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Development of LWR Fuels with Enhanced Accident Tolerance
Task 3: Licensing Plan for Accident Tolerant Fuel

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EXECUTIVE SUMMARY

The strategy required to license and commercialize the Westinghouse Electric Company LLC’s Accident Tolerant Fuel (ATF) is outlined in this report. This strategy focuses on licensing and commercialization in the United States. However, similar challenges may exist in other countries. Licensing challenges outside of the United States are not considered as part of this report. An analysis was performed as part of Task 1 of the ATF program to identify areas critical to the development and potential commercialization of ATF [1]. The analysis performed during Task 1 included discussion of potential Nuclear Regulatory Commission (NRC) requirements for ATF, proposed specifications and architectures of the fuel and cladding, as well as preliminary analysis of the ATF performance and accident tolerant features. Task 2 of the ATF program outlined the research and development (R&D) work required to implement the ATF fuel and cladding concepts in commercial reactors [2]. This report, Task 3 of the ATF program, outlines the licensing actions and timeline associated with implementation of ATF at commercial reactors. The licensing work associated with full region implementation of ATF includes the following areas:

- In-pile and out-of pile testing
- Code development and code updates
- Exemption Requests from current regulations governing fuel cladding and pellet materials
- Topical report submittals to the NRC for review and approval
- Rulemaking to relax current requirements within the regulations that would prevent the implementation of ATF in a full core configuration

Projected costs associated with this project account for all of the following:

- Testing
- Code development and code updates
- Engineering work associated with writing the topical reports and responding to RAIs
- NRC fees associated with the review topicals and work to support defense of approvals to the Advisory Committee on Reactor Safeguards (ACRS)

The costs associated with the licensing of ATF provided in this report do not account for activities associated with rulemaking. In total, the cost associated with the aforementioned activities is approximately $75 million over the course of 21 years. The cost and associated timeframe is based on a lead test rod (LTR) load date of 2022 with full batch implementation occurring in the 2034 timeframe.

Licensing of ATF is feasible. While there are significant challenges to overcome, based on past and ongoing licensing activities associated with fuel changes, these challenges can be overcome. Overcoming these challenges to meet the aggressive schedule outlined here will require successful coordination between industry and the NRC.

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1 INTRODUCTION

As part of the development of a credible technical concept for new, advanced light water reactor (LWR) fuels with enhanced accident tolerance, a licensing strategy is required. Currently there is no comprehensive plan available for the licensing of non UO₂/Zr alloy nuclear fuels and cladding. This document outlines the strategy for overcoming the hurdles associated with the licensing of a new advanced fuel and cladding composed of materials other than zirconium-based alloys and uranium-oxide (UO₂) fuel in the United States. There are many operating advantages and safety extensions associated with the advanced ATF concepts. Modifications to the current regulatory bases, establishing new acceptance criteria, and confirmatory testing are required to unlock these considerable advantages. The contents of this report address these modifications that will be required and identify the regulatory risks associated with this project. This report focuses solely on the United States’ licensing environment and does not address challenges that might exist in other countries wishing to implement ATF in the future.

Implementation of these ATF designs will occur through four major phases. Phase 0 consists of the pre-work required prior to loading of LTRs into commercial reactor cores. The licensing process and key tasks associated with Phase 0 are discussed in Section 4. Key tasks associated with Phase 1, the LTR phase of the program, are outlined in Section 5. Section 6 covers licensing actions required as part of LTA implementation slated to occur during Phase 2. Testing, inspections and examinations expected to occur during Phases 0 through 2 are also discussed within each respective section. Phase 3 is discussed in Section 7 and focuses on the NRC submittal required by vendors and utilities for use of ATF in full region implementation. Additionally, Phase 3 focuses on the regulatory modifications such as rulemaking that should occur prior to full batch reloads.

In order to license and obtain approval for ATF in full regions, proper scheduling must occur to align with the regulatory timeframes associated with regulation modifications. Section 8 contains a preliminary licensing schedule for the tasks required to obtain NRC approval for ATF designs. The projected cost estimate of such work is presented in Section 9.

The licensing strategy documented herein is based on similar, successful licensing of new cladding material. However, similar programs utilized zirconium-based cladding and therefore did not require as many regulatory actions. There are a number of risks associated with the introduction of ATF, as discussed in Section 3, but the advantages of ATF counterbalance the risks associated with its licensing and final implementation.
2 BACKGROUND

2.1 CURRENT FUEL DESIGNS

The fuel currently used in commercial nuclear reactors consists of UO$_2$ fuel pellets stacked inside of a zirconium-based cladding tube. These tubes are then bundled into square arrays held in place by support and mixing grids, also made of zirconium-based alloys, to form a full assembly. The following sections provide additional details on the design of the pellets, rods and fuel assemblies currently in use.

2.1.1 UO$_2$ Fuel Pellets

Fuel pellets used in today’s fuel designs are made of uranium dioxide enriched in U-235. Currently the maximum enrichment limit for commercial light water reactor fuel is 5 wt% U-235. These pellets are cylindrical in shape and made of a ceramic to mitigate the effects of the high temperature environment of the fuel rod and reactor core. While the ceramic pellets have high heat tolerance to melting, these pellets are prone to swelling and expansion. To account for this, pellets are dished and chamfered to ensure uniform swelling and densification during irradiation. After the UO$_2$ is properly enriched and formed into cylindrical pellets, the pellets are stacked on top of each other into a hollow tube made of a zirconium-based alloy to form a fuel rod.

2.1.2 Fuel Rods

Fuel rods are cylindrical tubes, which are sealed at both ends and contain the fuel pellets. The tubing is made from a zirconium-based alloy to maximize heat transfer while minimizing neutron absorption. Its main purpose is to keep the fuel pellets and fission gases that result from nuclear fission contained within the rod and to maintain a coolable geometry in case of a design basis accident such as a loss of coolant accident (LOCA).

