OPERATION AND MAINTENANCE AT SAFARI-1 RESEARCH REACTOR IN SOUTH AFRICA

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Abstract

In SAFARI-1 the rigorous maintenance programme, effective implementation of Structures, Systems and Components (SSC) upgrades since 1996 and well defined operational programmes have resulted in that the 20 MW reactor has operated for 1 million MWh in the last 7 years and in October 2010 surpassed the 3 million MWh mark [1]. Challenges to achieve this included replacement of skills lost through resignation and retirement, full utilization of reactor for the production of isotopes, changing operation from Monday to Friday to 24 hours - 7 days a week and planning all maintenance and upgrade tasks within the ten 5 days and one long 12 days shut downs annually. These challenges were met by changing the personnel culture and applying effective management measures. With a decreasing number of unscheduled reactor shut downs the operation days at 20 MW have increased over the last 20 years and are currently over 302 days per annum. This success can be ascribed to the ongoing upgrades and the maintenance programme which are executed by well experienced personnel, good infrastructure and support on the Necsa site at Pelindaba, in-house mechanical machining capability and a mechanical manufacturing facility at Pelindaba accredited to ASME VIII and recently to ASME III. Much experience has been gained and lessons learnt from some upgrade projects and failures of SSCs. These experiences are exchanged in annual meetings with the two sister reactors: HFR in the Netherlands and OPAL in Australia. The maintenance programme is implemented through a mature and well developed Integrated Management System (IMS) which covers Quality, Health, Safety and Environment (QHSE), nuclear material safeguards and physical security systems. The IMS is supported by a Necsa wide SEQH system which is applicable to all nuclear facilities (e.g. front and back end of the nuclear fuel cycle, SAFARI-1, nuclear waste, hot cells and laboratories) and complies with the requirements of the National Nuclear Regulator (NNR), international standards and relevant IAEA safety standards and documents. To ensure continued reliable reactor operation an ageing management programme was developed in 2010 in accordance with IAEA Guideline SSG-10 [2]. With the systematic methodology used not only were 18 ageing management projects, but also 38 development and upgrade projects as well as 24 maintenance projects identified for implementation over a 5 year period. This will enable that the SAFARI-1 operational life may be extended to 2030 and beyond. SAFARI-1 has a good safety record over its operational history. A Behaviour Based Safety (BBS) programme was implemented in 2003 which has resulted in that the total injury rate has been steadily decreasing. The ALARA and BBS programmes together with management commitment have been driving the safety culture in the reactor. In order to ensure safe reactor operation various IAEA safety standards, guides, TECDOCs and the Code of Conduct [3] are applied and implemented.

1. INTRODUCTION

On 18th March 1965, the first reactor in South Africa achieved criticality and reached full power (initially designed for 6.25 MW thermal power) on 10th April of that year. The purpose of this reactor was for R&D but throughout its operational history additional uses, such as for PWR fuel testing, were applied and lately a heavy emphasis was placed on production of ^{99}Mo, other isotopes and neutron transmutation doping of Si. The operational and capital funding of the SAFARI-1 reactor has since April 2010 been increased by NTP, a wholly owned subsidiary of Necsa, who funds presently about 90% of the SAFARI-1 budget from its commercial sales. NTP processes and markets all the SAFARI-1 irradiated products and the reactor has become strategically important for the business. Although the process for the acquisition of a Dedicated Isotope Production Reactor (DIPR) by NTP has begun, SAFARI-1 will be the only isotope production reactor in South Africa until the early 2020s and thus the operation, maintenance and ageing management upgrade projects are of fundamental importance.

2. OPERATION OF SAFARI-1

SAFARI-1 historical operational performance [1] is depicted in Figure 1 which shows 4 distinct phases:

— The initial R&D period which was the original purpose of the reactor (1965 to 1977);
— Duriing the next phase which was characterised by the SA sanction years fuel saving, local fuel manufacturing and qualification with minimal R&D (1977 to ~1992), including the development of isotope production processes (i.e. ^{99}Mo, ^{131}I, ^{35}S, ^{32}P, ^{33}P, ^{90}Y, ^{192}Ir) which are presently being utilised and the pool leak repair in 1988 when the reactor was down for about 9 months to perform the repair;
— The transition to an isotope production reactor (1993 to 2001) which included introduction of new management systems as per ISO and IAEA standards and a personnel culture change from R&D to isotope production with operational cycle change from Monday to Friday to 24 hours, 7 days a week, 3 to 5 weeks cycles with 5 day shutdowns in between, and;
— Over the last 10 years optimal and reliable operation for large scale industrial isotope production and introduction of new generation of staff due to retirement of maintenance engineering, reactor supervisors and reactor operational personnel (2001 to 2011).

