5.3 FUEL ASSEMBLIES

5.3.1 Introduction

5.3.1.1 General Description

The reactor core is loaded with plate type Fuel Assemblies (FAs) containing uranium silicide (U_3Si_2) powder dispersed in pure aluminium, with a maximum uranium density of 4.8 gcm^{-3}. This type of fuel has become internationally accepted and has been routinely fabricated for twenty reactors by four fabricators in four different countries.

The FAs are square-shaped, each with twenty-one flat fuel plates. Each fuel plate consists of a meat of U_3Si_2 powder (19.75% of U^{235} in weight enrichment) dispersed in an aluminium matrix. The fuel meat is hermetically sealed between two aluminium alloy covers (the cladding). There are two types of fuel plates which differ only in the cladding thickness. The core grid has sixteen FA positions inside the chimney in a 4 x 4 configuration. The core grid is divided into four zones by guide boxes that accommodate five control rod plates in a cross array. The maximum residence time of the FAs in the core is about 180 full power days.

5.3.1.2 Background

On the basis of extensive irradiation experience accumulated from the successful operation of many research and test reactors around the world, the technology of dispersion fuels is mature.

The international programme “Reduced Enrichment in Research and Test Reactors” (RERTR) for the conversion of a large number of research reactors from using highly enriched uranium (HEU) fuels to low enriched uranium (LEU) fuels has contributed to the knowledge of LEU dispersion fuels. This international co-operative programme has facilitated the development of advanced fuel materials using low enrichment uranium without significantly reducing research capabilities, performance, or reactor safety and without raising operation costs, or requiring significant component modifications (Travelli, A., 1999). To obtain comparable performance to the previously used HEU fuels, the new LEU fuels must be of higher density. Development of high-density LEU fuels is progressing, particularly of fuel consisting of uranium silicide dispersed in aluminium, and more recently of fuel based on uranium-molybdenum alloys (Snelgrove, J.L. et al., 2000).

Because of its excellent behaviour under irradiation, programme efforts have focussed on U_3Si_2-Al with a uranium density of 4.8 gcm^{-3}. Many experiments with mini-plates, plates and full-scale FAs were performed (Hofman, G., 1988; J.L. Snelgrove et al., 1996; Chaussy, J.M. et al., 1999) so that silicide fuel was established at uranium densities of 4.8 $gcm^{-3}$and below. This fuel was fully qualified for low and high power reactors in 1988 by the U.S. Nuclear Regulatory Commission. The Safety Evaluation Report is presented in the document NUREG-1313 (U.S. Nuclear Regulatory Commission, 1988).

Silicide fuel is widely used because its maximum practical uranium density is suitable for most research and test reactors. U_3Si_2 can be reliably produced and fabricated into fuel plates and assemblies and has satisfactory all-round properties, including excellent behaviour under irradiation. Silicide fuel has been or in some cases is fabricated by Babcock and Wilcox (USA), Cerca (France), CNEA (Argentina) and Nukem (Germany).

From the beginning of the RERTR programme, 36 reactors have converted from using HEU fuels to using LEU fuels. The U_3Si_2 dispersion fuel is at present used world wide by different research reactors, such as ISIS and OSIRIS in France, HANARO in Korea, NRU in Canada, HOR in The Netherlands, and JRR-3M, JRR-4 and JMTR in Japan. Their thermal power ranges from 0.7 MW to 135 MW, showing the wide range of conditions that this fuel material can withstand. Other reactors have scheduled their conversion from the use of dispersions of HEU oxides or aluminides into LEU silicides. For example, the HFR Petten Reactor in The Netherlands, will convert to LEU silicide in 2006.

As a part of CNEA's qualification program as a supplier of low enriched U_3Si_2-Al dispersion fuel for research reactors, a full scale prototype U_3Si_2 dispersion fuel was manufactured and irradiated in Argentina. The fuel element was irradiated in the RA-3 reactor. The overall irradiation behavior was in all aspects as expected and compares well with numerous previous results of LEU U_3Si_2 – Al dispersion fuel tests.

Studies are being done on converting other reactors to use LEU silicides, e.g. MARIA in Poland and SAFARI in South Africa. The FRM-II high flux reactor, which is being commissioned in Germany, uses highly enriched silicide fuel in its compact core. The characteristics, geometrical arrangement, materials and operation conditions of the fuel for the Reactor Facility fall within the range of conditions in which similar fuels are currently used.

5.3.2 Fuel Assemblies Design Basis

In this section, the most important criteria adopted in the design of the FA for the Reactor Facility are presented.

The design and manufacture of the FAs is carried out in accordance with the quality assurance practices applicable to nuclear fuel industry for research and testing reactors. The FAs are defined as Safety Category 1 and Seismic Class 1 and Quality Assurance Level A (see Chapter 2, Sections 2.5.2 and 2.3.1 respectively).

The general design goal is to ensure that the barriers for radioactive product containment are protected. The fuel matrix and cladding in the FA together form the first barrier against fission product release.

During fuel lifetime, which includes both core residence time and post-irradiation storage, the FA design provides a high degree of assurance that no systematic failures will occur.

5.3.2.1 Design Conditions

The FA is designed for normal operation states and anticipated operational occurrences. Normal operation states cover all events that are expected to occur regularly or frequently during the operation of the reactor and associated facilities. Normal operation states are defined in Section 5.1 of this chapter.

Anticipated operational occurrences cover the operational processes deviating from normal operation that can occur during the reactor lifetime. In view of appropriate design margin provisions, they do not cause any significant damage to items important to safety, nor lead to accident conditions. They may result in, at most, a reactor shutdown with the reactor being capable of returning to normal operation without repairs.

