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OF INDUSTRY

STEAM EXPLOSIONS IN LIGHT WATER REACTORS

Report of the Swedish Government Committee on Steam Explosions

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To the Ministry of Industry

By a decision of 11 September 1980, the Government authorized Minister Petri to set up a committee consisting of no more than five members for the purpose of evaluating the risks and effects of steam explosions in nuclear power plants.

With the support of the authorization, the following persons were summoned as members of the committee on 17 September 198C, Kurt Becker, professor of nuclear engineering at the Royal Institute of Technology in Stockholm, Arne Hedgran, professor of nuclear safety at the Royal Institute of Technology in Stockholm, Ingvar Jung, professor of steam engineering at the Royal Institute of Technology in Stockholm and, on 25 September 1980, Janne Carlsson, professor of strength of materials at the Royal Institute of Technology in Stockholm. Ingvar Jung was appointed chairman.

The following persons were appointed as experts: On 17 September 1980, Gösta Lindh, head of section at the Ministry of Industry, and on 22 September 1980, Lars Högberg, chief engineer at the Swedish National Defence Research Institute.

On 1 October 1980, Bo Olsson was appointed secretary and Dr. Gunilla Bergström of the Swedish National Defence Research Institute was appointed assistant secretary.

At a meeting on 23 September 1980, the committee adopted the name of the Steam Explosion Committee.

Lennart Agrenius, M. Eng., has been engaged as the committee's consultant with the function, as technical secretary, of coordinating the preparation of the committee's report.

At a meeting on 26 September 1980, the committee resolved to summon as consultants Dr. Hans Fauske of Fauske and Associates, Inc., Willowbrook, Illinois, USA and professor Franz Mayinger of the Hanover University of Technology, German Federal Republic.

Professor Bryan McHugh of the Department of Nuclear Engineering at the Chalmers University of Technology, Gothenburg, and Dr. Björn Kjellström of AB Fjärrvärme, Trosa, have been asked to examine Fauske's and Mayinger's reports. Kjellström declined the request.

As emerges in greater detail from the account of the investigation work, the committee has also had contact with a large number of research workers and technical experts. These persons have generously placed work material and time for discussions at the disposal of the committee. The committee would like to express its warm gratitude to all of those persons who assisted the committee in its work in this manner.

Owing to the very short period of time available, it has not been possible for the committee to carry out any of its own scientific calculations concerning the sequence of events connected with steam explosions. With the aid of the foreign consultants and through contacts with research workers in the United States, West Germany and at Euratom, however, it has been possible to keep up with the latest findings in the steam explosion field. It is therefore the opinion of the committee that even if more time had been available, its final position would not have been different.

A supplementary statement has been submitted by Kurt Becker.

The committee hereby submits its report
Stockholm, December 1980

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APPENDICES

1 BACKGROUND AND TERMS OF REFERENCE. THE INVESTIGATION WORK

1.1 Background

The current discussion of steam explosions in connection with reactor safety analyses can be said to have been initiated by the publication in 1975 of the WASH-1400 Reactor Safety Study. In this report, accident sequences which could occur if the reactor's cooling and safety systems were to fail are studied. According to the report, different accident sequences could lead to radioactive releases of varying extent. According to WASH-1400, steam explosions in the reactor vessel are among the events that could give rise to the most serious releases, including releases leading to long-lived radioactive ground contamination. By "steam explosion" is meant an explosion caused by a molten reactor core or parts thereof falling down into the water that may be present in the bottom of the reactor vessel and the containment. It was assumed in WASH-1400 that, under certain circumstances, the explosion could be so violent that a large rupture could occur in the massive containment of steel and concrete that surrounds the reactor.

In Sweden, the issue of steam explosions in reactors was taken up by the Energy Commission's expert group for safety and environment. By and large, reference was made to the analyses in WASH-1400. However, in its report (Ds I 1978:27), the expert group pointed out that the uncertainty in all of the absolute values for the probabilities of different types of damages to the containment was large.

In the German risk analysis "Deutsche Risikostudie Kernkraftwerke", published in the autumn of 1979, a severe steam explosion was judged to be extremely improbable on physical grounds. Deeper analyses of this problem complex were scheduled in the next phase of the German risk study work. Pending the results of these deeper analyses, the probability figures of WASH-1400 were used as an upper limit for the risk. These assumptions had the effect that steam explosions were given as the predominant potential cause of large releases of radioactivity in the German report.

The report entitled "More effective emergency preparedness", issued by the Swedish National Institute of Radiation Protection in December of 1979, presents calculations of the consequences of serious reactor accidents as a basis for proposals for improved emergency preparedness plans. The discussion in this report of the probabilities of serious accidents and associated radioactive releases was based primarily on WASH-1400 and the German risk study.

Thus, while a great deal of emphasis was being placed in Sweden on accidents involving steam explosions - among other things as a basis for proposals for emergency preparedness plans - experiments and refined calculations were being conducted in various parts of the world that led to a better understanding of the criteria for steam explosions and the sequence of events associated with them. This led in early 1980 to intensive discussions of whether the report "More effective emergency preparedness" had been based on realistic accident scenarios.

A more thorough review of how steam explosions have been dealt with in various reactor safety studies since 1975 is provided in chapter 3.

In connection with the Swedish parliamentary debate on the 1979/80 Government Bill concerning certain energy matters, a request was made in Opposition Bill 1979/80:2056 that the Government should appoint an expert group to analyse the probability and effects of steam explosions in nuclear power plants.

The Parliamentary Committee on Economic Affairs (NU 1979/80: 70, p. 23) also proposed to the parliament that a group of independent experts should be appointed to carry out an evaluation of the risks and effects of steam explosions in nuclear power plants.

The parliament decided in favour of the committee's proposal (rskr 1979/80:410).

1.2 Terms of reference of the Committee

By a decision taken at a cabinet meeting on 1980-09-11, the Government authorized Minister Petri to set up the above-mentioned committee.

In his statement for the record, Minister Petri elaborated in greater detail on the implications of the investigative directives, and stated the following:

"In view of what has now been reported, I direct that a committee be assembled for the purpose of compiling and reporting currently available facts concerning steam explosions in nuclear power plants and their possible consequences. The committee should further comment upon the reported material in the light of Swedish conditions. Moreover, the committee should describe which measures it finds appropriate in order to further deepen our knowledge concerning the possibilities of steam explosions at nuclear power plants. The committee should in particular determine whether the risks of accidents in nuclear power plants that lead to steam explosions and resultant releases of large quantities of radioactivity are such that they should be given particular consideration in the design of safety systems and emergency preparedness plans. The committee should also describe the measures that have been adopted in Sweden to study steam explosions.

A final report should be submitted on the work of the committee no later than 1 December 1980."

The terms of reference of the committee are given in their entirety in Appendix 1 (Swedish edition only).

1.3 The investigation work

The committee has held 14 meetings.

Professor Kurt Becker of the Department of Nuclear Engineering at the Royal Institute of Technology in Stockholm made trips to Italy and the United States during the periods 18-19 September and 4-25 October, 1980, in order to collect and discuss the most recent findings concerning steam explosions.

Appendix 2 to the committee's report is a report written by Professor Becker concerning steam explosions.

Professor Janne Carlsson of the Department of Strength of Materials and Solid Mechanics at the Royal Institute of Technology in Stockholm has written a report (Appendix 3 to the committee's report) that deals with the resistance of the reactor to steam explosions.

At the request of the committee, Dr. Hans K. Fauske of Fauske and Associates, Inc. in the United States and Professor Dr. Franz Mayinger of the University of Technology in Hanover, German Federal Republic, have submitted special reports that are included as appendices to the committee's report.

Dr. Fauske and Professor Mayinger were invited to visit Stockholm during the month of November for discussions with the committee. On 10 November, Dr. Fauske and his associate Dr. Robert Henry participated in a meeting of the committee, at which Fauske's report was discussed in detail. In addition to the members of the committee, Professor Bryan McHugh of the Chalmers University of Technology also participated in the meeting.

On 19 November, Professor Mayinger took part in a meeting of the committee at which his report was discussed.

Professor Bryan McHugh and Dr. Björn Kjellström of AB Fjärrvärme, Trosa, were asked to examine Fauske's and Mayinger's reports and offer their comments. Professor McHugh's statement of comment is appended to the committee's report as Appendix 6. Kjellström declined to comment.

On 17 October, presentations were made at a committee meeting by representatives of the PILTRA project (see section 3.8).

Through Sweden's technical attachés in Japan, France and the Soviet Union, the committee sought to ascertain whether any important studies concerning steam explosions have been made in these countries. Some information has been received from Japan.

2 NUCLEAR RLACTOR DESIGN - AN INTRODUCTION

(As the original Swedish report was also aimed at reader groups without specialized technical expertise in nuclear reactor technology, chapter 2 in the Swedish report gave a short technical introduction to the design of nuclear reactors, especially of the types built and operated in Sweden. Chapter 2 is omitted in this English translation with the exception of table 2.1 and figures 2.4 and 2.5, which give some pertinent data on Swedish reactors.)

Table 2.1 Swedish nuclear power reactors

Reactor	Commissioned year	Type	Net capacity MW	Number of fuel assemblies in core	Weight of uranium fuel (tonnes)	Weight of core (tonnes)
Oskarshamn 1	1972	BWR	460	448	90	133
Oskarshamn 2	1974	BWR	580	444	89	132
Ringhals 1	1976	BWR	750	648	130	192
Ringhals 2	1975	PWR	800	157	81	104
Barsebäck 1	1975	BWR	580	444	89	132
Ringhals 3	*	PWR	915	157	81	104
Barsebäck 2	1977	BWR	580	444	89	132
Forsmark 1	1980	BWR	900	676	136	201
Ringhals 4		PWR	915	157	81	104
Forsmark 2	*	BWR	900	676	136	201
Oskarshamn 3		BWR	1050	700	141	208
Forsmark 3		BWR	1050	700	141	208

* Being commissioned

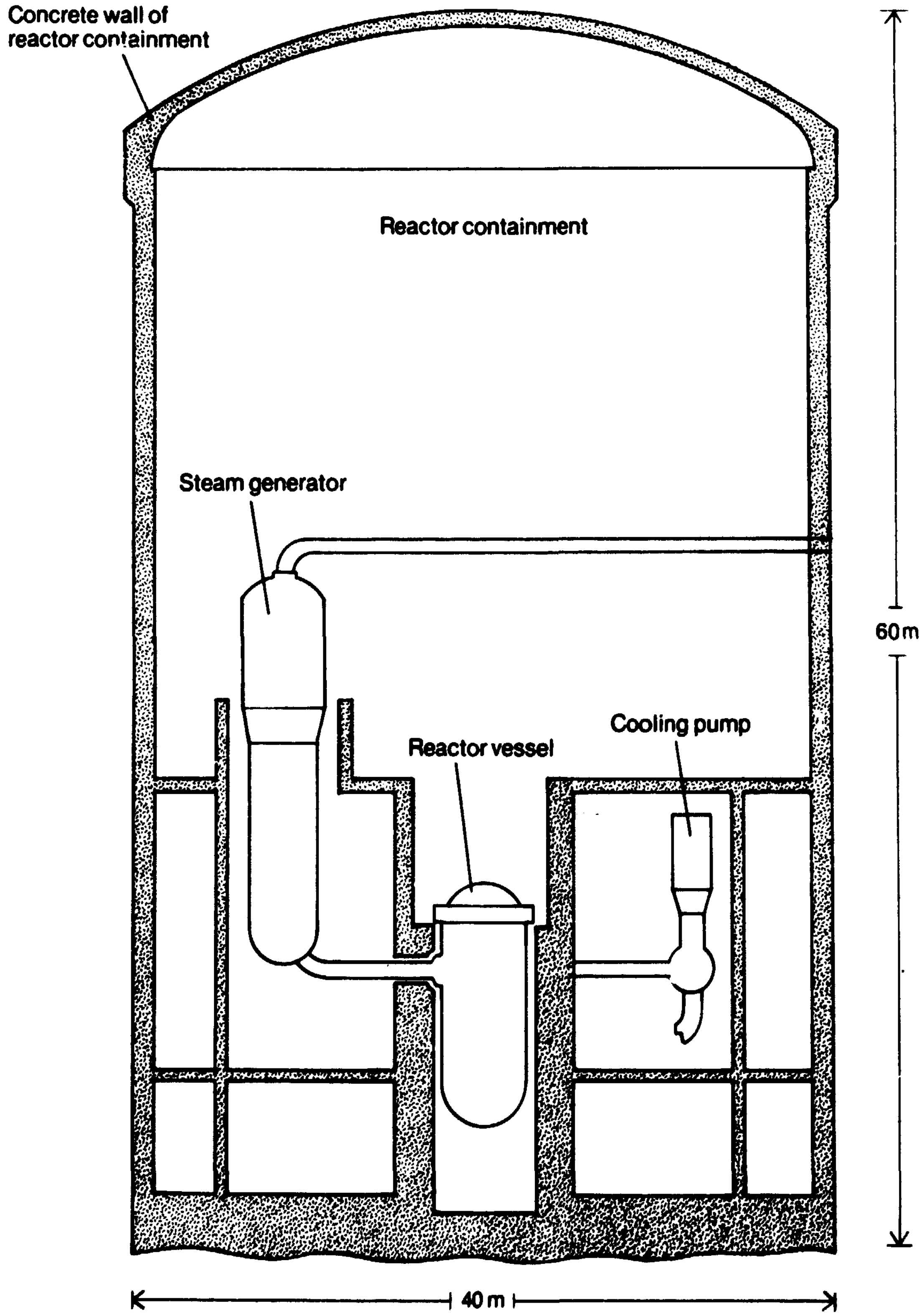

Fig. 2.4 Reactor containment for a pressurized water reactor.

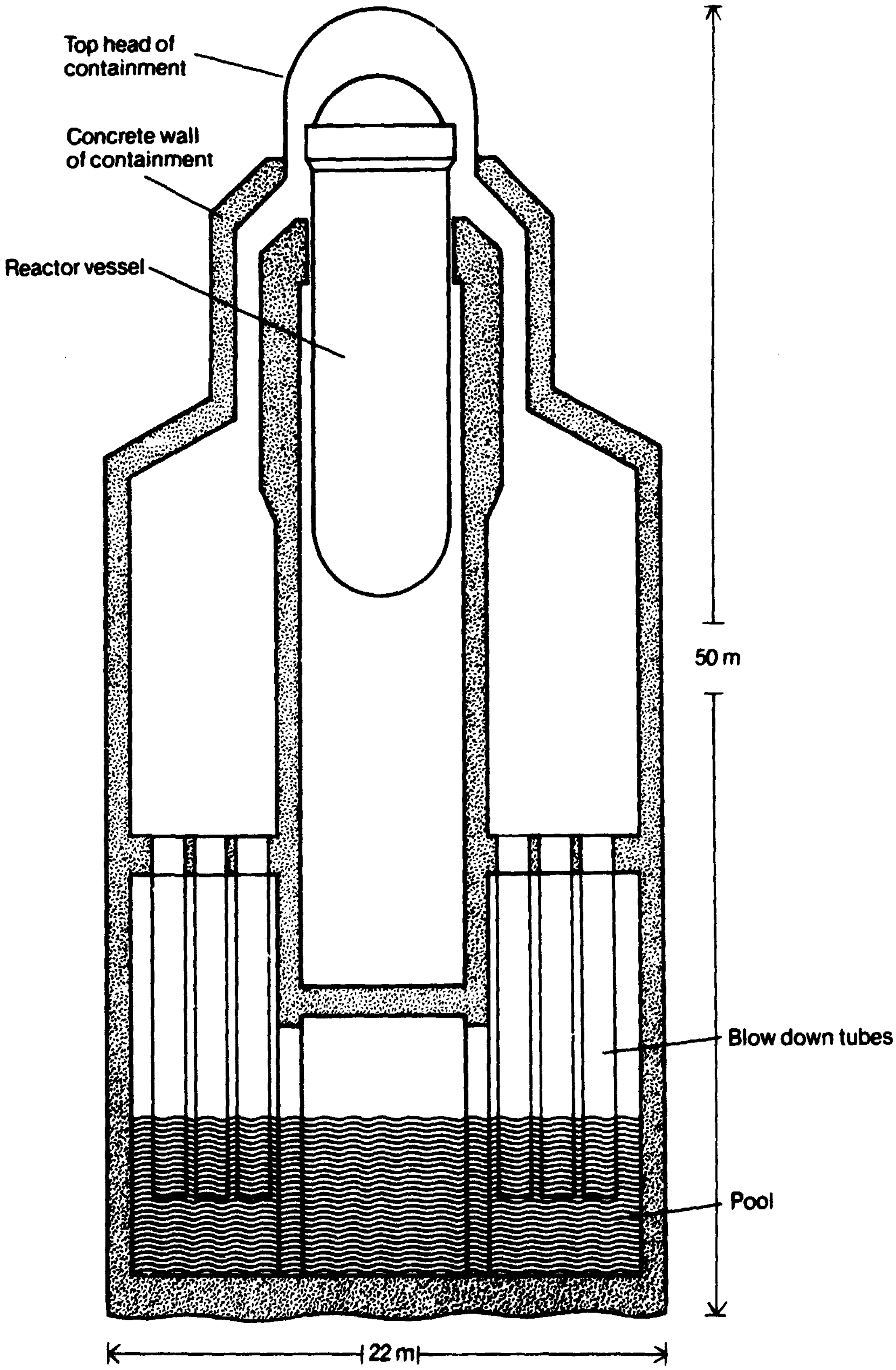

Fig. 2.5 Reactor containment for a boiling water reactor of the old type.

3 PREVIOUS RISK ANALYSES AND DESCRIPTIONS OF ACCIDENTS INVOLVING STEAM EXPLOSIONS

In order to put steam explosion questions in perspective, a brief description of possible accident sequences in light water reactors is provided in the beginning of this chapter. This is followed by a summary of how steam explosion questions have been dealt with in a number of Swedish and foreign risk studies.

3.1 General about core accidents and meltdowns

A light water reactor for commercial power production is equipped with several independent safety systems that are supposed to be able to take care of any malfunctions that may occur. An accident should be prevented or limited even if all of these systems do not work. In other words, in order for a major reactor accident to occur, with the release of large quantities of radioactivity, several of the safety systems must be put out of action simultaneously. The possibility of this occurring is studied in different types of risk analyses.

The most serious accident sequences lead to a loss of the cooling water that surrounds the reactor core. If the cooling water is lost, most of the energy generation in the reactor core is stopped.

The decay of fission products in the core still produces so much heat (known as decay heat, see Table 3.1) that the lack of cooling causes the nuclear fuel to overheat and, at worst, melt down. If the cladding temperature reaches 800-900^{o}C, as compared to a normal temperature of about 350^{o}C, the cladding tubes will crack. Gaseous fission products, such as inert gases and iodine, will then leak out through the cracks and into the reactor vessel and connected piping.

Table 3.1 Decay heat in a fully spent PWR core with a thermal power of 2700 MW thermal i.e. of a size similar to the cores in Ringhals units 2-4.

Time after reactor trip	Decay heat MW
1 sec	163
4 sec	145
10 sec	128
40 sec	103
100 sec	87
400 sec	67
1000 sec	54.6
1 hr	37.3
2 hr	30.3
5 hr	23.8
10 hr	19.9
20 hr	16.5
50 hr	11.5
100 hr = 4.17 days	8.90
200 hr = 8.3 days	6.57
500 hr = 20.8 days	4.31
1000 hr = 1.39 month	3.02
2000 hr = 2.78 month	2.03
5000 hr = 6.9 month	1.02
8760 hr = 1 year	0.609

Source: The Kemeny Commission: Technical Staff Analysis Report on Alternative Event Sequences.

At even higher temperatures, above approximately 1200-1400°C, the zirconium cladding is destroyed completely and the entire core can collapse and eventually melt down. If steam is flowing through the core which is probable, the course of events will be accelerated at these high temperatures by the zirconium combining with the oxygen in the water, producing large quantities of heat. Large amounts of hydrogen gas are also formed.

If the core melts, all the gaseous fission products that have been bound in the fuel pellets will be released. It is also expected that other fission products, such as cesium, will be liberated from the melt, which will reach a temperature of 2900^{o}C or higher.

Under certain circumstances, a core meltdown can give rise to such large pressure increases (due to steam or gas generation in the reactor containment) that the containment is damaged and some of the radicactive fission products in the core are released to the environment. It has been assumed that large radioactive releases can be caused by powerful steam explosions in connection with the molten core falling down into water present in the bottom of the reactor vessel or the containment - in the latter case, after the core material has melted through the bottom of the reactor vessel.

In keeping with its terms of reference, the steam explosion committee will restrict itself to discussing the risk of steam explosions under the assumption that an accident sequence has proceeded so far that the core melts down. This means that we will not discuss further the probability of a core meltdown occurring in the first place.

3.2 The WASH-1400 reactor safety study

In 1975, the final report of the large American reactor safety study, WASH-1400, was published. The report analysed various possible sequences of events that could lead to serious reactor accidents and releases of radioactivity. The analysis dealt with a reactor of the pressurized water type of Westinghouse manufacture and one of the boiling water type of General Electric manufacture. The results

Table 3.2 Probabilities of radioactivity releases of varying scope for pressurized water and boiling water reactors, according to WASH-1400

Release category	Probability per reactor year	Fraction of core inventory released			
		inert gases	inorganic iodine	cesium/ rubidium	barium/ strontium
PWR 1	$9 \cdot 10^{-7}$	0.9	0.7	0.4	0.05
PWR 2	$9 \cdot 10^{-6}$	0.9	0.7	0.5	0.06
PWR 3	$4 \cdot 10^{-6}$	0.8	0.2	0.2	0.02
PWR 4	$5 \cdot 10^{-7}$	0.6	0.09	0.04	$5 \cdot 10^{-3}$
PWR 5	$7 \cdot 10^{-7}$	0.3	0.03	$9 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
PWR 6	$6 \cdot 10^{-6}$	0.3	$8 \cdot 10^{-4}$	$8 \cdot 10^{-4}$	$9 \cdot 10^{-5}$
PWR 7	$4 \cdot 10^{-5}$	$6 \cdot 10^{-3}$	$2 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-6}$
PWR 8	$4 \cdot 10^{-5}$	$2 \cdot 10^{-3}$	$1 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$1 \cdot 10^{-8}$
PWR 9	$4 \cdot 10^{-4}$	$3 \cdot 10^{-6}$	$1 \cdot 10^{-7}$	$6 \cdot 10^{-7}$	$1 \cdot 10^{-11}$
BWR 1	$1 \cdot 10^{-6}$	1.0	0.4	0.4	0.05
BWR 2	$6 \cdot 10^{-6}$	1.0	0.9	0.5	0.10
BWR 3	$2 \cdot 10^{-5}$	1.0	0.1	0.1	0.01
BWR 4	$2 \cdot 10^{-6}$	0.6	$8 \cdot 10^{-4}$	$5 \cdot 10^{-3}$	$6 \cdot 10^{-4}$
BWR 5	$1 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$6 \cdot 10^{-11}$	$4 \cdot 10^{-9}$	$8 \cdot 10^{-14}$

PWR = pressurized water reactor; BWR = boiling water reactor

Source: WASH-1400, Main Report, page 78

of the study were summarized in a table of the probabilities of radioactive releases of various extents, see Table 3.2.

Steam explosions in the reactor vessel were said in WASH-1400 to be a typical cause of releases of categories PWR 1 and BWR 1. In connection with the planning of emergency preparedness planning, PWR 1 and BWR 1 have been regarded as the most serious release categories, due to both the extent of the release and the violence of the assumed sequence of events. Steam explosions in the reactor containment were discussed, but were not considered, in comparison with other types of event sequences, to contribute appreciably to the risk of very large releases. In the treatment of steam explosions in WASH-1400, a certain physical model was assumed for the energy conversion when a large quantity of molten core comes into contact with water. This model and others are critically examined in the following chapters in the light of more recent theoretical and experimental studies. In this context, it can be noted that more recent studies have also questioned the models used in WASH-1400 for other release sequences and release categories. This is evident from a comparison with the risk figures and release categories of the German reactor safety study, see Section 3.4 and Table 3.3 below. It has, however, been beyond the scope of the terms of reference of the committee to examine other release mechanisms than steam explosions.

3.3 Studies carried out by the Swedish Energy Commission

During 1977-1978, the Energy Commission conducted a number of risk studies for nuclear reactors through its expert group for safety and environment (EK-A). Several of these risk studies referred to WASH-1400, partly by critically examining methods and results and partly by studying Swedish reactors using the same methodology. Steam explosions were dealt with in a controversial study of Swedish boiling water reactors, of the Barsebäck type, carried out by the American consultancy firm MHB (Ds I 1978:1). In the MHB study, the risk of steam explosions in both the reactor vessel and the containment was judged to be considerably greater than had been indicated in WASH-1400. As far as can be concluded from the report, this is not due to the fact that the MHB study made use of a different physical model for the energy conversion that takes place upon contact between the molten core and water. By and large, the difference appears to stem from an attempt to quantify in probabilistic terms certain design differences between the two reactors types. In its comments on the MHB study, EK-A pointed out the large uncertainties that are associated with such probability estimates.

3.4 The German reactor safety study

In the autumn of 1979, a report was published on the first phase of a reactor safety study commissioned by the Ministry of Research in the German Federal Republic. The study concerned a German pressurized water reactor manufactured by Kraftwerk Union. As in WASH-1400, a table is provided in the German report on the probability of radioactive releases of different categories, see Table 3.3. According to the German table, steam explosion sequences (category 1 in the table) make the largest contribution to the risk of large releases. The text of the report, however, contains an analysis which arrives at the conclusion, based on physical grounds, that steam explosions that release large quantities of energy from meltdowns on the order of tons must be regarded as unrealistic and extremely improbable. For reasons of limited time, and pending the results of further studies, the WASH-1400 risk figures for steam explosion, given that a core meltdown occurs, were taken as an upper limit for the risk.

Table 3.3 Probabilities of certain large radioactive releases for a pressurized water reactor in accordance with the German reactor safety study, phase A. Release category 1 refers to steam explosions in connection with a core meltdown.

Release category	Probability per reactor year	Fraction of core inventory released			
		inert gases	inorganic iodine and bromine	cesium/ rubidium	barium/ strontium
1	$2 \cdot 10^{-6}$	1.0	0.79	0.50	0.067
2	$6 \cdot 10^{-7}$	1.0	0.40	0.29	0.032
3	$6 \cdot 10^{-7}$	1.0	0.063	0.044	0.005
4	$3 \cdot 10^{-6}$	1.0	0.015	0.005	$5.7 \cdot 10^{-4}$

Source: Deutsche Risikostudie Kernkraftwerke, p. 167.

Note. The German study describes a total of 8 release categories. Of these, only the first four are reported here. Considerable lower releases, mainly of iodine, bromine and metals, are reported for the other categories.

Since the German risk study arrived at lower probabilities for other mechanisms of major leakage from the containment, steam explosions, according to Table 3.3, emerged as the predominant cause of large radioactive releases. However, the German report emphasizes the fact that further studies of steam explosions are currently being conducted within the framework of the next phase of the safety study.

3.5 The Kemeny Commission

At the end of October 1979, the special commission of inquiry appointed by the American president to investigate the accident in the No. 2 reactor at Three Mile Island (TMI-2) submitted its report.

Expert appendices appended to the report described studies which the commission had had done in an attempt to answer the question of what could occur if the cooling of the severely damaged reactor core were not restored. One of the possible consequences dealt with was steam explosions in the reactor vessel and containment. With the given premises, i.e. the design of the reactor and the initial accident sequence, it was concluded that steam explosions cannot cause failure of the reactor vessel or containment.

3.6 The Reactor Safety Inquiry

Following the accident at TMI-2, the Swedish Government appointed a reactor safety committee with instructions to compile and examine various risk analyses. In its final report (SOU 1979:86), submitted at the end of November 1979, the committee did not explore the question of steam explosions. In the appendix portion (Ds I 1979:22), a number of researchers pointed out - although without any further analysis - that more recent experimental and theoretical studies cast doubts on the treatment of steam explosions in WASH-1400.

3.7 The report of the National Institute of Radiation Protection entitled "More effective emergency preparedness" and comments on it

The probabilities of serious accidents and associated radioactive releases are discussed in the report of the National Institute of Radiation Protection entitled "More effective emergency preparedness", which was published in December 1979. These discussions are based largely on the release categories and release mechanisms used in WASH-1400. The calculations of the consequences of serious accidents were based primarily on BWR 1 and PWR 1. The report was subsequently criticized for having made use of the physical models for steam explosions and associated release sequences described in WASH-1400, without considering more recent theoretical and experimental results. Thus, on the basis of a review and evaluation of more recent literature in the field of steam explosions, the Department of Nuclear Engineering at the Royal Institute of Technology in Stockholm, in their criticism of "More effective emergency preparedness", found that the possibility of reactor vessel failure and containment failures caused by steam explosions could be excluded.

3.8 The FILTRA project

On the basis of the proposals for safety-enhancing measures made by the reactor safety committee, for safety-enhancing measures, the Swedish Nuclear Power Inspectorate (SKI) started the FILTRA project in the beginning of 1980, after receiving the consent of the Government. FILTRA is a research project being conducted by SKI in cooperation with AB ASEA-ATOM, Studsvik Energiteknik AB and the Swedish nuclear utilities. The purpose of FILTRA is to analyse to what extent it is possible to significantly reduce the risk of releases of radioactivity that can cause extensive and long-lived radioactive ground contamination as a consequence of ruptures of the containment due to accident sequences other than steam explosions involving moderately rapid pressure increase sequences, i.e. sequences that can make large risk contributions to the release categories BWR 2-3 and PWR 2-3. This could occur through devices intended to relieve pressure in the containment when necessary by the blow-off of steam and gases to large condensation and filter chambers.

The FILTRA project includes detailed analyses of various pressure rise events in the reactor vessel and in the containment, including steam explosions.

During the time the Steam Explosion Committee has been working, FILTRA's and the Committee's studies of steam explosions have been coordinated.

FILTRA is planned as a three-year project. A status report on the first phase is planned for the spring of 1981.

3.9 Other current studies of steam explosions abroad

A number of current studies concerning steam explosions are dealt with in the expert analyses in the appendices.

4 STEAM EXPLOSIONS. THE COMMITTEE'S DELIBERATIONS

4.1 History of steam explosions

The fact that steam explosions can occur when molten metal comes into contact with water has long been known. Steam explosions have occurred within industry in connection with the handling of molten metals and water. Such accidents have caused numerous deaths or injuries, mainly as a result of flying molten metal.

Within the nuclear power field, steam explosions have occurred in a number of experimental reactors. In all cases, the steam explosions have occurred in connection with rapid power excursions. These events are summarized in WASH-1400 and are also dealt with in Fauske's and Mayinger's reports to this committee.

Steam explosions in commercial reactors were dealt with from the safety viewpoint for the first time in WASH-1400. Since WASH-1400 was published, significant theoretical and experimental studies have been conducted on the molten-core-and-water system.

4.2 What is a steam explosion?

If hot and cold liquids are mixed, for example molten metal and water or hot oil and water, a steam explosion can occur under certain circumstances. The heat transfer that takes place during the mixture can be so violent that the liquid is vaporized within a few thousandths of a second, giving rise to an explosion-like sequence. This sequence differs from a chemical explosion with e.g. dynamite, where the chemical reaction causes the evolution of gas in such large quantities and in such a short space of time that explosion results. Compared to a chemical explosion, a steam explosion is a slow sequence of event.

In order for the transfer of heat between the molten material and the water to be great enough to cause a steam explosion, the molten material must be finely dispersed into particles smaller than 1 mm and mixed well with the water.

The sequence of events connected with a steam explosion can be divided into three phases:

1 Coarse fragmentation of the molten material.
2 Fine fragmentation and mixing of the molten material with water.
3 Explosive vaporization.

A coarse fragmentation of the molten material occurs when it falls or runs down into the water. As regards fine dispersal there are various theories concerning the mechanisms involved. When a molten material falls down into water, it is immediately surrounded by a film of steam. If the steam film is stable, the molten material is cooled without an explosion taking place. If the steam film is not stable and collapses, forces are created that can disperse the molten material. The steam film can be brought to collapse if, for example, a chemical explosion causes a shock wave to be directed against the molten material. In a reactor, the collapse can be initiated by, for example, the molten core impacting against the bottom of the reactor vessel.

In order for a steam explosion to occur, and simultaneously throughout all the molten material, a fine dispersal of the molten material and mixing of the molting material and water must take place within a few thousandths of a second. If this dispersal and mixture takes place over a longer period of time, the 2000-2500^{o}C hot molten core will cause the water to vaporize due to heat radiation, whereby the water and molten material will separate.

Small quantities of molten material can be finely dispersed and mixed with water in this short period of time. The question is whether large quantities, such as we are dealing with in reactors, can be finely dispersed and mixed in such a short time as is required in order for a coherent steam explosion to occur throughout the entire molten core material. This is required in order for large quantities of energy to be liberated explosively.

Besides the size and composition of the molten material, a number of other factors affect the efficiency of the steam explosion, such as the material properties of the molten material, temperature, fall velocity, water temperature etc. How these factors affect the steam explosion sequence is dealt with in greater detail in Appendices 2, 4 and 5.

4.3 Steam explosions in light water reactors

4.3.1 Introduction

Decisive for how the reactor vessel is affected by a steam explosion is how much energy is liberated at the instant of explosion and to what extent this energy is transferred to the reactor vessel.

The energy transferred to the vessel is dependent upon the following factors:

- how much molten material can participate simultaneously in an explosion
- how much of the thermal energy in the molten material can be converted to mechanical work at the instant of explosion (the efficiency of the explosion)
- how the mechanical work is transferred to the reactor vessel.

In WASH-1400, it was assumed that large quantities of molten material fell down into the bottom of the reactor vessel within the course of a very short span of time. It was assumed that water has accumulated at the bottom of the vessel. Fragmenting and mixing of molten material and water was assumed to take place instantaneously. It was also assumed that a continuous water layer had formed above the mixture of molten material and water, see Fig. 4.1. In this situation, an explosion would be triggered with an efficiency of least 10 %. During the explosion, it was assumed that the energy was transferred from the molten core material to the tank via a water layer that was thrown like a piston against the top head of the vessel with such a force that the top head was torn off and made a hole in the containment ceiling.

The model in WASH-1400 is highly simplified and is not based on a realistic meltdown and explosion scenario. Nor has the actual design of the reactor been taken into account.

4.3.2 The meltdown process

In WASH-1400, it was assumed that tens of tons of molten core material remained in the core region and fell down into the water in the bottom of the reactor vessel all at once.

The scenario described in WASH-1400 is highly simplified and unrealistic.

If cooling of the reactor core fails, the fuel rods will be heated by the decay heat. The meltdown process will start in the central parts of the core, where the decay heat is highest. The uranium dioxide and cladding material are mixed and molten material runs down along the fuel rods and solidifies when it reaches the colder parts of the core. In this manner, a bowl can be imagined to be formed, which collects the molten material formed above.

Continued heating causes the bowl to move downwards. In this manner, it can be imagined that large quantities of molten material can accumulate in the core above the bottom tie plate. In order for large quantities of this molten material to be able to fall down onto the bottom of the vessel in a short period of time, the bottom tie plate must give way.

In PWR:s, this bottom tie plate is mechanically anchored in the reactor vessel, and in BWR:s, it is carried by about 100 control rod guide tubes.

In order for the bottom tie plate to collapse in a PWR, its anchorage must be weakened. In a BWR, a large number of guide tubes must fail simultaneously, which can occur if the components melt. The assumption that this would happen when water is present in the bottom of the tank appears to be unrealistic.

4.3.3 Energy development during a steam explosion

If molten material has fallen down into the bottom of the vessel, it is also necessary that the molten material be finely dispersed and mixed with water in order for a steam explosion to occur.

As is evident from Appendix 2 and our consultant reports, large quantities of energy are required to bring this about. The conclusion is that as a maximum, some hundreds of kilogrammes of molten material can be mixed with water during the short period of time available to bring about a coherent steam explosion.

The mechanical energy that can be developed by a steam explosion depends upon how much molten material participates in the same steam explosion and on the efficiency of the conversion of thermal energy to mechanical work. Figure 4.2 shows the results of experiments with steam explosions where measured efficiency is plotted as a function of the quantity of molten material. The figure shows that efficiency decreases the more molten material is used.

The curve shows that the difficulty of achieving a coherent steam explosion increases as the amount of molten material increases. This is because it becomes more difficult to obtain a homogeneous mixture of molten material and water in a short period of time the more molten material is participating. The figure shows experiments with up to about 20 kg of molten material. There is no physical mechanism whereby efficiency would not continue to decrease as the amount of molten material increases.

4.3.4 Transfer of energy to the reactor vessel

In WASH-1400, it is assumed that the energy that is liberated in a steam explosion is transferred to the reactor vessel via a compact water layer (water slug) that is thrust against the top head of the reactor vessel.

According to model calculations of steam explosions and the opinions of Fauske and numerous other experts, such a water layer cannot form in the first place. Even if there were a water layer, it could not act as a coherent slug that is accelerated against the top head. The layer would be broken up by the explosion or when it passes the internal components of the reactor, such as the control rod guide tubes in a PWR and the moderator vessel head, steam dryer and moisture separator in a BWR.

The shock wave resulting from a steam explosion has not been judged to be so powerful that it could break the vessel apart.

4.3.5 Maximum load on the reactor vessel

It is reported in Appendix 3 that intact reactor vessels in Swedish boiling water reactors can withstand a load caused by an accelerating water layer with an energy of 500-800 MJ impacting the top head. The corresponding value for pressurized water reactors is 900-1000 MJ.

4.3.6 The committee's deliberations concerning steam explosions in the reactor vessel

It is impossible for large quantities of molten material to fall down into the bottom of the vessel at one time. After having reviewed the available literature, it is the opinion of the committee that a 10 ton molten core for a PWR and 5 ton molten core for a BWR falling at one time down into the bottom of the vessel is a pessimistic upper limit.

The committee is of the opinion that the assumption of an efficiency of 1 % for 5-10 tons of molten core is an overestimate.

The committee does not believe it is possible for a water layer to transfer <u>all</u> of the mechanical work developed during a steam explosion to the reactor vessel.

If a molten core weighing on the order of 10 tons is assumed to participate in a steam explosion with an efficiency of 1 %, the maximum mechanical work that can be generated is 150 MJ.

In the case of a pressurized water reactor, a maximum of 150 MJ of mechanical work could then be developed in connection with the steam explosion. The corresponding amount of mechanical work in a boiling water reactor is 75 MJ.

The committee believes that if the maximum permissible load on a reactor vessel is set at 900 MJ for a pressurized water reactor and 500 MJ for a boiling water reactor, these are realistic values with a good margin of safety.

Accordingly, the committee's conclusion is that, even if a powerful steam explosion can occur when the molten core is streaming down into the bottom of the reactor vessel, the energy that is liberated will not be sufficient to damage the reactor vessel, even if the entire mechanical work of the explosion were to be transferred to the top head of the vessel via the postulated water layer. This is true even if there are cracks in the top head and bolts.

4.4 Steam explosions in the reactor containment

4.4.1 How can a steam explosion occur in the reactor containment?

If there is no water in the bottom of the reactor vessel, the molten core will collect there and heat up the vessel material. The molten core will melt through the bottom of the vessel and flow into the containment.

In the case of older boiling water reactors, the molten material will run down into the cavity below the reactor vessel. Here, it is possible that water will have accumulated, and the contact between the molten material and the water can give rise to steam explosions, which can in turn give rise to shock waves. The size of these shock waves is not sufficient to damage the containment.

There are no objects in the reactor cavity where the water collects that could act as missiles, i.e. that could be broken off and thrown against the walls of the containment. If drainage in this cavity is functioning, there will be no water where molten material can collect on the concrete floor. If we assume that the drainage pipes are blocked, up to 5 m^3 of molten core material will collect before the level reaches penetrations through which the molten material could run down into the pool.

The remaining core material will probably solidify. Even if the concrete floor were to be melted through, however, no steam explosions will occur of such strength that the containment will be damaged.

In the case of the <u>more recent boiling water reactors</u> of the Forsmark type, the cavity underneath the reactor vessel is not filled with water during normal operation. In the event of an accident with core meltdown, however, it is possible that the cavity will be filled with water, so that special consideration must be given to the possibility of steam explosions. For the reason discussed above, the steam explosions will not be so strong that the containment will be damaged by the shock wave. There are no objects that could function as missiles and thereby damage the containment.

In the case of <u>pressurized water reactors</u>, there is normally no water underneath the reactor vessel, but in the event of an accident, the cavity may be filled with water. Steam explosions can occur, but the containment is expected to be able to withstand the shock waves that occur without being damaged, with a good margin of safety.

4.4.2 The committee's deliberations concerning steam explosions in the reactor containment

On the basis of the reviewed literature, consultant opinions and its own deliberations, the committee has reached the conclusion that although steam explosions can occur in the reactor containment, they cannot be of such strength that the reactor containment is damaged.

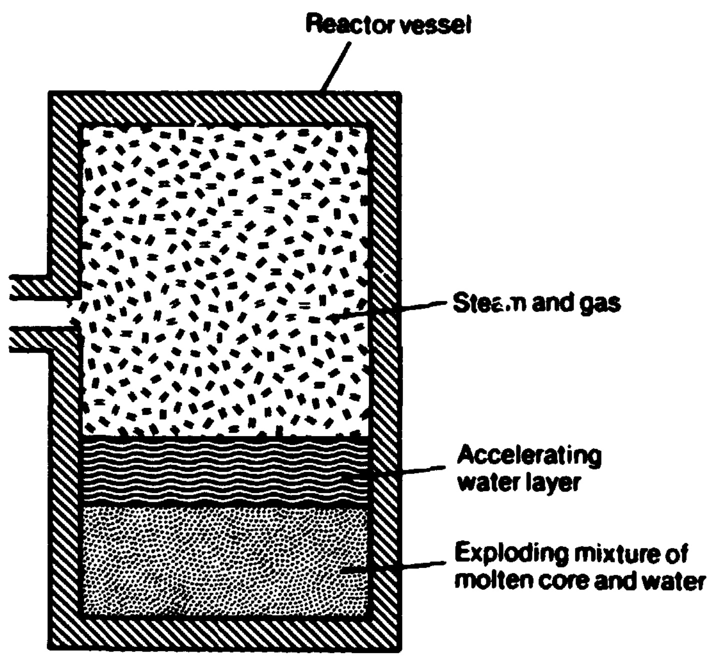

Fig. 4.1 Geometric model used in WASH-1400 to study steam explosions in reactor vessels

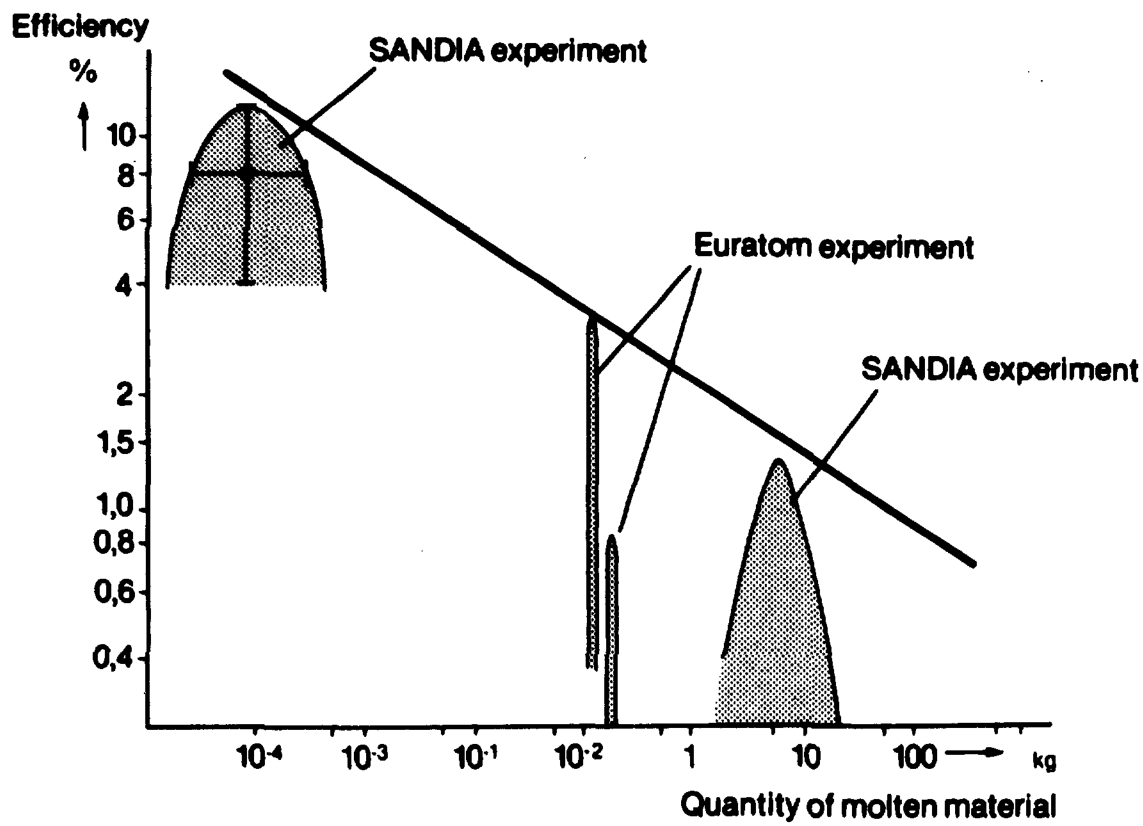

Fig. 4.2 Measured efficiency in steam explosion experiments. The efficiency is a measure of how much of the thermal energy is converted to mechanical work

5 THE COMMITTEE'S CONCLUSIONS AND RECOMMENDATIONS

Using partly different analysis models, the Committee's consultants on steam explosions, Fauske and Mayinger, who are internationally renowned authorities in the field, have arrived at the same conclusion. This conclusion is that although steam explosions can occur in connection with serious reactor accidents, it is possible to exclude completely the possibility of steam explosions of such force that they could lead to rupture of the reactor vessel and containment and thereby to releases of radioactivity to the environment.

