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CORE INSTRUMENTATION AND PRE-OPERATIONAL PROCEDURES FOR CORE CONVERSION HEU TO LEU

REPORT OF A CONSULTANTS' GROUP MEETING
ON IN-CORE INSTRUMENTATION AND PRE-OPERATIONAL PROCEDURES
FOR CORE CONVERSION HEU TO LEU
ORGANIZED BY THE
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Foreword

Research reactors are beginning to operate with low enriched, high uranium density fuels that have been developed as part of the international programme to convert research reactor cores from high enriched uranium (HEU) to low enriched (LEU). Irradiation tests, as part of the fuel qualification programme are underway with results and data from post-irradiation examinations becoming available. As these fuels become qualified, more research reactors will be converting to LEU. The decreasing availability of HEU fuels for research reactors mandate that reactor operators consider the conversion of their reactors to LEU.

The properties and characteristics of the new fuels differ from HEU fuels and need to be considered before, and measured at conversion. Many facilities have not had recent experience in the pre-operational instrumentation and startup and requirements for operating with new or mixed cores. The purpose of this Report is to present general guidelines covering these activities for facilities considering core conversion to LEU.

This report is the result of a Consultants' Group Meeting held in Vienna on 11-14 October 1982 with subsequent contributions from the participants. The assistance of the participants of the meeting in the preparation of this report is gratefully acknowledged and it is hoped that an even larger audience associated with research reactors would benefit from their efforts.

Other Agency publications related to Research Reactor Core Conversion to Low Enriched Fuel are as follows:

1) Research Reactor Core Conversion from the Use of Highly Enriched Uranium to the Use of Low Enriched Uranium Fuels, Guidebook, TECDOC-233, Vienna, 1980. [1]

2) Research Reactor Core Conversion from the Use of Highly Enriched Uranium to the Use of Low Enriched Uranium Fuels, Guidebook Addendum, Heavy Water Moderated Reactors (under preparation). Estimated publication date 1984 [2].

3) Safety and Licensing Issues Related to Core Conversion, Guidebook (under preparation). Vol. 1, Licensing and Analysis - Estimated date, 1984 Vol. 2, Fuels - Estimated date 1984-1985.

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1. Introduction

1.1 Overview

In the 1950s and 1960s, low power research reactors were built around the world which utilized MTR-type fuel elements containing ≤ 20% enriched uranium (LEU). This value was chosen because it was considered to be unsuitable as weapon usable material. However, the demand for higher specific power and/or longer fuel cycle length created a need for greater ^{235}U concentrations and led to the substitution of highly enriched uranium (HEU) in place of the LEU fuel previously utilized. HEU fuel also yielded other benefits including longer core residence time, higher specific reactivity, and somewhat lower cost. HEU then became readily available and was used for high power reactors as well as low power reactors where LEU would have sufficed.

In the 1970s, however, concern was again raised about the proliferation- resistance of fuels and fuel cycles [9], and since enrichment reduction to less than 20% is internationally recognized to be a fully adequate isotopic barrier to weapons usability certain Member States have moved to minimizing the international trade in highly enriched uranium and have established Reduced Enrichment Research and Test Reactor Programs (RERTR). The goal of these programmes is to develop the technical means, such as design modifications and development of new fuels, to assist in implementing reactor conversions to LEU fuels with minimum penalties. It is anticipated that through the continued efforts of these programmes, most reactors may be converted to the use of LEU fuel.

Concern has also been expressed about the presence of plutonium in spent fuel, especially when the fuel is irradiated in reactors utilizing very low enrichment and/or operating at high powers, and it is necessary to consider both the plutonium production and uranium enrichment in the overall assessment of the proliferation potential of a particular reactor. The safeguards and proliferation aspects of core conversion will not be dealt with in this report.

Operators of research and test reactors that use highly enriched uranium may consider converting their reactors to the use of low enriched uranium fuels for several closely related reasons. One could be the desire to reduce the proliferation potential of research reactor fuels. The second reason could be a desire to increase the assurance of continued fuel availability in the face of restrictions on the supply of highly enriched uranium. A third reason could be the possible reduction in requirements for physical security measures during fabrication, transportation, storage and use.

The IAEA can provide technical assistance to reactor operators who wish to consider conversion of their reactor from the use of HEU fuel to the use of LEU fuels.

1.2 Scope of the Report

This report is intended for the reactor operator, to be used as a manual or checklist for general guidance on pre-startup activities that need to be addressed in preparation for conversion to LEU fuel. All nuclear, thermodynamic and safety calculations should have been performed prior to this stage of the core conversion process. During these calculations and certainly before ordering the new LEU fuel elements the reactor operator needs to very carefully consider additional important factors concerning the new fuel: fuel reliability, reliability of fuel fabricator, reprocessing contract or fuel element storage and disposal, economics of the new fuel cycle (Chapter 6). At this stage, too, a preoperational experimental programme (Ch. 3,5) has to be developed and presented to the regulatory authorities for approval. This experimental programme could lead to additional requirements on: in-core instrumentation, out-of-core instrumentation or additional experimental devices. Detailed instructions on specific tests and measurements are not provided in this report since much information on the subject is available in the open literature.