For all operational states and anticipated operational occurrences the fuel plate is considered not to have failed when:

a) fuel cladding keeps its water tightness, avoiding contact between fuel meat and coolant

b) variations in geometry and dimensions during operation are below allowable tolerances

c) general functional capabilities are not reduced below specified limits.

In the case of postulated accidents, it is admissible for the FA to undergo some deformation that may require inspection or even replacement before normal operation can be resumed. Nevertheless, in order to limit fission product release to the environment, the damage to the FA shall be kept within acceptable limits, ensuring "minimum conditions of geometry and integrity" to:

a) maintain a geometry able to be cooled for residual heat removal from the fuel
b) contain radioactive materials in order to minimise their release to the environment.

To fulfil all requirements, the FA is designed with adequate and conservative limits and margins to cover the following functional requirements:

a) provide and maintain adequate geometric and dimensional stability
b) provide a barrier to separate the fuel and fission products from the coolant
c) provide for acceptable coolant flow and heat transfer
d) resist action of fluid forces, i.e. vibration, wear, lift and flow instabilities
e) provide burnable poison for reactivity control
f) accommodate chemical, thermal, mechanical and irradiation effects on materials
g) provide for handling, shipping and core loading
h) resist the specified seismic actions.

Design limits are specified for all the parameters relevant to FA performance, such as cladding and fuel meat temperature, stresses, radiation and chemical environment effects.

Suitable and conservative design margins are used to define the "operational limits" for reactor normal operation conditions.

A temperature threshold identifies the maximum operating temperature to which the fuel components can be subjected without failure or undue deformation (eg. due to blister formation or mechanical weakening).

5.3.2.2 Design Limits for Reactor Normal Operation and Specified Seismic Actions

In accordance with the selected design criteria, the following design limits are not exceeded during normal operating conditions of the reactor and the specified seismic actions. These limits are established to ensure that specified functional requirements are met and are for nominal power deposited in the core.

A summary of the design criteria is presented below.

Dimensional Stability of Fuel Plates	
Maximum Compressive Stress in Fuel Plate width direction	Shall not be greater than 80% of the critical buckling stress of fuel cladding in the as fabricated condition.
Maximum Equivalent Total Stress	Shall not be greater than70% of the minimum measured yield strength of fuel cladding in the as fabricated condition
Hydraulic Instability Due to Water	Maximum velocity of water through coolant channels

Coolant Flow	shall not be greater than 2/3 of the critical velocity.
Burnup	No design restrictions are imposed to burnup.
Coolant	The following conditions shall be met: a) Demineralised water b) Electric conductivity lower than 1μScm^{-1}, c) pH: 5 to 6.7 d) Fe and Cu content: ≤ 0.01ppm e) Cl content: ≤ 0.2ppm
Stresses on Fuel Plates due to Seismic Actions	Shall not be greater than 80% of the minimum measured yield strength of the fuel cladding in the as fabricated condition and operating temperature
Stresses on the End Box-Side Plate Screwed Joint due to Seismic Actions	Shall not be greater than 80% of the material yield strength at room temperature
Stresses on the Fuel Plate-Side Plate Joint due to Seismic Actions	Shall not be greater than 80% of the specified value

5.3.2.3 Analysis of Design Criteria and Limits

In this section, an analysis of the different design limits is presented. Calculations, which show that the design limits are not exceeded during normal operation, are presented in Section 5.3.4. Accident and abnormal conditions are considered in Chapter 16.

During their residence time in the reactor, the FAs are subjected to different types of loads arising from both heat generation and environment interaction (comprising hydraulic and mechanical, radiation and chemical environment effects).

In order to ensure proper performance of the FA under normal operating conditions, the following effects are considered in the mechanical design:

a) Heat generation effects:
   - (i) Reduction of coolant channel thickness due to thermal expansion of fuel plates.
   - (ii) Thermal stresses on fuel plates as a consequence of non-uniform temperature distribution and external restraints to thermal expansions.
   - (iii) Risk of plate elastic buckling due to lateral compressive loads.
   - (iv) Coolant flow instabilities caused by excessive plate heat flux.

b) Hydraulic and mechanical loads:
   - (i) Hydraulic instability due to excessive coolant velocities.
   - (ii) Mechanical stresses on FA end box due to interaction with reactor grid plate and fuel clamp.
   - (iii) Mechanical stresses on FA structure during refuelling operations.

c) Radiation effects:
   - (i) Swelling and blistering of fuel plates due to build-up of fission products.
   - (ii) Changes in physical and mechanical properties of FA materials (thermal conductivity, yield and ultimate strength and ductility).

d) Chemical interaction with coolant.

(i) Corrosion of exposed surfaces, especially on the hottest fuel plates.
(ii) Localised corrosion phenomena, such as pitting and galvanic corrosion.

In the following paragraphs, all the effects listed above are characterised, and the corresponding design criteria selected for Reactor Facility FAs are defined. In all cases conservative margins are adopted to show that the operational parameters are within allowable values.

5.3.2.4 Heat Generation Effects

Heat produced by nuclear fission is removed by water coolant flowing through the parallel channels defined by adjacent fuel plates. The mechanisms for heat transfer from the heat source (fuel particles) to the heat sink (water coolant) are:

a) heat conduction through the fuel meat (with internal heat source)

b) heat conduction through the cladding and external oxide layer (without internal heat source)

c) forced convection in single phase on plate surface (during Power State).

d) single phase natural circulation on plate surface (during Physics Tests State and Shutdown State)

Despite the high specific power of most research reactors, both the maximum temperature and thermal gradient in the fuel plates are quite moderate because of the good thermal conductivity of aluminium and its alloys and the high surface area to volume ratio of plate geometry.

