IAEA-TECDOC-467

STANDARDIZATION OF SPECIFICATIONS AND INSPECTION PROCEDURES FOR LEU PLATE-TYPE RESEARCH REACTOR FUELS

REPORT OF A CONSULTANTS MEETING
ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
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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 uranium (LEU). Most of the necessary irradiation tests, as part of the fuel qualification test, are being performed and results and data from post-irradiation examinations (PIE) are becoming available. As fuel up to an uranium density of 4,8 g U/cm^3 is qualified, more research reactors will be converting to LEU. The decreasing availability of HEU fuel for research reactors mandates that reactor operators consider the conversion of their reactors to LEU.

With the transition to high density uranium LEU fuel, fabrication costs of research reactor fuel elements have a tendency to increase because of two reasons. First, the amount of the powder of the uranium compound required increases by more than a factor of five. Second, fabrication requirements are in many cases nearer the fabrication limits. Therefore, it is important that measures be undertaken to eliminate or reduce unnecessary requirements in the specification or inspection procedures of research reactor fuel elements utilizing LEU.

An additional stimulus for standardizing specifications and inspection procedures at this time is provided by the fact that most LEU conversions will occur within a short time span, and that nearly all of them will require preparation of new specifications and inspection procedures. In this sense, the LEU conversions offer an opportunity for improving the rationality and efficiency of the fuel fabrication and inspection processes.

This report focuses on the standardization of specifications and inspection processes of high uranium density LEU fuels for research reactors. However, in many cases the results can also be extended directly to other research reactor fuels.

This report is the result of a Consultants' Group Meeting held in Geesthacht at the GKSS Research Centre-Geesthacht, GmbH, from 16 to 18 April 1986 with subsequent contributions from the participants.

The assistance of the participants of the meeting in the preparation of the report is gratefully acknowledged and it is hoped that an even larger audience associated with research reactors will benefit from their effort.

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, TECDOC-324, Vienna, 1985 [2]

3) Core Instrumentation and Pre-Operational Procedures for Core Conversion HEU to LEU, TECDOC-304, Vienna, 1984 [3]

4) Research Reactor Core Conversion from the Use of Highly Enriched Uranium to the Use of Low Enriched Uranium Fuels, Safety and Licensing Guidebook, Vol. I Summary, Vol. II Analyses, Vol. III Analytical Verification, Vol. IV Fuels, Vol. V Operations, TECDOC, Estimated date of publication 1988 [4]

EDITORIAL NOTE

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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 $\leq$ 20 wt% U-235 enriched uranium (LEU). This value was chosen because it was considered to be unsuitable as weapon grade material. However, the demand for higher specific power and/or longer fuel cycle length created a need for higher U-235 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 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 [5], and since enrichment reduction to less than 20% is internationally recognized to be an adequate isotopic barrier to weapons usability, certain Member States have moved toward minimizing the international trade in highly enriched uranium and have established Reduced Enrichment Research and Test Reactor Programmes (RERTR). The goal of these programmes is to develop the technical means, such as development of new fuels, and possible design modifications 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 fuels. Annual international meetings have been held since 1979 and proceedings published [6, 7, 8, 9].

Operators of research and test reactors that use HEU may consider converting their reactors to the use of LEU 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 HEU. The 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 fuels to the use of LEU fuels.

1.2 Scope of the Report

This report is intended for the research reactor operator, research reactor fuel element fabricator, licensing authorities and the consultants or experts of the licensing authority or the operator, to be used as a manual or checklist for designing, ordering, fabricating, inspecting and licensing research reactor fuel elements. The considerations and decisions to be made have to take into account the existing knowledge of the qualification status of the high density LEU fuel, design and safety demands, fabrication possibilities and economic questions. It is believed that there are many reasons for the details of the existing specifications and inspection procedures for research reactor fuel elements:

- tradition,
- others using the same specification or the same fuel element,
- proposals by the fabricators,
- operation experience,
- nuclear and thermodynamic design,
- safety demands,
- authority and/or consultants recommendations, and
- economic aspects.

The goal of this report is to provide a more documented, rational and economic basis for the specifications and inspection procedures. This will be especially important for the new LEU fuels, because many of them will contain high volume fractions of the fuel particles in the fuel meat that will be close to the fabrication limits. The uranium density has to be increased by a factor of 5,5 or even more if converting from HEU to LEU fuel.

While most HEU fuels have about 20 vol.% fuel or less in the meat with a maximum of around 33 vol.%, many LEU fuels will be close to 45 vol.%, which is considered the present fabrication limit. The uranium densities corresponding to 45 vol.% are as follows:

UAl_x	$\rho = 2{,}1$ g U/cm^3
U_3O_8	$\rho = 3{,}2$ g U/cm^3
U_3Si_2	$\rho = 5{,}1$ g U/cm^3
U_3Si	$\rho = 6{,}6$ g U/cm^3

With increasing vol.% of fuel the fabrication difficulties increase rapidly. These fabrication difficulties are related to: white spots, homogeneity, cladding thickness, dog boning, etc. For this reason fabrication prices for LEU fuel elements are at present by far higher than for HEU fuel elements if specifications are unchanged. To limit the number of refused or rejected fuel plates and/or fuel elements, efforts are undertaken to reduce specification demands wherever it is possible and acceptable. Hopefully this will limit the increase in LEU fuel fabrication prices to a reasonable amount without undue reduction in safety.

It should be emphasized that this report is intended to be used for general guidance and not to be construed as requirements that the reactor operator, consultant or licensing authority must follow. The report is meant to assist the operator in developing his own specifications and inspection procedures for the fuel elements of his research reactor taking all necessary considerations into account, including detailed discussion with the selected vendor.

