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Economic Model for Estimation of GDP Losses in the MACCS Offsite Consequence Analysis Code

N. E. Bixler, A. V. Outkin, D. Osborn, N. C. Andrews, and F. Walton

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

The MACCS (MELCOR Accident Consequence Code System) code is the U.S. Nuclear Regulatory Commission (NRC) tool used to perform probabilistic health and economic consequence assessments for atmospheric releases of radionuclides. It is also used by international organizations, both reactor owners and regulators. It is intended and most commonly used for hypothetical accidents that could potentially occur in the future rather than to evaluate past accidents or to provide emergency response during an ongoing accident. It is designed to support probabilistic risk and consequence analyses and is used by the NRC, U.S. nuclear licensees, the Department of Energy, and international vendors, licensees, and regulators.

This report describes the modeling framework, implementation, verification, and benchmarking of a GDP-based model for economic losses that has recently been developed as an alternative to the original cost-based economic loss model in MACCS. The GDP-based model has its roots in a code developed by Sandia National Laboratories for the Department of Homeland Security to estimate short-term losses from natural and manmade accidents, called the Regional Economic Accounting analysis tool (REAcct). This model was adapted and modified for MACCS and is now called the Regional Disruption Economic Impact Model (RDEIM). It is based on input-output theory, which is widely used in economic modeling. It accounts for direct losses to a disrupted region affected by an accident, indirect losses to the national economy due to disruption of the supply chain, and induced losses from reduced spending by displaced workers. RDEIM differs from REAcct in its treatment and estimation of indirect loss multipliers, elimination of double counting associated with inter-industry trade in the affected area, and that it is designed to be used to estimate impacts for extended periods that can occur from a major nuclear reactor accident, such as the one that occurred at the Fukushima Daiichi site in Japan. Most input-output models do not account for economic adaptation and recovery, and in this regard RDEIM differs from its parent, REAcct, because it allows for a user-definable national recovery period. Implementation of a recovery period was one of several recommendations made by an independent peer review panel to ensure that RDEIM is state-of-practice. For this and several other reasons, RDEIM differs from REAcct.

Both the original and the RDEIM economic loss models account for costs from evacuation and relocation, decontamination, depreciation, and condemnation. Where the original model accounts for an expected rate of return, based on the value of property, that is lost during interdiction, the RDEIM model instead accounts for losses of GDP based on the industrial sectors located within a county. The original model includes costs for disposal of crops and milk that the RDEIM model currently does not, but these costs tend to contribute insignificantly to the overall losses.

This document discusses three verification exercises to demonstrate that the RDEIM model is implemented correctly in MACCS. It also describes a benchmark study at five nuclear power plants chosen to represent the spectrum of U.S. commercial sites. The benchmarks provide perspective on the expected differences between the RDEIM and the original cost-based economic loss models. The RDEIM model is shown to consistently predict larger losses than the original model, probably in part because it accounts for national losses by including indirect and induced losses; whereas, the original model only accounts for regional losses. Nonetheless, the RDEIM model predicts losses that are remarkably consistent with the original cost-based model, differing by 16% at most for the five sites combined with three source terms considered in this benchmark.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
BEA	Bureau of Economic Analysis
CBO	Congressional Budget Office
CPI	Consumer Price Index
CGE	Computational General Equilibrium
COCO-2	Cost of Consequences Offsite Version 2
DOE	U.S. Department of Energy
EIS	Environmental Impact Statement
GDP	Gross Domestic Product
IAEA	International Atomic Energy Agency
I-O	Input-Output
MACCS	MELCOR Accident Consequence Code System
NAICS	North American Industry Classification System
NRC	U.S Nuclear Regulatory Commission
NTR	Net Total Requirements
OMB	Office of Management and Budget
PRA	Probabilistic Risk Assessment
RDEIM	Regional Disruption Economic Impact Model
REAcct	Regional Economic Accounting analysis tool
RIMS	Regional Input-Output Modeling System
SAMA	Severe Accident Mitigation Alternatives
SAMDA	Severe Accident Mitigation Design Alternatives
SecPop	Sector Population, Land Fraction, and Economic Estimation Program
SNA	System of National Accounts
SNL	Sandia National Laboratories
SOARCA	State-Of-the-Art Rector Consequence Analysis
TRII	Industry-by-Industry Total Requirements
UK	United Kingdom
U.S.	United States

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1. INTRODUCTION

The MACCS (MELCOR Accident Consequence Code System) code is the U.S. Nuclear Regulatory Commission (NRC) code used to perform probabilistic health and economic consequence assessments for atmospheric releases of radionuclides. MACCS is used by U.S. nuclear power plant license renewal applicants to support the plant specific evaluation of severe accident mitigation alternatives (SAMA) analyses as part of an applicant's environmental report for license renewal. MACCS is also used in severe accident mitigation design alternatives (SAMDA) and severe accident consequence analyses for environmental impact statements (EISs) for both existing and new reactor license applications. The NRC uses MACCS in its cost-benefit assessments supporting regulatory analyses that evaluate potential new regulatory requirements for nuclear power plants. NRC regulatory analysis guidelines recommend the use of MACCS to estimate the averted "offsite property damage" cost and the averted offsite dose cost elements, which are both benefits in the cost/benefit analysis (NRC, 1997; NRC, 2004).

The original cost-based MACCS economic model was published by Jow, et al. (1990) and is referred to in this document as the cost-based model. This cost-based model is a generalization of the one in CRAC2 (Ritchie, et al., 1983). Since the implementation of the cost-based economic model in MACCS, government-sponsored economic data related to gross domestic product (GDP) have become readily available, along with tools to gather and process the data. With the availability of government-produced, standardized data, an alternative MACCS economic model can be employed to implement a GDP-based estimation of offsite economic costs of a nuclear power plant incident. To implement the GDP-based economic model, a variant of the Regional Economic Accounting analysis tool (REAcct) created at Sandia National Laboratories, has been integrated into MACCS[♣][♠][1]. To signify that this model is significantly different than REAcct, it has been named RDEIM, which stands for the Regional Disruption Economic Impact Model. In this document, the terms RDEIM model and GDP-based model are used interchangeably.

The GDP-based (RDEIM) economic model achieves the following objectives:

- Estimating off-site costs for nuclear reactor accidents with state-of-practice methods commonly used for other disruptions that have the potential for large-scale economic impacts
- Developing estimates of the offsite cost impacts from business disruption using current state-of-practice input-output (I-O) economics

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♣ Parts of this document are based directly on our previous MACCS materials, reports, and publications, including Outkin and Vargas (2012) and Vargas et al. (2011).

♠ The authors would like to note that this approach departs from the conventional RIMS II treatment of a single industry change, and instead represents a multi-industry disruption over a region.

1 The model presented in this report differs from the current version of REAcct. In particular, it calculates the indirect and induced effects differently from REAcct and applies a different aggregation method for calculating the effects over time. The REAcct analysis tool has been used to rapidly estimate approximate economic impacts of natural and manmade disruptions (Ehlen et al., 2009; Vargas et al., 2011; Vargas and Ehlen, 2013). The original REAcct code uses geospatial data on the regional extent and disruption duration to produce county-level direct GDP and employment loss estimates for any region in the 48 contiguous States. In addition, REAcct estimates the indirect and induced GDP losses at the National level. REAcct contains the employment and GDP data for more than 400 industries for the entire U.S. economy at the county level. For use in MACCS, the larger set of industries was aggregated into 19 industrial sectors and two government sectors. External geospatial tools are not needed in the MACCS application because the spatial extent of contamination is determined inside of MACCS, which then uses the county-level data directly.

- Estimating the impact on the regional communities, industries, and infrastructure
- Estimating the impacts of multi-year disruptions when the region cannot be remediated quickly
- Estimating indirect effects on the national economy outside the directly affected region
- Estimating induced effects to the regional and national economies resulting from lost income to workers

This document provides an overview of both the original, cost-based, MACCS economic model and the newer, GDP-based economic loss model. Following a description of each model, the implementation of the GDP-based model into the MACCS framework is discussed. Verification exercises and benchmarking of the GDP-based model are then covered in significant detail for a variety of consequence scenarios. The GDP-based economic model is included with WinMACCS 4.0.0 and MACCS 4.0.0.0, which is the version tested and benchmarked in this report.

1.1. Cost-Based Model Overview

The original MACCS economic model calculates offsite consequences of nuclear power plant accidents that release radioactive materials into the atmosphere using a cost-based approach. The MACCS cost-estimation model is described in the MACCS Model Description document written by Jow, et al. (1990). The underlying economic methodology is described in an earlier document by Burke, et al. (1984). Specifically, the costs calculated in the original MACCS economic model include:

- Temporary evacuation and relocation costs, including food, lodging, and lost income for the displaced population during the emergency and intermediate phases of the accident
- One-time relocation costs during the long-term phase
- Cost of decontaminating land and property during the long-term phase
- Lost return on investments from properties that are temporarily interdicted
- Depreciation of temporarily interdicted property that cannot be maintained
- Value of lost crops in the first year of the accident
- Value of farmland and of private, commercial, public, and supporting infrastructure that is condemned during the long-term phase

MACCS costs are calculated based on protective measures and emergency response actions undertaken during and after the accident. The unit costs associated with protective actions and emergency responses are defined in the user input. The emergency responses include evacuation, sheltering, and relocation. The long-term protective actions include decontamination, temporary land interdiction and associated relocation of population, crop disposal, control/prohibition of food production, and condemnation of property.

1.2. GDP-Based Model (RDEIM) Overview

RDEIM calculates the indirect losses using net total requirements (NTR) multipliers based on the Regional I-O Modeling System (RIMS II) data. It uses employment by county, value added[2] gross output by industry, total requirements tables, final demand value-added multipliers (RIMS II model)

[2] Value added is defined as the sum of labor compensation, capital income, and net indirect taxes (producer taxes, import tariffs minus subsidies).

provided by the U.S. Bureau of Economic Analysis (BEA, 2012), and other data provided by the Bureau of Labor Statistics and other sources.

The total economic impact (loss) caused by a disruption is typically grouped into three categories (BEA, 2012):

- Direct[3] GDP impacts occur due to a loss of final demand, which occurs in the context of an accident because production is stopped for a period in the affected area, which represents a loss of the value added by the affected firms.
- Indirect GDP impacts occur because the loss of final demand also affects the supplier firms as their input to the curtailed production is no longer required. In the context of an accident, supplier firms are outside the affected area. GDP impacts represent value-added losses to indirectly affected firms.
- Induced GDP impact relates to the spending of workers whose earnings are affected by the disruption.[4] Induced GDP losses correspond to both workers inside and outside the directly affected area.

The GDP loss calculated by RDEIM estimates the losses accrued over time at the regional scale of the impacted area and at the national scale. It also allows the recovery schedules for regional and national scales to be varied independently of each other with the proviso that regional recovery is never faster than national recovery.

The RDEIM model includes indirect impacts to other sectors of the economy that are additional to but causally related to the direct impacts. However, the indirect impacts in RDEIM are restricted to the geographic areas not directly affected by the disruption. Induced impacts account for the effect of lost income on purchases (sales), which in turn affect the overall economy.

While direct economic impacts occur to known regions of the country, the same is not true for indirect impacts. Some, but not all, of the intermediate industries that sell to or buy from the industries in the directly impacted region are also located in the directly impacted region but the remainder, possibly the majority, are located outside of the directly impacted region; likewise, not all of the workers that potentially lose income from the directly or indirectly impacted industries spend all their income regionally or even nationally. Induced impacts are included as part of the values reported as total impacts at the national level.

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[3] The notion of direct (and by extension indirect and induced) impacts in this application does not map directly to the existing literature, due to the nature of disruption, where all industries are shut down in a region. Therefore, the impacts in the directly affected area that would have been indirect if only one industry were shut down, are treated as direct given that all industries are shut down. This is the reason for using the net value-added multipliers. The estimation of the value-added multipliers is described in section 2.4.1 of this report.

[4] For example, employers may lay off workers to reduce their realized losses and that in turn creates an induced loss from the reduced spending of their employees. The range of possible losses is estimated using Type I and Type II multipliers to calculate the direct, indirect, and induced components and thereby establish bounds for the likely total loss.

The spatial extent of disruption is represented in the model by two regions: "Intraregional" – the area directly affected by contamination to the extent that land is interdicted[5], and "Extra regional" – the area not affected by contamination, representing the rest of the nation (excluding Alaska and Hawaii). The intraregional/affected region is the region reporting the direct losses. All the intraregional losses are treated as direct even though some of the losses are to suppliers to other economic sectors. Intraregional and extra regional losses sum to the national value, where national refers to the 48 contiguous states.

The indirect and induced losses are assigned to the extra-regional losses (because all the intraregional losses are considered direct). In this treatment of direct, indirect, and induced losses, the model departs from the conventional RIMS II treatment of a single industry disruption and instead represents a multi-industry disruption over a region.

1.3. High-Level Comparison

The RDEIM model couples with MACCS to estimate the direct, indirect, induced, and total GDP impact of a nuclear power plant accident. Many of the losses are calculated using the same approach as in the original, cost-based model. Table 1 compares the losses that are calculated with the two economic models.

Table 1. Comparison of the Losses Considered when Using the Cost-Based and GDP-Based (RDEIM) Economic Consequence Models.

Components of Cost-Based Model	Components when using RDEIM Model
Evacuation/relocation costs	Evacuation/relocation costs
Long-term relocation	Long-term relocation
Decontamination costs	Decontamination costs
Expected return on investment	GDP losses, including direct, indirect, and induced
Depreciation on property improvements	Depreciation on property improvements
Value of condemned property	Value of condemned property
Milk and nonmilk crop disposal costs	

Economic losses for evacuation/relocation, long-term relocation, decontamination costs, depreciation on property improvements, and condemned property are calculated the same way for both models. GDP losses replace expected return on investment in the original, cost-based model.

The cost-based model includes milk and crop disposal costs, which represent the farming losses for the current growing season. When an accident occurs but farmers have not yet brought their crops from the current growing season to market, the economic losses to farmers extends back before the accident to the start of the growing season. This loss is not currently accounted for in the GDP-based model.

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[5] The actual size of the directly affected region may change over time because of restoration. However, as the size of the directly affected area shrinks due to recovery, the multipliers remain the same. While the multipliers would change with the size of the directly affected area, the authors believe this is a second order effect that does not warrant being included in the analysis. This analysis does not support multiple areas where industry recovery proceeds at a different pace. It is also assumed that for any shape of the affected area there is a single set of multipliers that describe the indirect and induced effects for such an area. In a case of two non-contiguous areas such two areas may need to be treated separately, each with its own set of multipliers. Alternatively, additional analysis may be needed to find out if such areas can be adequately described by a single set of multipliers.

1.4. External Peer Review

During 2015, Sandia National Laboratories (SNL) organized an external peer review of the GDP-based economic model as implemented in MACCS. The objective of the peer review effort was to have independent external economists familiar with disaster/disruption modeling review the approach, underlying assumptions, and economic algorithms in the MACCS GDP-based economic model to ensure they are defensible and represent the state-of-practice in economic disruption modeling.

The peer review committee consisted of Neil Higgins, Jeff Werling, and Haydar Kurban who were selected for their expertise and experience in the field of disaster/disruption economics. Neil Higgins was chosen for the panel because he had experience developing a similar economic model used in the UK called COCO-2 for estimating economic consequences of nuclear power plant accidents. At the time, Jeff Werling and Haydar Kurban were university professors in economics at the University of Maryland and Howard University, respectively, with specific knowledge and experience in areas analogous to the new modeling capability in MACCS.

The peer review committee convened for several in-person and remote meetings. The regulatory use of MACCS for estimating economic consequences, an overview of the GDP-based economic model, a detailed description of the theory and implementation of the GDP-based model, and an initial verification and assessment of the model implemented in MACCS were presented to the peer review panel by staff at the NRC and SNL at the kickoff meeting on April 21, 2015. The kickoff meeting generated several questions and comments, and those were discussed on a conference call on June 8, 2015. A final meeting to resolve peer review comments was held on August 11-12, 2015. On February 17, 2016, the peer review committee wrote a letter stating their acceptance of the GDP-based model implemented in MACCS as state-of-practice, subject to completion of the implementation of their recommendations. These recommendations concerned many areas including the use of RIMS II multipliers, the different durations of disaster impacts on regional vs. national scales, areas of potential double-counting of impacts, wealth effects, and the values of real GDP growth rate and social discount rate. At the time of that letter, most of the peer review panel recommendations had been implemented, but some were in progress. All the recommendations requested by the peer review panel are implemented with the RDEIM GDP-based model in WinMACCS 4.0.0 and MACCS 4.0.0.0.

1.5. Economic Model Limitations

MACCS is intended to be an offsite consequence analysis code. As a result, onsite losses like property damage, decontamination and interdiction costs, cost of replacement power, and costs associated with radiation exposure to onsite decontamination workers are not included in the cost accounting. Several offsite costs associated with radiation exposure are not part of the cost accounting and those include the costs related to medical treatments, life shortening, and psychological impacts. However, costs associated with offsite radiation exposure are commonly estimated simplistically by multiplying the population dose calculated by MACCS, which includes the dose to offsite decontamination workers, and a cost per person-rem. Finally, other costs not included are potential losses associated with the effect of stigma on tourism and other industries, potential shutdown of other nuclear power plants (like in Japan following the Fukushima accident), and litigation. This list is not intended to be exclusive; there may be other cost categories not included in the MACCS model. None of the costs mentioned in this paragraph are included with either the original cost-based or the GDP-based model. The specific cost categories that are included in the models are described in Sections 1.1 and 1.2.

SecPop is often used to create site files that define the population and property values within the 48 contiguous United States. By default, no populations or economic values are assigned to land external to the 48 states, including Canada, Mexico, or the Bahamas and Caribbean Islands. These values can be added by manually editing the site file, but by default, losses associated with these lands are not accounted for in either economic model. Furthermore, losses associated with federal lands that do not have much economic activity or commercial value, like national parks and forests, may be under-evaluated with both economic models. Finally, no economic losses are directly attributed to estuaries, rivers, lakes, and other fresh- and saltwater bodies onto which radioactive material is calculated to deposit.

For parts of the globe other than the 48 contiguous states of the U.S., site files must be created manually or by utilities created for specific countries or regions. Thus, in principle, economic losses for all parts of the globe can be included in a calculation with some effort on the part of the user.

2. COST-BASED ECONOMIC IMPACT MODEL

The MACCS cost-based economic model calculates offsite losses based on the cost of emergency, intermediate, and long-term actions. The CHRONC module in MACCS calculates the economic costs of the intermediate and long-term protective actions as well as those of the emergency response actions. Nearly all parameters for these calculations are user-inputs without defaults.

In addition to specifying the parameters of the model, the user has control over the output and must explicitly specify which results are to be produced. All this information is supplied through the input file. This model estimates the economic losses based on the following cost categories:

- Evacuation and relocation costs on a per diem basis during emergency and intermediate phases.
- Long-term relocation costs during the long-term phase, which is a one-time expense.
- Decontamination costs during long-term phase.
- Loss-of-use costs for farmland and non-farmland, including expected return on investment (property value). Loss-of-use costs are based on the entire time from the beginning of release until property is restored and made usable.
- Depreciation on property improvements. Depreciation costs are based on the entire time from the beginning of release until property is restored and made usable.
- The value of condemned property. When property is condemned, no losses are tallied for decontamination, loss-of-use, or depreciation.
- Disposal of contaminated crop and dairy products during the year of the accident.

Within the cost-based model, costs can be broken into three phases that have their origin in the Environmental Protection Agency (EPA) Protective Action Guides (PAGs): early (emergency), intermediate, and long-term. The early phase lasts from 1 to 40 days following the start of radionuclide release. During this phase, costs are incurred for evacuation and relocation, expected return on investment, and depreciation. The intermediate phase lasts from 0 days to 30 years after the completion of the emergency phase. The intermediate phase is commonly modeled in MACCS to last one year. Costs are incurred for relocation, expected return on investment, and depreciation during this phase. The long-term phase of an accident can last up to more than 300 years from the completion of the intermediate phase, but more typically it is chosen to be 50 years. During this phase, costs are incurred for one-time relocation, decontamination, expected return on investment, depreciation, condemnation of property, and disposal of contaminated crops and dairy products.

The offsite cost of the accident (C_{tot}) calculated by MACCS can be expressed with the following equation:

$$\boldsymbol{C_{tot} = C_{epa} + C_{ipa} + C_{ltpa}} \quad (1)$$

Where:

$\boldsymbol{C_{epa}}$: Cost of early-phase protective actions

$\boldsymbol{C_{ipa}}$: Cost of intermediate-phase protective actions

$\boldsymbol{C_{ltpa}}$: Cost of long-term-phase protective actions

These constituent costs are described in the following sections.

2.1. Early-Phase Cost (Emergency Response)

The emergency-response user-inputs define the compensation costs for people who are subject to the emergency actions of evacuation and relocation. Relocation of individuals can occur during all three phases, although it is treated differently in the long-term phase. The early-phase evacuation and relocation costs (C_{epa}) of the accident can be expressed in the following manner:

$$\boldsymbol{C_{epa} = n_e \times \Delta t_e \times C_e} \quad (2)$$

Where:

$\boldsymbol{n_e}$: Number of early phase individuals involved (persons)
$\boldsymbol{\Delta t_e}$: Duration of early phase action (days)
$\boldsymbol{C_e}$: Per diem cost during emergency phase ($/person-day)

In the presentation of economic cost results, the costs associated with the emergency phase (i.e., evacuation and short-term relocation) are reported separately from the costs associated with the intermediate phase (i.e., per-diem costs for relocation for the duration of the intermediate phase).

2.2. Intermediate-Phase Cost

When intermediate-phase exposures to members of the population in contaminated areas leads to doses more than a user-defined relocation criterion, the population is assumed to be relocated to uncontaminated areas for the entire intermediate phase, with a corresponding per-diem economic cost defined by the user. For this calculation, the decision to relocate is based on radiation exposure from groundshine and resuspension inhalation for a user defined dose-projection period. The intermediate phase costs (C_{ipa}) of the accident are expressed in the following manner:

$$\boldsymbol{C_{ipa} = n_i \times \Delta t_i \times C_i} \quad (3)$$

Where:

$\boldsymbol{n_i}$: Number of intermediate phase individuals involved (persons)
$\boldsymbol{\Delta t_i}$: Duration of intermediate phase action (days)
$\boldsymbol{C_i}$: Per diem cost during intermediate phase ($/person-day)

The form of the equation in the early and intermediate phase cost calculations is the same. The total cost of each of these phases is the product of the number of involved persons, the duration of the relocation or evacuation, and the associated per diem cost. These equations differ from the one used to estimate loss-of-use costs, which is described below.

2.3. Long-Term Phase Cost

In contrast to the early and intermediate phase costs, which are based on per diem, the long-term phase costs account for a one-time relocation cost, loss of property use, and depreciation (for all three phases), decontamination, and permanent interdiction (condemnation) of land. Decisions on mitigative actions in the long-term phase are based on two sets of independent actions: (1) decisions relating to whether land at a specific location and time is suitable for human habitation, or is habitable, and (2) decisions relating to whether land at a specific location and time is suitable for agricultural production, or is farmable.

The long-term phase distinguishes between the agricultural (farm) and non-agricultural (non-farm) land. Habitability decision making can result in four possible outcomes: (1) land is immediately habitable, (2) land becomes habitable after decontamination, (3) land becomes habitable after a combination of decontamination and additional interdiction, and (4) land cannot be restored to habitability within 8 years for farmland or 30 years for non-farmland. (The periods of 8 and 30 years are fixed in the MACCS cost-based economic model and are not user definable.)

The code evaluates potential mitigative actions for both farmland and non-farmland to determine if it is possible to satisfy the habitability criterion. If land cannot be restored to habitability after decontamination followed by the maximum-duration interdiction, then that land is permanently interdicted, or condemned. However, land is also condemned if the total cost involved in restoring it exceeds the user-specified value of the property. When land is condemned for either reason (i.e., the dose criteria cannot be satisfied or the cost of remediation exceeds the property value), the model calculates the corresponding long-term food and population exposures as zero and assesses an economic cost for the condemnation of the property.

Overall, long term costs (C_{ltpa}) are expressed as follows:

$$\boldsymbol{C_{ltpa} = (C_p \times n_{sp}) + (C_A \times A_{sp})} \tag{4}$$

Where:

- $\boldsymbol{C_p}$: Cost per person for long-term action for non-farm property
- $\boldsymbol{n_{sp}}$: Affected population
- $\boldsymbol{C_A}$: Cost per unit area for protective action for farmland
- $\boldsymbol{A_{sp}}$: Affected farmland area

The long-term protective action user-inputs define the intermediate and long-term action time periods as well as the maximum doses that people can receive during user-specified dose projection periods. The maximum allowable doses are used to determine the need for relocation, decontamination, interdiction, or condemnation.

