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Integration of New Experiments into the Reflood Map

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Abstract – *The reflood map, developed in the last decade, was designed as a tool to focus on preventive and mitigative measures to prevent severe core damage scenarios and to identify research areas. In the meanwhile, additional experiments were performed and their data are available, so that an update seems necessary. For homogeneous particulate debris configurations, several experimental programs shed light on coolability. For the transition from in-core early phase to in-core late phase i.e. the loss of the rod like geometry, experimental database is still rather scarce due to the difficulty to describe the state of the core components and the fluid adequately. According to the new insight, an update of the database and the reflood map is discussed, also with respect to assess available grace times.*

I. INTRODUCTION

Main aims of accident management during a severe accident in a light water reactor is to reflood the core, perhaps with external flooding capabilities, and so to achieve long-term coolability. A basic question is under which conditions these aims can be achieved.

An operator in the control room has only limited insight into the core status during an accident: After the reactor is shut down, no neutron flux measurements are available; the in-core instrumentation has already failed; only the sensors for the core exit temperature in the upper plenum may be in function. A support for decisions must therefore rely on another basis.

To find the conditions and limits of coolability, an ongoing activity since 2005 is focused on an overall analysis of the database on degraded core reflood, mostly experiments, available in open literature. For this aim, it is considered helpful to establish a relationship between core exit temperature and core damage state. It should, however, be kept in mind that the experimental boundary conditions differ significantly from those of a reactor due to inherent limitations in experiments. In addition, some uncertainties remain with are based on experimental limitations and peculiarities, intangible experimental domains and scaling barrier. E.g., the successful accident termination in TMI-2 cannot be extrapolated directly to large power plants.

Several papers have been published on establishing and updating of the core reflood map[1,2], focused on the early core melt phase. Due to the ongoing research, the reflood map is considered as a living document. Since the first presentations[2,3], further experiments have been performed so that an update is presented in this report.

II. EXPERIMENTAL DATABASE

The profound investigation of TMI-2, out-of-pile experiments in various test facilities, and some in-pile tests form the present database, listed in the first column of Table I. Except for TMI-2, which is only rather a small nuclear power plant, the scaling between experiments and existing reactors spans 50–9000 in volume and power and 1–20 in length. The Hungarian CODEX (X) tests[5] are performed in 3x3 bundles. The rather new Russian PARAMETER[6,7] (P) tests in Lutch, Podolsk, dedicated to top and bottom flooding, refer to 19 rods in VVER bundles. The FZK reflood experiments CORA (C) and QUENCH (Q) address bundle sizes between 18 and 48 (CORA) 21 and 31 (QUENCH) rods. The central fuel element in LOFT-LP-FP2 (L), amounts to 121 rods[8], and the TMI-2 (T) core had about 37000 rods. The characters in parenthesis are used as abbreviation of the experiments. Most of the experiments address PWR (P) conditions; there are only one BWR (B) and seven VVER (V) reflood experiments, two CODEX, one QUENCH, and four PARAMETER tests. System pressure is classified to be low (L), i.e. below 0.5 MPa, or high (H). Information about the various tests is available in the respective institutions and data bases like that of the Nuclear Energy Agency (NEA).

