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RELEVANT THERMAL HYDRAULIC ASPECTS OF ADVANCED REACTORS DESIGN

STATUS REPORT - November 1996

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Paris

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STATUS REPORT ON
"RELEVANT THERMALHYDRAULIC ASPECTS OF ADVANCED REACTOR DESIGNS"

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Abstract

This status report provides an overview on the relevant thermalhydraulic aspects of advanced reactor designs. Since all of the advanced reactor concepts are at the design stage, the information and data available in the open literature are still very limited. Some characteristics of advanced reactor designs are provided together with selected phenomena identification and ranking tables. Specific needs for thermalhydraulic codes together with the list of relevant and important thermalhydraulic phenomena for advanced reactor designs are summarized with the purpose of providing some guidance in development of research plans for considering further code development and assessment needs and for the planning of experimental programs.

Acknowledgment

The authors acknowledge receiving some of the very recent studies as draft reports from Dr. F. Eltawila (US NRC), and review provided by Dr. N. Lauben (US NRC) and Prof. Dr. G. Yadigaroglu (ETH Zurich, Switzerland).

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Nomenclature

ABB 80+	ASEA Brown Boveri, system 80+ reactor
ABWR	Advanced boiling water reactor
ADS	Automatic depressuirization system
ALWR	Advanced light water reactor
AP600	Advanced passive pressurized water reactor
ARD	Advanced reactor design
CANDU	Canadian, natural uranium fuelled, heavy water moderated and cooled reactor (Canada Deuterium Uranum reactor)
CMT	Core makeup tank
CSNI	Committee on the Safety of Nuclear Installations
ECC	Emergency core cooling
EPR	European pressurized water reactor
GDCS	Gravity driven coolant system
LWR	Light Water reactor
MSLB	Main steam line break
PIRT	Phenomena identification and ranking tables
PIUS	Process Inherent Ultimately Safe reactor
PWG-2	Principal Working Group no. 2
SB LOCA	Small break loss of coolant accident
SBWR	Simplified boiling water reactor
SGTR	Steam generator tube rupture
TG-THSB	Task Group on Thermalhydraulic System Behaviour
US.NRC	United States Nuclear Regulatory Commission

1. Introduction

As proposed and recommended by the Task Group on Thermalhydraulics System Behaviour (TG-THSB) of the Principal Working Group no. 2 (PWG-2) and approved by the Committee on the Safety of Nuclear Installations (CSNI) at the end of 1993, it was decided to write a status report on the relevant thermalhydraulic aspects of advanced reactor designs. In the mean time, there has been presentations on different advanced reactor designs (ARDs), e.g., ABWR, AP600, SBWR, EPR (European Pressurized Water Reactor), ABB 80+, PIUS, etc., at the meetings of the THSB Task Group (references 1-10). These presentations included various aspects of the ARDs, such as, general design criteria, certification process in licensing, experimental programmes, some selected results of experiments. Since most of the ARDs are at the design stage, the information and any data available in the open literature on these designs are limited.

This status report will provide a short summary on the important and relevant thermal-hydraulic phenomena for advanced reactor designs in addition to the relevant thermal-hydraulic phenomena identified for the current generation of Light Water Reactors (LWRs). The purpose of these relevant phenomena lists is that they can provide some guidance in development of research plans for considering further code development and assessment needs, and for the planning of experimental programs.

2. Some characteristics of Advanced Design Reactors

New designs -designs that have not yet been built or operated- are generally called advanced designs. These can be categorized into three groups (as given in table I):

1. Evolutionary ALWRs: If they are of current interest or merit, and if they do not deviate too much from their predecessors. The designers have retained many proven features of today's plant designs, and the evolutionary plant designs therefore require at most engineering and confirmatory testing of some components and systems prior to commercial deployment. Examples for this category are ABWR, ABB System 80+ and, EPR.

2. Passive ALWRs: ALWRs are also being developed with a great emphasis on utilization of passive safety systems and inherent safety features. Two typical examples in this context are the Advanced Passive PWR (AP-600) and the Simplified BWR (SBWR)

3. Other advanced reactors : In addition to the ALWRs mentioned above, there are other advanced designs e.g., PIUS, CANDU-3, etc.

All ALWRs incorporate significant design simplifications, increased design margins, and various technical and operational procedure improvements, including better fuel performance and higher burnup, a better man-machine interface using computers and improved information displays, greater plant standardization, improved constructability and maintainability, and better operator qualification and simulator training.

Design features proposed for the passive ALWRs include the use of passive, gravity-fed water supplies for emergency core cooling and natural circulation decay heat removal for the AP600 and SBWR, and natural circulation cooling within the SBWR core for all conditions. Both plants also employ automatic depressurization systems (ADSs), the operation of which are essential during a range of accidents to allow adequate emergency core coolant injection from the lower pressure passive safety systems. The low flow regimes associated with these designs will involve natural circulation flow paths not typical of current LWRs. These passive ALWR designs emphasize enhanced safety by means of improved safety system reliability and performance. These objectives are achieved by means of safety system simplification and reliance on immutable natural forces for system operation. Simulating the performance of these safety systems is central to analytical safety evaluation of advanced passive reactor designs.

Specifically, the passive safety principles of the next generation ALWR designs include:

(1) low volumetric heat generation rates

(2) reliance solely on natural forces, such as gravity and gas pressurization, for safety system operation,

(3) dependence on natural phenomena, such as natural convection and condensation, for safety system performance.

The engineered safety features which incorporate these passive safety principles achieve increased reliability by means of system redundancy, minimization of system components, non-reliance on external power sources, and integral long term decay heat removal and containment cooling systems. In the design of the current generation of operating reactors, redundancy and independence have been designed into the protection systems so that no single failure results in loss of the protection function. Since the new passive ALWR designs incorporate significant changes from the familiar current LWR designs and place higher reliance on individual systems, a thorough understanding of these designs is needed with respect to system interactions. These interactions may occur between the passive safety systems e.g., the core makeup tanks and accumulators in the AP600, and the ADS system and isolation condensers in the SBWR. In addition, there is a close coupling in both plant designs between the reactor coolant system and the containment during an accident.

