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Updating research reactors to meet the growing needs of today's world

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HIGHLIGHTS

- The core conversion in research reactors is investigated.
- Some of the main core conversions in the world are introduced.
- All technical and non-technical reasons and challenges of the core conversion are given.
- A comprehensive roadmap for the core conversion is given.
- All requirements and limitations for the core conversion is seen.

ABSTRACT

Due to the diverse uses of research reactors compared to power reactors, a variety of safety aspects must be considered in their design and operation. On the other hand, due to the high age of a large percentage of these reactors, the need to update them in order to respond to the growing needs of today's society is inevitable. One of the items that increase the features in terms of proliferation, economy, usability, security and nuclear to meet the requirements of today's society is core conversion. The advantages and necessities of using new fuel in research reactors include the possibility of forming a more compact core, reducing operating costs, reducing security challenges, protection, environmental effects, transportation and end-of-cycle processes. In this study, the roadmap for research reactors core conversion is drawn considering all aspects of this issue which would be very useful for research reactor roadmap of any country especially our country.

KEYWORDS
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Core conversion
Roadmap
Requirements
Limitations

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1 Introduction

Since many research reactors were built in the 1960s and 1970s, they are very old and need to be modernized to meet the needs of today's society. One of these options available for reactor upgrade is fuel modification, which ranges from testing fuel package prototypes to replacing the entire core which requires changes in structures and equally in reactor components.

There are many reasons for research reactor core conversion. Changing the fuel from oxide to silicide is one of options for changing fuel performed in many research reactors such as ORR and GTRR in America, NRU in Canada, RP-10 in Peru, TRR-II in Taiwan, PARR-1 in Pakistan, RA-6 in Argentina and GRR-1 in Greece (IAEA, 2009; Housiadas, 1999). Also, molybdenum is used as a suitable fuel in many newer reactors such as KIJANG in South Korea. Further, Oxide-to-molybdenum fuel conversion has been investigated in some reactors such as Hanoro Advanced Reactor (AHR) in Korea (IAEA, 2021; Sembiring and Kuntoro, 2005; Surbakti et al., 2020). U3Si2-Al material in high density has already been made as a completely suitable material for use in research reactor Fuel Assemblies (FAs). Its performance has been proven using well-documented test and development programs and it seems likely that would be used as the most material for low-enriched fuel plates. In 1988, the US National Regulatory Commission (NRC) approved low-enriched uranium fuel, up to a density of 4.8 $g.cm^{-3}$ (Finlay and Ripley, 2001; Mo, 1998). Due to successful history of using this fuel in low and medium power research reactors, this fuel has been considered as a low-enriched fuel for use in some reactors (Keiser Jr et al., 2020; Commission, 1988). Some of the reasons for changing fuel in research reactors include the following (Graham and Walker, 1967; Villarino and Padilla, 2011; Matos and Snelgrove, 1992b,e):

1. Maintaining or improving the reactor's current capabilities and safety margins,

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2. As closely as possible, maintaining the technical specifications and operating procedures of the current reactor core,
3. Using the design of a proven FA design that is economical to build,
4. The possibility of forming a more compact core to improve radiation fluxes,
5. Reducing operating costs by reducing the number of FAs,
6. Improving the fuel burnup through a higher discharge burnup,
7. Reduction in the cost of safety requirements for the construction, handling and storage of fuel,
8. Proliferation issues,
9. Probability of power increase.

The core conversion program requires irradiating different types of fuel, including complete and miniature fuels, up to normal burnup or beyond, and conducting tests to determine the effects of radiation using Post-Irradiation Tests (PIEs). This include some limitations and issues that must be analyzed for a specific design (Matos and Snelgrove, 1992d).

- The ability of cooling systems to remove residual heat.
- The ability of the control rods to shut down the reactor with the necessary margin.
- No changes in the absorber area of the control FA,
- The same absorber rods with the same safety specifications,
- No change in nuclear safety design criteria,
- Higher operational requirements such as higher fluxes,
- The same external dimensions of the current and new FA,
- Minimizing hydraulic perturbation in the core.

In general, core conversion requires increasing the content of uranium as there is a lot of incentive to maintain primary loop without making changes to it. Reducing the number of FAs has a very important effect on all parts of fuel cycle such as security, proliferation, environmental effects, procurement, transportation and back end (Matos and Snelgrove, 1992a).

According to the content, the two following scenarios could be used to the core conversion (Matos and Snelgrove, 1992a):

- Changes that involving only the fuel and reactor core,
- The changes that are with other principal modifications in structures and components.