The major components inside of the zirconium-based cladding of the fuel rod are the enriched fuel pellets, the plenum, and helium gas. The fuel pellets contain the fissile material needed to maintain the nuclear chain reaction used in commercial nuclear power plants to heat the water and eventually produce steam and electricity. Above the stack of fuel pellets is the plenum, which contains a plenum spring. This spring holds the pellets down during transport and handling and provides support as the pellets expand. Additionally the plenum provides an area inside the hermetically sealed tube to hold fission gases released during reactor operation. Lastly, the fuel rod is backfilled with helium gas. Helium gas improves heat conduction out of the fuel pellet and into the cladding across the pellet-cladding gap.

2.1.3 Fuel Assemblies

After the fuel pellets are loaded into the fuel rod, the rods are placed into an array to form a fuel assembly. These arrays can vary in size from 14x14 lattices to 17x17 lattices. The arrays are held in place with the support of grids placed incrementally over the height of the assembly. In addition to providing support for the fuel rods, these grids also provide mixing around the fuel rods to increase cooling capability and limit the potential for the rods to go into departure from nuclear boiling (DNB). Within the array of fuel rods are guide tubes, which provide support to the fuel assembly and maintain an opening for
control rods to insert during accidents and reactor shutdowns. The number of guide tubes ranges from 5 to 25 depending on the fuel design type and lattice array. Fuel rods and guide tubes sit on a component referred to as the bottom nozzle and sit beneath the top nozzle. The top and bottom nozzles are attached to the guide tubes and form the fuel assembly skeleton, which also plays a large role in the structural integrity of the assembly. The assemblies are loaded into the reactor core and used to produce the energy required by the Rankine cycle to create electricity. Current burnup limits for the highest duty fuel rods in a standard fuel assembly is between 60,000 and 62,000 MWD/MTU (megawatt days/metric ton uranium).

2.2 ACCIDENT TOLERANT FUEL DESIGN

There are two main differences between the current fuel designs described in Section 2.1 and ATF, both of which stem from material differences. These differences exist in the form of modifications to materials used in cladding and fuel pellet composition. With the exception of the material used in these two components, all of the features of ATF remain consistent with those of fuel currently in use. If in the future a higher burnup or higher enrichment limit is requested, additional licensing work will be required.

2.2.1 Accident Tolerant Fuel Cladding

Currently two different cladding types are being investigated for use in ATF designs: SiCf/SiCm Ceramic Matrix Composite (CMC) and Zr alloy coated cladding.

SiCf/SiCm CMC cladding consists of SiC fiber reinforced SiC composites; a two or three-layer tube of high purity beta or alpha phase stoichiometric silicon carbide covered by a central composite layer of continuous beta phase stoichiometric silicon carbide fibers infiltrated with beta phase SiC and, in the case of three layers, an outer protective layer of fine grained beta phase silicon carbide. Zr alloy coated cladding investigations currently consist of evaluating the performance of two separate coatings: Ti2AlC known as MAX Phase, and an amorphous stainless steel known as NanoSteel™. The coatings consist of fine particles of the coating materials that are sprayed onto the outside surface of the zirconium alloy rod at high velocity to form a 10 to 20 micron thick layer.

2.2.2 Accident Tolerant Fuel Pellets

Similar to the cladding, there are two different pellet types currently under investigation for use in ATF:

1. UN pellets which have been waterproofed by the addition of U3Si2 or UO2 using N enriched to >90% 15N.
2. U3Si2 pellets.
3 LICENSING ENVIRONMENT

To be in compliance from a licensing point of view, licensees must meet the requirements of a number of NRC rules and regulations governing the design and implementation of fuel used in commercial power reactors. These rules are documents in Title 10 of the Code of Federal Regulations (10 CFR). Title 10 specifically deals with the Energy sector. In addition to the requirements captured in the 10 CFRs, a number of other recommended guidelines are captured in Nuclear Regulations (NUREG). The main NUREG of interest for fuel designs is NUREG-0800, Sections 4.2-4.4. The NRC also issues documents referred to as Regulatory Guides (RG), which help to provide additional guidance on what needs to be included in documents seeking NRC review and approval. Currently there are two draft RGs that have the potential to impact this program. The requirements of each of these regulations and guidance documents are captured in the following sections. These regulations explicitly deal with the properties and failure mechanisms associated with zirconium-based cladding and therefore may not be applicable to the higher performing ATF in the future.

Additionally, each utility wishing to implement ATF will need to review the plant licensing basis for the facility to see if additional requirements must be addressed. Utilities should review plant Technical Specifications (TS) as well as the Final Safety Analysis Report (FSAR), at a minimum, for each unit wishing to use ATF and take the actions necessary to update these accordingly.

3.1 CODE OF FEDERAL REGULATIONS, TITLE 10

3.1.1 10 CFR Part 100

This regulation requires analyses to be performed to ensure that during a postulated accident the dosage to those outside the exclusion zone will be within regulatory limits. Specifically, reactors are currently licensed such that no persons outside of the exclusion zone will receive a dose greater than 1500 mREM during a postulated accident.

3.1.2 10 CFR Part 50.44

10 CFR 50.44 requires that the amount of combustible gas present in a containment structure be limited and monitored to ensure that the structural integrity of the containment is maintained. Under accident conditions with Zr clad fuels, the gas of main concern is hydrogen (H₂) that is released as part of the high temperature zirconium/water reaction.

3.1.3 10 CFR Part 50.46

This regulation governs the Emergency Core Cooling System (ECCS) design requirements in the event of a loss of coolant accident (LOCA). Based on the requirements of this regulation, there are five main design requirements for nuclear fuel used in commercial reactors, as specified in part c of the regulation:

1. The maximum fuel cladding temperature cannot exceed 2200°F.
2. The local cladding oxidation shall not exceed 17% of the total cladding thickness before oxidation. This assumes zirconium is converted to ZrO₂ locally on the cladding wall.
3. The maximum hydrogen generated shall not exceed 1% of the theoretical amount of hydrogen that could be generated during a steam-zirconium reaction in which all of the cladding surrounding the fuel pellets was to react excluding the cladding around the plenum volume.

