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INHOUD | **SOMMAIRE**

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PROBABILISTISCHE VEILIGHEIDS- EN RISIKOSTUDIES : HUIDIGE METHODES EN RECENTE EVOLUTIES.

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SAMENVATTING.

In dit artikel wordt een overzicht gegeven van de methodologie voor het uitvoeren van probabilistische veiligheids- en risikostudies.
De nadruk ligt op de studies van niveau 1 die de probabiliteit op kernsmelting bepalen.
De aanknopingspunten met de studies omtrent radiologische gevolgen (niveau 2 en 3) worden aangehaald. Er wordt een bondige toelichting gegeven omtrent het recent onderzoekswerk terzake en omtrent de toepassingsgebieden van deze studies.

1. INLEIDING.

In het begin van de jaren 1970 werd in de Verenigde Staten het initiatief genomen om een studie uit te voeren omtrent de gevolgen van ongevallen die erger zijn dan deze in acht genomen bij het ontwerp. Het bepalen van de probabiliteit van die ongevallen zou dan toelaten het residueel risiko beter te evalueren.
Deze studie werd gekoordineerd door Professor Rasmussen van het Massachusetts Institute of Technology (MIT) en is gekend onder de naam "Rasmussen Rapport", "WASH-1400" of nog "Reactor Safety Study" (RE 75). Ze werd gepubliceerd in 1975.

Na het ongeval van Three Mile Island in 1979, ontstond er een nog grotere interesse voor dergelijke probabilistische studies. Tot op heden werden een veertigtal dergelijke studies uitgevoerd, waarvan het grootste gedeelte voor centrales in de Verenigde Staten.

Het doel van dit artikel is een overzicht te geven van de methodologie voor het uitvoeren van studies die leiden tot het bepalen van de probabiliteit van kernsmelting. De aanknopingspunten met de studies omtrent de radiologische gevolgen worden aangehaald.

2. TYPES VAN PROBABILISTISCHE STUDIES.

In de Amerikaanse literatuur (NU 83) vindt men een indeling van de probabilistische studies in drie types, gebaseerd op hun einddoel. Men spreekt van studies van level 1, level 2 of level 3.

2.1. Level 1.

Een dergelijke studie omvat een grondige analyse van de initiële gebeurtenissen die kunnen leiden tot ernstige ongevallen en een analyse van de betrouwbaarheid van de veiligheidssystemen die in werking moeten treden bij dergelijke ongevallen. Zowel het ontwerp van de installatie als de uitbatingsomstandigheden worden derhalve in detail bestudeerd. Het eindresultaat van een dergelijke studie is de probabiliteit per jaar van kernsmelting. Het grootste deel van de resultaten vindt men terug in het interval van 1E-4/jaar tot 5E-6/jaar. Dergelijke studie laat bovendien toe om de dominante ongevalsscenario's te identificeren.

2.2. Level 2.

Naast alle aspekten van een level 1-studie, worden bovendien de mogelijke fysische processen tijdens het ongeval bestudeerd, alsook de weerstand van het reaktorgebouw. Bij deze fysische processen behandelt men bijvoorbeeld interakties tussen gesmolten corium en beton, de vorming van waterstofgas en mogelijke explosies, het neerslaan van de radioaktieve produkten. Het gedrag van het reaktorgebouw wordt bestudeerd, teneinde het eventuele tijdstip en de mogelijke faalwijzen (scheuren, barsten, katastrofale breuk) te bepalen. Door kombinatie van al deze informatie, kan men dan voor elk ongevalsscenario de hoeveelheid radioaktiviteit bepalen die vrijkomt in de atmosfeer.

2.3. Level 3.

Naast alle aspekten van een level 1 en 2-studie, bestudeert men nu bovendien de verspreiding van de vrijgekomen radioaktiviteit in de omgeving, o.a. rekening houdend met de meteorologische gegevens voor de omgeving van de vestigingsplaats van de centrale.
Uiteindelijk worden dan dosis-berekeningen uitgevoerd, die leiden tot het opstellen van risikokurven.

2.4. In de literatuur vindt men dikwijls de afkortingen PSA = Probabilistic Safety Assessment (korresponderend met een level 1-studie) en PRA = Probabilistic Risk Assessment (korresponderend met level 2 en 3-studies).

3. OMVANG VAN DE STUDIES.

Bij de aanvang van een dergelijke PSA/PRA studie, wordt in de eerste plaats vastgelegd wat men wel en wat men niet zal in acht nemen.

Zo zijn bijvoorbeeld de meeste studies die tot hier toe werden uitgevoerd beperkt gebleven tot de zogenaamde interne initiële gebeurtenissen, die hun oorsprong vinden in de centrale zelf. Het gaat hier dus o.a. om ongevallen van verlies van primair koelwater (LOCA), stoomleidingsbreuk,... en overgangsverschijnselen zoals het verlies van voedingswaterdebiet of ontijdig openen van een ontlastingsafsluiter op het drukregelvat. Doorgaans wordt ook het verlies van het uitwendig elektrisch net hierin opgenomen.

In sommige studies worden echter ook de externe initiële gebeurtenissen bestudeerd. Dit omvat zowel natuurlijke fenomenen (aardbeving, hevige wind,...) als menselijke aktiviteiten (val van vliegtuig, explosies,...). Inwendige brand en overstroming worden doorgaans behandeld bij de externe gebeurtenissen, gelet op hun gelijkaardige impakt (namelijk falingen met gemeenschappelijke oorsprong, zie par. 5.1) op de installatie.

Met de jaren is men meer en meer het belang gaan inzien van menselijke fouten en falingen met gemeenschappelijke oorsprong (common-cause-failures), zodat deze aspekten nu ook steeds meer in detail bestudeerd worden.

Een belangrijk gedeelte van een PSA/PRA studie is de onzekerheidsanalyse. Hierbij onderzoekt men enerzijds de spreiding op het eindresultaat tengevolge van de onzekerheid op de input-gegevens, en anderzijds de gevoeligheid van het eindresultaat ten opzichte van de gebruikte hypotheses en modellen. Een belangrijk principe van probabilistische studies is het gebruik van zo realistisch mogelijke gegevens en hypotheses, dit in tegenstelling tot deterministische veiligheidsstudies waar men doorgaans werkt met konservatieve basisveronderstellingen.

4. METHODOLOGIE VOOR LEVEL 1-STUDIES.

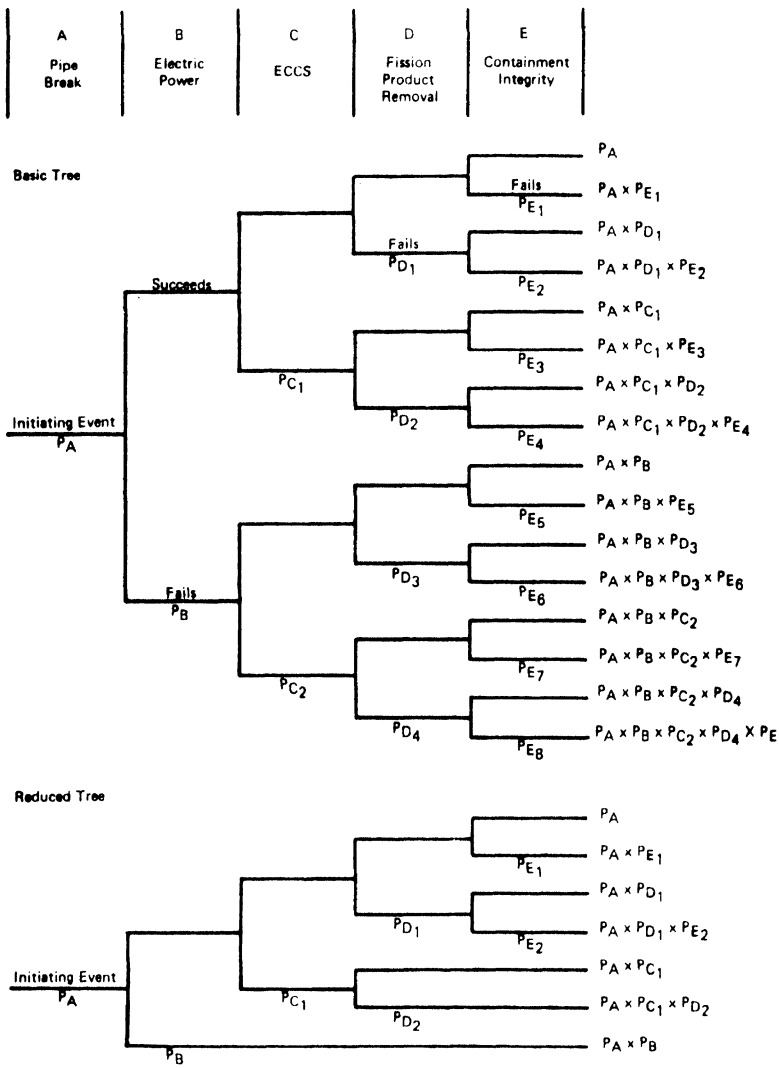
De meest toegepaste methodologie, grotendeels op punt gesteld door de Rasmussen studie (RE 75), bestaat uit het kombineren van twee types logische strukturen : gebeurtenissenbomen (event tree) en foutenbomen (fault tree).

4.1. Gebeurtenissenbomen.

Gebeurtenissenbomen worden gebruikt voor het beschrijven van ongevalsscenario's. Een voorbeeld is voorgesteld in figuur 1.

Voor elke initiële gebeurtenis (bv. grote LOCA) worden de veiligheidsfunkties en -systemen bepaald die moeten tussenkomen om het ongeval onder kontrole te houden.
Elk van deze systemen kan zijn opgelegde taak suksesvol uitvoeren ofwel falen, wat in de gebeurtenissenboom wordt voorgesteld door een tweeledige vertakking. Elk systeem i (in figuur 1 is i = B tot E) wordt gekenmerkt door een faalkans Pi en heeft bijgevolg een probabiliteit voor suksesvolle werking 1-Pi. Elk eindpunt in de gebeurtenissenboom stelt een welbepaald ongevalsscenario voor en de probabiliteit ervan wordt berekend door het produkt van de sukses - en faalprobabiliteiten begrepen in dit scenario.
Er dient op gewezen te worden dat het sukseskriterium voor eenzelfde systeem (bv. de veiligheidsinjektiekring) verschillend kan zijn naargelang de initiële gebeurtenis (bv. grote of kleine LOCA).

De mogelijke eindtoestanden van deze gebeurtenissenbomen dienen als inputgegevens voor de studies van level 2 en 3.



Note · Since the probability of failure, P, is generally less than 0.1, the probability of success (1-P) is always close to 1. Thus, the probability associated with the upper (success) branches in the tree is assumed to be 1.

Fig. 1 : Vereenvoudigde gebeurtenissenbomen voor grote LOCA (RE 75)

4.2. Foutenbomen.

De hogervermelde faalkans Pi voor een bepaald systeem wordt berekend door middel van foutenbomen. Een eenvoudig voorbeeld hiervan is voorgesteld in figuur 2. Voor het opstellen van de foutenbomen definieert men vooreerst de topgebeurtenis, die gebaseerd is op het sukseskriterium (vertaald in een faalkriterium) van het systeem voor de beschouwde initiële gebeurtenis (bv. slechts 1 van 3 treinen met elk 50% kapaciteit van de sproeikring van het reaktorgebouw geeft volle debiet). Vervolgens gaat men op deduktieve wijze de mogelijke faaloorzaken afleiden en deze worden op een korrekte manier verbonden door logische operatoren (OR, AND, K/N,...). De faaloorzaken worden verder ontwikkeld tot men op een niveau komt, de zogenaamde primaire gebeurtenissen, waarvoor men in de data-banken een probabiliteit vindt. Deze primaire gebeurtenissen kunnen van verschillende aard zijn : falingen van komponenten, menselijke fouten, test en onderhoud. Vervolgens wordt een logische analyse uitgevoerd van de foutenbomen. Hierbij worden, rekening houdend met de regels van Boolean algebra, alle zogenaamde minimale sneden (minimal cut sets) van de foutenboom bepaald. Een mimimale snede is elke kombinatie van primaire gebeurtenissen die nodig en voldoende zijn om de topgebeurtenis te bekomen. In het voorbeeld van figuur 2 zijn er 4 minimale sneden, namelijk C, A.B, F en D.E. De faalprobabiliteit van het systeem is dan de som van de probabiliteit van alle minimale sneden.

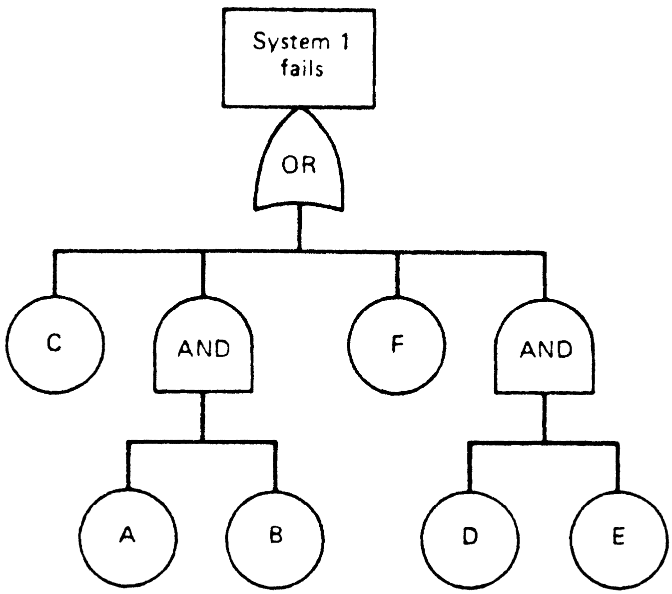


Fig. 2 : Eenvoudige foutenboom (NU 83)

4.3. Data.

Voor het bepalen van de probabiliteit van het smelten van de kern, moeten dus de gebeurtenissenbomen en de foutenbomen gekwantificeerd worden en hiervoor heeft men nodig :

- de probabiliteit van de initiële gebeurtenissen.
  Een voorbeeld is aangehaald in tabel 1. Sommige waarden kunnen afgeleid worden uit de ervaring (bv. verlies van voedingswater), terwijl andere waarden (bv. grote LOCA) eerder berekend of geschat worden.

- de betrouwbaarheid van de komponenten.
  Voor de faalprobabiliteiten kan men beroep doen op verschillende data-banken zoals NUREG/CR-2815 (NU 85) (waarvan een voorbeeld in tabel 2), nationale data-banken en de Europese "Component Event Data Bank", beheerd door JRC-ISPRA.
  Verder moet men ook de duur van de testen en het onderhoud van alle komponenten kennen.

