UPDATE ON WESTINGHOUSE BENEFITS OF ENCORE® FUEL

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ABSTRACT

This paper provides an update of the safety and economic benefits of Westinghouse EnCore® fuel. EnCore, Accident Tolerant Fuel (ATF) fuel concepts include surface-modified claddings (Cr coated zirconium-based cladding), SiC claddings and uranium silicide (U_3Si_2) and ADOPT™ pellets. Initial evaluations were performed in a previous paper indicating that Westinghouse EnCore fuel can provide some safety and economic benefits based on severe accident analyses and available data on the ATF materials. Further evaluations have been performed here using latest available data and models especially for describing fuel mechanical behavior at higher temperatures. These evaluations were performed for Beyond Design Basis Accidents (BDBAs) in a Station Blackout and for Design Basis Accidents (DBAs) to determine the safety and economic benefits. In the BDBAs key criteria for core damage are evaluated by performing evaluations with the MAAP code. The results of these evaluations show the potential for increased coping time under BDBA scenarios using ATF. This coupled with the use of FLEX and FLEX-like portable equipment and strategies, have the potential to reduce plant core damage and large early release frequencies. MAAP analyses confirm that integrating ATF benefits with focused operational strategies will provide needed operational margin to help avert the onset of core damage and/or reduce the consequences of risk-significant core damage events. Thus, reducing the likelihood of an event such as that experienced at Three Mile Island or Fukushima. There are also benefits of ATF in the context of DBAs in terms of improved margins or even the redefinition of acceptance limits which can provide significant operational and economic benefit.

1. Introduction

The Westinghouse EnCore accident tolerant fuel (ATF) program utilizes chromium (Cr) coated zirconium alloy cladding with uranium silicide (U_3Si_2) high density/high thermal conductivity fuel and ADOPT UO_2 pellets doped with Cr and Al for its lead test rod (LTR) program with irradiation beginning in 2019 [1]. The lead test assembly (LTA) program will use both SiC/SiC composites and Cr coated zirconium alloy claddings with the high density/high thermal conductivity U_3Si_2 pellet which will begin in 2022. A description of these materials is given in Figure 1.

Photo courtesy of General Atomics

Photo courtesy of Idaho National Labs

Fig. 1 Westinghouse EnCore Fuel Materials

A summary of the physical benefits of the materials is discussed in Reference 2 and summarized here qualitatively:

U_3Si_2 Pellets
- Higher density improves fuel cycle economics for 18 and 24 month cycles
- Increased thermal conductivity improves fuel thermal performance during transients
- Good irradiation behavior (reduced swelling and fission gas release)

ADOPT Pellets
- Higher density and better thermal stability
- Lower transient fission gas release at high burnups
- Better oxidation resistance (in presence of air and water)
- Increased Pellet Cladding Interaction, PCI margins at high temperatures
- Ability of dopants to trap corrosive fission products
- Higher fuel creep rate to mitigate Pellet Cladding Mechanical Interaction, PCMI (softer pellet)

Coated Claddings
- Higher accident temperature capability for accident conditions (1300 to 1400ºC)
- Reduced corrosion and hydrogen pickup, and resistance to rod wear
- Reduced exothermic reaction energy during high temperature transients,
- Improved LOCA PCT and RIA depositions limits for DBAs

SiC Cladding

- No ballooning and bursting, and resistance to rod wear
- Eliminate oxidation driven temperature spikes
- Maintain integrity under most severe beyond design basis accident conditions, decomposition near ~2000ºC (pending further research)
- Fuel performance beyond DNB and during LOCA can increase design basis margins
- Cladding provides fission product barrier to high temperatures
- Minimizes potential hydrogen generation to non-threatening levels

As a result of the physical benefits of these ATF materials, initial evaluations were performed using the EPRI MAAP version 5.05 beta release code in a previous paper [3] indicating that Westinghouse EnCore fuel can provide some safety and economic benefits based on severe accident analyses. One of the key conclusions resulting from this work indicated that the use of ATF materials can increase coping time approximately 1 to 2 hours in a PWR station blackout event (SBO) however the decay heat in the core would still result in core damage and possibly a hot leg rupture. However, the added coping time from the ATF materials in combination with injecting flow into the core using a FLEX pump, could prevent core damage and hot leg rupture. Figure 2 demonstrates the benefit of ATF materials in extending the coping time based on MAAP code analyses. Figure 3 shows how use of a FLEX pump to inject water into the core can mitigate core damage and hot leg rupture in a SBO (provided that the injection is initiated early enough). This paper discusses the FLEX-like mitigation strategies and presents further evaluations using MAAP for Beyond Design Basis Accidents (BDBAs).