4. Changes to core geometry shall not affect the ability to cool the core.

5. Long-term cooling of the core will be such that the fuel temperature will be maintained at an acceptably low value and decay heat will be removed for the duration of time required by the long-lived radioactivity remaining in the core.

3.1.4 10 CFR Part 50 Appendix A

10 CFR Part 50, Appendix A contains all of the General Design Criteria (GDC). GDCs are the minimum requirements that need to be met. The GDCs that are specifically applicable to fuel design are GDC 10-13, 20, and 25-28. These GDCs collectively hold that the fuel design criteria remain intact during all normal operations and anticipated operational occurrences (AOOs). Additionally, these design criteria are contained within the licensing basis of most reactors, as they are typically included in Chapter 3 of the plant FSAR. The following criteria are taken directly from 10 CFR Appendix A.

**GDC 10 – Reactor Design**

The reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.

**GDC 11 – Reactor Inherent Protection**

The reactor core and associated coolant systems shall be designed so that in the power operating range the net effect of the prompt inherent nuclear feedback characteristics tends to compensate for a rapid increase in reactivity. (This is negative feedback on a power transient).

**GDC 12 – Suppression of Reactor Power Oscillations**

The reactor core and associated coolant, control, and protection systems shall be designed to assure that power oscillations which can result in conditions exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed.

**GDC 13 – Instrumentation and Control**

Instrumentation shall be provided to monitor variables and systems over their anticipated ranges for normal operation, for anticipated operational occurrences, and for accident conditions as appropriate to assure adequate safety, including those variables and systems that can affect the fission process, the integrity of the reactor core, the reactor coolant pressure boundary, and the containment and its associated systems. Appropriate controls shall be provided to maintain these variables and systems within prescribed operating ranges.

**GDC 20 – Protection System Functions**

The protection system shall be designed (1) to initiate automatically the operation of appropriate systems including the reactivity control systems, to assure that specified acceptable fuel design limits are not
exceeded as a result of anticipated operational occurrences and (2) to sense accident conditions and to initiate the operation of systems and components important to safety.

**GDC 25 – Protection System Requirements for Reactivity Control Malfunctions**

The protection system shall be designed to assure that specified acceptable fuel design limits are not exceeded for any single malfunction of the reactivity control systems, such as accidental withdrawal (not ejection or dropout) of control rods.

**GDC 26 – Reactivity Control System Redundancy and Capability**

Two independent reactivity control systems of different design principles shall be provided. One of the systems shall use control rods, preferably including a positive means for inserting the rods, and shall be capable of reliably controlling reactivity changes to assure that under conditions of normal operation, including anticipated operational occurrences, and with appropriate margin for malfunctions such as stuck rods, specified acceptable fuel design limits are not exceeded. The second reactivity control system shall be capable of reliably controlling the rate of reactivity changes resulting from planned, normal power changes (including xenon burnout) to assure acceptable fuel design limits are not exceeded. One of the systems shall be capable of holding the reactor core subcritical under cold conditions.

**GDC 27 – Combined Reactivity Control and Systems Capability**

The reactivity control systems shall be designed to have a combined capability, in conjunction with poison addition by the emergency core cooling system, of reliably controlling reactivity changes to assure that under postulated accident conditions and with appropriate margin for stuck rods the capability to cool the core is maintained.

**GDC 28 – Reactivity Limits**

The reactivity control systems shall be designed with appropriate limits on the potential amount and rate of reactivity increase to assure that the effects of postulated reactivity accidents can neither (1) result in damage to the reactor coolant pressure boundary greater than limited local yielding nor (2) sufficiently disturb the core, its support structures or other reactor pressure vessel internals to impair significantly the capability to cool the core. These postulated reactivity accidents shall include consideration of rod ejection (unless prevented by positive means), rod dropout, steam line rupture, changes in reactor coolant temperature and pressure, and cold water addition.

3.1.5 **10 CFR Part 50, Appendix K**

Appendix K gives the allowable means to calculate emergency core cooling system (ECCS) needs due to a loss of coolant accident (LOCA). This Appendix lists the applicable methods and equations that are available for use to calculate the ECCS needs during a LOCA without further review by the NRC.

3.2 **REGULATORY GUIDES**

Regulatory Guides (RG) are used to give instruction to calculations and analyses of specific areas for nuclear power licensing, i.e. plume models for reactivity release. The RG is NRC approved methodology
that is meant as a guideline. These guidelines are meant to help facilitate the licensing process by increasing efficiencies when dealing with common calculations and common problems or questions that arise during licensing.

Currently one main RG, NUREG-0800, is of interest to the fuel design used in commercial reactors. Sections 4.2 through 4.4 of the Standard Review Plan (SRP) are a guideline for review by the NRC when licensing fuel system design, nuclear design, and thermal and hydraulic design. From these sections the needed documentation and analyses can be ascertained. These documents and analyses ensure that the requirements of the codes of federal regulations are followed when licensing a new fuel, cladding, or geometry.

These sections of the SRP are also directly reflected in Chapter 4 of most plant FSARs and therefore create a portion of the licensing basis for the operating fleet, and should be followed whenever possible. Deviation from the guidance is allowed, provided adequate justification for alternate methods is presented to and accepted by the NRC.

3.2.1 NUREG-0800, Section 4.2, “Fuel Systems Design”

Fuel system design is divided into four sections. These four sections are “Design Basis”, “Descriptions and Design Drawings”, “Design Evaluations”, and “Testing, Inspection and Surveillance Plans.” The first, “Design Basis”, is used when determining the limiting values for important parameters so that damage is limited to acceptable levels. The second, “Descriptions and Design Drawings”, is used when reviewing fuel systems and places an emphasis on product specifications. The third, “Design Evaluation” is used to evaluate and ensure that “Design Bases” are met during normal operation, AOOs, and postulated accidents. Finally, “Testing, Inspection, and Surveillance Plans”, ensures that before, during and after irradiation, all requirements that have been set forth in the previous three areas have been and will continue to be met.