This report complements the Guidebook TECDOC-233 [1], TECDOC-304 [3], TECDOC-324 [2] and the Guidebook [4], which is expected to be published in 1988. Therefore in this report reference will often be made to the Guidebooks as well as to other more specialized references. Appendix A contains the specifications of the U_3Si_2-fuel elements for the Oak Ridge Reactor, ORR.*

Chapter 2 gives a detailed discussion of many special specification subjects and informs the operator in some cases about the economic impact of specification variations. Influences of specification variations on fabrication cost should be carefully evaluated.

Some inspection procedures of a more general interest are discussed in Chapter 3.

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* The ORR specifications are in many instances more restrictive than the recommendations in this document.

2. SPECIFICATIONS

2.1 General

At present there are HEU and LEU production lines for UAl_x, U_3O_8 and U_3Si_2. In Vol. IV of the IAEA-Guidebook on Safety and Licensing Issues [4] and in [6, 7, 8 ,9] the qualification status of LEU plate-type fuel elements fabricated by three different vendors can be found. There is at present the tendency to reduce the number of production lines to reduce cost.

HEU as used above refers to 90 - 93% enrichment. In the case of U_xSi_y, HEU may still be necessary for new high performance reactor designs using the development potential of the high density uranium fuel. Several such studies are under way. It is believed that other vendors will follow those surveyed with emphasis on the U_xSi_y LEU fuel production line. Since U_3O_8 may continue to be used in some reactors, e.g. U_3O_8 in HFIR, RP-10, MPR-30 and UAl_x for reactors with peak burnups $\geq 2 \times 10^{21}$ fissions/cm^3, the possible cost reduction from having only one production line may not be realized.

High power reactors (unique purpose reactors) may need to convert to high-density uranium-silicide fuel with enrichments between 20% and 90%. For this reason one or more additional production lines will reduce the proliferation risk but may increase the fabrication cost.

One of the most important parameters for qualifying a fuel to certain limits of operation is the swelling behaviour as a function of burnup. For U_xSi_y the swelling rate is influenced by the porosity, the volume ratio of U_3Si/U_3Si_2 and vol.% of U_xSi_y in the fuel meat. Therefore, in some cases these values may need to be introduced into the specifications. There is absolutely no requirement to have these corresponding parameters specified if UAl_x or U_3O_8 is used as meat material.

General information about different topics on the specifications of research reactor fuel elements can be found in the literature ranging from a standard for quality control [11], remarks on related topics [12, 13] to very special topics [14 ... 15] and examples [Vol. IV in (4)].

It is not the intention to comment in detail on all parts of the specification since:

- many parameters are more or less standardized,
- other parameters have only a minor impact on fabrication cost, and
- some parameters come from the design of the reactor.

Nevertheless, it is strongly recommended that the specification and inspection procedures be reviewed and the unnecessary but restricting limitations be removed. This should be done before ordering the fuel elements for the conversion of the research reactor to LEU fuel.

Not all specified values are of the same safety level. Therefore during inspection by the customer slight deviations from the specified values should not automatically cause a rejection of the fuel plate or the fuel element.

2.2 Geometry

Most of the geometrical specifications are fixed since, e.g. grid plate dimensions cannot be changed. Some geometric design values can be adjusted in some cases if this is within the design limitations. For this reason a few values are given which are used in most of the fuel element designs:

fuel meat thickness	0,51 mm, a few 0,76 mm
fuel meat width	60 mm and 62,8 mm
(influences the peaking factor)	
fuel meat length	600 mm, a few up to 800 mm
number of plates	23, some less
plate thickness	1,27 mm, a few thicker

2.3 Fuels

2.3.1 Fuel phase composition

No comments on UAl_x and U_3O_8 are necessary. As mentioned in Chapter 2.1, the phase composition of the U_xSi_y fuel should be known for high density and high burnup U_3Si_x fuel. For the dependence of swelling on the volume ratio of U_3Si/U_3Si_2 see [7, 9, 10]. This can be determined with sufficient accuracy only by taking a large number of metallurgical cuts or powder samples. Therefore the vendors have developed correlations which are believed to be satisfactory in most cases.

The metallurgical cuts and the microscopic analyses are very expensive. They should be included in the specifications only if absolutely necessary for safety reasons. In most cases the correlations will be sufficient.

2.3.2 Particle size distribution

The particle size must be $\leq$ 150 µm. Up to 50 wt% of the fuel powder can have a particle size less than 40 µm (or 45 µm). Other existing limitations in particle size and % of fines are believed to be unnecessary based on the results of PIE (the existing specifications for UAl_x and U_3O_8 can also be used for U_xSi_y). However, the maximum particle size and the distribution of particle sizes will influence other parameters such as porosity and minimum cladding thickness. Therefore, a maximum particle size specification might be an advantage for some applications.

The control sieving must be carried out with a set of sieves of 40 µm or 45 µm, 150 µm and 180 µm. If all particles pass the sieve of 180 µm, it is allowed to have 1% of the fuel powder on the sieve of 150 µm.

2.3.3 Porosity

The swelling ratio for silicide fuel is higher than for aluminide or oxide fuel. For silicide fuel the porosity has a larger impact on swelling than for the other fuels [7, 9]. If there are limitations on swelling it may be necessary to know the porosity. The built-in porosity is dependent on the fabrication process and can be different for the same uranium densities.

2.3.4 Al-powder

There are slight differences in the existing specifications which are believed to be of minor importance. Care should be taken in limiting the amount of poisoning impurities such as B, Cd, and Li. Other impurities can normally be varied over a greater range. The current specification limits should be used as a guideline for operators and fabricators. In order to avoid unwanted nuclear and metallurgical behaviour some limits should be specified. These considerations can also be applied to the fuel powder.