In terms of performance, the following fuel operating parameters are considered in order to ensure the geometrical and dimensional stability of the fuel plates:

a) fuel cladding surface temperature

b) fuel meat temperature

c) fuel plate thermal expansion and maximum cladding surface stress induced by temperature

Constraints on the maximum allowable value of fuel cladding surface temperature arise from material performance issues such as the corrosion of fuel cladding.

In the case of the Reactor Facility, one of the constraining criteria arises from a “heat transfer limiting phenomenon”, which may lead to a change in cooling conditions. These are addressed in section 5.8.

5.3.2.4.1 Maximum Fuel Meat Temperature

Blister formation on fuel plates is the most limiting damage mechanism because it produces the earliest fission product release. Blisters are produced when the fuel cladding detaches from the fuel meat as a result of the expansion of trapped fission gases contained in the meat. This typically occurs at an elevated temperature when the cladding has lost much of its strength.

According to NUREG-1313, the blistering threshold temperature measured in U_3Si_2 fuel plates ranges from 515°C to 575°C. Blistering threshold temperature is not significantly affected by burnup or fuel volume loading. The high blistering threshold temperature provides excellent protection and is similar to that shown by aluminide fuels.

It is reasonable to expect that initial releases of fission products will occur at approximately 515°C, followed by a much larger release at about 575°C.

The reaction between U_3Si_2 and the Al matrix and cladding is a diffusion controlled process that is exponentially dependent on temperature. It could lead to the consumption of the aluminium matrix and result in the formation of excessive porosity. However, this reaction only occurs significantly above the solidus temperature of the aluminium alloy, 582°C, a temperature that is higher than the blister temperature.

This reaction is insignificant during normal irradiation at temperatures less than 300 °C The maximum calculated fuel meat temperature, is significantly lower than the above referenced temperature, therefore the fuel meat temperature is not considered a design limit for normal operation conditions.

It should be noted that although the cadmium wires, which are used as burnable poison, have a melting point of 321°C they are located away from the fuel meat. Thus, even in the case of an accident event, the integrity of the FA will not be affected.

5.3.2.4.2 Thermal Expansion and Stress

In terms of mechanical design, the most critical effects of thermal expansion are increases in the fuel plate thickness and width, with a consequent reduction of the coolant channel area.

For design purposes, the maximum allowable thermal expansion in plate thickness should be related to the minimum allowable value for coolant channel thickness, imposed by core thermal-hydraulic design considerations.

In the calculation for the reduction of the coolant channel thickness the following main contributions shall be accounted for:

- Thermal expansion
- Radiation-induced swelling
- Growth of oxide layer on aluminium cladding surface

Thermal expansion in fuel plate width is also relevant because lateral compressive thermal stresses are developed on fuel plates from the external constraints imposed by the colder side-plates. This can lead to elastic buckling of the plates if a certain critical value is attained. It can also produce instabilities and distortions of the fuel plates, which may cause partial blockages in coolant channels.

Stress analyses have shown that, if lateral compressive thermal stresses on the fuel plate remain below the yield stress of the aluminium cladding, the elastic buckling risk is precluded (IAEA, 1992). An even more conservative criterion was adopted here, which is attained by limiting the maximum compressive stress in the fuel plate width direction to less than 80% of the critical buckling stress of the fuel cladding in the as fabricated and unirradiated condition. The appearance of permanent distortions and deflections in the fuel plate is also prevented by limiting the maximum total equivalent stress in the fuel plates to a value lower than 80% of the minimum yield strength. The maximum total equivalent stress is defined as the linear superposition of the individual stresses in the three main directions, evaluated in accordance with Von Mises theory.

Under these conditions, the stability of the fuel plate is ensured .

5.3.2.5 Hydraulic and Mechanical Loads

High-velocity coolant flowing through the channels of a parallel-plate assembly has the potential to cause deflections of plates due to fluid-structure interaction phenomena. Severe deflections may produce local over-heating or lead to a blockage of coolant flow.

For a given plate assembly, a critical flow velocity exists above which plates become unstable. To avoid channel deformations and fuel overheating due to hydraulic instabilities of the fuel plates, the maximum calculated velocity of water through coolant channels shall not be higher than two thirds of the critical velocity.

The margin between the best-estimate velocity and the maximum velocity is sufficiently large to ensure that the critical velocity is not exceeded, even after uncertainties are taken into account. Similarly, the critical velocities in the external coolant channels and between FAs are not exceeded.

The most important mechanical and hydraulic loads under normal operating conditions are:

a) stresses developed on FA end box by interactions with reactor grid plate and fuel clamp.

b) stresses developed on FA structures during refuelling operations.

c) stresses developed in the screwed joint between the outer fuel plates and the end box due to the drag force on the FA.

Protective actions are adopted in the mechanical design:

a) A careful process of interface analysis is followed, evaluating all aspects of compatibility among reactor grid plate, end box and fuel clamp designs, involving compatibility of materials and of dimensions and geometry, with their corresponding manufacturing tolerances.

b) A maximum hold-down force on end box is specified, to prevent the development of excessive stresses.

c) A maximum pull-out force to be applied on the FA handling pin during refuelling operations is specified in order to prevent damage and distortions to any component of the FA.

5.3.2.6 Radiation Effects

Fuel plates exposed to extended burnup may undergo dimensional changes due to swelling and blistering.

5.3.2.6.1 Swelling

The fuel particles in the meat swell as a function of burnup to accommodate solid and gaseous fission products. The swelling of a fuel plate occurs almost totally in the thickness direction.

In terms of mechanical design, the main concern with irradiation swelling arises from the progressive reduction of coolant channel dimensions. This can lead to degraded core cooling conditions.

The dimensional variations of the FPs due to irradiation are related to burnup. The swelling due to irradiation results in an increase in FP thickness due to the boundary conditions of the meat. The maximum fission density for the burnup of the RRR FE is $1.4x10^{21}$ fis/cm^3.

