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Project Report

INVAP's Research Reactor Designs

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INVAP, an Argentine company founded more than three decades ago, is today recognized as one of the leaders within the research reactor industry. INVAP has participated in several projects covering a wide range of facilities, designed in accordance with the requirements of our different clients. For complying with these requirements, INVAP developed special skills and capabilities to deal with different fuel assemblies, different core cooling systems, and different reactor layouts. This paper summarizes the general features and utilization of several INVAP research reactor designs, from subcritical and critical assemblies to high-power reactors.

1. Introduction

INVAP is an Argentine technology company, born in 1976 as a spinoff from the Argentine Atomic Energy Commission (CNEA). INVAP develops state-of-the-art technology in the nuclear, aerospace, and radar fields and in other advanced technology areas.

INVAP has not only played a key role in the Argentine nuclear program, but it is also internationally recognized as a leader supplier of research reactors.

These facilities cover a wide spectrum of applications such as Education, Training, Radioisotope production, Beam Research, and Material Testing, among others. INVAP is capable of supplying turnkey research reactors designed to satisfy any client needs. INVAP also is able to work under different contractual agreements, involving varied degrees of client participation in the project activities.

INVAP designs and optimizes each facility according to the client's requirements but always having in mind the following approach.

(i) Priorize safety.

(ii) Simplify the design as much as possible.

(iii) Minimize technical risks by relying on proven technologies.

(iv) Follow the IAEA safety requirements and best international practices.

(v) Fulfill the nuclear regulation of the country where the reactor will be built.

(vi) Follow the Argentine nuclear regulation.

INVAP main experience is in water-moderated, pool-type reactors. INVAP has designed and built reactors using MTR type or rod fuels, downward, upward, and natural circulation cooling water, using graphite, Beryllium, or heavy water reflector and U-Al, U3O8, UO2, or U3SI2 fuel, cladded in aluminum or zircalloy.

In the following sections, a general description of the research assemblies and reactors that INVAP has designed is presented, showing the versatility and flexibility of the projects and the most relevant features of each group. The facilities are categorized according to their power as follows.

(i) Subcritical assemblies, where the facility cannot achieve criticality.

(ii) Critical facilities, generating less than 1 Watt.

(iii) Low-power research reactors.

(iv) Medium-power research reactors.

(v) High-power research reactors.

2. Subcritical Assemblies

This type of facility is used mainly for training and educational purposes, and it can be used also for validating neutron models.

The most important design criterion is that any core configuration must be subcritical, with a given margin, under any operating condition. An external neutron source is thus needed to provide a stable neutron flux.

This type of facilities is normally designed using rod-type fuel allowing the movement of any individual fuel rod. Perturbation devices, which may be water gaps, absorber rod, or other devices, allow carrying out a broad set of experiments.

The following experiments are a sample of the type of measurements that can be carried out in these facilities: critical approximation by U^{235} mass, critical approximation by moderator level, measurement of reactivity changes due to different core configurations, flux mapping (on line and using foils), and measurement of kinetic parameters.

3. Critical Assemblies

Critical assemblies are used for research purposes and for training and educational purposes.

As research tools, critical assemblies are usually mockups of higher power reactors, working at a very low power. This allows evaluating the neutron behavior of a given core without actually building the higher power reactor. It also allows tuning the calculation models with experimental data. For this use, critical assemblies usually have a fixed configuration, identical to the higher power reactor of which they are a model.

Critical assemblies are also an educational tool, making it possible to carry out similar experiments as those carried out in a subcritical assembly. In this use, critical assemblies usually have a core consisting of two different regions, (i) the external region, called *driver* region, with a given type of fuel and the same for all the experiments and (ii) the central region, called *experimental* region, where the type of fuel depends on the kind of experiments to be carried out. It is very easy to use the facility, and the core configuration can be easily modified, providing a large flexibility to perform several types of experiments.

One of the main features of these facilities is that the maximum thermal power involved is very low (<1 Watt), so that power and temperature feedback effects are negligible and, as burnup is minimum, radiation levels are very low, allowing, for example, the manual handling of the fuel elements. Additionally, the maximum excess of reactivity is limited to a small value, to allow only the compensation of the experimental reactivity requirements.

INVAP participated in the design of the RP-0 facility to perform neutronic measurements of the RP-10 RR in Peru, and RA-8 [1] facility of the Atomic Energy Argentine Commission was especially developed to perform neutronic measurements of the core of CAREM [2, 3] reactor, another CNEA project. The RA-8, as a design requirement, has the capability to reach criticality by changing the core water level. It also has an important number of devices to perform many detailed experiments, including devices for allowing detailed measurements of fluxes inside a fuel rod.

A design requirement in critical assemblies is that the core should be easy to modify. INVAP thus normally includes a redundant shutdown system in these facilities, as, with variable configurations, an independent and diverse shutdown system ensures an appropriate shutdown margin when it is required.