2.3.5 U-content of fuel plate

There is no problem with accuracy (approximately 2%). The total uranium content cannot be standardized.

2.4 Fuel Plate

2.4.1 Homogeneity

With increasing volume percentage of fuel and uranium density the present homogeneity limits will result in an increase in the number of rejected fuel plates. Homogeneity limits within the specifications may be a result of the hot spot analyses and therefore part of the overall safety features. However, it may be worthwhile to discuss these limits with relevant bodies to determine whether adequate safety margins can be maintained with less stringent homogeneity limits so that fabrication costs can be reduced.

With the standard technique, homogeneity deviations are determined over 1 cm^2 areas. Smaller measuring areas will give, for physical reasons, greater variations. All commonly used measuring techniques are acceptable.

Design or safety limitations on homogeneity come from the plus tolerances of the homogeneity. The existing minus tolerances are not as decisive. Greater minus deviations may be acceptable, therefore, but their control allows an insight into the overall quality of fuel plate fabrication.

2.4.2 Plate thickness

The tolerance of the overall plate thickness influences the minimum cladding thickness and therefore has to be limited. Also if there are tight demands on channel spacing, these cannot be achieved if the tolerances for the plate thickness are too large. For these reasons the tolerance of the plate thickness will follow the minimum cladding thickness and the tolerances on channel spacing.

2.4.3 Minimum cladding thickness

Corrosion is influenced by many factors: cladding material, surface treatment, copper or chlorine impurities, temperature, pH and conductivity of the water, water quality (e.g. Cu, Cl), lifetime of the fuel, overall operations conditions over years, etc. Some of these factors are or may be correlated. Typical types of corrosion occuring on plate-type fuel elements are pitting corrosion and uniform plate corrosion. Since fission product release from elements will cause many problems, any type of corrosion must be minimized to avoid such difficulties. Therefore the minimum cladding thickness can and will be different for different research reactors, e.g. if the fuel lifetime is 3 weeks or 3 years. Any change of the minimum cladding thickness should be based on reported operation experience and the documentation of the actual thickness obtained for a specified minimum. One has to be sure that the reported operation experience is not the result of other factors, but related only to the specified values of minimum cladding thickness. The correlation between specified and actual cladding thickness must be known.

Historically the cladding thickness has been specified as 0,38 ± 0,08 mm in most cases. Due to higher density fuel with a larger volume percentage of fuel in the meat (more fuel particles), an increasing number of fuel particles have been found violating the 0,30 mm minimum cladding thickness. In order to reduce the rejection rate and the fabrication cost, fuel plates have been accepted with fuel particles in the region down to 0,25 mm (0,23 mm) and for the HFIR to 0,20 mm. It is obvious that the acceptance of fuel plates with extremely low minimum cladding thickness will reduce the fabrication cost. But what is acceptable as a minimum, 0,25 mm or 0,20 mm or 0,15 mm or 0,10 mm? The acceptable minimum is closely related to the overall long-term operation conditions, the materials used and the fabrication technique. For this reason no general statement for the acceptable minimum cladding thickness can be given at present and may never be possible. Fission product release coming from pitting corrosion was found in the past even in cases where the minimum cladding thickness was 0,30 mm.

2.4.4 Cladding material

Fabricators normally using cladding materials with specified impurities following their national standards. In use have been: pure Al (99,5% Al), pure Al (99,85% Al), Al 1100, AlFeNi or Al-based Magnesium-alloys like Al 6061, AG1NE, AG2NE, AG3NE, AlMg1, AlMg2, AlMg3. With increasing uranium density and increasing coolant flow velocity, weak Al-cladding materials cannot be used as bonding and cladding thickness difficulties may arise during the fabrication process and mechanical stability difficulties of the fuel plate during operation. The advantage of the Al-based Magnesium alloys is their increased corrosion resistance. For this reason it is recommended to use Al-based Mg-alloys if possible.

But in most of the cases all cladding materials in use are acceptable. In order to reduce cost, the fabricators should limit the number of different cladding materials in their fabrication lines to one or two.

Demands on the acceptable impurities have to follow 2.3.4. In some cases an increase of the boron content from 10 ppm to 30 ppm can be accepted as this will be totally consumed during the lifetime of the fuel.

2.4.5 Surface defects

Significant surface defects may be caused by some lack of attention during the fabrication process or by removing foreign particles from the cladding. No foreign particles with unknown chemical composition can be accepted in the cladding. Surface defects have to be limited in size and depth to avoid fission product leakage during the expected lifetime of the fuel element. To date there has been no report that surface defects and pitting corrosion are correlated. But as there are other corrosion phenomena possible (plate-type, potential effects) the depth of surface defects has to be limited. The allowed depth should inversely follow the minimum cladding thickness. It is recommended that the difference between both not be less than 125 µm, otherwise, plates should be rejected. Example:

minimum cladding thickness	250 µm
maximum surface defects	125 µm.

In the dogboning zone, if there is evidence of dogboning in the plates, surface defects not deeper than 75 µm are acceptable. Outside the meat zone defects up to 300 µm may be acceptable depending on the number of these defects and the evidence and location of white spots.

2.4.6 Surface treatment

The surface treatment selected may influence the corrosion behaviour of the fuel plate. Therefore the surface must be absolutely free from Cl. In most cases only etching and cleaning with demineralized water is used and is sufficient. With an additional treatment with hot water (100°C) or steam a corrosion resistant layer of stable Boehmite is produced and the corrosion resistance is increased by more than a factor of 10, and may also reduce heat transfer.

