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Fuel Cycle Analysis Framework Base Cases for the IAEA/INPRO GAINS Collaborative Project

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FUEL CYCLE ANALYSIS FRAMEWORK BASE CASES FOR THE IAEA/INPRO GAINS COLLABORATIVE PROJECT

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Abstract

Thirteen countries participated in the Collaborative Project GAINS "Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle", which was the primary activity within the IAEA/INPRO Program Area B: "Global Vision on Sustainable Nuclear Energy" for the last three years. The overall objective of GAINS was to develop a standard framework for assessing future nuclear energy systems taking into account sustainable development, and to validate results through sample analyses. This paper details the eight scenarios that constitute the GAINS framework base cases for analysis of the transition to future innovative nuclear energy systems. The framework base cases provide a reference for users of the framework to start from in developing and assessing their own alternate systems. Each base case is described along with performance results against the GAINS sustainability evaluation metrics. The eight cases include four using a moderate growth projection and four using a high growth projection for global nuclear electricity generation through 2100. The cases are divided into two sets, addressing homogeneous and heterogeneous scenarios developed by GAINS to model global fuel cycle strategies. The heterogeneous world scenario considers three separate nuclear groups based on their fuel cycle strategies, with non-synergistic and synergistic cases. The framework base case analyses results show the impact of these different fuel cycle strategies while providing references for future users of the GAINS framework. A large number of scenario alterations are possible and can be used to assess different strategies, different technologies, and different assumptions about possible futures of nuclear power. Results can be compared to the framework base cases to assess where these alternate cases perform differently versus the sustainability indicators.

Introduction

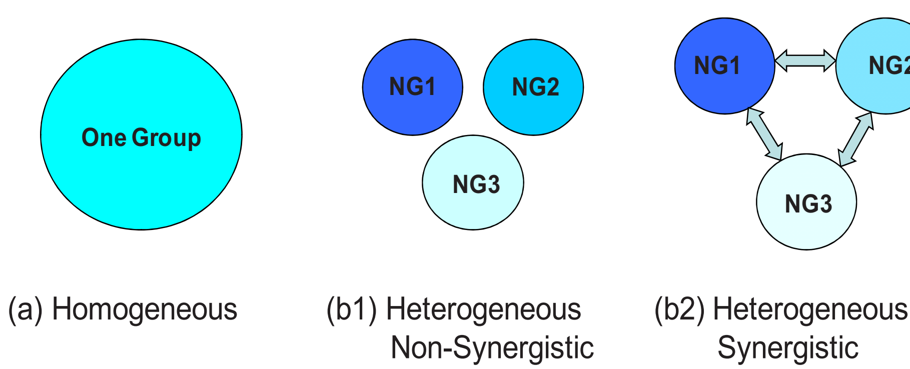
Phase 2 of the International Atomic Energy Agency (IAEA) International Project on Innovative Nuclear Reactors and Fuel Cycle (INPRO) has included several collaborative projects (CPs) established by INPRO members. The CP, “Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors, Including Closed Fuel Cycle” (GAINS) was conducted from 2008 to 2011 by Belgium, Canada, China, the Czech Republic, France, India, Italy, Japan, the Republic of Korea, the Russian Federation, Slovakia, Ukraine, the USA, and the European Commission, with Argentina as an observer. The objective of GAINS was to develop a standard framework for assessing future nuclear energy systems, taking into account sustainable development, and to validate the simulation results through sample analyses. The full GAINS report, “Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability” will be published by IAEA later this year.

This paper focuses on a specific portion of the GAINS effort, involving the development of eight “base cases” for the analysis framework. The framework base cases should not be considers as benchmarks, but rather as reference cases for users of the framework to start from in developing and assessing their own alternate systems. They were designed to present the major options supported by the framework. They are general cases for comparison, with no effort made to optimize on any particular set of performance objectives. They are also fairly straightforward cases using a minimal number of fairly standard generic reactor types to maximize the number of fuel cycle simulation codes that can use the framework.