The long-term costs for non-farm property (C_p) can be expressed after breaking them into their constituent costs:

$$\boldsymbol{C_p = C_d + C_f + C_l + C_{dp}} \tag{5}$$

Where:

- $\boldsymbol{C_d}$: Cost per person for decontamination
- $\boldsymbol{C_f}$: Cost per person for relocation
- $\boldsymbol{C_l}$: Cost per person for loss of property usage
- $\boldsymbol{C_{dp}}$: Cost per person for depreciation loss

The decontamination user inputs are based on a set of decontamination actions that may be taken during the long-term period to reduce doses to acceptable levels. These data define the decontamination effectiveness and cost. Each decontamination level represents an alternative strategy that would reduce the projected long-term groundshine and resuspension doses by a factor called the "dose reduction factor." Up to three levels of decontamination can be defined.

The objective of decontamination is to reduce projected doses below the long-term dose criterion in a cost-effective manner. If the maximum decontamination level is insufficient to restore an area to immediate habitability, a period of temporary interdiction following the maximum decontamination level is considered to allow for dose reduction through radioactive decay and weathering. If the property cannot be made habitable within 30 years or if the cost of reclaiming the habitability of the property exceeds the cost of condemning it, the property is condemned and permanently withdrawn from use.

Decontamination costs are divided into two land-usage categories and these are calculated separately. Within a single grid element, farmland decontamination cost is a function of the area of a grid element devoted to agriculture. Population-dependent decontamination represents the cost of non-farmland decontamination and is a function of the population residing in a grid element. The strategy of decontamination within a grid element is independent of the type of area being decontaminated. For a given decontamination level, the same decontamination time and effectiveness apply to both farmland and non-farmland, but the two costs are estimated separately. Owing to the requirement that the remediation of property must be cost-effective to be performed, it is possible in a grid element that decontamination of non-farmland is performed, but farmland is instead condemned. It is also possible, but unlikely, for farmland to be decontaminated but non-farmland to be condemned.

During the decontamination period, which begins at the start of the long-term phase, the populations in areas that are to be decontaminated are assumed to be relocated to uncontaminated areas, and the associated cost from loss of property use is calculated in the same manner as temporary interdiction. The long-term costs from loss-of-use and depreciation are expressed by the following equations:

$$\boldsymbol{C_l = V_w \times [1 - \exp(-r_{ir} \times \Delta t)]} \tag{6}$$

$$\boldsymbol{C_{dp} = V_w \times F_{im} \times \exp(-r_{ir} \times \Delta t) \times \left[1 - \exp\left(-r_{dp} \times \Delta t\right)\right]} \tag{7}$$

Where:

- $\boldsymbol{V_w}$: Per person value of non-farm property or per area value of farm property, including land, buildings, infrastructure, and non-recoverable equipment and machinery
- $\boldsymbol{F_{im}}$: Fraction of property value resulting from improvements
- $\boldsymbol{r_{ir}}$: Inflation adjusted rate-of-return on investment, also used as a discount rate to adjust future values to current
- $\boldsymbol{r_{dp}}$: Depreciation rate
- $\boldsymbol{\Delta t}$: Duration of interdiction

The above equations limit the combined losses from interdiction of property to be the original value of the property. Splitting the overall property loss into loss-of-use and depreciation is currently chosen in a way that ultimately (after a long time) assigns all losses to be from loss-of-use. Depreciation loss, on the other hand, increases for a time then gradually approaches zero as more of the losses are assigned as loss-of-use. This choice is somewhat arbitrary.

An alternative approach is to let both losses approach the value of property improvements after a long time. Because of the overarching philosophy of minimizing losses in the MACCS model, this alternative approach would lead to condemnation of more property, as elucidated in the remedial-action decision process discussed below.

MACCS generally allows most of the model parameters to be user defined and, as mentioned above, most of the parameters in the cost-based economic model are user defined. A NUREG/CR report titled "Technical Bases for Consequence Analyses Using MACCS (MELCOR Accident Consequence Code System)" that is soon to be published provides guidance on selecting the input parameters for the cost-based economic loss model; it does not provide guidance for the parameters that are unique to the GDP-based model because it is based on version 3.10 of MACCS that did not support this model.

While this economic model considers depreciation, loss of use, decontamination, and relocation costs, it does not include any onsite costs and it does not include several offsite costs. Onsite costs that are often calculated but not included in the economic model are the cost due to damage to the reactor and site itself, replacement power, remediation costs, and costs related to decontamination worker doses. Offsite costs not included are losses from medical and life-shortening (often estimated in a simple fashion based on population dose), psychological, litigation, stigma (lost tourism and trade), and the effect on the commercial nuclear power industry.

The following figures show the logic diagram of the decision processes that determine whether land is decontaminated, interdicted, or condemned. Figure 1 is for non-farmland; Figure 2 is for farmland.

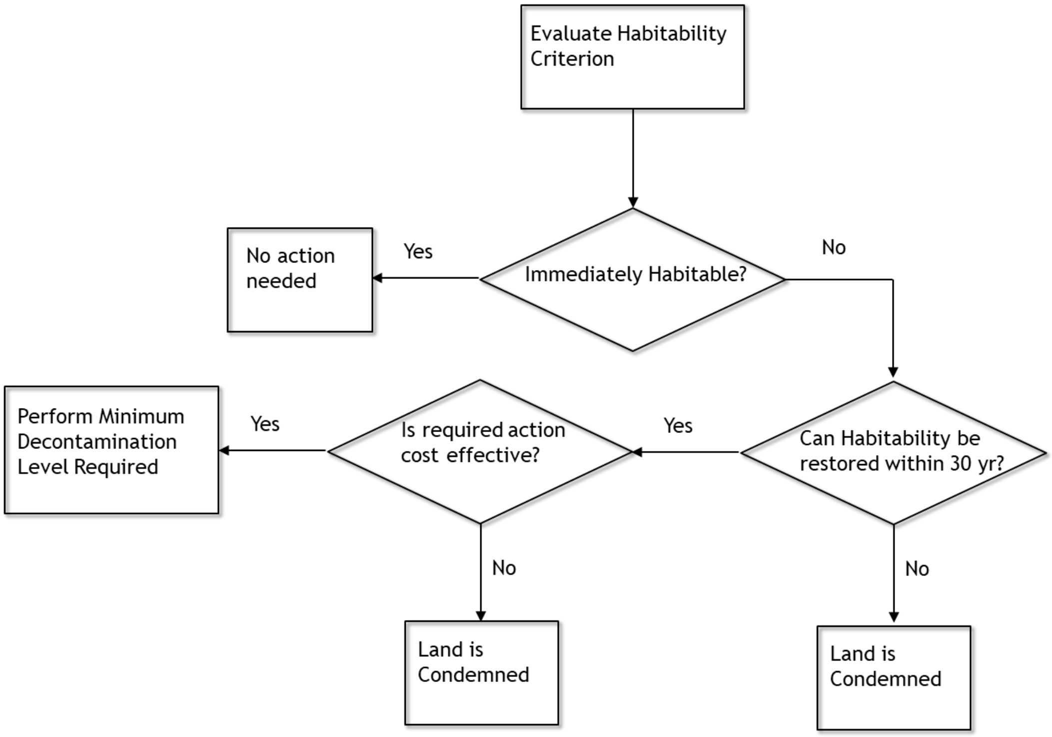

Figure 1. Logic diagram for determining the remedial action to apply to non-farmland.

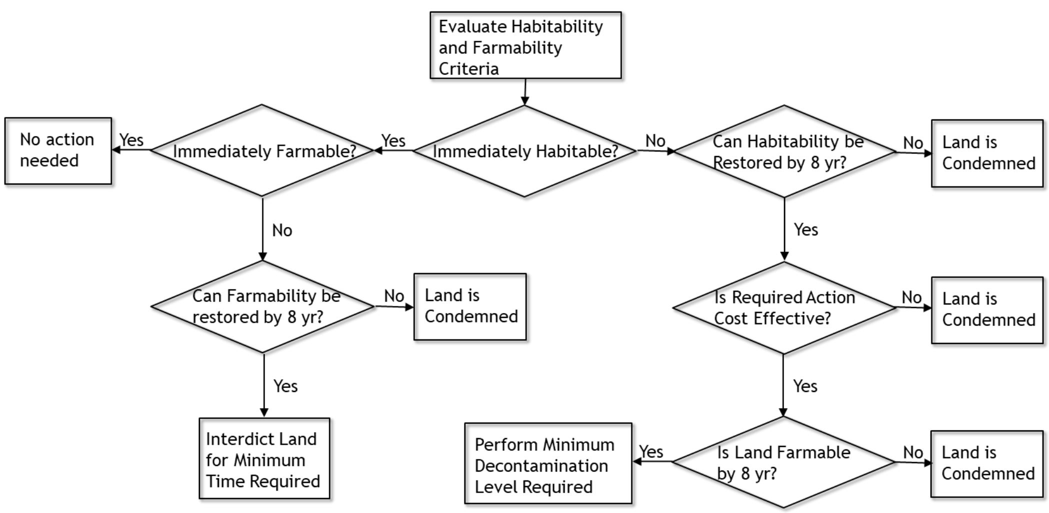

Figure 2. Logic diagram for determining the remedial action to apply to farmland.

The decision on cost effectiveness of performing an action is controlled by the following inequality. When the inequality is satisfied, decontamination is performed. The terms on the left side of the inequality are the per-person costs that are incurred when decontamination is performed; the terms on the right side of the inequality are the per-person costs that are incurred when property is condemned. Notice that $\boldsymbol{C_f}$ appears on both sides of the equation and could be subtracted.

$$C_d + C_f + C_l + C_{dp} < V_w + C_f \quad (8)$$

2.4. Cost Model Outputs

The economic costs output by the cost model include all the intermediate and long-term protective actions as well as the cost of the emergency response actions that were modeled for the early phase of the accident. Each request for economic results produces the block of 13 economic results described below. All the economic cost measures are reported in dollars.

1. *Total economic costs*—the sum of population- and farm-dependent costs
2. *Population dependent costs*—the sum of population-dependent decontamination, interdiction, and condemnation costs
3. *Farm-dependent costs*—the sum of farm-dependent decontamination, interdiction, and condemnation costs as well as milk and crop disposal costs
4. *Population dependent decontamination cost*—non-farm property (i.e., property associated with resident population) decontamination cost
5. *Farm-dependent decontamination cost*—farm property decontamination cost
6. *Population dependent interdiction cost*—depreciation and deterioration of non-farm property during the period it cannot be used during both decontamination and interdiction plus the cost of population removal
7. *Farm-dependent interdiction cost*—depreciation and deterioration of farm property during the period it cannot be used during both decontamination and interdiction
8. *Population dependent condemnation cost*—compensation paid for permanent loss of non-farm property plus the cost of population removal
9. *Farm-dependent condemnation cost*—compensation paid for permanent loss of farm property because it could not be returned to production within 8 years of the accident
10. *Emergency phase costs*—per-diem costs to compensate people for being away from home due to evacuation and relocation during the emergency phase
11. *Intermediate phase costs*—per-diem costs to compensate people for being away from home due to relocation for the duration of the intermediate phase if dose criterion exceeded
12. *Milk disposal costs*—compensation for a quarter of a year of lost milk and dairy sales if the current growing season requires milk disposal (original MACCS food model) or if first-year farming is restricted (COMIDA2 food model).
13. *Crop disposal costs*—compensation for one year of lost nonmilk crop sales if the current growing season requires nonmilk crop disposal (original MACCS food model) or if first-year farming is restricted (COMIDA2 food model).

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3. DESCRIPTION OF RDEIM MACROECONOMIC IMPACT MODEL

The GDP losses are estimated as the difference between a baseline scenario and a disruption scenario. For direct GDP, the loss is simply the GDP that would have been produced in the area if it were open for business. The direct GDP loss is represented by assuming the affected area is shut down for a specified period, and the GDP from the affected area is lost. Calculation of indirect and induced losses are described later in this section.

The potential increases in economic activity and GDP due to reconstruction, as observed after hurricanes, are not addressed in this model. Such gains are generally local and use resources transferred from elsewhere and thus do not represent actual gains at the level of the entire economy. Similar effects may also be experienced in neighboring areas that experience an influx of people and money due to the accident and subsequent population migration and reconstruction.

One of the principal differences of a radiological release compared with other hazards is the possibility that the contaminated area may be interdicted for a long period of time or even condemned. Recovery may never occur in such areas but should ultimately occur in areas unaffected by the accident. The affected population is assumed to move at least temporarily. Some may need to find new jobs, start new businesses, or otherwise relocate. There is little relevant historic precedent specific to nuclear power plant accidents to support estimating how long this process would take. Here, we assume that after some period, the overall economy can recover to its baseline trajectory, as illustrated in the Figure 3. The duration of recovery is calculated within MACCS but is subject to a user-defined parameter representing the Maximum Duration of the Regional Economic Impact. A separate parameter is used to define the duration of recovery at the national scale. Generally, national recovery is presumed to occur faster than regional recovery. The figure shows nominal GDP, which is unadjusted for inflation.

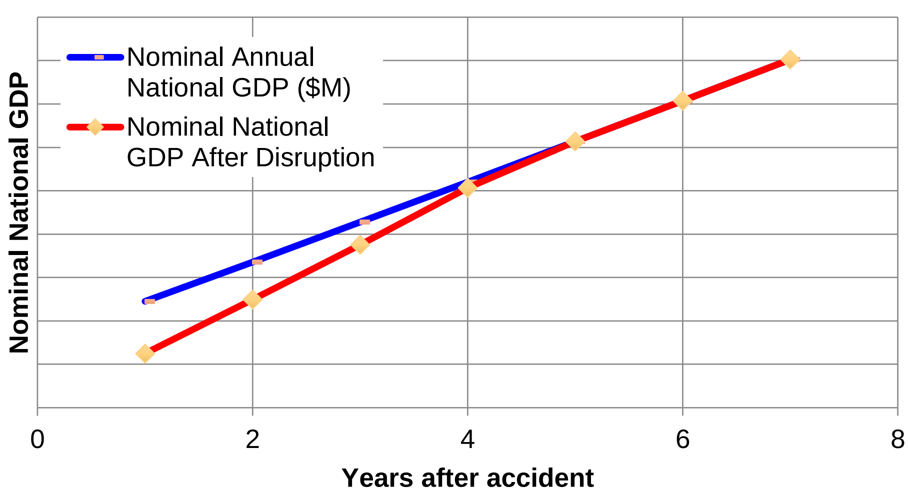

Figure 3. Nominal GDP recovery at the national scale assuming the GDP growth rate is higher than the social discount rate. Here the national GDP fully recovers to its pre-accident trajectory at the beginning of the 5th year after the accident.

3.1. Impact Estimation

RDEIM uses lost GDP to represent the macroeconomic impacts of a nuclear accident, where GDP is defined as the value of all final goods and services produced within the 48 contiguous states over a given period. The underlying assumption behind excluding Alaska and Hawaii from the national economy is that the inter-industry commodity flows from these states to the continental U.S. is negligible. Annual GDP is normally reported in nominal terms or in real, inflation-adjusted terms. The latter provides an estimate in the volume of goods and services produced, and its growth rate is the most common measure for trend growth and economic performance for a country or region.

Weather trials are generated to represent possible wind, precipitation, and other weather-related variabilities. Each weather trial produces an affected area corresponding to a land contamination footprint. Economic impacts are estimated for each weather trial for the affected area and statistics are generated for the set of weather trials.

The following describes the impact estimation for a single weather trial. The impacts are calculated on the level of individual affected counties or portions of those counties[6]. Collections of complete and partial counties correspond to disrupted areas. In the context of the code framework, an impacted region corresponds to one or more grid elements. A grid element is a portion of the overall problem domain and could represent anything from a small fraction of a single county to a large collection of counties and partial counties. MACCS determines for each grid element whether interdiction is needed and when the grid element recovers.

The affected area is represented as a set of grid elements $R = \{1, 2, \dots, n\}$ and a set of the industries as $I = \{1, 2, \dots, k\}$. It is assumed that all industries in a grid element, $r \in R$, are shut down for a period, $T_r < T_R$, where both quantities are measured in years, and T_R is the maximum duration of regional disruption, which is a user input parameter in MACCS. If $T_r > T_R$, economic losses beyond time T_R are not evaluated. The period, T_r, that the grid element is disrupted may differ across grid elements, depending on the level of contamination and the time it takes to restore it to use.

The following notation is used in the subsequent discussion and equations:

- i, j: industry indices
- V_i: annual value added for industry i
- ΔV_i: the direct value-added change in industry i
- $\Delta V_{i,r}$: the direct value-added change in industry i in the grid element *r*
- ΔV^D, ΔV^T, ΔV^{D+I}, ΔV^P: GDP (value-added) losses, with indices *D*, *T, D+I, and P* denoting the direct, total, direct plus indirect, and induced losses, respectively
- $b_{i,j}$: elements of the National Industry-by-Industry Total Requirements (TRII) Table
- v_i: average value added per worker for industry *i*
- Y_i: annual national gross output for industry i
- E_i: national employment for industry i
- g: expected real *GDP* growth rate

[6] Incomplete counties arise because contamination areas do not generally correspond with the county boundaries. The relative importance of partial counties diminishes with the size of the affected area.

ρ: social discount rate

t: Gregorian calendar time, expressed as a real number in units of years, so one day is 1/365.25, accounting for leap year.

t_0: database year. This is the year for which the economic data, such as value added, gross output, and employment, were collected.

t_I: accident year (starting time of accident year)

${m_i}^k$: net total requirements multiplier of Type k, where k can be I or II

${\widetilde{m}_i}^k$: final demand value-added multiplier of Type k, where k can be I or II

${m_i}^{k,N}$: gross national total requirements multiplier of Type k, where k can be I or II

${m_i}^{k,R}$: regional total requirements multiplier of Type k, where k can be I or II

${m'_i}^{k,R}$: net total requirements multiplier of Type k adjusted to account for a region where some of the suppliers for industry i are located within the disrupted region. This attempts to eliminate double counting indirect losses that are also included as direct losses. The superscript k can either be I or II.

${\widetilde{m}'_i}^{k,R}$: final demand value-added multiplier of Type k adjusted to account for a region where some of the suppliers for industry i are located within the disrupted region. This attempts to eliminate double counting indirect losses that are also included as direct losses. The superscript k can either be I or II.

$s_r(t)$: disruption function representing the state of grid element *r*. This dimensionless parameter allows a faster decontamination and recovery schedule for certain grid elements than the maximum duration of impacts parameter. It equals 1 when the grid element is completely disrupted and 0 when the grid element has been restored[7].

$l_{i,r}$: number of industry *i* employees in grid element r

T: an arbitrary period over which losses are integrated

T_r: interdiction period for grid element r, with an upper bound of T_R.

T'_r: minimum value of T_r and T_N for a grid element.

T_R: maximum duration of economic loss calculation for directly affected area, R, which is comprised of the set of grid elements, r, that that require some period of interdiction.

T_N: maximum duration of economic loss calculation for indirectly affected area. The national economy is assumed to fully recover by T_N years.

A nuclear accident affects a region composed of one or more full or partial counties, resulting in a direct economic impact[8]. The average GDP per worker in industry i at time t_0 is estimated as follows:

$$\boldsymbol{\nu_i = \frac{V_i}{E_i}} \tag{9}$$

[7] The formulation allows intermediate values as well; however, this option is not implemented in MACCS for disruptions due to radioactive releases. When the grid element recovers, it is considered fully recovered.

[8] The direct and indirect losses in this model are defined differently than normal for those terms. Specifically, given that an entire area is shut down for a period, all the losses in the area are deemed direct. In the input-output terminology, the losses due to inter-industry linkages inside of the affected area could also be considered indirect. However, calculating both direct and indirect losses inside the affected area would introduce double counting. The section 2.4.2 of this report explains how such double counting was eliminated.

where, V_i and E_i are respectively national annual value added and employment for industry i at the database year (2011 currently).

The number of employees in a county for industry i is obtained from the County Business Patterns provided by the U.S. Census Bureau[9]. The current dataset is from 2011. For grid elements that represent a fraction of a county, the number of affected employees is estimated by multiplying the number of employees in the county by the value determined as a fraction of the land area or population affected, as described below.

In the case of a different starting year (accident year) than the year of the dataset, it is necessary to adapt the GDP from year t_0 (base year) to a GDP consistent with the accident year, t_I. This is accomplished by using an input GDP growth rate and calculating the accident year GDP as a function of the base year GDP assuming a constant growth rate. The concept of a social discount rate is also applied to discount values to the base year. The losses are adjusted for projected GDP growth in real terms between the last year of available data (the base year) and the accident year. This growth is reflected by the exponential term discussed below[10]. This allows for GDP calculations to be performed based on real GDP in years following the accident year. Losses are reported in base-year dollars but account for real GDP growth between the base year to each year in the period for the economic analysis. The model assumes all sectors of the economy grow at the same rate, i.e., there are no structural changes in the economy.

3.1.1. Input-Output Modeling Overview

To estimate the economy-wide GDP impacts of any given incident, a GDP-based accounting and modeling framework is needed. A widely used approach is I-O modeling, developed by Wassily Leontief in the 1930s (see Leontief, 1936, for the original treatment and Miller and Blair (2009) for the current state of the art).

Leontief's starting premise is that macroeconomic changes, such as the effect of wage changes on price levels, propagates via a "…complex series of transactions in which actual goods and services are exchanged among real people" (Leontief, 1936). His original motivation was to quantify the relationships between the economic agents and to show how these transactions add up to macro variables such as income, household consumption, international trade, and, ultimately, GDP. Leontief notes: "…the individual transactions, like individual atoms and molecules, are far too numerous for observation and description in detail. But it is possible, as with physical particles, to reduce them to some kind of order by classifying and aggregating them into groups. This is the procedure employed by I-O analysis in improving the grasp of economic theory upon the facts with which it is concerned in every real situation" (Leontief, 1986).

[9] https://www.census.gov/programs-surveys/cbp/data/tables.html

[10] In MACCS analyses, GDP losses generally need to be calculated for variable time periods. However, the data and input parameters used by RDEIM to calculate GDP losses are available only for a specific year, which is defined as the "base year." To address this, GDP is treated as a continuous variable to simplify the treatment of time periods of arbitrary duration and arbitrary accident start times. This produces results that are slightly different than an approach where GDP is treated as a discrete annualized variable. However, where GDP growth rates, social discount rates, and their differences are small, this difference is also small.

I-O modeling starts with empirical tables of final demand, industry income, and interindustry transactions.[11] These are organized to show the industry requirements for various commodity inputs and primary factors (value added) to produce those industries' gross output. Given that output of one industry is an input to another industry or to a final consumption, the same data therefore shows how the supply of various commodities is allocated across demands of industry and final consumers such as households, capital investment, government, and foreigners. Given the final demand and inter-industry flows described by the I-O tables, various matrix transformations can be used to estimate, for example, direct and indirect gross output, value added, and employment impacts of changes to final demand, prices, or technology.

The original I-O framework has undergone various modifications and enhancements, especially the development of I-O tables and models at the level of individual regions such as states and counties, representation on the level of individual commodities (commodity by industry), dynamic I-O analysis, and many others. Miller and Blair (2009) provide an extensive and comprehensive overview of the current state of I-O modeling and its history.

I-O modeling is consistent with double-entry bookkeeping and is an integral part of the System of National Accounts (SNA) data collections across the world. SNA aims to measure the key descriptors of macroeconomic activity and includes production, consumption, investment, savings, and other measures. This commonly accepted SNA framework is formalized in the United Nations publication, "The System of National Accounts 2008" (United Nations, 2009).

I-O modeling has many practical uses. Some of the first uses of I-O analysis were to plan domestic production during World War II. After the war, it was used for reconstruction efforts. Subsequently, I-O modeling has been applied to hundreds of uses, including disruption modeling, such as estimating the impacts of hurricanes, earthquakes, and radiological releases; analysis of effects of various policies; and others (Rose, 1995 and 2005).

Leontief (1986) reports that by 1985, there were I-O tables available for more than 80 countries. This number is likely significantly higher at present. The collection and compilation of I-O data is a fundamental activity underlying the development of national accounts as specified in United Nations SNA Publications.[12] Most recently, researchers have constructed a World I-O Database[13] that shows how economies and industries are integrated through production and trade.

The intent of the current model is to capture the loss of GDP, or value added, due to a disruption in the economy. It does not include GDP boosts that may result from mitigation, decontamination, evacuation, and other recovery activities, because of the opportunity costs those activities entail. The goal of the model is to provide information adequate for the purposes of the Probabilistic Risk Assessment (PRA)[14] analyses. The costs included in the model are summarized in the Table 2.