2.4.7 White spots

With increasing uranium density and increasing vol.% of fuel in the meat a significant number of 'white spots' were detected on the x-ray film. These 'white spots' are fuel particles outside the specified meat zone. They are located between the frame and the cladding. Limits on location and clustering of the fuel particles are necessary for two reasons:

i) to avoid fission product leaks, and
ii) to assure the appropriate cooling of the plate even in zones where the plate is not cooled by turbulent flow.

At present it has not been established whether there is a correlation between blisters outside the meat zone and fuel particles at these positions. If such a correlation is found this will become important only for high burnup values. PIE's are going on and results will be reported.

The following specification is recommended for the acceptance of white spots: this proposed specification avoids the measurement of the distance between the white spots and/or the necessity to calculate the overall area of the white spots. These measurements and/or calculations were found in the past to be totally impractical and extremely expensive.

a) No particles (evidenced as white spots on the position radiograph) shall be within 0,4 mm of the edges or ends of the fuel plate.

b) The maximum dimension of the stray particle shall be 0,5 mm. Touching particles shall be considered as a single particle for the purpose of determining the largest dimension.

c) The maximum number of stray particles in any 20 mm^2 area located between the maximum core length or width and 0,4 mm of the plate edge or end shall not be greater than ten.

d) A stringer of fuel generated from the corners of the core ends is acceptable provided it comes no closer than 1,3 mm from the plate ends.

e) No stray particles shall be allowed in the comb or identification areas.

f) Stray particles found within 0,4 mm of the plate edge or end may be removed by filing. These handworked areas shall not be greater than 0,5 mm in depth.

2.4.8 Surface contamination

There is no present need to change the commonly specified values (ca. 5 - 10 µg U/plate).

2.4.9 Burnable poisons

Burnable poisons are in use for higher power research reactors. These burnable poisons can be in side-plates or at the top or bottom of fuel plates. The present knowledge is that some care may be necessary if the poison is mixed with fuel. Experiments are going on to determine the swelling behaviour in these cases especially for uranium silicide fuel.

2.5 Fuel Element

As stated in Chapter 2.2 no recommendations on most of the geometry factors can be given as they are specific to the overall design of the core.

2.5.1 Channel gap spacing

The minimum channel gap is one of the parameters in the calculations for the hot channel and for this reason the tolerances are in most cases included in the thermodynamic calculation and the safety report. But in general - as many reactors operate with large safety margins - the chosen tolerances should be rechecked, as fuel element fabrication costs are significantly influenced by the chosen tolerances and the inspection procedure.

In almost all cases only the minimum tolerance is of importance and controlled. Therefore, to specify a plus tolerance is unnecessary in most cases.

When specifying channel gaps one has to consider with the same care the gap between neighbouring fuel elements. The cooling conditions between neighbouring fuel elements are in many cases not as good as within the fuel elements.

2.5.2 Burnup warranty

The burnup warranty has to be discussed between the operator and vendor and depends on too many conditions for a general recommendation.

3. INSPECTION PROCEDURES

The chosen inspection procedure depends on many different factors, such as:

- license requirements,
- consultants' demands,
- fabricator experience,
- inspectors' experience,
- changed or unchanged fabrication process,
- evidence of defects, and
- reactor design.

The inspection can be performed by the independent quality control department of the fabricator and/or independent expert and/or customer. The extent of inspection ranges between 100%, sampling (extended to 100% if a given percentage of values are found out of the specified ones) and 0%. The extent and percentage of inspection may limit the throughput of the fabrication and it is therefore obvious that this may have a great impact on the fuel element fabrication cost. It is estimated that inspection cost ranges between 1/3 and 2/3 of the total fabrication cost depending on the chosen procedure. It is strongly recommended that all inspectors be well trained and that the customers not reject in all cases plates or elements if the values are slightly outside the specified ones. The customers should use their experience to decide to recommend acceptance or rejection in such cases.

Since the chosen detailed inspection procedure is influenced by many different factors, recommendations could be developed only for some selected parts.

3.1 Particle Size

See Chapter 2.3.2.

3.2 Bonding

The most effective quality check on bonding is the blister test. The chosen blister temperature depends on the selected cladding material and should be only slightly different from the hot rolling temperature. The temperature range is normally between 410°C and 500°C.

In addition to the blister test the ultrasonic test* is in use. With this method defects $\geq$ 2 mm Ø can be detected. With high uranium density there are increasing difficulties near the fuel core limits. The measurements need careful interpretation and the method should be discussed separately between the customer and the fabricator.

3.3 White Spots

See Chapter 2.4.7.

3.4 Radiographic Inspection

Fluoroscopy and/or x-ray film is in use. The selected method depends on the need for control and documentation. Care should be taken for absolutely symmetrical cutting of the fuel plate out of the rolled plate.

3.5 Surface Contamination

Smear test (sampling) and 100% control with α-counters are in use. Normally only background is detected. If there are positive measuring results the rolling process should be inspected.

3.6 Channel Gap Spacing

Minimum check with go gauge only, or for extremely high requirements, registered measurements are in use. See Chapter 2.5.1.

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* Excellent for discovering <u>no</u> bonding between Al-frame and cover plate

4. CONCLUSION

The specifications currently used for HEU fuel should not be taken as ultimate demands when going to high density LEU fuel. At that time the specification demands should be carefully reviewed to use this possibility for reducing the fuel element fabrication cost. This review should include the most important safety margins, the existing operation experience and the operation conditions of the plant. Within the general part and the annex of this guidebook, appropriate information can be found to allow the operator to make a proper decision for his special case. The operator should discuss the finally chosen specification in detail with the fabricator and licensing authority. Whether additional parties have to be involved depends on the special circumstances and the experience of the operator, of his experts and of his authority. The IAEA may be contacted for assistance.

