REFURBISHMENT OF THE SAFETY SYSTEM AT THE CROCUS REACTOR

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ABSTRACT

This report discusses the partial refurbishment of the first channel (VS-I) of the Reactor Protection System (RPS) at the teaching reactor CROCUS operated at the Swiss Federal Institute of Technology (EPFL) in Lausanne. The CROCUS facility is a zero-power reactor and it is mainly used for educational purposes for undergraduate and master students. The RPS uses two fully redundant and independent channels: VS-I and VS-II. These contain both the nuclear instrumentation and control units that were developed in-house during the reactor commissioning in the 80's. The nuclear instrumentation and control used was provided by Merlin-Gerin for flux measurements and the reactor SCRAM function. The neutron flux is measured by means of fission chambers connected to IS-I and IS-II. The reactor can be in different states, in particular the startup phases, for example the progressive auxiliary and reactor tanks water filling phase, the safety rods pull-up phase, etc. The logic functions corresponding to these states are designed and implemented in SS-I and SS-II. The refurbishment of the reactor SS-I and SS-II was necessary due to the lack of spare parts for some circuits and the difficulty of finding simple logic circuits in the market. The replacement of both safety channels SS-I and SS-II was performed with the resources available in-house at the reactor service laboratory at EPFL. The nuclear instrumentation is not directly impacted by the reported refurbishment activity. The first phase of the refurbishment project consists of the replacement of the first channel (VS-I) keeping the reactor available for operation services at EPFL. The paper focusses on the description of this technical project and the review and approval process conducted by the Swiss Federal Nuclear Inspectorate (ENSI). Details are provided concerning each regulatory phase of the project and also the technological choices (CPLD over TTL) for the newly developed system. The latter were specifically made to avoid computerized systems and simplify the licensing process. Since the electronic units were developed in-house, the project emphasis was put on the new hardware testing with a unit simulator. These tests were performed both for the old and new electronic cards for comparison. At present, the SS-I unit is undergoing final commissioning tests.

1. Introduction

This paper presents the recent refurbishment and licensing work at the CROCUS facility, a teaching and research reactor at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland [1]. The reactor is regarded in IAEA terminology as a zero power reactor. It is in fact limited to 100 W_{th}. The reactor is used mainly for teaching the reactor physics and radiation detection techniques.
The CROCUS reactor is equipped with two fully-redundant safety channels for instrumentation and control: VS-I and VS-II. These channels perform flux measurements, the reactor SCRAM function, the control and supervision of the auxiliary technical systems, and the coordination of pumps and valves. Complementary to the safety systems, the control command and human interface is done by another system called VF. A reactor SCRAM can

be triggered automatically by one of the two safety channels, if the power or the doubling time exceeds the preset levels and/or one of the technical parameters is not consistent with the corresponding states of the reactor (valves, pumps, etc.) depending on the logic state of the reactor.

The reactor operator controls the reactor and associated systems by using a state selector. Each state corresponds to a physical and logical system, which is precisely implemented in both SS-I and SS-II racks. These racks are analog systems detecting anomalies or device failures by level sensors, flow meters or detectors of position. A safety system rack may indicate an alarm to the operator and interrupt the process by locking the state progression sequence. It can also shutdown the installation by cutting off the power supply of the reactor active systems. Thus, besides the SCRAM function, the reactor can also be shutdown with alarms activated by SS-I and/or SS-II safety systems. The shutdown by SS-I and/or SS-II can be attributed to a technical failure (such as a sensor, a valve, etc.), while SCRAM of the reactor via IS-I and/or IS-II is created by either as an operational error (excess power for example) or an event exceeding the licensed operational conditions. The operation of the two racks is required to maintain active power reactor systems.

In 2005, it was decided to initiate a technical project aiming at renewing the RPS, mostly consisting of a partial refurbishment of its in-house developed electronics. It was clearly recognized as a weak point in the long-term operation due to the obsolescence of the components used and the absence of spare parts. As there were few electronic parts (TTL technology) available, or not at all, it was decided in 2011 to re-start the refurbishment with the logic part (SS-I) replacement of the first reactor security channel SS-I. To facilitate the design and integration, the new system uses the same logic and identical wiring diagrams. For licensing, it was crucial to "copy" the existing systems by new ones with identical functions.

