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Independent Review of AFC 2A, 2B, and 2E ATR Irradiation Tests

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Independent Review of AFC 2A, 2B, and 2E ATR Irradiation Tests

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SUMMARY

As part of the Department of Energy Advanced Fuel Cycle program, a series of fuels development irradiation tests have been performed in the Advanced Test Reactor (ATR) at the Idaho National Laboratory. These tests are providing excellent data for advanced fuels development. The program is focused on the transmutation of higher actinides which best can be accomplished in a sodium-cooled fast reactor. Because a fast test reactor is no longer available in the US, a special test vehicle is used to achieve near-prototypic fast reactor conditions (neutron spectra and temperature) for use in ATR (a water-cooled thermal reactor).

As part of the testing program, there were many successful tests of advanced fuels including metals and ceramics. Recently however, there have been three experimental campaigns using metal fuels that experienced failure during irradiation. At the request of the program, an independent review committee was convened to review the post-test analyses performed by the fuels development team, to assess the conclusions of the team for the cause of the failures, to assess the adequacy and completeness of the analyses, to identify issues that were missed, and to make recommendations for improvements in the design and operation of future tests. Although there is some difference of opinion, the review committee largely agreed with the conclusions of the fuel development team regarding the cause of the failures. For the most part, the analyses that support the conclusions are sufficient.

We believe that the most likely cause of failure in all three tests is a higher than anticipated heat generation rate in the fuel coupled with inadequate heat transfer thru the gas gap that exists between a test rod and the safety capsule. It was demonstrated by the detailed post irradiation thermal/mechanical analyses that when actual power levels were used in the analysis and a more detailed account of the gap conductance was included, the cladding temperatures that were achieved were sufficient to lead to cladding breach through fuel-to-cladding chemical and mechanical interactions. Although there were higher than nominal smear densities in some of the rodlets, the committee felt that this was a contributing factor rather than the primary cause.

Several recommendations were made for improvements to the design and operation of future tests (many have already been adopted by the fuels development team). A high priority should be given to reducing the sensitivity of the gap thickness to the cladding temperature. This is a critical dimension that controls the temperature of operation and therefore achieve near prototypic fast reactor conditions. We believe that the current design of the gap led to extensive fuel melting and data loss that would not have happened if the test were performed in a sodium-cooled fast reactor. Some ideas for design changes were presented for the fuels development team to consider that will reduce this risk, and obtain additional data that would be useful in post irradiation examination. Other recommendations were made for out of pile testing, fabrication, sensitivity studies, and design analysis strategy.

The AFC-3A test is currently at the ATR and has undergone several cycles of irradiation. This test includes a new design that separates the rodlets into individual capsules and therefore eliminates the possibility of rodlet failure propagation. The test has been removed from the reactor and will not be re-inserted until further analyses are complete. We believe that this is a prudent course of action and endorse the decision to do so. It may also be prudent to perform some kind of non-destructive

examination prior to further irradiation to ensure that fuel relocation or failure has not occurred. If a failure were to be identified then that defective rodlet could be sent to destructive examination rather than continued irradiation.

We recognize the very high difficulty in the design and operation of a fast reactor fuels test in the Advanced Test Reactor. This reactor was designed to test water-cooled thermal reactor fuels and materials rather than sodium-cooled fast reactor fuels. Although three metal fuel tests exhibited failure, we strongly recommend that metal fuel tests continue in the future. With improvements in the design and conduct of the tests, these experiments can be done more robustly and with reduced risk of data loss.

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AN INDEPENDENT REVIEW OF AFC-2A, 2B AND 2E IRRADIATION TESTS

1. INTRODUCTION

As part of the DOE funded Advanced Fuel Cycle Initiative, a series of advanced fuels irradiation tests are being performed in the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL). Both ceramic and metal fuels are being tested. Because the program is focused on the transmutation of higher actinides it was determined early in the program that this can be best accomplished in a sodium cooled fast reactor. Unfortunately the fast test reactors in the US, namely EBR-II and FFTF, were shut down in the 1990s and are no longer available to experimenters. Although some testing has been performed in a fast reactor in France (PHENIX), this reactor has also been shut down. The ATR is a water-cooled thermal test reactor built and operated to test naval reactor fuels. It is available to the AFCI program as well as other DOE programs for testing at a reasonable cost and therefore the optimum choice for fuels and materials testing.

To test the advanced fast reactor fuels in ATR, a special test vehicle was designed to achieve near-prototypic fast reactor conditions. This design is shown in Figures 1 and 2, below. The test assembly is made up of six individual rodlets, stacked inside a 52 inch long, thick walled stainless steel tube. This “safety capsule” is cooled by the reactor coolant flow, and prevents contamination of the coolant in the event of the rodlet failure. It is designed as an ASME qualified pressure boundary. The capsule sits inside another aluminum tube called the “basket”, which is placed into a test position in the reactor.

In the active core region (4 feet high), the basket is lined with a thin layer of cadmium that filters out the thermal neutrons. It is shown by analysis that this layer does an effective job in making the neutron spectra in the rodlet more prototypic of what is experienced in a fast reactor. Because of the cadmium, the test assembly is neutronically black with respect to the operation of the reactor, meaning that there is no neutronic feedback between the experiment and the reactor core. There is no active or passive instrumentation in the test. Therefore there is no direct knowledge of temperatures during irradiation. Because of the robust safety capsule, if a failure occurs it will not be discovered until the rodlets are removed for examination after irradiation.