The Framework Base Cases

The framework base cases include two world scenarios, a homogeneous world where all nuclear energy users follow the same strategy, and a heterogeneous world where different groups follow different strategies (see Figure 1). Most analyses of fuel cycles treat the world as a single technology group, where all users of nuclear energy systems follow the same strategy and use the same facilities.

Figure 1- World models supported by the GAINS framework



Within the homogeneous strategy, the framework base cases are divided between maintaining the current nuclear technologies and starting with the current technologies, but transitioning to a closed fuel cycle utilizing fast reactors. First, the "business as usual" (BAU) cases model a homogeneous world scenario with only 94% light water reactors (LWRs) and 6% heavy water reactors (HWRs) and no reprocessing. Next, the BAU-FR cases extend the BAU cases to include LWR used fuel reprocessing along with the introduction of fast reactors (FRs) starting in the first half of the century that slowly replace LWRs in the second half of the century. The rate of introduction of FRs is specified to 2050, after which they are commissioned based only on availability of plutonium for their start-up.

The GAINS framework also supports a heterogeneous world model, breaking the world into three separate nuclear strategy groups (NGs) following different fuel cycle strategies. Two of the groups, NG1 and NG2, are modeled to represent the existing global nuclear infrastructure, split between countries pursuing a closed fuel cycle with recycling and fast reactors (NG1) and countries continuing to use a once-through fuel cycle without reprocessing (NG2). The third group (NG3) represents new nuclear growth. Within the heterogeneous world model, the framework supports both a non-synergistic option, where there is no sharing of facilities or materials between NGs, and a synergistic option where sharing occurs:

- Nuclear Group (NG) 1 starts with Light Water Reactors (LWRs), then transitions to a closed fuel cycle with fast reactors.

- NG2 maintains an open fuel cycle with LWRs and Heavy Water Reactors (HWRs)

- NG3 starts with no reactors and deploys LWRs and some fuel cycle infrastructure during the course of the simulation.

How much fuel cycle infrastructure NG3 develops depends on whether the scenario includes synergy between NGs. In the non-synergistic base case, NG3 includes all of the necessary fuel cycle capabilities for fabricating new fuel, recycling used fuel, and disposing of waste. In the synergistic base case, NG3 works together with NG1 and NG2 to obtain fuel cycle services to support reactor deployment and operations. NG3 obtains all of its fuel from NG1 and NG2 (50/50 split) and returns all of its cooled used fuel back to NG1 and NG2. The GAINS participants acknowledged that other strategies and groupings are possible, but these strategies and NGs were identified as simply base cases to use for comparison.

The framework also includes both a moderate and a high growth scenario, with base cases for both. Generation is presented in units of GW(e)/a, or the amount of electricity produced by a gigawatt of net electric generating capacity running at a 100% load factor for a full year. This unit allows for modeling of reactors with different thermal efficiencies and/or different load factors. Both cases start with the current worldwide nuclear generation level of ~298 GW(e)/a in 2008, with the moderate case growing to 600 GW(e)/a by 2030, 1,000 GW(e)/a by 2050, and 2500 GW(e)/a by 2100. The high growth case values for the same time periods are 700, 1500 and 5000 GW(e)/a. After 2100, no additional growth occurs, not because the GAINS participants thought growth would stop, but because this allows analysts to check the simulation code behavior with no growth. For the heterogeneous base cases, the world electricity generation is initially divided in 2008 at a 50/50 split between NG1 and NG2, transitioning to a 40/40/20 split between NG1/NG2/NG3 by 2100.

To assist modelers, the framework includes tables providing the amount of generation for each year by reactor type. It also includes the generation levels to use from 1970 to 2008 to support initialization of models, including deployment of the existing reactors and the resulting used fuel inventories. These inventories are important for modeling of the fast reactor introductions later in most of the scenarios.

