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# **Updated Economic Model for Estimation of GDP Losses in the MACCS Offsite Consequence Analysis Code RDEIM Model Report for MACCS v4.2**

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## ABSTRACT

This report updates the Regional Disruption Economic Impact Model (RDEIM) GDP-based model described in Bixler et al. (2020) used in the MACCS accident consequence analysis code.

MACCS is the U.S. Nuclear Regulatory Commission (NRC) 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.

The update of the RDEIM model in version 4.2 expresses the national recovery calculation explicitly, rather than implicitly as in the previous version. The calculation of the total national GDP losses remains unchanged. However, anticipated gains from recovery are now allocated across all the GDP loss types – direct, indirect, and induced – whereas in version 4.1, all recovery gains were accounted for in the indirect loss type. To achieve this, we’ve introduced new methodology to streamline and simplify the calculation of all types of losses and recovery. In addition, RDEIM includes other kinds of losses, including tangible wealth. This includes loss of tangible assets (e.g., depreciation) and accident expenditures (e.g., decontamination).

This document describes the updated RDEIM economic model and provides examples of loss and recovery calculation, results analysis, and presentation. Changes to the tangible cost calculation and accident expenditures are described in section 2.2. The updates to the RDEIM input-output (I-O) model are not expected to affect the final benchmark results Bixler et al. (2020), as the RDEIM calculation for the total national GDP losses remains unchanged. The reader is referred to the MACCS revision history for other cost modelling changes since version 4.0 that may affect the benchmark.

RDEIM 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. It is based on I-O 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 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 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.

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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	Accident Consequence Analysis Code
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 Analyses
TRII	Industry-by-Industry Total Requirements
UK	United Kingdom
U.S.	United States

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## 1. INTRODUCTION

The MACCS 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<sup>\*†</sup>. 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.

<sup>1</sup> The model presented in this report differs from the current version of REAcct. 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. RDEIM (GDP-Based Model) Overview

RDEIM estimates both the economic losses and recovery. The RDEIM economic model includes the GDP losses from the I-O model as well as other kinds of losses, including tangible wealth. This includes loss of tangible assets (e.g., depreciation) and accident expenditures (e.g., decontamination).

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

- Direct<sup>2</sup> 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.<sup>3</sup> Induced GDP losses correspond to both workers inside and outside the directly affected area.

The sum of all three categories (direct, indirect, and induced) is often called total losses. We use this definition of “total” through the text and extend it to recovery as well, where the total recovery value is defined as the sum of direct, indirect, and induced recovery.

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<sup>2</sup> 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.

<sup>3</sup> For example, employers may lay off workers to reduce their net 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 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.

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<sup>4</sup> gross output by industry, total requirements tables, final demand value-added multipliers (RIMS II model) 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 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 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.

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<sup>5</sup>, 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 term region is used to describe a geographic area and a unit of analysis and results representation. It is generally used as described above – i.e., to represent affected and not affected areas of the country<sup>6</sup>.

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<sup>4</sup> Value added is defined as the sum of labor compensation, capital income, and net indirect taxes (producer taxes, import tariffs minus subsidies).

<sup>5</sup> 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.

<sup>6</sup> The example in section 3.1 uses the term region to represent the entire analysis area that includes both affected and unaffected areas for simplicity.

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.

Traditional static I-O models may over-estimate the economic impacts (see Okuyama et al., 2004) because such models do not represent recovery. Recovery reflects 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 regional and national recovery factors in the RDEIM I-O model considers recovery and allows for different regional and national recovery speeds as described in section 2.1.

## **1.2. 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 impact 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.

The RDEIM model update in MACCS version 4.2 is consistent with the peer review recommendations on representing the national recovery because the total recovery values are the same between the new and the previous version. The primary improvement to the recovery

estimation in this model is the explicit calculation of recovery by the corresponding impact type (direct, indirect, induced, and their possible combinations) vs. calculating the recovery as negative indirect losses as in the previous version.

### **1.3. 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.

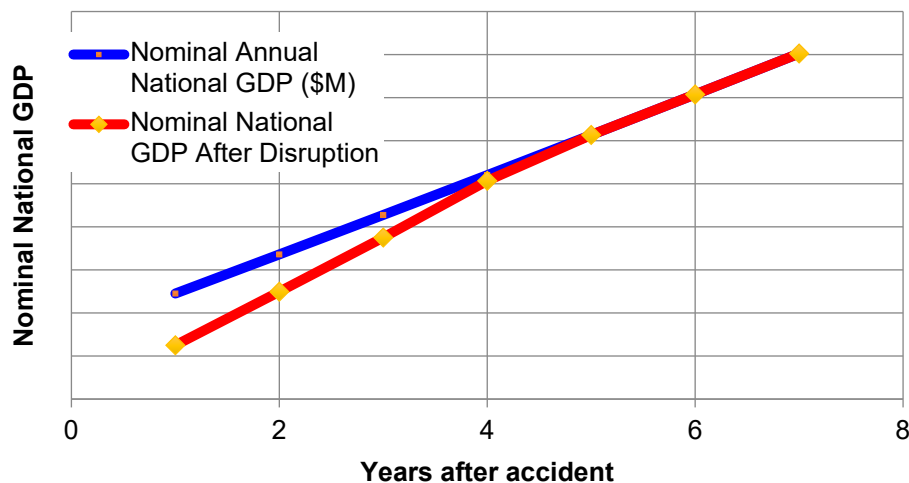


## 2. UPDATED RDEIM MACROECONOMIC IMPACT MODEL

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 recovers to its baseline trajectory, as illustrated in the Figure 1. 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 1. 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 5<sup>th</sup> year after the accident.**

## 2.1. GDP 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<sup>7</sup>. 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  $t$  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  $i$ .

$G, L, R$ : loss and recovery categories – gross loss, net loss, and recovery respectively<sup>8</sup>.

$D, I, P, T$ :

GDP and recovery type: direct, indirect, induced, and total<sup>9</sup>.

$\Delta V_i$ : the direct value-added change in industry  $i$ .

$\Delta V_{i,r}$ : the direct value-added change in industry  $i$  in the grid element  $r$ .

$\Delta V^D, \Delta V^T, \Delta V^I, \Delta V^{D+I}, \Delta V^P$ :

GDP (value-added) changes, with indices  $D, T, I, D+I$ , and  $P$  denoting the direct, total, indirect, direct plus indirect, and induced losses, respectively.

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<sup>7</sup> 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.

<sup>8</sup> We apply these categories to GDP losses at present. However, they can be applied to other losses, such as tangible asset losses.

<sup>9</sup> We refer to  $D, I, P$  and  $T$  collectively as GDP loss or recovery “types” to differentiate them from the loss “categories”. This allows expressing loss or recovery category by type. For example - “direct net loss”.

$b_{i,j}$ :	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 <i>GDP</i> growth rate.
$\rho$ :	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.
$\tilde{m}_i^k$ :	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. Note: we only use explicit index $N$ in the multipliers to indicate national multipliers. Otherwise, we assume the multipliers are regional by default and omit explicit index to indicate that, because it introduces no ambiguity and simplifies the notation.
$m_i^k$ :	regional total requirements multiplier of Type $k$ , where $k$ can be I or II.
$m'_i{}^k$ :	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.
$\tilde{m}'_i{}^k$ :	regional 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 <sup>10</sup> .
$s_N(t)$ :	function representing national recovery.
$l_{i,r}$ :	number of industry $i$ employees in grid element $r$ .
$t$ :	Represents an arbitrary period over which losses are integrated, when used as an argument in loss calculation. For example, $\Delta V^D(t)$ represents the cumulative direct losses incurred until time $t$ .
$t_r$ :	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.

<sup>10</sup> 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.

A nuclear accident affects a region composed of one or more full or partial counties, resulting in a direct economic impact<sup>11</sup>. The average GDP per worker in industry  $i$  at time  $t_0$  is estimated as follows:

$$v_i = \frac{V_i}{E_i} \quad (1)$$

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<sup>12</sup>. 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<sup>13</sup>. 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.

### 2.1.1. *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).

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<sup>11</sup> 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.

<sup>12</sup> <https://www.census.gov/programs-surveys/cbp/data/tables.html>

<sup>13</sup> 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.

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 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).

I-O modeling starts with empirical tables of final demand, industry income, and interindustry transactions.<sup>14</sup> 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

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<sup>14</sup> We somewhat 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.