Over the years, many research reactors have operated safely with a variety of mixed cores. Whenever the geometry of the FA or material is changed, the overall safety analysis must be performed again (IAEA, 1980).

There are three main parameters to the core conversion analysis (Roglans-Ribas and Landers, 2011):

1. Feasibility studies to determine standard FA plans for each reactor.
2. Safety and functional analysis,
3. Support for regulatory process to obtain legal approval.

In some core conversion cases, a two-stage approach was used to identify a core design that would allow the use of new fuel and still have the same peak thermal flux available for experiments and the same cycle length as in the former design (Hanan et al., 1996). New FAs are irradiated in a variety of conditions for the qualification program. This included, maximum practical fuel loadings of approximately 50 vol% and fuel burnup up to 98% of uranium 235. There should be no signs of fission products release, excessive swelling of the fuel plate, warping of the fuel plate, blistering and other unusual conditions. When the modification concerned only a part of the installation, the operator had to present a complement to the safety report, s start-up program at low and high power, and a new version of the general operating rules to obtain the conversion license (Pond et al., 1997; Matos et al., 1992).

2 Materials and Methods

A detailed investigation of core conversion consequences is necessary, especially whenever the geometry of a FA is changed. A reactor core conversion generally requires a license amendment or a new license. Within this context, there is a wide range of possibilities depending on its characteristics and national conditions. The amendment need address only factors, whether directly associated with the reactor or with ancillary plant and operations, which are affected by the changes in fuel composition, core configuration and operational requirements (Matos and Snelgrove, 1992a; IAEA, 1984a).

The range of work depends on the magnitude of changes in the core and system. Calculations include assumptions, physical models and mathematical methods, explaining how the accident happened and the effects of the accident on the behavior of the reactor during the accident. Re-analysis of accidents should be considered in the safety report amendment after the core conversion (Matos and Snelgrove, 1992a). In all practical examples, determining the maximum allowed power will be the first safety criterion. The subsequent analyzes will be limited to the calculation of the flow instability margin. Determining the maximum working power is necessary to core conversion without changing the first primary coolant (Matos and Snelgrove, 1992b,c). Since the mixed cores calculations are performed consecutively, the adequacy of the margin

Table 1: An example of probable licensing procedure.

Item	Condition	
	Core conversion only	Core conversion with modifications
Probable hardware variations	New fuel, new core Including control rods, new reflector	Major modifications of systems and components in addition to new fuel including control rods, new reflector
Documents for application	Amendment to Safety Report, revision of relevant chapters including fuel specification and fuel qualification	Completely revised Safety Report including fuel specification and fuel qualification
Licensing procedure	Application for a license amendment Examination of licensing documents by an expert body, Approval of Amendment to Safety Report	Application for new license Examination of the documents by all relevant bodies Approval of licensing documents by the authority

for the initiation of nuclear boiling and the limiting shutdown margin should be checked after each cycle. If one of the new fuel positions does not meet the safety criteria, others must be considered until reaching an acceptable answer (Matos and Snelgrove, 1992a; Villarino and Hergenreder, 2003).

The necessary tests and measurements in a core conversion program depend on the following (IAEA, 1984b):

1. Scope and results of thermal-hydraulic and nuclear calculations.
2. Scope and results of dynamics and safety calculations
3. The existence of major differences between core designs,
4. The presence of mixed cores,
5. The existence of significant changes in the design of FA,
6. The presence of significant changes in the design of control systems or control rods,
7. Minimum reactivity at the end of cycle.

Two possible approaches that can be used in different core conversions are listed in Table 1 for further explanation (Matos and Snelgrove, 1992a).

When there is a transition period with mixed cores, the accepted pattern for conversion of cores should be described. Many installations may operate with a temporary core using both old and new fuel until an equilibrium core with new fuel is reached.

2.1 Core conversion considerations

The first step in this process is the production of new fuel, which must be produced taking into account the necessary requirements such as mechanical integrity, inflation and accordance with quality control and assurance procedures. Radiation tests on small fuel plates are performed to confirm fission density ranges as a function of uranium density for different types of fuel. Full-size FAs are tested to prove that these fabricated plates have the expected behavior. Irradiation of full-size FAs leads to better statistics of fuel behavior than irradiation of miniature plates and checking the qualification of fuel manufacturers (Roglans-Ribas and Landers, 2011).