3.2.2 NUREG-0800, Section 4.3, “Nuclear Design”

The nuclear design is used to develop many of the analyses performed on the core where core performance analyses are concerned. This section is used to confirm the design bases established by the GDC are met. Specifically the neutronics are important here. From this section the core power distribution, reactivity coefficients, control requirements, rod patterns and reactivity worths, criticality, and pressure vessel irradiation can be determined. Finally the analytical methods used to determine many of the above criteria are addressed.

3.2.3 NUREG-0800, Section 4.4, “Thermal and Hydraulic Design”

The thermal and hydraulic (T&H) design section is used to determine the computer calculations that are needed to substantiate reactor analyses. Furthermore, the correlation of experimental data and verification of process and phenomena applied to reactor design are also included. This section is not as in depth as SRP 4.2 but is useful when determining the T&H portion of the licensing approach.
3.3 DRAFT REGULATORY GUIDES

3.3.1 DG-1261, “Conducting Periodic Testing for Breakaway Oxidation Behavior”

This draft RG deals with the testing required with respect to “breakaway oxidation” as it relates to the provisions of 10 CFR 50.46c. Because of the current fuel design, this document predominantly focuses on zirconium-based cladding and the requirements associated with it. However, similar requirements may be imposed on ATF cladding.

3.3.2 DG-1262, “Testing for Postquench Ductility”

This draft RG describes an approved technique for measuring ductile-to-brittle transition for a zirconium-based cladding material, as required by 10 CFR 50.46c. Postquench Ductility (PQD) predominantly focuses on zirconium cladding; however similar requirements may be required for ATF fuel as part of the licensing process.

Additional discussion regarding the implementation of the requirements of these draft RGs can be found in Section 4.1.

3.4 REGULATORY RISKS

Currently many unresolved regulatory risks exist that could have a significant impact on the licensing strategy associated with ATF. These risks fall into two categories; the first being regulation based and the second being process based.

3.4.1 Regulation Based Risks

The NRC is currently going through the rulemaking process for new requirements related to the requirements documents in 10 CFR 50.46. This new “LOCA Rule” will inevitably change the amount of oxidation allowed during long-term core cooling that occurs following a LOCA. While ATF shows significantly less oxidation, the resolution of this rulemaking could have a major impact on the marketability and need for ATF. Prolonged rulemaking could also potentially delay the approval of ATF designs, because the final rule could introduce additional changes that challenge the proposed ATF cladding concept.

In addition to the rulemaking associated with 10 CFR 50.46 that is currently underway, new reactivity initiated accident (RIA) limits are also being proposed by the NRC. This new rule limits the amount of hydrogen pick-up to limit the loss of ductility on the fuel. While this shouldn’t impact the ATF process for SiC_{f}/SiC_{m} cladding, rulemaking resolution now could impact the future rulemaking required to implement ATF using coated Zr with respect to cladding ductility.

3.4.2 Process Based Risks

Licensing of a new fuel design cannot occur in a vacuum. Instead, the entire fuel process must be evaluated, considered and licensed accordingly. Therefore, risks exist with the activities associated with transportation and long and short term storage of the ATF. Recent experiences and communications with
the NRC have revealed that new fuel products and designs will have to be flexible enough to address a variety of backend of the fuel cycle options. While these issues are currently beyond the scope of this document, the risks need to be considered moving forward. Note however, that if ATF can be shown to behave as well as or better than current Zr/UO2 fuels in terms of physical properties and reaction with environmental conditions, then this risk may be minimized. In addition, just about any version of ATF that increases performance also dramatically reduces the amount of spent fuel that is discharged per kilowatt of electricity produced.

A large number of Westinghouse topical reports will need to be resubmitted and reviewed. However, due to the long timeline needed for testing, analysis and reporting, any schedule risk due to implementation of a “Prioritization Process” by the NRC for review of the topical reports can be minimized if topical reports are resubmitted in parallel with the testing when possible.

3.5 FUTURE REGULATORY ACTIONS

Prior to full scale implementation of ATF, changes to a number of regulations will be required. While Phase 1 and 2 can be completed with the use of exemption requests, to move towards a more efficient loading process and implementation plan, rulemaking will be needed to remove the references to “zirconium-based” cladding and UO2 pellets. In particular, rulemaking will be required to modify the requirements contained in 10 CFR 50.46 and 10 CFR 50, Appendix K. Additionally, the specified acceptable fuel design limits (SAFDLs) may also need to be modified, resulting in the need for a modification to GDC 10.

10 CFR 50.46

10 CFR 50.46 specifically calls out Zircaloy and ZIRLO® cladding in the regulation. In order to extend this regulation to other cladding types, such as those being proposed for use in ATF, rulemaking will need to occur to remove this specificity.

10 CFR Part 50, Appendix K

This regulation takes into account the impact of both UO2 and zirconium-based cladding alloys on LOCA analysis and requirements. In order to extend applicability of this regulation to the fuel and cladding types under development for use in ATF, rulemaking will need to occur.

The rulemaking process can be quite lengthy and therefore must be accounted for in the overall licensing schedule. After rulemaking begins, the public has 75-90 days to comment on the proposed rule and/or rule change. Once public comments are received, the NRC reviews the comments and makes appropriate changes. Depending on the magnitude of the change, an additional public comment period may occur. After all comments have been resolved, the rule is sent for final approval and publication. The rule usually becomes effective 30 days after publication in the Federal Register. While the process can take as little as 6 months, it can also take a number of years before the rule is finalized.

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4 PHASE 0 – PRE – LEAD TEST ROD ACTIVITIES

Prior to the loading of rods or assemblies into a commercial reactor, a large amount of development work and testing must take place. Results from the testing provide the necessary data for claiming safe operation is achievable in a commercial reactor and that no substantial safety hazards will be introduced.

4.1 PROTOTYPE TESTING

Before loading ATF into any type of reactor, samples of the materials must be tested to obtain out-of-pile data that is needed to support the licensing requirements for new fuel and new cladding. In addition to the current types of data required for new fuel component material such as creep, growth and oxidation, two new draft RGs have been released with additional testing protocol and requirements.