Appendix A

ARGONNE NATIONAL LABORATORY: SPECIFICATION FOR LOW-ENRICHED URANIUM-SILICIDE FUEL PLATES FOR THE ORR

1.0 SCOPE

1.1 This specification covers the fabrication, inspection, and quality assurance provisions of aluminum-clad fuel plates containing low-enriched uranium (LEU) for fuel elements and shim rod fuel sections for the Oak Ridge Research Reactor (ORR), a light-water moderated and cooled, 30-MW(th) nuclear reactor. Each fuel-element grouping of fuel plates will contain 17 short and 2 long plates, and each shim-rod-fuel-section grouping of fuel plates will contain 15 short plates. The fuel plates will contain ^{235}U fuel in the form of an aluminum-clad U_3Si_2-aluminum dispersion. The cladding shall be metallurgically bonded to the fuel core, and the fuel core shall be hermetically sealed.

2.0 APPLICABLE DOCUMENTS

2.1 Applicable Standards

The following documents form a part of this specification except as modified by this specification. Where there is a conflict between the documents cited and the latest revisions thereof, the Contractor shall notify Argonne National Laboratory (ANL), hereinafter referred to as the Laboratory, of the conflict and use the latest revision unless otherwise directed by the Laboratory. NOTE: Contractors located outside the United States territory may submit standards comparable to the U.S. documents listed below to the Laboratory for approval as alternates.

2.1.1 ORNL Drawings

M-11495-OR-004-E	Fuel Plate Details, ORR Fuel Elements
M-11495-OR-012-E	ORR Shim Rod Fuel Section, Fuel Plate Details

2.1.2 American Society for Testing and Materials Standards

ASTM-B209-70	Aluminum Alloy Sheet and Plate
ASTM-B214-76	Method of Test for Sieve-Analysis of Granular Metal Powders

2.1.3 American Welding Society Standards

AWS-A5.10-69	Aluminum and Aluminum-Alloy Welding Rods and Bare Electrodes

2.1.4 Argonne National Laboratory Documents

AQR-001	Quality Verification Program Requirements
A0004-1020-SA-00	Specification for Low-Enriched Uranium Metal for Uranium-Aluminide and Uranium-Silicide Reactor Fuel Elements

3.0 TECHNICAL REQUIREMENTS

3.1 Materials

The Contractor shall provide a certified report of the chemical analysis of each material listed showing conformance to its respective requirements. The Contractor shall also provide a certified report of the chemical and isotopic analysis of each lot of U_3Si_2. In addition to other requirements, all materials specified in Paragraphs 3.1.4 and 3.1.5 shall be certified by the Contractor to contain less than 10 ppm boron, 80 ppm cadmium, and 80 ppm lithium. The quantities of these impurities (boron, cadmium, and lithium) in the finished plate shall not exceed those values.

3.1.1 Uranium Metal

The U.S. Department of Energy shall provide the uranium metal needed for the fabrication. The ^{235}U enrichment of the uranium metal shall be 19.75 ± 0.2 wt%. The uranium metal shall meet the technical requirements of ANL specification A0004-1020-SA-00 except for carbon impurity content, which shall be less than 350 ppm by weight.

3.1.2 Uranium-Silicide Powder

3.1.2.1 Uranium silicide, with U_3Si_2 as the primary constituent, shall be produced by melting together uranium metal and high-purity silicon. The silicon content of the uranium silicide, hereinafter called U_3Si_2, shall be $7.5\,^{+0.4}_{-0.1}$ wt%. It is desirable for the silicon content to be close to 7.5 wt%, but in no case should it be less than 7.4 wt%. Except for impurities, whose limits are specified in Subparagraph 3.1.2.2, the balance of the U_3Si_2 shall be uranium.

3.1.2.2 An analysis shall be required for each lot of U_3Si_2. The impurities in the U_3Si_2 shall not exceed the limits specified in Table 1.

Table 1. Maximum Impurity Levels for U_3Si_2 (ppm)

Al	600	Co	10	Li	10
B	10	Cu	80	N	500
C	1000	Fe+Ni	1000	O	7000
Cd	10	H	200	Zn	1000
Other Elements		Individual	500		
		Total	2500		

3.1.2.3 As used in the fuel core, the U_3Si_2 powder shall be -100 + 325 mesh (44 to 149 μm) and shall not contain more than 25% of -325 mesh particles, as determined in a standard screening test (ASTM B214-76).

3.1.2.4 A sample with a minimum weight of 10 g shall be obtained from each lot of U_3Si_2 by the Contractor and held at the Contractor's plant for the Laboratory's use. At the time of final delivery, all samples not called for will be considered part of the Contractor's scrap.

3.1.2.5 The Contractor shall obtain an independent isotopic analysis of each lot of U_3Si_2 and shall provide to the Laboratory a copy of the results.

3.1.3 Aluminum Powder

3.1.3.1 All aluminum powder shall be atomized spheroidal particles. One hundred percent of the powder shall pass through a 100 mesh (149 μm) U.S. Standard screen with 80% passing through a 325 mesh (44 μm) U.S. Standard screen.

3.1.3.2 The chemical composition of the aluminum powder shall be within the limits listed in Table 2.

Table 2. Composition Limits for Al Powder (wt%)

B	0.001 max	Fe	0.400 max	Ti	0.030 max
Cd	0.001 max	Li	0.001 max	Zn	0.030 max
Co	0.001 max	Mg	0.015 max	Al	99.500 min
Cu	0.008 max	Si	0.300 max		

3.1.4 Aluminum Plate and Sheet

The aluminum for the core frames and cladding shall conform to ASTM specification B209-70, alloy 6061-0. The core frames shall be one piece; frames made of multiple pieces welded together are not acceptable.

