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Report by an

OECD/NEA Group of Experts

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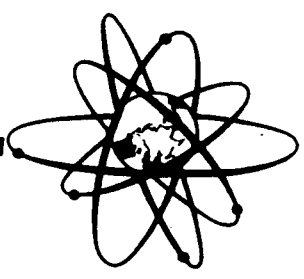

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS
OECD NUCLEAR ENERGY AGENCY
38, boulevard Suchet, 75016 Paris, France

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This report was prepared by a small expert group from CSNI's Principal Working Group on the Source Term and Environmental Consequences (PWG4) led by Dr. P.N. Clough (SRD, UKAEA), with contributions by Mr. M. Silberberg and Dr. J.C. Mitchell (USNRC), Dr. R.A. Brown and Dr. J.H.K. Lau (Ontario Hydro), and Mr. A. L'Homme (CEA/IPSN).

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The Relevance of the Chernobyl Accident to Source Terms for Severe Accidents in Water-cooled and Moderated Reactors of Western Design

1. INTRODUCTION

The accident at the Chernobyl Unit 4 nuclear plant in the USSR gave rise to the worst ever release of radioactivity to the environment from a civil power reactor. The repercussions of this accident on public attitudes towards nuclear power worldwide have been marked, and there has been a reaction in the nuclear industries of many OECD members to examine all aspects of the Chernobyl accident in order to determine whether there are lessons to be learned pertinent to the safety analyses of reactors of western design. An NEA group of experts has considered the broad safety implications of the Chernobyl accident for reactors in OECD member countries (1), and has concluded that there are no lessons to be learned with respect to the design, safety features, and operational practice regarding these reactors which would call into question the current assessments that severe accidents in them are extremely improbable. This expert group also concluded that no new phenomena concerning the prediction of severe accident source terms for OECD country reactors were observed from the Chernobyl accident. The purpose of the present report is to provide detailed technical support for this statement. Events at Chernobyl demonstrated that an RBMK reactor could give rise to an accident in which a significant fraction of the total core inventory of radioactivity was released. Because of this, there has been a tendency in some quarters to question the conclusions of a number of recent source term analyses for severe accidents in western water-cooled and moderated reactors (WCMR) pointing to substantial mitigation of releases in most severe accident situations. Correspondingly, there have been suggestions that the severe Chernobyl source term resulted from phenomena and mechanisms which have been neglected in analyses for western WCMR.

This report aims to define which, if any, features of the Chernobyl accident might be of relevance to source terms of western WCMR. Several important questions are addressed. Can we explain the details of the Chernobyl source terms by applying current knowledge of source term phenomenology and mechanisms? For these known phenomena and mechanisms, does the Chernobyl accident add significantly to our data base and understanding? Were there in fact important source term processes at Chernobyl which could be relevant to severe accidents in western WCMR, but have been overlooked? The answers to these questions provide the basis for an overall conclusion on whether there really are source term lessons to be learned from the Chernobyl accident.

2. BRIEF DESCRIPTION OF THE CHERNOBYL SOURCE TERM

A fairly complete description of the Chernobyl accident and resulting source term was provided by the USSR to the IAEA Experts' Meeting in Vienna, 25-29 August, 1986 (2). A synopsis of this material is first given, accompanied by an interpretation in terms of the probable conditions governing release and transport for radionuclides at various stages of the accident.

As is now well known, the accident originated from a series of operator mistakes and violations which put the reactor into an unsafe lower power operating regime with a positive power coefficient during the course of a

steam turbine run-down experiment. Voiding in the core coolant channels led to a prompt critical power excursion in which the reactor power is estimated to have risen to more than one hundred times normal operating power within a few seconds. Extremely high fuel temperatures, locally in excess of 3000°C, were generated resulting in fuel disintegration, fuel coolant interactions, and a steam spike which ruptured many of the reactor pressure tubes. Pressurisation of the core region then blew off the pile cap. This energetic event, possibly in combination with a rapid sequential explosion of hydrogen generated by a reaction between steam and hot zirconium alloy fuel clad and pressure tubing during the power excursion, destroyed the reactor building almost immediately. Thus a direct, massive breach was opened at the outset between the damaged core and the environment. As far as can be ascertained from Soviet information, fires then developed in the core and reactor building. The nature of these is unclear, but during the early stages burning of hydrogen from a continuing zirconium-steam reaction may have been important. Later on, combustion of the graphite moderator appears to have played a major role.

The Soviet account of the source term contains two main components. Firstly, there is a history of the total activity release from the plant. Secondly, a detailed breakdown of activity releases by specific isotopes at certain stages of the accident is provided. Four stages of release have been identified by the Soviets, related to the day-by-day total activity releases shown in Fig. 1. These values are all adjusted for radioactive decay to the 6 May, and thus represent the residual environmental burden on that date contributed by the activity released on the day in question. Certain inconsistencies in the Soviet information create difficulties in converting these data into actual daily activity releases. It is important to note that the Chernobyl release of radioactivity continued at a high level over a 10-day period. In this respect, the source term was very different from those predicted for severe accidents in western WCMR.

The stages of release defined by the Soviets are:

Stage 1 (26 April). This was the initiating in-core explosion at 01:24 on the 26 April. Fragmented fuel and moderator were ejected in the transient which blew off the pile cap, accompanied by enhanced releases of the noble gases and volatile fission products iodine, caesium and tellurium. Soviet estimates of the isotope-specific activity releases for the whole of the 26 April are shown in the first column of Table 2.1 (1). Expressed as release fractions, there is a clear distinction between the volatile fission products (release fractions 4-6%), and the more refractory species (barium, ruthenium and lanthanum groups of the Reactor Safety Study, release fractions typically 0.3 - 0.6%). The Soviet information does not specify how much the initial explosion contributed to the total release on the 26 April. Peak fuel temperatures may have exceeded 3000°C in some regions of the core. However, it has been stated that fuel temperatures fell rapidly to below 1500°C following the power excursion (Fig. 2), suggesting that most of the release occurred during Stage 1. The steam present probably reacted predominantly with the zirconium alloys composing the fuel clad and pressure tubing, producing a reducing environment for the fuel.

Stage 2 (26 April - 2 May). This was a period of steadily decreasing daily activity release. From the 27 April onwards, the decrease was

associated with the dumping onto the core of the large quantities of materials (boron carbide, dolomite, lead, sand, clay) designed to provide shielding, stifle the fires, and filter out non-gaseous radionuclides. By the 10 May, a filter bed of some 5000 te of these materials had built up. Nonetheless, substantial activity release continued during Stage 2, demonstrating that the filter bed was not fully effective. The composition of the released activity appears to have been whole fuel augmented in the volatile fission products by a factor of 3-5. The Soviets (Fig. 2) have quoted a fuel temperature of 1800K shortly after the initial transient, falling to 1000K during the 26 April and remaining at this level throughout Stage 2. Temperatures through the core must have varied considerably, and it is unclear whether these are peak or average values. Before dumping of material began, there was free air ventilation of the core debris, but this was restricted to some extent once the filter bed built up.

Graphite combustion was probably important in the hotter core regions through Stage 2. The Soviets have claimed that lift-off of previously impacted fuel particles during graphite burning was a major release mechanism. Even when the filter bed began to accumulate from the 27 April onwards, significant quantities of fission product vapours and fine aerosols continued to be released from the fuel debris and penetrated the filter bed.

Oxidation conditions probably varied considerably in different core regions during this stage. It is clear that releases must have originated mainly from the well-ventilated zones, otherwise transport out of the core would have been ineffective. Assuming an upwards airstream, conditions would have been strongly oxidising in the lower regions of the debris and would have become progressively more reducing as oxygen was consumed by reactions with graphite, fuel, and any unoxidised zirconium on passing upwards. The kinetics of the competing reactions will have played a key role in determining which processes predominated, and only a detailed modelling study is likely to shed further light on the prevailing redox conditions.

The Soviet account of the source terms is based only on measurements made in the USSR, and neglects the activity transported to western Europe and elsewhere. The fallout which reached Scandinavia and other western European countries shortly after the accident started was associated with the Stage 1 and Stage 2 releases. Some interesting observations made in the sampling of this activity are important in identifying the conditions and mechanisms of release. About three-quarters of the total airborne iodine was found to pass through particulate filters but be retained on charcoal beds, implying a high fraction of elemental or organic iodine. Also, examination of some micron-sized aerosol particles trapped on filters in Sweden revealed these to be composed almost entirely of ruthenium (3).

Stage 3 (3-5 May). This stage was characterised by a steadily increasing daily emission of activity in spite of continued additions to the filter bed. On the 3 May, a strong enhancement of the volatile fission product contribution to the activity release, notably of iodine, was observed. However, by the 5 May, the composition of released activity again assumed that of whole fuel with a modest enrichment of the volatiles. The reasons for the increasing release

during this stage are not entirely clear. The salient feature is that the core debris temperature was observed to rise steadily from the 2 May, peaking at around 2000°C on the 5 May. This probably resulted because the filter bed reduced heat losses from the core debris, trapping in the decay heat. The Soviets have suggested that during the high temperature latter period of Stage 3, reduction of the UO_2 by reaction with the graphite moderator may have played a role. However, it appears that oxidising conditions still prevailed in much of the core through Stage 3, limiting the possibilities of UO_2 reduction by graphite. The possibility that a core-concrete interaction occurred has been denied by the Soviet experts.

Stage 4 (6 May). The rate of activity release fell abruptly by a factor of almost 100 on the 6 May, and continued at steadily reducing levels thereafter. This fall is stated by the Soviets to have resulted from injection of nitrogen beneath the core, combined with the addition of "special materials" designed to trap radioactive species to the filter bed.

