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Management options for Fukushima corium

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ABSTRACT

The loss of core cooling for units 1–3 during the accident at Fukushima Dai-ichi caused major fuel damage. Although full details are not yet available, fuel melting produced corium within the reactor pressure vessels that has, to an unknown degree, melted through into the primary containment. The present priority is cooling the damaged reactors and managing contaminated water, but planning of longer term decommissioning has already begun. Management of highly damaged fuel and corium will be of primary concern, with the main options being recovery for reprocessing or packaging for direct disposal. Although the latter option may have significant cost advantages, it presents some novel safety challenges for both operational and post-closure phases. Concerns include criticality management and modelling of long-term dissolution of materials having highly variable composition. Further R&D is required to fill knowledge gaps – of which the most sensitive may involve determination of the extent to which small "hot particles" of corium have been produced.

1. Introduction

The 2011 earthquake off the pacific coast of Japan generated a devastating tsunami that triggered an unprecedented series of reactor severe accidents at the Fukushima Dai-ichi nuclear power plant (denoted here as "1F"). An overview of the progress of this incident and its consequences are described in detail elsewhere (Hatamura et al., 2012; Kurokawa et al., 2012). This paper focuses entirely on planning the decommissioning of the damaged reactors and, in particular, management of the corium produced as a result of core melting in units 1–3. The main technical issues involved are outlined in Fig. 1 although, as discussed below, socio-political and communication issues must also be taken into account before major actions are implemented.

Worldwide, there have been a number of accidents involving reactor core damage, most of which had little radiological significance (McKinley et al., 2011). Three-Mile Island (TMI) is probably most relevant for corium management, with defueling completed in 1990 (USNRC, 2009), after which the corium was transported to the Idaho National laboratory where it sits on a concrete plinth awaiting final disposal (IAEA, 1991, 1992; EPRI, 1990, 1992). Other reactors that suffered major core damage were either simply sealed, e.g. Windscale, UK; Chernobyl, Ukraine or decommissioned, with damaged fuel either reprocessed, e.g. Lucens, Switzerland (ENSI, 2012) or stored for eventual direct disposal, e.g. SRE (Sodium Reactor Experiment), USA. In addition, reactor severe accident experiments have been conducted for decades to study a wide range of phenomena. These include fuel rod dryout and degradation, e.g. Steinbruck et al., 2010; Toth et al., 2010, in-vessel (RPV) retention and cooling of corium (Bechta et al., 2001; Kang et al., 2006), vapour explosions (Kim et al., 2010; Magallon and Huhtiniemi 2001) ex-vessel corium spreading (Cognet et al., 2001; Journeau et al., 2003) and corium/concrete interactions and coolability (Journeau et al., 2009; Lomperski and Farmer, 2007). This paper considers management of the corium waste rather than accident phenomena and progression.

Loss of instrumentation and hydrogen explosions have obscured the extent of core damage. Even now, high radiation fields and contamination limit our ability to inspect and characterise the reactor cores and corium debris. Severe accident codes, e.g. MELCOR and MAAP, have used available data to produce the core

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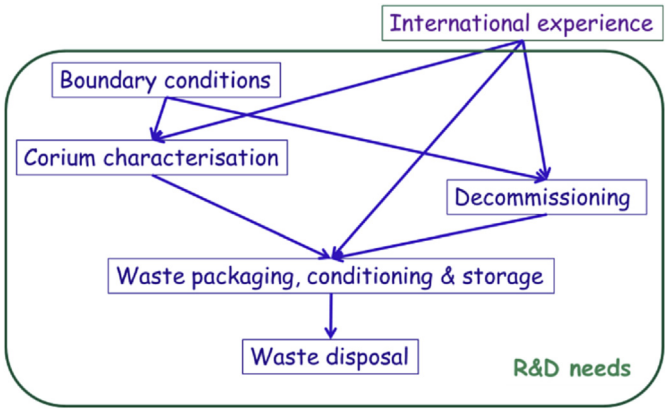

Fig. 1. Technical issues to be considered when developing a management plan for 1F corium.

damage estimates shown in Table 1 (JAEA, 2014).

The three BWR units contained a total of 1496 fuel assemblies, with 32 of them MOX in unit 3. Each assembly has 60 zirconium alloy-clad fuel rods. The fuel burnup histories vary between reactors, the original location of fuel assemblies in the core and location along the fuel rods (due to differing fuel loading patterns). The 1F reactors discharge fuel after 4 cycles with a burnup of 39.5 MW d kg^{-1} (GW d/t_{HM}) at which point, the remaining three quarters of the load would have burnups of about 10, 20 and 30 MW d kg^{-1} (NEI, 2012).