The metal fuels are composed of uranium, plutonium, and zirconium in varying amounts. As part of the tests, other components are added to the matrix, including higher actinides for transmutation and lanthanides to simulate fission product carryover during recycle. By adjusting 235U enrichment, a desired linear heat generation rate (LHGR) can be achieved that is prototypic of a fast reactor. This is done by analysis using the expected nominal power level for the experiment.

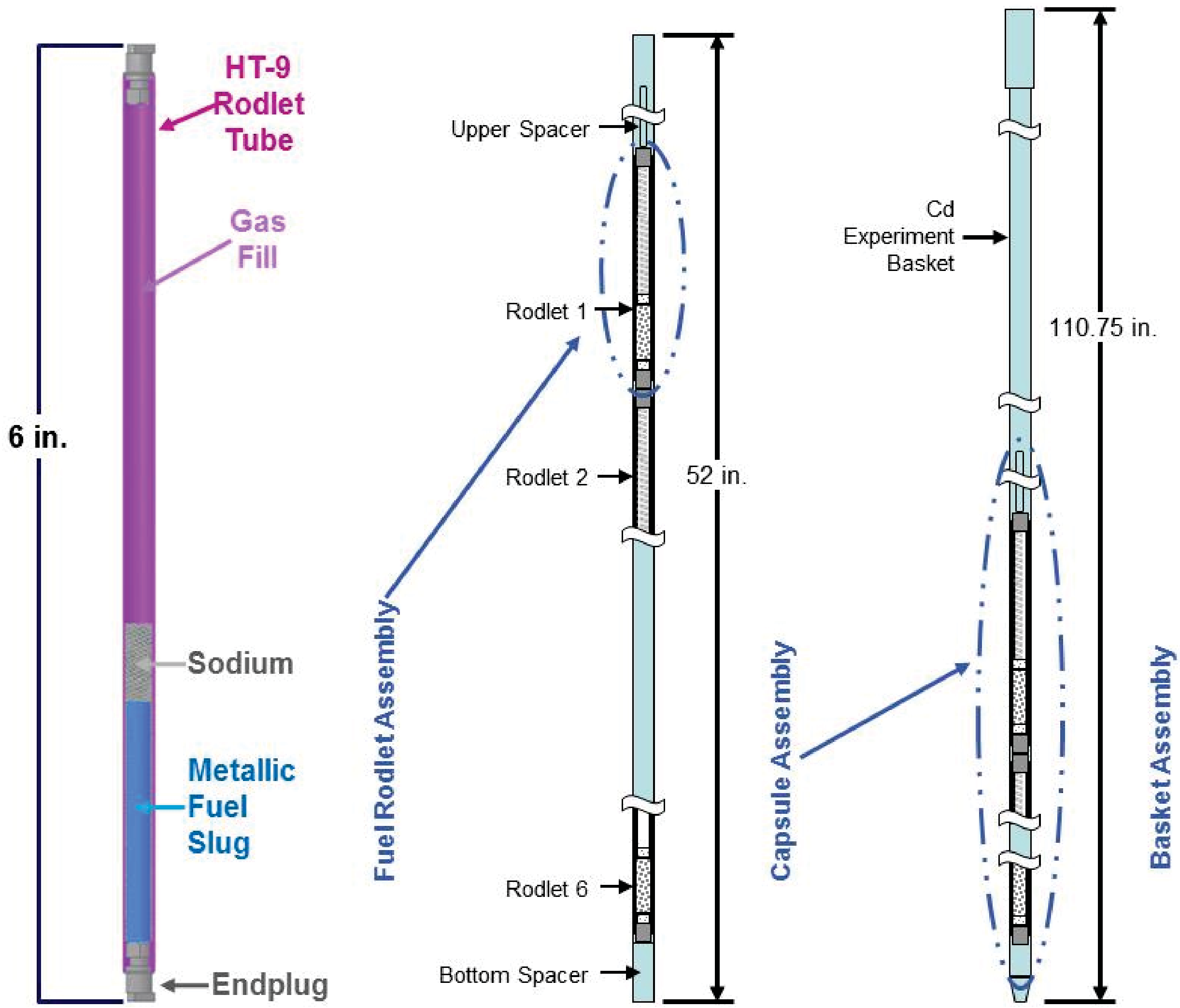

Figure 1. AFC-2 Experiment Design

To adjust the temperature of irradiation of the rodlet, the conductance in the gap between the rodlet and the capsule (which is cooled by the reactor coolant) is used. The gap thickness is a critical dimension that controls the temperature of operation and therefore achieves near prototypic fast reactor conditions. Filling this very small gap with helium at ambient pressure provides just the right amount of conductance to achieve the desired irradiation temperature.

As part of the testing program, there were many successful tests of advanced fuels. In this review we are focusing on the AFC-2 series, and in particular AFC-2A, AFC-2B and AFC-2E which experienced substantial failure of the rodlets. In all of the tests, the safety capsule remained intact and prevented the release of fission products to the reactor coolant thus demonstrating the robustness of this part of the design.