The reasons for termination of the release are again unclear. Two factors appear to have been important. The blanketing of the core in nitrogen probably extinguished residual graphite combustion and removed this heat source. It also terminated fuel oxidation, which may have had a significant impact. Additionally, the fuel temperature began to fall at this stage, so that more effective cooling must somehow have been achieved. One possibility is that fuel debris relocated from the moderator region to the lower vault, where increased contact with structures and the injected gas stream effected cooling.

Soviet estimates of the integral releases of activity for a selection of radionuclides in the Chernobyl source term as at the 6 May, corrected for radioactive decay to that date, are shown in the second column of Table 1. Corresponding integral release fractions are given in the final column. Overall, 100% of the noble gases, 10-20% of the volatile fission products, and 3-4% of refractory fission products, fuel and actinides, were released. The relative release fractions of these different groups show a pattern which is quite different from the patterns generally predicted in severe accident analyses for western WCMR. It should be emphasised again that the Soviet estimates exclude material which crossed the borders of the USSR. In the cases of the volatile fission products, there is evidence from integrated European ground sampling data that this limitation may have resulted in serious underestimates of the release fractions, by factors of about two.

In summary, it appears that the following phenomena and mechanisms were dominant in determining the radioactivity releases in the Chernobyl source term:

(i) Fuel overheating transient from 300 to 3000°C in a few seconds in a reducing steam environment. (Stage 1);

(ii) Fuel-coolant interactions, possibly involving molten fuel. (Stage 1);

(iii) Release from fuel in a predominantly oxidising (air) environment at temperatures between ~ 800K and ~ 2300K. No steam was present. Redox conditions varied with time and location, being determined locally by zircaloy, fuel or graphite oxidation.

(iv) Filtration of fission product vapours and aerosols by an ad hoc filter bed composed of boron carbide, dolomite, sand and clay, at temperatures up to 2300K (Stages 2, 3 and 4).

Table 2.1 Soviet assessment of the radioisotopic composition of the release from Chernobyl Unit 4 (ref. 1)

Isotope	Activity of release, MCi		Fraction of activity released from the core by 06.05.86, * %
	26.04.86	06.05.86	
Xe133	5	45	Possibly up to 100
Kr85m	0.15	-	-
Kr85	-	0.9	-
I131	4.5	7.3	20
Te132	4	1.3	15
Cs134	0.15	0.5	10
Cs137	0.3	1.0	13
Mo99	0.45	3.0	2.3
Zr95	0.45	3.8	3.2
Ru103	0.6	3.2	2.9
Ru106	0.2	1.6	2.9
Ba140	0.5	4.3	5.6
Ce141	0.4	2.8	2.3
Ce144	0.45	2.4	2.8
Sr89	0.25	2.2	4.0
Sr90	0.015	0.22	4.0
Pu238	0.1×10^{-3}	0.8×10^{-3}	3.0
Pu239	0.1×10^{-3}	0.7×10^{-3}	3.0
Pu240	0.2×10^{-3}	1×10^{-3}	3.0
Pu241	0.02	0.14	3.0
Pu242	0.3×10^{-6}	2×10^{-6}	3.0
Cm242	0.3×10^{-2}	2.1×10^{-2}	3.0
Np239	2.7	1.2	3.2

* Evaluation error $\pm$ 50%.

3. CHERNOBYL REACTOR DESIGN AND ACCIDENT SEQUENCE

The report prepared by the USSR for the IAEA Experts' Meeting (2) contains the details of the Chernobyl RBMK-1000 reactor and plant design. Further, a report on the accident at Chernobyl prepared in the US (4) contains a summary of information in Reference 2 and information on the RBMK-1000 design given elsewhere in the soviet literature. The information on the Chernobyl design presented here has been abstracted from the two references, and is included in order to highlight the marked differences in initiation, system response and accident progression as they impact on source terms compared with predicted scenarios for western reactor designs.

3.1 Reactor Design

The Chernobyl Unit 4 was an RBMK-1000 reactor, which utilised a boiling water, vertical pressure tube, graphite moderated design. While these aspects are shared with reactors of western design - US-designed Boiling Water Reactors (BWR) utilise the direct cycle; Canadian-designed CANDU reactors utilise pressure tubes; and gas cooled reactors utilise graphite for moderation - no western commercial power plant utilises all three.

Other features of the RBMK-1000 design that may have been important to the accident sequence include:

- single, low uranium enrichment level
- separation of core cooling into two halves
- use of computerised control systems
- separate flow control for each pressure tube
- slow scram system
- power setbacks (rather than scram) for various abnormal conditions
- accident localisation system including a pressure suppression system
- positive void reactivity coefficient under most operating conditions

Only the last two features will be further discussed, because of their impact on the source term.

The accident localisation system is designed to mitigate radioactive releases during accidents involving failure of certain piping of the reactor coolant system. It consists of a set of sealed compartments and rooms interconnected by valves and piping. Most of the accident localisation system is designed for pressures of 36 psig, except for a portion of the building enclosing the group distribution headers and the fuel channel inlet piping, which is designed for 12 psig. The pressure suppression system was designed to condense steam formed during an accident involving failure of some sections of the reactor coolant system, during the actuation of the main safety valves, or during leaks through the main safety valves under normal operating conditions. The pressure boundaries of the accident localisation system are shown in Figure 3. Notice that the ends of the outlet channels and the outlet manifold are outside of the accident localisation system boundary.

The unique design features of the reactor core, from a physics point of view, are its graphite moderator, large size and large core loading of uranium. These features lead to the characteristics of the reactivity coefficients, the core's loose coupling and the content of many critical masses. Table 3.1 gives reported values for the 5 major reactivity coefficients. Of those, the effects of the fuel density and the coolant

temperature are small, because the ranges of possible densities and coolant temperatures are small. However, the remaining three significantly affect the reactivity state of the core. First, the coolant void coefficient is positive under most operating conditions, because of the large graphite-to-fuel ratio, which produces a well-thermalised neutron spectrum with no water in the pressure tubes. Second, the graphite temperature coefficient is positive. Increasing the graphite moderator temperature hardens the spectrum of the thermalised neutrons. The reactivity coefficient is the net of three effects; decreased neutron absorption in the water coolant (positive); increased neutron absorption by U-238 (negative); and increased fission reactions in the plutonium isotopes (positive). Third, the fuel temperature coefficient is negative for all conditions. (In contrast, the design of US reactors has as a goal negative reactivity coefficients. For Pressurised Water Reactors (PWR), at the beginning of a cycle when the content of soluble boron in the water is high, the moderator temperature coefficient is slightly positive but is limited to an integrated reactivity of about 0.5%.)

Because of the characteristics of the reactor design, there were operating restrictions on the reactor. Especially important in the accident scenario were: the minimum effective number of control rods that must be inserted in the core at all times and the minimum power level that must be maintained. With too few effective rods in the core and the power level too low, the system was unstable and unforgiving of mistakes.

3.2 Accident Scenario

The accident at Chernobyl Unit 4 occurred on 25 April 1986 during a test of the turbine generator system. Through a series of violations of the operating restrictions, which are detailed in Table 3.2, the operators brought the reactor to a vulnerable condition. At that time, initiation of the test caused the steam volume in the core to increase. Because of the positive power coefficient and with the safety systems bypassed, a significant reactivity insertion resulted. Evaluations to date indicate that the core was brought to a prompt critical condition. Soviet and other assessments following the accident indicate that sufficient energy was deposited in the fuel pellets to have melted and even vaporized some of the fuel. It is likely that the expansion associated with the melting ruptured the fuel cladding and injected molten fuel into the coolant channel. Rapid generation of steam overpressurised the pressure tubes, rupturing them. Following failure of the pressure tubes, the cavity region around the graphite also overpressurised and ruptured. Sufficient force was generated to lift the top plate off the core region and possibly to fail the reactor building and eject core material. This sequence of events can be associated with the first explosion heard by the operators. A second explosion was heard about 3 seconds later; however, no explanation for it has been confirmed. Postulated reasons for the second explosion include a second criticality, a hydrogen detonation, debris landing on the roof, or even an echo or reverberation. Figure 4 shows the calculated power profile during the accident and the integrated energy deposited in the fuel. Experiments performed in the US and reported in 1980 (Figure 5) show that the energy calculated to have been deposited would have been more than sufficient to have fragmented the fuel pellets.

The counter-measures used by the operators to mitigate the accident during the next several days are discussed in Chapter 5.

3.3 Comparison with Western Reactors

The potential for accident initiators which can result in the addition of positive reactivity to the core has been recognised for all water cooled reactors. Therefore, designers of such reactors have incorporated inherent shutdown mechanisms (eg Doppler effect) and safety features designed to mitigate the consequences of such accidents. Reactivity transients that might lead to fast power surges have to be terminated immediately and automatically by the inherent mechanisms or by independent, diverse and testable features before damage occurs to any reactor system more severe than the system was designed to accommodate. Thus the fuel-disruption mechanisms which characterised the initial stage of the Chernobyl accident are of very low importance for western reactor designs, such as CANDU, PWR and BWR.

Before the CANDU was developed, the importance of fast acting shutdown capability was emphasised by the accident to the experimental NRX reactor which was extensively damaged by a power excursion in 1952. At the outset of the CANDU design, it was recognised that the reactor would have a positive void reactivity coefficient and that highly reliable fast shutdown action was imperative. The first commercial reactor at Pickering has a shutdown system which consisted of neutron absorbing rods supplemented by a moderator dump system.

A second shutdown system was installed on all reactors after Pickering. This second shutdown system (liquid poison injection) is physically and functionally independent of the first shutdown system and each is capable, on its own, of terminating reactivity transients associated with loss of regulation or loss of cooling accidents. Each shutdown system is designed to a high degree of reliability so that the combination of loss of coolant and shutdown failure is such a low probability event it is not considered in the licensing process.

