MACCS
A PROBABILISTIC CONSEQUENCE ASSESSMENT CODE

Presentation at the IAEA Postgraduate Educational Course in Radiation Protection and the Safety of Radiation Sources
Aghia Paraskevi , Greece, June 2003

MACCS:
MELCOR Accident Consequence Code System

MACCS, is designed as a Level 3 PSA tool, and performs probabilistic off site health and economic consequence assessments of hypothetical accidental releases of radioactive material from nuclear power plants

MACCS was developed at the US Sandia National Laboratories under the sponsorship of the USNRC, replacing the previous CRAC2 code (an improved revision of the Reactor Safety Study CRAC(1) code). It is one of the two most widely used probabilistic accident consequence assessment codes (the other being COSYMA)

MACCS was developed in the late eighties and was released in 1990.

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(1) CRAC - Calculation of Reactor Accident Consequences

MACCS2 - IMUG

Today a new improved code system, MACCS2, with an expanded nuclide list, a new food chain model, and an improved emergency response model is under development at Sandia NL.

The International MACCS Users Group (IMUG), established during the NEA/CEC "International Comparison of Probabilistic Accident Consequence Assessment Codes", 1991-93, participates also in this effort, mainly through testing of the code.

IMUG has as objective to provide the MACCS users with a forum for discussing future MACCS improvements and for exchange of experience in applying the code in various accident consequence evaluations

MACCS includes models for:

- atmospheric dispersion and transport
- wet and dry deposition
- the probabilistic treatment of meteorology
- environmental transfer
- countermeasure strategies
- dosimetry
- health effects
- economic impacts

MACCS is organized into three modules: ATMOS, EARLY, and CHRONC

ATMOS treats the atmospheric dispersion and transport of material and its deposition onto the ground

EARLY models direct exposure pathways, dosimetry, mitigative actions and health effects during the emergency phase

CHRONC models the direct and indirect exposure pathways, dosimetry, mitigative actions and health effects during the intermediate and long-term phases, and also the economic costs during all phases

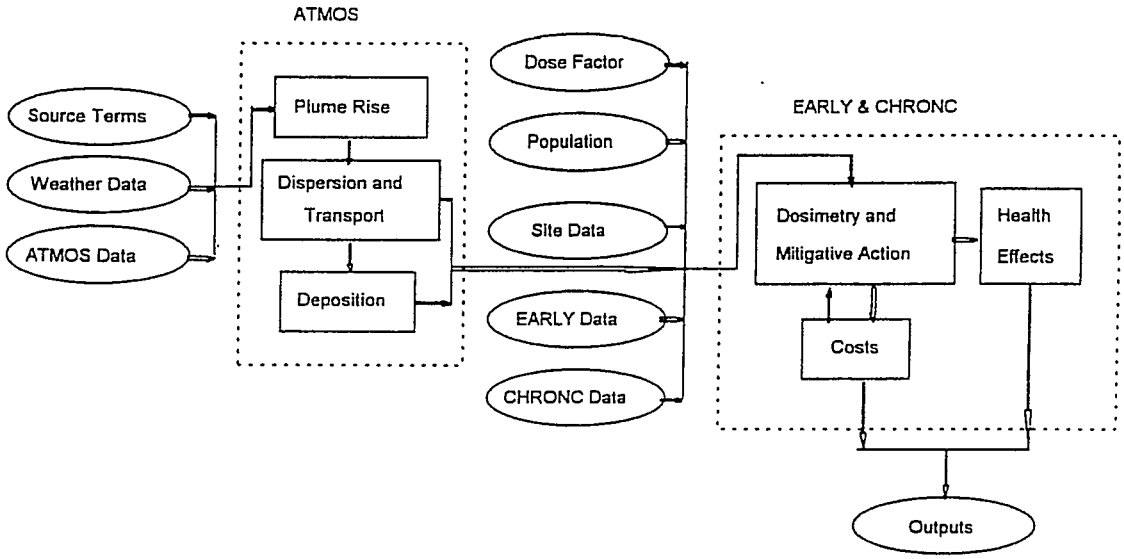


Figure 1. Progression of a MACCS Consequence Calculation.

Fundamental aspects of the organization of MACCS:

- The time scale after the accident is divided into various "phases"
- The region surrounding the reactor is divided into a polar-coordinate grid

The time scale is divided into:

- The emergency phase, beginning immediately after the accident and lasting up to seven days. Various protective measures can be specified for this phase, including evacuation, sheltering, and dose-dependent relocation
- The intermediate phase, used to represent a period in which evacuations are performed and decisions are made regarding the type of protective measures. This phase begins at the end of the emergency phase and may last up to one year
- The long-term phase, with a variety of possible protective measures, such as decontamination, interdiction, condemnation

The polar-coordinate spatial grid used to represent the region is centered on the reactor. Up to 35 radial divisions can be defined extending out to a maximum distance of 9999 km, while the angular divisions are fixed and correspond to the sixteen directions of the compass