The essential requirements for core conversion are highly dependent to extent of the final reactor specifications. If core conversion is accompanied by an increase in power, the requirements for the new power of the reactor should also be taken into account. In case of increasing the reactor power with core conversion, due to the existence of more stringent requirements in reactors with higher power, it is necessary to include some additional systems such as Engineered Safety Features (ESFs) in the new core. Significant changes in the cooling system of the reactor with the same nominal power will not happen in this case. For example, in Pakistan Research Reactor-1 (PARR-1), where the core conversion has been done along with the power increase, major modifications and additions have been made in the heat removal system. These changes include the installation of new primary pumps, heat exchangers and a cooling tower, and an emergency cooling system. In addition to the mentioned items, heating, ventilation and air conditioning systems (HVAC), diesel generators and compressors have also been replaced (Khan et al., 1989; Arshad et al., 1991). Some of related considerations for core conversion with increasing power are shown in Fig. 1.

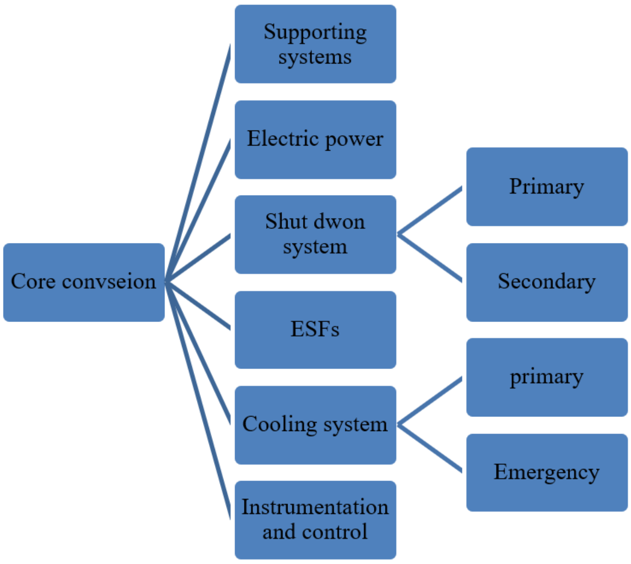

Figure 1: Required modifications for core conversion with increasing reactor power.

Since it will be possible to form the first, mixed and equilibrium core arrangements during core conversion, the investigation of physical components, burnup characteristics, shutdown, and etc. for all configurations is necessary. In other words, where the power of the reactor remains constant after the core conversion, if the new dimensions of the cooling and fuel flow channel are the same with the former, the heat removal characteristics is not studied in detail.

Considerations for core conversion without increasing power are shown in Fig. 2. The items of this figure would be explained in details as far as possible.

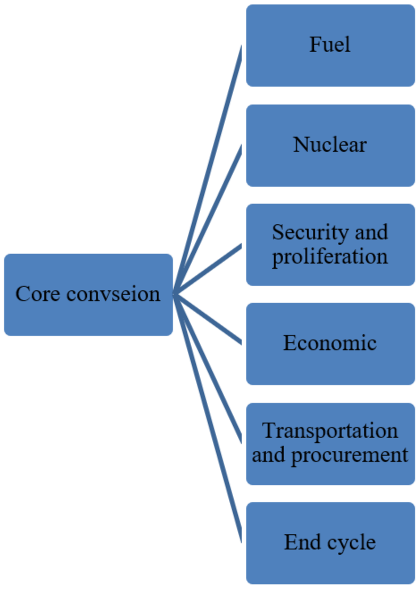

Figure 2: Core conversion considerations without increasing power.

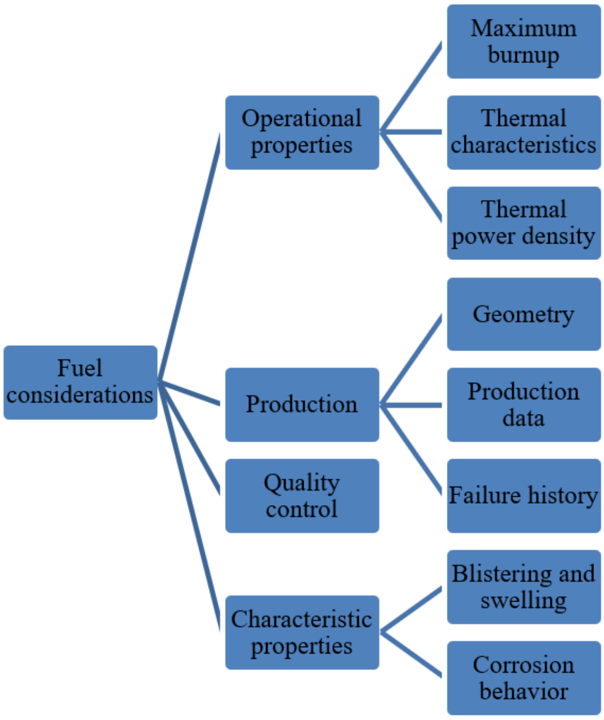

Figure 3: Fuel considerations for core conversion.