The Committee has found nothing to object to in the consultants' analysis, but notes that certain recently published reports express more cautious opinions. This caution is explained by, among other things, the fact that there is still incomplete understanding of different types of explosions and that any final conclusions should await the results of further studies, including some of an experimental nature.

In its examination of the available body of scientific evidence in the area, however, the Committee has found no descriptions of accident sequences based on more detailed technical-physical analyses according to which steam explosions in connection with reactor accidents could lead to rupture of the reactor vessel and containment.

The Committee particularly notes that it appears to be widely agreed that the assessment of the importance of steam explosion for serious accidents that was made in the American report WASH-1400 does not concur with more recent theoretical and experimental results. In this context, it should also be pointed out that the German report "Deutsche Risikostudie Kernkraftwerke" from 1979, due to lack of time and pending results of deeper studies, used the risk figures from WASH-1400 concerning steam explosions, although the German report argued on the basis of its own analyses that steam explosions that liberate large amounts of energy from meltdowns on the order of tons were extremely unlikely. The analysis in WASH-1400 appears to have been the main reason for the importance that has been attributed to steam explosions in connection with reactor accidents. In the opinion of the Committee, this analysis lacks a realistic physical basis.

In view of the above, it is the overall opinion of the Committee that steam explosions and associated releases of radioactivity do not have to be taken into consideration in designing safety systems and emergency plans.

As regards continued work on steam explosions, the Committee recommends the following:

The work being done abroad within the field of steam explosions should be followed. Small steam explosions and their importance for the sequence of events connected with a meltdown should continue to be studied. In general, various accident scenarios and associated releases of radioactivity should be studied more closely so that safety systems and emergency plans can be designed on the basis of better factual knowledge.

ADDITIONAL STATEMENT BY COMMITTEE MEMBER BECKER

I wish to comment that my interpretation of the conclusions by the committee completely agrees with the following conclusions, which I have presented in Appendix 2 of the present study:

Small steam explosions are possible during light water reactor accidents involving a core meltdown.

Steam explosions in the reactor vessel, which are so powerful that the integrity of the vessel is endangered, are, however, impossible.

Steam explosions in the reactor containment building, which are so powerful that the integrity of the containment is endangered, are impossible.

As a consequence of these conclusions follows that the report "Efficient Emergency", which was published by the National Institute of Radiation Protection, cannot be used as a basis for the planning of the emergency preparations around our nuclear power stations. A new analysis which deals with accidents which can occur, should be presented. This work should, however, be carried out in a broad cooperation between authorities, utilities, reactor vendors and other institutions, and in the analysis of the consequences of reactor accidents the most recent scientific progress should be considered in all the fields, which are included in the analysis.

My conclusions, which comprise pressurized water reactors as well as boiling water reactors, are based on a survey of experimental and theoretical studies carried out in the USA, Germany, England and at the Euratom laboratories in Italy. The statements by Doctor Hans K. Fauske and

Professor Dr.Ing. Franz Mayinger, which were prepared on the request by the committee, have substantially contributed to my conclusions, which are based on the following results:

1. In order to obtain a large coherent steam explosion, which can rupture a reactor vessel, it is necessary that tens of tons of molten core material with a temperature of more than 2500°C within a few milliseconds fragmentates into small particles less than 1 mm in diameter and mix homogenously with the water. Doctor Fauske has shown that for large melts the mixing process requires enormous amounts of energy, and that such quantities of energy are not available in the system when ton scale mixing is considered. Professor Mayinger has presented an independent analysis, which confirms Dr. Fauske's results. Both have found that a coherent steam explosion at most can include 200-300 kilo of melt.

   Large steam explosions with the potential of rupturing the reactor vessel or the reactor containment are therefore impossible. This includes both PWR and BWR.

2. A survey of steam explosion experiments carried out in the kilogram scale with UO_2 and corium melts shows that the steam explosion efficiencies are very low. The experiments also indicate that the steam explosion efficiency decreases when the size of the melt increases. The experiments therefore show that steam explosions with the potential of rupturing the reactor vessel or the reactor containment can be excluded. This includes both PWR and BWR.

3. Instantaneous supply of tens of tons of melt to the water below the reactor core requires a catastrophic collapse of the bottom plate of the core. Provided water is left in the bottom of the vessel, which is a pre-

requisite for a steam explosion, I find a catastrophic collapse of the bottom plate to be impossible. This concerns primarily BWR, where the core rests on more than 100 strong stainless steel tubes.

4. In WASH-1400 a steam explosion model for the reactor vessel was suggested, where the water, which is present above the melt during the explosion is accelerated by the expanding steam and as a compact liquid slug impacts the lid of the vessel with such force, that the lid or parts of it like missiles are hurled against the reactor containment, which is ruptured. I have found that this failure mechanism is not realistic, and that it is impossible in this manner to destroy the reactor vessel even if 10 tons of melt should mix with water and explode coherently.

5. In order to obtain a steam explosion in the reactor vessel with environmental consequences it is necessary that all of the conclusions 1-4 are wrong. If only one of the conclusions is correct the accidents PWR-1 and BWR-1 are impossible.

6. Postulating the occurrence of large steam explosions in the reactor containment, it is not possible to conceive of a mechanism which could accelerate missiles to penetrate the containment wall. The hypothetical shock wave occurring after a postulated large steam explosion is not sufficiently strong in order to rupture the reactor containment.

7. In the event of a core meltdown in the Swedish boiling water reactors it is evident that the supply of melt to the water in the containment building will be relatively slow, and large coherent steam explosions in the reactor containment building can therefore be excluded.

8. In order to obtain a steam explosion in the reactor containment with environmental consequences it is necessary that all of the conclusions 1, 2 and 6 are wrong. Considering a Swedish boiling water reactor the conclusion 7 must also be wrong.

APPENDIX 2

KTH - NEL - 28

STEAM EXPLOSIONS IN LIGHT WATER REACTORS

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STOCKHOLM, DECEMBER 2, 1980

KTH - NEL - 28

STEAM EXPLOSIONS IN LIGHT WATER REACTORS

Kurt M Becker

SUMMARY

An assessment of the world literature on steam explosions and their importance for the safety analysis of light water reactors have been carried out.

It was concluded that small steam explosions are possible during light water reactor accidents involving a core meltdown. Steam explosions in the reactor vessel, which are so powerful that the integrity of the vessel is endangered, are, however, impossible. This includes both BWR and PWR.

It was also concluded that steam explosions in the reactor containment building, which are so powerful that the integrity of the containment is endangered, are impossible. This includes both BWR and PWR.

The accident categories BWR-1 and PWR-1 should therefore be excluded from the safety analysis of light water reactors.

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1.0 INTRODUCTION

It is well known that explosions may occur when molten metal is brought into contact with water. The explosion is not a consequence of chemical reactions, but it depends only on the physical process of rapid evaporation of water. If the evaporation is fast enough a shock wave may be created, and the explosion may then cause damage to the surroundings. The destructive power, however, of this shock wave is small compared with chemical explosions. In order to obtain rapid evaporation, which causes an explosion, it is necessary that the water and the molten metal are mixed efficiently so that a large heat transfer area between the molten metal and the water is achieved. This can only be the case if the molten metal is divided into small particles, which mix with the water within a time scale of a few milliseconds.

Steam explosions have occurred in many industries when molten metal or a hot liquid, for instance oil, has been lost accidentally into water. Especially in the aluminium industry many accidents have been reported, causing many fatalities and severe damage in the surroundings of the explosions. The Aluminium Association of America (1) has collected information about 75 steam explosions, which occurred in North America during the period 1944-75. The list, which is incomplete, contains primarily aluminium-water explosions, but events involving molten steel, copper, magnesium and other materials are also included. Totally, 32 fatalities and 300 injuries were reported. It was observed that steam explosions involving aluminium were very violent, which perhaps is caused by simultaneous chemical reactions.

At the Toyama University in Japan (1) information was registered about 261 steam explosions occurring in Japan during the time period from 1935 to 1975. The explosions caused 80 fatalities and 800 injuries.

It should be pointed out, however, that the fatalities and the injuries were primarily due to burns from molten metal, which were thrown around in the factories. This, however, requires only small amounts of energy.

Steam explosions have also occurred during power excursion experiments with the experimental reactors BORAX and SPERT in USA and during an accident at the experimental reactor SL-1, where a strong power excursion occurred when a control rod was drawn out of the reactor. The conditions for steam explosions in these reactors were, however, completely different from the conditions, which one would encounter in power producing light water reactors after a core meltdown.

With regard to descriptions of steam explosions, which have occurred in different industries, reference is made to the reactor safety study WASH-1400 (2) and the British report "Molten Metal and Water Explosions" (1).

During a core melt one obtains molten UO_2, which has a melting point of approximately 2800°C. However, in the reactor core there are also other materials, for example zircaloy and stainless steel. These metals oxidize to ZrO_2 and Fe_2O_3. The core melt therefore consists of a mixture of UO_2, ZrO_2, Fe_2O_3, Fe and other materials. This mixture, which is called corium, has a melting point between 2000 and 2500°C.

The reactor core including construction materials may in the case of a large light water reactor have a weight of up to 200 tons. In molten condition the core therefore contains an extremely large amount of energy. If a substantial portion of the molten core would instantaneously fall into the water, which is assumed to be present below the reactor core, the thermal energy stored in the falling melt would be sufficient to destroy the reactor vessel, provided this energy or a substantial portion of it by means of a steam explosion could be transformed into mechanical work, and this work would load the reactor vessel in an undesirable manner.

The consequences of steam explosions in light water reactors were considered for the first time in the reactor safety study WASH-1400 (2). The largest release of radioactivity and the greatest consequences for the surroundings in the event of an assumed accident including a core meltdown, would occur for the sequence of events in which the molten core fell into the water, which remained in the bottom of the reactor vessel, causing a steam explosion when making contact with the water. For certain sequences of events assumed in WASH-1400, the explosion would be so powerful that it could tear off the lid of the reactor vessel and hurl it like a missil against the reactor containment building with such force that the latter would rupture. This would result in the escape of large amounts of radioactivity already 2-3 hours after the start of the accident transients.

In order to get such a powerful explosion the assumption was made in WASH-1400 that at least 20 % of the molten reactor core came into contact with water within one second, and became fragmented into small particles with temperatures of 2000-2500°C. Further, within a few milliseconds these hot particles were assumed to mix with the water without causing any significant evaporation. In this manner a thermodynamically unstable mixture of the molten core and water is obtained, which through an explosive evaporation is brought instantaneously to a stable condition.

A steam explosion, including the large quantities of molten core, which is necessary in order to be of significance during a reactor accident, was considered very unlikely, and in WASH-1400, Appendix VIII, page 18, the following conclusion was presented:

"Insufficient data exist for molten UO_2 in water to predict under any given conditions whether or not an explosive interaction will occur. From the observed behavior of other molten materials and water, particularly with regard to the significance of subcooling to known dispersal mechanisms, it is felt that the likelihood of steam explosions occurring under the given conditions in the primary vessel is small. Because of the lack of understanding of the UO_2-water interaction, however, the possibility of an explosion event must be recognized."

When WASH-1400 was written there was very little experimental evidence about steam explosions in the uranium dioxide-water system. Only two experimental studies (3,4) had been performed; one at Battelle Northwestern Laboratory and one at CENG in Grenoble. These studies were based on amounts of UO_2 of between 1 and 15 g.

Since insufficient information was available about the UO_2-H_2O system, it was assumed in WASH-1400 that a large scale steam explosion in the reactor vessel had to be included in the safety analysis of light water reactors. The probability for a steam explosion, which would result in failure of the reactor vessel and the containment, was assumed to be 0.01. This meant that only in the case of one core melt out of 100, steam explosions would cause consequences for the surroundings. Accidents caused by steam explosions in the reactor containment building were not included in the safety analysis in WASH-1400.

Since WASH-1400 was published in 1974 important theoretical and experimental work concerning steam explosions involving UO_2 and corium has been carried out, and the possibilities for assessing the risks of reactor accidents caused by steam explosions are today rather satisfactory compared to the situation in 1974.

In February 1980 the Institute for Reactor Technology at the Royal Institute of Technology presented a survey paper (5), including the experimental results, which had been carried out in the kilogramscale. The conclusion of this survey was that steam explosions in the reactor vessel could not be so powerful that they would cause the reactor vessel to rupture. A few months earlier the National Institute of Radiation Protection had published a 5 volume report (6) called "Effektivare beredskap" (Efficient Emergency), dealing with the consequences of nuclear reactor accidents. Unfortunately, a steam explosion in the reactor vessel was the accident chosen for the major analysis of the environmental consequences. In a letter (7) to the Department of Agriculture the Institute for Reactor Technology pointed out that the mentioned report was based on obsolete assumptions and therefore should be rewritten, basing the analysis on reactor accidents, which really could happen.

The purpose of the present investigation is to make a survey about steam explosions, and to present an assessment of the risks and the consequences of steam explosions in light water nuclear power stations.

2.0 PHYSICAL DESCRIPTION OF STEAM EXPLOSIONS

A steam explosion may occur when a hot liquid is brought into contact and mixes with a cold liquid, provided that the temperature of the hot liquid is higher than the saturation temperature of the cold liquid. For example, steam explosions have been observed when hot oil or molten metal have been lost into a vessel with water, or when water has come into contact with freon or liquefied air.

In order to obtain such a fast evaporation that one may characterize it as an explosion it is necessary that the hot liquid is divided or fragmented into small particles, and that the particles get into direct contact with the water. The division of the melt into small particles, less than 1 mm in size, is necessary in order to obtain a sufficiently large heat transfer area, which for a given size of the melt is inversely proportional with the mean diameter of the particles. Through the direct contact between the liquids efficient heat transfer is obtained. If, however, the molten metal should be surrounded by gases or a vapour film, which is the expected condition, the heat transfer between the molten metal and the water becomes too small in order to cause an explosive evaporation. Thus, the following conditions must be satisfied:

1. Fragmentation of the melt into particles with a size less than 1 mm.
2. Direct contact between the molten particles and the liquid phase of the water.

If one droplet of, for instance, molten steel or aluminium is lost into the water, it will immediately be surrounded by a vapor film. The heat transfer from the melt to the water through the vapor film is small. If the vapor film is stable, the rate of evaporation will be relatively slow, and an explosive event is prevented. The droplet cools down to its freezing point, where it solidifies, which makes further fragmentation impossible and the steam explosion has been avoided.

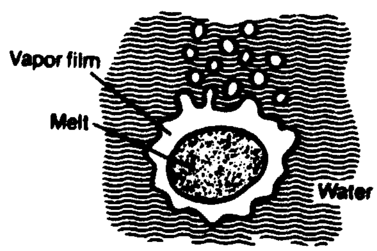


Fig. 1. Film boiling

The insulating vapor film, however, may be unstable and collapse at various points on the surface of the melt. This results in violent transients, which may fragment the melt into small particles surrounded by water. Various physical models have been proposed to explain the mechanism of the fragmentation. Briefly and somewhat simplified a couple of these models may be described as follows.

a. Powerful pressure waves are created when the water impinges upon the melt during the collapse of the vapor film. When these pressure waves propagate in different directions through the melt the droplet is broken up, and the water penetrates in between the fragments.

b. On the collapse of the vapor film, the water hits the melt with great force and by inertia penetrates into the melt, which becomes fragmented into small particles.

c. Instabilities of the Taylor and Helmholz types have also been used to explain the fragmentation process.

All of the mentioned mechanisms probably contribute to the fragmentation process, but it is difficult to decide which one is the most important. The physical conditions, which determine the fragmentation process, are very complicated, and there is no method available today, which can be used to predict in detail the rate and the extent of fragmentation.

After fragmentation a mixture of molten particles and water is obtained. The melt has now a very large contact surface area with the water, and the water therefore heats up very fast, and one obtains a thermodynamically unstable mixture of melt and superheated water. When the water temperature approaches the spontaneous nucleation temperature, which happens after a few milliseconds, the instability is released through an explosive evaporation of the strongly superheated water, and thus a steam explosion has occurred. This shows that a steam explosion depends only on a change of phase of a pure substance. A steam explosion is a relatively slow event compared to chemical explosions, which are caused by fast chemical reactions.

The stability of the vapor film surrounding the molten metal depends on several parameters. The stability increases for instance with the system pressure, the water temperature and the temperature of the melt. On the basis of experiments with heated spheres, Dhir (8) found that the minimum surface temperature, which was needed in order to sustain a stable vapor film at athmospheric pressure, depended on the water subcooling

$$T_{min} = 200 + 8\Delta T_{sub}, {}^{o}C \qquad (1)$$

where ΔT_{sub} is the water subcooling temperature. Several more detailed correlations are available for the calculation of ΔT_{min}, but it is outside the scope of the present study to survey this subject. When the temperature of the melt is larger than T_{min} stable film boiling is obtained. Equation 1, however, is only valid provided no disturbances are present in the system. By means of introducing disturbances one may cause the collapse of the vapor film also when the temperature of the melt is higher than T_{min}. This could perhaps happen when the melt is sinking through the water and collides with the bottom of the vessel. One may also use a trigger, which often is a chemical detonator directing a shock wave against the melt. When the shock wave reaches the droplet the surrounding vapor film may collapse because the pressure instantaneously becomes greater than the critical pressure. The collapse of the vapor film may as earlier explained cause the fragmentation of the droplet. It is therefore important to point out the difference between experiments carried out with and without triggers. The strength of the trigger is of course also of vital significance. Experiments, which have been carried out with strong triggers, are therefore not representative for reactor conditions, where only relatively weak triggers are possible, for example falling objects or the collision of the melt against the bottom of the vessel.

The efficiency of gram scale steam explosions is according to Berman (9) in the range of 0-10 per cent. The efficiency of a steam explosion is defined as the ratio between the mechanical work done by the system on the surroundings and the heat, which was initially stored in the melt.

The description of steam explosions given above is only valid for a single droplet or gram scale explosions. However, in the treatment of steam explosions in light water reactors, explosions involving tens of tons of molten core material have been discussed.

In different laboratories around the world steam explosion experiments in the kilogramscale have also been carried out. Buxton and Benedick (10) for example, carried out experiments with the reactor core simulants corium A and corium E, where melts weighing up to 27 kg were employed. Already in 1957 Long (11) reported the results of more than 800 steam explosion experiments for aluminium and water. For most of the experiments 50 lb aluminium were used, and rather strong explosions were observed.

Buxton and Benedick as well as Long observed that the melt fragmentated into small particles. The physical mechanism for the fragmentation is not known in detail. Somewhat simplified the fragmentation can be considered to occur in two steps:

1. When the melt pours into the water a rough fragmentation or pre-mixing occurs. The total surface area of the fragments is still relatively small, and since insulating vapor films are formed instantaneously around the different parts of the melt, the rate of heat transfer between the melt and the water is relatively small and one obtains a relatively slow evaporation. The extent of pre-mixing depends on the kinetic energy of the molten material when it hits the water surface. Thus the height from where the melt was dropped is of importance. Further, the viscosity, the specific weight, the thermal conductivity and the surface tension of the molten material is of great significance.

2. The vapor films, which now surround the different parts of the melt may be unstable and collapse. This may, as earlier explained for a single droplet, cause fragmentation and a steam explosion.

However, in order to obtain a powerful steam explosion the fragmentation of the melt and the mixing of the particles with water must occur almost instantaneously in the whole melt or within the timescale of a few milliseconds. This is called coherent fragmentation and we have obtained a coherent steam explosion. If coherency is not achieved the evaporation will proceed on a larger time scale and the power of the explosion becomes weaker.

The probability that the majority of the vapor films should collapse simultaneously is insignificant. A physical model is therefore needed in order to explain the observed fragmentation and steam explosions. The physical conditions, which would explain the fragmentation are rather complicated and not fully understood.

Board and Hall (12) have developed a shock wave theory, assuming that a shock wave has been established. When this shock wave propagates through the premixed melt the vapor films will collapse because of the pressure increase, and fragmentation of the melt will occur behind the shock wave as shown in the simplified model presented in figure 2.

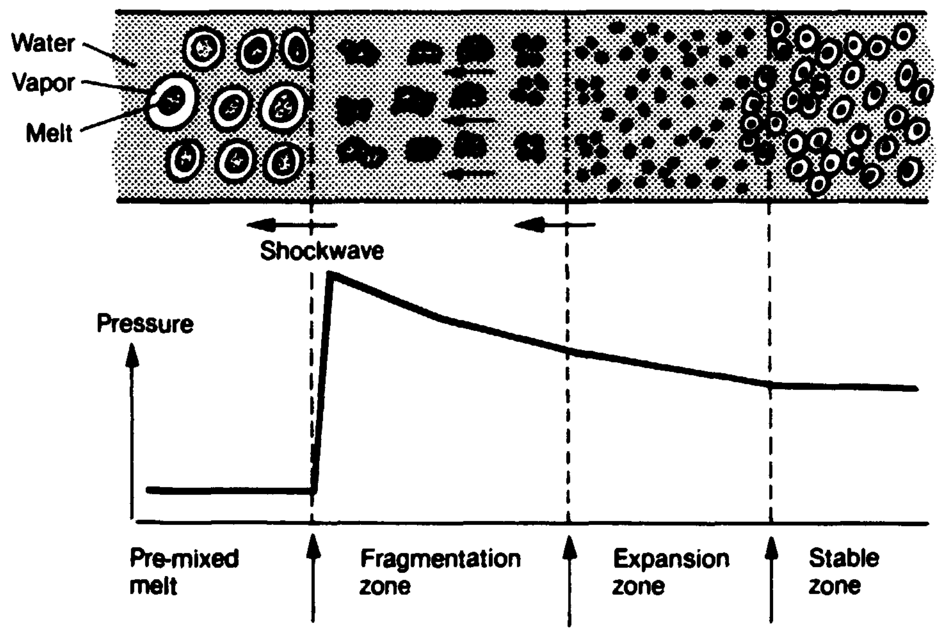


Fig. 2. Shock wave fragmentation

Schematically, the space behind the shock wave may be divided into three zones; fragmentation zone, expansion zone and a stable zone where a mixture of water, steam and melt particles has been obtained. In the expansion zone the molten particles are in direct contact with the water, the total heat transfer area is large and the heat transfer between the melt and the water is therefore very efficient. After a few milliseconds, however, the particles will be surrounded by vapor films, which drastically reduces the heat transfer and more stable conditions are approached. With regard to more detailed information about the different fragmentation mechanisms the reader is referred to reports by Bankoff (13) and by Benz, Frölich and Unger (14).

For the fragmentation of large melts and the mixing of the molten particles which water enormous amounts of energy are required and enormous forces are needed. The consultants of the steam explosion committee, professor Mayinger and Dr Fauske have dealt with this rather difficult and complicated process. For very conservative assumptions Mayinger (15) calculated the force, which is needed in order to fragmentate 10 tons of corium. Neglecting viscous forces and including only the acceleration forces necessary to move the particles during the fragmentation Mayinger found that a force of 28 000 tons was required in order to carry out the fragmentation of 10 tons of corium, and he concludes as follows:

"It seems to be physically impossible that these extremely high forces, fragmentating a larger amount of melt, can exist in the melt. Anyhow, these forces and time for fragmentation has to be taken from the starting steam explosion and would damp out the propagation of a shock wave within a short distance. From this deliberation one can draw the conclusion that large scale steam explosions are rather unlikely or even physically impossible."

The conclusion by Mayinger is supported by Fauske (16), who refers to a paper by Cho, Fauske and Grolmes (17), where the energy is calculated, which is needed for the mixing of the molten particles with water within the extremely short time, which is available for this process if a coherent steam explosion in the whole melt should be achieved. Mayinger used 3 milliseconds as a conservative value for the maximum mixing time, while Fauske (16) and Henry (18) suggest 10 milliseconds as the absolute upper limit for the mixing time. The results showed that the mixing energy for melts in the ton scale was larger than the amount of heat, which during the same time could be transferred from the melt to the water. It is therefore physically impossible to carry out in the ton scale the mixing of molten particles with water fast enough in order to achieve a coherent explosion in the whole melt. Fauske presented the following conclusion:

"Consequently, these simplistic energy considerations for the rapid intimate mixing of the core materials and water from initially separated state show that the mechanical energy requirements for mixing alone necessitates a trigger which is far larger than the explosion itself.

As a result of the above considerations for mechanical energy requirements in a rapid intermixing, one arrives at the substantial conclusions that such rapid interdispersion of cold and hot materials cannot be achieved."

The reason for the need of carrying out the mixing within a time scale of a few milliseconds is the high temperature ($\sim 2500^{\circ}C$) of the melt. Considering only the heat transfer by radiation between the melt and the water heat fluxes larger than 200 W/cm^2 are obtained. The evaporation is therefore very fast, initiating instabilities, which causes the melt and the water to separate before fragmentation of any larger portion of the melt can be accomplished. One may therefore obtain a minor explosion in the melt, but a coherent explosion in the whole or a substantial portion of the melt is impossible.

To summarize one may conclude that for ton scale interactions

1. mixing of melt and water within the short time scale necessary is impossible, since this requires an amount of work which is not available in the system and

2. mixing during a larger time scale, which requires less energy, is also impossible because one cannot maintain the stability of the system long enough, because the melt and the water through the fast evaporation will separate before fragmentation of any substantial portion of the melt has been accomplished.

The key issue in the discussion of steam explosions is therefore the fragmentation of the melt, and the mixing of the molten particles with the water. If one can show for the conditions considered that these processes are impossible, then a coherent steam explosion is also impossible for these conditions. We believe that Fauske's and Mayinger's calculations of the mixing energy and of the necessary force for fragmentating the melt demonstrate that a ton scale coherent steam explosion is impossible. We therefore conclude that small steam explosions are possible, but during light water reactor accidents no steam explosions can occur with such force that the integrity of the reactor vessel is endangered.

3.0 PARAMETERS OF IMPORTANCE TO STEAM EXPLOSION EFFICIENCY

The efficiency of steam explosions depends on the following parameters:

1. The composition of the melt
2. The pressure
3. The temperature of the water
4. Non-condensable gases
5. The melting point of the melt
6. The superheat of the melt
7. The fall velocity of the melt
8. The size of the melt
9. The magnitude of the trigger.

The composition of the melt

Experiments with metals, oxides and different mixtures of metals and oxides have shown that the composition of the melt is of utmost importance for the efficiency of the explosion. Uranium oxide yields weak reactions. A mixture of Fe_3O_4 and Al_2O_3, which simulates corium A also results in weak reactions, while corium E gives somewhat stronger explosions. The compositions of the corium melts simulated in the experiments, which were carried out at the Sandia Laboratories, are given in the table below, which is reproduced from a report by Nelson et al. (19).

	Weight		Percent		
	UO_2	Zr	ZrO_2	Fe	Fe_2O_3
Corium A	65	18		17	
Corium A	57.3		21.4		21.4
Corium E	35	10		55	
Corium E	27.6		10.7		61.8

Corium A is equivalent to a molten reactor core including the materials of the canning and the spacers. Corium E, which is more like metals, includes also internal parts of the reactor vessel, for example the thermal shield and the steam separators. The importance of the composition is explained by considering the viscosity, the thermal conductivity, the density, the surface tension and the specific heat of the melt. High viscosity renders fragmentation difficult, and for sufficiently viscous melts fragmentation becomes impossible. Decreasing the thermal conductivity reduces the heat transfer between the melt and the water. High surface tension and high density makes fragmentation more difficult, the latter because of the greater acceleration forces needed to separate the molten particles.

The importance of the composition of the melt has been demonstrated by means of several thousand steam explosion experiments, which have been reported in published works. In the next chapter some of the most important experiments relevant to light water reactors will be discussed in detail. In the present chapter, however, experiments demonstrating the significance of the composition will be discussed.

The Sandia experiments in kilogram scale, which were reported by Buxton and Benedick (20, 10) in 1978 and 1979, gave according to Corradini (21) steam explosion efficiences of maximum 0.05 % for the oxide rich material corium A, while steam efficiences up to 1.4 % were obtained for the metal rich corium E.

In the Ispra experiments with UO_2 in kilogram scale reported by Benz et al. (22) in 1979 no steam explosions were observed.

Steam explosion experiments especially with aluminium have shown strong reactions with explosion efficiences in the range up to 2 %. With regard to aluminium, however, one have to remember that molten aluminium has low viscosity, high thermal conductivity, low density and a low melting point. This explains the violent reactions, which perhaps also may depend on fast chemical reactions between water and aluminium.

According to Nazaré (23) aluminium has a viscosity of 1.1 cP, which is rather low compared with the value for UO_2, which is 7.0 cP. The viscosity of different melts are given in the following tables, which are reproduced from the paper by Nazaré.

Estimated Properties of Core Melts

Corium Melt Type		Melting Point (K)	Heat Capacity at the Melting Point (cal/g K) (J/g · K)	Viscosity (cP) (mPa · s)	Thermal Conductivity (at the Melting Point) $\left[\frac{cal}{cm\ K\ s}\right]$ $\left(\frac{J}{cm \cdot K \cdot s}\right)$
AX1	Metal phase	~2275	0.085 (0.356)	3.4 (at ~2675 K) 5.4 (at ~2275 K)	
	Oxide phase	~2675	0.071 (0.297)	5.7 (at ~2675 K)	
EX1		~2275	0.129 (0.540)	5.4 (at ~2275 K)	0.049 (0.205)
EX2	Metal phase	~1825	0.146 (0.611)	2.1 (at ~2675 K) 5.4 (at ~1875 K)	0.044 (0.184)
	Oxide phase	~2675	0.080 (0.335)	5.7 (at ~2675 K)	0.008 (0.033)
EX3		~2075	0.202 (0.846)	4.3 (at ~2075 K)	

Measured and Calculated Viscosities of Several Materials

Material	Viscosity	
	$\eta_{s_{measured}}$ (cP) (mPa · s)	$\eta_{s_{calculated}}$
Ag	3.9	4.1
Cu	4.1; 4.1; 3.8; 5.8	
Cs	0.69; 0.68	0.66
Fe	5.0; 5.6; 6.4	4.9
In	1.9	2.0
Li	0.6; 0.56; 0.59	0.56
Mg	1.32; 1.23	1.5
Na	0.69; 0.68	0.62
Ni	4.6; 4.9; 5.0	5.0
Pb	3.0; 2.52	3.0
Sn	2.1	2.1
U	6.5	6.3
Al (82.7 at.%)-Cu	1.6	2.1
Al (88.7 at.%)-Si	1.1	1.9
Ag (60 at.%)-Cu	5.5	4.1
Sn (96.2 at.%)-Ag	1.8	2.2
Sn (91 at.%)-Mg	2.1	1.9
Al_3Mg_2	1.4	1.2
Mg_2Pb	2.3	2.1
Tl_2Te	2.3 ± 0.1	2.4
AgCl	2.3	2.1
NaCl	1.5	1.4
KCl	1.2	1.3
Al_2O_3	82.0	4.2
UO_2	7 ± 1; 46; 4.3	5.7

One should notice that the oxide phase of corium has a higher viscosity than the metal phase.

The physical explanation for the importance of the viscosity is found by considering the fragmentation processes. It seems obvious that increased viscosity renders the coarse fragmentation or the premixing as well as the final fragmentation and mixing more difficult, because the energy required to achieve the mixing increases when the viscosity increases. For materials with very high viscosity spontaneous fragmentation is impossible. The Ispra experiments with UO_2 in kilogram scale showed that for the conditions studied, the fragmentation of molten materials was not efficient enough in order to produce steam explosions.

According to Blottner (24) the viscosity of the molten material increases dramatically when SiO_2 is mixed into the melt. This may be of significance for the assessment of steam explosion risks in certain types of reactor containment buildings.

The pressure

Henry and Fauske (25) and Buchanan (26) have presented theories, which predict that the steam explosions become less powerful when the pressure increases. These models have been verified by a great number of experiments with different liquid mixtures. It was found that for pressures above a certain level called the cutoff pressure steam explosions are impossible. For water systems without triggers Henry and Fauske found that the cutoff pressure is 10 bar, while Buchanan suggested a pressure of 13 bar.

However, at the Sandia Laboratories (21) a steam explosion has been observed at the pressure of 10.4 bar. It should be noticed. however, that this explosion was released by means of a trigger, which involved a chemical explosion of 30 kJ. Without triggers the cutoff pressure suggested by Fauske and Henry is verified experimentally, but in order to determine the cutoff pressure for systems including triggers it is necessary to carry out experiments at higher pressures. During a light water reactor accident it is, however, difficult to conceive that triggers should exist, which in efficiency can be compared with chemical explosions. In all circumstances, however, it is verified that the explosions become less energetic when the pressure increases.

The temperature of the water

The water temperature is of importance, but its influence on the steam explosion efficiency is not fully understood. For gram scale (10-35 g) experiments with corium E Nelson et al.

(19) found that the explosions became less powerful when the water temperature increased. This is demonstrated in figure 3, which is reproduced from Nelson's report. One observe that for sub-cooling temperatures below 20°C, which corresponds to water temperatures above 80°C, no steam explosions were observed.

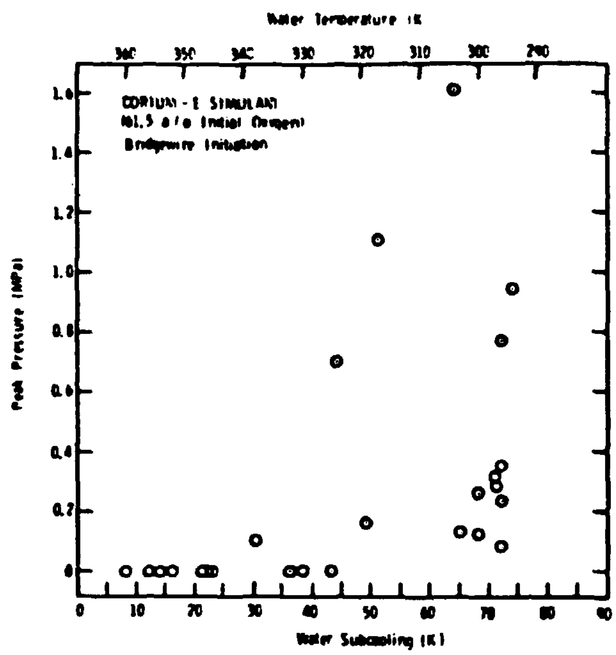


Fig. 3. Steam explosion peak pressure versus water sub-cooling. (From ref. 19.)

For experiments in the kilogram range, however, Buxton and Benedick (10) found that the water temperature did not have any significant influence on the steam explosion efficiency. Figure 4, which is reproduced from the mentioned report, shows that steam explosions are obtained for boiling water as well as for standard conditions. It was, however, observed that when the water temperature increased the explosions occurred less spontaneous. For all temperatures, including boiling conditions, explosions could always be initiated by means of a trigger.

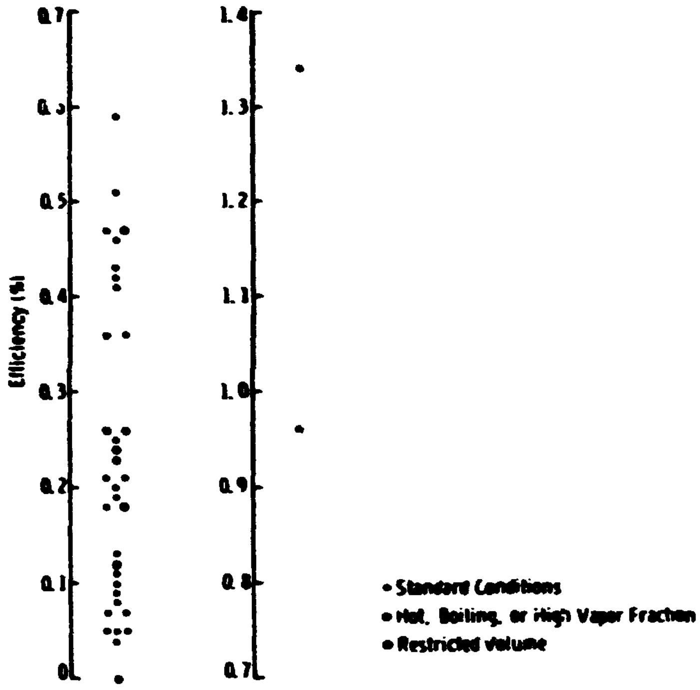


Fig. 4. Water temperature and steam explosion efficiency. (From ref. 10.)

During a reactor accident, including a meltdown of the core, it is most likely that the water below the core is saturated or boiling. This, however, does not exclude the possibility of obtaining steam explosions.

Non condensable gases

Since non condensable gases may prevent the direct contact between molten particles and water, it seems reasonable to assume that the presence of non condensable gases would reduce the steam explosion efficiences. However, on the basis of the available experimental data it is difficult to obtain any conclusive evidence about the effects of non condensable gases.

The melting temperature

When the molten material pours into the water it will pre-mix with the water because of the shear forces between the water and molten material. Because of the high temperature film boiling will be encountered, and the different parts of the melt will immediately be surrounded by vapor films. If the vapor films are stable, no steam explosions can occur and the molten material is cooled down slowly. It is well known that the stability of the vapor film increases when the surface temperature increases. Above a certain surface temperature, which varies with the pressure, the film boiling is normally stable. However, by means of a trigger, which produces a shock wave, it is possible to cause the collapse of the vapor films. Since the stability of the vapor films increases with increasing surface temperature, the possibilities of vapor film collapse decreases when a material with a high melting temperature is employed. It is therefore expected that for UO_2 with a melting temperature of $2800^{\circ}C$ the film boiling will be rather stable in comparison with the film boiling obtained with aluminium, which has a melting point at $660^{\circ}C$.

The superheat of the melt

The superheat of the molten material may be of significance. When the temperature increases, the viscosity decreases, which promotes pre-mixing, fragmentation and mixing. The time needed to reach the freezing point will also increase, which may increase the probability of obtaining film collapse. Bird and Millington (27) observed steam explosions employing UO_2 in the temperature range between 3100 and $3400^{\circ}C$, while Benz et al. (22) did not obtain any explosions at a UO_2 temperature of $2850^{\circ}C$.

The falling speed of the melt

According to WASH-1400 the efficiency of the steam explosion will increase with increasing falling speed of the melt.
A high falling speed promotes pre-mixing and the probability for obtaining coherent fragmentation will therefore increase. Further, at low falling speeds the whole melt may not reach

to be submerged in the water before explosive events take place in parts of the melt, which would reduce the efficiency of the process. Berman (28), for instance, reports that for the experiment FITS2A at the Sandia Laboratories the melt exploded spontaneously 30 milliseconds after the melt reached the surface of the water, but before the whole melt was submerged in the water. The melt in this experiment consisted of a mixture of Fe and Al_2O_3 and had a weight of 3 kg.

<u>The size of the melt</u>

Unfortunately, steam explosion experiments have so far only been carried out with melts weighing up to 27 kg. The 27 kilogram experiment was performed at the Sandia Laboratories with corium E, but no explosion was observed in this experiment. Figure 5, which is reproduced from a report by Haag and Körber (29), summarizes some steam explosion experiments. One observes that the steam explosion efficiency decreases when the size of the melt increases.

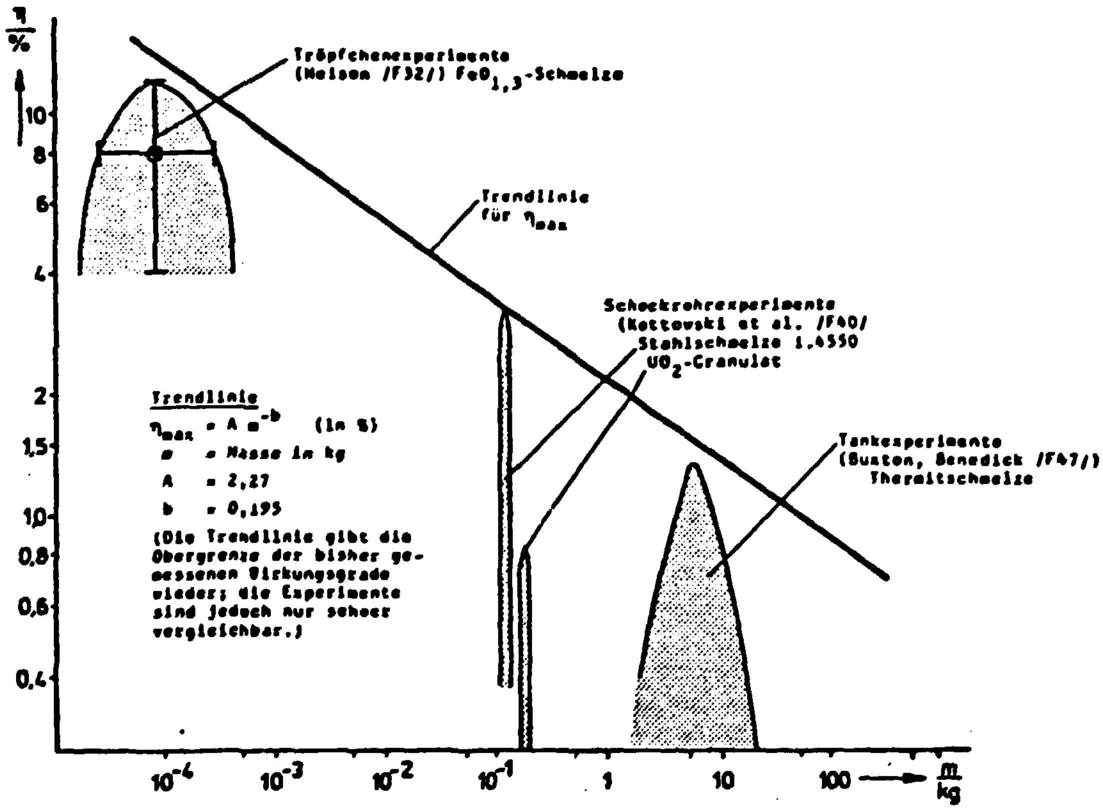


Fig. 5. Steam explosion efficiency versus the size of the melt. (From ref. 29.)

In order to extrapolate to larger melts Haag and Körber suggested the following equation:

$$\eta_{max} = 2.27\, M^{-0.195} \quad (2) \qquad (M \text{ in kg, } \eta \text{ in per cent})$$

It is of course not satisfactory to use equation 2 for extrapolations to melts weighing several tons, which may be the case during postulated core meltdown accidents. However, the equation is very conservative because for medium sized melts in the kilogram scale the equation is based on the largest efficiency obtained with corium E, which was 1.34 %, while for the oxide material corium A the maximum efficiency observed was as earlier mentioned 0.05 %.

The shock wave experiments with molten UO_2 and molten stainless steel, which were reported by Kottowski (30), showed that when the quantity of fragmentated material increased then the specific energy consumtiom for the fragmentation also increased. This means that it becomes more and more difficult to carry out the fragmentation when larger quantities of melt are involved. Kottowski's experiments therefore explain the falling trend of the steam explosion efficiency curve in figure 5 and support the extrapolation to larger quantities of melt.

In the report to the steam explosion committee Mayinger (15) refers to calculations, which shows that in case of a core meltdown accident in a PWR at most 5 tons of melt can be submerged in the water before an eventual steam explosion is released. For 5 tons equation 2 yields an efficiency of 0.43%, which corresponds to 33 MJ of mechanical work. In the Kemeny report (31) and in Deutsche Risikostudie Kernkraftwerke (32) one suggests that 10 tons of melt is the largest quantity to be expected to participate in one steam explosion in a PWR. For 10 tons equation 2 yields 0.38 %, and one then obtains 57 MJ of mechanical work. These results should be compared with the calculations carried out at the Los Alamos Scientific Laboratory with the SIMMER and ADINA computer codes. These calculations, which will be discussed in chapter 5.2, showed that the vessel for a PWR can survive steam explosions generating 1200 MJ of mechanical work.

The Kemeny report suggests that in the case of 10 tons of molten material a steam explosion efficiency of 1 % is considered to be a conservative value. This would yield 150 MJ of mechanical work, demonstrating that even for conservative assumptions with regard to the quantity of the melt and the efficiency, very large margins exist before the integrity of the pressure vessel is endangered. In addition, one have used the wrong assumption that large coherent steam explosions are possible.

Instead of one violent coherent steam explosion, one would in a large melt obtain a number of smaller explosions spread out in time. These explosions cause relatively lenient pressure transients, which cannot threaten the integrity of the pressure vessel. Mayinger (15) as well as Fauske (16) concluded that maximum 200-300 kg of melt can be expected to participate in one coherent steam explosion. Assuming 1 % efficiency and 300 kg of melt yields a mechanical work of 4.5 MJ.

In a BWR the core rests on a great number of stainless steel tubes; 109 tubes in the Barsebäck reactor. In comparison with PWR this design permits only relatively small quantities of melt to fall instantaneously into the water left below the core. The maximum conceivable generation of mechanical work for a postulated steam explosion in a BWR is therefore much smaller than the mentioned value of 150 MJ, which was obtained for a PWR employing very conservative assumptions. With regard to steam explosions BWR therefore appears to have larger safety margins than a PWR. This will be discussed further in a later chapter.

To summarize the discussion of the different parameters, which influence the efficiency of steam explosions, it should be pointed out that in the event of a reactor accident involving a core meltdown one would expect conditions, where the water is saturated or boiling, and in most cases the pressure would be relatively high. The molten material would to a large extent consist uf UO_2 or corium A. The melting point is therefore high, but the superheat temperature is expected to be low. The melt would have a relatively high viscosity, a low thermal conductivity and a high specific weight. Non condensable gases will be present. The mentioned conditions are not especially favourable to the development of a large and violent steam explosion.