TABLE I

Overview on experiments about degraded core reflood

Core damage evolution in reflood experiments	Reactor type	Pressure at reflood	Intact / loc. ballooning	Absorber damaged	Fuel rod damaged	Metallic melt relocated	Local debris	Local debris / pool	Global debris / pool	Material relocation ->LH	PCT prior to reflood / during test	Heat-up rate	Steam starvation prior to reflood	Reflood medium	Reflood mass flow rate (RMFR)	Hydrogen before quench	Corrected H2 mass during quench	H2 due to facility effects	Total measured Hydrogen mass	Corrected fraction of total H_2 mass released during quench	Original fraction of total H_2 mass released during quench	Fraction of available Zry mass consumed for H2 production
Data source			0	1	2	3	4	5	6	7	K	K/s			$\frac{g}{s*rod}$	g	g	g	g	%	%	%
CODEX 3/1	V	L									1420 / 1430	0,3		W	0,9	?	?	?	?	?		?
CODEX 3/2	V	L									1773 / 1923	0,6		W	0,9	1	0	?	1	<5		<5
PARAMETER 2	V	L	B								1700 /~1700	?	No	W	5	---	---	?	---	---		---
PARAMETER SF1 (top)	V	L						Tiny			2123 /~2300	2	No	W	1,4	20	54	17	91	73	78	60
PARAMETER SF2 (t+b)	V	L									1770 / 1850	0,2	No	W	5	23,5	1,5	0	25	6	6	
PARAMETER SF3 (top)	V	L									1870 / 1900	0,3	No	W	1,4	31	4,5	0	35,5	13	13	
PARAMETER SF4 (air)	V	L									1900 / 2300	"	Air	W	3,2	21	66	20	107	76	80	
QUENCH IBS05	P	L									1700 / 1750	?	---	W	2,6	20	33	5	58	62	66	34
QUENCH-01	"	L									1830 / 1900	0,7	No	W	1,8	36	1	2	39	3	8	24
QUENCH-02	"	L									2470 / 2500	"	No	W	1,7	20	109	31	160	84	88	83
QUENCH-03	"	L						Tiny			2450 / 2500	"	No	W	1,4	18	103	17	138	85	87	78
QUENCH-04	"	L									2110 / 2340	"	No	S	1,7	10	1	1	12	9	17	7
QUENCH-05	"	L			Partial						2020 / 2270	"	No	S	1,7	25	1	1	27	4	7	17
QUENCH-06 (ISP45)	"	L									2060 / 2150	"	No	W	1,5	32	3	1	36	9	11	22
QUENCH-07	"	L		B_4C							2100 />2300	"	No	S	0,6	62	94	26	182	60	66	*100*
QUENCH-08	"	L			Partial						2070 />2300	"	No	S	0,6	46	35	3	84	43	45	52
QUENCH-09	"	L		B_4C				Tiny			2100 />2500	"	Yes	S	1,8	60	269	131	460	82	87	*211*
QUENCH-10 (Q-L1)	"	L									2180 / 2300	"	Air	W	1,8	46	5	2	53	10	13	33
QUENCH-11 (Q-L2)	"	L						Tiny			2300 />2500	0.6	Yes	W	0,6	9	*83*	*48*	*140*	*90*	*94*	*59*
QUENCH-12 (E110)	V	L									2060 / 2160	0,65	No	W	1,5	34	22	*2*	58	*38*	41	*36*
QUENCH-13	P	L		SIC							2086 / 2086	0,5	No	W	1,7	42	1	*0*	43	*2*	2	*<40*
QUENCH-14 (M5)	"	L									2053 / 2308	0,65	No	W	1,5	34	6	*0*	40	*15*	15	26
QUENCH-15 (ZIRLO)	"	L									2100 / 2130	0,65	No	W	1,5	40	8	*0*	48	*17*	17	31
QUENCH-16	"	L									1870 / 2400	"	Air	W	1,8	16	81	*43*	140	*58*	89	62
QUENCH-17 (DEBRIS)	"	L						Debris			1800 / 1800	"	No	W	0,3	110	1	*0*	111	*1*	1	71
QUENCH-L00	"	L									1330 / 1350	2,5	No	W	3,3	0,7	0,3	*0*	1	*30*	30	*1*
QUENCH-L01	"	L									1340 / 1370	6,5	No	W	3,3	0,7	0,0	*0*	0,71	*1*	1	*0*
QUENCH-L02	"	L									1300 / 1330	7,5	No	W	3,3	0,7	0,0	*0*	0,71	*1*	1	*0*
PBF SFD ST	"	H									>2100 />2700	0.1	?	W	0,5	132	40	0	172	23	?	~23
PHEBUS-CD B9R2	"	L									? / 2150	<0.2	Yes	S	S		0	?			?	?
CORA-12	"	L		SIC							~2000 / 2273	~1	---	W	1,4			?				?
CORA-13 (ISP-31)	"	L		SIC				Tiny			~2100 / 2500	~1	---	W	1,4	142	68	?	210	60		~39
CORA-17	B	L		B_4C							~2000 / 2300	~1	Yes	W	1,4	32	118	?	150	79		?
LOFT LP-FP2	P	H		SIC							2310 /~2700	2.2	---	W	<130	205	819	0	1024	56		~80
TMI-2	P	H		SIC							2100 /~2900	0.5	?	W	~50			0	4.6e5			~30
Paks (CTI)	V	L									1600 / ?	0.1	?	W	?			0				?