2. Description of the reactor and reactor protection system

2.1 The zero-power reactor CROCUS

The CROCUS zero-power teaching and research reactor (Fig 1) is a light-water moderated facility limited to a fission power of 100 W_{th}, corresponding to a neutron flux of ~2.5 X 10^9 neutrons per seconds at the center of the core [1]. First criticality was achieved in July 1983 and the reactor is in normal operation at low power since that date for teaching and research purposes. Up to now, most of the important systems are still original, implying the importance of future maintenance and modernization. The core is approximately 60 cm in diameter and 100 cm in height. The facility operates at room temperature with forced water circulation near to atmospheric pressure. The core is located in a 1.5 m thick concrete square structure as physical and shielding protection.

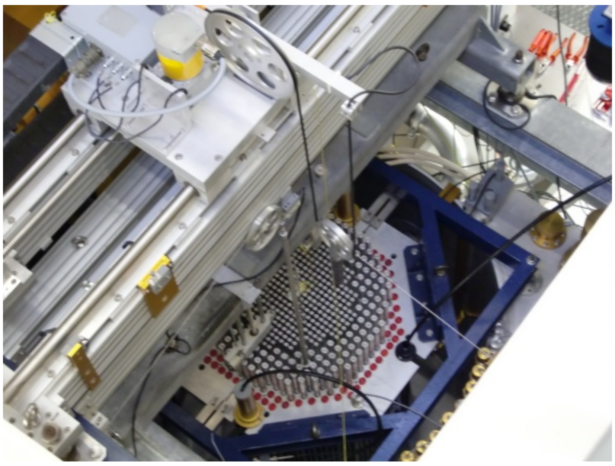

Fig 1. Top view of the CROCUS reactor with most of the important systems visible

The fuel rods are maintained in square lattice geometry by two octagonal stainless grid plates, each one having a thin Cd-layer in order to limit the axial thermal neutrons leaking out of the core. The core contains two zones of different fuel rods. The inner zone consists of 336 uranium ceramic fuel rods (with pure aluminum cladding) with an enrichment of 1.806 wt% ^{235}U and a pitch of 1.837 mm. The outer zone consists of 176 metallic uranium fuel rods with an enrichment of 0.947 wt% and a pitch of 2.917 cm. The total length of each fuel rod type is 120 cm; the active fuel-height is 100 cm. These rods are immersed vertically in an open-cylindrical aluminum 6060-typ grade vessel, ~132 cm and ~164 cm, diameter and height respectively, filled with demineralized water at 20°C. The water acts as a moderator, coolant, and also as a radial reflector.
The maximum excess reactivity of the core is limited to 200 pcm and it is controlled by a variation of the water level with an accuracy of $\pm$0.1 mm (equivalent to $\pm$0.4 pcm) and/or by means of two independent control rods ($\pm$0.3 mm or $\pm$0.2 pcm) containing B_4C (natural enrichment) sintered pellets located symmetrically within the outer core. The control rods are moved up and down by stepping motors driven by a LabView application. It is of importance to notice that the control rods are only used for the fine power regulation and are not considered as a safety system. Below the core, there is a metallic structure containing a Pu-α-Be source used for start-up of the reactor. Finally, a dedicated support in-between four UO_2 fuel rods at the core center can be used for various experiments, e.g. thin gold foil activation.

