FACTAR VALIDATION

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ABSTRACT

A detailed strategy to validate fuel channel thermal mechanical behaviour codes for use in current power reactor safety analysis is presented. The strategy is derived from a validation process that has been recently adopted industry wide. Focus of the discussion is on the validation plan for the code, FACTAR, for application in assessing fuel channel integrity safety concerns during a large break loss of coolant accident (LOCA).

Ontario Hydro is validating its fuel channel, thermal mechanical behaviour code, FACTAR (Fuel And Channel Temperature And Response). This task is one of the main requirements for AECB acceptance of the Ontario Hydro large break LOCA generic safety analysis methodology. In the short term, validation will focus on demonstrating sufficiency of modelling accuracy for assessing parameters key to fuel channel integrity concerns during large break LOCAs.

The validation process used is based on an industry wide approach recently adopted for validating computer codes used in reactor safety analyses. The initial part of the validation process is code independent and applicable to all disciplines used in safety analyses. It is based on the matrix format which the AECB has recommended as the most efficient, currently available vehicle to transmit understanding of the extent of validation. It also represents a movement to a more formalized level of validation in which confidence limits in modelling predictions for specific safety concerns can be established.

As illustrated in Figure 1, the validation process is broken down into code dependent and independent tasks. The development of a Technical Basis Report (TBR), which identifies all phenomena associated with the various accident scenarios, and the Validation Matrix Report (VMR), which relates these phenomena to validation data sets, are code independent tasks and they are intended as a resource for the validation plans of specific codes. Ontario Hydro is proceeding with the code specific validation of FACTAR in parallel with the development of the TBR and VMR. Hence, the initial focus is to ensure that these reports include a certified subset of information sufficient to carry out this code specific validation work.

The Technical Basis Report identifies the phenomena that are dominant for each phase of each accident scenario of each selected discipline. It also provides a ranking of importance of these phenomena by relating them to specific safety concerns and the measurable, key parameters used to define the margin for each safety concern. Tables 1 and 2 illustrate the steps used to interrelate scenarios to safety concerns to key parameters for the discipline of fuel and fuel channel behaviour. The TBR also serves to establish a relationship between the disciplines involved in an accident scenario including system thermalhydraulics, containment behaviour, moderator behaviour, reactor physics, fuel and fuel channel thermal/mechanical behaviour, and fission product release and transport.

For thermal mechanical behaviour of a fuel channel, the phenomena governing each safety concern are defined in terms of key parameters. A phenomenon is defined as an observable process, and thus does not include material properties, which are addressed separately by the code specific validation plans. To aid in identifying all significant phenomena during any of the in-core accident scenarios, the accidents are divided into generic phases (ie; for large break LOCAs, the initial overpower transient period, a degraded cooling period prior to the initiation of emergency coolant injection (ECI), a cooling period following ECI initiation, and a refill period in which the fuel is quenched). Phenomena are then identified for each of these categories in terms of the major physical, chemical, and thermodynamic processes including heat generation, heat redistribution, heat losses, chemical changes, and physical changes. The phenomena list is thus generic, not limited to the suite of models incorporated within any one code, but the industry's best attempt at outlining the physical and chemical phenomena that would be expected to occur in the postulated accident.

Phenomena are then ranked according to whether they are governing, or secondary within a particular accident phase. A phenomenon is judged to be governing if it strongly influences behaviour, while a secondary phenomenon is evident, but does not dominate behaviour. The development of the code-independent validation knowledge base means that results can easily be applied to any fuel channel code or scenario. Table 3 presents the resulting list of phenomena groups and subgroups ranked for importance in the context of large break LOCAs where ECI is available.

The Validation Matrix Report identifies all data sets (eg; experimental data bases, analytical techniques, operational accidents, and cross code comparisons) that are of potential use as validation material. These validation data sets are cross referenced against the governing phenomena identified in the TBR for each discipline. Each validation data set is characterized in terms of which phenomena are represented, the level of uncertainty in data and the quality of documentation as illustrated in Table 4.

For the discipline of fuel and fuel channel behaviour there are few large integrated effects experiments. Rather, there exists a large number of separate effects and partially integrated effects experiments. In addition , many of the existing integrated effects experiments were designed more for exploratory investigation rather that quantifying phenomena behaviour. This is a result of an ongoing evolution in defining licensing accident scenarios to encompass greater extremes in boundary conditions where the behaviour of fuel channel materials is at the frontier of current knowledge. This makeup of the data base significantly affects the current strategy for its application in validating codes in that a synthesis of many code/experiment comparisons are required rather the more convenient prototypic proof type tests used in other disciplines.

