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ABSTRACT

In the near future, experiments on high-burnup (HBu) fuel under loss-of-coolant accident (LOCA) and reactivity-initiated accident (RIA) conditions will be performed in the Transient Reactor Test Facility (TREAT) at Idaho National Laboratory. These experiments will be conducted using the Transient Water Irradiation System for TREAT (TWIST) experiment vehicle. To support these experiments, fuel-coolant interaction (FCI) energetics are being analysed. This paper discusses FCIs in the context of light-water reactor (LWR) safety, differentiating between the severe accident focus of commercial reactors and the experimental RIA test programs in which FCIs have occurred. However, it is to be emphasized that as the nuclear industry aims to increase burnup limits, the FCI events observed in RIA test programs may become relevant to commercial LWR safety analyses. This paper then presents developments made to the UW-FCI computer program so as to enable simulation of FCIs initiated by solid fuel particles dispersing into the coolant during RIAs.

1. Introduction

The term fuel-coolant interaction (FCI) describes the phenomenon in which a hot material (i.e., the fuel) transfers its internal energy to a colder, more volatile liquid (i.e., the coolant). This causes the coolant to vaporize at high pressures, and to do work on the surrounding structures and overlying coolant as it expands. In the context of nuclear reactors, the fuel is typically nuclear fuel, the coolant is reactor coolant, and the surrounding structure is the reactor vessel. If the FCI is severe enough, the work done on the surroundings can threaten the vessel's structural integrity, either through overpressurization of the vapor, or, as the vapor expands, the overlying liquid coolant can be accelerated into the vessel wall at high speeds. A subset of FCIs known as energetic FCIs (or vapor explosions) take place when the vapor generation occurs on a timescale shorter than the length of time it takes the system to acoustically relieve itself. Under these conditions, liquid-phase shockwaves can also threaten the structural integrity of the surrounding vessel [1].

In the nuclear industry, the focus regarding FCI behaviour has historically been on molten FCIs, as molten fuel has the propensity to fragment into small particles, thus increasing the heat transfer surface area to the coolant—as is required to sustain rapid vapor generation [2]. However, with the nuclear industry now aiming to increase burnup limits for light-water reactors (LWRs), solid FCIs have become a possibility, as high-burnup (HBu) solid fuel can also fragment into fine particles conducive to rapid vapor generation under postulated accident scenarios [3].

In the near future, experiments on HBu fuel under loss-of-coolant accident (LOCA) [4] and reactivity-initiated accident (RIA) [5] conditions will be performed in the Transient Reactor Test Facility (TREAT) at Idaho National Laboratory. These experiments will be conducted using the Transient Water Irradiation System for TREAT (TWIST) experiment vehicle. To support these experiments, FCI energetics are being analysed. This paper discusses FCIs in the context of

LWR safety, differentiating between the severe accident focus of commercial reactors and the experimental RIA test programs in which FCIs have occurred. However, it is to be emphasized that as the nuclear industry aims to increase burnup limits, the FCI events observed in RIA test programs may become relevant to commercial LWR safety analyses. This paper also presents developments made to the UW-FCI computer program [6][7] so as to enable simulation of FCIs initiated by solid fuel particles dispersing into the coolant during RIAs.

2. Context of FCIs in Reactor Safety

2.1 Commercial LWRs

In commercial LWRs, analyses of FCI energetics have mostly focused on severe accident scenarios in which large amounts of molten core material called corium come into contact with the liquid coolant. The general consensus is that there are two primary “contact modes” which the molten corium may encounter the liquid coolant [8]. In a pouring contact mode, the molten corium falls into a water-containing cavity. On the other hand, fuel and coolant may also come into contact in a stratified geometry in which the corium and liquid coolant are initially separated by a vapor film that ultimately collapses, causing local mixing and fuel fragmentation at the interface. Of these two mechanisms, the pouring contact mode is considered the most severe and has thus received more attention from the research community, both in terms of experiments as well as modelling such events [8]. Fig 1 illustrates the two contact modes.