2.2 Reactor protection system and nuclear instrumentation

Despite the low power of the reactor, various safety systems and automatized mechanisms have been designed and installed at CROCUS. The reactor encompasses six independent shutdown mechanisms allowing the reactor to obtain a sub-critical state in less than one second: two cross-shaped Cd-blades (two safety rods) at the core center and four safety air tanks operated by a valve system on top allowing the moderator level to be dumped quickly. In case of a SCRAM signal coming from the I&C, the magnetic clutch will be released and the two safety rods will fall by gravity in the core in less than 1 s. Simultaneously the air tank valves will be passively opened to purge the air content of the tanks and fill with the moderator. A water dump will occur resulting the opening of the valves.
Of importance in the context of describing the RPS, the nuclear instrumentation consists of four channels; two ionization (measurement range from 10^{-10} A to 10^{-4} A) and two fission chambers (sensitivity of 0.01 cps/nv) located near the peripheral fuel in the radial reflector. The electric pulses of the detectors are measured and shaped in the appropriate processing unit within the Merlin-Gerin unit containing multiple safety relays. The count rates (cps) can be adjusted internally to trigger the safety relays at the desired neutron flux or reactor period. The measured neutron flux is displayed on an analog panel in a logarithmic scale in the range from 10 to $3 \cdot 10^6$ cps in the control room. The reactor doubling time is also measured in the same monitoring unit in the range -3 s to +3 s. The neutron range measurement covered by the instrumentation is sufficient for the licensed reactor power of 100 W. Using optoelectronic devices allows, after the Merlin-Gerin safety instrumentation units, a connection to various counters or multi-channel systems (MCS) for experimental purposes.

3. Original safety system description

3.1 General description

The CROCUS reactor is controlled by two independent identical channels VS-I and VS-II. A general scheme of the RPS of CROCUS is presented in Fig 2.

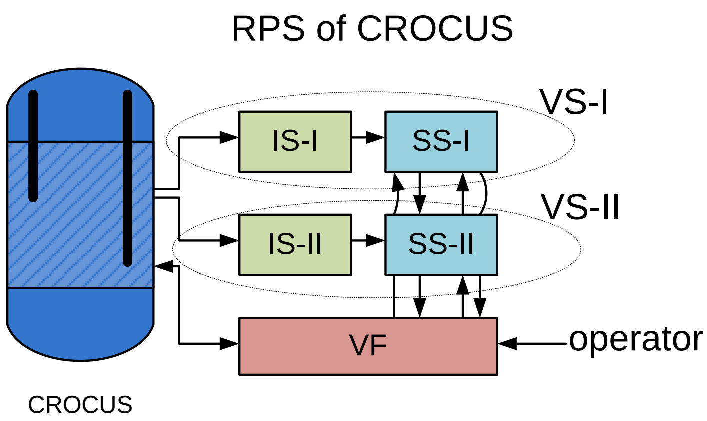

Fig 2. General schematic of CROCUS I&C and RPS

The technical systems, such as valves and pumps are switched on or off by the control system VF. One safety channel of the RPS consists of three main components: a fission chamber, the nuclear instrumentation and control (I&C, or called here IS) with a connection to it, and the analog logic safety systems (SS). In terms of the electrical and signal connections, starting from the fission chamber, the instrumentation and control rack is connected to the logic safety system SS. The logic part of the RPS takes care of verifying the semi-automatic actions of the VF. The VF is responsible to actuate the corresponding valves, pumps and motors, operate or shutdown the reactor as a response to the reactor operator actions on the selector.

The hydraulic circuit of CROCUS is quite complex for the size of the reactor: it contains the reactor vessel, a main tank, an auxiliary tank, two heat exchangers, 5 electric pumps, 11 hydraulic valves, a dozen of position and water levels sensors, and multiple thermocouples for monitoring the feed water temperature at different locations in the reactor. For this principal reason, a human-free interaction safety system was developed in-house when the reactor was commissioned to assist the operator in the start-up and shutdown phases, but also to detect remotely any potential technical failure.

It is interesting to note that the two independent channels are cross-linked together allowing a channel to detect anomalies on the other channel. This will also avoid having to operate the reactor having technical problems on one channel of the RPS and relying on the second channel for instance. At the end, it is necessary to have VS-I, VS-II and VF in full operation to successfully operate the reactor.

3.2 Alarms and automatic actions

The automatic actions of the RPS are designed to keep the reactor subcritical in case of one (or more) operational parameter crosses its validity domain according to a truth table implemented in the logic circuits of the SS. The reactor can be shutdown completely (Alarm III) or at an intermediate level (Alarm II) depending on the severity of the parameter being outside the truth logic table. The reactor can also be scrammed directly by the nuclear instrumentation and control in case of the neutron flux is outside the allowed operating values (flux corresponding to a thermal power of more than 100 W_{th}) or a too fast increase of the power resulting in a reactor period of less than 9 s.