INPUT - OUTPUT (1)

MACCS calculations require the following input data:

- The inventory at accident initiation (at the end of the fuel cycle) of those radioactive nuclides important from a radiological perspective
- The atmospheric source term produced by the accident
- Meteorological data characteristic of the site region
- The population distribution around the reactor site
- Emergency response assumptions for evacuation, sheltering and post-accident relocation
- Long-term protective measures such as decontamination, temporary relocation, condemnation of contaminated crops and farmland production prohibition
- Land usage, such as habitable land fractions and farmland fractions
- Economic data, such as the worth of crops, land and buildings for the region around the reactor site

Given the preceding input data MACCS estimates the following:

- The downwind transport, dispersion and deposition of the radioactive materials released to the atmosphere from the failed containment
- The short- and long-term radiation doses received by exposed populations via direct and indirect pathways
- The mitigation of those doses by protective actions
- The early fatalities and injuries expected to occur within one year after the accident
- The late cancer fatalities and injuries expected to occur over the lifetime of the exposed population
- The off site costs of short-term emergency response actions , of crop and milk disposal, and of the decontamination, temporary interdiction, or condemnation of land and buildings

Results available from ATMOS:

- Centerline Air Concentration ($Bq \cdot s/m^3$)
- Ground Level Air Concentration ($Bq \cdot s/m^3$)
- Centerline Ground Concentration (Bq/m^2)
- Total Centerline Ground Concentration (Bq/m^2)
- Ground Level χ/Q Dispersion Factor (s/m^3)
- Plume Sigma-y, Crosswind Size (m)
- Plume Sigma-z, Vertical Size (m)
- Plume Centerline Height (m)
- Plume Arrival Time at Centerpoint (s)

MACCS OUTPUT (2)

Results available from EARLY:

- Cases of Health Effects (fatalities, injuries)
- Early Fatality Radius
- Population Exceeding a Dose Threshold
- Average Individual Risk
- Population Dose (organs, effective)
- Centerline Dose vs. Distance
- Centerline Risk vs. Distance
- Population Weighted Risk
- Peak Dose on the Spatial Grid

Results available from CHRONC:

Population Dose Results

- Total Long-Term Pathway Dose
- Long-Term Direct Exposure Pathways Dose
- Total Ingestion Pathways Dose
- Long-Term Groundshine Dose
- Long-Term Resuspension Dose
- Population Dependent Decontamination Dose
- Area Dependent Decontamination Dose
- Milk Growing Season Dose
- Crop Growing Season Dose
- Milk Long-Term Dose
- Crop Long-Term Dose
- Water Ingestion Dose

MACCS OUTPUT (4)

Economic Costs Results

- Total Economic Costs
- Population Dependent Costs
- Area Dependent Costs
- Population Dependent Decontamination Cost
- Area Dependent Decontamination Cost
- Population Dependent Interdiction Cost
- Farm Dependent Interdiction Cost
- Population Dependent Condemnation Cost
- Farm Dependent Condemnation Cost
- Milk Disposal Costs
- Crop Disposal Costs

MACCS OUTPUT (5)

Action Distance Results

- Area Dependent Decontamination Distance
- Population Dependent Decontamination Distance
- Area Dependent Interdiction Distance
- Population Dependent Interdiction Distance
- Area Dependent Condemnation Distance
- Population Dependent Condemnation Distance
- Milk Disposal Distance
- Crop Disposal Distance

MACCS OUTPUT (6)

Impacted Area/Population Results

- Decontamination Area
- Decontamination Population
- Interdiction Area
- Interdiction Population
- Condemnation Area
- Condemnation Population
- Milk Disposal Area
- Crop Disposal Area

Maximum Individual Food Ingestion Dose at Given Distance (effective or thyroid dose)

Atmospheric Dispersion and Transport

Releases of radioactive materials are allowed in MACCS to be divided into successive plume segments, which can have different compositions, release time, duration, release height, and energies.

Plume segment lengths are determined by the product of the segment's release duration and the average wind speed during release, and are unaffected by diffusion during downwind transport.

A lift-off criterion determines whether buoyant plumes are subject to plume rise.

MACCS neglects wind trajectories

Dispersion of the plume through an empirical straight line Gaussian plume model.