Since a positive void reactivity situation requires reliable, fast acting shutdown capability, both systems are designed to be tested with the reactor at power. The shutoff rods are individually dropped over a predetermined distance and must be shown to be at least as fast as claimed in the safety analysis. The poison injection valves are also tested in a way which precludes the gadolinium nitrate solution from being injected into the core, and the tanks containing the poison are routinely sampled to ensure adequate poison concentration.

The results of the ongoing testing programme are submitted in the Atomic Energy Control Board as part of the licensing requirements and demonstrate in a quantitative manner the high degree of reliability of CANDU shutdown systems.

Reactivity insertion accidents are considered in the design and design-basis safety evaluation of US designed reactors. Both PWR reactors operate with negative power coefficients. However, PWR reactors may operate with a positive moderator coefficient at low power, as discussed above. In that case, the total integrated reactivity that can be promptly added to the system is limited and the rapid scram of the control rods (assuming the rod with the highest worth to be stuck in the operating position) is designed to accommodate the reactivity insertion. Another cause of a possible reactivity insertion accident is the boron dilution event, either during refuelling, or by startup of an inactive reactor loop. The first event is of long duration, that is the time to possible criticality is long, and the conditions of operation are set so that the operators have

sufficient time (at least 15 minutes) to recognise the event in progress and to take corrective action. The second event is possible only for a few plants, since most plants do not have the stop valves necessary for shutdown of a loop. These plants are being reviewed on a case-by-case basis.

Ejection (PWR) or drop (BWR) of the highest worth control rod is the most severe reactivity insertion accident considered in the design basis of US plants. The scram system, in combination with the inherent shutdown of the Doppler effect, is required to affect shutdown assuming the rod with the next highest worth to be stuck in the operating position. Although fuel rod damage is allowed in the licensing basis, pressures generated during the accident are required to be limited so that pressure vessel integrity would be maintained.

A reactivity insertion accident beyond the design basis could be a LOCA with injection of ECCS water which contains boron below the level required for shutdown. Other events beyond the design basis included multiple control rod ejection and ATWS with no recirculation pump trip. These are insignificant contributors to the assessed frequencies of severe accident initiation, as discussed below.

3.3.1 Core-melt Frequency Important Scenarios and In-vessel Characteristics

Reactivity insertion accidents have been considered for 5 US operating plants in the framework of risk analyses (5) and found not to be significant contributors. Reference 5 shows that the station blackout scenario is an important contributor to the core melt frequency for Peach Bottom (BWR), Grand Gulf (BWR), and Surry (PWR), but is of less importance for Sequoyah (PWR) and Zion (PWR). Additional contributors to the core melt frequency for Surry include LOCA, ATWS, interfacing system LOCA, loss of off site electrical power, and loss of a particular electrical bus. Loss of component cooling water is important for both Zion and Sequoyah; in Zion it is the dominant sequence, while for Sequoyah LOCA events provide more than half of the core melt frequency.

All of these events are characterised by relatively long times to core uncovery and melting, certainly when compared with the rapid progression of core damage possible from reactivity insertion events. The times to core uncovery vary from plant to plant and sequence to sequence (6), ranging from slightly over half an hour for an ATWS sequence at Peach Bottom to more than two days for a large LOCA with failure of containment heat removal for Surry (assuming no success of operator actions to recover, a highly unlikely scenario). For the station blackout sequences, core uncovery times vary from slightly less than one hour for the sequence at Grand Gulf that includes immediate failure of station batteries to about 10 hours for the long-term scenario at Sequoyah.

Compared with the reactivity insertion transient, fuel heat-up times are also long, with collapse of the fuel estimated to be delayed by half an hour from core uncovery for rapidly-developing sequences and longer for other sequences. Moreover, the initial release associated with reactivity insertion at Chernobyl involved a short, direct path from the core out of the coolant system, with radioactive material transported at high velocity. These conditions, which are highly unfavourable for retention, contrast with the generally more complex flow paths and much slower flow rates in the coolant systems predicted for accidents in reactors of western design.

Because of all the differences between the plant design and the scenario, the accident at Chernobyl does not provide data or insights relative to in-vessel processes that can be applied to source term evaluations for western water reactors. That is, first, the fission product release mechanism is one that is not applicable; and second, immediate, large scale failure of the pressure boundary negated the opportunity for in-vessel retention of fission products, a process believed to be important in western water reactor scenarios.

3.3.2 Containment

Although the Chernobyl reactor had an accident localisation system with a design pressure not very different from containment design pressures for US reactors, the volume of the system is smaller than containment volumes. The importance of the containment in limiting the release of radioactive material has long been recognised (7) and the loss of the containment function as an important aspect of any severe accident scenario has only been strongly reconfirmed by the Chernobyl accident.

A possible accident in US designed reactors in which the containment function is lost at the time of the start of the accident is the interfacing system LOCA, or V sequence. In the V sequence, the low pressure piping ruptures outside containment because of failure of the valves between the high pressure reactor coolant system and the low pressure residual heat removal system. In this case, two of the three barriers to release of radioactivity are breached at the same time by the accident initiator. However, the loss of the third barrier, the fuel rod cladding, is slow (requiring of the order of half an hour) in comparison with the virtually simultaneous breaching of the three barriers at Chernobyl. In addition, the pathway from the core region of the vessel to a secondary building is long, typically tens of meters, providing for retention of material along its path. Also, expansion from the small diameter, low pressure piping into the building volume provides some hold-up time and additional retention opportunity. This last effect probably also occurred at Chernobyl as the ejected material entered the Reactor Building.

In general, because reactivity insertion accidents have not been found to be significant to the risk profile for the plants studied to date, the accident sequences found to be important are characterised by times to release of radioactive material to the environment ranging from many minutes to many hours.

Again in the containment area, the Chernobyl accident will not provide data or new insights for source term evaluations for western water reactors. Retention processes for aerosols and vapours in containment, an important aspect of scenarios for western water reactors, was not a factor because of immediate bypass of the accident localisation system. Further, bypass of the system also bypassed the pressure suppression system, again providing no information about performance of such pools during severe accidents.

Table 3.1 Calculated Reactivity Coefficients for RBMK*

Item	State of core			
	1.8% U-235		2.0% U-235	
Exposure (MWD/kg)	0	5	10	10.3
Reactivity per $ (β)	0.0065	0.005	0.0042	0.0048
Number of equivalent rod worths	30	20	20	30
Number of supplemental absorbers	236	118	0	1
Coolant void ($\Delta\rho/\Delta\alpha$)*	-1.0×10^{-2}	$+0.15\times10^{-2}$	$+0.92\times10^{-2}$	$+0.02\times10^{-2}$
Graphite temperature (ρ/°C)	0	$+3.2\times10^{-5}$	$+5.4\times10^{-5}$	$+6.0\times10^{-5}$
Water temperature (ρ/°C)	-5.1×10^{-5}	$+0.42\times10^{-5}$	$+5.0\times10^{-5}$	-
Fuel temperature (ρ/°C)	-1.0×10^{-5}	-1.0×10^{-5}	-1.1×10^{-5}	-1.2×10^{-5}
Fuel density (ρ/gm/cm3)	$+1.44\times10^{-2}$	-0.22×10^{-2}	-1.3×10^{-2}	-

*α= % void.

*From Reference 4 Table 2.4

Table 3.2 Violations of the Reactor Operating Restrictions*

No.	Violation	Motivation	Consequences
1.	Reducing the operational reactivity margin substantially below the permissible value	Attempt to emerge from "iodine well"	Emergency protection system of reactor was ineffective
2.	Power dip well below the level provided for by the test programme	Operator error in switching off local automatic control	Reactor proved to be in a condition difficult to control
3.	Connecting of all the main circulation pumps to the reactor, with individual pump discharges exceeding the levels specified in the regulations	Meeting the requirements of the tests	Coolant temperature in the multiple forced circulation circuit approached saturation temperature
4.	Blocking of reactor protection system relying on shutdown signal from two turbogenerators	Intention, if necessary, of repeating the experiments with turbogenerators switched off	Loss of possibility of automatic shutdown of the reactor
5.	Blocking of protection systems relying on water level and steam pressure in the drum-separator	Effort to perform tests despite unstable reactor operation	Reactor protection system based on heat parameters was completely cut off
6.	Switching off of the protection system for the design-basis accident (switching off of the emergency core cooling system)	Wish to avoid spurious triggering of the emergency core cooling system while the experiment was going on	Loss of the possibility of reducing the scale of the accident

* From Reference 2, pages 22-23

FISSION PRODUCT RELEASE MECHANISMS IN THE CHERNOBYL ACCIDENT

Previous sections have discussed the sequence of events, the key observations and the radioactivity measurements following the Chernobyl accident. Given the nature of plant damage, the accident boundary conditions which determine the radiological source term (such as core debris temperatures, gas mixture flow rates and gas and debris chemistry) could only be highly non-uniform both spatially throughout the core and transiently during the accident.

Major axial (i.e. bottom-to-top) temperature gradients must have invariably developed in the Chernobyl core which experienced a strong air circulation from the bottom of the core debris. The bottom portion of the debris will have remained at low or moderate temperatures throughout much of the accident because a major heat sink (i.e. a substantial flow of cool air) was available. The bottom temperatures would have been maintained well below 800K with the observed gas velocities of 1 m/s or higher. The chemical heat generation due to oxidation of Zircaloy or graphite is negligible at these temperatures, and the fuel decay heat is the only major heat source. Temperatures could, of course, be much higher at higher debris elevations. The heat sink temperature increases with increasing elevation due to heating of gas as it passes through the debris. Also and more importantly, a major and sustained source of chemical heat was introduced at higher elevations in the debris by the burning graphite. The top of the debris will have therefore reached and maintained high temperatures (i.e. in excess of 1500K) throughout the period of graphite combustion. Large spatial variations in the chemical boundary conditions must have developed at the same time. An oxidising environment likely prevailed at the bottom of the debris until the core was inerted by nitrogen, while strongly reducing conditions would have prevailed simultaneously near and above the elevation of the burning graphite.