4.0 EXPERIMENTAL INVESTIGATIONS

The heat transfer and fluid flow conditions, which are encountered during a steam explosion, are extremely complicated. Therefore, it is, indeed, important to carry out steam explosion experiments, which can be used for comparisons with computer codes and theoretical models, and for estimations of the mechanical work, which would be the result of eventual steam explosions during postulated light water reactor accidents. Thousands of steam explosion experiments have been reported in published works. These experiments comprise many different liquid combinations and have been of great importance to the understanding of steam explosion phenomena.

It has been established that steam explosions are quite different from chemical explosions. The maximum transient pressure in a steam explosion is according to the Kemeny report (31) limited to 200-300 bar, while for chemical explosions pressures of several millions bars may be encountered, for example in the case of TNT. Henry (33) suggests that the maximum pressure occurring in a steam explosion is 110 bar or one half of the critical pressure. The pressure rise time for a steam explosion is in the order of 100 times longer than for a violent chemical explosion. The propagation velocity of the shock wave is 100 times slower in the case of a steam explosion. All of these factors contribute to the observation that a shock wave, which is created by a steam explosion, has a very small destructive capacity in comparison with a shock wave originating from a chemical explosion of equal energy.

A survey, covering some of the experiments up to 1977, has been presented by Hohmann et al. (34). The experiments covered the UO_2-Na system as well as metal-water systems for steel, Al, Cu, Pb, Sn, Zn, Ag and Au. A number of experimental investigations is also reviewed by Bankoff (13).

Of great interest for light water reactors are the more recent experiments with corium simulants in the kilogram scale, which were carried out at the Sandia Laboratories, and which were reported by Buxton and Benedick (20,10) in 1978 and 1979 and by Berman in 1980 (28,35). Experiments with UO_2 and water were reported in 1979 by Bird and Millington (27) at UKAEA in England and in 1977 and 1979 by Benz et al. (36,22) in Ispra.

Buxton and Benedick carried out experiments with a thermite generated melt, which consisted either of a mixture of Fe_3O_4 and Al_2O_3 or a mixture of Fe and Al_2O_3. The temperature of the melts was approximately 2700^oC. The physical properties of the melts were very close to the properties of corium A and corium E.

In 1978 (20) the results of 20 experiments were reported. In 16 of the experiments at least one steam explosion occurred. The melt generator contained up to 13.6 kg melt, which could fall freely into a tank containing between 175 and 840 kg of water.

The table below contains the efficiency of the explosions. Except for one measurement, in which the efficiency was 0.96 %, the efficiency was less than 0.4 %.

Summary of Efficiency Test Results

Experiment Number	Quantity Melt (kg)	Quantity Water (kg)	Test Sequence	Number of Explosions	Efficiency (%)
1	1.0	840	Melt Generator	Frag.	.00
2	3.0	840	Melt Generator	Frag.	.00
3	6.3	320	Melt Generator	Frag.	.00
4	13.6	270	Melt Generator	Frag.	.00
5	3.0	200	Melt Generator	1	.05
6	3.6	200	Melt Generator	4	.05
7	3.5	200	Water Level	1	.21
8	9.2	420	Water Level	3	.11
9	6.6	840	Water Level	1	.41
10	3.0	250	Water Temp.	1	.23
11	3.4	350	Water Temp.	1	.00
12	2.0	200	Trigger Elim.	1	.13
13	4.4	400	Water Temp.	2	.26
14	2.0	175	Trigger Elim.	1	.08
15	5.0	840	Pour Rate	1	.96
16	3.5	175	Trigger Elim.	1	.07
17	3.3	840	Trigger Elim.	2	.05
18	7.6	840	Trigger Elim.	1	.21
19	4.1	340	Trigger Elim.	2	.19
20	5.9	840	Trigger Elim.	2	.36

A more detailed description of the continued experiments at the Sandia Laboratories was presented in 1979 by Buxton and Benedick (10). The experimental equipment is shown in fig. 6. Up to 27 kg thermite melt, which simulated corium A and corium E, could be supplied in a melt generator and could then fall freely into a tank containing water. The amount of water varied between 175 and 840 kg. In 37 out of 48 tests one or more steam explosion occurred. When more than one explosion occurred during a single test, the conversion of the thermal energy in the melt to kinetic energy was spread over a period of time. This reduced the strain on the vessel. Lower efficiences were also noted in such experiments. The efficiency of the explosions or the conversion of thermal energy in the melt to kinetic energy of the water was determined using a high speed camera, and by measuring the de-

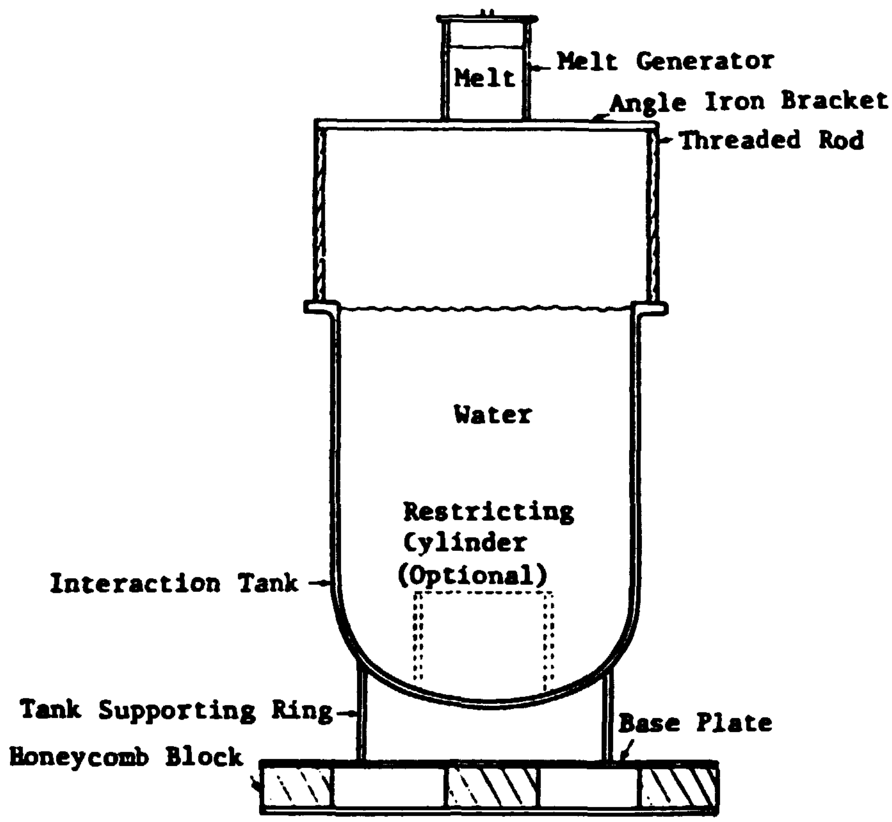
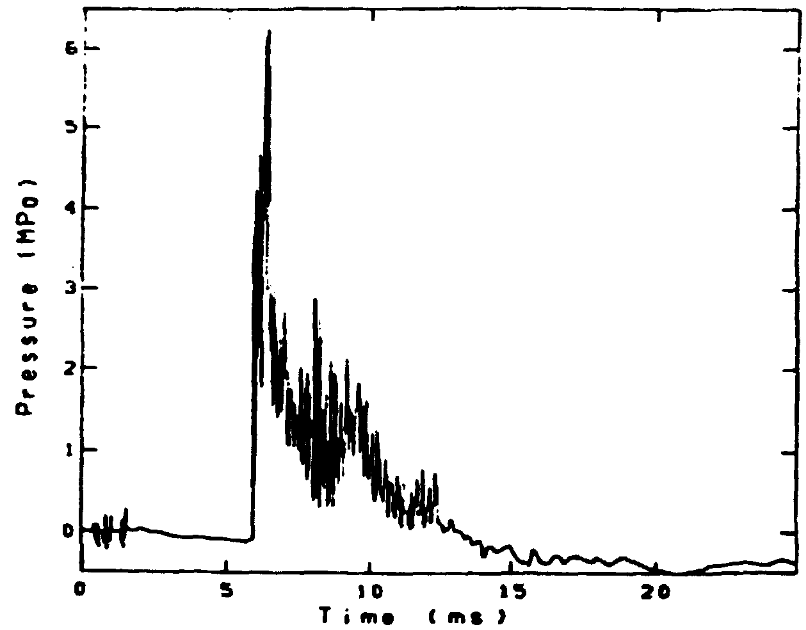


Fig. 6. Apparatus employed by Buxton and Benedick

formation of a honeycomb block below the vessel. The pressure measurements, which were obtained during the explosions, indicated peak pressures between 20-70 bar. After the explosion the pressure decreased rapidly, as shown in fig. 7, where the pressure returned to its initial value after 0.013 seconds.

In figure 8 the efficiences of the explosions are shown as a function of the amount of water in the vessel, and in figure 9 as a function of the quantity of melt. It can be seen that for water quantities up to 600 kg, the efficiency is < 0.3 %. Only with 840 kg of water, which corresponds to a full tank, is the efficiency greater, and in one case the maximum value of 1.34 % was measured. During a core meltdown the reactor vessel can of course not be full of water. The experimental results for 840 kg of water in the tank are therefore not representative for reactor conditions.



Pressure Trace - Experiment 43

Fig. 7. Measured pressure transient by Buxton and Benedick

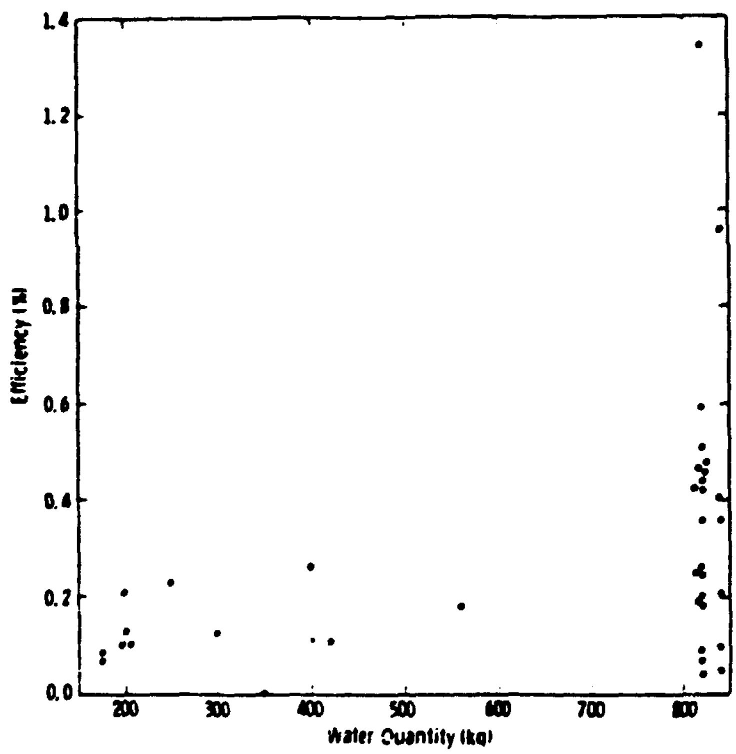


Fig. 8. Steam explosion efficiency versus water quantity. (From Buxton and Benedick.)

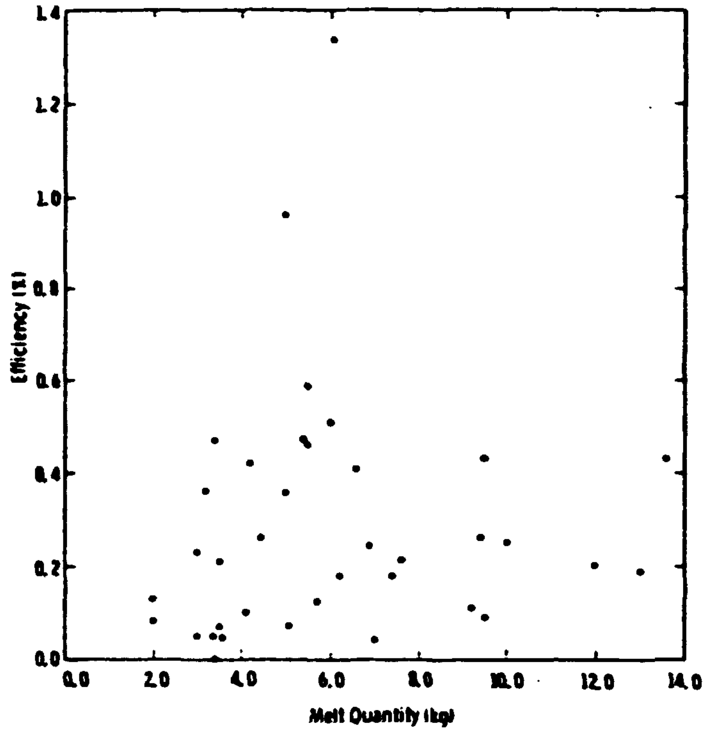


Fig. 9. Steam explosion efficiency versus quantity of melt. (From Buxton and Benedick.)

The large quantity of water, which is present above the melt, keeps the molten particles and the water together a rather long time in comparison with the case of a low liquid level in the tank. This increases the time period for efficient heat transfer and explains the high efficiences. It should especially be pointed out that the experiment with the highest measured efficiency of 1.34 % was carried out with a lid on the tank, which further kept the molten particles and the water together.

Only one experiment was performed with 27 kg of melt, and no explosion occurred in this case.

As earlier mentioned the experiments comprised simulants of corium A as well as of corium E. It is, indeed, important to notice that for corium A, which is the material to be expected to be involved in a steam explosion in a reactor vessel, the observed efficiency was always below 0.05 %.

After the experiments the particle size spectrum was analysed. As expected, the smallest particles were found in experiments with relatively violent explosions.

In order to carry out experiments with better instrumentation, at higher pressures and with more efficient equipment for the discharge of melt into the water, a new test facility was built at the Sandia Laboratories. This facility was called FITS, Fully Instrumented Test Series, and the tank is shown in figure 10. The result of two experiments, FITS 1A and FITS 2A, carried out at 0.83 bar and involving 2.1 respectively 3.0 kg of molten material have been reported by Berman (28,35), and the results of one experiment obtained at 10.4 bar have been reported by Corradini (21). For FITS 1A and the 10.4 bar experiment a corium E simulant was used, while for FITS 2A a corium A simulant was employed. The efficiencies of these experiments have not been reported, but according to Corradini they did not differ significantly from the results by Buxton and Benedick, and the maximum efficiency of 0.05 % for corium A is up to now also valid for these experiments.

Figure 11 shows the particle size distribution of the solidified debris for the experiments FITS 1A and FITS 2A. One observes that corium A (FITS 1A) yields coarser fragments than corium E (FITS 2A), which explains the higher efficiences obtained with corium E.

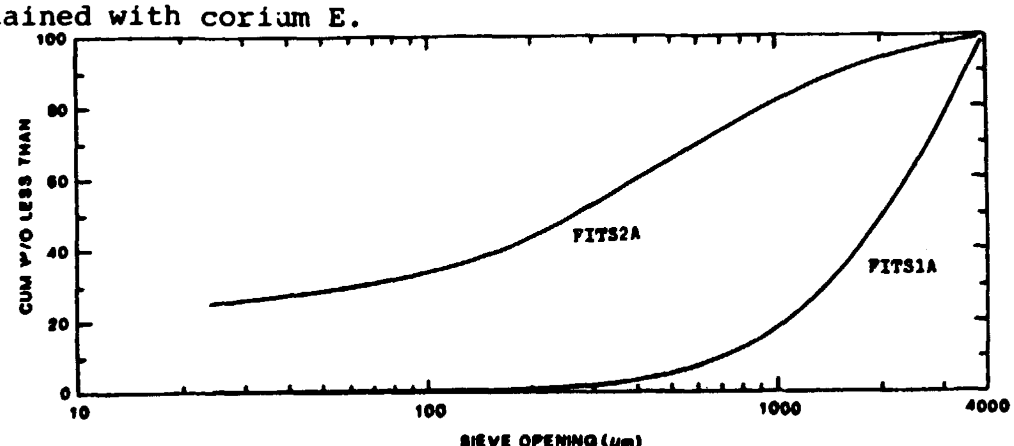
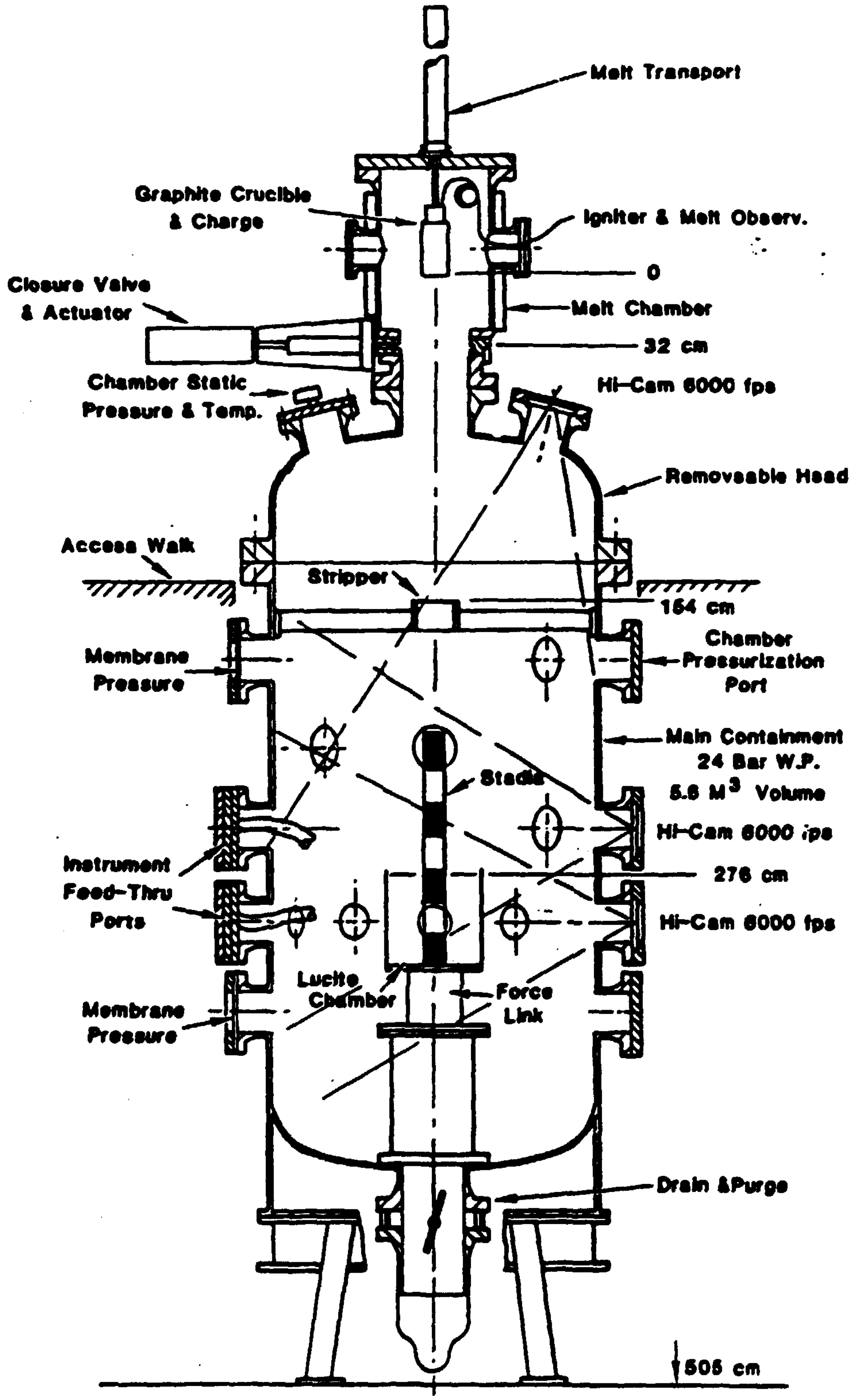


Fig. 11. Particle sieve size data for corium A and corium E. (From ref. 28.)



Typical FITSA Series Experiment

Fig. 10. Apparatus employed for the FITS-experiments. (From ref. 35.)

As earlier mentioned the steam explosion obtained at 10.4 bar was rather unexpected, but the event is explained by considering that a chemical explosion was used as a trigger and that Henry's and Fauske's theory (25), which predicts a cut-off pressure of 10 bar is only valid for systems without triggers. Buxton's experiments have shown that the explosion efficiency of at least 10 %, which was used in WASH-1400, is unrealistic and therefore cannot be used in calculations concerning reactor accidents.

Bird and Millington (27) at UKAEA in England have performed steam explosion experiments in which 0.5 kg UO_2 have been introduced into a vessel containing 52 litres of water. A volume, varying between 1.2 and 3.6 l, above the water was filled with gas. The explosions were photographed using a high speed camera. Pressure transients were measured at a number of positions on the vessel wall. The pressure transients in the gas volume above the water were also determined.

The main difference between this experiment and that of Buxton and Benedick is that in this case, the melt is introduced below the water surface, whereas Buxton and Benedick let the melt fall into the water, which is what would happen in the event of a reactor accident.

37 tests are reported, but explosions occurred only in 8 tests. The highest efficiency was 1.8 %, but on the average it was less than 1 %.

For the following reasons these experiments resulted in higher explosion efficiencies than those, which are to be expected in a reactor vessel during an accident:

1. The melt is introduced below the surface of the water. The time required for the melt to come into complete contact with the water is thus reduced, and this increases the efficiency of the explosion.

2. The melt was only 0.5 kg. As earlier pointed out, the efficiency of the steam explosion decreases as the size of the melt increases.

3. The tank is closed and the gas volume above the water is small. This prevents the separation of melt and water during the explosion, and explains why the efficiencies were higher in comparison with the corium A experiments by Buxton and Benedick.

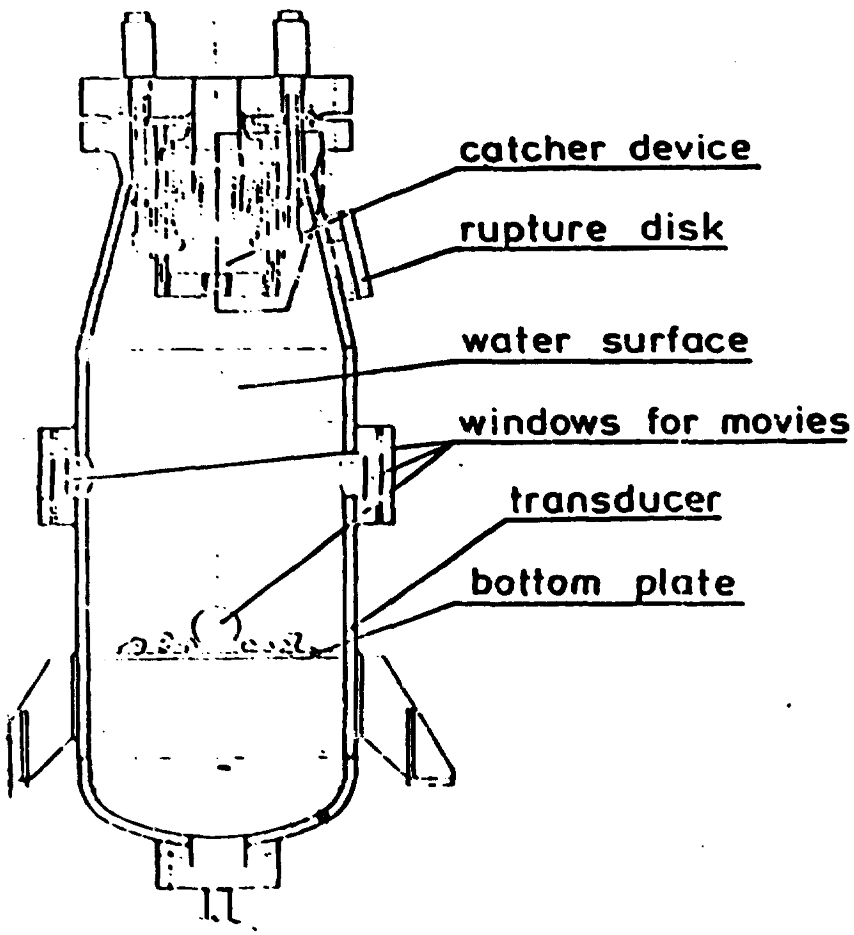
Despite these factors, the maximum efficiency measured is six times less than the values used in WASH-1400.

In 1979 Benz et al. (22) reported the results of several years of experimental work on steam explosions at the Euratom Laboratory in Ispra. In these experiments it was possible to allow molten steel, molten UO_2 or granulate UO_2 to fall freely into a vessel containing water. Two vessels with volumes of 350 and 6.5 l respectivelv were used. The vessels are shown in figure 12. Up to 4 kg of melt at temperatures up to 3000°C could be dropped into the water. The pressure in the tanks was measured at various positions. Strain gauges were also applied to the vessels so that the stresses in the walls could be determined. The experiments in the larger vessel could be watched through a window, and by means of a high speed camera movie pictures were tanken. The particle size distribution was studied after the experiments. In all, 50 successfull experiments were carried out.

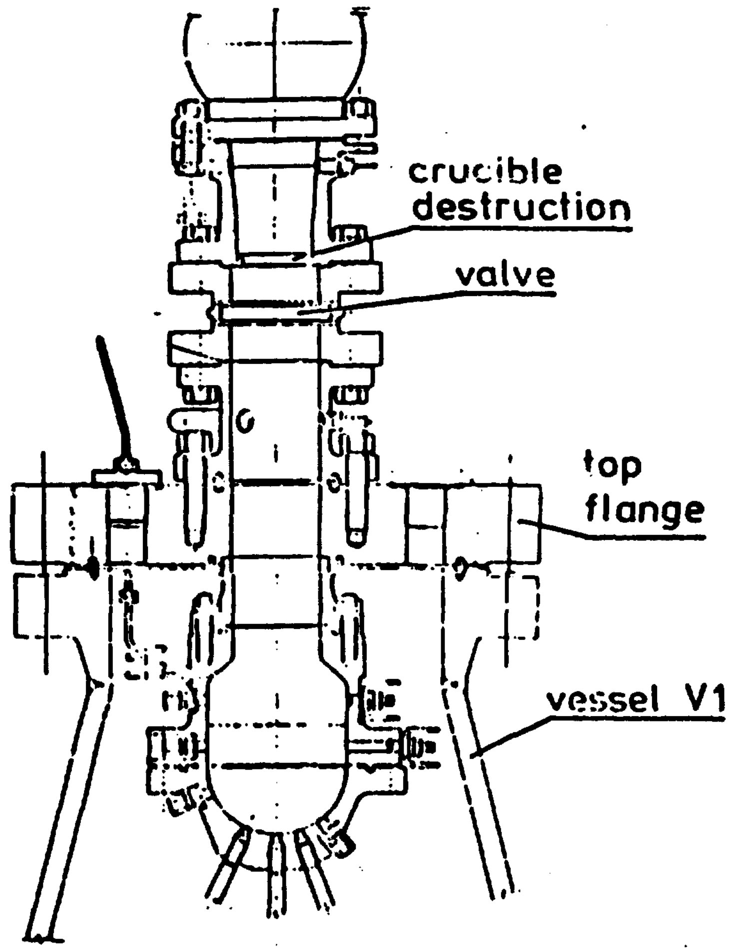
All the experiments in the large vessel were performed with 200 liters of water in the vessel, yielding volume ratios of ~1:1000 between the melt and the water.

The small vessel geometry was similar to that in a PWR. The size of the tank, 6.5 l, was determined by the maximum quantity of melt, 4 kg, which was taken to represent 70 % of a reactor core. The volume ratio between the melt and water

Fig. 12. Apparatus used by Benz et al.



Vessel V 1
(Volume: 350 l)

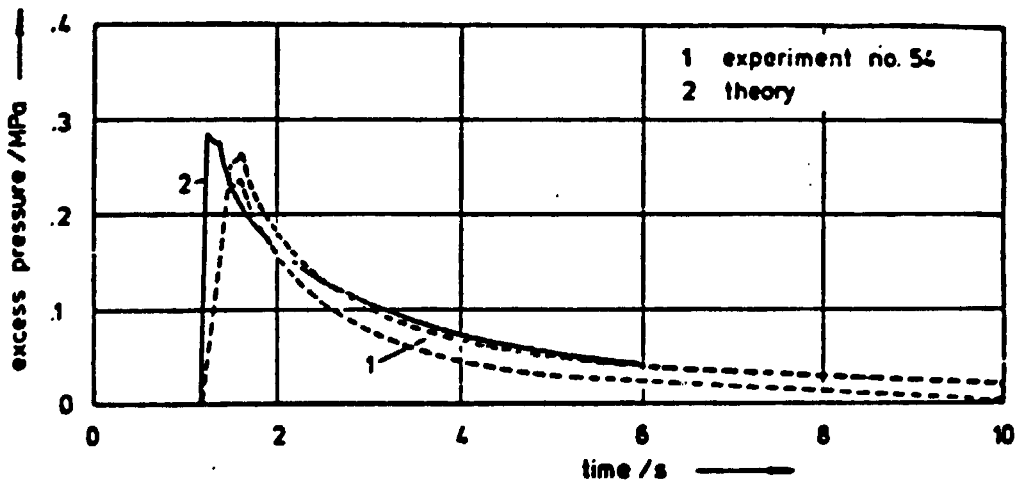


"PWR" scaled down vessel
(Volume: 6.5 l)

varied between 1:2 and 1:5, which encompass realistic values for the situation in a postulated reactor accident.

In order to study uranium dioxide with a known particle size distribution, experiments were also performed with granulate uranium dioxide at temperatures up to 1800°C. The aim of those experiments was to obtain data for comparison with the theoretical model and computer program TANDEM (Tank Dampfexplosionsmodell), which was developed by Benz et al. (36).

No steam explosions were observed in any of the 50 experiments. On the other hand fast pressure transients up to 2 bars in the large vessel and up to 25 bars in the small vessel were observed. A comparison between the pressure transient in one of the experiments with granulate uranium dioxide (T = 1800°C) and the computer program TANDEM, is shown in figure 13. As can be seen the experimental and theoretical results are in good agreement.



Excess pressure versus time in the large tank (V1) during the UO_2-granulate experiment no. 54 (water temperature 30° C)

Fig. 13. Theoretical and experimental pressure transients. (From ref. 22.)

The absence of steam explosions was explained as follow:

"The reason for these mild interactions can be seen on the high speed movies and from the sieving data of the fragments. The movies show that a remarkable part of the fuel is cooled down under film boiling conditions over a long time. Additionally the fragmentation is rather poor as compared to other fragmentation data taken from the literature. In the case of molten UO_2 and SS approximately 60 % of the mass had particle diameters of more than 4000 µm. Additionally in the small tank the melt has been collected on the bottom as a large lump with relatively small surface area; thus the mild interactions can be understood."

The Ispra experiments with UO_2 and the Sandia experiments with corium A demonstrate that for reactor core materials in the range between 2 and 27 kg the steam explosion efficiencies are rather small. The highest efficiency encountered was below 0.05 %. In comparison, calculations carried out at the Los Alamos Scientific Laboratory, employing the SIMMER program (37), have shown that 10 tons of melt and an efficiency larger than 8 % is needed in order to endanger the integrity of the reactor vessel in a PWR.

Figure 5, which was discussed in chapter 3, shows that in the range up to 15 kg the steam explosion efficiency decreases when the size of the melt increases. It seems, indeed, impossible to conceive of a physical model, which would change this trend so drastically that steam explosion efficiencies in the order of 8 % should be obtained in the range between 1 and 10 tons of melt.

On the basis of the experiments, which have been discussed in the present chapter, the conclusion is obtained that steam explosions cannot cause failure of the reactor vessel or the reactor containment. Besides the SIMMER calculations this conclusion is also supported by Hassman et al. (38), who carried out the calculations by means of the PISCES program (39).

5.0 STEAM EXPLOSIONS IN LIGHT WATER REACTORS

The consequences of steam explosions in light water reactors were considered in detail for the first time in the reactor safety study WASH-1400. As previously mentioned in chapter 1 it was assumed that in the case of 1 core meltdown out of 100, the pressure vessel and the reactor containment would be destroyed by a steam explosion in the pressure vessel; and thus causing large radioactive releases to the environment. This assumption included BWR as well as PWR. Steam explosions in the reactor containment were not included in the safety analysis. In addition to the treatment in WASH-1400, it exists today sufficient information showing that postulated steam explosions in the reactor containment are not forceful enough in order to rupture the containment building.

A safety study of the Barsebäck reactor was presented in 1978 by MHB Technical Associates (40). Without including any new data or information about steam explosions MHB increased the probability of catastrophic steam explosions with 2400 %. The large probability used in the MHB report was primarily based on the assumption that steam explosions in the containment building would cause catastrophic accidents for 21 core meltdowns out of 100. No references or scientific arguments were presented in order to explain the large deviations from the WASH-1400 analysis.

In the present chapter the consequences of postulated steam explosions in the reactor vessel and in the reactor containment will be discussed. The discussion will deal with pressurized water reactors of the Ringhals type, boiling water reactors of the Barsebäck type, where steam explosions can be postulated at two locations in the containment and boiling water reactors of the Forsmark type, where a steam explosion only can be postulated at the lowest level in the central part of the containment. However, at this location water is normally not present.

5.1 STEAM EXPLOSIONS IN THE REACTOR VESSEL

Considering a steam explosion in the reactor vessel the sequence of events may schematically be divided into the following three stages:

1. Meltdown of the core and an eventual catastrophic collapse of the lower support plate.
2. Fragmentation of the melt into particles with diameters less than 1 mm and mixing of the particles and the water.
3. Conversion of the heat into mechanical work, which loads the walls and the lid of the reactor vessel.

The fragmentation process is the key issue in the steam explosion analysis. In chapter 2.0 it was demonstrated that ton scale fragmentation and mixing with water is impossible because of the enormous requirements of energy. According to Mayinger (15) and Fauske (16) maximum 200-300 kg of melt can be fragmentated and mixed with water within the short time, which is available for the mixing process. Coherent steam explosions, involving this quantity of melt, yields mechanical work with an order of magnitude, which is negligible compared with the work, which is needed in order to rupture the vessel.

Although it is possible in the present stage of the study to exclude steam explosions from the analysis of the environmental consequences of severe reactor accidents, it is still of great interest to look at the model presented in WASH-1400 and the results of more recent analytical models. Employing conservative assumptions these theoretical models calculate the mechanical work, which is needed in order to rupture the reactor vessel, and the results are therefore valuable for an assessment of the magnitude of the safety margins.

Meltdown of the core and the eventual collapse of the core bottom plate

The melting process starts in the central zone of the reactor core, where the largest residual heat is encountered. In the physical model for the core meltdown shown in figure 14, which is reproduced from a report by Haag and Körber (29), the molten material flows down along the fuel rods and falls as droplets into the water below the core. For this melting sequence steam explosions with significant strength can be excluded. Therefore, another melting model has been proposed. In this model the melt freezes when it flows downwards between the fuel rods, forming a crust which collects the molten material as shown in figure 15, which is reproduced from the Zion-Indian Point study (41).

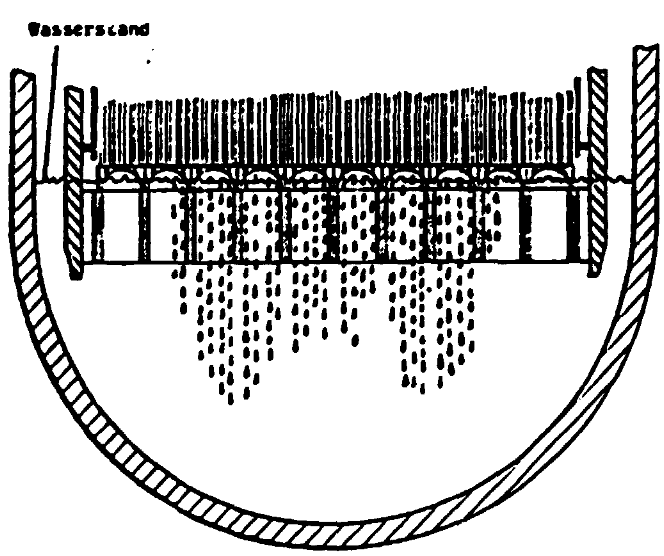


Fig. 14. Core meltdown model.
(From ref. 29.)

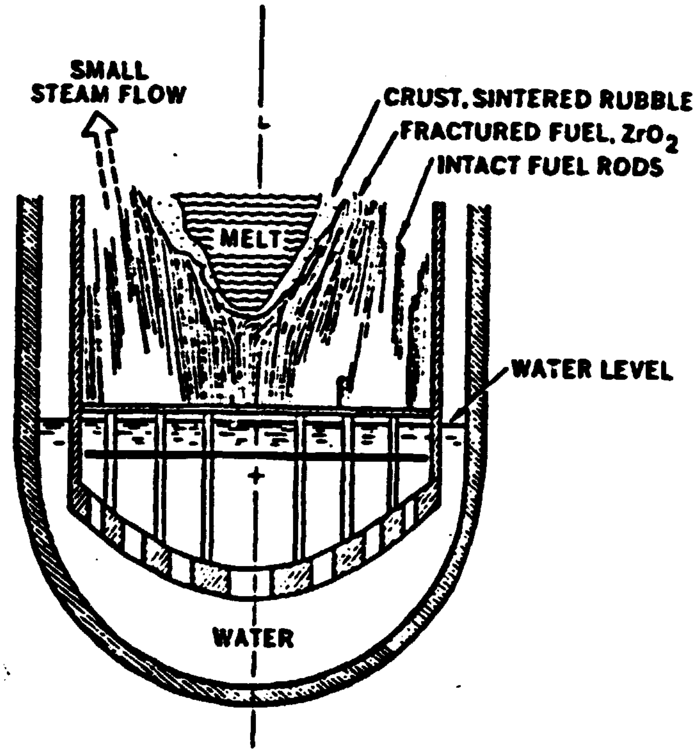


Fig. 15. Core meltdown model.
(From ref. 41.)

During the melting process the crust moves downwards, the amount of melt increases and finally the melting front reaches the core bottom plate. This plate has relatively large openings for the coolant, and the melt may therefore flow into the lower plenum, as shown in figure 16, which is reproduced from reference (29).

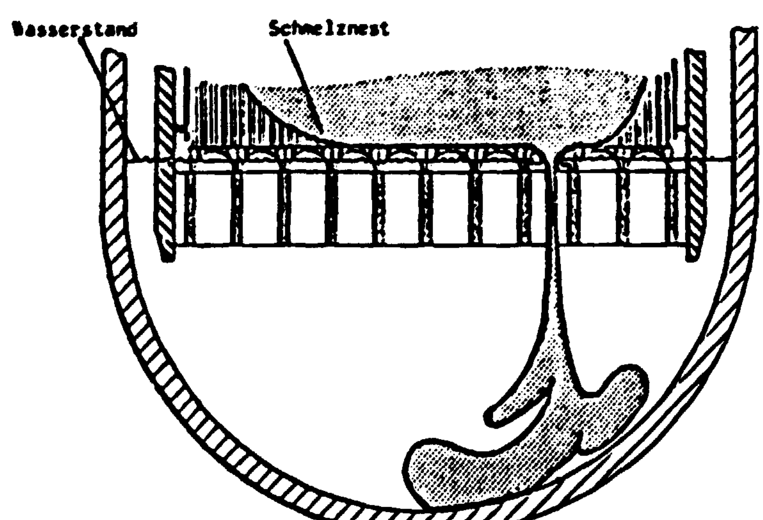


Fig. 16. Core meltdown model.
(From ref. 29.)

Also for this melting model it is not possible to supply sufficient molten material in sufficiently short time to the water in the lower plenum. A sufficient amount of melt can only be supplied to the water within the short time-scale needed by postulating a catastrophic collapse of the bottom plate, as shown in figure 17, which is reproduced from the report by Haag and Körber (29).

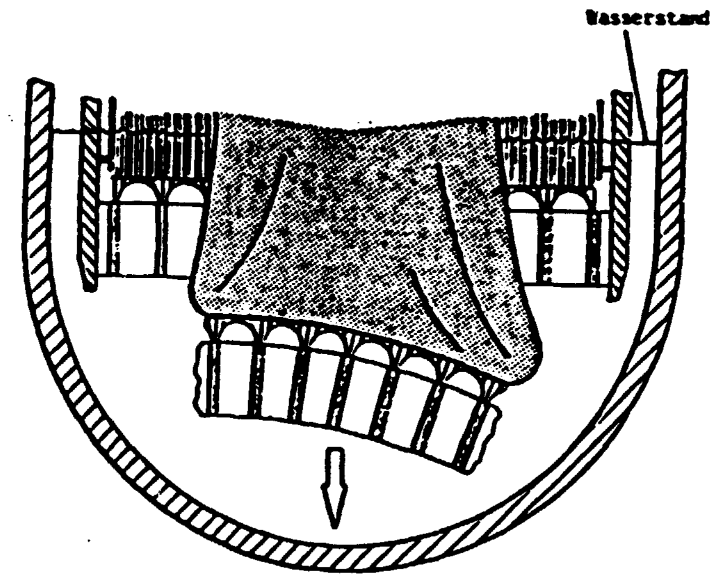


Fig. 17. Collapse of the bottom plate

In the case of boiling water reactors, however, a catastrophic collapse of the bottom plate is impossible as long as water is left in the lower plenum of the vessel. If all the water should have boiled off, steam explosions are of course not possible at all. The collapse of the bottom plate is prevented since the plate rests on a large number of 295 mm diameter stainless steel tubes with 4.5 mm wall thickness. These tubes also serve as guide tubes for the control rods, and the Barsebäck reactors, for instance, are supplied with 109 such tubes, which are shown in figure 18.

For boiling water reactors we therefore conclude that at most a few tons of melt may instantaneously come into contact with water. In WASH-1400 the control rod guide tubes were not considered, and it was assumed that up to 160 tons or

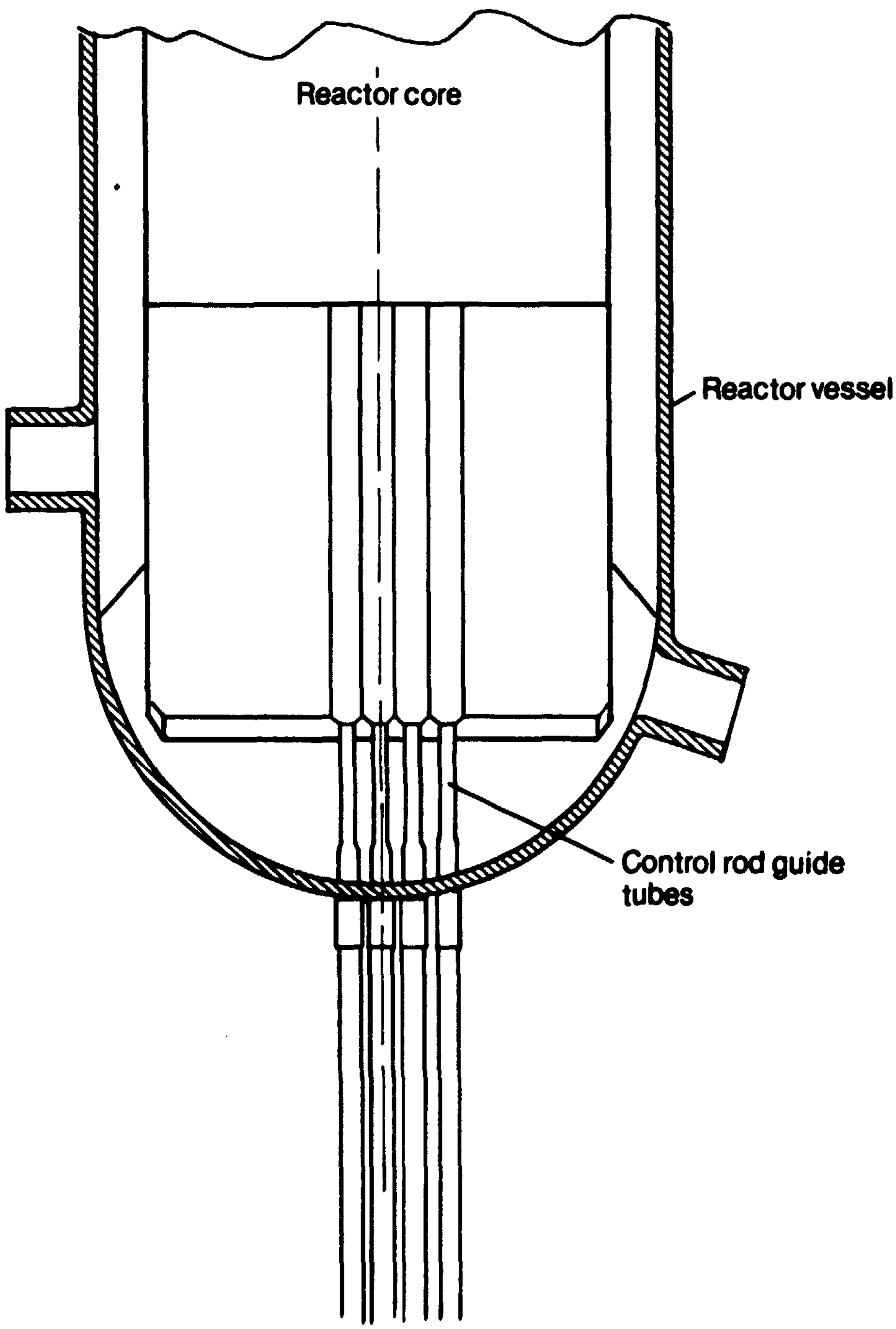


Fig. 18. Control rod guide tubes in Swedish BWR's

80 % of the reactor core could be supplied instantaneously to the water. Also because of this reason the results in WASH-1400 are not applicable to an assessment of the steam explosion risks, which may be encountered in the Swedish boiling water reactors.

