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STEAM EXPLOSIONS - THEIR RELATIONSHIP TO LWR SAFETY ASSESSMENTS

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ABSTRACT

The physical characteristics of steam explosions are evaluated in terms of first principle arguments, which are compared to experimental results reported in the literature. In addition, these are also compared to industrial experience for such events including both non-nuclear and nuclear systems, i.e. BORAX, SPERT, and SL-1. The summation of this state of the art knowledge is then applied to postulated LWR accident conditions.

INTRODUCTION

Core damage and overheating of reactor fuel and cladding material to the molten state could only occur in commercial light water reactors (LWRs) if the supply of water to the core is inadequate to remove power under accident conditions. This could eventually result in molten debris in the core with water remaining in the lower plenum of the reactor pressure vessel (RPV). Simultaneous presence of molten core debris and water in the later stages of a hypothetical core meltdown accident has been postulated, in the Reactor Safety Study (WASH-1400) [1], to be a condition that could lead to an energetic steam explosion sufficient to rupture both the RPV and the containment building. The basis for this postulate arose mainly from destructive testing

of early experimental LWR cores under severe excess reactivity insertion conditions and the history of industrial accidents in the steel, aluminum, copper and pulp and paper industries. Considerable analytical and experimental research over the past several years has resulted in a greater understanding of the necessary and sufficient conditions required for large scale steam explosions. This understanding of both the physical conditions and processes involved in steam explosions plus a general knowledge of the configuration of a LWR in the later stages of postulated severe accidents, leads to the conclusion that in-vessel steam explosions of sufficient magnitude to rupture commercial LWR pressure vessels are physically impossible.

This paper is a summary of a much larger report titled, "Assessment of Steam Explosion Potential in Hypothetical LWR Core Meltdown Accidents," submitted to EPRI/NSAC [2] and presents the basic supporting arguments in a question and answer format. Detailed discussions of the major issues, analyses, and experiments are contained in the complete report.

BACKGROUND

- *What is a steam explosion?*

A classical steam or, more generally, vapor explosion is an exclusively physical, non-chemical, phenomenon which results from an extremely rapid thermal energy transfer between two intimately contacted liquids at different temperatures. The temperature of the hottest liquid, usually a molten metal or refractory material, must be far above the normal boiling point of the second liquid to produce explosive vaporization rates which generate the high pressures and shock waves characteristic of an explosion.

- *Why were steam explosions considered a LWR safety issue?*

For hypothetical LWR core meltdown accidents, molten core material and water can co-exist in a separate state within the RPV with the potential of a steam explosion occurring if the two are intimately mixed. The analytical model used to calculate rupture of the Reactor Pressure Vessel (RPV) in WASH-1400 was based principally upon extrapolating experience in small, low pressure test reactors undergoing prompt critical nuclear excursions (i.e. the BORAX-1 and SPERT-1 destructive tests and the SL-1 accident). Further, industrial experience with steam explosions due to accidental spills of molten material into water in metal foundries as well as in the pulp and paper industry were used as general support that large scale steam explosions could occur. However, the pressures generated in such industrial accidents, while sufficient to damage light industrial buildings, are very low compared to those required to challenge RPV integrity. Also the injuries have been generally due to burns from splashing molten metal as opposed to the explosion itself, i.e. an observation which implies that such events are weak compared to chemical explosions.

- *Are steam explosions and chemical explosions comparable?*

Steam explosions and chemical explosions differ in several fundamental ways. Steam explosions are dependent upon rapid thermal energy transfer between extremely hot and cold liquids, while chemical explosions are driven by rapid chemical reaction rates. Steam explosions, require coarse premixing and rapid fine scale mixing on an explosive time scale while chemical explosions are finely intermixed prior to the explosion for oxidizing systems or require no intermixing if the chemical reaction is one of decomposition. Pressure rise times for steam explosions are of the order of a millisecond to levels of a few tens to a hundred atmospheres while chemical high explosives can achieve local pressures of 250,000 atmospheres in microseconds. Further, since the energy density of chemical explosives is much higher than that

experienced in steam explosions, the severe damage caused by high explosives derives principally from the shock wave itself. Large steam explosions, in contrast, derive most of its damage producing energy from the relatively slowly expanding steam and not the shock wave.