The validation matrix, illustrated in Table 5, is subdivided by type of validation data set including in-reactor tests, integral effects tests, separate effects tests, numerical benchmark problems, fundamental analytical solutions, cross code comparisons, and operational incidents. At present about 100 potentially useful validation data sets have been identified.

The code-specific tasks of the validation process outlined in Figure 1 include the development of a validation plan, validation exercises for each relevant experiment and the integration of the results of this work into a validation manual. The validation plan references the TBR to identify relevant safety concerns, parameters and phenomena for the specific application. It then references the Validation Matrix Report to identify relevant experimental data sets and outlines a detailed strategy to achieve a particular validation target including methods to be used to judge code-to-data comparisons, with emphasis on the analysis of experimental errors and modelling errors. In this initial case it is the assessment of uncertainty in prediction (ie; by FACTAR and associated auxiliary codes) of the key parameters that are used to determine the accuracies and uncertainties during the simulation of a large break LOCA with ECI available.

Tables 1 and 2 identify the channel integrity safety concerns, and associated key parameters that are used as a measure of margin, currently addressed for the large break LOCA (with ECI) scenario. During the initial power pulse period, molten UO_2 contact with the pressure tube is the dominant safety concern with the centerline UO_2 temperature the governing parameter. During the subsequent degraded cooling period, prior to ECI injection, the main safety concern is pressure tube rupture due to the formation of local hot spots by molten material contact or forced element contact. The governing parameters are sheath/end cap temperatures, axial expansion of the elements, and pressure tube strain rate. Secondary safety concerns include pressure tube strain at very high coolant pressure, when small temperature gradients could potentially affect pressure tube integrity, and pressure tube strain under low pressure conditions, which affects the overall extent of pressure tube contact with calandria tubes, hence affecting heat load to the moderator and the potential for calandria tube dryout and consequent potential channel rupture. The governing parameter used for both cases is pressure tube strain rate. Secondary parameters, such as steady state UO_2 temperature, are also defined in cases where it makes sense to subdivide a governing parameter into measurable quantities for direct validation.

For the current large break LOCA channel integrity plan there are not any prototypic integral tests available for an all effects check of models used to assess fuel and fuel channel behaviour. Hence, the validation plan has to focus on synthesizing a composite of validation exercises which demonstrates the uncertainty and accuracy in the model's predictions for these key parameters; and ensures that interactions between phenomena are properly assessed. The primary code used in the analysis of fuel channel integrity concerns is FACTAR and most of the required validation is needed for its subcodes which include ELESIM, ELOCA, its heat transfer package, and the pressure tube strain model. Significant validation work has been carried out to date for these subcodes, although not in a validation matrix format consistent with the current industry validation process. The existing work provides a strong initial basis to expand upon. Integrated model validation can be done to a certain extent with experiments such as the Blowdown Test Facility Experiment 104 (BTF-104), an in-reactor "mini channel" configuration.

BTF-104 is one of the most integrated all effects tests identified in the matrix. This test was done in September 1993 in the NRU reactor at Chalk River Laboratories. The experiment consisted of subjecting a single CANDU fuel element to an in-reactor coolant blowdown transient to degraded cooling conditions. Measurements of thermal mechanical fuel behaviour such as axial oxide thicknesses and hydrogen production rates are compared against the FACTAR predictions using measured boundary conditions. Good agreement is indicative of realistic integration of major separate physical "channel" models including those that track cumulative heat removal axially in this "mini channel" and the dynamic feedback of a prototypic fuel element. This in-reactor data, though limited, serves a valuable purpose in enabling the interaction between the various models to be assessed for realism.

Each validation exercise report assesses a specific validation data set. The report provides an overview of the resource, discusses measurement error, model biases, *etc.*, and provides direct code-to-data comparisons, analyzed with the aim of judging the code's ability to model the phenomenon in question. In some cases existing work/documentation can be used directly. However, since early experimentation was largely focused on exploratory research, it often did not include quantitative assessment of experimental error and thus requires reassessment.

The scatter in experimental and predicted values, which account for the uncertainty in measured phenomena/parameters and boundary conditions, respectively, are used to define confidence limits on model predictions. For example, if the code is able to predict the experimental results within a 1σ band, then the agreement is said to be excellent, within $2\ \sigma$ is acceptable, and $3\ \sigma$ is poor. For a transient analysis, these different confidence levels can be compared to that required of modelling for different phases of an accident. For example, agreement may be good during the initial blowdown period, but poor, although acceptable, during the interval of degraded cooling after ECI initiation. Current safety analysis requires more accurate predictions of key parameters during the initial blowdown/ power pulse period of a LOCA and progressively less accuracy as the ECI is triggered and becomes effective in cooling the core.