Critical assemblies can be used to perform similar measurements as subcritical facility, but they are more flexible, and flux measurement can be done with higher details. Examples of experiments that can be carried out are

(i) *fission products spectrum*. The fission products spectrum can be measured using the dismountable rods and a high-purity germanium detector (HPGe). The gamma spectrum of a fresh (not irradiated) uranium pellet can be compared with the spectrum after irradiation. It is possible to identify the different fission products and to compare the spectrums after different decay times,

(ii) *Axial flux profile measurement using the fission products gamma spectrum*. The flux profile can be obtained using the gamma spectrum of the pellets located in different axial positions.

Figure 1 shows the core grid and block of the RA-8 facility.

4. Low-Power Research Reactors

These facilities provide the same capabilities as critical assemblies while, due to higher neutron fluxes, they can also be used for neutron activation analysis (NAA) and to produce a limited quantity of radioisotopes.

The design of low-power reactors provides flexibility regarding core configurations, and the maximum thermal power adopted is normally below 100 k Watts.

Although the cooling of the facility is by means of natural circulation, as in the previous groups, in contrast to subcritical and critical facilities, the temperature of the pool water must be controlled as it plays the role of the heat sink. Thus a pool cooling system must be included in the design.

Additionally, and due to the heat fluxes involved, some thermal-hydraulic tests and measurements can be carried out, such as thermal balance or core flow distribution. A thermal-hydraulic analysis is performed to verify that safety margins are fulfilled.

Regarding the protection system, only one shutdown system is enough as this kind of reactors has few and simple systems, and any modification of the core configuration is limited and carried out under strict procedures.

5. Medium-Power Research Reactors

Research reactors always can be used for training and education purposes, but sometime this is not the most relevant purpose. Although they are a valuable tool for personnel training, normally they are designed to provide an NAA and

(a) (b)

Figure 1: RA-8 criticality assembly.

(a) (b)

Figure 2: RA-6 research reactor.

other irradiation facilities, to produce radioisotopes for local demand such as Molybdenum and Iridium and to conduct advanced scientific and applied neutron research. Present designs include even cold neutron source devices.

This group presents a qualitative jump compared with the previous ones. Not only due to the total power (it has changed from tenths to thousands of kilowatts) and utilization but also to the forced cooling systems and associated components.

New devices as neutron beams, service, and/or storage pools appear implying the coupling of different teams with different requirements.

Examples of this group are the RA-6 and NUR [4] reactors in which INVAP was the main contractor.

The RA-6 reactor is also an indigenous reactor of CNEA, built in Bariloche, Argentina within the Instituto Balseiro campus. With a power of 500 kW, it was initially dedicated to the training and education of the nuclear physics and nuclear engineering careers besides material testing and applied neutron research activities. Nowadays, it was upgraded up to 3 MW increasing its capabilities and uses. Figure 2 shows the RA-6 core and building.

Regarding the NUR, it is a 1 MW reactor designed, constructed, and commissioned by INVAP for the Algerian government and located in the city of Algeri. This open-pool reactor consists of a core with MTR-type fuel elements and graphite reflector blocks providing flexible configurations. A thermal column allows for different irradiation tests and beam research like neutron radiography.

Figure 3 shows the NUR reactor building and control room.

As in the case of the RA-6, there is one shutdown system. It consists of a set of control plates arranged by pairs and moving inside modified fuel assemblies. This arrangement is known as “fork type” control plates and the absorber is Ag-In-Cd.

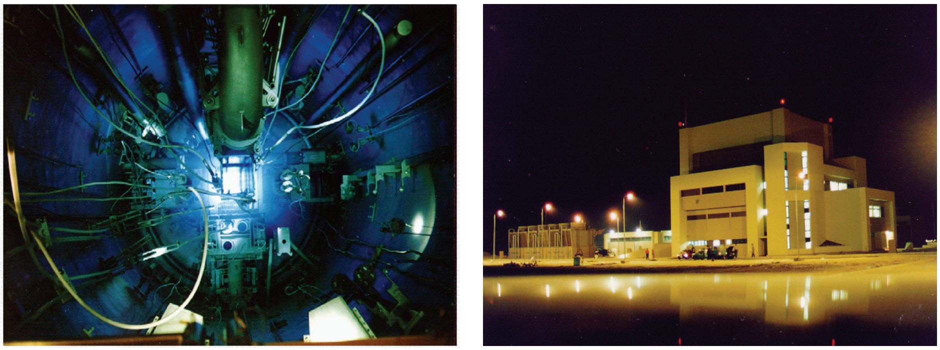
According to the power density characteristics, the core of both reactors is cooled by light water in forced convection flowing downwards.

