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Theory of Consequence Analysis using MACCS (Part 4-6)

A.J. Nosek, PhD
US Nuclear Regulatory Commission

PROTECTIVE ACTIONS

Outline

- Introduction
- Early phase
  - Evacuation and sheltering model
    - Evacuation and sheltering timeline
    - Evacuation transit and routing
    - Evacuation region (circular vs keyhole model)
  - Early Relocation
  - Potassium iodide ingestion
- Intermediate phase
  - Intermediate-phase relocation
- Long-term phase
  - Decontamination
  - Long-term actions for non-farm areas
  - Long-term actions for farm areas

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PROTECTIVE ACTIONS

Introduction

- Protective actions reduce radiation exposures.
- Protective actions are a tradeoff: They reduce radiogenic health effects but at a cost of other types of societal and economic impacts.
- MACCS treats the three accident phases as being independent of each other.
- Early phase protective actions (i.e., “emergency response”):
  - Evacuation and sheltering
  - Early relocation
  - Potassium iodide ingestion
- Intermediate phase protective actions:
  - Temporary relocation (i.e., habitation restrictions)
- Long-term phase protective actions:
  - Temporary and permanent relocation (i.e., habitation restrictions)
  - Decontamination
  - Farming restrictions

PROTECTIVE ACTIONS

Introduction

- Many protective actions are dose-dependent
  - If a projected dose exceeds a dose criterion during a specified exposure period, it triggers a protective action.
  - Dose projections for relocation are used for the early, intermediate, and long-term phase.
  - Currently, MACCS dose projections assume normal activity.

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PROTECTIVE ACTIONS
Early Phase

- Spatial grid is divided into two areas according to the user-specified radial interval (NUMEVA)
  - Inside NUMEVA: Evacuation and sheltering region
  - Outside NUMEVA: Early relocation region
  - When NUMEVA = 0, there is no evacuation or sheltering region (only early relocation)

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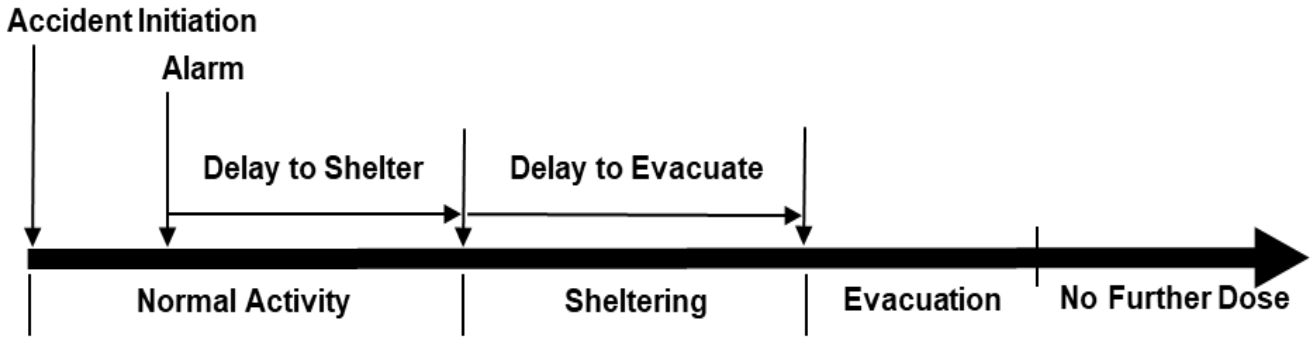
PROTECTIVE ACTIONS
Evacuation and Sheltering Timeline



Evacuation and Sheltering Timeline for a Generic Cohort

- Three states of activity based on timeline
  - Normal activity, sheltering, and evacuation
  - Each cohort may be assigned unique activity-specific protection factors and breathing rates

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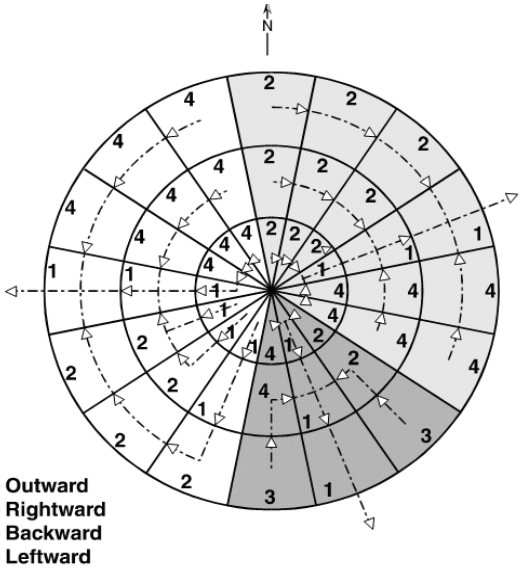
PROTECTIVE ACTIONS
Evacuation Transit and Routing