Tabel 1 (NU 85)

Table G.4 Generic Frequencies for PWR Transient Initiators

Int.	PWR Transient Categories	Mean	Variance	Median
1	Loss of RCS Flow (1 Loop)	4.4 E-1	1.3 E-1	3.2 E-1
2	Uncontrolled Rod Withdrawal	2.0 E-2	3.2 E-4	1.3 E-2
3	CRDM Problems and/or Rod Drop	6.1 E-1	3.1 E-1	4.2 E-1
4	Leakage from Control Rods	2.3 E-2	5.0 E-4	1.6 E-2
5	Leakage in Primary System	1.1 E-1	1.1 E-2	7.3 E-2
6	Low Pressurizer Pressure	3.1 E-2	6.5 E-4	2.3 E-2
7	Pressurizer Leakage	9.6 E-3	1.5 E-4	6.0 E-3
8	High Pressurizer Pressure	2.8 E-2	5.5 E-4	2.0 E-3
9	Inadvertent Safety Injection Signal	5.4 E-2	2.3 E-3	4.0 E-2
10	Containment Pressure Problems	1.0 E-2	1.8 E-4	5.9 E-3
11	CVCS Malfunction-Boron Dilution	3.6 E-2	8.3 E-4	2.7 E-2
12	Pressure/Temperature/Power Imbalance-Rod Position Error	1.5 E-1	2.2 E-2	1.0 E-1
13	Startup of Inactive Coolant Pump	4.8 E-3	5.7 E-4	2.3 E-3
14	Total Loss of RCS Flow	2.8 E-2	5.4 E-4	2.0 E-2
15	Loss or Reduction in Feedwater Flow (1 Loop)	1.8 E+0	9.2 E-1	1.5 E+0
16	Total Loss of Feedwater (All Loops)	1.8 E-1	3.0 E-2	1.1 E-1
17	Full or Partial Closure of MSIV (1 Loop)	2.3 E-1	4.8 E-2	1.5 E-1
18	Closure of All MSIV	3.0 E-2	6.6 E-4	2.1 E-2
19	Increase in Feedwater Flow (1 Loop)	6.4 E-1	3.3 E-1	4.4 E-1
20	Increase in Feedwater Flow (All Loops)	1.6 E-2	3.0 E-4	1.0 E-2
21	Feedwater Flow Instability - Operator Error	1.8 E-1	3.2 E-2	1.1 E-1
22	Feedwater Flow Instability - Mechanical Cause	2.0 E-1	4.0 E-2	1.3 E-1
23	Loss of Condensate Pumps (1 Loop)	1.0 E-1	9.8 E-3	6.8 E-2
24	Loss of Condensate Pumps (All Loops)	4.8 E-3	5.7 E-4	2.3 E-3
25	Loss of Condenser Vacuum	2.3 E-1	4.2 E-2	1.7 E-1
26	Steam Generator Leakage	3.7 E-2	8.0 E-4	2.7 E-2
27	Condenser Leakage	5.3 E-2	2.6 E-3	3.8 E-2

Table C.1 Generic Component Failure Rates (All Values per Hour)

Component and Failure Modes	Minimum Value (L)	Mean	Maximum Value (M)	Remarks
1. Pumps				
1.1 Motor driven				Pump and motor; excludes control circuits.
1.1.1 Failure to start	2E-7	1E-5	5E-5	
1.1.2 Failure to run, given start	2E-6	1E-4	5E-4	
1.1.2.1 Extreme environment	6E-5	3E-3	2E-2	Considered as interface with heavy chemical environment such as concentrated boric acid.
1.2 Turbine driven				Pump, turbine, steam and throttle valves, and governor.
1.2.1 Failure to start (includes under and over speed)	2E-6	1E-4	5E-4	
1.2.2 Failure to run, given start	8E-6	2E-5	1E-4	
1.3 Diesel driven				Pump, diesel, lube oil system, fuel oil, suction and exhaust air, and starting system.
1.3.1 Failure to start	2E-7	1E-6	5E-5	
1.3.2 Failure to run, given start				
2. Valves				Catastrophic leakage or "rupture" values assigned by engineering judgment; catastrophic leakage assumes the valve to be in a closed state, then the valve fails.
2.1 Motor operated				
2.1.1 Failure to open	2E-7	1E-5	5xE-5	
2.1.2 Failure to remain open	8E-8	2E-7	1E-6	
2.1.3 Failure to close	2E-7	1E-5	5E-5	
2.1.4 Internal leakage (catastrophic)	1E-10	1E-7	7E-7	
2.2 Solenoid operated				
2.2.1 Failure to operate	8E-7	2E-6	1E-5	
2.3 Air/fluid operated				
2.3.1 Failure to operate	2E-7	1E-5	5E-5	
2.4 Check Valves				
2.4.1 Failure to open	8E-8	2E7	1E-6	
2.4.2 Failure to close	6E-7	2E-6	1E-5	

Voor de keuze van de bron van deze kwantitatieve data bestaan twee grote opties :

- ofwel doet men beroep op bestaande data-banken, die dan meestal generieke data leveren, dwz. dat deze data afgeleid werden uit gegevens afkomstig van meerdere centrales en zelfs verschillende types (PWR, BWR,...) van centrales.

- ofwel gebruikt men specifieke waarden voor de bestudeerde centrale, welke afgeleid werden uit de uitbatingservaring.

Bepaalde mathematische methodes (Bayesian Statistics) laten toe de twee soorten data te kombineren.

5. RECENT ONDERZOEKSWERK.

Twee aspekten die de laatste jaren veel aandacht hebben gekregen zijn de falingen met gemeenschappelijke oorsprong (common-cause-failures) en de menselijke fouten. Door de Europese Gemeenschap werden recent twee "Reliability Benchmark Exercises" georganiseerd omtrent deze onderwerpen (PO 87, PO 88).
Hieronder volgt een kleine toelichting betreffende beide fenomenen.

5.1. Fouten van gemeenschappelijke oorsprong.

Onderstel dat in een systeem drie redundante pompen A, B en C voorkomen met een kapaciteit van elk 100% en dat een dergelijke pomp een faalkans heeft van 1E-3 bij het starten.

Wanneer de faaloorzaken strikt onafhankelijk zijn, is de probabiliteit dat de drie pompen niet starten gelijk aan :

$P_3 = P_A \cdot P_B \cdot P_C = 1E\text{-}9$

De ervaring leert echter dat in bepaalde gevallen wel degelijk een afhankelijkheid bestaat, waarvoor men dan konditionele probabiliteiten invoert. Is $P_{B/A}$ de probabiliteit dat pomp B faalt gegeven zijnde dat pomp A reeds gefaald is, en is $P_{C/BA}$ de probabiliteit dat pomp C faalt gegeven zijnde dat A en B reeds gefaald hebben, dan wordt de faalkans van het systeem (met enkele gebruikelijke waarden uit de literatuur)

$P_3 = P_A \cdot P_{B/A} \cdot P_{C/BA} =$
$= 1E\text{-}3 \times 0{,}05 \times 0{,}3 = 1.5E\text{-}5$

wat aanzienlijk hoger is dan de vorige waarde.
Dergelijke afhankelijke faaloorzaken kunnen bv. te wijten zijn aan het ontwerp, het onderhoud of aan ongunstige omgevingsvoorwaarden.

5.2. Menselijke fouten.

Voor de analyse van de mogelijke menselijke fouten bij het uitvoeren van "routine-taken", waarbij meestal schriftelijke procedures worden gebruikt (bv. voor test en onderhoud of in post-accidentele faze), wordt heel dikwijls de THERP-methodologie gebruikt ontwikkeld door Swain en Guttmann (SW 83).

Het recente onderzoekswerk heeft zich vooral toegespitst op nieuwe methodes of modellen voor de analyse van "cognitive behaviour", waarbij de operatoren beoordelings- en beslissingsopdrachten moeten uitvoeren. Het "Human Cognitive Reliability" model ontwikkeld door Hannaman (HA 87) bv. levert de "non-response probability" in funktie van de beschikbare tijd. Een interessant aspekt is de mogelijkheid tot validatie van deze modellen door middel van simulatoren.

6. GEBRUIK VAN PSA/PRA STUDIES.

Oorspronkelijk werden deze studies vooral uitgevoerd voor het beoordelen van de veiligheid en de risiko's van kerncentrales. Men probeerde een inzicht te krijgen in de dominante scenario's die leiden tot het smelten van de kern of tot grote radioaktieve lozingen. Op basis van de resultaten werden dan eventueel te nemen maatregelen onderzocht.

Langzamerhand begint echter het koncept van de "Living PSA/PRA" meer en meer ingang te vinden. Hierbij is het belangrijkste deel van de studie on-line toegankelijk op komputer (soms zelfs op een "Personal Computer", waardoor dit een werkinstrument kan worden in de dagelijkse uitbating. Wanneer de uitbater bijvoorbeeld gekonfronteerd wordt met gekombineerde onbeschikbaarheden, kan hij op een vlugge manier een inzicht krijgen in de toename van het ogenblikkelijke risiko.

Ook de Technische Specifikaties, die de uitbatingsvoorwaarden van de centrale vastleggen, worden meer en meer gerechtvaardigd op basis van probabilistische studies.

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RESUME.

Cet article donne une vue générale sur la méthodologie des études probabilistes de sûreté et de risques. L'accent est mis sur les études de niveau 1 qui étudient la probabilité de fusion de coeur. Les interactions avec les études sur les conséquences radiologiques (niveau 2 et 3) sont indiquées. Une description succincte de la recherche récente à ce sujet et des domaines d'application est présentée.

ABSTRACT

This paper gives an overview of the methodology for probabilistic safety and risk analysis. The emphasis is on level 1 studies which determines the probability of a core melt accident. The interactions with studies on the radiological consequences (level 2 and 3) are indicated. A short discussion of recent research in this field and of the application fields is presented.

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THE CEC PROGRAMME ON ACCIDENT CONSEQUENCE ASSESSMENT

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Abstract

The Commission of the European Communities, in the framework of its Radiation Protection Programme, initiated in 1983 a two-year project on "Methods for Assessing the Radiological Impact of Accidents-MARIA". Major contractors were the Kernforschungszentrum Karlsruhe (KfK-FRG) and the National Radiological Protection Board (NRPB-UK). Within the 1985-1989 Radiation Protection Programme, the MARIA programme was continued and enlarged (MARIA 2) through complementary research contracts in several Member States. At present, 28 projects contribute to the MARIA-2 programme, the priorities of which are shortly presented.

In the aftermath of the Chernobyl accident, the priorities of the MARIA-2 programme were evaluated and additional projects were started. A total of ten actions, of which five are directly relevant for the MARIA-2 programme, was launched. These actions are briefly described.

1. Introduction

Methodologies aiming at the assessment of the radiological consequences of accidental releases of radioactivity through a probabilistic approach are increasingly used to assess the risks presented by nuclear installations, and as an input into decisions on siting, to develop emergency planning arrangements and to choose between alternative countermeasures. These issues have led the Commission of the European Communities, in the framework of its 1980-1984 Radiation Protection Research Programme, to promote a co-ordinated research action at the European level to review, and above all, to improve the probabilistic accident consequence assessment methods in use in the Member States of the European Community. Therefore the Commission initiated in 1983 a two-year project on "Methods for Assessing the Radiological Impact of Accidents-MARIA" mainly carried out by the Kernforschungszentrum Karlsruhe (KfK) and the National Radiological Protection Board (NRPB) (1,2). Recent years have not only seen a growth of international exchanges of information in probabilistic off-site accident consequence assessment but also of active co-operation leading to improved co-ordination of the work in this field.

In the frame of the new pluriannual Radiation Protection Research Programme 1985-1989, the MARIA programme was continued and enlarged (MARIA 2).

At present, 18 contracts representing 28 projects are considered in the MARIA 2 programme. They amount to an overall cost of about 11 Mio ECU with a financial participation of the Radiation Protection Programme of the Commission of about 4 Mio ECU. The programme represents a total manpower effort of 116 man/years and 16 European institutions are involved.

2. The MARIA 2 programme

The MARIA 2 programme aims at the development of a generic probabilistic accident consequence assessment code by the end of 1989. This code will be made available to national authorities and research groups within the Member States. In order to facilitate the application of the code to particular situations, a modular structure, enabling the incorporation of site-specific data and modules, is foreseen. In principle, the code will be able to deal with all possible source terms and will address all environmental transfer processes and exposure pathways. One of the most beneficial applications will be to serve as an input in the optimization of emergency planning and envisaged countermeasures, considering the risks and benefits for man and society. The main priorities of the MARIA 2 programme can be grouped in six different categories.

2.1. Atmospheric dispersion

The implications of using trajectory models instead of straight line models were quantified. A comparison of the two approaches led to the conclusion that significant differences in the assessed consequences appear if models of different degrees of complexity are being used. Therefore, for assessing the far field consequences, a Gaussian-type trajectory model will be applied.

A mathematical model for calculating dry deposition velocities of gases and particulates to a vegetative canopy was completed. This model reproduces well the experimental data on the deposition velocity of Pb-212 atoms and particles to an artificial grass canopy over a wide range of wind speeds.

In order to improve the wet deposition modelling, an extensive data base on precipitation has been completed, meteorological sampling techniques were established and the data bases are used in conjunction with a mesoscale trajectory model.

Studies of wind flow fields and of dispersion over complex terrain and water bodies are underway. The ADREA-I code (3) was applied to predict the natural circulation of the atmospheric boundary layer and to the development of sea breeze circulation in case of an opposing synoptic scale wind.

One aspect not yet considered is the modelling of the in-cloud physico-chemical modifications of the radionuclides. These have an influence on deposition processes and on the bio-availability of deposited material and should be studied.

2.2. Shielding calculations for plume irradiation

Dose reduction factors were assessed by calculating the photon field characteristics in open air, in dwellings and the whole-body absorbed dose outdoors and indoors. This work will yield representative shielding factors for typical European houses.

Detailed Monte-Carlo photon transport calculations were applied to a row of 4 large terrace houses in a suburban environment. The gamma dose rates were tabulated for different kinds of contamination, and allowed to assess the corresponding shielding factors. It has been found that European houses, in general, have a better shielding capacity against gamma radiation than was previously assumed.

2.3. Assessment of exposure due to deposited radioactive materials

The relative contributions of the different pathways of exposure, namely external exposure, internal exposure by ingestion (including studies on the transfer of radioactivity through the foodchain), and exposure by inhalation of airborne and resuspended material are calculated.

The estimation of doses resulting from external exposure is performed with age-dependent conversion factors calculated with Monte-Carlo techniques assuming a contaminated soil layer of 2-4 mm depth and taking diffusion to deeper soil layers into account. Dose conversion factors for 141 radionuclides, 13 organs and 26 integration times have been included in the new version of the UFOMOD computer code developed by the KfK (4). A dynamic model for the transfer of radionuclides to root crops, incorporating seasonal effects, is required for use in accident consequence assessments. A model considering the translocation mechanism of deposited activity from the aerial part of the plant to the edible root is developed by NRPB. Previously used models significantly underestimated the contamination of root crops for deposits of caesium isotopes at some times of the year.

Great effort is given to the study of the pathways and systems pertaining to the urban environment. Matrices were developed for the indoor dose rates at different locations in a variety of buildings and surroundings for standardized contamination of each of the significant surfaces.

Some important contributors in determining indoor doses were disclosed, e.g. the fraction of surface which is paved and deposition to tree canopies adjacent to buildings. Progress was made on the estimation of the indoor dose via inhalation. Tracer techniques, using fluorescent particulates, are used to investigate the indoor mechanical transport of particulate material of different size.

2.4. Countermeasures for reducing the radiological impact

In case of uncontrolled releases of radioactivity, the exposure of the population can only be reduced by setting up appropriate interventions. This may range from simple recommendations like staying indoors, careful washing of fresh food or even bans on some foodstuffs to reduce long term exposure up to compulsory evacuation of a region. Obviously, the measures taken will differ for the near-, medium- and far-field regions. A model, flexible enough to compare the feasible alternatives of emergency response planning, of emergency management is developed and the behavioural reactions of the public on the efficiency of a given intervention are evaluated. This holds for near, medium and far field implications.

2.5. Evaluation of socio-economic consequences

All countermeasures taken entail social and economical consequences, and in all cases, the introduction of a countermeasure brings about benefits and risks. At the social level, the compulsory introduction of a countermeasure will have a strong psychosociological impact, due to the fact that to some extent normal life is disrupted. The economical losses also are obvious, and these are to be assessed. An indicated way of doing this is to use a macro-economic approach for long duration countermeasures at a regional level whereas a micro-economic approach is best suited to deal with local problems.

Following Chernobyl, tremendous confusion existed with respect to the introduction of countermeasures and the setting of derived intervention levels for foodstuffs. It is a direct interest of the worldwide Radiation Protection Society to perform supportive work in this respect.

2.6. Uncertainty analysis

Work in this field deals with a review of all the methods available for probabilistic uncertainty analysis, with an investigation of their limitations and advantages. New developments aim at an enhancement of their applicability, efficiency and reliability. Through an application of various techniques available for uncertainty and sensitivity analysis of large computer models, a selection of the most appropriate techniques for analysing the uncertainty in the predictions of accident consequence assessments is made.

3. The revision of the 1985-1989 Radiation Protection Programme

Although the current research programme is quite comprehensive, the Chernobyl accident influenced its implementation at three different levels:
- new contracts will have to bridge gaps in the implementation of the programme,
- ongoing contracts may be reoriented to cover additional topics, as far as the objective of the contract allows,
- further work to be committed in areas where the accident pinpointed need for additional research.

With respect to the latter, and in collaboration with the Coordination and Management Committee of the Programme, collaborative actions were commissioned (5). The aim is to improve the prediction of two aspects of any accidental release: immediate and late radiological consequences and increased preparedness for possible future accidents. A total of 10 collaborative actions was launched:
- evaluation of the reliability and meaningfulness of long-distance atmospheric transfer models,
- evaluation of data on the transfer of radionuclides in the foodchain,
- feasibility of studies on health effects,
- radiological aspects of nuclear accident scenarios,
- underlying data for derived emergency reference levels,
- improvement of practical countermeasures against nuclear contamination in the agricultural environment,
- improvement of practical countermeasures against nuclear contamination in the urban environment,
- improvement of practical countermeasures through preventive medication,
- monitoring and surveillance in accident situations,
- treatment and biological dosimetry of exposed persons.

These actions were approved by Council decision of 21st of December, 1987, and the majority of the projects will run till the end of 1989. A total budget of 10.10^6 ECU was approved. Five of these actions are directly relevant for the MARIA 2 programme.