The above spatial temperature and chemistry gradients can be expected to apply through much of the fission product release period, but they cannot be quantified unambiguously. For example, materials other than graphite could have participated in the exothermic chemical reactions for a period of time, thus temporarily affecting the local debris conditions. A hot Zircaloy metal or melt generated by the initial power excursion could have acted as the dominant oxygen-getter and the dominant source of chemical heat in the early stages of the accident. Subsequently, the spatial distribution of temperature and the local chemistry must have changed with time according to changes in the gas flow patterns and movement of the burning front. The maximum air flow rates probably existed in the first few days of the accident. Large amounts of filtering and absorbing materials were then deposited on top of the core debris for many days. This action was bound to have an effect on the local boundary conditions within the debris, simply by virtue of gas flow obstruction and perhaps by means of chemical interactions. The filtering also affected the transport of fission products from the debris into the environment. Some fraction of the fission products was likely trapped at the top of the core and exposed to high temperatures in a reducing environment for long periods of time. These trapped fission products may have experienced further thermal transients and chemical interactions with the deposited materials, leading either to their permanent retention or a subsequent release at a rate which can differ substantially from the fuel release rate.

Because of the complex and highly non-uniform accident boundary conditions, and the general lack of detail pertaining to the Chernobyl debris

geometry, gas flow patterns, temperature measurements and activity release measurements, the release and retention mechanisms that were actually at play in the accident can only be inferred qualitatively. A number of analyses of the Chernobyl accident have been published (References 1, 8, 9 and 10) containing several hypotheses of the dominant fission product release mechanisms. The main release mechanisms responsible for the observed source term characteristics are thought to be:

(a) reactivity-induced fuel fragmentation and ejection; and

(b) reactions of UO_2 with oxygen; or

(c) reactions of UO_2 with carbon.

A considerable data base is available on the subject of fuel behaviour and fission product release in severe power excursions. Numerous experiments have been performed in the USA and Japan, yielding a fundamental understanding of the governing processes and phenomena. An active research programme is in progress in Japan.

The oxidation of UO_2 in air and in other oxidising environments, and the corresponding fission product releases, have been studied extensively in many countries. The oxidation and release processes are complex and they are quite sensitive to the local boundary conditions. The fundamental understanding of oxidation release mechanisms has emerged only recently from active research programmes in Canada and in the USA.

Carburization of UO_2 has been studied quite extensively from the standpoint of chemical kinetics, but little data is available on the mechanisms and kinetics of fission product release during the formation of uranium carbides. There is no active research programme on this subject in the OECD countries since graphite is not widely used in the western nuclear power reactors.

The fission product release phenomenology considered in current source term research and analytical programmes is briefly described in the following section. The relevance of this phenomenology to the Chernobyl source term is then discussed. The available Chernobyl data, ranging from reported temperature trends, through source term release rates, to fission product composition, is shown to be fully consistent with the first two fission product release processes listed above: the fuel fragmentation and ejection, and the UO_2 oxidation. The interactions of UO_2 with carbon may have contributed to the release, but the evidence supporting a dominant role of carburization appears to be more contradictory than that for oxidation.

4.1 Fission Product Release Phenomenology

During normal reactor operation, fission products are contained in sealed fuel rods or elements. The fission product species can reside in the open cavities of fuel rod (such as the gap between pellet and cladding), in closed cavities of fuel matrix (such as grain-boundary bubbles) or within fuel grains (such as intragranular cavities). Following a fuel cladding failure, each of the three inventory components will be released from the fuel rod in a manner distinct from the other two components. For example, the "gap" or "free" inventory of volatile fission products can escape readily when the cladding fails. On the other hand, the grain-boundary and grain inventories

require some additional driving forces (such as a temperature gradient or a chemical potential) in order to contribute appreciably to the overall release. Although the grain inventory component is the least susceptible to the release, it constitutes the largest fraction of the total inventory in a fuel rod (typically on the order of 90% for the radiological significant nuclides such as iodine). The following discussion concentrates only on the release mechanisms from the fuel grains since the grain inventory presents the largest potential for public harm and the severe accidents are capable of releasing a substantial fraction of this inventory.

In a non-oxidising environment, thermal diffusion is the dominant mechanism for the release of volatile fission product species for low and intermediate temperatures (i.e. less than about 2000K), as schematically illustrated in Figure 6. The volatiles are defined here as noble gases, elemental iodine, and any other species which have a low boiling point (i.e. less than about 1300K). At higher temperatures, the semi-volatile species (i.e. those with boiling points between about 1300K and 2300K) will also be released by diffusion, but the grain growth with its attendant grain-boundary sweeping of fission products becomes the dominant release mechanism (i.e. it has a faster release rate). Alloying reactions of Zircaloy cladding with UO_2 can also contribute to the release at higher temperatures. Zircaloy reduces UO_2 to form a low melting point eutectic (11). Upon liquefaction, the volatile and perhaps some semi-volatile fission products contained in the alloyed volume will become mobile and can rapidly escape. The volume of alloyed UO_2 strongly depends on the interfacial pressure between the UO_2 and the cladding, the relocation patterns of molten Zircaloy and the presence of other oxygen sources (12). Almost all the volatile fission products, and to a lesser extent the semi-volatile species, would be released rapidly via diffusion and grain growth at temperatures exceeding about 2600K. Also, some non-volatile species (i.e. nuclides with boiling points higher than about 2300K) will become mobile and can be released through vapour phase transport.

The release mechanisms acting in an oxidizing environment are strongly affected by the UO_2 oxidation behaviour (13 and 14). In air, UO_2 first oxidises along the grain-boundaries at temperatures between 600 K and 1000K, followed by the oxidation of individual fuel grains. Because of a rather large specific volume of U_3O_8 relative to that of UO_2, fuel becomes fragmented. The low temperature oxidation produces U3O8 fragments of sub-grain size. These fragments can become airborne at a gas stream velocity as low as 2 cm/s. Thus, the fission products laden fragments can easily be carried far from the source through complex transport paths, providing for a direct release of grain inventory.

At temperatures between 1000K and 1500K, the oxidation front moves into the fuel according to a parabolic rate law rather than proceeding preferentially along the grain boundaries. U_3O_8 fragments are still formed, but they are in a grain size range or larger. Higher gas stream velocities are required to transport these fragments out of the system. Fine fuel particles are not formed by oxidation at temperatures higher than 1500K.

Some fission products may form volatile compounds in the process of UO_2 oxidation. For example, ruthenium release was measured in air oxidation tests at temperatures higher than about 850K, consistent with the rather low boiling points of ruthenium oxides. Conversely, certain fission products may reduce their release potential by oxidizing to less volatile compounds. For example, barium was not measured in air oxidation experiments at temperatures as high as 1850K.

During fuel oxidation at temperatues above approximately 1500K, one of the intermediate oxide phases is UO_3. Since this particular uranium oxide has a relatively high vapour pressure, a surface erosion of fuel occurs resulting in a substantial mass loss over extended periods of time (13). All fission products in the affected volume are released by the erosion process, whether or not they are vaporized at the oxidation temperature. Because the rates of vaporization and surface erosion increase rapidly with temperature, this release process can be important for accidents involving a prolonged exposure of fuel to an oxidising environment.

In parallel with the above oxidation-assisted release mechanisms, thermal diffusion and grain growth continue to be important, particularly for the volatile fission products. The release rates via diffusion and grain growth tend to increase substantially in an oxidising environment. For example, a significantly faster release of noble gases was observed from U_3O_8 than from UO_2. Similarly, it was found that the grain growth rate is also substantially enhanced by the presence of excess oxygen (14), possibly due to an increase in the surface or volume diffusion coefficient (15). Consequently, both of these mechanisms are effective at temperatures lower than they would be if they acted in a non-oxidising environment. As an example, grain growth could become a significant contributor to the release at about 1500K in air, as compared to about 1800K in an inert atmosphere.

If the accident involves an extreme and rapid power excursion, energetic fuel disintegration or fragmentation can occur (16, 17) at local fuel temperatures in excess of the UO_2 melting point. This results in a rapid and direct release of fuel materials and the contained fission products. The release due to fuel disintegration is not sensitive to the chemistry of the surrounding environment, however, the hot and finely fragmented fuel particles are likely to undergo rapid subsequent chemical interactions. The average isotopic composition of release due to fuel disintegration will be essentially the same as the fission products composition in the fuel, but the physical and chemical speciation of individual aerosol particles may be substantially altered by these subsequent interactions.

The release mechanisms schematically shown in Figure 6 delineate two extremes of accident environments covered by the current source term phenomenology. Many intermediate environments are typically considered in plant specific accident analyses. For example, the release in a mildly oxidising atmosphere such as steam would exhibit features somewhere in between the two illustrated extremes. Of the release mechanisms described above, diffusion, grain growth and vapour transport all result in a release composition which is substantially different from the fission product content in the fuel. The volatile species are more readily released by these mechanisms than the less volatile species. The latter are released with much slower rates which are highly dependant on the individual nuclide diffusion and transport characteristics (18). However, there are three release mechanisms illustrated in Figure 6, which can result in a release composition akin to that in the fuel. One of them is fuel disintegration due to a severe power excursion. The other two are related to UO_2 oxidation. They involve formation of fine U3O8 fragments at low temperatures, and vaporization of UO3 at intermediate and high temperatures.