Fauske (16) points out that also for pressurized water reactors the bottom plate is supported from below, as shown in figure 19, and this support excludes the kind of catastrophic collapse described in WASH-1400. For PWR's Fauske concluded as follows: "Therefore the total collapse of the core debris into the lower plenum could not occur in a catastrophic manner with water present."

For the prediction of the meltdown of the core several computer programs are available. In WASH-1400 and in Deutsche Risikostudie Kernkraftwerke (32) the program BOIL was used, and in the Zion-Indian Point study the program MARCH was applied. In the Kemeny report it was concluded that at most 10 tons of melt could instantaneously be supplied the water below the core. This value was also employed in Deutsche Risikostudie Kernkraftwerke. For a PWR Mayinger (15) found that the largest amount of melt, which could fall into the water within the short time available, was in the range between 1 and 5 tons.

We conclude that the largest amount of melt, which can be supplied sufficiently fast to the water, is at most 2-3 tons for the Swedish BWR's and at most 5 tons for the Swedish PWR's. Conservative assessments for 5 respectively 10 tons will, however, also be presented.

<u>Conversion of steam explosion energy to mechanical work</u>

In the models, which has been discussed in the literature, a catastrophic collapse of the bottom plate was postulated, and further, it was assumed that small molten particles with

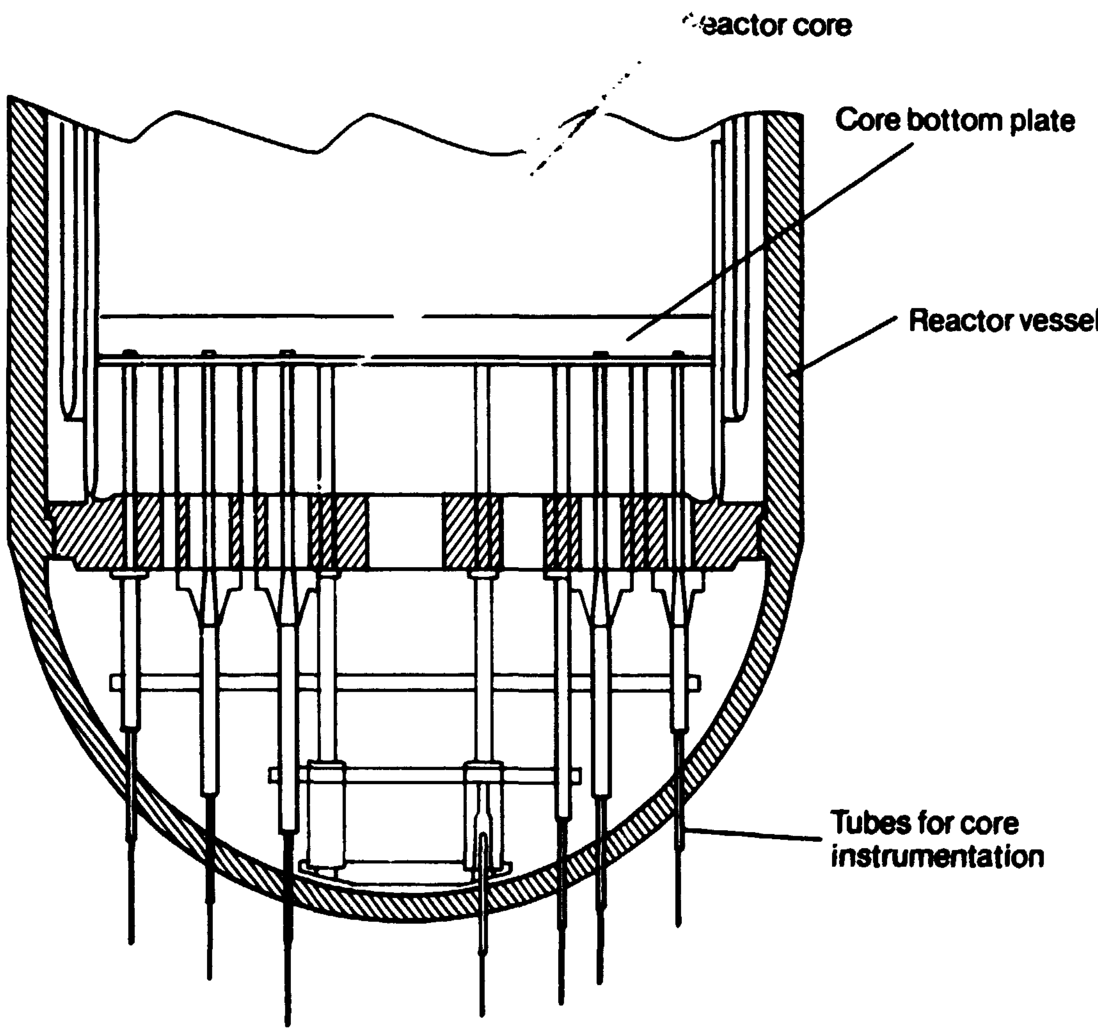


Fig. 19. Support of core bottom plate in a PWR

a diameter less than 1 mm were mixed homogenously with the water. Thus, the analysis starts from physical impossible conditions, and the models as well as the calculated results are therefore only of academic interest.

In WASH-1400 the following assumptions were made with regard to the process of converting the stored heat in the melt to mechanical work, which loads the reactor vessel. The heat transfer from the small, uniformly distributed molten particles with the temperature 2500°C was calculated assuming direct contact between the particles and the water. Above the exploding mixture the presence of a contineous liquid slug was postulated. This liquid slug, which may contain core debris is accelerated vertically upwards like a piston by the expanding steam as shown in figure 20. The displacement of the slug continues until it impacts upon the lid of the vessel, and for certain conditions the impact is forceful enough to rupture or tear off the lid, parts of the lid or a control rod. The latter concerns only pressurized water reactors.

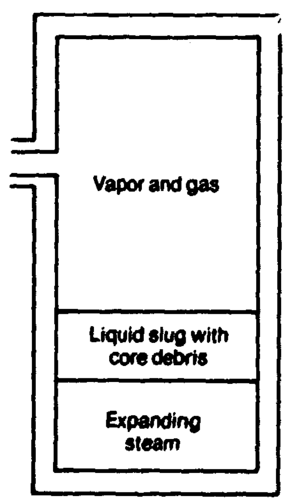


Fig. 20. Steam explosion model in WASH-1400

Thus, it was postulated that missiles could be formed, and that these missiles could be hurled against the reactor containment wall with such force that the latter would rupture. Already 2-3 hours after the start of the reactor accident a steam explosion could therefore cause large releases of radioactivity and severe consequences for the environment.

The WASH-1400 model is, however, extremely simplified and of the following reasons it is useless for realistic accident predictions.

1. The internal components below the reactor core are neglected. As earlier pointed out these parts are of great significance.

2. The internal components above the reactor core are neglected. These parts will, however, break up the liquid slug and thus reduce the mechanical loads on the lid of the reactor vessel. Especially in a BWR the moderator tank, the steam separators and the steam dryers will prevent the liquid slug from performing a direct impact on the lid. The energy in the liquid slug can only be transferred to the lid by vertical movement of the steam separators and the steam dryers, which are lifted against the lid. In this chain of events, however, large quantities of energy will be consumed by the deformation of the steam separators, and the available mechanical work for rupturing the vessel therefore decreases.

3. The content of vapor bubbles in the liquid slug, which reduces the impact force of the slug, was neglected.

4. It was assumed that the integrity of the liquid slug was preserved until the impact with the lid. This,

however, is impossible since Taylor and Helmholz instabilities cause entrainment of water droplets and the destruction of the liquid slug. Henry and Cho (42) have shown that the steam, which is generated during the explosion, would penetrate the water above the melt, and therefore only permit an annular liquid slug around the periphery of the vessel. In Deutsche Risikostudie a compact liquid slug is excluded, commenting as follows: "Das Wasser bewegt sich nach dem Durchbrechen der Wasseroberfläche in Form einer Ringströmung weiter gegen den Deckel."

5. In WASH-1400 a one-dimensional analysis was used, yielding too large mechanical loads on the lid of the vessel.

6. The assumed initial conditions were a homogenous mixture of small molten particles and water.

7. The analysis was based on the assumption of a catastrophic collapse of the bottom plate, and up to 88 % of the core was assumed to fall instantaneously into the water.

The steam explosion model in WASH-1400 was discussed in detail by Fauske (16), who presented the following conclusion:

"The failure mechanism in WASH-1400 was the formation and the transmission of a liquid-like slug, but an evaluation of the potential for such a slug formation shows that it could not be formed because of 1) the available structure in the lower plenum region, and 2) the necessary intimate dispersion for an explosive interaction would preclude the formation of a continuous slug. Hence, even for low pressure systems where steam explosions are possible, the impact failure mechanism is incredible."

We conclude that the WASH-1400 steam explosion failure model is not realistic and extremely conservative. The results obtained with this model can therefore not be used in connection with serious reactor safety analysis.

5.2 RECENT ANALYTICAL MODELS AND RESULTS

Since WASH-1400 was published several analytical steam explosion models have been used for the calculation of the mechanical work, which loads the reactor vessel. Some of these models are two-dimensional, for example SEURBNUK (43), which was used in Deutsche Risikostudie and SIMMER, which was developed at the Los Alamos Scientific Laboratory, and which was used for the Zion-Indian Point study (37). Hassman et al. (38) employed the PISCES program for the analysis of a German PWR. All of the published studies concerns German or American pressurized water reactors, and the results can therefore be used for steam explosion assessments in the pressurized water reactors in Ringhals, which were constructed by Westinghouse. With regard to boiling water reactors, studies, which will be published during 1981, have been carried out in the United States.

In all of the models the initial conditions consist of a homogenous mixture of small molten particles and water. According to the discussions in chapter 2.0 this condition is impossible to achieve in a ton scale system. The analytical results, however, are still of great interest since they yield the order of magnitude of the mechanical work, which is necessary to apply in order to endanger the integrity of the pressure vessel. It should further be pointed out that these models also neglect the presence of the internal parts in the reactor vessel, and the results are therefore conservative.

Pressurized water reactors

Hassmann et al. (38) analysed the consequences of a steam explosion in a German PWR. A catastrophic collapse of the bottom plate was assumed, causing 129 tons of molten material to participate in the explosion. The meltdown of the core was calculated by means of the programs BOIL and MELSIM. It was postulated that all of the melt became fragmentated into small particles with the size distribution given in figure 21.

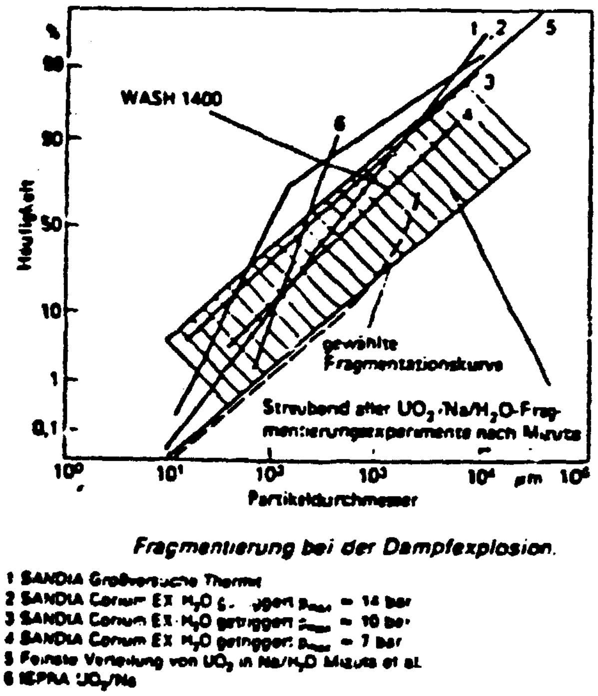


Fig. 21. Particle Size Distribution.
(From ref. 38.)

By employing the PISCES program one found that the pressure vessel with substantial margins would carry the loads developed by postulated steam explosions. The maximum strain in the tank was 0.25 %. According to Deutsche Risikostudie, Fachband 5 (45), the integrity of the vessel is not endangered as long as the strain is less than 1 %. The maximum strain of 0.25 % was obtained for an explosion involving 129 tons of melt and an efficiency of 0.2 %, yielding mechanical work on the vessel of approximately 360 MJ.

At the Los Alamos Scientific Laboratory in USA the SIMMER-2 program (37) was used for the calculations of the dynamic loads on a PWR vessel. The stress calculations were carried out employing the ADINA program (46). The results were included in the Zion-Indian Point study (47). The SIMMER program was calibrated on the basis of run 43 in Buxton's and Benedick's investigations at Sandia. The calibration involved efforts to reproduce the measured steam explosion efficiency and the measured pressure transient. A relatively satisfactory agreement between the calculations and the measured values was obtained. The SIMMER-2 program, which is two-dimensional, permits the liquid slug above the melt to break up because of instabilities. The initial conditions for the reactor calculations were assumed to consist of 10 respectively 20 tons tons of melt, which was fragmentated into particles with a diameter of 0.3 mm and homogenously mixed with water. Figure 22 shows an example of the configuration of the premixed initial conditions. Calculations were also carried out for the case, where the melt initially was located around the vessel wall.

According to Anderson (48), who carried out the ADINA calculations, 1200 MJ of mechanical work could be developed without endangering the integrity of the reactor vessel. For an explosion, yielding 3000 MJ of mechanical work, the bottom of the reactor vessel would rupture, but large missiles with the potential of rupturing the reactor containment were considered unlikely to develope.

The following conclusion was presented in chapter IV of the Zion-Indian Point study:

"Thus, our main conclusion is that for the postulated dynamic loading from SIMMER, the possibility of generating missiles is remote."

It should be emphasized that 1200 MJ corresponds to a steam explosion with an efficiency of 8 % and where 10 tons

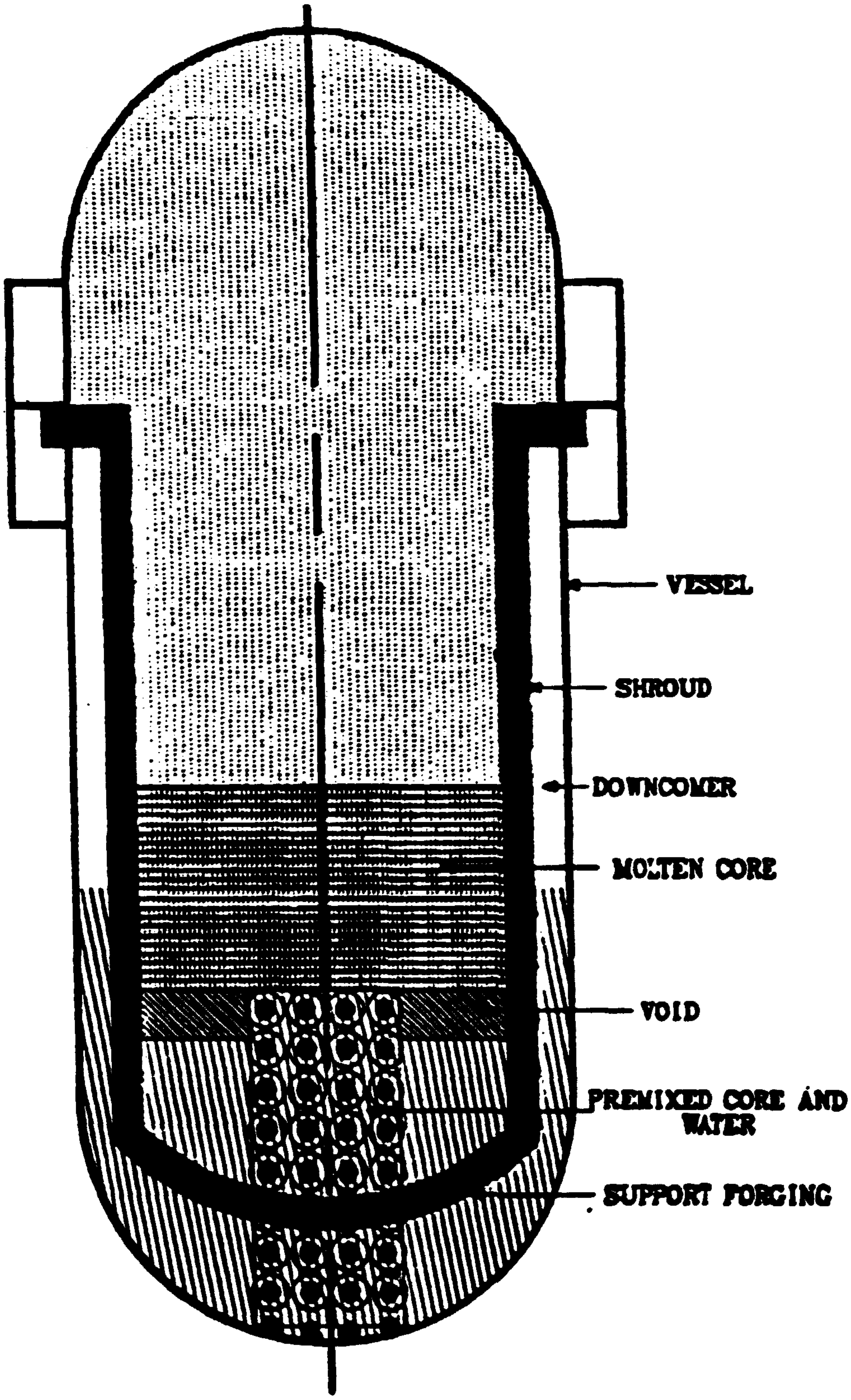


Fig. 22. Initial condictions for SIMMER calculations. (From ref. 47.)

of melt is employed. It seems to be evident that a steam explosion of this character is impossible.

Further, it should also be noted that the results of the SIMMER calculations agree fairly well with the PISCES results reported by Hassman et al.

In a previous section the conservative hypothesis was adopted that at most 10 tons of melt could instantaneously be supplied to the water below the core in a PWR. Assuming a steam explosion efficiency of 1 %, which is in accordance with the Kemeny report and, which is rather conservative in comparison with the experimental results for UO_2 and corium A, a mechanical work of 150 MJ is obtained. This shows that even if ton scale mixing of molten particles with water was possible, the steam explosions would not be so forceful that the integrity of the reactor vessel was in danger.

It should also be emphasized that a great deal of the conservatism used in the WASH-1400 model is still present in the SIMMER and the PISCES models. The results obtained from these codes are therefore conservative.

Swedish boiling water reactors

The operating pressure in a BWR is approximately one half of the pressure in a PWR. Neglecting the influence of the internal parts, the BWR pressure vessel is therefore weaker than the PWR vessel with respect to steam explosions. The core in a BWR, however, rests on a great number of stainless steel tubes. This design reduces substantially the amount of molten material, which instantaneously can be supplied to the water below the core. In case of an explosion the steam separators and the steam dryers would also absorb a significant amount of energy from the liquid slug, which is accelerated upwards from the explosion zone.

The narrow deadline of our investigation has not permitted to carry out any SIMMER or PISCES calculations for a Swedish boiling water reactor. However, on the basis of the above mentioned features of a BWR, we conclude that the BWR is actually safer with respect to steam explosion accidents than the PWR. The large safety margins obtained for PWR's are therefore also relevant for steam explosion assessments of BWR's. An approximate scaling between PWR and Swedish BWR pressure vessels indicates that a dynamic loading of at least 600 MJ is possible without rupturing the BWR vessel. As earlier mentioned a steam explosion efficiency of 1 % and 3 tons of molten material yields 45 MJ of mechanical work. Considering the Swedish BWR's the safety margin with respect to a steam explosion is therefore, indeed, satisfactory. In addition, we should bear in mind that ton scale steam explosions are not at all possible.

We therefore conclude that an eventual steam explosion in the pressure vessel of a light water reactor cannot occur with such force that the integrity of the vessel is in danger. This conclusion is supported by the following studies:

1) The Kemeny report, Appendix A (49): Any of the above would inhibit the coupling of released energy to process mechanisms which would compromise the vessel or containment.

2) The Kemeny report, Appendix C (31): Recognizing (1) the long time scale required for fuel melting relative to required mixing times for coherent steam explosions; (2) the inherent phenomena mitigating against coherency for the large molten masses required for projectile generation; and (3) with all of the dissipative mechanisms between the pool in the vessel or the reactor cavity and the containment building, it is difficult

to conceive of a scenario in which enough molten material could mix coherently with a pool to generate a steam explosion that would rupture the reactor vessel or the containment building.

3) Fauske (16): The above conclusions added together show that a steam explosion within the vessel does not provide any threat to the integrity of the reactor vessel or any of its components.

4) Deutsche Risikostudie Kernkraftwerke (32): Dabei tritt kein Wasserhammer am Deckel auf, so dass auch durch diese Druckbelastung ein Versagen des Deckels nicht zu erwarten ist.

5) Mayinger (15): During a hypothetical core meltdown accident small scale steam explosions up to an instantanteously reacting mass of a few hundred kilograms may occur if water comes in contact with the molten CORIUM. The mechanical energy of these reactions, however, do not endanger the integrity of the pressure vessel or the containment as certainly can be shown by a simple stress calculation.

6) And, as earlier mentioned, Hassmann et al. (38) and the SIMMER calculations.

5.3 STEAM EXPLOSIONS IN THE REACTOR CONTAINMENT

In the previous chapters it was shown that only small steam explosions can occur in the pressure vessel of a light water reactor, and that the vessel cannot be destroyed by means of a steam explosion. In case of a core meltdown the molten core material will therefore be collected at the bottom of the vessel. The melt, which has a temperature of about 2500°C, will because of insufficient cooling melt its way through the bottom and flow into the reactor containment building.

Locations for eventual steam explosions in the reactor containment of the Barsebäck reactors are in the compartment just below the reactor vessel and in the wet well, which is located on the bottom of the containment. The occurrence of a steam explosion in the former compartment is, however, very unlikely, because the water, which during an accident may be supplied to this compartment, will drain through a 300 mm diameter hole in the floor and flow into the wet well. However, the possibility that the drain is blocked during an accident is not discarded. With regard to the Forsmark boiling water reactors steam explosions can only be postulated to occur at the bottom of the containment.

In case of an accident in the Ringhals pressurized water reactors it is assumed that water from the primary loop is present on the floor of the reactor containment, and steam explosions in the compartment just below the pressure vessel must therefore be considered. The figures 23, 24 and 25 show the containments of the mentioned reactor types, and the locations where eventual steam explosions can be postulated are also indicated in the figures.

Supply of core melt to the reactor containment

The control rod guide tubes, which penetrate the bottom of the Swedish boiling water reactors have a wall thickness of 4.5 mm, while the bottom of the tank is 125 mm thick. The molten material will therefore melt through the tubes to the ambient. The mass velocity of the melt out of the vessel will therefore be rather limited, which excludes large coherent steam explosions in the compartment below the vessel. In Forsmark this compartment is located at the bottom of the containment.

In Barsebäck the melt will be collected on a 1 meter thick concrete floor. In the wall of this compartment a steel door is placed 8.5 cm above the floor. The melt will penetrate

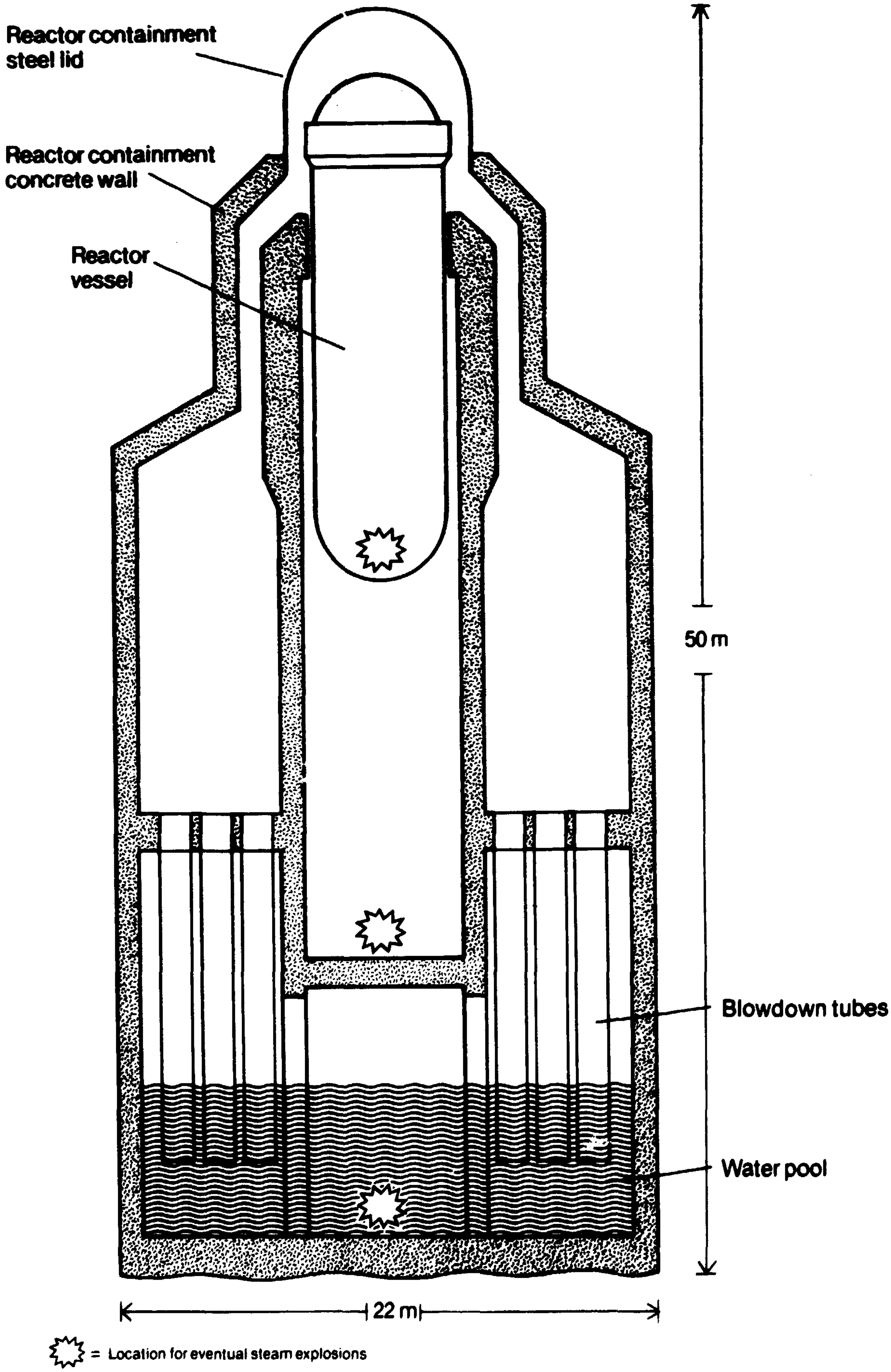


Fig. 23. Reactor containment in Barsebäck

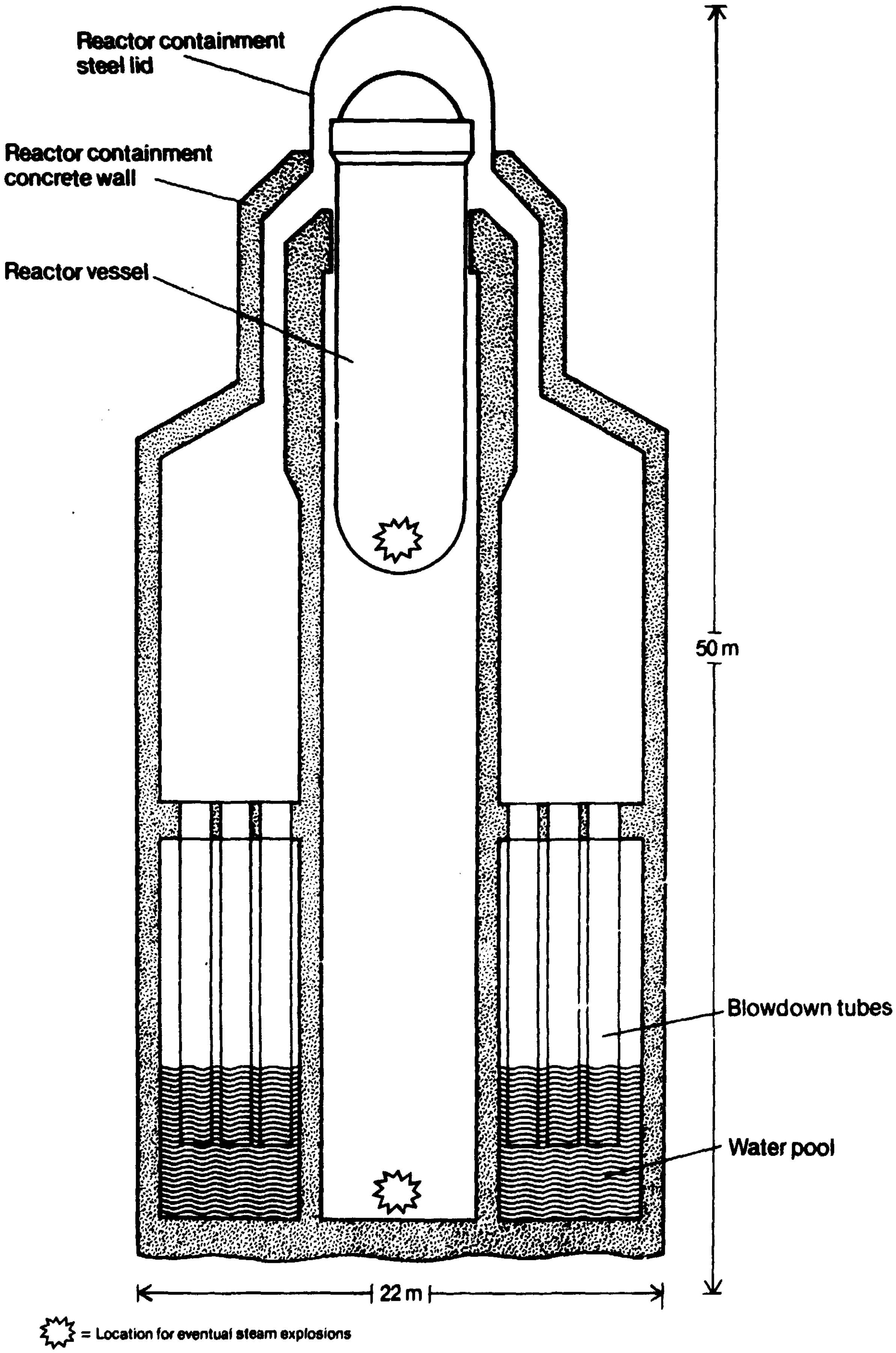


Fig. 24. Reactor containment in Forsmark

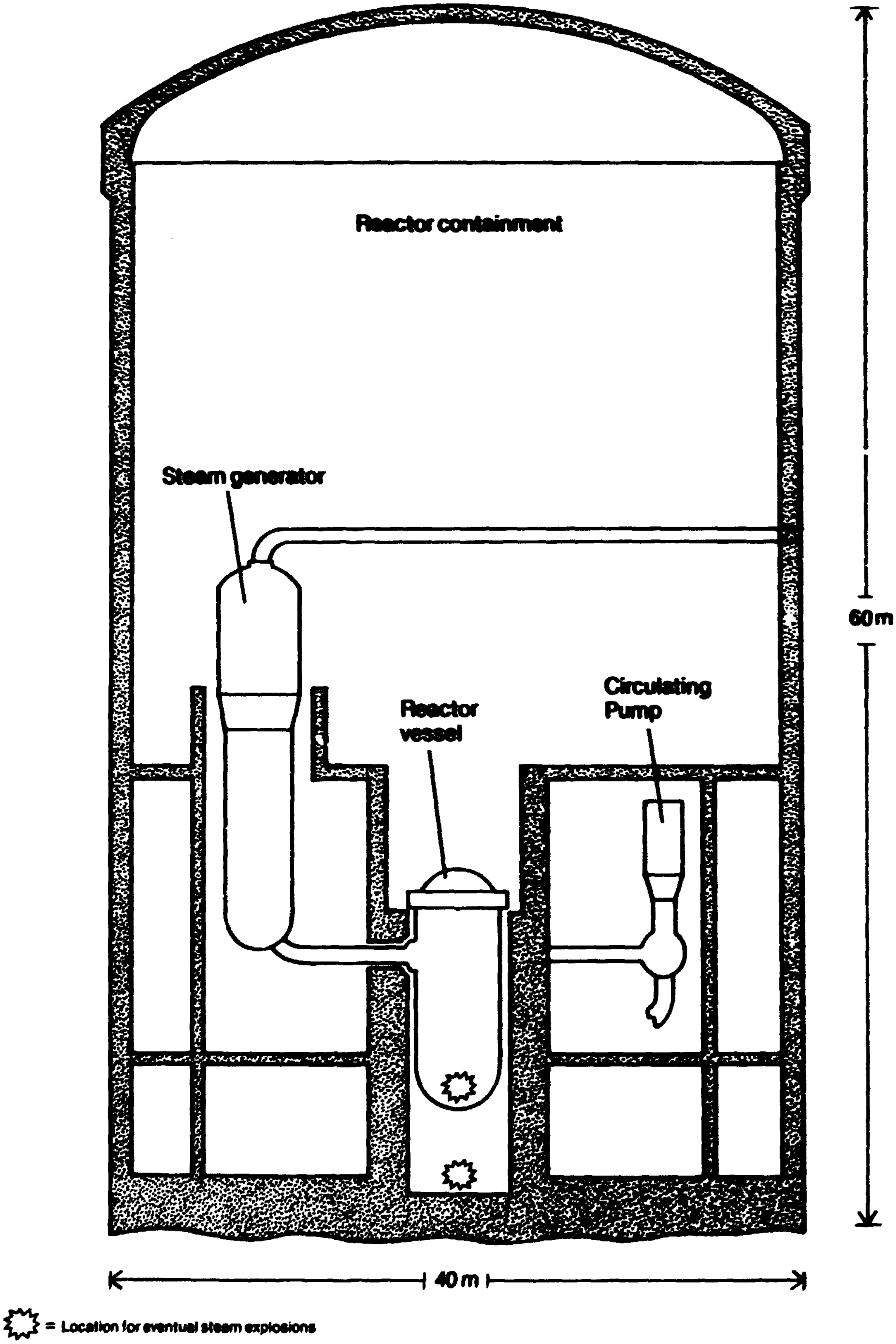


Fig. 25. Reactor containment in Ringhals (PWR)

this door, and flow with a limited mass velocity into the water pool in the wet well below. Large coherent steam explosions are therefore impossible in the water pool because the supply of melt to the water is too slow.

On the upper concrete floor a 8.5 cm thick layer of melt may thus be established. This layer, however, will freeze because of heat losses, primarily by radiation. Of several reasons it is desirable that all core material is collected in the water pool. This can be achieved by lowering the steel door to the level of the floor, or by supplying a few additional drains in the concrete floor.

The bottom of the reactor vessel in a PWR is only supplied with the penetrations for the core instrumentation. The inner diameter of these tubes are in Ringhals less than 10 mm. Without detailed calculations, which unfortunately are not possible to carry out within the time limit of this investigation, one cannot exclude that the melt will freeze in these tubes. A meltthrough of the bottom of the tank may therefore be possible, and this could cause a sudden supply of large quantities of melt to the compartment below the vessel.

The requirement that the melt must fragmentate into small particles and mix homogenously with the water within a few milliseconds must, however, also be satisfied for the case of steam explosions in the reactor containment. Large, coherent steam explosions in the reactor containment are therefore impossible.

The hypothetical shock wave, which could be created by a large postulated steam explosion, do not possess sufficient destructive power in order to rupture the reactor containment. For PWR's Henry (33) has shown that the over pressure on the outer wall of the containment would be approximately

1 bar, and he concluded:

"The end of these considerations is that the shock waves themselves do not pose a threat to the containment integrity, and this is also the same conclusion arrived at in WASH-1400."

By means of Henry's discussions it is readily demonstrated that also for the Swedish boiling water reactors the hypothetical shock wave, which is created by a postulated large steam explosion, can only cause pressures on the containment wall, which are lower than the design pressure.

This conclusion is supported by Deutsche Risikostudie Kernkraftwerke (32), Fauske (16) and the Zion-Indian Point study (50), where one concluded:

"Furthermore, the shock pressures due to ex-vessel steam explosions are not significant for the containment structure."

With regard to the creation of missiles in the reactor containment building, this possibility is excluded by several studies, for instance Henry and Cho (41), Deutsche Risikostudie Kernkraftwerke (32), the Kemeny report (31) and the Zion-Indian Point study (50). These studies, however, concerns only PWR.

Also in the case of the Swedish boiling water reactors, it seems, however, impossible to imagine that the expanding vapor should accelerate a missile or a liquid slug, which should have the potential of rupturing the containment building. This assessment is also in agreement with Fauske (16).

We therefore conclude that even if large steam explosions in the reactor containment were possible, such explosions would not threaten the integrity of the containment.

6.0 CONCLUSIONS

Small steam explosions are possible during light water reactor accidents involving a core meltdown.

Steam explosions in the reactor vessel, which are so powerful that the integrity of the vessel is endangered, are, however, impossible.

Steam explosions in the reactor containment building, which are so powerful that the integrity of the containment is endangered, are impossible.

As a consequence of these conclusions follows that the report "Efficient Emergency", which was published by the National Institute of Radiation Protection, cannot be used as a basis for the planning of the emergency preparations around our nuclear power stations. A new analysis, which deals with accidents which can occur, should be presented. This work should, however, be carried out in a broad cooperation between authorities, utilities, reactor vendors and other institutions, and in the analysis of the consequences of reactor accidents the most recent scientific progress should be considered in all the fields, which are included in the analysis.

My conclusions, which comprise pressurized water reactors as well as boiling water reactors, are based on a survey of experimental and theoretical studies carried out in USA, Germany, England and at the Euratom Laboratories in Italy. The statements by Dr Hans K Fauske and Professor Dr.Ing Franz Mayinger, which were prepared on the request by the committee, have substantially contributed to my conclusions, which are based on the following results:

1. In order to obtain a large coherent steam explosion, which can rupture a reactor vessel, it is necessary

that tens of tons of molten core material with a temperature of more than 2500^{o}C within a few milliseconds fragmentates into small particles less than 1 mm in diameter and mix homogenously with the water. Dr Fauske has shown that for large melts the mixing process requires enormous amounts of energy, and that such quantities of energy are not available in the system when ton scale mixing is considered. Professor Mayinger has presented an independent analysis, which confirms Dr Fauske's results. Both have found that a coherent steam explosion at most can include 200-300 kilo of melt.

Large steam explosions with the potential of rupturing the reactor vessel or the reactor containment are therefore impossible. This includes both PWR and BWR.

2. A survey of steam explosion experiments carried out in the kilogram scale with UO_2 and corium melts shows that the steam explosion efficiencies are very low. The experiments also indicate that the steam explosion efficiency decreases when the size of the melt increases. The experiments therefore show that steam explosions with the potential of rupturing the reactor vessel or the reactor containment can be excluded. This includes both PWR and BWR.

3. Instantaneous supply of tens of tons of melt to the water below the reactor core requires a catastrophic collapse of the bottom plate of the core. Provided water is left in the bottom of the vessel, which is a prerequisite for a steam explosion, I find a catastrophic collapse of the bottom plate to be impossible. This concerns primarily BWR, where the core rests on more than 100 strong stainless steel tubes.

4. In WASH-1400 a steam explosion model for the reactor vessel was suggested, where the water, which is present above the melt during the explosion is accelerated by the expanding steam and as a compact liquid slug impacts the lid of the vessel with such force, that the lid or parts of it like missiles are hurled against the reactor containment, which is ruptured. I have found that this failure mechanism is not realistic, and that it is impossible in this manner to destroy the reactor vessel even if 10 tons of melt should mix with water and explode coherently.

5. In order to obtain a steam explosion in the reactor vessel with environmental consequences it is necessary that all of the conclusions 1-4 are wrong. If only one of the conclusions is correct the accidents PWR-1 and BWR-1 are impossible.

6. Postulating the occurrence of large steam explosions in the reactor containment, it is not possible to conceive of a mechanism which could accelerate missiles to penetrate the containment wall. The hypothetical shock wave occurring after a postulated large steam explosion is not sufficiently strong in order to rupture the reactor containment.

7. In the event of a core meltdown in the Swedish boiling water reactors it is evident that the supply of melt to the water in the containment building will be relatively slow, and large coherent steam explosions in the reactor containment building can therefore be excluded.

8. In order to obtain a steam explosion in the reactor containment with environmental consequences it is necessary that all of the conclusions 1,2 and 6 are wrong. Considering a Swedish boiling water reactor the conclusion 7 must also be wrong.

7.0 EPILOGUE

On December 1, when this report was already written, a message (51) was received on telex from the Swedish Embassy in Tokyo. This message contained a very brief summary of steam explosion studies carried out in Japan. I find the following quotation to be a suitable conclusion of the present investigation:

"The analysis performed so far shows that the thermal energy released in a steam explosion is not enough to destroy the pressure vessel or the containment".

8.0 ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr Hans K Fauske, Professor Dr-Ing Franz Mayinger and Dr Robert E Henry for their co-operation during the course of the present investigation and for the very interesting and stimulating discussions.

I also gratefully acknowledge the valuable suggestions and information received from Dr Kottowski at the Euratom laboratories in Italy, Dr Marshall Berman and Dr Michael Corradini at the Sandia Laboratories in New Mexico, Dr William Stratton at the Los Alamos Scientific Laboratories in New Mexico and their colleagues. Their information comprised the latest results of the research in the field.

I would also like to thank Dr Banaschik at Gesellschaft für Reaktorsicherheit in Cologne, Germany, who sent me the latest German reports.

Without the assistance of these scientists it would not have been possible to carry out the investigation within the narrow time limit, which was at the disposal of the Steam Explosion Committee.

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Appendix 3.

THE EFFECT OF A STEAM EXPLOSION ON A REACTOR PRESSURE VESSEL

by

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THE EFFECT OF A STEAM EXPLOSION ON A REACTOR PRESSURE VESSEL

Loads

Experts are today agreed that steam explosions which have sufficient energy to damage a reactor pressure vessel cannot occur in conventional PWR and BWR plants. Despite this, powerful explosions have been simulated using computer calculations, and their effect on a PWR reactor pressure vessel has been studied.

In calculations made at Los Alamos Scientific Laboratory (LASL) for the USNRC it is assumed that 20% of the reactor core is motlen and mixed homogeneously with the water in the bottom of the reactor pressure vessel, Ref. 1. This is calculated to result in a piston-like slug of water, diameter 1.8 m, which shoots up to the top of the vessel. It impinges first on the centre of the top of the vessel and is deformed as it is slowed down so that it spreads over the entire inner surface of the top of the vessel. The resultant variation in pressure with time has been calculated using the SIMMER model. The load pulse has been calculated, using this model, to correspond to a kinetic energy of 1200 MJ, and is one of the loading cases used in the calculations carried out at LASL concerning the strengh of a pressure vessel.

In calculations performed at Sandia National Laboratories, Ref. 2, the above loading case has also been considered. The strength of the pressure vessel has been calculated for two other cases as well.

In one of those it is assumed that 10% of the core melts and is homogeneously mixed with 10 tons of water. This results in a slug of water which has a kinetic energy of 300 MJ. As opposed to the case of the LASL calculations, it is assumed that it moves as a single entity and impinges on the top of the vessel at the same instant over its entire area. This assumption leads to an unrealistically serious load on the top of the vessel as compared with the energy of the slug. The uneven pressure distribution over the top of the vessel given by the LASL calculations is more realistic.

Another loading situation has also been considered by Sandia: 40% of the core mixed with 2C tons of water. The slug of water moves as a single entity in this case as well. The kinetic energy is 3000 MJ which is considered, in the report, to be completely unrealistic considering the amount which could be generated. This case is aimed only at determining the ultimate capacity of the pressure vessel.