The impact of these confidence limits on safety concerns is gauged by carrying out sensitivity analyses, using these limits, for the most severe licensing cases. This involves generating a matrix of cases in which the code is run with the upper and lower confidence limits defined from the validation exercises for major input parameters. Identification of confidence limits that have an unacceptably large impact on safety margins will be used as a basis for recommending future experimentation to expand the validation data base.

The short term outcome of this work will be the development of a Validation Manual for FACTAR, and its auxiliary codes, which demonstrates sufficient accuracy and model correctness for use in analysis of channel integrity safety concerns of a Large Break LOCA. The generic validation matrix for the fuel and fuel channel discipline will be prepared in parallel, with the reources required for this validation plan finalized first. This will constitute the initial stage of an industry wide effort into computer code validation for this discipline.

FIGURE 1 - VALIDATION PROCESS

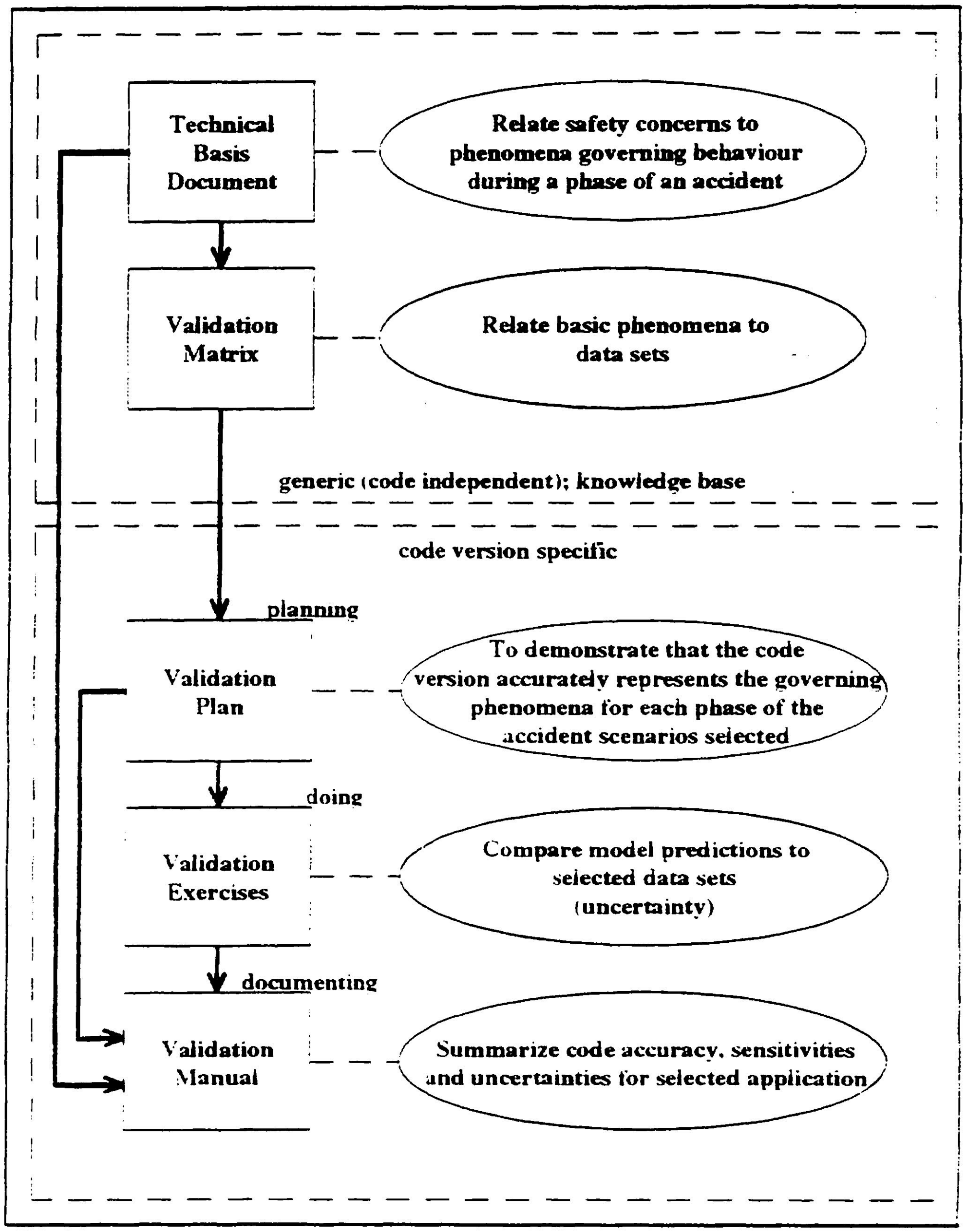

TABLE 1 - LIST OF ACCIDENTS VERSUS PRIMARY SAFETY CONCERNS

ACCIDENT	PRIMARY SAFETY CONCERNS						
LARGE LOCA	pt rupture via molten UO2 contact	pt rupture via strain at high pressure & dTs	pt rupture via molten Zr contact	pt rupture via element contact	channel rupture after pt ballooning	short term FP release	long term FP release
SMALL LOCA				pt rupture via element contact		short term release	long term release
LOCA+ LOECI	pt rupture via molten UO2 contact	pt rupture via strain at high pressure & dTs	pt rupture via molten Zr contact	pt rupture via element contact	channel rupture after pt ballooning (late times also)	D2 release	FP release
TRANSITION BREAKS (&rih)	pt rupture via molten UO2 contact			pt rupture via element contact			FP release
FLOW BLOCKAGE	channel failure propogation	calandria vessel failure	moderator drain	pt rupture via element contact	SOR guide tube impairment		FP release
STAGNATION FEEDER BREAK	channel failure propogation	calandria vessel failure	moderator drain	pt rupture via element contact	SOR guide tube impairment		FP release
FH ACCIDENT	channel failure propogation					short term release	
EFF ACCIDENT						short term release	
IN-CORE BREAK	C.T. failure due to annulus pressurization	channel failure propogation	calandria vessel failure	pt rupture via element contact	SOR guide tube impairment	short term release	

TABLE 2- SUMMARY OF PARAMETERS WHICH GOVERN EACH SAFETY CONCERN FOR LARGE LOCA

KEY PARAMETERS	SAFETY CONCERNS					
	PT rupture via molten UO2 contact	PT rupture via strain at high pressure & dTs	PT rupture via molten Zr contact	PT rupture via element contact	Channel rupture after PT ballooning	Short term FP release	Long term FP release
Temperature distribution in UO2 at start of accident	*	*	*	*	*	*	
Temperature distribution in UO2 during transient	**	*	*	*	*	*	