Horizontal dispersion unconstrained
Vertical dispersion bounded by the ground and by the top of the mixing layer (modeled as totally reflecting layers using mirror image sources)

Eventually vertical distribution becomes uniform (the number of reflections increases with travel time)

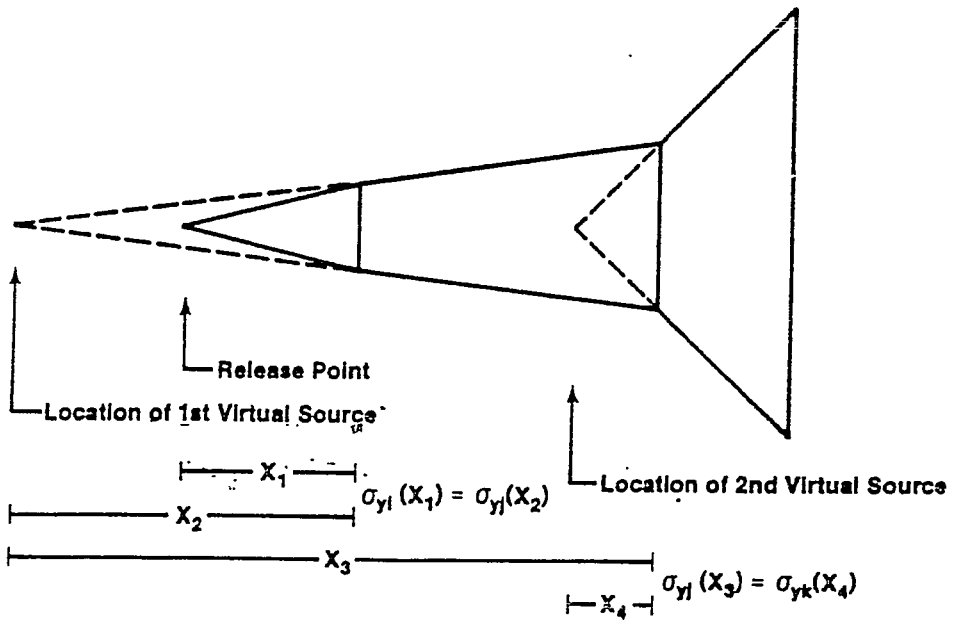


Figure 2.2 Growth of σ_y During Three Time Periods Characterized by Different Atmospheric Stabilities i, j, and k

