APPENDIX G:

CONSENSUS SUMMARY ON DIRECT HEATING

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Subcommittee on Direct Heating: Members

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Appendix G - Consensus Summary on Direct Heating

1. Definition of Subcommittee Task

The objectives of the direct-heating subcommittee were:

(i) to evaluate the various approaches to dealing with the high-pressure melt ejection direct heating problem offered by the various members,

(ii) to make recommendations, based upon as broad a consensus as possible, for calculation of the containment loading due to the combined effects of water quench (steam spike), direct heating of the containment atmosphere and chemical energy release, as appropriate to Standard Problems (SP) 1 (Zion) and 2 (Surry).

The recommendations are based upon experimental data and models available as of April 1984.

2. Constraints

The subcommittee, with broad consensus, felt that the analysis of the direct-heating problem in its broad context was being constrained by the initial conditions as posed in the definition of SP-1 and SP-2. It was felt that a broader approach to the problem is required which considers (i) the melt mass available for discharge from the vessel upon failure, (ii) the temperature of the melt upon ejection and, (iii) the mass of unreacted metals available for ejection from the vessel. All of these issues call for methods of treating in-vessel core degradation events.

It was broadly recognized that analytical treatment of the direct-heating problem is currently constrained by the lack of an adequate experimental data base to support development of appropriate calculational models required for objective, mechanistic assessment of the transport processes. This constraint is aggravated by the recognition that "generic" solutions are not possible and that each containment system must be dealt with individually.

3. Mitigating Mechanisms

The subcommittee heard many plausible arguments relating to physical mechanisms which would mitigate the effects of direct heating and chemical reactions. These include:

(i) incoherent core melting and melt injection from the reactor vessel,

(ii) plausibility of lower melt temperatures,

(iii) two-phase melt injection dynamics,

(iv) melt freezing to structures in cavity,

(v) melt flow across obstructions above cavity,

(vi) melt droplet fallout in containment,

(vii) melt deposition on structures,

(viii) water-melt mixing and heat transfer in containment atmosphere.

The subcommittee recognizes that these mechanisms may indeed be mitigative. It was generally accepted, however, that the relevant mechanisms are not understood and that objective, mechanistic methods to treat most of these processes are not in place at the present time. It was also observed that augmenting mechanisms also exist, e.g., H_2 recombination with oxygen in containment on the surface of hot suspended debris.

As a result of the lack of an adequate data base, an inability to reliably extrapolate the available data to full-scale, prototypic accident conditions, and the lack of appropriate modeling, it was generally recognized that the individual subcommittee quantitative recommendations would be subjective in nature.

4. Prior Approach to High-Pressure Melt Ejection Sequence: SP-1

At prior CLWG meetings an approach was taken which neglected the question of direct heating of the containment atmosphere by core melt and chemical energy release.

For SP-1, in which adequate water was assumed to be present in containment prior to melt ejection, it was recommended that the containment loading be computed assuming that within a 1-hour time frame:

(i) 100% of the available core melt would be quenched by heat transfer to water,

(ii) 30% of the zirconium would react with steam, with the liberated chemical energy also transferred to the water to produce steam.

This recommendation was adopted for the "high, best estimate and low" calculations.

5. Recommendations

5.1 Approach

Despite the lack of an adequate technological base, the subcommittee was charged with prescribing a method for computation of containment loading, based upon the judgment of its members, which includes the effects of core melt water quench, direct melt heating of the atmosphere and chemical energy release.

The parametric approach adopted is an extension of the approach described in Section 4 above. It was assumed that the entire core melt inventory specified in the standard problem is available for ejection from the vessel. In the context of a global containment energy balance calculation, subcommittee members were asked to specify, on a best judgment basis:

(i) The fraction of the core melt stored energy which is transferred to water, f_w,

(ii) The extent of metallic chemical reaction energy release of the melt which is quenched in water. This is specified as extent of reaction with steam.

(iii) The fraction of core melt stored energy which is transferred directly to atmospheric heating.

(iv) The extent of metallic chemical reaction energy release of the fraction of core melt which transfers energy directly to the atmosphere. This is specified as the extent of reaction with either steam or with oxygen.

It is recognized that large uncertainties exist in specification of the parameters characterized above. The subcommittee members were therefore asked to specify the above parameters for three calculational estimates of containment loading: "high, best judgment, low." The "high" represents a subjective judgment that the numbers would give an estimate of containment pressure and temperature, when used in a containment calculation, that is at the high end of the uncertainty band. The "low" estimate would correspond to an estimate at the low end of the uncertainty band. All of the estimates are based upon the subjective assessment of the individual of the various mechanisms involved in the interaction process, the available experimental evidence and analytical model. The estimates apply only to the stated initial conditions of SP-1 and SP-2, and should not be applied to any other set of initial conditions.