The source term phenomenology in Figure 6 does not consider any release mechanisms due to reactions of UO_2 with carbon, simply because such

reactions are not relevant to western power reactors. Carburization requires an intimate contact of UO_2 and graphite at high temperatures (9) and it results in a change of the fuel crystalline structure similar to that occurring during fuel oxidation. The structural changes of fuel matrix may enhance the release of volatile species, but there is no apparent reason for an enhanced release of non-volatile species. Any finely dispersed fuel particles embedded in graphite (i.e. a prerequisite of carburizatrion) may well be the source of subsequent release of contained fission products, if and when these particles become liberated by the combustion of graphite, but this process is related to the initial fuel disintegration mechanism covered by Figure 6.

4.2 Activity Release Mechanisms Relevant to Chernobyl

It is likely that most, if not all, of the mechanisms outlined in Figure 6 were involved in the activity release at one time or another during the Chernobyl accident.

In Stage 1 of the accident (defined here as the first day), the disintegration of UO_2 occurred in a portion of the core. Although the bulk or average core temperatures may have been relatively low at the time of fuel disintegration, the temperature of the affected fuel would have been high. A forced ejection of hot fuel fragments and UO_2 vapour into the environment would be the primary release mechanisms. A subsequent release of volatile fission products from overheated UO_2 fragments via vapour transport, grain growth and diffusion are the most likely release mechanisms for noble gases, iodine and caesium. Some, if not all, of the ejected fuel particles would have completely oxidised upon exposure to air, thus providing the conditions for the release of certain less volatile species such as ruthenium from the particles.

In Stage 2 (days 2-6), the average fuel temperature was estimated to decrease to approximately 950K as shown in Figure 2 (extracted from Reference 2), coincident with a substantial air circulation through the core debris. Considerable temperature gradients likely prevailed in the debris as discussed previously, with the fuel being exposed to a range of chemical environments. Low temperature UO_2 oxidation by air would be the dominant release mechanisms for the fuel located in the lower portion of the damaged core, releasing both volatile and non-volatile fission products along with fuel aerosols . Fuel located at higher elevations would experience moderate or high temperatures in a reducing environment. Less volatile fission products would tend to be retained in the fuel, but the volatile fission products would be released, enriching the release from lower elevations. Carburization of embedded UO_2 fines could have contributed to the release if the graphite temperatures become highly elevated (i.e. far above the temperatures suggested by the average temperature trends in Figure 2). Also, a considerable retention of fuel particles and fission product aerosols may have occurred in the bed of filtering and absorbing materials which was progressively deposited on the core debris during Stage 2. The trapped aerosols would subsequently be exposed to elevated temperatures in a reducing environment for prolonged periods of time. Because of the small particle size of trapped aerosols (i.e. a short diffusion distance), the trapped particles could have contributed to the total release to some extent, particularly towards the end of Stage 2.

In Stage 3 (days 7-9), the average fuel temperature was estimated to increase to about 2000K, presumably because of changes in the air flow patterns through the debris caused by either the deposited materials or relocation of debris. The release from the fuel during this period would be by the same mechanisms as during Stage 3, but with some enhancement of the diffusion releases due to higher temperatures. A temperature escalation of core debris would also induce an escalation in filter bed temperatures. The composition of the total release from the plant would therefore tend to be enriched in the less volatile fission product species released from trapped aerosols.

In Stage 4 (day 10 and beyond), liquid nitrogen was introduced below the core which started to cool the core debris and terminated the graphite combustion process by displacing oxygen. Fuel oxidation would also be terminated, leaving thermal diffusion of fission products as the only release mechanism which could act during the gradual debris cooldown.

The bulk of the Chernobyl activity release occurred during Stages 1, 2 and 3 (2). Thus, with the exception of a one-day period in Stage 1, low temperature UO_2 oxidation likely played a key role in determining the magnitude as well as the release rate of fission products. The presence of oxidation is supported by activity measurements which show that, apart from an enhanced release of volatile fission product gases, the releases of condensed species had an average composition akin to that in the fuel. UO_2 oxidation in air is the only release mechanism that can accomplish such similar compositions at temperatures consistent with the reported average temperature trends in Figure 2. This mechanism is not overly sensitive to temperature, particularly at lower temperatures which are expected due to the axial temperature gradients in the debris.

As pointed out earlier, UO_2 carburization has been postulated to be the dominant release process in Stage 2 and 3 instead of UO_2 oxidation (9). Although the reactions of fuel with graphite are possible near the zone of the graphite fire, graphite temperatures at which the reaction rates become significant must be quite high (i.e. in excess of 2000K). Such high temperatures are not readily attained by the combustion of solid fuels. Also, an intimate contact of fuel and graphite would have to occur on a wide scale for the carburization to become a major contributor to the total release. Zircaloy pressure tubes will have provided a substantial barrier for the embedment of fuel in graphite, particularly when considering a limited degree of freedom for pressure tube failure modes in the Chernobyl reactor design. Fuel disintegration experiments indicate that the shroud tube tends to fail locally, due to thermal ablation. Such failures are not conducive to a widespread embedment of UO_2 in graphite. Finally, fission products must still vaporize in order to be released from carbide grains. Since the carburization can only proceed at strongly reducing conditions, the vaporization would have resulted in a sharp discrimination in the releases of barium and cerium, for which the reduced states are relatively volatile, and ruthenium and molybdenum, for which the reduced states are refractory. There is no evidence for such a sharp discrimination in the Chernobyl release measurements.

4.3 Chernobyl Source Term Characteristics

Considering that UO_2 oxidation has likely been one of the key processes of activity release, the Chernobyl activity measurements can be interpreted as follows:

During Stage 1, the high fuel temperature and the fuel fragmentation and ejection were the primary causes of activity release into the environment. The ejection of UO_2 fragments accounts for the particulate deposits with fuel-like composition which were found on the ground in the near vicinity of the plant. A substantial release of volatile species from both the ejected fuel fragments, and the hot fuel debris retained in the core, also occurred due to high-temperature release mechanisms. Some of the volatile fission product vapours would have condensed on the ejected fuel fragments resulting in fuel particles enriched in volatiles. During a flight of hot UO_2 fragments, fuel oxidation would have taken place, resulting in the release of volatile Ru directly into the atmosphere. This may explain the particles composed almost entirely of Ru detected in Sweden (3).

During Stage 2, the relatively low average fuel temperatures reported in Figure 2 are consistent with high air flow rates through the core debris. These conditions would have promoted low temperature oxidation of UO_2 by air, at least near the bottom of the debris. Some fraction of U_3O_8 fines would have been carried through the debris into the environment. Towards the end of Stage 2, an increasing amount of fuel particles would become deposited in the filter bed at the top of the core debris. Ruthenium was not necessarily volatilized and released from the fuel particles by low temperature oxidation (recall that temperatures in excess of about 850K are required to volatilize Ru, but fine U_3O_8 particles can be formed at lower temperatures). Any Ru that was oxidised at temperatures higher than 850K and released as RuO_x vapour would be reduced again to a non-volatile metal by the passage through the zone of graphite fire and readily immobilized by the interactions with structural metals or filtering and absorbing materials. Therefore, no enhanced release of Ru relative to the fuel composition should be expected during Stage 2.

During Stage 3, the core debris temperatures escalated in conjunction with substantially reduced air flow rates through the debris. The production and transport of U_3O_8 aerosols would both drop relative to the early stages of the accident. However, as the average fuel temperatures increased, other fission product release mechanisms came into play. The release may have continued due to the formation of UO_3 vapour and due to the diffusion of fission products from U_3O_8 fines which were previously formed and retained in the system. The diffusion releases could be quite rapid in Stage 3 because the higher temperatures act in conjunction with an enhanced diffusion release from the small U_3O_8 particles. In fact, heating of fine fuel particles and deposited fission product aerosols would account for the "burst" release of volatile fission product species which was detected as the core temperatures started to rise. The reduction in the measured activity of barium and zirconium during this period is consistent with the reduced formation and release of U_3O_8 fines.

During Stage 4, the core debris was inerted by nitrogen and the fuel temperature started to decrease. Due to the lack of oxygen in the vicinity of the fuel, any subsequent release could only be caused by the diffusion of fission products from remaining fuel pellets and U_3O_8 fines. Diffusion is a relatively slow process at low temperatures and non-oxidising atmospheres. The change of the dominant release mechanism to diffusion may account for the dramatic reduction of all the fission product release rates.

In summary:

(1) The source term characteristics of the Chernobyl accident are consistent with current fission product release phenomenology. UO_2 oxidation by air appears to be one of the key mechanisms responsible for the fission product releases during the accident.

(2) The Chernobyl release measurements show that a substantial fraction of volatile fission product inventory in the core was released from the fuel into the environment. This is not unexpected in light of prolonged exposures to elevated temperatures and the lack of retention capabilities for gases and vapours. The release of less volatile species, which requires fuel temperatures well in excess of 2000K, was relatively small and occurred in a compositin akin to that in the fuel. This may indicate that a large portion of the damaged core has remained below about 2000K throughout the accident and it is consistent with the Soviet temperature estimates (2).

(3) A drastic reduction of activity release occurred upon inerting of the core with nitrogen. Apart from the cooling effects of low temperature gas, nitrogen effectively terminated all oxidation reactions and thus eliminated sources of chemical heat as well as one of the key release mechanisms.