The combination of all of the above options results in the following list of the eight framework base cases:

- Homogeneous world
    - Business-as-usual (BAU) scenario
        - Moderate growth case
        - High growth case
    - BAU with fast reactor (BAU-FR) scenario
        - Moderate growth case
        - High growth case
- Heterogeneous world for BAU with fast reactor scenario
    - Non-synergistic
        - Moderate growth case
        - High growth case
    - Synergistic
        - Moderate growth case
        - High growth case

Reactor Types

The GAINS framework includes a reactor/fuel data template in Excel for modeling of different reactor types. The template provides a standard representation of reactor/fuel data for use by fuel cycle simulation codes. The template includes basic performance characteristics of the reactor, such as the thermal and net electric output, the average load factor, cycle length, and core inventory. It also includes more specific information for the power density, residence time, burnup, etc. of the core, axial blanket and radial blanket regions. The second sheet of the template provides a summary isotopic listing of the core composition for the initial loading, reloads, reload discharges and full core discharge at retirement. This listing includes 16 of the most important actinide isotopes along with the total fission products.

The framework database contains a number of populated templates for a range of thermal and fast reactors at different burnup levels. The fast reactors include burners, break-even converters and breeders. These cases are provided for users of the framework, and users can also provide their own reactor/fuel options.

For the framework base cases, only three of these reactor/fuel templates are used. These include an LWR (a pressurized water reactor using low enriched uranium oxide fuel with a burnup of 45000 MWd/t), an HWR (a CANDU-type reactor using natural uranium oxide fuel with a burnup of 7500 MWd/t), and a break even fast reactor (breeding ratio ~1.0) running on mixed U/Pu oxide fuel.

Other Simulation Parameters

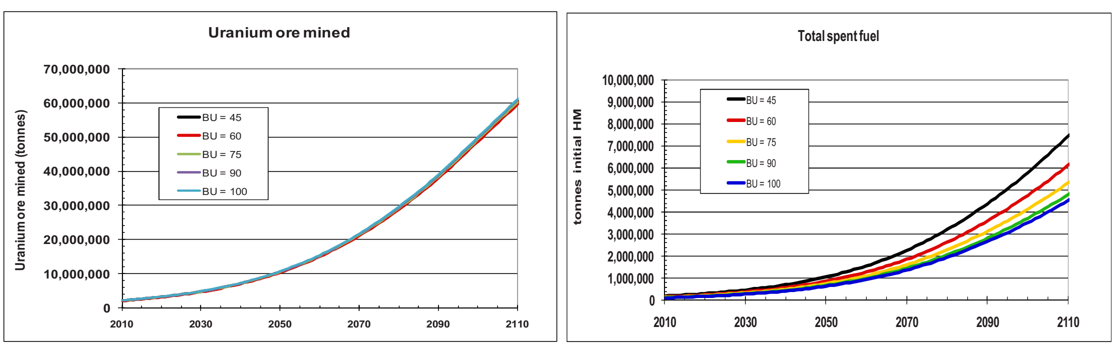
A number of additional parameters are necessary for simulating a nuclear energy system. These include everything from the U235 assay of the depleted uranium from enrichment to the minimum fuel cooling time after reactor discharge and before reprocessing or disposal. The framework base cases include numerous such parameters, generally taking a simple generic approach wherever possible rather than attempting to model the world exactly.

Since some fuel cycle simulation codes support dynamically varying some of these parameters while others do not, the approach taken in the base cases is to keep as many parameters constant as possible. For this reason, even though parameters such as average burnup or average load factors have changed considerably over the last few decades, these values are set as constants for the framework base cases. Users of the framework should note that if their code supports changes to these parameters during the course of a simulation, they can still vary these values in their own analyses.

For a similar reason, minimum times are used for periods such as the material transit time from mining to fuel insertion. Again, this is to support as many simulation codes as possible. Some codes require steps such as conversion, enrichment, and fabrication to be explicitly modeled with at least one time step at each stage.