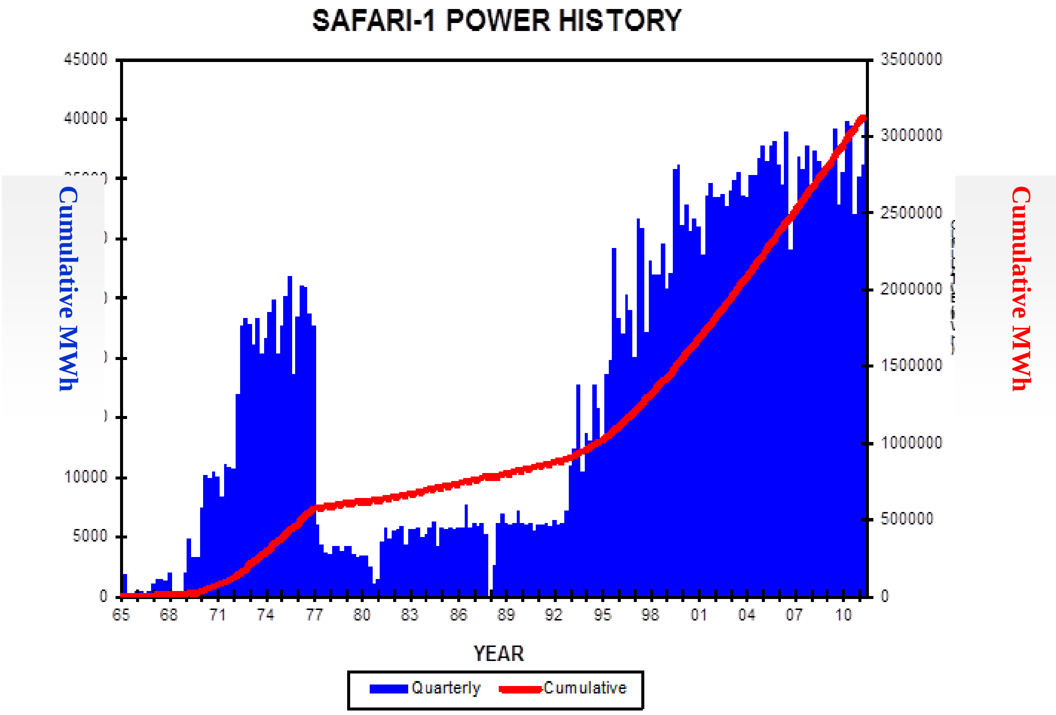

Fig. 1. SAFARI-1 Power History.

The attainment of power milestones in Table 1 indicates the increased usage to a reliable and sustainable reactor operation for industrial isotope production.

TABLE 1: SAFARI-1 POWER MILESTONES

Thermal Power	Years
1st 1000 GWh	30
2nd 1000 GWh	8.8
3rd 1000 GWh	7.0

Initially in the early 2000s the reactor scheduled down time was ~ 50 days per annum which was not sustainable since certain maintenance tasks were done over a longer schedule. This eventually lead to increased unscheduled downtime in the mid 2000s due to failures e.g. in the conical strainer sieves and demineralizer anion bottom sieves which in both cases released debris into the primary loop. Subsequently the maintenance scheduled period was increased to ten 5-days and one 12-day i.e. ~ 62 days per annum with 21 to 35-day operating cycles. The last 3 years since 2008 has shown that unscheduled downtime has decreased and operational time has increased, which has increased reliability and overall good performance. In 2010 the actual lower operational time exceeded the actual scheduled time for the first time since 1996.