5. MITIGATION OF RADIONUCLIDE RELEASE AT CHERNOBYL

5.1 Brief description of short term counter-measures taken by the Soviets

A series of short term counter-measures were taken by the Soviets to contain radioactivity inside the installation. In chronological order, they were as follows:

(a) There was an attempt to restart core cooling by injecting water into the core, using the emergency feedwater pumps. It was unsuccessful because the water, unable to penetrate into the core, since the pressure tubes had been destroyed, flowed out into other parts of the primary circuit and towards Chernobyl units 1 and 2, involving the risk of transferring radioactivity to these units. The operation was consequently stopped.

(b) Starting on 27 April, helicopters dropped a variety of appropriate materials into the crater formed by the explosion of the reactor (40 tons of boron carbide, 800 tons of dolomite, 1 800 tons of sand and clay, 2 400 tons of lead), in order to smother the graphite fire, stop radioactive releases and provide radiation shielding. This operation, rapidly carried out, proved successful since the radioactive releases were observed to decrease rapidly between 28 April and 1 May. But, starting from 2 May, radioactive release began again increasing, probably as a result of core heating.

(c) On 4 and 5 May, it was attempted to cool the reactor by means of nitrogen gas pumped in through piping installed beneath the reactor. The second purpose of this action was to expel the oxygen feeding the graphite fire. This operation was also successful since, by 6 May, the radioactive release had dropped.

(d) Despite the results obtained by the above operations and the indications derived from calculations performed, it was decided to take measures to protect against possible core meltdown and melt-through the base mat, damaged by the explosion and weakened by the additional loading described above. Using a tunnel dug under the reactor, work on which started very soon after the accident, the Soviets built beneath the core a flat heat exchanger installed on a concrete slab. Although it very quickly became evident that all corium-concrete reaction had been prevented, the Soviets continued this action to its completion at the end of June.

5.2 Efficiency of these counter-measures

As we wrote before:

-- the attempt to cool the core by injecting water was unsuccessful because all connections to the core were destroyed by the explosions;

-- the cooling system installed under the core basemat appeared unnecessary, because corium-concrete interaction did not occur.

So the only actions on the efficiency of which we can give a judgement, are the dropping of materials on the disrupted core and the nitrogen injection into the core cavity.

It is clear that these last actions have been efficient in controlling radioactive release only when used in conjunction, i.e. core cooled, graphite fire stifled and downstream gas filtered. The discrepancy between radioactive releases per day, resulting from these concerted actions, can be evaluated in looking at releases before and after 5 May. From what happened between 2 and 5 May, i.e. increasing in release resulting from fuel temperature increase, one can conclude that the essential action was the nitrogen injection, stopping the graphite fire and cooling down the destroyed core.

5.3 Knowledge of OECD countries in the field of rough filtration for mitigating consequences of severe accidents (Spring 1987)

The efficiency of simple materials, such as sand and stones, for filtering radioactive release and absorbing energy by steam condensation in accidental situations, has been studied by several OECD countries. Two of these countries have decided to install on their nuclear reactors systems using such materials for mitigating consequences of severe accidents: Sweden (FILTRA concept on Barsebäck BWR's), France (sand filters on PWR's).

The Swedish system functions principally as an additional volume set on the leakage path of the radioactive products to the environment, providing steam condensation and radioactive products plateout area, rather than as a conventional filter, in particular because of the size.

The French system is more like a conventional filter, using a sand bed 0.80m high as filtering material. The efficiency of this filter is very dependent on the sand average diameter. Filters to be installed on the French PWR's use a calibrated sand of 0.6mm diameter. In this case efficiency is between 10 and 100 for aerosols and a little bit less than 10 for molecular iodine. Experiments were made at room temperature and do not give information on filter behaviour at higher temperature.

5.4 Conclusions

The performance of designed containment venting filters which are fitted or planned as mitigation devices for western WCMR has been thoroughly assessed. There can be considerable confidence that they will fulfil their role effectively. The limited effectiveness of the ad hoc filter bed at Chernobyl is of no relevance to the performance of such pre-designed filters. This filter bed suffered not only from the limitations imposed by its ad hoc nature, but also from a temperature challenge far exceeding anything which is anticipated in severe accidents for western WCMR. The main interest in the Soviet response to source term mitigation is in the fact that a combination of control measures was required to bring the release of radioactivity under control.

6. CONCLUSIONS

1. Although a few aspects of the Chernobyl accident are not fully understood the main features are well-characterised, and there is no evidence that any new phenomena of relevance to source terms for western WCMR were involved. Past and present research programmes in OECD member states are comprehensive in their coverage of the relevant source term issues.

2. The accident, initiated by a reactivity excursion, was of a type considered near-impossible in western WCMR. Nonetheless, there is a good understanding of fuel behaviour in such excursions based on both LWR and Fast Reactor studies. Data on fission product release is more limited, although a basis for extrapolation exists in the data and models relating to slower overheating transients.

3. The role of fuel-coolant interactions in the Chernobyl accident is not fully understood. However, such phenomena have been and still are the subject of extensive experimental study and modelling in OECD countries, and the Chernobyl accident will add little of source term relevance on this topic.

4. Fuel oxidation was a major release mechanism in the Chernobyl accident. Oxidative release from fuel can arise in the containments of PWR and BWR, following steam explosions or high pressure melt ejection, but the conditions are very different from those at Chernobyl. Oxidative release under the relevant conditions has been studied in the past, and is the subject of several current research programmes in OECD countries. Though these studies will help in interpreting the Chernobyl source term, it is doubtful where useful information will emerge from the latter itself.

5. The existence of particles of near-homogeneous elemental composition (e.g. ruthenium, cerium) in the aerosols released from Chernobyl is an interesting feature. Whilst mechanisms accounting for the ruthenium aerosols have been proposed, the formation of cerium and other refractory particles remains unexplained. An account of the origins of such particles would be of interest, although their formation is probably of little relevance for western WCMR source terms.

6. The conditions of the ad hoc filter bed at Chernobyl differed so markedly from those of pre-designed filters fitted to or planned for PWR and BWR that the performance at Chernobyl is of no relevance. Nonetheless, the Soviet response to source term mitigation provides some lessons on the conflicting effects which can arise following particular emergency actions, and points to a need for contingency planning in source term management.

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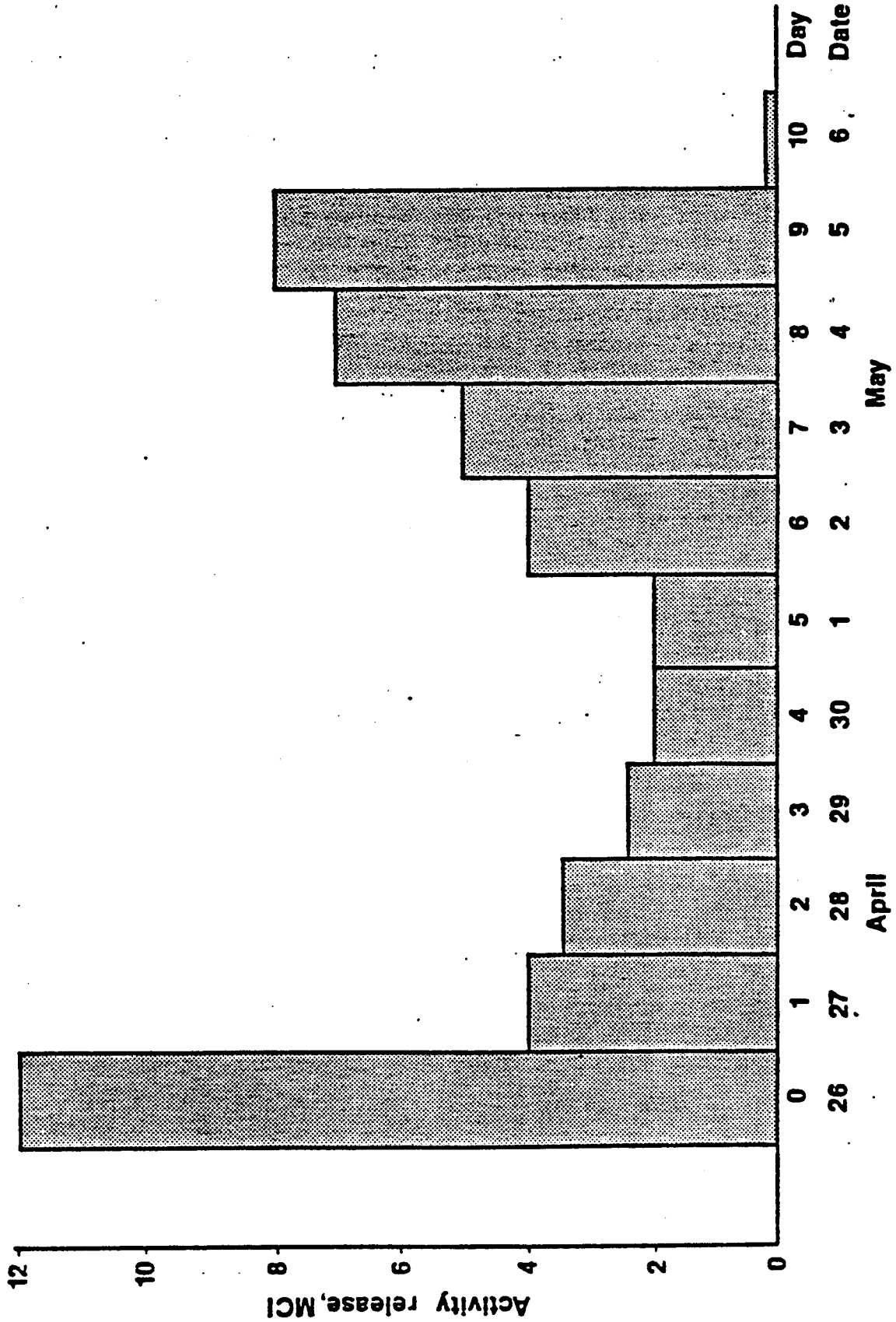