The increase in the average volume observed in miniplates fabricated by ANL, with the same enrichment and with uranium densities in the fuel from 3.72 to 5.6 g/cm^3 and for fission densities of approximately $2x10^{21}$ fis/cm^3, was below 5%.

Measurements of the thickness of U_3Si_2 FPs, of similar characteristics to those of the RRR, irradiated at ORR (Oak Ridge Reactor), up to average burnups of 77% of ^{235}U atoms (from 1.0 to 2.2 $x10^{21}$ fis/cm^3) showed thickness increases below 4%.

In the case of the Reactor Facility, the maximum burnup for a FA is approximately 49%.

5.3.2.6.2 Blistering

Blistering is described in Section 5.3.2.4.1.

To minimise blistering, the bonding between meat and clad and the quality of the fuel material are strictly controlled during the fuel manufacturing. The presence of U_3Si in the meat and excessive oxidation of the fuel particles are avoided in the plate fabrication process to prevent unbonded areas that could lead to premature failure. These factors are controlled by manufacturing and quality assurance procedures and by adequate material specifications (see Section 5.3.3.4).

Blistering as the result of high temperatures is avoided by the low fuel meat temperature (Section 5.3.4.2.4).

The amount of matrix material (aluminium) in the dispersion is also important because it prevents the migration of fission gases and the subsequent formation of large inter-particle gas bubbles that can lead to blistering or pillowing. The volume fraction of aluminium in the meat material in this case is greater than 50%, which exceeds the minimum requirements to prevent fission gas migration.

5.3.2.6.3 Other Irradiation Effects

An additional effect of the radiation environment is the change in physical and mechanical properties of fuel and structural materials. This is taken into account in fuel in the analysis in Section 5.3.4. The most important radiation effects are:

a) fuel thermal conductivity decrease with burnup.

b) aluminium yield strength increase and ductility reduction with burnup.

5.3.2.7 Chemical Environment Effects

There is extensive world-wide experience in the use of aluminium as cladding material in an ample range of reactor conditions. The corrosion of aluminium and its alloys can be a limiting factor of fuel lifetime.

The formation of a corrosion film (bohemite) can represent a barrier to the removal of heat, increasing fuel temperature, reducing coolant channel dimensions, and eventually affecting the mechanical properties of the FA. Due to this reason, for fuel performance analysis the maximum thickness of oxide layer in the hottest channel at the end of irradiation is estimated, to evaluate the fuel cladding integrity and the reduction of coolant channel dimensions, according to the thermal-hydraulic design criterion defined above.

Operational conditions of research reactors such as RRR are characterised by moderate temperatures (less than 200°C) and a cooling system of demineralised water with provisions for water quality control, to minimise conductivity. In such an environment, uniform and localised corrosion could develop.

Different laboratories have carried out research on aluminium corrosion on various set-ups, heat fluxes, temperatures, coolant velocities and water chemistry. (IAEA, 1992), (Griess, 1964), (Pawel, 1995)

These experiments have concluded that uniform corrosion of aluminium and its alloys is sensitive to residence time, temperature, pH and water flow rate. The lower the temperature, the lower the corrosion rate.

Nevertheless, for fuel performance analysis, the maximum thickness of oxide layer at the end of the irradiation is estimated, with a proper and conservative corrosion rate design value, in order to evaluate the fuel cladding integrity, maximum fuel meat temperature, and reduction of water channel dimensions.

In the case of the RRR, the moderate operational temperatures, the low heat flux and the core residence time are mild from a corrosion and oxide formation perspective. This condition is further favoured by the requirements imposed on coolant water pH and conductivity described in Chapter 6, which ensures a low corrosion environment.

These features, plus the proper selection of materials during design and the rigorous control of water chemistry throughout the reactor lifetime prevent uniform corrosion from being a hazard.

Localised corrosion can be produced by pitting and by galvanic corrosion.

Pitting is associated with water containing chlorides and heavy metals, which can arise from an improper water quality control, and/or from external contamination of primary system components. In order to prevent pitting, the rigorous control of water chemistry is maintained throughout the reactor lifetime. There are also restrictions on the cleanliness of all components introduced into the core and Operational Limits and Conditions (see Chapter 17 Section 17.4) for fresh fuel handling.

Galvanic corrosion arises from dissimilar materials put together in presence of an electrolyte. This is prevented by an appropriate selection of materials and a proper design of contact zones when dissimilar materials are present, in conjunction with the tight control of water chemistry.

5.3.2.8 Fuel Assembly Seismic Design

The FA is designed to withstand the dynamic loads and impacting forces occurring as a consequence of the Design Basis Earthquake identified for the Reactor Facility site (Section 5.3.4.4).

5.3.3 Fuel Assembly Description

In this section a general description of the FA and its main components is provided.

5.3.3.1 General Assembly

The FA is “plate type” with an external square section. The end box has external square section, with a circular internal centring hole for coolant flow.

The lower end of the inner fuel plates is held by a comb located at the middle of the plates along their width.

FAs are positioned in a square array in the core. The FAs are placed in the core in a vertical position, housed in orifices in the reactor grid. The coolant is driven by forced convection in an upward direction when the Primary Coolant System pumps are operating during the Power State.

All FAs are identical, but special FAs with a lower uranium load are used for the first core.

5.3.3.2 Main Components

The following sections provide data on FA components.

5.3.3.2.1 Fuel Plate

There are two types of fuel plates: inner fuel plates and outer fuel plates. Each FA has 19 inner fuel plates and 2 outer fuel plates. The outer fuel plates have greater length and thickness because of structural considerations.

In order to attain a proper heat removal from the external sides of the outer fuel plates and side plates, an opening is located in the lower part of the outer fuel plates, which allows a by-pass coolant flow outside the FA.