It can also be noted that in order to fully profit from the safety benefits due to the introduction of the passive safety systems, the behaviour of plants in which engineering safety features involving active components have been replaced with completely passive devices must be carefully studied to ensure the adequacy of the new design concepts for a wide spectrum of accident conditions. In fact, choice of passivity is an advantage in reducing the probability of the wrong operator interventions, especially in the short-term period after an accident, although passive systems require more sophisticated modelling techniques to ascertain that the natural driving forces that come into play can adequately accomplish the intended safety functions. Hence, there is also the need for an in-depth study of the basic phenomena concerning the design of ALWRs which make use of passive safety features. Consequently, although other advanced reactor designs are listed for completeness here, mostly the passive ALWRs are discussed.

3. Phenomena identification and ranking tables

The process of analysis and qualification of the performance of the ALWRs starts with the identification of the physical phenomena that are important to the thermalhydraulic behaviour of a particular plant during a particular accident scenario. For this purpose, phenomena identification and ranking tables (PIRT) is developed, using the similar process identified in ref. 11. This is done by assembling a team of experts knowledgeable about thermalhydraulics and transient analysis, and obtaining consensus on relative importance of various phenomena. In addition, each phenomenon that is deemed of significance is assigned a relative importance ranking, e.g. high (H), medium (M), or low (L) importance. The PIRT is developed by first identifying the plant and the accident scenarios with subdivision of time phases. For each accident phase, a key response is identified, along with important plant parameters affecting that response. The processes that dominate the evolution of the important parameters are then identified, leading to the phenomena to be evaluated. The phenomena and their respective importance are then judged by examination of available experimental data, code simulations related to the plant and scenario, and the collective expertise and experience of the expert team.

Examples of PIRTs established by US.NRC for AP600 (SBLOCA, MSLB and SGTR accidents) and for SBWR (MSLB, Bottom drain line break, GDCS line break transients) are provided in tables 2, and 3, respectively, references 12 and 13. A summary of SBWR PIRTs is presented in table 4 (ref. 14) as composite SBWR PIRT, showing for each phenomenon only the highest rank that it received in the three transients with five time phases each (Table 3). This table can serve as a first overview of code modeling requirements and data base needs for SBWR-LOCA analyses.

In table 2, PIRT results for AP600 include accident scenarios at the top of the table. The accident phases (numbered 1 through 5 near the top of the table) correspond to the chronological order, of phases described for accident scenarios. These accident phases are as follows:

Phases of SB LOCA transient

1: Short-term phase (High pressure phase, ADS blowdown)
2: Long-term phase (Long-term in-containment refueling water storage tank (IRWST), Long-term sump)

Phases of MSLB without ADS and SGTR without ADS transients:

1: Initial depressurization
2: Passive decay heat removal

Phases of MSLB with ADS, and SGTR with ADS transients:

1: Initial depressurization
2: Passive decay heat removal
3: CMT draining to ADS actuation
4: ADS blowdown
5: In containment refueling water storage tank and sump injection

The left hand columns of the table is organized alphabetically by component name; with the exception that containment components are listed last. Within each component listing, the phenomena are marked with H (high), M (medium), L (low). The similar layout is also used for the combined SBWR PIRT tables (Table 3).

4. Expected Relevant Phenomena

Thermalhydraulic phenomena relevant to the evolutionary type ALWRs can be considered the same as those valid for the current generation LWRs. A suitable review of applicable phenomena can be found in CSNI reports 132 (ref. 15) and 161 (ref. 16) and in NRC report NUREG-1230 (ref. 17). For completeness, the list is reported in Tab. 5. A limited specific research activity in this area appears necessary, if one excludes new domains like Accident Management and special topics like instability in boiling channels where the interest is common to the present generation reactors.

In the case of passive and other advanced reactors (only water cooled cases) the foreseeable relevant thermalhydraulic phenomena can be grouped into two categories (ref. 18):

a) phenomena that are relevant also to the present generation reactors;

b) new kinds of phenomena and/or scenarios.

For the category a) the same considerations apply as for the evolutionary ALWRs and the phenomena of concern are therefore well documented in references 15 to 17. However, it has to be noted that significance of various phenomena may be different for the passive and advanced reactors. Nevertheless, it is believed that the data base, understanding and modelling capabilities acquired for the current reactors are adequate for phenomena in category a).

Phenomena of the category b) can be subdivided into three classes, also considering the PIRTs (Tables 2,3 and 4) for AP600 and SBWR:

b1) phenomena related to the containment processes and interactions with the reactor coolant system

b2) low pressure phenomena

b3) phenomena related specifically to new components, systems or reactor configurations

In current generation LWRs the thermalhydraulic behaviour of the containment system and of the primary system are studied separately. This is not any more possible in most of the new design concepts; suitable tools must be developed to predict the performance of the integrated system.

A speciality common to almost all the advanced design reactors is the presence of devices that depressurize the primary loop essentially to allow the exploitation of large amount of liquid at atmospheric pressure and to minimize the risk of high pressure core melt. In this case, the phenomena may be similar (or the same) as those reported for current generation LWRs (Tab. 5) but the range of parameters and their safety relevance can be much different.

Finally, the presence of new systems or components and some geometric specialities of advanced design reactors require the evaluation of additional scenarios and phenomena.

A list of identified phenomena belonging to subclasses b1, b2 and b3 is given in Tab. 6; comments related to few of these are reported below.

Behaviour of large pools of liquid (item 1 in Tab. 6)

Large pools may have a very wide spectrum of geometric configurations. Heat transfer in one very limited zone in terms of volume (e.g. by condensing injected steam or by heat transfer from an isolation condenser) does not imply homogeneous or nearly homogeneous temperature in the pool. Three-dimensional convection flows develop affecting the heat transfer process. Liquid drain from relatively small openings may cause rotation of the fluid and entrainment of the gas phase (vortex formation).

Tracking of non-condensables (item 2 in Tab. 6)

The non-condensable gases play much more important role in safety evaluation of the advanced design reactors than for the current generation reactors, particularly because of the coupling of the containment with the primary system. Flow of the non-concensables within the containment and potential stratification and separation of steam and non-condensables constitute an important factor to consider, since it may affect heat transfer within the containment and out of the containment. Also, within the primary system the nitrogen transport from accumulators may affect the coolant distribution and pressure response to the degree that gravity driven safety injection may be impacted.