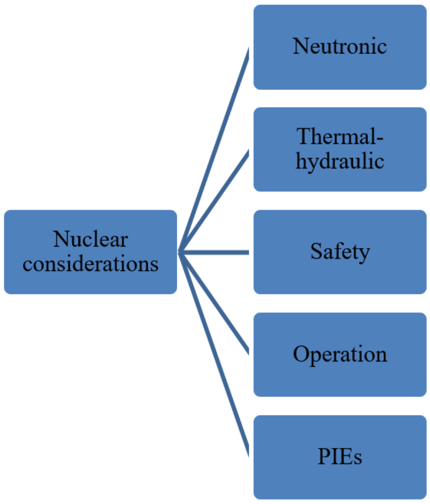

Figure 4: Nuclear considerations for core conversion.

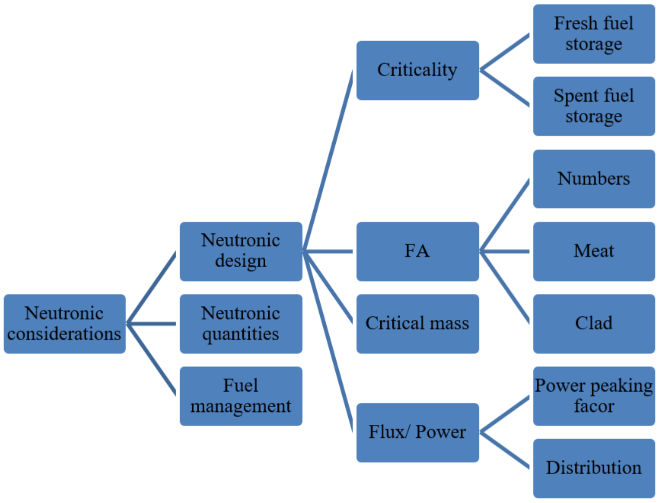

Figure 5: Neutronic considerations for core conversion (Neutronic design).

2.2 *Fuel considerations*

Fuel considerations in core conversion are shown in Fig. 3.

2.3 *Nuclear considerations*

Nuclear considerations in core conversion are shown in Fig. 4.

Each of Fig. 4 processes is given separately below to some extent. It is worthwhile to mention that neutronic considerations include neutronic design criteria, neutronic quantities, and fuel management strategy, which are shown Figs. 5 and 6. Nuclear considerations of core conversion are shown in Fig. 5. Neutronic quantities of core conversion is shown in Fig. 6.

A comparison with the old design is recommended. A list of materials and specifications should be provided for each component of the control rod system and internal components of the reactor that have had changes. If uranium mass in the new core is changed, detailed critical tests for the reactivity behavior of the new FAs and control rod worths for these core configurations are required. It is possible that the core conversion requires a re-calculation of the fissile material mass in the beginning and subsequent cores, re-statement of reactivity and shutdown reactivity worths, power peaking coefficients and fuel burnup data for different operational states during the core life. Reflector changes should be discussed, as sometimes it is possible to affect quantities such as core size, fuel burnup, and shape coefficients. Investigation of fuel burnup including discharge burnup for first, subsequent, full replaced and final equilibrium cores. If the control rod design has been changed, information must be provided to demonstrate that the control rod actuation system, which includes the main auxiliary equipment and hydraulic systems, is still capable of performing the required function. Effects of changed irradiation conditions on materials should be discussed if significant. If there are no changes in FA geometry, core size, or reduction of safety margins, only discussion of thermal design is necessary.

If the geometric shape of the FAs changes, it is possible that the performance of the first primary coolant has changed, which requires checking the hydraulic and thermal design. In this case, it is possible to obtain a set of normal operation specifications.

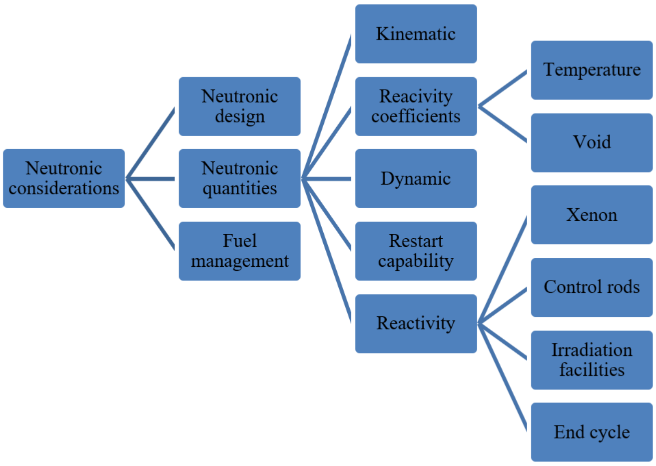

Figure 6: Neutronic considerations for core conversion (Neutronic quantities).