FIG. 1 SOVIET ACCOUNT OF DAY-BY-DAY ACTIVITY RELEASE, CORRECTED TO 6 MAY 1986

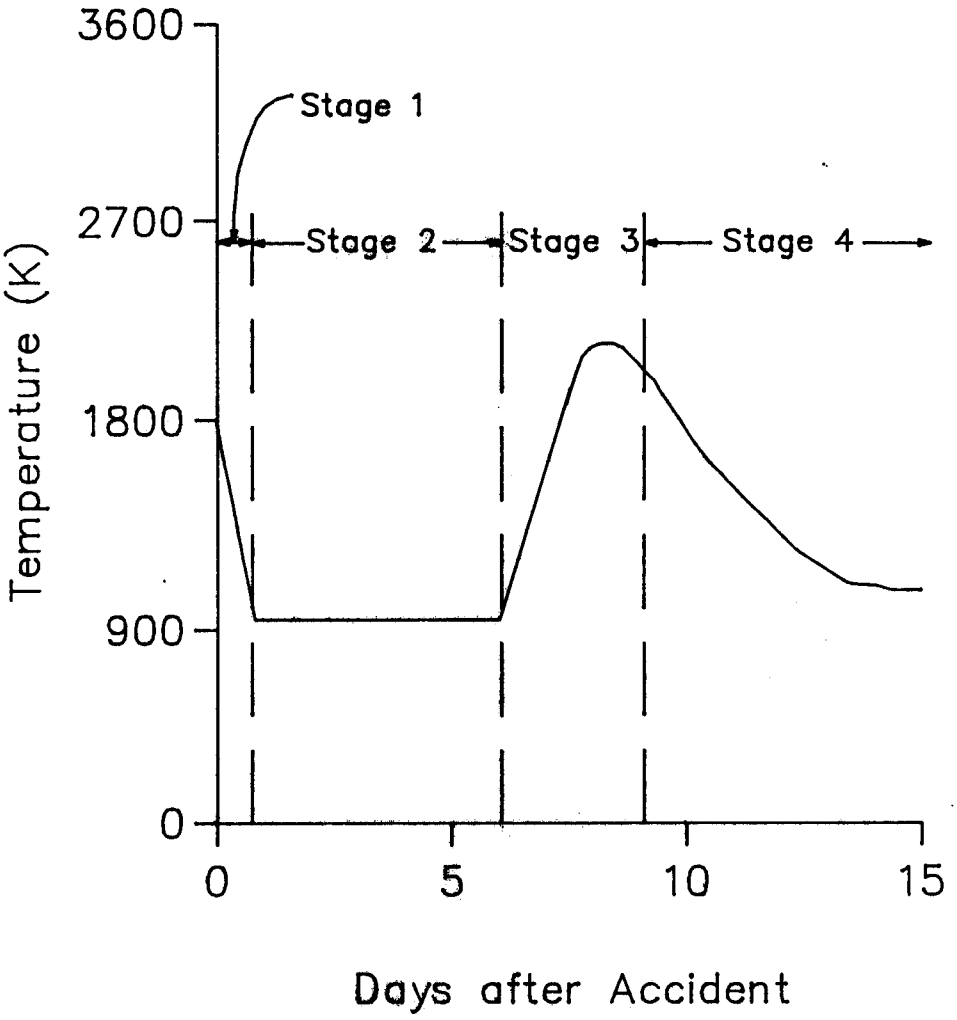


FIGURE 2

Soviet estimate of temperature history of Chernobyl fuel

1. First-stage condensate pump
2. 125/20-t overhead travelling crane
3. Separator-steam superheater
4. K-500-65/3000 steam turbine
5. Condenser
6. Additional cooler
7. Low-pressure heater
8. Deaerator
9. 50/10-t overhead travelling crane
10. Main circulating pump
11. Electric motor of main circulating pump
12. Drum separator
13. 50/10-t remotely controlled overhead travelling crane
14. Refueling mechanism
15. RBMK-1000 reactor
16. Accident containment valves
17. Bubbler pond
18. Pipe aisle
19. Modular control board
20. Location beneath control board room
21. House switchgear locations
22. Exhaust ventilation plant locations
23. Plenum ventilation plant locations

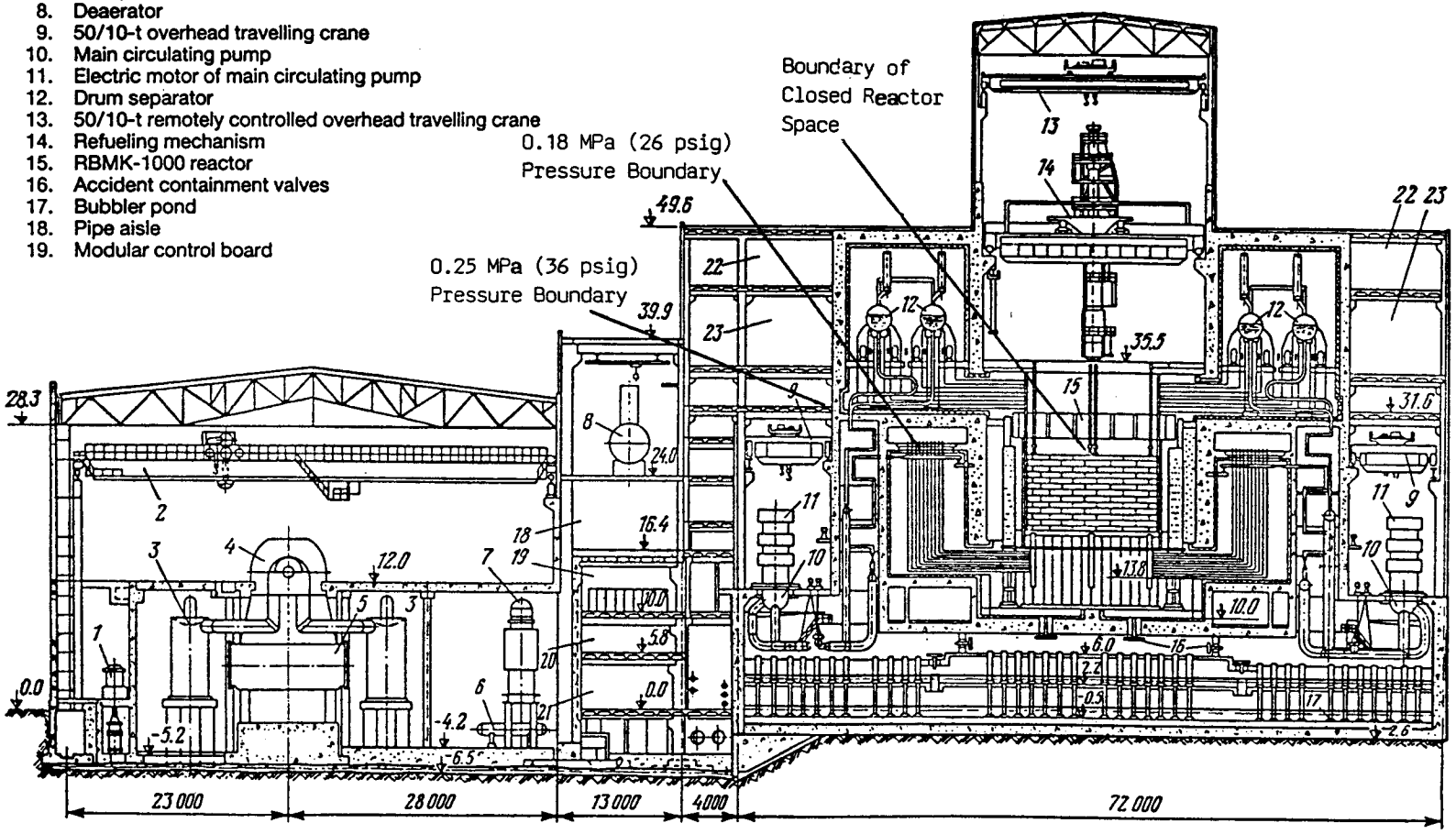
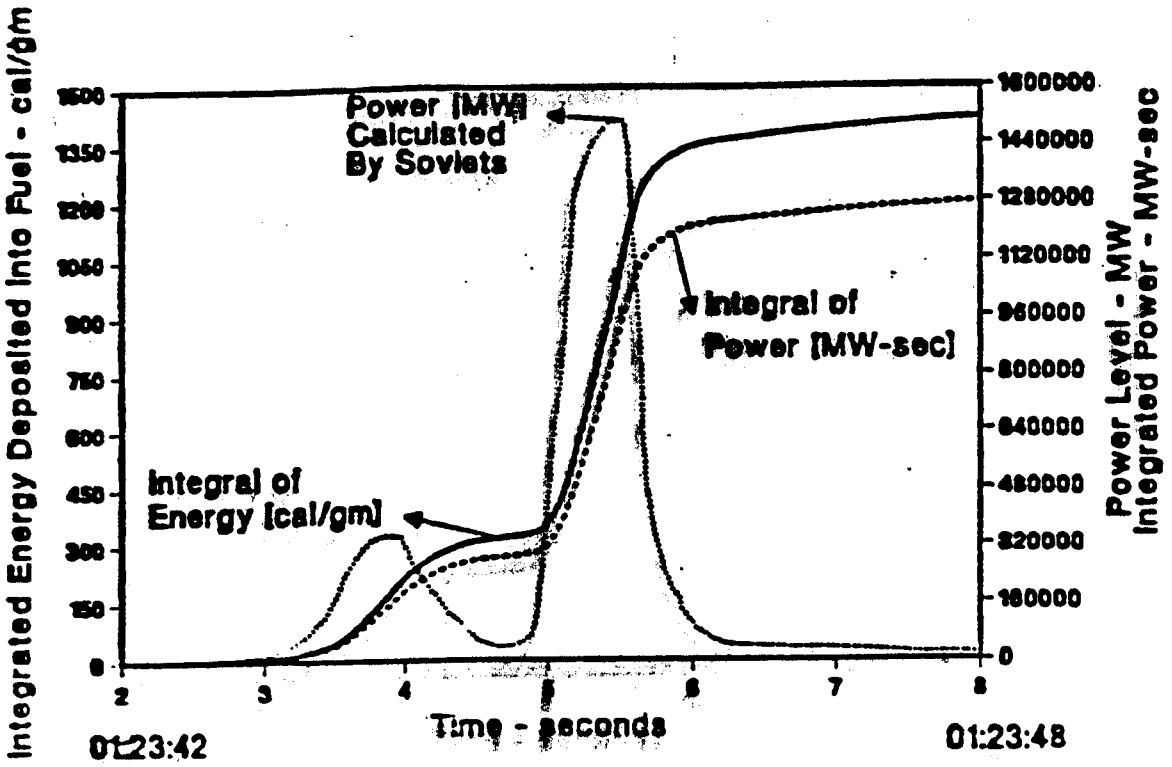