3.1. Long distance atmospheric transfer

The general aim of this action is to develop a reliable long distance atmospheric transfer model using forecast meteorological data to display where and when countries - even those at large distance from the release point - are likely to be affected during the course of and following a protracted release. The approach will make optimum use of existing codes and will concentrate on some key issues:
- Analysis and quality assurance of radiological data.
  The radiological measurements from Chernobyl will generally exhibit variability of two kinds: intrinsic variability due to atmospheric turbulence and patchy rainfall and spurious

variability due to the lack of quality assurance and systematic measuring errors. Careful examination of the data may help to remove some of the spurious variability and render the data more reliable for model validation.

- Source-term estimation.
  Following Chernobyl, attempts were made to use radiological data from a large geographical area in conjunction with a model of atmospheric transfer and deposition in order to work back to an estimate of the source term. This involves an "iterative procedure" and now the feasibility of using a direct mathematical solution will be investigated.
- Emergency response.
  The principal goal is to have a facility at hand to provide an early indication of when and where material may be expected to appear in the days following the accident. It will be based on the construction of air - parcel trajectories using forecast wind-field data covering Western-Europe. Selection of the best elevation will be done by using Chernobyl data.
- Complex terrain modelling.
  Especially when trajectories pass over complex terrain topographics, the uncertainties for selecting the best elevation are very important. Moreover, topographical features have a significant influence on transport and deposition. The aim is to clarify the influence of large topographical disturbances on long-range transport of pollutant material.

3.2. Evaluation of data on the transfer of radionuclides in the foodchain

Five aspects of the transfer of radionuclides in the foodchain for which important uncertainties still persist have been identified. If transfer coeffecients are more or less substantially documented for routine releases, there is indeed a need to provide evidence of their reliability for predicting post-accident behaviour.

- Impact of chemical speciation on radionuclide transfer.
  Radionuclides released in accidental situations are potentially subject to very special condition (high temperature, abundance of water vapour, presence of corrosion products, etc.). The post-Chernobyl fall-out therefore differs from the weapon-test fall-out. Chemical speciation of both will be carried out and correlations with deposition characteristics, long term behaviour in soil and subsoil mobility will be established.

- Contamination of natural ecosystems and their role in the foodchain contamination.
  In the pre-Chernobyl period, natural and semi-natural ecosystems were given rather poor attention. However, a number of pathways lead directly to man primarily by way of meat, dairy products and water supplies. The assessment of the movement of radionuclides through natural and semi-natural ecosystems will enable to prepare more realistic models.

- Transfer of radionuclides to animal products.
  Animal studies under controlled conditions allowing an accurate estimation of daily intakes will be performed on various species of lactacting ruminants, e.g. cow, sheep, goat. This will be combined with field studies in various ecological conditions in view of determining the critical environments. Age and metabolic dependencies will be evaluated.

- Contamination of aquatic ecosystems.
  Based on the existing data bases, both from post-Chernobyl and earlier weapons fallout, a predictive capability of dynamic nature for assessing the contamination of impounded freshwater systems will be developed.

- Validation of soil-plant transfer coefficients.
  A long-term follow-up of post-Chernobyl soil to plant transfer coefficients for different soils, crops and in various climatological conditions will be conducted.

3.3. Radiological aspects of nuclear accident scenarios

The objective within this action is double: development of a real-time assessment model for emergency situations and the development of a computer system to aid decisions following accidental releases into the environment. The system is not only meant to have a predictive and decision making facility at hand to serve in event of emergencies, but also to be used for emergency training purposes. Quite a number of methodological aspects are already addressed in the MARIA 2 programme and optimum use will be made of the available information.

- A real time model for short and medium range atmospheric dispersal of radionuclides.
  Through an adjustment of the already existing Gaussian puff models, a real time local system enabling feed-back with early environmental radiometric measurements will be developed. The time-varying meteorological conditions and source characteristics will be included.

- Treatment of complex terrain configuration.
  The ongoing work in the MARIA 2 programme for modelling complex terrain implications will be adapted to be incorporated in the real time model. This will necessitate to guarantee sufficiently efficient computer usage.

- Use of weather radar data.
  The Chernobyl accident has illustrated the potential importance of local precipitation, intensive rain and thunderstorms. Adequate coupling of detailed weather radar data with accurate information on the passage of the radioactive cloud will indicate localities to be more highly contaminated by wet deposition.

- Real-time countermeasure modelling.
  A real-time prognostic exposure assessment programme with sufficient resolution in time and space will be combined with a fast computer-aided decision making module for the introduction of adequate countermeasures based on cost-effectiveness considerations. A more comprehensive module to be incorporated in the probabilistic MARIA code will cover the medium- and far-field long term implications.

3.4. Monitoring and surveillance in accident situations

Off-site monitoring and surveillance during and after an accidental release of radioactivity requires interrelated physical and radiological measurements. If methods for high-grade physical and radiological measurements are well understood, they are too time consuming and a high spatial density is unrealistic. They need therefore to be supplemented by lower grade, simpler and more rapid measurements.

- Sampling and measurement of air concentrations.
  Evaluation of the influence of filter construction and sample preparation on the detection of alpha and beta emitters.

- Dose rate instruments and alarm monitors.
  Development of instruments having improved sensitivity at environmental dose-rate levels and enabling to discriminate against short-term variations of natural radiation due to radon and its decay products.

- Measurement of the ground contamination.
  Development of simple movable systems to carry out rapid field measurements of exposure from gamma emitters present in the soil and interpretation of the readings in terms of ground concentrations.

- Specific activity determination in the laboratory.
  Formulation of recommendations with respect to standard methods, sample sizes and measuring geometries.

3.5. Underlying data for derived emergency reference levels

The Article 31 Group of Experts of the Commission of the European Communities elaborated a methodology for fixing maximum concentration levels of radionuclides in foodstuffs. Several hypotheses underlying this approach need to be verified and the methodology is to be compared with other approaches such as dynamic radioecological modelling and optimization.

- Dynamic radioecological models.
  In the light of the experience acquired after the Chernobyl accident, the existing dynamic radioecological models FOOD-MARC and ECOSYS will be extended in order to enable their application to specific regions of the Community.

- Distribution and consumption of food.
  Food distribution patterns at the regional, national and international level may significantly modify the average intake of radioactivity by the public. Its influence, as well as the impact of modifications after an accident, will be assessed.

- Metabolic and dosimetric dose assessment models.
  A review of available metabolic and dosimetric data will be undertaken in view of developing procedures for age dependent dose calculations following inhalation and ingestion of contaminated foodstuffs.

- Measurement of the internal contamination of man.
  Whole body counting and/or excretion measurements of selected groups of volunteers (patients or hospital staff, soldiers) of various ages and origins are performed. This will allow to check the reliability of modelling results and the validity of the "Standard European Food Basket".

- Optimization of Derived Intervention Levels for Foodstuffs.
  Application of derived intervention levels for foodstuffs entails considerable disruption of food production, processing and trade. Optimization of their application will be studied by modelling and the beneficial effects of information of the public and recommendations for domestic food preparation will be assessed.

4. Conclusion

By the end of the current 1985-1989 programme, two comprehensive ACA methodologies will be available. One will be of probabilistic generic nature and the other will be a comprehensive and updated real-time model. Both will be available for national authorities and research institutions. Further development and upgrading of these models will be considered in the forthcoming 1990-1994 Radiation Protection Research Programme.

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Samenvatting

In het kader van het Stralingsbeschermingsprogramma heeft de Commissie van de Europese Gemeenschappen in 1983 een tweejarig MARIA-projekt gelanceerd (Methods for Assessing the Radiological Impact of Accidents - Methoden voor het afschatten van de stralingsgevolgen van ongevallien). De voornaamste kontrakten waren met het Duitse "Kernforschungszentrum Karlsruhe - KFK" en het Engelse "National Radiological Protection Board - NRPB". Door het afsluiten van additionele onderzoekkontrakten in andere lidstaten werd het MARIA-2 programma voor de periode 1985-1989 voortgezet en verbreed. Momenteel omhelst dit MARIA-2 programma 28 projekten waarvan de hoofddoelstellingen kort worden beschreven.
Volgend op het Tchernobyl ongeval werd het MARIA-2 programma doorgelicht en nieuwe projekten werden gestart. Op een totaal van 10 gekoordineerde projekten zijn 5 rechtstreeks belangrijk voor het MARIA-2 programma en ook deze worden in het kort beschreven.

Résumé

Dans le cadre de son programme Radioprotection, la Commission des Communautés Européennes a lancé en 1983 un projet biennal baptisé MARIA (Methods for Assessing the Radiological Impact of Accidents - Méthodes d'évaluation de l'impact radiologique des accidents). Les contractants chefs de file de cette action furent le "Kernforschungszentrum Karlsruhe - KFK" de la République Fédérale d'Allemagne et le "National Radiological Protection Board - N.R.P.B." du Royaume Uni. Dans le cadre du programme Radioprotection 1985-1989, l'action MARIA s'est prolongée et élargie (MARIA-2) grâce à des contrats de recherche complémentaire établis avec des établissements de plusieurs états membres. Actuellement, le programme MARIA-2 comprend 28 projets décrits succinctement ci-dessous.
Suite à l'accident de Tchernobyl, les priorités du programme MARIA-2 ont été évaluées et des projets supplémentaires on été initiés. Au total, dix actions dont cinq sont directement liées au programme MARIA-2 ont été lancées, elles sont décrites brièvement ci-dessous.

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BLOOTSTELLINGSWEGEN VAN DE BEVOLKING IN GEVAL VAN EEN ERNSTIGE RADIOAKTIEVE LOZING IN DE ATMOSFEER.

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KORTE INHOUD

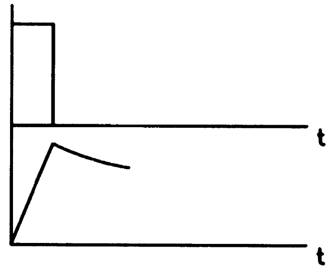
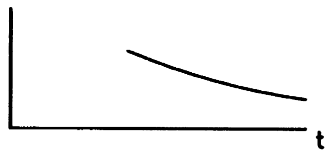
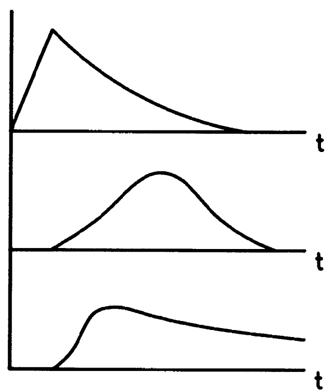
Het relatieve belang van de blootstellingswegen, waarlangs de bevolking ingeval van een ernstige radioaktieve lozing in de atmosfeer wordt geëvalueerd vanuit het oogpunt van de te nemen beslissingen om haar te beschermen. Er wordt nader ingegaan op de blootstellingswegen die de evaluaties gedurende de eerste fase van het noodplan beheersen. Voor iedere blootstellingsweg wordt aangeduid hoe de dosis van de bevolking op een meer realistische wijze kan afgeleid worden, dan tot hiertoe in de modelberekeningen gebruikelijk was.

1. INLEIDING

De bevolking wordt door de radioaktieve stoffen die in de atmosfeer kunnen worden geloosd ingeval van een ernstig reaktorongeval blootgesteld via verschillende wegen (tabel 1).
Deze bijdrage wil nader ingaan op de fenomenen die een rol spelen bij de relatie tussen de omgevingsbesmetting en de reële dosis die de bevolking kan oplopen, vooral gedurende de eerste fase van een noodsituatie, die hier arbitrair beperkt wordt tot de eerste vierentwintig uren na het begin van de lozing. Een goed inzicht in de fenomenen die deze dosis beïnvloeden is onontbeerlijk voor een realistische risikoëvaluatie en een juiste interpretatie van meetresultaten. Alhoewel de kwalitatieve beschouwingen algemeen geldig zijn, hebben de numerieke gegevens slechts betrekking tot ongevallen met een 1000 MWe drukwaterreaktor.

2. SAMENSTELLING VAN DE LOZINGEN

De aktiviteit in de kern van een reaktor bestaat uit splijtingsprodukten, geaktiveerde struktuurmaterialen en brandstof. Tabel 2 geeft een overzicht van de massa van de voornaamste aanwezige elementen. Deze lijst is beperkt tot de isotopen die relevant zijn voor de blootstelling van de bevolking. Het is merkwaardig dat materialen die de hoofdrol spelen bij grote ongevallen, zoals Iodium en Caesium slechts een beperkte massa betekenen. Zo is er slechts ongeveer 700 g Iodium-131 aanwezig in de kern van een 1000 MWe reaktor.

BLOOTSTELLINGSWEG	*TIJDSVERLOOP VAN BLOOTSTELLING*	*KONTROLE VAN BLOOTSTELLING*	*VOORNAAMSTE RISIKO*
WOLKBESTRALING INHALATIE DEPOSITIESTRALING eerste dag		SCHUILEN I-TABLETTEN EVACUATIE	VROEGE EFFEKTEN
DEPOSITIESTRALING later RESUSPENSIE		RELOKATIE DEKONTAMINATIE	BEWOONBAARHEID
VOEDSEL – RECHSTREEKSE BESMETTING – TRANSFERT VIA DIEREN – TRANSFERT VIA BODEM		VOEDSELDISTRIBUTIE GRAASVERBOD	LATE EFFEKTEN

<u>Tabel 1</u> : Overzicht van blootstellingswegen.

Al deze stoffen worden ingeval van bijv. een ongeval met smelten van de reaktor niet in gelijke mate vrijgezet. Tabel 3 geeft een overzicht van de smelt- en kookpunten van diverse chemische verbindingen waarin zich de voornaamste radionukliden manifesteren. Het is duidelijk dat ingeval van oververhitting van de kern, de gassen, Xenon en Krypton, het gemakkelijkst zullen vrijkomen. Daarop volgen Iodium, Caesium en Tellurium in chemische vormen met een kookpunt van om en bij de 1000°C of lager. Andere relevante materialen hebben kookpunten van tweeduizend graden of hoger en zullen dus in beduidend kleinere hoeveelheden worden vrijgezet.

Tabel 2 Massa van de voornaamste materialen aanwezig in de kern van een 1000 MWe Drukwaterreaktor.

Element	Massa (kg)	Element	Massa (kg)
Kr	13,4	Ba	61,2
Sr	47,6	Ce	131
Ru	104	U	70.210
Te	25,4	Pu	469
I	12,4	Zr	16.460
Xe	260	Fe	6.484
Cs	131		

Tabel 3 Smelt- en kookpunt van enkele belangrijke verbindingen aanwezig in een reaktorkern.

	Smeltpunt (°C)	Kookpunt (°C)
Kr	-157	-152
Xe	-112	-107
I_2	114	185
CsI	626	1280
CsOH	315	990
Te	450	988
BaO	1923	2808
Ru	2250	4150
SrO	2430	3249
B_4C	2470	> 3500
Zr	1852	4409
Fe	1535	2862
UO_2	2840	3293

De grote ongevallen kunnen aldus ingedeeld worden in verschillende types, gekarakteriseerd door de frakties van de chemische groepen die vrijgezet worden. Deze methode werd eerst toegepast in WASH - 1400 en sindsdien in de opeenvolgende veiligheidsstudies.
Fig. 1 toont de lozingsfrakties van enkele reële accidentsscenario's, nl. Chernobyl, Windscale en TMI. Voor Windscale werd genormaliseerd op de inventaris van het gedeelte van de reaktor dat bij het ongeval beschadigd werd.
Men ziet dat het profiel van de relatieve frakties van Chernobyl en Windscale identiek zijn. Dit profiel is blijkbaar typisch voor een vrijzetting ten gevolge van een open brand.
Bij het TMI-ongeval werden slechts kleine frakties van edelgassen en iodium vrijgezet tengevolge van de aanwezigheid van een gesloten reaktorgebouw en de interaktie van de splijtingsprodukten met het overvloedig aanwezige water. De volle lijn in figuur 2 geeft een beeld van het te verwachten profiel ingeval van een ernstig ongeval met een drukwaterreaktor waarvan het reaktorgebouw zou falen.
In de verdere diskussie zullen de types van de brontermen gekarakteriseerd worden door de frakties Iodium, Caesium en Tellurium die wordt vrijgezet naast 100 % van de edelgassen. Men neemt aan dat de drie voormelde groepen met een gelijke fraktie worden vrijgezet en dat de andere groepen niet geloosd worden.