It should be emphasized that this report may be used for general guidance and not construed as requirements that the reactor operator has to follow. The report will help the reactor operator to develop tests and measurements necessary for not only the safety assessment of the conversion process but also for information regarding the reactivity and flux behaviour of the new core. In this regard the listing of instrumentaton and measurements is presented as a collection of useful and hopefully helpful information. In each individual case the requirements for doing one or the other experiment depends on:

- the completeness of nuclear and thermodynamic calculations.
- the completeness of dynamic and safety related calculations.
- the comparison of the actual old (HEU) and new (LEU) core design.
- operation with mixed (HEU + LEU) or only new (LEU) fuel reactor cores.
- the old and new ^{235}U content.
- whether the fuel element design is changed or unchanged.
- whether the control rod design is changed or unchanged.
- knowledge of thermal flux distribution (power distribution).
- knowledge of burnup values.
- the safety system trip values and margins.

On the basis of this information, the reactor operator needs to perform startup experiments to:

- check the calculations.
- learn from experiments, flux and power distributions and reactivity values for the different core configurations as normally research reactor cores are not fixed.

This report complements Guidebook, TECDOC 233 [1] and the Guidebooks [2, 3] that are expected to be published in 1984 dealing with safety and licensing issues of core conversion and in 1985 dealing with LEU fuel. Therefore, in this report reference will often be made to Guidebooks as well as other more specialized references. Appendix A describes experience of the FNR (USA), the only whole core conversion to the new 20% LEU fuel. The OSIRIS (France) has also been converted from HEU to 7% LEU fuel [5].

In some cases reactor operators and/or regulatory bodies will take the core conversion procedure as an opportunity to upgrade some parts of the facility. Of special importance will be the reactor protection system and the conventional reactor instrumentation. While this upgrading of these systems of the reactor is not necessary for, or directly related to core conversion, it is felt that this would be a common situation [14, 15]. For this reason a short section on this topic is included (Chapter 2, 4.1).

Chapter 3 discusses pre-operational procedures emphasizing the necessity for collecting all physical and technical data from calculations, measurements, etc. and to develop very early in the process, experimental programmes for the core conversion procedure. This programme should be critically reviewed by the operating organization prior to submission to the regulatory authorities.

For safety and reactor physics measurements special instrumentation may be necessary to provide data and supplement existing in and ex core instrumentation. Examples of some currently used instrumentation and measurement techniques are given in Chapter 4.2.

The reactor physics and safety parameters believed to be important or helpful during the conversion process are described in detail in Chapter 5.

Chapter 6 summarizes information about expected differences between HEU and LEU fuel and also suggests special topics to be considered by the reactor operator before ordering the new fuel.

2. Assessment of LEU Core Safety

The conversion of a reactor facility from a highly enriched uranium core to lower enrichment will generally require either a license amendment or a new license [3].

Within this range there is a wide spectrum of possibilities. The actual requirements for a core conversion to LEU depend on the reactor characteristics and on the national regulatory situation.

In this regard, the facility operator would be required to submit an amendment to, or a revision of the Safety Analysis Report (SAR), 1983 Edition. In either case, the report would contain technical information and an experimental programme to show that the converted facility could continue to be operated without undue risk to the reactor personnel and to public health and safety. The SAR should demonstrate that the degree of safety in the new reactor core is at least equivalent to that of the previous core. Reference is also made to IAEA Safety Series No. 35 for a description of Technical Information to be included in a SAR [4].

Core conversion is not expected to lead to any major change in the safety assessment, consequently there should be no need for major changes in the instrumentation and safety systems of the reactor. The SAR should however point to those measurements that will be made for validation of the calculations and this in turn will lead to the specification of the special instrumentation that may be required.

3. Pre-operational Programme

3.1 Planning

The preparatory work to be done before any physical changes are started depends upon the method of conversion to be adopted - a whole core change or a gradual introduction of LEU fuel elements. A whole core conversion may be a simpler case for safety analysis but will be more expensive in the utilization of the fuel. An incremental change permits more economic use of both the HEU and the LEU fuel during the conversion but as it involves mixed cores of HEU and LEU fuel elements the safety analysis is more complex.

The choice of method will already have been made during the preparation of the SAR and this must therefore form the basis for planning the conversion. The incremental conversion method will probably be the one chosen by most facility operators, but if the thermal-hydraulic design of the fuel elements or the core configuration is to be different then a whole core change may be necessary.

Additional factors which will influence the pre-operational programme will be any decisions made about modifications to the reactors e.g. new control absorbers, upgrading of the installed instrumentation and control circuits. Calculations and experimental measurements indicate that a small reduction in the worth of absorbers is to be expected and this may be a limiting factor. Consideration has therefore to be given to the need to change the absorbers e.g. from oval to forked type or to change a fine control rod to a full worth shim rod. In the latter case, it is possible to consider dual or variable speed drive if necessary to maintain fine control for the operator.

It is necessary to calculate the changes that will occur in the main reactor parameters. Much of this will have been done in the preparation of the revised SAR but it may be necessary to summarize or convert the data into a format suitable for prediction of and direct comparison with, the measurements to be made, as outlined in Chapter 5.