The fuel plates contain a fuel meat hermetically sealed by a cladding that isolates the meat from the coolant. The meat is made of a fine and homogeneous dispersion of particles of U_3Si_2, with an enrichment of 19.75% in weight of uranium-235 in a continuous matrix of commercially pure aluminium (see Section 5.3.3.3).

There are two types of start-up FAs to be used in the first core, and one standard FA. They are all geometrically identical.

A frame and two claddings of aluminium alloy constitute the cover . During manufacture, gaseous inclusions are kept within strict limits as they may induce fuel plate blistering during irradiation.

The fuel plates are manufactured by the picture frame technique. This consists of locating the fuel meat within the frame and sandwiching them between two claddings held in position by welding.

The similarity between the mechanical properties of the fuel meat and cladding permits a uniform reduction in the thickness of the fuel pate. The process is enhanced by adhering to the correct calibration and qualification procedures for the co-lamination process.

Main meat data are:

Parameter	Value
Enrichment	19.75 % U^{235}
Al density	2.7 gcm^{-3}
U_3Si_2 density	12.2 gcm^{-3}
Uranium density in meat	4.8 gcm^{-3}
Meat density	6.5 gcm^{-3}

Aluminium data are:

Parameter	Value
Cladding material	Aluminium alloy
Density	2.7 gcm^{-3}

5.3.3.2.2 End Box

The end box has an external square section and an internal circular hole for the flow of coolant.

The internal duct for the circulation of the coolant is designed to minimise pressure losses and optimise coolant circulation.

The end box is manufactured by machining a square section bar of aluminium. It initially receives a thermal hardening treatment to provide mechanical resistance to fulfil the design requirements. The thermal hardening does not affect the thermal properties or the behaviour to aqueous corrosion.

5.3.3.2.3 Side Plates

The side plates are flat, with grooves in their internal faces to allow the positioning and fixing of fuel plates.

A file-off in its lower end allows a correct assembly with the end box.

The side plates are manufactured in aluminium.

Both side plates are engraved with the identification of the FA, with large normalised characters for easy reading.

5.3.3.2.4 Handling Pin

The handling pin is a cylindrical rod used to insert and withdraw FAs to/from the core.

The handling pin is located at the top of the FA. There is sufficient clearance between the handling pin and the top of the fuel plates so that the latter are not touched by manipulation tools. This is assured by the provided clearance and by complying with the established procedures for fuel manipulation.

The handling pin is manufactured from a rod of aluminium.

The identification of the FA is also engraved on the handling pin.

5.3.3.2.5 Comb

The comb is used to space the lower end of the inner fuel plates.

The comb is manufactured by machining from an aluminium bar.

5.3.3.2.6 Screws

Different screws are used to fix the outer fuel plates and side plates to the end box, the handling pin to the side plates, and the comb to the outer fuel plates.

Screws are manufactured from a rod of aluminium

5.3.3.2.7 Cadmium Wires

Cadmium wires are used as burnable poison.

5.3.3.3 Semi-Finished Materials

The main technical features of semi-finished materials for FA manufacturing are described in the following sections.

5.3.3.3.1 Meat Materials

5.3.3.3.1.1 U3Si2 Powder

a) Isotopic composition of uranium: The content of U-235 isotope of uranium in the powder is within the range of 19.75 ± 0.20% by weight of total uranium.

b) Total uranium content: The content of total uranium in the powder is greater than or equal to 91.3% in mass.

c) Silicon content: The content of silicon in the powder is greater than or equal to 7.4% in mass.

5.3.3.3.1.2 Aluminium Powder

The base material for powder manufacturing is at least 99.5% aluminium in mass.

After the atomisation process, the content of free metallic aluminium powder is at least 98.5% in mass.

5.3.3.3.2 Frame and Cladding Material

Aluminium chemical composition is in agreement with the ASTM standard.

Mechanical properties at room temperature are specified by the ASTM standard.

5.3.3.3.3 Structural Material

The end box, side plates, handling pin, screws and comb are structural components made of aluminium.

Mechanical properties at room temperature are those specified in the ASTM standard .

5.3.3.4 Testing, Inspection and Surveillance

a) Testing and Inspection during manufacturing

The manufacturing of the fuel powder and fuel plates and the assembly of the FA are performed following an integrated manufacturing and inspection test plan.

Different analyses, verifications and tests are carried out along the manufacturing stages for every plate, including the following:

Aspect tested & verified	Method
Material certification	Chemical analysis
Fuel-plate uranium load	Weighing
Dimensional inspection	Measuring devices
Cleanliness	Visual inspection and radiation count
Surface conditions and defects	Visual inspection

Dimensional controls of every finished FA are also done, as well as a visual inspection prior to the reception from the manufacturer.

b) Inspection prior to loading into the reactor

After transportation from the manufacturer to the reactor pool and before loading into the reactor core, a visual inspection of all FAs is performed.

Certificates of conformity and complete manufacturing documents issued by the corresponding Quality Assurance (QA) section are provided for each FA, together with all the transportation documents.

5.3.4 Evaluation of the Fuel Assembly

5.3.4.1 Introduction

In this section the methodology and analyses carried out to show that the FA can withstand the conditions established in the design criteria and limits are presented.

The design evaluation is accomplished through the verification and validation of the FA behaviour, on the basis of the following:

a) Analytical calculus and calculation codes, in which - on the basis of the input data - it is demonstrated that the previously-established design limits for normal operation conditions are not exceeded.

b) Seismic analysis of the FA, where it is demonstrated that the limits established are observed, showing their suitability to withstand the additional loads imposed by this anticipated operational occurrence.

c) Laboratory tests to determine the structural stability of the screwed joints for the specified seismic conditions.

d) Laboratory tests on the aluminium to determine its corrosion behaviour and determine through experimental tests the final mechanical properties achieved as a result of the fabrication processes.

e) Results of irradiation tests on miniplates and prototypes at full scale.

f) Hydrodynamic tests on prototypes at full scale similar to that proposed in the design.