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[11] We informally define final demand as goods sales to final markets (personal consumption purchases, sales to federal and regional governments, investment and net exports), factor income as income to capital and labor, and interindustry flows as sales across different industries. The reader is referred to Miller and Blair (2009), as well as Raa (2005) for a more complete and precise definition.

[12] http://unstats.un.org/unsd/nationalaccount/pubsDB.asp?pType=4. Accessed 12/3/2015.

[13] http://www.voxeu.org/article/new-world-input-output-database. Accessed 6/5/2014.

[14] See http://www.nrc.gov/about-nrc/regulatory/risk-informed/pra.html for more information. Accessed 1/25/2016.

Computational general equilibrium (CGE) models allow evaluation of long-term economic change. However, CGE models require a significant amount of accident-specific input and therefore would place a high demand on the analyst to supply all the required input. Similarly, agent-based modeling that allows detailed representation at the causal level of the scenario-response and proactive planning are too fine-grained at the short time scale. As a result, RDEIM does not attempt to represent economic adaptation, but uses an estimated length of the economic recovery at the national level to estimate the magnitude of impacts.

An I-O based approach was considered during development of the original cost-based MACCS economic model, but was determined to not be practical at the time for the following reasons (Burke et al., 1984):

1. Costs involved in creating an I-O model and generating the GDP-based estimates
2. Non-equilibrium nature of the disruption

The first reason is no longer applicable because data and models are now readily available. The integrated application with the MACCS engine allows large numbers of simulations for different meteorological conditions with minimal computational effort.

The second reason is vague but does not appear to be a differentiating factor in the selection of a cost impact method. Neither the original cost-based model nor the I-O model explicitly treats non-equilibrium adaptation processes associated with severe nuclear accidents. Such non-equilibrium processes include adaptation to the disruption in areas that are not directly affected as well as structural changes to the economy at large. Such structural changes can be significant; for example, the shutting down of all nuclear power plants in Japan following the Fukushima nuclear accident. However, the model does include a user-defined maximum period over which the national economy returns to normal, and thereby implicitly accounts for adaptation in the economy.

The Office of Management and Budget (OMB) methodology is used as described in OMB Circular A-94[15] for evaluating the real present value of future GDP losses and for factoring in social discount rates, as described in sections 3.4.5 and 3.4.6.

3.1.2. Direct Economic Impact Estimates

Once the disruption scenario is specified, the RDEIM calculation of direct losses in a single year is the same for each grid element. MACCS scales losses appropriately to account for partial or multiple years, as described below.

For simplicity, the following description is for a single grid element, r. The rate of direct, value-added losses for industry i in grid element r at time t_I can be found by multiplying the per-employee value added by the number of affected employees and projecting the GDP to the year of the accident:

[15] https://www.whitehouse.gov/omb/circulars_a094/. Accessed 3/17/2015.

$$\frac{dV^D{}_{i,r}}{dt} = e^{g(t_I - t_0)} v_i l_{i,r} \tag{10}$$

where $v_i l_{i,r}$ denotes the value-added loss for industry i in grid element r per time. To calculate the cumulative scenario losses for industry i at grid element r starting from time t_I until time $t_I + T$, the above expression is integrated over time, considering the economic real GDP growth rate g, the social discount rate ρ, and that a specific grid element may recover sooner than T.

$$\Delta V^D{}_{i,r}(T) = e^{g(t_I - t_0)} v_i l_{i,r} \int_{t_I}^{t_I + T} s_r(t) e^{(g-\rho)(t - t_I)} dt \tag{11}$$

Here the disruption function, $s_r(t)$, reflects the decontamination schedule and is more precisely defined in the Equation (13). By redefining t as time relative to the start of the incident, the above equation can be further simplified as follows:

$$\Delta V^D{}_{i,r}(T) = e^{g(t_I - t_0)} v_i l_{i,r} \int_0^T s_r(t) e^{(g-\rho)t} dt \tag{12}$$

where the disruption function $s_r(t)$, takes the following form:

$$s_r = \begin{cases} 1, \mathrm{t} \le T_r \\ 0, t > T_r \end{cases} \tag{13}$$

where T_r is the recovery time for grid element r, with an upper bound of T_R.

In the special case of $g = \rho$ the part of Equation (12) under the integral is the number of years the grid element r is disrupted. In general, it can be interpreted as an exponentially discounted number of years a grid element has been disrupted. It is therefore clear that the Equation (12) can be interpreted as the multiplication of the annual value added per grid element and industry by the effective number of years that industry was disrupted.

By introducing $S_r(t) = \int_0^T s_r(t) e^{(g-\rho)t} dt$, Equation (12) can be re-written as follows:

$$\Delta V^D{}_{i,r}(T) = e^{g(t_I - t_0)} v_i l_{i,r} S_r(T) \tag{14}$$

The direct losses for the entire affected area, R, and for all industries, I, are found by summing over all industries and grid elements in the affected area:

$$\Delta V^D(T) = e^{g(t_I - t_0)} \sum_I v_i \sum_R l_{i,r} S_r(T) \tag{15}$$

The above equations involving integrals could be expressed as sums over years and the results would be the same provided that all losses are for complete years. The integral equations allow for partial years and so they provide more generality. The implementation of this economic model in MACCS uses the integral formulation expressed in the preceding equations and allows for partial years of GDP losses.

3.1.3. Total, Indirect, and Induced Losses

The total, indirect, and induced losses are calculated using the net total requirements multipliers. The net total requirements multipliers can be of Type I or Type II, representing either direct plus indirect or direct, indirect, and induced losses, respectively. This usage is analogous to the BEA Type I and Type II multipliers (BEA, 2012). The net total requirements multipliers are calculated as national and regional (as in the directly affected region) multipliers. The differences between net total requirements and value-added multipliers are two-fold: 1) net total requirements multipliers attempt to eliminate the double counting of losses[16], and 2) adjust for the fact that direct losses are calculated as value added, not final demand losses. The motivation and methodology for calculating the net total requirements multipliers is described in section 3.4.1.

The total impact includes direct, indirect, and induced losses, and can be calculated with the following equation:

$$\boldsymbol{\Delta V^{T}(T) = e^{g(t_I - t_0)} \sum_I v_i m^{II}{}_i \sum_R l_{i,r} \int_0^T s_r(t) s_N(t) e^{(g-\rho)t} dt} \qquad (16)$$

where the time-dependent parameter $s_N(t)$ reflects the national recovery progress, which is typically faster than regional recovery, and is expressed as follows:

$$\boldsymbol{s_N = \begin{cases} 1 - \frac{t}{T_N}, & t \leq T_N \\ 0, & t > T_N \end{cases}} \qquad (17)$$

Equation (15) and subsequent equations in this section are written with national level net total requirements multipliers, but they are more generally applicable. The implemented framework, as discussed subsequently, uses final demand value-added multipliers that are adjusted for the size and industrial composition of the affected area. Equation (16) and similar equations below are also applicable with final demand value-added multipliers. For example, $m^{II}{}_i$ in Equation (16) can be replaced by $\widetilde{m'}_i^{II,R}$, as discussed below.

By substituting Type I multipliers for Type II multipliers in equation (16), induced effects are excluded and the expression yields the combined direct plus indirect losses, as expressed in Equation (18), where $m^I{}_i$ is the Type I multiplier for industry $\boldsymbol{i}$.

$$\boldsymbol{\Delta V^{D+I}(T) = e^{g(t_I - t_0)} \sum_I v_i m^{I}{}_i \sum_R l_{i,r} \int_0^T s_r(t) s_N(t) e^{(g-\rho)t} dt} \qquad (18)$$

The difference between the results from Equations (16) and (18) provides the cumulative induced losses. The cumulative direct losses are given by Equation (15). The indirect losses are represented by the difference between Equations (18) and (15).

[16] This double counting arises because in a scenario when all industries in an area are shut down, some of the indirect impacts would also be direct, given that regional industries use each other's production in part.

Only offsite economic impacts are evaluated by MACCS. These are cost impacts that occur beyond the site boundary of the affected nuclear power plant. To exclude the onsite losses incurred by the nuclear power plant, GDP losses for the Nuclear Electric Power Generation industry (North American Industry Classification System (NAICS) 221113) should in principle be subtracted from the direct losses for the Utilities industry. This can be equivalently represented in Equations (15), (16), and (18) by adjusting the employment for the Utilities industry in grid element r as follows:

$$\boldsymbol{l_{Utilities,r} -> max(l_{Utilities,r} - l_{NP,r}, 0)} \tag{19}$$

where $l_{NP,r}$ is the employment of the affected nuclear power plant facility. The "max" in the Equation (19) is needed to avoid the possibility of inferring a negative number of employees affected due to exact employment data not being available[17]. MACCS does not currently have an option for subtracting utility workers at nuclear plant sites, so it is possible that the GDP-based model might include some on-site losses, although this should be a small fraction of the overall losses in most cases.

It is believed that static I-O models tend to over-estimate the economic impacts (see Okuyama et al., 2004) because such models do not represent certain processes that enable economic adaptations and impact reductions, including product substitutions and price changes in response to shortages or to demand increases.

Time-dependent factors in Equations (16) and (18) allow different speeds for regional and national recovery. The speed of the regional recovery is represented to a degree by the parameter T_R (the maximum time for the directly affected region to recover) and the speed of the national recovery is reflected in the functional dependency of $s_N(t)$ with respect to time, which in turn depends on T_N. Zeroing national losses after period T_N that is shorter than T_R allows national recovery to be faster than regional recovery and alleviates the over-estimation associated with the static nature of I-O models.

3.2. Analytic Expressions for Impact Estimates

Given the relatively simple functional dependence of the regional and national recovery schedules versus time, the integrals in the equations for different losses can be evaluated analytically, therefore only leaving a summation over different grid elements and industries. This allows explicit analytical understanding of the dependencies on the parameters. The direct losses can be calculated as follows:

1) $\boldsymbol{g \neq \rho}$

$$\boldsymbol{\Delta V^D(T) = e^{g(t_I - t_0)} \sum_I v_i \sum_R l_{i,r} \frac{e^{(g-\rho)T_r} - 1}{g - \rho}} \tag{20}$$

2) $\boldsymbol{g = \rho}$

$$\boldsymbol{\Delta V^D(t) = e^{g(t_I - t_0)} \sum_I v_i \sum_R l_{i,r} T_r} \tag{21}$$

[17] Employment data at a county level are available from the County Business Patterns data provided by the US Census Bureau. The county level employment data are generally provided as a range for a particular industry if there is only a single business within that industry for the county. This is done intentionally to protect private information. It is possible the power plant data are only available as a range, rather than an exact number, because most nuclear power plant sites are owned by a single utility company.

where T_r is actual recovery time for the grid element r bounded by the parameter T_R, the maximum duration of regional disruption. The total impacts at the national level from Equation (16) can be expressed as follows:

1) $g \neq \rho$

$$\boldsymbol{\Delta V^T(T_N) = e^{g(t_I - t_0)} \sum_I v_i m^{II}{}_i \sum_R l_{i,r} \left[\frac{e^{(g-\rho)T'_r} - 1}{(g-\rho)} - \frac{((g-\rho)T_r{}' - 1)e^{(g-\rho)T'_r} + 1}{T_N (g-\rho)^2}\right]} \quad (22)$$

2) $g = \rho$

$$\boldsymbol{\Delta V^T(T_N) = e^{g(t_I - t_0)} \sum_I v_i m^{II}{}_i \sum_R l_{i,r} T'_r \left[1 - \frac{T'_r}{2T_N}\right]} \quad (23)$$

where $T_r{}' = \min(T_r, T_N)$. ΔV^T does not continue to increase for $T > T_N$ because the national economy has fully recovered at time T_N. The two parts of the last term in the Equations (22) and (23) have the following interpretations: the first term inside the brackets reflects the cumulative losses as though the losses did not diminish over the recovery period and the second term accounts for the linear reduction of the losses over the recovery period.

The cumulative direct plus indirect losses at the national level, denoted ΔV^{D+I}, are expressed by the same equations as the Equations (22) and (23) by replacing the Type II multipliers with the Type I multipliers:

1) $g \neq \rho$

$$\boldsymbol{\Delta V^{D+I}(T) = e^{g(t_I - t_0)} \sum_I v_i m^I{}_i \sum_R l_{i,r} \left[\frac{(e^{(g-\rho)T'_r} - 1)}{(g-\rho)} - \frac{((g-\rho)T_r{}' - 1)e^{(g-\rho)T'_r} + 1}{T_N (g-\rho)^2}\right]} \quad (24)$$

2) $g = \rho$

$$\boldsymbol{\Delta V^{D+I}(T) = e^{g(t_I - t_0)} \sum_I v_i m^I{}_i \sum_R l_{i,r} T'_r \left[1 - \frac{T'_r}{2T_N}\right]} \quad (25)$$

The induced effects, $\Delta V^P(T)$, are expressed as follows:

$$\boldsymbol{\Delta V^P(T) = \Delta V^T(T) - \Delta V^{D+I}(T)} \quad (26)$$

Similarly, indirect losses, $\Delta V^I(T)$, are expressed as follows:

$$\boldsymbol{\Delta V^I(T) = \Delta V^{D+I}(T) - \Delta V^D(T)} \quad (27)$$

3.3. Other Losses

The implementation of the RDEIM model accounts for one type of loss. Table 2 shows GDP losses from RDEIM as well as other types of losses, including tangible wealth. This includes loss of tangible assets (e.g., depreciation) and accident expenditures (e.g., decontamination). On the one hand, accounting for losses in both tangible wealth and GDP can double count overall losses, given that many assets such as factories or machinery exist specifically to create profit and, by extension, to generate GDP. On the other hand, not accounting for losses in tangible wealth could lead to undercounting these losses. The philosophy used to develop this model, motivated by an external peer review, is that it is better to include some degree of double counting rather than to undercount the losses. Therefore, losses of tangible wealth are reported in addition to the GDP losses and decontamination costs, as described below.

The original economic model in MACCS, the cost-based model, uses estimated per-capita property values for each county in the USA to determine losses when property is condemned or temporarily interdicted. The per capita property values are based on national values scaled by the ratio of per capita income at the county level to per capita income at the national level. The national property values include reproducible tangible wealth and the value of land. Since these values are already available as input to MACCS, they are used to augment the current model to account for losses of tangible wealth.

Losses in tangible wealth are simplest to estimate for the case of condemned property. Currently, the I-O model accounts for regional GDP losses over the Maximum Duration of Economic Impact (a user-defined input that defaults to 10 years). In addition, the value of the condemned property is reported as a loss. This accounts for both lost land value and future GDP generation associated with that land.

Losses in wealth are more complicated to estimate for the case of a relatively short period of interdiction. The cost-based model includes depreciation of property improvements over the period of interdiction. Depreciation losses are included in the GDP-based model and are estimated in the same way as in the cost-based model. The model accounts for an increase in depreciation losses as the duration of interdiction increases.

The decision on cost effectiveness of performing decontamination is controlled by the following inequality, which is similar to the one in Equation (8), but the loss-of-use term on the left side of the inequality is replaced by direct GDP loss for the period of interdiction. Equation (28) has an additional term on the right side that accounts for the direct GDP loss over the maximum period of regional losses (an input parameter with a default of 10 years) that has no counterpart in Equation (8). This extra term is needed because both property value and direct GDP loss are accrued when a grid element is condemned in the GDP-based model. The GDP losses for condemned property may be overestimated with the current model when the maximum period of regional losses is more than a few years since the time needed to reestablish a business is likely to be relatively short. This may be a form of double counting because the full property value is accrued as a replacement cost and GDP losses may extend beyond the time when the business could be reestablished. On the other hand, a similar loss term is not accounted for in the cost-based model (Equation (8)) at this time, and this may lead to an underestimation of actual losses. The difference between the two inequalities expressed in Equations (8) and (28) account for some differences in the decision process between the two models, as displayed in Section 6.2. The additional term tends to increase the likelihood that property is decontaminated instead of condemned when using the GDP-based model.

$$\boldsymbol{C_d + C_f + \Delta V^D(r) + C_m < V_w + C_f + \Delta V^D(R)} \tag{28}$$

When the inequality is satisfied, decontamination is performed. The terms on the left side of the inequality are the per-person costs that are incurred when decontamination is performed; the terms on the right side of the inequality are the per-person costs that are incurred when property is condemned. Notice that $\boldsymbol{C_f}$ appears on both sides of the equation and could be subtracted.

3.4. Inputs to the Impact Estimation Methodology

3.4.1. Net Total Requirements Multipliers

Two unique features of the scenarios considered for this application motivate creation of modified Type I and Type II multipliers[18]. First, the initial disruption is presented as value-added losses in the impacted area, thus requiring "national"[19] multipliers that operate on regional changes in the value added, rather than on regional changes to the final demand. The value-added losses in a closed economy can be estimated based on direct regional value-added losses using the appropriate net total requirement multipliers. Second, all industries are shut down at the same time, so some of the losses are direct that would have been indirect if only one industry was shut down.

The gross total requirement multipliers of Type k are defined as follows:

$$\boldsymbol{m_i}^{\boldsymbol{k,N}} = \frac{\boldsymbol{Y_i}}{\boldsymbol{V_i}} \sum_{\boldsymbol{j}} \boldsymbol{b_{i,j}^k} \frac{\boldsymbol{V_j}}{\boldsymbol{Y_j}}, \boldsymbol{k} \in \{\boldsymbol{I}, \boldsymbol{II}\} \tag{29}$$

where $b_{i,j}^k$ represents the elements of the TRII Table (see Raa, 2005 for a definition and an explanation of TRII Table and related concepts). For the purposes of this development, the calculation of the net total requirements Type I multipliers is done by using the TRII Table without households. The calculation of the Type II multipliers is identical except for using the TRII Table with households[20].

Given that the sum in (29) is just a national final demand value-added multiplier $\widetilde{m}_i{}^k$, the same gross total requirements multiplier can be expressed as follows:

$$\boldsymbol{m_i}^{\boldsymbol{k,N}} = \frac{\boldsymbol{Y_i}}{\boldsymbol{V_i}} \widetilde{\boldsymbol{m}}_{\boldsymbol{i}}{}^{\boldsymbol{k,N}} \tag{30}$$

where $\widetilde{m}_i{}^{k,N}$ is the national final demand value-added multiplier of Type $\boldsymbol{k}$ for industry *i*. The ratio of national gross output to national value added on the left side of the equation serves to convert the value-added regional losses into equivalent final demand losses. The multipliers are therefore analogous to the BEA's final demand value-added multipliers, but are applied to the value added, rather than the final demand losses.

The multipliers for the impacted region[21] can be calculated in the same way using the corresponding TRII Table:

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[18] The estimation method for net value-added multipliers was proposed by Jeff Werling in an unpublished memo (Werling, 2015). This section presents a slightly modified algorithm for calculating the net total requirements multipliers.
[19] In the BEA terminology, these are regional multipliers with the region composed of the 48 contiguous States. These multipliers are called national in this report.
[20] Miller and Blair (2009) show that the ratio of Type I and Type II multipliers is a constant across all sectors, thus potentially simplifying the estimation of Type II multipliers, once the Type I multipliers are known.
[21] These multipliers are calculated for the entire impacted region and not for separate grid elements.

$$\boldsymbol{m_i}^{\boldsymbol{k,R}} = \frac{\boldsymbol{Y_i}}{\boldsymbol{V_i}} \widetilde{\boldsymbol{m}}_{\boldsymbol{i}}^{\boldsymbol{k,R}} \quad (31)$$

where the superscript R represents the impacted region. To account for the possibility that some suppliers may be within region R, the net total requirements Type $\boldsymbol{k}$ multipliers are calculated as follows[22]:

$$\boldsymbol{m'}_{\boldsymbol{i}}^{\boldsymbol{k,R}} = \boldsymbol{m_i}^{\boldsymbol{k,N}} - \boldsymbol{m_i}^{\boldsymbol{k,R}} + \mathbf{1} \quad (32)$$

Ultimately, the multipliers used in Equations (22) to (23) to calculate losses in final demand value added and to eliminate the potential double counting introduced when all industries in a region are simultaneously disrupted are expressed by the following equation:

$$\widetilde{\boldsymbol{m'}}_{\boldsymbol{i}}^{\boldsymbol{k,R}} = \frac{\boldsymbol{V_i}}{\boldsymbol{Y_i}} \boldsymbol{m'}_{\boldsymbol{i}}^{\boldsymbol{k,R}} \quad (33)$$

Given the requirements to this model, the net total requirements multipliers in Equation (32) need to be calculated for an ad-hoc area, given multiple sites and given multiple weather trials for the same site. It is not practical and likely not feasible to acquire the TRII Tables or the multipliers for each possible impacted area. The rest of the section therefore presents an approach for estimating the net total requirements multipliers based on limited data.

Based on calculated multipliers for a set of different impacted regions, the multipliers for an ad-hoc region are calculated by introducing a dampening factor for the national multipliers that reflects the fact that when the affected area is large, the indirect impacts are relatively small, and when the area is small, the indirect impacts are relatively large. To create a model for the variation of the multipliers with the size of the affected area, several different empirical equations were considered: log-linear, normalized exponential, a few variants of the COCO-2 model, and other models. The models were compared based on the goodness of fit to the BEA (2012) data. The data used for the models are based on the multiplier tables from BEA (2012) for all States, external data on State area size, Bureau of Labor Statistics employment quotient, and other data. The normalized exponential was ultimately chosen as the best model to fit the BEA data and has the following functional form:

$$\boldsymbol{m'}_{\boldsymbol{i}}^{\boldsymbol{k,R}} = (\boldsymbol{m'}_{\boldsymbol{i}}^{k,N} - 1) * \frac{\exp(\alpha_i) - \exp(\alpha_i * s_R)}{\exp(\alpha_i) - 1} * \exp(\beta_i * e_{i,R}) + 1 \quad (34)$$

where $s_R = A_R / A_N$ is the relative area size of region R defined as ratio of the area of region R to the total area of the 48 contiguous United States, and $e_{i,r}$ is the employment location quotient for the industry i in region R, defined as follows:

$$e_{i,R} = \frac{l_{i,R} / \sum_{i=1}^{I} l_{i,R}}{l_{i,N} / \sum_{i=1}^{I} l_{i,N}} \quad (35)$$

α_i and β_i are empirically derived coefficients constructed by using BEA data at the state level to obtain the best fits, and $l_{i,R}$ and $l_{i,N}$ are respectively the industry i employment in the region R and

[22] The resulting net total requirements multiplier is therefore specific to the impacted region. However, the superscript R is omitted here and in the following for simplicity.

nationally. Because the size of the directly affected area typically diminishes with time as recovery progresses, the time variation of the affected area is included in the implementation of the RDEIM model.

3.4.2. Maximum Duration of Local and National Economic Impacts

Direct economic losses arising from a nuclear accident are the household and business incomes lost because of released radiation. If the affected area can be decontaminated and restored to use relatively quickly, then the interruption period might be the same for both the regional and national economies. However, if the area remains interdicted over a longer period, or if it is condemned, then the recovery time path for the regional economy tends to lag the national recovery. The difference depends on how quickly the rest of the economy can redeploy the businesses, residents, and workers who have been relocated from the affected area. National recovery is also boosted through the economy's "natural resilience," which is normally very high due to the size and flexibility of the US economy, as demonstrated by a relatively quick national recovery after such events as Hurricane Katrina.

Therefore, this model contains two different time recovery (disruption) parameters to limit recovery duration: the maximum duration of impacts at the regional level, T_R, and the maximum duration of impacts at the national level, T_N. The actual duration of regional impacts is variable, depending on the initial level of contamination and the time needed for decontamination. The duration is designated as T with no subscript and is estimated by MACCS as part of the consequence analysis. Its value depends largely on the magnitude of the atmospheric release, but it can also depend on the specific weather conditions being evaluated.

A maximum duration for regional impacts of 10 years was selected from the range of 1 to 30 years as a default value. This 10-year period represents an upper bound in the simulation on the duration of impacts. For example, if the model estimates that the affected area would be decontaminated much faster than the Maximum Duration of Economic Impact, based on the level of contamination, the Maximum Duration of Economic Impact input parameter has no effect on the calculation.

A national recovery period of 3 years was selected as the default value with a national recovery period of between 1 and 10 years allowed. The capacity of the national economy to recover from regional disruptions is much greater than that of the directly affected areas because of adaptation and price adjustments that support economic resilience.

Economic recovery to a new normal condition requires that the population and businesses from the affected area relocate to other parts of the country, restore employment in these regions, and that the economy generates the same level of income as it would have done had the accident never occurred. Data used to evaluate time frames for economic recovery were obtained from: 1) the length of U.S. recessions, 2) past disruption events, like Hurricane Katrina, and 3) similar models.