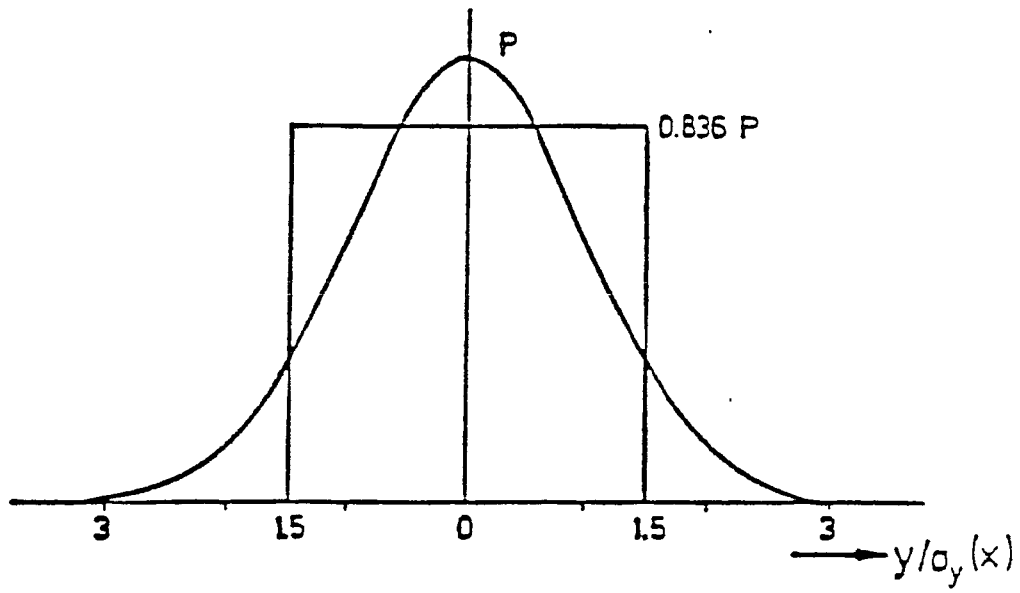


Figure 3.1 Top-Hat Approximation of the Gaussian Crosswind Distribution

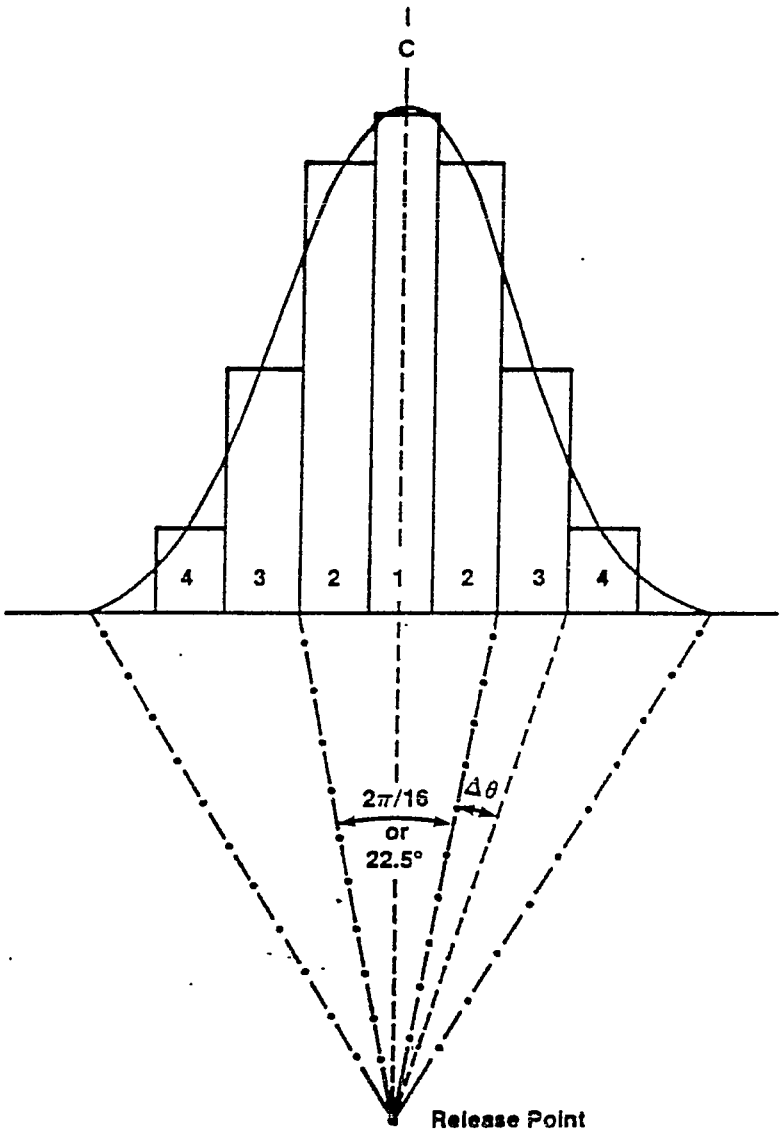


Figure 3.2 Approximation of a Gaussian Distribution by a Seven-Step Histogram (the number of fine grid divisions, m_o = 3)

Deposition

Aerosols are removed from the plume:
- by radioactive decay,
- by washout, which varies with rainfall rate, and
- by diffusion to, impaction on, and gravitational settling onto surfaces.

The last three processes are modeled by a combined removal rate using an empirical dry deposition velocity

Unlike dry deposition, which is a continuous and slow process, wet deposition is not continuous and often quite rapid

Water bodies are contaminated:
- by direct deposition (dry and wet), and
- by washoff from land

Surface concentrations of radioactive materials deposited on the ground decrease:
- by weathering,
- by resuspension,
- by washoff, and
- by radioactive decay

All these processes are modeled accordingly

Weather Data

Plume rise, dispersion, downwind transport, and deposition depend on prevailing weather conditions (wind speed, atmospheric stability, rain rate)

In MACCS these may either be invariant or may vary hour by hour. If variable, they can be user specified or can be read from a weather file.

There are five ways to specify the required weather data that constitute a weather sequence:

- Constant weather conditions
- User specified weather sequence (120 hourly readings)
- User specified start time (day and hour in a one-year-long file)
- Stratified random sampling (length of time)
- Structured Monte-Carlo sampling (user specified number)

Dosimetry

The dosimetry model consists of three interacting processes:

- projection of individual exposures to radioactive contamination for each of the seven exposure pathways modeled over a given time period,

- mitigation of these exposures by protective measures, and

- calculation of the actual exposures incurred after mitigation by protective measures

The total dose to an organ is obtained by summing the doses delivered by each of the individual pathways

Dose Mitigation

MACCS models for the following actions:

- Emergency phase: Doses are reduced by evacuation, sheltering and temporary relocation of people

- Intermediate phase: Doses may be avoided by temporary relocation of people, and ground contamination surveyed to prepare for decontamination actions

- Long-term phase: Doses are reduced by decontamination of property that is not habitable, by temporary interdiction of property that can not be restored to habitability by decontamination alone, by condemnation of property, by disposal of contaminated crops, and by banning farming of contaminated farmland

Evacuation: Potentially the most effective method of avoiding radiation exposure and can provide total protection if completed prior to arrival of the plume

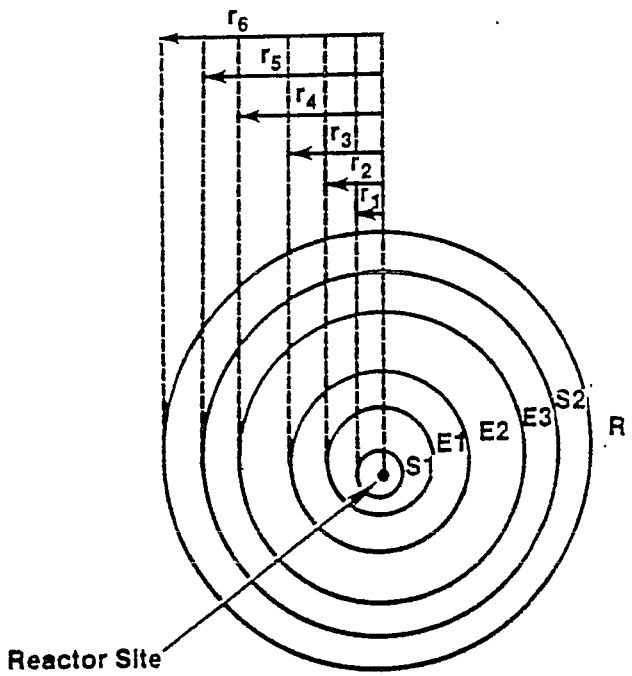


Figure 5.1 · Schematic of Emergency Response Zones

People relocation (a post accident protective measure): Only if projected doses from cloudshine, groundshine, cloud inhalation and resuspension inhalation exceed a specified dose criterion.