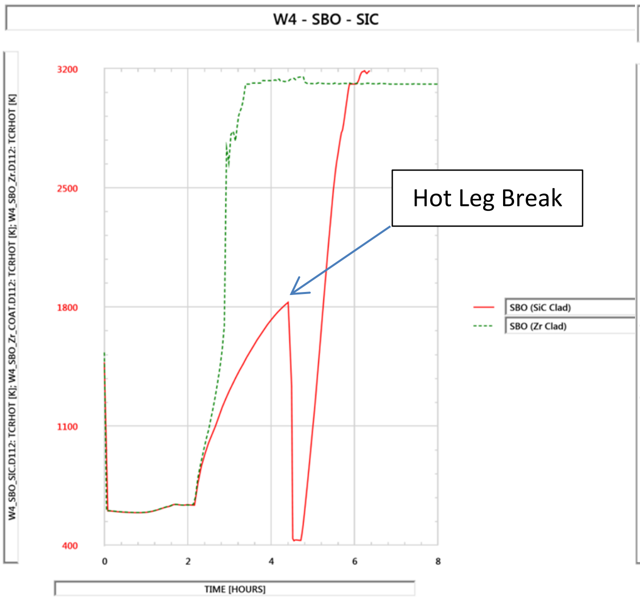

Fig. 2 SBO for 4 Loop PWR no FLEX Injection

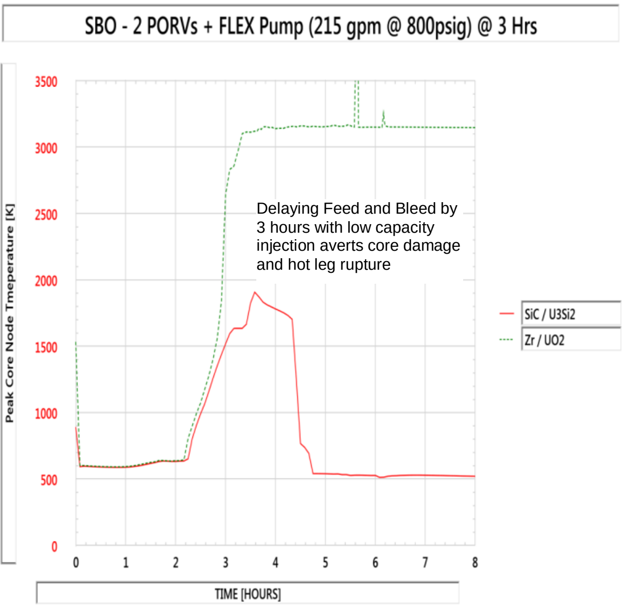

Fig. 3 SBO for 4 Loop PWR with FLEX pump

After performing analyses for BDBAs it became clear there are also potential significant plant benefits for using ATF materials for Design Basis Accidents and normal operation. This paper also summarizes the potential benefits for these conditions and defines the framework for performing further analyses to assess these benefits in the future.

2. FLEX-like Mitigation Strategies

Following the events at Fukushima, the industry implemented a program to all operating reactors to increase plant defense in depth strategies by adding diverse and flexible mitigation strategies (term FLEX) to address beyond design basis accidents resulting in an extended loss of AC Power (ELAP) and a loss of normal access to the ultimate heat sink (LUHS) occurring simultaneously at all units on site [4]. The overall strategy considers the ability of the plant to initially cope with a loss of off-site power (LOOP) using bunkered resources that are shown to survive severe challenges to plant equipment. For PWRs these resources typically include limited operation of turbine driven auxiliary feedwater (TDAFW) pumps. TDAFW is assumed available so long as the plant can provide battery power; providing the operator with the ability to maintain steam generator (SG) level and avoid SG overfill and moisture carryover/flooding of the TDAFW. This time interval is plant specific and optimally relies on operator actions to shed loads not directly needed for decay heat removal. In general load shedding can extend battery lifetimes to 6 to 8 hours. During this “coping period”, the plant staff is charged with implementing the FLEX mitigation strategy, positioning and implementing portable power supplies and pumps to continue the decay heat removal process for an indefinite time period.

FLEX adds a valuable layer of protection to the plant mitigation strategy. However, FLEX is a stylized response. Successful implementation of FLEX for the stylized ELAP scenario ensures the PWR core remains covered (or the BWR core to be adequately cooled) throughout the BDBA. While FLEX does focus on the more likely beyond design basis scenarios, failures of the TDAFW pumps or unforeseen complications of FLEX implementation can benefit from a more forgiving core response and/or alternative strategies. Such delays could result in extended periods of core uncovery lasting from tens of minutes to many hours. For example, early loss of TDAFW heat removal could require the need for early implementation of alternate strategies to avoid core damage, or alternative sequences with LOCAs and LOOPs (for instance, following a seismic hazard) may require different mitigation strategies. Under these circumstances, alternative FLEX-like strategies implemented with accident tolerant fuel could enable the plant to extend the scope of the plant’s ability, dependent on fuel design, to cope with beyond design basis events without significant fuel damage. The level of complexity of the plant enhancements to FLEX would depend on the ATF selected, with greatest benefits associated with SiC, and for PWRs could include accelerated implementation of low capacity diesel driven reactor coolant system (RCS) and SG injection equipment.