3. HET RELATIEF BELANG VAN DE BLOOTSTELLINGSWEGEN.

Tabel 1 geeft een overzicht van de verschillende blootstellingswegen, ingedeeld in drie groepen, namelijk :

1. De blootstellingswegen belangrijk voor de eerste dag, wolkstraling, inhalatie en depositie gedurende de eerste dag. Zij zijn belangrijk voor het eventueel aantal vroege slachtoffers onder de bevolking.
   De blootstelling wordt gekontroleerd door de maatregelen voorzien in de eerste fase van de noodplannen, namelijk : schuilen, inname van stabiel iodium en evakuatie.
   Wolkstraling en inhalatie zijn alleen te beschouwen tijdens de aanwezigheid van de besmetting, terwijl de depositie straling zich dan opbouwt en relatief weinig afneemt gedurende de eerste dag.
   De kontrolemaatregelen hebben het meeste kans op slagen indien ze preventief worden genomen.
2. De blootstellingswegen belangrijk voor de bewoonbaarheid van een besmet gebied, namelijk de straling van neergezette aktiviteit na

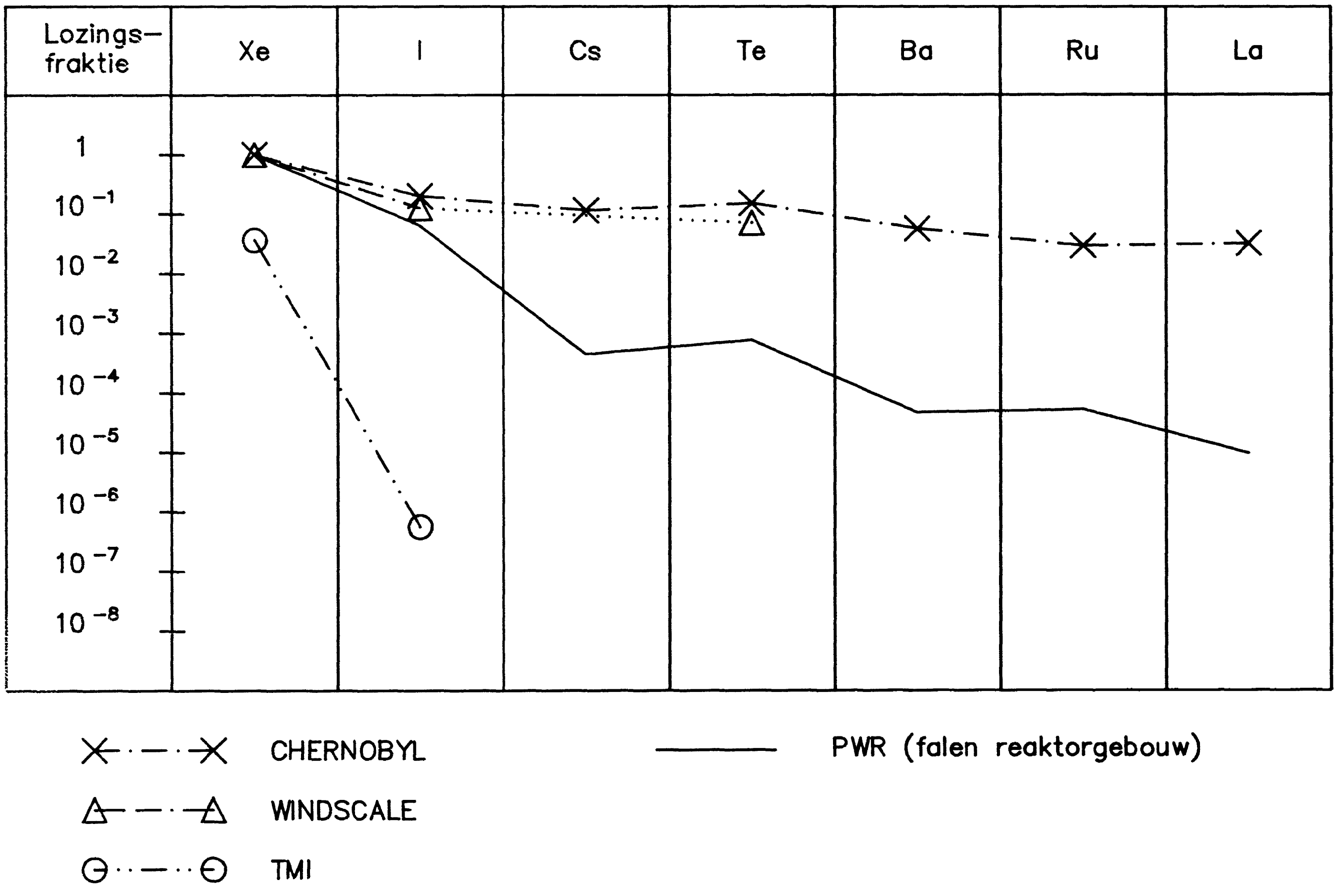


Fig. 1 : Lozingsfrakties van grote reaktorongevallen.

de eerste dag, en de inademing van neergezette aktiviteit die via resuspensie terug in de lucht komt.
Het effekt van deze blootstellingswegen kan eventueel verminderd worden door relokatie van de bevolking uit het besmette gebied en dekontaminatie van de ontruimde zone. In tegenstelling tot evakuatie worden ingeval van relokatie, bewoonde zones georganiseerd ontruimd nadat de luchtbesmetting verdwenen is en men uit metingen en laboratorium analyses een duidelijk beeld heeft verkregen van hoe de besmetting van de omgeving over langere termijn zal evolueren. Het is dus best denkbaar dat een gedeelte van de bevolking een week na het ongeval gerelokeerd wordt, om te vermijden dat haar leden een onaanvaardbare jaardosis zouden oplopen.

3. De voedselbesmetting.
Op lange termijn kan de voedselbesmetting verantwoordelijk zijn voor de grootste bijdrage tot het effektieve dosisekwivalent dat het aantal vertraagde effekten onder de bevolking bepaalt. Men maakt onderscheid tussen rechtstreekse besmetting, die belangrijk is vanaf het voorbijtrekken van de wolk doch vrij vlug afneemt, de besmetting overgebracht via de konsumptie van dierlijke produkten (melk, vlees,..) die slechts enkele dagen na het begin van het ongeval een maximum kent en de besmetting via opname uit de bodem die minder belangrijk is dan de vorige wegen, doch veel trager in funktie van de tijd afneemt. De blootstelling kan gekontroleerd worden door een graasverbod of maatregelen met betrekking tot de voedseldistributie.

Tabel 4 toont de relatieve effektieve dosis tengevolge van deze blootstellingswegen, in de omgeving van de getroffen installatie (enkele km) voor doorsneekondities qua meteorologie en gedrag van de bevolking, wanneer de vluchtige produkten totaal zouden geloosd worden.
De effektieve dosis is een maat voor het risiko op lange termijn-effekten.
Figuur 2 toont het relatief belang van de blootstellingswegen gedurende de eerste dag voor de rood-beenmerg-dosis in openlucht. Deze dosis is karakteristiek voor de niet-stochastische fatale effekten met de laagste drempelwaarde.
Voor figuur 2 gelden dezelfde hypothesen als voor tabel 4.

Wolk	:	3	100 (Wolk + Inhalatie + Depositie 1e dag)
Inhalatie	:	93	
Depositie 1e dag	:	4	
Later	:	41	
Resuspensie	:	0,5	
Voedsel	:	890	

Tabel 4 : Relatieve verdeling van de effektieve dosis nabij het lozingspunt
(volwassene, doorsnee voorwaarden, 100 % lozing van Edelgassen, I, Cs en Te)

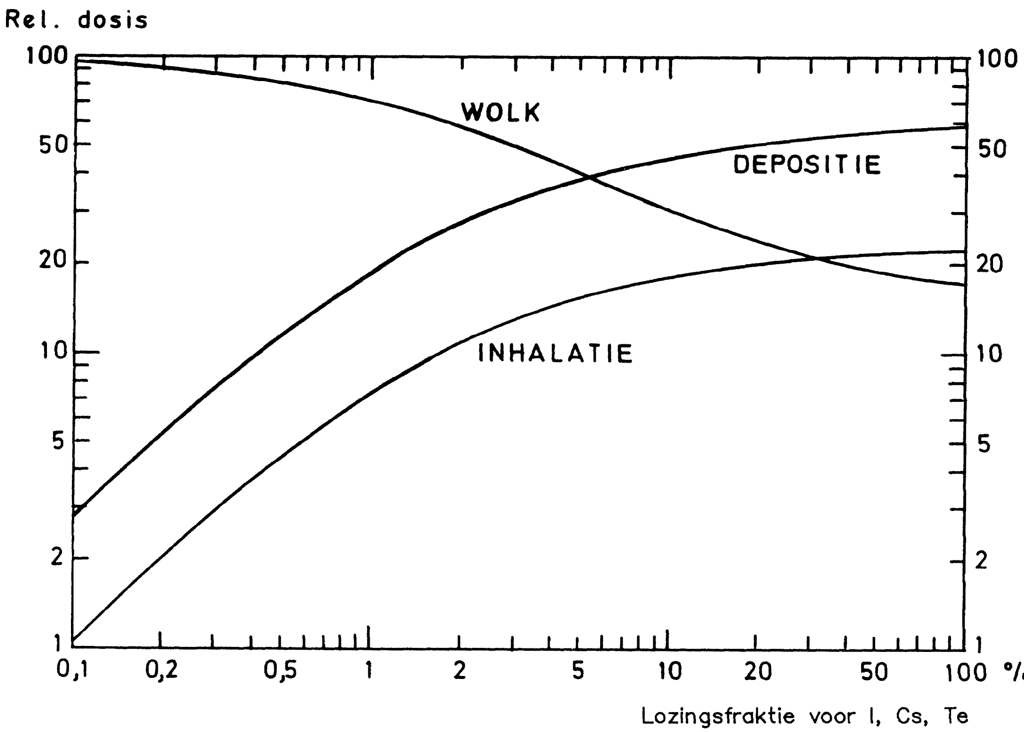


Fig. 2 : Relatief aandeel van de blootstellingswegen gedurende eerste dag van een lozing in funktie van de geloosde fraktie van de I,Cs,Te—inventaris. (100 % lozing van edelgassen). (Dosis van het rood beendermerg — in open lucht).

De lozingsfrakties van Iodium, Caesium en Tellurium worden echter als veranderlijk beschouwd. Deze figuur leert dat in geval van een zeer groot ongeval de depositie het belangrijkst is (bv. Chernobyl).
Deze rol wordt voor kleinere ongevallen overgenomen door de wolkstraling (bv. TMI). Inhalatie is vooral belangrijk voor ongevallen die het vrijzettingsspektrum van grote ongevallen kennen, doch waarvan de absolute grootte van de lozing niet van die aard is dat de drempel voor niet-stochastische effekten voor de bevolking wordt overschreden (bv. Windscale), zodat de effektieve dosis bepalend is. Het relatieve belang van de blootstellingswegen wordt dan weergegeven door tabel 4.

4. BLOOTSTELLINGSWEGEN BELANGRIJK VOOR DE EERSTE DAG.

4.1. Bestraling door de wolk.

De bestraling door de wolk onderscheidt zich van andere blootstellingswegen, o.a. door het feit dat de blootstelling niet noodzakelijk evenredig is met de lokale koncentratie, doch opgebouwd wordt door bijdragen afkomstig uit heel de halve ruimte waarin de besmetting zich verplaatst. Dit heeft vooral belang dichtbij het blootstellingspunt waar de wolk veruit de belangrijkste blootstellingsvorm wordt, ingeval van een hoge lozing, die geen aanleiding geeft tot luchtbesmetting op grondniveau.
Een ander specifiek element in de evaluatie van de blootstelling tengevolge van wolkstraling is het belang van kortlevende radionukliden. Deze zenden meestal fotonen met een hogere energie uit dan langlevende radionukliden. Zo is bijvoorbeeld de dosisfaktor van Kr-88 ongeveer vijftig maal hoger dan deze van Xe-133. Het relatief belang van de wolkstraling neemt dus af met de koeling van de kern na het stoppen van de kernreaktor.
Voor de besluitvorming in verband met de noodplanning is de reduktie van de blootstellingssnelheid binnen in de huizen van het grootste belang. De modelberekeningen veronderstellen meestal een reduktiefaktor gelijk aan 0,6. De reële reduktiefaktor hangt af van de massadensiteit van de wanden, het relatief belang van de glasoppervlakte en het feit of de luchtbesmetting al dan niet in de woning kan binnendringen. Het effekt van deze faktoren wordt geïllustreerd door figuur 3. Men ziet dat bij goed afgeschermde woningen het belang van de glasoppervlakte en van de luchtbesmetting binnen de huizen toeneemt.

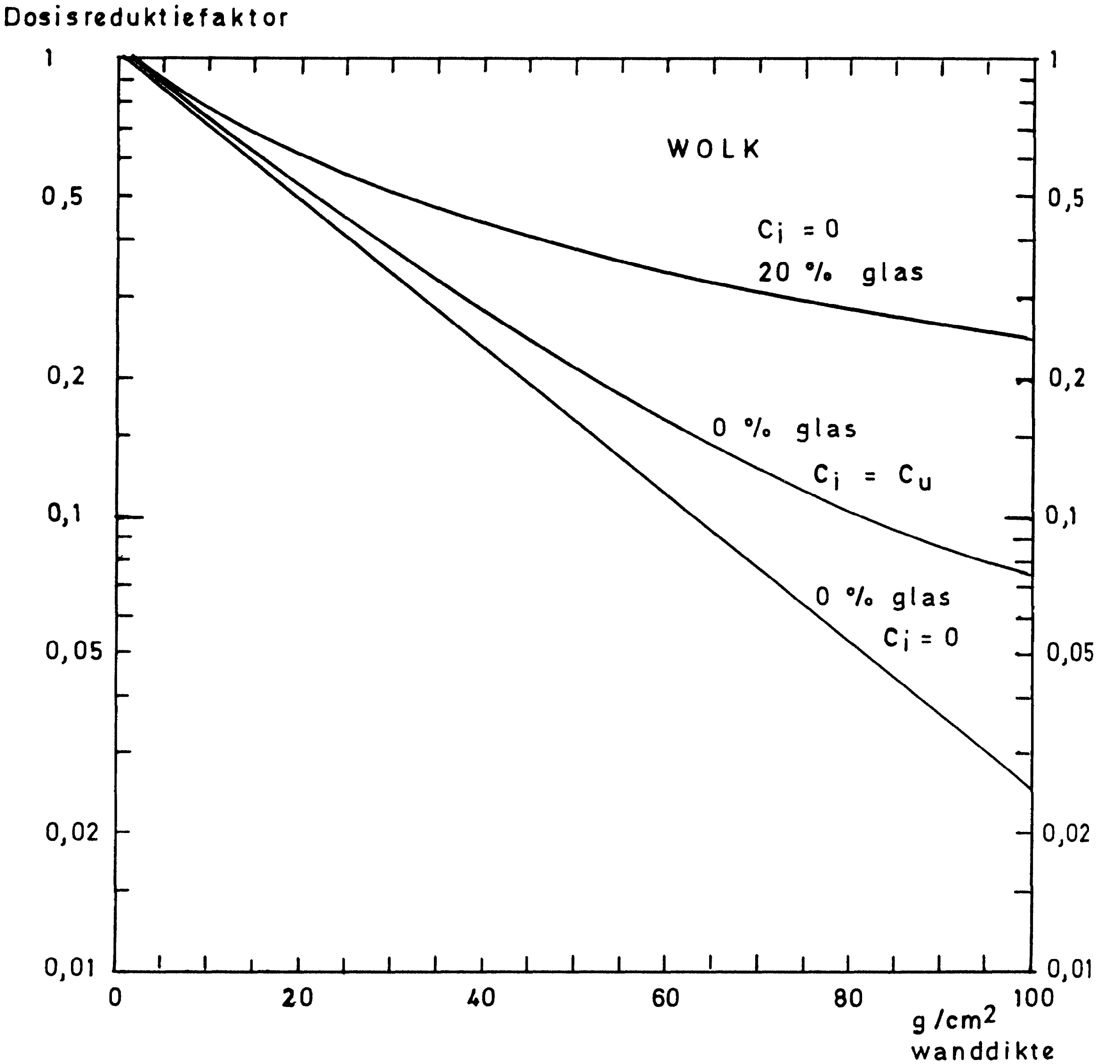


Fig. 3 : Typische dosisreduktiefaktor voor woningen in funktie van de wanddikte, relatieve glasoppervlakte en besmetting van de binnenlucht.