The predicted flux spectra and flux distributions will be important to the users of the reactor and this data should be made available to them as early as possible so that they can plan any necessary changes to their experimental equipment or programme. Any alteration in the reactor availability or length of the operating cycle will also be important and should be formulated according to the reactor usage.

An overall programme for the conversion should be prepared with sub-programmes for each stage or sub-division of the work. The SAR will again form the basis for this programming but it will be necessary to translate principles into work programmes for the various groups involved. The availability of staff will be a governing factor and the resources of manpower and expertise will be an important point to be settled at the programming stage.

Each sub-programme should give appropriate emphasis to any safety related aspects of the work and should contain detailed procedures for the operators to follow. These must be formally authorized at an appropriate level in the facility management and should cover procedures for the special experimental measurements as well as the fuel change and operating procedures. (See 3.2, 3.3) [4]

The sequence of the experiments will be influenced by the need to assure safety at each stage and the appropriate measurements must have been made and assessed as acceptable before proceeding to the next stage or to higher power or full power operation. The overall plan must take this into account and allow time for appropriate approval at management or licensing levels.

The Ford Nuclear Reactor at the University of Michigan, USA, has been successfully converted to LEU fuel (initial criticality - 8 December 1981) and the experience obtained during this test programme may be of use to other reactor installations for preparation of their overall programme. Reference 24 should be consulted for details of this project.

3.2. Experimental Programme

An experimental programme has to be written, discussed and agreed upon at a very early stage of the core conversion procedure, as these discussions impact on the whole conversion procedure, the instrumentation and the measurement techniques. The experimental programme should describe experiments believed necessary

- to verify calculations
- for safety limitations
- to give useful additional information.

A detailed listing has to be presented of the proposed experiments and measuring techniques. Such a programme is normally arranged sequentially for comparing the results with calculations or estimations and considering the possible safety implications arising from the results. For this reason the experimental programme may have to be adjusted during the conversion procedure, taking the experimental results into account. This could affect the schedule of the conversion procedure since changes to the SAR may require regulatory approval and a revised experimental programme.

3.3 Operating Programme

The experiments will necessitate preparatory work, e.g, changes to the core configuration, resetting of trip levels, installation and testing of special instrumentation, variation of cooling to effect temperature changes, etc. These requirements should be set out in a detailed programme for the operating staff, which should additionally specify the levels of authorization and supervision needed at each stage.

4. Instrumentation

4.1 Permanent Instrumentation for Startup and Operation

4.1.1 Influence of Core Conversion

In principle no change in the permanent instrumentation system is necessary, to accommodate a conversion from HEU to LEU fuel as the main design parameters for the instrumentation system and the reactor safety system are unchanged. It is nevertheless recommended that the existing permanent instrumentation be assessed for adequacy in the light of current techniques and principles. Three main cases can be distinguished and are discussed in more detail.

a) unchanged geometric design of the fuel element and the core configuration,

b) altered geometric design of the fuel element and/or the core configuration,

c) mixed core configuration of HEU and LEU fuel elements in the reactor core at the same time.

Case a)

Only small adjustments of the channels measuring thermal neutrons (e.g. safety, linear channels) are necessary. Similar procedures have to be done with the present core after refuelling or long time operation at full power.

Case b)

If a change in pressure drop across the reactor core is measured, then the influence of these alterations should be investigated carefully. In the case where the primary coolant flow through the fuel elements is dependent on the core size and/or the positions occupied with fuel elements the Δ T (temperature) over the core will also change. Changes of Δ p and Δ T must be taken into account. In addition, the case a) procedure has to be followed.

Case c)

Beside case a) procedure, in most cases additional safety considerations are necessary. As form factors (max/mean power) may increase (see chapter 6) one or a combination of the following actions may be necessary

- reduced safety settings (trip values) for all power measuring channels (e.g. linear, safety, N^{16}, N^{17} channels),
- reduction of the nominal power limit if new safety settings are not possible or practical,
- increase of the primary coolant flow and/or reduction of its temperature with corresponding changes to trip settings to keep the margins the same.

4.1.2 Design Considerations

In some cases the reactor operators and/or regulatory bodies will take the core conversion procedure as an opportunity to upgrade parts of the facility [3]. The permanent reactor instrumentation for monitoring, control and reactor protection will be of special importance. For this reason a short guidance to these topics is given. Typical demands on reactor protection systems for research reactors as part of the safety system are included in e.g. [12, 13].

Descriptions of a renewed instrumentation system for a 250 kW Triga and a 15 MW MTR-type research reactor can be found in [14,15]. Today design critera for a reactor protection system are partly based on the concepts of [12,13,15,35,38,39]:

- Redundancy	parallel, backup equipment with the same function, multiplication of channels, including independence such as physical separation of sensors and cables, functional isolation, etc
- Diversity	different types of independent channels for controlling the same process.

The most important parts of the system should preferably be based on both the principles of redundancy and diversity. The channels should be selected as part of a complete accident analysis which must prove that the selected channels with their safety settings reduce the accident probability and accident consequences to acceptable levels.