3. BDBA ATF Benefit Analyses

3.1 ATF Performance Indicators

Before the benefit of ATF for BDBAs can be discussed, it is helpful to introduce the concept of performance indicators for ATF. These performance indicators can be used for the purpose of measuring and comparing the benefit of ATF among various ATF concepts. An LWR severe accident code such as MAAP or MELCOR will be required to determine these performance indicators. Here, MAAP5.05 beta [5] is used for the calculations of accident scenarios. Three key ATF performance indicators, as illustrated in Figure 4, are defined and discussed below:

(1) Coping time: Maximum time available to prevent core damage if water injection (to remove decay heat out of fuel), that is not available initially, becomes available. The coping time is specific for each plant, portable equipment (e.g. FLEX) setup and accident scenario. The coping time is dependent upon reactor type, core power, FLEX pump characteristics, pilot-operated relief valve (PORV) size, and number of PORVs used for depressurization. For example, the coping times for the FLEX-like RCS injection strategy vs the FLEX-like SG injection strategy for the same accident scenario will be different. For the same FLEX-like strategy being applied to the same accident scenario, the coping time will be different for different ATF concepts.

The coping time is not necessarily measured from the beginning of the accident. In this paper, the clock for the coping time starts from the moment the system has no decay heat removal of any kind to remove heat from the fuel that renders the core in the heat-up mode. For example, if we were to determine the start of the coping time of the accident of Fukushima Daiichi Unit 2 which unexpectedly avoided core damage during the first three days due to the reactor core isolation cooling system (RCIC) system running continuously for three days [6], the coping time would start from the time when the RCIC stopped running which is approximately 3 days into the accident. Six hours later the safety relief valve (SRV) was manually opened, and then two hours later, an injection into the RPV from a firetruck was initiated. The Fukushima Unit 2 accident mitigation experience was in fact the FLEX-like RCS injection strategy which began by opening SRV (or PORVs for PWRs) and followed by injection from a mobile, low (to intermediate)-head pump. The length of time with no decay heat removal was about 8 hours for Fukushima Unit 2 that ended up in core melt. However, it has been shown that if the SiC cladding and U_3Si_2 fuel are used in the Fukushima Unit 2 accident scenario, the core damage would not happen [7]. In this case, with the use of SiC cladding and U_3Si_2 fuel, the coping time of 8 hours is sufficiently long to avoid core damage.

The ability to calculate the coping times for a selected ATF under accident scenarios requires the ability to model the severe accident behavior of the ATF materials up to the point of the ultimate failure of the materials at the prevailing high temperatures and pressures that are typical of LWR severe accident conditions. SiC is a new cladding material candidate whose behavior at high temperatures and high steam pressures is not fully understood and is considered an R&D item that requires further study [8].

(2) Hydrogen Generation: This is the total amount of hydrogen produced during the course of an accident with a successful FLEX-like SG or RCS injection operation. The hydrogen generation is a direct measure of the oxidation resistance of ATF materials and therefore represents a surrogate for the extent of cladding oxidation experienced by the core during an accident.

(3) Early Fission Product Release

This metric represents the fractional release of volatile fission products species (here, cesium iodide (CsI) is selected) from the fuel rods during the course of an accident. Of particular interest for this metric is the point of onset of gap releases which can significantly vary among the various ATF clad concepts. Prevention of gap releases limits public fission product exposure and simplifies post-accident recovery actions. This is a useful metric as gap release resulting from ballooning and bursting of fuel clad material may occur even with successful FLEX-like injection operation.

A release of 100% noble gases is expected following rod ballooning and bursting. But only a certain fraction of CsI (~3-5% of the CsI core inventory) is expected to exist in the gap depending on the temperatures experienced by the rods. Early gap related fission product releases are expected for metal clad fuels. Rod bursting does not occur with SiC cladding, however, alternate mechanisms for fission product release may exist. The mode of fission product release from SiC clad is not well understood at this time. The release of fission product from SiC cladding is considered an R&D item. Since U_3Si_2 is a new fuel, the release of fission products from a U_3Si_2 cladded with coated ZIRLO is also an R&D item. The fission product indicator is an important measure of performance of the ATF concepts. Ultimately, radiological impacts of ATF would need to be considered together in addition to the coping time.