- Two evacuation routing options (EVATYP = "RADIAL" or "NETWORK")
  - Radial evacuation: Evacuees travel radially outward
  - Network evacuation: Evacuees travel along user-specified grid
- During transit, MACCS models evacuees as moving from spatial grid midpoint to midpoint in a stepwise fashion until they reach the travel boundary (LASMOV)
- MACCS reports doses to an individual according to where the individual originates
- Time spent in each spatial element depends on
  - Grid size
  - Travel speed (ESPEED) for each travel phase
  - Speed multiplier (ESPGRD) for each spatial element
  - Speed multiplier (ESPMUL) for precipitation



Network evacuation direction with corresponding IDIREC values on a spatial grid.

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PROTECTIVE ACTIONS
Early Relocation

- Early relocation is a dose-dependent response that occurs outside the evacuation and sheltering boundary (NUMEVA).
- Projected dose includes early exposure pathways: cloudshine, groundshine, direct and resuspension inhalation (skin deposition doses not included).
- The projected dose is for a single period, which occurs when the first plume arrives.
- Early relocation has two areas, hotspot and normal relocation.
- The user specifies:
  - The early relocation dose criteria (DOSHOT / DOSNRM)
  - The relocation times after plume arrival (TIMHOT / TIMNRM)
  - The dose projection period (DPPEMP)
  - The critical organ (CRIORG)
- Once relocation occurs, displaced individuals receive no dose for the remainder of the early phase (ENDEMP).

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PROTECTIVE ACTIONS
Intermediate-Phase Relocation

- Intermediate-phase relocation is a dose-dependent response.
- Projected dose includes late exposure pathways: groundshine and resuspension inhalation (ingestion doses not included).
- The projected dose is for a single period, which occurs at the start of the intermediate phase (ENDEMP). Relocation occurs immediately.
- The user specifies:
  - The intermediate-phase habitability dose criterion (DSCRTI)
  - The dose projection period (DPP_INTPHAS)
  - The critical organ (CRTOCR)
- Displaced individuals receive no dose during intermediate phase period (DUR_INTPHAS).

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PROTECTIVE ACTIONS
Long-term Phase

- Land divided into farm and non-farm areas
- Non-farm areas:
  - Habitation restrictions occur when non-farm area exceeds the habitability criterion.
  - The user specifies:
    - The long-term habitability dose criterion (DSCRLT)
    - The dose projection period (TMPACT)
    - The critical organ (CRTOCR)
- Farm areas:
  - Farming restrictions occur in farm areas when food ingestion doses exceed farmability criteria. (The farmability criteria depend on which food chain model the user selects.)
  - Farming restrictions also occur when farmland exceeds the habitability criterion, as MACCS assumes farmland is otherwise not farmable.

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PROTECTIVE ACTIONS
Decontamination

- Decontamination reduces groundshine and resuspension inhalation doses.
- Decontamination may occur in both non-farm and farm areas to help restore habitability
- Decontamination does not affect modeled concentration of radioactivity in agricultural products
- User can specify up to three decontamination levels. Each decontamination level requires the user to specify:
  - a dose reduction factor (DSRFCT)
  - a decontamination time (TIMDEC)
  - a decontamination cost (*$/hectare*) for farm areas (CDFRM)
  - a decontamination cost (*$/capita*) for non-farm areas (CDNFRM)

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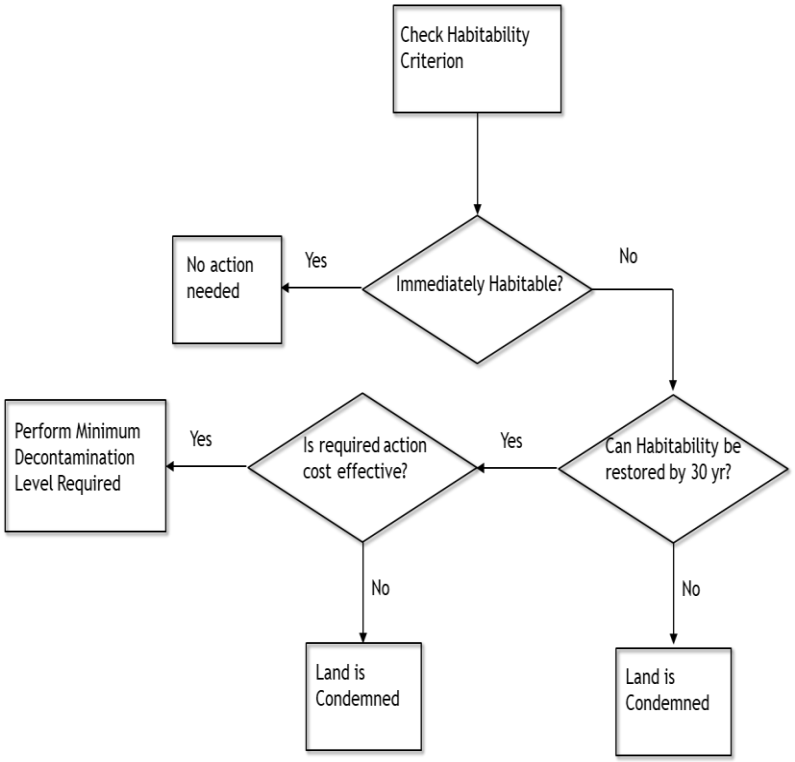
PROTECTIVE ACTIONS
Long-Term Actions for Non-farm Areas