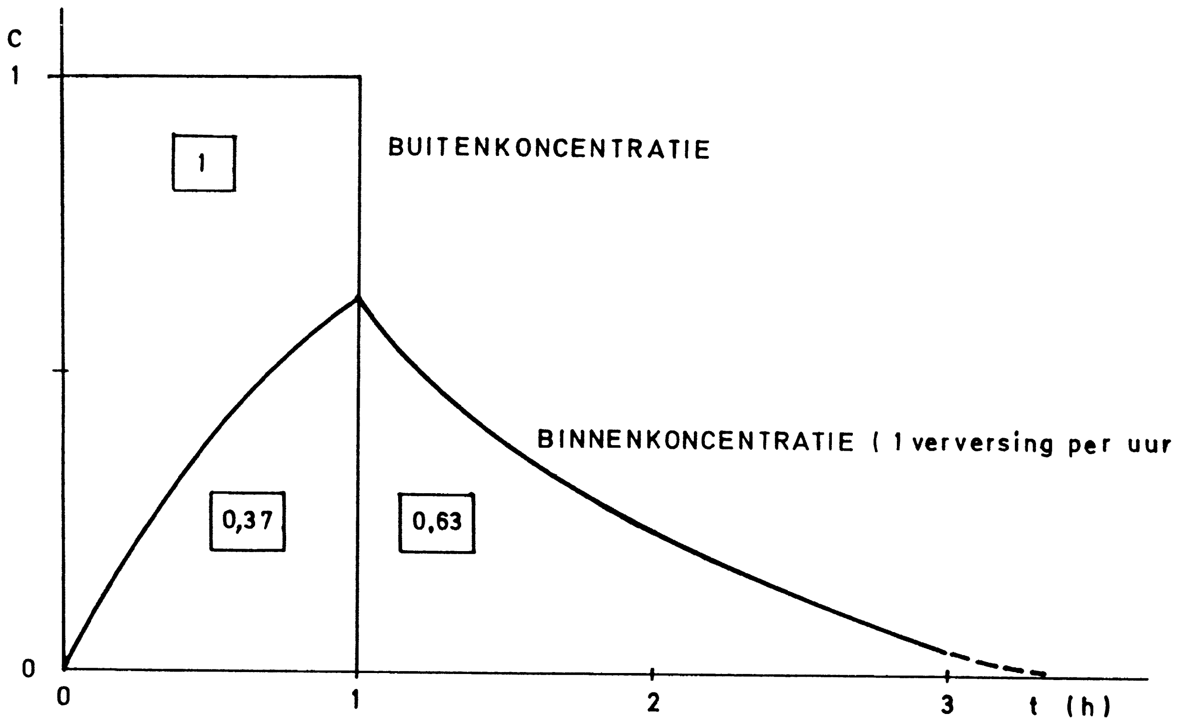
4.2. Inhalatie

De dosisfaktoren voor inhalatie gebruikt in de meeste modellen gelden voor een AMAD van 1 μm en voor de chemische vormen vastgelegd in WASH-1400. De invloed van de chemische vorm beperkt zich tot de keuze uit één van de longretentieklassen waarvoor voor een bepaald element in ICRP-30 dosisfaktoren worden bepaald. In reële omstandigheden kan de deeltjesgrootteverdeling leiden tot een andere mediane diameter. Dit blijkt echter geen beduidende invloed op het inhalatierisiko bij grote reaktorongevallen te betekenen. De keuze van de chemische vormen is gesteund op de evaluatie van WASH-1400 die sedertdien door de latere veiligheidsstudies werden overgenomen. Een belangrijk deel van de inhalatiedosis is te wijten aan organisch Iodium, dat zich in een reaktorgebouw quasi als een edelgas gedraagt zodat de lozingsfraktie praktisch onafhankelijk is van het ogenblik van het falen van het reaktorgebouw.

Het relatieve belang van de organische komponenten wordt dus erg belangrijk, bij gereduceerde brontermen, waarbij bijvoorbeeld ongeveer 1 % van het Iodium ingeval een kernsmelting, zou vrijkomen. Zulke brontermen maken waarschijnlijk het grootste risiko uit voor de moderne centrales. De vraag rijst dan ook of voor de berekening van de inhalatiedosis geen onderscheid gemaakt moet worden tussen organisch, elementair of particulair Iodium, daar deze vormen zich toch bij andere retentieprocessen verschillend blijven gedragen. Tot hiertoe werd meestal aangenomen dat de inhalatiedosis binnen in huizen gelijk is aan deze in openlucht. Soms werd een reduktiefaktor toegepast steunend op het feit dat bij korte periodes van luchtbesmetting, de binnenatmosfeer tijdens het voorbijtrekken van de wolk niet in evenwicht komt met de buitenbesmetting (figuur 4), zodat de dosis kan beperkt worden op voorwaarde dat na het voorbijtrekken van de wolk zeer snel geventileerd wordt. Ondertussen werd onderzoek verricht op het filtereffekt van huizen en op de neerzetting van deeltjes binnen in de huizen. Beide fenomenen leiden tot een reduktie van de inhalatiedosis na het schuilen. Tabel 5 geeft een overzicht van de verdeling van de inhalatiedosis over de periodes tijdens en na de aanwezigheid van buitenbesmetting voor een duur van één uur voor een typische woning en een typische werkplaats.

4.3. Straling van neergezette aktiviteit.

De bepaling van de hoeveelheid aktiviteit die zich op de bodem neerzet ten gevolge van een gegeven luchtbesmetting en meteorologische omstandigheden, maakt het voorwerp uit van omvangrijke onderzoeksprogramma's,



Figuur 4 : Verloop van de koncentratie binnen en buiten een geventileerde struktuur.

	Ventilatie-graad (h^{-1})	Filter-rendement	Depositie-snelheid ($m.s^{-1}$)	Oppervlakte per volume (m^{-1})	Fraktie van buitendosis		
					Tijdens wolk	Na wolk	TOTAAL
MODEL	1	0	0	–	0,37	0,63	1
HUIS	0,5	0	10^{-4}	2	0,17	0,24	0,41
WERKPLAATS	2	0,3	10^{-4}	0,3	0,17	0,12	0,29

Tabel 5 : Reduktie van inhalatiedosis in huizen.
(Besmetting gedurende 1 uur)

waardoor men tracht aan de hand van van wiskundige modellen, windtunnel-experimenten, veldexperimenten en analyse van bijvoorbeeld de neerzetting van de lozingen van het Chernobyl ongeval, een inzicht te verwerven in de komplexe problematiek van de verschijnselen in de grenslaag tussen bodem en de onderste luchtlagen.
Men maakt een onderscheid tussen zogenaamde "droge neerzetting" en zogenaamde "natte neerzetting".
De eerste wordt gekarakteriseerd door de verhouding van de neerzettingsflux op de bodem tot de luchtkoncentratie op 1 m hoogte.
De laatste heeft betrekking op de neerzettingsflux ten gevolge van het uitregenen van besmette wolken en het uitwassen van de luchtlagen tussen de wolken en de bodem. Beide fenomenen hangen af van een lange reeks parameters die specifiek kunnen zijn voor het ogenblik (meteorologische omstandigheden), of voor de plaats (toestand van de bodem). Men tracht nochtans bij gebrek aan een inzicht in de fenomenen en gebrek aan kennis van de bepalende parameters, de neerzetting met een eenvoudig, empirisch afgeleid model te beschrijven. Het spreekt van zelf dat deze benadering tot moeilijkheden leidt, wanneer men tracht een realistische veiligheidsstudie te maken en a fortiori ingeval van evaluaties tijdens een reëel ongeval.
Sinds enige tijd wordt er speciale aandacht besteed aan de relatieve verdeling van de oppervlaktebesmetting op vegetatie en strukturen en aan de analyse van het heterogene blootstellingsveld dat hiermee overeenstemt. Dit is vooral van belang in een stedelijke omgeving, met zijn typische mozaïek van doorlaatbare en ondoorlaatbare, horizontale en vertikale oppervlakken. Figuren 5 en 6 tonen een typische verdeling zoals die o.a. op basis van de observaties na het Chernobyl-ongeval afgeleid werden door P. Jacobs (referte) voor droge en natte situaties. De referentie is de initiële bodembesmetting op een open grasveld. Tabel 6 toont de relatieve dosissnelheid op enkele typische lokalisaties binnen en buiten de woningen.
Men ziet dat de verdeling erg afhankelijk is van het relatieve besmettingsniveau binnen de huizen en de aanwezigheid van bomen die bijvoorbeeld een extra stralingsbron kunnen betekenen ter hoogte van de vensters, waar de afscherming van de huizen minimaal is.

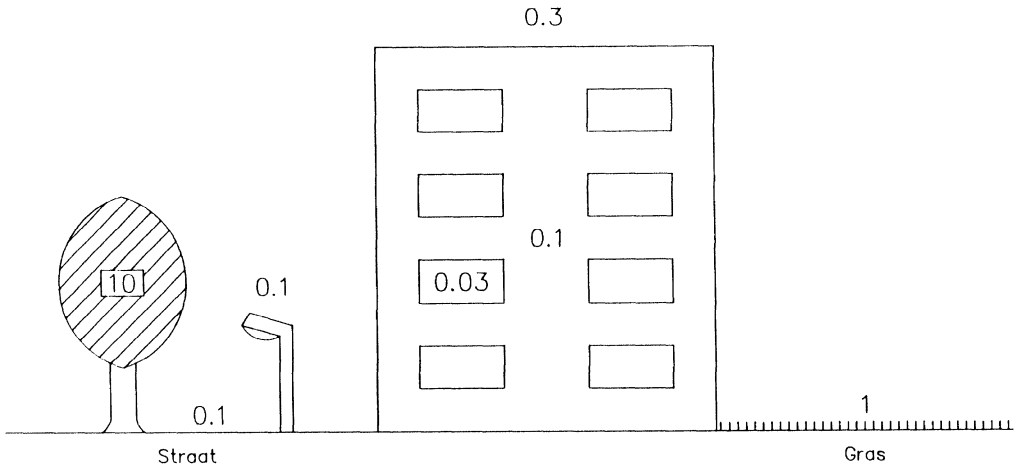


Fig. 5 : Verdeling van besmetting 1 week na droge depositie.

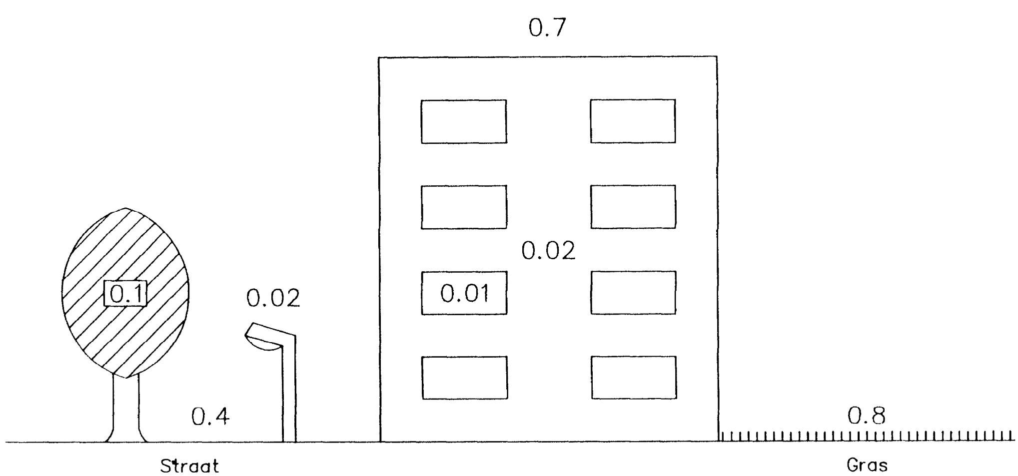


Fig. 6 : Verdeling van besmetting 1 week na natte depositie.

	DROOG			NAT		
Situatie	1	2	3	1	2	3
GRASPERK	1	1	1	0,8	0,8	0,8
STRAAT	0,2	0,2	0,2	0,4	0,4	0,4
BINNEN (0^e verdieping)	0,004	0,03	0,05	0,009	0,009	0,009
BINNEN (4^e verdieping) (onder dak)	0,006	0,007	0,05	0,008	0,008	0,008

1 : Invloed van bodem, wanden, dak.

2 : 1 + invloed bomen naast huis.

3 : 1 + invloed binnenbesmetting (Rel. Dep. : 4.10^{-2}).

<u>Tabel 6</u> : Relatieve dosissnelheid via depositie.

5. BESLUIT.

De voor beslissingen in het kader van een noodplan meest relevante blootstellingsweg hangt af van de aard van het ongeval. Bij ongevallen waarbij de drempels voor niet-stochastische effekten in de omgeving niet bereikt worden (bv. TMI, Windscale) wordt de eerste fase naargelang de geloosde Iodiumfraktie beheersd door wolkstraling of inhalatie, de latere fase door voedselbesmetting. Wanneer de bronterm voldoende groot is om aanleiding te geven tot niet-stochastische effekten, worden de evaluaties op korte afstand beheersd door de uitwendige straling van de bodem, op lange afstand door de voedselbesmetting (bv. Chernobyl).

Alle blootstellingswegen stellen bepaalde problemen wanneer men de evaluaties zo realistisch mogelijk wil uitvoeren.

Vooral de realistische evaluatie van de blootstelling binnen in de huizen in belangrijk gezien het belang van schuilen als beschermingsmaatregel.

Referentie

P. Jacob, R. Meckback, Shielding Factors and External Dose Evaluation - Radiation Protection Dosimetry, Vol. 21 n° 1/3, pp. 79-85 (1987).

RESUME

L'importance relative des voies d'exposition de la population en cas de rejet sévère vers l'atmosphère est évaluée, du point de vue des décisions à prendre pour la protéger. On analyse en détail les voies d'exposition qui dominent les évaluations pendant la première phase du plan d'urgence. Pour chaque voie, les façons, par lesquelles on peut augmenter le réalisme des prédictions de doses, sont discutées.

ABSTRACT

The relative importance of the exposure pathways of the public in case of a severe release to the atmosphere is discussed, from the point of view of the decisions to take in order to protect it. The exposure pathways dominating the early phase of the emergency response are analysed in more detail. For each pathway the author indicates how the realism of the dose assessment can be increased.

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RISK ASSESSMENT AND SAFETY CRITERIA - *THE SIZEWELL B PUBLIC INQUIRY*

by R R Matthews,
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Abstract

The Sizewell B Public Inquiry was established by the UK Government to carry out an independent examination of the CEGB's proposal to build the first commercial PWR in the UK. It was conducted by the appointed Inspector, Sir Frank Layfield, and lasted from January 1983 to March 1985, covering a wide range of economic, safety and environmental issues. The final Report was completed in December 1986, and the lecture summarises the CEGB's approach to Risk Assessment and Safety Criteria together with the Inspector's comments and conclusions on these topics contained in his Report. He concludes that the CEGB's approach to safety assessment is sound and that the criteria used are generally satisfactory.

Lecture

I am very pleased to have the opportunity of speaking to you about some safety aspects of the Sizewell B Public Inquiry on the CEGB's proposal to construct the first PWR in the United Kingdom. The Government appointed an eminent barrister, Sir Frank Layfield, as the Inspector to conduct the Inquiry and he opened the proceedings on 11 January 1983. They ended on 7 March 1985 after 340 days of hearing evidence and cross-examination of a large number of witnesses for and against the proposal, of whom I was one being the CEGB's chief witness on safety policy. It was a very comprehensive investigation and covered a wide range of economic, safety and environmental topics.

The CEGB welcomed the Inquiry and there were high hopes that it would provide an opportunity for giving a lot of information and explanation to the public about the various aspects of nuclear power, and dispel once and for all the claims of secrecy so often made by its opponents. Indeed, at the start, the Inspector said that his Report would be written in simple language that the public could understand, and he was adamant that witnesses should give their evidence in similar fashion. In some ways I was disappointed at the impact of the Inquiry as the public interest and attendance seemed minimal, and I think this was due to the length of the Inquiry, combined with the legalistic approach that was adopted. Nevertheless the Inspector's Report certainly created a large amount of public interest. It is comprehensive, it weighs the arguments put forward by the proponents and the opponents and gives an independent and authoritative view on a wide range of safety topics by an eminent person not in any way associated with the nuclear industry. Many of the conclusions may to us in the industry seem obvious, but they would not have been arrived at if the arguments had not been correct, well supported, logical and capable of withstanding very fierce scrutiny.

The main conclusion of the Inspector was that the PWR should go ahead, and this carried a great deal of weight in the public debate that followed; in Government circles, the Parliamentary debate, and in the news media. His Report was completed in December 1986, the Government gave consent for the project in March 1987, site construction started in June 1987 and currently the foundation and concrete work is proceeding well.

Now I have been asked to talk about the Section of the Report dealing with Risk Assessment and Safety Criteria, but I will make use of other relevant chapters to give an indication of the Inspector's comments and conclusions.

In the first two chapters of this Section the Inspector discusses the nature and assessment of risk from the Sizewell PWR, and he stated that weighing up the risks and benefits, and judging whether the estimated risks are tolerable, were vital parts of his task. The benefits are economic and hence a large part of the Inquiry was devoted to examining this subject, but he expressed the view that it is hard to define and quantify the benefits, and even harder to define and quantify the risks. Moreover the respective natures of the risks and benefits are so different that it is difficult to weigh them in the same scale, and he realised he had an extemely difficult task ahead of him. He accepted the general philosophy that there are two kinds of risk; the risk to the individual and the risk to a population, and that the risk can arise from the two main components; those from accidents and those from normal operation. These themes were examined during the course of the Inquiry, and in the case of accidents much time was spent on the probabilities of them occurring and their consequences.