- *How did the Reactor Safety Study consider steam explosions?*

The Reactor Safety Study (RSS), commonly referred to as WASH-1400, considered both in-vessel and ex-vessel steam explosions. Energetic in-vessel steam explosions were assumed to cause containment rupture in all accident sequences which led to the most severe radiological release consequences. Specifically, the calculated energy release from an assumed steam explosion within the RPV was sufficient to not only fail the reactor vessel head but also the containment wall. It was assumed in the RSS that the molten fuel was not only pre-dispersed into the water in the RPV lower head, but that a coherent liquid slug existed to transmit the energy from the expanding steam to the RPV upper structure. These assumptions, as will be discussed, do not represent physically attainable states.

Ex-vessel steam explosions were also considered. However, they were not deemed to be of any significant consequence because there was no coherent water slug or missile to transmit the energy from the expanding steam to the structure.

PHENOMENOLOGICAL CHARACTERISTICS

- *What are the general requirements for a large scale steam explosion?*

Analogous to the preparation of chemical explosives in which energy rich fuels and oxygen-rich compounds are uniformly and finely intermixed, the hot and cold liquids must also be intermixed in order to obtain the necessary thermal energy transfer on a time scale consistent with explosive behavior. In contrast to chemical explosives, the hot and cold liquids are initially in a separated state and the intermixing occurs after they come into contact. Consequently, this fine-scale mixing must occur quickly so that the hot liquid retains its thermal energy. For an efficient, large scale, steam explosion to occur three required stages or conditions have been identified. They are:

* Pre-mixing
* Triggering
* Propagation

- *What is premixing and why is it necessary?*

For a steam explosion to occur there must be sufficient surface area contact between the molten fuel and water to sustain the required high heat transfer rate. Since the molten fuel is only produced in the absence of water, the molten corium must be broken up and dispersed upon entering the water, i.e. premixing. In general, tons of molten corium, in the form of millions of particles, must be premixed to provide enough surface area and sufficient energy to fail the RPV and containment. Premixing has been demonstrated to only be possible when film boiling can occur for the liquid-liquid system. However, energy transfer from the high temperature molten corium causes vaporization during the premixing process and this tends to separate the two liquids.

- *Does a criterion exist which indicates if liquid-liquid film boiling and thus premixing can occur?*

Yes. Stable liquid-liquid film boiling and subsequent coarse premixing appear to be possible only if the contact interface temperature, T_i, between the hot and cold liquids exceeds the "spontaneous" nucleation temperature, T_{sn}, of the volatile cold liquid [3]. The spontaneous nucleation-interface temperature criterion represents the minimum temperature needed for stable liquid-liquid film boiling and as such assures the initiation of the premixing stage. The non-violent molten fuel breakup and intermixing (generally called coarse premixing) resulting in the pre-dispersed configuration must be stable, i.e. the dispersed configuration must be retained to assure that the subsequent trigger and propagation may occur. The evidence for the criterion is very persuasive, ranging from tests with single drops through a large number of pouring and mixing experiments in the kilogram and tens of kilograms range [4]. These tests, which involved many different liquid combinations, consistently showed coarse intermixing and explosions when the contact interface temperature exceeded the spontaneous nucleation temperature of the cold, volatile, liquid.