- Relocation at the start of the long-term phase occurs when the ambient dose is projected to exceed the habitability dose criterion
- MACCS determines whether habitability can be restored by evaluating a set of increasingly aggressive protective actions.
- Residents return when the habitability criterion is satisfied by either decontamination or decontamination plus a period of subsequent interdiction.
- Grid elements for which habitability cannot be restored, or for which the restoration of habitability is cost-prohibitive, are permanently condemned and no doses are accrued in the long-term phase



Logic Flowchart for Non-farm Areas

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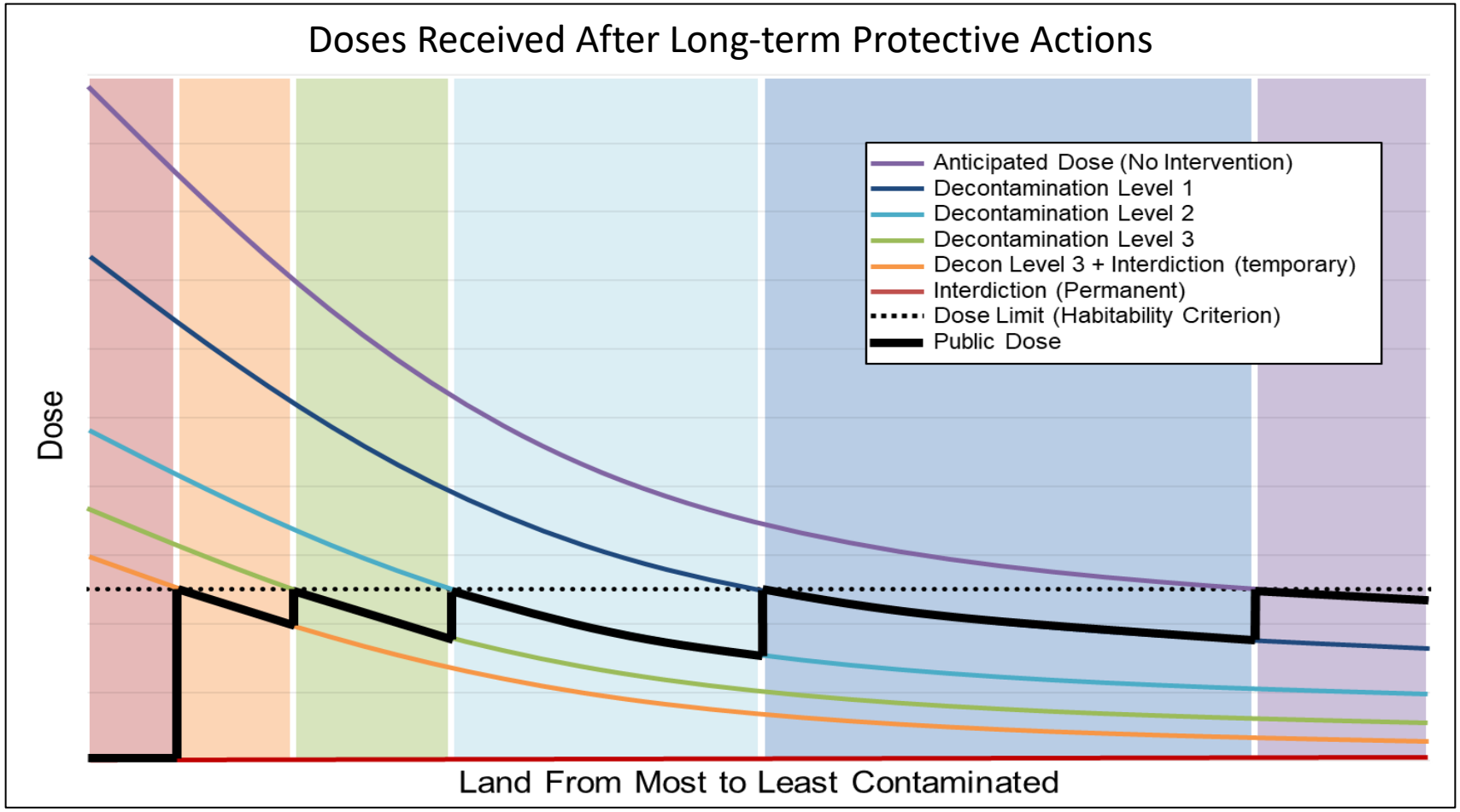
PROTECTIVE ACTIONS