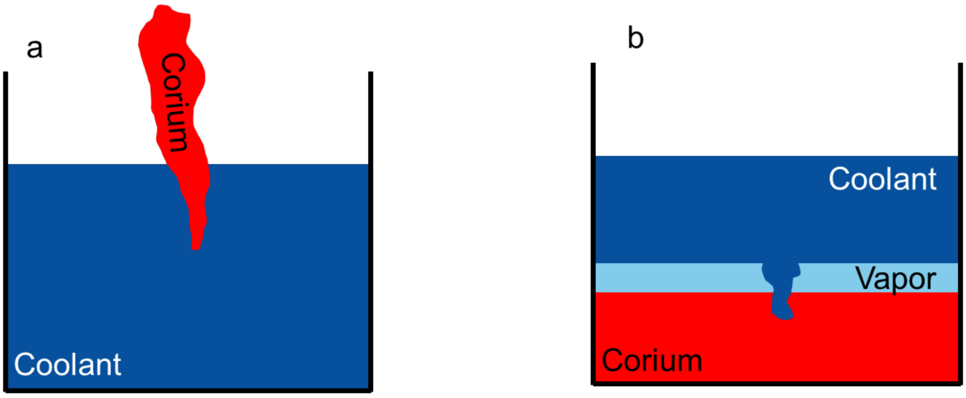

Fig 1. Illustration of the (a) pouring and (b) stratified geometry contact modes considered in severe accident LWR FCI scenarios

Under design-basis accident (DBA) conditions such as RIAs and LOCAs, and given the current burnup limits, U.S. regulations have been established to ensure that an FCI is not deemed a credible event. For RIAs, this is achieved through Regulatory Guide 1.236, which specifies limits on peak radial average enthalpy and fuel melting in order “to prevent catastrophic fuel rod failure and avoiding [sic] molten fuel-coolant interaction[s] [9].” For LOCAs, this is accomplished by the emergency core cooling system acceptance criteria in 10 CFR 50.46 to ensure that the fuel remains within the cladding [10]. And because these regulatory measures have been implemented to avoid the occurrence of FCIs during commercial LWR DBAs, research into FCIs under such conditions has been quite limited.

As the U.S. nuclear industry aims to increase burnup limits [11], it is unclear whether current regulations are sufficient to preclude FCIs from occurring during RIAs. Over the last 25 years, HBu fuel experiments under both simulated RIA and LOCA conditions have observed finely fragmented fuel being dispersed out of the cladding upon failure, despite not exceeding current regulatory limits [12][13]. Given the large heat transfer surface area of finely fragmented fuel particles, the potential for solid FCIs under DBA RIA conditions has been deemed a potential safety concern [3]. Under these conditions, the contact mode between the fuel and coolant

differs from those considered under severe accident conditions. Here, the solid fuel particles come into contact with the coolant via direct injection upon cladding failure (Fig 2a).
Although direct injection of fuel into the coolant upon cladding failure has not been the focus of commercial LWR FCI events, this type of event has been studied in support of experimental programs researching RIAs.

2.2 Experimental Programs

Numerous experiments have been performed in facilities around the world to simulate RIA scenarios on LWR fuel segments. Many of the early tests, beginning in the 1960s, were performed on fresh fuel and served as the basis for establishing RIA regulatory limits [13]. Although the exact experiment designs varied, the typical approach to these experiments was to subject a single fuel rod segment contained inside a static water capsule to a power pulse driven by a test reactor. In the process of establishing these limits, some of the experiments resulted in a large amount of energy to be deposited into the fuel rod specimen, resulting in molten fuel being ejected from the cladding and into the surrounding water. This can lead to the type of FCI initiated by direct injection of molten fuel into the coolant (Fig 2b). Fig 2a shows the same process but for solid fuel, the difference being that molten fuel may break up into smaller particles as a result of inertial forces stemming from the relative velocity difference between the injected fuel and the coolant [14] as well as from other hydrodynamic forces experienced during the event [1].

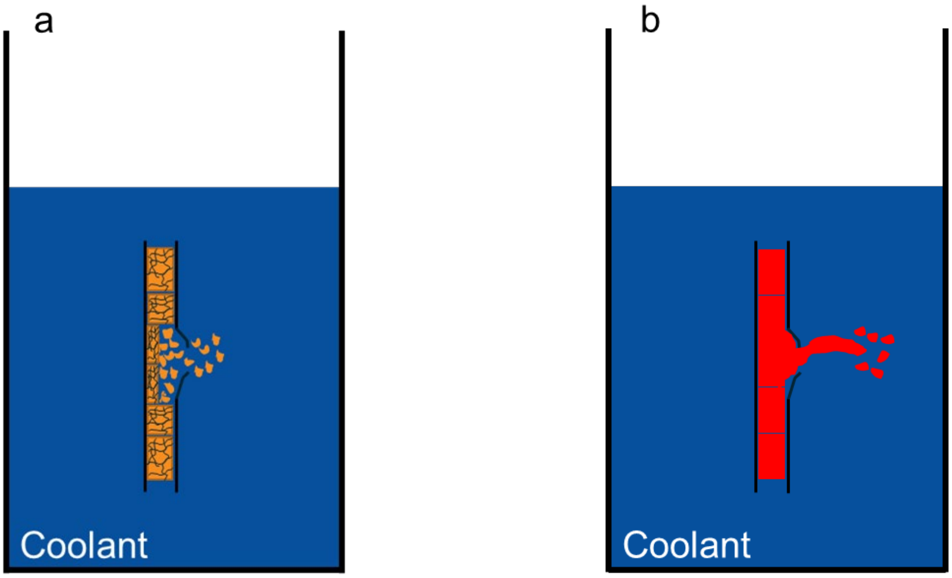

Fig 2. Illustration of direct injection of (a) solid and (b) molten fuel into the coolant