1. According to the National Bureau of Economic Research, the average length of U.S. recessions calculated using all available data from 1854 to 2009 is 17.5 months, and 11.1 months if only using the period from 1945 to 2009[23]. National economic disruptions from recession tend to be short, around 1 to 3 years.

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[23] More information can be found at www.nber.org/cycles.html. Accessed January 15, 2015.

2. Regional recovery after hurricanes has been analyzed by Deryugina (2013a), who concludes that the employment rate decline following a hurricane persists even 5 to 10 years after the event. Deryugina et al. (2013b) analyzed the effects of Hurricane Katrina and concluded that the nominal wages recovered relatively quickly for those who returned to New Orleans after the hurricane, and even exceeded their pre-hurricane levels in two years after the hurricane. But for those who chose not to return or were unable to return, it took approximately five years for their wages to reach pre-hurricane levels. Basker and Miranda (2014) also analyzed the post-Katrina recovery along the Mississippi coast and concluded that the areas with most damage "had not recovered within five years despite significant help from both federal and state sources."

3. The COCO-2 model, which is an I-O model used to assess the economic impact of a nuclear accident in the United Kingdom, assumes a maximum period of 2 years to restore national production to pre-accident levels (Higgins, 2008)[24].

The length of the U.S. recessions and the COCO-2 period of 2 years to restore production represent lower bounds on the duration of impacts of a potential incident. The time for recovery after hurricanes such as Hurricane Katrina, where the regional impacts persisted for many years, shows that long time periods may be needed, especially for the regional economy. However, it must be recognized that Hurricane Katrina was 400 miles wide by tens of miles inland (on the order of 10,000 mi^2) while the regional economic losses after a potential nuclear power plant accident would typically be confined to a smaller area.

Based on the above considerations, a value of 10 years was selected as the default time frame for the Maximum Duration of Regional Economic Impact, T_R, and 3 years as the maximum duration of the national economic impacts T_N. Those two parameters, T_R and T_N, determine the relative speed of regional vs. national economy. The parameter T_N being set to 3 years implies that the national economy recovers more quickly than the regional one, which is modeled as taking up to 10 years to recover. A MACCS user can adjust these durations to be longer or shorter than the defaults. T_R can be chosen to be as large as 30 years. However, the implementation of the RDEIM model requires that T_N must be less than or equal T_R.

3.4.3. List of Industries in RDEIM

The BEA (2012) provides detailed information on the structure of the U.S. economy and covers approximately 400 industries.[25] For use in MACCS, the 400+ industries were aggregated into 2-digit NAICS codes covering 21 industries (19 private industrial sectors and 2 government sectors), which are provided in a table in the following section. The loss estimation method for industries is based on affected area or population, as described below.

3.4.4. Treatment of Partial Counties

In the integrated model framework, the county is the smallest geographic entity for which employment data are available. However, nuclear power plant accidents in some cases could have

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[24] The published COCO-2 documentation does not provide a justification for the 2-year period. This was confirmed via email by M. Munday.

[25] See http://www.bea.gov/papers/pdf/IOmanual_092906.pdf for a detail description of BEA methodology.

very limited offsite consequences that affect less than one county or could affect many whole counties and portions of others. Therefore, an approach was developed for estimating the GDP losses for a fraction of a county.

The fraction of a county land area and the fraction of a county population in the affected zone are the two quantities considered for calculating GDP losses for partially affected counties. The industries were reviewed to consider whether they tend to be geographically distributed or geographically concentrated in urban areas and whether the industry operations are labor intensive. For industries that are geographically distributed and do not depend on concentrated labor, such as agriculture, it was decided fractional impacts should be based on affected area. For industries that are geographically concentrated and depend on concentrated labor, such as manufacturing, it was decided fractional impacts should be based on affected population. Each industry in Table 2 was reviewed and some judgment was used to select area or population.

Table 2. GDP Impact Calculations by Area or Population for Partial Counties

Industry	By Area	By Population
Agriculture, forestry, fishing, and hunting	X	
Mining	X	
Utilities	X	
Construction	X	
Wholesale trade		X
Retail trade		X
Transportation & Warehousing	X	
Information		X
Finance & Insurance		X
Manufacturing		X
Real estate & rental leasing	X	
Professional, scientific, and technical services		X
Management of companies & Enterprises	X	
Administrative & Waste management services	X	
Educational services		X
Health care & Social assistance		X
Arts, entertainment & recreation		X
Accommodations & food services		X
Other services, except government		X
Federal civilian		X
State & local government		X

3.4.5. Social Discount Rate

A social discount rate was employed in the MACCS cost-based estimate (Jow et al., 1990) and is continued in the RDEIM model. Three methods were considered in establishing a social discount rate to use with the RDEIM model, including:

- Benchmark financial rate approach, which suggests that the discount rate be based on the social opportunity cost of capital, a weighted average of the pre-tax and after-tax rates of return, where the weights reflect the fractions of funds that are obtained from displaced investment, postponed consumption, and incremental funding from abroad when the government borrows to finance a project (OMB, 2014);
- Rate of time preference using an appropriate rate of growth in per-capita consumption; and
- The Marginal Cost of Funds criterion, which discounts within generation benefits at the after-tax rate, between generation benefits at the pre-tax rates, and costs at the pre-tax rates (Liu et al., 2004).

The OMB approach was selected for the integrated modeling framework. OMB Circular A-94 (OMB, 2014) advises using 3% and 7% discount rates for regulatory analyses, and advocates using 7% as a default, when the regulation primarily affects the allocation of capital, because this is a before-tax rate of return to private capital in the U.S. The circular further states that when "regulation primarily and directly affects private consumption…, a lower discount rate, 3%, is appropriate." The 3% discount rate is based on real returns to 10-year Treasury notes. The average rates quoted by the OMB for 10-year maturities are 0.9% and 1.4% for 30-year maturities (Circular A-94 Appendix C). For the integrated model, a 3% rate was selected as the default value. However, the user can select to override this default. Lower and upper bounds on the social discount rate of 0% and 8% were chosen. The upper bound is very near the larger value identified in Circular A-94.

In practice, different (or even the same) entities may use different discount rates for different purposes. Those can range from pure people-oriented time preference to expected costs of financing or required rates of returns for businesses. The discount rate used in this model is interpreted as the societal preference but can be changed by the user to different values to represent alternative interpretations.

In the formal model, the social discount rate ρ only appears as a part of the expression $r - \rho$, where r is the GDP growth rate. Therefore, this difference $r - \rho$ can be treated as the "effective" discount rate, representing the "effective" societal preference applied to future losses.

3.4.6. MACCS Input Parameters

Table 3 provides default values and lower and upper bounds for specific parameters described in this report and used in RDEIM.

The real GDP growth rates can be estimated using historic data on U.S. GDP growth rates, where 3 to 3.5 percent is typically considered healthy, and greater than 5 percent is considered very rapid. The Congressional Budget Office (CBO) considers a value of 2.2% to 2.4% to be sustainable in the future. A value of 3.3% is based on historical averages is the default.

Table 3. Default and Boundary Values for Real GDP Growth Rate and Loss Calculation Duration

	Default Value	Lower Bound	Upper Bound
Real GDP Growth Rate (%/yr)	3.3	0	10
Social Discount Rate (%/yr)	3	0	10
Maximum Duration of Regional Impact (yr), T_R[26]	10	1	30
Time at which National Economy recovers (yr)	3	1	10

[26] T_R does not influence actual losses for grid element r when recovery within the grid element occurs prior to that time.

4. IMPLEMENTING RDEIM MODEL IN MACCS

The previous section describes the methods employed in RDEIM to estimate the total GDP impact. The total cost impact includes additional elements that are estimated in MACCS. These include the cost of evacuation and relocation of the public and the cost of decontamination. The integrated model results represent the overall cost impact and are provided as output from the integrated model.

RDEIM performs the following steps to estimate economic impact:

- An analysis area is defined. SecPop is an auxiliary code that is used to develop the site-specific land-use, population, and economic data into a site file for MACCS. SecPop version 4.0 and newer creates a file containing the counties or fractions of counties contained in each MACCS grid element. Fractions of counties are estimated both by area fraction and population fraction. RDEIM uses this information to estimate GDP losses for each industry within each grid element.
- RDEIM computes total GDP losses (direct, indirect, and induced) for each MACCS grid element. This information is stored in a file that is used by MACCS.
    - The number of employees for each industry within a MACCS grid element is calculated and this information is used to estimate direct GDP losses. An estimate of the impacts to other industries that are indirectly affected by the disruption is performed using I-O multipliers.
    - All economic activities within a MACCS grid element are disrupted for the same duration of time[27], except for farmland, which may have a different recovery schedule.
- For a specific source term and weather trial, MACCS determines the affected area and the duration of the disruption for each grid element. MACCS aggregates the GDP losses over the region and over the duration of disruption.
- RDEIM estimates the base-year value of future year GDP losses by accounting for an annual GDP growth rate and an annual social discount rate. All dollars are reported in base-year (currently 2011) dollars for an accident that is assumed to occur in the accident year specified by the user. The user can adjust the value of the dollar to another year as a post processing step, if desired.
- MACCS sums the GDP losses.[28] A suggestion for how this information can be used in a cost-benefit analysis is provided in Section 5.
- MACCS repeats the process for a set of weather trials and provides statistical results to characterize the variability from uncertain weather. The footprint of the affected area, the degree of contamination, and the duration of economic losses can be different for each weather trial; thus, the direct, indirect, and induced economic losses are generally different for each weather trial.

For some scenarios, the extent of contamination may cause the land to be interdicted for a short period of time (e.g., a few years) or condemned (i.e., not recoverable within the Maximum Duration

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[27] The current framework is sufficiently flexible to allow differential recovery times by industry. However, it is not done in the current version of the model.

[28] The new model is fine-grained enough to represent the losses at the regional and national levels as they are projected to occur over time. Such data can be used to analyze possible accident impacts in detail or to investigate tradeoffs between different restoration policies.

of Economic Impact) in the model. The user specifies the number of years of direct GDP loss (Maximum Duration of Economic Impact) that are evaluated for an area that is condemned while MACCS estimates the required interdiction period based on the extent of contamination. In most cases, the interdiction period estimated by MACCS is less than the default value for Maximum Duration of Economic Impact (10 years). When this is true, the GDP of the affected area is only considered a loss for the interdiction period estimated by MACCS, not the full 10 years. For agricultural land use, the minimum interdiction period is assumed to be one year because of the seasonal nature of this industry.

4.1. Simple Example

This section describes a simple example to illustrate the model.

For simplicity, the affected area is composed of three grid elements, $R = \{A, B, C\}$, and four industries, $I = \{Utilities, Manufacturing, AdmService, FoodService\}$. In this example, grid element A is a partial county, and the grid elements B and C are complete individual counties. The counties are also called A, B, and C, corresponding to the grid element that contains the county. The region in the following discussion represents a 50-mile radius surrounding the reactor site. The region is made up of the disrupted counties, A, B, C, and several other counties that are not disrupted.

Other scenario parameters are as follows

> Maximum duration of regional disruption, T_R = 10 years.
> The time needed for national recovery, $T_N = 4$ years.
> GDP growth rate, g = 2.4%.
> Social discount rate, ρ = 3.0%.
> Base year = database year = 2011.

GDP of the region is $3 billion, and national GDP is assumed to be $100 billion[29] in 2011. The employment by industry and county is described in Table 4.

Table 4. Employment by Industry in Affected Counties

Industry	County Employment		
	A	B	C
Utilities	100	45	55
Manufacturing	995	4000	30
Adm. Serv.	10	15	20
Food Serv.	50	300	5

The fraction of each county affected is represented in the Table 5.

[29] These numbers are made for illustration purposes and do not intend to represent any real geographic data.

Table 5. Fraction of Each County Affected

	County Fraction in Grid Element		
	A	B	C
By population	0.5	1	1
By area	0.7	1	1

Given the weighting indicated in Table 2 for each industry, the lost employment for each grid element (each containing all or part of the county of the same name) is estimated as shown in Table 6.

Table 6. Lost Employment by Grid Element and Industry

Industry	Lost Employment in Grid Element		
	A	B	C
Utilities	70	45	55
Manufacturing	498	4000	30
Adm. Serv.	5	15	20
Food Service	25	300	5

The grid element recovery schedule is shown in the Table 7.

Table 7. Grid Element Recovery Schedule

	Grid Element		
	A	B	C
Recovery Time (yr)	3.5	6	11

Table 8 describes the value added per worker for each industry.

Table 8. Value Added per Worker for Each Industry

	Industry			
	Utilities	Manufacturing	Adm. Serv.	Food Service
Value added per worker/year ($/yr)	150,000	170,000	120,000	100,000

The value-added Type I and Type II multipliers are presented in Table 9. Values close to unity for Type I National multipliers indicate that disruption of an industry has very little effect on all other national industries; whereas, values significantly larger than unity indicate a large effect on all other national industries when an industry is disrupted. Type II multipliers are always larger than Type I multipliers because they also account for the effect of income losses by affected workers on national GDP. Type I Regional multipliers are always less than or equal to Type I National multipliers because they only account for the effect on suppliers within the directly affected region. A large difference between the Type I National and Type I Regional multiplier indicates that a significant portion of the supply chain to an industry is from outside the disrupted region.

Table 9. Value Added Multipliers of Type I and Type II

Industry	Value Added Multipliers			
	Type I National	Type II National	Type I Regional	Type II Regional
Utilities	1.40	1.81	1.20	1.55
Manufacturing	1.87	2.41	1.35	1.74
Adm. Serv.	1.48	1.91	1.40	1.81
Food Serv.	1.87	2.41	1.60	2.06

These are adjusted for double counting by taking the difference between the national and regional values and adding one. The resulting multipliers are shown in Table 10. These multipliers only account for the effect of a disrupted industry on suppliers outside the directly affected region.

Table 10. Regional Type I and Type II Multipliers Adjusted for Double Counting

Industry	Adjusted Regional Multipliers	
	Type I	Type II
Utilities	1.20	1.26
Manufacturing	1.52	1.67
Adm. Serv.	1.08	1.10
Food Serv.	1.27	1.35

Applying Equations (20), (22), and (24), various losses are calculated. Table 11 represents the summary of direct losses.

Table 11. Summary of Direct Losses for the Region. All Values are Discounted to 2011 (Year 1 in the Table) using the Social Discount Rate.

Year	Cum. Dir. Loss ($M)	Annual Direct GDP Loss ($M)	Baseline Cum. GDP ($M)	Baseline Annual GDP ($M)	Percent Loss of Regional GDP (%)	Regional GDP after Disruption ($M)
1	830	830	2,991	2,991	27.8	2,161
2	1,656	826	5,964	2,973	27.8	2,148
3	2,477	821	8,919	2,955	27.8	2,135
4	3,244	768	11,857	2,938	26.1	2,170
5	3,959	715	14,777	2,920	24.5	2,205
6	4,670	711	17,680	2,903	24.5	2,192
7	4,686	16	20,565	2,885	0.5	2,870
8	4,702	16	23,433	2,868	0.5	2,852
9	4,717	15	26,284	2,851	0.5	2,835
10	4,732	15	29,118	2,834	0.5	2,818
11	4,732	-	31,935	2,817	0.0	2,817

The annual direct losses ($M) are represented in Figure 4 and as a percent of the regional GDP in Figure 5.

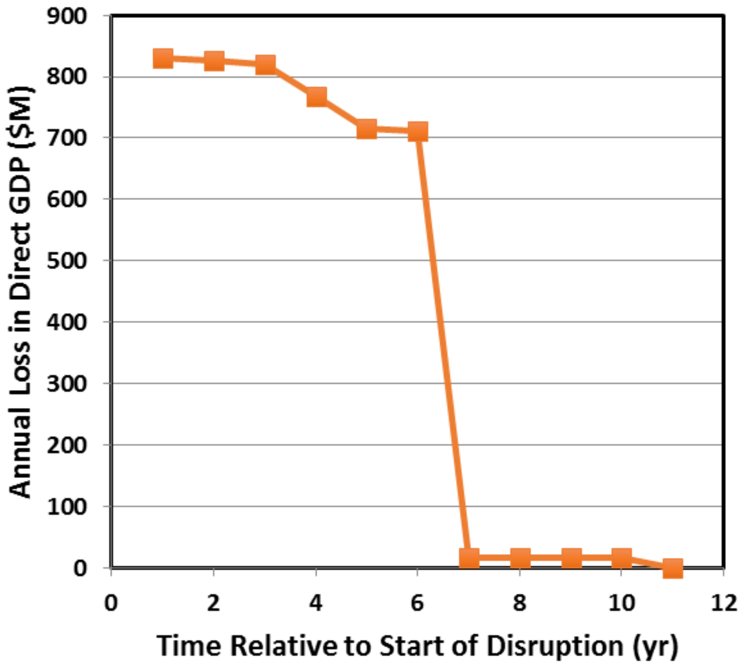

Figure 4. Annual direct loss in GDP ($M) to regional economy. All values are discounted to 2011 (year 1) using the social discount rate.

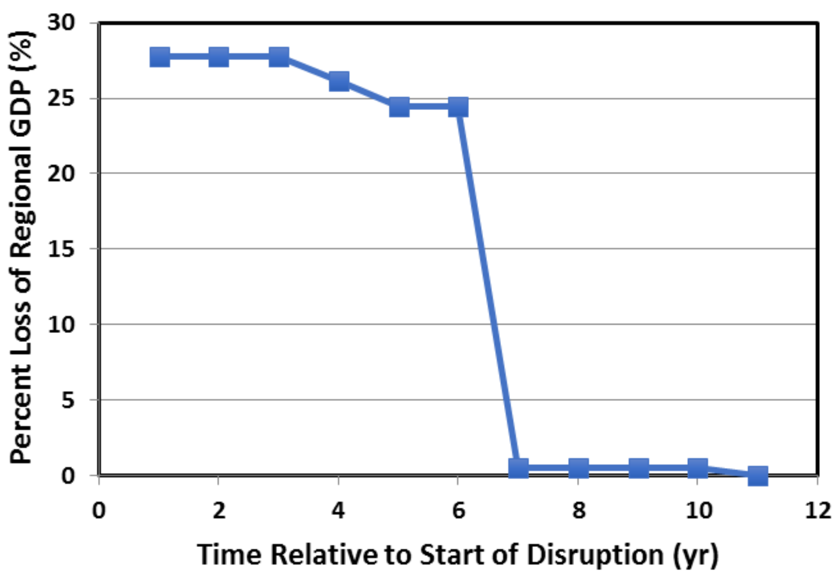

Figure 5. Direct annual losses as percent of regional GDP.

The projected regional GDP without the disruption and estimated regional GDP accounting for the disruption are shown in Figure 6.

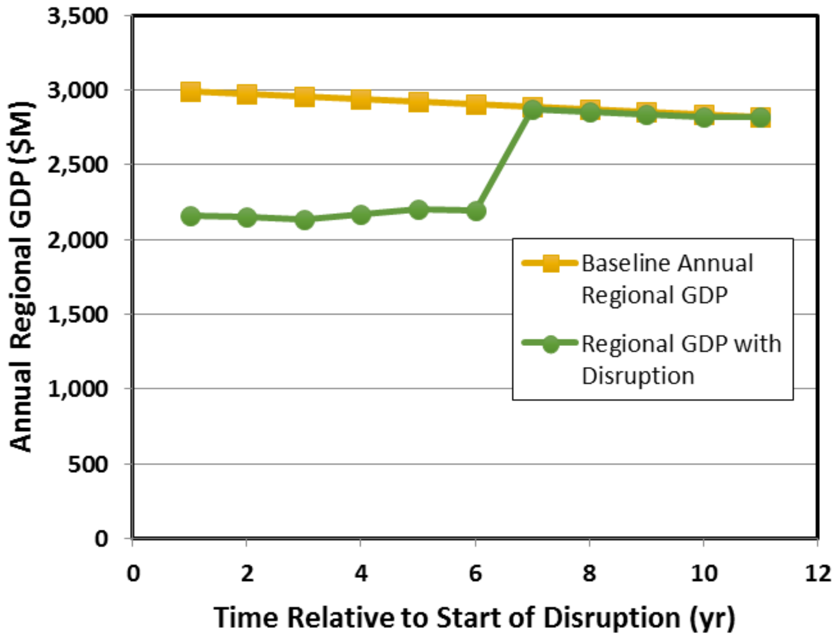

Figure 6. Regional annual GDP with and without the disruption. All values are discounted to 2011 (year 1) using the social discount rate.

Table 12 represents the loss estimates on the national level.

Table 12. GDP Losses at the National Level. All Values Are Discounted to 2011 (Year 1) Using the Social Discount Rate.

Year	Cum. Total GDP Loss ($M)	Annual Total GDP Loss ($M)	Cum. Dir. + Indir. GDP Loss ($M)	Annual Dir. + Indir. GDP Loss ($M)	Annual Indir. GDP Loss ($M)	Annual Induc. GDP Loss ($M)	Baseline Cum. GDP ($M)	Baseline Annual GDP ($M)	Annual GDP Loss (%)	Total GDP after Disruption ($M)
1	1,193	1,193	1,089	1,089	258	105	99,701	99,701	1.20	98,507
2	2,041	847	1,861	773	(53)	74	198,805	99,104	0.86	98,257
3	2,546	505	2,322	461	(360)	44	297,316	98,511	0.51	98,006
4	2,672	126	2,437	115	(653)	11	395,238	97,922	0.13	97,796
5	2,672	-	2,437	-	(715)	-	492,574	97,336	0.00	97,336
6	2,672	-	2,437	-	(711)	-	589,328	96,754	0.00	96,754
7	2,672	-	2,437	-	(16)	-	685,504	96,175	0.00	96,175
8	2,672	-	2,437	-	(16)	-	781,104	95,600	0.00	95,600
9	2,672	-	2,437	-	(15)	-	876,132	95,028	0.00	95,028
10	2,672	-	2,437	-	(15)	-	970,591	94,460	0.00	94,460
11	2,672	-	2,437	-	-	-	1,064,486	93,894	0.00	93,894

The trajectory of national GDP with and without the disruption is represented in Figure 7.

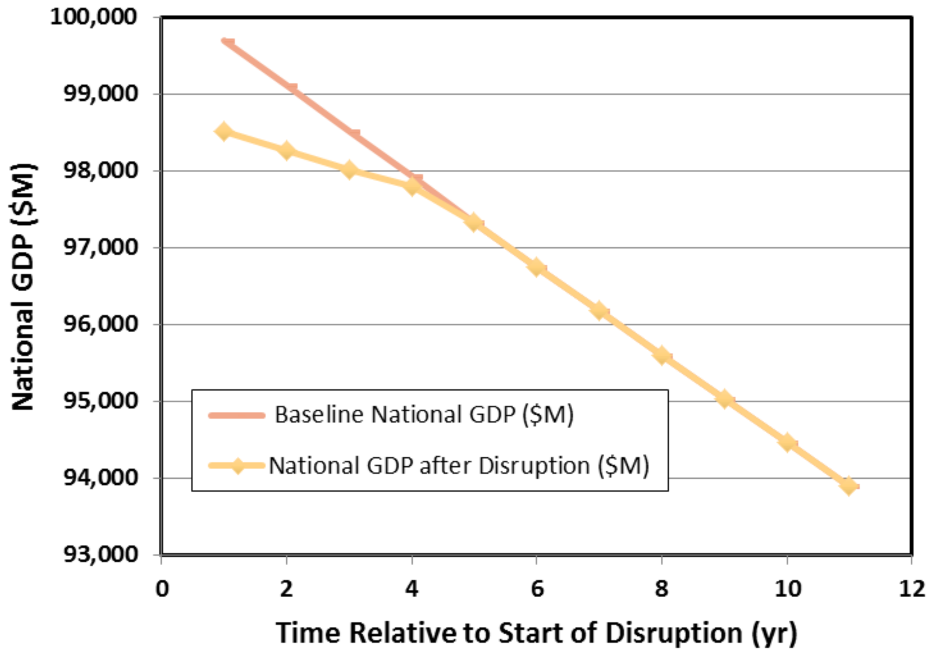

Figure 7. National GDP with and without disruption. All values are discounted to 2011 (year 1 in the plot) using the social discount rate.

It is notable that the baseline future regional and national GDP appear to decline over time in Figures 6 and 7. This occurs because the projected GDP growth rate of 2.4% is less than the social discounting rate of 3.0% used in the calculations. If those parameters were reversed, the baseline trends in Figures 4 and 5 would show an upward slope, as is shown for example in Figure 3. The users of the model could make such changes.

The total national GDP losses as a percentage of the unaffected national GDP are represented in Figure 8.