The starting point was the CEGB's statement that the basis for its radiological protection procedures is the ICRP recommended dose limits and the dose-risk relationship. Several witnesses were called and notably Sir Edward Pochin, Emeritus Member of the ICRP, was cross-examined at length on the stochastic and non-stochastic effects of radiation, and the role of the ICRP. Opposition witnesses included the well known critics, Dr. Bertell and Dr.Stewart, who questioned the role of the ICRP and claimed that the dose limits and risk factors were too low. After cross-examination the Inspector commented that in view of the nature of her evidence he did not give serious weight to Dr. Bertell's criticisms, and also concluded that Dr. Stewart did not effectively substantiate her assertions.

The Inspector agreed that it is prudent for the time being to assume that there is no threshold of radiation dose below which there is no effect, accepted that are doubts about the accuracy of the ICRP's risk factors, but agreed overall that the CEGB were generally right to adopt the ICRP recommended limits as the basis for their safety criteria. But he entered some recommendations on the need for more research on the effects of low level radiation, and the need to reconsider the risk factors when the results of the current international review of the estimates of the doses received by the Japanese survivors of the atom bombs were known. The revision of data for this review was commenced at a late stage in the Inquiry hearings.

The next chapter dealt with Risk Evaluation and Tolerability of Risk. The Inspector agreed that absolute safety could not be achieved, and therefore there was some point at which the risk was tolerable in the light of the benefits to be obtained. The CEGB in its evidence used the phrase 'acceptability of risk' but the Inspector did not like the idea of 'accepting' risk and preferred to 'tolerate' it. The CEGB stressed very clearly that there were no national or international standards for acceptability or tolerability of risk, in other words, there were no standards defining 'How safe is safe enough?' Plants had always been licensed on the basis that the safety characteristics and protective systems were judged to be satisfactory by the engineers and scientists of the CEGB, the design contractors and the licensing authority, and that risks were kept as low as reasonably practicable, or ALARP.

The CEGB's basic objectives are to ensure that a nuclear station should give no significant addition to existing public risks, and give a risk to power station workers no greater than that in industries regarded as safe. There are five principles fundamental to its safety policy:

- no person's radiation exposure in normal circumstances should exceed the appropriate limits (those set by the ICRP);
- any dose to any individual should be ALARP;
- collective doses to operators and to the public should be ALARP.
- all reasonably practicable steps should be taken to prevent accidents;
- all reasonably practicable steps should be taken to minimise the radiological consequences of accidents

There was considerable discussion on the application of ALARP and the evaluation of risk. Some of the more important comments of the Inspector on risk evaluation were:

- that it is highly subjective and there are no widely accepted methods for carrying it out.
- the public's views must be reflected in estimating a tolerable level of risk. These views should reflect the fullest possible understanding by the public of the volume and size of the risks and benefits.
- it is difficult to find risks which are properly comparable with those from nuclear power. No firm conclusions could be drawn from attempts to compare the risks of coal-fired and nuclear electricity generation.

He commented that the highly subjective nature of the risks arises for many reasons, of which outstanding ones are:

- different types of risks are often seen as differing in seriousness, even if their magnitudes are similar: for example, the risk may be voluntary, as in a decision to smoke, or involuntary, as in having a nuclear power station built in the locality;
- risks with the potential to kill many people at once are usually regarded as more serious than risks involving the death of the same number of people in many smaller accidents;
- the type of death may be important; for example, whether death is immediate, or whether it occurs decades later as the result of cancer;
- factors other than death, such as injury or economic loss, may be important;
- new risks are often viewed as more serious than existing risks of a similar magnitude.

The comment that the public's views should be taken into account arose out of extensive criticism by the opposition that the public's views on the tolerability of risk had not been adequately researched. It was correct of them to argue that the CEGB had done little work on this subject, but the CEGB did not consider that it had a responsibility to do so. The CEGB's responsibility is to satisfy the Nuclear Installations Inspectorate, which is the licensing authority, on safety requirements, and the NII is established as a public watchdog to safeguard the public and hence, so far as possible, reflect the public's views on the requirements of safety. However, the Inspector commented that as yet there appears to be no reliable means of measuring the public's attitude towards the risk of nuclear power. Nevertheless, public attitudes are crucial to decisions on risk evaluation; in the absence of other reliable means, public attitudes must be taken into account through the normal political processes. The Inspector also stated that there had not yet been sufficient public and political consideration of the basis for regulating nuclear safety. This led to the Inspector recommending that the UK's national Health and Safety organisation should publish consultation and policy papers on nuclear safety, including guidance on tolerable levels of risk and ALARP, to enable public, expert and Parliamentary opinion to be expressed. I think it may be of interest that the Health and Safety Executive has just recently published such a document called "The Tolerability of Risk from Nuclear Power Stations".

The next chapter on Safety Criteria considers the criteria developed by the CEGB for specifying to the design contractor the standards of safety that should be achieved. First there are the radiological standards governing the risk to the workers and the public during normal operation.

In anticipation of a possible reduction of the ICRP limits, or a more stringent interpretation of them, the CEGB in the late 1970s selected a design target for the effective dose-equivalent for station workers, during normal operation, of 10 mSv per year. Coupled with this was a collective annual dose target of 2 man-mSv per MW(E) which for the PWR gave a collective dose of 2.4 man-sv per year. These targets were stringent and the intended effect was to ensure that the designers took every opportunity at the design stage to minimise radiation doses from operational and refuelling activities, and from maintenance of equipment. They meant that the designer had to ensure that the activities of operators throughout the life of the station were properly assessed at the design stage, and radiation dose commitment carefully budgetted.

Considerable time was spent on this topic with several trade unions and opposition groups arguing that the targets and limits should be lower, and questioning the application of ALARP. Some argued that the setting of targets and the use of ALARP were incompatible, as once the target was achieved there was no incentive to obtain any further reduction in dose, even if it were practicable to do so. The CEGB's view was that it was necessary to provide targets based on experience, and then in individual cases make use of ALARP to check whether any reasonable improvement could be obtained. It had to be accepted that the interpretation of ALARP depended very much on the judgement and experience of designers and assessors, particularly as a formal application required an agreed monetary value for the avoidance of a man-sievert, and this was very much a subject for debate.

The Inspector made several recommendations on this topic and noted that the CEGB's targets were ambitious, so that, if achieved, operator doses at Sizewell B would be similar to those at the best 10% of PWRs operating in the U.S.A. during 1982. He recommended that an average annual dose equivalent of 5 mSv should be set for the workforce as an operational investigation level, and anything above this should be investigated to ensure that ALARP is being achieved. Overall he did not think that the CEGB had justified its optimism in assessing doses to workers, but nor was there sufficient evidence to justify refusing consent for Sizewell B on the grounds that dose would be too high.

During normal operation some small radiation doses may arise to members of the public from discharge of gaseous and liquid effluents. These are carefully controlled in accordance with the terms of authorisation issued by Government departments, and should not exceed one thirtieth of the ICRP limit for the general public, i.e. 170 microSv per year. The Inspector agreed that doses to members of the public would be considerably less than those from the

Sizewell A station, and therefore small compared with the target for the site as a whole.

Then more controversially are the criteria dealing with accident conditions, and to understand the approach I need to describe some of the background.

When the first nuclear stations were designed in the 1950s the requirements of safety were of course a major consideration, and designers had to keep the risk of accidents as low as reasonably practicable. They achieved this by insisting on high quality of construction, and by providing diversity and redundancy of equipment in the safety systems which protected the plant from the variety of faults which were assumed might occur. For example, at least two different and independent methods of shutting down a reactor were provided, three of or four lines of protective instrumentation were fitted, at least three Diesel generators were required for emergency electrical supplies, and so on. Decisions on the extent of the requirements were based on the judgement and experience of engineers in the CEGB, the design companies and the NII; they were taken on a qualitative basis in accordance with what is known as the deterministic approach. When carrying out accident analysis it was then a requirement then all faults judged to be credible should have acceptable consequences, while those judged to be incredible were so unlikely to occur that they did not need to be taken into account.

However, during the 1970s the CEGB encouraged the use of probability reliability assessment or PRA, which provides a numerical method of estimating the probability of ocurrence of plant and system failures causing releases of radioactivity. No dout many of you are familiar with this technique which involves the construction of elaborate fault and event trees, together with the compilation of data giving the probability of failure of a large number of components in the plant. The technique can be extended to give an assessment of the radiological consequences of serious accidents and, for example, the probability of causing harm to members of the public. Arising out of this it became necessary to give designers some numerical targets for guidance, as they had to know whether the probability of failure of a system was satisfactorily low, or whether more components or protection had to be built into the system.

The CEGB decided that such targets should be simple and easy to understand. The risk of death to an individual was considered to be the most important parameter, although many other factors ought to be taken into consideration, and the CEGB spent many years in trying to obtain authoritative advice on the value of tolerable risk. The CEGB was not able to initiate research on this topic, nor did we think it had a responsibility to do so, but based on discussions and information from safety organisations and colleagues we judged that if a plant gave a risk of death to an individual member of the public of less than 10^{-6}per year then it could be regarded as acceptable. This was later generally confirmed by an authoritative Risk Study Report published by the Royal Society.

Accordingly the CEGB adopted a design target that the total frequency of occurrence of all accidents leading to uncontrolled releases of radioactivity to the environment resulting from some or all of the protective systems being breached or failed should be less than 10^{-6} per reactor year. Because most sequences can be segregated into about 10 different categories a second target stated that any single accident sequence should have a probability of less than 10^{-7} per reactor year. No definition was given of the size of the uncontrolled release, although it implied major core failure, as this could only be estimated when the design was complete, while the criteria were provided to guide the designer during the development of his design. The criteria ensured that, if met, no early deaths at a probability greater than 10^{-6} per year would occur, while taking into account weather conditions and the dose/risk relationship they ensured that the probability of any member of the public suffering latent death would be very much less.

The PRA technique was used in the PWR safety reports, but the CEGB emphasised that it was used as a supporting tool and was not the sole or primary basis for making major decisions on safety. This was because the method was in early stages of development and could not be regarded as fully complete. The essential data on probable failure of components like pumps, motors, instruments, control rod mechanisms, were reasonably well established in reliability data banks, but data on failures due to external events such as earthquakes, aircraft crash, and due to human factors were less well defined. Reliance was therefore still placed on the deterministic approach.

The opposition groups however concentrated their attack on the PRA method, claiming that the method was unreliable and inaccurate, and that in any case the targets were too low. The Friends of the Earth witness claimed that there should be no practical possibility of an accident which might require counter measures such as sheltering or evacuation, and therefore the annual probability of such an accident should be less than 10^{-12} per reactor. This arguement was dismissed by the Inspector as unduly demanding, largely impracticable, and not justified. Other opposition witnesses tried to demonstrate that the 10^{-6} per year risk of death criterion was too high and not fully justified. The Inspector agreed that it had not been justified as did the CEGB, which in its own evidence stated that it was a matter of judgement, but at the end of the day the Inspector in his Report concluded that an annual level of individual risk of death of the order of one in a million is likely to be broadly tolerable if justified by associated benefits, and that the CEGB's targets are reasonable. This I think was the most important conclusion made by the Inspector with regard to safety, as if he had disagreed then the safety case would have been seriously damaged.

The CEGB's accident criteria are of two types, reflecting the Board's approach to safety analysis. These are the numerical design targets for the probability and severity of accidents which I have already described, and engineering criteria based on long experience which should be incorporated into the design.

These engineering criteria specified particular requirements that had to be taken into account, and examples are:

- ways of defining incredible faults
- the single failure criterion. Designers must assume failure on demand of at least one of the safety systems intended to give protection against serious core failure
- common mode failure. The designer must take account of a common failure such as loss of electric power causing failure of more than one system, and this must be avoided.
- independence of safety systems. The safety systems should be designed exclusively to fulfil safety requirements, and should not share any function with the normal operating systems.

There are many other criteria of this kind but they attracted very little criticism. This was rather surprising as the layout and overall safety of the plant was developed from these principles and they were a major influence in obtaining a high standard of safety.

The PRA technique is not only used for assessing the reliability of the plant, but can also be extended by the use of appropriate dispersion models to give estimates of harm to the public and the environment, as exemplified by the original Rasmussen Study. Although the NII did not require the formal safety report to include studies of the consequences of beyond-the-design-basis accidents, the CEGB decided to produce such studies for the Sizewell Inquiry. The opposition submitted exaggerated reports of the consequences of severe core accidents, and amongst other things claimed that a serious accident at Sizewell would cause London to be evacuated. Much argument took place on these issues.

The CEGB's submission estimated that the annual probability of a degraded core would be about 10^{-5}. The subsequent ways in which the accident sequence developed could be broadly clasified into 12 categories depending for example on how the core melted, or whether the containment itself leaked or failed. The worst sequence was in fact a rupture of the residual heat removal system allowing a significant proportion of the core fission products to escape into the environment. The probabilities and consequences of this and other sequences were calculated, and from these source terms the National Radiological Protection Board used their MARC dispersion model to estimate the effects on the public and the environment of these accidents, and the probabilities of these effects occurring. They estimated that 98% of degraded core accidents would result in no early deaths. The probability of an accident causing more than a thousand early deaths was estimated to be about one in a thousand million, while the probability of early death to someone living close to the site was estimated to be about one in five hundred million. The annual probability of at least one fatal cancer was estimated to be less than one in a million, while for ten thousand or more deaths it was less than one in a hundred million. For someone living near the site the maximum annual risk of fatal cancer from byond design basis accidents was estimated to be about one in 3,000 million.

In summing up his conclusions on the risks from accidents the Inspector stated that the CEGB's criteria were judged to be generally satisfactory and are likely to be generally satisfied by the design. He accepted that nuclear power includes the possibility of accidents which could kill hundreds or even thousands of people, but that nuclear power is not unique among industrial activites in this respect. He stated that an accident at Sizewell B, if built, would almost certainly have tolerable consequences, at worst requiring measures such as the banning of milk near the station. Theoretically possible accidents which could cause hundreds or thousands of deaths would almost certainly not occur.

So after months and indeed years of detailed argument and cross-examination, in which opposition groups had every opportunity of putting forward what we considered to be exaggerated and unsupported views of the risks, the Inspector and his Assessors publicly dismissed these claims and put the risks from the PWR in perspective and comparable with other industrial risks. The CEGB was more than satisfied with these conclusions. At the present time the criteria I have described remain essentially unchanged and are being used in the plans for building additional PWRs after Sizewell B.

RESUME.

L'enquête publique Sizewell B a été décidée par le Gouvernement du Royaume Uni afin d'effectuer un examen indépendant de la proposition du CEGB de construire le premier réacteur PWR commercial dans le R.U. L'enquête menée par l'inspecteur désigné, Sir Frank Layfield, a duré de janvier 1983 à mars 1985 et a porté sur un large éventail de points relevant de l'économie, de la sureté et de l'environnement. Le rapport final a été terminé en décembre 1986 et le présent article résume les considérations du CEGB sur l'Estimation du Risque et les Critères de Sécurité complétées par les commentaires et conclusions de l'Inspecteur sur ces sujets tels que présentés dans ce rapport. Il conclut que l'approche du CEGB dans l'appréciation de la sécurité est fondée et que les critères utilisés sont satisfaisants dans l'ensemble.

SAMENVATTING.

De openbare enquête Sizewell B werd door de regering van het V.K. ingesteld om een onafhankelijk onderzoek uit te voeren van het voorstel van de CEGB de eerste commerciele PWR in het V.K. te bouwen. De enquête geleid door de aangestelde Inspecteur, Sir Frank Layfield, duurde van januari 1983 tot maart 1985 en omvatte een brede waaier van onderwerpen op vlak van de economie, de veiligheid en de omgeving. Het eindverslag werd in december 1986 afgesloten en in dit artikel worden de beschouwingen van de CEGB i.v.m. Risicoevaluatie en Veiligheidscriteria alsook de kommentaar en conclusies van de Inspecteur over deze onderwerpen als opgenomen in het verslag samengevat.
De Inspecteur komt tot het besluit dat de benadering van de CEGB inzake veiligheidsbeoordeling gegrond is en dat de gebruikte criteria over 't algemeen voldoende zijn.

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Accident consequence assessment modelling in the new program system UFOMOD with illustrative results

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Abstract

The program system UFOMOD is a completely new accident consequence assessment (ACA) code. Its structure and modelling is based on the experience gained from applications of the old UFOMOD code during and after the German Risk Study - Phase A, the results of scientific investigations performed within both the ongoing Phase B and the CEC-project MARIA, and the requirements resulting from the extended use of ACAs to help in decision-making.