Long-term Non-farm Areas



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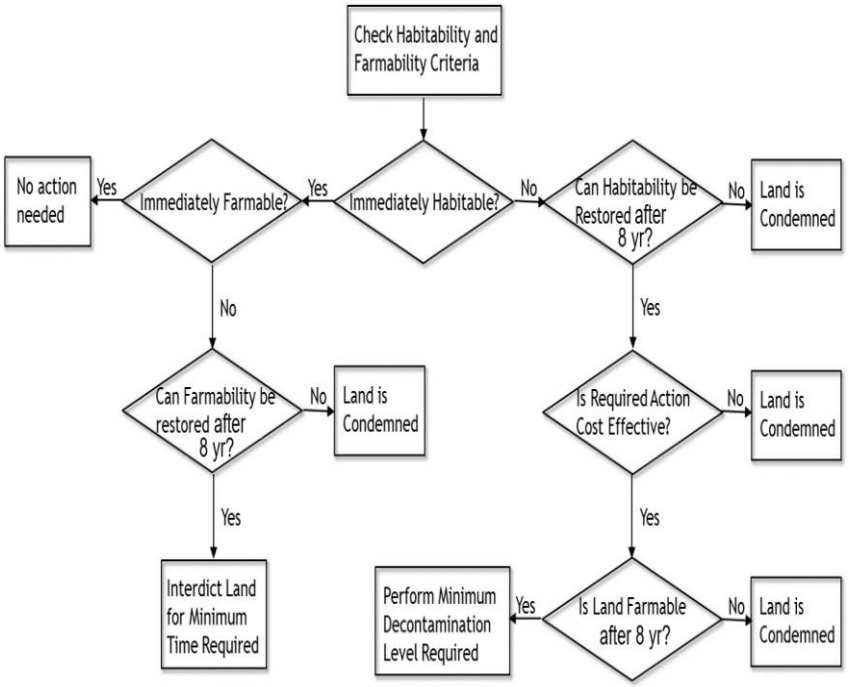
PROTECTIVE ACTIONS
Long-Term Actions for Farm Areas

- Farming restrictions occur beginning at the end of the early phase when either
  - Food ingestion doses exceed farmability criteria, or
  - The ambient dose exceeds the habitability criterion.
- If a farm area is not immediately habitable, it must become habitable before the MACCS considers lifting the long-term farming restrictions.
- If it is not possible to restore farmability, MACCS condemns the farm area and assumes no action is taken to restore habitability.
  - Otherwise, MACCS uses the same process for lifting habitability restrictions in both farm and non-farm areas.
  - Decontamination can occur in farm areas, but only to help restore habitability and only if it is cost effective, just as in non-farm areas.
  - Decontamination does not reduce long-term food ingestion doses or the minimum interdiction period required for farmability.
- Ultimately, the total farm interdiction period is the larger one of two time periods: (1) the minimum farm interdiction period due to farmability criteria, or (2) the habitation restriction period.



Logic Flowchart for Farmland Areas

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DOSIMETRY AND PROTECTIVE ACTIONS

QUESTIONS?

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SOCIAL AND ECONOMIC IMPACTS

Outline

- Introduction
  - Market impacts
  - Non-market impacts
- Market impacts
  - Evacuation and early relocation costs
  - Intermediate phase relocation costs
  - Long-term costs in non-farm areas
  - Long-term costs in farm areas

SOCIAL AND ECONOMIC IMPACTS

Introduction

- Nuclear accident impacts can be divided into two categories: market and non-market
- Market impacts (sometimes called “financial impacts” or “special damages”) include:
  - Onsite and offsite property damage
  - Economic disruptions
  - Accident-related expenditures
- Non-market impacts (sometimes called “noneconomic impacts” or “general damages”) include:
  - Health effects
  - Societal disruptions
  - Environmental damage