Non-condensable gases are also an important factor in determining the efficiency of isolation condensers and condensing heat exchangers.

Thermofluiddynamics and pressure drops in various geometrical configurations (item 5 in Tab. 6)

Owing to the lack of pumping power, the circulation among the various zones of the system constituted by the primary circuit and the containment depends upon relatively small driving forces. The presence of obstacles like bends, valves, etc., that have no special relevance when pumps are running, can be important for the evolution of the phenomena. Various mechanisms of phase separation at very small Reynold number may interfere with the establishment of flowrates.

Natural Circulation (item 6 in Tab. 6)

Natural circulation is a complex phenomenon depending upon some other phenomena mentioned in Tab. 6. The interaction between multiple parallel flow paths may be critical, especially in long lasting transients.

Gravity driven reflood (item 8 in Tab. 6)

Reflood has been widely considered in safety studies related to the present generation reactors. Additional aspects of interest in the advanced design reactors are the presence of feedback between the velocity of the quench front, the pressure rise due to vaporization (at the quench front) and the condensation of steam possibly in the same tank supplying liquid for reflood.

Behaviour of density locks (item 10 in Tab. 6)

The stability of the interface of the density locks, especially when two density locks are present, appears a critical aspect; possible long term variations of static head in the pool (e.g. due to stratification or heating) may change the interface position in each density lock and the stability characteristics.

Behaviour of check valves (item 11 in Tab. 6)

Check valves connect the primary circuit with very large volumes through large pipes. Conditions in the piping with check valves may arise that cause rapid condensation on one side resulting in slam closure of the valve. The small driving forces may not reopen the valves again. The failure to open may prevent the coolant to flow into the primary circuit; the failure to close may cause draining of primary circuit; opening and closure cycles cause critical oscillations in the flow rates.

5. Some Specific Deficiencies and Needs for Thermalhydraulic Codes

Deficiencies and capabilities of system codes are widely discussed by the international community (e.g. ref. 19). Findings relevant to the new generation reactors are discussed hereafter; these are the direct outcome of the experience acquired in the use of Relap5/mod2, but can be extended to recent versions of RELAP5 and to other advanced system codes.

In connection with use of codes in predicting transient scenarios in the advanced design reactors, essentially two phases in the event time sequences can be distinguished:

a) primary system pressure greater than about 0.5 Mpa;

b) subsequent period including a tight interaction between the primary loop and the containment system and the long term behaviour of the passive safety systems.

The physical situations foreseeable in the first period are characterized by parameter ranges for which a very wide data base (experiments and code calculations) already exists. However, this data base does not cover all of the new design features. Some of those will operate in ranges for which models were not developed or properly assessed. Example of such are the CMTs in the AP600 design. The large thermal gradient in the CMTs causes very high condensation rate. One can expect that during CMT draining a layer of saturated liquid will form over the subcooled water significantly reducing the condensation rate. A model for such thermal stratification does exist in present codes. Code capabilities and limits can be retained the same as applicable for the present generation reactors and will not be discussed further in this report.

On the other hand, most of the phenomena foreseeable in phase b) should be considered outside the qualification boundary of the codes. Some of them are also outside the validity limits of the correlations and of the numerical structure of the codes.

For a systematic evaluation of the codes limits and capabilities, all the phenomena listed in Tab. 6 should be considered in the assessment process. The results of the assessment process are only partly and to very limited degree available for the time being. Consequently, based on this limited assessment, some apparent code limitations can be listed as follows:

List of deficiencies and needs

1. At pressure close to atmospheric, very large oscillations may occur in the physical quantities. In some cases this is the result of the applied numerical scheme and of discontinuities of the functions simulating the water properties with main concern to the derivatives. As a consequence of this, very small time steps must be used (this is not practical for long lasting transients) and frequent interruption of the calculation may occur.
2. The simulation of the fluid behavior downstream of a critical section (supercritical flows) is not allowed in any geometric situation. Steam superheating may be important in the condensation process inside pools.
3. The transition between use of the critical flow model and the ordinary differential equation model to calculate flowrate leads to oscillations in the calculation.
4. The possible occurrence of multiple critical sections in a complex piping appears to be outside the prediction capabilities.
5. The stratification of temperatures in pools or tanks (e.g. simulation of the core makeup tank) is not well calculated by the present system codes, as well as, the natural convection circulation establishing when a heat source and sink are present are not calculated. This may result in wrong prediction of gravity head, and errors in mass flowrates and heat exchange coefficients.
6. The natural circulation occurring in several parallel loops (the common element to almost all of these being the reactor core) largely depends upon local loss coefficients in complex three-dimensional geometries. These have much more importance when pumping power is lacking and must be supplied as input by the user. Integral system data will be required to asses the capability of the codes to predict the natural circulation in complex systems.
7. The capability to track non-condensable gases in the whole spectrum of foreseeable conditions of temperature, velocity and gas fraction does not appear adequate. Especially the steam-gas separation process is not considered.
8. The evaluation of both direct (e.g. at ECC port, inside large pools, etc.) and indirect condensation (e.g. inside IC tubes) does not appear adequate, particularly in presence of non-condensable gases.
9. The zero-dimensional neutronic kinetics is not suitable for simulating 3D behaviour of large cores especially of BWR type (this important limitation also applies for current reactors).
10. The numerical solution scheme should be improved to handle transients efficiently lasting several hours, i.e. simulation of long-term cooling is still an issue.

As a consequence, especially of items 5, 6, 8 and 10, computer codes are not able to simulate the integral behaviour of primary system and containment.

6. Conclusions

An overview has been given in this report of relevant thermalhydraulic aspects applicable to some of the advanced design reactors. The thermalhydraulics of evolutionary reactors do not imply the occurrence of new accident scenarios compared to current generation reactors. The same conclusion does not apply to the innovative reactors, e.g. passive reactors.

The SBWR and AP-600 have been specifically considered summarizing some results of PIRT studies and of code applications. Some discussions has also been given to phenomena expected for the PIUS reactor. The main outcomes are the classification of a series of phenomena important for the evaluation of transient performance of the mentioned reactors and the identification of specific code limits.