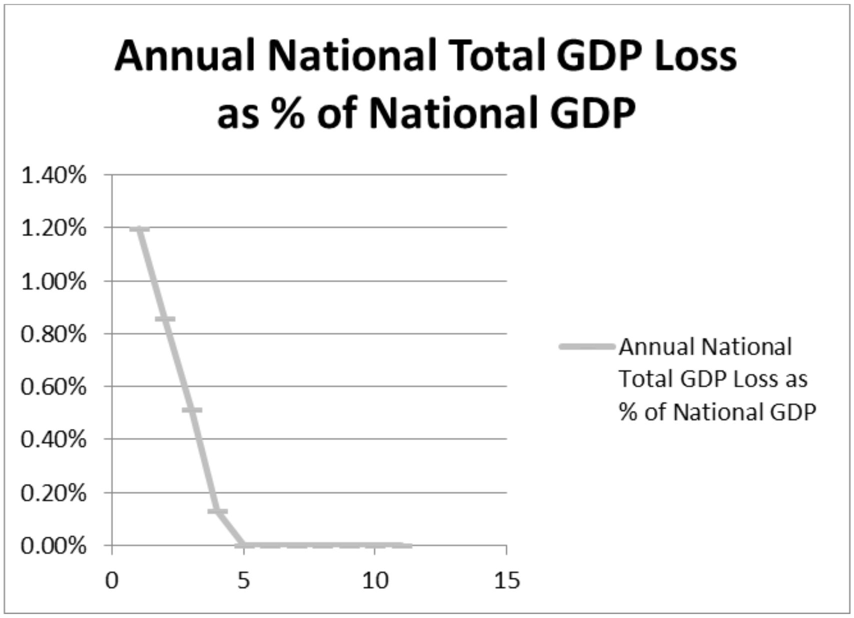

Figure 8. GDP losses as a percent of national GDP.

A summary of annual direct, total, indirect, and induced losses is represented in Table 13 and in Figure 9. These show that most of the losses within the directly affected region are eliminated by year 7, but a small portion of the losses continue through the period of regional disruption, which is 10 years. Annual Total GDP Losses are for the national economy, and these losses are assumed to recover by the end of year 4. In the first year, national losses are greater than direct losses because of the effect on other industries in the larger national economy. However, as the national economy recovers, regional industry closures are compensated by rebuilding within the national economy outside the disrupted region, allowing the national economy to recover faster than the regional economy. The faster national recovery forces the induced losses to become negative for a period, which reflects the fact that losses within the directly affected region become gains to the national economy as industries are rebuilt outside the affected region. Finally, induced losses that account for lost income to directly and indirectly affected workers reduces to zero on the same schedule as the national GDP losses because work lost in the disrupted region is restored at the national level and so losses to worker pay are eliminated.

Table 13. Annual Losses Summary at National Level. All Values are Discounted to 2011 (Year 1) Using the Social Discount Rate.

Year	Annual Direct GDP Loss ($M)	Annual Total GDP Loss ($M)	Annual Indirect GDP Loss ($M)	Annual Induced GDP Loss ($M)
1	830	1193	258	105
2	826	847	-53	74
3	821	505	-360	44
4	768	126	-653	11
5	715	0	-715	0
6	711	0	-711	0
7	16	0	-16	0
8	16	0	-16	0
9	15	0	-15	0
10	15	0	-15	0
11	0	0	0	0

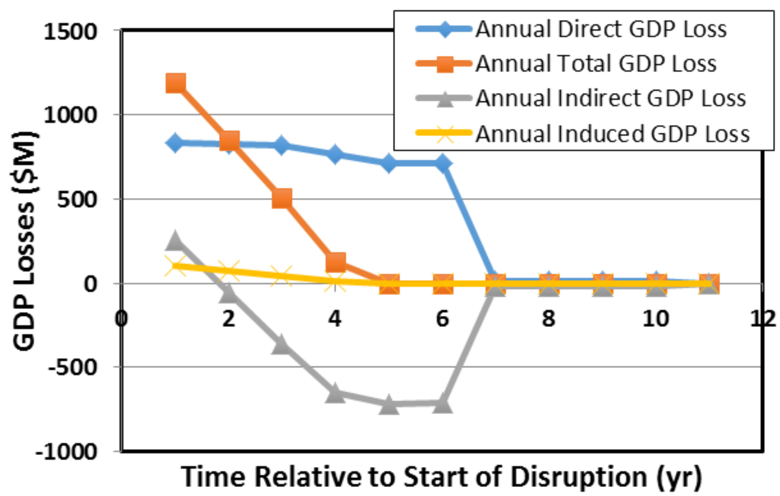

Figure 9. Direct, total, indirect, and induced annual losses at the national level. All values are discounted to 2011 (year 1 in the plot) using the social discount rate.

The temporal representation of the losses is valuable for understanding the effects of different parameters, such as restoration schedules and can be used for optimizing the decontamination and recovery schedules. For convenience, this example was implemented in an Excel worksheet, which allows further experimentation with different parameters.

4.2. Presentation and Use of Results

The output of the model can be interpreted as shown in Table 14. Direct losses ($\boldsymbol{\Delta V^D}$) only occur in the directly affected areas and are therefore included under national but not the extra-regional area. Indirect losses ($\boldsymbol{\Delta V^{D+I} - \Delta V^D}$) are only in the extra-regional area and are therefore included under national but not the intraregional area. Induced losses ($\boldsymbol{\Delta V^T - \Delta V^{D+I}}$) occur in both the intraregional and extra-regional areas and the losses are assumed to be apportioned according to the size of the other losses in the two areas, where $x = \Delta V^D / \Delta V^{D+I}$. After the national economy has fully recovered, only direct losses continue, as shown in Table 15; indirect losses are actually gains, as indicated by the negative sign in the table. Indirect gains compensate for the direct losses to account for industries being reestablished in the extra-regional area. This means total losses at the national level are zero because the intraregional losses are compensated by the extra-regional gains.

In addition to the GDP losses shown in Table 14 and Table 15, the implementation in MACCS reports costs from evacuation and relocation of members of the public, for both short- and long-term, and decontamination costs. Capital losses are also reported corresponding to condemned property and depreciation of property improvements that cannot be maintained during periods of interdiction. This represents a reasonably complete accounting of the types of losses that can be attributed to the occurrence of a nuclear reactor accident or other release of radioactive material into the atmosphere. However, it does not account for other potential types of losses, such as legal, health, and stigma costs.

Table 14. GDP Losses in the First Accident Year

	GDP			
Impact Type / Region	Direct ($)	Indirect ($)	Induced ($)[30]	Total ($)
Intraregional	ΔV^D	0	$x(\Delta V^T - \Delta V^{D+I})$	Row sum
Extra Regional	0	$\Delta V^{D+I} - \Delta V^D$	$(1-x)(\Delta V^T - \Delta V^{D+I})$	Row sum
National	ΔV^D	$\Delta V^{D+I} - \Delta V^D$	$\Delta V^T - \Delta V^{D+I}$	Row sum

Table 15. GDP Losses in Year 4, Assuming $T_N = 3$

	GDP losses			
Impact Type / Region	Direct ($)	Indirect ($)	Induced ($)	Total ($)
Intraregional	ΔV^D	0	0	ΔV^D
Extra Regional	0	$-\Delta V^D$	0	$-\Delta V^D$
National	ΔV^D	$-\Delta V^D$	0	0

For the purposes of a cost-benefit analysis, the authors suggest reporting national GDP losses (including direct, indirect, and induced losses) plus evacuation and relocation costs, decontamination costs, depreciation losses, and condemned property values. This may entail some degree of double counting as well as summing up fundamentally different cost types, such as GDP losses and losses of tangible wealth. However, the combination of these values represents a reasonable estimate of the total impact of a nuclear reactor accident. In some cases, like the example shown above, direct GDP losses can exceed total GDP losses, but the authors believe that national GDP losses are a better indication of the effect on GDP of a nuclear reactor accident. The benchmarking results in Section 6.2 provide more perspective on this issue for a set of realistic accidents at representative nuclear power plant sites.

[30] The variable x is the ratio of ΔV^D to ΔV^{D+I}. It approximates the ratio of the induced losses attributable to the directly affected area and to the entire economy based on the ratio of economic impacts, excluding induced losses, to those same areas.

5. VERIFICATION PLAN

This section is intended to describe the plan to assess the implementation of the RDEIM, GDP-based, economic model now integrated with WinMACCS/MACCS. Some of the tests are purely verification and compare results generated with MACCS using the REAcct model, the parent of RDEIM, with independently generated results to demonstrate that the implementation is correct. Other parts of this section describe results that are comparisons of the cost-based approach and the GDP-based approach. While there is no expectation that the two models, which are very different, should produce the same results, there is an expectation that the two results should not differ greatly and that trends should be similar. Both types of results presented in the following section serve to verify the new model, but do not validate the model against actual data, such as those from Fukushima. Validation may be the topic of a future study.

5.1. Objectives

There are two main objectives for this verification and benchmarking study:

1. Verify that the incorporation of the RDEIM model into MACCS produces direct GDP losses that agree with the standalone version of REAcct. Indirect and induced GDP losses are not compared because they are calculated using different multipliers in REAcct and RDEIM, so the results are not expected to agree.

2. Compare the new RDEIM economic model against the original MACCS, cost-based, economic model to demonstrate that the two independent models provide results that are in reasonable agreement. Economic results are compared on a relative basis; other results are compared on an absolute basis.

An adequate set of tests is crucial to ensuring that the two primary objectives of this plan have been met. The tests in each of the series are designed to address one or both of the objectives. The test series are the following:

Test A-1: A test that estimates the economic impact of contaminating the contiguous US to verify that the loss in GDP is the same as that for the contiguous US.

Test A-2: A test that estimates the economic impact of contaminating a single county in the US to demonstrate that the result is the same as the standalone version of REAcct for that county's direct and indirect GDP.

Test A-3: A test that calculates the economic impact of contaminating a portion of a single county (not the same county as Test A-2) to verify that the result is consistent with the standalone REAcct output for that county's direct and indirect GDP.

Series B: Tests that calculate the economic impact of contaminating a region near five typical nuclear power plant sites using three State-of-the-Art Reactor Consequence Analysis (SOARCA) source terms documented in Bixler et al. (2013) and SNL (2013) to compare the RDEIM model with the original, cost-based, economic model.

Table 16 provides the test matrix for these tests and describes each of the Series B tests.

Table 16. Test Matrix

Test Series/Case No.	Description
A-1	Verify that the first-year, direct GDP loss from contaminating the contiguous US is the same as the entire annual GDP for that same region.
A-2	Verify that the GDP loss of contaminating a single county in the US matches that county's direct and indirect GDP.
A-3	Verify that the GDP loss of contaminating a portion of a single county (not the same county as in A-2) in the US reasonably matches that county's direct and indirect GDP.
B-1a	Compare the economic impacts of contaminating a region near Site 1 based on SOARCA input parameters using a small source term, i.e., cesium release fraction of about 0.005%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-1b	Compare the economic impacts of contaminating a region near Site 1 based on SOARCA input parameters using a medium source term, i.e., cesium release fraction of about 4%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-1c	Compare the economic impacts of contaminating a region near Site 1 based on SOARCA input parameters using a large source term, i.e., cesium release fraction of about 36%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-2a	Compare the economic impacts of contaminating a region near Site 2 based on SOARCA input parameters using a small source term, i.e., cesium release fraction of about 0.005%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-2b	Compare the economic impacts of contaminating a region near Site 2 based on SOARCA input parameters using a medium source term, i.e., cesium release fraction of about 4%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-2c	Compare the economic impacts of contaminating a region near Site 2 based on SOARCA input parameters using a large source term, i.e., cesium release fraction of about 36%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-3a	Compare the economic impacts of contaminating a region near Site 3 based on SOARCA input parameters using a small source term, i.e., cesium release fraction of about 0.005%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-3b	Compare the economic impacts of contaminating a region near Site 3 based on SOARCA input parameters using a medium source term, i.e., cesium release fraction of about 4%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-3c	Compare the economic impacts of contaminating a region near Site 3 based on SOARCA input parameters using a large source term, i.e., cesium release fraction of about 36%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-4a	Compare the economic impacts of contaminating a region near Site 4 based on SOARCA input parameters using a small source term, i.e., cesium release fraction of about 0.005%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-4b	Compare the economic impacts of contaminating a region near Site 4 based on SOARCA input parameters using a medium source term, i.e., cesium release fraction of about 4%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-4c	Compare the economic impacts of contaminating a region near Site 4 based on SOARCA input parameters using a large source term, i.e., cesium release fraction of about 36%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-5a	Compare the economic impacts of contaminating a region near Site 5 based on SOARCA input parameters using a small source term, i.e., cesium release fraction of about 0.005%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-5b	Compare the economic impacts of contaminating a region near Site 5 based on SOARCA input parameters using a medium source term, i.e., cesium release fraction of about 4%, predicted by the GDP-based (RDEIM) model and by the cost-based model.
B-5c	Compare the economic impacts of contaminating a region near Site 5 based on SOARCA input parameters using a large source term, i.e., cesium release fraction of about 36%, predicted by the GDP-based (RDEIM) model and by the cost-based model.

5.2. Verification and Benchmarking Case Assumptions

For all verification cases, the year 2011 is assumed as the year during which the accident occurs, which is the same as the basis year for the GDP data. SecPop has a 2010 US census data base and a 2007 US Bureau of Labor Statistics data base. For these test cases, SecPop used a population multiplier adjustment of 1.009135 to approximate the 2011 population. This population multiplier is based on the annual estimates of the population growth for the United States between April 1, 2010 (i.e., the basis of the 2010 U.S. Census) and mid-year 2011. The economic multiplier used in SecPop for these test cases is 1.06346, which is intended to adjust 2007 values to 2011 values. This is based on the change from 2007 to 2011 of the core Consumer Price Index (CPI) maintained by the US Department of Labor Bureau of Labor Statistics for all urban consumers. The CPI is a U.S. city average and does not include food and energy.

For the Test Case A series, a Cs-137 source term sufficient to contaminate the entire U.S. was used in the analysis. For the Test Case B series, the same three source terms were used for all five reactor sites. Table 17 provides a brief source term description for the low (Test Case B-a series), medium (Test Case B-b series), and high (Test Case B-c series) source terms. These are the same source terms discussed in Table 16.

Table 17. Brief Source Term Description for Test Case B Series Analyses

Scenario	Integral Release Fractions by Chemical Group									Atmospheric Release Timing	
	Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La	Start (hr)	End (hr)
Small ST	1.0E-4	5.4E-5	5.0E-5	1.8E-6	5.8E-7	4.0E-6	2.4E-8	1.6E-7	5.0E-6	6.1	8.6
Medium ST	1.0E+0	4.0E-2	2.3E-2	1.5E-3	3.2E-4	3.7E-4	6.5E-6	7.2E-5	3.2E-4	7.1	9.4
Large ST	9.7E-1	3.6E-1	3.4E-1	1.3E-3	2.4E-3	2.2E-2	9.9E-5	1.6E-4	8.6E-3	5.9	8.4

For Benchmark Case B series source terms, For the Test Case A series, the weather is user-supplied and constant. For the Test Case B series, the weather is sampled from a user-supplied meteorological file developed for NUREG/CR-7110 Volume 1 (Bixler et al., 2013).

Table 18 provides the mean (over weather), peak (around the compass) long-term effective dose to individuals at specified radial distances. This is the MACCS-calculated, long-term, effective dose an individual would receive if not relocated during the long-term phase. Since MACCS imposes a limit for long-term habitability, individuals would not receive these doses at distances where they exceed the habitability criterion, which is specified to be 0.5 rem/yr. In other words, an area is habitable when the annual effective dose is less than 0.5 rem (0.005 Sv).

For the Test Case A series, the weather is user-supplied and constant. For the Test Case B series, the weather is sampled from a user-supplied meteorological file developed for NUREG/CR-7110 Volume 1 (Bixler et al., 2013).

Table 18. Test Case B Mean, Long-Term Peak Dose Found on the Spatial Grid

Inner Radius (mile)	Outer Radius (mile)	Small ST (rem)	Medium ST (rem)	Large ST (rem)
0.3	0.7	1.42	183	8,670
0.7	1.0	0.90	119	5,510
1.0	1.3	0.67	94.5	4,130
1.3	2.0	0.46	73.4	2,780
2.0	2.5	0.32	61.1	1,940
2.5	3.0	0.25	54.3	1,510
3.0	3.5	0.20	49.0	1,210
3.5	5.0	0.13	40.0	823
5.0	7.0	0.079	28.8	483
7.0	10.0	0.046	19.6	282
10.0	13.0	0.029	13.3	287
13.0	16.0	0.020	9.57	194
16.0	20.0	0.014	6.67	130
20.0	25.0	0.009	4.63	94.0
25.0	30.0	0.007	3.34	64.5
30.0	40.0	0.005	2.31	42.1
40.0	50.0	0.003	1.72	29.2
50.0	70.2	0.002	1.15	18.5
70.2	100	0.001	0.76	12.0
100	150	0.001	0.45	7.13
150	200	0.0005	0.26	4.38
200	350	0.0003	0.16	2.58
350	500	0.0003	0.15	2.15
500	1000	0.0001	0.04	0.62

5.3. Site Selection for Benchmarking Cases

The site selection of the Test Case B series is based on total non-farmland property value within a 50-mile radial distance for all 68 commercial US nuclear power plant sites. Generally, farmland property value is relatively small so that non-farmland value is a good indicator of the overall property value. Figure 10 shows the total non-farmland property value for the selected Test Case B series sites (black dots) along with all other US reactor sites (green curve). Figure 11 shows the same Test Case B series sites (shown as red dots) but with their respective percentile ranking for non-farmland property value within a 50-mile radial distance. Table 19 lists the five sites that were selected and gives the percentile ranking for each site in terms of non-farm property value.

The authors intentionally chose sites that represent the statistical range of wealth values. Additionally, the two SOARCA sites of Peach Bottom and Surry were included in the set. The selection of sites is intended to show that the cost- and GDP-based models give relatively consistent results over a broad spectrum of sites. Because the intention is to show that the two models are reasonably consistent, the economic losses are presented on a relative basis, where the denominator is the total loss predicted by the GDP-based model.

Table 19. Description of Selected Sites

Site Number	Site Name	Percentile Non-Farm Property Value Among U.S. Sites
1	Peach Bottom	93%
2	Surry	68%
3	Callaway	16%
4	Susquehanna	52%
5	Braidwood	87%

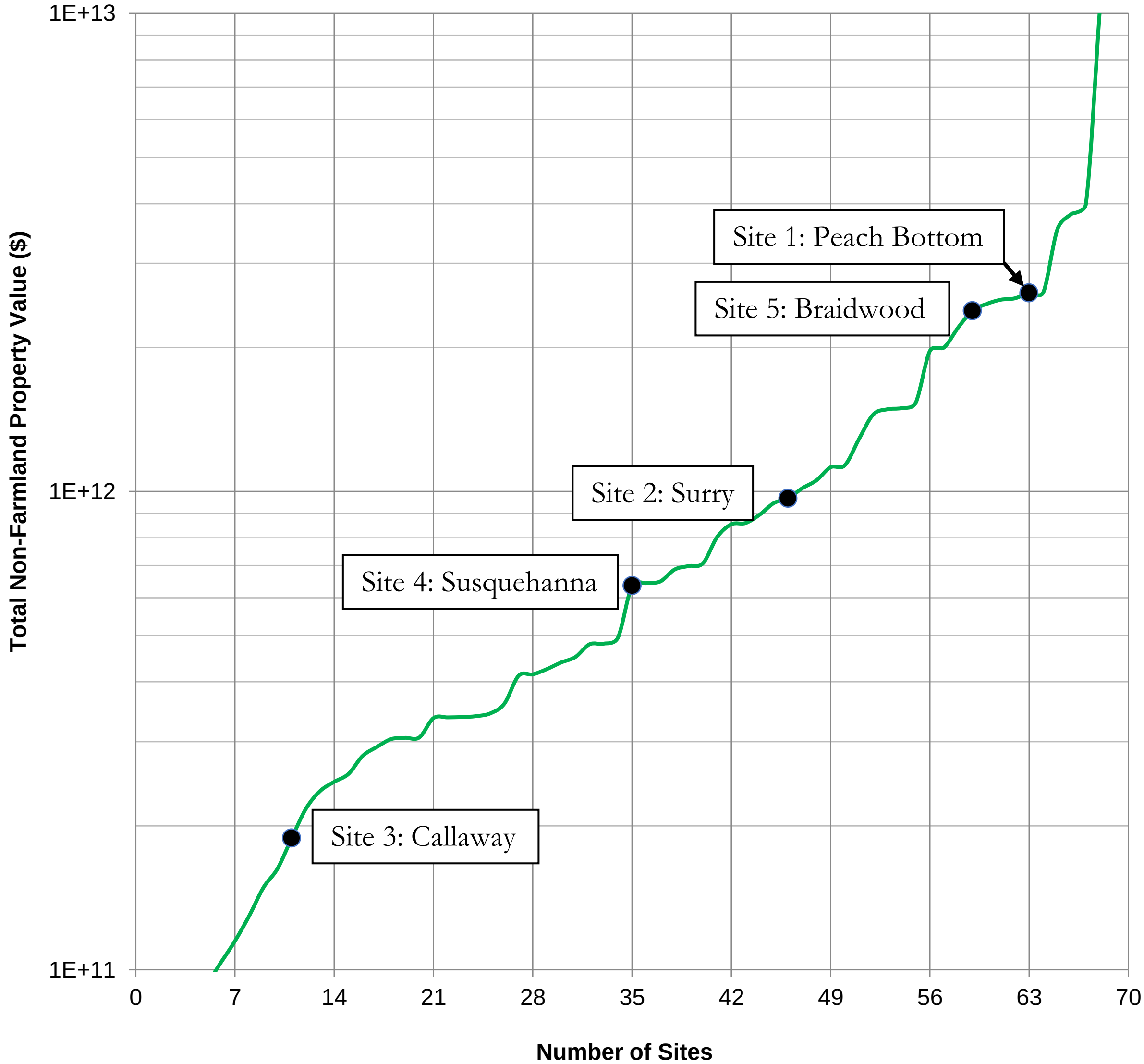

Figure 10: Test Case B series site selection for population and non-farmland property value data at the 50-mile radial distance

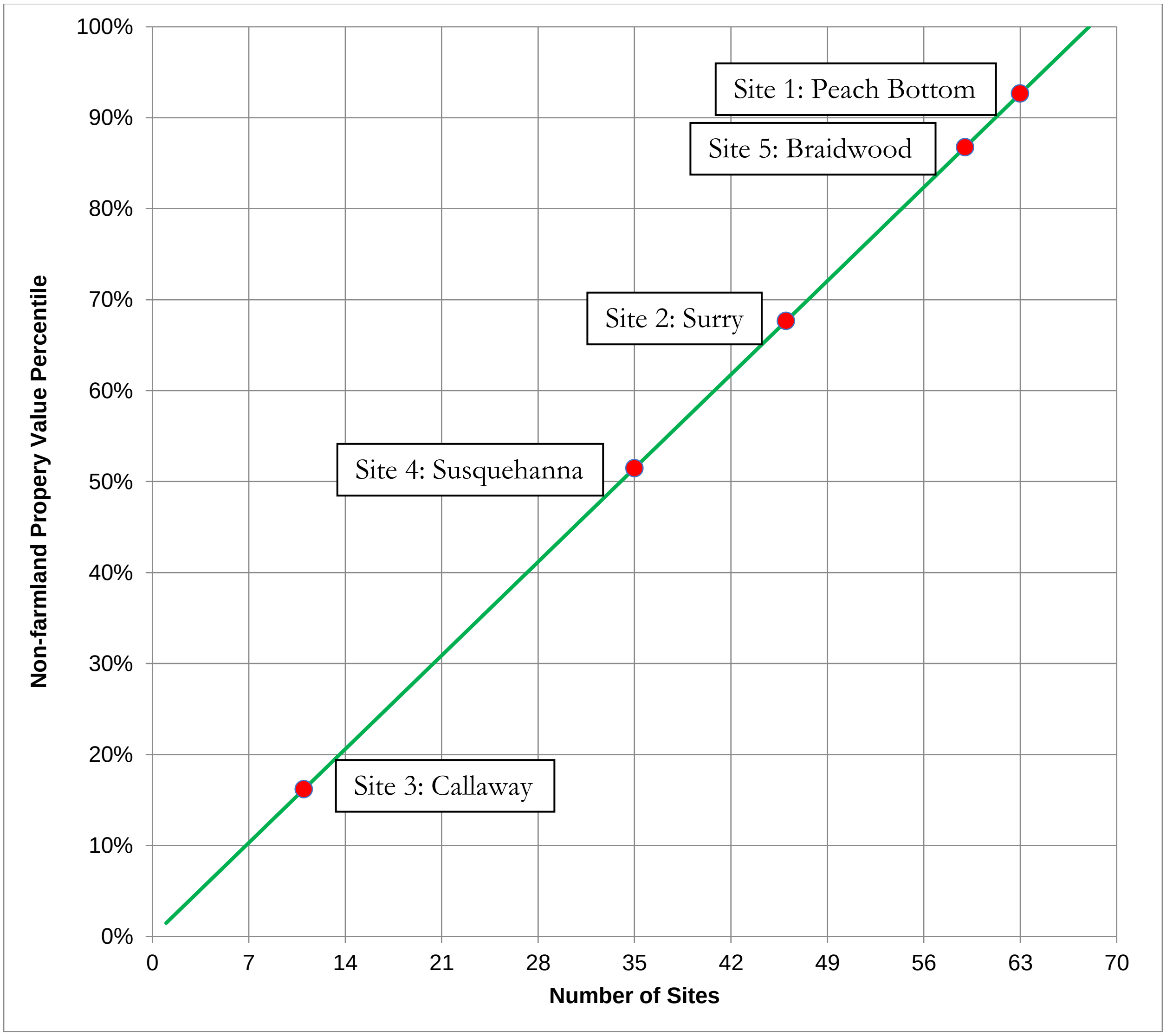

Figure 11: Test Case B series site selection for non-farmland property value percentile data at the 50-mile radial distance

5.4. Reporting Benchmarking Results

Land areas contaminated above a threshold level can be calculated several ways in MACCS, the simplest of which is to report land areas that exceed activity levels per unit area for an isotope. This approach is used here based on the same threshold levels of Cs-137 as were reported following the Chernobyl accident (IAEA, 2001).