In the paper, the structure of the program system and essential characteristics of important submodules are described. Selected results of recent investigations illustrate the flexibility and applicability of the new UFOMOD code.

1. Introduction

The coordination of various institutions was organized in the Federal Republic of Germany to upgrade the accident consequence models and their data bases for the calculations of the German Risk Study - Phase B (DRS-B). Recent scientific results and computational techniques led to the development of the new program system UFOMOD /1,2/ described in this paper. The cooperation and continuous exchange of information between many laboratories throughout the EC, especially the close connection to the NRPB, UK, organized within the European project MARIA as part of the CEC Radiation Protection Research Programme, ensured an appplication-oriented modelling and presentation of results. Not all aims in establishing accident consequence assessment (ACA) methodologies /3/ could be considered adequately in the new UFOMOD code system; but it can be regarded as an important step forward to the comprehensive code system planned for the end of the MARIA project.

2. Structure of the program system UFOMOD

The design of the new UFOMOD was strongly influenced by the results of investigations to substitute the straight-line Gaussian plume model by more realistic atmospheric dispersion models /4,5/. The main conclusion was, that at present Gaussian like trajectory models can be applied in ACA codes and they provide more realistic results within distances up to some 10 kilometres. A Gaussian like dispersion over longer distances, however, is hard to defend even over flat land. Therefore, long-range dispersion models are needed to describe the transport of radioactive material over hundreds and thousands of kilometres.

The use of different, completely decoupled and non-linkable atmospheric dispersion models requires the division of the ACA code into subsystems for the near and the far range. But there are some more reasons, which support such a subdivision:

- the quality and quantity of actions and consequences in the near range (like fast protective measures and early health effects) are different from the far range (where long-term countermeasures and stochastic health effects are assessed);
- site specific characteristics are only relevant in the near range and their influences on ACA vanishes at farther distances; in addition, the near range can be modelled much more in detail;
- many applications of ACAs refer to only one of both distance ranges.

Therefore, the new program system UFOMOD is subdivided into three subsystems, each designed to assess accident consequences occurring in different time periods or distance ranges (Fig. 1):

The two subsystems NE and NL cover the near range up to about 50 km; each of both systems contains models and data to assess one type of consequences, namely

- the extent and duration of early protective measures, short-time integrated organ doses and non-stochastic health effects;
- lifetime integrated organ doses and stochastic health effects including countermeasures.

The subsystem FL covering the far range up to about 3000 km is designed mainly to estimate long-term doses and countermeasures and the resulting stochastic health effects in the population.

Each subsystem of UFOMOD has an almost identical modular structure. It consists of several program units designed to assess subsequently the various types of

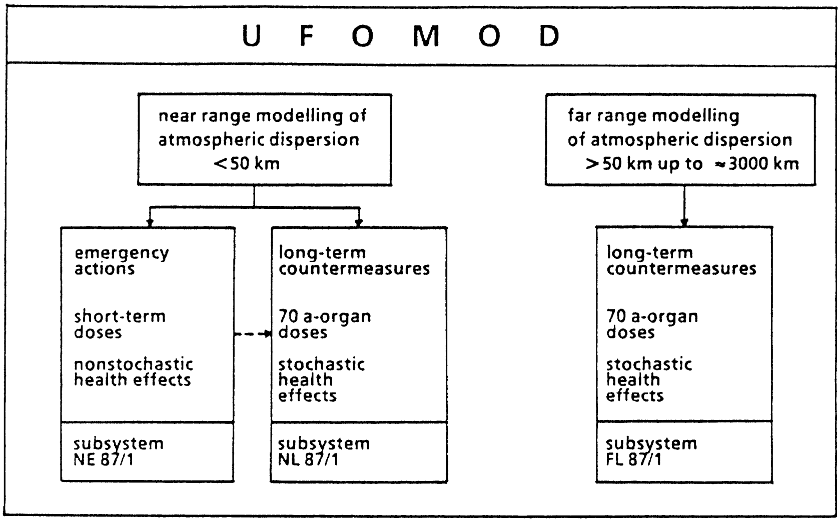


Fig. 1: General structure of the program system

UFOMOD	
Near range model ($\lesssim$ 50 km)	Far range model ($\gtrsim$ 50 km)
Atmospheric dispersion	
MUSEMET (KFA) RIMPUFF (RISØ)	MESOS (ICST) Windfields in the regions 10°W - 50°E and 36°N - 62°N
10 measuring stations synoptic data of 1982 and 1983 recorded at 1 h intervals	≈800 measuring stations synoptic data of 1982 and 1983, recorded at 3 h intervals

Fig. 2: UFOMOD: Modelling of atmospheric dispersion

accident consequences. The intermediate results calculated in each program unit are stored on temporary and/or permanent input/output units. Each of the program units can be called separately by the steering main program. According to that structure, each of the UFOMOD subsystems can be run as a whole or step by step dependent on the desired results and the mode of application. Especially, sensitivity and uncertainty analyses of single submodels can be easily performed without the repetition of preceding computational steps. In addition, special evaluation programs have access to the data sets stored from each program unit to provide numerical and graphical presentations of the various intermediate and final results and their correlations.

In the following, the most important modules of UFOMOD are described together with some examples of illustrative results gained from recent studies.

3. Description of important modules

3.1 Atmospheric dispersion

The task of the atmospheric dispersion module is to calculate space-dependent time-integrated air and ground concentrations of radionuclides resulting from an accidental release of radioactive material for a large number of different weather sequences. At present, 3 different models are used (see Fig. 2): in the near range (<50 km), modified versions of the trajectory models MUSEMET /6/ and RIMPUFF /7/ are applied to calculate the spread of radionuclides; for far range assessments, the code MESOS /8/ is available. Dry and wet deposition processes are considered for aerosols, elemental and organically bound iodine. Dependent on the source term characteristics, buoyant plume rise, building wake effects and lift-off are taken into account. In addition, the arrival time of the radioactive plume at each grid element and a correction factor for gamma radiation from the cloud in the near range are determined.

The interface between the atmospheric dispersion module and the subsequent program unit is universal in such a sense, that any arbitrary computer code describing atmospheric transport and deposition processes can be implemented, if it provides time integrated air and ground concentrations in a polar coordinate grid system. Therefore, future developments leading to improved trajectory models applicable in complex terrain can be easily taken into account by this modular structure of UFOMOD.

3.2 Exposure pathways

The exposure pathways considered in the program system UFOMOD are those, which are known as the most important ones. In the subsystem NE, irradiation from cloudshine, groundshine and inhalation is modelled; the long-term subsystems NL and FL additionally evaluate doses from inhalation of resuspended activity deposited on ground surface and from the ingestion of contaminated foodstuffs. In the modelling of the ingestion pathway, local production and consumption of the foodstuffs is assumed.

Eight foodstuffs are considered according to German consumption habits, namely milk (including milk products), beef, meat from pork, grain products, potatoes and three types of vegetables (leafy-, nonleafy-, root). For these foodstuffs, age dependent consumption rates have been derived /9/. Data for the time dependent activities per unit mass of the foodstuffs have been provided by the Gesellschaft für Strahlen- und Umweltforschung (GSF) mbH, Neuherberg, FRG. They were calculated with the dynamic terrestrial foodchain transport model ECOSYS /10/. The processes considered in ECOSYS are direct deposition, root uptake, translocation, washing of the foodstuffs etc. To approximate seasonal effects, two ingestion data sets are implemented, one for a release at 1st of January to represent an accident in winter ("November-March") and one for a release at 1st of July to represent an accident in summer ("April-October"). In ACA calculations with UFOMOD, for each weather sequence from the two time periods the corresponding foodchain data set is selected by the program.

3.3 Health effects models

The assessment of nonstochastic health effects is based on the "Health Effects Model for Nuclear Power Plant Accident Consequence Analysis" /11/. All fatal effects specified in this model are also considered in UFOMOD. They comprise the effects following the irradiation of the bone marrow (hematopoietic syndrome), the lung (pulmonary syndrome) and the GI-tract (gastrointestinal syndrome). In addition, the mortality of pre- and neonates after exposure in utero are quantified. Of the possible non-fatal effects only the most severe ones are quantified in UFOMOD (impaired pulmonary function, hypothyroidism, cataracts, and mental retardation after irradiation in utero).

Both fatal and non-fatal stochastic somatic health effects are considered in UFOMOD. The corresponding age-, sex- and time-dependent dose-risk coefficients of 10 cancer types (see Fig. 3) have been provided by GSF /12/. The coefficients for leukemia and bone cancer are based on the assumption of an absolute risk model, for all other coefficients, relative risk models have been used. For cancer morbidity, GSF recommended the use of correction factors from the BEIR-III study /13/.

After an accidental release of radionuclides from a nuclear facility, the average risk and thus the number of cancer fatalities in the exposed population is made up from many different contributions of individual risks by the following reasons:

- the exposed population includes members of both sexes and a wide distribution of ages;
- the exposure can be protracted in time as for instance for the internal exposure by inhaled or ingested radionuclides or for external exposure from activity deposited on the ground;
- the necessity to introduce countermeasures may locally lead to the interruption of exposure pathways for some time after the accident.

The estimation of the cumulative number of cancer fatalities in an exposed population at some given time after a release therefore in general involves equations containing multiple time integrals, e.g. over the age and life expectancy distributions of the population, the time patterns of exposure etc. The numerical solution of these integrals can be very time-consuming even with fast mainframe computers.

For the new program system UFOMOD the concept of activity-risk-coefficients (ARC) has been developed /14,15/. These precalculated coefficients are normalized to the initial unit activity concentrations in air and on ground, respectively, and contain all informtion of age and lifetime distributions in the population, the time and age dependence of the intake of activity for internal exposure pathways, the time and age dependence of dose accumulation for all exposure pathways, and the time and age dependence of the individual risk. During an

Fig. 3: Estimates of life-time fatal cancer risk for the population of the FRG /12/

organ/tissue	effect	model[1]	fatal cancers per 10^6 persons and 10^{-2} Sv (GSF) (LQ)[2]	(L)[2]
red bone marrow	leukemia	A	21	52
bone surface	cancers	A	1	1
breast	cancers	R	80	80
lung	cancers	R	36	90
stomach	cancers	R	90[3]	224[3]
colon	cancers	R		
liver	cancers	R		
pancreas	cancers	R		
thyroid	cancers	R	17	17
remainder	cancers	R	15	38

[1] A: absolute risk model. R: relative risk model

[2] L: linear dose-risk relationship. LQ: linear quadratic dose-risk relationship

[3] summarily for the GI-tract

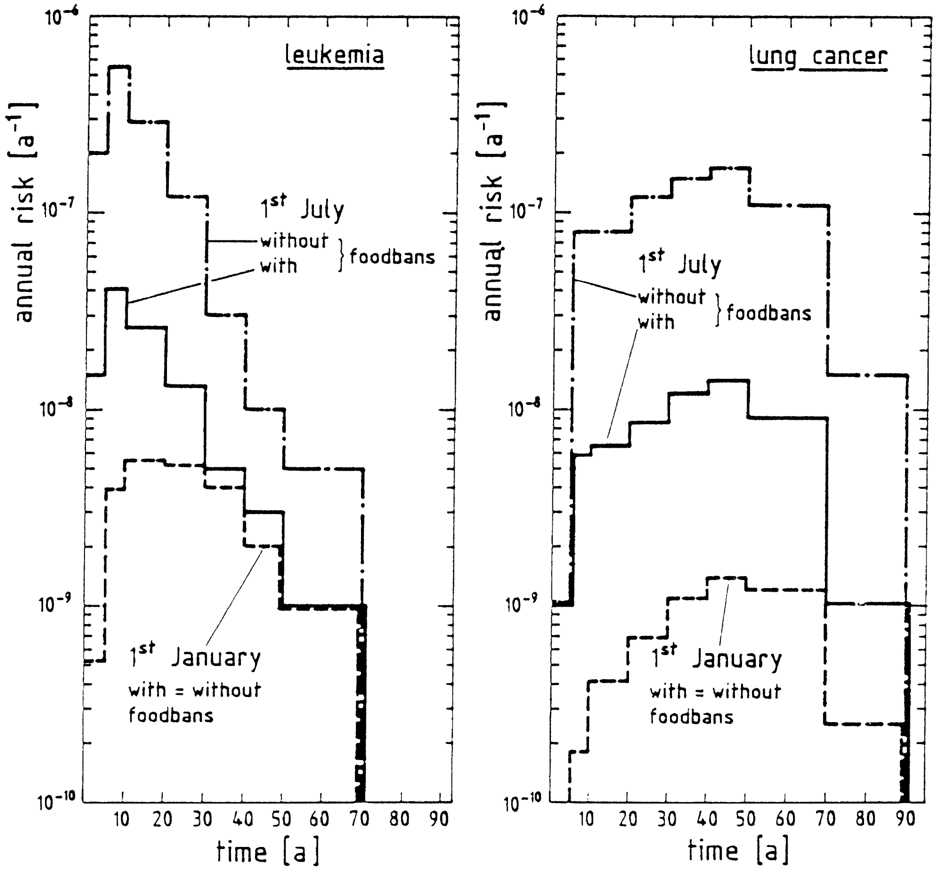


Fig. 4: Expectation values of the annual risk of cancer mortality by ingestion at 500 km distance (living generation)

ACA run, the number of fatalities from each cancer type is simply calculated by multiplication of these coefficients with the initial activity concentrations and the number of individuals affected. With this new algorithm, the UFOMOD code provides for the first time the possibility to estimate within an ACA the occurrence of the late health effects in the population as a function of time after the accident.

In the following, some examples for time-dependent results are given. The figures and tables are not intended to be discussed quantitatively but qualitatively as possible results of an ACA obtainable with the program system UFOMOD. As source term, the release RL 2 (see next Chapter 3.4) was assumed.

The expectation values of the annual average risk of mortality from leukemia and lung cancer by ingestion at 500 km distance to the site are shown in Fig. 4 (living generation). To investigate the influence of seasonal effects, the results are given separately for assumed releases at 1st of January and 1st of July.

Due to the different latency and manifestation periods of the two types of health effects, their time patterns in the population are rather different: the risk of leukemia is highest relatively short after the accident and declines afterwards, whereas the risk of lung cancer increases up to 40-50 years, when it reaches its maximum.

The risks of both cancer types - without foodbans - for a release in July quantitatively exceed those for a release in January by about two orders of magnitude, but the slopes of the curves are also significantly different. These observations reflect the fact, that for an assumed release in the summer seasons the effects of direct deposition lead to a much higher contamination of the foodstuffs in the first year after the accident than in the subsequent years, when the more inefficient processes of root uptake and resuspension are the only ways of activity transfer to the foodstuffs, as it is also the case for an accident in the winter seasons.

The differences in the slopes are less expressed when foodbans are taken into account. In the case of the summer release, foodbans strongly reduce the influence of the higher contaminated foodstuffs in the first year. Releases in winter lead to much lower contamination levels and foodbans are imposed in

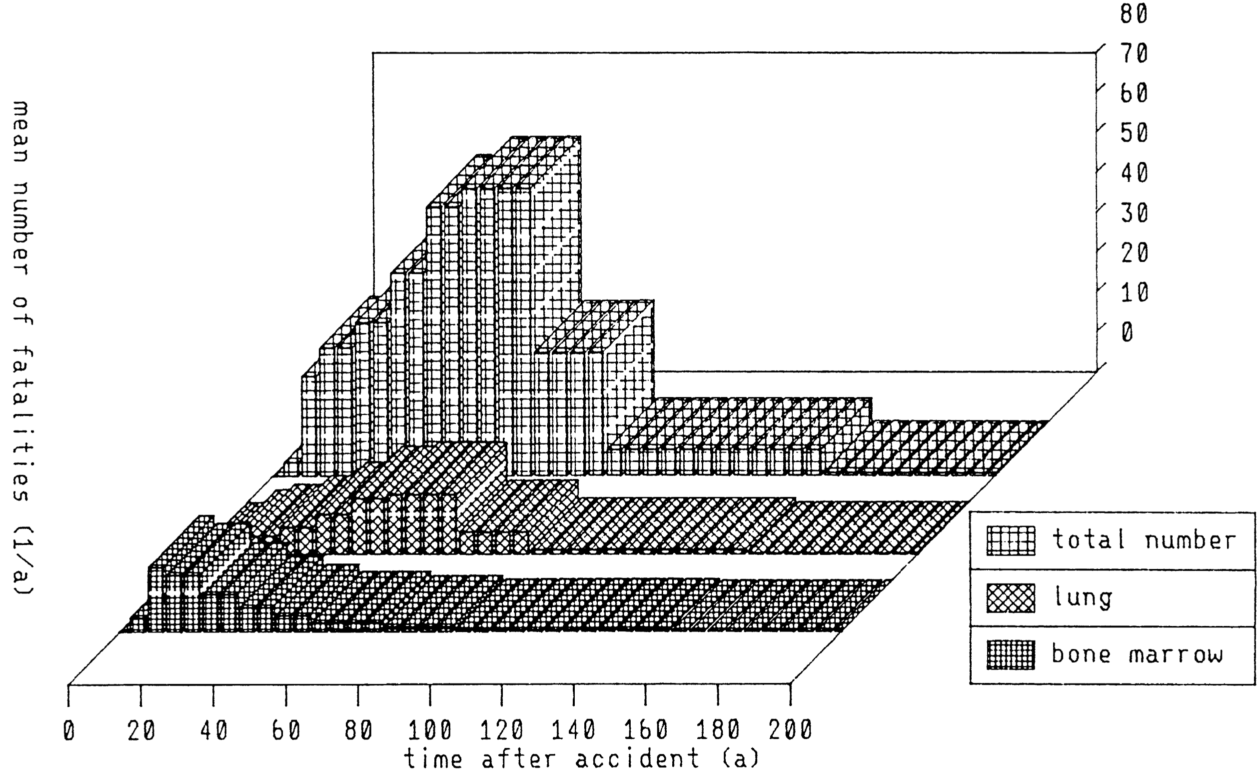


Fig. 5: Annual number of cancer fatalities from all exposure pathways (release RL2)

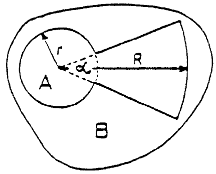
much smaller areas. Therefore, with the given source term, the foodbans do not affect the risk at a distance of 500 km for the release assumed in January.