Relevant differences between scenarios in current and advanced design reactors can, e.g. passive reactors, be attributed to two facts:

- evolution of the largest part of scenarios at low pressure (near the atmospheric value) in the advanced design reactors;
- tight interaction between primary system and containment and the passive safety systems also implying the occurrence of several parallel natural circulation loops each one including (possibly) pools where direct steam condensation takes place and the transport of large amounts of non-condensible gas.

The comparison between the forseeable new plant phenomena and the objectives of the documented experimental researches, demonstrate that some critical issues have been considered, but the spectrum of potentially interesting thermalhydraulic aspects is far larger than the number of phenomena taken into account. Furthermore the available data base must be considered still preliminary and not fully exploited. New research areas can be planned on this basis.

The application of currently available system codes to off-normal conditions typical of the advanced design reactors allowed to distinguish two periods that are separated by a pressure boundary set at about 0.5 Mpa. When the primary system pressure is above this value, the code suitability and applicability is essentially the same as in current generation codes. At pressures below this set value, the occurrence of new phenomena and intrinsic code limitations (is also of interest for current reactors, in relation to transients leading to severe accidents) prevent, in the general case, the possibility of a reliable simulation of plant scenarios. A list of 10 specific areas that need improvement in the codes has been provided.

Finally advanced desgin reactors contain technological features that are common to the present generation reactors. From a thermalhydraulic point of view, PIUS is characterized by the largest innovation. The safety of it is not dependent upon added external circuits or components but is intrinsic to the reactor concept. As such it requires larger investigation to prove its suitability.

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Tables

Reactor System	Approx. Thermal Power Output (MW)	Approx. Electrical Power Output (MW)	Manufacturer
I. EVOLUTIONARY ALWRs			
Advanced Boiling Water Reactor (ABWR)	3926	1356	General Electric
System 80 + Reactor	3817	1300	ABB / Combustion Eng.
European Pressurized Water Reactor (EPR)	4250	1500	Nuclear Power International (NPI) (Parent Co.: Framatome and Siemens)
II. PASSIVE ALWRs			
Advanced Passive Reactor (AP-600)	1818	600	Westinghouse
Simplified Boiling Water Reactor (SBWR)	1800	670	General Electric
III. OTHER ADVANCED REACTORS			
Process Inherent Ultimately Safe Reactor PIUS	2000	640	ABB / ASEA
Advanced Liquid Metal Reactor (ALMR-PRISM)	3 x 471	465	General Electric
Modular High-Temperature Gas Cooled Reactor (MHTGR)	4 x 350	540	General Atomics
Canadian Deuterium-Uranium Reactor (CANDU-3)	1440	450	Atomic Energy of Canada Limited (AECL)

Table 1 Categories of Advanced Design Reactors

Component	Phenomena	SBLOCA		MSLB w/o ADS		MSLB with ADS					SGTR w/o ADS		SGTR with ADS				
		1	2	1	2	1	2	3	4	5	1	2	1	2	3	4	5
Accumulators	Flow	H							H							H	
	Noncondensible effects	M	L						M							M	
ADS	Energy release	H	H						H	H						H	H
	Mass flow	H	H						H	H						H	H
	Choking in complex geometry	M															
	Flow resistance	M							M	M						M	M
	Noncondensible effects	M	L						M	L						M	L
	Condensation in stages 1, 2, and 3 ADS and spargers (in IRWST)	L	L														
Break	Choking in complex geometries										H	H	H	H	M	M	M
	Energy release	M	M	H		H					M	H	M	H	H	M	M
	Flow resistance	M	L	L		L					M	M	M	M	M	L	L
	Mass flow	H	M	H		H					H	H	H	H	H	M	M
	Noncondensible effects	L	L														
Cold legs	Condensation	L	L							L							L
	Flashing	M							L						L	L	
	Loop asymmetry effects	L		M		M		M							M		
	Noncondensible effects	L							L	L						L	L
	PBL-to-cold legs tee phase separation	H	L											H	H	L	
	Stored energy release	L	L	L		L			L			L		L		L	
	Thermal Stratification	M															
Core	Boiling	M	M														
	Core channeling			H	L	H	L										
	Flashing	H	L	M	M	M	M		M						L	M	
	Flow resistance	L	L		L		L	L		M		L		L	L		M
	Loop asymmetry effects	L	L											L	L		
	Mass flow, including bypass	M	M												L		
	Noncondensible effects			L		L	L										
	Stored energy release	M	M	L		L			L			L		L		L	
	Subcooling margin	H	M									M		M			
	Two-phase mixture level	H	H						H	H						H	H
	Voiding			M	M	M	M										
CMT	CMT-to-loop differential density	M		L	L	L	M					M		H			
	CMT-to-IRWST differential head	M	M														
	Condensation	M	M					L							L		
	Flashing	M						L	L						M	L	
	Flow resistance	H	L		L		L	L				L		M	L		
	Level	H			M			H	H			M			H	H	
	Noncondensible effects	L	M	L	L	L	L										
	Thermal stratification and mixing	M		L		L	M	L	L			M		M	L	L	
	Voiding				L		L										
Downcomer/lower plenum	Condensation	M	M							M		L		L	L	L	M
	Flashing	L							L							L	
	Flow distribution	L			L		L	L									
	Level	M	H						L	H					L	L	H
	Loop asymmetry effects	L	L	M		M								M	M		
	Noncondensible effects	L							L							L	
	Stored energy release	L	L	L		L			L			L		L		L	
Fuel rods	Boron reactivity feedback			L		M											
	CHF/dryout	M	L	M		M											
	Core power/decay heat	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
	Moderator temperature feedback			L		M											