3.1.5 Aluminum Welding Rods

Aluminum welding rods shall conform to AWS-A5.10-69, Type ER-4043.

3.2 Mechanical Requirements

3.2.1 Fuel Core Fabrication

The fuel core shall consist of 19.75%-enriched U_3Si_2 powder dispersed in aluminum powder. The fuel core shall be fabricated according to standard powder-metallurgical, roll-bonding techniques, modified if necessary, such that excessive oxidation of the fuel core prior to the first hot rolling pass does not occur. The Contractor shall provide to the Laboratory a written procedure for the initial hot rolling step which describes the method used to prevent excessive oxidation or shall provide written certification that the procedure used is the same as that used previously to produce similar U_3Si_2-Al test elements for the ORR.

3.2.2 Fuel Core Location

3.2.2.1 As verified by fluorscopic and/or x-radiographic examination, the location of the fuel core shall satisfy either of the following criteria:

3.2.2.1.1 The location of the fuel core shall comply with the requirements specified on the drawings referenced in Section 2.0.

3.2.2.1.2 The outline of the fuel core shall lie within the maximum fuel core dimensions specified on the drawings referenced in Section 2.0, shall be of an area greater than the area of the minimum fuel core dimensions specified on the drawings referenced in Section 2.0, and shall be centered with respect to the edges of the fuel plate. The responsibility for proving that the fuel core area meets this requirement shall lie with the Contractor.

3.2.2.2 The Contractor shall endeavor, through use of adequate compacting pressure and care in assembling the rolling billet, to minimize the occurrence of fuel flakes outside the maximum fuel core dimensions specified on the drawings referenced in Section 2.0. Fuel particles will be allowed in the nominally fuel-free zone except under the following conditions, however:

3.2.2.2.1 Particles (evidenced as white spots on the position radiograph), of any size, closer than 0.5 mm to the ends or edges of the fuel plate or under the comb or plate-identification-number area.

3.2.2.2.2 Particles (white spots) with largest dimension greater than 0.5 mm which are outside the maximum fuel core dimensions specified on the drawings referenced in Section 2.0. Touching particles (white spots) shall be considered to be a single particle for the purpose of determining the largest dimension.

3.2.3 Cladding and Core Thickness Determination

Prior to full production, at least 24 fuel plates shall be manufactured. Two outer fuel plates and two inner fuel plates shall be randomly selected and sectioned as shown in Fig. 1 to verify that cladding and core thicknesses as specified on the drawings referenced in Section 2.0 are met. Further verification of cladding and core thickness shall be demonstrated by randomly selecting one fuel plate from each 100 fuel plates processed. (A plate which has been rejected for reasons not affecting the cladding and core dimensions may be used for this determination.) If production procedures relative to fuel plate fabrication are changed, cladding and core thickness must be requalified.

3.2.4 Cladding Temper

Each fuel plate shall be rolled by a combination of first, hot rolling, and second, cold rolling. The final reduction of the plate thickness shall be accomplished by cold rolling and shall not be less than 4% nor greater than 25% of the final hot-rolled thickness.

3.2.5 Metallurgical Bond

The existence of a metallurgical bond shall be verified by blister test, ultrasonic test, and bending test on a strip sheared from the plate end trimming. The bending test may be replaced by demonstration of at least 40% grain growth across the cladding/frame interface for all plates sectioned to verify fuel core and cladding thickness.

3.3 Physical Properties

3.3.1 Fuel loading

The loading of each fuel plate shall be as specified below. The amount of ^{235}U in the fuel core is to be determined by a uniform, statistically sound sampling procedure, proposed by the Contractor and approved by the Laboratory. The weight of each core shall be measured and recorded to within 0.01 g along with the calculated value of the ^{235}U content. Fuel content may be confirmed by the Laboratory by the use of reactivity measurements.

3.3.1.1 Fuel plates for fuel elements -- Each fuel plate shall contain 17.9 ± 0.35 g of ^{235}U.

3.3.1.2 Fuel plates for shim rod fuel sections -- Each fuel plate shall contain 17.9 ± 0.35 g of ^{235}U unless a smaller loading is specified in the procurement contract.

3.3.2 Homogeneity

The tolerance on the surface density in g/cm^2 of ^{235}U within the maximum fuel core outline shall be +27 -100% of the nominal value of that spot as measured for any 5/64-inch (2.0-mm) -diam spot. The tolerance on an average ^{235}U surface density within the minimum core outline shall be $\pm 12\%$ of the nominal value. In the area between the maximum and minimum core outlines, the variation of the average shall be within +12% -100% of the specified value. These averages shall be measured for a surface area 5/64-inch (2.0-mm) wide and ~1/2-inch (12.7-mm) long, or over an equivalent circular surface area of diameter 7/32-inch (5.6 mm). The scans shall be tangent one to the other.

3.4 Dimensional Requirements

3.4.1 Each fuel plate shall be in conformance with the dimensions specified on the drawings referenced in Section 2.0. Preassembly fuel plate width and curvature shall be chosen so that they will be compatible with the value specified for the fuel element or shim rod fuel section in its assembled condition.

3.5 Surface Conditions

3.5.1 Surface Finish

The surface of the finished fuel plates shall be smooth and free of gouges (scratches, pits, or marks) in excess of 0.005 in. (0.127 mm) in depth. Dents in the fuel plate shall not exceed 0.012 in. (0.3 mm) in depth or 0.25 in. (6.4 mm) in diameter. In the dogboning zone, if there is evidence of dogboning in the plates, surface defects not deeper than 0.003 in. (0.076 mm) are acceptable. No degradation of the fuel plates beyond these limits shall be permitted.