TABLE 2: SAFARI-1 REACTOR AVAILABILITY (IN DAYS)

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Operational time	317.0	310.3	314.2	308.0	312.5	290.9	298.2	304.8	300.9	306.7	~306
Scheduled downtime	45.4	53.3	49.0	53.3	50.6	55.4	55.0	55.5	62.5	62.5	62.5
Unscheduled downtime	2.6	1.5	1.8	4.7	1.8	18.7	11.3	4.8	1.5	0.2	~0.1

3. MAINTENANCE OF SAFARI-1

The SAFARI-1 maintenance system has evolved over the past 15 years where more emphasis has been placed on identification and formal control of the various maintenance processes, training therein and recording of results within the QHSE system. The maintenance procedures and detailed instructions were prepared and continuously developed to ensure consistent and reliable performance of maintenance activities. This has also been helped on by a core of maintenance staff who has gained in experience and competence and who, with a low level of staff turnover, have maintained a large knowledge base. An example of this is a recent retiree who worked at the reactor for 46 years i.e. since start up.

Furthermore, during the period of 2000 to 2008 with tight austerity measures, many low cost components and systems were upgraded as part of the preventative maintenance system to ensure reliability and safety but also due to under staffing not all upgrades planned could be accomplished.

3.1. Maintenance programmes

The maintenance programme lists responsibilities, frequencies, schedules (i.e. daily, weekly, monthly, yearly and more than one year), criteria and controls for the maintenance tasks, identified systems that can be isolated while the reactor is in operation, applicable restrictions for on line maintenance and records to be kept. Routine (1919 per annum), shutdown (572 per annum) and ad hoc (434 per annum) maintenance tasks are covered by the maintenance programme as well as operational checks, functional tests and periodic, routine and in-service inspections. Maintenance instructions and tasks comply with the Operating Technical Specification (OTS) and Safety Analysis Report requirements. According to experience gained on instrumentation, electrical, mechanical and safety critical Systems, Structures and Components (SSC) the type and format of maintenance frequency were optimized.

3.2. Maintenance schedules and shutdowns

Reactor SSCs and other items to be repaired or replaced are subject to the necessary controls, depending on the safety classification, such as design and procurement control, project management and Quality Control (QC) release. This also applies to the in-house SAFARI-1 design and manufacturing capability and to the Necsa Nuclear Manufacturing facility which is accredited to ASME VIII and recently to ASME III. This means that safety critical mechanical SSCs can be manufactured on the Necsa site. Product record files are maintained containing supplier, SSC, inspection and test data information. In order to ensure integrity and safety of SSCs and other items, they can only be installed once being QC released.

Prior to the reactor shutdown a meeting is held with relevant maintenance and other staff and users to schedule all maintenance and inspections, tests and operational check activities thereafter, which are approved in the specific Maintenance Shutdown Plan (MSP). During the reactor shutdown tasks are performed in accordance with the plan and the NNR performs regular surveillances. On completion of the maintenance tasks and jointly during the post shutdown meeting, management and senior maintenance and engineering staff review various reports to ensure compliance with the MSP, OLC and OTS.

3.3. In service inspection

An In-Service Inspection (ISI) procedure and plan were drawn up which require ISIs to be performed on SSCs, the results of which are also reported to the NNR. Most of the ISIs (some 22) are integrated in and performed as part of the MSP, thereby ensuring that they are performed timely.

4. AGEING MANAGEMENT

The IAEA SSG-10 Safety Guide [2] provides guidance for ageing management for research reactors proposes an ageing management system approach over the life of the research reactor. As part of the SAFARI-1 integrated management system a system for ageing management was established by way of a procedure prescribing the system requirements for managing, implementing and assessing the activities required for preventing (e.g. preventative maintenance) , detecting (e.g. the ISI in 3.3 above), assessing and mitigating (i.e. Ageing Management Programme (AMP)) ageing affects. It is also required that the safety culture should be promoted in the AMP.

4.1. Ageing management programme

An AMP has been developed in SAFARI-1 [4] and is currently being implemented. The AMP was drawn up by holding internal workshops performing ageing assessments and formulating remedial actions to mitigate ageing issues. The design basis of SAFARI-1 contains no information on the designed lifetime of the facility and this can only be deduced from the effect of fluence on the fixed core structures, since no samples for tests are presently in the reactor. However, first assessments and calculations indicate that the soundness of structures can be projected to 2020. Beyond that a proactive approach for life extension will be followed through the AMP which has been formalized for implementation over a 5 year period with provisions made for expansion of engineering capability, capacity and financial resources.