SOCIAL AND ECONOMIC IMPACTS
Market Impacts

- Evacuation and early phase relocation costs
- Intermediate phase relocation costs
- Long-term costs in non-farm areas (*$/capita*)
  - One-time relocation
  - Decontamination (habitation restricted area)
  - Loss of use and property depreciation
- Long-term costs in farm areas (*$/farm-hectare*)
  - Milk and crop disposal
  - Decontamination (habitation restricted area)
  - Loss of use and property depreciation
- Cost models do not consider
  - Onsite damages or disruptions
  - Property losses due to housing market impacts
  - Certain expenditures (e.g., decontamination in habitable areas, removal of condemned structures, cost of litigation and a compensation system, medical expenses)
  - Economic disruptions due to stigma effects (e.g., tourism, trade)

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SOCIAL AND ECONOMIC IMPACTS
Non-Market Impacts

- MACCS cost models do not estimate an economic value for non-market impacts.
- MACCS does evaluate important metrics related to non-market impacts, including:
  - the number of cancer fatalities and other health effects
  - the number of displaced individuals
  - the amount of land contamination

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ECONOMIC IMPACTS

Evacuation and Early Relocation

Cost of the early protective action CE_i for cohort *i* (for either evacuation or early relocation) is the following:

$$CE_i = CEV \cdot \Delta t_i \cdot POP_i$$

Where

- CE_i is the early protective action cost (*$*) for cohort *i*,
- CEV is the daily per capita cost (*$/person-day*), as specified by the parameter EVACST,
- Δt_i is the duration (*days*) of the protective action for cohort *i*, and
- POP_i is the population of cohort *i*.

Costs accrue for all early relocated population and all evacuees affected by the plume.

Costs are not accrued for evacuees who may immediately return because their residence was unaffected by the plume

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ECONOMIC IMPACTS

Intermediate Phase Relocation

The cost of intermediate phase relocation in a spatial element is the following:

$$CI = CIR \cdot \Delta t \cdot POP$$

where

- CI is the cost of intermediate phase relocation (*$*),
- CIR is the daily per capita cost (*$/person-day*) of intermediate phase relocation per individual, as specified by the parameter RELCST,
- Δt is the duration (*days*) of intermediate phase relocation period, and
- POP is the displaced population (*persons*) of a spatial element due to intermediate phase habitation restrictions.

Costs associated with loss of use and depreciation of property during the intermediate phase are captured in the long-term phase cost estimation

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ECONOMIC IMPACTS

Long-Term Costs

In a spatial element, the cost of long-term protective actions is determined as follow:

$$CL = C^{NF} \cdot POP + C^{F} \cdot AF$$

where

- *CL* is the total cost incurred as a result of long-term protective action taken within a given spatial element (*$*),
- C^{NF} is the per capita cost (*$/person*) of long-term protective actions in a non-farm area,
- *POP* is the displaced population (*persons*) from a spatial element due to long-term habitation restrictions,
- C^{F} is the unit cost (*$/hectare*) of long-term protective actions in a farm area, and
- *AF* is the size of the restricted farm area (*hectares*) in the spatial element.