6. High-Power Research Reactors

This last group of reactors represents a challenge as they are more and more demanding when neutron flux is concerned.

(a) (b)

Figure 3: NUR research reactor.



(a) (b)

Figure 4: ETRR2 research reactor.

This kind of facilities is mainly dedicated to radioisotope production in large scale and to the advanced scientific and applied neutron research, for which incore and excore irradiation devices and loops are supplied. Frequently they are known as multipurpose reactors.

On the other end of reactors utilization, stands the "dedicated reactors" aiming to fulfill singular purposes such as testing of new materials and fuel elements and producing specific radioisotopes or beam application; INVAP has developed new strategies and competence to comply with these demands.

Depending on power, mainly on the power density, different features arise. For example, the coolant flow direction can be downwards or upwards; the core cooling system can be slightly pressurized or not, which means to design a tank-in-pool reactor instead of an open-pool type one.

Another relevant aspect is the performance of the core, stable, and uniform fluxes on the irradiation facilities pushed INVAP to explore new absorber materials and strategies to reach the client's requirements.

The following sections give a summary of the relevant features of INVAP designs for this group of reactors, ETRR-2 [5–7], OPAL [8–11], and a 100 MW design.

6.1. ETRR-2 Design. The first experience of INVAP with this group of reactors was the ETRR-2, the Egyptian reactor of 22 MW in which the design, construction, procurement, and commissioning were carried out matching our personnel with the local companies culture.

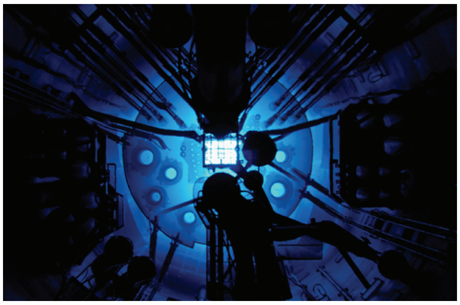
Even though it was an open-pool type reactor with an MTR-type fuel element, the demand on neutron flux required a power density that put a strong requirement on the core cooling system. The flow direction was changed (from downwards to upwards) to make it more effective and take the advantage, for example, of avoiding the flow reversal on a blackout event.

This decision made INVAP to rethink of the control devices design, among other issues. A new design of control plates was developed consisting of independent plates inside control guide boxes entering from below the core. This innovation, together with the upward flow, required the development and design of new component such as fastener tools for the control plates and the fuel assemblies and seals for the rods of the control plates, as they have to penetrate the pool from the bottom.

Additionally, a second shutdown system was designed consisting of an absorber solution of gadolinium injected between the core and the beryllium reflector.

Figure 4 shows the ETRR2 core and reactor building.

6.2. OPAL Design. After the Egyptian reactor project, a new challenged arose for INVAP, the OPAL reactor, a turn-key project for the Australian government. This 20 MW reactor is a first-class facility designed and constructed for a large-scale production of radioisotopes, silicon doping, and research.



(a)

(b)

Figure 5: OPAL research reactor.

Table 1: Comparison of different facilities.

Facility	Power	Core modification	Experimental capability	Utilization
Sub-critical	0	Very easy. Manually	Very flexible	Training and education
Critical	<1 W	Very easy. Manually	Very flexible	Training and education nucleonic measurements
Low power	<100 kW	Easy under water	Very flexible	NAA, low-scale RI production.
Medium power	<10 MW	Easy under water Some verification	Flexible/production facility	NAA, NTD, several RI production, beams.
High power	≥10 MW	Fixed core or it requires detailed verification	Production facility	NAA, NTD, RI, high performance beams, material irradiation, loops

Based on our previous experience, our design included the main features of the core design, control devices, and cooling systems, among others, but in this case, the challenge was the compactness of the core. This new characteristic made INVAP to review the design to fulfill the requirements of the client. The product was a compact core with silicide fuel, control plates made of hafnium absorber, and burnable poisons of cadmium wires in the fuel assemblies.

The core flow direction was upwards, but now the coolant velocity was almost twice the one in our previous design which resulted in modifications, not only to the fasteners and seals but also to the fuel assembly.

As the reflector material was heavy water instead of beryllium, new skills on dealing with this reflector and with the Zircaloy tank of the reflector had to be developed. Several irradiation facilities were placed inside the reflector deserving a special mention, the cold neutron source. This device, a one-of-a-kind project, was managed by INVAP to get the best performance in type and time from the real constructor.

As in the previous case, two shutdown systems were designed; the first one consisted of shutdown plates, while the second system was the drainage of the reflector tank.

Figure 5 shows the OPAL core and reactor building.

6.3. 100 MW Design. Reactors power is increasing more and more following the market demands, not only to produce radioisotopes for medical and industrial uses but also for fuel assemblies for next generation power plants and material testing. To comply with the new requirements, several engineered features were implemented.