3.5.2 Surface Contamination

The Contractor shall verify that the surface contamination of the fuel plates is less than five micrograms of uranium per square foot (5 μg per 929 cm^2).

3.5.3 General Cleanliness

Precautions must be taken to maintain a high standard of cleanliness during fabrication and assembly to insure that no foreign materials or corrosion products are present in the finished elements. All surfaces must be free from moisture, dirt, oil, organic compounds, scale, graphite, or other foreign matter. Use of graphite for marking purposes is prohibited. The use of abrasives for cleaning the fuel plates or for any other purposes is prohibited, as is any procedure which removes more than 0.0004 in. (0.01 mm) of aluminum from the surface of the finished fuel plates. If any chlorine-bearing material is used for cleaning, it must be completely removed following the cleaning procedure before any elevated temperature treatment or welding. Moreover, the finished element must be free of any chlorine-bearing material.

3.6 Plate Identification

After rolling, a serial number shall be placed on each fuel plate for identification as to U_3Si_2 powder lot number and compact number using procedures approved by the Laboratory. The identification number shall be over the unfueled region of the plate, as shown on the drawings referenced in Section 2.0.

4.0 QUALITY CONTROL AND QUALITY ASSURANCE REQUIREMENTS

4.1 Responsibility

Unless otherwise specified, the Contractor shall be responsible for the performance of all tests and inspections required prior to submission to the Laboratory of any fuel plate for acceptance. However, the performance of such tests and inspections is in addition to, and does not limit, the right of the

Laboratory to conduct such other tests and inspections as the Laboratory deems necessary to assure that all fuel plates are in conformance with all requirements of this specification. The Contractor may use either his own or any commercial laboratory acceptable to the Laboratory. Records of all tests and examinations shall be kept by the Contractor, complete and available to the Laboratory as specified in the contract or purchase order.

4.2 Quality Verification Plan

The Contractor shall develop and submit for approval with his bid a quality verification plan fulfilling the requirements of ANL Document AQR-001.

4.3 Prequalification Inspection

Before the contract is awarded, the Laboratory may send a representative to the Bidder's plant to judge the capability of the Bidder to carry out the provisions of the contract and the adequacy of the steps to be taken in executing the quality verification program.

4.4 Manufacturing Procedures

A written general description of the manufacturing procedures, shop drawings, detailed cleaning procedures, and inspection report forms shall be supplied to the Laboratory by the Contractor for approval prior to initiation of any fabrication, and any subsequent changes in the above shall be supplied to the Laboratory for approval prior to their use.

4.5 Quality Conformance Inspections

The tests listed in Table 3 are to be performed by the Contractor and documented in accordance with the requirements of the specification. The Laboratory may observe the performance of these tests and/or audit the documentation of same at any point during the procedure.

Table 3. Quality Conformance Inspection

Test	Requirements	Acceptance Criteria	Test Method
Dimension	3.4	4.7.4	4.8.1
Fuel Core Location	3.2.2	4.7.2.1	4.8.2
Cladding and Core Thickness Determination	3.2.3	4.7.2.2	4.8.4
Cladding Temper	3.2.4	4.7.2.3	4.8.5
Metallurgical Bond	3.2.5	4.7.2.4	4.8.6
Surface Finish	3.5.1	4.7.5	4.8.7
Surface Contamination	3.5.2	4.7.5	4.8.8
Cleanliness	3.5.3	4.7.5	4.8.9
Fuel Loading	3.3.1	4.7.3.1	4.8.10
Homogeneity	3.3.2	4.7.3.2	4.8.3

4.6 Extent of Inspection

The tests listed in Table 3 are to be performed for each fuel plate except for the following:

Cladding and core thickness determination - At least one randomly-selected plate from each group of 100 plates processed is to be tested.

4.7 Acceptance Criteria

Acceptance and/or rejection criteria for the technical requirements (Section 3.0) are as follows:

4.7.1 Materials

All materials are to be in accordance with the requirements of this specification and the specified standards without exception.

4.7.2 Mechanical

4.7.2.1 Fuel core location -- The fuel core location shall be in accordance with the requirements of Paragraph 3.2.2.

4.7.2.2 Cladding and core thickness determination -- If any plate fails to meet specifications, two more plates randomly selected from the same group of 100 plates are to be sectioned for thickness measurements. If either of the latter two plates fails to meet specifications, all plates manufactured or in the process of manufacture since the last acceptable sectioning shall be rejected.

4.7.2.3 Cladding temper -- Cold reduction shall be in accordance with the requirements of Paragraph 3.2.4.

4.7.2.4 Metallurgical bond -- Plates exhibiting visible raised or blistered areas shall be rejected. Plates exhibiting nonbond indications greater than 2 mm in diameter on the ultrasonic scan record shall be rejected. Plates showing delamination of the cladding and frame during the bending test shall be rejected.

4.7.3 Physical Properties

4.7.3.1 Fuel loading -- The loading shall, without exception, be within the specified tolerances.

4.7.3.2 Fuel core quality -- Homogeneity and fuel location will be acceptable if they fall within the limits specified in Paragraphs 3.2.2 and 3.3.2.

4.7.4 Dimensional Requirements

All dimensions must be within the tolerances shown on the drawings unless a deviation from these dimensions is granted by the Laboratory.

4.7.5 Surface Conditions

All requirements of the specification are to be met; no nonconformance will be allowed.

4.7.6 Plate Identification

Markings are to be made exactly as approved by the Laboratory.