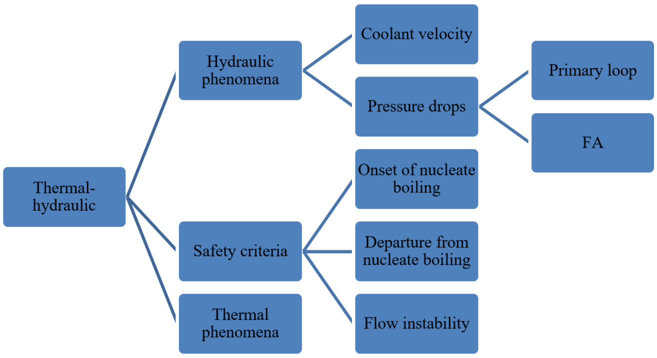

Figure 7: Thermal-hydraulic considerations for core conversion (part-1).

The thermal-hydraulic components are shown in Figs. 7 and 8. It is necessary to remember that it is necessary to consider two modes of natural and forced convection for these mentioned items.

The decay heat of new core should be calculated and the deviation between the decay heats of the two fuels in short and long times should be investigated. The safety components are shown in Figs. 9 and 10.

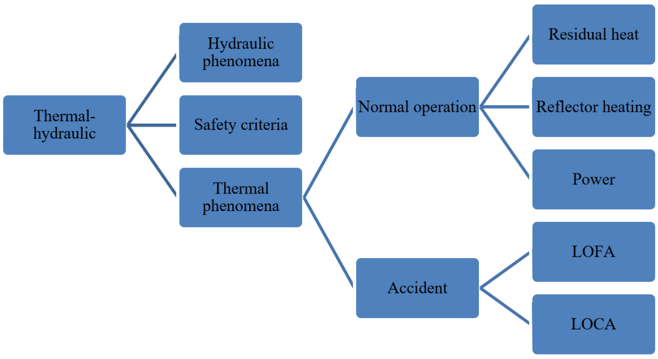

Figure 8: Thermal-hydraulic considerations for core conversion (part-2).

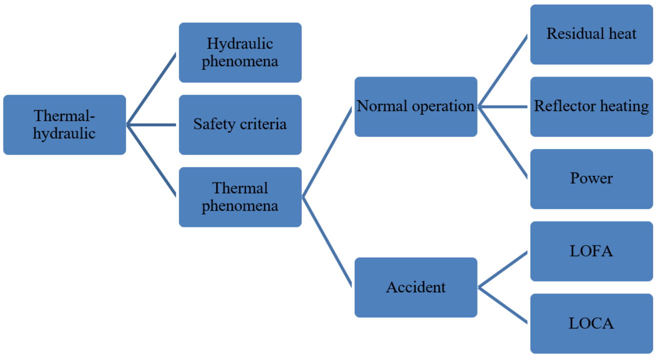

Figure 9: Safety considerations for core conversion (part-1).

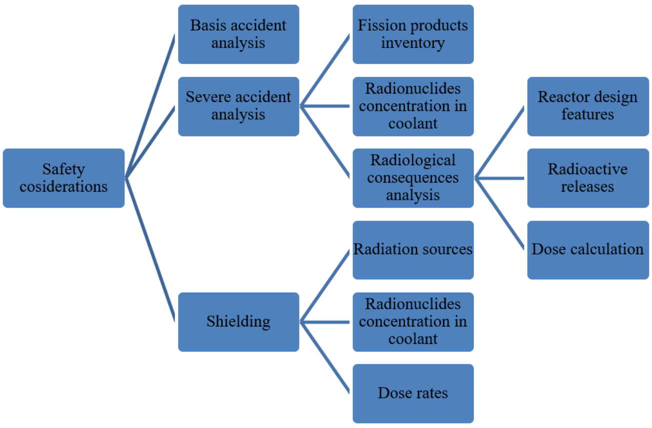

Figure 10: Safety considerations for core conversion (part-2).