In contrast: Evacuation and sheltering take place automatically within some specified region

Decontamination, Interdiction, Condemnation

In the long-term phase mitigative actions are taken in the following order:

(1) Decontamination alone, with up to three successive levels of increasing effectiveness specified by the user
(2) maximum level of decontamination followed by an interdiction period
(3) permanent interdiction (condemnation) of the property

MITIGATION (3)

At the beginning of the long-term phase doses are projected without countermeasures and compared to a user specified criterion.

If the long-term dose criterion is not met, an attempt is made to meet the criterion, first by decontamination alone, and if necessary, by decontamination followed by a period of temporary interdiction to allow nuclide removal by weathering and radioactive decay.

These action are taken only if they are cost effective, i.e. the worth of the recovered property is greater than the sum of the following recovery costs: decontamination costs, earnings from investments that are lost by temporary interdiction of property, and the cost of any repairs necessitated by lack of maintenance of property during the temporary interdiction period

The longest possible period of temporary interdiction is 30 years. If this is insufficient property is automatically condemned

Food Restrictions

Dose is also avoided by controlling the consumption and production of contaminated foodstuffs.

When the accident occurs during the growing season and thus contaminates crops and pasture by direct deposition to plant surfaces, disposal of crops and milk occurs:

- if ground concentrations of food pathway nuclides exceed user specified maximum allowable ground concentrations for those nuclides, or
- if the habitability dose criterion is exceeded for the area where the foodstuffs are grown. Farming is prohibited in subsequent years until farmland is habitable, and then crops are grown only if ground concentrations do not exceed the maximum allowable ground concentrations

A fundamental constraint on food production in contaminated areas is that the land must be habitable for it to be farmable

No mitigative actions for drinking water is considered in MACCS

Shielding Factors

Three groups are distinguished:

- evacuees
- people actively taking shelter
- people who continue normal activities indoors, outdoor, and riding in vehicles

Shielding factors for these groups are calculated outside of the code for cloudshine, groundshine, inhalation, and skin, and are specified by the user

They depend on structural materials, fraction of time outdoors vs. indoors, etc., and are used as multipliers in the dosimetry calculations ($SF \leq 1.0$)

Typical relations:

$0.0 \leq SF(\text{sheltering}) \leq SF(\text{normal activity}) \leq SF(\text{evacuees}) \leq 1.0$

Exposure Pathways

MACCS models seven exposure pathways:

- cloudshine
- skin deposition
- cloud inhalation
- groundshine
- resuspension inhalation
- food ingestion
- water ingestion

Early Exposure

During early exposure the first five pathways are considered to calculate:

(1) acute doses for calculating early fatalities and injuries, and
(2) lifetime dose commitment for calculating cancers resulting from the early exposure

In general the dose equation for an early exposure pathway in a given spatial element is the product of the following:

- radionuclide concentration,
- dose conversion factor,
- duration of exposure, and
- shielding factor

Cloudshine doses are calculated by applying a correction factor for finite cloud size to the dose of an infinite extent cloud. Skin dose is modeled assuming that skin is contaminated only by dry deposition, and skin dose is only caused by β particles

Long-term and intermediate phases

Only groundshine and inhalation of resuspended materials produce doses during the optional intermediate phase.

Long-term doses are caused by groundshine, resuspension inhalation, and ingestion of contaminated foodstuffs and water.

Ingestion produces societal doses both on and off the computational grid, and there is no provision for ingestion doses incurred by specific individuals

Ingestion Doses

Ingestion doses are produced by consumption of drinking water, milk, meat, or crops. Crops are divided into categories (default: pasture, stored forage, grains, green leafy vegetables, legumes and seeds, roots and tubers, and other crops)

The drinking water pathway is modeled by assuming a fixed fraction of all contaminated fresh water is consumed by man (seas are permanent sinks for radioactivity)

The ingestion models are based on the simple principle that the dose produced by any radionuclide to an organ via a pathway is the product of:

(1) the ground concentration of the nuclide
(2) the integrated transfer factor for the nuclide to human intake for the pathway, and
(3) the ingestion dose conversion factor

The population dose to organ k from a specific radionuclide i via the ingestion pathway for crop category j is calculated by the following equation:

$$D_{ijk} = GC_i \cdot DF_{ik} \cdot FA \cdot FAC_j \cdot TF_{ij}$$

where:

D_{ijk} the food ingestion population dose to organ k of radionuclide i from a spatial element via crop category j (Sv),

GC_i the initial ground concentration of radionuclide i in the spatial element (Bq/m^2),

DF_{ik} the ingestion dose conversion factor for nuclide i to organ k (Sv/Bq), from the MACCS DCF File,

FA the area in the grid element which is devoted to farming (m^2),

FAC_j the fraction of the farmland area in the spatial element which is devoted to crop j (dimensionless), and

TF_{ij} the overall transfer factor (dimensionless) from soil to population for nuclide i via crop j

All variables on the RHS of the equation except GC_i are user supplied

Transfer Factors

At the heart of the MACCS food pathway model is the determination of the fraction of the radioactive material deposited onto farmland that will ultimately be consumed by the population

The transfer of radionuclides is affected not only by processes that facilitate transfer, but also by processes limiting in some manner the amount actually consumed.

These are:

- radioactive decay between time of deposition and time of consumption,
- movement downward through the soil compartment to a depth that excludes taking up by the plant,
- irreversible chemical binding with the soil that prevents taking up by the plant
- food processing and preparation methods that discard part of the contaminated portion of food, and
- biological filtering by meat or milk producing animals

The following are modeled using transfer factors:

- transfer of radioactivity through root systems or from plant surfaces to edible portions of plants
- losses during harvesting
- incorporation into meat and milk
- retention in meat, milk, or edible portions of plants during
  - processing
  - shelf-storage
  - cooking

Economic Effects

Economic consequences are calculated by summing the following:

- evacuation costs
- temporary relocation costs (food, lodging, lost income)
- costs of decontaminating land and buildings
- lost return on investments from properties that are temporarily interdicted to allow contamination to be decreased by decay of nuclides
- the cost of repairing temporarily interdicted property
- the value of crops destroyed (direct contamination) or not grown (indirect contamination)
- value of farmland that is condemned
- value of individual, public, and non farm commercial property that is condemned

ECONOMIC EFFECTS (2)

Not included in the economic consequences are the following costs:

- costs associated with damage to the reactor
- the purchase of replacement power
- medical care costs
- costs associated with radiation induced deaths, injuries , and cancers
- litigation costs

Expanded Nuclide List

MACCS contains dose conversion factors for only the 60 radionuclides considered important for NPP analyses, and models only simple parent-daughter decay (two member chains)

→ The MACCS2 list: Incorporates decay-chain data for 825 nuclides and allows the consideration of ingrowth and decay chains with lengths of up to six members

CCDFs of Atmospheric Parameters

No such capability in MACCS

→ The MACCS2 ATMOS model: Generates CCDFs of ten atmospheric modeling parameters for user-specified distances and plume segments

Improved Emergency Response Model

The MACCS evacuation model allows only radially outward travel (radial evacuation)

→The MACCS2 evacuation model allows for:

- **evacuation paths that are not radial (e.g. road networks)**
- **evacuation travel speed which varies with time (e.g. traffic jams)**
- **up to three population distributions with different patterns of emergency response (e.g. guards and health physics teams)**

Foodchain Model

The MACCS foodchain model is specified in terms of maximum allowable ground concentrations for each food nuclide and has the following limitations:

- Requires unitless transfer coefficients for each nuclide and crop type, that are not readily available in the literature
- Does not have the capability to handle time dependence in a dynamic way
- Does not have the capability of modeling radionuclide ingrowth

→The MACCS2 foodchain model:

- Is specified in terms of maximum individual dose resulting from all food nuclides combined
- Dynamic modeling
- Allows ingrowth (up to 4 members)

PROBABILISTIC ACCIDENT CONSEQUENCE ASSESSMENT CODES

SECOND INTERNATIONAL COMPARISON

OVERVIEW REPORT

A joint Report by the OECD Nuclear Energy Agency
and the Commission of the European Communities

