Progress in Nuclear Energy 70 (2014) 266–269

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Assessing the safety of new nuclear fuels – Focus on degradation behaviors

Julian F. Kelly [a,b,*], Hubert Druenne [b]

[a] World Nuclear Association, 22a St. James' Square, London SW1Y 4JH, UK
[b] GdF-Suez, Avenue Ariane 7, Brussels 1200, Belgium

ARTICLE INFO

Article history:
Received 7 January 2013
Received in revised form 25 April 2013
Accepted 5 October 2013

Keywords:
Nuclear fuel
Safety criteria
Degradation behavior

ABSTRACT

New nuclear fuels offering enhanced operational safety levels are being developed. A tool for qualitatively assessing their safety credentials is proposed in the form of twelve key "behavioral characteristics" at the level of the 'fuel meat'-cladding-coolant system. The assessment of safety credentials for new fuel variants should be made using guidelines that are more generic than the industry criteria for standard Zr-clad uranium oxide fuels, otherwise safety margin benefits may not be adequately recognized.

1. Introduction

Nuclear utilities have always placed a high priority on maintaining fuel integrity. Now, however, there is higher awareness among all nuclear power stakeholders about the nature of nuclear fuel and how it behaves. The Fukushima accident highlighted for everyone just how much stored energy is contained in operating fuel materials and what can happen if this cannot escape to a heat-sink.

The accident progression included sequences in which the fuel cladding weakened at elevated temperatures and underwent exothermic reaction that produced flammable hydrogen gas. The ceramic fuel material de-gassed and melted - at least in part.

This terrible event has provided impetus for the development of safer fuels forms, *ie*, those in which the classic "melt-down" path cannot occur. There are numerous groups now working to develop, test and license new fuel forms that have higher safety margins. Industry discussion on "accident tolerant fuels" is now well established (Goldner, 2012; Wachs, 2012) and funding for such appears to have increased.

A short list of promising enhanced-safety fuel types is given in Table 1, categorized in an arbitrary manner aimed at ease of communication. The intensified level of R&D activity into 'safe-fuel' technologies has raised the question: "How can a specific new fuel be rated in terms of its safety credentials?"

Current guidance in the form of fuel safety criteria used in the industry today are entirely specific to the zirconium-clad uranium oxide fuel system (Zr-clad UOX). They do not necessarily apply in entirety to fuels comprised of materials other than zirconium and UO_2.

This paper identifies a finite number of safety-related fuel degradation behaviors that are generically applicable to all solid fuels. These behaviors occur at the *'fuel meat'-cladding-coolant* level.[1] The paper contends that this list of 'agnostic' behaviors may serve as an efficient safety screening tool for making quick comparative assessments of a new fuel's safety credentials. The methodology should useful for those dealing with the design, testing, funding and regulation of accident tolerant fuels.

2. Assessing 'new fuel' safety

2.1. Existing fuel safety criteria

The OECD Nuclear Energy Agency (NEA) has been continually deliberating and advising on how nuclear fuel safety is best assessed. It publishes a comprehensive set of criteria that includes

* Corresponding author. World Nuclear Association, 22a St. James' Square, London SW1Y 4JH, UK.
E-mail address: kelly@world-nuclear.org (J.F. Kelly).

[1] The term 'fuel meat' is defined as the material that hosts the fissioning component (uranium &/or plutonium) for the fuel. Most commonly this is an oxide ceramic, however, with metal and composite forms under development a generic term is deemed preferable to refer to this heat-generating part of the fuel-system.

0149-1970/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.pnucene.2013.10.002

Table 1
New fuel technology categories.

Category	Specific enhanced-safety fuel types
'Dispersion' fuels	•UO_2 ceramic containing a high thermal conductivity ceramic (BeO or SiC) additive •Multi-coated fissile particles embedded in a robust matrix of graphite or other thermally conductive material
Thoria-based fuels	•Mixed $(Th,Pu)O_2$ ceramic pellets
Enhanced thermal pathway fuels	•Annular cross-section Zr-clad fuel rods with dual inner & outer surface cooling • All-metal enriched uranium fuel
Robust fuel claddings	• SiC-clad fuels • Stainless steel or molybdenum clad UOX fuel

all dimensions of fuel use, from microscopic to macroscopic phenomena, and they cover all components of a fuel assembly. These criteria (Fuel Safety Criteria Technical Review, 2011) are periodically updated with the most recent revision having been completed and published in 2012.

The International Atomic Energy Agency has its general INPRO framework for assessing new nuclear fuel cycle technologies (INPRO Guidance, 2008), a component of which is safety, though the methodology does not provide guidance at the detailed chemical level that is most useful for fuel developers.