As a consequence of and in addition to the previous demands, a modern safety system must offer a high standard of reliability in internal signal processing, high availability, suitability for self-monitoring and self-annunciation of malfunctions, failure to safety, a high quality and constant operational performance even when subjected to extreme conditions.

4.1.3 Typical Permanent Instrumentation

The permanent instrumentation at a research reactor serves three purposes: 1) monitoring of operations, 2) control and 3) protection

Typical channels used in a reactor protection system of research reactors are listed in the following. When considering a specific reactor only some of these channels may actually be installed. Typical channels:

four main types of nuclear channels with neutron and/or gamma sensitive detectors in the active zone:

startup channel (fission detector or BF_3 counters),

linear channel (gamma compensated ion chamber or fission chamber in a combined counting rate and wide range variance mode),

logarithmic channel with period meter (compensated or uncompensated ion chamber or fission chamber in wide range mode).

safety channel (uncompensated ion chamber or gamma chamber

primary coolant $N^{16}(\gamma)$ and N^{17} (n) activities, fuel temperature, primary coolant temperature, primary coolant flow, primary coolant pressure, pressure drop across the core, current of primary pump motors, water height in the pool.

secondary coolant Secondary coolant flow, Secondary coolant temperature, water level in the basement, etc.

area monitoring - gamma dose rate in the reactor hall

These types of channels (in practice not all) and malfunction of essential equipment are used to automatically activate reactor protection functions when a signal reaches the maximum value, or in some cases a minimum value.

Beside the instrumentation for automatic reactor protection demands, similar and additional instrumentation is necessary e.g. for the measurement of pH and electric conductivity in the primary coolant, temperatures (pool, primary and secondary coolants, heat exchangers, motors), pressures at elevated locations in primary and secondary piping, control rod positions, health physics instrumentation (neutron and gamma dose rates, gas and aerosol activities etc. in the reactor hall, experimental hall, chimney, coolant loops etc.) including fuel cladding failure detection (fission product monitoring).

The signals are also displayed or recorded for data collection and manual feedback and some are used for automatic control. For more details see relevant references [12,13,14,15,28,35,36,37,38].

It is not the purpose of these remarks on reactor instrumentation to present complete design information as this topic is far too complex to be covered in this report. The intention is to give some guidance if alterations of the instrumentation are under investigation.

4.2 Special instrumentation

The basic starting point for core conversion is that it should be carried out in a controlled manner. The state of the reactor should be monitored in more detail than under normal operation and the core properties and influence of the core conversion on various quantities should preferably be experimentally verified.

Thus in addition to the normal, pemanently installed reactor instrumentation, which is used at the start-up, low power and high power operation, there may also be a need to use some special instrumentation in the transition phase only. The amount and type of this extra instrumentation should be assessed and planned in advance based on the SAR, on the need for special physical parameter measurements, (Chapters 5,6) and on the need for other process parameter measurements. For example the need for an extra low power trip should be assessed.

The amount and type of special instrumentation also depends on whether the reactor core is converted in incremental steps or whether the whole core is converted at the same time. The most common measurements are reviewed in Chapter 5.

Due to the wide range of measurements (e.g. 9-10 decades of power) different types or locations of the transducers may be used at the start-up, low power and high power operation.

4.2.1 Options for In-core Instrumentation [16,39]

The special additional in-core instrumentation for the transition phase may include the following types of transducers:

- instrumented fuel elements (for loss of flow, temperature, etc. measurements) are important if thermal hydraulics is a major concern [17, 18, 26]

- miniature fission chambers for the measurement of the thermal neutron flux distribution, kinetic measurements, etc. [19]

- SPN detectors for measurement of the neutron flux distribution (e.g. Rh and V) and for kinetic measurements (e.g. Co-59 with prompt response) [20,32]

- self-powered beta current detectors for gamma flux measurements (e.g. Pt, Zr)

- neutron sensitive thermocouples (with a neutron absorber e.g. B-10, Li-7 and U-235 dissipating energy on neutron absorption)
- thermocouples for temperature measurements (e.g. PtRh-Pt, NiCr-Ni, Fe Konst., Chromel-Alumel) and resistance thermometers (e.g. Pt, Ni)

- activation detectors (wires, foils, etc. sensitive to thermal neutrons, intermediate energy range neutrons and to fast neutrons, threshold detectors) to measure the neutron flux and neutron spectra [19,24,29,30,31,36]

- flow measurements (e.g. with turbine flow meters or throttling by contraction) to measure flow distribution and fluctuations due to turbulence or vortices [16,20,35,37]

Relevant references include more data about available special instrumentation [e.g. 16-20].

The special instrumentation actually provided will depend upon the particular conversion being undertaken, and may differ from this list which should not be taken as complete or mandatory.

4.2.2 Options for Ex-core instrumentation

The previous transducers and others can also be used for ex-core measurements to indicate in-core parameters, to obtain neutron and gamma flux, temperature, flow and other distributions outside the core, at irradiation facilities, beam tubes etc. More bulky detectors can of course be used outside the core and outside the radiation shield.

Proton recoil spectrometers (fast neutrons), crystal diffractometers and neutron time of flight equipment (thermal neutrons) outside the reactor shielding may be used to measure the neutron spectra, e.g. in the beam tubes at research facilities etc.