A number of sensitivity studies were conducted as part of the GAINS effort to examine the impact of varying several of the simulation parameters. Figure 2 is an example, showing the impact of varying the burnup of the LWR fuel in the BAU scenario. While the total amount of used fuel generated is very sensitive to burnup, the amount of uranium required is not.

Figure 2 - Impact of varying LWR burnup on uranium usage and used fuel generation



The Output Template

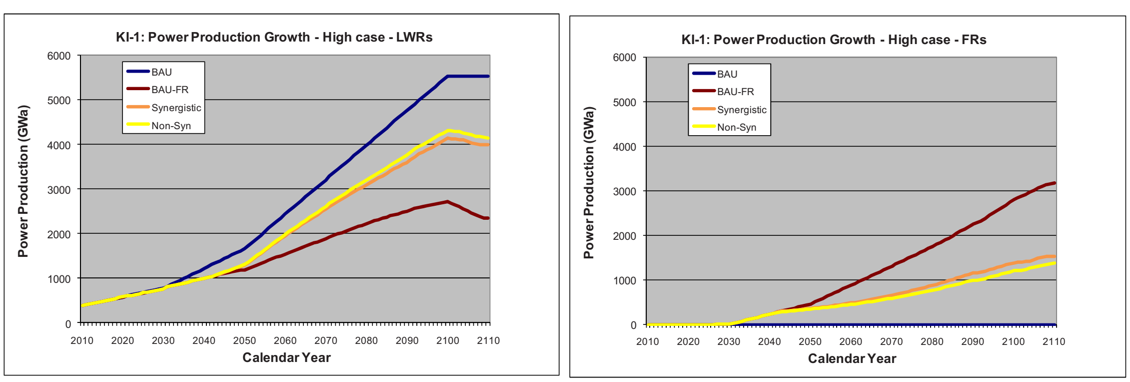
The GAINS framework also includes a set of two standard Excel output templates, one for the homogeneous world model and one for the heterogeneous world model. The heterogeneous template includes output sheets for each NG, along with a global summary sheet. Both templates include a number of columns for annual data generated by the simulation along with 36 built-in graphs for presenting the data. These standard graphs facilitate comparison of cases, as the data is always presented in the same manner each time. The template reports results for the 100 year period from 2010 to 2110. The heterogeneous template can also be used to compare up to three cases by using the three NG sheets instead for three separate runs, with the global summary sheet providing comparison graphs. This is useful for sensitivity studies and for comparison of base cases to alternate cases.

Excel was selected for the output template because a number of simulation codes already use Excel for their output. To use the output template, the analyst will likely want to build a translation table that takes output values provided by their simulation code and converts the values into the units used in the GAINS framework.

The standard output graphs include 20 key indicators and evaluation parameters identified by the GAINS participants to assess fuel cycle performance. These indicators were derived from a larger list of indicators developed in the INPRO Methodology (TECDOCs 1434 and 1575) for assessing the potential for an individual country to use a nuclear energy system. Since many of the indicators in the INPRO Methodology are for evaluation of the specific conditions of an individual country, some adaptation was necessary for use on a global scale. The indicators used in the output template cover the INPRO assessment areas of resource sustainability, waste management and environmental stressors, proliferation resistance and physical protection, and infrastructure. Safety and economics were also intended to be supported, but many of the current simulation codes do not provide capabilities in these areas.

Figure 3 shows a comparison of the power production from LWRs and FRs for the four main base case scenarios using the high growth rate. For the BAU case, there are no FRs and the left graph shows the LWRs growing until 2100, when the scenarios level out. The homogeneous world BAU-FR case has the most FRs because all of the world's LWR used fuel is being reprocessed to start up FRs. (Each FR needs Pu from the LWR used fuel for a start-up core and initial refueling. Since the base cases use break even FRs, once their own used fuel is available for reprocessing they require no additional material from the LWRs.) Note the decline in LWRs after 2100 for this case, as FRs replace LWRs. Up until 2100, there were not enough new FRs to meet the growth in demand, so new LWRs continued to be built. The heterogeneous world cases fall between the two homogeneous cases, because only a portion of the used LWR fuel is reprocessed; only the NG1 fuel in the non-synergistic case and the NG1 fuel plus half of the NG3 fuel in the synergistic case.