Guidance on fuel safety is also to be found in some specific reactor safety licensing documents, *eg*, those prepared by nuclear utilities as part of their regulatory reviews (Fuel Qualification Plan", January 2000; Standard Review Plan – C, March 2007). However, these are not easy to apply to the 'new fuel' context, nor are they written with the view that major improvements in fuel safety margins can be achieved. Also, they tend to be framed in a manner that is country-specific.

2.2. Providing guidance for fuel technologists

The NEA fuel safety criteria are a mature set of industry-derived considerations that guide fabricators and operators of current LWR and PHWR fuels. This high level guidance is important for industry practitioners, but it has been necessarily crafted solely for the zirconium-clad uranium oxide fuel form (Zr-clad UOX) – a de-facto standard in the nuclear generating industry.

Quite a few of these 'standard' fuel safety considerations apply to new fuel-forms, however, some Zr-clad UOX safety criteria have little or no relevance to certain new types of nuclear fuel. Examples include: 'fuel fragmentation' which is a safety consideration for UOX fuel ceramic but is barely relevant for all-metal fuels, and, 'cladding collapse' which is of minimal concern for ceramic composite claddings. The specification of operating limits based on inapplicable criteria may lead to a failure to capture safety benefits offered by new fuel technologies.

Thus, there is a need for safety assessment guidance that applies to the operation of evolutionary 'enhanced-safety' power reactor fuels such as those listed in Table 1. In recognition of this, the World Nuclear Association (WNA) established a Working Group to tackle the issue of how to assess the safety credentials of the various new nuclear fuels being developed for near-term deployment. The Working Group used the NEA fuel safety criteria[2] as an excellent basis for developing a list of generic safety-significant fuel behaviors (WNA Assessment Framework, 2013), and it is proposed that this can serve as a basic comparative assessment tool for those in the nuclear industry seeking to develop (&/or license) new fuel-types with enhanced-safety features.

3. Generic safety-significant fuel behaviors

Generic safety considerations were drafted for a non-specific solid nuclear fuel operating in a current generation water cooled reactor (PHWR, PWR, BWR). The list of safety-significant guidance points is notable in that: (i) primary focus is put on the fuel meat – cladding – coolant system and its interfaces, and, (ii) that a fuel *behavior* focus is most useful for preparing a 'checklist' that can be used for quick and comparative assessment of fuel safety credentials.

A number of broad fuel safety *requirements* are also presented to provide a context of operating scenarios – emphasizing that a new nuclear fuel technology must perform safely in normal and accident conditions, as well as during the post-discharge phase of life for the fuel.

3.1. Focus on the 'fuel meat' – clad – coolant level

It is at the fuel meat–cladding–coolant level where temperatures and radiation fluxes are highest and thus where materials experience the most severe physical and chemical stresses. It is a *necessary condition* that a new fuel-type performs safely at both the fuel-cladding interface and at the cladding-coolant interface. Physical and chemical degradation processes at these points are inevitable over extended in-core periods and yet they should not lead to fuel failure and release of radioactive material.

Assessing (and comparing) fundamental damage pathways at these critical interfaces in a new fuel-type is therefore a logical prerequisite check to undertake before laborious macroscopic safety performance criteria are taken into account, *eg*, the ability to stay upright in the event of an abnormal force (as in an earthquake). Also, a focus on this part of the fuel system is justified by the fact that the safety-enhancement features under current development mainly involve new fuel-meat and cladding materials, and/or arrangements of these.

3.2. Key behavioral characteristics

"Behavioral characteristics" are the processes, effects, behaviors and responses that the fuel system manifests in response to the reactor conditions to which it is exposed. For example; 'fission gas release' is a behavioral characteristic whereas 'fuel rod pressure' is a resulting macroscopic state; 'clad hydriding' is a behavioral characteristic, with embrittlement being a resulting state.

Twelve behavioral characteristics are identified as of key significance in the comparative assessment of safety credentials for new nuclear fuels. These are derived from a more detailed exposition of safety considerations for generic fuels, including those incorporating features such as SiC cladding and more thermally conductive fuel-meat (WNA Assessment Framework, 2013). The degradation behaviors are described below, along with an indication of the fuel safety requirement/s to which they pertain.

3.2.1. Cladding oxidation & hydriding

Oxidation and hydriding reactions may affect cladding materials, in particular metal claddings. This can be of safety significance because oxide and hydride products can compromise the strength, corrosion resistance and heat transfer properties of the cladding. Developers of fuels with cladding that is not susceptible to such

[2] Several of the NEA criteria were taken as premises because they are either necessarily in place (*eg*, neutronic safety design) before the fuel is even tested, or, they are unlikely to manifest as problematic before the fissioning 'fuel meat' is shown to perform in a satisfactory manner. NEA safety criteria taken as premises are: reactivity coefficients, criticality & shut-down margins, critical heat flux/linear heat rate limits, fuel enrichment limits, coolant activity.