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

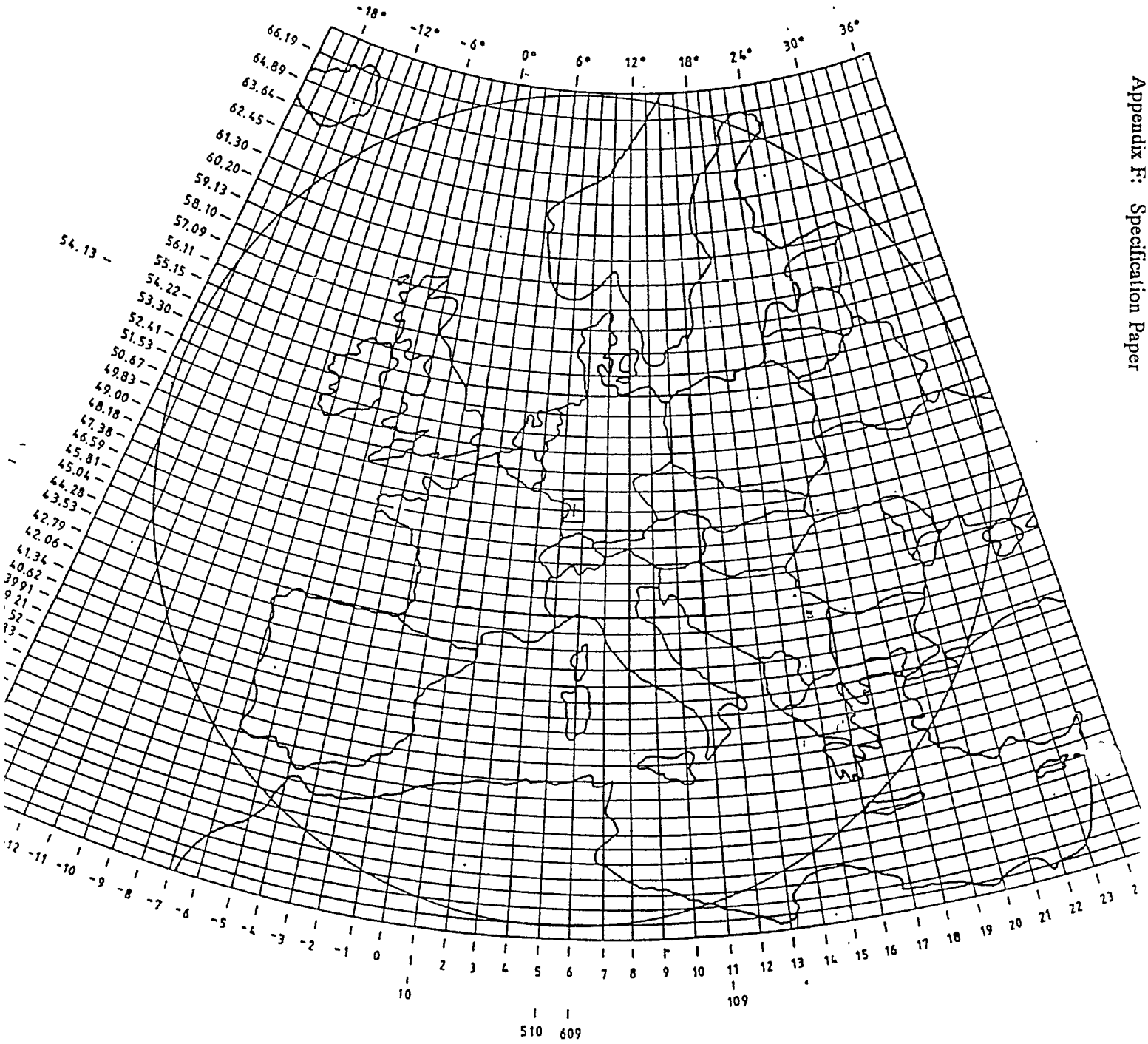
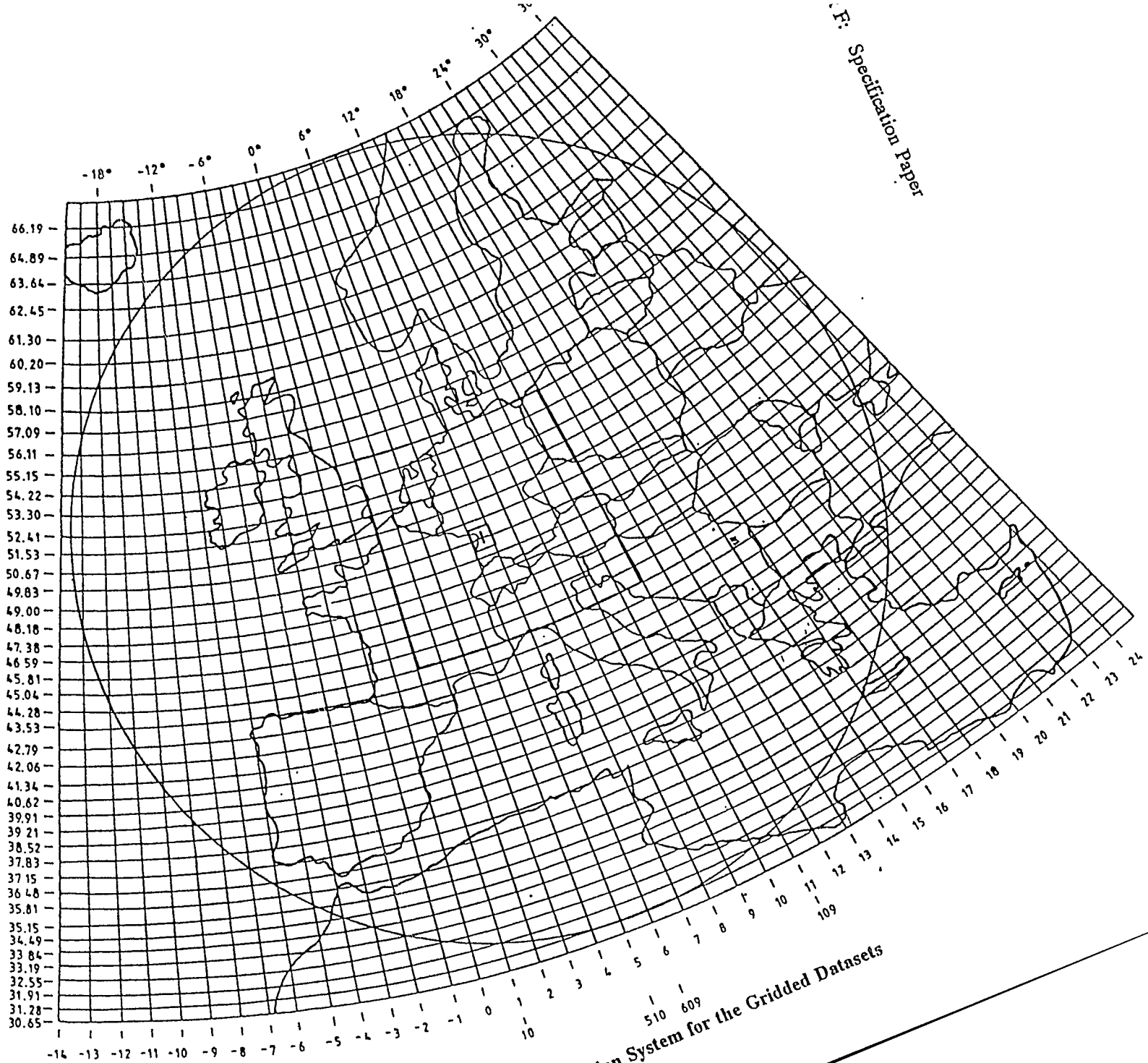