SNA Publications.<sup>15</sup> Most recently, researchers have constructed a World I-O Database<sup>16</sup> 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. However, this model includes the national recovery component that reflects movement of disrupted business activity and affected people to other parts of the country. The goal of the model is to provide information adequate for the purposes of the Probabilistic Risk Assessment (PRA)<sup>17</sup> analyses.

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. In the course of this project, we have developed processes and methodology to update RDEIM with the new data quickly and with relative ease. 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<sup>18</sup> for evaluating the real present value of future GDP losses and for factoring in social discount

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<sup>15</sup> <http://unstats.un.org/unsd/nationalaccount/pubs.asp>. Accessed 12/21/2022.

<sup>16</sup> <http://www.voxeu.org/article/new-world-input-output-database>. Accessed 6/5/2014.

<sup>17</sup> See <http://www.nrc.gov/about-nrc/regulatory/risk-informed/pr.html> for more information. Accessed 1/25/2016.

<sup>18</sup> [https://www.whitehouse.gov/omb/circulars\\_a094/](https://www.whitehouse.gov/omb/circulars_a094/). Accessed 3/17/2015.

rates, as described in sections 3.4.5 and 3.4.6.

### 2.1.2. Gross Loss, Net Loss, and Recovery Gains

The RDEIM model in MACCS version 4.2 estimates the GDP impacts in terms of gross loss, net loss, and recovery. The loss estimation in this document is an improvement and a departure from Bixler et al. (2020) primarily because it introduces the concept of gross losses and splits them into net losses and recovery gains. The resulting values of total gross losses and total net losses are the same as in Bixler et al. (2020). However, the recovery is now allocated to all loss types (direct, indirect, and induced). Previously, the recovery was represented by negative indirect losses. Specifically:

- We now represent the national recovery explicitly. Therefore, there is no longer any need for negative losses.
- Every gross loss type (direct, indirect, induced) is now split into “net loss” and recovered portions.
- Instead of associating the recovery with indirect losses, we associate it with all types of losses, including direct<sup>19</sup>.

The speed of the regional recovery is represented 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.

Because the total gross loss, total net loss and total recovery remain the same as in Bixler et al. (2020)<sup>20</sup>, the updated methodology would not affect the overall results of the verification exercises in Bixler et al. (2020).

To calculate the gross loss, the net loss, and the recovery gains of each loss type, the previous approach in Bixler et al. (2020) is no longer practical. We also simplify the expressions for the direct, indirect, and induced losses by representing them using the same general form. This section describes the model for loss and recovery calculation and outlines the steps in deriving the expressions for all losses and gains. The section 2.1.3 derives closed-form expressions used in RDEIM implementation and the section 2.1.4 describes all the loss and recovery expressions implemented in MACCS 4.2 RDEIM model.

To simplify the exposition and reduce the number of possible permutations associated with three multiplier types (direct<sup>21</sup>, indirect, and induced), treatment of losses and recovery at the same time, and treatment of two special cases when  $\rho = g$  and when  $\rho \neq g$ , we introduce the incremental regional multipliers defined as following:

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<sup>19</sup> This does not preclude reporting direct losses without any recovery as is done in Bixler et al. (2020) if needed, as for example is shown in Table 15.

<sup>20</sup> Total recovery in RDEIM 4.2 is equal to the total recovery in RDEIM 4.0 and 4.1 in absolute value. It is now reported as a positive number. It was previously calculated as negative losses.

<sup>21</sup> We define direct multipliers for any industry as 1, and only introduce them for notational convenience, so that all permutations loss / recovery and direct/indirect/induced can be treated uniformly.

$$\begin{aligned}
\bar{m}'_i{}^D &= 1 \\
\bar{m}'_i{}^I &= \tilde{m}'_i{}^I - 1 \\
\bar{m}'_i{}^P &= \tilde{m}'_i{}^P - \tilde{m}'_i{}^I
\end{aligned} \tag{2}$$

The above definition of multipliers allows treating the direct, indirect, and induced losses and recovery using the same functional form. We therefore show how a particular type of a gross loss is calculated as a function of multiplier and other factors as defined in Bixler et al. (2020). We then show that calculation of net losses and recovery can be expressed in the same functional form where both can be expressed as a linear function of the gross loss.

We define the incremental direct, indirect, and induced gross losses to correspond to incremental multipliers and denote them as  $\Delta V^D$ ,  $\Delta V^I$ , and  $\Delta V^P$ . We sometimes call those gross losses and use the superscript  $G$  to represent them. We define gross total gross losses as the sum of the incremental direct, indirect, and induced losses:

$$\Delta V^{G,T} = \Delta V^{G,D} + \Delta V^{G,I} + \Delta V^{G,P} \tag{3}$$

These incremental gross losses of any type  $K$  are split into the national recovery and net loss components:

$$\Delta V^{G,k} = \Delta V^{R,k} + \Delta V^{L,k} \tag{4}$$

where  $R$  and  $L$  designate the recovered (due to national recovery) and lost components of the gross losses and  $k \in \{D, I, P\}$ .

We assume that the recovery, both local and national will start at the time of the accident. We derive the expressions for the general case for any loss type and apply them later to calculate the metrics for specific loss.

The gross cumulative incremental loss of type  $k$  at time  $t$  denoted as  $V^{G,k}(t)$  can be split into two components: net losses  $\Delta V^{L,k}(t)$  and national recovery  $\Delta V^{R,k}(t)$ . We will omit the loss type and incremental symbols in the rest of this section for clarity because the expressions derived below apply to any loss type. We use the symbol  $m_i$  to represent an incremental multiplier of any type in  $\{D, I, P\}$ . The following identity holds by definition:

$$\Delta V^G(t) = \Delta V^L(t) + \Delta V^R(t) \tag{5}$$

We derive the expressions for all three components from this definition of the gross incremental losses of any type from this definition:

$$\Delta V^G(t) = e^{g(t_I - t_0)} \sum_I v_i m_i \sum_R l_{i,r} \int_0^t s_r(x) e^{(g-\rho)x} dx \tag{6}$$

We then use the identity  $1 = (1 - s_N + s_N)$  to split the  $\Delta V^G(t)$  from equation (6) into  $\Delta V^L(t)$  and  $\Delta V^R(t)$  as following:



$$\Delta V^G(t) = e^{g(t_I - t_0)} \sum_I v_i m_i \sum_R l_{i,r} \int_0^t s_r(x) (1 - s_N(x) + s_N(x)) e^{(g-\rho)t} dx \quad (7)$$

$$e^{g(t_I - t_0)} \sum_I v_i m_i \sum_R l_{i,r} \int_0^t s_r(x) s_N(x) e^{(g-\rho)t} dx + \quad (= \Delta V^L(t))$$

$$e^{g(t_I - t_0)} \sum_I v_i m_i \sum_R l_{i,r} \int_0^t s_r(x) (1 - s_N(x)) e^{(g-\rho)t} dx \quad (= \Delta V^R(t))$$

We define  $\Delta V^L(t)$  as:

$$\Delta V^L(t) = e^{g(t_I - t_0)} \sum_I v_i m_i \sum_R l_{i,r} \int_0^t s_r(x) s_N(x) e^{(g-\rho)t} dx \quad (8)$$

To evaluate all parts of Equation (7) analytically, we need to calculate three following functions:

$$F^L(t, r) = \int_0^t s_r(x) s_N(x) e^{(g-\rho)t} dx \quad (9)$$

$$F^G(t, r) = \int_0^t s_r(x) e^{(g-\rho)t} dx \quad (10)$$

and

$$F^R(t, r) = \int_0^t s_r(x) (1 - s_N(x)) e^{(g-\rho)t} dx \quad (11)$$

We can now rewrite all items from Equation (7) as following:

$$\Delta V^L(t) = e^{g(t_I - t_0)} \sum_I v_i m_i \sum_R l_{i,r} F^L(t) \quad (12)$$

$$\Delta V^G(t) = e^{g(t_I - t_0)} \sum_I v_i m_i \sum_R l_{i,r} F^G(t) \quad (13)$$

and

$$\Delta V^R(t) = e^{g(t_I - t_0)} \sum_I v_i m_i \sum_R l_{i,r} F^R(t) \quad (14)$$

The functional form of  $F^L(t, r)$ ,  $F^G(t, r)$  and  $F^R(t, r)$  is independent of the loss type. This allows creating a parsimonious representation for metrics calculations. The RDEIM model calculates all incremental loss and recovery component using the following expression:

$$\Delta \bar{V}^{m,k}(t) = e^{g(t_I - t_0)} \sum_I v_i \bar{m}'_i{}^k \sum_R l_{i,r} F^m(t, r), \quad (15)$$

where  $m \in \{G, L, R\}$  and  $k \in \{D, I, P\}$ .