On-line reactivity meters with signals from neutron flux detectors are obviously also very useful at the transition phase. The recorded time behaviour and kinetic measurements on the reactor may also be analyzed off-line based on inverse reactor kinetics, etc. [20].

5. Measurement of Converted Reactor Parameters

This section provides guidance for the measurement of neutronic and thermal/hydraulic parameters of the reactor following core conversion. While most of the discussion is directed toward measurements for whole core replacement, portions are relevant to a gradual replacement of the HEU core with LEU fuel elements. References 1 and 3 should be consulted for additional guidance.

5.1 Determination of Critical Mass

The method for the determination of the initial critical mass of the LEU core (whole-core replacement) should not differ from that normally employed for HEU fuel [22]. Previous experience and procedures that are applicable may be used, as appropriate. Depending on the available startup channels incorporated with the reactor to measure low neutron intensities, additional instrumentation (e.g., a movable fission chamber) may be needed to provide reliable measurements of the multiplication at each loading step. A suitable neutron source may be necessary for a whole core replacement. It may also be desirable to conduct a control rod calibration since it is unlikely that the critical core will be obtained with all control rods out unless partially loaded fuel elements are available during the initial startup. If possible, direct measurement of the specific control rod worth in the critical assembly is to be preferred, since the normal control rod calibrations will be performed with a somewhat larger core (to provide the excess reactivity needed to perform the control rod calibrations). In this way an accurate estimate of critical mass for a cold, clean LEU core can be obtained.

This section is not applicable to a gradual LEU conversion.

5.2 Control Rod Calibrations

The control rod worth in the LEU core is expected to be less than in a corresponding HEU core, as mentioned in Section 6. This will ordinarily be addressed in the appropriate safety analysis report (SAR) and experimental verification of the estimated control rod worths should be performed. There is no reason that the LEU core per se will require a change in the procedures for measuring the rod worth; however, certain of the kinetic parameters are expected to be different for the LEU fuel and care should be taken in inferring control rod worth as such determination depends on the kinetic parameters. For example, the effective delayed neutron fraction, βeff, is needed to infer control rod worth from a measured period. As noted in Section 6, calculations indicate that βeff is somewhat smaller for LEU fuel than for HEU fuel.

This section is applicable to the gradual LEU core replacement as well as to whole-core replacement, although the determination of an appropriate βeff for the mixed core may require additional analysis.

5.3 Reactivity Coefficients

In addition to the measurement of control rod worth, the measurement of certain reactivity coefficients may be required to assess the shutdown margin of the LEU configuration. In particular it will probably be necessary to measure the xenon and power reactivity coefficients. These coefficients, along with the fuel burnup coefficient, will allow a determination of the actual shutdown margin. Procedures for measuring these coefficients are well-known and will not be different on account of the LEU fuel. However, the reactor installation may also decide to measure the isothermal temperature coefficient and/or void coefficient. Since these measurements are not typically performed, a brief description of possible methods to perform these measurements is included.

Isothermal temperature coefficient: This coefficient can be measured in the following ways.

(i) Reduce the secondary coolant flow or shut-down the secondary heat removal system at power and use the resultant temperature increase and control rod position change to calculate the moderator temperature coefficient (caution is necessary to avoid unacceptable temperature of the primary coolant.

(ii) Individually heat the water moderator of each element by circulating hot water through a plenum from the top of the element and measure the resultant reactivity change while the primary cooling system remains on in order to avoid heat convection to the rest of the moderator. By using a dummy element the temperature coefficient at various positions of the reflector can be measured by the same method [33].

(iii) Heat the pool water either directly by electrical resistance (depending on the amount of water) or indirectly by heating the secondary cooling system (in some reactors this is feasible) and circulating the primary system.

Void coefficient: This coefficient can be determined by inserting either aluminium stringers between the fuel plates or air voids by means of specially constructed plastic devices or stringers and measure the resultant reactivity change [23,34].

While the measurement of these coefficients is primarily directed towards the whole-core LEU replacement, it may be necessary to perform similar measurements during the mixed-core transition to the LEU core for a gradual core replacement.

5.4 Flux Distributions

Significant differences are expected in the thermal flux distribution in-core and ex-core for the LEU fuel, as discussed in Section 6 below. Therefore, it may be desirable to perform full core flux maps of the LEU core to verify predicted flux distributions as well as to furnish information concerning flux peaking in the core [25]. There are no effects due to the LEU fuel which will necessitate modifying the procedures for performing such flux maps; however, the significant spectral differences with the LEU fuel may warrant some care when interpreting absolute flux from the measurements. Self-powered neutron detector (SPND) measurements or iron wire activation measurements are possible approaches for obtaining flux maps. Methods for obtaining fast rhodium or vanadium SPND measurements have been reported [20, 24, 30, 32], which eliminate the need to equilibrate the detector at each measurement location. For example, axial scans of a 24" MTR fuel element can be performed in 10-12 minutes versus 2-3 hours if equilibrium is achieved at each location.

5.5 Spectrum Measurements

Significant spectral differences are expected for LEU vs. HEU fuels. Depending on the available equipment, a reactor operator may decide to perform experiments to assess the spectral differences. This may be important to some users who rely on a particular reaction due to specific energy neutrons or whose experiment may be sensitive to changes in the energy spectrum.