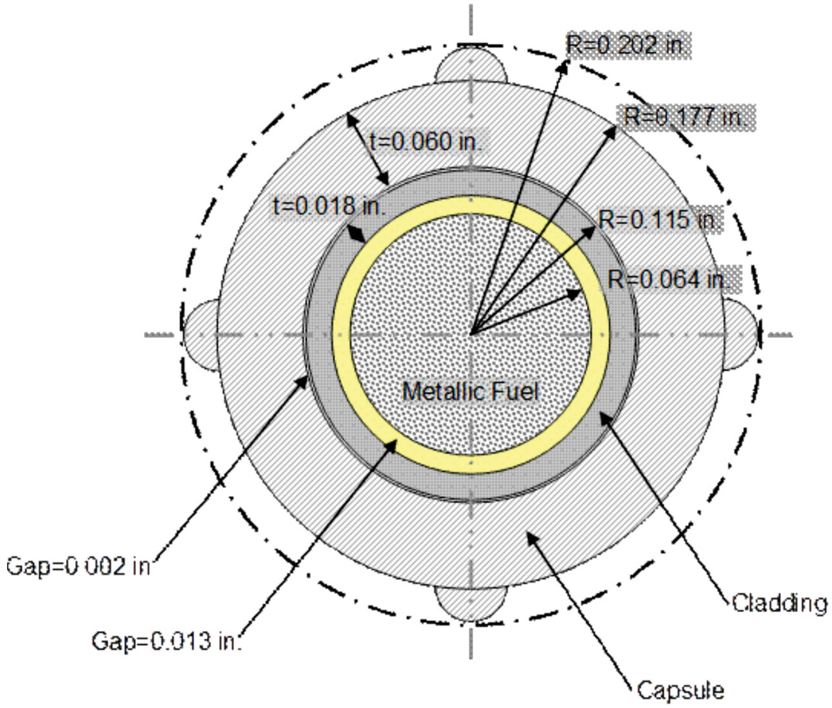

Figure 2. Metallic Fuel Cross-Section

The AFC-2 test series began with the start of AFC-2A irradiation in ATR in October 2007. The series was completed with AFC-2E discharge from the reactor in December 2011. Tests were performed with metallic and ceramic fuels, some with additions of minor actinides and some with additions of lanthanides. The nominal operating conditions were 350 W/cm linear power, and 550°C peak cladding temperature. The tests were irradiated in the ATR East Flux Trap inside cadmium-shrouded positions. As mentioned above, each experiment consisted of 6 rodlets contained inside a single secondary capsule and therefore shared a common He-filled gas gap.

Irradiation occurs over multiple reactor power cycles. A typical cycle is on the order of 40 days, so to achieve high burnup a test may operate for 10 or more cycles. To maintain the neutron spectra requires an adequate cadmium liner. This will burn out (neutronically) in one or two cycles, making it necessary to change out the basket on a regular basis. Therefore the typical irradiation would require several test removals from the reactor into the adjacent canal, removal of the capsule(s) and re-insertion into a new basket.

The AFC-2A and 2B tests were metallic fuels with the addition of lanthanides to simulate carryover of rare earth fission products from electro-metallurgical recycle. The test matrix for AFC-2A and AFC-2B were identical. The AFC-2A was irradiated for 214 Effective Full Power Days (EFPDs), and discharged at peak burnup of 7% Heavy Metal (HM). The AFC-2B was irradiated for 364 EFPDs, and discharged at a peak burnup of 11% (HM). It had been intended to go to higher burnup, but failures observed in AFC-2A during Post Irradiation Examination (PIE) led to the decision to discharge AFC-2B early. The PIE revealed that 5 of 6 rodlets in AFC-2A failed during irradiation, and all fuels experienced some melting. All 6 rodlets in AFC-2B failed and experienced fuel melting. The post-test analyses suggested that the pollution of the common He-filled gas gap between rodlets and secondary capsule by argon and fission gas from a single rodlet would likely raise temperatures of all rodlets to levels where fuel melting/cladding breach could be expected.

The AFC-2C and 2D tests were made of mixed uranium and plutonium oxide ceramic fuel. Additions of Am, Np and two different oxide to metal ratios were investigated. The test matrix for AFC-2C and AFC-2D were identical. The AFC-2C was irradiated for 262 EFPDs, and discharged at a peak burnup of 8% (HM). The AFC-2D was irradiated for 685 EFPDs, and discharged at peak burnup of 19% (HM). These tests were completed without incident. The

PIE has shown the rodlets performed as expected, with no fuel failures. The location of the fuel zone undergoing restructuring (resulting in central hole formation) gave confidence that fuel power and thermal analyses were reasonably accurate. Although the review team pointed out that the oxide fuel restructuring appearance is not particularly sensitive to irradiation temperature.

The AFC-2E was a metallic fuel test to investigate effects of fuel fabrication methods. Arc-cast slugs and archived EBR-II slugs fabricated by injection casting were tested. The AFC-2E was irradiated for 483 EFPDs and discharged at peak burnup of 12% (HM). The PIE thus far only includes visual, neutron radiography, and gamma-scanning; indications are that 3 of 6 rodlets in AFC-2E failed during irradiation.