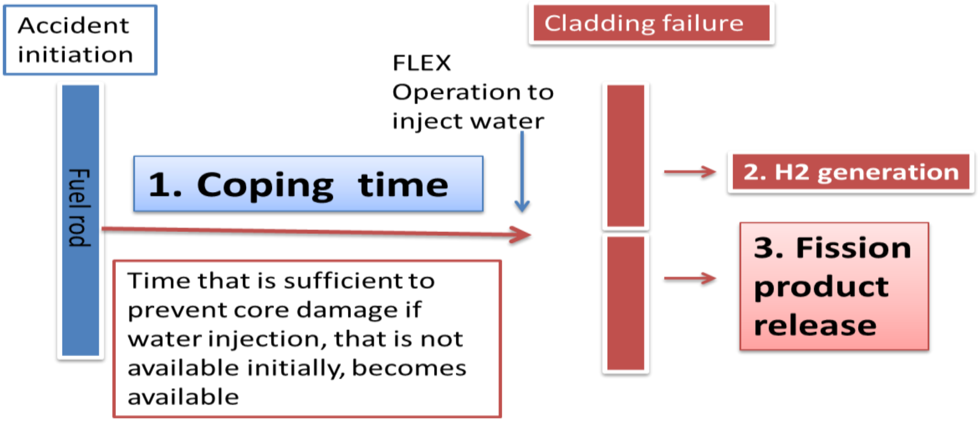

Fig. 4 Illustration of ATF performance indicators: (1) coping time, (2) hydrogen indicator, and (3) fission product indicator

3.2 FLEX-Like Mitigation Strategies

Two mitigation strategies with ATF are examined to explore the benefit of ATF for accident conditions that require FLEX-like injection operations.

(1) **RCS Injection:** This strategy involves a feed-and-bleed (F&B) operation using PORVs and low-to-intermediate-pressure injection FLEX pumps. The RCS needs to be depressurized until the RCS pressure is lower than the pump head before the RCS injection takes place. Hence, there will be an injection delay until the RCS pressure drops below the pump injection pressure.

(2) **SG Injection:** This is an alternate feed water injection using atmospheric dump valves (ADVs), a low-head FLEX pump, and four passively-injected accumulators. A tie-in line to the auxiliary feed water line must be installed for injection from the FLEX pump. The SG injection approach can be a critical strategy for RCS cooling and depressurization of high-pressure Non-LOCA accidents. As the RCS is depressurized, the accumulators passively actuate when the RCS pressure falls below the accumulator initial pressure setpoint (about 615 psia for a typical Westinghouse designed PWR).

3.3 MAAP Analyses

The accident scenario analyzed in this paper is a total station blackout of a typical generation II 1000-MWe Westinghouse PWR with a small Reactor Coolant Pump and RCP seal LOCA (no credit is taken for SHIELD®[1] availability). Two FLEX mitigation strategies are evaluated:

- RCS injection using 600-psi pump with 400-gpm max. flow after opening two PORVs,
- or SG injection using a 300-gpm pump to 2 SGs after opening ADVs

In the RCS injection strategy, RCS depressurization which is required for successful FLEX injection is accomplished by opening two PORVs using, for example, mobile battery power. In the SG injection strategy, supplemental battery power may likewise be required to support monitoring of SG level, however for some strategies “blind feeding” may also be successful. In this assessment, the coping time is defined as the time available to initiate a FLEX injection without damaging the core based on the MAAP cladding creep failure criteria. Core damage in this context is associated with significant cladding degradation and core-wide fuel melting. This level of degradation is well beyond the localized cladding swell and burst behaviors discussed above. Details of the MAAP cladding creep rupture models and core

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[1] SHIELD® is a reliable protective low leakage seal, independent of Westinghouse normal RCP seal package, that may be added to Westinghouse RCP seals to limit leakage from RCP seal package to very low levels.

degradation models are discussed in [8]. Coated cladding failure models are based on expected cladding behaviors within the current state of knowledge. However, additional research on the extent of the ability of coatings to delay cladding balloon and burst and cladding oxidation remain the subject of continued research. Conservative failure criteria relative to current understanding and testing of SiC are used for SiC cladding.

Results of the ATF scenario simulations are summarized in Tables 1 and 2. Table 1 shows the calculated plant response and mitigation strategy coping times along with an estimate of hydrogen generation for the RCS injection strategy while Table 2 shows the calculated results for SG injection strategy. In Table 1, several key timings are provided including the core uncovery time, cladding bursting time, time when the core exit temperature (CET) exceeds 650°C[2], latest estimated PORV opening time (representative of the plant coping time), time of actual RCS injection, peak temperature during sequence, and coping time for prevention of core damage. Table 1 also introduces a time metric tied to accident response time available after the time after CET reaches 650°C. This metric can be viewed as the "incremental" coping time the ATF design affords the operator to take the mitigating action. In Table 2, the FLEX injection time is used to represent the maximum time available for initiation of operator action implement injection to the SGs instead of PORV opening time, and accumulator injection time is in place of actual RCS injection time. Figures 5 and 6 show the dynamics of the RCS pressure, core water level, peak core temperature, and pump flow (for RCS injection) or accumulator pressure (for SG injection) during the FLEX-like operations. Note that for the SG injection strategy, the RCS is depressurized via the steam generators and direct make-up of core inventory is not required in the short term as RCS inventory losses are small.