DG-1261 discusses the need for periodic testing requirements for breakaway oxidation. Details are given regarding the types of testing that should be conducted as well as the appropriate way in which results should be reported to the NRC. Appendices to this RG contain procedures for testing zirconium-based alloys. While the CMC cladding may not be subject to these testing requirements, the Zr-coated cladding may be subject to the procedures contained within.

DG-1262 discusses testing requirements for PQD utilizing ring-compression testing for zirconium-based cladding. Similar to the applicability of DG-1261, the requirements of this RG may not include CMC cladding. Zr-coated cladding may be subject to the procedure and requirements identified within the document.

Similar growth and expansion testing will need to be conducted on the fuel pellet prototypes as well. These tests will need to confirm that pellet swelling is limited to a value that will not result in fuel failures from cracking, pellet-cladding interaction (PCI) or other contact related failure mechanisms.

4.2 TEST REACTOR IRRADIATION

ATF will most likely have significantly different operational properties from the current UO2/Zr fuel types in use today. As such, significant basic data on ATF material properties in operating reactor environments will be required to support the analysis and model development required to license ATF.

Similar to the approach used on Optimized ZIRLO™ High Performance Fuel Cladding Material, irradiation testing should occur on both fueled and unfueled rodlets. Irradiation of unfueled rods will provide the unconstrained growth and creep data that will be needed for future licensing actions as well as help to understand the characteristics of the ATF materials. Additionally, these tests will ensure the structural integrity and corrosion characteristics associated with irradiation environments.

Fueled rodlets should contain both types of pellets proposed for ATF as well as the standard UO2 pellets to use as a control. This will provide preliminary data on the pellet behavior as well as provide for a
comparative evaluation to be performed. In order to show the safety benefit of ATF, this type of data will need to be provided to the NRC prior to loading into a reactor core.

Upon completion of the test reactor program, preliminary results can be used to justify the safe operation of lead test rods, which will be required as part of the exemption requests needed in Phase 1.

In addition to irradiation testing of the materials, DNB testing and seismic testing will be needed to show there are no adverse consequences to nuclear safety by the introduction of these rods. While it is still uncertain, a new DNB correlation may be required based on grid design and fuel rod surface modifications. In order to develop this correlation prior to LTR and LTA loading, DNB and flow testing will need to be carried out on prototype rods and assemblies. Seismic testing will be needed as well to show that the rods can withstand the forces imposed during a Safe Shutdown Earthquake (SSE) or Seismic LOCA event.

In all of the Phase 0 testing, the fuel and cladding that is tested should be made using the processes and designs that will be used to make the final commercial product. Otherwise, the data developed from test reactors can be questioned as to its applicability to the final commercial product.

4.3 CODES AND MODEL ANALYSIS

Results from the prototype testing will be used to update current design codes and models so that the new fuel properties can be calculated and analyzed before LTR implementation. The new fuel and cladding will have different operational properties that must be accounted for in the standard fuel assembly. This will require new fuel and cladding, models and analyses.

For currently used LWR fuel, the codes (i.e. software) used to model fuel performance, fuel design, and fuel safety are intended for use with and for licensing of the Zr/UO₂ fuel system. Generally, for implementation of ATF, similar performance, design, and safety models will be required to test and license this fuel. Because the thermo-physical properties and possibly the fissile response of ATF are different and better than the Zr/UO₂ fuel system, the codes and the standards used will require significant modification or new code development. Code modification and/or new code development will require very large labor and financial investments, as captured in the cost estimates in Section 9.

Westinghouse uses many software products to model nuclear fuel in steady state and transient behavior. Some of the software applied by Westinghouse for fuel performance, design, and safety are presented in Table 1.
Table 1. Fuel performance, design, and safety codes currently used by Westinghouse.

<table>
<thead>
<tr>
<th>Presently used codes</th>
<th>purpose</th>
<th>ATF applicability</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>fuel performance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAD</td>
<td>single fuel rod performance</td>
<td>probable; requires appropriate material data</td>
<td>used for licensing, primary fuel performance code</td>
</tr>
<tr>
<td>STAV</td>
<td>single fuel rod performance</td>
<td>possible</td>
<td>used for US BWR licensing, has PWR fuel modeling capability</td>
</tr>
<tr>
<td>FRAPCON</td>
<td>single fuel rod performance</td>
<td>possible</td>
<td>not used for licensing, NRC audit code</td>
</tr>
<tr>
<td>Enigma</td>
<td>single fuel rod performance</td>
<td>possible</td>
<td>used for PWR licensing in UK</td>
</tr>
<tr>
<td>High Duty Drive</td>
<td>core wide fuel rod performance</td>
<td>possible</td>
<td>not used for licensing, used for corrosion calculations</td>
</tr>
<tr>
<td>VIPRE</td>
<td>fuel thermal hydraulics</td>
<td>possible, requires appropriate material data such as fuel thermal conductivity</td>
<td>used for licensing; EPRI code licensed by Westinghouse</td>
</tr>
<tr>
<td>STAR-CCM+</td>
<td>computational fluid dynamics</td>
<td>probable; requires appropriate material data</td>
<td>nonconfigurable code</td>
</tr>
<tr>
<td>ANSYS</td>
<td>finite element analysis with many applications</td>
<td>probable; requires appropriate material data</td>
<td>used for stress calculations, configurable code</td>
</tr>
<tr>
<td><strong>fuel design</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANC</td>
<td>neutronics core design</td>
<td>probable; requires appropriate material data</td>
<td>used for licensing, primary Westinghouse core design code</td>
</tr>
<tr>
<td>STAR-CCM+</td>
<td>computational fluid dynamics</td>
<td>probable; requires appropriate material data</td>
<td>nonconfigurable commercial code</td>
</tr>
<tr>
<td>ANSYS</td>
<td>finite element analysis with many applications</td>
<td>probable; requires appropriate material data</td>
<td>configurable commercial code</td>
</tr>
<tr>
<td><strong>fuel safety</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANC</td>
<td>version of ANC used in evaluating transients such as RIA</td>
<td>probable, requires appropriate material data</td>
<td>used for licensing</td>
</tr>
<tr>
<td>RELAP5</td>
<td>thermal hydraulic safety</td>
<td>probable; requires appropriate material data</td>
<td>commercial code</td>
</tr>
<tr>
<td>ASTRUM</td>
<td>Automated Statistical Treatment of Uncertainty Method, used for realistic large-break LOCA evaluation methodology</td>
<td>probable; requires appropriate material data</td>
<td>used for licensing</td>
</tr>
</tbody>
</table>
4.3.1 Fuel Performance Code Updates

For steady state fuel performance, Westinghouse applies the internally developed PAD code for NRC fuel licensing. PAD is a single fuel rod performance code incorporating different fuel behavior models such as cladding corrosion, cladding creep, fuel pellet swelling, fuel fission gas release, and many others. For test reactor experiments and subsequent licensing of ATF, the models comprising PAD and the data used to develop these models will require redevelopment. Table 2 offers a preliminary compilation of steady state cladding and fuel performance data required for redevelopment of various PAD models.