Under steady-state reactor operation, there is a thermal balance between the heat produced and removed, with a spatial temperature distribution established in the fuel plates that may produce dimensional variations or thermal stresses. The influence of the velocity of the coolant flow is taken into consideration to prevent the collapse of the fuel plates at high velocities.

In the present section information is provided on the evaluation of the maximum temperatures developed, the stresses and strains produced, and the critical velocity of the coolant for standard reactor operating parameters. Further consideration of fuel cladding failure as a result of manufacturing errors, normal operation or reactor events are given in Chapter 16, Section 16.13.2. Mechanical damage due to mishandling or dropped loads is considered in Section 16.13.3.

The following hypotheses are considered for the calculation of stress and temperature distribution in the fuel plates:

a) Reactor operation in steady-state condition.

b) Cosine distribution of neutron fluxes.

c) Unidirectional and symmetrical heat flow with respect to the central plane of the fuel plate.

The calculation is performed for sixteen standard FAs in the core. The hottest fuel plate and coolant channels are considered.

5.3.4.2 Temperature Distribution Calculation

The heat produced through nuclear fission within the fuel plates of an MTR-type reactor FA is removed by the coolant flow circulating through the FA.

The following heat transfer mechanisms are involved in this process:

a) conduction through the fuel, with inner heat source

b) conduction through the cladding and oxide layer, without inner heat source

c) forced convection on the fuel plate coolant interface

5.3.4.2.1 Temperature Distribution in the Fuel Plates

The average linear power per fuel plate is directly proportional to the reactor thermal power, and inversely proportional to the active length of the plates, the number of plates per FA, and the number of FAs in the core.

The temperature distributions inside the fuel plate are calculated using the heat flux, coolant temperature and fuel plate surface temperature axial distribution given in Section 5.8, for the following positions:

a) Oxide – cladding interface

b) Cladding – meat interface

c) Centerline of the fuel meat

5.3.4.2.2 Maximum Cladding – Oxide Interface Temperature

The exposure of aluminium under typical research reactor conditions leads to the growth of an adherent oxidation product (bohemite) on the fuel plate surface.

To calculate the oxide film thickness present at the FA at the end of its residence time in the core, the model developed by ANL (Argonne National Laboratory) is used.

The maximum oxide-cladding temperature for this film thickness can be calculated applying Fourier´s heat conduction equation and using bohemite thermal conductivity of 2.25 $Wm^{-1}°K^{-1}$.

This temperature gradient across the oxide ensures that no spallation and subsequent subsurface corrosion will occur.

5.3.4.2.3 Maximum Cladding Inner Temperature

The maximum cladding inner temperature can again be calculated by applying Fourier's heat conduction equation:

$$q''(z) = -k_{Al} \frac{dT}{dx}$$

where:

q”(z) (W cm^{-2}): heat flux in the direction of the fuel plate thickness,

k_{Al}(W cm^{-1} C^{-1}): thermal conductivity of aluminium,

$\frac{dT}{dx}$ (°C cm^{-1}): temperature gradient in the direction of the fuel plate width.

The highest inner temperatures of the fuel plates are registered in the outer fuel plates, because of their higher cladding thickness.

5.3.4.2.4 Maximum Fuel Meat Temperature

For the calculations, a perfect metallurgical joint without thermal resistance is assumed between the fuel meat and the aluminium cladding.

The reactor is assumed to be operating at steady-state. With the conservative hypothesis that the heat flux goes only in the direction of the plate thickness, temperature variations are produced only in that direction. This applies to a fuel plate located close to the reactor core maximum temperature point, where the temperature gradient is small. The fuel thermal conductivity is assumed to be constant.

The thermal conductivity value for the meat is 0.48 W cm^{-1} $°C^{-1}$, which corresponds to a U density in the fuel core of 4.8 g cm^{-3},

This value is consistent with those reported in the literature.

Fourier's equation in this case gives

$$\frac{d^2T}{dx^2} = -\frac{q'''(z)}{k_n}$$

where:

$q'''(z)$(W cm^{-3}) is the volumetric heat generation, and

k_n (W $cm^{-1}$$°C^{-1}$) is the meat thermal conductivity.

The thermal conductivity of the meat varies with burnup, diminishing at high burnup values.

The central fuel meat temperature is always significantly lower than the blistering threshold temperature.

5.3.4.3 Structural Stability of the Fuel Plates

5.3.4.3.1 Thermal Expansion Calculation

Thermal expansion of the fuel plates is calculated considering the conservative hypothesis that fuel plate temperature is uniform and the mean value between the maximum temperature of the meat and the maximum cladding-oxide interface temperature.

The reference temperature for fuel plate thickness and width increase calculations is the mean temperature between the inlet and outlet temperatures of the coolant in the hottest channel.

The thermal expansion coefficient of aluminium is used, because it is higher than the thermal expansion of the fuel meat.

The increase in fuel plate thickness calculated under these assumptions is 0.20% of its initial value. The same percentage increase is obtained for fuel plate total width. These values are well within the design limit.

5.3.4.3.2 Thermal Stress Calculation

The following effects are considered in calculating the thermal stresses developed in a fuel plate:

a) stress from a possible non-uniform temperature distribution in the plate, assuming that it is free of external restrictions.

b) stress from external restrictions or boundaries, for instance FA sideplates

Paul's relation gives the maximum and minimum limits for the modulus of elasticity and other properties of a composite material from the values of its components and their volume fractions. The value of a property is assumed to be the mean between the maximum and minimum. Paul's relation is used to determine the meat modulus of elasticity from that of U_3Si_2 (77800 MPa) and Al (68900 MPa). A similar expression is used to determine the meat's Poisson´s ratio from that of U_3Si_2 (0.17) and Al (0.33).