Experiments performed under these conditions have observed pressure pulses on the order of 10s of MPa, with a strong correlation between energy deposition and peak pressure. In [15], the FCI energetics observed during RIA experimental test programs are summarized. This time period of high-energy testing saw the development of simulation tools (e.g., Stress-strains from Pressures Instigated by Reactor Transients) for simulating RIA-initiated molten FCIs [16]. However, development of these capabilities ceased as regulatory criteria moved FCIs into the severe accident space. As will be discussed later, efforts have recently been made to simulate RIA-initiated molten FCIs initiated from an RIA using tools originally developed for simulating severe accident FCIs [7].

Following the fresh fuel RIA testing programs, which established regulatory limits on fuel enthalpy and melting so as to preclude molten FCIs from the RIA design basis, experimental programs shifted focus to the testing of pre-irradiated fuel specimens. These experiments investigate the impact of burnup on RIA safety limits and are typically performed at energy depositions below what is required to melt the fuel [13]. As alluded to earlier, RIA testing on higher burnup fuel indicated the potential for finely fragmented solid fuel particles to be ejected upon fuel rod failure. This was observed in experiments the Japan Atomic Energy Agency conducted at the Nuclear Safety Research Reactor (NSRR), revealing that, at burnups exceeding ~45 GWd/MTU, a significant amount of fuel may become dispersed into the coolant upon cladding failure [13]. In some of these experiments, pressure pulses indicative of solid FCIs were observed [17].

In an attempt to decouple pressurization mechanisms due to FCI and those associated with rod plenum gas injection and transient fission gas release into the coolant, separate-effects experiments were performed at NSRR. In these experiments, UO_2 particles were placed in a vinyl bag in the centre of the static water capsule and subjected to a power pulse [17]. For the present work, these separate-effects experiments served as a basis for assessing the models that were implemented into UW-FCI to simulate solid FCIs.

Fig 3 gives a schematic of the NSRR test capsule containing the vinyl bag of fuel. The capsule has an inner diameter of 74 mm [17] and an overall height of 680 mm [18]. The amount of water the capsules contained in these experiments was not reported, so for the purpose of this work it was assumed the capsule was 70% full of water.

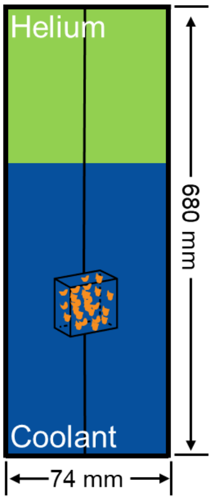

Fig 3. Schematic of the powder fuel NSRR separate-effects experiments

Overall, four experiments were performed, with each one varying the size and geometry of the UO_2 particles. Experiment P-250 employed 250-μm-diameter spherical particles, whereas the particles used in the other three experiments were obtained by crushing UO_2 pellets. These experiments were performed at room temperature and atmospheric pressure. Each involved 30 grams of UO_2 and was subjected to a power pulse that caused the fuel enthalpy to reach approximately 500 J/gm-UO_2, which corresponds to ~1600°C. Tab 1 summarizes these experiments, with the energy conversion ratio describing the kinetic energy of the overlying water column to the total energy deposited in the fuel at the time of peak water column velocity. In [17], the reactor power, capsule pressure, and water column velocity are presented for two of the four experiments (i.e., P-250 and P-47). These results are reflected in Fig 4 and Fig 5.