Table 2. Steady state cladding and fuel performance data required for applying the fuel performance code PAD to ATF

<table>
<thead>
<tr>
<th>cladding data</th>
<th>associated PAD model</th>
<th>fuel data</th>
<th>associated PAD model</th>
</tr>
</thead>
<tbody>
<tr>
<td>cladding</td>
<td>corrosion</td>
<td>fuel densification</td>
<td>pellet – clad interaction</td>
</tr>
<tr>
<td>corrosion rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cladding creep rate</td>
<td>creep</td>
<td>fuel swelling</td>
<td>pellet – clad interaction and clad strain</td>
</tr>
<tr>
<td>cladding creep rate</td>
<td>pellet – clad interaction</td>
<td>fuel fission gas release</td>
<td>rod internal pressure</td>
</tr>
<tr>
<td>cladding irradiation damage</td>
<td>mechanical property change</td>
<td>fuel temperature</td>
<td>fuel melt and feedback to core physics code</td>
</tr>
<tr>
<td>cladding elongation</td>
<td>dimensional change</td>
<td>fuel rod length</td>
<td>fuel assembly sizing</td>
</tr>
</tbody>
</table>

For the development and subsequent licensing of ATF, NRC accepted fuel performance, design, and safety codes should be applied whenever possible. If required, FRAPCON modifications can be supplied to the NRC to enable NRC audit calculations of ATF designs.

Other fuel performance codes are used for modeling specific fuel performance phenomena. For example, STAR-CCM+ is used to model the T&H performance of fuel. Generally this code is not used for NRC licensing of fuel. However, this code is extremely useful in developing and predicting the T&H behavior of ATF cladding and fuel. For application of this code, data such as cladding surface roughness and thermal conductivity of both fuel and cladding is required.

4.3.2 Nuclear Design Codes

Similar to PAD, ANC is the Westinghouse internally developed steady state code used for neutronics design in NRC licensing of nuclear fuel. For application to ATF, ANC will require data detailing the neutronics behavior of the ATF fuel used. For application of ANC to ATF fuels, known cross-sections for U, Si and N can be used. For UN, using the desired enrichment in the $^{15}$N isotope will also be required. There should be cross-sections for Si and N available that are then included in the code input. The main objective would be optimization of the $^{15}$N enrichment.
4.3.3 Fuel and Mechanical Design Codes

STAR-CCM+ and ANSYS are both commercially available software with many applications in fuel design. Some of these applications include coolant fluid flow, fuel heat transfer, mechanical or structural fuel assembly design, fuel assembly component design, and fuel rod mechanical behavior. STAR-CCM+ is nonconfigurable software making it limited in applications such as repeatable design calculations. However, STAR-CCM+ is very useful in predicting the behavior of designs or design modifications making it very useful for reducing the number of experiments required to confirm design behavior. ANSYS is a configurable code and allows for the development of repeatable fuel behavior routines. In this way ANSYS is more useful in developing designs for licensing in that various design behaviors (i.e.; mechanical, thermal, etc.) can be evaluated using verified behavior routines. Much of the data required for application of this software is the same as that presented in Table 2.

4.3.4 Safety-Related Codes

The fuel safety-related codes applied by Westinghouse include ANC, RELAP5, and ASTRUM. These codes are used to model various fuel safety transients such as RIA, DNB, and LOCA. For application of these codes to ATF during safety transients, significant amounts of ATF data during these postulated accidents are required. As an example, the thermal conductivity of both ATF cladding and fuel are required to model an RIA. To model ATF during DNB, again thermal conductivity and various surface properties of ATF cladding are required. Significant effort and funding will be required to collect the required ATF safety behavior data and then modify the different fuel safety codes.

Once the new models have been completed, they will need to be resubmitted to the NRC for evaluation and acceptance, as will be discussed in Phase 3.

Preliminary data from the test reactor can be used to perform necessary analyses for LTR and LTA implementation during Phases 1 and 2.

4.4 MANUFACTURABILITY

The manufacturing challenges for CMC tubing associated with tube length and cladding thickness will be addressed before LTR or LTA implementation. Fuel fabrication facilities will also need to install and qualify equipment to process the new fuel pellet. Because of the licensing requirements of Part 72 facilities, additional licensing may be required for manufacture of U3Si2 and U3Si2-doped pellets. However these fuel facility licensing issues are beyond the scope of this licensing strategy and will be handled at a later time.
5 PHASE 1 – LEAD TEST ROD ACTIVITIES

5.1 EXEMPTION REQUESTS

The number of LTRs per core will be approximately 30 rods distributed among four assemblies, which is well within the “limited number” listed in most plant TS. Because regulations governing fuel design and analysis are all written in terms of zirconium-based cladding and UO$_2$ fuel pellets, utilities wishing to implement LTRs in the reactor core will need to file exemption requests with the NRC prior to fuel load and start up. Ideally, at least two plants would operate with a limited number of LTRs. Utilities interested in participating will need to confirm that the plant specific TS allow for LTAs and lead use assemblies (LUAs) in non-limiting locations.