Stresses imposed on the pressure vessel

Calculations of the stresses and deformation of the PWR pressure vessels in Zion and Indian Point have been performed, Z/IP (Westinghouse). The most important dimensions of the pressure vessels are given in Table 1. The calculations were carried out at LASL and Sandia using the computer programs ADINA and HONDO II, respectively. Both are designed to take dynamic events into consideration, the latter for the case of axially symmetrical bodies. The relevant materials data has been used: that for ASTM A533 B for the pressure vessel and SA 540 for the bolts. The critical positions of the pressure vessel which have been specifically analysed regarding the possibility of failure (Fig. 1) are :

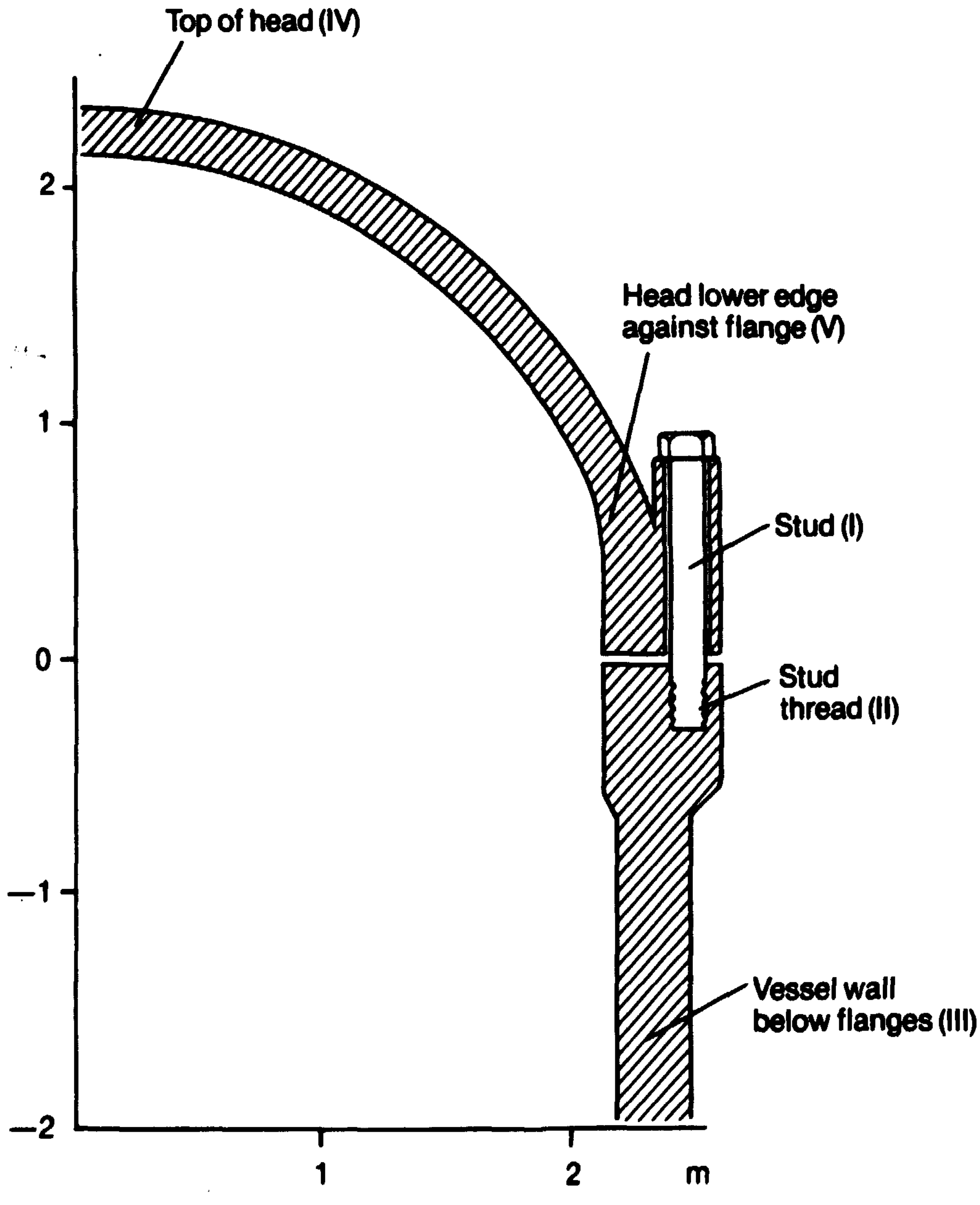

Fig. 1 Points in vessel especially analysed with respect to failure.

Source: Zion/Indian Point App. 2A.

1) Head bolts (I)
2) Bolt threads (II)
3) Vessel wall below the flange (III)
4) Top of the vessel (IV)
5) Edge of the head near the flange (V)

Failure was analysed with respect to

1) the criterion for maximum stress during the loading pulse
2) the criterion for maximum strain
3) the crack propagation criterion assuming a 50 mm deep crack in the top of the head and a 7.6 mm deep crack around the bolts.

The calculations were carried out for the three loading cases described above: The homogeneous water rams with 300 and 3000 MJ kinetic energy and for a sudden pressure pulse, corresponding to an energy of 1200 MJ, at the top of the vessel as in the LASL case. These loads are imposed booth dynamically and as a static pressure corresponding to the maximum pressure during the dynamic event as calculated by the SIMMER program. The latter is for the 1200 MJ case equal to 75 MPa evenly distributed over the head of the vessel or 125 MPa concentrated to the top of the vessel and decreasing towards the flange (45 MPa). The pressure increases from zero to a maximum and decreases aganin to 25 MPa within 0.06 seconds.

Results

The pressure vessel operates under a pressure of 15.5 MPa. It is proof tested prior to commissioning to 23.2 MPa. For the dynamic pressure pulses of 75 and 125 MPa, mentioned above, the maximum effective stresses at the top of the vessel (IV) are

480 and 520 MPa, respectively, These are below the ultimate tensile strength of the material: 570 MPa. The maximum strains in the top of the vessel are 5 and 7% for the two cases respectively, as given by LASL. The stress levels as stated can however be calculated to correspond to an effective strain of 9-13%. Sandia also quotes values of 14% for similar calculations of this case. The uniaxial strain at fracture is 20% for this material. The bolts will not fail under the loads in question.

The lower part of the vessel is judged to fail at at static pressure of 44 MPa. For short load pulses the pressure at which failure will occur is higher; thus for the load pulses in question which last for less than 0.2 ms it will fail at a pressure of 70 MPa.

The case in which there are cracks in the top of the vessel and the bolts is at the limit for failure with an energy in the ram of 300 MJ according to Sandia, and for the pressure time sequence of LASL (corresponding to an energy of 1200 MJ).

For the loading cases studied the top of of the vessel (IV) is the point in the upper part of the vessel which is the most critical. This means that if the vessel were to fail it would be by collapse of the head. The pressure vessel would thus be unloaded and the head would not be thrown away as a missile.

The loading case 1200 MJ of LASL and 300 MJ of Sandia are approximately equally extreme with regard to the resultant deformation of the top of the pressure vessel and the bolts. This can appear surprising considering that the energy differs by a factor four. The explanation is probably that in the 300 MJ case, a homogeneous water ram, is supposed to impinge over the entire top of the vessel at one time.

Application of the results of the LANSL and Sandia calculations to Swedish reactor pressure vessels

The calculations carried out at the LANSL and Sandia Laboratories, Refs. 1 and 2, can basically be applied directly to the Swedish PWR installations Ringhals 2, 3 and 4, which are manufactured by the same vendor as the reactor for which the calculations were made. The dimensions of the pressure vessels are approximately the same and the same sort of material was used.

The other Swedish installations are BWR. They are dimensioned for a lower working pressure: about 7 MPa as compared with 15 MPa for PWR. This means that the pressure vessel in a BWR has smaller dimensions than a PWR and thus less resistance to the effects of an explosion.

A rough estimate of the ram energy necessary to cause the same amount of deformation and damage in a BWR vessel as a PWR vessel can be made for a given set of conditions (according to LANSL, Sandia).

It is first and foremost the dimensions of head and the head bolts which are of interest in this case. These, and other dimensions, are given in Table 1 for the Z/IP vessel, upon which the American calculalations are based, as well as for the Swedish reactor pressure vessels.

The kinetic energy of the slug which impinges on the top of the vessel is absorbed in the upper part of the vessel. The plastic deformation of the head from a 300 MJ slug would be 10% according to the Sandia calculations. This means that slightly more than half of the energy is absorbed by the head.

According to LASL the strains in the head are about the same in the 1200 MJ case. This means that almost 15% of the energy is absorbed by the head. This illustrates the more diffuse nature of the slug of water in the LASL calculations as compared to Sandia.

The strain in the bolts would be less than 2%. The bolts also have a small volume in comparison to the head, which means that less than 4% of the energy in the 300 MJ case is absorbed by them.

A large amount of the kinetic energy of the water slug is absorbed by the top of the vessel partly as a "membrane" strain and partly as local plastic deformation around the edge at the flange. A negligible amount is absorbed by the bolts. The bolts in the Swedish PWR vessels are as strong, or at least almost as strong, as in the Z/IP vessels whereas the heads are considerably thinner. This means that the head in Swedish pressure vessels will absorb most of the energy from the water slug as in the US stations. For the top of the vessel to be deformed to the same extent as the Z/IP head in the calculations of Refs. 1 and 2 less energy will be required from the slug. Its magnitude can be estimated by scaling. Different scaling rules are valid in the latter case for the membrane strain over the entire head and for the flow strain at the edge. The results of such a scaling are given in Table 2 in which, amongst other things, the equiavalent slug energies with respect to the strain are quoted for various pressure vessels. The scaling has been performed for slug energies used in the LANSL-Sandia calculations. In Table 2, for example, it is shown that for the strain at the top of the head a 1200 MJ slug of water in the Z/IP vessels is equivalent to a slug energy of 500-800 MJ for a Swedish BWR.

For the case with cracks the stress in the head or bolts and the relationship between the crack depth and thickness are decisive for the risk of failure. In the 1200 MJ case in Ref. 2, the stress in the bolts is a function of time. The stress at the top of the head resulting from the loading pulse can also be estimated from the available data. This information has been used to assess, from the crack propagation aspect, equivalent slug energies in Swedish reactor pressure vessels, Table 2. The calculations are based upon the assumption of a 5 cm deep crack at the top of the head and a 7.6 mm deep crack around the bolts.

According to Table 2 a water slug with an energy of 500-800 MJ is as dangerous for a Swedish BWR with a crack at the top of the head, as the LASL case of 1200 MJ in the Z/IP vessels.

The lower portion of the Swedish BWR pressure vessel can be expected to fail under a static pressure of 20 MPa and at a short load pulse of 35 MPa. These values are proportional to the values of 44 and 70 MPa in the PWR vessel of Refs. 1 and 2.

In order to reach a pressure of 35 MPa it is necessary according to an extrapolation of the data in Ref. 1, to have an explosion energy of the same order of magnitude as those for the undamaged head, Table 2.

Conclusions

According to the calculations of Los Alamos National Laboratories and Sandia National Laboratories a PWR pressure vessel can withstand a steam explosion resulting in a water slug with a kinetic energy of the order of magnitude of 1200 MJ. This assumes that the pressure vessel does not contain any sizeable cracks. The water slug can admittedly result in leakage from the vessel into the containment, but will not constiute large missiles.

Assuming a homogeneous water slug which moves as one entity and impinges upon the entire underside of the head at one instant in time, the head would fail at the top for a slug energy of 300 MJ. It is deemed impossible however for this type of water slug to be formed.

Calculations from Sandia, Ref. 2, show that in the 1200 MJ case 7-8 mm deep cracks are acceptable around all the head bolts without them failing. For the same loading case the ultimate tensile load is exceeded slightly if there is a 5 cm deep and relatively long crack in the top of the head.

If these calculations are considered in terms of Swedish BWR pressure vessels (and PWR pressure vessels) equivalent values are obtained for the slug energies with regard to strain and fracture citeria. These values are given in Table 2. It can further be seen that in Swedish BWR pressure vessels the head will not open in its most sensitive point for dynamical loads below a slug energy of 500 MJ.

In these calculations the shock absorbing effects of the internal components in the pressure vessel have not been taken into account. These effects should be relatively large. The head will also absorb considerable amounts of energy before failing - according to Refs. 1 and 2 an estimated energy of 100-200 MJ. It should also be possible to accept the presence of cracks in the head and around the bolts, without there being a risk for failure at energy values for the slug of less than about 300 MJ.

Table 1. Data for reactor pressure vessels.

Reactor	Pressure vessel, diameter/thickness (m)	Head		Head bolts, diameter/number (m/no.)
		Radius/thickness of top (m)	Thickness near flange (m)	
Z/IP	4.40/0.25	2.12/0.19	0.16	0.15/58
R2	3.99/0.20	1.9 /0.15		0.15/58
R3,R4	4.40/0.24	2.0 /0.16	0.16	0.15/58
01	5.0 /0.13	2.5 /0.13	0.11	0.13/54
R1	6.0 /0.14	3.0 /0.09	0.10	0.18/76
02,B1,B2	5.2 /0.13	2.6 /0.8 0.93	0.13	0.13/54
F1,F2	6.4 /0.16	3.2 /0.11	0.16	0.15/65
03,F3	6.4 /0.15	3.5 /0.13	0.13	0.15/66

Table 2. Estimation of the explosion's energy to result in the same effect on Swedish reactor pressure vessels as a steam explosion with an energy of 1200 MJ would have on the Z/IP vessel according to calculations.

		Z/IP PWR	Swedish PWR	Swedish BWR	Failure/no failure according to LASL - Sandia
Equivalent slug energy with respect to strain					
top of head (V)	MJ	1200	900-1000	500- 800	LASL: No failure San.: No failure
side of head (V)	MJ	1200	1100-1200	500-1200	LASL: No failure San.: ------
head bolts (I)	MJ	1200	1100-1200	1000-1800	LASL: ------ San.: No failure
Equivalent slug energy with respect to crack propagation					
top of head (IV), 5 cm deep crack	MJ	1200	900-1000	500- 800	San:: Failure*
bolts (I), 7.6 mm deep crack around bolt	MJ	1200	1100-1200	> 1000	San.: Failure*

*Marginal

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2. "Report of the Zion/Indian Point Study: Volume I". SAND 80-0617/1, NUREG/CR-1410, Sandia National Laboratories, April 1980. Appendix 2A by Daniel Swenson.

Appendix 4

AN ASSESSMENT OF STEAM EXPLOSIONS IN THE SAFETY ANALYSIS OF LIGHT WATER REACTORS

By

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Prepared for the Swedish governmental committee on steam explosion in Light Water Reactors, October 1980.

Hans K. Fauske

Hans K. Fauske, President of Fauske and Associates, Inc., earned the D. Sc. degree from the Norwegian Institute of Technology in 1963. He has been a visiting professor in chemical and nuclear engineering at Northwestern University and was most recently Director of the Fast Reactor Safety Technology Management Center at the Argonne National Laboratory. Prior to forming his own company in 1980, he was affiliated with Argonne National Laboratory for 18 years where he held various research and management positions. In 1975 he received one of the first University of Chicago awards for Distinguished Performance at Argonne National Laboratory.

Dr. Fauske was elected Fellow of the American Nuclear Society in 1979, and is serving on the Editorial Board, International Journal of Multiphase Flow. He has also served as a consultant to the U.S. Advisory Committee on Reactor Safeguards and has actively participated in numerous hearings with the U.S. Nuclear Regulatory Commission relative to licensing of nuclear reactors. Most recently he served as a consultant to the President's Commission on the accident at Three Mile Island.

In connection with his scientific work Dr. Fauske has been invited as technical chairman and panel member at numerous national and international meetings. He has also been invited as a seminar speaker to over twenty of the major universities in the United States, and has been a visiting lecturer at the Massachusetts Institute of Technology (1964, 1967, 1971, 1973, 1977), the University of Illinois (1969), Carnegie-Mellon Institute of Technology (1970), the University of Tennessee Space Institute (1970, 1971, 1972), Northwestern University

(1972, 1973, 1974, 1975, 1976, 1977, 1978), the Karlsruhe Research Center, West Germany (1975), PNC, Tokyo, Japan (1976), and Korean Atomic Energy Research Institute, Seoul, Korea (1976). In 1967 he was a member of the U.S. fast reactor safety team visiting European installations and was chosen to participate in the joint U.S. - U.S.S.R. Seminars on Fast Reactor Safety in 1976 and 1979, and the joint U.S. - Japan Seminar on Fast Reactor Safety in 1978. He has also served as an active member of the International Working Group on the Science of Vapor Explosions and as the U.S. ERDA Representative to the European Liquid Metal Boiling and Fuel-Coolant Interaction Working Groups (1973, 1975, 1976, 1978).

Dr. Fauske has published more than 200 scientific articles in the areas of reactor safety, multi-phase flow, heat transfer and explosion-related phenomena, and is currently authoring two books on reactor safety and boiling and two-phase flow.

TABLE OF CONTENTS

I. INTRODUCTION

Steam explosions were considered in the Reactor Safety Study (RSS), WASH-1400 [1], as a possible containment failure mechanism for hypothetical core melt accidents. More specifically, given the mathematical modeling, a steam explosion within the reactor vessel was calculated to cause a failure of the vessel and propelled the conceptual missile against the containment wall with sufficient energy to fail this boundary as well. Since essentially the same sequences were considered for both boiling water reactors (BWRs) and pressurized water reactors (PWRs), the event as envisioned in WASH-1400 will be reviewed along with the experience with small test reactors. With this background, the specific reactor structural configurations for both types of reactors will be compared to that considered in the RSS. This is then followed by a review of the pertinent literature on steam explosions and a comparison to the assumed and calculated behavior described in WASH-1400. Finally, the possibility and magnitude of steam explosions within the containment building, assuming a hypothetical release of core material from the primary system, is evaluated.

II. STEAM EXPLOSIONS AS MODELED IN THE REACTOR SAFETY STUDY (WASH-1400)

As an initial condition for the event, a degraded core state was assumed in which the core was uniformly molten and totally separated from the water contained in the lower plenum by the grid plate. It was considered unlikely that a partially molten core would drain into the lower plenum. Consequently, the core was assumed to collect on the grid plate and this was assumed to fail in a catastrophic manner releasing all the molten debris into the water. This failure causes the debris to be instantaneously fragmented to some specified fragment size as well as instantaneously and uniformly dispersed throughout the coolant. These conditions are assumed and not the result of mechanistic calculations describing the grid plate failure, the fragmentation process, and the mixing of the water and core material; all of which are certainly rate dependent phenomena but not represented in the WASH-1400 analyses.

Once this intimate dispersal is assumed, the thermal energy transfer is calculated by considering convection, conduction, and radiation between the core debris and water. Energy transfer results in a rapid ($\sim$10 msec) pressure rise in interaction zone and this accelerates an assumed continuous, overlying liquid slug, made up of half water and half core debris, vertically upward through an open vessel in a piston-like manner as shown in Fig. 1. The various processes modeled are summarized in Table I and illustrated in Fig. 2. Calculations are carried out for various levels of fragmentation and melt-drop times (melt addition interval). Acceleration and displacement of the postulated slug (inertial layer) continues until it impacts upon the vessel head and for some cases this is calculated to occur with sufficient energy to cause the head to fail and propel it against the containment wall with the energy necessary to fail the containment. One such set of calculated results for an instantaneous melt addition and a particle size of 400 μm is shown in Fig. 3. This illustration shows that the pressures required to fail the vessel approach 75 MPa which is more than 3 times the thermodynamic critical pressure of water and 5 times greater than the normal operating pressures for a PWR. Specific details of these calculations and their relation to the available experimental results will be discussed in the section on pertinent literature.

Many different cases were calculated with varying particle sizes and melt-drop times, and the results showed that for either particle sizes greater than approximately 1 cm or a melt-drop time exceeding two seconds, the reactor vessel was not ruptured. These "cutoff" parameters were essentially identical for both the BWR and the PWR geometries considered. Such calculational results from a highly conservative model are particularly important in light of subsequent work on mixing energies and debris release times which will be discussed later.

The analytical description used in WASH-1400 is certainly a very simplistic representation of both the specific configurations in question and the explosive phenomenon itself. Without doubt, these calculations misrepresent the explosive behavior in that 1) they assume that all liquid-liquid systems with a substantial temperature difference can explode, 2) no consideration is given to the rate at which the materials are brought into contact, 3) mixing is assumed to be instantaneous, uniform, and require only negligible energy, and 4) they grossly overestimate the rate of mechanical energy released by a steam explosion. Clearly, such oversimplistic analytical representations are of use in safety evaluations only if they show that even with these overwhelming conservatisms, there is still no concern for public health and safety. On the other hand, if the conclusion of such calculations is that the phenomenon does provide a considerable risk, then the basic assumptions used in the calculational model must be scrutinized to discern if such a conclusion, derived from an overly simplistic model, is indeed valid. This will first be addressed in terms of the experiences with small test reactors and then with regards to the in-vessel structural components, both above and below the core, which were discussed in the RSS but essentially ignored.

III. RELATIONSHIP TO PREVIOUS REACTOR EXPERIENCE

The explosion model used in WASH-1400 resulted principally from concerns generated by the low pressure BORAX and SPERT destructive experiments and the SL-1 accident. Reactor conditions leading to this accident and the destructive transients in BORAX and SPERT produced a fundamentally different system than that representative of a postulated severe accident in a LWR. It is not only important to realize these differences, but it is essential to understand the resulting implications on the phenomenon as well.

A. All three events were produced by power excursions in which the core was driven to molten conditions in 30 msec or less. Such reactivity transients are not possible in power reactors and were neither addressed in WASH-1400 nor are they considered here.

B. For these three reactors which were fueled with uranium-aluminum alloy fuel plates clad with aluminum, the fuel and water were uniformly premixed and finely divided in a cold condition prior to the excursion.

C. The reactor was essentially at atmospheric pressure and water was at room temperature, hence, net vaporization was not required in the fragmentation stage.

D. With the specific core design, the SL-1 reactor could be brought to criticality by the withdrawal of one control rod. In the accident this rod was rapidly withdrawn which caused a nuclear excursion with sufficient energy deposition to melt the high thermal response fuel-clad plates while in an extensively premixed state. This was also true for the BORAX and SPERT test reactors.

E. Since the reactors were essentially at room temperature prior to the excursion, the vessels were filled with water except for a small freeboard volume at the top, i.e. a coherent overlying liquid slug was already in place.

F. The internal geometry of the vessels were very simple and open, which provides little attenuation or dispersion of any slug movement.

With these pre-transient conditions, the configuration established was essentially that assumed in the RSS. The essential feature of the strong reactivity transient is that it brought the fuel and clad to melting before this configuration could substantially change. Given these particular characteristics, a slug impact following a steam explosion within the core would indeed be the expected chain of events. *However, this is fundamentally different than an initially separated system of high temperature molten core material and saturated water existing at an elevated pressure with substantial internal structure to prevent catastrophic collapse, intimate mixing, and slug formation.*

IV. TYPICAL PWR CONFIGURATIONS

While there are small variations in the detailed designs of the light water cooled, pressurized water reactors (PWRs) manufactured by the different vendors, the general configurations are similar in many respects. In particular, the Swedish PWRs are Westinghouse reactors of the three loop design. In these designs the reactor core is supported from above at the internal support ledge. As illustrated in Fig. 4, the reactor fuel assemblies rest on the core support plate with the 53 control rod drives penetrating through the vessel from above. In-core instrument tubes enter the reactor vessel from the bottom and extend upward through the reactor core. These operational components require extensive structure within the vessel.

As discussed in Section II, the RSS analyses assumed no structure in the lower plenum. In actuality, the plenum contains not only the in-core instrument tubes, but also the flow distribution plate and the core support structure. These components present a dense array in the plenum where the water is assumed to accumulate. In addition, a lower plate and shock absorber structure is included as part of the design to guard against any potential of a core "drop" due to degradation of internals. With water in this region, these components would have a strength essentially equal to that under normal operating conditions. Consequently, any collapse of core material into the lower plenum where intimate mixing is postulated to occur would also require the simultaneous failure of these structural components, but these can only be weakened in the absence of water. In addition, the lower support plate, which is approximately 20 cm thick, would require many minutes in direct contact with core debris before it could be substantially weakened. As illustrated in Fig. 4, this plate has many large holes and would not significantly hold up the penetration of the molten debris into the lower plenum. *Therefore, the total collapse of* *the core debris into the lower plenum could not occur in a catastrophic manner with water present.*

It is worthy of note that while the lower core support structure will not hold up material to create a "coherent" core drop, it can play a significant role in determining where and at what rate the material is delivered to the bottom of the vessel. This plate has many holes with a total coolant flow area of about 4 m^2 and if a gravity pour of the entire core were assumed to occur through this porous plate, the time required would be approximately one second, i.e. a melt-drop time comparable to that calculated in WASH-1400 has no vessel rupture. In addition, it should also be noted that an "equal volume mixture" of core material and water would engulf this plate. Therefore, the postulated rapid intimate mixing must occur in the presence of these sizable and cold below core structures. Also, as will be discussed later, experiments have shown that if a steam explosion can occur, one type of triggering event observed is contact between the high temperature melt and a solid wall. Contact between the core debris and the lower core support plate could provide such a contact, which would dictate a very early interaction thereby driving the materials apart. The discussions in WASH-1400 did not consider the below core components.

The above core structure is comprised of the upper core plate, the control rod guide tubes, the control rods, and the upper internal support are shown in Fig. 5. These components were ignored in the RSS in assuming that a coherent slug could be formed and driven upward through the vessel in a piston-like manner. As illustrated in Fig. 5, such upper internals would provide considerable dispersive capability assuming a coherent slug could be formed and transmitted, which as will be discussed later, it cannot. *Consequently, coherent slug impact cannot be generated.*

V. TYPICAL BWR CONFIGURATIONS

Boiling water reactors are substantially different in their designs than PWRs. The obvious differences are that the core inventory is larger for the same thermal power, the vessel is larger and there are additional components within the vessel including the steam separators and the steam dryers. Another major difference is the manner in which the core is supported, i.e. for BWRs the foundation is made up of many tubes (1 per assembly) which extends upward from the bottom of the vessel with the control rod spindles between the tubes.

Given this core support configuration, which is illustrated in Fig. 6, it is virtually impossible to conceive of a sequence whereby a degraded core would catastrophically collapse into water. In addition, it is equally difficult to envision any process whereby rapid and intimate mixing could occur. The specific details of this reasoning process are given below.

A. Under normal operating conditions, the structure is designed to support the entire core. The major change in the material properties occurs when substantial overheating takes place, but this can only occur in the absence of water. If water is absent then the question of a steam explosion becomes a moot point.

B. In addition, each assembly is, in effect, individually supported and if a degraded core condition is assumed, the most likely way in which molten core material would eventually travel to the lower plenum is through the assembly orifice located within the support tube. This would undoubtedly be a very incoherent process and the molten core material would freeze within the tube, thus thermal attack of the tube itself would not begin until the water had been boiled away outside of the tube. Consequently, not only would the melt progression be incoherent, but the core material could not participate in a global interaction until the water was vaporized, i.e. the potential for a steam explosion again becomes a moot point.

C. If all the above physical restraints are completely disregarded and one assumes that coherent core collapse occurs in any event, then one must consider the forest of support tubes, control rod thimbles, and instrument tubes which exist below the core. This massive, cold structure, which could freeze the core debris on contact, would prevent any large scale, intimate mixing of the molten debris and coolant.

These three points, all dealing with the below core structure, show that catastrophic collapse in the presence of water cannot occur, the downward progression of any postulated scenario would be incoherent and occur within the support tubes (and only in the absence of water), and large scale, intimate mixing could not be achieved. Therefore, large scale steam explosions involving substantial masses of core material can be ruled out on geometric considerations alone. In addition, these can be considered in light of the massive, coherent interaction required in WASH-1400 before vessel failure was calculated. Like the PWR, the below core structure was ignored for the WASH-1400 BWR analyses.

One can be equally critical of the slug formation, displacement, and impact model from WASH-1400 as it relates to the actual design.

A. With the below core structure segmenting the water with the core support tubes, the formation of a continuous, overlying liquid slug can also be discarded.

B. If such a slug is postulated the core grid at the top of the fuel assemblies and the moderator tank cover would destroy the coherence as the material travels upward through the vessel.

C. Steam separators, located above the core as shown in Fig. 6, are large structural components which do not provide straight-through flow paths. Hence, this would also prevent the upward transmission of a coherent liquid slug.

D. Steam dryers are positioned above the steam separators. These components, like the steam separators, also have a tortuous flow path, and thus, provide another barrier to the postulated coherent behavior.

These arguments have been formulated on the basis of specific components available in the reactor vessel but ignored in the Reactor Safety Study. As discussed, these differences are indeed extensive and the discussion of each shows that their neglect in WASH-1400 grossly overestimated 1) the likelihood of an event, 2) the amounts of material involved, and 3) the damage potential represented by an event. Considerations of the structural components allows one to individually rule out a) catastrophic collapse, b) rapid and intimate mixing, c) coherent slug formation, d) coherent slug transmission, and e) coherent slug impact. As summarized in Table I, all of these are required for the WASH-1400 analysis. However, there is even a more fundamental misrepresentation in the RSS and that is the characterization of steam explosion themselves. This is addressed in the next section.

VI. STEAM EXPLOSION PHENOMENA

The assessment of the relevant phenomenology for in-vessel steam explosions must be considered in light of the specific sequences of interest. These generally can be divided into three different areas characteristic of accident evaluations for both BWRs and PWRs: 1) a large break LOCA, 2) a small break LOCA, and 3) a transient condition in which the core degradation occurs at a pressure close to the nominal operating pressure. More specifically the sequences can be characterized in terms of the system pressure at potential core melting by: a) a low system pressure such as 0.4 - 1.0 MPa, b) an intermediate pressure in the range of 1.0 to 5.0 MPa, and c) high pressures ranging up to 7.0 MPa for BWRs and 17.0 MPa for PWRs. In the evaluation of in-vessel steam explosions, the phenomena was considered in terms of these sequences and their characteristic pressure regimes.

1. High Pressure Systems

Two models have been published [2,3] which predict that explosive interactions can be suppressed by increasing system pressure. Both of these models predict essentially the same pressure level for termination of explosive events and the reason for this behavior is the strong decrease of "energetic boiling" with increasing pressure. Because this predicted characteristic clearly sets these models apart from other models proposed in the literature, such as that utilized in WASH-1400, specific experiments were performed to test this behavior. Table II summarizes the vapor explosion (vapor explosion is the general category of which a steam explosion is one specific type) data where various pressure levels were tested [2,4-8]. As illustrated this data includes both large and small scale systems, simulant and real reactor materials, and both "free contacting" mode and "externally triggered" events. A comparison of these latter two methods for initiating an explosive event show a slight sensitivity to the "trigger" magnitude, i.e. the cutoff pressure is slightly higher for a system with a strong external trigger. A comparison between Figs. 7 and 8 illustrate such an effect for the interaction between Freon-22 and mineral oil. For an ambient pressure of 0.1 MPa energetic explosions can be generated with either an external trigger (Fig. 7) or in the free contacting mode (Fig. 8), and the shock waves generated by these events may be in excess of 2.0 MPa. When the ambient pressure is increased to 0.23 MPa, the free contacting mode experiments demonstrate no explosive interactions while the externally triggered tests experience explosive interactions with peak shock wave pressures again approaching 2.0 MPa. With a small additional increase in the ambient pressure to 0.3 MPa, the externally triggered systems record only very weak explosions and a further pressure increase to 0.5 MPa is sufficient to suppress explosive interactions, even in the presence of a 25J exploding wire.

Both of these models were used to provide pre-test predictions for the large scale molten sodium chloride-water tests carried out at the Euratom Ispra Laboratory. These pre-test predictions are documented in the test plan for these experiments [9], and the results are summarized in Table III. As illustrated the Buchanan model has a prediction for both homogeneous and preferred site nucleation characteristics, whereas the Henry-Fauske model which is based upon spontaneous nucleation, (homogeneous nucleation is assumed in this case) predicts a single value for a given fluid. Pressure level predictions for the homogeneous nucleation mechanism in the Buchanan model are in good agreement with those of the Henry-Fauske model, although somewhat higher, and both are in agreement with the experimental data. Those predictions based upon preferred site nucleation in Ref. [3] are considerably greater than the experimental observations. It should also be noted that both of these models represent a "free contacting" mode configuration, but since the sensitivity to an external trigger has been experimentally demonstrated to be small, they also provide a good representation of these events as well.

Since there is some variation in the predicted cutoff levels and since data is available for a large scale water system as well as small scale experiments with reactor materials, a designation of the actual cutoff level for water is best guided by the experimental results. The Ispra tests [6] were free contacting mode experiments and these provided vigorous explosions at 1 atm. For a pressure of 0.5 MPa, the results could perhaps contain some very weak explosive interactions, but at the pressure level of 1.0 MPa all explosive activity was suppressed. These are in agreement with the small scale, externally triggered tests carried out at Sandia with reactor materials [7], in which explosive interactions could be triggered for pressures as high as 0.5 MPa, but not at a level of 0.75 MPa. In the Winfrith UO_2-water experiments [8], which can be considered to be lightly triggered, the explosive interactions were suppressed by a system pressure of 0.9 MPa. Therefore, a cutoff value of 1.0 MPa bounds the available experimental steam explosion results for water, and this is a valid basis upon which to evaluate the potential for such phenomena in LWR reactor systems.

When the pressures predicted by both models and the experimental data are compared to the conditions typical of the various accident categories, only the large break sequences result in such reduced pressure levels.

Consequently, for these sequences in which the lowest primary system pressure is greater than this cutoff level, the probability of a steam explosion itself is insignificant and it follows that the probability of containment failure is also negligible.

2. Low System Pressures (Large Break Sequence)

For low pressures within the reactor coolant system (less than 1.0 MPa) the probability of a steam explosion, given direct contact between molten core material and water, must be assumed to be essentially unity. This is based on the experimental evidence at these pressures as well as the numerous events which have occurred in the foundary and paper industries. As discussed in WASH-1400 steam explosions have done extensive damage to light industrial structures and are a hazard to operating personnel. However, the information compiled with regards to these foundary explosions shows that the injuries to personnel result from hot molten metal dispersed by the explosive event, as opposed to the shock waves generated by the explosion. This suggests that steam explosions are a mild event compared to those associated with chemical detonations, i.e. the concussion from the shock wave itself can be lethal. This is in agreement with the measured wave propagation velocities which can be several thousand meters per second for chemical detonations, but is of the order of 100 m/sec for steam explosions.

Since the major concern of this evaluation is the damage potential represented by in-vessel steam explosions, one must evaluate the amounts of material which can come into contact and mix on an intimate scale prior to the onset of an explosive interaction. The calculations performed in WASH-1400 assumed that all the material within the core was instantaneously and intimately mixed with all the water in the lower plenum. Obviously this is not the case, and as will be discussed below, only very small fractions of this material can be mixed to provide an explosive interaction. Also the liquid-liquid film boiling mixing process itself makes the formation of a coherent slug essentially impossible. These effects will be discussed individually beginning with the ability to trigger such an interaction within a reactor pressure vessel.

Both large and small scale experiments with molten metals and reactor materials have demonstrated that explosive interactions with water require an external trigger. In many experiments, this trigger has been produced by the contact of the melt and the bottom of the vessel. Such a "trigger" provides a mechanism whereby the amount of material and the level of mixing can both be identified for a given system.

The mechanical energy available for mixing prior to the explosive interaction is that energy available in the gravity drop, or pour, of the material from the lower portion of the core to the bottom of the reactor vessel. It should be noted that this energy is directed such that the result is to continue and sustain the mixing process. This will be contrasted with thermal energy effects later. Since the time interval between predicted first melting at the central region of the reactor and that required for melting in the outer zones of the core is tens of minutes, large quantities interacted on a very short time scale could only occur if some mechanism exists whereby substantial quantities of the core could be accumulated within the core prior to release of this material into the lower plenum, i.e. the grid plate accumulation and failure assumed in the RSS. Given the below core structure for a PWR discussed in Section IV, this could only occur within the core itself, i.e. a blockage of core debris allows material to accumulate within the original core configuration. However, it is difficult to conceive of a blockage within the core which would be sustained for tens of minutes until the outer regions achieved a molten condition, and even if this were the case, the additional below core structure shown in Fig. 4 would limit the rate at which the material would be discharged to the lower plenum. This lower plate, which is approximately 20 cm thick, has numerous large holes, but these holes would certainly limit the time for mass accumulation to several seconds. If this is anticipated to fail catastrophically, it would result in a drop of approximately 2 m. If the entire core is assumed to fall this distance, the potential energy change is about 2 MJ.

Anticipated events for these low pressure conditions are discussed with respect to 1) the trigger, 2) intimate mixing, 3) pool boil up (slug formation, and 4) rapid liquid-liquid intimate mixing.

Trigger

The time for pouring the material into the lower plenum becomes significant when considering how much material can be available before the explosion is initiated. Large scale aluminum-water experiments conducted by Long [10], and Hess and Brondyke [11] have shown that large scale explosions are initiated when the melt contacts the bottom of the vessel. For a gravity pour, assuming all available flow area in the lower core support structure, this would correspond to a time interval between initiation of the pour and the onset of the explosion of about 0.6 seconds, as compared to the one second or longer time to discharge the core material into the plenum. Consequently, the amount of material involved in the interaction would be substantially less than the total core.

Mixing

The next issue to be addressed is the rate at which material can be intimately mixed before an explosion is initiated. The mixing energy required for an intimate dispersion has been evaluated by Cho, Fauske and Grolmes [12], and the details of such an evaluation are included here as Appendix A. These calculations reflect two different types of mixing processes, one in which the intimate dispersion is accomplished in a one-step process, and another in which it is postulated to occur with the minimum mixing energy, which has been entitled progressive mixing. If the above discussions on the pouring rate are ignored, and it is postulated that the total core is instantaneously dropped into the lower plenum, the mixing energy would be that available from a gravity drop. If the end state of the mixing process is assumed to be particle sizes of approximately 1 cm in diameter, as required for vessel failure in the WASH-1400 calculations, this mixing energy would require a time of 1.9 s for progressive mixing and 10.4 s for the one-step process for mixing the entire core. These mixing intervals are long compared to the melt-drop times used in WASH-1400 for conditions in which the vessel was predicted to fail. As will be seen, these times are also much longer than the characteristic times for vapor generation due to film boiling alone and the resultant "boilup" of any overlying liquid pool. Therefore, there is insufficient energy associated with a gravity drop of the entire core to affect a rapid and intimate mixing on a size scale modeled in the RSS, which ignored the necessity of such requirements.

Pool Boilup (Slug Formation)

As the mixing and inner dispersion progresses, the hot and cold liquids, are in liquid-liquid film boiling. Since the hot liquid is at a temperature of approximately 2500°C, the principle mode of energy transfer would be via radiation from the hot particles to the water. This energy transfer can be expressed as

$$q = 4\pi r^2 \sigma (T_F^4 - T_f^4) \qquad (1)$$

and the resulting energy transfer is calculated by the product of this radiation heat transfer and the number of particles involved. The particle number is calculated from a consideration of the total mass involved in the interaction

$$N = m_T/[\rho_F \; 4/3\pi \; r^3] \qquad (2)$$

For these low pressure sequences, the thermal energy in the below core structure as well as the radiant energy from the degraded core will ensure that the water in the lower plenum is essentially saturated. Consequently, any boiling (or vaporization) during the mixing phase will result in net vapor formation. This vapor will either cause any overlying pool to "boilup" until the average void fraction is sufficiently large to allow the vapor to be transmitted through the pool at a rate equal to its generation. The vapor production rate is given by

$$\dot{m}_v = Nq/h_{fg} \tag{3}$$

Since the mass flow rate is a product of the vapor density, the area of the vessel, and the superficial vapor velocity (this reflects the stability of the overlying pool), this latter term can then be evaluated from the expression

$$U = \frac{3m_T\sigma(T_F^4 - T_f^4)}{\rho_f A_v \rho_F r_F h_{fg}} \tag{4}$$

If this superficial vapor velocity is tabulated for various particle sizes and system pressures, the results are shown in Tables IV and V for pressures of 0.1 and 1.0 MPa respectively. These tables show the particle size, the number of particles, and superficial vapor velocity. In order to prevent pressurization of the pool, this amount of vapor must "slip" through any overlying slug. In order to allow this "slippage" the overlying pool must "boilup" to a given void fraction. The relationship between the superficial velocity and the void fraction can be represented by

$$U = 1.53 \sqrt[4]{\frac{g\sigma}{\rho_f}} \left[\frac{\alpha}{1 - \alpha}\right] \tag{5}$$

The resultant pool void fractions are listed in Tables IV and V and it is obvious that a continuous overlying liquid slug could not exist in the presence of this vapor flow. In fact, for the superficial velocities characteristic of the amount of material and particle sizes discussed in WASH-1400, the core debris itself would be levitated and blown out of the pool. This is in agreement with Long's [10] experiments in which explosions were not observed for water temperatures exceeding 60°C, i.e. the net vapor formation could have been sufficient to disperse either the water or the aluminum or both. In addition, Long also observed that breaking up the molten aluminum stream before it entered the water prevented explosions; probably the result of a large film boiling heat transfer due to the increased surface area.

If vapor "slippage" is assumed not to occur, then the pool must pressurize. An underestimate of the pressurization rate can be calculated by assuming all the energy transferred is uniformly dispersed in the liquid and the pressure is the corresponding saturation value. The temperature rise rate of the liquid resulting from the film boiling energy transfer and the corresponding rise in the saturation pressure of the water are also shown as a function of the particle size. These calculations were carried out for an equal volume mixture of core debris and water and the salient conclusion of these calculations is that fine particle sizes would provide significant pressures so as to quickly separate the system if the vapor is not allowed to escape. If the vapor is not dispersed, then the pool would begin to pressurize from within which would disperse the pool, terminate the energy transfer, and destroy any coherent slug. As mentioned, a lower bound on the pressurization rate is given by assuming all the energy transferred uniformly increases the sensible heat of the water. An upper bound on such a rate can be calculated by assuming the energy transferred equals the vaporization rate and the vapor volume remains constant, which is a rate given by

$$\frac{dP}{dt} = \frac{3Pm_T\sigma(T_F^4 - T_f^4)}{r\rho_F m_g h_{fg}} \tag{5}$$

These rates were calculated for a 10% void fraction and are also given in Tables IV and V. The differences between the minimum and maximum pressurization rates are large and these are only meant as general bounds for the assumed behavior. The conclusion from both rates is that pressurization of the mixture due to film boiling alone would disperse the constituents and stop the mixing if the vapor were not allowed to "slip" through the pool.

Therefore, in a slowly developing dispersion (time scale of 1 sec or longer) the vapor throughput would be substantial and preclude the formation of a continuous overlying liquid slug. If the vapor is assumed to be retained in the pool, the pressurization would disperse the pool, hence no slug formation. Without the continuous slug formation, the only pressure imposed on the vessel is that due to the explosion itself, which experiments have shown to be a few MPa typically [13], and could conceivably be as high as 10 MPa. However, such pressure levels do not even threaten the integrity of the vessel, (see Fig. 3), let alone the containment structure.

Rapid Liquid-Liquid Intimate Mixing

The only mechanism which could even be postulated for overcoming these large vapor fluxes is a very rapid mixing of these materials under very high sustained pressures. In this hypothetical configuration, the mixing would be forced into a liquid-liquid configuration, which is exactly the question addressed by the authors in Ref. [12]. To achieve such mixing requires enormous amounts of energy and this is clearly illustrated by the tabulated results in Table VI. In this calculation, the core debris was assumed to mix on a very short time scale. These calculations were carried out for both the one-step process and progressive mixing. The thermal energy transferred was evaluated from internal conduction within the fuel particle, which maximizes the energy transferred. In this tabulation, the mixing energy is compared to the thermal energy released in a typical explosive time frame. As illustrated, the thermal energy transfer is itself much less than the mixing energy required to intimately disperse one material throughout the other, i.e. the mixing necessary for the event would require a "trigger" larger than the explosive interaction itself. Therefore, this represents an unachieveable state for a self-sustaining propagating interaction. However, even this calculation overlooks one very essential physical feature of an intermixing process in which materials at greatly different temperatures are assumed to be rapidly interdispersed within each other; the heat transfer is assumed to not impede the mixing process.

As a material at very high temperature is forced into water at a high speed (rapid intimate mixing), the energy transfer occurs first on that face of the particle which initially contacts the water. This initial energy transfer is extremely high, and in the normal case, promotes the rapid formation of a stable vapor film. However, to achieve the single-phase state discussed above, which is required to prevent the pool from dispersing, this stable vapor film must be suppressed. If this is suppressed, then the surface will experience rapid, subcooled nucleate boiling, and the heat flux resulting from such a state would be enormous. The energy transferred to the coolant is stored in the liquid as an increase in the sensible heat. However, the temperature rise at the interface is also accompanied by a corresponding rise in the saturation pressure, which is also the pressure acting on the surface of the particle as it attempts to move through the water. This local pressurization is directed to impede the mixing process by slowing down the hot fragments. This type of transient behavior was observed by both Walford [14] and Stevens and Witte [15] in their convective film boiling experiments in which the sphere was rapidly driven through subcooled water. In these experiments, explosive vaporization off the leading surface of the particle was observed for specific conditions. This vaporization occurred as the particle penetrated the vapor film ahead of the leading surface. In this regime, Walford estimated that the local heat fluxes could achieve values approaching 170 megawatts per square meter, and when the experiment was conducted in a darkened room, the loading surface of the sphere was clearly much cooler than the trailing surface. The local pressure generated upon contact can be estimated by the saturation pressure corresponding to the interface contact temperature given by

$$T_i = \frac{T_F + T_f\sqrt{\dfrac{k_f\rho_f c_f}{k_F\rho_F c_F}}}{1 + \sqrt{\dfrac{k_f\rho_f c_f}{k_F\rho_F c_F}}} \qquad (6)$$

For the high temperature melts considered in these postulated events, the resulting pressure would be supercritical. As a result of these experiments and others relating to rapid nucleate boiling, it is evident that a hot particle attempting to rapidly penetrate through a cold media would achieve a self-limiting condition, i.e. if rapid relative velocity is initiated, the pressure at the interface upon contact acts to slow down the particle and perhaps even reverse its movement. Therefore, rapid energy exchange itself, which is vectored opposite to the intermixing, limits the rate of penetration of the two media. This particular aspect of the intermixing process has been neglected by the various models proposed in the literature in which a fine interdispersion is assumed to pre-exist and further fragmentation and intermixing is not opposed by any forces resulting from energy transfer between the hot and cold liquids. Clearly, this is a major shortcoming of such models in their attempt to represent the physics of the explosion process itself. This criticism is particularly valid for the steam explosion formulation in WASH-1400, since both intimate dispersion and fine scale fragmentation were assumed to exist, and were achieveable instantaneously.

As a result of the above discussions, a picture of an actual process for a steam explosion is one in which slow intermixing, via liquid-liquid film boiling, is developed over an extended time period with limited quantities of materials involved. Therefore, while an explosive interaction has a unity probability of occurrence, the amounts of materials involved are severely limited and the resulting explosive energy is far less than that represented in WASH-1400. In addition, no continuous overlying slug is available and the pressures experienced in the vessel are 10 MPa or less.