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ECONOMIC IMPACTS

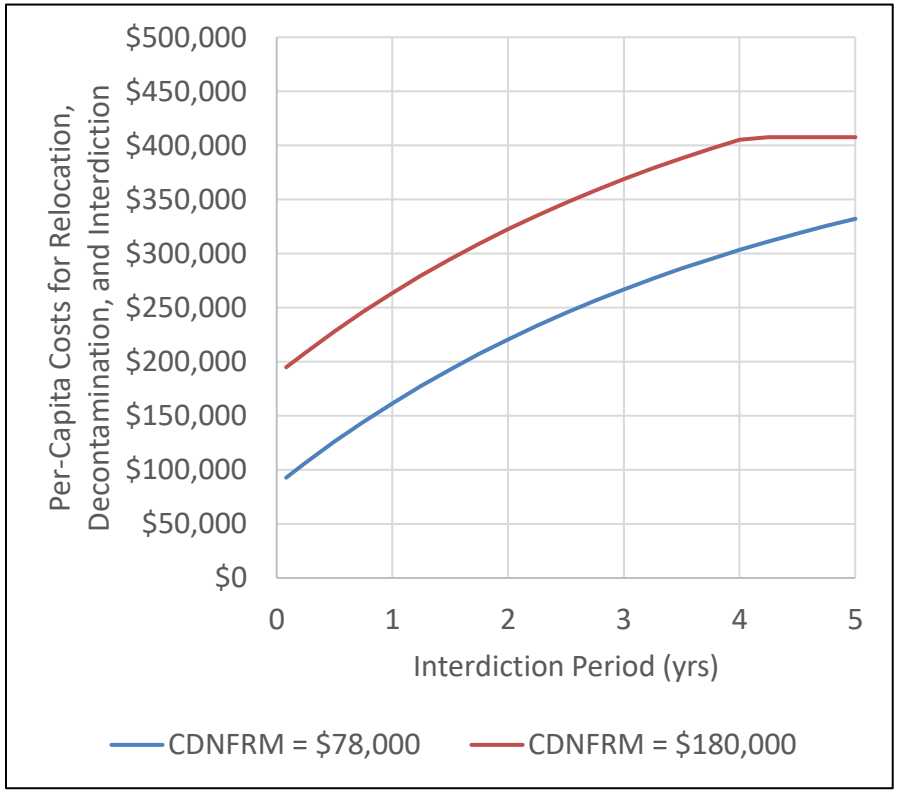
Long-Term Costs in Non-Farm Areas

When the non-farm area in a grid element is subject to temporary restrictions due to habitability limits, the unit cost in the non-farm area of the spatial element is:

$$C^{NF} = CF + CD_{\ell}^{NF} + \left(1 - e^{-rt} \cdot [(1 - a^{NF}) + a^{NF} \cdot e^{-dt}]\right) \cdot VW^{NF}$$

where

- CF is the per-capita one-time relocation cost (*$/person*).
- CD_{ℓ}^{NF} is the per-capita decontamination cost of the minimum decontamination level ℓ that can restore habitability in non-farm areas (*$/person*),
- VW^{NF} is the per capita value (*$/person*) of non-farm wealth in the non-farm area,
- a^{NF} is the regional fraction of wealth (unitless) for non-farm areas that is from land improvements
- d is the depreciation rate (yr^{-1}),
- r is a rate of return (yr^{-1}), and
- t is the interdiction period (*yr*) caused by habitability restrictions in the grid element.



Example of long-term per-capita non-farm losses as a function of length of interdiction period

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ECONOMIC IMPACTS

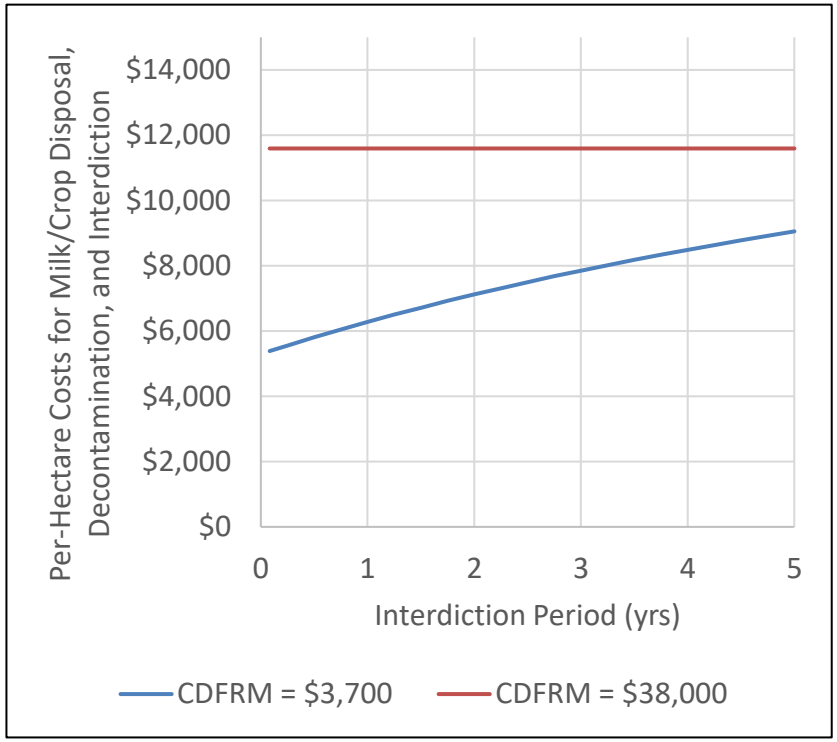
Long-Term Costs in Farm Areas

When the farm area in a grid element is subject to temporary restrictions due to either habitability or farmability limits, whichever is longer, the unit cost in the farm area of the spatial element is:

$$C^F = CMD + CNMD + CD_{\ell}^F + \{1 - e^{-rt} \cdot [(1 - a^F) + a^F \cdot e^{-dt}]\} \cdot VW^F$$

where

- CMD is the unit cost of lost milk sales (*$/hectare*),
- $CNMD$ is the unit cost of lost non-milk sales (*$/hectare*),
- CD_{ℓ}^F is the unit decontamination costs ($) of the minimum decontamination level ℓ that can restore habitability in farm areas (*$/hectare*),
- VW^F is the unit value (*$/hectare*) of farm wealth in farm areas,
- a^F is the fraction of the wealth (unitless) for farm areas that is from land improvements,
- d is the depreciation rate (yr^{-1}),
- r is the rate of return on investment (yr^{-1}), and
- t is the interdiction period (*yr*) caused by either habitability or farmability restrictions in the grid element