Whilst there is yet no direct evidence that corium reached the primary containment of any of the three reactor units, as illustrated in Fig. 2 (TEPCO, 2014), accident progression simulations generated by reactor severe accident codes clearly indicate corium breach for at least unit one (Yamanaka et al., 2014; Gauntt et al., 2012). The extent to which melt through has occurred is, however, unknown and probably varies significantly between reactors. In addition, there is considerable uncertainty in what little data is available, for example a recent press release has suggested possibly more melt through in unit 3 than had been previously reported (TEPCO, 2014). More recently, preliminary data from a cosmic-ray muon radiography installation at unit one suggests that most or all of the core has melted and relocated (IRID, 2015). Though this measurement technique has low spatial resolution, it can remotely map the disposition of reactor internals using the density difference between reactor fuel and structural materials (Miyadera et al., 2013; Takamatsu et al., 2015).

2. Characterisation of 1F corium

Corium is a somewhat vaguely defined term applied to the mixture of nuclear fuel and structural materials produced during a reactor core melt accident (EPRI, 2014). Its composition depends on the original type of fuel (UO_2 or MOX, in this case), burnup, the design and materials in the fuel assembly, the temperature profile of the incident, and the extent to which molten fuel reacts with other materials. Before fuel melting, cladding cracks at about 1200 °C, its oxidation begins at about 1300 °C (releasing hydrogen from steam). The zirconium cladding melts at about 1850 °C and reacts with uranium oxide to form a molten eutectic, which would release volatile fission products such as iodine and caesium. However, any bulk UO_2 not in contact with zircaloy will begin to melt at about 2800 °C.

Table 1
Characteristics of units 1–3 at 1F.

Unit	Power (MW)	Fuel load (t_{HM})	No. of assemblies	% melt (JAEA)	% melt (TEPCO)
1	460	77	400	100	100
2	784	107	548	70	57
3	784	107	548	64	63

In the case of TMI, molten fuel interactions were restricted to core components (control rods, fuel assembly, instrumentation, etc.) and the inner wall of the pressure vessel. The material in the case of 1F is likely to be much more complex due to melt through and reaction with the concrete base of the primary containment (Fig. 2). Such liquid fuel/concrete reaction is exoenergetic and would result in a complex range of solid products, further complicated by quenching reactions when the core and containment were flooded, initially with sea water. Corium is inherently heterogeneous and will contain varying quantities of uranium and plutonium along with activation and fission products. Physical forms would include metallic phases, mixed oxides, and aluminosilicates, chlorides and carbonates from reactions with concrete and sea water.

As our focus here is on the management of corium and corium-contaminated materials, we define terminology as the following:

1. “corium” is the main bulk or mass of melted core material that has interacted with other materials such as concrete or steel
2. “corium-contaminated materials” are structure surfaces such as the RPV that have been coated or spattered with corium
3. “fine particles” of fuel debris produced during exoenergetic reactions, which may not be confined solely to surfaces in the RPV or primary containment but may be mobile and transported significant distances (e.g. turbine buildings, water filters, ground water etc.). Fine particles may exist in the form of aerosols (when transported in the gaseous phase), or colloids or suspended particles (when transported in the liquid phase)

After solidification, corium properties will change over the years as it interacts with cooling water – initially including seawater or recycled water with relatively high chloride content. Transformation of corium and corium contaminated material may be confined to surface layers, but, for thin layers or finely dispersed particulate material, complete alteration may occur with loss of soluble elements and erosion of fine-grained reaction products by water flow.

3. Decommissioning approach

There can be advantages in delaying decommissioning to allow decay of shorter-lived radionuclides e.g. 80 years in the case of Windscale (The Engineer, 2011). However the current strategy is to initiate 1F decommissioning as soon as practicable, within the next few decades, and thus planning has already begun. Although the management of corium is only a small component of the required work, it does present some special challenges due to its heterogeneity and potential for localised risks of criticality, flammability and release of highly active fine particles.

Planning of decommissioning is inherently linked to waste storage and disposal concepts. The extreme variants for corium contaminated material and corium would be:

a) Emplacement in transport casks for shipping to off-site storage and final conditioning/packaging/disposal
b) Conditioning, packaging and direct disposal performed on or near site.

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