For completeness, a PHEBUS SFD in-pile experiment (PHEBUS SFD B9R2, ISP-28) with forced convection cool-down is added[9]. The licensing for the PHEBUS experimental facility did not allow using liquid water due to neutronics feedback with the driver core – so the tests were terminated by shut-down of the driver core and cooling down with helium. For the same sake of completeness, the Cleaning Tank Incident (CTI) at Paks NPP[10] is added.

Local blockages prior to reflood initiation were detected only in CORA-13 by video inspections[11]; in QUENCH-03 and QUENCH-09, some thermocouple readings may be interpreted as affected by a local blockage. Similarly, the only candidate for reflooding of extended local debris is the in-pile test LOFT LP-FP2, due to the high peak cladding temperature (PCT) of ~ 2310 K prior to reflood initiation. Due to the lack of information, reflood with large debris and/or molten pools is discussed elsewhere[12].

The OECD International Standard Problem No. 45, ISP-45, on QUENCH-06 showed that in thermal hydraulics system codes[13], coupled with core degradation modules, and integral codes reflood of a slightly damaged core is principally understood. In the meanwhile, the ongoing code development has improved description of the fuel rod and absorber rod behavior, and of reflood.

Rather a new topic is air ingress. It may happen in maintenance states, spent fuel pool accidents, or in the in-vessel late phase after RPV failure. Presently, the database for air-ingress prior to reflood is relatively scarce. In CODEX-AIT[5], QUENCH-10[14], QUENCH-16[15], and PARAMETER-SF4[7], the bundle was exposed to a mixture of oxygen and nitrogen and cooled down by steam in CODEX-AIT or quenched with water in the other tests.

In the top flooding experiment PARAMETER-SF1, the temperatures in the upper part of the heated part of the bundle (0.6–1.0 m) exceeded 2300 K during reflood similarly to bottom flooding, while the other parts of the bundle were quenched quickly. At a first glance, the reflood occurred similarly to respective tests in the Upper Plenum Test Facility[16,17] (UPTF) facility at Grafenrheinfeld, Germany.

In Table I, the final core damage state (CDS) of the various SFD reflood experiments is given next to information about the reactor type and pressure level, classified in seven stages. Additional information about absorber rod materials (SIC and B_4C) is added as well as information on localized effects found during destructive post-test analysis. “B” stands for ballooning, “tiny” means tiny molten pools between adjacent fuel rods, and “partial” indicates a heterogeneous final state. Furthermore, the spatial extension of a CDS is sketched by light and bright colors.

For LOFT and TMI-2, the CDS can be estimated to 3 or 4 (debris without pool formation). A more precise classification is difficult due to the different histories before quench initiation. In QUENCH tests, the bundle degradation prior to reflood initiation can mostly be classified to CDS 1 to 3. The debris test QUENCH-17[18,24,25] is difficult to interpret in this context, since the temperatures were below 1800 °C, no temperature increase was measured during reflooding, and no additional damage was observed. However, it turned out that due to the long pre-oxidation time with steam and air, the remaining oxidation potential is rather low so that only decay heat driven temperature increase can transform the debris to a molten pool. In case of a faster heat-up rate, the temperature would exceed 1800 °C, leading to clad and fuel damage. The QUENCH-Debris test has not reached CDS 6, since the outer ring of fuel rods (with tungsten heaters) and the four corner rods remained intact. This means that about 76 % of the bundle cross section inside the shroud is filled by debris.