Because of the failure propagation issue identified during AFC-2A and 2B irradiations, the AFC-3 series of tests was built with the individual rodlets inside separate capsules. These are stacked inside the basket and therefore no longer share a common gas gap. The first AFC-3 tests have begun irradiation, but are now on hold until more detailed analyses are performed.

At the request of the technical program leader for fuels and materials, an independent review committee was convened to review the post-mortem analyses performed by the fuels development team of these experiments, to assess the conclusions of the team for the cause of the failures, to assess the adequacy and completeness of the analyses, to identify issues that were missed, and to make recommendations for improvements in the design and operation of future tests. This review was conducted at the end of January, 2014 at the INL. The review committee is listed in Appendix A, the documentation provided to the committee is listed in Appendix B, and the agenda for the review which includes the list of presentations made to the committee is given in Appendix C. The questions charged to the committee are as follows:

- Assess the analyses and conclusions of the INL fuels development team. Are the analyses and conclusions sufficient? Are additional measures recommended?
- Identify any technical issues that were missed.
- Recommend opportunities for improvement in design, analyses, fabrication, and conduct of the experiment.

This report documents the result of our review and is of unanimous concurrence among the committee members. Each of the questions outlined above is discussed separately below.

2. ASSESSMENT

The Independent Review Team was tasked to assess the analyses and conclusions of the INL fuels development team. Are the analyses and conclusions sufficient? Are additional measures recommended? The major findings and conclusions from the INL fuels team based on their post irradiation examinations and analyses are summarized below. Following each conclusion is the review team assessment.

Regarding the Cause of Failure in AFC-2A and AFC-2B

INL Fuels Team:

The INL fuels team believes that AFC-2A and AFC-2B most likely failed because of high smear densities in some rodlets in both test series. As built data show that smear densities up to 82% were realized in the fuel, although the fabrication specification was for 75%. Despite the non-conformance, it was decided to continue with the irradiation as planned. Although the data are sparse, there are irradiation data from EBR-II indicating that smear densities above 75% would cause excessive cladding deformation. These tests also included lanthanides to simulate recycle conditions. Although it was thought initially to be the major cause of failure, the fuels team concluded after more analysis that the lanthanide affect was not significant. Indeed, data from a French experiment showed that metal fuel with even higher lanthanide content did not cause failure at approximately 10% burnup.

From detailed analyses the team also concluded that a failure in one rodlet propagates to the other five rodlets because all rodlets sit in a common gas annulus. The argon and fission gas leakage from a failed rodlet into the annulus reduces the conductivity and therefore leads to failures in the other rodlets.

Review Committee Assessment:

We agree that the lanthanides were not a significant factor contributing to the failures. However, the smear density may not have been the major reason for the failures either. In our view the smear densities were most likely a contributing factor. Based on the BISON analysis that was presented to the committee, cladding temperatures over 640C were predicted. This more recent detailed analysis included the actual power levels realized in the irradiation cycles rather than the nominal target power level used for design. Also included in the analysis was a more realistic model of the gap conductance. This effect alone was shown to raise the clad temperature 50 -70C above the value achieved using the original model. At temperatures of 640C the strength of HT9 cladding is reduced about 50% from the nominal. This can lead to increased strain from mechanical interactions with the fuel. In addition to FCMI the diffusion couple experiment results presented to the committee show significant FCCI behavior at 650C. Applying the observed rate of cladding degradation to the irradiation test, it was estimated that a breach in the cladding would occur within a couple weeks at this temperature.

With respect to failure propagation to the rodlets sharing the common gas annulus, we are in agreement with the INL team's conclusion and believe the analyses were sufficient to prove it.

This is a very complex system that requires coupled thermal, mechanical, and hydraulic analysis. These analyses should be performed during the design of the experiment and again with the as-built dimensions. The design analyses need to include more realistic reactor power levels that properly account for the expected power excursions on return to power.

The analysis needs to capture the irradiation-induced deformation in the cladding. If a specific model is not available, e.g., for HT9 creep strain, then sensitivity analyses should be performed to determine the importance.

Overheating during transport or storage was dismissed as an improbable cause for failure. Worse case analysis of the heat up during vacuum drying prior to transport, shows that the samples stay below 400ºC, which is insufficient to cause failure. This analysis needs to be repeated with the more refined gap conductance model. Also, one should look for the potential loss of data if high temperatures occur when samples are not oriented in their upright vertical position during this temperature excursion.

Although excessive smear density may not have been the major cause of the failures, all tests in the future should confirm that the as-built smear density over the length of the slug is less than or equal to 75%.

Regarding the Cause of Failure in AFC-2E

INL Fuels Team:

INL concluded that AFC-2E failed because of the temperature increase due to the approximately 10% higher power. In addition, an important term was not considered in the helium gap conductance model that resulted in an additional temperature increase above what was predicted.

Detailed analysis, which included the over power condition and the more detailed gap conductance model clearly shows cladding temperatures of 650C or higher were experienced which would lead to failure. Smear densities for this experiment were 75% or less; therefore, excessively high smear density was not considered a failure mode. The irradiation of fuel pins in EBR-II and FFTF of identical composition to that in AFC-2E at higher power, cladding temperatures, and burn up resulted in no failures. These observations gave additional support that AFC-2E capsules experienced higher temperatures than expected.

