Integration of New Experiments into the Reflood Map

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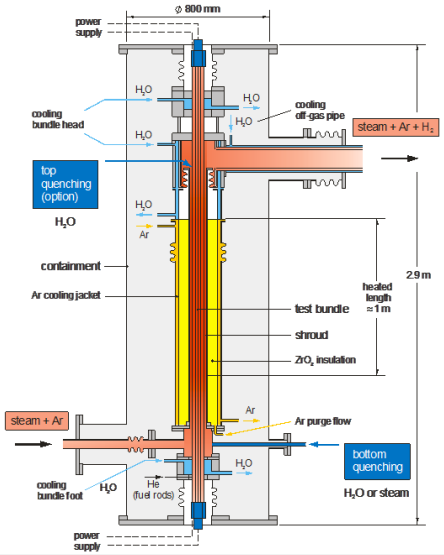

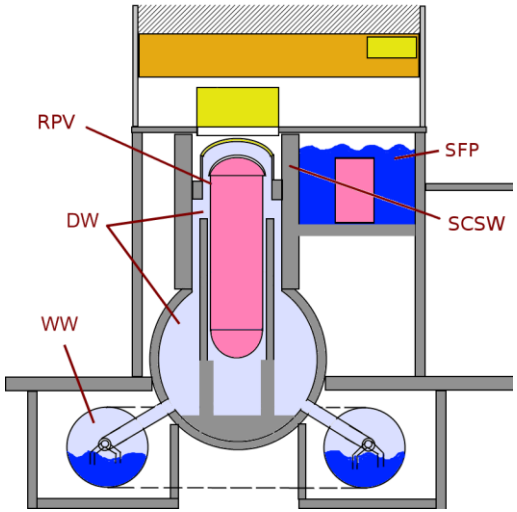

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Motivation

General objectives

- Foster code development and validation
- Provide fast selection for adequate code qualification based on data from open literature
- Selection of local and global parameters
- Identification of vacancies in the database

➔ Living document on accident termination by reflood

Long term aspects

- Education and training:
  Long time span starting with first LWR accidents
  Gundremmingen (1977), TMI-2 (1979),…
- Identify weaknesses in existing code families
- Extension to long term coolability:
  Successful reflood does not enforce long term coolability
- Provide necessary insights to owners and operators
  Support SAMGs

Database: contents

Core damage state and evolution	Temperatures, heat-up rates, steam starvation prior to reflood	Reflood medium and mass flow rate	H_2 data	Fraction of Zry consumed for H_2 production

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

Database

Total contents: 36 experiments

Type & Scale:

- Prototypic: LOFT, TMI-2
- Integral (bundle) experiments

  In-pile:
  LOFT(1),PHEBUS SFD(1), PBF(1)

  Out-of-pile:
  CORA(3), QUENCH(18+3),
  PARAMETER(5), CODEX(2)

- Prototypic materials: 15
- Syst. Pres: Low: 34
  High: 2

- PWR: 26
- VVER: 9
- BWR: 1

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
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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	
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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				?

Database: new experiments

- New cladding materials (restricted)
- QUENCH-12: VVER
- QUENCH-17: DEBRIS
- PARAMETER: top, top + bottom flooding

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QUENCH-10 (Q-L1)	"	L									2180 / 2300	"	Air	W	1,8	46	5	2	53	10	13	33
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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*