FIGURE 3 CROSS-SECTIONAL VIEW OF REACTOR BUILDING ELEVATION*

* From Reference 4 Figure 2.6

FIGURE 4 CHERNOBYL DATA EVALUATION OF POWER VS. TIME DURING CORE DESTRUCTION PHASE*



*FROM REFERENCE 4 FIGURE 4.3

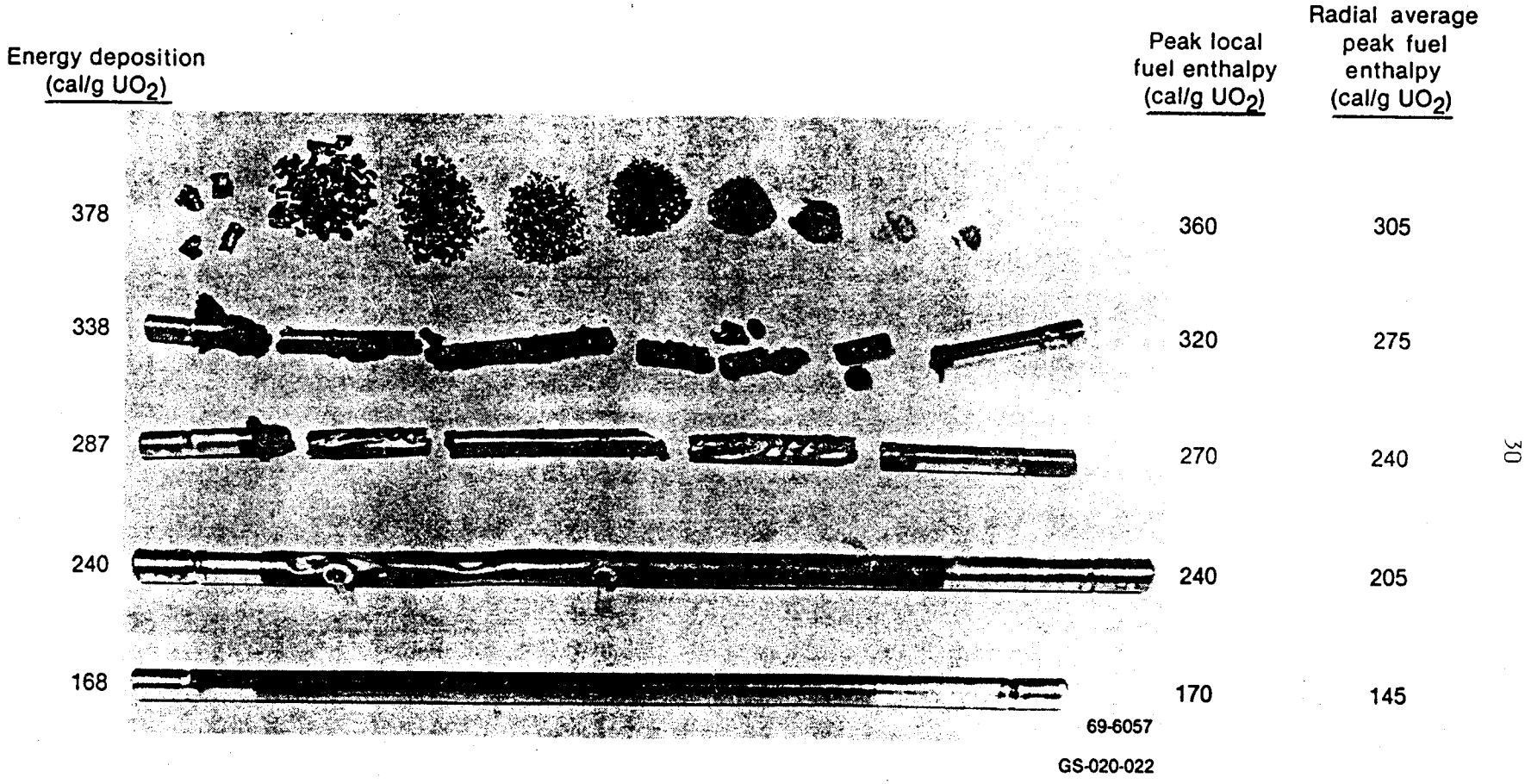


FIGURE 5 PHOTOGRAPHS OF THE RESIDUES FROM MODEL FUEL PINS AFIER TESTS IN THE CDC SIMULATING POWER EXCURSIONS FROM REACTIVITY INSERTION ACCIDENTS*

*FROM REFERENCE 4 FIGURE 4.4

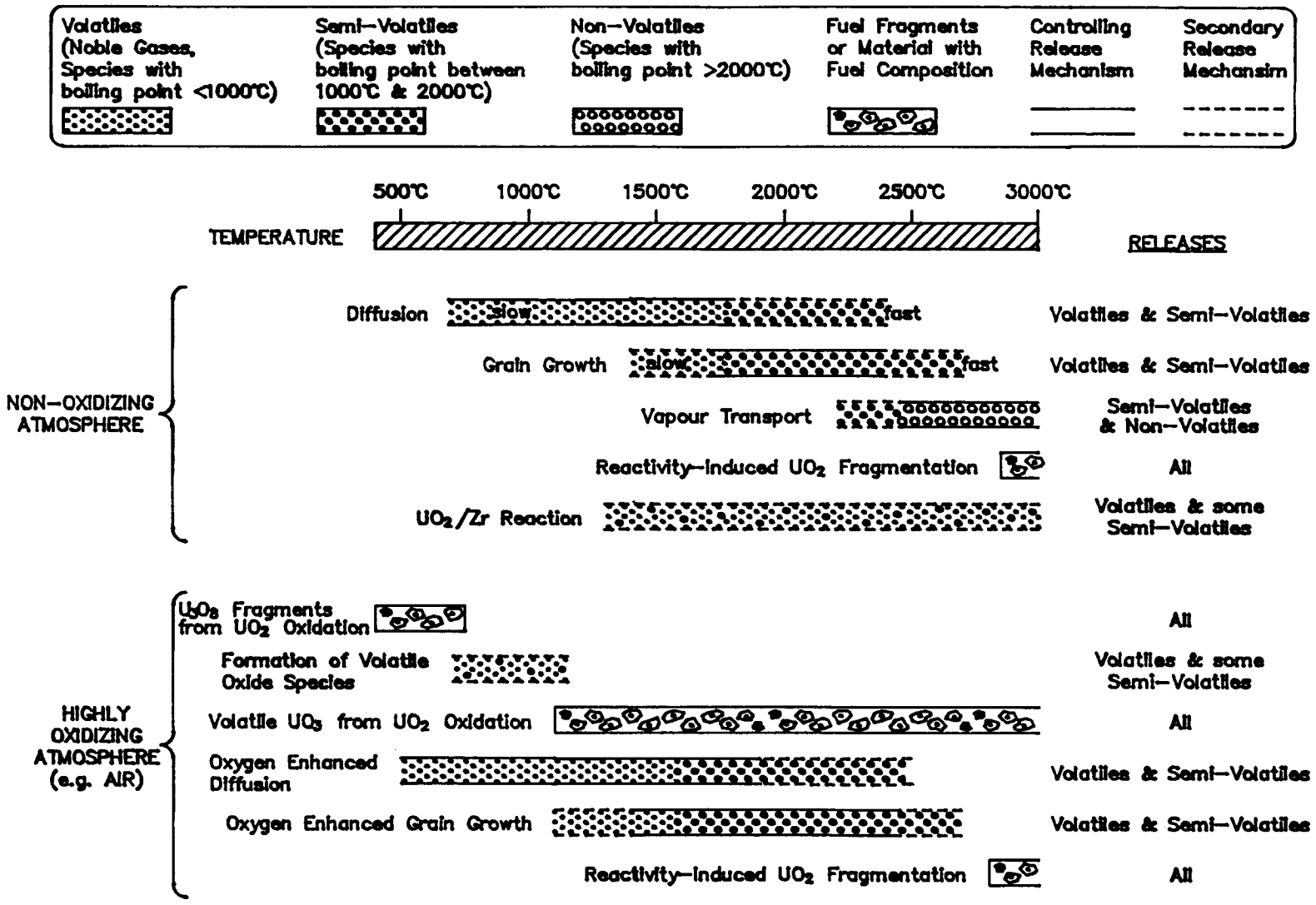


FIGURE 6

Dominant Fission Product Release Mechanisms from UO_2