All the terms needed for the calculation of the regular losses and recovery are fully specified in the Equation (15). We derive the expressions for  $F^G(t)$ ,  $F^L(t)$  and  $F^R(t)$  in the next section. We call the first two “effective loss” functions and the last one “effective recovery” function.

### 2.1.3. Derivation of Analytical Expressions for Effective Loss and Recovery Functions

To simplify the model implementation, given the relatively simple functional dependence of the regional and national recovery schedules versus time, the effective loss and recovery functions  $F^{\{G,L,R\}}(t, r)$  is expressed analytically. This allows explicit analytical understanding of the dependencies on the parameters and simplifies the implementation in RDEIM model.

$s_N(t)$  is defined as following:

$$s_N = \begin{cases} 1 - \frac{t}{t_N}, & t \leq t_N, \\ 0, & t > t_N, \end{cases} \quad (16)$$

and

$$s_r = \begin{cases} 1, & t \leq t_r \\ 0, & t > t_r \end{cases} \quad (17)$$

By definition,  $F^R(t, r) = F^G(t, r) - F^L(t, r)$ . Therefore, we derive explicit analytic expressions only  $F^G(t, r)$  and  $F^L(t, r)$ .

We define  $t_r' = \min(t_r, t_N)$ , where  $t_r$  is actual recovery time for the grid element  $r$  bounded by the parameter  $t_N$ , the maximum duration of regional disruption. There are two special cases:  $\rho = r$  and  $\rho \neq r$ . We treat them separately.

#### 2.1.3.1. Special case $g = \rho$

After substituting  $g - \rho = 0$ , we obtain:

$$F^L(t, r) = \int_0^t s_r(x) s_N(x) dx = 1 - \frac{t_r'}{2t_N} \quad (18)$$

$$F^G(t, r) = \int_0^t s_r(x) dx = t_{r'} \quad (19)$$

#### 2.1.3.2. Special Case $g \neq \rho$

For this case, we obtain:

$$F^L(t, r) = \int_0^t s_r(x) s_N(x) e^{(g-\rho)t} dx = \frac{e^{(g-\rho)t_{r'}} - 1}{(g - \rho)} - \frac{((g - \rho)t_{r'} - 1)e^{(g-\rho)t_{r'}} + 1}{t_N(g - \rho)^2} \quad (20)$$

$F^L(t, r)$  does not change for  $t > T_N$ . This is consistent with the assumption that the national economy has fully recovered at time  $t_N$ . The two parts of the last term in the above equation 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 reduction of the losses over the recovery period.

$$F^G(t, r) = \int_0^t s_r(x) e^{(g-\rho)t} dx = \frac{e^{(g-\rho)T_{r'}} - 1}{g - \rho} \quad (21)$$

By comparing Equations ( 20 ) and ( 21 ) we immediately see that

$$F^R(t, r) = \frac{((g - \rho)t_{r'} - 1)e^{(g-\rho)t_{r'}} + 1}{t_N(g - \rho)^2} \quad (22)$$

#### 2.1.4. Losses and Recovery Estimation in Single Grid Element and Entire Affected Area

The purpose of this is to provide a simple example for a single grid element and to preserve a continuity with Bixler et al. (2020).

Once the disruption scenario is specified, the RDEIM calculation of gross 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.

This description is for a single grid element,  $r$ . This simplifies the exposure but is completely general because the loss and recovery metrics for the entire affected region and the nation are calculated by summing up those variables for all affected grid elements. The rate of direct, value-added losses for industry  $i$  in grid element  $r$  at time  $t_I$  is found by multiplying the per-employee value added by the number of affected employees and projecting the GDP to the year of the accident:

$$\frac{dV^D_{i,r}}{dt} = e^{g(t_I-t_0)} v_i l_{i,r} \quad (23)$$

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  $t_I + t$ , for the loss type  $k$ , where  $k \in \{D, I, P\}$  we integrate the above expression over time, considering the economic real GDP growth rate  $g$ , the social discount rate  $\rho$ , and that a specific grid element may recover sooner than  $t$ .

$$\Delta V^k_{i,r}(t) = e^{g(t_I-t_0)} v_i l_{i,r} \bar{m}'_i{}^{P,R} \int_{t_I}^{t_I+t} s_r(x) e^{(g-\rho)(x-t_I)} dx \quad (24)$$

Here the disruption function,  $s_r(t)$ , reflects the decontamination schedule and is defined in the Equation (17). By redefining  $t$  as time relative to the start of the incident, the above equation is simplified as follows:

$$\Delta V^k_{i,r}(t) = e^{g(t_I-t_0)} v_i l_{i,r} \bar{m}'_i{}^{P,R} \int_0^t s_r(x) e^{(g-\rho)x} dx \quad (25)$$

In the special case of  $g = \rho$  the part of Equation (25) under the integral is the number of years the grid element  $r$  is disrupted. We interpret it as the exponentially discounted number of years a grid element has been disrupted. Therefore, the Equation (25) can be understood as the multiplication of the annual value added per grid element and industry by the effective number of years that industry was disrupted.

By the definition for  $F_r(t)$  above ( $F_r(t) = \int_0^t s_r(x) e^{(g-\rho)x} dx$ ), Equation (25) is identical to:

$$\Delta V^k_{i,r}(t) = e^{g(t_I-t_0)} v_i l_{i,r} \bar{m}'_i{}^{P,R} F_r(t) \quad (26)$$

The 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:

$$\Delta V^k(t) = e^{g(t_I-t_0)} \bar{m}'_i{}^{P,R} \sum_I v_i \sum_R l_{i,r} F_r(t) \quad (27)$$

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.

### 2.1.5. *Direct Indirect, Induced, and Total Losses and Recovery*

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 in RDEIM 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<sup>22</sup>, 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 2.3.2.

The total impact includes direct, indirect, and induced losses. Its gross, loss, and recovery components are calculated as, based on Equations ( 28 ) and ( 29 ):

$$\Delta V^{T,m}(t) = \sum_{k \in K} \Delta \bar{V}^{k,m}(t), \quad (28)$$

where  $K = \{D, I, P\}$  and  $m \in \{G, L, R\}$ .

RDEIM calculates the sum of direct and indirect losses and recovery in the same way by omitting the summation by induced losses.

$$\Delta V^{D+I,m}(t) = \sum_{k \in K'} \Delta \bar{V}^{k,m}(t) \quad (29)$$

where  $K' = \{D, I\}$  and  $m \in \{G, L, R\}$ .

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 by adjusting the employment for the Utilities industry in grid element  $r$  as follows:

$$l_{Utilities,r} \rightarrow \max(l_{Utilities,r} - l_{NP,r}, 0) \quad (30)$$

where  $l_{NP,r}$  is the employment of the affected nuclear power plant facility. The “max” in the Equation ( 30 ) is needed to avoid the possibility of inferring a negative number of employees affected due to exact employment data not being available<sup>23</sup>. MACCS does not currently have an

<sup>22</sup> 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.

<sup>23</sup> 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

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.

## 2.2. Other Losses

The implementation of the RDEIM I-O model accounts for GDP or value-added loss or recovery. The RDEIM economic model includes the GDP losses from the I-O model as well as other kinds of losses, including tangible wealth. This includes loss of tangible assets (e.g., depreciation) and accident expenditures (e.g., decontamination), as described below. The inclusion of the tangible assets into the loss estimation is necessary in part because this allows differentiating the disruptions where business was disrupted but the tangible assets were not destroyed against the scenarios where the tangible assets were destroyed. It further allows more fully reflecting the effects of different accident response strategies and decontamination expenditures.

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. When a property is condemned, the full value of the condemned property from both the land and improvements are tallied as an immediate loss.