Other than the noble gases, each of the isotopes can deposit onto surfaces and cause contamination, but most of them have short half-lives and only remain in the environment for days or weeks. For example, iodine-131 has an eight-day half-life. Thus, in 80 days (i.e., 10 half-lives) its concentration is diminished to $2^{-10} \approx 0.001$ of its initial activity. As a result, it contributes to short-term doses but does not normally require decontamination because it disappears on its own. A relatively small number of the isotopes that could potentially be released from a nuclear reactor are radiologically important and require effort to decontaminate. Among these are Cs-134, Cs-137, and Sr-90, which have half-lives of about 2, 30, and 29 years, respectively. Of these, Cs-137 is usually the most important in terms of decontamination requirements.

Cs-137 land contamination discussed by the International Atomic Energy Agency (IAEA) for the Chernobyl accident were reported at levels of 1, 5, 15, and 40 Ci/km^2, which are the same values in units of μCi/m^2. Based on these land contamination levels, the IAEA report was able to estimate the corresponding annual effective external doses. Table 20 provides these effective dose estimates (IAEA, 2001).

Table 20. Chernobyl Annual Effective External Dose Estimates for 1986 to 1995

Cs-137 Soil Deposition (μCi/m^2)	Annual Effective External Dose (rem)									
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
1	0.06	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
5	0.25	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.04	0.04
15	0.79	0.20	0.19	0.18	0.18	0.18	0.17	0.15	0.14	0.13

5.5. Success Criteria

Success criteria for the verification cases are as follows:

- Good agreement is when the RDEIM results are within 5% of the independently calculated results. Some results described below have some uncertainty in the exact inputs used to calculate them. This uncertainty stems from not knowing the exact grid elements that are disrupted as a function of time. This uncertainty can cause 5% errors in the evaluated results. As a result, a 5% error in cases where there is some uncertainty in the affected grid elements is considered good agreement.
- Excellent agreement is when the RDEIM results are within 1% of the independently constructed results.

Analogous success criteria for the benchmark cases are less strict because the comparison is between two models, the cost-based and the GDP-based models, that are very different and are not expected to provide the same results. The expectation is that all results should be within a factor of two of each other. The criteria adopted for the benchmark cases are as follows:

- As an expected upper bound, the total cost-based losses should be within -50% to +100% of the RDEIM results. The expectation for some nonlinear results, like areas and populations associated with a remedial action such as condemnation, is that the agreement should usually be within the same bounds but in some cases may not be within these bounds. In particular, the expectation is for poorer agreement in cases with small values. In the worst case, one of the models could have a finite result and the other a zero result because a small area or population is right at the threshold for being counted or not being counted.
- Good agreement between the two models is within 50%.
- Excellent agreement between the two models is within 20%.

Test results are documented and were reviewed to assure that the tests meet the requirements of this verification project. Some tests are verified by hand calculations. Any discrepancies discovered are noted in this report.

The results of the RDEIM model evaluation are fully documented in Section 6. This section provides a clear indication of how the requirements and the objectives of this verification plan were met. Specific detailed discussions are provided for each test together with documentation of the results. Results of the program testing are also summarized for convenient review. For traceability, all test case inputs, outputs, and spreadsheet calculations are preserved as part of the program QA documentation.

6. VERIFICATION AND BENCHMARKING RESULTS

The verification results presented in this section used MACCS Version 3.11.0.16 (SVN-6798) with WinMACCS Version 3.11.6 (SVN-6662), SecPop Version 4.2.1, and REAcct Version 41. For the Test Case A and B series, the base MACCS inputs were modified from those developed for the SOARCA project documented in NUREG-1935 (Chang et al., 2012) and its supporting documentation (Bixler et al., 2013, Sandia National Laboratories, 2013). The MACCS inputs used in this verification exercise use the generic COMIDA2 food pathway model discussed in Chanin and Young (1998) and Bixler et al. (2020); whereas, the SOARCA project did not include the food-ingestion pathway. For the Test Case A series, the evacuation model uses a generic circular evacuation with a single cohort. The network evacuation model used in the Test Series B series is taken directly from one of the SOARCA pilot plants (Bixler et al., 2013) and applied to all five reactor sites in the series. Thus, the site-specific aspects treated in Test Series B are limited to the spatial distributions of population, property values, and industry. The economic results depend solely on land areas that are contaminated above a specified level, so many of the site-specific details, like evacuation routing, do not affect the estimated costs with either of the economic models.

6.1. Verification Cases

6.1.1. Verification Case A-1

The goal of Test Case A-1 is to verify that the direct GDP losses from contaminating the contiguous US using the GDP-based model in MACCS matches the loss from a standalone version of REAcct and the BEA-estimated GDP for the contiguous US for the year 2011 (BEA, 2012). The land contamination information is provided in Table 21 and verifies that the entire contiguous US is affected by the source term. The source term release is centered near the geographic center of the contiguous U.S. (i.e., near Lebanon, KS).

The land fraction estimated by MACCS to have been contaminated in this analysis is 112% the area of the contiguous US. This is because MACCS uses a polar coordinate system that does not match the shape of the US. Because of this, there is some approximation of the land area in the grid elements that extend beyond the contiguous US. However, this error does not affect the calculation of GDP losses because the fraction of a county within a grid element is limited to be no more than unity, so none of the county contributions to GDP are overcounted. Furthermore, no GDP values are assigned to areas within Canada and Mexico, so these areas do not contribute to the estimated GDP losses.

Table 21. Test Case A-1: Land Contamination Information

Land Information	Contiguous U.S.
Total Land Area ($mile^2$)	2,959,064
Percent of Total Land Area Contaminated (MACCS output)	112%
Total Number of Counties in Contiguous US	3109
Number of Counties in MACCS Calculation	3109

Table 22 provides MACCS direct GDP-based output for Test Case A-1 and compares it with standalone REAcct output and with the reported GDP from BEA for 2011 (BEA, 2012). The BEA value for GDP excludes the contributions from Alaska and Hawaii and also excludes the Federal Military Industry. The MACCS direct GDP loss agrees to three significant digits with the standalone REAcct model result and is in excellent agreement with the BEA value (within 1%). This verifies that MACCS using the GDP-based model produces the correct result for the case of contaminating the contiguous US. Standalone REAcct and the MACCS RDEIM models both slightly overestimate GDP loss compared with the BEA values, but this is attributed to roundoff error.

Table 22. Test Case A-1: GDP Loss Reported in Trillions of 2011 Dollars when the Contiguous US is Disrupted for a One-Year Period

	Contiguous U.S.		
Impact Type	**Standalone REAcct Model**	**BEA (2012)**	**MACCS RDEIM Model (version 3.11.6)**
Direct GDP	$14.8	$14.7	$14.8
Percent Difference	0.68%	-	0.68%

6.1.2. *Verification Case A-2*

The goal of Test Case A-2 is to verify the GDP losses created by contaminating a single county using the GDP-based model in MACCS with the losses calculated for the same county using the standalone version of REAcct. Although the attempt was to contaminate all of Cameron County, Texas, without contaminating any other county, it turns out that a small fraction of Willacy County, Texas, was contaminated while slightly less than 100% of Cameron County was contaminated, as shown in Table 23.

Table 23. Test Case A-2: County Fraction Information

	Cameron County, Texas	**Willacy County, Texas**
Population Fraction	99.7%	8.2%
Area Fraction	97.9%	4.8%

Table 24 provides the MACCS direct and indirect GDP-based output for Test Case A-2 and shows a comparison with the standalone REAcct output. The results for the REAcct output considers both affected counties and is adjusted according to the fractions shown in Table 2, assuming that half of the GDP loss is based on area fraction and half is based on population fraction. In other words, the GDP-based results are assumed to account for 98.8% of the direct and indirect GDP for Cameron County and 6.5% of the GDP for Willacy County. Since the population and area fractions are similar, especially for Cameron County, the uncertainty introduced by using the average of the population and area fractions is not large. The MACCS output is in excellent agreement with the standalone REAcct results (within 1%) and this verifies the MACCS GDP-based model produces results that are well within the uncertainty in the overall weighting fraction for Test Case A-2 (about 3.4%).

Table 24. Test Case A-2: Direct GDP Loss Comparison in Billions of 2011 Dollars when Most of One County and a Small Fraction of Another Are Disrupted for a Single Year

	Cameron County, Texas	
Impact Type	**REAcct Standalone Model**	**MACCS RDEIM Model (Version 3.11.6)**
Direct GDP	$12.1	$12.1
Percent Difference	-	0%

6.1.3. Verification Case A-3

The goal of Test Case A-3 is to verify the direct GDP losses that would result from contaminating a portion of a single county (not the same county in Test Case A-2) by comparing the GDP-based model in MACCS with the standalone REAcct model. The release occurs from near the southern boundary of the county and moves toward the north. Lake Erie and southern Canada lie to the north of Ashtabula County, Ohio, so no other US counties are affected by the release.

Table 25 provides the population and area fractions of Ashtabula County for five compass sectors centered on north (based on a 64-compass-sector grid) within a radius of about 45 km, which includes the outer extent of Ashtabula County. These values are from SecPop data for Ashtabula county. However, the fractions may not precisely account for the boundary of the affected area because it may not align with sector boundaries. The imprecision should not be larger than the difference between population and area fractions shown in Table 25 (about 22.5%) and is expected to be significantly less than that.

Table 25. Test Case A-3: Population and Area Fraction of Ashtabula County, Ohio

	Area within 45 km and 5 Compass Sectors Centered on North
Population Fraction	47.4%
Area Fraction	24.9%

Table 26 provides the MACCS direct GDP-based output for Test Case A-3 and compares it with the standalone REAcct results. The result for standalone REAcct is for the entire county assuming the period of disruption is one year; the result for the MACCS RDEIM model ($1.12 B in the first year) is extrapolated to the entire county based on the population and area fractions shown in Table 24. To use the area and population fractions, the MACCS direct GDP losses are split into the ones based on area fraction ($463 M) and the ones based on population fraction ($652 M). The industries and the method used for partial counties is provided in Table 2. The MACCS RDEIM result in Table 25 is calculated as follows:

$$Direct\ GDP\ Loss\ in\ first\ year = \frac{\$463\ \mathrm{M}}{0.249} + \frac{\$652\ \mathrm{M}}{0.474} = \$3.24\ B$$

The MACCS RDEIM model appears to overestimate the losses for the county based on the population and area fractions shown in Table 24. However, as explained above, the land and area fractions in the table may not be precise, i.e., the plume boundaries may not precisely follow the sector boundaries as assumed in the table. The comparison shown in Table 26 is considered to be good agreement (less than 5%, as defined in the acceptance criteria in the previous section) given the uncertainties in the fractions of the area and population of the affected area, as discussed above.

Table 26. Test Case A-3: One-Year Economic Result Comparison for Direct GDP Losses when Part of Ashtabula County is Affected by a Release

	Estimated for All Ashtabula County, OH	
Impact Type	**Standalone REAcct Model**	**MACCS RDEIM Model (Version 3.11.6)**
Direct GDP	$3.09 B	$3.24 B
Percent Difference	-	4.9%

6.2. Benchmark Cases

6.2.1. Benchmark Case B-1

The purpose of Case B-1 is to compare the MACCS GDP-based and cost-based economic losses created by an assumed nuclear reactor accident at Reactor Site 1 (93rd percentile data point from Figure 11) using modified WinMACCS parameters from the body of SOARCA work and using small, medium, and large source terms, i.e., cesium environmental release fractions of about 0.005%, 4%, and 36% of the core inventory, respectively, as shown in Table 17. All analyses use the default 10 years for the duration of the economic impact, 3 years for national recovery, and the other default values in the GDP-based model. Non-economic parameters used in the GDP-based and cost-based economic models are the same. However, it should be noted that the discount rate used in the cost-based model is 12%, the value used in NUREG-1150, as this is the value that has traditionally been used with MACCS. This value is used in the cost-based model in two ways: (1) it is used to determine the expected rate of return on the value of property to estimate the value of loss of use of property and it is used to discount future year losses to a present worth in the cost-based model. This value, 12%, is much higher than the 3% social discount rate used in the GDP-based model, which is used to discount future year losses to a present worth in the GDP-based model. This is expected to increase losses for the GDP-based model relative to the cost-based model when losses extend significantly beyond one year.

Table 27 provides a summary of the cost-based and GDP-based results for Reactor Site 1 for a low-activity source term. The results are all normalized by the total cost for the GDP-based model. The results in the table include decontamination, loss of use, depreciation, condemnation, relocation, and disposal costs. Values in the table are blank when they are not calculated by one of the economic models. A value of 0.00% indicates that the value is calculated to be approximately zero.

Losses predicted by the cost-based model are lower (about 3%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are lower when only direct GDP losses are included (direct GDP contribution is 2.39% as compared with 4.16% for total GDP), which makes the cost-based result about 1% lower. Comparing just the direct GDP losses rather than total GDP losses is reasonable because the cost-based model does not account for any losses beyond the directly affected region.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses are greater than the loss-of-use costs, which are respectively 2.39% and 0.71% + 0.51% = 1.22%. Most of the other costs are evaluated to be the same in the two models. The exception is that the milk and crop disposal costs are not included in the GDP-base model, but those contributions (0.03% and 0.39%) have a relatively minor effect on the total cost-based losses.

Table 27. Benchmark Case B-1a: Mean, GDP-Based Losses within 50 Miles of Reactor Site 1 Using the Small Source Term

	Small Source Term (B1-a)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	97.33%
TOTAL NATIONAL GDP LOSSES	4.16%	
ALL DIRECT INDUSTRIES GDP LOSSES	2.39%	
ALL INDIRECT INDUSTRIES GDP LOSSES	0.91%	
ALL INDUCED INDUSTRIES GDP LOSSES	0.85%	
POP.-DEPENDENT DECONTAMINATION COST	0.64%	0.64%
FARM-DEPENDENT DECONTAMINATION COST	0.12%	0.12%
POP.-DEPENDENT LOSS OF USE COST		0.71%
FARM-DEPENDENT LOSS OF USE COST		0.51%
POP.-DEPENDENT DEPRECIATION LOSSES	0.58%	0.58%
FARM-DEPENDENT DEPRECIATION LOSSES	0.16%	0.16%
POP.-DEPENDENT CONDEMNATION COST	0.00%	0.00%
FARM-DEPENDENT CONDEMNATION COST	0.00%	0.00%
EMERGENCY RELOCATION COST	93.33%	93.33%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	1.07%	1.07%
MILK DISPOSAL COST		0.03%
CROP DISPOSAL COST		0.39%

Table 28 provides a summary of the cost-based and GDP-based results for Reactor Site 1 with a medium-activity source term. The losses for the cost-based model are lower (about 14%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are lower when only direct GDP losses are included (direct GDP contribution is 21.90% compared with of 38.21% for total GDP losses that include indirect and induced losses). Thus, if only direct GDP losses had been included, the GDP-based model would have been lower by 16.31%, which makes the result a little smaller than the cost-based model prediction. Since the cost-based model does not attempt to include indirect and induced losses, it is reasonable to compare the GDP-based predictions excluding these losses.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP contribution (21.90%) is less than the loss-of-use contribution, which is 22.87% + 1.06% = 23.93%. Some of the other costs are evaluated to be the same in the two models and the costs match to the precision of the table. However, the logic to determine whether decontamination should be performed is slightly different for the two models. The GDP model uses direct GDP losses; whereas, the cost-based model uses loss of use in the decision process. Thus, the losses for decontamination, depreciation, and condemnation are similar but different for the two models. More populated land is condemned with the GDP-based model, but less farmland is condemned; more farmland and less populated land is decontaminated with the GDP-based model. The milk and crop disposal costs are not included in the GDP-based model, but those contributions (0.05% and 0.74%, respectively) contribute less than 1% of the total losses.

Table 28. Benchmark Case B-1b: Mean, GDP-Based Losses within 50 Miles of Reactor Site 1 Using the Medium Source Term

	Medium Source Term (B1-b)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	86.33%
TOTAL NATIONAL GDP LOSSES	38.21%	
ALL DIRECT INDUSTRIES GDP LOSSES	21.90%	
ALL INDIRECT INDUSTRIES GDP LOSSES	5.93%	
ALL INDUCED INDUSTRIES GDP LOSSES	10.39%	
POP.-DEPENDENT DECONTAMINATION COST	18.55%	18.55%
FARM-DEPENDENT DECONTAMINATION COST	0.60%	0.59%
POP.-DEPENDENT LOSS OF USE COST		22.87%
FARM-DEPENDENT LOSS OF USE COST		1.06%
POP.-DEPENDENT DEPRECIATION LOSSES	17.43%	17.57%
FARM-DEPENDENT DEPRECIATION LOSSES	0.33%	0.32%
POP.-DEPENDENT CONDEMNATION COST	0.32%	0.13%
FARM-DEPENDENT CONDEMNATION COST	0.19%	0.26%
EMERGENCY RELOCATION COST	2.27%	2.27%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	22.04%	22.04%
MILK DISPOSAL COST		0.05%
CROP DISPOSAL COST		0.74%

Table 29 provides a summary of the cost-based and GDP-based results for Reactor Site 1 for a high-activity source term. The losses predicted by the cost-based model are lower (about 12%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are higher by a fraction of a percent when only direct GDP losses are included (direct GDP contribution is 41.96% instead of 41.61% for the total GDP contribution), so the comparison is nearly the same either way.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP contribution (41.96%) is greater than the loss-of-use contribution, which is 32.06% + 0.37% = 32.43%, and this accounts for most of the difference between the two models.

The logic to determine whether decontamination should be performed is slightly different for the two models. The GDP model uses direct GDP losses; whereas, the cost-based model uses loss of use in the decision process. Thus, the losses for decontamination, depreciation, and condemnation are similar but different for the two models. The only cost category that is the same for the two models is emergency-phase relocation costs; all the long-term costs are at least slightly different. In terms of predicted losses, more populated land is condemned with the GDP-based model, but less farmland is condemned; on the other hand, more farmland and less populated land are decontaminated and interdicted with the GDP-based model. The milk and crop disposal costs are not included in the GDP-based model, but those contributions (0.02% and 0.33%, respectively) contribute well under 1% of the total losses predicted by the cost-based model.

Table 29. Benchmark Case B-1c: Mean, GDP-Based Losses within 50 Miles of Reactor 1 Using the Large Source Term

	Large Source Term (B1-c)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	88.11%
TOTAL NATIONAL GDP LOSSES	41.61%	
ALL DIRECT INDUSTRIES GDP LOSSES	41.96%	
ALL INDIRECT INDUSTRIES GDP LOSSES	-11.68%	
ALL INDUCED INDUSTRIES GDP LOSSES	11.33%	
POP.-DEPENDENT DECONTAMINATION COST	15.59%	15.77%
FARM-DEPENDENT DECONTAMINATION COST	0.33%	0.32%
POP.-DEPENDENT LOSS OF USE COST		32.06%
FARM-DEPENDENT LOSS OF USE COST		0.37%
POP.-DEPENDENT DEPRECIATION LOSSES	17.27%	17.48%
FARM-DEPENDENT DEPRECIATION LOSSES	0.11%	0.11%
POP.-DEPENDENT CONDEMNATION COST	10.24%	6.47%
FARM-DEPENDENT CONDEMNATION COST	0.71%	0.79%
EMERGENCY RELOCATION COST	1.37%	1.37%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	12.97%	13.18%
MILK DISPOSAL COST		0.02%
CROP DISPOSAL COST		0.33%

Table 30 and Table 31 show the affected areas, i.e., the areas that require some level of remediation, estimated by the cost-based and GDP-based economic models, respectively. These results indicate good to excellent agreement for all three source terms. The agreement is best and poorest for the small and large source terms, respectively. The poorest comparison is for the condemned populated areas with the large source term, for which the cost-based prediction is about 30% lower than the GDP-based one. The differences between the models are because the logic to determine whether it is economical to decontaminate an area is different. For the cost-based model the decision to decontaminate includes the cost associated with loss of use of the property for the period of interdiction; for the GDP-based model the decision to decontaminate includes the loss of GDP for the period of interdiction. Since these values are different, the decision process can be different for the two models. The largest relative differences are for the areas that are condemned. The decision to condemn populated areas is also affected by the maximum number of years of interdiction considered in the model, which is 10 years for the GDP-based model and 30 years for the cost-based model.

Table 32 and Table 33 show the affected populations corresponding to the populated areas shown in Tables 29 and 30. The populations are the same for the small source term, but somewhat different for the medium and large source terms. The largest relative difference is for the populations associated with condemned land, which is about 37% smaller for the cost-based model. This is acceptable agreement considering that this is a highly nonlinear result with a small magnitude.

Table 30. Benchmark Case B-1: Mean, Affected Area for the Cost-Based Model within 50 Miles of Reactor 1

AFFECTED AREA ($mile^2$)	Small ST (B1-a)	Medium ST (B1-b)	Large ST (B1-c)
FARM DECONTAMINATION AREA	0.05	81	142
POP. DECONTAMINATION AREA	0.04	107	244
FARM INTERDICTION AREA	0.09	105	147
POP. INTERDICTION AREA	0.04	107	244
FARM CONDEMNATION AREA	0.00	3	42
POP. CONDEMNATION AREA	0.00	0	6

Table 31. Benchmark Case B-1: Mean, Affected Area for the GDP-Based Model within 50 Miles of Reactor 1

AFFECTED AREA ($mile^2$)	Small ST (B1-a)	Medium ST (B1-b)	Large ST (B1-c)
FARM DECONTAMINATION AREA	0.05	81	146
POP. DECONTAMINATION AREA	0.04	107	242
FARM INTERDICTION AREA	0.09	106	152
POP. INTERDICTION AREA	0.04	107	242
FARM CONDEMNATION AREA	0.00	2	38
POP. CONDEMNATION AREA	0.00	0	9

Table 32. Benchmark Case B-1: Mean, Affected Population for the Cost-Based Model within 50 Miles of Reactor 1

AFFECTED POPULATION	Small ST (B1-a)	Medium ST (B1-b)	Large ST (B1-c)
DECONTAMINATION (INDIVIDUALS)	12	119,000	282,000
INTERDICTION (INDIVIDUALS)	12	119,000	282,000
CONDEMNATION (INDIVIDUALS)	0	22	4,000

Table 33. Benchmark Case B-1: Mean, Affected Population for the GDP-Based Model within 50 Miles of Reactor 1

AFFECTED POPULATION	Small ST (B1-a)	Medium ST (B1-b)	Large ST (B1-c)
DECONTAMINATION (INDIVIDUALS)	12	119,000	280,000
INTERDICTION (INDIVIDUALS)	12	119,000	280,000
CONDEMNATION (INDIVIDUALS)	0	52	6,350

6.2.2. Benchmark Case B-2

The purpose for Case B-2 is to compare the MACCS GDP-based and cost-based economic losses created by an assumed nuclear reactor accident at Reactor Site 2 (68th percentile data point from Figure 11) using modified WinMACCS parameters from the body of SOARCA work and using small, medium, and large source terms, as shown Table 17. The inputs are intentionally kept the same for the two economic models, with the caveat discussed in Section 6.2.1.