The SAFARI-1 IMS was applied to the AMP and management systems for design control, project and configuration management and calculation control, which were strengthened in order to ensure that ageing management projects are executed in a safe, timely and effective manner. To this effect a dedicated Programme Manager was sourced and projects are formally registered, project managers appointed and detailed project schedules are being prepared.

4.2. Grouping of structures, systems and components

According to the IAEA guideline the SSCs were grouped into the following:

- Reactor block, fuel and internals;
- Cooling systems;
- Confinement and containment;
- Instrumentation and controls;
- Power supply;
- Auxiliaries (e.g. fire protection, crane, hot cells and radioactive waste handling);
- Experimental facilities, and;
- Non SSC:
  - Documentation (e.g. SAR, OTS, management systems), and;
  - Staff training.

4.3. Ageing mechanisms

To ensure a uniform approach to evaluation, rating and assigning risk factors the following ageing mechanisms are defined:

- Radiation resulting in changing of properties;
- Temperature causing changes of properties;
- Creep due to stress or pressure;
- Mechanical displacement, fatigue or wear from vibration and cyclic loads;
- Corrosion;
- Material deposition (e.g. crud);
- Flow induced erosion (e.g. orifice and concrete);
- Obsolescence through technology change;
- Damage due to power excursions, operational events;
- Flooding causing deposition and chemical contamination;
- Fire resulting in effects of heat, smoke and reactive gases;
- Changes in requirements such as legislation or acceptable standards, and;
- Other time dependent phenomenon.

4.4. Remedial action and prioritisation

A simple mathematical methodology was developed in the prioritization of the remedial actions. Once the ageing SSC was selected and the ageing mechanism(s) determined then the remedial action for each ageing mechanism is identified (i.e. replace, refurbish, redesign or maintain). If a remedial action is not performed then the relevant nine impact factor(s) (i.e. non-availability, reportable nuclear event, radiological exposure, injury to any one, environmental releases, license complication, lifetime limitation, public non-acceptance and stakeholder non-acceptance) are selected and a rating factor of 0, 5 or 10 is assigned to each impact factor, which are then summed together for all impact factors of the remedial action. To obtain the final prioritization factor the sum of impact factors is multiplied by a weighting factor on a scale from 1 to 10 for the remedial action (i.e. considering if controllable, implementable, viable, cost and urgency).

$$\text{i.e. Priority of Remedial Action} = \sum^{9} \text{Impact } (0, 5 \text{ or } 10)_i \times \text{Weighting Factor } (1 \text{ to } 10)$$

i=1

The resulting prioritization factor is used for resource allocation and scheduling purposes in the AMP.

4.5. Projects

The 57 remedial actions were expected to devolve into some 80 separate projects. For SAFARI-1 the ageing management process was used to list, prioritise, schedule and budget not only ageing management projects but also development, refurbishment, infrastructure upgrade and larger maintenance projects. Some of the following are projects given in Table 3 which are currently being implemented (a more complete list can be found in [4]):

TABLE 3: REMEDIAL ACTION LIST AND PRIORITIZATION

Remedial Action Description	Priority
Safety-Critical Ageing Management	
Upgrade (modernise) safety-critical neutron and gamma detectors and instrumentation.	400
Safety-Critical Instrumentation Segregation and Separation of Routing ("SCISSOR")	280
Implement remote shut down of reactor, selected plant & dedicated emergency control room	250
Evaluate, where necessary, redesign and re-implement all confinement penetrations	200
Periodic safety review (10 yearly) possible safety assessment by IAEA (INSARR mission)	200
Mission (Operation)-Critical Ageing Management	
Refurbish/replace reactor hall crane	400
Upgrade (modernise) radiation/contamination monitoring ,including fission product monitor	400
Upgrade (modernise) ventilation stack monitors and data transmission	400
Robotic eddy current ISI of built-in reactor, pool primary pipes and emergency spray nozzle	400
Convert to LEU fuel #	350
Convert to LEU targets #	350
Implement standard charcoal ventilation filter efficiency/effectiveness measurement	350
Adequacy of hot cell ventilation filters for an expanded commercial programme and upgrade	350
Re-evaluate basic design package and safety of the reactor and all experimental facilities	350
Replace Beryllium reflector elements #	240
Lifetime Extension Ageing Management	
Assess reactor vessel lifetime for recommendation for surveillance and/or replacement	400
Refurbish electrical gensets, UPSs, batteries, switchgear and reticulation: emergency	400
Modernise/rationalise ventilation logic, machinery & control and switchgear	400
Assess reactor building structure and stack integrity for lifetime extension of facility.	350
Replace/upgrade/modernise process instrumentation/control systems & isolate control room	350
Refurbish control room	350
Organisational (Management Control) Ageing Management	
Review, revise and update procedures	300
Controlled storage areas for critical spares, handling tools, maintenance equipment, etc.	300
Controlled storage areas for non-radioactive solid waste and materials (e.g. $ZnBr_2$)	300