For temporarily interdicted property, MACCS separates the value of property into the value of land and the value of land improvements. Since interdicted property cannot be properly maintained, the RDEIM economic model estimates loss in wealth based on the following expression using a depreciation rate:

$$C_{dp} = V_w \times F_{im} \times [1 - \exp(-r_{dp} \times \Delta t)]$$

Where:

- $V_w$ :** Per person value of non-farm property or per area value of farm property, including land, buildings, infrastructure, and non-recoverable equipment and machinery
- $F_{im}$ :** Fraction of property value resulting from improvements
- $r_{dp}$ :** Depreciation rate
- $\Delta t$ :** Duration of interdiction

This loss only affects land improvements, as land does not depreciate. For temporarily interdicted property, the RDEIM economic model does not model direct or immediate impacts from contamination as it does for condemned property.

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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.

In version 4.0, the RDEIM economic model for depreciation in Bixler et al. (2020) included a rate of return on investment so that the calculation for depreciation would match the original cost-based model. However, this expression has an issue in that the annual depreciation losses could become depreciation gains, which is erroneous. The new depreciation expression removes the rate of return from the expression, which simplifies the depreciation calculation and fully separates income and property losses.

Beginning in MACCS version 4.1, the RDEIM economic model includes milk and crop disposal costs. This is a change from MACCS version 4.0 when these costs were only considered in the cost-based model. Milk and crop disposal costs 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 loss to farmers extends back before the accident to the start of the growing season. Since the RDEIM I-O model evaluates economic losses after the accident, accounting for milk and crop losses provides a better cost estimate.

Decontamination cost modelling is the same as before, however, MACCS version 4.2 has a separate input for the cleanup dose level. As such, the cleanup level can now be different from the relocation dose level, which allows users to model decontamination in habitable areas. Relocation cost modelling for early, intermediate, and long-term phase relocation remain unchanged. The decision on cost effectiveness of performing decontamination is described in detail in Bixler et al. (2020).

## 2.3. Inputs to the GDP Impact Estimation Methodology

### 2.3.1. Data Sources

This section briefly describes the data used as a part of RDEIM calculations. The primary inputs to losses and recovery calculations described in Section 2.1 include value added by industry, employment by grid element, and NTR multipliers. These inputs and their sources are listed below. The calculation or data generation for parameters listed as external is done outside of RDEIM.

- Value added by industry ( $V_i$ , where  $i$  is an industry):  
External. The value added by industry is derived from the data provided with RIMS II model (BEA, 2012). This value is used in all calculations for losses and recovery. In most of the calculation it is converted to value added by employee by industry using the national-level value-added and employment data. Additional BLS data with a more fine-grained industry resolution have been used to determine the functional form for the Net Total Requirements multipliers.
- Employment by county, region, grid element:  
The employment by country is external. It describes the number of employees for each county for each industry. We use the data provided by the BEA and BLS. The county employment data is then used to calculate employment by grid element and region.

The employment by grid element or a region is a part of the disruption scenario specification and analysis. Both are calculated internally. The terms region and grid element and their interrelation are described in section 2.1. The employment by grid element  $r$ . For industry  $i$  is denoted as  $l_{i,r}$ .

In short, a region is defined as an area covered by one or more grid elements. The employment for the region for each industry is the sum of industry employment for all grid elements the region is composed of.

A grid element could represent anything from a small fraction of a single county to a large collection of counties and partial counties, as defined in section 2.1. The grid employment by industry is the sum of employment by industry for each entire or partial county in that grid element.

The employment for partial counties is calculated according to the procedure described in the Section 2.3.5 (Treatment of Partial Counties).

The employment by grid element is used in all calculations for losses and recovery.

- NTR multipliers ( $m_i^k$ , where  $i$  is industry and  $k$  is the multiplier type as defined in section 2.1) :  
External. We use both the BEA and BLS data to estimate the NTR multipliers. This estimation is described in Section 2.3.2. It is based on RIMS II multipliers and the value-added data and gross output data provided by the BEA. It uses the BLS QCEW Location Quotient data<sup>24</sup> to augment the BEA employment data and to estimate the effects of area size and area employment on the multipliers. NTR multipliers used in all calculations for indirect, induced, and total losses and recovery.

Additional data used in RDEIM calculation is listed below. The specific data and methodology to calculate those inputs is described in a more detail in corresponding sections of this document.

- Maximum Duration of Local and National Economic Impact (Section 2.3.3):  
External.
- Industries in RDEIM (Section 2.3.4):  
External.
- Functional form for loss estimation for partial counties (Section 2.3.5):  
External. It was originally based on the subject-matter expertise. It was later reconciled and refined based on the functional form estimation for the NTR multipliers. It is therefore indirectly based on BEA and BLS employment, BLS QCEW Location Quotient and other data.
- Social Discount Rate ( $\rho$ , Section 2.3.6):  
External. Based primarily on literature review and OMB (2014).

### **2.3.2. Net Total Requirements Multipliers**

Two unique features of the scenarios considered for this application motivate creation of modified Type I and Type II multipliers<sup>25</sup>. First, the initial disruption is presented as value-added losses in the impacted area, thus requiring “national”<sup>26</sup> multipliers that operate on regional changes in the value

<sup>24</sup> See <https://www.bls.gov/cew/about-data/location-quotients-explained.htm>. Accessed December 9, 2021.

<sup>25</sup> 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.

<sup>26</sup> 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.



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.

We define the gross total requirement multipliers of Type  $k$  as follows:

$$m_i^{k,N} = \frac{Y_i}{V_i} \sum_j b_{i,j}^k \frac{V_j}{Y_j}, k \in \{I, II\} \quad (31)$$

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<sup>27</sup>.

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

$$m_i^{k,N} = \frac{Y_i}{V_i} \tilde{m}_i^{k,N} \quad (32)$$

where  $\tilde{m}_i^{k,N}$  is the national final demand value-added multiplier of Type  $k$  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<sup>28</sup> are calculated in the same way using the corresponding TRII Table:

$$m_i^{k,R} = \frac{Y_i}{V_i} \tilde{m}_i^{k,R} \quad (33)$$

where the superscript  $R$  represents the impacted region. To account for the possibility that some suppliers may be within region  $R$ , we define the net total requirements Type  $k$  multipliers as follows<sup>29</sup>:

$$m_i'^{k,R} = m_i^{k,N} - m_i^{k,R} + 1 \quad (34)$$

<sup>27</sup> 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.

<sup>28</sup> These multipliers are calculated for the entire impacted region and not for separate grid elements.

<sup>29</sup> 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.

Ultimately, we define the multipliers used 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 by the following equation:

$$\tilde{m}'_{i^{k,R}} = \frac{V_i}{Y_i} m'_{i^{k,R}} \quad (35)$$

Given the requirements to this model, the net total requirements multipliers in Equation (35) 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. We chose the normalized exponentials the best model to fit the BEA data and has the following functional form:

$$m'_{i^{k,R}} = (m'_{i^{k,N}} - 1) * \frac{\exp(\alpha_i) - \exp(\alpha_i * s_R)}{\exp(\alpha_i) - 1} * \exp(\beta_i * e_{i,R}) + 1 \quad (36)$$

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 by the BLS<sup>30</sup> as follows:

$$e_{i,R} = \frac{l_{i,R} / \sum_{i=1}^I l_{i,R}}{l_{i,N} / \sum_{i=1}^I l_{i,N}} \quad (37)$$

We constructed the coefficients  $\alpha_i$  and  $\beta_i$  empirically 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 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.

### 2.3.3. 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

<sup>30</sup> See <https://www.bls.gov/cew/about-data/location-quotients-explained.htm>. Accessed December 9, 2021.

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.

We selected the maximum duration for regional impacts of 10 years from the allowed 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.

We selected the national recovery period of 4 years as the default value with a national recovery period of between 1 and 10 years allowed, based on literature review and external review recommendations. 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<sup>31</sup>. National economic disruptions from recession tend to be short, around 1 to 3 years.
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.

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<sup>31</sup> More information can be found at [www.nber.org/cycles.html](http://www.nber.org/cycles.html). Accessed January 15, 2015.

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)<sup>32</sup>.

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<sup>2</sup>) 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  $T_R$ .

### **2.3.4. List of Industries in RDEIM**

The BEA (2012) provides detailed information on the structure of the U.S. economy and covers approximately 400 industries.<sup>33</sup> 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.

### **2.3.5. 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 very limited offsite consequences that affect less than one county or could affect many whole counties and portions of others. Therefore, we developed an approach 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 that can be used as the basis for calculating GDP losses for partially affected

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<sup>32</sup> The published COCO-2 documentation does not provide a justification for the 2-year period. This was confirmed via email by M. Munday.