Information about CDS 5 and subsequent ones is scarce, because related integral experimental investigations are expensive and very difficult to perform, especially because sophisticated on-line instrumentation is required to detect bundle status prior to reflood. In addition, the loss of bundle geometry cannot be simulated correctly by electrically heated rods. Moreover, the lateral damage progression cannot be represented correctly so that dedicated small-scale two-dimensional-model experiments have to be performed for code qualification[19].

All CORA, QUENCH, and PARAMETER tests were terminated before reaching CDS 6, which, in contrast, is achieved in all PHEBUS FPT tests. Due to the forced convection, a flow path is established between debris/molten pool and the colder shroud allowing sufficient steam to pass. For the small bundle size, this channel is sufficient to quench this configuration. A successful review requires a detailed knowledge of the test facility and detailed analysis of the test sequence to identify time and locations of the deviation from prototypical behavior based on destructive post-test examinations[19].

In the next section of Table I, the peak cladding temperature (PCT) is given prior to and after reflood initiation indicating the additional energy release due to Zry oxidation, which intensifies the core degradation and hinders fast quenching. Heat-up rate and information about steam supply are added, because these factors determine the oxide layer thickness as well as the reflood medium steam or water is added. The reflood mass flow rate is given as an injection mass flow rate per rod (RMFR), the shroud and other relevant structure elements being taken into account as additional rod surfaces. RMFR is related to the interaction between fluid and rods such as oxidation and melt relocation.

Hydrogen production before reflood initiation, contributions from non-prototypical reactions (formation of molybdenum and tungsten oxides in QUENCH tests[20]) and measured total hydrogen mass are given explicitly in Table I. The latter might be overestimated in QUENCH tests[21] and needs some further clarification. The contributions from non-prototypical reactions are subtracted from measured hydrogen production after reflood initiation and labelled “Corrected H_2 mass during quench”. The ratios of corrected and measured hydrogen production during quench to the respective hydrogen production during the whole test are added for comparison. The last column shows the fraction of consumed Zry, normalized to bundle sections at temperatures above 1500 K, corresponding to a bundle segment from about 0.6 to about 1.2 m elevation. For two experiments, QUENCH-07 and QUENCH-09, these values are close to or even exceed 100 % for unknown reasons.

III. NEW EXPERIMENTS

Two QUENCH experiments are of large interest for the reflood database. QUENCH-11 was dedicated to investigate the reflood behavior under low mass flow rates and QUENCH-17 dealt with reflood of a fuel rod bundle with particulate debris. A follow up experiment on debris-quenching is planned in the near future.

III.A. QUENCH-11

Test QUENCH-11[22] covers the whole accident scenario: It consists of a LOCA pre-test which leads to a certain pre-oxidation, which was followed by the simulation of boil-down, dry-out, core heat-up, and early degradation phases until the damaged bundle was flooded slowly. An RMFR of 0.6 g/s*rod was chosen to be below the critical value of ~ 1 g/s*rod, deduced from PBF SFD-ST and LOFT LP-FP 2 analyses[23]. This low value was selected to account for the shroud in the QUENCH facility, which only contributes by oxidation.

In a first step (Q11v3), this test sequence was performed for normal design basis conditions, hence at temperatures below 1500 K, giving a complete set of experimental data. In the main test, the water in the filled test section was evaporated by means of bundle power and an auxiliary heater in the lower plenum, which was necessary to provide a sufficient evaporation rate in case of low water level. The auxiliary heater simulates the decay heat released in the lower sections in the core and produces steam for cooling and oxidation in the upper part. The boil-down phase was extended by injecting additional water to simulate the water in the downcomer of an LWR. Finally, to protect the lower electrode zones, the water level was stabilized below the heated zone. Due to its relevance for possible AMM (Accident Management Measures) situations, QUENCH-11 was chosen as a SARNET code benchmark. The benchmark[31] indicated the need for further experimental and analytical work to get reliable predictions under such extreme situations. However, it becomes clear that degraded core reflood under such conditions should not be considered for AMM.