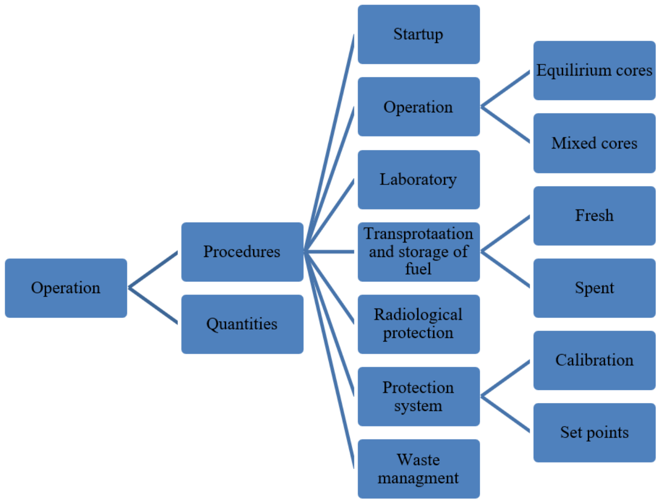

Figure 11: Operation considerations for core conversion (procedures).

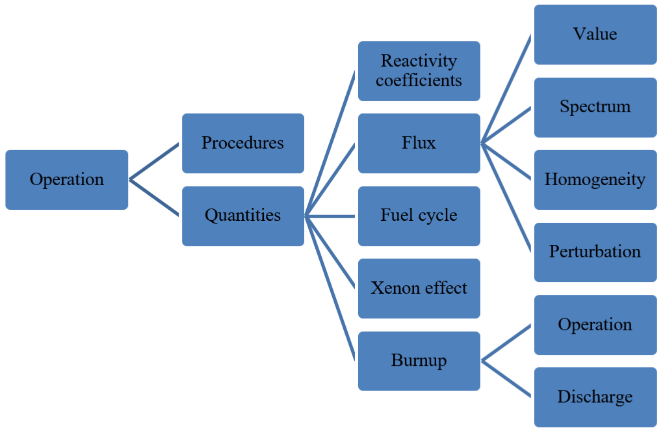

Figure 12: Operation considerations for core conversion (quantities).

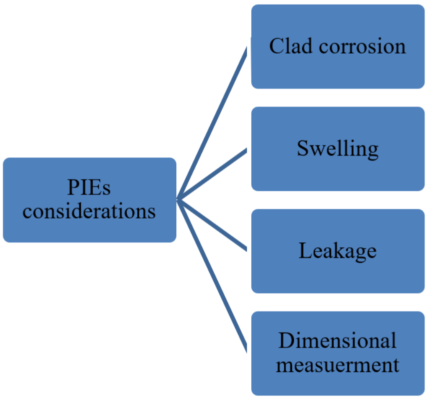

Figure 13: PIEs considerations for core conversion.

In the case of using a fuel for the first time in the core or changing the power in a way that according to the existing standards and requirements requires taking into account stricter safety criteria, necessary safety systems such as the automatic shutdown system should be installed in the reactor.

The analysis of severe accidents includes considering a hypothetical accident and the radioactive materials leakage from the core to the reactor building and finally release into the atmosphere. Its consequences for the surrounding population are usually evaluated in terms of the estimated radiological doses. Reactor core modification generally requires reviewing the effect of core modification on these predetermined radiation outcomes, which in many cases is very small. The radiation level outside of water or concrete is only partially affected due to changes in the size of the core or reflector. Therefore, radiation levels are not expected to be affected by the core conversion, unless major changes to the facility are required. Depending on the detailed design of the reactor, it is possible that radiation in the components of the primary loop is very sensitive to the delay times in the output of the core. If the coolant flow rate increases, the adequacy of the delay system may need to be re-evaluated. The operation components are shown in Figs. 11 and 12.

The type of startup experiment required for each case will be different. A start-up program is necessary to verify the calculations and training of the reactor operators. This program, especially if a mixed core is used, is required to ensure adequate margins are maintained for thermal-hydraulic safety and shutdown. The hydraulic and physics tests of the reactor for the design of the new FA must be done before operating at full power, and it is necessary to verify the performance of all reactor heat removal systems.

Operational procedures include start-up procedures (pre-start-up, start-up, zero power and power range tests), radiochemical and chemical measurements, radiation level measurements, shutdown reactivity measurements and reactivity coefficients, power calibration procedures, normal and emergency shutdown, residual heat removal, and emergency and transportation procedures.

Transportation and storage of FAs including storage provisions of fresh and spent fuels, their location and capacity, criticality safety considerations, necessary measures to deal with the fall of heavy loads for the transportation of FAs, and regulations for identifying and monitoring leakages.