Fig. 5 shows the expectation values of the estimated annual numbers of fatalities from all late health effects considered in UFOMOD and exemplarily from leukemia and lung cancer. The difference in the time dependent occurrence of leukemia and lung cancer can again be observed. The overall incidence rate has a maximum at about 40 to 70 years after the accident; after 100 years, the rates become comparatively small.

3.4 Protective measures

The countermeasure models of UFOMOD are designed to determine the extent and duration of protective measures, like sheltering, evacuation and relocation, decontamination and food-bans. The areas, which are affected by the different countermeasures, are defined by means of angles and distances or isodose lines resulting from dose criteria. In the latter case, the corresponding action is assumed to take place in the grid element considered, if potential organ doses exceed certain intervention levels. It is withdrawn as soon as the potential organ doses are below a second set of dose thresholds /2/. The imposement of protective measures is oriented at the recommendations of ICRP 40, but all dose levels can be specified by the user.

The area covered by the near range subsystems of the new program system UFOMOD is chosen in such a manner that exclusively in this area fast protective actions may be necessary and early health effects may occur. As alterntive or sequential countermeasures in the near range, evacuation of a keyhole shaped area (A) determined by 2 radii (r,R) and an angle (α) and/or evacuation of an area (B) determined by an isodose line are modelled (Fig. 6). Since radii and angles are easier to be established than isodose lines, evacuation of area A is modelled to take place first. The sequence of actions is presented in Fig. 7. The spectrum of individual driving times for leaving the evacuation area is approximated by four 3-step distribution functions; each distribution function is representative of a certain range of the population density /16/. Exposure during evacuation is taken into account.



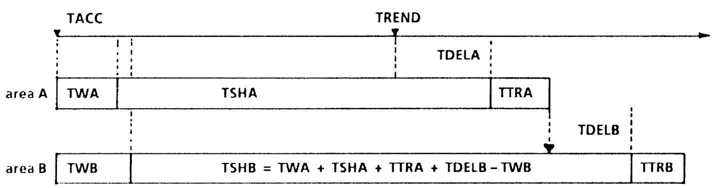
area A:

actions:	sheltering and/or evacuation
definition:	keyhole shaped area with inner radius r, outer radius R and sector angle α (r = 2.4 km, R = 5.6 km, α = 60°)

area B:

actions:	sheltering, evacuation
definition:	acute dose to lung, bone marrow or GI-tract > 500 mSv (external exposure and inhalation)

Fig. 6: UFOMOD: Modelling of countermeasures in the early phase and current default intervention levels



TACC	=	time of accident (end of chain reaction)
TREND	=	time of end of release (≈ 95 %)
TWA, TWB	=	initial delay, area A, B
TSHA, TSHB	=	duration of sheltering period, area A, B
TDELA	=	delay time between end of release and end of sheltering period, area A
TDELB	=	delay time between end of evacuation in area A and begin of evacuation in area B
TTRA, TTRB	=	driving time to leave area A, B

Fig. 7: UFOMOD: Timing of fast countermeasures

Special cases like prophylactic evacuation, evacuation of a disk shaped or sector shaped area, unintended reactions of the population, like spontaneous evacuation (flight) and disregard or misinterpretation of alarm signals and requests of the authorities, and the eventual existence of unattainable persons, are covered due to the possibility of choosing the input data occordingly.

First calculations related to emergency preparedness demonstrated the high flexibility of the new UFOMOD code system /17/. As DRS-B is not yet completed, artificial source terms were generated (Fig. 8). RL 1 is an example of a long lasting release, presented in 1986 /18/. RL 2 was gained from the release category FK2 of DRS-A by multiplying the amount of iodine and aerosols with the arbitrary factor 0.2, leaving the nobel gases unchanged and disregarding the energy content of the release. In view of the arbitrariness of the source terms, the absolute values of early fatalities presented in the following do not have any meaning related to reactor safety. They are nothing else than a yardstick for the comparison of the efficiency of different countermeasures and emergency response strategies.

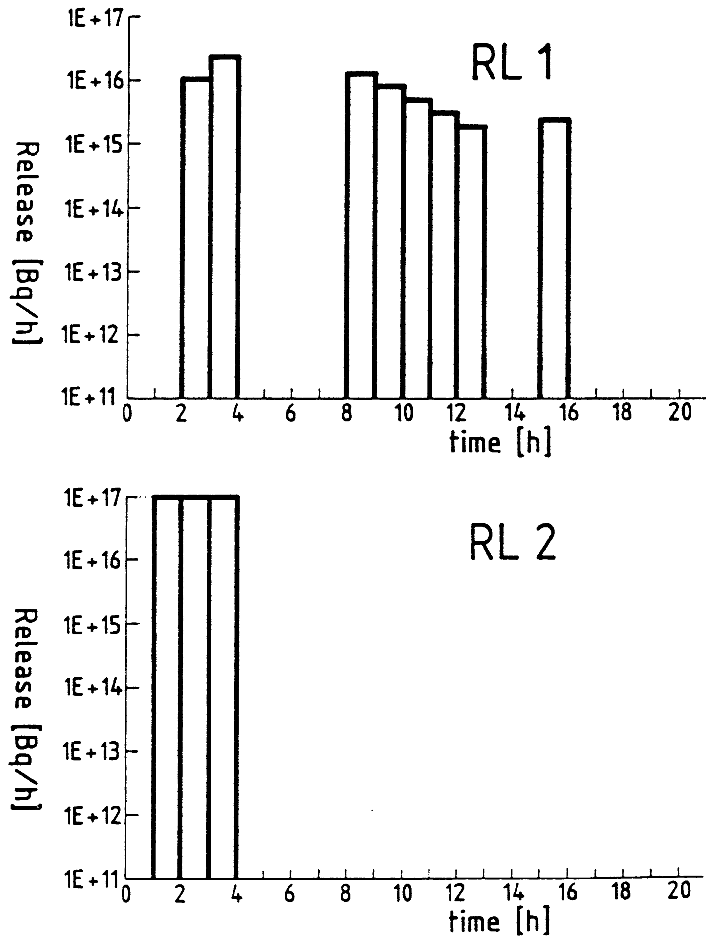
In Fig. 9, CCFDs of early fatalities due to doses to the red bone marrow (hematopoietic syndrome) are shown assuming different fractions of the population staying outdoors until evacuation after 11 hours: 100% (curve 1), 10% (curve 2 = standard case), 0% (curve 4). The early fatalities are occurring almost exclusively among the persons remaining outdoors. This result leads to the following conclusions for this type and amount of release:

- successful sheltering within 2 hours followed by evacuation after 11 hours is sufficient to avoid early fatalities in the population;
- the number of early fatalities is decisively depending on an input parameter difficult to assess (percentage of persons remaining outdoors because they are unattainable, misunderstanding alarm signals, reluctant to shelter or whatever reason);
- a main aim of emergency preparedness should be to keep this percentage small, if possible zero;
- an effective alert system in a small area, leading to small initial delay for sheltering or evacuation is much more important than vast plans covering large areas but being more prone to failure;
- if sirens are used for alarming ,the population should be familiar with the signals.

Fig. 8: Releases assumed in the calculations (rates for I-131)

Main groups of elements

RL 1:	100%	Noble gases
	2%	I
	2%	Cs
	1%	Te
RL 2:	100%	Noble gases
	8%	I
	6%	Cs
	4%	Te



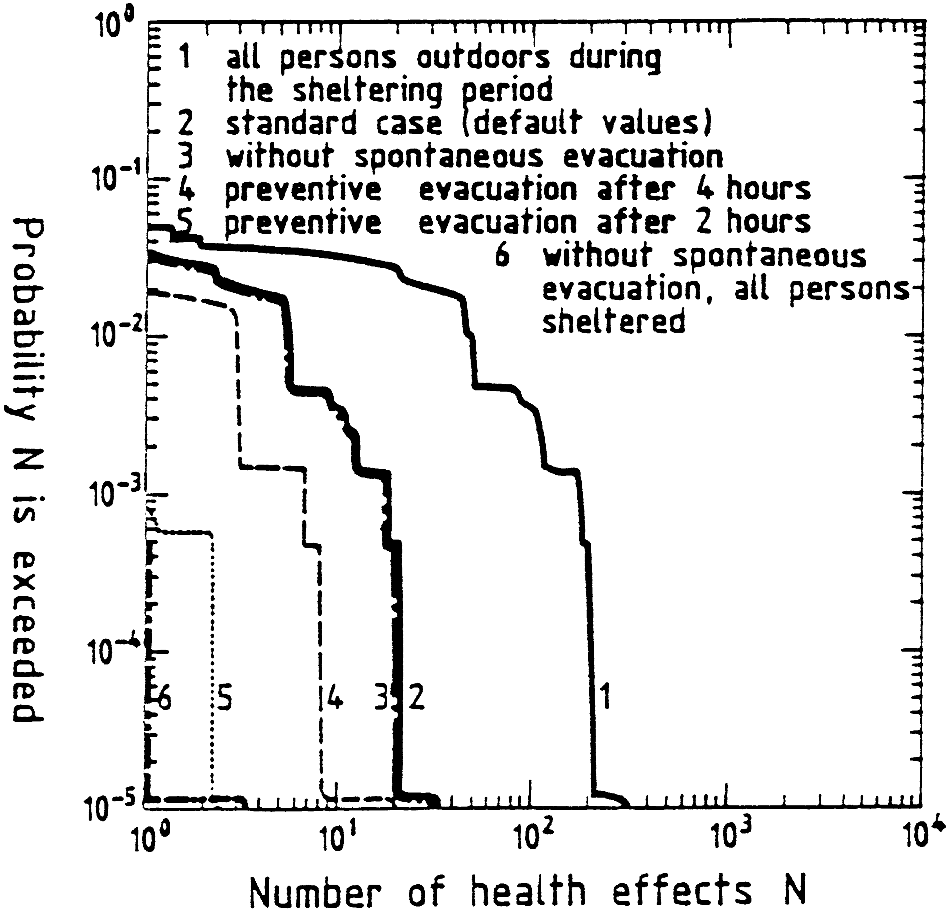


Fig. 9: CCFDs of early fatalities due to doses to the red bone marrow (hemato-poietic syndrome); release RL1

A successful prophylactic evacuation allows to prevent all evacuees from substantial exposure. Areas of prophylactic evacuation can be supposed to be surrounded by areas of sheltering, because sheltering is much less disruptive than evacuation and may therefore be implemented in larger areas. The key problems of prophylactic evacuation are

- to forecast the most exposed area in order to evacuate the (right) persons most at risk of nonstochastic health effects,
- to avoid evacuation into the plume of a short release,
- to avoid unnecessary evacuations.

The last point is not of interest in the context of this paper. If the "wrong" persons are evacuated, the right persons are sheltered in any case and the evacuation part of a combined evacuation/sheltering strategy is useless but does not lead to more radiation induced early fatalities than a mere sheltering strategy.

Curve 5 in Fig. 9 describes the result of calculations assuming complete evacuation starting after 2 hours, i.e. simultaneously with the beginning of the long lasting release RL 1. The curve shows that this scenario is slightly but not substantially worse than successful sheltering after 2 hours (100% sheltered/curve 4). Curve 6 stands for complete evacuation starting after 4 hours. The increased initial delay entails increased numbers and probabilities of early fatalities.

The general considerations explained above and the result of the calculations lead to the following conclusions:

- if an appropriate area for a justified prophylactic evacuation can be determined and if sufficient time is available, prophylactic evacuation should be tried,
- since prophylactic evacuation can only be based on the plant status, suitable criteria in terms of plant conditions need to be developed,
- close links to the national weather service and its forecast capabilities need to be established in order to provide the optimal tools for determination of the likely most exposed area,
- if the warning time is short, but an impending release is likely to be long lasting, early evacuation entails no undue risk even if the release happens to start shortly after beginning of the evacuation.

Calculations for RL 2 showed that evacuation into a short release is generally of similar benefit, but may be no good strategy in case of long driving times (long transition times to safe areas) /17/.

4. Summary and future improvements

The new program system UFOMOD with its flexible modular structure and the improved models and computational techniques is a step foreward to the development of the MARIA code system. The division into three subsystems for acute and chronic exposure and the incorporation of different trajectory models reflects the problem-oriented modelling of site-specific conditions and problems arising at far distances. The detailed parameterization of protective measures allows parameter studies for investigation of alternatives in emergency response planning and emergency management, and for studies about the influence of the behaviour of the population on the effectiveness of measures. Long term countermeasures can be discussed on the basis of individual and collective dose saved or risk reduction. The possibility to comprehensively present intermediate and final results of ACAs and their correlation facilitates the interpretation of the results.

Not all modelling aspects planned for the new program system UFOMOD could be realized in the versions described in this report. At present, investigations are under way or projected aiming at the development of three completing submodels to enable the assessment of economic consequences in the form of monetary costs, of genetic effects and of the radiological consequences of tritium releases. The decontamination of rural, urban and agricultural areas, presently modelled by one single decontamination factor, will be treated in more detail as far as the economic module is available. By the inclusion of cost-(effort-) benefit analyses, more reliable results of the extent and duration of long-term countermeasures can be expected. The radiation exposure by the contamination of the skin and of clothes will be included in the dose modules. Future versions of UFOMOD will be extended to allow loss of life expectancy assessments and their adequate presentation.

Together with an increased application of the new program system UFOMOD, data gaps may become obvious, like missing radionuclides in the list of dose-conversion factors, the partial dependency of dose-conversion factors from particle size distributions and the chemical form of radionuclides. Further requirements may emerge from the economic module, like land-use data and grids with information on the economic structure.

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RESUME

Le programme système UFOMOD est un code entièrement nouveau d'appréciation des conséquences d'un accident (ACA). Sa structure et ses modèles sont basés sur l'expérience acquise dans les applications de l'ancien code UFOMOD pendant et après l'étude de risque allemande Phase A, sur les résultats de recherches scientifiques effectuées au cours de la Phase B et sur le projet CEC-MARIA, ainsi que sur les exigences résultant de l'extension de l'usage de l'ACA comme aide dans la prise de décisions.
Sont décrits dans cet article : la structure du système des programmes et les caractéristiques essentielles de sous-modules importants. Une sélection de résultats d'investigations récentes illustre la flexibilité et les facilités d'application du nouveau code UFOMOD.

SAMENVATTING.

Het programma volgens het UFOMOD systeem is een totaal nieuw code voor appreciatie van de gevolgen van een ongeval. (ACA : Accident Consequence Assessment). Haar structuur en modellen berusten op de opgedane ervaring in de toepassingen van de vroegere UFOMOD code gedurende en na de Duitse risico studie fase A, op de uitslagen van wetenschappelijk onderzoek verricht onder fase B en het CEC-MARIA project en op de vereisten die resulteren van de uitbreiding van het gebruik van ACA als hulp bij het beslissen.
Worden beschreven : de structuur van het programma systeem en de essentiële kenmerken van belangrijke sub-modules. Bij middel van een selectie van recente onderzoeksuitslagen worden de flexibiliteit en de gemakkelijkheid van toepassing in het licht gesteld.