<sup>33</sup> See [http://www.bea.gov/papers/pdf/IOmanual\\_092906.pdf](http://www.bea.gov/papers/pdf/IOmanual_092906.pdf) for a detail description of BEA methodology.

counties, given the data used for this analysis. We have reviewed the industries to evaluate 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 1 was reviewed and some judgment was used to select area or population.

**Table 1. 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

### **2.3.6. 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.
- 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  $\rho$  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.

### 2.3.7. MACCS Input Parameters

Table 2 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% based on historical averages is the default.

**Table 2. 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), $T_R$ <sup>34</sup>	10	1	30

<sup>34</sup>  $T_R$  does not influence actual losses for grid element  $r$  when recovery within the grid element occurs prior to that time.

Time at which National Economy recovers (yr)	3	1	10
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### 3. 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<sup>35</sup> 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<sup>36</sup>, 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.<sup>37</sup> 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.

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<sup>35</sup> The original economic impact estimation model was envisioned as REAcct working as a preprocessor to MACCS. Because of the changes to the economic methodology, the current model largely uses the REAcct data, a modified version of REAcct called RDEIM, and algorithms internal to MACCS for calculating the impacts.

<sup>36</sup> 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.

<sup>37</sup> 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.

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 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.

### 3.1. 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,  $I = \{\text{Utilities}, \text{Manufacturing}, \text{AdmService}, \text{FoodService}\}$ . The 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,  $\rho = 1.5\%$ .

Base year = database year = 2011.

GDP of the region is \$3 billion, and national GDP is assumed to be \$100 billion<sup>38</sup> in 2011. The employment by industry and county is described in Table 3.

**Table 3. 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 4.

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<sup>38</sup> These numbers are made for illustration purposes and do not intend to represent any real geographic data.

**Table 4. 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 1 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 5.

**Table 5. 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 6.

**Table 6. Grid Element Recovery Schedule**

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

Table 7 describes the value added per worker for each industry.

**Table 7. 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 8. 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 8. 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 9<sup>39</sup>. These multipliers only account for the effect of a disrupted industry on suppliers outside the directly affected region.

**Table 9. 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

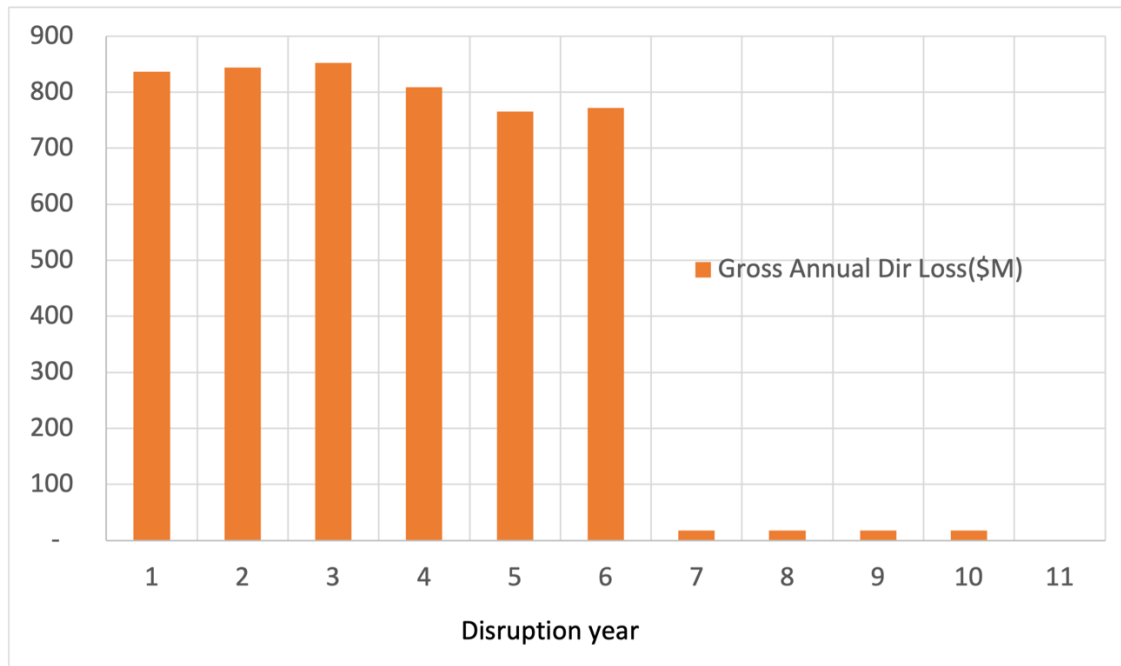
Various losses and recovery estimates are calculated applying appropriate parameters as summarized in Table 10.

**Table 10. Summary of Net Direct Losses for the Region. All Values are Discounted to 2011 (Year 1 in the Table) using the Social Discount Rate.**

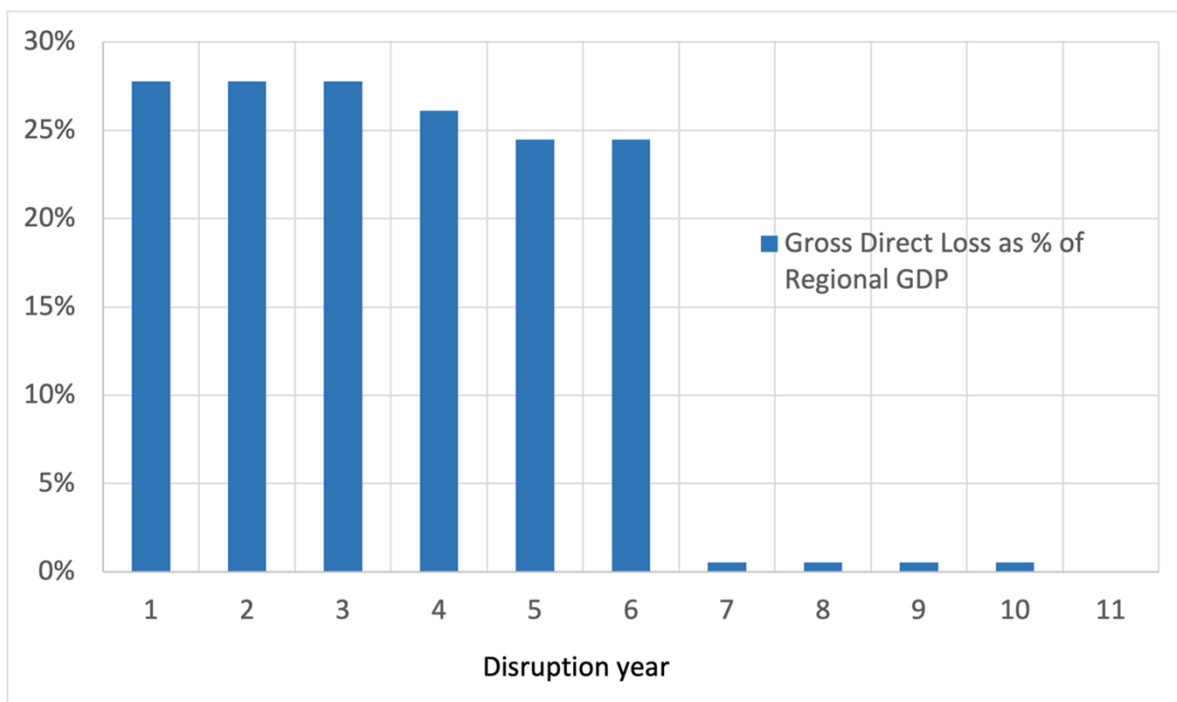
Year	Net Cum. Dir. Loss (\$M)	Net Annual Direct GDP Loss (\$M)	Baseline Cum. GDP (\$M)	Baseline Annual GDP (\$M)	Net Percent Loss of Regional GDP (%)	Annual GDP after Disruption (\$M)
1	732	732	3,014	3,014	24.3	2,177
2	1,260	528	6,054	3,041	17.4	2,196
3	1,579	319	9,123	3,068	10.4	2,216
4	1,683	104	12,219	3,096	3.4	2,287
5	1,683	-	15,343	3,124	0.0	2,359
6	1,683	-	18,495	3,152	0.0	2,380
7	1,683	-	21,676	3,181	0.0	3,164
8	1,683	-	24,885	3,210	0.0	3,192
9	1,683	-	28,124	3,239	0.0	3,221
10	1,683	-	31,391	3,268	0.0	3,250
11	1,683	-	34,689	3,297	0.0	3,297

The annual gross direct losses (\$M) are represented in Figure 2 and as a percent of the regional GDP in Figure 3. The gross losses are shown here instead of net losses because the recovery of direct losses before the end of interdiction times occurs outside of the affected region, at the national level.