Rodlet failure propagation occurred in this test because the rodlets all shared the common gas gap.

Reactor flow was shown to be adequate during irradiation. This was based on a pressure difference measurement from the inlet to outlet plenum in the reactor quadrant where the test was placed.

Review Committee Assessment:

We are in agreement with the INL team's conclusion on the reason for initial failure and failure propagation. We believe that the analyses to support the conclusion are sufficient.

We note that the smear densities were stated to be less than 75% for all the rodlets. These were measured in three elevations and two azimuthal positions with a micrometer. Although the average smear density is less than 75%, there may be a higher smear density locally. For EBR-II, fabricated slugs exhibiting high local smear density were discarded. We recommend that future experiments ensure that the local smear densities are less than or equal to 75%.

With respect to experiment coolant flow there are data showing that the total reactor flow and the flow to the quadrant where the experiment was placed were adequate during irradiation. Local flow blockage in the east flux trap was considered to be improbable, as this would have been discovered during basket change-out. We encourage the team to investigate other data from the reactor operation to verify that claim. For example, were there any other failures in the reactor during irradiation that could have introduced loose parts? It is recommended to review the loose parts monitor log for the irradiation cycles of interest.

Identify Technical Issues that were Missed

Power peaking during ascent to power sometimes occurs during normal operation. From the reactor power traces that were provided to the team, it was observed that in many occasions during the cycle irradiation, an ascent to power included an overshoot of one or two MW for some hours. These power excursions are sometimes necessary to overdrive the buildup of Xenon in the reactor after shutdown. Because they occur on a regular basis as part of normal reactor operations, the design team should include these overshoots in the design analyses.

During the course of an irradiation, the testing continues through many reactor power cycles. There may be 10 or more irradiation cycles where the test is cooled down completely to approximately 50ºC, and there may be other interruptions during the cycle where a complete cool-down occurs (this is demonstrated in the power traces provided to the committee). Because of this, there may be low cycle fatigue and transient thermal stresses that have not been taken into account. It is recommended that analyses be performed to ensure that this issue is not impacting the test rodlets.

For completeness, we encourage the team to further analyze other common mode failure mechanisms such as weld failure at the top or bottom of the rodlets and capsule. It may be prudent to perform some thermal cycling, and burst tests to validate the analyses.

Investigate the effect of local He gap closure on one side of the rodlet as a potential failure mechanism. Closure on one side means an opening on the opposite side therefore causing a hot spot.

3. RECOMMEND OPPORTUNITIES

The review team identified opportunities for improvement in design, analyses, fabrication, and conduct of the experiment,

Design

We recognize that it is very difficult to design a fast reactor experiment that will operate at prototypic conditions in a water-cooled thermal test reactor. It is also recognized that the designer/experimenter must balance the desire to provide adequate margin to avoid failure and at the same time design a test that will push the limits so that failure points can be identified.

The experimenters understand these issues and have created a design that tries to achieve the right balance. Nevertheless we believe that improvements can be made. Some of the major issues and ideas for improvements are discussed below:

Mode of failure: At the initiation of cladding breach of one rodlet the capsule gap will fill with argon and fission gas causing over heating over the entire fuel slug length. This quickly destroys the characteristics of the initial failure, and in the case of the common plenum in AFC-2 will propagate the failure to the other rodlets. If the test were done in a sodium cooled fast reactor, the cladding breach would have been fairly benign because the sodium coolant would keep the rest of the rod well below the failure point. Separation of rodlets into individual safety capsules is being done in AFC-3. This solves the problem of failure propagation and we encourage continuing this design strategy. But, as will be discussed below, using the helium gap in the current design still leads to non-prototypic destruction of the rodlet for even a minor leak from the cladding because of the reduction of conductivity when argon and fission products enter this gap. Thus even in the AFC-3 design if a breach occurs at a point in the cladding, total loss of information on the characteristics of the failure occurs.

Knowledge of the time of failure or the burnup level: In the current design, without active sensors, it is very difficult to determine at what point in the irradiation that a failure occurred. With the separated rodlet design, the rodlets will need to be removed from the basket after 1-2 cycles to perform the basket replacement. We recommend that the team explore possible NDE tests that could be performed at that time in the ATR canal to identify rodlet failure. Because each cycle provides about 1-2% burnup, one could at least identify the timing of failure to that accuracy. Rodlets identified to be defective could then undergo PIE rather than be re-inserted into the reactor.

Knowledge of temperature of cladding and fuel during irradiation: Currently there are no active or passive temperature measurements of the experiment. These values are calculated using neutronic and thermal analyses. To rectify this we recommend the following:

- Explore passive measurement techniques that will supply peak cladding/fuel temperatures during irradiation. These measurements could be used to calibrate the thermal analysis model.
- Compare zone formation from EBR-II experiments to metallographic observations to gain a qualitative understanding of the temperature during irradiation. By using some U-Zr rodlets in an irradiation, the zones are more easily related to the phase diagram, enabling estimates of temperature.