In the absence of significant changes in the nuclear and thermal-hydraulic characteristics of the core, the core conversion is not expected to affect the core instrumentation and control system, except for possible re-calibration at initial start-up after conversion is necessary. If the new designed fuel is similar to the previous one, all existing fuel handling facilities and methods can be used for the new fuel. The different parts of the PIEs are shown in Fig. 13.

2.4 Security and proliferation

Plans related to protection should be given in the safety report. The difference between protection of facilities and fuel should be distinct. Proliferation considerations have been one of the most important factors that have created a global movement to the core conversion in research reactors from Highly Enriched Uranium (HEU) to Low Enriched Uranium (LEU). Security and proliferation considerations are shown in Fig. 14.

2.5 Economy

Economic benefits of the core conversion are largely dependent on the cost of new FAs production and the reactor in question. One of the most important goals of the core conversion is the possibility of using a more compact core to improve the neutron flux and decreasing the operating costs. These happens by reducing the number of FAs due to the use of uranium with a higher density. Uranium burnup can also be improved through the use of higher discharge burnup. Considering the possible economic benefits of using higher density fuels in research reactors, the IAEA is planning an activity to conduct a comprehensive study of the effect of fuel density on research reactor fuel cycle costs (Villarino, 2013).

2.6 Transportation and end cycle

Reducing the number of FAs required for the operation of the reactor leads to a reduction in the number of fuels that must be prepared. This means reducing the transportation and logistics processes for new FAs. It is reminded that the layout of the fresh fuel storage should be re-examined in terms of having sub-critical conditions. Also, reducing the number of needed FAs used in the reactor operation has a direct impact on reducing handling and transportation, maintenance facilities, possible accidents and spent fuel reprocessing activities.

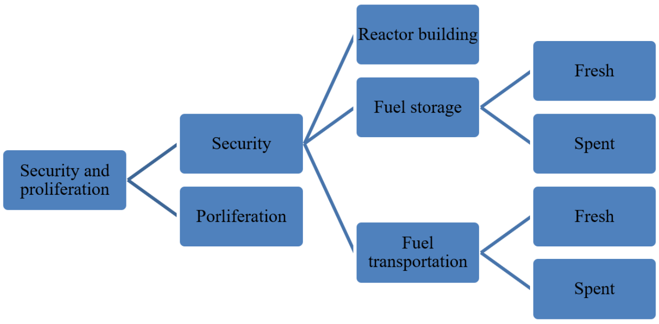

Figure 14: Security and proliferation considerations for core conversion.

3 Conclusions

Before starting a detailed study for the core conversion, the priority of the design criteria should include the least modification in the reactor core. Operating characteristics should be considered for the least problems for licensing, the least costs of the fuel cycle and also re-optimization for the highest performance. When changing fuel, there is a lot of incentive to maintain the primary loop without making changes to it. In case of changing the fuel without increasing the power of the reactor, if there are no significant changes in the geometry of the FA or reducing the safety limits, there will not significant changes in the cooling system of the reactor. In case of increasing the power of the reactor when changing the fuel, it is necessary to include some additional systems and analyses such as engineered safety features in the new core. Whenever significant changes are made, their effects should be considered. In some cases, it is necessary to re-evaluate the content of fission products, fission product releases, and radiological consequences.

Conversion of a reactor core will generally require either a license amendment or a new license. The tasks required to prepare the necessary information for a safety report amendment related to the core conversion should be written in such a way that it is possible to do logically. In this case, there is a wide range of possibilities, depending on the characteristics of the reactor and the national situation.

After a core conversion, the operator must create new documents, procedures and policies depending on the extent of the changes. A new safety analysis report or an amendment should include things such as quality control and testing necessary to ensure the validity of the safety-related design. Also, a detailed safety analysis should be done which includes items such as the core, the primary cooling loop, the ventilation system, and fuel transportation and storage.

The core conversion of research reactors could upgrade these facilities and improve their capabilities for better answering to the requirements of the todays society. Also, nuclear knowledge acquisition for future research reactors design and construction is another important consequence of core conversion in research reactors.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

References

Arshad, M., Bakhtyar, S., Hayat, T., et al. (1991). Neutronic calculations of PARR-1 cores using LEU silicide fuel. Technical report, Pakistan Inst. of Nuclear Science and Technology.

Commission, N. R. (1988). Safety evaluation report related to the evaluation of low-enriched uranium silicide-aluminum dispersion fuel for use in non-power reactors. Technical report, Nuclear Regulatory Commission.