III.B. QUENCH-17

The bundle degradation and deformation were investigated during the experiment QUENCH-17 on debris formation[18,24,25]. Its primary aims were to examine the formation of a debris bed inside the completely oxidised region of the bundle without melt formation and to investigate the coolability phenomena during the reflood of the damaged bundle with debris particles of fuel simulators without active volumetric heat sources.

Post-test examination showed the formation of a debris bed between elevations 400 and 750 mm, which was indicated by the stagnation of water front propagation and oscillations of evaporation rate in this region. The debris bed above 750 mm was formed mostly by the post-test dismounting of the bundle head. The debris particles are randomly distributed without formation of dense packing. Partial blockages (maximum 85 % at 400 mm) by relocated pellet segments and oxide scales spalled from Zircaloy claddings as well as large empty volumes between bended rods were detected.

Most of the Zry-4 claddings experienced relatively limited damage, and there was generally only minor damage of the geometrical integrity of the nine inner rods. Ceramic debris collected at the top of spacers consists of separate pellet segments and relatively large oxidized cladding segments. The porosity of the debris bed is significant, no dense packing of debris particles was observed. Large empty volumes formed due to bending of rods. The maximum bundle blockage is about 85 %. This blockage does not affect noticeably coolability of the bundle until the end of the test. However, this effect is a consequence of an unavoidable difference of such laboratory experiments and nuclear reactors. In the experiment, the mass flow rate is prescribed and as far as there is a remaining flow passage, the entire mass flow passes through the bundle. In a reactor, however, a large number of parallel channels (subassemblies) exist. If one of them or even a number of them is blocked seriously, the flow bypasses the blocked subassemblies easily.

IV. INTERPRETATION OF THE DATABASE

The instrumentation of integral experiments delivers a huge amount of data, which have to be assessed and compared with each other for consistency before any interpretation. The consistency check has to consider the individual sensitivity as well as the uncertainties caused by position, type, and characteristics of the sensors. Therefore, especially for integral data such as hydrogen mass or amount of core degradation, separation between facility based and reactor specific or prototypic effects is necessary to qualify the measured values.

Such detailed knowledge is only available for the QUENCH tests. In these tests, it was seen in post-test examination that oxidation of tungsten heaters and molybdenum electrodes[20] may contribute markedly to overall hydrogen production. It only plays a role for temperatures above 2300 K, when the tungsten and molybdenum heater material may become exposed to steam atmosphere like in the quench phase of a QUENCH experiment.

In case of bundle degradation, quantification of the facility related effects is very difficult because of the essentially one-dimensional type of bundle experiments and the facility specific electrical heaters that stabilise decladded pellet stacks.

An important finding can be derived from Table I: If reflood mass flow rates are sufficiently high, the fuel rod bundles including localized debris are quenched or cooled-down successfully, if their final damage level does not exceed CDS 4. In such cases, the final configuration allows long-term coolability. In case of CDS 5, the experimental findings are not conclusive for commercial reactors, since in such conditions the spatial extension of the debris/pool becomes significant. In case of QUENCH-17, the temperatures were too low to derive a reliable assessment.

V. RELEVANT PARAMETERS

A number of important parameters that influence the course of an accident can be deduced from the available experimental database. They are listed in Table II together with the parameters they depend on and the parameters they influence. Their possible range and the range, covered by available experiments, indicate the field of open issues.

The CDS prior to reflood can be assessed from PCT and experience from CORA tests. It reflects the scenario history, e.g. heat-up rate, steam availability, etc. and is therefore the most important parameter. As a first approach, the CDS was characterized by the PCT alone. According to the present knowledge, it seems promising also to take into account the core heat-up rate as well as steam availability at high temperature. Presently, the influence of steam starvation turns out to be the most dominant parameter for hydrogen production during reflood. However, such evaluations of the integral tests have to be clarified by separate effects tests and code calculations. The respective data available from the QUENCH facility are included in Table I; however, a comprehensive analysis is still open.