3.4 Calculation of Coping Times

In Table 1, the coping time is measured from time zero when the accident begins until the PORV opening time. The injection delay time (which is not provided) can be found by subtracting the actual RCS injection time by the PORV opening time. In Table 1 for RCS injection strategy, it is noted that the coping time for the SiC/U_3Si_2 ATF concept is much longer than the core uncovery time (or the 650°C CET signal time), while the same cannot be said for the coated Zr/U_3Si_2 ATF concept. For the coated cladding, a much earlier injection is needed to avoid damaging the coated layers > 1300°C. SiC cladding has higher oxidation resistance as well as higher failure temperatures. These differences have some implications related to the benefit of SiC cladding. In order to explain this particular benefit, additional coping time relative to the 650°C CET signal is also provided in Table 1. Note that as depressurization of the RCS is required for RCS injection to occur, the PORV opening time can significantly precedes the time of incipient core damage (as identified by core exit steam temperature in excess of 650°C for Zr clad cores). In this example, the required PORV action precedes incipient core damage by 0.65 hours for coated clad ATF designs[3] and is delayed by 0.71 hrs for the SiC clad ATF concept. That is when comparing ATF concepts, only SiC cladding is expected to provide a positive large coping time relative to the 650°C CET signal. The non-SiC cladding has a negative coping time relative to 650°C CET signal.

In Table 2, the coping time is measured from time zero when the accident begins until the FLEX SG injection time. The accumulator injection delay (which is not provided) time can be found by subtracting the SG injection time from the accumulator time.

The coping times for SG injection are longer than the corresponding counterparts for RCS injection as there is no pre-condition for the start of decay heat removal. That is heat removal is assumed to start once the injected water reaches the SG tubes. For the FLEX-

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[2] Typical of entry to the Severe Accident Management Guidelines (SAMGs)

[3] The 650°C steam exit temperature is typically assumed to correlate to an incipient near core-wide oxidation condition, indicating the onset of significant exothermic reactions, in a Zr clad core. This "signal" is also assumed to be valid for coated cladding designs. For SiC clad cores the CET "signal" will no longer correlate with an incipient change in core heat-up behavior and therefore the operator can successfully mitigate the event without gross core damage up to the clad temperatures near the SiC failure temperatures.

like equipment set in this example, this comparison indicates that the SG injection strategy (with passive accumulators) provides greater time margin to significant core damage than the RCS injection strategy. It should be noted that “SG injection only strategies” require that RCS inventory losses be minimal and RCS depressurization to shutdown conditions be implemented sufficiently early to avoid a significant period of core uncover.

Note that a coping time for a given strategy that is positive relative to the onset of cladding damage means that from the time of the onset of cladding damage there is still time to take mitigation actions of that given strategy in order to avoid core damage (i.e., fuel/cladding melting). On the other hand, a negative coping time indicates that from the time of the onset of cladding damage, by the time the core reaches 650°C (for a Zr-clad core) it is already too late to take actions to avoid a core damage using that strategy.

ATF Type	**PORV opening time**	**Core Uncovery Time**	**Cladding bursting (gap release)**	**Time when CET > 355 C**	**Time when CET > 650 C**	**Time of actual RCS injection**	**Peak core temperature during sequence**	**COPING TIME**	**COPING TIME after CET signal**	**H2 generation**
SiC/U3Si2	11928 s (3.31 hr)	7800 s (2.17 hr)	N/A	7831 s (2.18 hr)	8630 s (2.40 hr)	13159 s (3.66 hr)	2061 K (13971 s)	3.31 hr	0.71 hr	28.0 kg
Coated Zr/U3Si2	5476 s (1.52 hr)	7265 s (2.02 hr)	7874 s (2.19 hr)	7384 s (2.05 hr)	7823 s (2.17 hr)	7675 s (2.13 hr)	1530 K (8689 s)	1.52 hr	-0.65hr < 0	0 kg
Zr/UO2								smaller than coated Zr		

Table 1 Calculation of coping times for FLEX-like RCS injection strategy

ATF Type	**Core Uncovery Time**	**Cladding bursting (gap release) time**	**Time when CET > 650 C**	**FLEX SG injection time**	**Accumulator injection time**	**Peak core temperature during sequence**	**COPING TIME**	**COPING TIME after CET signal**	**H2 generation**
SiC/U3Si2	7800 s (2.17 hr)	N/A	8630 s (2.40 hr)	12551 s (3.49 hr)	15457 s (4.29 hr)	2088 K	3.49 hr	1.09 hr	44.4 kg
Coated Zr/U3Si2	7674 s (2.13 hr)	7874 s (2.19 hr)	8447 s (2.35 hr)	10416 s (2.89 hr)	13374 s (3.72 hr)	1530 K	2.89 hr	0.54 hr	0 kg
Zr/UO2	6734 s (1.87hr)	7380 s (2.22 hr)	8387 s (2.33 hr)	9162 s (2.54 hr)	13374 s (3.72 hr)	1250 K	2.54 hr	0.32 hr	27 kg