<sup>39</sup> These are notional multipliers and are used for illustration purposes only. In addition, we do not attempt to illustrate the methodology for calculating the area specific multipliers here, and only illustrate the application of these multipliers.

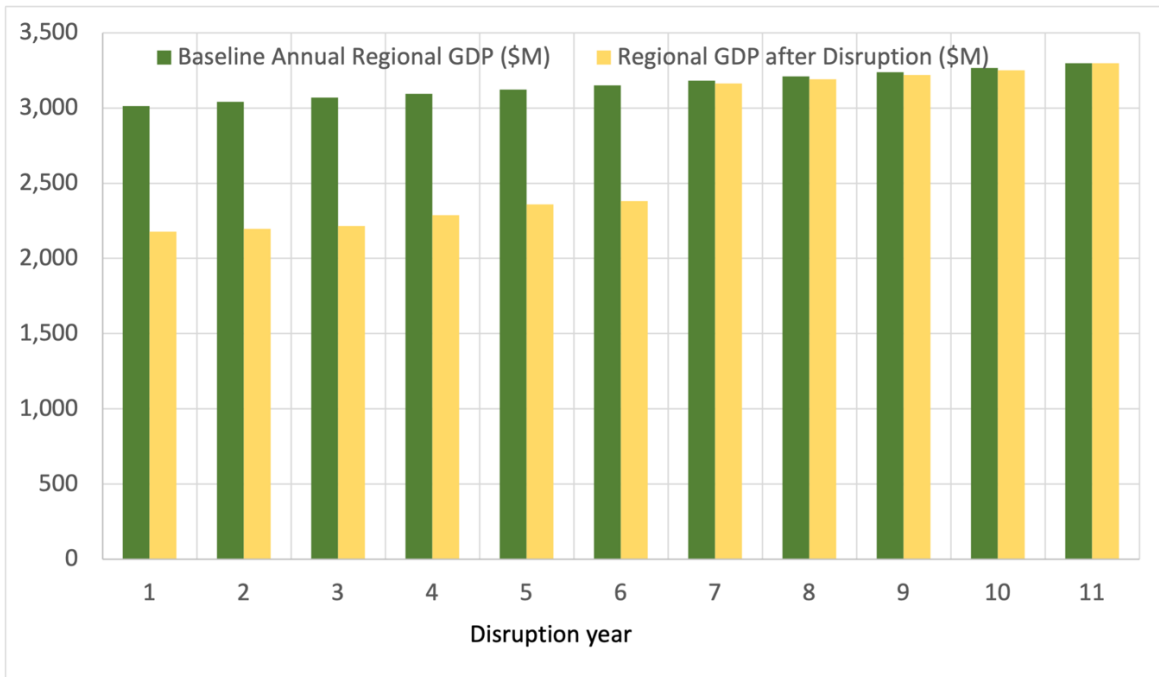


**Figure 2. Gross annual direct GDP loss to regional economy. All values are discounted to beginning of 2011 (year 1) using the social discount rate.**



**Figure 3. Gross annual direct 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 4.



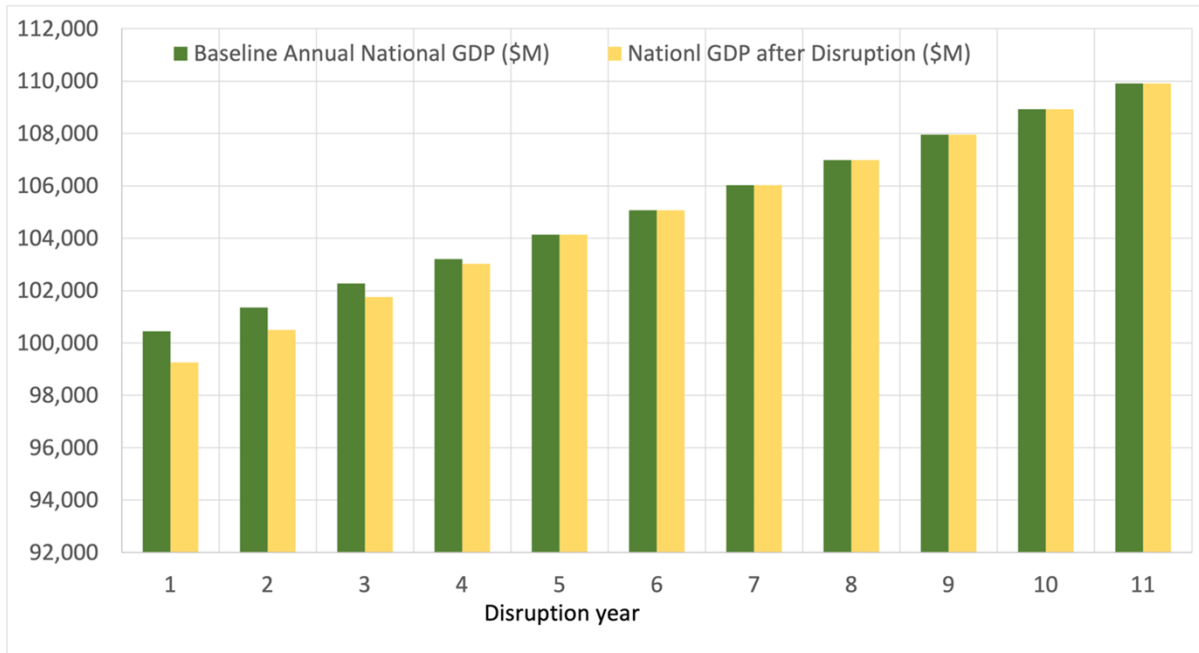
**Figure 4. Regional annual GDP with and without the disruption. All values are discounted to beginning of 2011 (year 1) using the social discount rate.**

Table 11 represents the loss estimates on the national level.

**Table 11. GDP Losses at the National Level. All Values Are Discounted to 2011 (Year 1) Using the Social Discount Rate.**

Year	Net Cum. Total GDP Loss (\$M)	Net Annual Total 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	1,202	1,202	364	105	100,451	100,451	1.20	99,250
2	2,067	866	263	76	201,811	101,359	0.85	100,494
3	2,592	524	159	46	304,087	102,376	0.51	101,752
4	2,763	171	52	15	407,287	103,300	0.17	103,029
5	2,763	-	-	-	511,421	104,133	0.00	104,133
6	2,763	-	-	-	616,496	105,075	0.00	105,075
7	2,763	-	-	-	722,520	106,025	0.00	106,025
8	2,763	-	-	-	829,504	106,983	0.00	106,983
9	2,763	-	-	-	937,454	107,951	0.00	107,951
10	2,763	-	-	-	1,046,381	108,927	0.00	108,927
11	2,763	-	-	-	1,156,292	109,911	0.00	109,911

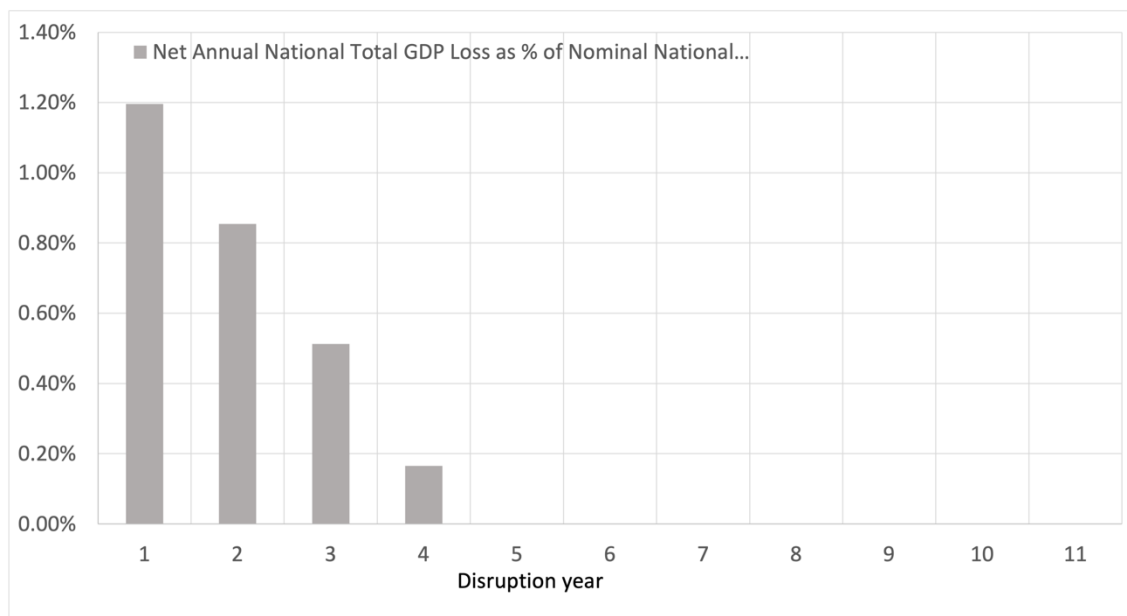
The trajectory of national GDP with and without the disruption is represented in Figure 5.