The entire safety of the installation is based on the “fail-safe” principle. The reactor can only be made critical by maintaining actively closed valves allowing filling-up the reactor vessel with water, but also to maintain by a magnetic system the safety rods above the core and not inserted. In case of alarm (II, III or SCRAM signal), the power of the safety devices (valves, pumps, safety rods magnets …) will be interrupted and no active system is needed to keep the reactor subcritical. An alarm with no automatic feedback (Alarm I) can also be active as a response to a minor problem on a system [1]. The RPS does not stop the reactor with an alarm of first category but, the state selector will be locked up at the state that alarm occurred.

In other words, if the alarm is occurring in the startup-phase, the reactor will not reach critical until the problem will be solved. This is an additional safety measure.

4. Modernization and refurbishment of safety system channel I (SS-I)

This Section presents the modernization of the logic rack of the safety system channel I (SS-I) of CROCUS. In addition to the technical steps of the projections, i.e. the validation of the technology, the first prototype, testing of the manufactured cards and racks, etc., the authorization steps are presented as well to explain the specificity of this project at a teaching reactor in Switzerland.

4.1 Project technology description

The original safety system racks for the two safety channels have been built using Transistor-Transistor Logic (TTL) in-house in the 80’s. The desired functions are obtained by combining TTL circuits on 19 different Printed Card Boards (PCB) in a 19’’ rack. The safety functions of the safety channel are physically located on the PCB cards. The cards are connected to a bus, where the cable connectors are wired to it. The SS-I rack is connected to power supplies, relays, control panels, human-machine interface, etc. by cables with connectors. This offers the possibility to easily disconnect the entire electronic rack for testing of repair in the electronic workshop adjacent to the reactor.
For the new safety system, the rack format and the electrical connection system in the back were kept identical to simplify the integration in the control room and to limit the modifications to be licensed to the first rack of the first safety channel. To replace the TTL circuits, a more modern approach was chosen based on Computerized Programmable Logic Device (CPLD) which offers the main advantage of having much more logic capacity on a chip compared to the TTL circuit. Therefore, the 19 cards of the existing rack were reduced to three and integrated on PCB cards connected to the rear bus of a 19’’ rack. The connection with identical connectors was maintained, as said, to limit the modification of the installation, but also due to space constraints in the electrical cabinet in the control room of the reactor.
An important part of the project was to design, based on the original safety documentation of the reactor with the software Altium designer, the new electronic schemes of the PCB and logic functions to be programmed in the CPLD chips [1].
After the development phase, a first prototype was manufactured by the reactor team and a pre-tests phase started. The testing phase of the prototype was realized with the manufacturing of a separate test unit operating with LabView. In summary, three test units were produced to fully test automatically all logic functions of the three cards of a safety rack. The logic circuits of the test units were designed in LabView in association with DAQ units of National Instruments to interrogate the cards and read the alarm outputs (Fig 3).

Fig 3. Testing of one PCB card developed for the safety system SS-I in a test unit connected to the computer

For a complete test of the cards, all logic permutations for the input cards were realized, first with the original safety rack, and, second, with the manufactured rack. The functionality tests were successfully passed if the alarm signals (rack outputs) of both racks were strictly identical. After the test phase with the prototype, two safety system racks VS-I-001 and VS-I-002 were manufactured. The reason of having two identical racks for the first channel is explained in the following Sub-section 4.2. The manufactured racks were then tested with the test units described above. The quality control checks and results of the function tests were documented in a design specifications report (450 pages) for the formal authorization from ENSI to continue the modernization of the safety channel at CROCUS.

4.2 Authorization steps

The refurbishment project was initiated formally in 2005 with the conceptual project presentation to the Swiss Federal Nuclear Inspectorate (ENSI). According to the Swiss nuclear law (KEV), the modification at a power plant or research reactor might require a preliminary approval from the regulatory body, depending on the importance and impact on the safety the modification might have. The modernisation and replacement of a safety channel at CROCUS is clearly of safety relevance and the national guideline ENSI-A04 has been followed [2]. In this context, the authorization process is divided into four main steps as illustrated in Fig 4, and each step requires approval from the regulatory body.