Sheath temperature during accident	*	*	**		*	*	
End cap temperature during accident			**				
Rate of pressure tube strain		**	**	**	*	*	
Relative pressure tube to UO2 axial expansion				**			
Fuel to pressure tube contact pressure				*			
Onset of CT dryout (Calandria tube temperature rise)					**		
Fuel sheath failure						**	
Fuel damage upon rewet							**

* parameter which has a major impact on safety concern

** parameter which provides measure of margin for safety concern

Table 3 - PHENOMENA RANKING - LARGE LOCA

ID	Phenomena Group	Phenomenon	ACCIDENT PHASE				
			Initial Condn's	Power Pulse	Cooling pre ECI	Cooling post ECI	Refill
1	***Element Heat***	end flux peaking	*	**	*	*	
2	***production***	radial flux depression	**	**	*	*	
3		gamma heating			*	*	
4		fission product release			*	*	
5		heating via fission product decay			**	**	
6	***Element Heat***	conduction through UO2	**	**	*	*	
7	***redistribution***	heat transfer from UO2 to sheath	**	**			
8		heat stored in UO2	**	**			
9	***Element Heat***	radiation from sheath		*	**	**	
10	***removal***	convective cooling of sheath	*	**	**	**	
11		conduction from append. to PT			**	**	
12	***Elem Physical***	fission gas release to gap	*		*	*	
13	***changes***	sheath strain	*		*	*	
14		element bowing/ bending		*	*	*	
15		sheath failure	*	*	**	**	**
16		pellet bottoming		*	*	*	
17		pellet cracking	*	*			*
18		UO2 swelling/densification	*				
19		cracking due to impacts			*	*	
20		radial expansion	*	*	**	**	
21		UO2 powdering/fragmentation					**
22		element sag			*	*	
23	***Elem Chemical***	Zr oxidation		*	**	**	*
24	***changes***	Zr hydriding	*		*	*	
25		canlub deterioration	*		*	*	
26		UO2 oxidation & grain growth	*		*	*	*
27	***Bundle Heat***	coolant mixing		*	**	**	
28	***Redistribution***	radiation heat transfer		*	**	**	
29		coolant bypass			**	**	
30		axial conduction to end plate			*	*	
31	***Bundle Physical***	cracking due to impact			*	*	
32	***changes***	slumping			*	*	
33		differential element expansion		**	**	**	
34		melting and relocation		**	*	*	
35	***PT Heat***	gamma heating			*	*	*
36	***production &***	conduction from melt contact					
37	***redistribution***	conduction across annulus gap			*	*	
38		contact conductance to CT			*	*	
39		axial conduction to shield region			*	*	
40	***PT Physical***	strain			**	**	
41	***changes***	axial expansion			**	**	
42		slumping			*	*	
43		axial bundle impact damage			*	*	*
44	***PT Chemical***	hydriding			*	*	
45	***changes***	oxidation			*	*	
46	***Channel Heat***	convection to moderator			**	**	
47	***prod'n & redist'n***	gamma heating			*	*	
48	***Channel physical***	garder spring collapse			*	*	*
49	***changes***	CT and PT strain					*
50		annulus pressurization					
51		crack propagation					
52	***Channel Rupture***	melt interaction with moderator					
53		projectile impact onto CT					
54		projectile impact onto guide tubes					
55		shock wave onto adjacent channels					