Table 2 Calculation of coping times for FLEX-like SG injection strategy

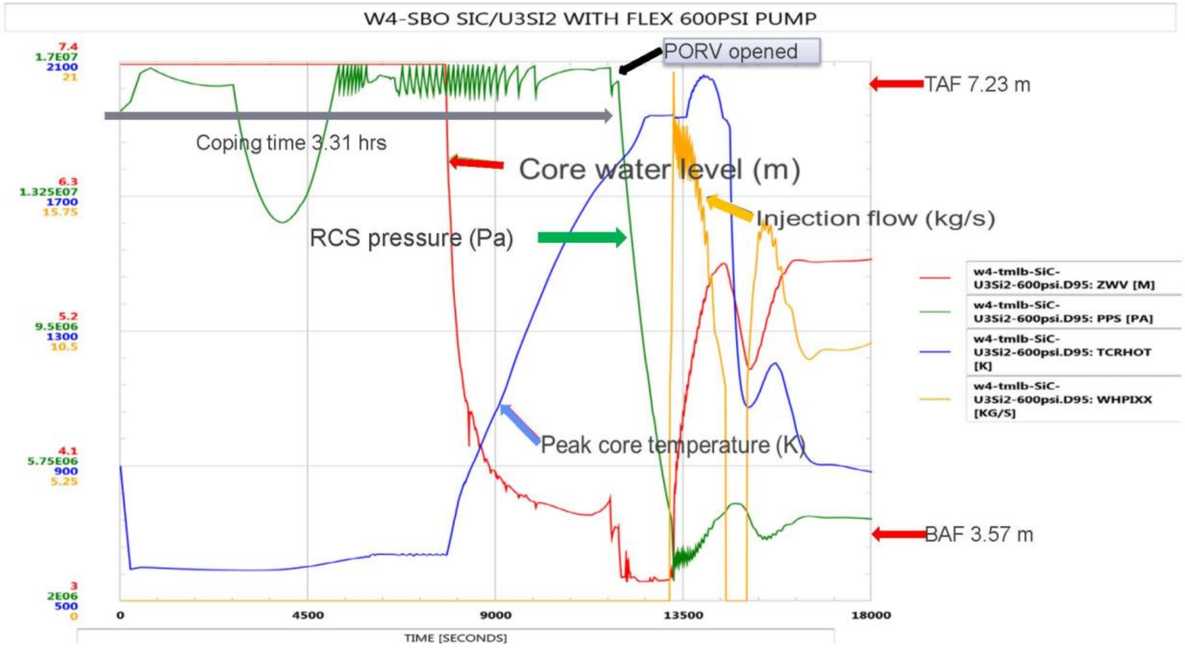

Fig. 5 Calculated reactor responses to FLEX-like RCS injection strategy implemented with SiC cladding and U_3Si_2 fuel

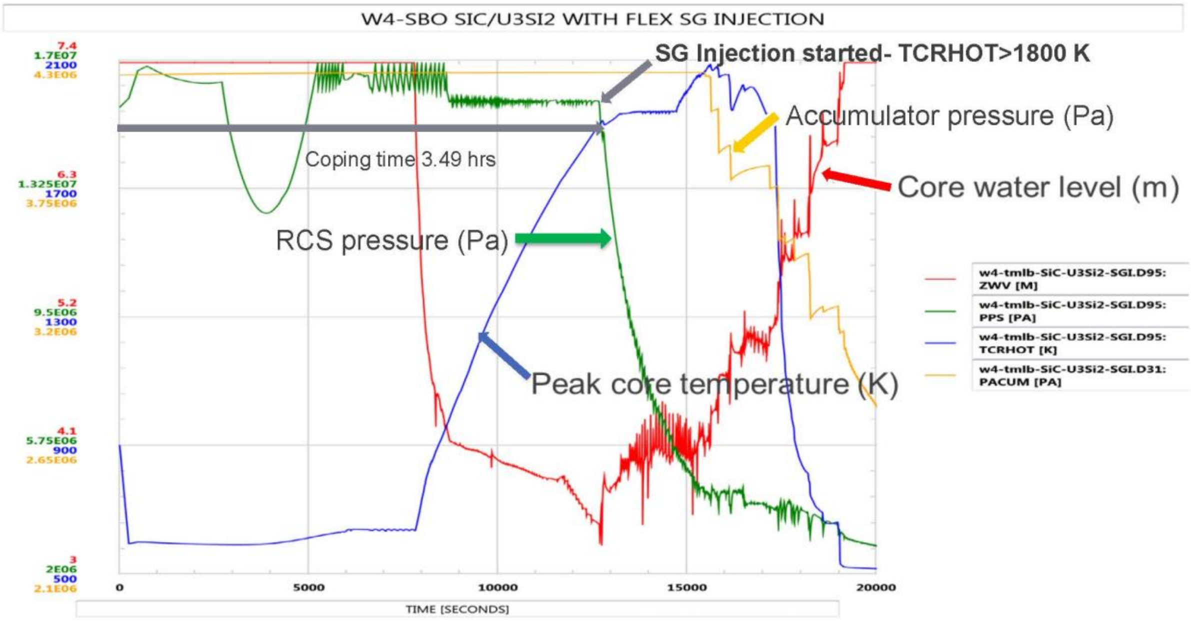

Fig. 6 Calculated reactor responses to FLEX-like SG injection strategy implemented with SiC cladding and U_3Si_2 fuel