Example of long-term per-hectare farm losses as a function of length of interdiction period

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RADIOGENIC HEALTH EFFECTS

Outline

- Introduction
- Early health effects dose-response model
- Cancer incidence/fatality dose-response model
  - Linear, no threshold
  - Linear quadratic
  - Annual threshold
  - Piecewise linear

RADIOGENIC HEALTH EFFECTS

Introduction

- Health effects from ionizing radiation are broadly categorized into two main categories:
  - Stochastic effects, which include:
    - Cancer incidence / fatality
    - Heritable effects
  - Tissue reactions (i.e., deterministic effects), which include:
    - Early injury / fatality
    - Degenerative conditions (i.e., cataracts, cardiovascular disease, and cerebrovascular disease [ICRP, 2012; NASA, 2016].
- MACCS analyses typically model cancer and early health effects.

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RADIOGENIC HEALTH EFFECTS

Early Health Effects

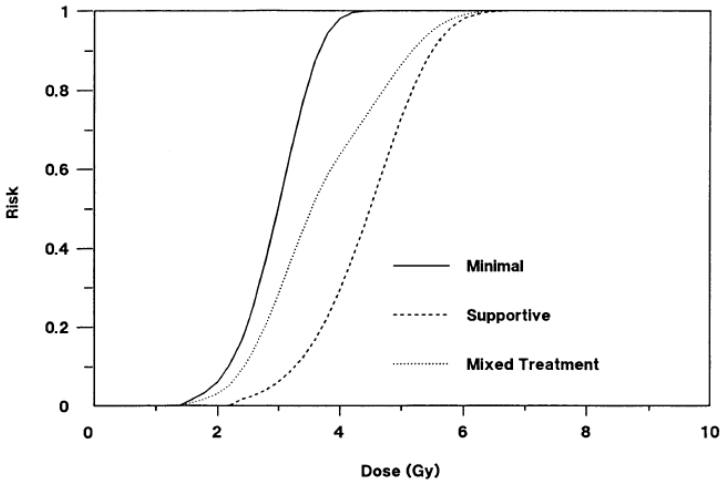
MACCS estimates risk of early health effects (injury or fatality) using a sigmoid dose response model based on a Weibull distribution (Evans 1989):

$$r_k = 1 - exp(-H_k)$$

$$H_k(D_k) = \begin{cases} 0 & D_k < D_{T,k} \\ ln(2) \cdot \left(\frac{D_k}{D_{50,k}}\right)^{\beta_k} & D_k \geq D_{T,k} \end{cases}$$

where

- D_k is the acute dose (*Gy*) to a target organ
- $D_{T,k}$ is the threshold dose (*Gy*)
- $D_{50,k}$ is the acute dose (*Gy*) that would induce an early health effect *k* in half the exposed population, and
- β_k is the shape parameter (dimensionless).



Hematopoietic Syndrome Mortality Risks for Minimal Treatment, Supportive Treatment, and Mixed Treatment - Central Estimates for Exposure at High Dose Rate. (reproduced from Figure 3.1 of Evans 1989)

The early health effect estimates use acute doses, which account for the sparing effect.

Early fatalities are estimated using a "pooled" risk model, i.e.: $H_{EF} = H_R + H_L + H_{GI}$