In addition to satisfy the film boiling criterion, the hot material must remain in the liquid state while the premixed configuration develops. In an initially *separated* system, film boiling is a necessary but not sufficient condition for assuring these conditions. For the reactor accident conditions, the contact interface temperature between corium (molten fuel) and water is far greater than the spontaneous nucleation temperature and molten core debris can penetrate water in a liquid-liquid film boiling state. Mechanistic evaluations have been proposed for describing both the rate of material fragmentation [5] in liquid-liquid film boiling and the size to which the particulation can continue given the material quantities, temperatures, and sizes of the potential mixing zone [6]. Application of these models to large scale experiments and to the reactor systems with sufficient corium mass to threaten the vessel integrity shows that (1) fine scale premixing would be expected in the large scale experiments and (2) virtually no premixing would occur in the reactor system. Table I illustrates the application of the order of magnitude particulation model to pertinent experiments and general agreement is observed between the model and the experiments. When this is extended to the reactor case as illustrated in Table II for both perfect (100% efficient) interactions and 10% efficient events, the limiting size particles are orders of magnitude larger than that considered to be capable of supporting a propagating interaction. If the description for the rate of fragmentation are also considered, a similar conclusion is reached, i.e. the experiments reported in the literature should observe considerable premixing, but the mass fragmented in a reactor system is orders of magnitude less than that required to threaten a reactor pressure vessel. In essence, both approaches predict that the fragmentation and premixing in the reactor system would be virtually non-existent. This variation of particulation scale as a function of the respective material masses was demonstrated experimentally by Theofanous and Saito using water and liquid nitrogen [10].

- *What is a "trigger" and why is it necessary?*

To achieve the necessary heat transfer rates for explosive vaporization a mechanism must exist to ensure that direct liquid-liquid contact occurs. This can only happen if the steam film between the corium and the water, which limits the heat transfer rate is penetrated. Triggers can be spontaneous, perhaps due to either instability in the steam film or its being stripped as the molten fuel moves through the coolant, and leads to the propagation of the steam film collapse across the interaction zone. This collapse or stripping can be caused by locally high pressures resulting from the thermal expansion and vaporization of the coolant at the high heat transfer rates associated with liquid-liquid contact. Triggering can also result from an external stimuli, such as the exploding wires or mini-detonators used in many experiments. Table III shows that the mini-detonator triggers used in the Sandia tests is capable of not only collapsing the steam film but also providing sufficient energy to rapidly mix [11] enough material to achieve the measured energy release. As

Table I

Fragmentation Experiments
Pressure = 0.1 MPa

Reference	Melt	Melt Quantity kg	Temperature		Fragment Sizes	
			Melt K	Water K	Reported mm	Predicted mm
Amblard, et al. [7]	UO_2	∿ 1	3070 (Freezing)	293	2 - 30	60
Benz, et al. [8]	SS	1.65	2000	353	2 - 4	2.8
			1770 (Freezing)	353	2 - 4	2
	UO_2	1.24	3270	293	1 - > 4	5
			3070 (Freezing)	293	1 - > 4	4
Sandia [9]	Iron	13	3000	293	∿ 10	20
	Thermite		1770 (Freezing)	293	∿ 5	3.8

Table IIA

Predicted Fragmentation Limits for Hypothetical Accident Conditions in a Boiling Water Reactor

	Without CRDs*	With CRDs	Without CRDs	With CRDs
System Pressure, MPa	0.3	0.3	0.3	0.3
Melt Temperature, K	2500	2500	2500	2500
Water Temperature, K	407	407	407	407
Mass, kg	3800	3800	38,000	38,000
Vessel Area, m^2	29	16	29	16
Particle Diameter, m	0.17	0.30	1.7	3.0
Number of Particles	219	38	2	1

*CRDs = control rod drives.