4.8 Test Methods

All test methods and procedures must be submitted by the Contractor and approved by the Laboratory prior to actual fabrication. Any subsequent changes in the procedures must also be supplied for approval by the Laboratory prior to their use. The granting of any approval or approvals by the Laboratory shall not be construed to relieve the Contractor in any way or to any extent from the full responsibility for delivering fuel plates conforming to all requirements of this specification.

4.8.1 Dimensional

The Contractor shall furnish a written procedure for dimensional examination of the fuel plates. This procedure must be approved by the Laboratory.

4.8.2 Fuel Core Location

The Contractor shall furnish a written procedure for fluoroscopic and/or x-ray examination of the fuel plates. This procedure must be approved by the Laboratory.

4.8.3 Fuel Core Quality

The Contractor shall furnish written procedures for radiography and scanning of the plates. These procedures must be approved by the Laboratory.

4.8.4 Cladding and Core Thickness Determination

Each plate to be examined shall be completely sectioned according to Fig. 1 of this specification.

4.8.5 Cladding Temper

The Contractor shall furnish a written procedure for the Laboratory's approval.

4.8.6 Metallurgical Bond

The Contractor shall furnish a written procedure for the Laboratory's approval.

4.8.7 Surface Finish

The Contractor shall furnish a written procedure for the Laboratory's approval.

4.8.8 Surface Contamination

The Contractor shall furnish a written procedure for the Laboratory's approval.

4.8.9 Cleanliness

The Contractor shall furnish a written procedure for the Laboratory's approval.

4.8.10 Fuel Loading

The Contractor shall furnish a written procedure for the Laboratory's approval.

4.9 Documents

4.9.1 Two certified copies of inspection and test records covering the items listed below shall be supplied the Laboratory. A duplicate copy of the records of each fuel assembly shall be included in the shipping container with the fuel plates.

4.9.1.1 The serial number of each plate within each unit, the calculated fuel loading of uranium and ^{235}U in each fuel plate, and the total calculated loading of U_3Si_2 and ^{235}U. The fuel loadings are to be as specified in Paragraph 3.3.1 of this specification.

4.9.1.2 Data on the examination of the surfaces of the fuel plates as specified in Section 3.5 of this specification.

4.9.1.3 Data regarding the location of fuel cores as prescribed in Paragraph 3.2.2 of this specification.

4.9.1.4 Results of the cladding and core thickness determination as specified in Paragraph 3.2.3 of this specification.

4.9.1.5 Results of the inspection of bonding in each fuel plate examined as specified in Paragraph 3.2.5 of this specification.

4.9.1.6 A certified report of the chemical and isotopic analysis of each U_3Si_2 lot as specified in Paragraph 3.1.2 of this specification.

4.9.1.7 A certified report of the chemical analysis of all other materials used in the fabrication of the fuel plates as specified in Section 3.1 of this specification.

4.9.1.8 A certificate of compliance for each fuel plate unit stating that the element meets all requirements of the contract.

4.9.2 Manufacturing Procedures

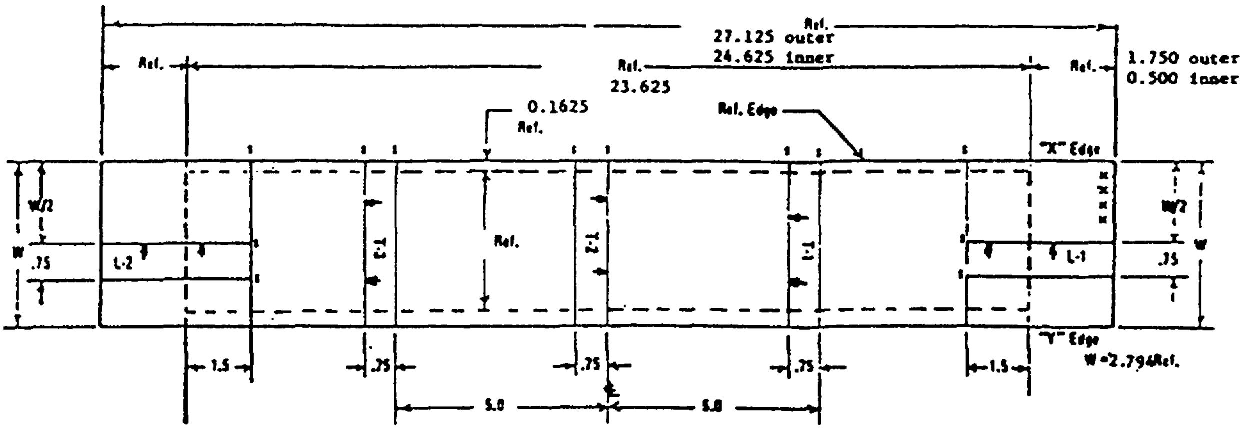
The Contractor shall submit to the Laboratory three copies of the manufacturing procedures required by Paragraph 3.2.1 and Section 4.4.

4.9.3 Test Procedures

The Contractor shall submit to the Laboratory three copies of the test procedures required by Section 4.8.

4.9.4 Quality Verification plan

The Contractor shall submit to the Laboratory with the bid three copies of the quality verification plan required by Section 4.2.



Required measurements

1. Maximum core and clad
2. Minimum core and clad
3. Average core and clad

TYPICAL LAYOUT OF ORR FUEL PLATE • RWK 4/4/84

Figure 1.

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GLOSSARY OF ABBREVIATIONS

HEU	Highly Enriched Uranium ($\geq$ 20% U-235)
LEU	Low Enriched Uranium (< 20% U-235)
PIE	Post Irradiation Examination

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