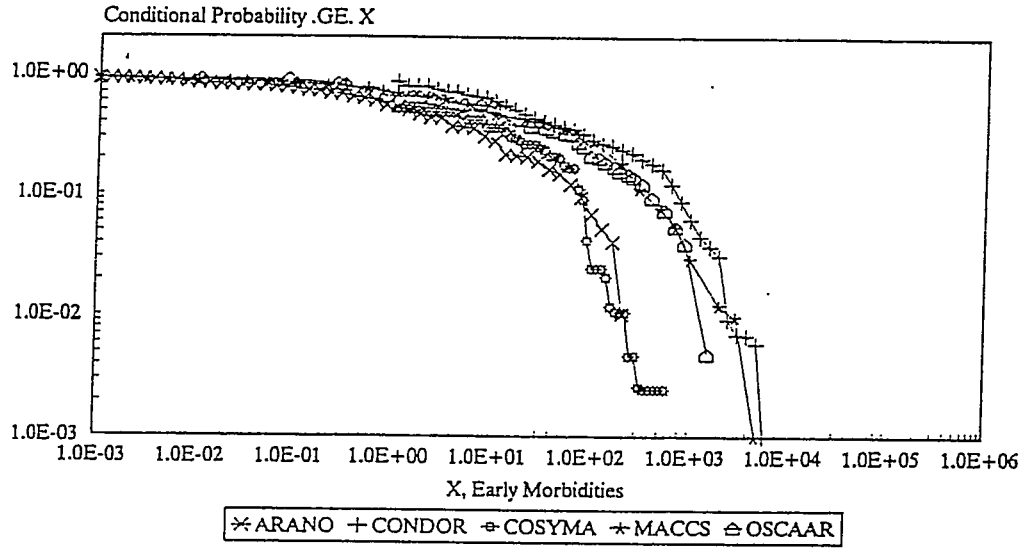
Figure F.1 Illustration of the Notation System for the Gridded Datasets



...ion of the Notation System for the Gridded Datasets

b(vi) Number of Early Morbidities from Hypothyroidism

Calculation C1



Sheet 17a

International Comparison of PCA Models							
Sheet 17a	b(vi) Number of Early Morbidities from Hypothyroidism						
Calculation C 1	Expectation Value	Value of the pth Percentile					Probability of zero effects
		p = 50	p = 90	p = 95	p = 99	p = 99.9	
ARANO	2.07E+01	1.23E+00	7.29E+01	1.35E+02	NOT FOUND	NOT FOUND	
CONDOR	2.42E+02	1.58E+01	7.19E+02	1.15E+03	2.47E+03	6.09E+03	1.44E-01
COSYMA	2.20E+01	1.00E+00	7.90E+01	8.30E+01	2.51E+02	6.03E+02	4.90E-01
LENA							
MACCS	1.54E+02	6.99E+00	3.42E+02	7.24E+02	2.82E+03	4.87E+03	1.00E-01
OSCAAR	1.16E+02	1.11E+01	3.78E+02	7.71E+02	1.34E+03	1.55E+03	9.73E-02