Interested utilities will need to file exemptions from at least 10 CFR 50.46 and potentially Appendix K, depending on the LOCA Analysis of Record (AOR). Other exemption requests may be required to address the departure from UO$_2$ fuel pellets. These exemption requests will need to be filed at least two years prior to LTR loading. Two years is approximately the average time it takes the NRC to review and approve and exemption requests. Adequate data must exist from Phase 0 to provide support and justification for safe operation of the reactor with ATF LTRs.

5.2 INSPECTION AND TESTING

Upon receiving NRC approval for implementation of LTRs in the core, the reactor will operate as it normally would during any cycle. During the refueling outage, preliminary inspections will be carried out on the LTRs in the form of Post Irradiation Exams (PIEs). These tests will consist of both visual inspections and measurements. PIEs will continue to occur during refueling outages to collect necessary irradiation data from the LTRs.

When the assembly containing the LTRs reaches its design limit, the LTRs will be sent for hotcell examination to obtain additional, more detailed data regarding the performance of ATF under reactor conditions. Data should be taken from more than one LTR to account for process or product variability, meaning that at least two hotcell evaluations should be conducted on LTRs from at least two different reactor cores.

Preliminary data obtained from the LTR phase will be used to move forward into the LTA phase, Phase 2. In order to minimize the delay in submitting the LTA exemption request, intermediate PIEs will be carried out after each of the cycles. This will provide data that can be used to prepare the LTA exemption request and perhaps serve as a basis for the early submission of an exemption request if the early PIE data indicates performance as the design intends. This approach implies the use of the largest number of LTRs as is feasible to provide a sufficient number of LTRs that reach full burnup.

Data obtained during this phase of the process will also go into the code development required to support Phase 2. Additional data will continue to be obtained to further refine the models and data used in code development.
6  PHASE 2 – LEAD TEST ASSEMBLY ACTIVITIES

6.1  EXEMPTION REQUESTS

Similar to the LTR process, exemption requests from NRC regulations regarding cladding and fuel pellet material will be required during the LTA phase. As with the LTRs, these exemption requests will need to be filed 2 years in advance of LTA load. Data collected from the preliminary LTR PIE exams and the prototype testing will be used to justify loading of LTAs into reactor cores. LTAs should be loaded into non-limiting locations of the reactor core so as to not violate plant Technical Specification (TS). Additionally, LTAs should be irradiated in more than one reactor if possible. Utilities interested in loading ATF LTAs will need to confirm that this is allowable per plant specific TS.

6.2  ENGINEERING REPORT

To facilitate the licensing activities and engineering work required of the utility, Westinghouse will provide an LTA Engineering Report. This report covers the technical justification for analysis and evaluations carried out in support of reload calculations related to the LTAs. The LTA report also discusses how regulatory requirements continue to be met even with the presence of LTAs in the core. This document is not meant to be a licensing report sent to the NRC, but is instead intended to provide input for the licensing actions that are required of the utility.

In order to provide the technical justification, sufficient code development work will have to be completed prior to and during Phase 2 to ensure codes and models appropriately reflect the behavior of ATF in reactor conditions. Code modifications completed during this phase will ultimately go to support the submittal of licensing topical reports in Phase 3 of the process.

6.3  INSPECTION AND TESTING

As with the LTRs, a number of inspections, examinations and testing will be conducted on the LTAs in the reactor core. PIE exams will be carried out after each cycle of operation to capture both visual and measurement data.

After reaching the peak rod licensed burnup limit of 62,000 MWD/MTU, LTAs will be sent for hotcell examination to obtain additional, more detailed data regarding the performance of ATF under reactor conditions. Data should be taken from more than one LTA to account for process or product variability, meaning that at least two hotcell evaluations should be conducted on LTAs from at least two different reactor cores.

Data collected from post irradiation inspection and testing will be used to update the analysis codes and methods and for input into the fuel mechanical design topical report, which will be finalized as part of Phase 3. As with the LTRs, in order to minimize the delay in submitting the fuel mechanical design topical report, intermediate PIEs will be carried out after each of the cycles. This will provide data that can be used to prepare the topical report and perhaps serve as a basis for the early submission if the early PIE data indicates performance as the design intends. This approach implies the use of the largest number of LTAs (up to 8 per unit) as is feasible to provide a sufficient number of LTAs that reach full burnup.
7 PHASE 3 – TOPICAL REPORT UPDATES AND SUBMITTALS

Currently all Westinghouse safety analysis and core design codes are written to address UO₂ fuel pellets in a zirconium-based cladding material. To continue to accurately analyze and predict behavior of fuel in reactor, these codes will need to be updated to reflect the change in material properties and behaviors associated with ATF.

7.1 SAFETY ANALYSIS AND CORE DESIGN CODES

Because all operating reactor fuel is currently based on the UO₂/Zr design, all Westinghouse analysis codes are currently designed to only handle this combination of fuel components. In order to move to the full implementation phase, these codes and their associated manuals will need to be updated so that the irradiation behavior of ATF is accurately modeled in safety calculations, as discussed in Section 4.3. As part of this phase, all safety analysis code updates will need to be finalized to confirm they accurately capture the impact of the new fuel. Additionally, the topical reports submitted to the NRC for approval of these codes will also need to be updated to reflect this change. These updated codes and reports will then need to be resubmitted to the NRC for review and approval to extend applicability to ATF fuel and its properties.

7.2 FUEL MECHANICAL DESIGN REPORT

Westinghouse typically uses the Fuel Checklist Evaluation Process (FCEP) to make fuel modifications under 50.59 for minor changes to approved fuel designs. However, the change to ATF will require the submittal of a topical report containing a large amount of design and test data before full region implementation begins. This report will contain all of the design specifications and drawings as well as the structural analyses performed as part of the testing process in the previous 3 phases. Upon approval of this report and all of the safety analysis code reports, utilities will be able to load ATF in full regions.
8 LICENSING STRATEGY TIMELINE

The proposed Licensing strategy is presented in Table 3. This timeline is based on a LTR load date of 2022.