Figure 3 - Comparison of LWR and FR power production for the base case scenarios



Some of the key indicators and evaluation parameters are normalized per unit of energy produced. This was intended to neutralize the impact of growth on the indicators, since without normalization most of the graphs would show exponentially increasing values tracking with generation growth, masking other information in the output data.

Figure 4 shows one of the normalized key indicators, the energy production per tonne of natural uranium, for the homogeneous BAU-FR case. At the start of the simulation, the system average is dominated by the LWRs because only 6% of the system is HWRs. Note that once FRs are introduced the system annual average starts to increase because the FRs are breeding their own fissile material from the depleted uranium left over from enrichment for the LWR fuel. The cumulative average also increases, but more slowly. The annual average is not smooth because uranium is being mined several years before it produces electricity. After growth ends in 2100, the impact of new cores is reduced and there is a small step improvement in the uranium utilization by both the LWRs and HWRs, with the impact greater for the LWRs due to the effects of enrichment. The rate of improvement of the total system increases more rapidly after 2100 because LWRs are retiring and being replaced by FRs. This is an example of the type of behavior that would be masked if the key indicator was not normalized.

Figure 4 - Key indicator of uranium utilization for the BAU-FR scenario

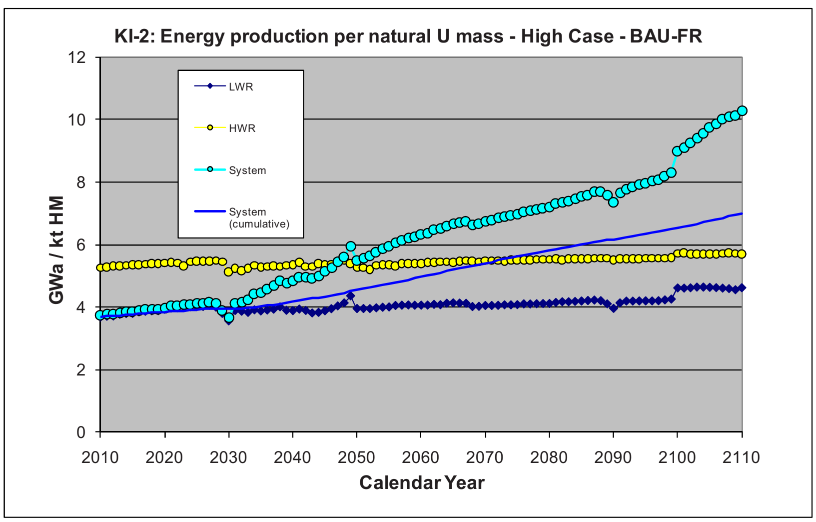
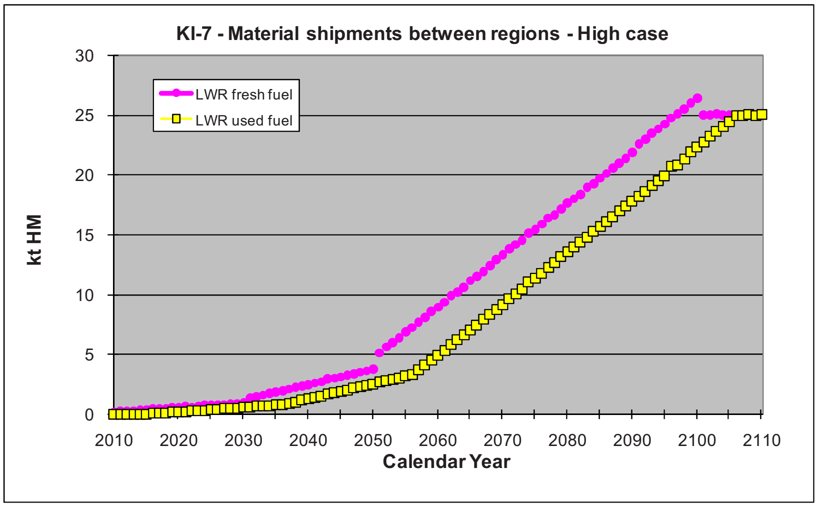