SHADED = PRIMARY　　　* = SECONDARY　　　CLEAR = NEGLIG OR NA

TABLE 4 - CHARACTERIZATION OF VALIDATION EXPERIMENTS

CHARACTERIZATION	SEPARATE EFFECTS VALIDATION EXPERIMENTS																			
	SE01	SE02	SE03	SE04	SE05	SE06	SE07	SE08	SE09	SE10	SE11	SE12	SE13	SE14	SE15	SE16	SE17	SE18	SE19	SE20
SELECTION CRITERIA																				
Documentation complete																				
Accuracy of BC measurements																				
Accuracy of Phenomenon measurements																				
Accuracy of integrated behaviour measurements																				
Range of applicability																				
PHYSICAL SETUP OF EXPERIMENT																				
UO2/Zr element ?																				
Full length ?																				
Number of elements																				
Burnup																				
Pressure tube																				
Calandria tube																				
garder springs																				
TEST CONDITIONS																				
Heating method																				
Heatup rate																				
Oxidizing conditions																				
Coolant pressure																				
Special conditions																				
BEHAVIOUR MEASURED																				
SS temperature distribution in UO2																				
Transient temperature distribution in UO2																				
Transient sheath temperature																				
Transient end cap temperature																				
Rate of pressure tube strain																				
Relative pressure tube to UO2 axial expansion																				
Fuel to pressure tube contact pressure																				
Onset of calandria tube dryout (CT temp rise)																				
Fuel sheath failure																				
Fuel damage upon rewet																				
Special behaviour																				

1=excellent, 2= sufficient
3= incomplete/limited
4= insufficient for practical application

n = not applic or no, y=yes q=quantitative, s= scoping

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Table 5- Validation Matrix

ID	Phenomenon (observable processes)	IN-REACTOR EXPERIMENTS									
		IR21	IR22	IR23	IR24	IR25	IR26	IR27	IR28	IR29	IR30
1	end flux peaking										
2	radial flux depression										
3	gamma heating										
4	fission product release										
5	heating via fission product decay										
6	conduction through UO2										
7	heat transfer from UO2 to sheath										
8	heat stored in UO2										
9	radiation from sheath										
10	convective cooling of sheath										
11	conduction from append. to PT										
12	sheath strain										
13	element bowing/ bending										
14	sheath failure										
15	pellet bottoming										
16	pellet cracking										
17	UO2 swelling/densification										
18	cracking due to impacts										
19	radial expansion										
20	UO2 powdering/fragmentation										
21	element sag										
22	Zr oxidation										
23	Zr hydriding										
24	UO2 oxidation & grain growth										
25	coolant mixing										
26	radiation heat transfer										
27	coolant bypass										
28	axial conduction to end plate										
29	cracking due to impact										
30	slumping										
31	differential element expansion										
32	melting and relocation										
33	gamma heating										
34	conduction from melt contact										
35	conduction across annulus gap										
36	contact conductance to CT										
37	axial conduction to shield region										
38	strain										
39	axial expansion										
40	slumping										
41	axial bundle impact damage										
42	hydriding										
43	oxidation										
44	convection to moderator										
45	gamma heating										
46	garder spring collapse										
47	CT and PT strain										
48	annulus pressurization										
49	crack propagation										
50	melt interaction with moderator										
51	projectile impact onto CT										
52	projectile impact onto guide tubes										
53	shock wave onto adjacent channels										