Possible methods to measure the spectrum include:

(1) Unfolding techniques utilizing the activation of multiple foils with differing threshold, resonance and thermal neutron induced reactions (fast, epithermal and thermal spectra) [29,30,31,36]

(2) Crystal diffractometer measurements of the thermal spectrum. [28]

These methods are mainly directed towards whole-core replacement. Assessing spectral differences in a mixed core may not be very useful.

5.6 LEU Fuel Element Reactivity Worth Measurements

The reactivity worth of a fresh LEU element versus the worth of a fresh HEU element in various locations of the "old" HEU core may be of use to the operator. For example, it provides for a first observation of the neutronic behaviour of the new fuel in a manner that is quite safe. Secondly, it may provide some basis for the operator to plan the critical loading experiment. Finally, it can be used to compare predicted values for the relative reactivity worths of the HEU and LEU fuels.

A possible approach is to begin with the "old" HEU core with its spectrum of depleted fuel elements and replace a depleted HEU element with the fresh HEU element and then the fresh LEU element. [25] Measurement of the relative worths can be inferred from rod positions if each configuration is made critical or period measurements if desired. If this is repeated for both the centre and periphery of the HEU core, it may be sufficient for providing information concerning the relative worth anywhere in the core. This information could also be used in the SAR regarding reactivity insertions during refueling.

Although this procedure may be most useful for gradual replacement of the HEU core with LEU fuel, it may be of use for the whole core replacement because of the "experience" obtained with the new fuel.

5.7 Thermal/Hydraulic Measurements

The measurement of thermal/hydraulic parameters may not be necessary if the heat transfer characteristics of the LEU fuel elements are similar to those of the HEU elements (i.e. same waterchannel dimensions and same power rating). In addition, this section is intended for the whole-core replacement option, since it seems unlikely that fuel elements of variable heat transfer capabilities would be mixed in one core configuration. However, these measurements may be of interest to those installations which choose the gradual core replacement option because they provide independent data for the power distribution of the core. Some typical thermal/hydraulic measurements might include:

(1) Loss of primary coolant flow (LOFA) - depending on the availability of instrumented fuel elements, a loss of flow condition could be initiated and the fuel temperature measured at the core position of maximum flux as a function of time. [17,18] Under normal conditions, the reactor would automatically shutdown and decay heat removed by natural convection or a decay heat removal system. Also see 6.1.7(a). In connection with this experiment it may be of interest to determine the time sequence of various functions (magnets off, scram signal from low flow rate, scram signal from flapper open) after a loss of pumps as well as the water flow and power decrease after scram as a function of time.

It is also recommended to follow the temperature rise with the instrumented fuel element as a function of power at various core positions.

(2) Axial water temperature distributions [21] - e.g. with movable sensitive thermocouples inserted in the water channels, axial temperature measurements can be obtained. If the flow rate is known, the power of the element can then be calculated and compared with other measurements, such as SPND flux maps. For low power reactors, the small measured temperature differences may introduce large uncertainties in this measurement.

(3) Flow measurements - depending on the availability and location of flow meters, flow rate distribution measurements can be made to be used in conjunction with the temperature measurements and both can be used to detect flow instabilities due to turbulence or vortices [21]

6. Reactor Core and Fuels

6.1 Summary of Differences - Benchmark Problem

IAEA publications [1, 2, 3] were intended to assist reactor operators and physicists in converting their specific reactors from HEU to LEU fuel. A wide variety of information is presented on the physics, thermal-hydraulic, safety, licensing and fuels of light and heavy water moderated and cooled research reactors.

The three guidebooks [1, 2, 3] contain detailed information on calculated changes of nuclear and safety related parameters and properties when converting from HEU to LEU. In addition, the different contributor organizations performed calculations on one fixed Benchmark core configuration.

The Benchmark core contains:

- 6 x 5 element core reflected by a row of graphite on two opposite sides
- 23 standard MTR elements containing 23 fuel plates
- 5 control elements containing 17 fuel plates
- UAl_x-Al meat

HEU: 93% enrichment
280 g ^{235}U per element (standard)
12.174 g ^{235}U per plate

LEU: 20% enrichment
390 g ^{235}U per element (standard)
16.957 g ^{235}U per plate

The intention for these Benchmark calculations was to compare the different calculational methods and cross section data of the different organizations and to show the order of changes of nuclear and safety related parameters. The results of the calculations by the different organizations were in very good agreement. Since those calculations were for a hypothetical core, the results are used here primarily only as qualitative information. Quantitiative information can be obtained by performing specific calculations and/or performing a more or less extended experimental programme during the conversion phase. The following listing presents the more important results from these Benchmark calculations (see Table 1.)

6.1.1 ^{235}U content

Compensating the increasing parasitic absorption from the ^{238}U an increase of the ^{235}U content between 14% and 18% will be necessary.

6.1.2.Reactivity effects

a)βeff will decrease by approximately 5%.