Figure 5 shows the key indicator of material moving in and out of NG3 in the base case heterogeneous synergistic scenario. This is an important indicator for the synergistic scenario, as cooperation in the use of fuel cycle facilities requires an increase in shipments. In the base case, all new fuel is imported and all used fuel exported, with no waste returned. Alternatives could be examined that move other materials. The delay between import and export is due to the time the fuel is in the reactor and in the used fuel pool cooling before it can be exported. Note the step increase in fresh fuel shipments when the growth rate increases around 2050 due to the additional fuel needed for start-up cores. Another smaller increase happens around 2030, again when the growth rate increases. The subsequent step decrease in 2100 is because growth stops and the only new cores needed are for replacing retiring reactors. The used fuel shows changes in slope corresponding to changes in the growth rate, but does not show these same step changes because the discharge rate is constant.

Along with the key indicator and evaluation parameter graphs, 16 additional graphs included in the output template display general mass flow and other data. These graphs are useful for confirming proper behavior of the simulation model and comparison to other studies that do not use the normalized GAINS parameters.

Figure 5 - Material imported / exported for NG3 - heterogeneous synergistic scenario



Using the Framework

Users of the GAINS framework should first familiarize themselves with the templates and other parameters included in the framework base cases to consider how to model these cases in their own simulation codes. The full GAINS report will include considerable information on how the framework is set up and why.

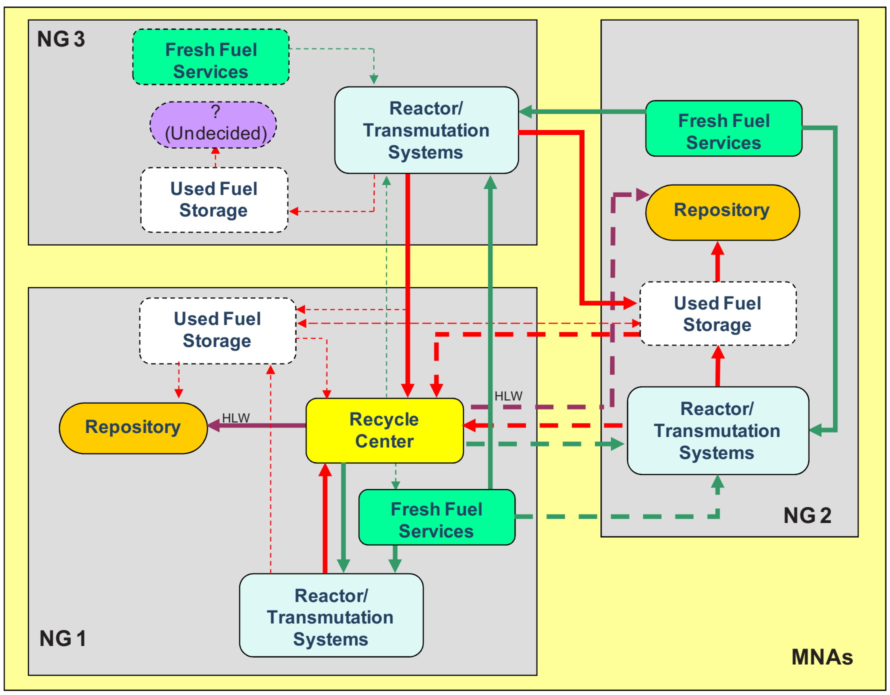
Next, the user should set up their code to run one or more of the base cases and compare the results. This is primarily to ensure they are interpreting the parameter values in the same way as the framework developers and to understand where the specific modeling method of their code may vary from that assumed in the framework base cases. Specific attention should be given to minimum delays, facility lifetimes, and reprocessing capacities in recycle cases.