Remedial Action Description	Priority
Develop expertise by filling vacancies and training personnel (SQEPs, criteria & procedure)	240
Improve OHS monitoring/tracking systems (SHEQ, BBS, safety culture, etc.)	200
IMS compliant to ISO 9001/14001, OSHAS 18001, RD-0034, NQA-1, NS-R-4, SHEQ-INS	150

completed or nearing completion.

5. INTEGRATED MANAGEMENT SYSTEM

The IMS integrates Quality, Health, Safety and Environmental (QHSE), Security and Safeguards management systems. The SAFARI-1 quality management system has evolved out of the Pressurized Water Reactor (PWR) fuel manufacturing plant's quality management system which was based on the American National Standards Institute (ANSI)/ASME NQA-1 Quality Assurance Programme Requirements for Nuclear Power Plants. Several SAFARI-1 staff members (Senior Manager, Manager Operation, Management Representative, Radiation Protection Supervisor and a few others) have come from the stringent control environment of the PWR fuel manufacturing plant. The National Nuclear Regulator (NNR) and Necsa SHEQ system has with time introduced many additional SHEQ requirements which over time have been incorporated in the SAFARI-1 integrated management system.

5.1. Assessments and certification of the Integrated Management Systems

The SAFARI-1 integrated management system has been certified to ISO 9001:2008, ISO 14001: 2004 and recently to OHSAS 18001:2007. The benefit of these independent external certification audits helped to improve the system. Other compliance audits are performed by NNR, Necsa Internal Audit Function and the Necsa SHEQ Department. In general audit results show an improving trend with the recent ISO 9001 external audit yielding no findings and the internal SHEQ Department audit showed that compliance increased by 10% to 91.8% in 2010.

Recently SAFARI-1 performed an internal audit (self-assessment, which is also prescribed by the NNR) with a 6 member management team. As expected management should know the strengths and weaknesses in the integrated management system and thus the audit yielded many findings and observations which are used now to further improve the system.

An IAEA Independent Safety Assessment of Research Reactors (INSARR) mission to perform an independent technical safety assessment of SAFARI-1 and the supporting infrastructure (e.g. licensing and waste management organizations) is envisaged.

5.2. Nuclear safety performance

Over the last two financial years the number of reactor scrams halved to about 10 from the previous year. Over the same period the number of nuclear occurrences more than halved from the previous financial year, see Table 4.

TABLE 4: NUCLEAR OCCURRENCES

Nuclear Occurrences	2009 FY	2010 FY	2011 FY
Level 2 (NNR reportable)	5	1	2
Level 3 (Event in Necsa)	26	10	11

5.3. Occupational health and safety

The excellent occupational health and safety record in SAFARI-1 has improved by means of a Behaviour Based Safety (BBS) programme. In this programme every person in the reactor is trained to observe personnel (on average once per month) doing a work activity. Observations on average take about 10 minutes and are done in accordance with a one page check list, where unsafe conditions are reported as either closed out or requiring follow-up actions. Personnel observed are notified at the start of the observation and at the end feedback is given about safe and unsafe behaviour, with the principle of "no-name and no-blame" assigned. The results since inception of the programme in 2003 are given in Figure 1 with the Total Injury Rate (TIR equal to annual average monthly injuries x 200 000/ possible annual man hours) now down to zero for the last two months (i.e. from about 16 annual injuries down to zero) and the contact indicator (total number of personnel observed/ total number of personnel) increasing to 1.8 (i.e. the number of observations and personnel observed increased).