The stress on the fuel plate cladding from a possible non-uniform temperature distribution can be calculated using Smith's analytical expression

Smith's expression is valid for a homogeneous stress state in the length and width directions of the fuel plate, and a symmetric temperature distribution in the thickness direction.

Cladding and fuel meat temperatures are calculated for z= 2 cm.

The stress developed on the fuel plates by the restriction to thermal expansion imposed by the side-plates has two components: compression stress due to the effect of the pressure difference between both sides of the side plates arising from different coolant velocities, and compression stress due to side plate resistance to flexion. Both are evaluated in the following sections.

5.3.4.3.2.1 Stress due to Pressure Difference

The velocity of the coolant between two fuel plates is different to the velocity of the coolant between the adjacent FAs. This generates a pressure difference at both sides of the side plate producing a compressive stress on the fuel plates.

5.3.4.3.2.2 Stress Due to Side-Plate Resistance to Buckling

The side plates resist the thermal expansion of the fuel plates, which generates a stress in the fuel plates. To estimate this stress, a distributed load acting on a length equal to that of the inner fuel plates is considered, with the side-plate built-in in its joint with the end box.

5.3.4.3.3 Equivalent Total Stress

The equivalent stress is calculated through the linear overlapping of individual components, and in accordance with the Von Mises theory for a homogeneous elastic state.

Alternatively, the equivalent stress was also determined by means of a finite element model carried out using the COSMOS program, in which the fuel plate is modelled in its joint to the side-plates, with a temperature distribution in axial direction equal to the difference between the fuel meat temperature and coolant for each position.

Even in the most demanding position of the fuel plate, the acting stress is lower than the imposed limit.

5.3.4.3.4 Critical Buckling Stress of Fuel Plates

To calculate the critical buckling stress for the fuel plates, the fuel plates are considered as being built-in on both sides on their joints with the side plates and compressed on the mid-plane by forces distributed along the built-in sides. These forces would originate in the thermal expansion of the plates, should the restriction imposed by the side plates be sufficiently rigid to produce their buckling if the critical stress value were to be exceeded.

This critical compressive stress can be calculated and depends on the plate supporting condition, the geometry, the modulus of elasticity and Poisson's ratio. Accordingly, the fuel plates should not buckle due to this effect.

5.3.4.3.5 Fuel Plates Hydraulic Stability

A coolant critical velocity that can lead to hydraulic instability was determined in a conservative way, taking into account the worst conditions on all the factors included in the calculations. Using conservative values with worst-case tolerances, the critical velocity between fuel plates is obtained.

As the established design criterion is to limit the coolant velocity to 2/3 of the critical velocity or 9.9 ms^{-1}, the nominal coolant velocity does not pose a risk to the hydraulic stability of the fuel plates.

5.3.4.4 Fuel Assembly Seismic Design

The FA is designed to withstand the dynamic loads and impacting forces occurring as a consequence of the maximum Design Basis Earthquake, identified for the Reactor Facility site.

The FA seismic design has been performed with a well-validated seismic analysis methodology, comprising analytical and numerical approaches and tension tests.

For the seismic verification of the FA, it is considered as input data the response spectrum of a Level 2 Earthquake, the properties of the materials of each component, the dimensions of the FA and its mounting conditions.

The verification implies that the mechanical and geometrical integrity of the FA shall be maintained during and after a Level 2 Earthquake

5.3.4.5 Stresses on Fuel Plates

The maximum stresses developed on the FPs are at the windows area. The calculated values are below the limit of 60 MPa.

5.3.4.6 Stresses on the End Box-Side Plates Screwed Joint

The end box-side plates joint was verified through analytical calculus and tension tests.

The analytical verification was carried out considering that 100% of the acting force is withstood by the screws that fix the end box to the side plates. The acting force is taken as the sum of the drag forces under normal operation conditions plus that produced by the seismic effect.

Thus, the maximum equivalent stress produced on the screws is below 80% of the material yield strength.

The experimental verification was carried out through tension tests.
The results indicate that the screwed joint adequately withstands the imposed load conditions for normal operation conditions superposed to a Level 2 Earthquake, verifying its structural stability even for loads quite above the maximum one established.

To break the screwed joint a load 7 times higher than that produced by a Level 2 Earthquake is required.

5.3.4.7 Fuel Plate – Side Plates Joint

The seismic analysis included a verification of the rolled-swaged joint between the FPs and the side plates, evaluating the maximum loads that could produce the relative displacement between both components.

The analysis carried out shows that the FA design meets the established requirements, in view of which it is considered that it will behave adequately under the hypothetical event considered for the reactor site.

5.3.5 Verification of Design Limits and Conclusions

5.3.5.1 Temperature Calculations

Using the heat flux, coolant temperature and fuel plate surface temperature axial distribution given in Section 5.8, the fuel plate internal temperatures were calculated.

The maximum temperature at the centre of the meat (considering a reduction of 30% in the thermal conductivity of the meat with the burnup) is below 200°C, all for normal operation conditions.

5.3.5.2 Dimensional Stability

The minimum thickness of the cooling channel considering the spacing between adjacent fuel plates with the negative design tolerances, the increases in FP thickness due to the three effects considered earlier, and the minimum local value of the cooling channel thickness at the end of the irradiation is above the limit value.

5.3.5.3 Thermal Stress

The equivalent total stress obtained is lower than the limit imposed on the design.

As the stresses are within the design limits, no twisting, buckling or bending of the plates is expected.

