of
    - the identification of the full scope of supply (type and quantity for the complete system or the components: detectors, cables and connectors, signal processing units)
    - Specification of all interfaces to the plant and to the existing peripherals
    - Specification of environmental conditions for all operation modes
    - Establishing the requirements regarding the qualification and the licensing of the equipment based on the existing licensing or, if applicable, the current standards and regulations.

3.2. Modernization Neutron Flux Channels at the NC State University (NCSU)

For the NCSU PULSTAR research reactor Mirion supplied two identical neutron monitoring channels named Linear and Safety Channel consisting of:

- A gamma-compensated neutron ionization chamber (CIC) from Mirion (IST) in Horseheads / NY,
- the intermediate range digital neutron flux monitoring channel DAK 260-g from Mirion's proTK product line including an analog display unit for the neutron flux, and the
- pre-amplifier NV 102.20 H, both for mounting in an existing I&C cabinet in the control room (see Figure 7)

The scope of supply was later altered/completed to include:

- A gamma-compensated neutron ionization chamber (CIC) with integrated mineral insulated (MI) cables instead of a fission chamber with HN connectors only, and
- organic field cables to transition from the MI cables up to the cabinet.

The change in the scope resulted due to the performed requirements engineering revealing that due to the expected radiation and moisture at the detector position a CIC with integrated MI cables is advantageous and the (classical) misunderstanding on what is already present on site and what shall be supplied by the vendor.

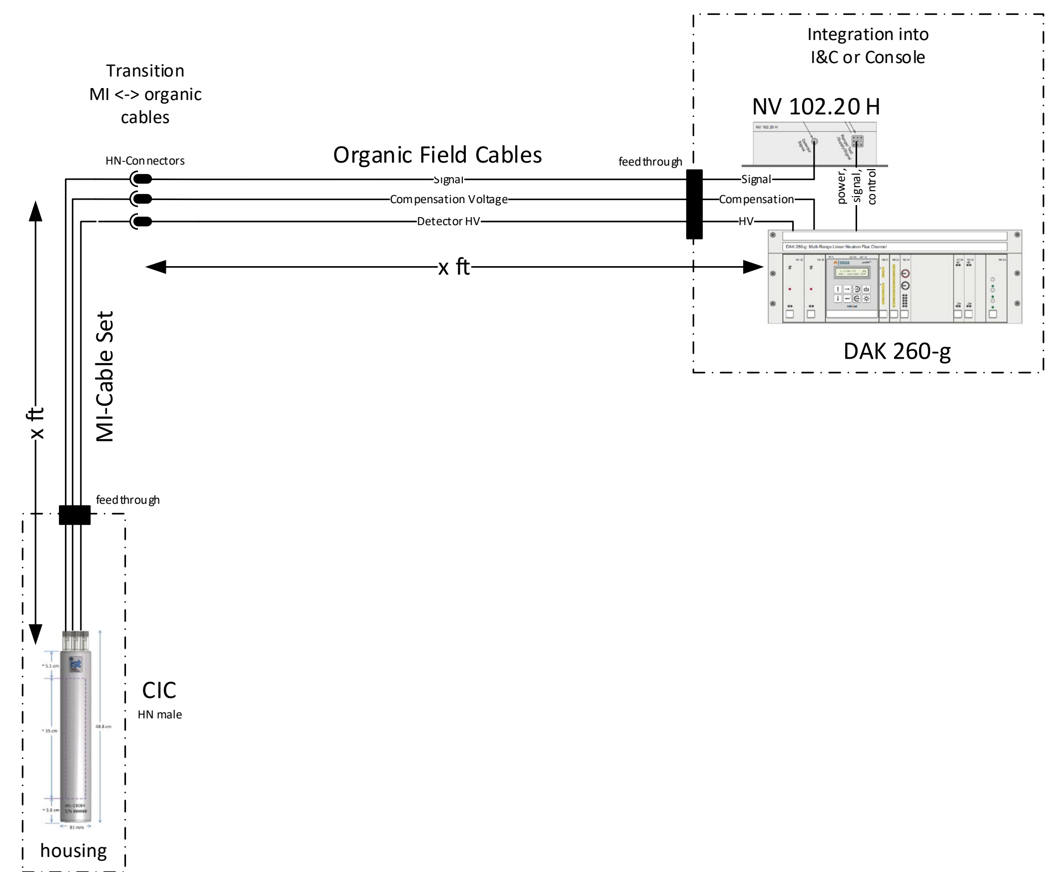

Figure 6: Schematic of the typical scope of a neutron flux channel. Shown here is a gamma-compensated neutron ionization chamber (CIC) operated with the

intermediate range digital neutron flux monitoring channel DAK 260-g of Mirion's proTK product line.