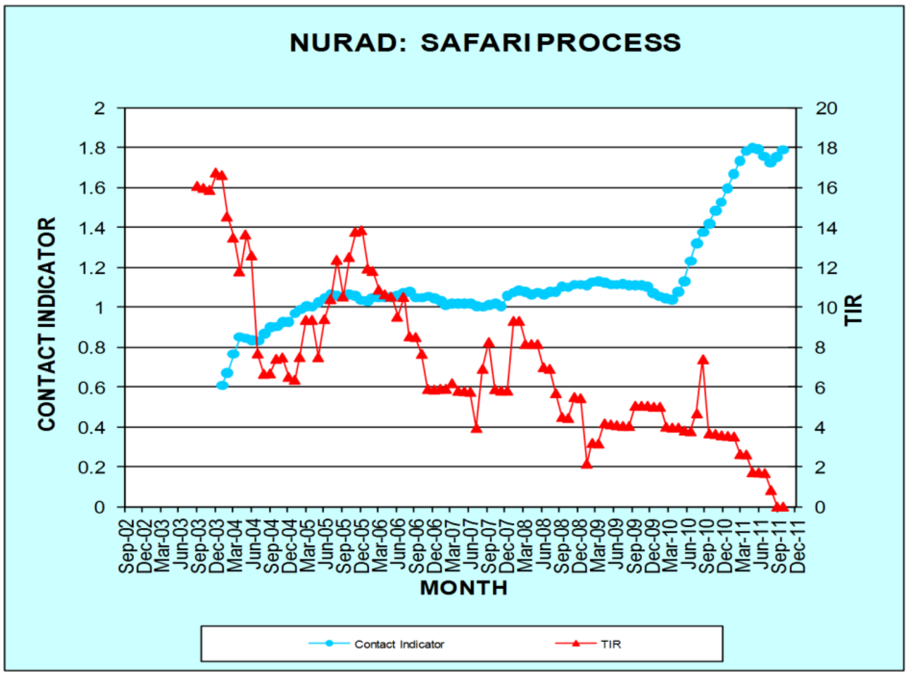

Fig. 2. SAFARI-1 BBS Performance.

5.4. Physical security

Physical security at SAFARI-1 has been strengthened over the years with a separate security fence, hardening of building perimeter doors, installation of a building camera system covering all areas such as administrative, workshops and radiological areas, parcel scanner and biometric access to the building and various areas therein. A person scanner will be installed in the upgraded entrance foyer. The recently completed repatriation of SAFARI-1 Highly Enriched Uranium (HEU) spent fuel of US origin being returned to the US at the Savannah River [5] and Low Enriched Uranium (LEU) to be received has required additional security measures such as further hardening of the building inner protection areas for conformance to INFCIRC/225/Rev.5. The IAEA will perform a security assessment to verify that all requirements have been implemented and are effective.

5.5 Safeguards

SAFARI-1 research reactor had an IAEA INFCIRC/66/Rev.2 safeguards agreement prior to South Africa acceding to the Non Proliferation Treaty (NPT) and the Comprehensive

Safeguards Agreement (CSA) in 1991. During 2002 South Africa signed the Additional Protocol (AP) and in 2011 it received the broader IAEA safeguards conclusion i.e. that there is no undeclared nuclear material and no undeclared nuclear facilities in the State. To support the non-proliferation objectives SAFARI-1 fuel was successfully converted from HEU to LEU in 2009 and routine ^{99}Mo production from LEU target plates was licensed by mid-2010. This achievement has made SAFARI-1 the first large scale LEU commercial ^{99}Mo production reactor in the world. In order for the IAEA to develop the integrated safeguards (IS) approach for South Africa various State-level verification activities according to an annual implementation plan will incorporate on-line reactor power monitoring and a new approach to spent fuel transfer.

6. FINAL REMARKS - CONCLUSIONS

Whereas the reactor operation and maintenance has resulted in a reliable and safe irradiation service to NTP for isotope production and NTD Silicon irradiation SAFARI-1 is actively implementing the ageing management programme for life extension as well as ensuring the safe operation of the reactor. The operation, maintenance and ageing management programme are being driven by the IMS which has contributed much to the successful operation and safety of the reactor.

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