Experiment ID	Diameter (µm)	Total Surface Area of Fuel (m^2)	Peak Water Column Velocity (m/s)	Energy Conversion Ratio (%)
P-250	250	0.07	1.8	0.04
P-92	92	0.19	5.4	0.21
P-47	47	0.37	6.3	0.27
P-20	20	0.86	6.0	0.41

Tab 1. Summary of the NSRR powder fuel experiments [17]

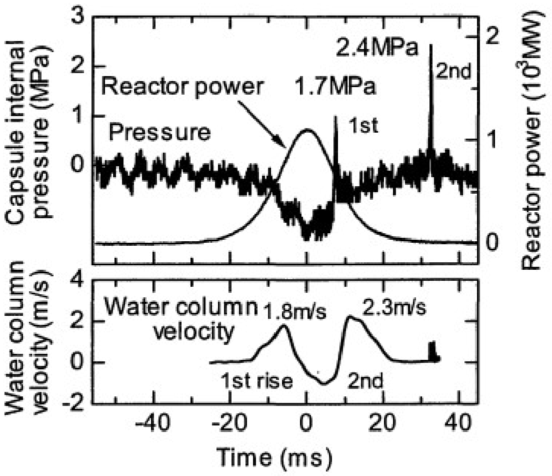

Fig 4. P-250 measured capsule pressure and water column velocity [17]

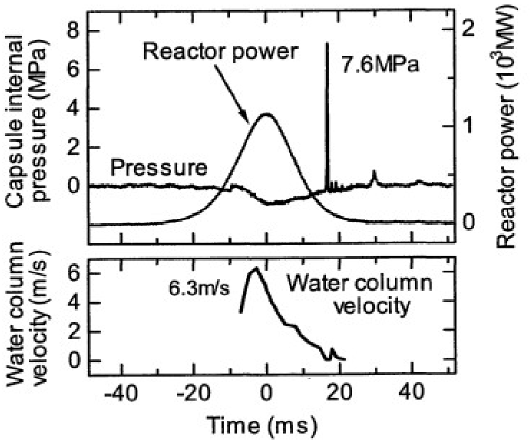

Fig 5. P-47 measured capsule pressure and water column velocity [17]

In all four experiments, the pressure spikes were observed approximately 30 ms after the water column began to rise. The width of these pressure spikes were on the order of 1 ms, and thus too narrow to be caused by any steam generation. Instead, these pressure spikes are hypothesized to correspond to vapor bubble collapse having caused water compression and the propagation of a pressure wave [17]. For P-250, the second peak in the water column velocity is hypothesized to have been caused by rapid steam generation upon contact being made between the fuel particles and liquid coolant. This contact is believed to have been initiated by vapor film collapse, as triggered by the first pressure spike [17].

3. UW-FCI

UW-FCI is a 1-D non-equilibrium model for predicting the energetics associated with FCIs. It was initially developed at the University of Wisconsin-Madison to simulate FCIs initiated via pouring contact mode [6]. UW-FCI is able to track two particle sizes: a parent fuel size and a fragmented fuel size. The code assumes all fuel particles to be evenly dispersed throughout a specified "explosion zone." Heat transfer between a fuel particle and the vapor and liquid coolant is modelled in a lumped parameter fashion. Production of vapor surrounding the fuel causes a local pressure increase that expands the explosion zone in a 1-D fashion, accelerating the overlying coolant slug. A qualitative description of this is provided in Fig 6. Recently, UW-FCI was used to simulate molten FCIs initiated via direct injection of fuel into the coolant [7]. In the time since, UW-FCI was rewritten from its original programming language (i.e., FORTRAN77) into Python so as to make it easier to perform modifications and add new models to the code.

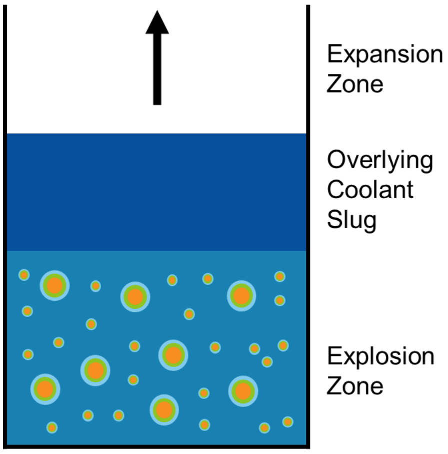

Fig 6. Qualitative representation of UW-FCI

2.3 Modifications to support solid FCI simulations

Unlike with molten FCIs, the fuel in solid FCIs is not expected to break apart during an event. Because UW-FCI was initially written for molten FCIs, a modification was added to turn off the fragmentation model so that all the fuel remained at one size. UW-FCI was also modified to be able to model the internal heat generation that occurs during the transient. Since UW-FCI was originally developed to analyse FCIs during severe accidents in which the core has melted down, this feature was not included, as fission heating of the fuel is no longer occurring and the amount of decay heat generated during the timescale of an FCI is minimal.

In the event of an RIA-initiated FCI, it is important that continued fission heating of the fuel particles be simulated. Since rod failure and ejection of fuel particles from the rod may take place before the RIA power pulse is complete, an FCI may occur while significant heat is still being generated within the fuel.