VI. REFLOOD MAP

If we restrict the further analysis on two parameters only, namely RMFR and the CDS prior to reflood initiation, the results of the tests can be arranged in a reflood map (Table III), focused on the damage progress (left) and the relative amount of hydrogen production during reflood with respect to total hydrogen production (right). For this variable, also called H_2 in the table, corrected values are used to exclude the non-prototypical reactions in the experiments. The range of the RMFR, together with a typical number of active emergency core cooling (ECC) systems, shown in the left column, refers to both parts of the figure. The experiments are located according to the CDS and indicated literally as mentioned in section II. The light green fields in the left part of Table III indicate reflood without serious damage propagation, while the yellow color indicates significant bundle damage. Light blue fields show that experimental evidence is unreliable because of lacking data. For such scenarios, simulations and experimental analyses are required, especially for the debris/molten pool region. The relative hydrogen production H_2 is divided into three categories: i: below 20%, ii: above 20% but below 50% and iii: above 50%. In some cases, a clear identification is doubtful, because of the experimental uncertainties. Therefore, intermediate categories (i-ii, ii-iii) are included. Due to the difficult interpretation of the debris test QUENCH-17, labelled QD, – temperatures below 1800 °C, no temperature increase measured during reflooding, and no additional damage observed – the color coding has to be green.

Accident sequence analyses with S/R5 and ASTEC cover the light blue region in Table III. They reveal that low mass flow rates can lead to unexpected adverse effects, if nearly all evaporated water is consumed by the Zircaloy in the core and nearly pure hydrogen is released into the containment. Such situations may occur, if an unsufficient number of ECC systems is activated by AMM or the performance of the activated ECC system is too low. From the results of QUENCH-11, the RMFR of 0.6 g/(s rod) is sufficient to cool a 1.2 m long rod bundle, but it is not sufficient to cool a fully dry core without formation of a large in-core pool.

Table III demonstrates that the reflood initiated core damage progression and the additional hydrogen production show a similar behavior as can be expected, because all physical and chemical effects that contribute to damage progression need a high and increasing temperature for their continuation and enhancement. In addition, the table indicates a limit for successful core reflood. Including TMI-2 as an extreme case, the conclusion may be drawn that with increasing core damage increased reflood capability is necessary to maintain coolability. The unfavorable effect, however, is that hydrogen release increases with damage progression, and this affects the hydrogen countermeasures in the containment, if not sufficient steam is fed into the containment to avoid hydrogen deflagration or explosion. A high steam mass flow rate into the containment leads to a temporal inertisation of the containment.

TABLE II

List of global parameters and their dependencies

Parameter		Variable	Depending on	Influence on	Total range	Exp. Range	Unit	Data base	Extension possible
1	Core Damage state	CDS	PCT, CABU, Psys, Reactor, Clad-Material	Long term cooling	1-8	1-5+	Phase	C,Q,X, P,L,T	QD: Debris P: molten pool
2	Reflood mass flow rate	RMFR	WIP, Psys	Core damage progression	0.5-180	0,6-130	g/s*rod	Q	---
3	System pressure	Psys	Reactor, AMM	Fluid entrainment, RMFR	1-17	~0.2	MPa	T	P-STLOC cancelled
4	Injection position	WIP	Reactor, AMM	Fluid entrainment	top/ bottom	bottom, top/bottom	---	P	PARAMETER-SF2, SF3
5	Core average burn-up	CABU	Core loading & age	FP release, power density	0-55	<1	GWd/t	--- (T)	?
6	Core loading MOX	MOX	Core loading & age	FP release, power density	0-50	0	% MOX	---	?
7	Core size	CS	Reactor type power density	pool spreading & crust failure	1-3	1,5	radius m	--- (T)	

The abbreviations in column "Database" is explained in section II.

From an inspection of the database, addressed in section II, and best estimate calculations we learn that below about 2200 K the risks of adverse effects during reflood, such as massive hydrogen release or accelerated damage progression, can be practically excluded, if sufficient reflood capacity is activated. In particular, the QUENCH experiments strongly support the existence of a minimum RMFR value for successful core reflood of about 1 g/(s rod)[29]. Above 2200 K, the behavior is difficult to predict and depends on parameters such as core configuration and size, reflood mass flow rate, water injection position (top/bottom or both positions), system pressure, fuel type, and maybe burn-up. Under such extreme conditions, a quantification of the hydrogen source term is difficult to achieve[21]. It is emphasized, however, that this result is strictly speaking constricted to the available data basis. Parameters like the speed of the transient or material aging is not covered by the available data basis and might give further insight or restrictions.