Table 3. Proposed Timeline for ATF Licensing Activities

<table>
<thead>
<tr>
<th>Phase</th>
<th>Action</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 0</td>
<td>Out-of-Pile and In-Pile Testing</td>
<td>2013</td>
</tr>
<tr>
<td></td>
<td>In-Pile Test Reactor Testing of Short Prototype</td>
<td>2016</td>
</tr>
<tr>
<td></td>
<td>In-Pile Hotcell Exam</td>
<td>2018</td>
</tr>
<tr>
<td></td>
<td>Code Development and Updates</td>
<td>2018</td>
</tr>
<tr>
<td>Phase 1</td>
<td>Submit Exemption Request for LTR</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td>Load LTR into core</td>
<td>2022</td>
</tr>
<tr>
<td></td>
<td>First PIE Exam on LTR</td>
<td>2023</td>
</tr>
<tr>
<td></td>
<td>Code Development and Updates</td>
<td>2023</td>
</tr>
<tr>
<td></td>
<td>Submit Exemption Request for LTA</td>
<td>2023</td>
</tr>
<tr>
<td></td>
<td>Second PIE Exam on LTR</td>
<td>2025</td>
</tr>
<tr>
<td>Phase 2</td>
<td>Code Development and Updates</td>
<td>2025</td>
</tr>
<tr>
<td></td>
<td>Load first LTA into core</td>
<td>2025</td>
</tr>
<tr>
<td></td>
<td>Third PIE Exam on LTR</td>
<td>2027</td>
</tr>
<tr>
<td></td>
<td>First PIE Exam on LTA</td>
<td>2027</td>
</tr>
<tr>
<td></td>
<td>Second PIE Exam on LTA</td>
<td>2029</td>
</tr>
<tr>
<td></td>
<td>First Hotcell Exam on LTR</td>
<td>2030</td>
</tr>
<tr>
<td></td>
<td>Code Development and Report Writing</td>
<td>2025</td>
</tr>
<tr>
<td>Phase 3</td>
<td>Third PIE Exam on LTA</td>
<td>2031</td>
</tr>
<tr>
<td></td>
<td>Submit Reports to NRC</td>
<td>2027</td>
</tr>
<tr>
<td></td>
<td>Petition for Rulemaking</td>
<td>2030</td>
</tr>
<tr>
<td></td>
<td>NRC Approves Topicals</td>
<td>2032</td>
</tr>
<tr>
<td></td>
<td>Rulemaking Complete</td>
<td>2034</td>
</tr>
<tr>
<td></td>
<td>Full Region Implementation Begins</td>
<td>2034</td>
</tr>
</tbody>
</table>
9 COST ESTIMATE

The cost estimates provided in this section are based on a preliminary look into the licensing requirements and associated fees. Anytime there are regulators, lawyers and interveners involved or potentially involved, the costs are very difficult to predict.

In today’s regulatory environment, even simple topical reports are taking over 2 years to review and costing close to $70,000. More complex topicals have already taken 3 years and cost millions of dollars. That being said, this cost analysis assumes a simple topical report will cost $70,000 to review and a complex topical will cost $1,500,000 to review. Additionally, this cost estimate assumes the average engineering cost per engineer is $200/hour.

Based on these assumptions, Table 4 provides an estimate of the total cost to license an ATF fuel product.

Table 4. Cost estimate for Licensing of ATF fuel product

<table>
<thead>
<tr>
<th>Activity</th>
<th>Dates</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Pile and Out-of-Pile Testing</td>
<td>2013-2018</td>
<td>$25,000,000</td>
</tr>
<tr>
<td>Code Development and Updates</td>
<td>2016-2030</td>
<td>$20,000,000</td>
</tr>
<tr>
<td>LTR Exemption Request Submittal and Review</td>
<td>2020-2022</td>
<td>$1,000,000</td>
</tr>
<tr>
<td>LTA Exemption Request Submittal and Review</td>
<td>2023-2025</td>
<td>$1,000,000</td>
</tr>
<tr>
<td>Topical Report Writing</td>
<td>2025-2030</td>
<td>$6,500,000</td>
</tr>
<tr>
<td>NRC Review</td>
<td>2027-2032</td>
<td>$20,500,000</td>
</tr>
<tr>
<td>Full Region Exemption Request</td>
<td>2030-2032</td>
<td>$1,000,000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$75,000,000</td>
</tr>
</tbody>
</table>

The NRC Review entry in the table accounts for both NRC Review fees associated with reviewing the topical and the engineering effort associated with responding to any RAI s received as part of the process. Additionally, this $20.5 million includes fees that would be incurred as part of ACRS reviews.

Cost estimates provided in Table 4 address activities from the beginning of test reactor tests all the way through to full region implementation. However, the costs associated with Rulemaking are not included since this could vary greatly and is difficult to predict. Additionally, the total presented in Table 4 does not account for initial research and development work completed to-date.
10 REFERENCES


APPENDIX A: LIST OF ACRONYMS

ACRS    Advisory Committee on Reactor Safeguards
AOO     Anticipated Operational Occurrence
AOR     Analysis of Record
ATF     Accident Tolerant Fuel
CFR     Code of Federal Regulations
CMC     Ceramic Matrix Composite
g     Draft Regulatory Guide
DNB     Departure from Nucleate Boiling
ECCS    Emergency Core Cooling System
FCEP    Fuel Checklist Evaluation Process
FSAR    Final Safety Analysis Report
GDC     General Design Criteria
LOCA    Loss of Coolant Accident
LTA     Lead Test Assembly
LTR     Lead Test Rod
LUA     Lead Use Assembly
LWR     Light Water Reactor
MAX     Max Phase Material
mREM    Mille Roentgen Equivalent Man
MWD/MTU Megawatt days/Metric Ton Uranium
NRC     Nuclear Regulatory Commission
NUREG   Nuclear Regulation
PIE     Post Irradiation Exams
PQD     Postquench Ductility
RG      Regulatory Guide
RIA     Reactivity Initiated Accident
SAFDLs  Specified Acceptable Fuel Design Limits
SiC     Silicon Carbide
SRP     Standard Review Plan
SSE     Safe Shutdown Earthquake
T&H     Thermal and Hydraulic
TS      Technical Specifications
US      United States