Table 2 Summary of PIRT results for AP600

Component	Phenomena	SBLOCA 1	SBLOCA 2	MSLB w/o ADS 1	MSLB w/o ADS 2	MSLB with ADS 1	MSLB with ADS 2	MSLB with ADS 3	MSLB with ADS 4	MSLB with ADS 5	SGTR w/o ADS 1	SGTR w/o ADS 2	SGTR with ADS 1	SGTR with ADS 2	SGTR with ADS 3	SGTR with ADS 4	SGTR with ADS 5
Fuel rods (cont'd)	Stored energy release	M	L	L		L			L		L	L	L	L		L	
Hot legs	CCFL	L	M						M	M						M	M
	Condensation	L	L														
	Countercurrent flow	L	L						M	M						M	M
	Entrainment	L	M						M							M	
	Flashing	M		M		M		L	M			M		M	L	M	
	Horizontal fluid stratification	L	M					M	M	M					M	M	M
	Loop asymmetry effects	L		M		M						M		M			
	Noncondensible effects	L		L	M	L	M		L							L	
	Phase separation in tees	H			M		M	L	H	H					L	H	H
	Stored energy release	L		L		L		L	L			L		L		L	
	Voiding	L		M	M	M	M					M		M			
IRWST	Discharge line flashing									M							M
	Flow and temperature distribution in PRHR bundle region	L			M		M	M				M		M	M		
	Flow resistance	H	H							M							M
	Interphasic condensation	L	L		L		L	L	M			L		L	L	M	
	Pool flow	M			L		L	L	M			L		L	L	M	
	Pool level	L	H		M		M	M	L	M		M				L	M
	Pool to tank structure heat transfer	L	L						L	L						L	L
	Pool thermal stratification	M	L	L	M	L	M	M	M	M		M		M	M	M	M
	Sparger pipe level	M	L														
Pressurizer	Condensation				L												
	CCFL	L							M							M	
	Entrainment/de-entrainment	M							M							M	
	Flashing	M		M		M					H	M	H	M			
	Heater power										H		H				
	Level (inventory)	H	M	M	M	M	M	M			H	M	H	M			
	Level swell	M							M							M	
	Noncondensible effects	L		M	M	M	M		L		L	L	L	L		L	
	Stored energy release	L							L		L		L			L	
	Vapor space behavior			M	M	M	M				H		H				
PRHR	Condensation	L		M	M	M						M		M	M		
	Differential density	L		M	M	M	M	M	L			M		M	M	L	
	Flow resistance	L			M		M	M	L			M		M	M	L	
	Flashing	L							L							L	
	Heat transfer between PRHR and IRWST	M		M	H	M	H	H	M	L		H		H	H	M	L
	Noncondensible effects	L		M	M	M	M	M	L			M		M	M	L	
	Phase separation in tees	L							L							L	
	Voiding	L		M	M	M	M	M				M		M	M		
Pumps	Coastdown performance	L		H		H						L		L			
	Flow resistance	L		L	L	L	L	L				L		L	L		
	Mixing	L															
Steam generators	Asymmetric behavior				M		M	M									
	Condensation in U-tubes											L		L	L		
	Noncondensible effects				M		M	M									
	Primary to secondary heat transfer	M	L		M-		M	M	L	L	H	H	H	H	H	L	L
	Secondary level	L			L		L	L				M		M	M	L	L
	Secondary pressure	L			L		L	L			M	M	M	M	M	L	L
	SRV energy release										M	H	M	H	H		
	SRV mass flow										M	H	M	H	H		
Steam generators (cont'd)	Tube voiding	L			M		M	M				M		M	M		

Table 2 Summary of PIRT results for AP600 (continued)

Component	Phenomena	SBLOCA 1	SBLOCA 2	MSLB w/o ADS 1	MSLB w/o ADS 2	MSLB with ADS 1	MSLB with ADS 2	MSLB with ADS 3	MSLB with ADS 4	MSLB with ADS 5	SGTR w/o ADS 1	SGTR w/o ADS 2	SGTR with ADS 1	SGTR with ADS 2	SGTR with ADS 3	SGTR with ADS 4	SGTR with ADS 5
Steam generator(primary)	Noncondensible effects			L		L											
	Preferential loop cooldown			H		H											
	Primary to secondary heat transfer			H		H											
	Thermal driving head			M		M											
	Voiding (unaffected loop)			M		M											
Steam generator(secondary)	Entrainment			H		H											
	Flashing (SG and feedwater line)			H		H											
	Level swell and depletion			H		H											
	Tube dryout (affected SG)			M		M											
Steam generator (separator/dryer)	Liquid carry-over			H		H											
Sump	Discharge line flashing									M							M
	Flow resistance		M							M							M
	Fluid temperature		H							M							M
	Level	M	H							M							M
Upper head/upper plenum	Condensation	L	L														
	Entrainment/de-entrainment	M	M						M	H						M	H
	Flashing	L		M		M			M			M		M	L	M	
	Flow split(upper plenum)			M	M	M	M										
	Loop asymmetry effects	L		M		M						M		M			
	Noncondensible effects	L	L														
	Stored energy release	L		L		L			L			L		L		L	
	Two-phase level in upper plenum	L	H														
	Upper head/downcomer bypass flow	L															
	Vapor space compression				M												
	Voiding	M		M	M	M	M	M								L	M
Containment (interior)	Condensate transport			L	M	L	L	L	L	M		M				L	M
	Condensation			L	M	L	L	L	M	M		M				M	M
	Interior to wall heat transfer			M	H	M	L	L	M	H		H				M	H
	Liquid distribution	M	M	L	M	L	L	L	L	M		M				L	M
	Liquid holdup			L	M	L	L	L	L	M		M				L	M
	Liquid subcooling	L	L														
	Natural convection			L	M	L	L	L	L	M		M				L	M
	Noncondensible effects			L	M	L	L	L	L	M		M				L	M
	Nonuniform steam/air distribution			L	M	L	L	L	L	M		M				L	M
	Noncondensible segregation			L	M	L	L	L	L	M		M				L	M
	Passive heat sink			M	M	M	L	L	M	M		M				M	M
	Pressure	M	M														
	Steam-noncondensible mixing			L	M	L	L	L	L	M		M				L	M
Containment (exterior)	Air flow				M				L	M		M				L	M
	Atmospheric temperature				M				L	M		M				L	M
	Chimney effects				M				L	M		M				L	M
	Exterior to ambient heat transfer			L	H	L	L	L	M	H		H				M	H
	Humidity				M				L	M		M				L	M
	PCCS evaporation				M				M	M		M				M	M
	PCCS water flow				M				L	M		M				L	M
	PCCS wetting				M				L	M		M				L	M
	PCCS mixture convective heat transfer				M				L	M		M				L	M
	Radiation heat transfer				M				L	M		M				L	M