Global parameters for degraded reflood

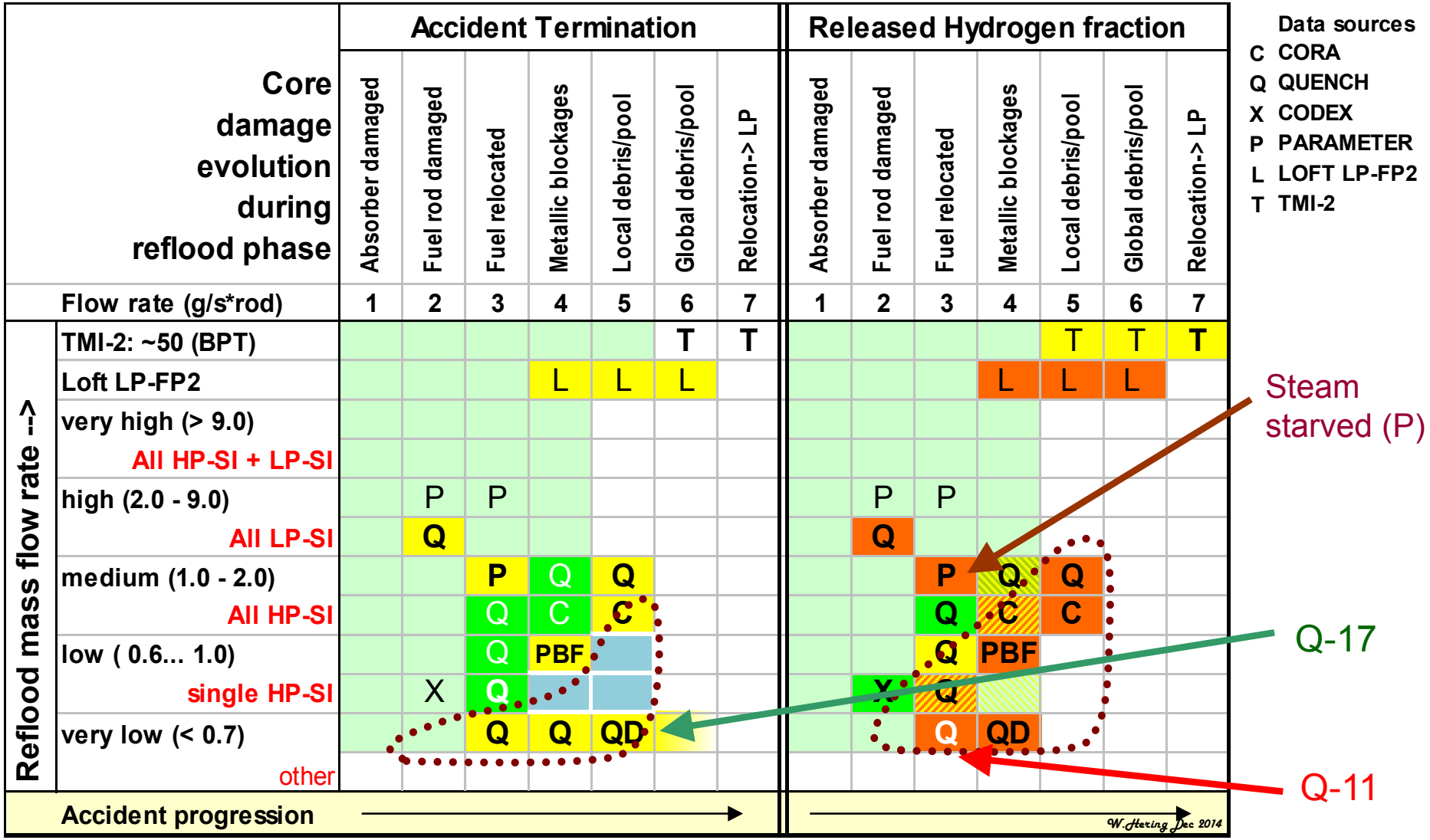
Parameter	Variable		Depending on:	Influence on:	Total range	Exp. Range		Data base	Extension possible
1	Core Damage state	CDS	PCT, CABU, Psys, Reactor, Clad-Material	Long term cooling	1-8	1-5+	Phase	C,Q,X, P,L,T	Q: Clad, debris P: molten pool
2	Reflood mass flow rate	RMFR	WIP, Psys	Core damage progression	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	
4	Injection position	WIP	Reactor, AMM	Fluid entrainment	top/ bottom	bottom, top/bottom	---	P	PARAMETER-SFxx
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)	PEARL ? DEBRIS ?

Data sources

C	CORA	P	PARAMETER
Q	QUENCH	L	LOFT LP-FP2
X	CODEX	T	TMI-2

Experimental limitations (transition to late phase):
- heat source redistribution (only in L, T)
- 3 D only in TMI-2 or LOFT

Reflood Map


Accident Termination
Released Hydrogen fraction
Core damage evolution during reflood phase
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
Reflood mass flow rate -->
TMI-2: ~50 (BPT)
Loft LP-FP2
very high (> 9.0)
All HP-SI + LP-SI
high (2.0 - 9.0)
All LP-SI
medium (1.0 - 2.0)
All HP-SI
low (0.6... 1.0)
single HP-SI
very low (< 0.7)
other
Accident progression
Data sources
C CORA
Q QUENCH
X CODEX
P PARAMETER
L LOFT LP-FP2
T TMI-2
Steam starved (P)
Q-17
Q-11
W.Hering Dec 2014