VII. EX-VESSEL STEAM EXPLOSIONS

In evaluating the effects of steam explosions for the various hypothetical core melt sequences, one must also consider such interactions after vessel failure when the core debris is assumed to be released into the containment. Given these conditions, the probability of a steam explosion should again be assumed to be close to unity since the pressure is below that required for suppression of such events. However, the issues discussed in the previous section with respect to 1) amount of material involved, 2) available trigger, 3) intimate mixing, and 4) slug formation are equally applicable in the assessment of ex-vessel steam explosions.

While the specific details would be dependent upon the individual containment design, one aspect which is common to all systems is the rate at which core material is discharged into the containment building and perhaps, depending upon the design directly into water. This rate is certainly no faster than the rate at which material is lost from the reactor pressure vessel. Here again, the method of analysis used in WASH-1400 was essentially an instantaneous failure of the entire lower head of the vessel, instantaneous loss of all core material, and intimate mixing with the containment water. Given the large number of penetrations through the lower vessel head, for both PWRs and BWRs, and the limited penetration welds characteristic of these penetrations, the major mode of vessel failure for such events would be one or several penetration failures. Given the size of this breach in the primary system, and even including the ablative nature of the subsequent release, the degraded core material would be discharged on a time scale of 20-30 seconds. As discussed in the previous section, this is much longer than any identifiable delay time before such explosions would occur, i.e. typically 1-2 seconds. Therefore, the amount of material involved in a steam explosion would be a small fraction of the core inventory.

An explosion involving the material first released from the vessel will disperse the following materials and impede further explosions. Subsequent explosive interactions could occur but they will be limited by their ability to intermix the constituents on a rapid time scale. In addition, any long term dispersal would also result in substantial vapor production in film boiling and "boil up" of the water pool thereby eliminating any continuous slug behavior.

In summary, while steam explosions can certainly occur in the containment structure, given the assumed conditions of core melt and release from the reactor pressure vessel, they do not provide a threat to the containment integrity. It should be noted that this was also concluded in WASH-1400 for ex-vessel steam explosions.

VIII. CONCLUSIONS

Given the total evaluation of the steam explosion phenomenology for both pressurized and boiling water reactors, the following conclusions can be made.

1. The formulation provided in WASH-1400 is an overly simplistic and highly conservative representation of the state-of-knowledge for steam explosions.

2. Prior experience in small test reactors have related solely to configuration of a pre-existing intimate dispersion of fuel and water in a cold condition, as well as a pre-existing continuous, overlying liquid slug. These reactions were then initiated by a strong reactivity ramp induced by the rapid withdrawal of a single control rod. This is a fundamentally different condition than a totally separated system at greatly different temperatures which is assumed to mix and interact in this state. Consequently, these previous systems are irrelevant for the particular conditions being addressed.

3. Previous analyses have ignored the above and below core structures in their formulations. As discussed, these structures have a major role in determining where, when, and how much material is distributed throughout the core region as well as the lower plenum. In addition, these structures would play a major role in the movement of any assumed continuous, overlying liquid slug through the vessel itself. In essence, these structures would not allow catastrophic collapse, intimate mixing, formation of a continuous overlying slug, and the transmission of this slug upward through the vessel in a piston-like fashion.

4. An evaluation of the experimental data available for systems at elevated pressures shows that explosive interactions can indeed be suppressed by

elevated system pressures in many of the accident sequences of interest for LWR accident analyses. In these high pressure sequences, the potential for a steam explosion itself is insignificant, thus there is no threat to the containment integrity.

5. Evaluations of the available trigger, mixing, and intimate dispersion, show that the available models which assume a pre-existing intimate dispersion and resulting fragmentation mixing on a rapid scale have either assumed away or grossly misrepresented the physical processes involved in attempts to rapidly interdisperse one liquid into another in the presence of strong temperature differences.

6. The failure mechanism in WASH-1400 was the formation and transmission of a liquid-like slug, but an evaluation of the potential for such a slug formation shows that it could not be formed because of 1) the available structures in the lower plenum region, and 2) the necessary intimate dispersion for an explosive interaction would preclude the formation of a continuous slug. Hence, even for low pressure systems where steam explosions are possible, the slug impact failure mechanism is incredible.

7. Steam explosions outside the reactor vessel are possible for the conditions postulated, but they provide no threat to the containment integrity.

The above conclusions added together show that a steam explosion within the vessel does not provide any threat to the integrity of the reactor vessel or any of its components. Table VII compares the sequence of events envisioned in the WASH-1400 model and the actual behavior in both PWRs and BWRs. This comparison shows that <u>each and every</u> element of the model represents a physically unachieveable state. Consequently, such a mechanism does not provide a *threat to the integrity of the reactor vessel and thus no threat to the containment building. Steam explosions within the containment structure also provide no threat to its integrity*.*

*We, therefore, concur with the principle conclusions made in Ref. [16].

IX. NOMENCLATURE

A_v - cross-sectional area of the reactor vessel

c_f - coolant specific heat

c_F - coolant specific heat of core debris

h_{fg} - latent heat of vaporization

k_f - coolant thermal conductivity

k_F - coolant thermal conductivity of core debris

m_T - total mass of core material

$\dot{m}_v$ - vapor mass flow rate

N - number of particles

q - energy transfer rate

r - particle radius

T_f - coolant temperature

T_F - core debris temperature

U - superficial vapor velocity

α - void fraction

ρ_f - coolant density

ρ_F - density of core debris

σ - Stephan-Boltzmann constant

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Table I

In-Vessel Steam Explosion Sequence - WASH-1400

1. Uniformly molten core, totally separated from the water in the lower plenum.
2. Catastrophic collapse of the core support such that the molten core material falls into the water.
3. Rapid (instantaneous) intimate mixing of the water and core material.
4. Coherent interaction between the molten core debris and water.
5. Slug formation and acceleration upward through the vessel in a piston-like manner.
6. Coherent slug impact on the vessel head.

Table II

Experiments Demonstrating a High Pressure Cutoff

Laboratory	Materials Used	Explosive Pressures Measured (MPa)	System Pressure Required to Eliminate Explosion (MPa)	Reduced Pressure
Argonne [2]	Freon-22 and Mineral Oil	2.5	0.2	0.04
*Argonne [4]	Freon-22 and Mineral Oil	2.0	0.5	0.10
Argonne [5]	Sodium and Water	2.0	1.0	0.05
Ispra [6]	Sodium Chloride and Water	6.0	1.0	0.05
*Sandia [7]	Corium and Water	1.5	0.75	0.04
Winfrith [8]	Uranium Dioxide and Water	3.0	0.9	0.05

*Externally triggered systems.

Table III

Cutoff Pressure Predictions

System	Henry-Fauske [2] MPa	Buchanan et.al. [3] Homogeneous Nucleation MPa	Buchanan et.al. [3] Preferred Site Nucleation MPa
Freon-22	$\sim$0.15	0.21	0.66
Water	1.0	1.3	6.7

Table IV

Pool Boil Up (Slug Dispersal)
Pressure = 0.1 MPa, Core Debris - 10^5 kg

Particle Radius (m)	Number of Particles	Superficial Velocity m/sec	Pool Void Fraction	Temperature Rise Rate ^oC/sec	Pressure Rise Rates MPa/sec Min	Pressure Rise Rates MPa/sec Max
1	3.4	5.5	0.99	1.6	0.007	4.4
0.1	3,400	55	0.99	16	0.07	44
0.01	3,400,00	550	0.99	164	0.7	440
0.005	27,300,000	1100	0.99	329	1.4	880

TABLE V

POOL BOIL UP (SLUG DISPERSAL)
PRESSURE = 1.0 MPa, CORE DEBRIS - 10^5 KG

PARTICLE RADIUS (M)	NUMBER OF PARTICLES	SUPERFICIAL VELOCITY M/SEC	POOL VOID FRACTION	TEMPERATURE RISE RATE °C/SEC	PRESSURE RISE RATES MPa/SEC	
					MIN	MAX
1	3.4	0.71	0.75	1.6	0.04	6.2
0.1	3,400	7.1	0.97	16	0.4	62
0.01	3,400,00	71	0.99	164	4.0	620
0.005	27,300,000	710	0.99	329	8.0	1240

Table VI

MIXING REQUIREMENTS

Time Scale (sec)	Penetration Depth (μm)	Percent Energy Release (%)	Particle Radius (μm)	Mixing Energy One-Step J	Mixing Energy Progressive J	Thermal Energy Transferred J	Mixing Energy / Thermal Energy One-Step	Mixing Energy / Thermal Energy Progressive
0.001	22	100	66	7.2×10^{14}	1.0×10^{12}	1.2×10^{11}	6000	8.3
		10	660	7.2×10^{13}	8.1×10^{11}	1.2×10^{10}	6000	67.5
		1	6600	7.2×10^{12}	5.8×10^{11}	1.2×10^{9}	6000	483
0.010	69	100	210	2.3×10^{12}	9.2×10^{9}	1.2×10^{11}	19.2	0.077
		10	2100	2.3×10^{11}	6.9×10^{9}	1.2×10^{10}	19.2	0.58
		1	21000	2.3×10^{10}	4.6×10^{9}	1.2×10^{9}	19.2	3.83

Table VII

Comparison of WASH-1400 Model and Actual Behavior for PWRs and BWRs

WASH-1400	PWRs	BWRs
1. All core melt sequences can produce steam explosions.	High pressure sequences prohibit steam explosions, only low pressure sequences can have steam explosions.	
2. Coherent core melt involving all the core.	Axial and radial power profiles dictate a three-dimensional incoherent core melt taking tens of minutes.	
3. Hold up and catastrophic collapse of core debris into water.	Below core structure prohibits hold up and catastrophic collapse.	Core supported from below - no catastrophic collapse.
4. Instantaneous and intimate dispersal throughout the coolant.	Rapid mixing requires several orders of magnitude more energy than is available.	Support tubes preclude any rapid and intimate mixing.
5. Coherent interaction between core debris and water.	1. Lower core support and instrument tubes would prevent any coherent interaction. 2. Lower support structure would dictate minimum time for material discharge to plenum, i.e. guarantees an incoherent event.	1. Support tubes contain the fuel until the water is vaporized, i.e. no coherent interaction. 2. Support tubes and control rod spindles would prevent and coherent intermixing.
	3. Slow intermixing in liquid-liquid film boiling would disperse the mixture before substantial amounts are involved.	
6. Slug formation and acceleration through the vessel in a piston-like manner.	1. Structure would greatly impede any slug formation.	1. Support tubes and control rod spindles would prevent any slug formation.
	2. Since only low pressure systems can explode, calculations for film boiling during intermixing show any continuous overly liquid layer would be broken up, i.e. slug could not be formed.	
7. Coherent slug impact on the vessel head.	1. Above core structure would disperse any slug movement.	1. Steam separators do not provide a straight-through flow path and disperse any slug movement. 2. Steam dryers also would disperse any slug.

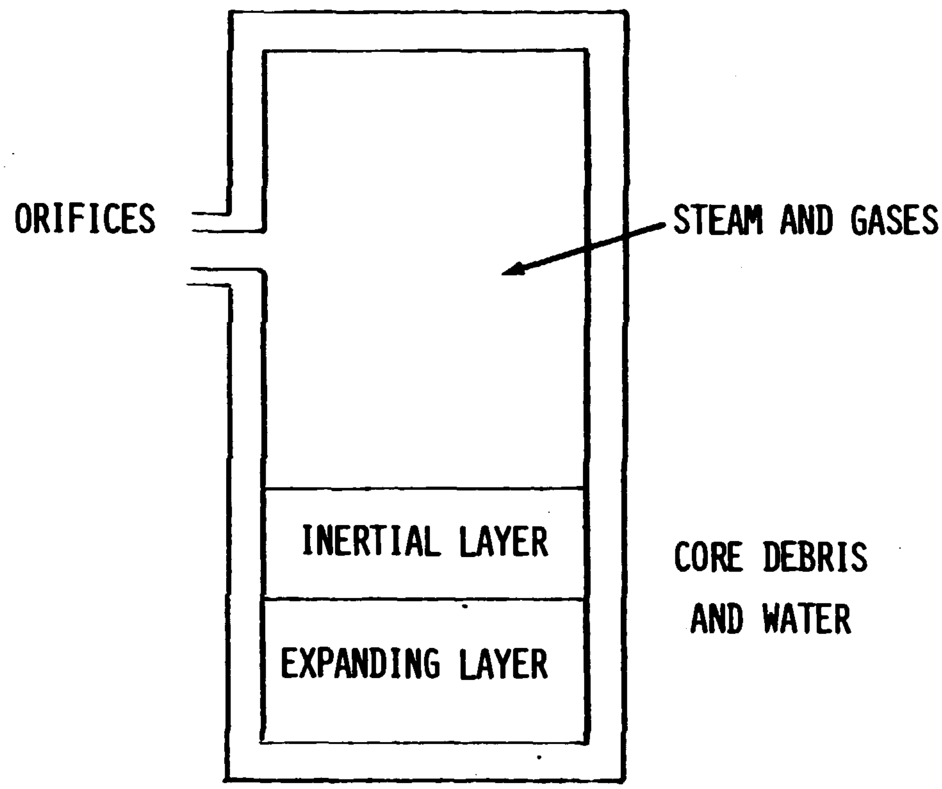

Fig. 1, Model Geometry Used in WASH-1400 Steam Explosion Analyses.

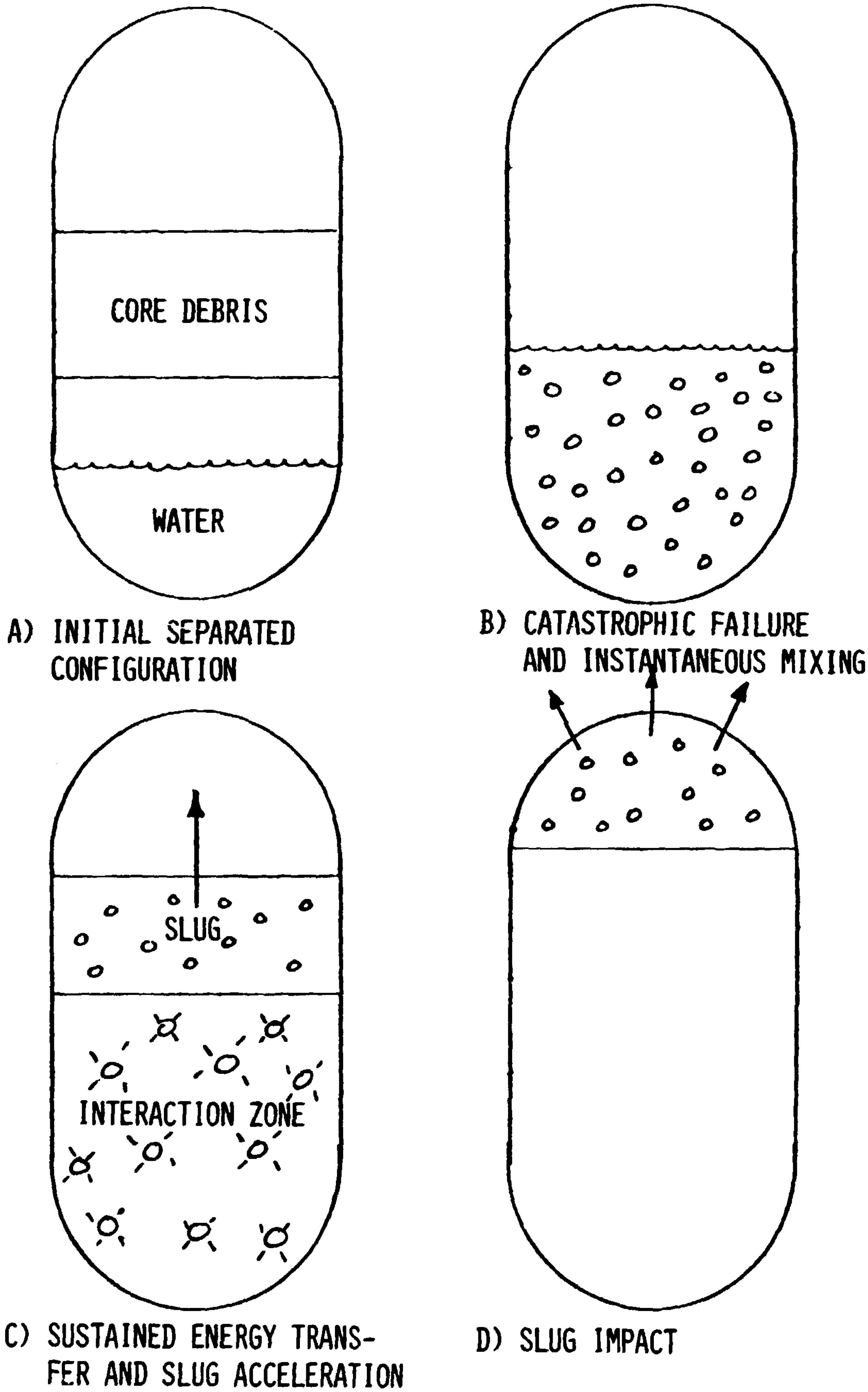

Fig. 2, Behavior Modeled in WASH-1400.

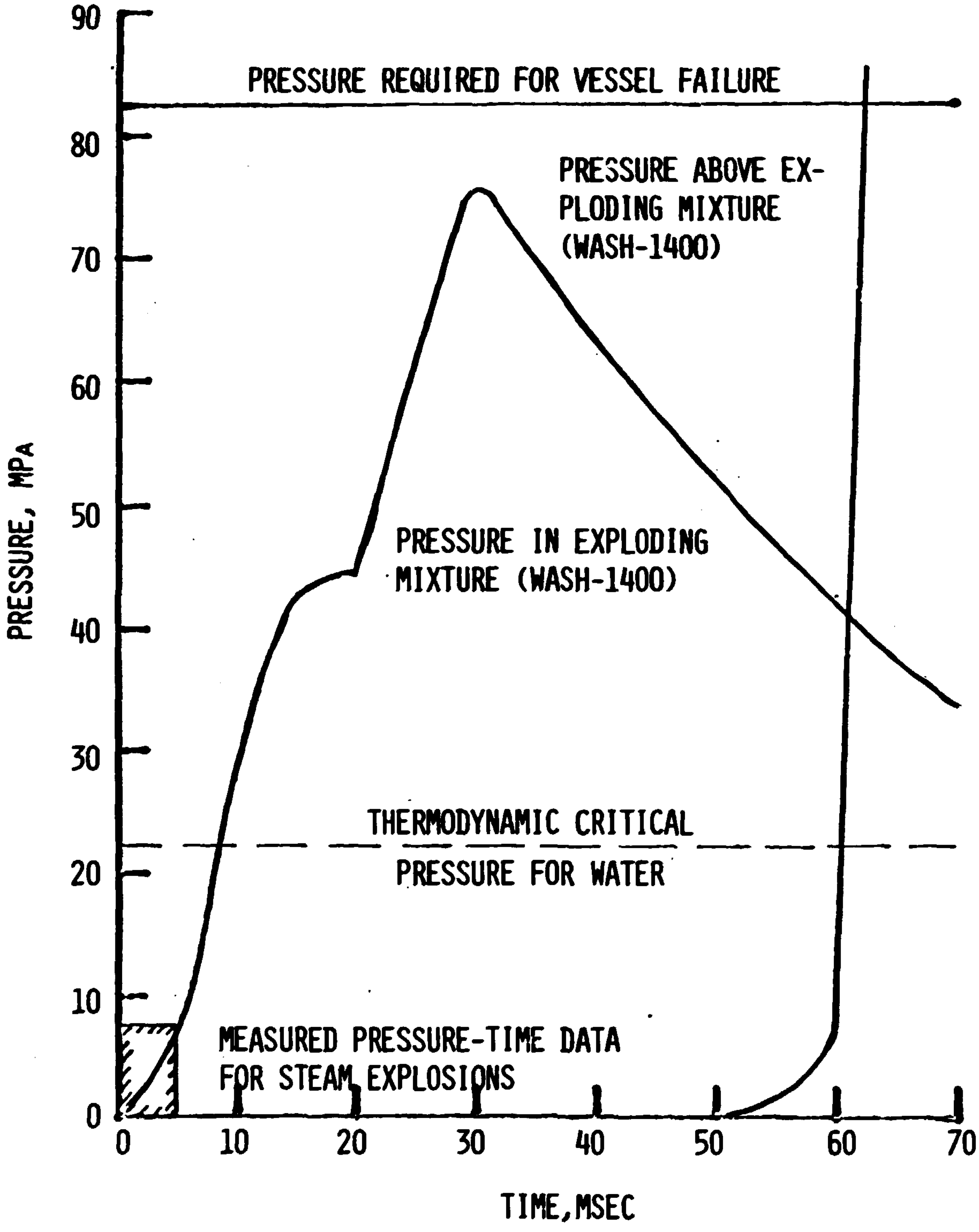

Fig. 3, Comparison of Predicted Pressure-Time Behavior from WASH-1400 (400 μm particle size) and Available Experimental Results for Steam Explosions.

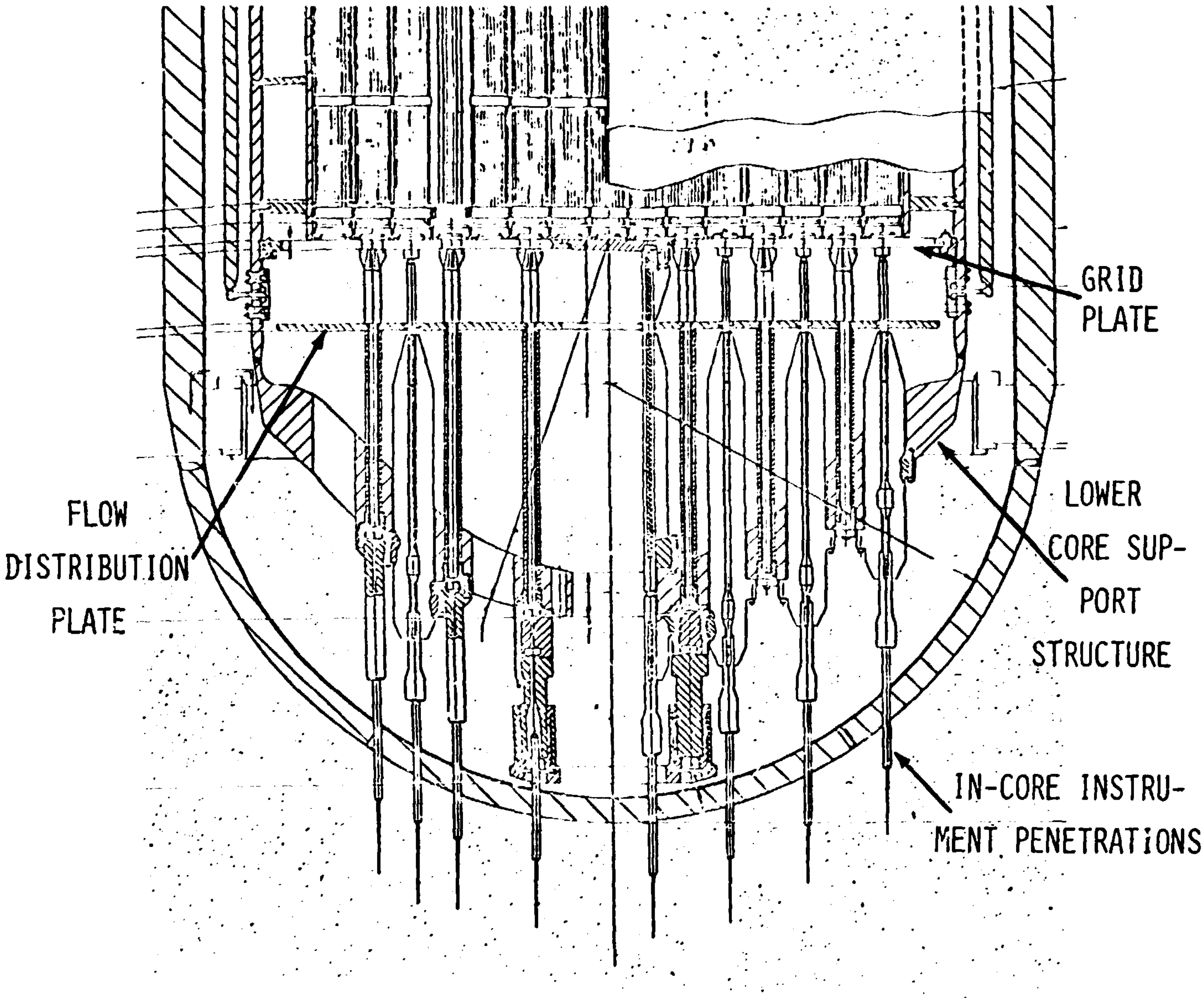

Fig. 4, PWR Below Core Vessel Structure.

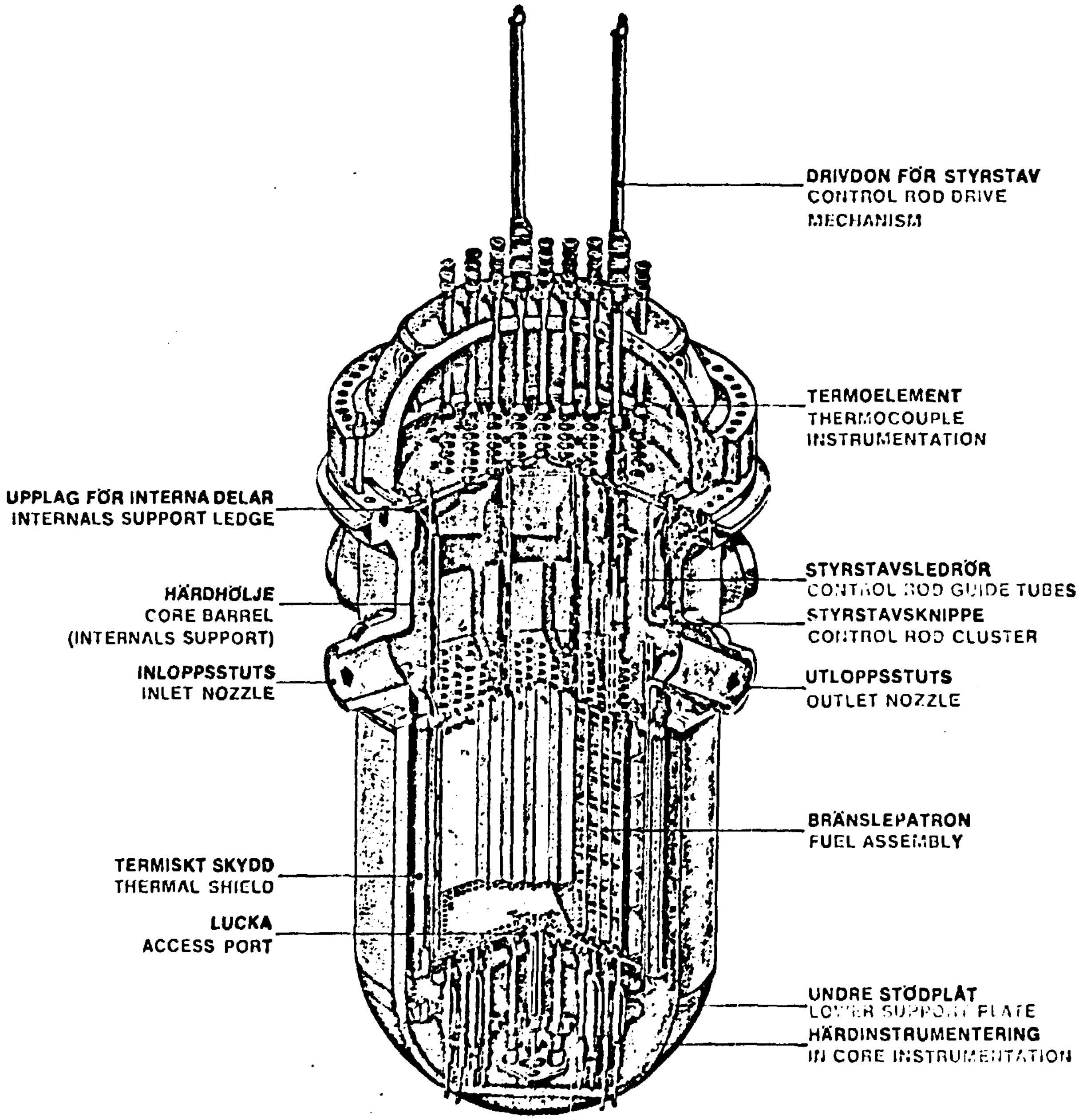

Fig. 5, PWR Internal Structures.

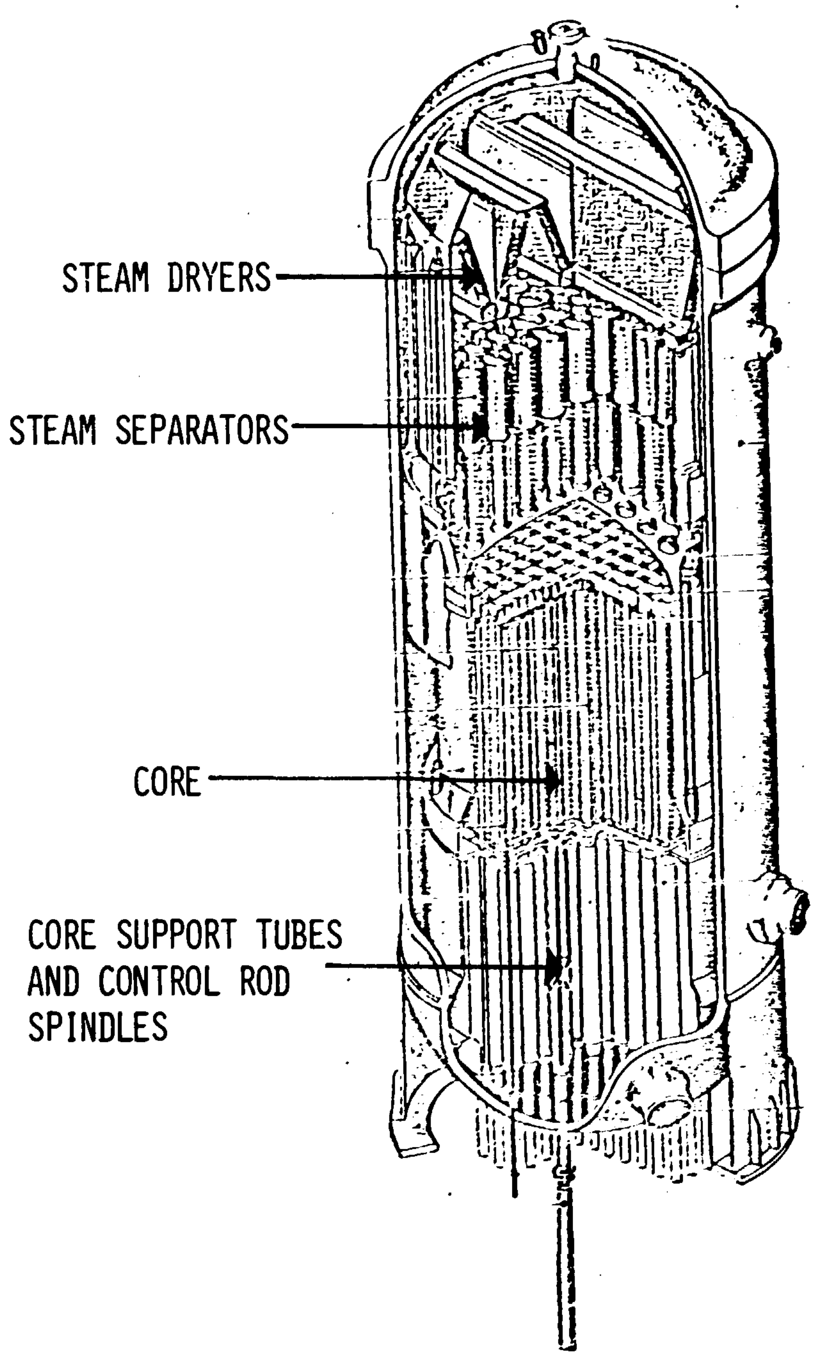

Fig. 6, Typical BWR In-Vessel Structure.

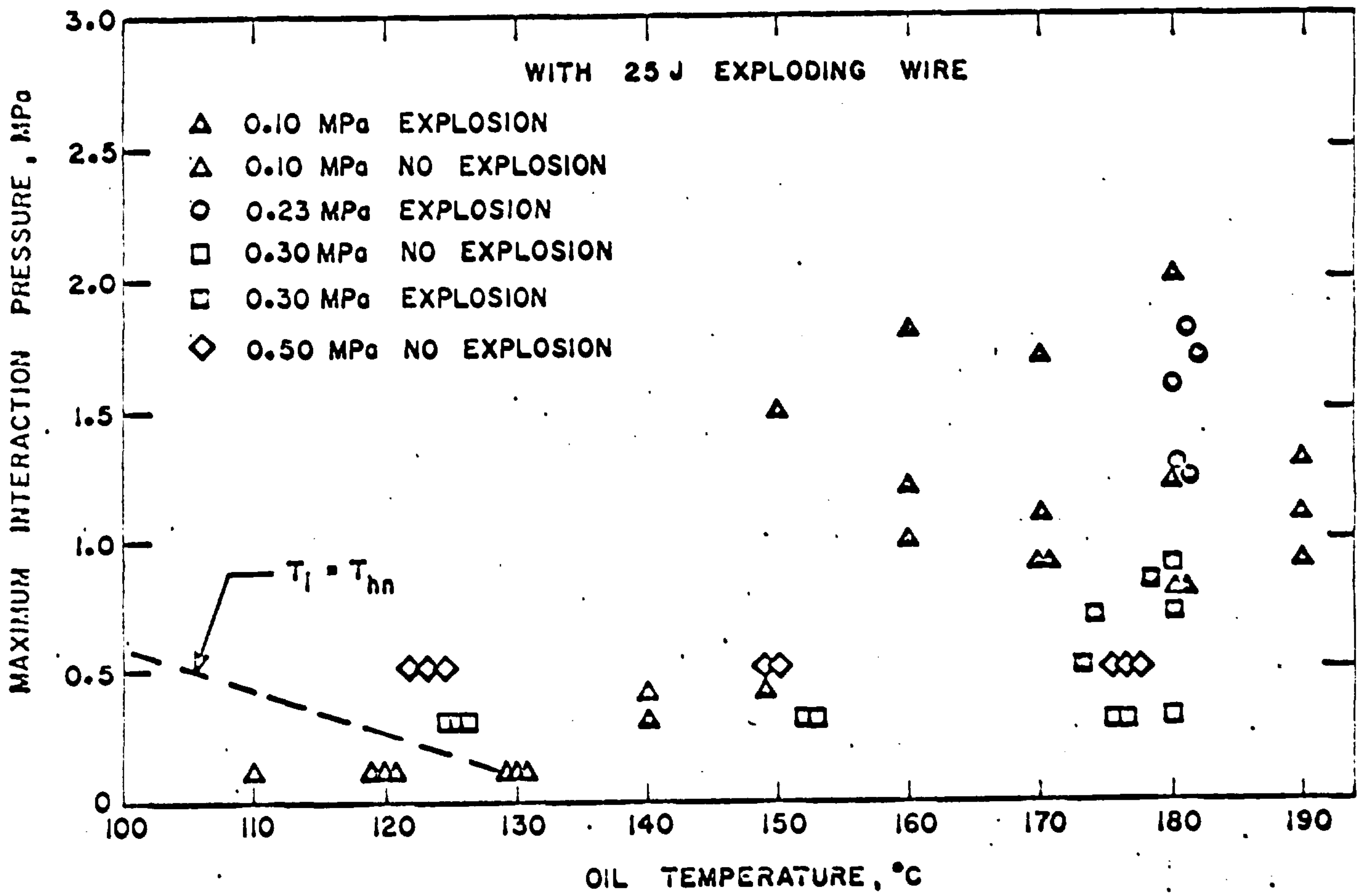

Fig. 7, Illustration of Pressure Effect in the Presence of Trigger.

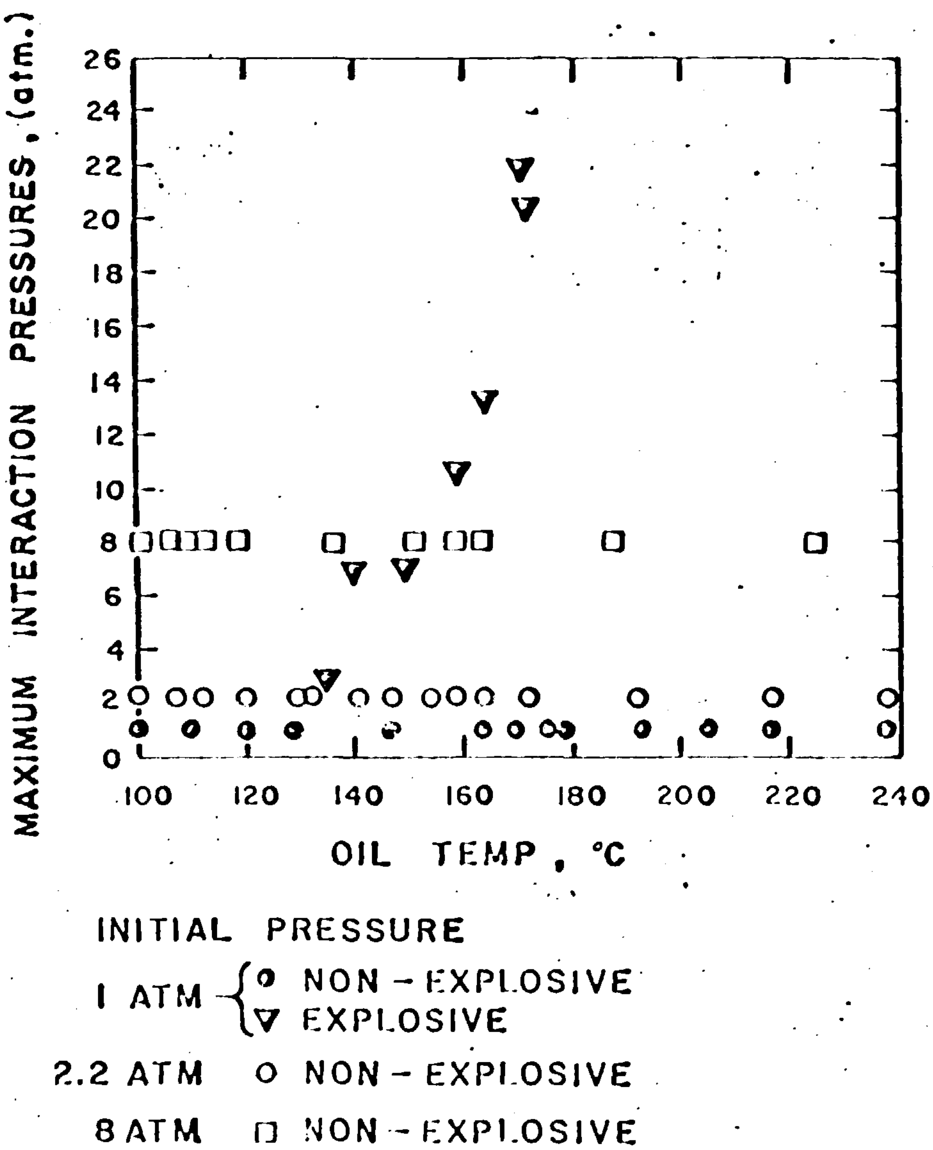

Fig. 8, Illustration of Pressure Effect in the Absence of Trigger.

APPENDIX A

Mixing Considerations

When considering the intermixing of hot and cold materials which are initially in a totally separate state, one must consider the energy requirements for the fine scale intimate mixing of these two materials, particularly if this is assumed to occur on a rapid time scale. Such an evaluation was presented by Cho, Fauske, and Grolmes (12) at the 1976 International Meeting on Fast Reactor Safety and Related Physics. In this assessment, the energy requirements to overcome the frictional dissipation were found to be substantial for rapid intermixing.

The assessment of frictional dissipation was based upon two different types of intermixing processes. The first of which assumed that the total intermixing occurred in a "one-step" manner as illustrated in Fig. A-1, and the other formulation assumed a progressive mixing pattern as graphically illustrated in Fig. A-2. The frictional dissipation for such a mixing process is expressed by

$$\text{frictional dissipation} = NC_D \pi R^2 (\tfrac{1}{2}\, \rho_f U_m^2) L_m \qquad \text{(A-1)}$$

where N equals a number of fuel particles, R is the radius of the fuel particle being mixed, U_m equals the mixing velocity, L_m is the mixing distance, ρ_f equals the water density, and C_D equals the drag coefficient, which in these order of magnitude analyses is usually taken to be unity. The mixing energy is generally dominated by the frictional dissipation term, especially if rapid intermixing is postulated as was done in the WASH-1400 analyses. While its term is designated as frictional dissipation, it is principally characterizing the form drag and is not representative of a truly viscous characteristic. If the mixing velocity is assumed to be equal to the mixing length divided by the mixing time (t_m) and the mixing length is approximated by the cube root of the volume to be mixed,

($L_m \sim V^{1/3}$) the one-step mixing energy is then given by

$$(E_m) \text{ one-step} = 3/8 \frac{\rho_f V^2}{t_m^2 R} \tag{A-2}$$

As discussed by the above authors in their paper, the mixinq energy depends upon the mode of breakup in intermixing of the hot and cold materials. The "one-step" mechanism requires the maximum energy and the actual energy requirements could be considerably less if the intermixing process occurs in a progressive fashion involving a number of steps. If this is assumed to occur in a finite number of steps, the expression for the energy required in progressive mixing is given by

$$E_n = V \; 3/8 \; \rho_f \frac{L_o^2}{t_m^2} \left(\frac{1 - \gamma^n}{1 - \gamma}\right) \frac{n}{\gamma} \tag{A-3}$$

where n is the number of steps in the mixing process and γ is the reduction factor of fuel particle size in each step. This energy expression exhibits a minimum energy level when

$$n = \frac{1}{1.74} \ln (L_o/R) \tag{A-4}$$

and if this minimum number of steps is considered, the progressive mixing formulation is then expressed as

$$(E_m)_{min} = 1.81 \; \rho_f V \left(\frac{V^{2/3}}{t_m^2}\right) \left(1 - \frac{R^2}{V^{2/3}}\right) \ln \left(\frac{V^{1/3}}{R}\right) \tag{A-5}$$

where the mixing length has again been assumed to be equal to the cube root of the mixing volume.

For analyses such as those conducted in WASH-1400, the rapid intermixing of hot and cold materials results in thermal energy transferred from the hot material and this is then realized as rapid vaporization of the water, which expands and performs mechanical work. The mechanical work estimated from large scale steam explosion experiments is a small fraction of the thermal energy transfer from the melt, typically less than 1%, (13). However, the amount of thermal energy extracted from the melt is a useful reference to compare against the energy required simply for mixing these materials on a very rapid time scale. This energy cannot be transferred faster than the thermal energy can be conducted to the surface of the core material and, the rate of thermal penetration into the core material can be estimated by using linear approximation of the error function solution as given by

$$x = 2\sqrt{\alpha_F t} \tag{A-6}$$

where x is the thermal penetration distance, t is the mixing time, and α_F is the thermal diffusivity of the molten core material. For a time scale of 1 millisecond, the thermal penetration given by this linear approximation is approximately 22 microns. Consequently, if one assumes that all the thermal energy is transferred in this time scale, a particle radius of 66 microns would be necessary since the equivalent thermal length for spherical particle is approximately 1/3 of its radius. This is illustrated in Table VI for the cases of 100%, 10% and 1% thermal energy release. A similar calculation is also provided for the mixing time of 10 milliseconds, and these two time scales bracket the mixing times of interest for rapid intermixing. (In this context, rapid intermixing infers that the mixing process takes place on the time scale of the explosive event.)

Table VI lists the mixing energies required for the various particle si s determined from the percent energy released. The salient feature depicted in the table is the immense amount of energy required to rapid by mix such particle sizes; particularly when large volumes are considered. (The volume considered in this analysis is approximately 14 m^3, which represents 100,000 kg of core material.) The table also shows the level of thermal energy transfer and this can then be compared with that required for the mixing process itself.

Since a vapor explosion is a self-sustaining process the thermal energy transferred must be far greater than mechanical work delivered by the explosion. Such a comparison shows that the one-step mixing process requires far more energy to mix the two materials than can be transferred from the fuel as thermal energy. The progressive mixing conditions also require more mechanical energy than is transferred as thermal energy from the core material, with the exception of the two smallest particle sizes in the time scale of 10 milliseconds. These two conditions, for particle radii of 210 microns and 2,100 microns show that the mixing energy is about 10% to 50% of that thermal energy transfer. As mentioned above, the large scale steam explosion experiments reported in the literature have measured a mechanical work output which is 1% or less of the thermal energy contained in the melt. Consequently, these simplistic energy considerations for the rapid intimate mixing of the core materials and water from initially separated state show that the mechanical energy requirements for mixing alone necessitates a trigger which is far larger than the explosion itself.

As a result of the above considerations for mechanical energy requirements in rapid intermixing, one arrives at the substantial conclusion that such rapid interdispersion of hot and cold materials cannot be achieved. Consequently, the only means of achieving such a state is by a slowly developing, progressive mixing state.

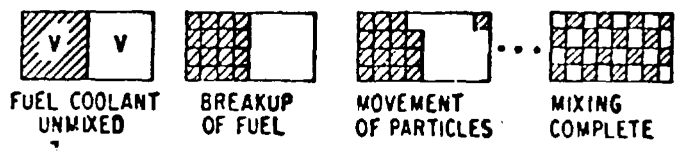

Fig. A1, Illustration of One-Step Mixing.