To incorporate continued heating of the fuel particles, the ability to input a power history in terms of power per mass of fuel (W/gm-UO_2) was added to UW-FCI. Users can either supply a csv file containing the power as a function of time, or describe the power pulse as a Gaussian function in which the user provides the full width at half maximum of the pulse along with the peak power. A term for the fuel particle heat generation rate was also added to the differential equations governing the energy in the fuel particles. Although discussed as a modification for solid FCIs, this new feature is also relevant to molten FCIs, as continued fission heating can occur in such cases as well.

2.4 Assessment of UW-FCI Modifications

To assess UW-FCI's ability to model the energetics associated with solid FCIs, the separate-effects powder-fuel experiments were simulated. Although these cases did not reveal large pressure pulses caused by FCIs, assessment of these cases was nonetheless valuable in terms of providing key insights into the behaviour of the heat transfer between the fuel particles and the coolant.

Here, comparison to the P-250 experiment is made. Fig 7 compares the measured water column velocity to the UW-FCI-predicted values. As observed, UW-FCI is in good agreement with the experiment results in regard to both magnitude and duration. An initial mixing time of 10 ms was set in UW-FCI to match the initial water column movement observed in the experiment. Following this specified mixing time, the FCI event was initiated in UW-FCI and rapid vapor generation began. Due to this modelling approach, UW-FCI lacks models to predict fuel-to-liquid contact and thus cannot capture the double hump behaviour observed in the experiment.

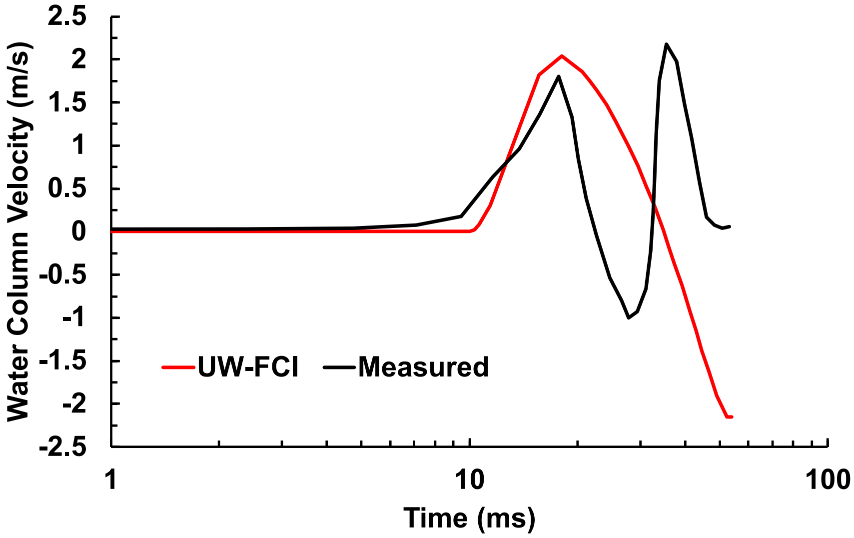

Fig 7. Comparison of the P-250 water column velocity measurements against the UW-FCI-predicted values.

4. Conclusions

In the event of an FCI, rapid coolant vaporization at high pressures has the potential to do work on the surrounding structures and overlying coolant as it expands. For the safety of commercial LWRs, regulatory criteria were established to prevent molten FCIs from occurring within the DBA scope. The research focus has thus primarily centered on FCIs stemming from severe accidents. However, with the nuclear industry aiming to increase burnup limits for LWRs, solid FCIs have become a possibility. To support upcoming HBu experiments performed in the TWIST experiment vehicle at Idaho National Laboratory, solid FCI energetics are being analysed. This paper also presents developments made to the UW-FCI computer program to enable simulation of FCIs initiated by solid fuel particles dispersing into the coolant during RIAs. These developments were then assessed in comparison to a separate-effects experiment performed at the NSRR, where solid fragments of UO_2 were subjected to a power pulse and rapidly transferred heat to the surrounding coolant. UW-FCI was shown to adequately predict the overlying liquid coolant velocity as the interaction zone expanded.

Future work to expand modelling capabilities will include simulation of HBu RIA experiments in which finely fragmented fuel disperses into the coolant upon rod burst. Initial conditions for fragment size, burst timing, and rod pressure will leverage fuel performance simulations using BISON [19]. Models that simulate the additional coolant pressurization caused by fuel rod burst and fission gas release are areas of development targeted for UW-FCI.

5. Acknowledgments

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