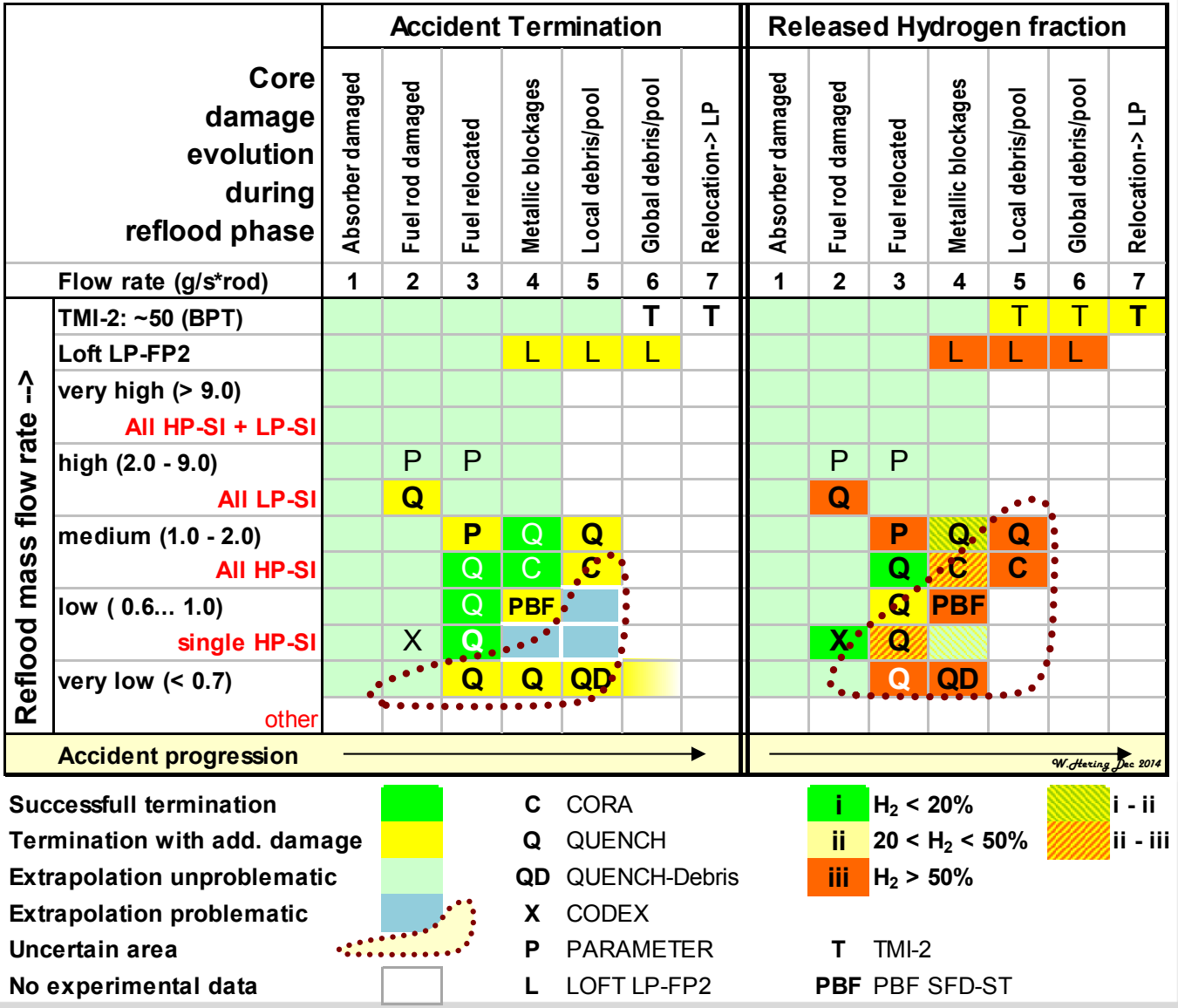
Insight

Solved:

1. PWR
2. Reflood above water > 1 g/s*rod
3. Local blockages
   - metallic
   - ceramic

Lacking data:

1. BWR
2. Debris reflood
3. Core size: 3D effect ?



Summary

- Data base and reflood map are living documents and require constant update
  - Included new experiments fit into reflood map
  - QUENCH debris test opened new field
- For new experiments: reduced budget requires more efficient preparation and performance
- Database to foster education and training (AREVA Nuclear Professional School)
- Efficient transfer of knowledge to owners and operators has to be promoted

- Still open issues:
  1. BWR database and
  2. Debris reflood

Outlook: BWR experiment similar to Q-11

Start from shut down state

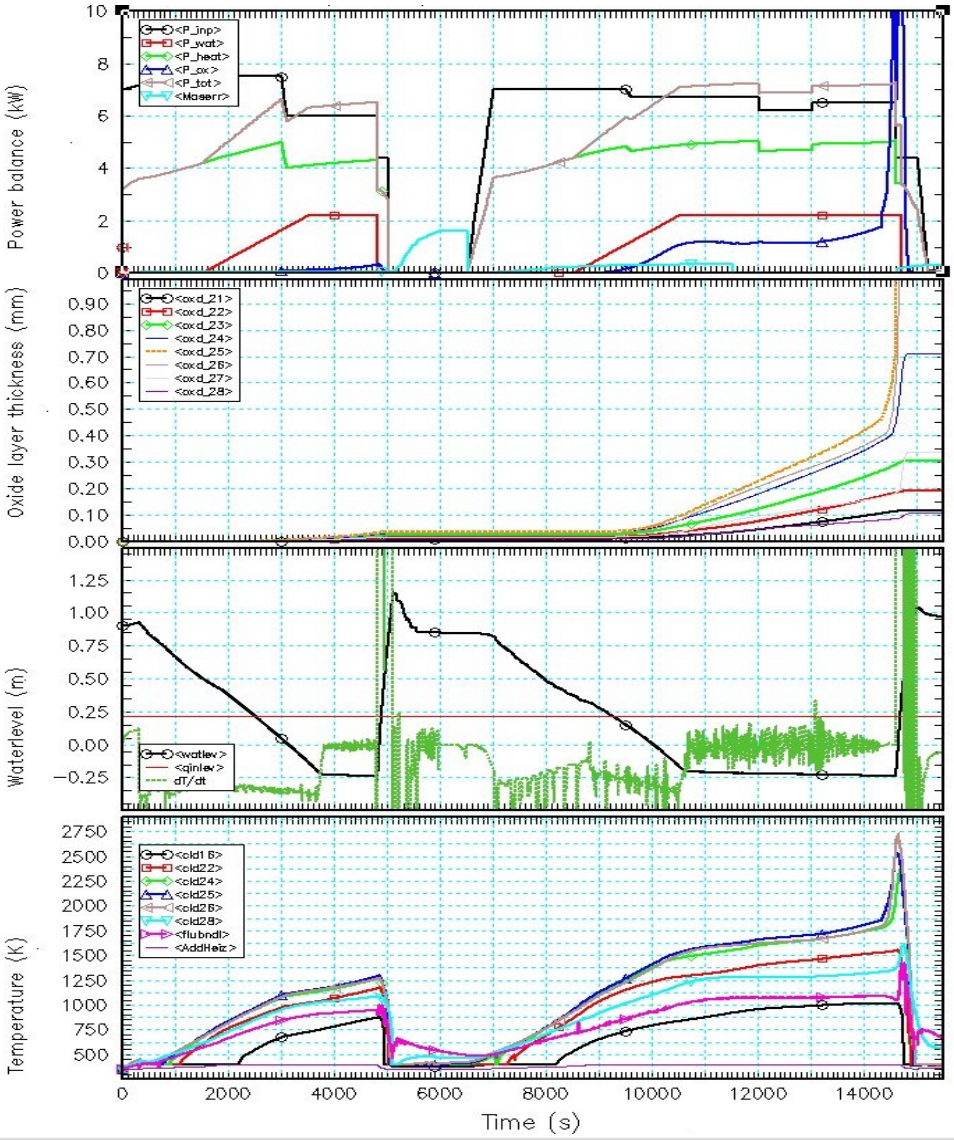
Pre-test:

Refill by RCIC

Main test:

1. Steaming rate t.b.d. before reflood
2. Water reflood with t.b.d. g/s*rod

→ simplified Fukushima sequence



HELMHOLTZ ASSOCIATION

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THANK YOU FOR YOUR ATTENTION

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