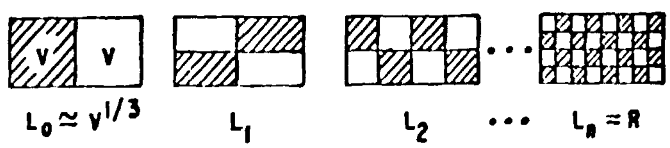

Fig. A2, Illustration of Progressive Mixing.

REPORT

ADDRESSED
TO THE

COMMITT ?OR INVESTIGATING RISKS
OF STE EXPLOSION

REVIEW OF THE STATE OF ART OF STEAM EXPLOSIONS

POSSIBILITY OF THE OCCURANCE OF LARGE SCALE STEAM EXPLOSIONS

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1955:	Diploma Engineer at the Technical University Munic
1961:	Doctor Engineer, Technical University Munic
1956 - 1961:	Research Assistant at the Institute of Thermodynamics at the Technical University Munic
1962 - 1969:	Manager of a Research Department for Nuclear Engineering at the Maschinenfabrik Augsburg-Nürnberg, at Nürnberg
Since 1969:	Full Professor für Verfahrenstechnik (Process Engineering)at the Technical University Hannover and Director of the Institute für Verfahrenstechnik

Committees and Advisory Groups

Since 1970:	Member of the German Reactor Safety Commission and Chairman of the Subcommittee for Emergency Core Cooling
Since 1971:	Chairman of the Advisory Group for Core melt down (including steam explosions) at the Federal Minister of Research and Technology
Since 1971:	Chairman of the Advisory Group for Research in Emergency Core Cooling at the Federal Minister for Research and Technology

Scientific Associations

Since 1978:	Member of the Braunschweigische Wissenschaftliche Gesellschaft

1. Melt down process

In the German risk analysis /1/ the highest probability for hypothetical accidents was found for small leaks and for loss of electrical power. The first category of accidents belongs to the loss of coolant accidents, and in the second case the loss of coolant is a secondary consequence if due to over-pressure the safety valve on the pressurizer opens. Core melt down would happen if all mergency core cooling systems would not become active and if also the decay heat removal via the blow down of the secondary side of the steam generators would not be available as a heat sink.

The probability for large leaks is smaller, however, certainly also in this case core melt down would occur if all emergency core cooling systems would fail. Best estimate calculations showed that one low pressure emergency core cooling sub system is enough to prevent a core melt down even if the temperature of the cladding rises upon the value of 1200°C, fixed as upper limit in the licensing procedure. Due to its low probability core melt down is not taken in account in the official licensing procedure in the Federal Republic of Germany.

If one insinuates core melt down in nuclear safety deliberations one has to distinguish 4 phases in the melt down process.

1. The desintegration of the core and the slumping of the core.
2. The behaviour of the molten debris in the lower plenum of the pressure vessel and the penetration of the pressure vessel.
3. The behaviour of the melt approaching the cavern below the pressure vessel and interactions with the concrete.
4. Penetration of the concrete.

Interactions between the melt and water may occur in the first phase, when the melt - also called CORIUM - flows or falls into the lower plenum of the pressure vessel and if one assumes that there is still water present. There are different possibilities for this melt down process. Calculations of this process were done with the code MELSIM II /2/ and tests to assess this code were performed in /3/. From this research work one can conclude that the melt down process would have the following sequence.

During the temperature increase of the fuel rods due to decay heat,the gap between the fuel pellets and the cladding is decreasing and as soon as there is direct contact between the UO_2-pellet and the Zry-cladding a melting mixture is formed. The melt penetrates the cladding which at the outside may be oxidized and runs down - candle like - the fuel rod until it freezes again in lower and colder parts of the core. Due to further heat addition it melts again after a period and it finally reaches the lower plenum.

This melt down process has an important consequence for steam explosion deliberations. If the CORIUM comes down more or less continuously in small mass flow rates the available energy for interaction with the water in an assumed steam explosion is limited and the pressure pulses can not be very high. The water in the lower plenum would continuously evaporate without an evident pressure rise due to steam explosions.

Experiments have shown that the melt has a low viscosity, and it is physically hardly imaginable that a larger quantity of the liquid melt can be hold up in the core region without an early flowing down into the water of the lower plenum.

If one assumes that the upper structure, holding the core, fails before the core melts down then also no large quantities of the core can be in a liquid phase. The evaporation then mainly starts at solid surfaces of the damaged core which again can not result in a large steam explosion because the fragmentation process can not start, which is an important prior condition for a steam explosion as explained later.

Even if one neglects these physical phenomena and if one assumes that very large amounts of liquid CORIUM - in the order of several tons - a calculation with the code SEURBNUK /1, 4/ showed that the pressure vessel would only be stretched up to 1% but would not fail catastrophically.

The penetration of the lower part of the pressure vessel by the molten debris is depending from the melt down process. If there is a strong flow of molten material from the core to the bottom then the pressure vessel will first fail at its lowest point due to the high heat transfer coefficient at the stagnation point as demonstrated in fig. 1 /5/. In this case a continuous and limited flow of melt would arrive in the concrete cavern below the reactor pressure vessel.

If the unmolten core due to a failure of the core support structure would reach the lower plenum of the pressure vessel a free convection during the following melting process would start and then the highest heat transfer coefficient would be present near the surface of the molten pool which has the consequence that the bottom of the pressure vessel could fail as a whole and suddenly large amounts of melt would reach the cavern below the pressure vessel. However, also in this case a very filigree fragmentation is necessary for the occurance of a large scale steam explosion.

Finally during the penetration of the molten debris through the concrete, chambers and caverns filled with water could be damaged and water can flow over the surface of the molten debris. The interaction between the concrete and the melt produces gas - H_2O, H_2 - which bubbles through the melt and this bubbling effect is intensifying the interaction between the melt and the water. This may produce local steam explosions, however, on the other side the gas bubbles disturb the propagation of the shock wave which is necessary for enlarging the steam explosion to a large scale effect.

In unit number 1 of the Ringhals site the water reservoir for the pressure subpression system is below the reactor cavern. This large amount of water certainly would interact with the melt and would cool the melt by evaporation of water. As studies of the interaction between concrete and melt have shown /6/ the bottom of the concrete cavern would not fail at once but the melt would penetrate the concrete first at these positions where the highest iron concentration is present. So it is likely that the melt is flowing in distinct jets into the water pool, avoiding that large amounts of molten debris can react at once with the water.

2. Mechanisms of steam explosions

In the literature not always a clear distinction is made between a so called steam explosion and a violent evaporation of water in connection with a hypothetical core melt down accident. These interactions between hot liquid metal and water are not a reactor specific phenomenon. In the conventional industry, where hot melts are handled, already accidents occured which today sometimes are defined as steam explosions /7/, however, by a careful examination of the accident reports one can realize that the fatalities were very often due to scalding by hot particles or droplets of the metal. In the nuclear history themodynamic reactions between fuel and water occured in connection with accidents and also with nuclear safety tests which produced large damage. In the case of the SL-1 reactor 3 persons were killed by an accident. A first hint for a melt-cooling fluid interaction in a water cooled reactor was the accident in the Canadian NRX-Test reactor in December 1952, where after a power excursion probably some fuel elements did melt and afterwards an explosion occured /8/. However, in this case it could not clearly be proofed whether the highly exothermal chemical reaction between aluminium and water and the combustion of the free hydrogen with air did not play an very important role too.

During tests with the BORAX-boiling water reactor a steam explosion occured in July 1954. In this case a strong trigger mechanism for the steam explosion was given by the strong power excursion which within 30 ms did melt most of the fuel element plates. This excursion produced an intensive fragmentation which is a condition for the steam explosion.

1961 the boiling water reactor SL-1 had the wellknown accident/9/ which again was caused by a power excursion. It is assumed that during this excursion the fuel not only did melt but also may be partially evaporated. This excursion again produced a very violent mixing between the fuel and the water.

Finally during the tests in the SPERT-1B plant 15 ms after the power excursion a high pressure pulse was observed which again may be due to a steam explosion. In this case approximately 35% of the core were molten during the power excursion.

In all these accidents or tests an exponential increase of the reactivity was the reason for the melting process. And the large gradient of the power excursion produced a sudden and high superheating of the fuel elements which may result in a fine fragmentation. During a core melt down process no power excursion is possible and it takes much longer - by several orders of magnitude - time to melt the core. The mixing between the melt and the water is also much less violent.

Due to the superheating of the fuel elements in the water a very good premixing is achieved which enhances a coherent thermal reaction. In most of the tests uranium / aluminium alloys were present which behave different from UO_2 and Zry.

2.1 Theoretical models for steam explosions

In the literature two theories can be distinguished to explain the strong transient phase of a steam explosion. These are the theories of

the spontaneous nucleation and
the pressure induced detonation.

The theory of the spontaneous nucleation was proposed by Fauske /10/ and can be simply explained by the help of fig. 2. In this figure the temperature course is shown which may occur if hot melt is coming in contact with the water. In addition there is plotted the nucleation rate as a function of the temperature. At the beginning the nucleation rate is increasing only slowly with temperature, however, when the temperature approaches the so called spontaneous nucleation temperature T_{SN}, the nucleation rate is increasing exponentially. From these deliberations the criterion was deduced that a steam explosion can only occur if the temperature at the contact between melt and water is higher than the spontaneous nucleation temperature. This is the temperature where at the phase interface spontaneous vapour nuclei are formed. For water this spontaneous nucleation temperature is approximately 300°C if the melt can be wetted.

If this criterion is fulfilled a large number of steam bubbles are created around a molten droplet within a very short time. If the melt is sufficiently fragmentated and wellmixed with water, a steam explosion may occur. Many experiments and detailed theoretical studies seem to support this criterion for steam explosions /11/, however, there are also theoretical deliberations in the literature which arise doubt about the spontaneous nucleation theory /12/. Also experiments seem to proof that not always this criterion is valid /13/.

In the theory of the spontaneous nucleation no information is given how the mechanism should work which has to produce the very filigree fragmentation of the melt. However, only taking in account the complete physical phenomena, that is the fragmentation, the heat transfer and the pressure rise and comparing a more general physical model with the experiments can proof whether the theory of the spontaneous nucleation is valid or not. The mechanisms producing the fragmentation are not to well understood up to now.

The detonation model was at first presented by Board and Hall /14/. It treats the propagation of the steam explosion similar to the behaviour of a shock wave during a chemical detonation and tries to transform the physical models of this process to the steam explosion. In fig. 3 a simple schematic explanation of this model is given.

In the detonation model it is assumed that the melt is present in more or less large particles or droplets which are homogeneously distributed in the water. This means that the starting condition is a roughly, however, homogeneously premixed melt/water volume. Through this volume a shock wave has to travel. The pressure rise in the shock wave has to be so large that each potentially existing vapour is condensed. In the moment when the pressure wave travels over the prefragmented lump, velocity differences are created due to the different densities of melt and water. These velocity differences are assumed to fragmentate in detail the melt lumps. Behind the pressure wave there is a region where filigreely fragmentated melt has close contact with the water. In this zone a very violent and rapid evaporation - like an explosion - can occur which depending from the geometrical conditions and can produce a very large pressure pulse. From this pressure pulse the shock wave gets its energy.

In this model it is presumed that an initial pressure pulse is present. It may be produced by several phenomena. Sometimes entrapment explosions are assumed to be the reason for this initial pressure pulse. Entrapment explosions may occur if the melt is confining a water droplet. The evaporation may cause a small thermal detonation. Sometimes it is assumed that filmboiling is changing in transition boiling and the sudden collaps of the vapour film is producing a violent evaporation with pressure pulses. This again may cause fragmentation. And in consequence of these pulses also vapour films in the neighbourhood may collaps again producing violent evaporation and so the phenomenon may propagate.

As well as in the spontaneous nucleation theory also in the detonation theory the reason for the premixing of the melt and water is not explained. The filigree fragmentation has to be performed within an extremely short time because only under this condition a so high evaporation rate can be produced which is needed to sustain the shock wave. Shock waves may interfere with each other and they even can distinguish each other if a low pressure and a high pressure wave meet together.

There are many activities in the world to get a more satisfying explanation and theory for thermal detonations /13, 15, 16, 17/. A scaling to the geometrical conditions of a nuclear reactor, however, is very difficult. There is also a hint in the literature /18/ that a nuclear reactor may be to small and may have not favorable enough conditions for the propagation of small thermal detonations to produce a large scale steam explosion.

2.3 Fragmentation of the melt

Fragmentation of the melt may be due to
- hydrodynamic effects
- evaporation effects
- pressure pulses in the melt.

Hydrodynamic forces are occuring when the melt is flowing from the core region into the lower plenum of the pressure vessel, filled with water or when the melt is ejected through the cladding by overpressure into water or when, as assumed in the thermal detonation model, melt and water have a relative velocity. With all models, concerning the hydrodynamic fragmentation, it is assumed that the surface of the melt is not freezing.

If the molten particle is a liquid droplet it can only be fragmentated by the kinetic energy of the flow around it, which has to overcome the surface tension energy. This means that the critical Weber number has to be greater than ten. A model which takes in account the flow forces in the droplet acting against the surface tension and producing fragmentation is presented in /16/. Also instability criteria according to Helmholtz and Taylor are taken in account to explain fragmentation /20/. Also surface waves at the phase boundaries are assumed to create fragmentation if the amplitudes of the waves exceed a certain critical value.

From experiments /21/, however, one can also draw the conclusion that thermal effects are much more important for fragmentating the melt. Such thermal effects may be the growing and the collapsing of vapour bubbles in the regions of transition- and bubble boiling. This phenomena may be especially important if melt is submerged in subcooled water. An originally formed vapour film may condense at the subcooled water which produces a high momentum versus the hot molten surface. Due to this momentum a water jet is expected to be formed /22/ which penetrates through the surface into the melt and produces a fragmentation. The dynamics of bubble collaps and formation of microjets is also researched in /23/. By the local momentum an elastic wave is produced in the melt which, however, can transduce only a small part of the maximum possible bubble energy.

In another model /24/ the potential energy of the bubble collaps is regarded and considered as an energy available for the enlargement of the surface. In this model also freezing effects at the surface are taken in account when the melt comes in direct contact with the water. Finally a collaps of the vapour film can be triggered artificially by a pressure pulse from outside. The model predicts that there should occur no violent melt/water interaction at small subcooling /23/. This was however only proofed in tests with an Sn/H_2O mixture.

Boiling effects especially collapsing steam bubbles are regarded not as the only, however, as the most important mechanism for fragmentation /24/. This seems to be proven by small scale experiments with reactorlike materials.

A number of other models takes in account the pressure increase in the melt as a reason for the fragmentation. This pressure increase may be caused by the fact that small droplets of water are enclosed by a frozen layer of melt and the pressure is increasing in this small cavern by violent evaporation. This finally can fragment the melt /25/. It is also assumed that due to very rapid boiling, pressure pulses are created which produce cavitation-bubbles in which a small amount of water is entraped in the melt.

Other models start from the idea that in the hot melt non-condensable gases are solved. If the melt cools rapidly this gas can not escape quickly enough, so that after freezing fragmentation is produced /26/. Gas as a reason for fragmentation is also postulated in /27, 28/. Here the gas-bubble growth when the gas goes out of solution is regarded as a fragmentation mechanism. In tests measuring the interaction between concrete and hot melt /6/ it could be observed that gas bubbles which for example become free in form of vapour or hydrogen out of the concrete can produce a very violent interaction between water and melt.

3. Mixing of fragmented melt with water

Even if we assume that due to any mechanism the melt is fragmented in an extreme large number of very tiny droplets - in the order of 10^{-3}m diameter - we have to think about where the energy and the force comes from to mix the melt and the water homogeneously in an optimal ratio.

In /29/ an estimation was performed up to what extent heat can be transfered from the fragmented melt to the water. To calculate the heat transfer coefficient between the melt and the water the unsteady temperature- and heat conduction equation was numerically solved. The calculations started from the assumptions:

- The fragmented melt particle have spherical shape and the heat transport can be assumed to be spherical symmetric
- The thermodynamic properties are constant
- The water around the molten particle can be assumed semi-infinite
- At the contact between water and melt there is a transport resistance which can be described by the heat transfer coefficient
- The water can be superheated up to a certain temperature from which a spontaneous evaporation starts.

Details about the equations used and the numerical integration can be taken from /29/.

From experiments in the literature the mean fragmentation spectrum was taken and also with the help of information from the literature /30, 31, 32/ the fragmentation spectrum was extrapolated to reactor conditions. The result of these deliberations concerning the fragmentation distribution is shown in fig. 4. In this figure the curve number 2 is an upper pessimistic limit for the fragmentation. For both curves in fig. 4 the energy dissipation from the melt was calculated which results in a maximal and in a best estimate energy transfer to the water.

For estimating the energy needed to form new surface areas, that is to produce the fragmentation, a molten debris, called CORIUM E-X2, was assumed which composition is shown in table 1. From the thermodynamic properties of the components the mean density can be calculated as

$$\bar{\varrho} = 8{,}61 \cdot 10^3 \text{ kg/m}^3 \tag{1}$$

and the mean molar mass as

$$\bar{M} = 64{,}86 \text{ kg/kmol} \tag{2}$$

The specific heat capacity was calculated as

$$\bar{C} = 0{,}54 \text{ kJ/kg} \cdot \text{K} \tag{3}$$

For calculating the specific surface tension energy, two different methods were used. Assuming that the dependence of the surface energy on the melting temperature is not only valid for pure metals but also for alloys, the specific surface energy for the mentioned CORIUM composition can be taken from fig. 5 and one gets according to Nazaré /33/ a value of

$\gamma = 1{,}9 \cdot 10^{-3}$ kJ/m²

On the other hand the specific surface energy of liquid metals at the melting point can be calculated according to the Eötvos-rule taking the mean density and the mean molar mass.

$$\gamma = \frac{0{,}64\,(6{,}5\,T_S - T)}{\sqrt[3]{(\bar{M}/\bar{\varrho})^2}} \tag{4}$$

With this method one gets a surface energy of

$$\gamma = 2{,}13 \cdot 10^{-3}\ \mathrm{kJ/m^2} \tag{5}$$

The difference between both values is only 10 %.

From the fragmentation curve 1 in fig. 4 one gets a specific surface of the melt of

$$A_{Frag} = 1{,}399\ \mathrm{m^2/kg} \tag{6}$$

The fragmentation curve 2 in fig. 4 gives a specific surface of

$$A_{Frag} = 34{,}767\ \mathrm{m^2/kg} \tag{7}$$

Due to the small size of the particles it can be assumed that the fragments have the shape of spheres. If one assumes that the the surface of the melt before the fragmentation starts is negligible, the maximal energy consumption for the fragmentation,according curve 1, is

$$\Delta q = \gamma \cdot A_{Frag} = 2{,}97 \cdot 10^{-3}\ \mathrm{kJ/kg} \tag{8}$$

and according curve 2

$$\Delta q = \gamma \cdot A_{Frag} = 7.41 \cdot 10^{-2}\ kJ/kg \tag{9}$$

For the fragmentation, however, one needs an addition energy to move the particles for allowing water to penetrate between the particles and another energy for deformation. The deformation energy could not be calculated because there is no information in the literature.

As mentioned the fragmentated particles have to be moved quite a way to produce a homogeneous mixture of melt and water. To produce this mixture, the particles have to be highly accelerated. Due to the fact that the fragmentation has to be performed within a few milliseconds very large forces are needed for the acceleration of the molten particles. These forces will be roughly calculated in the following.

If one assumes that the non-fragmentated melt has spherical form and that after the fragmentation melt and water are homogeneously mixed, each molten particle has to be moved the distance

$$\Delta r = r_1 \cdot \left[\left(\frac{V_2}{V_1} \right)^{1/3} - 1 \right] \tag{10}$$

In equation 10, V_1 is the volume of the melt before the fragmentation, V_2 the volume of the mixture of fragmentated melt and water and r_1 the coordinate of the radius before fragmentation starts.

For the total mass of the melt one gets as mean value for the distance over which the particles have to be accelerated

$$\overline{\Delta r} = \frac{1}{V_1}\int_{V_1} \Delta r \, dV_1 \tag{11}$$

$$\overline{\Delta r} = \frac{3}{R_1^3}\left[\left(\frac{V_2}{V_1}\right)^{1/3} - 1\right] \int_0^{R_1} r_1^3 \, dr \tag{12}$$

$$\overline{\Delta r} = \frac{3}{4} R_1 \left[\left(\frac{V_3}{V_1}\right)^{1/3} - 1\right] \tag{13}$$

If one assumes that the particles are undergoing a steady accelerated movement during the fragmentation the mean acceleration needed to reach Δ r in the given time calculates as

$$b = \frac{2\Delta r}{t^2} \tag{14}$$

The force needed for acceleration then - as wellknown - calculates according to the first law of Newton

$$F = b \cdot m \tag{15}$$

If one assumes that 10 t melt participate in the fragmentation process one gets with the density of the melt $\rho = 0{,}61 \cdot 10^3$ kg/m³ an initial volume V_1 of 1,116 m³. In addition it shall be assumed that the mixing ratio between the masses of melt and water after the fragmentation is 1:1. Then the volumetric ratio with the densities of both materials is

$$\frac{V_2}{V_1} = 2 \tag{16}$$

and the inititial radius of the sphere

$$R_1 = 0{,}652\,\mathrm{m} \tag{17}$$

With these values a mean moving distance

$$\Delta r = 0{,}127\,\mathrm{m} \tag{18}$$

is calculated.

The whole procedure of the fragmentation has to be finished within a very short time to sustain the steam explosion and probabely does not take more than one millisecond. If one assumes - pessimistically - a time of 3 ms for the fragmentation, the above mentioned simple calculation gives a acceleration of

$$b = 2{,}822 \cdot 10^4\,\mathrm{m/s^2} \tag{19}$$

with 10 t molten mass the force for this acceleration is necessary

$$F = 2{,}82 \cdot 10^8\,\mathrm{N} \tag{20}$$

With a molten mass of 100 t the acceleration force would be

$$F = 6{,}08 \cdot 10^9\,\mathrm{N} \tag{21}$$

It seems to be physically impossible that these extremely high forces,fragmentating a larger amount of melt,can exist in the melt. Anyhow these forces and time for fragmentation has to be taken from the starting steam explosion and would damp out the propagation of a shock wave within a short distance. From this deliberation one can draw the conclusion that large scale explosions are rather unlikely or even physically impossible.

However, even if one hypothetically supposes that a large steam explosion may occur, the energy transport from the melt to the water is limited. In /29/ a computer programm and results are reported concerning upper limits of energy transport from the melt to the water, in a supposed reactor accident.

One has to take in account that the energy transport take place during the very short time of direct contact between liquid melt and liquid water substance. The energy remaining in the melt is shown in fig. 6 for various diameters of the molten droplets and for various contact times. In this figure is assumed that the water volume around each melt droplet can be treated as infinite compared to the particle volume, because this gives the highest heat transport rate in the heat transfer calculation. From the figure it can taken out that most heat is destored from the very small droplets - below 10^{-3}m - mainly.

To get a better information of the energy transport from the droplets to the water, the droplet spectrum has to be averaged. This can be done with the help of fig. 4. In this figure are 2 curves - a pessimistic one and a best estimate one - drawn for the probability of the droplet diameter distribution. If we take curve number 2 - the pessimistic one - we get the destored energy as shown in fig. 7. From this figure we can read that for a contact time of 10 ms, and this is a rather pessimistic assumption, approximately 12,5 % of the heat, stored in the fragmented melt, could transported to the water and could there contribute to steam explosion.

The conversion from thermal energy into mechanical energy during the explosive steam evaporation has again a very low efficiency as will be shown later.

If we take from fig. 4 the best estimate diameter distribution of the droplet spectrum the destored heat from the melt is much smaller and one gets for a contact time of 10 ms, as shown in fig. 8, an energy transport of only 3 % of the originally stored heat in the melt.

To get an impression how large the water volume has to be for these favourable conditions, with respect to a steam explosion, in fig. 9 the volumetric ratio between water and melt is plotted under the condition that the boundary layers around each droplet are just not influencing each other. One can see from this figure, that the water volume must be especially with very small particles much larger than the melt volume, which means that the acceleration of the droplets during the fragmentation has to be much greater than calculated in the previous chapter for an optimal reaction between melt and water. A smaller distance between the droplets and a smaller water volume would reduce the heat transport from the melt to the water because the boundary layers would interfere with each other and the unsteady heat conduction would be reduced.

4. Conversion of thermal into mechanical energy during a steam explosion

There are many experiments reported in the literature dealing with steam explosions, most of them, however, are performed under idealized conditions and study primary the phenomena and not quantitatively the conversion ratio between energy in form of heat and in form of mechanical work which acts on the structure of the pressure vessel or of the containment. A detailed survey of the experimental literature is given in /34/.

It is difficult to measure in a reactor like geometry the conversion ratio or the efficiency of a steam explosion. From an experimental point of view the best measuring conditions are given in a shock tube geometry. These channel like geometries have the advantage that the pressure wave is one dimensional which makes a theoretical description and calculation easier. There Al- and Pb-melts where used.

With steel- and UO_2-melt systematic tests, studying the interaction between water and melt, were performed in the Euratom research center at Ispra /36, 37/. In these experiments a water column which is accelerated by a gas pressure is impinging onto the melt. By changing the acceleration of the water column it was possible to influence the fragmentation and the mixing between water and melt. With increasing kinetic energy in the accelerated water column, the amount of fragmentated melt becomes larger /37/. The connection between kinetic energy and fragmentated mass of melt, however, is not linearly and the gradient of the fragmented melt is strongly decreasing at high values of kinetic energy, as shown in fig. 10 /37/. This means that it becomes more and more difficult if large quantities of melt have to be fragmentated. From this result one can conclude that it is not permissible to extrapolate from small scale experiments to large melt quantities linearly.

The conversion ratio between the total thermal energy stored in the melt and the mechanical energy becoming free in form of a pressure pulse was in the order between 0 and 3,3 % for steel and 0 and 0,85 % for UO_2 granulate /37/. The order of magnitude of these conversion ratios can be easily checked by a very simple thermodynamic deliberation. In chapter 3 we found that under best estimate conditions the heat destored from the melt to the water is in the order of 3 %.

If we now take Carnot's law or the second law of thermodynamics, we get with a maximal temperature of the superheated water of 400°C and the temperature of the produced vapour of 150 °C a thermal efficiency of 0,6 %. This is an overall efficiency between 1 and 2 %. Carnot's law is the upper limit for the thermal efficiency which is certainly lower even under ideal test conditions.

In a shock tube the conditions for the energy conversion are by far better than in the three-dimensional geometry of the reactor pressure vessel or of the containment. In /37/ therefore the conclusion is drawn that the ideal boundary conditions of shock tube experiments by far can not be reached in reactor geometries. Therefore transforming shock tube experiments to reactor conditions the effects of steam explosions certainly will be overestimated. It can be assumed that the measured efficiencies can not be reached with larger amounts of melt and water. These measured values certainly are an upper limit.

Tests in which a layer of water was put over a pool of melt, through which gas was bubbling, did show very violent interactions between melt and water, however, no steam explosion with a very high and sudden pressure increase /6/. A visual inspection of the frozen fragments showed that much entrapment took place which could have been a trigger mechanism for a steam explosion. The experiments were done with Bi-Pb-alloys up to 40 kg.

Experiments with tank-geometry are reported in /39,40, 41/. These tests were performed with steel-, UO_2-, NaCl- and Thermit-melts. In most of these experiments steam explosions were not observed but only violent reactions between melt and water.

Large scale experiments were performed at the SANDIA laboratories /41/. The main aim of these experiments was to determine the thermal-mechanical efficiency in a steam explosion. The molten material was represented by a thermit melt. The melt was injected into the water by a falling jet accelerated by normal gravity. The temperature of the melt was around 2700° C and the water temperature was varied between 20 and 96°C.

In most of the experiments steam explosions were observed which started after 0,5 s until 3 s after injecting the molten thermit into the water. In 90% of all tests the thermal-mechanical efficiency was lower than 0,5 %. The highest conversion ratio was measured as 1,34 %. From the geometrical conditions these SANDIA tests are certainly more reactor like than other tests reported in the literature. However, it has to be taken in account that thermit-melts behaves different from a CORIUM melt due to other thermodynamic properties and due to the fact that the melting temperatures in the reactor are probably lower than in the tests.

In /34/ an attempt was made to extrapolate with a simple empirical equation the thermal-mechanical conversion ratio from the experiments, reported in the literature, to reactor conditions. With this equation from /34/

$$\eta_{max} = Am^{-b} \qquad (m \text{ in kg}, \eta \text{ in } \%)$$

$$A = 2{,}27 \qquad (22)$$

$$b = 0{,}195$$

one would predict for a molten mass of 10^3 kg a thermal-mechanical efficiency of 0,59 %.

In the SANDIA experiments /41/ a free falling thermit-jet was penetrating the water pool and this penetration certainly produce a pre-fragmentation. If the water is put in layer over the molten pool, not the same violent interaction and no steam explosion was observed /6/. The amount of melt which penetrates the water during a core melt down process, simulating the conditions in the SANDIA experiments /41/, however, is limited due to the fact that latest after 2 ÷ 3 s the ignition of the steam explosion starts, as proved by the SANDIA experiments. A simple calculation shows that the maximum mass of melt which can come down during this period is in the order of $1 - 5 \cdot 10^3$kg. With the conversion ratio, discussed above, the energy of this mass is not high enough to destroy the pressure vessel even if one supposes that the whole mass is reacting in a steam explosion which seems rather unlikely taking in account the forces needed for fragmentation of such large masses.

The above mentioned mass of melt coming down until the steam explosion may be ignited is certainly too high. In reality during a hypothetical core melt down accident certainly only a few hundred kilogramms of melt would reach the water in the lower plenum until the first violent interaction between the melt and the water takes place.

5. Conclusions

During a hypothetical core melt down accident small scale steam explosions up to an instantaneously reacting mass of a few hundred kilogramms may occur if water comes in contact with the molten CORIUM. The mechanical energy of these reactions, however, do not endanger the integrity of the pressure vessel or the containment as certainly can be shown by a simple stress calculation.

For a steam explosion the melt participating in the reaction must be pre-fragmented, a shock wave must travel through the homogeneously pre-fragmented volume and then the explosion could start. During the pre-fragmentation no nominal value of heat must be transported from the melt to the water because then already an evaporation would start, partially freezing the melt and disturbing the following shock wave by reflecting and damping. To propagate the mixing and fragmenting of the interacting material by a detonation wave and avoiding a to early evaporation the pressure must be super critical. Finally a delay of the propagation wave takes place due to non-condensable gases, solid particles in the melt and structures in the pressure vessel or in the containment.

The theory of the spontaneous nucleation is only applicable if the mixing and the fragmentation takes place under the conditions of liquid-liquid contact. This can be only the case at super critical pressures or during an extremely short time - below the boiling delay. The thermal detonation theory presumes a pre-fragmentation of the melt and a pre-mixing of the interacting masses and in addition behind the shock wave there must be an area in which sound velocity is present. In multi component mixtures, however, there is usually no uniform sound velocity.

Finally the energy and the forces which have to become available during a few milliseconds for mixing melt and water in such a way that large scale steam explosions with strong mechanical effects can result, are so large that it is physically not imaginable where they should come from.

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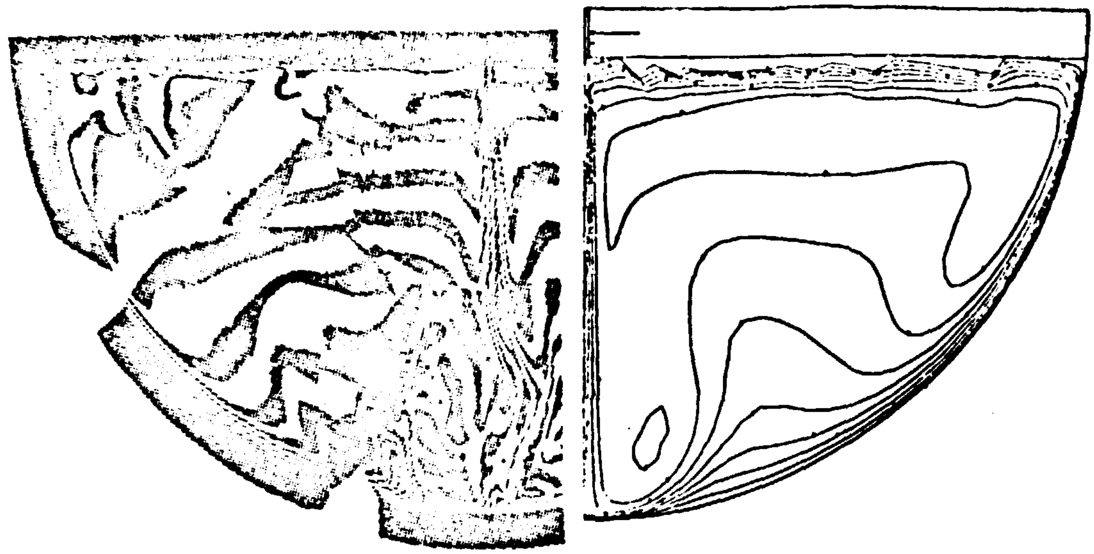


Measurement   Calculation

Fig. 1: Temperature field from measurement and calculation

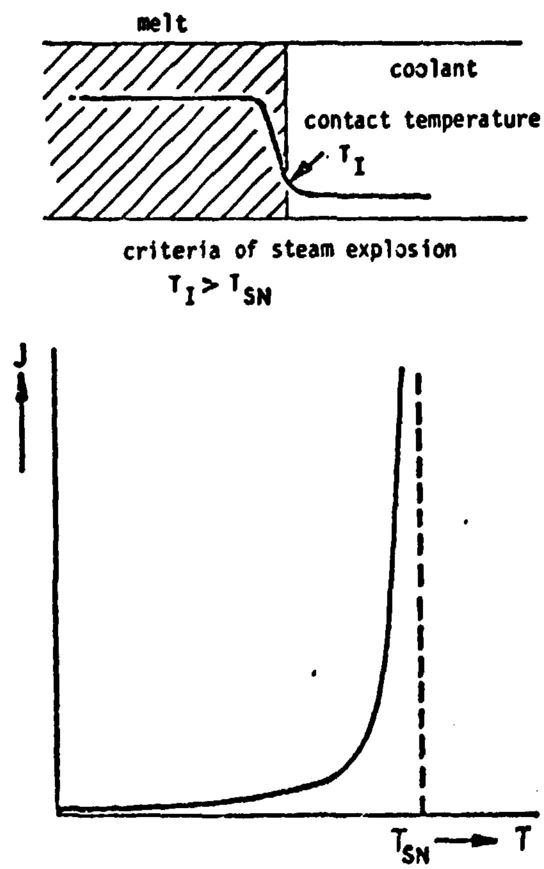


Fig. 2:

Spontaneous nucleation:
Direct contact between melt and coolant results the contact temperature T_I.
The rate of steam bubble formation J increases slowly with the absolute temperature but rapidly near the spontaneous - nucleation - temperature T_{SN}.

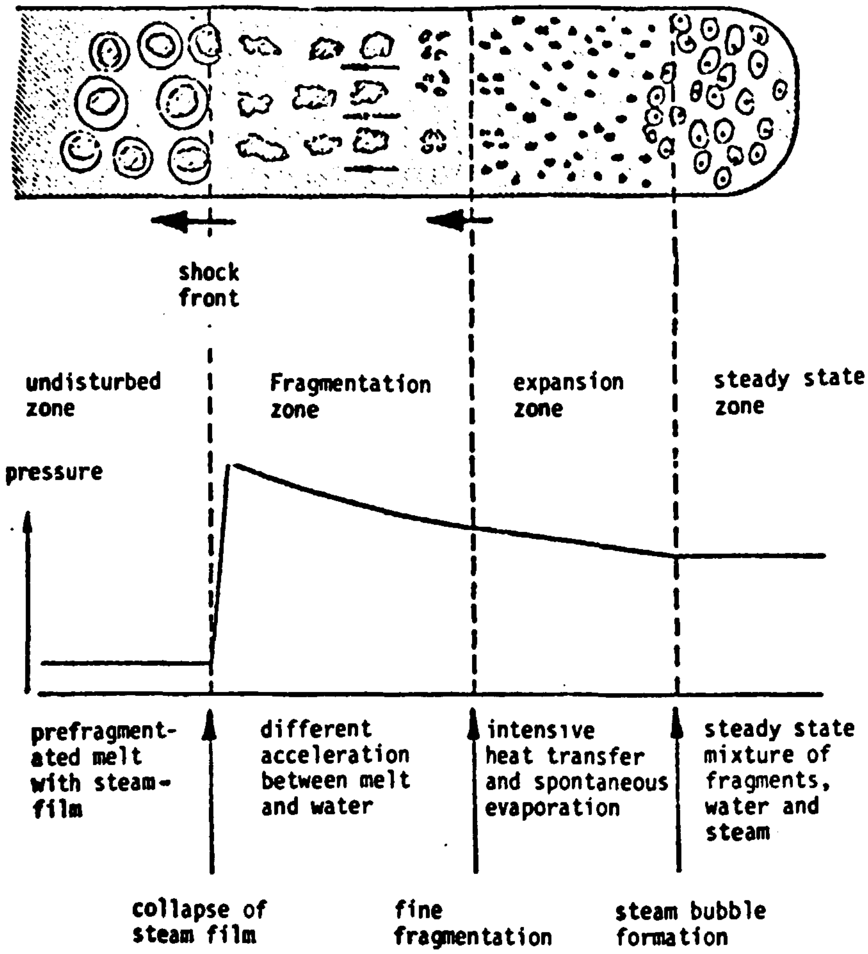


Fig. 3: Pressure induced detonation:
Diagrammatic description of the one dimensional shock front with fragmentation, expansion and evaporation

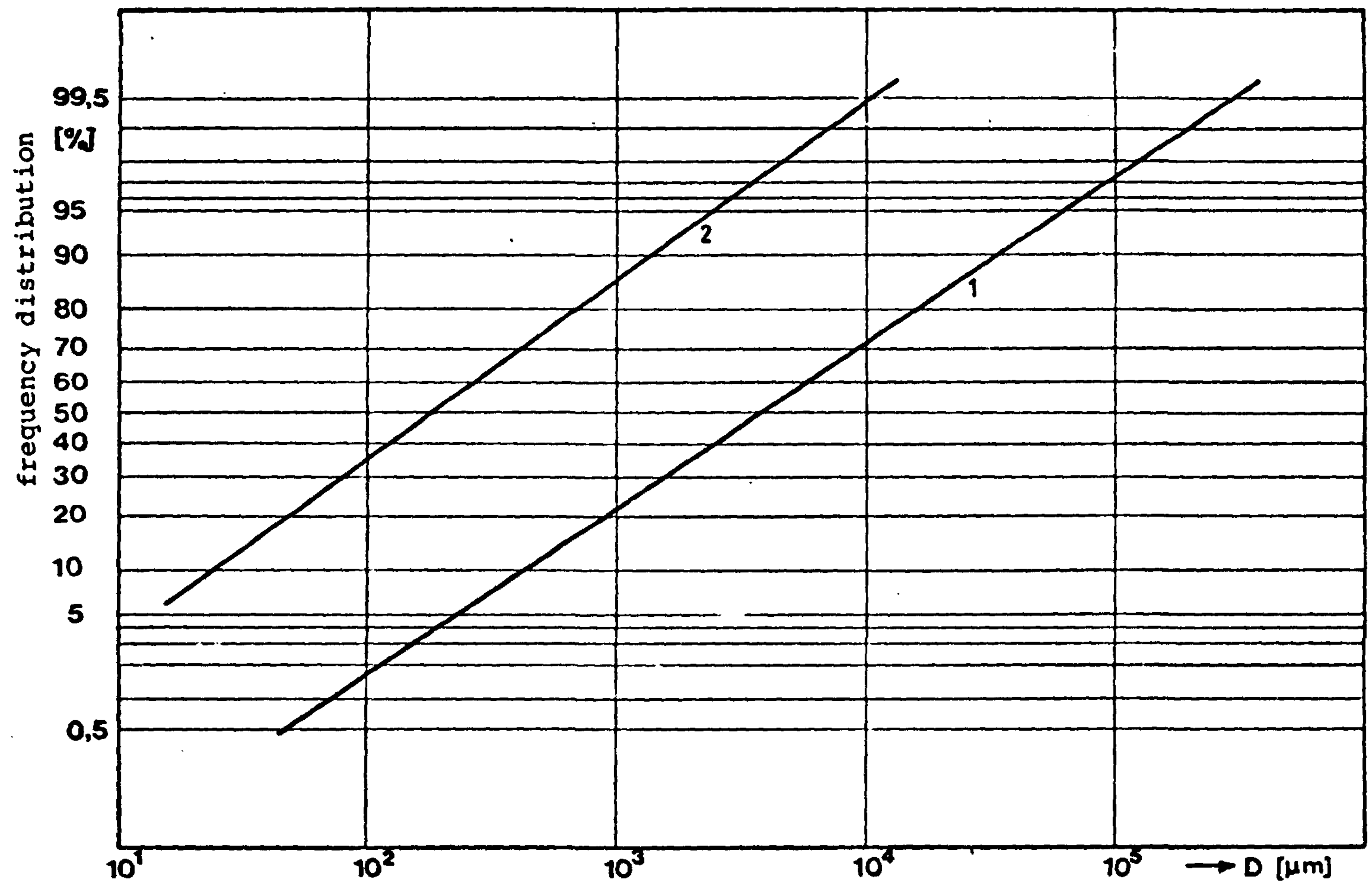


Fig. 4: Range of fragmentation determed from experiments (frequency distribution curve as function of the sphere diameter)