5.2 Differing Points of View

After some discussion, the subcommittee members generally agreed that the available experimental data (ANL/SNL) suggested that some quantitative modification of the prior recommendations (Section 4) was required in order to

reflect the possible effects of chemical energy release to, and direct heating of, the containment atmosphere in the high-pressure melt ejection accident sequence. There was, however, a major difference of opinion in the proposed recommendations of the extent of direct heating and chemical reaction to be accounted for in containment load calculations. This difference in opinion was greatest for the "high"-prediction, and was irreconcilable. It was agreed that only additional experimentation could lead to resolution.

The opinions of the subcommittee members (those that participated in the estimation process) split along two lines. The opinions of the two groups can be represented as follows:

Group A: Small Direct Heating Effect on Basis of Present Data(1)

This group strongly argued that:

(i) The initial conditions, principally the quantity of molten fuel available for ejection from the vessel, was preventing realistic assessment of the direct heating process,

(ii) The EPRI-ANL experiments clearly demonstrated the effectiveness of water as the heat transfer medium in the simulated Zion containment atmosphere,

(iii) The above-cavity structures, as simulated in the EPRI-ANL experiments, are significant in removal of dispersed core melt material from the containment atmosphere,

(iv) The SNL experiments provide evidence only for the mass of material ejected from the reactor cavity.

(v) The available experimental evidence supports the conclusion that thermal energy no greater than 2% of the initial melt simulant stored energy entered into direct atmospheric heating.

The group concluded that the available experimental data base supports direct heating effects of masses of core melt no greater than 2% of both SP-1 and SP-2.

Group B: Significant Direct Heating Effects Cannot be Ruled Out(2)

The arguments supporting the group's opinion were:

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(1) Group A: Seghal, Sienicki, Spencer, Squarer, Corradini (SP-1).

(2) Group B: Bergeron, Ginsberg, Pilch, Powers, Theofanus, Williams, Wright, Corradini (SP-2).

(i) The ANL and SNL experiments (Zion simulations) both suggest nearly complete melt entrainment from the reactor cavity under prototypic conditions,

(ii) The effectiveness of water as the quenching medium has not been conclusively demonstrated by experiment. The ANL experiments, which included water, cannot be reliably scaled to prototype conditions.

(iii) Based upon their expected size (<1 mm), the core debris can release its thermal and chemical energy on a time scale of just a few seconds.

(iv) The ANL experiments did not contain an air atmosphere and, hence, conclusions with respect to chemical reaction effects cannot be drawn from these experiments.

(v) Hydrogen recombination with oxygen following metallic reaction with steam cannot be precluded.

The group concluded that large uncertainties exist in specification of the key parameters involved in the perceived major direct heating mechanisms. As a result, major uncertainties exist in prediction of the containment loading resulting from the combination of direct heating, chemical reaction and water quench. The group concluded that, at present, "...it is not possible to rule out occurrence of sufficient direct heating to present a severe challenge to PWR large dry containments."

5.3 Recommendations

The individual estimates of the direct heating parameters defined in Section 5.1 were received and sorted out. The estimates were divided into Group A and Group B responses. The estimates are presented in Tables 2-5. As shown in Table 1, each respondent proposed a "High," "Low" and a "Best Estimate" judgment. For each of these categories the respondent gave an estimate of the percentage of melt thermal energy (assumed proportional to the equivalent melt mass) transferred directly to the atmosphere. This is presented as the "Thermal"-"Direct Heat" contribution. The respondent also presented an estimate of the percentage of melt thermal energy transferred to available water to produce steam. This is presented as the "Thermal"-"Water Quench" contribution. For each of the "Direct Heat" and "Water Quench" contribution estimates, the individuals provided an estimate of the associated chemical reaction energetics. These estimates are presented in Tables 2-5, under the "Chemical" heading, in terms of the percentage of available metallic phase which enters a chemical reaction, either in a steam, or in an air, environment.

Consider the sample table, Table 1. Under "Best Estimate" column, x% of the available corium thermal energy is transferred directly to the atmosphere. In addition, y% of the metallic content of material ejected to the atmosphere is assumed to react with oxygen. The associated chemical energy is transferred directly to the atmosphere. Looking again at Table 1, w% of the available corium thermal energy is assumed quenched in water. Of the corium mass which is quenched, z% of its metallic phase chemically reacts with steam with no hydrogen recombination. The chemical energy is transferred to the water.