Finlay, M. and Ripley, M. (2001). A new fuel for research reactors.

Graham, W. W. and Walker, D. M. (1967). *Safety Analysis Report for the 5 MW Georgia Tech Research Reactor*. Engineering Experiment Station, Georgia Institute of Technology.

Hanan, N., Mo, S., Smith, R., et al. (1996). An alternative LEU design for the FRM-II. Technical report.

Housiadas, C. (1999). *Thermal-hydraulic calculations for the GRR-1 research reactor core conversion to low enriched uranium fuel*. National Centre for Scientific Research" Demokritos," Institute of Nuclear .

IAEA (1980). Research reactor core conversion from the use of highly enriched uranium to the the use of low enriched uranium fuels. *IAEATE CDOC-233.*

IAEA (1984a). IAEA Safety Series No. 35, codes on the safety of nuclear research reactors. *International Atomic Energy Agency.*

IAEA (1984b). IAEA-TECDOC 304. Core Instrumentation and Pre-Operational Procedures for Core Conversion HEU to LEU. *International Atomic Energy Agency.*

IAEA (2009). IAEA-TECDOC 625. Research Reactor Modernization and Refurbishment. *International Atomic Energy Agency.*

IAEA (2021). IAEA Nuclear Energy Series, NF-T-2.7, Impact of fuel density on performance and economy of research reactors. *International Atomic Energy Agency, Vienna.*

Keiser Jr, D. D., Wachs, D. M., Robinson, A. B., et al. (2020). The use of U_3Si_2/Al dispersion fuel for high power research reactors. *Journal of Nuclear Materials*, 528:151820.

Khan, L. A., Qazi, M. K., Bokhari, I. H., et al. (1989). Analysis of the critical and first full power operating cores for PARR using leu oxide fuel. Technical report, Pakistan Inst. of Nuclear Science and Technology.

Matos, J., Mo, S., and Woodruff, W. (1992). Analyses for Conversion of the Georgia Tech Research Reactor from HEU to LEU fuel. Technical report, Argonne National Lab.(ANL), Argonne, IL (United States).

Matos, J. and Snelgrove, J. (1992a). Research reactor core conversion guidebook (Summary). Technical report, Technical Report IAEA-TECDOC-643.

Matos, J. and Snelgrove, J. (1992b). Research reactor core conversion guidebook-Vol 2: Analysis (Appendices A-F). Technical report, Technical Report IAEA-TECDOC-643.

Matos, J. and Snelgrove, J. (1992c). Research reactor core conversion guidebook-Vol 3: Analytical verification (Appendices G-H). Technical report, Technical Report IAEA-TECDOC-643.

Matos, J. and Snelgrove, J. (1992d). Research reactor core conversion guidebook-Vol 4: Fuels (Appendices I-K). Technical report, Technical Report IAEA-TECDOC-643.

Matos, J. and Snelgrove, J. (1992e). Research reactor core conversion guidebook-Vol 5: Operations (Appendices L-N). Technical report, Technical Report IAEA-TECDOC-643.

Mo, S. (1998). A neutronic feasibility study for LEU conversion of the high flux isotope reactor (HFIR). Technical report, Argonne National Lab.

Pond, R., Hanan, N., and Matos, J. (1997). A neutronic feasibility study for LEU conversion of the High Flux Beam Reactor (HFBR). Technical report.

Roglans-Ribas, J. and Landers, C. (2011). Research and test reactor conversion to low enriched uranium fuel: technical and programmatic progress. In *Proceedings of the IAEA International Conference on Research Reactors: Safe Management and Effective Utilization.*

Sembiring, T. and Kuntoro, I. (2005). Core conversion study from silicide to molybdenum fuel in the Indonesian 30 MW multipurpose reactor GA Siwabessy (RSG-GAS).

Surbakti, T., Surian, P., Farisy, Y., et al. (2020). Analysis of Safety Reactivity Factor on RSG-GAS Core using New Fuel. In *Journal of Physics: Conference Series*, volume 1485, page 012007. IOP Publishing.

Villarino, E. A. (2013). Core performance improvements using high density fuel in research reactors. *RRFM St Petersburg Rusia.*

Villarino, E. A. and Hergenreder, D. (2003). Neutronic characteristics of the RRR. Technical report.

Villarino, E. A. and Padilla, A. G. (2011). Core Performance improvement using U_3Si_2-Al fuel in the RP-10 modernization. *Proc. Int. Mtg on Reduced Enrichment for Research and Test Reactors, Santiago.*

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