(b) reactivity worth of the control rods. Depending on the design of the control rods, the control rod guide elements, the position of the control rods in the core, the size of the core, the reactivity worth for the equilibrium core can decrease approximately 20% of the HEU total reactivity worth. Therefore in some cases, a redesign of the control rod may be necessary. This effect may be offset by the reduction in the excess reactivity of the core (See c).

(c) Excess reactivity
The excess reactivity to compensate for burnup will be reduced.

(d) Shut down margin

The shut down margin will be decreased. In some cases difficulties may arise in meeting the stuck rod criteria especially during mixed core operation.

(e) Temperature Coefficient
The negative isothermal temperature coefficient will be approximately unchanged.

(f) The Doppler coefficient will be significantly larger due to the increased amount of ^{238}U. The Doppler coefficient may be about 10% of the isothermal temperature coefficient.

(g) Void coefficient

Will be more negative.

(h) Reactivity rate from control rod removal

Will decrease (see b).

(i) Xe-reactivity
The Xe reactivity worth will be approximately the same.

(j) Neutron Lifetime

Will decrease

6.1.3 Pu production

At the end of the fuel lifetime the Pu-inventory will increase due to the larger amount of ^{235}U for an equivalent fuel cycle length and due to the much larger amount of ^{238}U and increased conversion of ^{239}Pu in the LEU fuel.

6.1.4 Safety Margins

For an unchanged core configuration, power and fuel element design the safety margins for burnout and flow instability will be the same. The exception may be the transition phase using mixed cores.

6.1.5 Form factors (max. to average ratio)

Nuclear calculations show a reduction of the form factor for the LEU case. But there can arise severe problems during the transition phase with mixed cores.

6.1.6 Neutron fluxes

a) Reactor core

The thermal neutron flux for the same specific power generation will be decreased in the reactor core due to the increased amount of ^{235}U per fuel element. The fast neutron flux will be nearly unchanged.

a. in core irradiation positions

thermal flux - decrease up to about 15% depending on design
fast flux - nearly unchanged

b. reflector region
thermal flux - slightly decreased
fast flux - nearly unchanged

All statements are made for the same % burnup.

6.1.7 Accidents

a) Loss of flow (LOFA)

The fuel temperature increase during the first phase of this accident - reactor running at full power, primary flow decreases - will be higher for the LEU case due to less thermal conductivity. The SAR will show whether this can be tolerated. In some cases a new setting of the trip point coupled with a direct trip from electrical monitoring of the pump motor may solve this problem.

b) Startup

The continuous withdrawal of control rods will result in less total energy release in the LEU case. This is an effect of the prompt Doppler coefficient.

c) Other reactivity accidents

Refer to the safety and licensing guidebook [3].

6.1.8 Miscellaneous

Additional impacts on properties can be found in chapters 6.2 and 6.3.

6.1.9 Conversion Studies

Some converson studies have been performed and more will be done within the RERTR-Programs.

First conversion studies are completed and papers presented at the IAEA Seminar on Research Reactor Operation and Use, Jülich 1981, for BER-II and FRM[7], TR-2 [8], ...

Table 1 Summary of Differences of Nuclear Parameters Based on the Benchmark Core**

Parameter	LEU/HEU
Excess Reactivity	decrease
Control Rod Worth	decrease
Flux Intensity	Fast/epithermal - small diference in core, reflector thermal - decrease 12-15% in core, slight decrease in reflector
235 U Max*	increase 14-18%
Delayed Neutron Fraction	small decrease
Neutron Lifetime	decrease
Doppler Coefficient	more negative
Water Temp. Coef.	small difference
Void Coefficient	more negative
Plutonium Production	increase

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*Assuming loading to maintain same cycle length and EOC excess reactivity.

**The reader is reminded that this summary is based on a hypothetical core and may not be applicable to his specific reactor.

6.2 Fuel supplies, reprocessing and safeguards

The following points should be checked by the facility operator and/or the regulatory body before ordering the new fuel:

6.2.1 Reliability of the new fuel

Relevant information will be found in volume 2 of the guidebook on safety and licensing issues [3].

6.2.2 Reliability of the fuel element fabricator

It is important to choose a fabricator with adequate references for the selected new fuel [3].

6.2.3 Reprocessing [11]

Reprocessing of HEU UAl_x and U_3O_8 fuel is a standard procedure. For LEU UAl_x and U_3O_8 fuel no acceptance for reprocessing and no prices are available at present. This is expected to change in the future when there will be a stock of spent fuel elements at the reprocessing plant. LEU U_xSi_y fuel is presently not commercially available and therefore there are unresolved questions on reprocessing. For these reasons it is necessary and of fundamental interest for the facility operator and the licensing authority to have a reprocessing contract or as a minimum a spent fuel disposal possibility for the new LEU fuel.

6.2.4 Economics

The increase in fuel cycle costs has been rapid in past years despite decreasing natural uranium prices. It is assumed that for LEU fuel elements the fabrication costs will increase between 30% and 100% [6, 42, 43]. This increase may be offset by the expected longer fuel cycle for the LEU fuel.