5.3.1 Group A Response

Table 2 presents the Group A response for both Standard Problems 1 and 2. The table reflects the opinion of Group A that currently available data support direct heating effects involving no more than 2% of the ejected core material stored thermal energy. The 80% water quench estimates are based upon the expected loss of melt to locations where water might not be available for quenching.

5.3.2 Group B Response

Table 3 presents the range of responses from those individuals who support the Group B position of Section 5.2. Note that in Table 3 the top-line parameters under "Direct Heat" is associated with the top-line parameters of "Water Quench" (and similarly for the bottom line parameters). Thus, under the "Best Estimate" parameters of Table 3-1, one respondent proposed that 25% of the core melt transferred its thermal energy directly to the atmosphere, while 75% was presumed quenched in water. A second respondent proposed a 50%-50% split between energy transfer via direct heating and water quench. Similarly, individual differences in judgment pertinent to chemical reaction are also shown.

It is noted that there was a spread in the quantitative estimates of the parameters even within Group B. This should not be surprising, considering the subjective nature of the estimation process. This group believes, however, that the differences observed in Table 3 lie within, and are representative of, the uncertainties in the physical parameters which govern the direct heating and chemical energy release phenomena.

As far as Group B is concerned, the figures shown in Table 3 are meant to imply that the uncertainty in the range of expected physical behavior is large. Therefore, it is not possible to rule out direct heating effects of such a magnitude that would present a severe challenge to large dry PWR containments. The Group stresses that the absolute values of the numbers presented were arrived at subjectively and are quite uncertain. The numbers pertain only to the initial conditions of Standard Problems 1 and 2, and should not be scaled in any way for a change in initial conditions.

6. Summary: Recommendation to CLWG

The differences in technical judgment between Group A and Group B could not be resolved. As a result the Subcommittee on Direct Heating presents two sets of best-judgment recommendations on direct-heating parameters.

Tables 4 and 5 are presented as consensus of Group A and Group B, respectively.

Table 1

Sample Parameter Table

	Low		Best Estimate		High	
	Thermal	Chemical	Thermal	Chemical	Thermal	Chemical
Direct Heat			x%	y% O_2		
Water Quench			w%	z% STM		

Table 2

Group A: Parameters for SP-1 and SP-2

	Low		Best Estimate		High	
	Thermal	Chemical	Thermal	Chemical	Thermal	Chemical
Direct Heat	≤2%*	---	≤2%	---	≤2%	---
Water Quench	~80%	---	~80%	---	~80%	---

*The 2% estimate was derived from the available ANL experiments. Corradini analyzed the ANL results, applied them to prototypic conditions, and obtained 5%. The 2% figure is presented as the best judgment of most of Group A. The difference, as far as impact on containment loading, is small.

Table 3-1

Group B: Range of Parameters for SP-1

	Low		Best Estimate		High	
	Thermal	Chemical	Thermal	Chemical	Thermal	Chemical
Direct Heat	0	0	25%	50% STM*	50%	50% O_2
			50%	50% O_2**	55%	100% O_2
Water Quench	50%	30% STM	75%	30% STM	50%	30% STM
	100%	0	50%	0	45%	30% STM

*STM refers to metal-steam reaction. Because of the small heat of reaction of iron-steam, this is nearly equivalent to zirconium reaction only.
**O_2 refers to oxidation of both iron and zirconium in an atmosphere which allows for hydrogen recombination with oxygen.

Table 3-2

Group B: Range of Parameters for SP-2

	Low		Best Estimate		High	
	Thermal	Chemical	Thermal	Chemical	Thermal	Chemical
Direct Heat	0	0	16.5%	50% STM	33%	100% O_2
	50%	10% O_2	50%	50% O_2	100%	50% O_2
Water Quench	50%	30% STM	83.5%	30% STM	67%	30% STM
	85%	0	50%	0	0	0

Table 4

Group A: Parameters for SP-1 and SP-2

	Low		Best Estimate		High	
	Thermal	Chemical	Thermal	Chemical	Thermal	Chemical
Direct Heat	≤2%	---	≤2%	---	≤2%	---
Water Quench	~80%	---	~80%	---	~80%	---

Table 5-1

Group B: Representative Parameters for SP-1

	Low		Best Estimate		High	
	Thermal	Chemical	Thermal	Chemical	Thermal	Chemical
Direct Heat	0	0	27.5%	50% STM	50%	50% O_2
Water Quench	100%	0	72.5%	30% STM	50%	30% STM

Table 5-2

Group B: Representative Parameters for SP-2

	Low		Best Estimate		High	
	Thermal	Chemical	Thermal	Chemical	Thermal	Chemical
Direct Heat	15%	50% STM	25%	50% STM	50%	50% O_2
Water Quench	85%		75%	30% STM	50%	30% STM