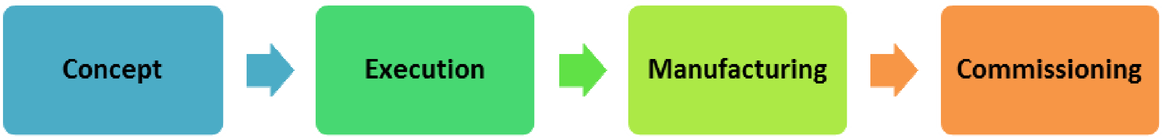

Fig 4. A four-step-authorization for formal approval of the refurbishment of SS-I at CROCUS

In the first phase, the modernization and refurbishment project was presented to the regulatory body as a replacement of the logic rack of the RPS, while keeping identical the safety functions and based on electronic circuits that do not require a computer to run a "code" [3-4]. The latter option would have made the licensing process longer considering the fact that the electronic system is developed in house with a rather small team.
Following the formal approval of the project, testing and prototypes were realized in the workshop to certify the adequacy of the CPLD technology to replace TTL circuits. These intermediate milestones were reported to ENSI and positive feedbacks were obtained. The project continued with the manufacturing of the first prototype and test unit bench for the whole safety system rack. In addition to the manufacturing in the electronic workshop, significant effort was put in the writing up of the fully documentation, technical specifications, control quality of the function tests and to answer the specific requirements of the relevant guidelines and documents [2-4]. This documentation consisted the basis to ask the formal authorization step II, Execution (based on the prototype) and step III, Manufacturing (racks VS-S-001 and VS-I-002). The authorization has been obtained from ENSI in early 2013. As just mentioned, two racks were manufactured at the same time as it was one of the requirement of the regulatory body. At present, no spare piece exists for the safety systems and, to avoid this situation, we were asked to have for each channel of the RPS two identical licensed racks. In case of failure, the unit can be replaced with an identical tested and licensed unit.

4.3 Commissioning test on the reactor

The last part of the refurbishment project is the commissioning tests on the reactor and the commissioning and exploitation authorization from ENSI (step 4 in Fig 4). This step is not formally accomplished at present since the authorization is not yet granted. The commissioning tests were realized on the reactor for the two manufactured and tested racks into two steps: (1) without fuel in the core and (2) with the standard core configuration (see Section 2). The tests without fuel in the core allowed testing in the depths of the active components (as valves and pumps) without using the automatic surveillance unit from the safety channels. This procedure was used to test independently each active component with impact on the safety of the installation. After successful completion of the tests, the fuel was reloaded into the core and the reactor was operated with the new SS rack. The different states of the reactor were obtained (stop, tank 50%, tank 100%, manual mode) to measure the response of the safety channel and comparison was made against the second channel. No problems occurred during the commissioning tests of the two manufactured racks VS-I-001 and VS-I-002. A complete documentation of the tests was submitted to ENSI in August 2013.

5. Conclusions

The teaching reactor CROCUS has been safely operated for three decades with the original reactor protection system (RPS) partly developed in-house at the commissioning of the reactor. In the past years, it was decided to start a modernization and refurbishment project aiming at replacing, as a first step, the logic part of the safety channel I of the reactor. The reactor operates with two identical safety channels I and II with, first, the nuclear instrumentation and control (IS) and the safety system unit (SS). The project was conducted as originally thought, in particular in developing in house the new systems and by replacing one channel at a time, keeping the reactor available for operation services at EPFL.
The paper presents the development, manufacturing and testing of two safety racks VS-I-001 and VS-I-002 to replace the logic unit of the first safety channel. An important aspect of the project was the constructive interaction with the regulatory body and the authorization steps that the replacement of a safety channel required.
At present, the commissioning tests are performed at the facility and the formal approval for operation will be done in 2013 if all goes as scheduled. This would end the refurbishment project of the first channel. Other refurbishment and aging management projects would then start to keep running the reactor in a good technical condition. However, for these require more human resources in order to speed up the refurbishment compared to the safety system channel I.

6. References

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