Knowledge of neutron flux, neutron spectrum, and fluence during irradiation: Currently these values are calculated using the actual power levels in the surrounding quadrants as a scaling factor. We recommend exploring the use of passive measurement techniques, such as flux wires/foils to provide data on neutron fluence and spectrum. This will help understand the average power level of the rodlet during irradiation and provide additional data for validation of the neutronics calculations.

Cladding and fuel temperature azimuthal variation: Currently the design of the test vehicle employs a very small gap between the rodlet cladding and the inside surface of the safety capsule. The purpose of the gap is to thermally insulate the cladding from the coolant and control the temperature of the irradiation. Without the gap, the test rodlet would be cooled directly by the water (which operates at about 50C and flows at about 40 ft/s). This would create a non-prototypic irradiation temperature because typical fast reactors operate with a sodium coolant temperature of approximately 450C. The irradiation temperature is a very important variable that affects many if not all of the thermal, chemical and mechanical processes that occur in the fuel and cladding during operation. Thus making the irradiation temperature as prototypical as possible is of high priority to the experimenters.

The nominal design gap width is only 0.002 inch (50.8 microns). It is filled with 99.8% pure helium gas at a pressure slightly less than one atmosphere (the pressure at which the glove box operates). To keep the rodlet centered in the capsule, small buttons (or foils) are placed on the top and bottom end caps in a triangular pattern (i.e. at 120 degree intervals, azimuthally). If the capsule inside surface and the rodlet cladding tube are perfectly straight and are of the correct diameter, then at the beginning of irradiation the gap will be 0.002 inch over the entire 6-inch length of the rodlet and through the entire 360 degrees azimuthally.

Performing a detailed thermal analysis, it was found by the design team that the temperature of the cladding changes by 10C for every 1 micron change in the gap thickness. Sensitivity this large makes it extremely difficult to ensure the desired cladding temperature. The review committee believes that it would be nearly impossible to ensure a perfectly straight rodlet, in a perfectly straight capsule with perfect centering so that there is no more than a one micron variation in the gap thickness during the test. There will certainly be some bowing of the rodlet and the capsule will not be absolutely straight as there is always some fabrication tolerance on both of these. We therefore concluded that there will most likely be temperature variations in the cladding azimuthally during irradiation. For instance, a mere 10-micron increase in the gap on one side of the rodlet (0.0004 inch) would bring about a 100C increase in cladding temperature above the nominal. A worst case situation where the rodlet is touching the capsule on one side and has a 100 micron gap on the other would lead to a cladding temperature approaching 500 C above the nominal. Although this thought experiment neglects the conduction of heat in the fuel and cladding that would mitigate the temperature increase, it underscores the problem in the current design.

The committee recommends that the design team explore design improvements to the test vehicle for future irradiations to provide more prototypic test conditions and more robust temperature control. One idea that came up during discussion surrounds the rodlet cladding with a layer of sodium and an additional tube. This will necessitate reducing the capsule thickness, the basket thickness or the water annulus to provide the additional space for the extra sodium layer and containment tube. A design change such as this will provide three significant improvements:

- First, it will significantly reduce azimuthal temperature variations in the cladding during irradiation because the sodium has such a high conductivity and will shunt the heat away from hot spots;
- Second, it will increase the heat transfer area into the gap and allow for an increase in gap thickness thereby reducing the sensitivity of this variable on heat transfer;
- Third, it will reduce the risk of rodlet destruction (and attendant data loss) in the event of a cladding breach because the argon and fission products would be released into the sodium layer rather than the helium gap. These gases should percolate up through the molten sodium into the plenum.

Another possible change is to increase the pressure of the gas gap. This is particularly important if it is not possible to add the sodium layer in the design. If there is a leak or failure, then the change in conductivity would be smaller, and the risk of complete rodlet destruction and data loss would be reduced.

Heat Transfer Testing: The gap dimension has been shown to be uniquely important in achieving prototypic cladding temperature. The current analyses show a major difference depending on the gap conductance model. We recommend performing out-of-pile heat transfer measurement to determine the appropriate conductance model.

Design Analyses

Currently the team uses a Sequential Design Analysis Process. We recommend an analysis using as-fabricated test hardware be performed as part of the process as illustrated by the red arrow in Figure 3 below. This final analysis would have likely identified problems with the high smear density in AFC-2. Current techniques need to use the more detailed coupled analyses as e.g., BISON (in addition to the safety related analyses). As part of the normal design process, worse case analysis using as-built dimensions and any fabrication uncertainties (enrichment, Pu content, gas composition and pressure) should be performed. Peer checks should be performed on all analyses.