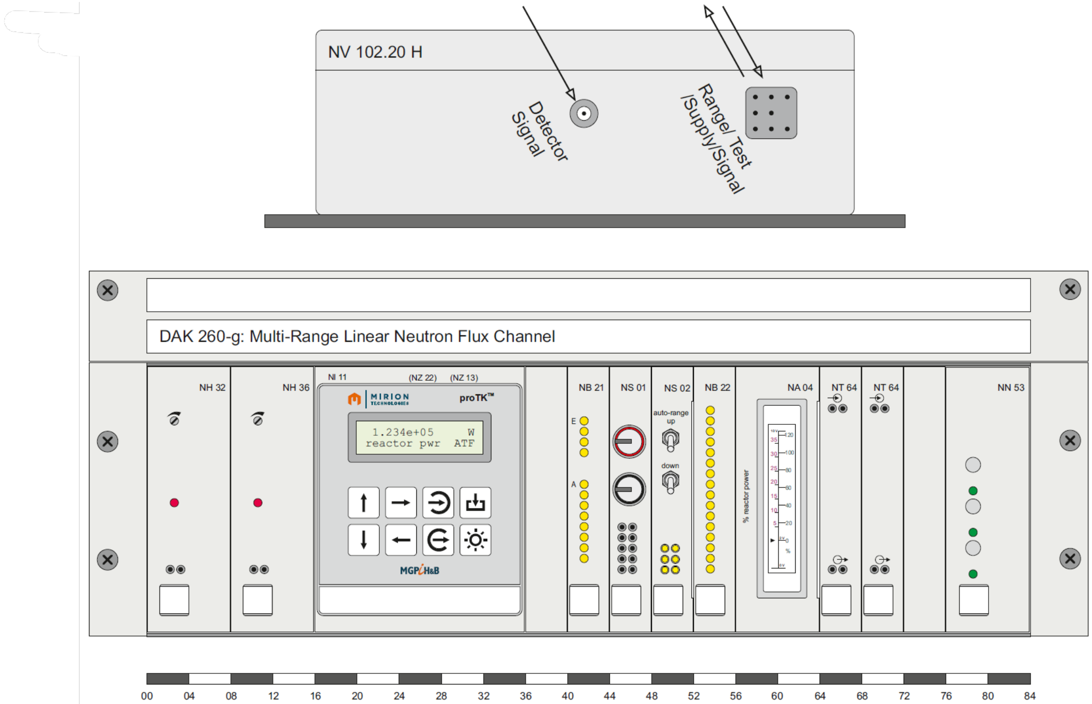

Figure 7: Front view of a typical signal processing unit including the corresponding pre-amplifier as what was offered and implemented for the PULSAR research reactor at the NCSU.

Further clarification points that became necessary after the modernization project has already started:

Clarify the position of the pre-amplifier.

Mirion's systems are carefully engineered especially concerning the aspect of electromagnetic interference and compatibility (EMI/EMC). Therefore, through proper shielding of the components including the cable and a suitable grounding concept it is possible to position the pre-amplifier in the same cabinet as the digital signal processing unit DAK 260-g. Having them both in the same enclosure enhances the protection from outside electromagnetic disturbances.

Specify feeding of the field cables into I&C cabinet.

Clarification of the interface to the reactor protection and control system.

4. Conclusion

Mirion's proTK™ product line offers a full range of equipment for neutron flux monitoring as well as for other safety critical applications, which are vital for operating nuclear power generating stations or research reactors.

The provided engineering services by Mirion and the modularity of proTK™ channels as well as the micro-controller-based signal processing that is central to those units, enables an efficient customized implementation of all the required safety functions, which in turn helps owners to operate their reactor in a comfortable, safe and economic way.