4. DBA and Normal Operation ATF Benefits

Historically, a small subset of fuel-related DBA accident scenarios has the smallest margins, and thus acts as the effective set of DBA design constraints for plant operations. One such accident is the large break loss-of-coolant accident (LBLOCA), an American Nuclear Society (ANS) Condition IV event resulting in design constraints related to core power, fuel peaking factors (local linear heat rates), and emergency core cooling systems (ECCS).

ANS Condition 2 and 3 fuel-related events also impose design constraints. Departure from nucleate boiling (DNB) restrictions in pressurized water reactors (PWRs) impose limitations on fuel peaking factors and establish requirements for reactor protection systems. The constraints in terms of plant operations and requirements in terms of supporting equipment impose some cost, so relaxation of these constraints and requirements can yield benefit.

The benefits enabled by ATF technologies arise from two main sources. First, improvement in the fuel design can yield improvement in margins through improved physical response. An example of this is the lower stored energy of U_3Si_2 pellets compared to UO_2 pellets, which reduces PCT in a LBLOCA accident. Second, the failure mechanisms of ATF designs will differ from existing fuel products, allowing for less restrictive accident design constraints as the accidents limits themselves increase. Examples include the current LBLOCA peak cladding temperature (PCT) limit, which is associated with the oxidation and embrittlement of zirconium-based cladding as well as stresses encountered during quenching. Such a limit, or at least the specific value of the limit, might not be relevant for a particular ATF design. Also, DNB limits are designed to preclude fuel failure during at-power operational occurrences; ATF designs such as those including SiC cladding can likely tolerate some limited time in DNB conditions. ATF designs, in essence, move the conditions for fuel failure away from the conditions expected in DBAs.

Benefits in plant operations are thus realizable through changes enabled by improved DBA performance and more resilient fuel. Plant operations can then be optimized to reflect the improved performance. A comprehensive assessment across the range of constraining DBAs is needed to holistically take advantage of these DBA improvements, considering the specific equipment availability and operational constraints, and their associated costs, placed on the plant by the respective constraining DBAs.

Table 3 provides an excerpt from a DBA benefits assessment for the U_3Si_2 / SiC design, focusing on two scenarios - the LBLOCA and a rod-withdrawal DNB event. For the LBLOCA, successful mitigation is defined acknowledging the low likelihood of accident occurrence, and some amount of fuel failure is tolerated if coolable geometry is maintained. The current limits in place for the UO_2 / Zr design are specific to the failure mechanisms of that design. For the rod withdrawal event, reactor protection systems are in place to prevent fuel damage by ensuring positive DNB ratio (DNBR).

For the current UO_2 / Zr design under LBLOCA conditions, initial stored energy of the UO_2 pellet is transferred to the cladding during the initial phases of the accident, as heat transfer from the cladding to the coolant inventory is lost. However, because the fission reaction shuts down as a result of core voiding, the UO_2 pellets reduce in temperature. Decay heat can promote pellet temperature increase later in the LBLOCA transient, but typically not above the initial, at-power operating temperature. The mitigation objective of maintaining coolable geometry places more stringent temperature limits on the cladding such that the UO_2 pellet melt limit is not plausibly approached if the cladding criteria are upheld.

The U_3Si_2 / SiC design changes the limiting phenomena for the LBLOCA accident. Because the SiC cladding is expected to remain resilient to much higher temperature in comparison to Zr, a LBLOCA under current plant design conditions would not realistically challenge the SiC cladding's ability to maintain coolable geometry. However, if plant operations or supporting systems were modified (relaxed / removed) to take advantage of this improvement in a manner such that the LBLOCA event became more significant, it is possible that U3Si2 pellet melt could become the most limiting phenomenon through extended decay-heat-driven heating with limited cooling. Under such conditions, the pellet and/or cladding failure mechanisms would need to be defined to establish appropriate design limits. The definition of "mitigation" would need to be re-defined.

For DNB events, the current protection systems precluding DNB for UO_2 / Zr designs ensure that damage (rupture, swelling, mechanical cladding failure) does not occur. For the U_3Si_2 / SiC design, some amount of time in DNB may be tolerable, since the cladding temperature limits are expected to be significantly higher than Zr-based cladding. Again, the definition of "mitigation" would need to be revised, possibly from the current DNBR to a limited time-in-DNB or more specific operational limits linked to the fuel failure mechanisms. This would allow for relaxation of protection system trip set-points and/or additional flexibility in core loading patterns (e.g. increased peaking factors) and operational limits (e.g. load follow).