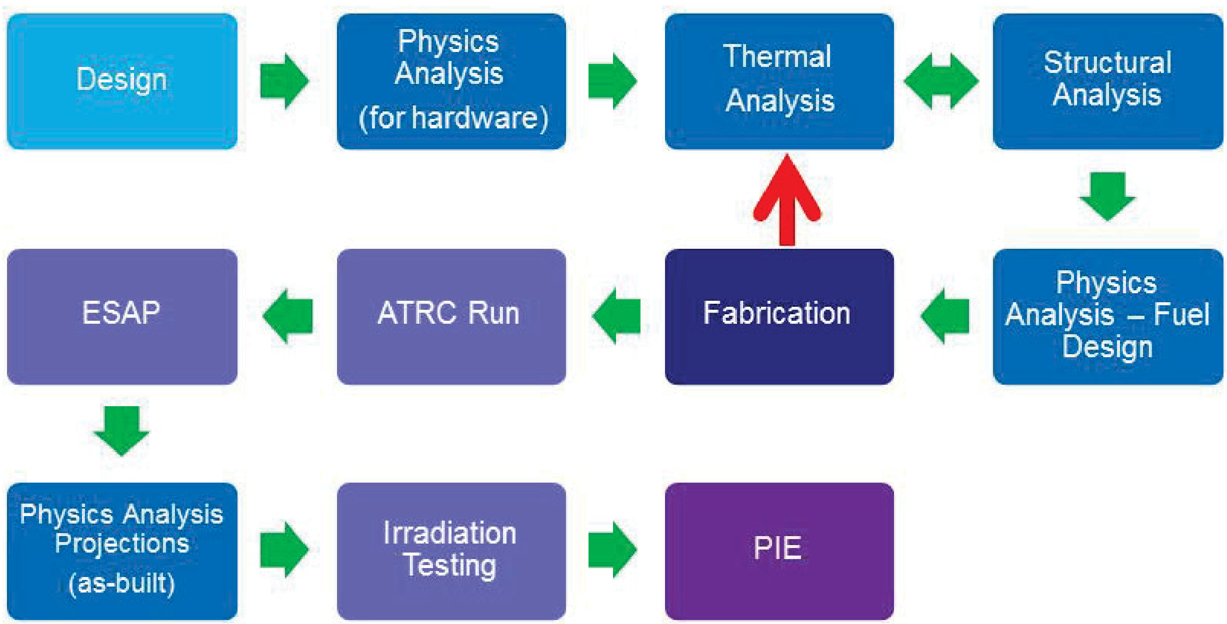

Figure 3. Sequential Analysis Process

The BISON code suite is a wonderful tool now available for performing very detailed steady state and transient analysis. We recommend that sensitivity analyses be performed wherever there is a question regarding a particular fabrication tolerance, material property or constitutive model. These analyses will quickly identify the importance of that variable and help decide if more effort is needed in that area.

Fabrication

We recommend that the fuels development team consider a scheme by which an adequate gap can be guaranteed, e.g., a mix-and-match scheme with cladding and capsules. It is recommended that the team explore improved fuel slug casting techniques to ensure the correct shape that meets the specification and ensures 75% smear density. One possibility is grinding after casting. Also the team should consider a testing program on the rodlet to end-cap weld to further qualify the weld procedure. This program may include burst and thermal cycling tests.

Operation

Peaking of the reactor power during cycle start up or recovery from transients should be included in the design analysis. To account for the reactor power over-shoot on startup the design LHGR may need to be reduced accordingly to avoid over heating the experiment.

The team should provide an observer at basket change out to ensure proper re-insertion of rodlets. Also the team should observe to the extent possible handling of the experimental rodlets during vacuum drying, and transfer to the hot cell.

4. SUMMARY AND CONCLUSIONS

Several recommendations were made for improvements to the design and operation of future tests (many have already been adopted by the fuels development team). A high priority should be given to reducing the sensitivity of the gap thickness to the cladding temperature. This is a critical dimension that controls the temperature of operation and therefore achieve near prototypic fast reactor conditions. We believe that the current design of the gap led to extensive fuel melting and data loss that would not have happened if the test were performed in a sodium-cooled fast reactor. Some ideas for design changes were presented for the fuels development team to consider that will reduce this risk, and obtain additional data that would be useful in post irradiation examination. Other recommendations were made for out of pile testing, fabrication, sensitivity studies, and design analysis strategy.

The AFC-3A test is currently at the ATR and has undergone several cycles of irradiation. This test includes a new design that separates the rodlets into individual capsules and therefore eliminates the possibility of rodlet failure propagation. The test has been removed from the reactor and will not be re-inserted until further analyses are complete. We believe that this is a prudent course of action and endorse the decision to do so. It may also be prudent to perform some kind of non-destructive examination prior to further irradiation to ensure that fuel relocation or failure has not occurred. If a failure were to be identified then that defective rodlet could be sent to destructive examination rather than continued irradiation.

We recognize the very high difficulty in the design and operation of a fast reactor fuels test in the Advanced Test Reactor. This reactor was designed to test water-cooled thermal reactor fuels and materials rather than sodium-cooled fast reactor fuels. Although three metal fuel tests exhibited failure, we strongly recommend that metal fuel tests continue in the future. With improvements in the design and conduct of the tests, these experiments can be done more robustly and with reduced risk of data loss.