The overall results should be similar to those reported for the base cases, though some variation is to be expected. Results will typically not match exactly for a number of reasons, including how each code models time, when during the year output is generated (year start or yearend), and what specific features are enabled in their code. If possible, some features should initially be turned off to better match the framework results, then reactivated. Codes handle a number of operations differently, such as isotopic decay during storage, and these differences can impact results. Key features to look for are if changes in slope of inventories occur within a year or two of the documented base case results and if the slopes are nearly equivalent.

Once the analyst is satisfied with their modeling of the framework base cases, they can develop their own scenarios that are variations from the base cases. It is recommended to only change a few parameters at a time to better understand why the results are changing as compared to the reference base case. For example, use the same growth curve and transition timing while introducing a different reactor type. Next, modify an additional parameter such as the timing for transitioning to the new reactor type. Note that with each change, other parameters such as reprocessing capacity may need to be modified to have a consistent simulation.

One particular area ripe for investigation of alternative strategies and scenarios is the heterogeneous synergistic world model. The framework base cases in this area only address one simple scenario where new nuclear energy system users obtain their fuel from others with established nuclear energy systems and return the used fuel. Figure 6 shows some of the different options for mass flows between NGs.

Figure 6 - GAINS heterogeneous world model showing alternate mass flow options



Additional options arise by varying the fraction of material flowing from NG1 or NG2, changing the timing of flows, and other considerations. These may include special strategies for minor actinide management, impacts of returning high level waste after reprocessing, focusing used fuel returns from NG3 to NG1 to more quickly build the NG1 fast reactor fleet, etc. The GAINS participants also anticipated modeling of multilateral nuclear approaches (MNAs), where countries collaborate on shared fuel cycle facilities.

A follow-on INPRO project is investigating many of these options. The "Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability" (SYNERGIES) project is using the GAINS framework as a starting point for identifying and evaluating mutually beneficial collaborative architectures that may help improve the sustainability of nuclear energy systems. Where GAINS deliberately modeled the nuclear groups as non-geographic groups of unnamed countries, SYNERGIES may look at specific regions and specific countries or other entities to assess drivers and impediments to achieving collaborative systems. SYNERGIES is also expanding on the sensitivity studies conducted in GAINS to better understand the behavior of both the homogeneous and heterogeneous world models as individual parameters are varied.

Additional NGs could also be considered. The GAINS effort limited the number of NGs due in part to limitations of simulation codes to model multiple interacting groups. At the start of GAINS, most simulation codes were only configured to model one group (e.g. a homogeneous world) and three groups were a practical limit. Now newer versions of some codes may be able to handle more simultaneous groups.

Conclusions

The INPRO collaborative project GAINS has established a framework for analyzing the dynamics of transitioning from the current thermal reactor based fuel cycle to a more sustainable closed fuel cycle using fast reactors. The framework can be used to analyze a range of reactor types and different scenarios. The framework supports both the standard homogeneous world model and a heterogeneous model where multiple simultaneous fuel cycle strategies are employed by different groups, with or without cooperation between groups. The framework includes data for numerous reactors and fuels and has a template for adding additional reactors/fuels. Another template standardizes the output produced by analyses, such that analysts using different fuel cycle codes can easily share and compare results. A follow-on INPRO project, SYNERGIES, is using the GAINS framework to examine how different groups following different fuel cycle strategies can work together to mutual benefit. Others should also find the GAINS framework useful for their own fuel cycle studies.