Being the fuel assembly almost the same as in OPAL reactor, the cooling requirements pushed the design to a tank-in-pool reactor, slightly pressurized and with downwards flow.

The reflector was beryllium blocks housing several irradiation positions and providing flexible configurations according to the uses and operational requirements.

Two shutdown systems were designed to cope with safety requirements, while an emergency core cooling system was included.

7. Conclusions

In the previous chapters, the general features of different facilities have been presented focused on INVAP experience and summarized in Table 1 according to power, easiness of core modification, experimental capability, and utilization.

Since its creation, INVAP has played an important role within the local nuclear industry. Starting as the main contractor of RA-6, a low-power reactor, it went through several projects encompassing different characteristics and uses requisites.

Needless to say that INVAP has gained good experience to satisfy different clients and face different challenges. Its tailored designs fulfill not only the users' requirements but also the best international practices.

Along its trajectory, we became mature enough to be recognized by the international community as a good nuclear supplier.

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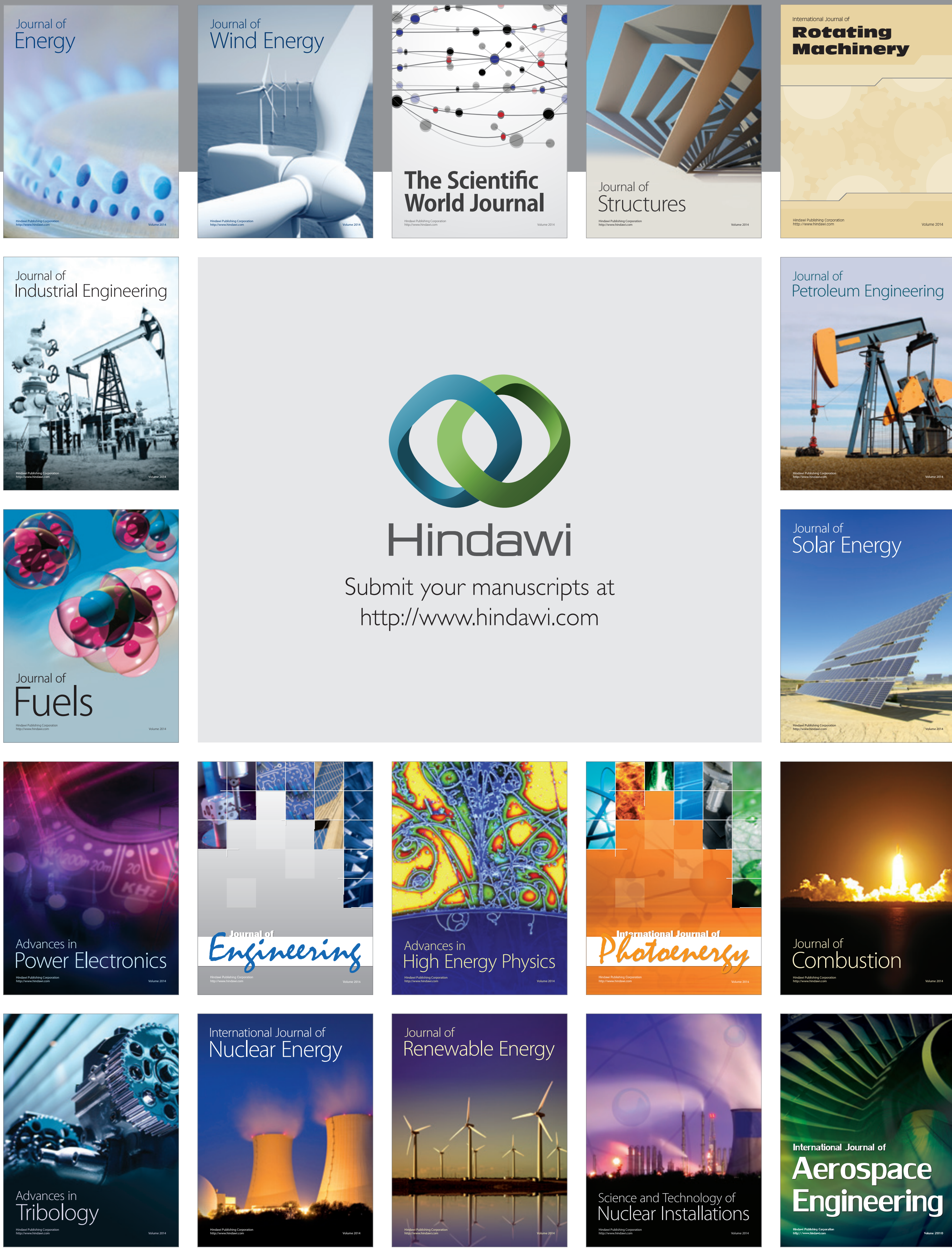

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