**Figure 5. National GDP with and without disruption. All values are discounted to beginning of 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 Figure 4 and Figure 5 respectively. 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 Figure 4 and Figure 5 would show an upward slope, as is shown for example in Figure 1. 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 6.



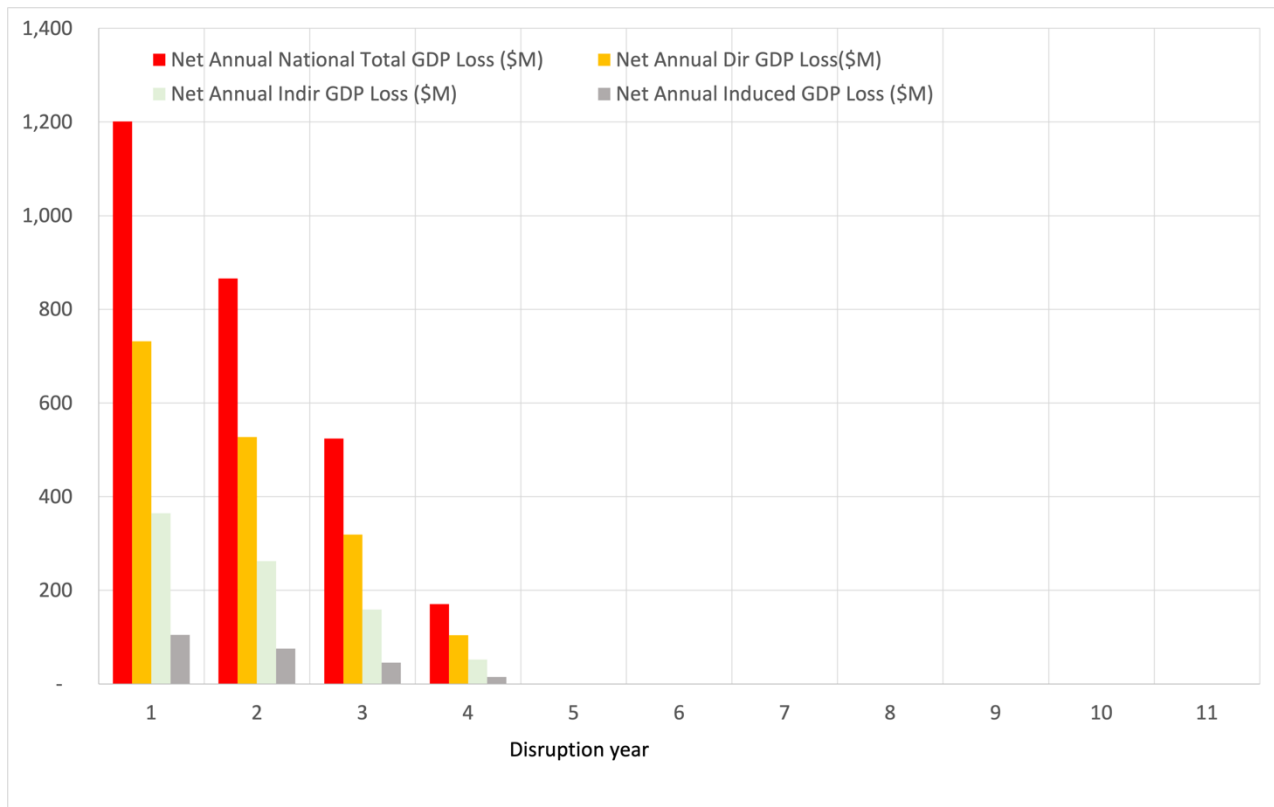
**Figure 6. Net Annual GDP loss as a percent of national GDP.**

A summary of annual direct, total, indirect, and induced losses is represented in Table 12 and in Figure 7. 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 12. Annual Losses Summary at National Level. All Values are Discounted to 2011 (Year 1) Using the Social Discount Rate.**

<b>Year</b>	<b>Net Annual Direct GDP Loss (\$M)</b>	<b>Net Annual National Total GDP Loss (\$M)</b>	<b>Net Annual Indirect GDP Loss (\$M)</b>	<b>Net Annual Induced GDP Loss (\$M)</b>
1	732	1202	364	105
2	528	866	263	76
3	319	524	159	46
4	0	171	52	15
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0