APPENDIX A – INDEPENDENT REVIEW COMMITTEE

Review Committee Members and Their Roles

Name		Phone	E-Mail	Role
Mike	Cappiello	505-412-5115	mwcappiello@gmail.com	Chair- Independent Reviewer
Richard	Hobbins	307-739-0604	rhobbins@wyoming.com	Independent Reviewer
Keith	Penny	208-533-7001	s.penny@inl.gov	Independent Reviewer
Leon	Walters	208-524-1386	leonw@cableone.net	Independent Reviewer

APPENDIX B – DOCUMENTATION

Documentation Provided to the Committee

Date Sent	Document #	Title
Jan 9, 2014	N/A	AFC-2 Quick Fact Sheet
Jan 9, 2014	ECAR-46	AFC-2A And AFC-2B As-Built Constituent Data
Jan 9, 2014	ECAR-299	Cycle 142B Physics Evaluations Of AFC-1H, -2A, And -2B Tests In The East Flux Trap
Jan 9, 2014	ECAR-545	Cycle 144A Physics Evaluations Of AFC-2B, -2C and -2D Tests In The East Flux Trap
Jan 9, 2014	ECAR-597	AFC-2E Pressure Estimates And Accident Analyses
Jan 9, 2014	ECAR-1762	Cycle 150B As-Run Physics Evaluation Of The AFC-2 Experiment In The East Flux Trap
Jan 9, 2014	EDF-7714	Pressure Estimates For AFC-2A And AFC-2B Metallic Fuel Experiments
Jan 9, 2014	EDF-7808	Thermal Analysis For AFC-2A And AFC-2B Metallic Fuel Experiments
Jan 9, 2014	EDF-7813	Structural Integrity Evaluation Of The AFC-2 Experiment Components
Jan 9, 2014	EDF-8004	Irradiation of Metallic Fuels with Rare Earth Additions for Actinide Transmutation in the ATR: Final Experiment Description and Design & Data Package for AFC-2A and AFC-2B
Jan 9, 2014	EDF-8175	Analysis of DNBR And FIR For The AFC Capsules At A LHGR 500 W/cm (Safety Limit)
Jan 9, 2014	PLN-2992	Irradiation of AFC-2E Metallic Fuels for Actinide Transmutation in ATR
Jan 13, 2014	INL-EXT-07-13027	The Phase and Microstructure Characterization of AFC-2A Metallic Transmutation Fuels: FY 2007 Report.
Jan 13, 2014	INL-EXT-07-13128	Thermal Analysis of AFC-2A Metallic Transmutation Fuels FY 2007 Report

Date Sent	Document #	Title
Jan 13, 2014	INL-EXT-08-14499	AFC2-A,B Metal Fuel Characterization FY-08 Supplemental Rpt
Jan 13, 2014	INL-EXT-09-16296	AFC-2E General Fuel Characterization Report
Jan 13, 2014	INL-EXT-09-16759	Out-of-pile Effects of Lanthanides on Fuel-Cladding Compatibility
Jan 13, 2014	INL-EXT-09-16781	Phase Studies and Property Measurements of Some Ternary Fuel Alloys - AFC-2 B General Fuel Characterization Report
Jan 14, 2014	INL-EXT-07-13279	Fuel-Cladding Compatibility of AFC-2A Transmutation Alloys: FY07
Jan 14, 2014	INL-EXT-08-14833	FY-08 Fuel Cladding Chemical Interaction Studies
Jan 14, 2014	INL-LTD-10-20611	FY 2010 FCCI Studies – Draft Report
Jan 14, 2014	INL-LTD-12-24830	FY 2011 FCCI Studies Update
Jan 14, 2014	INL-EXT-06-11707	Irrad of Metallic Fuels with Rare Earth Additions for Actinide Transmutation in the ATR
Jan 14, 2014	PLN-2443	AFC-2 Fuel Rodlet & Capsule Final Inspection Plan
Jan 14, 2014	TFR-452	Specification for the AFC-2A and AFC-2B Fuel Specimen and Fuel Capsule Irradiation Experiment in the ATR.
Jan 14, 2014	TFR-585	Specification for the AFC-2E Fuel Capsule Experiment in the ATR
Jan 14, 2014	PLN-3078	AFC-2E Rodlet and Capsule Inspection Plan

APPENDIX C – AGENDA

Agenda: January 28, 2014

7:30	Pick up visitor badges at Willow Creek Building	
8:00	Welcome/Introductions/Purpose/Charter	Jon Carmack
8:30	AFC Drop-In Capsule Test Program – Overview/Objectives	Steve Hayes
9:00	ATR Operations – Overview	Dave Schoonen
9:30	ATR Experiment Process	Kristine Barrett
10:00	***Break***	
10:15	AFC-2 A, B, E Test objectives/Target Irradiation Conditions	Steve Hayes
10:45	Fabrication	Tim Hyde
11:30	Characterization	Dawn Janney
Noon	***Working lunch: FCCI***	***Jim Cole***
1:00	AFC-2 A&B PIE Results	Heather Chichester
1:30	AFC-2 E PIE Results	Jason Harp
2:00	As-Run Power History and Thermal Analysis (BISON)	Pavel Medvedev
3:00	***Break***	
3:15	Lessons Learned / Corrective Actions	Steve Hayes
4:00	Open Discussion / Q&A	
5:00	***Adjourn***	

Agenda: January 29, 2014

8:00	Independent Review Team – Internal Discussions
Noon	***Working lunch -***
2:00	Independent Review Report out with Technical Leads

APPENDIX D – ATTENDEES

Technical Area Leads, Presenters, Attendees

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Kristine	Barrett	208-526-7007	kristine.barrett@inl.gov	ATR ATF PE	INL
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