Table 2 Summary of PIRT results for AP600 (continued)

Combined SBWR PIRT

Component Description	Phenomenon Description	Main Steam Line Break: Pre-Isolation	Isolation	Depressurization	GDCS Refill	Long Term Cooling	Bottom Drain Line Break: Pre-Isolation	Isolation	Depressurization	GDCS Refill	Long Term Cooling	GDCS Line Break: Pre-Isolation	Isolation	Depressurization	GDCS Refill	Long Term Cooling
Reactor																
Break No 1	Critical Flow	H	H	H			H	H	M			H	H	M		
	Subcritical Flow			H	M	L			M	M	M			M	M	L
	Entrainment	L	H	L			L	L	L	L		H	H	M		
	Spilling														H	H
Break No 2	Critical Flow						H	H	M							
	Subcritical Flow								M	M	L					
	Entrainment						H	H	M							
	Spilling									H	H					
Intact Steam Line	Critical Flow	H														
	Subcritical Flow						H					H				
	Entrainment						H					H				
	Inventory Depletion	L														
DPV (ADS)	Critical Flow			H					H					H		
	Subcritical Flow			H	M	L			H	M	L			H	M	L
	Entrainment			L					H*					H*		
	Spilling				L					L					L	
SRV (ADS)	Critical Flow			H					H					H		
	Subcritical Flow			H	L				M	L				M	L	
	Entrainment			L					L					L		
Turbine Stop Valve	Subcritical Flow						H					H				
Turbine Bypass Flow Valve	Critical Flow						H					H				
Feedwater Flow; CRD Flow	Flow/BC	H	H				H	H				H	H			
Core	Parallel Channel Flow Distribution	L	M	M	L	L	M	M	M	L	L	M	M	M	L	L
	Pressure Drop, 2-Phase	L	M	M	L	L	L	L	M	L	L	L	L	M	L	L
	Flashing	M	H	H	L	L	H	M	H*	L	L	H	M	H*	L	L
	Evaporation	L	H	H	L	L	H*	L	L	L	L	H*	L	L	L	L
	Void Distribution	M	H	H	L	L	H*	M	H*	L	L	H*	M	H*	L	L
	Core Power: Critical/Decay	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
	Heat Transfer Coefficient	L	H	H	L	L	M	L	L	L	L	M	L	L	L	L
	Fuel Stored Energy	M	H	L	L	L	M	M	M	L	L	M	M	M	L	L
	Structure Stored Energy	L	M	L	L	L	L	L	M	L	L	L	L	M	L	L
	Internal Flow Circulation		M	H	M	L	L	L	M	L	L	L	L	M	L	L

Table 3 Combined PIRT for MSLB, BDLB and GDLB Scenarios for SBWR

Combined SBWR PIRT

Component Description	Phenomenon Description	Main Steam Line Break					Bottom Drain Line Break					GDCS Line Break				
		Pre-Isolation	Isolation	Depressurization	GDCS Refill	Long Term Cooling	Pre-Isolation	Isolation	Depressurization	GDCS Refill	Long Term Cooling	Pre-Isolation	Isolation	Depressurization	GDCS Refill	Long Term Cooling
Chimney	Flashing	M	H	H	L	L	H*	M	H*	L	L	H*	M	H*	L	L
	Level/Void Distribution	M	H	H	L	L	H*	M	H*	L	L	H*	M	H*	L	L
	Structure Stored Energy	L	M	L	L	L	L	L	M	L	L	L	L	M	L	L
Separator/Dryer	Phase Separation	M	H	H	L	L	H*	L	H*	L	L	H*	L	H*	L	L
	Friction - Two Phase	L	L	L	L	L	L	L	M	L	L	L	L	M	L	L
	Structure Stored Energy	L	M	L	L	L	L	L	M	L	L	L	L	M	L	L
	Flooding	L	H	L			M	L	M			M	L	M		
Downcomer	Fluid Mixing	L	M	L	L	L	M	H*	M	L	L	M	H*	M	L	L
	Flashing	M	H	H	L	L	H	M	H*	L	L	H	M	H*	L	L
	Level/Void Distribution	M	H	H	L	L	H	M	H*	L	L	H	M	H*	L	L
	Direct Contact Condensation	L	H	M	L	L	M	H*	M	L	L	M	H*	M	L	L
	Structure Stored Energy	L	M	M	M	L	M	L	M	L	L	M	L	M	L	L
	Entrainment	L	H	H	L	L	H	H	M	L	L	H	H	M	L	L
Lower Plenum	Fluid Mixing	L	M	L	L	L	L	L	M	L	L	L	L	M	L	L
	Flashing	L	H	H	L	L	H	M	H*	L	L	H	M	M	L	L
	Structure Stored Energy	L	M	M	L	L	L	L	M	L	L	L	L	M	L	L
	Void Distribution	L	H*	L	L	L	H	M	H*	L	L	H	M	M	L	L
Isolation Condenser	Condensation inside tubes		H	H	L	L		H	M	L	L		H	M	L	L
	Pool side heat transfer		H	H*	L	L		H*	M	L	L		H*	M	L	L
	Natural circulation		H	H	L	L		H	M	L	L		H	M	L	L
	Degradation of condensation due to NCs		M	M	L	L		M	L	L	L		M	L	L	L

Table 3 Combined PIRT for MSLB, BDLB and GDLB Scenarios for SBWR (continued)