Table IIB

Predicted Fragmentation Limits for Hypothetical Accident Conditions in a Pressurized Water Reactor

System Pressure, MPa	0.3	0.3
Melt Temperature, K	2500	2500
Water Temperature, K	407	407
Mass, kg	2260	22,600
Vessel Area, m^2	16	16
Particle Diameter, m	0.18	1.8
Number of Particles	104	1

Table III

Sandia Thermite Experiment
SAND/79-1399, NUREG/CR-0947
Fragmentation and Mixing Analysis
Single Step Mixing
Equal Volume Mixing

Quantity	Run Number					
	27	29	30	35	38	41
Melt mass, Kgm	4.2	3.4	3.2	12.0	13.0	9.4
Reported efficiency, %	0.42	0.47	0.36	0.20	0.19	0.26
Measured work, KJ	23.9	21.6	15.6	32.5	33.4	33.0
Fragment radius prior to the trigger, mm	1.071	0.884	0.782	3.065	3.381	2.815
Mixing energy J/particle, 10^{-4}	2.090	0.658	0.317	1147	2067	689
Potential work by expl., KJ	1639	1337	1228	4687	5130	3826
Energy required to mix all melt, J	32.8	14.9	9.7	2194.4	3192.1	1332.7
Detonator available energy, J	3683	3683	3683	3683	3683	3683

illustrated in Table III, the mechanical work delivered by the trigger is sufficient to mix all the melt in each of the experiments. Since the energy release is much less than that characteristic of all the melt, these experiments also demonstrate the inefficiency of the initiation and propagation processes in thermal interactions. For the large molten masses evaluated for LWR systems, extremely large external triggers would be required to initiate an event. In fact the trigger energy would be greater than the energy required to fail the pressure vessel. No such triggers could be identified in LWR systems.

- *Why is propagation necessary?*

Given a sufficient amount of coarse premixing and the existence of a trigger, propagation of a local explosion across the entire interaction zone is required to ensure that a sizeable fraction of the available explosive work is utilized. If propagation does not occur, then the process would be either inherently self-limiting or would require a continuously acting external trigger to sustain the interaction. In an LWR system a significant external trigger mechanism does not exist, and with the limited premixing for such systems propagation could not be sustained. In general vapor explosions are found to have efficiencies between 1% and 10% of the thermodynamic maximum. This demonstrates that the propagation is not an efficient process.

CONSIDERATIONS FOR REACTOR SYSTEMS

- *Have explosions been observed in experiments with reactor-like materials?*

Yes, because the thermal characteristics of these materials satisfy the spontaneous nucleation explosion criterion. However, in both small-scale tests with single drops and a number of intermediate scale experiments (molten UO_2 and mixtures of molten UO_2, ZrO_2 and steel) which sometimes included the use of an external trigger, only a few explosive interactions have been produced using typical molten core debris temperatures (> 2500°C). The usually non-explosive behavior of these materials can be explained by: (a) the absence of premixing, (b) the non-existence of a sufficient trigger, (c) the lack of a timely external trigger, or (d) the rapid solidification of the fuel surface which prevents liquid-liquid contact. More importantly, these intermediate scale laboratory tests grossly misrepresent the explosion potential under typical LWR core meltdown conditions because of the scale involved in the masses of corium and water used and also in the vessel dimensions [10].

- *Are steam explosions sensitive to system pressure level?*

Yes. A pressure-related cut-off point for vapor explosions was first indicated through two different analyses and later demonstrated by extensive intermediate scale and large experiments [12]. These experiments have covered a range of fluid combinations including corium and water. Based on thermophysical properties alone analysis indicates that the explosion cut-off pressure for water is about 1 MPa (145 psia). This is important to note because LWR core meltdown events can result in primary system pressures that are several times greater than this value, thus precluding an explosive interaction. While experiments have shown that the pressure cutoff can be somewhat overridden by a strong external trigger [13,14], they also show that moderate increases in the ambient pressure can suppress the effect of the external trigger.