Therefore core conversion may be taken by research reactor operators as a good opportunity for trying to lower this trend. If the ^{235}U content per fuel element is increased by more than that needed, ca. 15% for compensating the ^{238}U absorption, more MWd per fuel element will be produced. This leads to a reduction of the fuel cycle costs. Some guidance for performing fuel cycle calculations can be found in [1, 6, 10, 27]. When repeating these calculations, it is necessary to use current real prices as they sometimes change very quickly.

6.2.5 Safeguards and Physical Protection

There are possible options to reduce safeguarding and physical protection demands for the fresh fuel storage when using LEU fuel [3].

6.3 Fuel- Miscellaneous

In the guidebook on safety and licensing issues [3] useful information and calculations can be found on some additional points of interest. Some are presented here very briefly as an indication of what may be needed.

6.3.1 Criticality of fuel storage

The safety from criticality of the fresh and spent fuel storage for the LEU fuel elements have to be recalculated. In the case of the spent fuel storage these calculations should be performed assuming fresh fuel elements, i.e. no burnup of ^{235}U.

6.3.2 Decay heat

A comparison of the decay heat after full power operation of a 280 g ^{235}U (HEU) and a 390 g ^{235} (LEU) shows only a small increase within the first hours and only up to 10% increase within the first 30 days for the LEU fuel.

6.3.3 Maximum fission product content

The long term maximum fission product content after full power operation will be increased for the LEU fuel by less than 1%.

6.3.4 Fuel transportation

Information on fresh and spent fuel transportation are presented in [3]. No special problems arise when using LEU fuel.

6.3.5 Weight

The weight of one fuel element will increase by more than one kg due to the higher uranium density necessitated by the use of low enrichment fuel. It may be necessary in some cases to confirm the static calculations for the spent fuel storage and the grid plate.

7. Conclusions

The impacts of core conversion upon nuclear, thermodynamical and safety design of a research reactor have to be considered in close correlation to fuel reliability as soon as possible. Depending on the results of these calculations or investigations an experimental programme will be necessary for the whole conversion phase. The conversion procedure includes pre-operational procedures, instrumentation and safety system, validation, additional instrumentation for measurements during the conversion phase and the type and extent of the measurement programme. The guidance provided in this report is necessarily of a general nature. Specific details would depend on the reactor under conversion and the detailed calculations and measurements that would need to be performed.

The IAEA can provide the following:

1. Support expert(s) to visit the requesting developing country to develop and advise on the experimental programme necessary and to assist in the measurements during the conversion phase.

2. Sponsor a training programme on all aspects necessary to be considered for the research reactor core conversion.

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APPENDIX A

Summary of Ford Nuclear Reactor Experience with LEU Fuel

The Ford Nuclear Reactor (FNR) is the demonstration reactor for the utilization of LEU fuel in research reactors. The initial LEU core went cricical on 8 December 1981, and was followedd by a series of low power and high power measurements and experiments. The FNR is proceeding with a gradual conversion from HEU to LEU fuel and has operated with a mixed core with no difficulty. Since the thermal/hydraulic characteristics of the LEU and HEU fuels are almost identical, this is to be expected. In the next paragraph is a summary of the pertinent differences observed for the HEU and LEU cores. However, it must be understood that these observed differences may be unique to the FNR and its specific configuration and should be treated as such. Secondly, it is important to note that measurements taken on the LEU core cannot be directly compared with corresponding measurements on the equilibrium HEU core, since the LEU core consisted of fresh fuel and was therefore considerably smaller than the HEU core, which has a significant effect on the measured flux intensities, both in-core and ex-core.

Before the full LEU core was loaded, a fresh HEU fuel element in the centre of the equilibrium HEU core was replaced with a fresh LEU element. The thermal fluxes were measured in the centre of each element and the thermal flux ratio (HEU/LEU) was 1.19, which is equal (within experimental uncertainty) to the LEU/HEU U-235 mass content (168.3g in LEU; 140.0g in HEU). Measurements of the subcadmium flux over the five central fuel elements in the 38 element HEU core and a 31 element LEU core (less than 3% depleted) indicated a reduction in the subcadmium flux by a factor of 1.17, again consistent with the increased U-235 loading. Simultaneous with the in-core measurements, measurements of the flux peaking in the reflectors indicated an increase by 1.53 in the H_2O reflector and 1.17 in the D_2O reflector. These measurements are very sensitive to the core geometry (both LEU and HEU) and are expected to be considerably different for an equilibrium LEU core. The final effect of the LEU conversion is a mild hardening of the core spectrum, as indicated by measured cadmium fractions for the HEU and LEU cores. No spectral hardening was evident for the leakage currents measured from beam ports facing the D_2O reflector.

Further information and details concerning the experimental results and analytical predictions can be obtained from References 24, 40 and 41.

APPENDIX B

GLOSSARY OF ABBREVIATIONS USED IN THE REPORT

BOC = Beginning of Core - often BOL
BOL = Beginning of Life
EOC = End of Core - often EOL
EOL = End of Life
HEU = Highly Enriched Uranium (20%), usually 80%)
LEU = Low Enriched Uranium (20%)
LOFA = Loss of Flow Accident
LOCA = Loss of Coolant Accident
RERTR = Reduction of Enrichment for Research and Test Reactors
SAR = Safety Analysis Report
SPND = Self Powered Neutron Detector

APPENDIX C

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