Combined SBWR PIRT

Component Description	Phenomenon Description	Main Steam Line Break: Pre-Isolation	Isolation	Depressurization	GDCS Refill	Long Term Cooling	Bottom Drain Line Break: Pre-Isolation	Isolation	Depressurization	GDCS Refill	Long Term Cooling	GDCS Line Break: Pre-Isolation	Isolation	Depressurization	GDCS Refill	Long Term Cooling
Containment																
Dry Well	Non-Condensibles Amount	M	L	M	L	H	H	L	M	L	H	H	L	M	L	H
	Non-Condensibles Distribution	M	L	M	L	H	H	L	M	L	H	H	L	M	L	H
	Condensation on wall with NC present	M	L	L	L	M	H	L	M	L	M	H	L	M	L	M
	Water Accumulation	L	L	L	L	H	L	L	M	M	H	L	L	M	M	M
	Transient Conduction in Structures	L	L	M	L	L	H	L	M	L	L	H	L	M	L	L
	Non-Equilibrium Mixing of N2 & Steam	H	L	M			H	L	L			H	L	L		
	Surface Condensation (on Liquid Surfaces)	M	L	M	L	M	H	L	M	L	M	H	L	M	L	M
Horizontal Vent	Horizontal Vent Clearing	L	L	M			L	L	M			L	L	M		
Suppression Pool	Suppression Pool Heat & MassTransfer	L	L	M	L	L	L	L	M	L	L	L	L	M	L	L
	Condensation for SRV Sparger flow			M	L	L			M	L	L			M	L	L
	Condensation with NC for PCC purge line flow	L	L	M	L	L	L	L	M	L	L	L	L	M	L	L
	Temperature Stratification	L	L	M	L	L	L	L	M	L	L	L	L	M	L	L
Suppression Chamber	Non-Condensibles Amount	L	L	M	L	H	L	L	M	L	H	L	L	M	L	H
	Non-Condensibles Distribution	L	L	L	L	M	L	L	L	L	M	L	L	L	L	M
	Condensation on wall with NC present	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
	Heat and Mass transfer at pool surface	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
GDCS	Friction/Form Losses				H	L				H	L				H	L
	Hydrostatic Head				H	L				H	L				H	L
	Pressure Difference from GDCS Tanks to RPV				H	L				H	L				H	L
PCCS Heat Exchanger	Condensation Inside tubes	L	L	M	L	H	L	L	L	L	H	L	L	L	L	H
	Pool side heat transfer	L	L	M	L	H	L	L	L	L	H	L	L	L	L	H
	Natural Circulation	L	L	M	L	H	L	L	L	L	H	L	L	L	L	H
	Degradation of condensation due to NCs	L	L	M	L	H	L	L	L	L	H	L	L	L	L	H
	Accumulation of NCs in tubes	L	L	M	L	H	L	L	L	L	H	L	L	L	L	H
	Submergence	L	L	M	L	H	L	L	L	L	H	L	L	L	L	H
	Condensate Draining	L	L	M	L	H	L	L	L	L	H	L	L	L	L	H
Vacuum Breakers (VB)	Friction and form losses for Steam & NCs				L	H				L	H				L	H
	Pressure Drop across VB				L	H				L	H				L	H
Equalization Lines	Flow					H					H					H

Table 3 Combined PIRT for MSLB, BDLB and GDLB Scenarios for SBWR (continued)

Composite SBWR PIRT

Component Description	Phenomenon Description	Composite Rank
Reactor		
Break No 1	Critical Flow	H
	Subcritical Flow	H
	Entrainment	H
	Spilling	H
Break No 2	Critical Flow	H
	Subcritical Flow	M
	Entrainment	H
	Spilling	H
Intact Steam Line	Critical Flow	H
	Subcritical Flow	H
	Entrainment	H
	Inventory Depletion	L
DPV (ADS)	Critical Flow	H
	Subcritical Flow	H
	Entrainment	H*
	Spilling	L
SRV (ADS)	Critical Flow	H
	Subcritical Flow	H
	Entrainment	L
Turbine Stop Valve	Subcritical Flow	H
Turbine Bypass Flow Valve	Critical Flow	H
Feedwater Flow; CRD Flow	Flow/BC	H
Core	Parallel Channel Flow Distribution	M
	Pressure Drop 2-Phase	M
	Flashing	H
	Evaporation	H
	Void Distribution	H
	Core Power: Critical/Decay	H
	Heat Transfer Coefficient	H
	Fuel Stored Energy	H
	Structure Stored Energy	M
	Internal Flow Circulation	H

Table 4 Composite PIRT for SBWR

Composite SBWR PIRT

Component Description	Phenomenon Description	Composite Rank
Chimney	Flashing	H
	Level/Void Distribution	H
	Structure Stored Energy	M
Separator/Dryer	Phase Separation	H
	Friction - Two Phase	M
	Structure Stored Energy	M
	Flooding	H
Downcomer	Fluid Mixing	H*
	Flashing	H
	Level/Void Distribution	H
	Direct Contact Condensation	H
	Structure Stored Energy	M
	Entrainment	H
Lower Plenum	Fluid Mixing	M
	Flashing	H
	Structure Stored Energy	M
	Void Distribution	H
Isolation Condenser	Condensation inside tubes	H
	Pool side heat transfer	H
	Natural circulation	H
	Degradation of condensation due to NCs	M

Table 4 Composite PIRT for SBWR (continued)

Composite SBWR PIRT

Component Description	Phenomenon Description	Composite Rank
Containment		
Dry Well	Non-Condensibles Amount	H
	Non-Condensibles Distribution	H
	Condensation on wall with NC present	H
	Water Accumulation	H
	Transient Conduction in Structures	H
	Non-Equilibrium Mixing of N_2 & Steam	H
	Surface Condensation (on Liquid Surfaces)	H
Horizontal Vent	Horizontal Vent Clearing	M
Suppression Pool	Suppression Pool Heat & MassTransfer	M
	Condensation for SRV Sparger flow	M
	Condensation with NC for PCC purge line flow	M
	Temperature Stratification	M
Suppression Chamber	Non-Condensibles Amount	H
	Non-Condensibles Distribution	M
	Condensation on wall with NC present	L
	Heat and Mass transfer at pool surface	L
GDCS	Friction/Form Losses	H
	Hydrostatic Head	H
	Pressure Difference from GDCS Tanks to RPV	H
PCCS Heat Exchanger	Condensation inside tubes	H
	Pool side heat transfer	H
	Natural Circulation	H
	Degradation of condensation due to NCs	H
	Accumulation of NCs in tubes	H
	Submergence	H
	Condensate Draining	H
Vacuum Breakers (VB)	Friction and form losses for Steam & NCs	H
	Pressure Drop across VB	H
Equalization Lines	Flow	H