Table 34 provides a summary of the cost-based and GDP-based results for Reactor Site 2 for a small source term. The results in the table include decontamination, loss of use, depreciation, condemnation, relocation, and disposal costs. Values in the table are blank when they are not calculated by one of the economic models. A value of $0 indicates that the value is calculated to be zero.

The cost-based model is slightly lower (about 0.4%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are slightly lower when only direct GDP losses are included (direct GDP contribution is 0.63% instead of 0.86% for the total GDP contribution), but his difference is a trivial portion of the total losses for this case.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses are greater than the loss-of-use costs, which are respectively contribute 0.63% and 0.38% + 0.03% = 0.41%. Most of the other costs are evaluated to be the same in the two models. The exception is that the milk and crop disposal costs are not included in the GDP-base model, but those contributions (0.00% and 0.01%) are trivial for this case.

Table 34. Benchmark Case B-2a: Mean, GDP-Based Losses within 50 Miles of Reactor Site 2 Using the Small Source Term

	Small Source Term (B2-a)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	99.56%
TOTAL NATIONAL GDP LOSSES	0.86%	
ALL DIRECT INDUSTRIES GDP LOSSES	0.63%	
ALL INDIRECT INDUSTRIES GDP LOSSES	0.09%	
ALL INDUCED INDUSTRIES GDP LOSSES	0.13%	
POP.-DEPENDENT DECONTAMINATION COST	0.27%	0.27%
FARM-DEPENDENT DECONTAMINATION COST	0.01%	0.01%
POP.-DEPENDENT LOSS OF USE COST		0.38%
FARM-DEPENDENT LOSS OF USE COST		0.03%
POP.-DEPENDENT DEPRECIATION LOSSES	0.30%	0.30%
FARM-DEPENDENT DEPRECIATION LOSSES	0.01%	0.01%
POP.-DEPENDENT CONDEMNATION COST	0.00%	0.00%
FARM-DEPENDENT CONDEMNATION COST	0.00%	0.00%
EMERGENCY RELOCATION COST	98.25%	98.25%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	0.46%	0.46%
MILK DISPOSAL COST		0.00%
CROP DISPOSAL COST		0.01%

Table 35 provides a summary of the cost-based and GDP-based results for Reactor Site 2 for a medium source term. The cost-based model is lower (about 13%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are lower when only direct GDP losses are included (direct GDP contribution is 22.88% compared with a total GDP contribution of 37.29%). If only direct GDP losses had been included, the GDP-based model would have been about 14% lower, which makes it less than the cost-based model prediction. It is reasonable to compare just the direct GDP losses with the cost-based losses because the latter do not include economic effects beyond the impacted area.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP contribution (22.88%) is less than the loss-of-use contribution, which is 23.94% + 0.61% = 24.55%.

The logic to determine whether decontamination should be performed is slightly different for the two models, as explained above. Thus, the losses for decontamination, depreciation, and condemnation are similar but different for the two models. The maximum difference is for the losses associated with condemned populated land, which is about 50% less for the cost-based model. This is at the limit of the expected differences described in Section 5, but this difference is acceptable for a nonlinear result that only contributes slightly to the total losses. While more populated land is condemned with the GDP-based model, less farmland is condemned; decontaminated land is nearly the same with the two models. The milk and crop disposal costs are not included in the GDP-based model, and those contributions 0.01% and 0.34%, respectively) represents a very small fraction of the overall losses.

Table 35. Benchmark Case B-2b Mean, GDP-Based Losses within 50 Miles of Reactor Site 2 Using the Medium Source Term

	Medium Source Term (B2-b)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	87.29%
TOTAL NATIONAL GDP LOSSES	37.29%	
ALL DIRECT INDUSTRIES GDP LOSSES	22.88%	
ALL INDIRECT INDUSTRIES GDP LOSSES	4.68%	
ALL INDUCED INDUSTRIES GDP LOSSES	9.64%	
POP.-DEPENDENT DECONTAMINATION COST	19.39%	19.41%
FARM-DEPENDENT DECONTAMINATION COST	0.53%	0.53%
POP.-DEPENDENT LOSS OF USE COST		23.94%
FARM-DEPENDENT LOSS OF USE COST		0.61%
POP.-DEPENDENT DEPRECIATION LOSSES	17.65%	17.71%
FARM-DEPENDENT DEPRECIATION LOSSES	0.19%	0.19%
POP.-DEPENDENT CONDEMNATION COST	0.76%	0.38%
FARM-DEPENDENT CONDEMNATION COST	0.05%	0.06%
EMERGENCY RELOCATION COST	2.39%	2.39%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	21.61%	21.61%
MILK DISPOSAL COST		0.01%
CROP DISPOSAL COST		0.34%

Table 36 provides a summary of the cost-based and GDP-based results for Reactor Site 2 for a large source term. The cost-based model prediction is lower (about 12%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are higher by about 7% when only direct GDP losses are included (direct GDP contribution is 45.78% as compared with a total GDP contribution of 38.69%). Thus, only including direct GDP losses would make the gap larger between the two models in this case.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (45.78%) are greater than the loss-of-use costs, which are 29.90% + 0.25% = 30.15%. The logic to determine whether decontamination should be performed is slightly different for the two models, as explained previously. Thus, the losses for decontamination, depreciation, and condemnation are similar but different for the two models. The largest difference is for losses from condemned populated land, which are about 24.5% lower for the cost-based model. This is considered good agreement. The only cost category that is the same to the precision shown in the table for the two models is emergency-phase relocation; all the long-term costs are at least slightly different. More populated land is condemned with the GDP-based model, but less farmland is condemned; on the other hand, more farmland and less populated land are decontaminated and interdicted with the GDP-based model. The milk and crop disposal costs are not included in the GDP-based model, but those contributions (0.00% and 0.17%, respectively) are only a small fraction of the overall losses predicted by the cost-based model.

Table 36. Benchmark Case B-2c Mean, GDP-Based Losses within 50 Miles of Reactor 2 Using the Large Source Term

	Large Source Term (B2-c)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	88.44%
TOTAL NATIONAL GDP LOSSES	38.69%	
ALL DIRECT INDUSTRIES GDP LOSSES	45.78%	
ALL INDIRECT INDUSTRIES GDP LOSSES	-17.09%	
ALL INDUCED INDUSTRIES GDP LOSSES	10.05%	
	0.00%	
POP.-DEPENDENT DECONTAMINATION COST	14.87%	15.08%
FARM-DEPENDENT DECONTAMINATION COST	0.34%	0.33%
POP.-DEPENDENT LOSS OF USE COST		29.90%
FARM-DEPENDENT LOSS OF USE COST		0.25%
POP.-DEPENDENT DEPRECIATION LOSSES	15.73%	16.03%
FARM-DEPENDENT DEPRECIATION LOSSES	0.08%	0.07%
POP.-DEPENDENT CONDEMNATION COST	16.03%	12.11%
FARM-DEPENDENT CONDEMNATION COST	0.28%	0.32%
EMERGENCY RELOCATION COST	1.34%	1.34%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	12.41%	12.71%
MILK DISPOSAL COST		0.00%
CROP DISPOSAL COST		0.17%

Table 37 and Table 38 show the affected areas, i.e., the areas that require some level of remediation, estimated by the cost-based and GDP-based economic models, respectively. These results indicate good to excellent agreement for all three source terms. The agreement is best for the small source term and poorest for the large source term. The largest difference is for the condemned populated land area, which is about 26% lower for the cost-based model than for the GDP-based one. This is considered good agreement. The differences between the models are because the logic to determine whether it is economical to decontaminate an area is different. For the cost-based model the decision to decontaminate includes the cost associated with loss-of-use of the property for the period of interdiction; for the GDP-based model the decision to decontaminate includes the loss of GDP for the period of interdiction. Since these values are different, the decision process can be different for the two models. As mentioned above, the largest differences are for the areas condemned. The decision to condemn populated area is also affected by the maximum number of years of interdiction considered in the model, which is 10 years for the GDP-based model and 30 years for the cost-based model.

Table 37. Benchmark Case B-2 Mean, Affected Area for the Cost-Based Model within 50 Miles of Reactor 2

AFFECTED AREA ($mile^2$)	Small ST (B2-a)	Medium ST (B2-b)	Large ST (B2-c)
FARM DECONTAMINATION AREA	0.01	50	103
POP. DECONTAMINATION AREA	0.04	104	220
FARM INTERDICTION AREA	0.02	68	108
POP. INTERDICTION AREA	0.04	104	220
FARM CONDEMNATION AREA	0.00	1	22
POP. CONDEMNATION AREA	0.00	0	8

Table 38. Benchmark Case B-2 Mean, Affected Area for the GDP-Based Model within 50 Miles of Reactor 2

AFFECTED AREA ($mile^2$)	Small ST (B2-a)	Medium ST (B2-b)	Large ST (B2-c)
FARM DECONTAMINATION AREA	0.01	49	106
POP. DECONTAMINATION AREA	0.04	104	218
FARM INTERDICTION AREA	0.02	68	110
POP. INTERDICTION AREA	0.04	104	218
FARM CONDEMNATION AREA	0.00	1	19
POP. CONDEMNATION AREA	0.00	0	11

Table 39 and Table 40 show the affected populations estimated by the cost-based and GDP-based economic models, respectively. These results are generally consistent for all three source terms, but the agreement is best for the small term and poorest for the medium source term, especially for those whose property is condemned. That result is about 52% lower for the cost-based model with the medium source term, which is at the upper limit of the expected differences between the two models. The reason for the differences is the same as described in the previous paragraph.

Table 39. Benchmark Case B-2 Mean, Affected Population for the Cost-Based Model within 50 Miles of Reactor 2

AFFECTED POPULATION	Low (B2-a)	Medium (B2-b)	High (B2-c)
DECONTAMINATION (INDIVIDUALS)	8	77,100	188,000
INTERDICTION (INDIVIDUALS)	8	77,100	188,000
CONDEMNATION (INDIVIDUALS)	0	34	5,130

Table 40. Benchmark Case B-2 Mean, Affected Population for the GDP-Based Model within 50 Miles of Reactor 2

AFFECTED POPULATION	Low (B2-a)	Medium (B2-b)	High (B2-c)
DECONTAMINATION (INDIVIDUALS)	8	77,100	186,000
INTERDICTION (INDIVIDUALS)	8	77,100	186,000
CONDEMNATION (INDIVIDUALS)	0	70	6,880

6.2.3. Benchmark Case B-3

The purpose for Test Case B-3 is to compare the MACCS GDP-based and cost-based economic losses created by an assumed nuclear reactor accident at Reactor Site 3 (16^{th} percentile data point from Figure 11) using modified, SOARCA, WinMACCS parameters and using small, medium, and large source terms. The inputs are intentionally kept the same for the two economic models, with the caveat discussed in Section 6.2.1.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (2.92%) are about 1% greater than the loss-of-use costs, which are 0.89% + 1.08% = 1.97%. The logic to determine whether decontamination should be performed is slightly different for the two models, as explained previously; however, the losses for decontamination, depreciation, and condemnation are the same to the precision shown in the table for the two models. The milk and crop disposal costs are not included in the GDP-based model, but those costs (0.00% and 0.48%, respectively) are a small fraction of the overall losses.

Table 41 provides a summary of the cost-based and GDP-based results for Reactor Site 3 for a small source term. The cost-based losses are smaller (about 2%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are smaller when only direct GDP losses are included (direct GDP contribution is 2.92% and total GDP contribution is 4.58%). If only the direct GDP losses had been included, the GDP-based prediction would be only 0.45% greater than the cost-based prediction for total losses.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (2.92%) are about 1% greater than the loss-of-use costs, which are 0.89% + 1.08% = 1.97%. The logic to determine whether decontamination should be performed is slightly different for the two models, as explained previously; however, the losses for decontamination, depreciation, and condemnation are the same to the precision shown in the table for the two models. The milk and crop disposal costs are not included in the GDP-based model, but those costs (0.00% and 0.48%, respectively) are a small fraction of the overall losses.

Table 41. Benchmark Case B-3a: Mean, GDP-Based Losses within 50 Miles of Reactor 3 Using the Low-Activity Source Term

	Small Source Term (B3-a)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	97.89%
TOTAL NATIONAL GDP LOSSES	4.58%	
ALL DIRECT INDUSTRIES GDP LOSSES	2.92%	
ALL INDIRECT INDUSTRIES GDP LOSSES	0.78%	
ALL INDUCED INDUSTRIES GDP LOSSES	0.88%	
POP.-DEPENDENT DECONTAMINATION COST	1.05%	1.05%
FARM-DEPENDENT DECONTAMINATION COST	0.61%	0.61%
POP.-DEPENDENT LOSS OF USE COST		0.89%
FARM-DEPENDENT LOSS OF USE COST		1.08%
POP.-DEPENDENT DEPRECIATION LOSSES	0.72%	0.72%
FARM-DEPENDENT DEPRECIATION LOSSES	0.35%	0.35%
POP.-DEPENDENT CONDEMNATION COST	0.00%	0.00%
FARM-DEPENDENT CONDEMNATION COST	0.00%	0.00%
EMERGENCY RELOCATION COST	90.85%	90.85%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	1.77%	1.77%
MILK DISPOSAL COST		0.00%
CROP DISPOSAL COST		0.48%

Table 42 provides a summary of the cost-based and GDP-based results for Reactor Site 3 for a medium source term. The losses predicted by the cost-based model are slightly lower (about 2%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are lower when only direct GDP losses are included (direct GDP contribution is 20.28% instead of 32.86% for total GDP). If only direct GDP losses had been included, the GDP-based model would have been lower by 12.58%, which would make it lower than the cost-based model prediction by 7.32%. This is a reasonable comparison because the cost-base model only attempts to capture direct losses within the disrupted region.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (20.28%) are about 5% less than the loss-of-use costs, which are 19.38% + 5.57% = 24.95%.

Table 42. Benchmark Case B-3b: Mean, GDP-Based Losses within 50 Miles of Reactor 3 Using the Medium Source Term

	Medium Source Term (B3-b)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	94.74%
TOTAL NATIONAL GDP LOSSES	32.86%	
ALL DIRECT INDUSTRIES GDP LOSSES	20.28%	
ALL INDIRECT INDUSTRIES GDP LOSSES	4.27%	
ALL INDUCED INDUSTRIES GDP LOSSES	8.40%	
POP.-DEPENDENT DECONTAMINATION COST	18.23%	18.23%
FARM-DEPENDENT DECONTAMINATION COST	8.38%	8.28%
POP.-DEPENDENT LOSS OF USE COST		19.38%
FARM-DEPENDENT LOSS OF USE COST		5.57%
POP.-DEPENDENT DEPRECIATION LOSSES	14.63%	14.63%
FARM-DEPENDENT DEPRECIATION LOSSES	1.75%	1.72%
POP.-DEPENDENT CONDEMNATION COST	0.53%	0.31%
FARM-DEPENDENT CONDEMNATION COST	0.60%	0.83%
EMERGENCY RELOCATION COST	2.18%	2.18%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	20.80%	20.92%
MILK DISPOSAL COST		0.03%
CROP DISPOSAL COST		2.72%

The logic to determine whether decontamination should be performed is slightly different for the two models, as explained above. Thus, the losses for decontamination, depreciation, and condemnation are similar but slightly different for the two models. The largest difference is for the losses associated with condemned populated land, which are about 41% lower for the cost-based model. This is within the expectations for the two models, as discussed in Section 5, and especially so because this is for a nonlinear result that contributes a small fraction of the overall losses. More populated land is condemned with the GDP-based model, but less farmland is condemned; decontamination costs are nearly the same with the two models. The milk and crop disposal costs are not included in the GDP-based model, and those contributions (0.03% and 2.72%, respectively) reduce the gap between the two models.

Table 43 provides a summary of the cost-based and GDP-based results for Reactor Site 3 for a large source term. The cost-based model prediction is lower (about 7%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are greater by about 6% when only direct GDP losses are included (direct GDP contribution is 41.14% instead of 35.45% for total GDP). It is reasonable to compare results excluding indirect and induced GDP losses because the cost-based model does not include these losses.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (41.14%) are greater than the loss-of-use costs, which are 26.92% + 2.35% = 29.27%.

Table 43. Benchmark Case B-3c: Mean, GDP-Based Losses within 50 Miles of Reactor 3 Using the Large Source Term

	Large Source Term (B3-c)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	92.64%
TOTAL NATIONAL GDP LOSSES	35.45%	
ALL DIRECT INDUSTRIES GDP LOSSES	41.14%	
ALL INDIRECT INDUSTRIES GDP LOSSES	-14.85%	
ALL INDUCED INDUSTRIES GDP LOSSES	9.03%	
	0.00%	
POP.-DEPENDENT DECONTAMINATION COST	14.92%	15.08%
FARM-DEPENDENT DECONTAMINATION COST	5.12%	4.92%
POP.-DEPENDENT LOSS OF USE COST		26.92%
FARM-DEPENDENT LOSS OF USE COST		2.35%
POP.-DEPENDENT DEPRECIATION LOSSES	14.35%	14.55%
FARM-DEPENDENT DEPRECIATION LOSSES	0.72%	0.69%
POP.-DEPENDENT CONDEMNATION COST	12.44%	8.93%
FARM-DEPENDENT CONDEMNATION COST	3.25%	3.71%
EMERGENCY RELOCATION COST	1.33%	1.33%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	12.54%	12.84%
MILK DISPOSAL COST		0.02%
CROP DISPOSAL COST		1.40%

The logic to determine whether decontamination should be performed is slightly different for the two models, as explained previously. Thus, the losses for decontamination, depreciation, and condemnation are similar but different for the two models. The only cost category that is the same to the precision shown in the table for the two models is emergency-phase relocation; all the long-term costs are at least slightly different. The largest difference is for condemned populated land, which is about 28% less for the cost-based model. This is considered good agreement for the two models. More populated land is condemned with the GDP-based model, but less farmland is condemned; on the other hand, more farmland and less populated land are decontaminated and interdicted with the GDP-based model. The milk and crop disposal costs are not included in the GDP-based model, and those contributions (0.02% and 1.40%, respectively) only contribute a small fraction of the total losses for the cost-based model.

Table 44 and Table 45 show the affected areas estimated by the cost-based and GDP-based economic models, respectively. These results indicate good to excellent agreement for all three source terms. The largest relative difference is for condemned populated land area for the medium source term, which is about 40% smaller for the cost-based model than the GD-based model. The differences between the models are because the logic to determine whether it is economical to decontaminate an area is different, as described in a previous section.

Table 44. Test Case B-3: Mean, Affected Area for the Cost-Based Model within 50 Miles of Reactor 3

AFFECTED AREA (mile^2)	Low (B-3a)	Medium (B-3b)	High (B-3c)
FARM DECONTAMINATION AREA	0.02	125	231
POP. DECONTAMINATION AREA	0.02	76	178
FARM INTERDICTION AREA	0.06	165	240
POP. INTERDICTION AREA	0.02	76	178
FARM CONDEMNATION AREA	0.00	4	61
POP. CONDEMNATION AREA	0.00	0	5

Table 45. Test Case B-3: Mean, Affected Area for the GDP-Based Model within 50 Miles of Reactor 3

AFFECTED AREA (mile^2)	Low (B-3a)	Medium (B-3b)	High (B-3c)
FARM DECONTAMINATION AREA	0.02	126	238
POP. DECONTAMINATION AREA	0.02	76	177
FARM INTERDICTION AREA	0.06	166	247
POP. INTERDICTION AREA	0.02	76	177
FARM CONDEMNATION AREA	0.00	3	54
POP. CONDEMNATION AREA	0.00	0	6

Table 46 and Table 47 show the affected populations estimated by the cost-based and GDP-based economic models, respectively. The results are generally consistent for all three source terms, but the agreement is poorer for the medium and large source terms for the population associated with condemned land. The largest relative difference is for individuals displaced by condemnation for the medium source term, which is about 40% lower for the cost-based model. This is considered good agreement.

Table 46. Test Case B-3: Mean, Affected Population for the Cost-Based Model within 50 Miles of Reactor 3

AFFECTED POPULATION	Small (B3-a)	Medium (B3-b)	Large (B3-c)
DECONTAMINATION (INDIVIDUALS)	2	12,200	28,500
INTERDICTION (INDIVIDUALS)	2	12,200	28,500
CONDEMNATION (INDIVIDUALS)	0	8	722

Table 47. Test Case B-3: Mean, Affected Population for the GDP-Based Model within 50 Miles of Reactor 3

AFFECTED POPULATION	Small (B3-a)	Medium (B3-b)	Large (B3-c)
DECONTAMINATION (INDIVIDUALS)	2	12,200	28,200
INTERDICTION (INDIVIDUALS)	2	12,200	28,200
CONDEMNATION (INDIVIDUALS)	0	13	981

6.2.4. Benchmark Case B-4

The goal of Test Case B-4 is to compare the MACCS GDP-based and cost-based economic losses created by an assumed nuclear reactor accident at Reactor Site 4 (52nd percentile data point from Figure 11) using a modified, SOARCA-project, WinMACCS model and using small, medium, and large source terms. All analyses use the default 10 years for the duration of the economic impact in the GDP-based model. The inputs are intentionally kept the same for the two economic models, with the caveat discussed in Section 6.2.1.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (4.22%) are greater than the loss-of-use costs, which are 1.54% + 0.10% = 1.64%. The logic to determine whether decontamination should be performed is slightly different for the two models, as explained previously; however, the losses for decontamination, depreciation, and condemnation are the same to the precision shown in the table for the two models. The milk and crop disposal costs are not included in the GDP-based model, but those costs (0.00% and 0.03%, respectively) are a trivial part of the overall losses.

Table 48 provides a summary of the cost-based and GDP-based results for Reactor Site 4 for a small source term. The cost-based model prediction is larger (about 6%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The total GDP-based losses are lower when only direct GDP losses are included (direct GDP contribution is 4.22% instead of 7.46%, which reduces the total loss by 3.24%), but nonetheless remain larger than the cost-based losses by about 2.5%.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (4.22%) are greater than the loss-of-use costs, which are 1.54% + 0.10% = 1.64%. The logic to determine whether decontamination should be performed is slightly different for the two models, as explained previously; however, the losses for decontamination, depreciation, and condemnation are the same to the precision shown in the table for the two models. The milk and crop disposal costs are not included in the GDP-based model, but those costs (0.00% and 0.03%, respectively) are a trivial part of the overall losses.

Table 48. Benchmark Case B-4a: Mean, GDP- and Cost-Based Losses within 50 Miles of Reactor Site 4 Using the Small Source Term

	Small Source Term (B4-a)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	94.26%
TOTAL NATIONAL GDP LOSSES	7.46%	
ALL DIRECT INDUSTRIES GDP LOSSES	4.22%	
ALL INDIRECT INDUSTRIES GDP LOSSES	1.55%	
ALL INDUCED INDUSTRIES GDP LOSSES	1.68%	
POP.-DEPENDENT DECONTAMINATION COST	1.48%	1.48%
FARM-DEPENDENT DECONTAMINATION COST	0.04%	0.04%
POP.-DEPENDENT LOSS OF USE COST		1.54%
FARM-DEPENDENT LOSS OF USE COST		0.10%
POP.-DEPENDENT DEPRECIATION LOSSES	1.25%	1.25%
FARM-DEPENDENT DEPRECIATION LOSSES	0.03%	0.03%
POP.-DEPENDENT CONDEMNATION COST	0.00%	0.00%
FARM-DEPENDENT CONDEMNATION COST	0.00%	0.00%
EMERGENCY RELOCATION COST	86.89%	86.89%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	2.42%	2.42%
MILK DISPOSAL COST		0.00%
CROP DISPOSAL COST		0.03%

Table 49 provides a summary of the cost-based and GDP-based results for Reactor Site 4 for the medium source term. The cost-based model prediction is lower (about 15%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are lower when only direct GDP losses are included (direct GDP contribution is 23.87% instead of 38.00%). If only direct GDP losses had been included, the GDP-based model would have been about 14% lower, which is close to the cost-based model prediction. This comparison is reasonable because the cost-based comparison only considers losses to the directly affected area.

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (23.87%) are less than 1% greater than the loss-of-use costs, which are 21.77% + 1.21% = 22.98%.