VII. DEBRIS REFLOOD

An open issue for the reflood map is the flooding of debris at high temperature, when melting transforms the particulate debris into cohesive debris with melt inclusions. That situation can turn a coolable configuration into an uncoolable one, if the pool grows despite of reflood. The decay heat in the pool has to be released to the fluid via the crust and the surrounding debris. If debris dry-out occurs, pool temperature rises. Numerical investigation revealed that successful cool-down is only possible, if the molten pool thickness does not exceed app. 0.2 m.

Respective experiments are very challenging: volumetric heating, done by inductive heating, is difficult to achieve, since only metals couple sufficiently to the electromagnetic field. Therefore, the maximum temperature is limited. However, the general findings can be summarized and updated for integration into a future reflood flow map. Here several experiments (DEBRIS[26,27], PEARL[28]) have been performed and/or are under way. Their results have to be scaled up to higher temperatures to include the findings into the reflood flow map.

VIII. SUMMARY AND CONCLUSIONS

The reflood map on core degradation and hydrogen release reflects the actual status of research on degraded core reflood and identifies white areas for effective future experimental work[2]. Steam starvation before reflood with the consequence that oxide scales may be reduced and oxidation is enhanced during reflood is not yet addressed correctly, mainly because of lacking experimental data. Besides, system pressure, core composition (MOX or high burn-up), and core size have to be investigated analytically using validated code systems. The present knowledge is summarized in a proposal[30] to assess the probability ranges for plant internal phenomena during core melt down scenarios for German LWRs.

TABLE III

Reflood map

Core damage evolution during reflood phase	Accident Termination							Released Hydrogen fraction						
	Absorber damaged	Fuel rod damaged	Fuel relocated	Metallic blockages	Local debris/pool	Global debris/pool	Relocation-> LP	Absorber damaged	Fuel rod damaged	Fuel relocated	Metallic blockages	Local debris/pool	Global debris/pool	Relocation-> LP
Flow rate (g/s*rod)	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Reflood mass flow rate -->														
TMI-2: ~50 (BPT)						T	T					T	T	T
Loft LP-FP2				L	L	L					L	L	L	
very high (> 9.0)														
All HP-SI + LP-SI														
high (2.0 - 9.0)		P	P						P	P				
All LP-SI		Q							Q					
medium (1.0 - 2.0)			P	Q	Q					P	Q	Q		
All HP-SI			Q	C	C					Q	C	C		
low (0.6... 1.0)			Q	PBF						Q	PBF			
single HP-SI		X	Q						X	Q				
very low (< 0.7)				Q	QD						Q			
other														
Accident progression →														

W.Hering Dec 2014

Successfull termination	C CORA	i H_2 < 20%	i - ii
Termination with add. damage	Q QUENCH	ii 20 < H_2 < 50%	ii - iii
Extrapolation unproblematic	QD QUENCH-Debris	iii H_2 > 50%	
Extrapolation problematic	X CODEX		
Uncertain area	P Parametr	T TMI-2	
No experimental data	L LOFT LP-FP2	PBF PBF SFD-ST	

In the table, experiments are aligned by available reflood mass flow rate (vertical) and core damage state (horizontal) for damage progression (left) and additional hydrogen release during reflood (right). The status is of June 2014.

Nevertheless, extrapolation can be performed using qualified codes until melting transfers particulate debris via cohesive debris into a molten pool. For that situation, only experiments performed for long term cooling of corium in a core catcher are available.

A very important issue for AMM is the grace time for plant operators. When design basis conditions regime are exceeded, i.e. above 1200 °C, the time to reach transition from localized debris to molten pool can range between 20 and 30 minutes depending on the scenario. This is not that much, but it may help to bring additional systems on-line so that a sufficient reflood mass flow rate can guarantee successful accident termination.

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