Table 4 Composite PIRT for SBWR (continued)

0	BASIC PHENOMENA	1	Evaporation due to Depressurisation
		2	Evaporation due to Heat Input
		3	Condensation due to Pressurisation
		4	Condensation due to Heat Removal
		5	Interfacial Friction in Vertical Flow
		6	Interfacial Friction in Horizontal Flow
		7	Wall to Fluid Friction
		8	Pressure Drops at Geometric Discontinuities
		9	Pressure Wave Propagation
1	CRITICAL FLOW	1	Breaks
		2	Valves
		3	Pipes
2	PHASE SEPARATION/VERTICAL FLOW WITH AND WITHOUT MIXTURE LEVEL	1	Pipes/Plena
		2	Core
		3	Downcomer
3	STRATIFICATION IN HORIZONTAL FLOW	1	Pipes
4	PHASE SEPARATION AT BRANCHES	1	Branches
5	ENTRAINMENT/DEENTRAINMENT	1	Core
		2	Upper Plenum
		3	Downcomer
		4	Steam Generator Tube
		5	Steam Generator Mixing Chamber (PWR)
		6	Hot Leg with ECCI (PWR)
6	LIQUID-VAPOUR MIXING WITH CONDENSATION	1	Core
		2	Downcomer
		3	Upper Plenum
		4	Lower Plenum
		5	Steam Generator Mixing Chamber (PWR)
		6	ECCI in Hot and Cold Leg (PWR)
7	CONDENSATION IN STRATIFIED CONDITIONS	1	Pressuriser (PWR)
		2	Steam Generator Primary Side (PWR)
		3	Steam Generator Secondary Side (PWR)
		4	Horizontal Pipes
8	SPRAY EFFECTS	1	Core (BWR)
		2	Pressuriser (PWR)
		3	Once-Through Steam Generator Secondary Side (PWR)
9	COUNTERCURRENT FLOW / COUNTERCURRENT FLOW LIMITATION	1	Upper Tie Plate
		2	Channel Inlet Orifices (BWR)
		3	Hot and Cold Leg
		4	Steam Generator Tube (PWR)
		5	Downcomer
		6	Surgeline (PWR)
10	GLOBAL MULTIDIMENSIONAL FLUID TEMPERATURE, VOID AND FLOW DISTRIBUTION	1	Upper Plenum
		2	Core
		3	Downcomer
		4	Steam Generator Secondary Side
11	HEAT TRANSFER: NATURAL OR FORCED CONVECTION	1	Core, Steam Generator, Structures
	SUBCOOLED/NUCLEATE BOILING	2	Core, Steam Generator, Structures
	DNB/DRYOUT	3	Core, Steam Generator, Strucutres
	POST CRITICAL HEAT FLUX	4	Core, Steam Generator, Strucutres
	RADIATION	5	Core
	CONDENSATION	6	Steam Generator, Structures
12	QUENCH FRONT PROPAGATION/REWET	1	Fuel Rods
		2	Channel Walls and Water Rods (BWR)
13	LOWER PLENUM FLASHING		
14	GUIDE TUBE FLASHING (BWR)		
15	ONE AND TWO PHASE IMPELLER-PUMP BEHAVIOUR		
16	ONE AND TWO PHASE JET-PUMP BEHAVIOUR (BWR)		
17	SEPARATOR BEHAVIOUR		
18	STEAM DRYER BEHAVIOUR		
19	ACCUMULATOR BEHAVIOUR		
20	LOOP SEAL FILLING AND CLEARANCE (PWR)		
21	ECC BYPASS/DOWNCOMER PENETRATION		
22	PARALLEL CHANNEL INSTABILITIES (BWR)		
23	BORON MIXING AND TRANSPORT		
24	NONCONDENSABLE GAS EFFECT (PWR)		
25	LOWER PLENUM ENTRAINMENT		

Table 5 Relevant thermalhydraulic phenomena identified for the current generation reactors

PHENOMENA OCCURRING DUE THE INTERACTION BETWEEN PRIMARY SYSTEM AND CONTAINMENT

1. Behaviour of large pools of liquid:	– thermal stratification – natural/forced convection and circulation – steam condensation (e.g. chugging, etc.) – heat and mass transfer at the upper interface (e.g. vaporization) – liquid draining from small openings (steam and gas transport)
2. Tracking of non-condensibles (essentially H2, N2, air):	– effect on mixture to wall heat transfer coeficient – mixing with liquid phase – mixing with steam phase – stratification in large volumes at very low velocities
3. Condensation on the containment structures:	– coupling with conduction in larger structures
4. Behaviour of containment emergency systems (PCCS, external air cooling, etc.):	– interaction with primary cooling loops
5. Thermofluiddynamics and pressure drops in various geometrical configurations:	– 3-D large flow pths e.g. around open doors and stair wells, connection of big pipes with pools, etc. – gasliquid phase separation at low Re and in laminar flow – local pressure drops

PHENOMENA OCCURRING AT ATMOSPHERIC PRESSURE

6. Natural circulation:	– interaction among parallel circulation loops inside and outside the vessel – influence of non-condensables
7. Steam liquid interaction:	– direct condensation – pressure waves due to condensation
8. Gravity driven reflood:	– heat transfer coefficients – pressure rise due to vaporization – consideration of a closed loop
9. Liquid temperature stratification:	– lower plenum of vessel – downcomer of vessel – horizontal/vertical piping

PHENOMENA ORIGINATED BY THE PRESENCE OF NEW COMPONENTS AND SYSTEMS OR SPECIAL REACTOR CONFIGURATIONS

10. Behaviour of density locks:	– stability of the single interface (temperature and density distribution) – interaction between two density locks
11. Behaviour of check valves:	– opening/closure dynamics – partial/total failure
12. Critical and supercritical flow in discharge pipes and valves:	– shock waves – supercritical flow in long pipes – behaviour of multiple critical section
13. Behaviour of Isolation Condenser	– low pressure phenomena
14. Stratification of boron:	– interaction between chemical and thermohydraulic problems – time delay for the boron to become effective in the core

Table 6 **Relevant thermalhydraulic phenomena of interest in the advanced design reactors**