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RADIOGENIC HEALTH EFFECTS

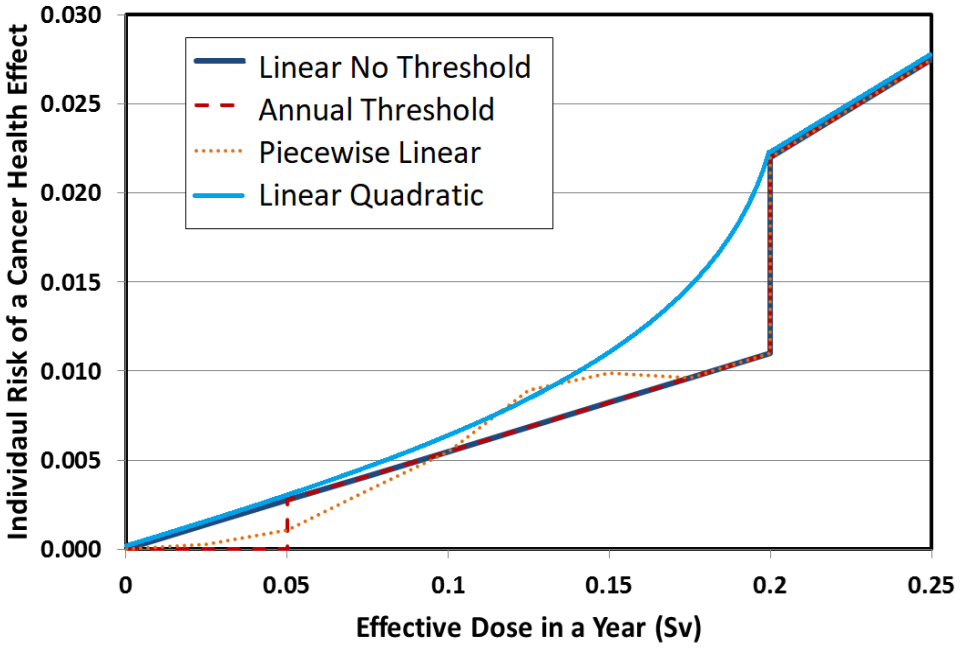
Cancer Incidence/Fatality

Four dose-response models are available in MACCS to calculate cancer incidence and fatalities:

- Linear, no threshold (LNT) with a dose and dose rate effectiveness factor (DDREF)
- Linear quadratic
- Annual threshold
- Piecewise linear

The linear no-threshold and the linear-quadratic models use lifetime doses.

The annual-threshold and piecewise-linear models use annual doses that exceed specified thresholds.



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RADIOGENIC HEALTH EFFECTS

LNT Model for Cancer Incidence/Fatality

In the LNT dose-response model, the risk r_k^E of stochastic health effect *k* is given by:

$$r_k^E = f_k \cdot RC_k \cdot D_k^E \cdot I_k$$

$$I_k = \begin{cases} 1 & D_k^E \geq D_\alpha \\ \dfrac{1}{\alpha_k} & D_k^E < D_\alpha \end{cases}$$

where

- f_k is the fraction of the population that is susceptible to the risk of health effect k,
- RC_k is the lifetime risk factor (*1/Sv*) of health effect k,
- D_k^E is the early dose (*Sv*) contribution to the lifetime dose
- α_k is the dose and dose-rate effectiveness factor (dimensionless) for health effect k,
- D_α is the dose threshold (*Sv*) of the dose and dose-rate effectiveness factor

Because doses after the early phase are assumed to stay below the low-dose threshold, the dose and dose-rate effectiveness factor α is always applied to long-term (CHRONC) doses

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SOCIAL, ECONOMIC, AND HEALTH IMPACTS

QUESTIONS?

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SUPPLEMENTAL SLIDES

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PROTECTIVE ACTIONS
Evacuation and Sheltering Region

- Two evacuation options (EVAKEY = "CIRCULAR" or "KEYHOLE")
- Circular evacuation:
  - 360-degree area
  - Evacuation occurs as soon as timeline allows
- Keyhole evacuation:
  - Keyhole-shaped area, with an inner and an outer region
    - Radius of inner region (KEYDIS)
    - Number of sectors in outer region (NSECTR)
  - Evacuation in keyhole area occurs as soon as timeline allows
  - Evacuation expands to remaining area in outer region based on wind-shift weather forecast

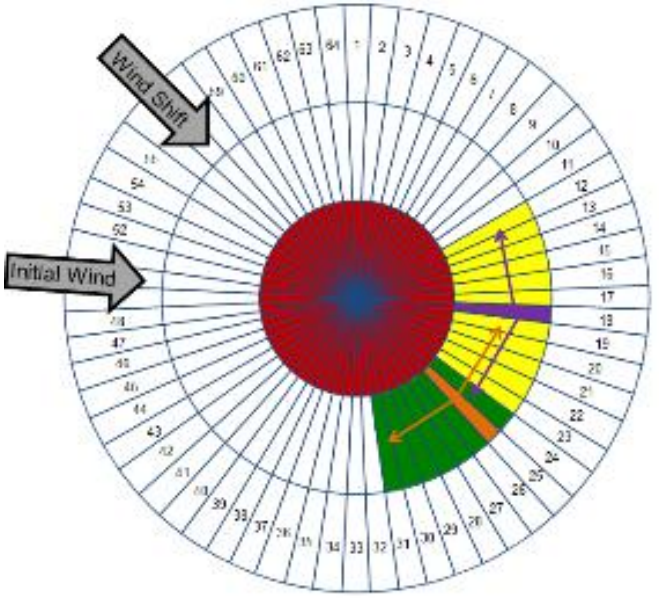

Illustration of a Keyhole Evacuation With a Wind Shift

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