- *What are the requirements for significant work potential?*

In contrast to chemical high explosives, where much of the destructive energy is in the shock wave, a vapor explosion produces most of its destructive energy from the expanding steam or vapor and not from the shock wave. Thus, for a steam explosion to have significant structural damage potential, such as causing rupture of the RPV, the

generated steam must be contained and directed, i.e. the presence of a coherent liquid slug with good fluid/structure coupling is required in addition to the requirement of a pre-dispersed system. For the conditions characterizing the core configuration in the postulated accidents, the formation of a coherent slug could only occur in the absence of significant premixing. Thus, if such premixing is postulated, no strong fluid/structure coupling would exist.

- *Were these physical and configurational requirements satisfied in the BORAX-1 and SPERT-1 destructive tests as well as the SL-1 incident?*

Yes. It is important to recall that the idea for an energetic, large-scale, steam explosion in an LWR system stems principally from experiences with steam explosions in small experimental test reactors undergoing prompt critical nuclear excursions. This evidence includes both the BORAX-1 and SPERT-1 destructive tests and the SL-1 incident. The fuel of these reactors was fully enriched uranium-235 alloyed with aluminum (rapid thermal response) and formed into ≈ 0.5 mm thick flat plates. These fuel plates were then covered with aluminum clad, also fast thermal response, i.e. a thermal time constant equal to or less than the nuclear period. Thus the fuel and the water coolant (which favors film boiling) provided an intimately dispersed configuration even prior to the rapid energy deposition in the fuel by the nuclear excursion. Therefore, the combination of the initial geometry, a well mixed cold state, and the rapid energy deposition in the fuel provided conditions (molten fuel and molten cladding sufficiently premixed in the coolant and only separated by thin vapor blankets) ideal for producing a propagating steam explosion. In fact, the combination of the rapid power excursion and the fuel design characteristics (initial premixing) eliminated the need for any significant fragmentation and intermixing either before or during the explosion. In addition to satisfying the requirement of a pre-dispersed system, the coherent liquid slug requirement was satisfied in both the SPERT-1 and SL-1 incidents since the systems were nearly full of cold water prior to the nuclear excursion. This provided a means for containing and directing the energy of the expanding steam, which helped to optimize the destructive work potential of the explosion. *The characteristics of these early experimental, plate-type, reactor incidents produced a significant amount of damage; but they are fundamentally different from current commercial water reactor fuel designs as is the configuration developed during hypothetical core meltdown accidents.*

- *Given the criteria required for both steam explosions and structural damage to occur, how do these apply to the analysis of hypothetical core meltdown accidents in commercial LWRs?*

The rapid power transients, like those designed into the experimental destructive tests of the early, plate-type fast response, reactor designs, are impossible with the large, low-enrichment, oxide fueled, cores used in commercial LWRs. Hypothetical core meltdown accidents in LWRs are, therefore, related to the inability to provide water to the core over an extended time period. Consequently, at the time of fuel melting, water is already removed from both the core region and above, i.e. the molten fuel debris and water are initially separated. In addition to the absence of a dispersed corium-water configuration, this separated state implies the absence of a continuous water column for containing and directing the steam explosion even if it could be initiated. Additionally, even if a water slug could be ejected much of its energy would be absorbed in structural damage to reactor internals - a fact which is overlooked in most analyses.

CONCLUSIONS

- *Are the WASH-1400 steam explosion modeling assumptions overly conservative?*

Yes. Given the above arguments and evidence, it is clear that the assumptions in the WASH-1400 report which result in estimates of significant damage from steam explosions are overly conservative for essentially two reasons. These are: (1) it is not possible to obtain the required molten corium-water premixing, triggering and propagation for a significant steam explosion and (2) even if the steam explosion were to occur the reactor configuration at the time of the postulated event does not have an overlying liquid slug which can coherently impact on the vessel head.