While one particular constraining DBA might result in opportunities to relax constraints with ATF, other DBAs, some not related to fuel failure, might still require that particular equipment. Examples include core design parameters such as peaking factors; DBA improvement via ATF might enable larger peaking factor increases than can be realizable under current enrichment limits. A holistic design exercise is needed to establish the appropriate set of design and equipment changes for optimum benefit.

The important equipment in Table 3 may place a varying level of economic burden on the plant operator, and so the process by which DBA margin improvement is translated into performance and economic improvement must consider the relative priority of the various constraints. Table 4 illustrates an example of economic benefit consideration for the LBLOCA accident for the equipment identified in Table 3. While some equipment is important for mitigating the LBLOCA, it might not be burdensome from an economic standpoint (e.g. the accumulators). Margin gains from ATF should therefore target the equipment and constraints most economically beneficial for relaxation or removal, while retention of existing equipment still allows for a net increase in overall plant safety.

Tangible economic benefits can also be achieved through normal operational improvement, or the reduction in unplanned costs. Grid-to-rod-fretting for current Zr-based claddings can lead to leaking fuel rods, which increase primary coolant activity and require action for reload, storage, cleaning, etc. ATF designs such as Cr-coated cladding and SiC cladding have the potential to improve performance and/or eliminate this concern.

Additional operational restrictions could be relaxed by some ATF concepts. Burnup limits related to cladding performance or UO_2 pellet considerations (fragmentation and dispersal) could be increased in the presence of concepts which minimize the likelihood of rod rupture. In combination with small enrichment limit increases, operational flexibility enabled by ATF designs has significant economic benefit potential related to fuel cycle costs.

Accident Scenario	**Mitigation Objective**	**Current Limit**	**Current Phenomena to Avoid**	**ATF Limit (TBD)**	**ATF Phenomena to Avoid**	**Important Equipment**
LBLOCA	Coolable geometry; Containment integrity	PCT < 2200F MLO, Max Local Oxidation <17% CWO, Core Wide Oxidation <1%	Zr oxidation & embrittlement; hydrogen generation	TBD	Pellet melt & clad stress	Core operating axial and radial peaking limits (F_Q, $F_{\Delta H}$) Low & intermediate pressure ECCS pumps; Accumulators; Emergency diesel generators
Rod withdrawal at power	No fuel damage	DNBR	DNB	TBD	Fuel damage	**Reactor Protection System Trips** Power Range High Neutron Flux (Low and High); OTΔT; High Pressurizer Pressure Trip; Variable Overpower Trip – CPC; High Local Power Density – CPC; Low DNBR– CPC (Core Protection Calculator) **Control Rods**

Table 3: Framework for DBA benefits assessment for U_3Si_2 / SiC ATF design

Equipment/Constraint	**Role**	**Margin Importance**	**Economic Importance**
Core operating limits (F_Q, $F_{\Delta H}$, Axial Offset)	Limit initial conditions: power, initial stored energy.	H	H
High Pressure ECCS Pumps	Refill the vessel at high pressure	L	L
Intermediate Pressure ECCS Pumps	Refill the vessel at intermediate pressure	L	L
Low Pressure ECCS Pumps	Refill the vessel at low pressure	H	L
Accumulators	Refill the vessel during blowdown	H	L
Emergency Diesel Generators	Provide power for ECCS pumps in the event of a LOOP.	M (start time) H (existence)	M

Table 4: Framework for DBA benefits assessment for LBLOCA equipment requirements

5. Summary of Benefits using ATF Materials

The Westinghouse EnCore accident tolerant fuel will produce benefits for BDBAs and DBAs. For BDBAs there will be increased coping time ranging from 1 to 2 hours for the most severe short-term SBO, and with the use of FLEX-like mitigation strategies coping times can be increased with the possibility of averting core damage and hot leg rupture for PWRs. For DBAs and normal operation a framework for benefit assessments was presented. Future DBA benefit assessments will be performed based on this framework to determine the potential benefits resulting in additional safety margin and economics. The following is a summary of possible ATF benefits for DBAs and for normal operation:

- Peak linear heat rates, power distributions, fuel cycle economics
  - Longer cycle lengths, higher peaking factors, smaller batch sizes further discussed in Reference 9
- DNB core safety limits
  - Time in DNB, OTΔT relaxation, rod drop time increase
- Fretting Resistance
  - Improvement in grid to rod fretting and resistance to debris leakers
- Higher Burnup Capability
  - ATF materials may better support higher burnups, reduced fuel dispersal, etc
- Improved Flexible Plant Operation
  - Possible improvement in PCMI
- Hydrogen mitigation & control systems
  - Surveillance and safety classification
- Diesel start times
  - Extend (maintenance savings)
- Safety-related SI pump availability (# of pumps)
  - Remove from safety grade classification
- Accumulator availability (and pressure)
  - Relax Tech Spec requirements

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7. References

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