5.3.5.4 Hydraulic Stability

The nominal coolant velocity in the internal coolant channels is below the coolant velocity limit of imposed for the internal channels and well below the critical velocity. The coolant velocities in the other channels are also below the critical velocities, hence there is no risk of hydraulic instability on fuel plates.

The design verification and evaluation carried out using analytical calculation methods is further supported by hydrodynamic testing on natural-scale prototypes.

5.3.5.5 Irradiation Behaviour

A number of factors combines to minimise the risk of a FA from swelling, blistering or corrosion. These are:

a) calculated cladding and meat temperature, which are below the established limit

b) the short residence time of the fuel in the core (less than 200 days)

c) the composition of the meat, which provides adequate proportions of fuel, aluminium and voids

d) the rigorous control of water chemistry

e) the international experience of fabricators and users.

5.3.5.6 Conclusions

The analysis carried out to verify the Reactor Facility fuel design shows that the FA complies with specified design limits.

Calculations for the maximum temperature, dimensional variations and stresses have been done using ample safety margins and conservative hypotheses. These ensure structural stability and adequate cooling under normal operating conditions.

Strict control is maintained over impurities dissolved in the water, particularly chlorides, in order to avoid localised corrosion. Water pH and temperature are also controlled. This is a normal practice in research reactors.

Irradiation experience in test samples and full-scale FAs, and operational experience of twenty reactors around the world, with powers ranging from 0.7 MW to 135 MW, show that U_3Si_2 can be reliably produced and fabricated into FAs, and has very satisfactory all-around properties, including excellent behaviour under irradiation. Calculations and experimental evaluations show that a very low swelling of the plates is expected.

In summary, it is concluded that the FAs designed for the Reactor Facility are fully suited for operation through the projected period during which they are loaded in the core of the reactor, without systematic failure as a result of their design.

5.3.6 References

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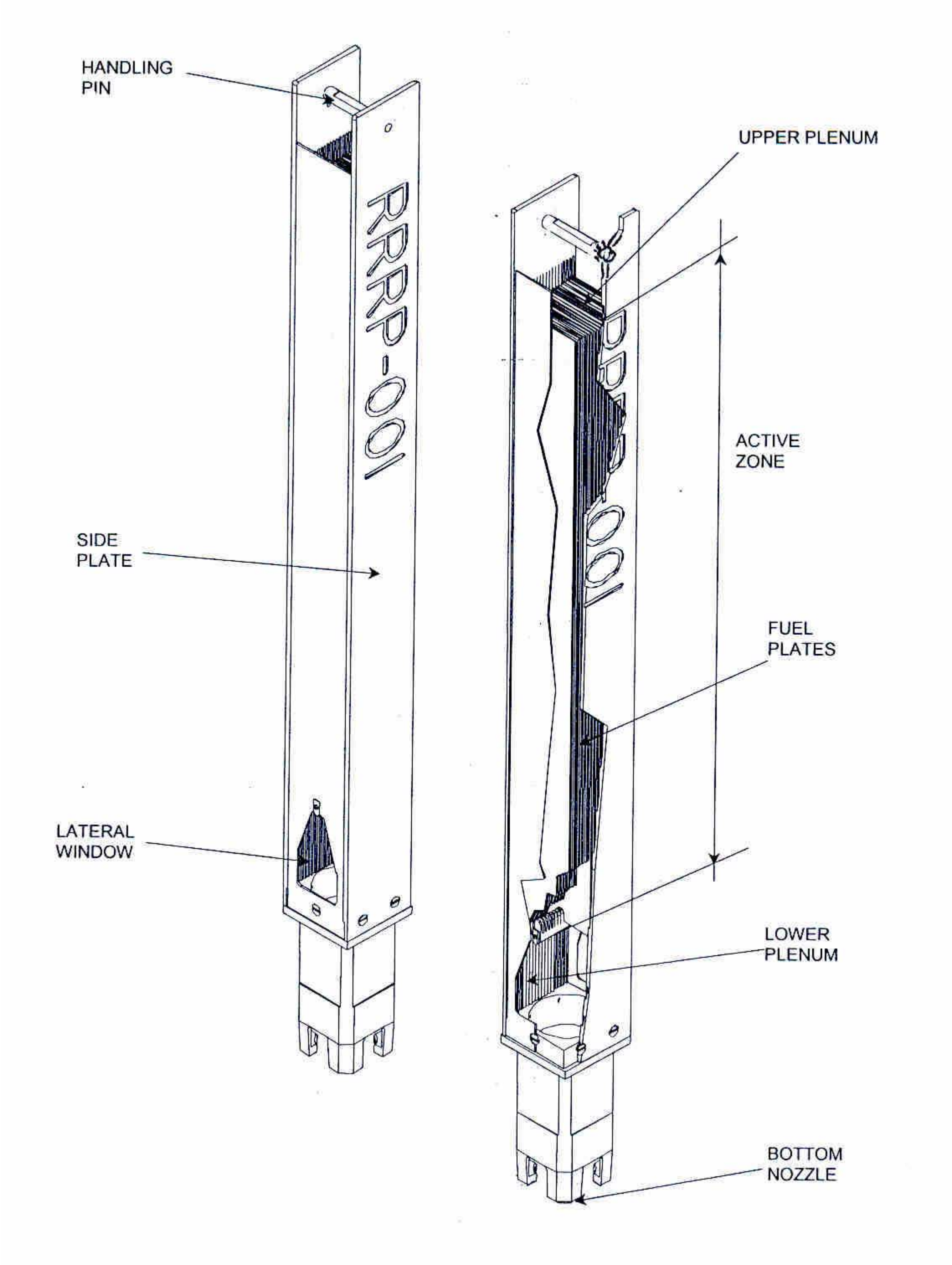
End of Section

Figure 5.3/1 3-D View of the Fuel Assembly



End of Figures