Table 49. Benchmark Case B-4b: Mean, GDP- and Cost-Based Losses within 50 Miles of Reactor Site 4 Using the Medium Source Term

	Medium Source Term (B4-b)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	85.00%
TOTAL NATIONAL GDP LOSSES	38.00%	
ALL DIRECT INDUSTRIES GDP LOSSES	23.87%	
ALL INDIRECT INDUSTRIES GDP LOSSES	4.07%	
ALL INDUCED INDUSTRIES GDP LOSSES	10.20%	
	0.00%	
POP.-DEPENDENT DECONTAMINATION COST	19.17%	19.20%
FARM-DEPENDENT DECONTAMINATION COST	1.02%	1.01%
POP.-DEPENDENT LOSS OF USE COST		21.77%
FARM-DEPENDENT LOSS OF USE COST		1.21%
POP.-DEPENDENT DEPRECIATION LOSSES	15.93%	16.00%
FARM-DEPENDENT DEPRECIATION LOSSES	0.38%	0.38%
POP.-DEPENDENT CONDEMNATION COST	1.08%	0.39%
FARM-DEPENDENT CONDEMNATION COST	0.10%	0.14%
EMERGENCY RELOCATION COST	2.36%	2.36%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	21.80%	21.83%
MILK DISPOSAL COST		0.02%
CROP DISPOSAL COST		0.62%

The logic to determine whether decontamination should be performed is slightly different for the two models, as explained above. Thus, the losses for decontamination, depreciation, and condemnation are similar but slightly different for the two models. Losses for condemned populated land are larger with the GDP-based model, but condemned farmland losses are smaller; decontamination costs are nearly the same with the two models. The milk and crop disposal costs are not included in the GDP-based model, but those costs (0.02% and 0.62%, respectively) represent a small fraction of the overall losses.

Table 50 provides a summary of the cost-based and GDP-based results for Reactor Site 4 for a large source term. The cost-based model prediction is lower (about 14%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are greater when only direct GDP losses are included (direct GDP contribution is 44.56% instead of 40.48%). If direct GDP losses had been included in place of total GDP losses, the GDP-based model would have been about 18% higher than the cost-based model prediction.

Table 50. Benchmark Case B-4c: Mean, GDP- and Cost-Based Losses within 50 Miles of Reactor Site 4 Using the Large Source Term

	Large Source Term (B4-c)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	86.40%
TOTAL NATIONAL GDP LOSSES	40.48%	
ALL DIRECT INDUSTRIES GDP LOSSES	44.56%	
ALL INDIRECT INDUSTRIES GDP LOSSES	-15.20%	
ALL INDUCED INDUSTRIES GDP LOSSES	11.12%	
	0.00%	
POP.-DEPENDENT DECONTAMINATION COST	15.76%	15.84%
FARM-DEPENDENT DECONTAMINATION COST	0.67%	0.65%
POP.-DEPENDENT LOSS OF USE COST		28.00%
FARM-DEPENDENT LOSS OF USE COST		0.52%
POP.-DEPENDENT DEPRECIATION LOSSES	15.52%	15.68%
FARM-DEPENDENT DEPRECIATION LOSSES	0.16%	0.15%
POP.-DEPENDENT CONDEMNATION COST	12.24%	9.76%
FARM-DEPENDENT CONDEMNATION COST	0.56%	0.65%
EMERGENCY RELOCATION COST	1.41%	1.41%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	13.44%	13.68%
MILK DISPOSAL COST		0.01%
CROP DISPOSAL COST		0.30%

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (44.56%) are greater than the loss-of-use costs, which are 28.00% + 0.52% = 28.52%. This difference is largely the cause for the overall differences between the two model predictions.

The logic to determine whether decontamination should be performed is slightly different for the two models, as explained previously. Thus, the losses for decontamination, depreciation, and condemnation are similar but different for the two models. The only cost category that is the same to three significant figures for the two models is emergency-phase relocation; all the long-term costs are at least slightly different. More losses associated with populated land are accrued with the GDP-based model, but condemnation losses are less for farmland; on the other hand, more losses for decontamination and interdiction of farmland and less for populated land are tallied for the GDP-based model. The milk and crop disposal costs are not included in the GDP-based model, and those costs (0.01% and 0.30%, respectively) only contribute a small fraction of the overall costs for the cost-based model.

Table 51 and Table 52 show the affected areas estimated by the cost-based and GDP-based economic models, respectively. These results indicate good agreement for all three source terms, but the agreement is poorer for the condemned areas for the large source terms. The largest difference is for the condemned populated area, which is 20% lower for the cost-based model. This agreement is considered good. The differences between the models are because the logic to determine whether it is economical to decontaminate an area is different, as described in previous sections.

Table 51. Test Case B-4: Mean, Affected Areas for the Cost-Based Model within 50 Miles of Reactor 4

AFFECTED AREA (mile^2)	Small (B-4a)	Medium (B-4b)	Large (B-4c)
FARM DECONTAMINATION AREA	0.01	60	129
POP. DECONTAMINATION AREA	0.08	146	310
FARM INTERDICTION AREA	0.03	83	135
POP. INTERDICTION AREA	0.08	146	310
FARM CONDEMNATION AREA	0.00	1	27
POP. CONDEMNATION AREA	0.00	0	11

Table 52. Test Case B-4: Mean, Affected Areas for the GDP-Based Model within 50 Miles of Reactor 4

AFFECTED AREA (mile^2)	Small (B-4a)	Medium (B-4b)	Large (B-4c)
FARM DECONTAMINATION AREA	0.01	60	133
POP. DECONTAMINATION AREA	0.08	145	307
FARM INTERDICTION AREA	0.03	83	138
POP. INTERDICTION AREA	0.08	145	307
FARM CONDEMNATION AREA	0.00	1	23
POP. CONDEMNATION AREA	0.00	0	14

Table 53 and Table 54 show the affected populations estimated by the cost-based and GDP-based economic models, respectively. These results are generally consistent for all three source terms, but the agreement is poorer for the medium and high source terms for the populations affected by condemnation. The largest difference is for the medium source term where the number of individuals is 64% less for the cost-based model than for the GDP-based model. This difference is acceptable for a nonlinear result that is relatively small. The reason for the differences is the same as described above.

Table 53. Test Case B-4: Mean, Affected Populations for the Cost-Based Model within 50 Miles of Reactor 4

AFFECTED POPULATION	Small (B-4a)	Medium (B-4b)	Large (B-4c)
DECONTAMINATION (INDIVIDUALS)	22	49,300	127,000
INTERDICTION (INDIVIDUALS)	22	49,300	127,000
CONDEMNATION (INDIVIDUALS)	0	30	3,070

Table 54. Test Case B-4: Mean, Affected Populations for the GDP-Based Model within 50 Miles of Reactor 4

AFFECTED POPULATION	Small (B-4a)	Medium (B-4b)	Large (B-4c)
DECONTAMINATION (INDIVIDUALS)	22	49,200	126,000
INTERDICTION (INDIVIDUALS)	22	49,200	126,000
CONDEMNATION (INDIVIDUALS)	0	84	3,840

6.2.5. Benchmark Case B-5

The goal of Test Case B-5 is to compare the MACCS GDP-based and cost-based economic losses created by an assumed nuclear reactor accident at Reactor Site 5 (87th percentile data point from Figure 11) using a modified, SOARCA-project, WinMACCS model and using small, medium, and large source terms. All analyses use the default 10 years for the duration of the economic impact in the GDP-based model. The inputs are intentionally kept the same for the two economic models, with the caveat discussed in Section 6.2.1.

Table 55 provides a summary of the cost-based and GDP-based results for Reactor Site 4 for a small source term. The GDP-based model prediction is higher (about 4%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are lower when only direct GDP losses are included (direct GDP contribution is 11.70% instead of 22.89% when total GDP contribution is included), and the value excluding indirect and induced losses is about 7% lower than the cost -based losses for this case.

Table 55. Benchmark Case B-5a: Mean, GDP- and Cost-Based Losses within 50 Miles of Reactor Site 5 Using the Small Source Term

	Small Source Term (B5-a)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	96.34%
TOTAL NATIONAL GDP LOSSES	22.89%	
ALL DIRECT INDUSTRIES GDP LOSSES	11.70%	
ALL INDIRECT INDUSTRIES GDP LOSSES	4.84%	
ALL INDUCED INDUSTRIES GDP LOSSES	6.27%	
POP.-DEPENDENT DECONTAMINATION COST	16.07%	16.07%
FARM-DEPENDENT DECONTAMINATION COST	0.26%	0.26%
POP.-DEPENDENT LOSS OF USE COST		19.13%
FARM-DEPENDENT LOSS OF USE COST		0.06%
POP.-DEPENDENT DEPRECIATION LOSSES	15.46%	15.46%
FARM-DEPENDENT DEPRECIATION LOSSES	0.02%	0.02%
POP.-DEPENDENT CONDEMNATION COST	0.00%	0.00%
FARM-DEPENDENT CONDEMNATION COST	0.00%	0.00%
EMERGENCY RELOCATION COST	18.21%	18.21%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	27.16%	27.16%
MILK DISPOSAL COST		0.00%
CROP DISPOSAL COST		0.00%

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (11.70%) are smaller than the loss-of-use costs, which are 19.13% + 0.06% = 19.19%.

The logic to determine whether decontamination should be performed is slightly different for the two models, as explained previously; however, the losses for decontamination, depreciation, and condemnation are the same to the precision shown in the table for the two models. The milk and crop disposal costs are not included in the GDP-based model, but those costs 0.00% and 0.00%, respectively) do not add to the cost-based losses in this case.

Table 56 provides a summary of the cost-based and GDP-based results for Reactor Site 5 for the medium source term. The cost-based model prediction is lower (about 15%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are lower when only direct GDP losses are included (direct GDP contribution is 26.32% instead of 40.95% for total GDP losses). If only direct GDP losses had been included, the GDP-based model would have been almost the same as the cost-based model prediction for this case.

Table 56. Benchmark Case B-5b: Mean, GDP- and Cost-Based Losses within 50 Miles of Reactor Site 5 Using the Medium-Activity Source Term

	Medium Source Term (B5-b)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	84.96%
TOTAL NATIONAL GDP LOSSES	40.95%	
ALL DIRECT INDUSTRIES GDP LOSSES	26.32%	
ALL INDIRECT INDUSTRIES GDP LOSSES	3.62%	
ALL INDUCED INDUSTRIES GDP LOSSES	11.06%	
POP.-DEPENDENT DECONTAMINATION COST	22.28%	22.28%
FARM-DEPENDENT DECONTAMINATION COST	0.24%	0.23%
POP.-DEPENDENT LOSS OF USE COST		25.77%
FARM-DEPENDENT LOSS OF USE COST		0.10%
POP.-DEPENDENT DEPRECIATION LOSSES	18.52%	18.52%
FARM-DEPENDENT DEPRECIATION LOSSES	0.03%	0.03%
POP.-DEPENDENT CONDEMNATION COST	1.55%	1.52%
FARM-DEPENDENT CONDEMNATION COST	0.13%	0.18%
EMERGENCY RELOCATION COST	1.30%	1.30%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	15.04%	15.04%
MILK DISPOSAL COST		0.00%
CROP DISPOSAL COST		0.07%

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (26.32%) are slightly greater than the loss-of-use costs, which are 25.77% + 0.10% = 25.87%, but the two only differ by about 0.5%.

The logic to determine whether decontamination should be performed is slightly different for the two models, as explained above. Thus, many of the losses for decontamination, depreciation, and condemnation are similar but slightly different for the two models. Losses for condemned populated land are larger with the GDP-based model, but condemned farmland losses are smaller; decontamination costs are nearly the same with the two models. The milk and crop disposal costs are not included in the GDP-based model, but those costs (0.00% and 0.07%, respectively) have a minor contribution to the cost-based model prediction.

Table 57 provides a summary of the cost-based and GDP-based results for Reactor Site 5 for a large source term. The cost-based model prediction is lower (about 16%) for this case when total national GDP losses (direct, indirect, and induced GDP losses) are included. The GDP-based results are greater when only direct GDP losses are included (direct GDP contribution is 63.51% instead of 41.05% for the total losses). For this case, excluding the indirect and induced GDP losses increases the gap between the two models.

Table 57. Benchmark Case B-5c: Mean, GDP- and Cost-Based Losses within 50 Miles of Reactor Site 5 Using the Large Source Term

	Small Source Term (B5-c)	
ECONOMIC COST MEASURES ($) 0-80.5 km	**GDP Based**	**Cost Based**
TOTAL LOSSES	100.00%	83.86%
TOTAL NATIONAL GDP LOSSES	41.05%	
ALL DIRECT INDUSTRIES GDP LOSSES	63.51%	
ALL INDIRECT INDUSTRIES GDP LOSSES	-33.44%	
ALL INDUCED INDUSTRIES GDP LOSSES	11.02%	
POP.-DEPENDENT DECONTAMINATION COST	6.21%	7.16%
FARM-DEPENDENT DECONTAMINATION COST	0.03%	0.03%
POP.-DEPENDENT LOSS OF USE COST		42.46%
FARM-DEPENDENT LOSS OF USE COST		0.02%
POP.-DEPENDENT DEPRECIATION LOSSES	12.42%	14.07%
FARM-DEPENDENT DEPRECIATION LOSSES	0.00%	0.00%
POP.-DEPENDENT CONDEMNATION COST	34.91%	14.07%
FARM-DEPENDENT CONDEMNATION COST	0.20%	0.20%
EMERGENCY RELOCATION COST	0.50%	0.50%
INTERMEDIATE RELOCATION COST	0.00%	0.00%
LONG-TERM RELOCATION COST	4.49%	5.23%
MILK DISPOSAL COST		0.00%
CROP DISPOSAL COST		0.03%

The direct GDP losses calculated in the GDP-based model are the analogue of the loss-of-use costs in the cost-based model. For this case, the direct GDP losses (63.51%) are greater than the loss-of-use costs, which are 42.46% + 0.02% = 42.48%. The logic to determine whether decontamination should be performed is slightly different for the two models, as explained previously. Thus, the losses for decontamination, depreciation, and condemnation are similar but mostly different for the two models. More losses associated with condemnation of populated land are accrued with the GDP-based model, but condemnation losses are the same for farmland; on the other hand, less losses for decontamination and depreciation for populated land are tallied for the GDP-based model. The milk and crop disposal costs are not included in the GDP-based model, and those costs (0.00% and 0.03%, respectively) only contribute a tiny fraction of the total for the cost-based model.

Table 58 and Table 59 show the affected areas estimated by the cost-based and GDP-based economic models, respectively. These results indicate good agreement for all three source terms. The agreement is poorer for the condemned areas for the medium and large source terms. The largest relative difference between the two models is for the medium source term; the cost-based prediction is 48% smaller than the GDP-based value, but this is within the expected range. The differences between the models are because the logic to determine whether it is economical to decontaminate an area is different, as described in a previous section.

Table 58. Test Case B-5: Mean, Affected Area for the Cost-Based Model within 50 Miles of Reactor 5

AFFECTED AREA (mile^2)	Large (B-5a)	Medium (B-5b)	Large (B-5c)
FARM DECONTAMINATION AREA	0.64	215	119
POP. DECONTAMINATION AREA	0.92	190	214
FARM INTERDICTION AREA	0.64	215	119
POP. INTERDICTION AREA	0.92	190	214
FARM CONDEMNATION AREA	0.00	34	218
POP. CONDEMNATION AREA	0.00	3	44

Table 59. Test Case B-5: Mean, Affected Area for the GDP-Based Model within 50 Miles of Reactor 5

AFFECTED AREA (mile^2)	Large (B-5a)	Medium (B-5b)	Large (B-5c)
FARM DECONTAMINATION AREA	0.64	224	119
POP. DECONTAMINATION AREA	0.92	188	190
FARM INTERDICTION AREA	0.64	224	119
POP. INTERDICTION AREA	0.92	188	190
FARM CONDEMNATION AREA	0.00	24	218
POP. CONDEMNATION AREA	0.00	5	69

Table 60 and Table 61 show the affected populations estimated by the cost-based and GDP-based economic models, respectively. These results are generally consistent for all three source terms, but the agreement is poorer for the large source term, especially for populations associated with condemned areas. The cost-based prediction is 59% lower than the GDP-based one for this result, which is acceptable for this type of result but larger than typically expected. The reason for the differences is the same as described in Section 6.2.1.

Table 60. Test Case B-5: Mean, Affected Population for the Cost-Based Model within 50 Miles of Reactor 5

AFFECTED POPULATION	Large (B-5a)	Medium (B-5b)	Large (B-5c)
DECONTAMINATION (INDIVIDUALS)	2,010	811,000	1,090,000
INTERDICTION (INDIVIDUALS)	2,010	811,000	1,090,000
CONDEMNATION (INDIVIDUALS)	0	2,450	91,500

Table 61. Test Case B-5: Mean, Affected Population for the GDP-Based Model within 50 Miles of Reactor 5

AFFECTED POPULATION	Large (B-5a)	Medium (B-5b)	Large (B-5c)
DECONTAMINATION (INDIVIDUALS)	2,010	811,000	960,000
INTERDICTION (INDIVIDUALS)	2,010	811,000	960,000
CONDEMNATION (INDIVIDUALS)	0	2,510	223,000

6.2.6. Benchmark Case Summary

For Test Case A verification, comparisons between the MACCS RDEIM model produces results within a few percent of those produced independently by a standalone version of REAcct or directly from BEA (2012). Three cases are considered: (1) reproducing the entire GDP of the contiguous US by creating a source term and conditions that contaminate the entire US and disrupt the whole economy; (2) creating a release that approximately contaminates a single county; and (3) creating a release that contaminates a fraction of a county. In all three cases, the MACCS GDP-based losses compared well with independently estimated results. In two of the three cases the agreement was within 1% (excellent agreement, as defined in the acceptance criteria in Section 5.5) and in the third the agreement was within 5% (good agreement, as defined in Section 5.5).

For the Test Case B benchmark cases, the losses predicted by the cost-based and GDP-based models agree to within 20% when total GDP losses are included, as shown in Table 62. This is considered excellent agreement for these cases, which compare two distinctly different economic models. The following trends are observed for all 5 sites:

- The losses predicted by the RDEIM model are consistently larger for all source terms and for all five sites considered in this benchmark. This is likely attributable to the inclusion of indirect and induced losses, which are types of losses not included in the cost-based model. Another influencing factor is that a lower discount rate is used to discount future year losses with the RDEIM model than with the cost-based model. This means future-year losses are assigned a higher value in the GDP-based model. Thus, larger source terms that induce longer recovery periods tend to have larger losses with the GDP-based model than with the cost-based model. These discount rates could have been made more similar for the two models, but the objective of this benchmark was to run both models with recommended or commonly used parameter values to provide a typical comparison. Furthermore, the same discount rate is used to estimate expected rate of return on the value of property and to discount future year losses in the cost-based model, so a change to the discount rate has a two-fold effect on losses and it may not be possible to bring the two models into closer agreement under all circumstances by modifying this rate. For example, the cost-based losses for the small source term are almost entirely in the first year, so better aligning the first-year losses would require increasing the discount rate for the cost-based model; however, this would also have the effect of reducing future year losses for the cases of medium and large source terms, which might not improve the comparisons for the larger source terms.

- There is a clear trend between the size of the source term and the relative difference between the two models. The relative difference is smaller for smaller source terms and larger for larger source terms at all five sites compared in this report, so the correlation is positive but not entirely linear since the relative difference is smaller for the large than for the medium source terms at some of the sites. This trend is likely related to differences in future-year discounting, as discussed under the previous bullet.
- There appears to be a weak trend between population density in the 50-mile area surrounding a site and the trends shown in Table 61, as demonstrated in Figure 12. The trends are clear for the medium and large source terms but not for the small source term. It appears that source-term magnitude and perhaps other factors influence the trends as well as population density.

Table 62. Test Case B Percent Difference in the Mean, Cost-Based to GDP-Based Losses within 50 Miles of the Site. Positive Percentages Indicate that the Cost-based Result is Smaller.

Description		Source Term Magnitude		
Test Case	Non-Farmland Wealth Percentile	Low	Medium	Large
B-1	93%	3%	14%	12%
B-2	68%	0%	13%	12%
B-3	16%	2%	5%	7%
B-4	52%	6%	15%	14%
B-5	87%	4%	15%	16%

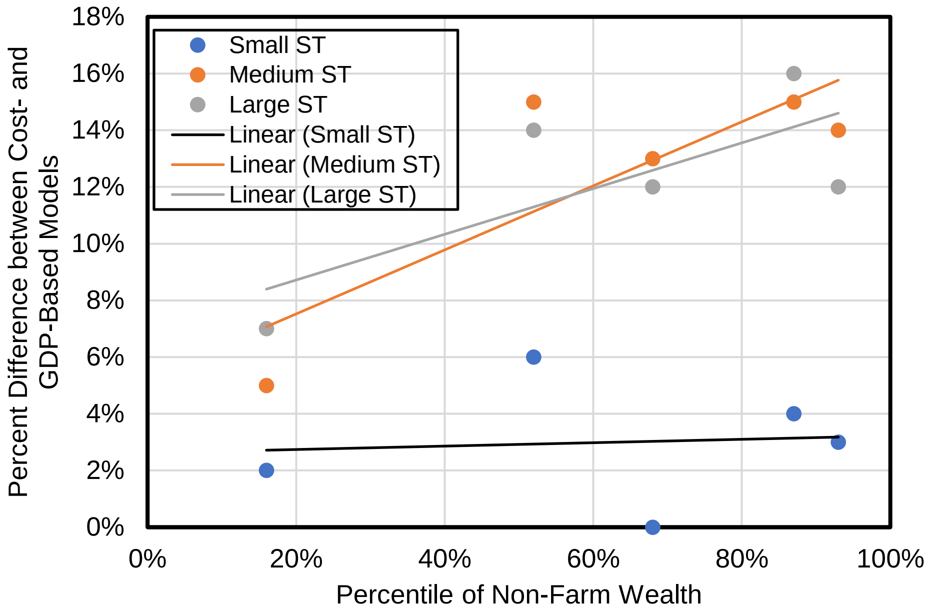

Figure 12: Relative difference between cost-based and GDP-based total losses versus percentile of non-farm wealth for each source term (ST) with trendlines.

7. SUMMARY

This report describes the modeling framework, implementation, verification, and benchmarking of a GDP-based model for economic losses that has recently been developed as an alternative to the original cost-based economic loss model in MACCS. The GDP-based model has its roots in a code developed by Sandia National Laboratories for the Department of Homeland Security to estimate short-term losses from natural and manmade accidents, called the REAcct. This model was modified for MACCS and is now called the RDEIM. It is based on input-output theory, which is widely used in economic modeling. It accounts for direct losses to a disrupted region affected by an accident, indirect losses to the national economy due to disruption of the supply chain, and induced losses from reduced spending by displaced workers. RDEIM differs from REAcct in that it is intended to be used for extended periods that can occur from a major nuclear reactor accident, such as the one that occurred at the Fukushima Daiichi site in Japan. Most input-output models do not account for economic adaptation and recovery, and in this regard RDEIM extends the capabilities of its parent, REAcct, because it allows for a user-definable national recovery period. Implementation of a recovery period was one of several recommendations made by an independent peer review panel to ensure that RDEIM is state-of-practice. RDEIM represents the economic disruption from a nuclear accident over time and distinguishes between national and regional scales and recovery progress.

Both the original and the RDEIM economic loss models account for costs from evacuation and relocation, decontamination, depreciation, and condemnation. Where the original model accounts for an expected rate of return, based on the value of property that is unusable during interdiction, the RDEIM model instead accounts for losses of GDP based on the industrial sectors located within an affected county. The original model includes costs for disposal of crops and milk that the RDEIM model currently does not, but these costs tend to contribute insignificantly to the overall results.

Verification testing indicates that the GDP-based model produces results in close agreement with the standalone code (REAcct) upon which the MACCS GDP-based model (RDEIM) is based. Benchmarking analyses performed for five US nuclear reactor sites represent a broad range of population densities and three source terms with varying magnitudes taken from the SOARCA study. The conclusion is that the two models produce total losses that are remarkably similar, within 20% at all five sites and source term magnitudes that were tested. Observed trends include the following:

- The losses predicted by the RDEIM model are consistently larger for all source terms than those predicted by the cost-based model.
- The relative differences between the two models are generally larger for larger source terms.
- There is a weak trend with population density in the 50-mile area surrounding a site that causes differences between the two models to be greater when population density is greater. This is much more evident for medium and large source terms. The trend is insignificant for small source terms.

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Name	Company Email Address	Company Name
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Email—Internal

Name	Org.	Sandia Email Address
Leonel Juarez	08162	ajuare@sandia.gov
Doug Osborn	06812	dosborn@sandia.gov
Alexander Outkin	08724	avoutki@sandia.gov
Nathan Andrews	08855	nandrew@sandia.gov
Nathan Bixler	08855	nbixler@sandia.gov
Daniel Clayton	08855	djclayt@sandia.gov
John Fulton	08855	jdfulto@sandia.gov
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