- *Should steam explosions be considered as a RPV threat under core meltdown conditions?*

Considering the necessary physical and configurational requirements to produce a sufficient steam explosion to threaten the reactor pressure vessel integrity and the inherent physical limitations in providing a coarse premixture and an overlying liquid slug, such events represent an incredible set of physical processes. Consequently, a steam explosion should not be considered as a potential threat to the integrity of either the reactor pressure vessel or the containment building. Similarly, such an interaction and resultant steam explosion that may occur ex-vessel following RPV melt-through can be dismissed as an event to threaten the containment as was concluded in the Reactor Safety Study.

REFERENCES

1. Reactor Safety Study, WASH-1400, NUREG/75-0114, 1975.

2. S. G. Bankoff, D. H. Cho, A. W. Cronenberg, H. K. Fauske, R. E. Henry, T. J. Marciniak, R. C. Reid and G. R. Thomas, "Assessment of Steam Explosion Potential in Hypothetical LWR Core Meltdown Accidents," Draft submitted to Nuclear Safety Analysis Center, Electric Power Research Institute, August 1982.

3. H. K. Fauske, "Some Aspects of Liquid-Liquid Heat Transfer and Explosive Boiling," Proc. Fast Reactor Safety Mtg., Beverly Hills, California, April 2-4, 1974.

4. S. G. Bankoff, "Vapor Explosions: A Critical Review," Proc. 6th Intl. Heat Transfer Conference, Vol. 6, pp. 355-360, 1978.

5. H. K. Fauske and R. E. Henry, "Mechanisms of Liquid-Liquid Vapor Explosions," paper presented at the AIChE Mtg., Anaheim, California, June 7-9, 1982.

6. R. E. Henry and H. K. Fauske, "Core Melt Progression and the Attainment of a Permanently Coolable State," ANS/ENS Topical Mtg. on Reactor Safety Aspects of Fuel Behavior, Sun Valley, Idaho, August 1981, pp. 2-481 - 2-495.

7. M. Amblard, et al., "Experimental Results of Contact Between Molten UO_2 and H_2O: Statement of Thermal Interaction Models," OECD CSNI Specialist Mtg. on the Behavior of Water Reactor Fuel Elements Under Accident Conditions, Spatind, Norway, September 1976.

8. R. Benz, et al., "Melt/Water Interactions in Tank Geometry: Experimental and Theoretical Results," Proc. of 4th CSNI Specialist Mtg. on Fuel-Coolant Interaction in Nuclear Reactor Safety, CSNI Report No. 37, Vol. 2, Bournemouth, UK, April 1979, pp. 363-386.

9. L. D. Buxton and W. B. Benedick, "Steam Explosion Efficiency Studies," NUREG/CR-0947, SAND 79-1399, November 1979.

10. T. G. Theofanous and M. Saito, "An Assessment of Class-9 (Core Melt) Accidents for PWR Dry-Containment Systems," Purdue University Report No. PNE-81-148, June 1981.

11. D. H. Cho, H. K. Fauske and M. A. Grolmes, "Some Aspects of Mixing in Large Mass, Energetic Fuel-Coolant Interactions," Proc. of Intl. Mtg. on Fast Reactor Safety and Related Physics, CONF-761001, Vol. 4, Chicago, Illinois, October 1976, pp. 1852-1861.

12. H. Hohmann, R. E. Henry and H. M. Kottowski, "The Effect of Pressure on NaCl-H_2O Explosions," 4th CSNI Specialist Mtg. on Fuel-Coolant Interactions in Nuclear Reactor Safety, Bournemouth, UK, CSNI Report No. 37, April 1979, pp. 308-323.

13. R. E. Henry and L. M. Mc Umber, "Vapor Explosion Experiments with an External Trigger," 2nd CSNI Experts Mtg. on the Science of Vapor Explosions, Grenoble, France, September 1978.

14. M. L. Corradini, D. E. Mitchell and L. S. Nelson, "Recent Experiments and Analysis Regarding Steam Explosions with Simulant Molten Reactor Fuels," ASME Symposium on Fuel-Coolant Interactions, Winter Annual Mtg., Washington, D.C., November 1981, pp. 49-63.