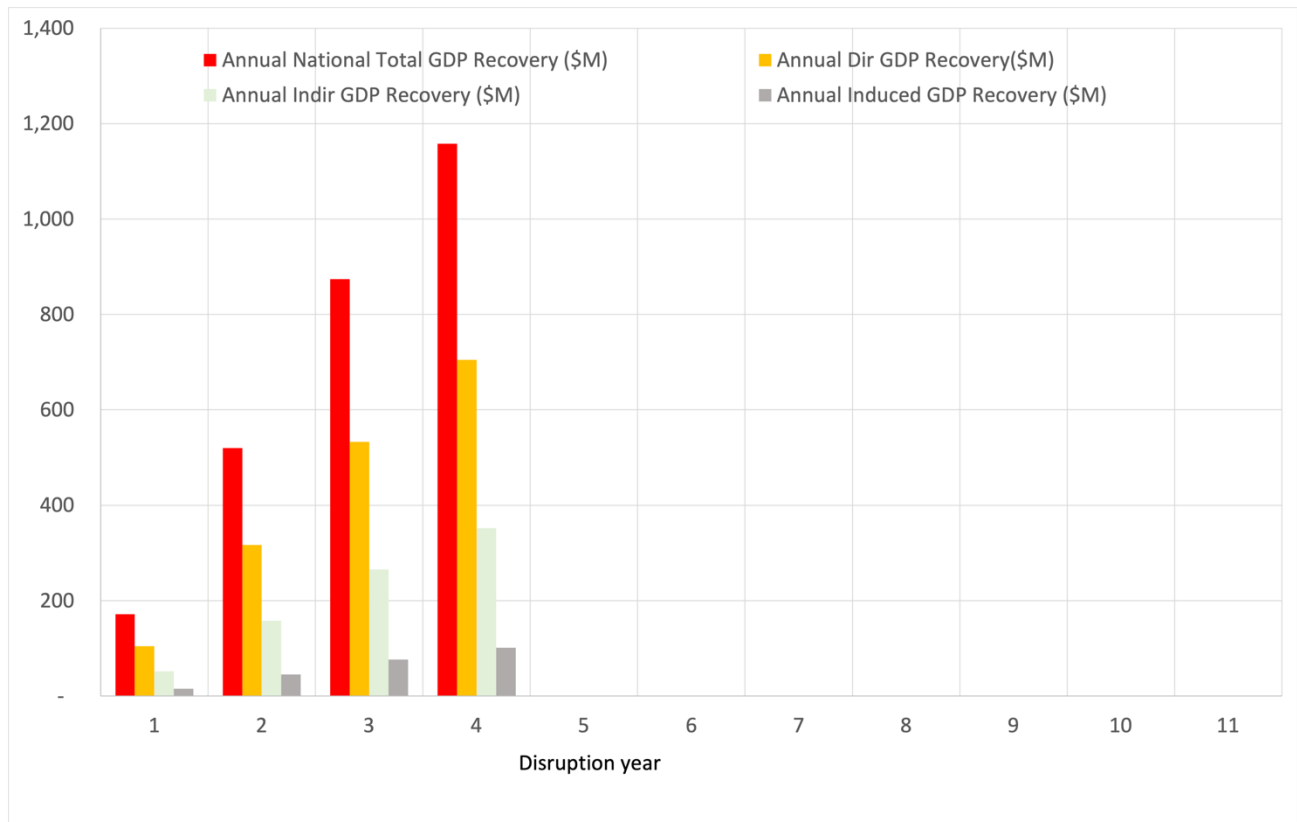




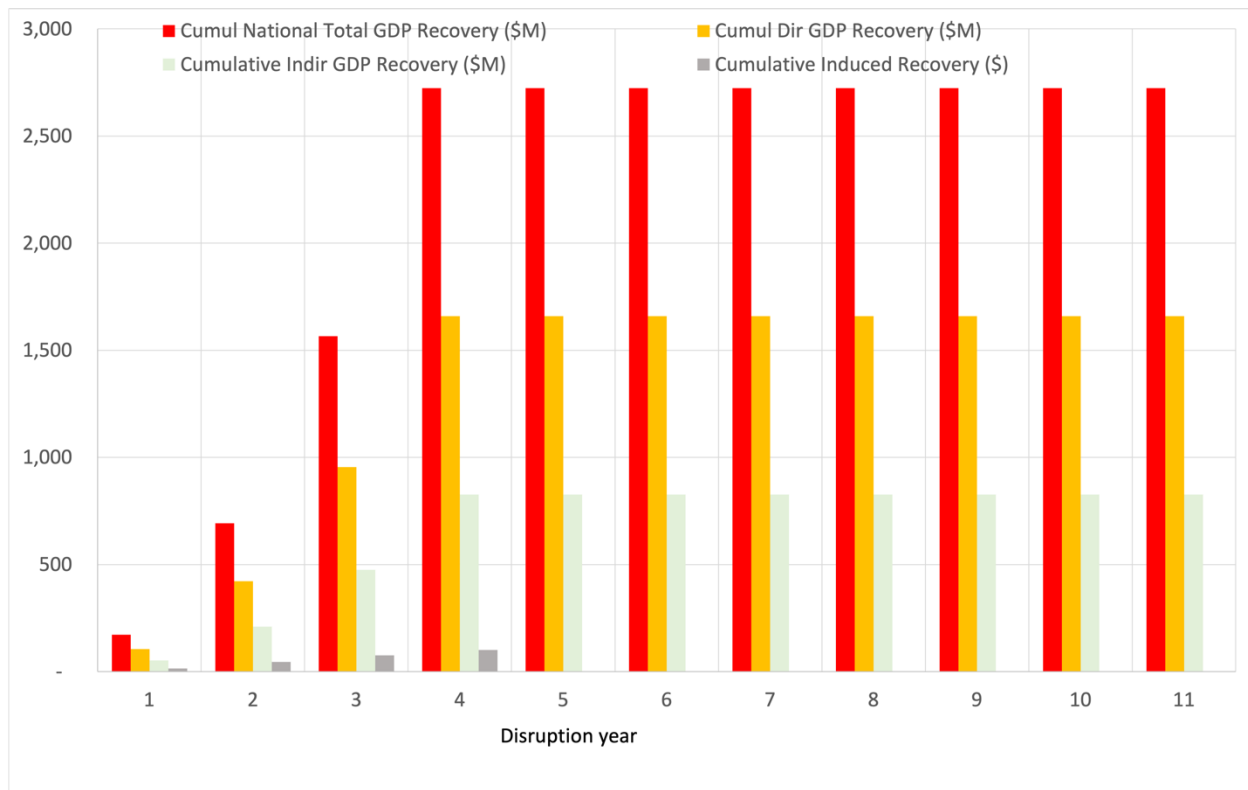
**Figure 7. Direct, total, indirect, and induced annual losses at the national level. All values are discounted to 2011 (year 1 in the plot) using the social discount rate.**

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.

As shown in Section 3, national recovery can be calculated similarly to loss calculation. The annual and cumulative recovery numbers are shown in Figure 8 and Figure 9.



**Figure 8. Annual Recovery Estimates.**



**Figure 9. Cumulative Recovery Estimates.**

For convenience, this example was implemented in an Excel worksheet, which allows further experimentation with different parameters.

### 3.2. Presentation and Use of Results

The output of the model includes both losses and recovery, as specified in Section 3.1.2. Loss values can be interpreted as shown in Table 13. Direct losses  $\Delta V^{D,L}$  only occur in the directly affected areas and are therefore included under national but not the extra-regional area. Indirect losses  $\Delta V^{I,L}$  only occur in the extra-regional area and are therefore included under national but not the intraregional area. Induced losses  $\Delta V^{P,L}$  occur in both the intraregional and extra-regional areas and are 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 at the intraregional level, as shown in Table 14.

Recovery values can be interpreted as shown in Table 15. Table 15 represents the national recovery, that is separate from local decontamination and recovery. The national recovery reflects the fact that even permanent local losses will be recovered at least to a degree at the extra regional and national levels<sup>40</sup> because people and business activities will move and start anew, even if local recovery does not occur. Specifically direct, indirect, and induced losses are compensated to a degree by industries being reestablished in the extra-regional area. This is why total losses in Table 14 at the national level are zero - the intraregional losses are compensated by the extra-regional gains.

In addition to the GDP losses shown in Table 13 and Table 14, and national recovery shown in 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. It does not account for other potential types of losses, such as legal, health, and stigma costs.

**Table 13. GDP Losses in the First Accident Year**

Region \ Impact Type	GDP			
	Direct (\$)	Indirect (\$)	Induced (\$) <sup>41</sup>	Total (\$)
Intraregional	$\Delta V^{D;L}$	0	$x \Delta V^{P,L}$	Row sum
Extra Regional	0	$\Delta V^{I,L}$	$(1 - x) \Delta V^{P,L}$	Row sum
National	$\Delta V^{D,L}$	$\Delta V^{I,L}$	$\Delta V^{P,L}$	Row sum

<sup>40</sup> This explicit accounting for recovery is new in this version of the report. The recovery has been treated in the previous version by introducing the negative losses.

<sup>41</sup> The variable x is the ratio of  $\Delta V^D$  to  $\Delta V^{D+I}$ . 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.

**Table 14. GDP Losses in Year 4, Assuming  $T_N = 3$** 

Region \ Impact Type	GDP losses			
	Direct (\$)	Indirect (\$)	Induced (\$)	Total (\$)
Intraregional	$\Delta V^{D,L}$	0	0	$\Delta V^{D,L}$
Extra Regional	0	0	0	0
National	0	0	0	0

**Table 15. National Recovery in the First Accident Year**

Region \ Impact Type	GDP			
	Direct (\$)	Indirect (\$)	Induced (\$) <sup>42</sup>	Total (\$)
Intraregional	0	0	0	Row sum
Extra Regional	$\Delta V^{D,R}$	$\Delta V^{I,R}$	$\Delta V^{P,R}$	Row sum
National	$\Delta V^{D,R}$	$\Delta V^{I,R}$	$\Delta V^{P,R}$	Row sum

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 kinds of losses, 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. 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.

<sup>42</sup> The variable  $x$  is the ratio of  $\Delta V^D$  to  $\Delta V^{D+I}$ . 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.



## 4. SUMMARY

This report is an updated and shortened version of the Bixler et al. (2020) report. The purpose of this version is to introduce the national recovery calculation explicitly, rather than implicitly as in the previous version. The recovery is no longer calculated as a negative loss, but rather treated in the same way as GDP losses. The calculation of the total national GDP losses remains unchanged. However, anticipated gains from recovery are now allocated across all the GDP loss types – direct, indirect, and induced – whereas in version 4.1, all recovery gains were accounted for in the indirect loss type. The report describes this new methodology to streamline and simplify the calculation of all types and categories of losses and recovery.

In addition, RDEIM includes other kinds of losses, including tangible wealth. This includes loss of tangible assets (e.g., depreciation) and accident expenditures (e.g., decontamination). We expect that RDEIM benchmarking from Bixler et al. (2020) to remain valid, because the gross GDP RDEIM model results used are in benchmarking are not expected to be affected by the RDEIM model changes.

This methodology applies within the GDP-based model for economic losses that has 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.

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