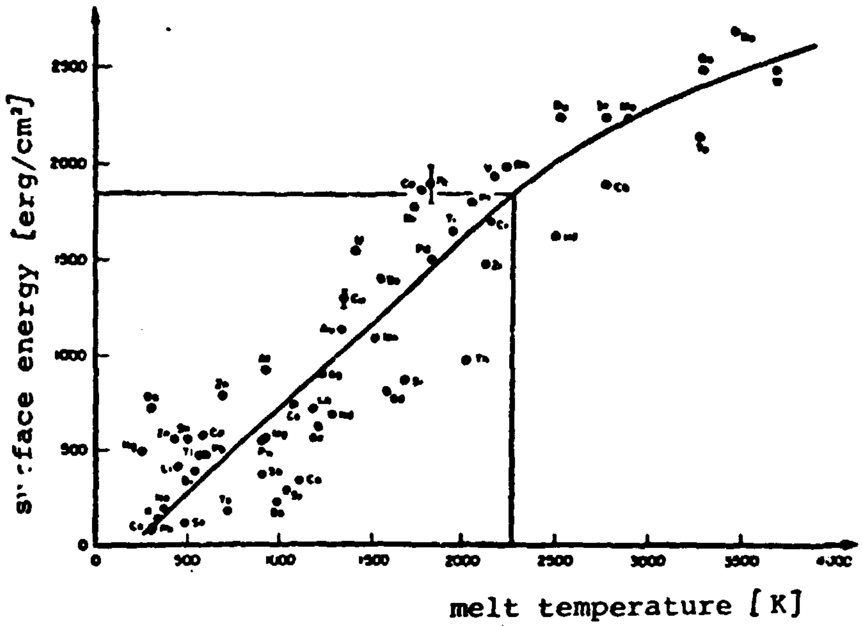


Fig. 5: Surface energy of different metals as function of melt temperature

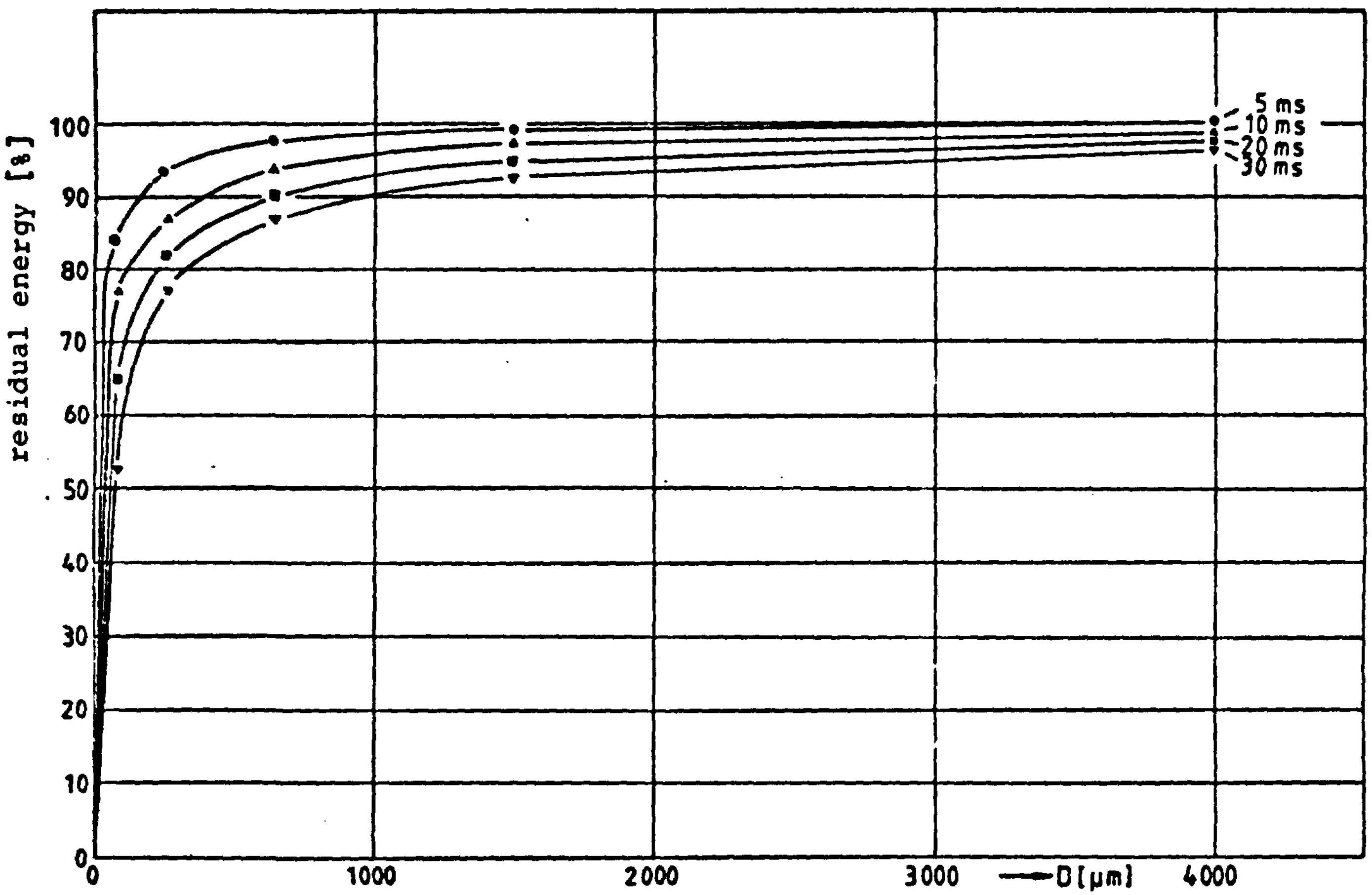


Fig. 6: Residual energy of the melt as function of the particle diameter

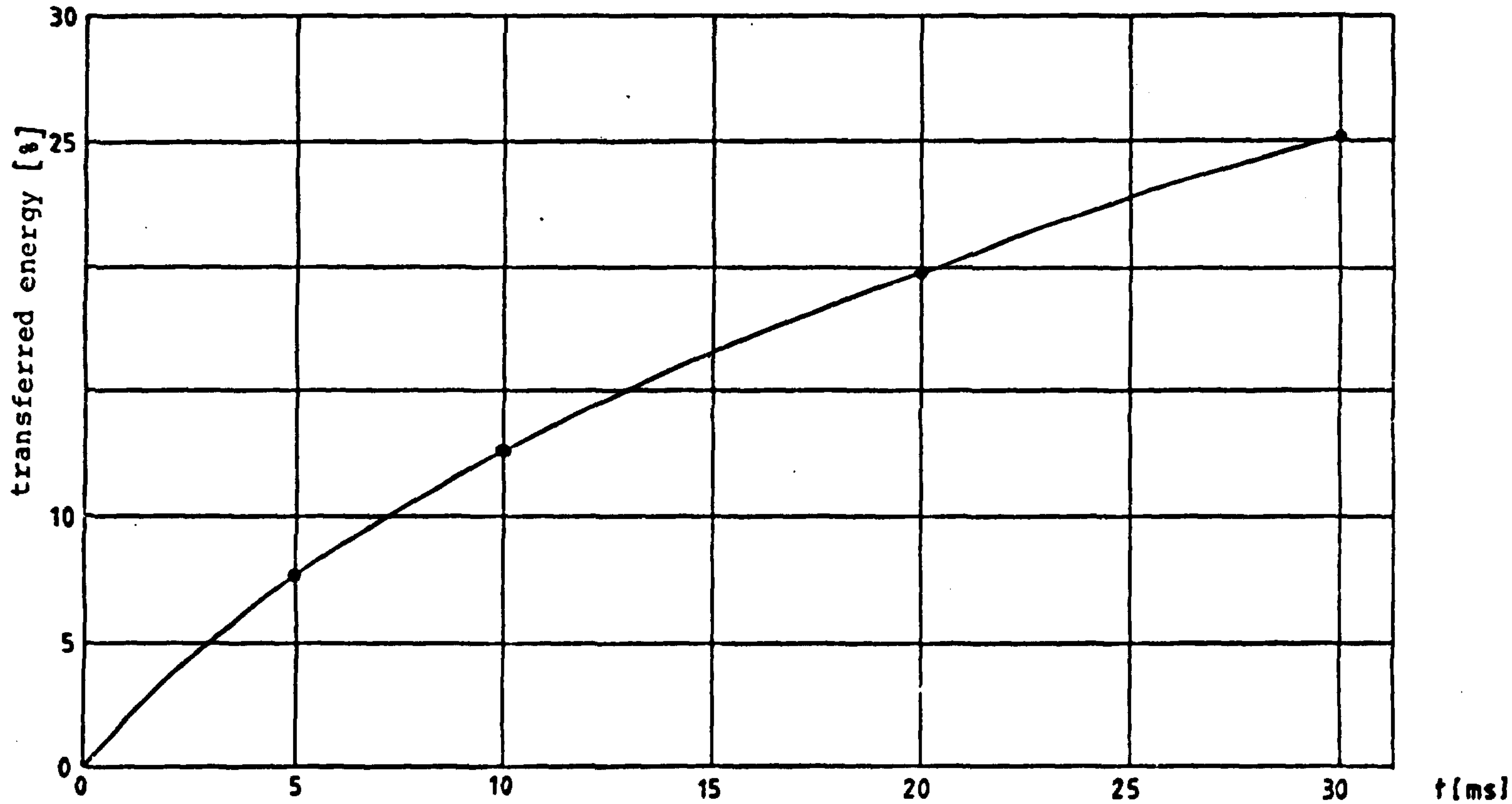
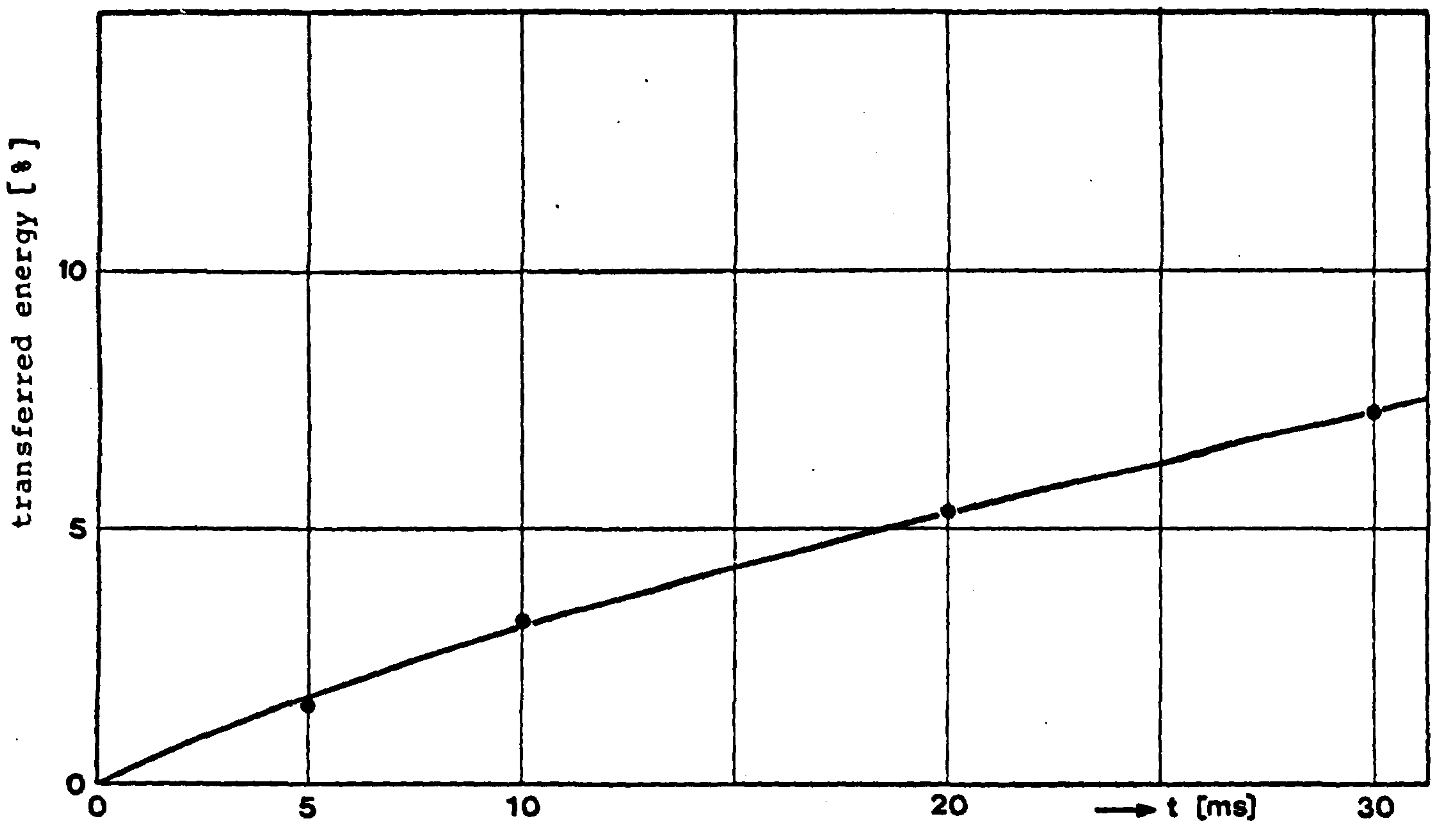


Fig. 7: Transferred energy from the melt to the water as function of the heat transfer time. (based on curve 2 in fig. 4)



<u>Fig. 8:</u> Transferred energy from the melt to the water as function of the heat transfer time
(based on curve 1 in fig. 4)

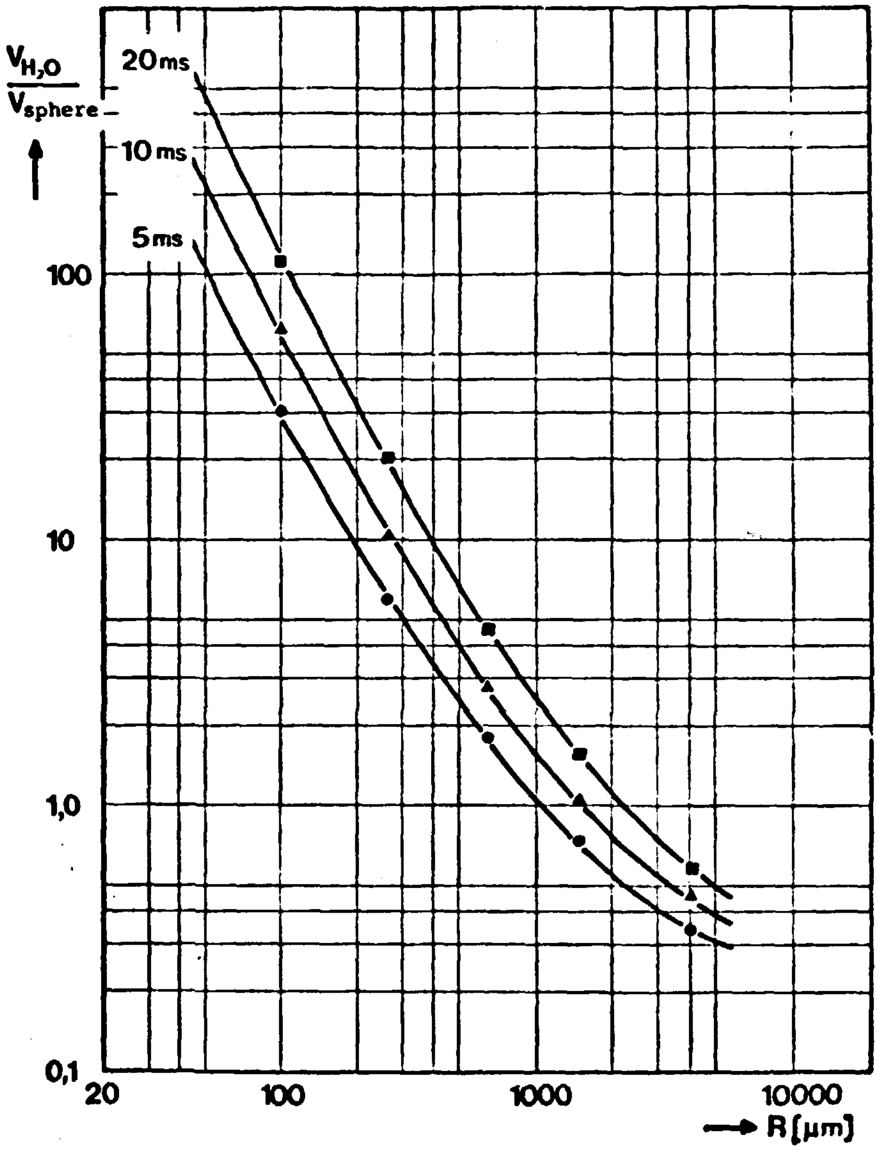


Fig. 9: Water volume calculated by the thickness of the temperature boundary layer referred to the particle volume as function of the particle radius

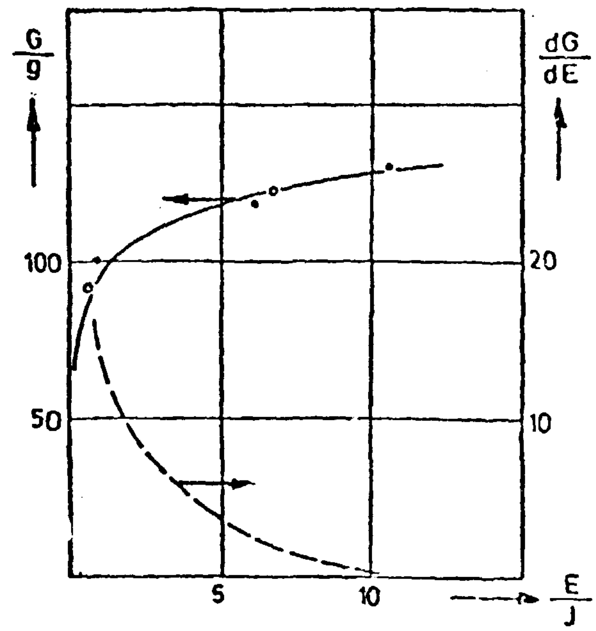


Fig. 10: Molten mass G taking part in the interaction as function of the energy E. The energy E is absorbed from the melt during the falling of the water column.
With increasing energy of impact decreases dG/dE.

CORIUM E-X2:	one-phase melt	T_{melt} = 2000° C
	weight %	At.- %
Cr	14,7	17
Ni	8,4	9
Fe	52,4	64
O	0,1	0
U	15,7	4
Zr	8,7	6

Table 1: Components of CORIUM E-X2

Appendix 6

ASSESSMENT OF CERTAIN INVESTIGATIONS CONCERNING THE ENERGETIC INTERACTION OF MOLTEN FUEL AND COOLANT IN LWRs

Professor Bryan McHugh
Chalmers Tekniska Högskola
14th November 1980

Study performed for the Ångexplosionskommittee, Stockholm

Assessment of certain investigations concerning the energetic interaction of molten fuel and coolant in LWRs

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At the request of the Swedish Steam Explosion Committee an assessment has been made of the two reports:

"An Assessment of Steam Explosions in the Safety Analysis of Light Water Reactors" by Fauske October 1980

"Review of State of Art of Steam Explosions" by Mayinger Undated

together with certain supporting material.

This assessment has been carried out as a matter of urgency and has been based on very little supporting material outside of that provided by the Committee itself. A certain amount of elementary calculations were done to check the main quantitative conclusions drawn by the two authors in their work however.

This assessment is aimed at providing a judgement as to the veracity of the conclusions presented and the support provided for them.

No general survey of the problem is given here, since the Committee is well informed on these matters.

As a summing up of this assessment it must be said that both authors conclude that the magnitude of any steam explosion in a LWR plant is of limited size. This conclusion is based on an engineering judgement of the situation rather than calculated phenomena.

Whether this conclusion is acceptable to the general public in Sweden is open to question. Hopefully it can be presented in such a manner that the low risk can be accepted until such time as ongoing research programmes lay to rest such uncertainty as is evident.

Assessment of Fauskes report

In my judgement the following passages are pertinent in an assessment of the contents of the report:

The WASH-1400 calculations showed that the 'cutoff' parameters of particle size greater than 1 cm or melt drop-times greater than 2 s apply to both BWR and PWR with respect to the rupturing of the reactor vessel. These calculations 'misrepresent the explosive behaviour in that 1)they assume that all liquid-liquid systems with substantial temperature differences can explode. 2) no consideration is given to the rate ...(of)..contact, 3)mixing is assumed to be instantaneous..'

Next the point is made that in actual explosive reactor experience (BORAX SPERT SL-1) very rapid power excursions, premixing of fuel and coolant, and low pressures were necessary ingredients which are not present in commercial PWRs.

There next follows a discussion of the actual configuration in real LWRs with regard to possible core drop-times and mode of core-support failure. THe treatment is essentially qualitative and discursive, with no experimental or theoretical support.

The same comment can be made with regard to the subsequent treatment of the likelihood of a massive slug of water rupturing the reactor head closure. Jet effects and other detailed events are ignored as irrelevant. Furthermore the reactor vessel is assumed to be in a non-degraded condition fully capable of withstanding considerable attack. Questions of prior vessel damage from earlier events in an accident sequence, or from bad operational practice (fatigue or faulty handling of bolts etc)are ignored.

Next follows what is essentially a discussion of the effects of pressure. The thesis is proposed that above about 1MPa significant explosions are precluded in water. 'the probability of a steam explosion itself is insignificant .... the probability of containment failure is also negligible' for situations where the 'lowest system pressure is greater than ... cutoff level'.

Triggering of violent events is not expanded upon - it is admitted to exist and some influence on the 'cutoff' pressure level is allowed. For lower water system pressures the probability of a steam explosion 'must be assumed to be essentially unity'. This conclusion is mitigated by the fact that 'only ... very small fractions ... can be mixed to provide explosive interaction' and 'the formation of a coherent slug (is) essentially impossible'.

The use of the many qualifications as to degree and likelihood concerning these violent events should be noted.

The questions of mixing and the formation of coherent slugs seem to lie at the heart of Fauskes judgement as to the innocuous nature of steam explosions in LWR plant.

With regard to mixing, energy requirements would seem to preclude the breakup and dispersal of larger quantities of molten fuel in water. This conclusion is based on considerations of available times and the energies available. The rather detailed calculations presented are based on a rather rapid event sequence prior to the triggering of an explosion. No justification for these assumptions is presented. In the presence of the very large amounts of thermal energies in the molten material it would seem better to study the triggering and/or delays of the violent events before establishing the relatively benign scale of the subsequent reactions.

The problem of pool boilup which is assumed to prevent the formation of a dangerous coherent water slug above the site of an explosion is also presented in a rather general manner. No attempt is made to treat possible channelling or focusing effects. The generation of internal missiles in the vessel or the questions of deformation and damage to vessel internals with possible effects on vessel intergity are also not mentioned.

In summary engineering judgement is invoked to a very large extent when reducing the problem of a steam explosion to that of no significance with regard to vessel or containment integrity. The possible consequences of explosions violent in themselves, but not sufficient to cause an immediate rupture are surely worth investigating.

Assessment of Mayingers report

For present purposes the interaction of the core melt with water in the vessel, and the possible subsequent interaction with water in the containment are the phases of dominating interest among the four identified in the report.

The meltdown process - relatively leasurely - has been studied theoretically and experimentally, and recent work is cited to support the thesis that molten fuel reaches the lower plenum 'more or less continuously in small mass flow rates'. 'It is physically hardly imaginable that a larger quantity of the liquid melt can be hold (sic) up in the core region without an early flowing down into the water of the lower plenum'. Thus Mayinger - like Fauske - uses qualitative arguments to postulate that only small quantities of molten fuel are of interest in a given time scale.

In what follows is postulated that a fine degree of fragmentation is required for a 'large scale steam explosion'

It is concluded, in a rather discursive passage, that the chances of larger explosions outside the reactor vessel on the containment floor are diminished by the heterogeneous nature of the problem.

Meyinger then cites actual reactor experience and draws the same conclusions as Fauske as to their relevance to commercial LWRs.

From a discursion on the two current theories or models of steam explosions no conclusion can be drawn as to which theory is preferred. 'There are many activities in the world to get a more satisfactory explanation and theory for thermal detonations'. 'A scaling to the geometrical conditions of a nuclear reactor, however, is very difficult' - even if very desirable.

Since the fragmentation and dispersal of the molten mass in water is of vital influence on the magnitude of the possible reaction considerable space is devoted to calculations (or estimation) of these phenomena. First can be noted that thermal effects are felt to be more important than possible kinetic energies from the necessary drop. A number of investigations in the field are cited - however no direct support is demonstrated. It thus remains an open questionas to the possible mechanisms dominating melt fragmentation under different conditions, and thus the actual amounts to be experienced under real conditions.

With regard to the dispersal of the melt fragments agreement with Fauske is obvious as to the excessive amounts of energy required. Investigations by other workers are cited in support of this postulation. It seems that the energy to deform the melt and to propell droplets through water dominates any realistic energy budget - based on a time scale in the millisecond class.(As Fauske). Some rather simple estimates indicate that fuel masses of the order of 10^4 kr require toomuch of the available energy to disperse to the required degree.
The question of the time scale available in practice receives no real treatment. As a saving grace the very low efficiencies of energy conversion are demonstrated in the many cases of violent reaction events - although real steam explosions on a larger scale seem luckily very infrequent events.

In summary Meyinger feels that given a reasonably even rate of melt addition to water the reaction will be self-limiting - 'during a hypothetical core melt down accident certainly only a few hundred kilogrammes of melt would reach the water in the lower plenum until the first violent interaction between the melt and the water takes place .

Thus Meyinger - in agreement with Fauske - concludes that small scale explosions 'up to instantaneously reacting mass of a few hundred kilogrammes may occur'.

Summing up

As a summing up of the two reports studied here it can be concluded that the actual nature of steam explosions and the mechanisms of their initiation are not yet understood in quantitative detail. This makes the question of scale up from available experience to a full reactor core open to different interpretations.

In view of this the two authors are in agreement in trying to put an upper limit on the fragmentation and dispersal of the melt which seems indispensable for any explosion. By assuming that these processes must take place inside milliseconds it is possible for both of them to reach the judgement that only very limited explosions will occur (order of 10^2 kg)
Explosions of this magnitude are assumed not to be capable of rupturing the reactor vessel and/or containment building.

As a further qualification both authors cite low probabilities for conceivable events - or that they can be 'unimaginable'.

Thus it must be concluded that as a matter of engineering judgement destructive steam explosions are not to be expected in our LWR plant. The conversion of this judgement into a calculated and verified fact needs further work.

Whether this conclusion is acceptable to the general public, as opposed to the consensus of the competent engineering profession cannot be resolved here. Hopefully it will be possible to present a favourable picture of the situation by citing the positive programme of work aimed at reducing in an orderly manner the uncertainties inherent in the situation.

In mid October Dr W R Stratton of the Los Alamos Scientific Laboratory in New Mexico was asked by the Committee to submit a short review of the steam explosion phenomenon.

Due to delays in the postal service Dr Stratton's report arrived in Sweden on December 3, or two days after the Committee's report was finished. However, it was decided to include Dr Stratton's report as an appendix to the Committee's report.

Appendix 7

COMMENTS ON THE STEAM EXPLOSION PHENOMENON

BY

WILLIAM R STRATTON

REPORT SUBMITTED

TO

THE SWEDISH STEAM EXPLOSION COMMITTEE

LOS ALAMOS, NEW MEXICO

NOVEMBER 1980

Dr. William R. Stratton has been a staff member at the Los Alamos Scientific Laboratory (LASL) since 1952. He has been intimately involved in a wide spectrum of reactor safety studies during his professional life, and has made outstanding contributions to the overall United States power reactor program.

He has been a leader in theoretical studies connected with criticality safety, parameters associated with critical and near critical systems, and studies of the dynamic behavior of supercritical reacting systems. Dr. Stratton has had extensive experience in research connected with critical assemblies. He was a leader in research involving the 17-year Rover Program at the LASL, in which a series of very high-power-density, very high-temperature, gas-cooled reactors was designed and tested. Dr. Stratton was also involved in design of -- and prediction and analysis of -- the Kiwi-TNT experiment at this Laboratory, which established an experimental baseline for theoretical prediction of reactor excursions.

In 1958, Dr. Stratton used, for the first time, a rigorous, physically and mathematically correct computer code for the analysis of postulated accidents in fast reactors and critical assemblies. The accuracy of this code was later confirmed

-more-in many experiments, and the prediction of the Kiwi-TNT event in 1965 was completed by use of a code derived from the 1958 code developed by Dr. Stratton.

Extensions of these early codes have been developed at Los Alamos in recent years, and they have reduced the magnitude of postulated accidents to the point of becoming unimportant. These efforts are demonstrating inherent safety factors in the liquid metal fast breeder reactor.

Dr. Stratton was the United States representative to the Cadarache Laboratory in France from 1965 to 1966, with his special interest during this tenure being in the fields of fast reactor safety, criticality safety, and critical experiments. He was a member of the Advisory Committee on Reactor Safeguards from 1966 to 1975, and now serves as a consultant to this committee. He has served as a member of the Los Alamos Criticality Safety Committee since 1960.

The LASL physicist was a member of the Washington, D.C.-based "Killian Committee" in 1954 and 1955. The Killian Committee was an ad hoc advisory group to the President's Science Advisory Committee.

He is a member of a committee created by the National Academy of Sciences to perform a broad and thorough literature survey and evaluation of the hazards and measures of risk associated with the entire commercial nuclear industry. The group reports to the Academy's well-known Committee on Science and Public Policy.

Dr. Stratton was a member of the U.S. team of experts that assisted Canadian Atomic Energy personnel in the evaluation of the hazards presented by the Russian spacecraft reactor that disintegrated in the upper atmosphere over Canadian Northwest Territories. Dr. Stratton acted as advisor on criticality and safety.

Past activities at LASL have included theoretical nuclear weapon design, Rover reactor design and safety research, and criticality safety studies in parameters appropriate to criticality. A continuous effort since 1957 has been in the general area of fast reactor safety.

A member of the American Physical Society, the Society of Sigma Xi, and the American Association for the Advancement of Science, Dr. Stratton is also a Fellow of the American Nuclear Society (ANS) and is a member of the ANS Board of Governors. He is a consultant to the U.S. Division of Reactor Development and Demonstration, and is the author of more than 50 scientific papers dealing with reactor safety, development, and analysis. He is coauthor, with Dr. R. B. Lazarus of LASL, of a book, "Computer Methods in Reactor Physics."

Dr. Stratton's contributions to the rapidly expanding field of reactor technology are many. He is internationally recognized for his outstanding contributions to this most important field of research.

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COMMENTS ON THE STEAM EXPLOSION PHENOMENON

Introduction

The matter to be discussed is the "steam explosion phenomenon," and whether or not this physical effect can be regarded as a serious, credible threat to the integrity of a reactor vessel and the containment building.

The plan of this report will be to: (I.) state the assumptions and conditions required if a steam explosion is to threaten containment; (II.) discuss these conditions and assumptions, their credibility, reasonableness, and conservatism or non-conservatism; (III.) discuss at least some of the pertinent experimental information; (IV.) discuss the application of hydrodynamic theory to the experiments and to postulated reactor conditions; and (V.) finally, offer my personal conclusions as to whether the steam explosion is a serious and credible threat to the integrity of the containment building.

I. Assumptions Necessary if a Steam Explosion is to Threaten Containment:

1. An accident must occur that leads to the melting of fuel. A significant fraction must become molten.
2. Subsequent to the melting of fuel, some fraction of core must fall or stream into the water in the lower plenum of the reactor vessel.
3. Fragmentation of the streaming or bulk fuel must take place after it falls into the water. The particles

in this phase will not cause a steam explosion. This phase of the event is known as "pre-mixing" in the jargon of this specialized technology.

4. After the molten fuel has fallen into water, but prior to any actions creating turbulence or large steam pressures, the liquid water and/or molten fuel is assumed to reestablish a uniform and continuous layer above the pre-mixing zone in (3) above -- a piston-like structure.

5. Either spontaneously or following a "trigger" event, a rapid interaction (transfer of heat) between particles and water must occur. This is the beginning of the "steam explosion."

6. The steam (at high pressure) forces the layer of water and, perhaps, fuel upwards at high velocity without loss of integrity of the piston-like structure.

7. Any remaining structures (undamaged or only partly damaged fuel assemblies, control rod guide tubes, lower grid assembly, flow distributor, etc.) will not influence the shape or motion of the water or fuel-water piston.

8. The water or fuel-water piston must strike the top of the vessel in a manner with impulse sufficient to create a large missile out of the top of the reactor vessel. This missile, then, is the threat to the containment building.

II. Comments on the Assumptions in Section II:

1. Since the occurrence of the accident at Three Mile Island, an accident during which fuel melts is regarded with more credibility than was the case before. The consequences of a fuel melting accident, however, may be less severe than is sometimes postulated.

2. To my knowledge and belief, the heating of a reactor core to and through the melting phase has not been calculated with adequate rigor. Such a calculation would require the inclusion of decay heat, radiation heat transfer, heating of support structures, convective cooling by any water vapor present, etc. In lieu of such calculations, reasonable assumptions must be made. In this discussion, I assume that when fuel becomes molten it flows or streams downward, sometimes freezing and remelting, but eventually falling, dripping, or streaming into the lower plenium. Such streaming may be only semi-continuous, but to postulate that all or even a significant fraction of the core becomes molten and falls a unit is unreasonable and is rejected as a working hypothesis.

3. The "pre-mixing" postulated here has, in fact, been seen during experiments designed for visual observation. The fragments are coated with steam and lose heat by the film boiling mechanism. This phenomenon will be mentioned again in the discussion of experiments.

4. This assumption is very conservative if the streaming assumption of (2), above, is accepted. The phenomenon of molten fuel falling into water demands turbulence; much of the core may not be liquid when molten fuel first falls into water, and most

of the support structure, guide tubes, etc., will be intact. Thus, to assume a uniform layer of water and/or molten fuel is both very conservative and unrealistic. In defense of the theorists, the exact computational model would be near-impossible. Simplifying assumptions are necessary.

5. The "trigger" event is an action that destroys the vapor film on some of the pre-mixed fragments. This event can be mild like the touching of fragments against the bottom of the vessel, or something forceful like the explosion of a small H.E. detonator. The interaction is seen as a very rapidly expanding wave which (to my understanding) destroys the vapor film on some particles, allowing water to touch the surface. This leads to rapid heat transfer and sometimes to additional fragmentation which in turn allows more heat to move from fuel to water. The action creates a high steam pressure and leaves behind a spectrum of particle sizes, some very small, some relatively unchanged. The phenomenon has been observed a number of times. Subsequent motion of the water is a spectacular spray, giving the impression of a violent explosion; the violence is the question to be investigated and made quantitative, not the existence of the effect.

The steam explosion is dependent on a number of variables, and the conductivity and freezing characteristics are very important. As will be discussed below, it is not clear that reactor fuel mixed with steel will at all go into this phase of a steam explosion. Thus, this key assumption correct for some materials, may be very conservative if not false for reactor fuel.

6. The accleration of a dense but thin fluid layer by a much lighter fluid is inherently unstable. The distance to be

covered before the fluid layer impacts the vessel head is about five times its thickness. This distance (and ratio) is sufficient for the development of instabilities, and these are seen in the computation discussed below. The "piston" effect will be destroyed.

7. This assumption is unreasonable and overly conservative. Structures in the reactor vessel, as discussed above, will remain in place and certainly will perturb the motion of the liquid as it is moved upward. Again, simplifying assumptions are necessary in order to perform a calculation, but the conservatism must be recognized.

8. A large missile can be created only if the water piston strikes a flat surface. The top of the vessel is curved as a sphere, thus focussing any motion to the topmost point. A large missile if any is therefore unlikely. The forest of control rod guide tubes would tend to destroy the coherence of any motion of a fluid piston.

In summary, assumption postulates (1) is a low probability event, lower than calculated in WASH-1400, the Reactor Safety Study, because a significant fraction of the core must become molten. Assumption (4) is very conservative, as are assumptions (5) (by nature of the fuel), (6), and (7). Some of these same matters are discussed in reference 9, a communication by Professor A. B. Reynolds, University of Virginia.

III. Discussion of Experimental Information:

The discussion of experiments will be brief and in summary manner. A detailed review would require a very considerable effort over a long time, and is not necessary for the purpose of this report. The general character of two important classes of experiments will be discussed, but without reference to specific experiments.

The experiments performed with liquid metals or liquid metallic oxides in water bear on the efficiency and speed of the interaction (heat transfer to water). Experiments 1, 2, and 3, at the Sandia Laboratories in Albuquerque, New Mexico, have included use of at least two materials, a mixture of Fe and Al_2O_3 and a mixture of UO_2 and steel, the latter called, "Corium-A." The former has a relatively high conductivity and a sharp melting point. Experiments using this material generally were started well above the melting temperature, and steam explosions were almost invariably observed after dropping the molten material into water. If the efficiency is defined as the ratio of the water's kinetic energy to the heat energy released when the material is quenched to ambient temperatures, this efficiency varied, apparently randomly, between zero and about 0.6%. Some very few experiments showed a higher value. One of these experiments was used (as discussed below) as a test case for the SIMMER hydrodynamic code.

The experiments with the second material, UO_2 mixed with some steel, showed an entirely different character. This material has a low conductivity, a broad range of melting temperatures, and the initial temperature for experiments was barely above the melting region. No violent steam explosions were observed. Efficiencies were less than 9.1%, probably below 0.05%. The initial fragmentation (pre-mixing) seemed to occur, but the material was cooled primarily by the film boiling mechanism. The film is near-stable with this material, as opposed to apparent instability with high conductivity material.

These experimental results are sufficient in themselves be disqualify the steam explosion as a serious threat to the reactor vessel and containment building.

Very similar experimental results were obtained at the University of Stuttgart[8], over a year and a half ago*, prior to the Sandia experiments. The results are best described by including some brief quotations from the report: "The main result is that no explosive interaction has taken place, but a rapid evaporation with a rather weak pressure rise..." "The time of this pressure rise is approximately 2 seconds the condensation time some 10 seconds in all experiments." "The movies show that a remarkable part of the fuel is cooled down under film boiling conditions over a long time." "In the case of molten UO_2 and SS, approximately 60% of the mass had particle diameters of more than 4000 $m\mu$(=0.4cm)."

*These experimental data (Reference 8) were not known to me or to others working with the staff of the President's Commission to Investigate the Accident at Three Mile Island. Some conclusions might have been strengthened[10] if the results had been known.

Thus, the experimental situation shows that for metallic-like materials (e.g., Fe-Al_2O_3), steam explosions occur but with very low efficiencies. The efficiencies vary between zero and 0.6% with an occasional experiment showing a higher value. Experiments with core-like materials (UO_2+SS≡Corium), on the other hand, show no steam explosion or only film boiling.

I fully expect that experiments will continue in the future with larger masses of Corium/and with better instrumentation and control of conditions. It is important to be sure about scaling laws and to look for the unexpected phenomena; however, I believe that future experiments will be confirmatory in nature rather than exploratory for new phenomena.

THE APPLICATION OF THEORY TO THE EXPERIMENTS AND TO A REACTOR VESSEL

1. Two hydrodynamic computer programs have been applied at Los Alamos to the steam explosion phenomenon. These are the SIMMER Code[6] and the SOLA-VOF Code[7], each of which will be described briefly. The response of the reactor vessel (for a pressurized water reactor) was examined with the aid of ADINA[1], a finite-element program created for purposes comparable to the application herein. Results from the application of this program will be given, but the code itself will not be discussed.

2. SIMMER and SOLA-VOF:

Both of these computer programs are so-called Eulerian hydrodynamic codes that make use of the doner-acceptor model for fluid motion. By this is meant that the coordinate mesh which defines geometry and location of material remains fixed in space, and the fluid (liquid or vapor) moves across mesh boundaries as may be required by the pressure in each region of the mesh. Geometric details may be as fine grained as desired in order to simulate adequately the desired physical motion. Both programs derive from the same differential equations and, basically, use the same scheme for conversion to difference equations.

To this point, the two programs are essentially the same. Differences will be mentioned as more details are discussed.

The SIMMER code includes provision for the transfer of heat from material particles to water, allowing for size, conductivity, phase change, etc., and makes use of the local (cell) density and temperatures to generate a local pressure. This pressure function can be recalculated for each cell for each time step. The SOLA-VOF code does not have the provisions and depends on a Pressure-Volume function generated by SIMMER to provide the driving pressures.

Both codes allow for the calculation of gross instabilities associated with accelerations. For example, if one section of a liquid layer is thinner than an adjacent section the acceleration of the former will be larger and thus increase the discrepancy. Eventually the high pressure vapor will "break through" the liquid and tend to equilibrate pressures and decrease gross accelerations. This effect is seen in the results from both codes.

Given the distortion of a layer of liquid so that vapor bypass occurs, a model for the motion of high velocity vapor streaming against the liquid must be part of the program. The SIMMER code has provision for shear forces between vapor and liquid, thus allowing for entrainment of liquid drops into this moving vapor. This action probably is a very reasonable simulation of the spectacular spray effect seen in the experiments. This entrainment or spray spreads out in time the impact of water on the vessel head and is important for this reason. The entrainment model was found to be a very important variable in the testing of SIMMER against experiments (pages 19, 23, reference 4). The elimination of entrainment was found to increase the kinetic energy by a factor of about seven. The SOLA-VOF program does not have any entrainment model, as one objective of the program was to maintain the "Volume of Fluid". Neither was the SOLA-VOF tested against experiment. To summarize briefly: The SOLA-VOF code does not allow for any entrainment of liquid in the streaming vapor and does not any instability at the surface of the liquid. These are serious limitations in a conservative sense, and significantly reduce the value of the studies. This point will be touched on below in Section V.

Similarly, the bottom and top surfaces of the liquid as calculated by SIMMER are subjected to change simply because the motion of one fluid into a cell filled by another creates a "softness" and a spread of impact in time. This calculational effect reflects real phenomena similar to the entrainment - spray model. The SIMMER code allows for this effect, while the SOLA-VOF code denies it and in fact, has a scheme to suppress the phenomenon and maintains the volume of fluid.

Both codes allow for the free slip (no friction) of fluid against the core barrel or vessel structure, whichever is appropriate.

Both codes assume that all core, support and reactivity control structure has become molten or disappeared, even though for example, the "forest" of control rod guide tubes has no source of heat to cause them to melt. This assumption of both programs is very conservative.

It is certainly the case that much structure will remain and interfere seriously with the motion of a liquid "piston" up the vessel.

3. SIMMER CODE, COMPARISON TC EXPERIMENT:

In order to establish whether or not the SIMMER code[6] could reproduce the results of steam explosion experiments, one experiment was examined carefully and reported in Reference 4. This experiment was number 43 as described in Reference 12. The materials in the experiment were kilogram quantities of hot Fe-Al_2O_3 poured into water. Assumptions about particle size and relative volume fractions of fuel, water and steam had to be made for calculational purposes. The particle size was taken to be 300 microns while the fuel: water: vapor fractions were 50:25:25, a large fraction of liquid metal in the interacting volume.[5] The material constants were assumed to be those of Corium-A rather than Fe-Al_2O_3 and thus the particle size is smaller than would have been the case if the lower conductivity material (I believe that the Corium-A experiments were nto completed at the time of the theoretical study) had been modelled. These assumptions enabled the SIMMER code calculation to reproduce the pressure heating of the experiment quite well and the efficiency was close to the measured value. However, we must note that the initial assumptions are not unique. The particle size and volume fractions of materials can be changed and moreover, the distribution of particle size and spatial distribution of material may be important. Nevertheless, it was demonstrated that the SIMMER can reproduce, reasonably well, the thermodynamics and dynamics of a steam explosion. To my knowledge, this is the best calculation extant of the phenomenon.

4. SOLA-VOF:

This testing of the code was not completed for the SOLA-VOF code; it depended on the testing for SIMMER. Additionally, because of the special provisions in SOLA-VOF code to maintain well-defined liquid vapor boundaries, some question would be raised as to how to proceed with the testing.

5. STUDIES SIMULATING A REACTOR VESSEL:

Four studies of reactor steam explosions were completed using the SIMMER code[6]. The material constants were the same as those discussed above; Corium-A particles of 300 micron diameter, and 10% to 20% of the mass of the core was assumed to be pre-mixed in the lower plenum water, either directly below the core or around the periphery of the vessel. The remainder of the core was assumed molten and distributed uniformly across the vessel. No core support or other structures were accepted as remaining in the vessel and the fluid was allowed to slip without friction as it was forced upward. When appropriate fluid forced near the inlet or outlet nozzles was allowed to disappear through the nozzle. Two equations-of-state were used for the very high temperature, super-critical state of water. The code predicted that the thin liquid layer was unstable and did break up into large, discrete regions. This allowed open paths for high pressure vapor to flow at high velocity past the large discrete masses, entraining liquid as it passed and a equilibrating pressures throughout the vessel in a few tens of milleseconds. The entrainment of liquid and the surface instabilities described earlier essentially softened or extended in space the liquid forced upward.

This extension lessened the blow as the (now somewhat diffuse) ($\int Fdt$) was lowered. The calculated kinetic energies of these calculations were between 1100 and 3400 megajoules. Loading on the vessel was concentrated at the very top which would produce a localized strain at this point. Data from these computations were incorporated into the ADINA code to allow an estimate of the distortion or strain or rupture of the reactor vessel. It was found that the 1130 MJ result would be contained rupture but a more important calculational discovery became evident during the study. This was the observation that at some level of energetics, the first failure of a vessel would be in a downward sense, as the lower head region is the weakest area of a pressure vessel. The sustained pressure to force a piston of fluid upwards will strain and possibly fail the lower head. The estimates for the maximum upward directed kinetic energy before failure of the bottom head had to be assumed were not fixed precisely. First estimates were as low as 500-800 MJ, but qualitative arguments were made (Reference 4) that this was too low and that a range between 1000-1500 MJ might be more nearly correct and "used with considerably increased confidence"*. As mentioned above, the ADINA code predicted that this magntude of kinetic energy, as calculated by the SIMMER code, would not lead to vessel failure.

Clearly, a number of conservatisms exist in this computer study; these and their importance, will be discussed briefly in Section VI, below.

The SOLA-VOF code was applied to three reactor vessel problems. As mentioned above, heat transfer, boiling and equation-of-state subroutives were not incorporated. The driving pressure as a function of time taken from the SIMMER problems with comparable initial conditions. Vessel nozzles were not a part of the geometric model. The special provisions to maintain the volume of fluid prohibited any entrainment of liquid and any "softening" of the

*I Interpret this phrase on the part of the authors to mean increased conservatism.

liquid at the vapor boundaries. One case was a perfect one-dimensional slab, accelerated upward, while the other two were two-dimentional problems with slightly different pressurized regions at the beginning. The slug shape for the first is admitted to be "a near-physical impossiblity;" I agree, and dismiss this case as grossly conservative and not useful. The second two predict kinetic energies very comparable to the corresponding SIMMER problem, and, again, forces are focussed to the center of the vessel head, but because of the constraints forcing maintenance of this volume of fluid, the impulse ($\int Fdt$) given to the vessel head is very much larger. The ADINA code predicts failure given the forces and their distribution in space and time. These computations are much more conservative than SIMMER because of the rigid requirement to maintain the volume of fluid, and for this reason are unrealistic. Furthermore, the program has not been tested against experiment and does not have incorporated models of heat transfer, boiling, and equations-of-state. My conclusions in regard to these calculations are discussed in the final section below.

IN SUMMARY AND CONCLUSION

Before giving my conclusions I wish to state a point of philosophy about safety studies to which I subscribe. A study that is clearly conservative in assumptions and methods and which predicts a benign or non-hazardous result is useful and can be used for purposes relating to public health and safety, (but not for design). A comparable study that predicts a danger or a hazard is equivocal (and nearly useless) and should not be used for matters relating to public health and safety without additional investigation to find the source of danger -- whether the physical situation or the study assumptions. A realistic or best-estimate study, however, that predicts a hazard or danger must be taken seriously.

Given this point, I judge the combined experimental work at Sandia and theoretical work with the SIMMER code at Los Alamos as a study, conservative in nature and assumptions, that predicts survival (no failure) of the reactor vessel should it be subjected to a molten fuel induced steam explosion. On the other hand, the Sandia work and the SOLA-VOF code predict a contrary result; but given the rule above, which I accept, I reject this second combination as equivocal; it does not contribute useful information to solution of the problem; and a more realistic, but still conservative study (SIMMER) predicts a safe result.

I will repeat some of the conservatism in the entire study:

1. In the testing of the SIMMER code against experiment physical constants for Corium-A were chosen instead of constants for $Fe\text{-}Al_2O_3$. The particle size was therefore, apparently too small.

2. Steam explosions with Corium-A are seldom if ever observed.

3. A particle size distribution was not used.

4. A very large amount of fuel (10,000 - 20,000 kg) was assumed to be mixed uniformly in the lower plenum water.

5. The particle size was 300 microns.

6. All remaining fuel and structure was molten and shaped as a layer across the vessel. This geometry is most unlikely.

7. The slug accelerated was high-density molten fuel.

8. The curvature of the vessel head focusses forces toward the central point at the top. This action places maximum forces at a point rather than throughout the head. If a rupture were indicated, an opening at the top would be much more probable than a large missile.

9. Steam explosions under pressurized conditions are more difficult to cause to happen because of greater stability of the vapor film. The expected conditions are usually at high pressure.

In conclusion, then, for the several reasons discussed above, I believe that failure of the reactor vessel of a pressurized water reactor from a steam explosion caused by molten fuel falling into the lower plenum is a physical impossibility. I believe that this postulated accident need not be considered further in the analyses of hypothetical reactor accidents.

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